Real-Time Systems

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Time and Order
(following Tanenbaum for Logical and Kopetz for Physical Time)

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Overview

- Events, computer generated and environmental
- (Real) Time
- The order of events, temporal and causal
- Logical Clocks, 2 versions
- Physical Clocks and their properties
- Global (real) time in distributed systems

Topics

- 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 have clocks to be synchronized?

Time in Distributed (Real-Time) Systems

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

Events 1

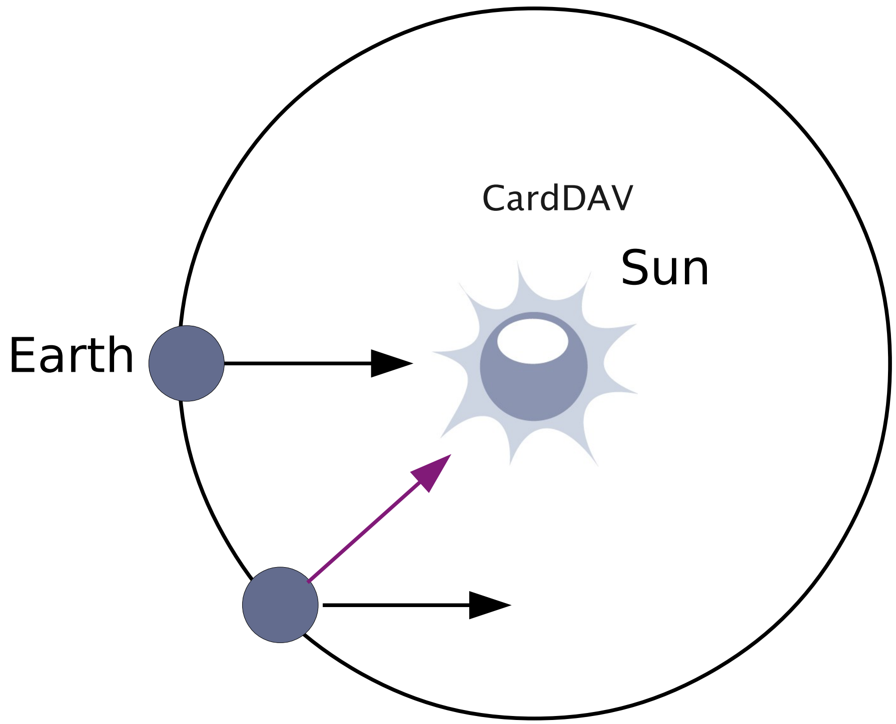
- Computer Generated Events:
  - execution of statement
  - sending/receiving a message
  - start and end of a compilation
  - creation/modification of a file
  - ...
- Sequence of states is determined by
  - instructions, disk accesses, …
  - discrete steps

Events 2

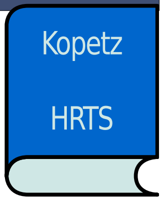
- Environmental Events:
  - newton mechanics
  - pipe rupture
  - human interaction
  - ...
- Sequence of states is determined by
  - laws of physics
  - physical (or real) time: „second“
  - continuous

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 of the radiation of a specified transition of the caesium atom 133“ (Kopetz)

Time Standard(s)

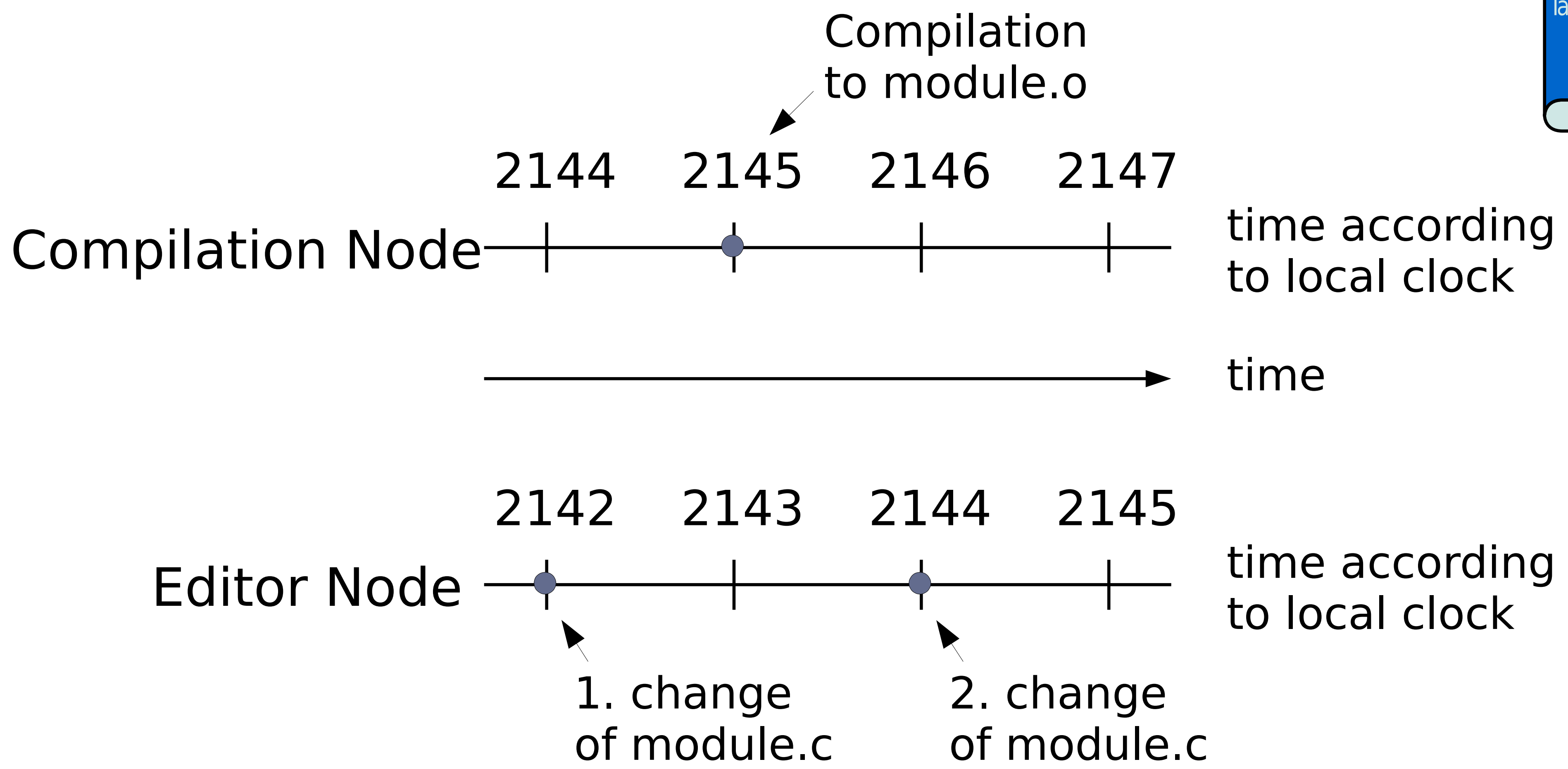
- **UTC** ... Coordinated Universal Time
  - TAI adjusted to Astronomical time

- Sources:
  - earth-bound radio
  - Geos satellites
  - GPS

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.

Another Example



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

Causal Order (for Computer Generated Events)

Tanenbaum MOS

Partial Order for Computer Generated Events

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

1) If a, b events within a sequential process then a → b, if a is executed before b.
2) If a is „sending of a message“ by a process and b the „reception of that message“ by another process, then a → b.
3) → is transitive.

Temporal Order

Kopetz HRTS

- 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 ...

Temporal Order, Timestamps, Duration, Clocks

- ... Instants are totally ordered
- **Events** occur at an instant of the timeline
  => **Timestamp**.

- Events in a distributed system are partially ordered.
- Total order can be achieved by addition of process id.

- **Duration** is a section of the timeline.
- **Clocks** measure time imperfectly, create imperfect Timestamps.

Clocks: Physical and Logical

Physical Clocks

- devices to measure time
- necessarily imperfect (more later)

Problems:

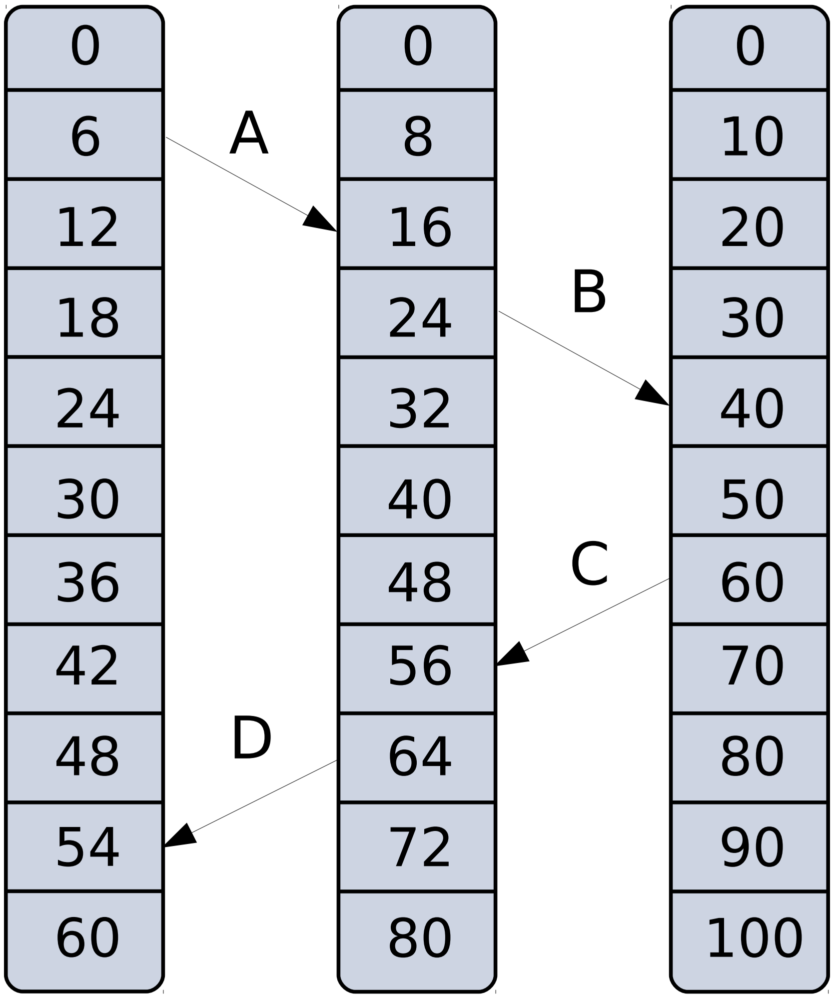
- how to create knowledge about causal dependency of computer events without relying on physical clocks? => **Logical Clocks**
- how to establish a x certainly occurred after y relation (temporal order) for environmental events? => **Global Time**

Logical Clocks

Tanenbaum MOS

- **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:
  - $a \rightarrow b \quad \Rightarrow \quad C(a) < C(b)$
  - $a \rightarrow b \quad \Leftrightarrow \quad C(a) < C(b)$


Tanenbaum
MOS


0
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32
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56
64
72
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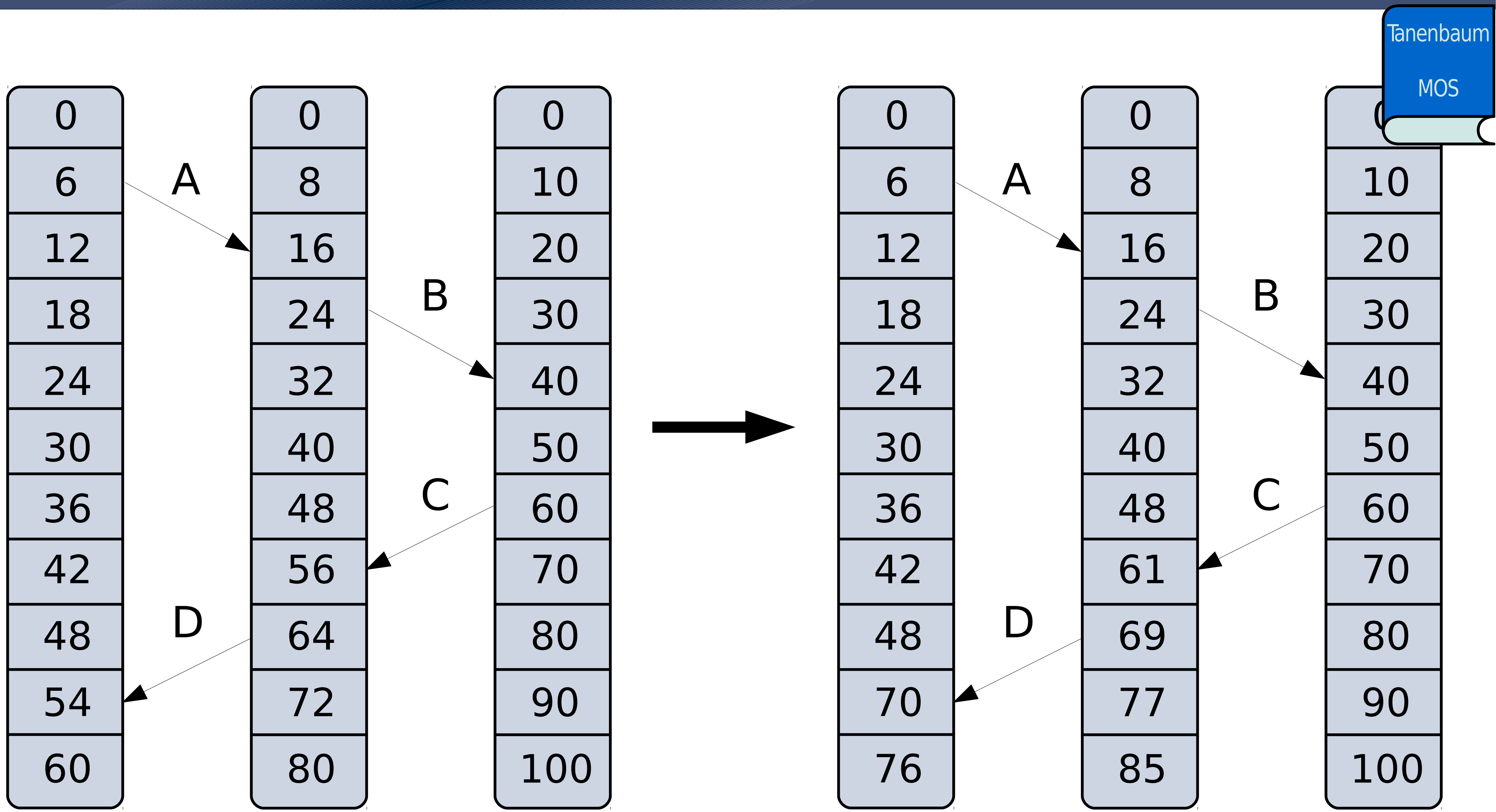
10
20
30
40
50
60
70
80
90
100
A
B
C
D

Lamport's Logical Clocks

Tanenbaum MOS

- 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 (LC_i,m)
  - with each reception of a message „(M,LC_m)" by P_j:
    $LC_j := MAX(LC_m, LC_j)$; $LC_j := LC_j + 1$


Tanenbaum
MOS
0 6 12 18 24 30 36 42 48 54 60
0 8 16 24 32 40 48 56 64 72 80
0 10 20 30 40 50 60 70 80 90 100
A
B
C
D
0 6 12 18 24 30 36 42 48 70 76
0 8 16 24 32 40 48 61 69 77 85
0 10 20 30 40 50 60 70 80 90 100
A
B
C
D

Lamport Clocks

Properties:

- $a \rightarrow b \Rightarrow C(a) < C(b)$,

  but not:

  $C(a) < C(b) \Rightarrow a \rightarrow b$
- partial order
- sometimes total order convenient:

  extend it: e.g. by LC.Process_number

Vectortime (Mattern 1989)

Tanenbaum MOS

- Each process Pi has its own vector clock C_i.
- C_i: n-dimensional vector (n: number of processes).

Intuition

- $C_i[j]$: the timestamp of the last event in P_j

  by which P_i has potentially been effected

Vectortime Ticks

Tanenbaum MOS

- Initial:

  $C_i := (0, \ldots, 0)$ for all i

- Local event in P_i:

  $C_i[i] := C_i[i] + 1;$

- Sending message m in P_i:

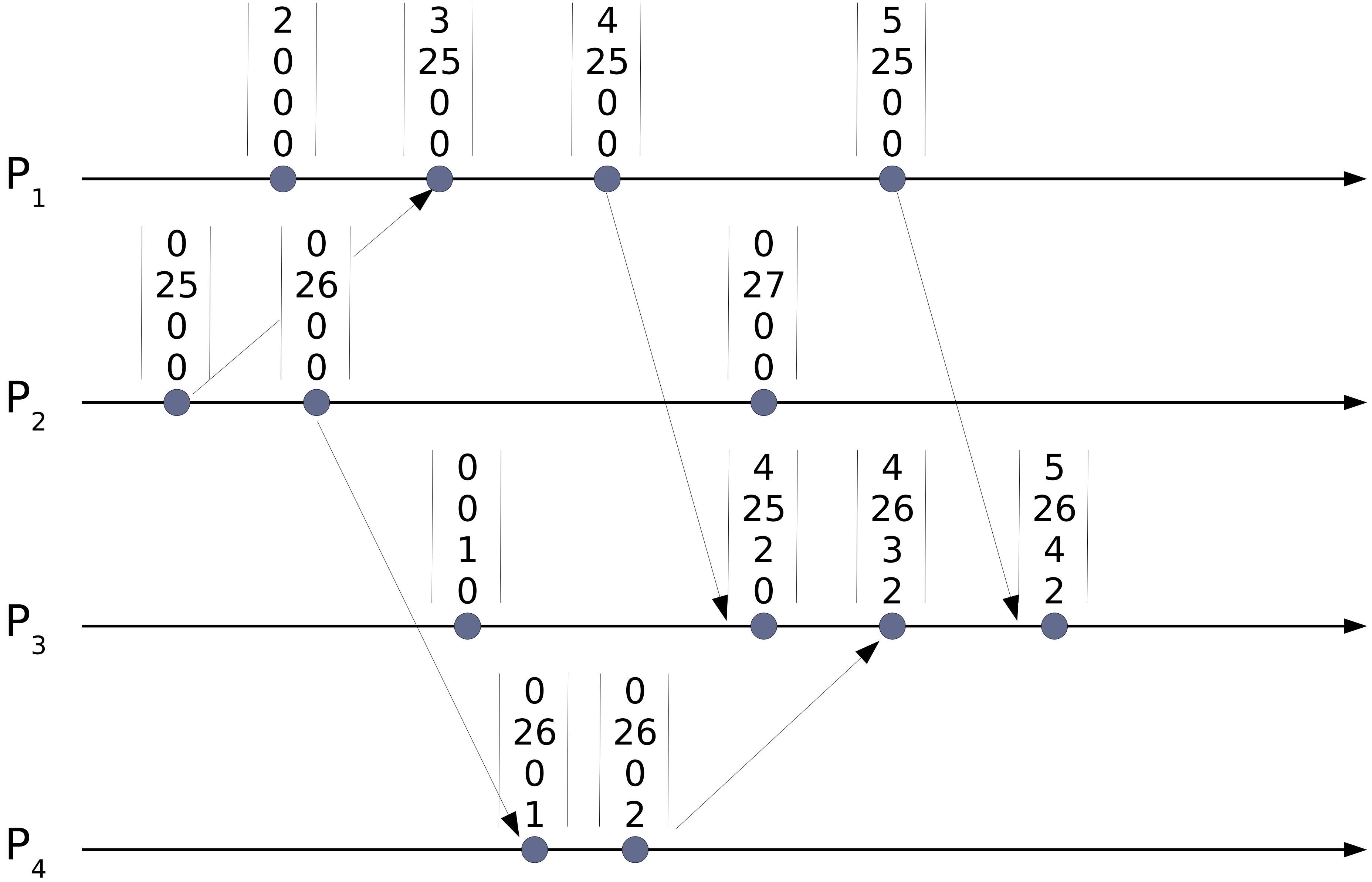
  $C_i[i] := C_i[i] + 1;$ send (m, C_i)

- 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



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P3
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26
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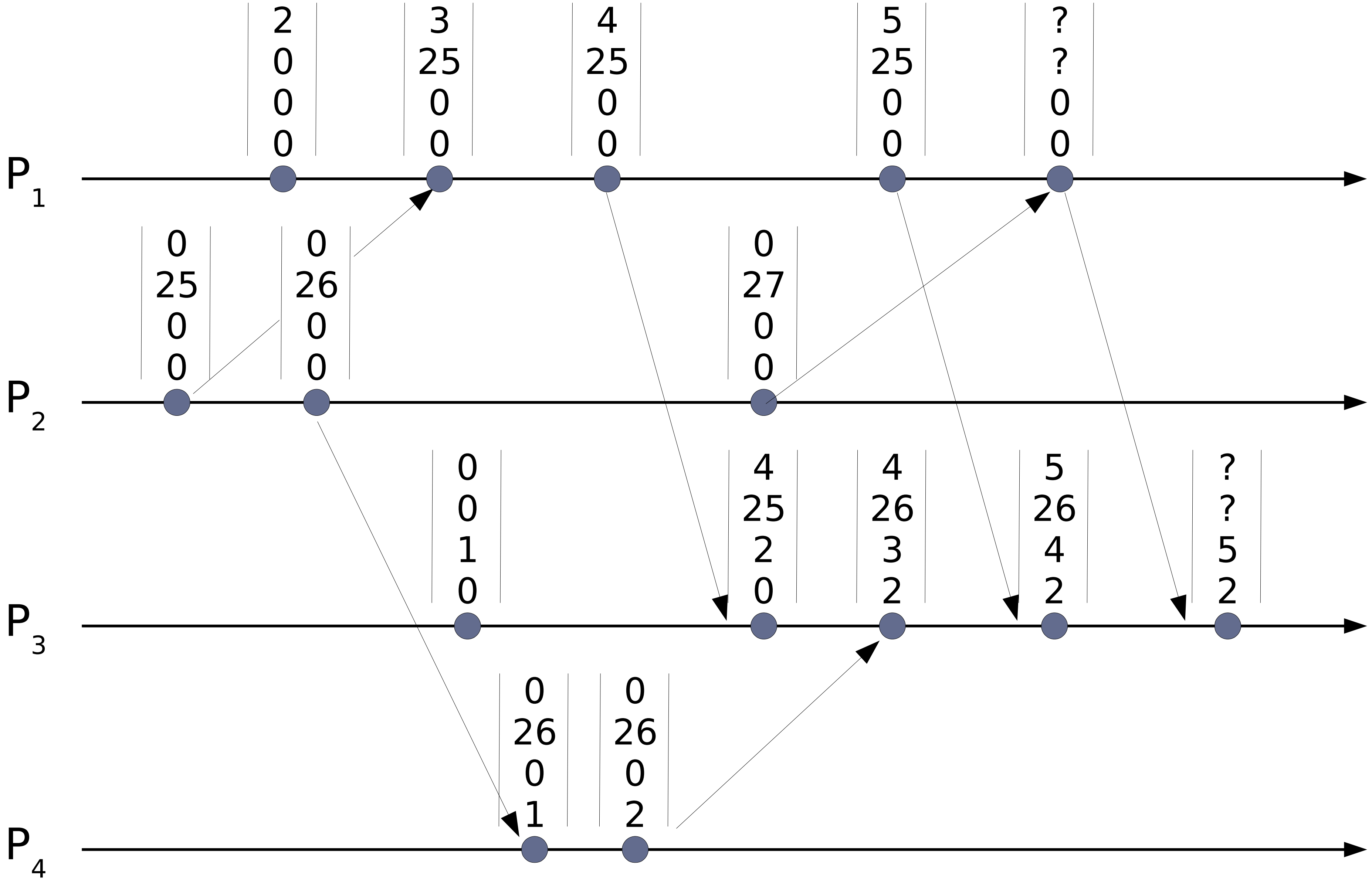
P4

Example



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

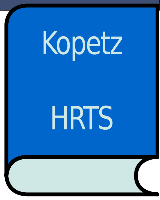
Properties of Vector Time

Tanenbaum MOS

- Definition
  - $C_a \leqslant C_b :\Leftrightarrow \forall k : C_a[k] \leqslant C_b[k]$
  - $C_a < C_b :\Leftrightarrow C_a \leqslant C_b \wedge C_a \neq C_b$

    $C_a \| C_b :\Leftrightarrow not(a < b) \wedge not(b < a)$
- 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}, $microtick^{clock}_{\text{number of tick}}$
- To discuss properties of physical clocks, we invent the perfect *reference* clock as purely theoretical construct

Reference Clock, Notations (Kopetz)

Kopetz

HRTS

- Reference Clock z
  - perfect with regard to UTC
  - very small granularity
    (to disregard digitalisation 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)

Kopetz HRTS

- Reference Clock z
  - perfect with regard to UTC
  - dense (no ticks, to avoid digitalisation error)

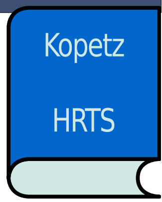
- z(event): (Absolute) Timestamp from reference clock establishes temporal order
- g^k granularity of clock k in terms of z-durations as specified (vs. real behavior)

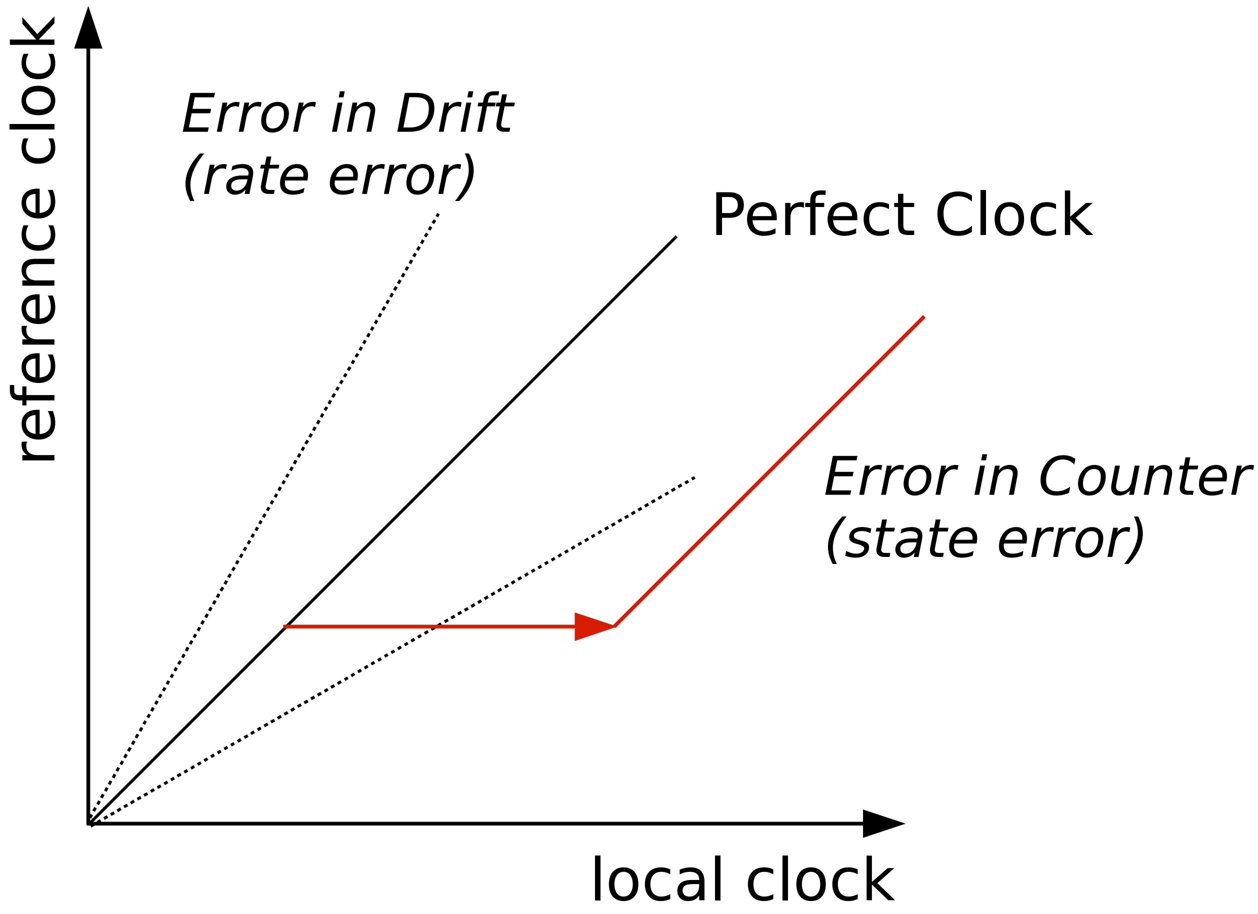
Tick Tack Terms

Kopetz HRTS

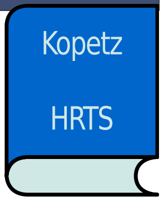
• Micro Ticks	Ticks generated by the physical oscillator of a clock
• Macro Ticks	Multiple of Micro Ticks chosen by designer of clock
• t^k(event)	Timestamp in number of micro ticks of clock k
• Granularity	Unit of a clock Value exposed by a clock micro or macro (dep on context)

Failure Modes of Clocks: Drift and Counter Errors





Maximum Drift Rate



- Drift-Rate:
  - Varying
  - Influenced by environmental conditions (temperature,...)
  - clocks specify maximum drift rate (10-2 ... 10-7)

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

Precision of an Ensemble of Clocks

Kopetz HRTS

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

Kopetz HRTS

Accuracy

- of a given clock in the period of interest:

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

- If all clocks of an ensemble have accuracy A, the precision of the ensemble is ??

Resynchronisation

Kopetz HRTS

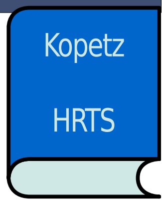
External Resynchronization

- resynchronization with reference clock

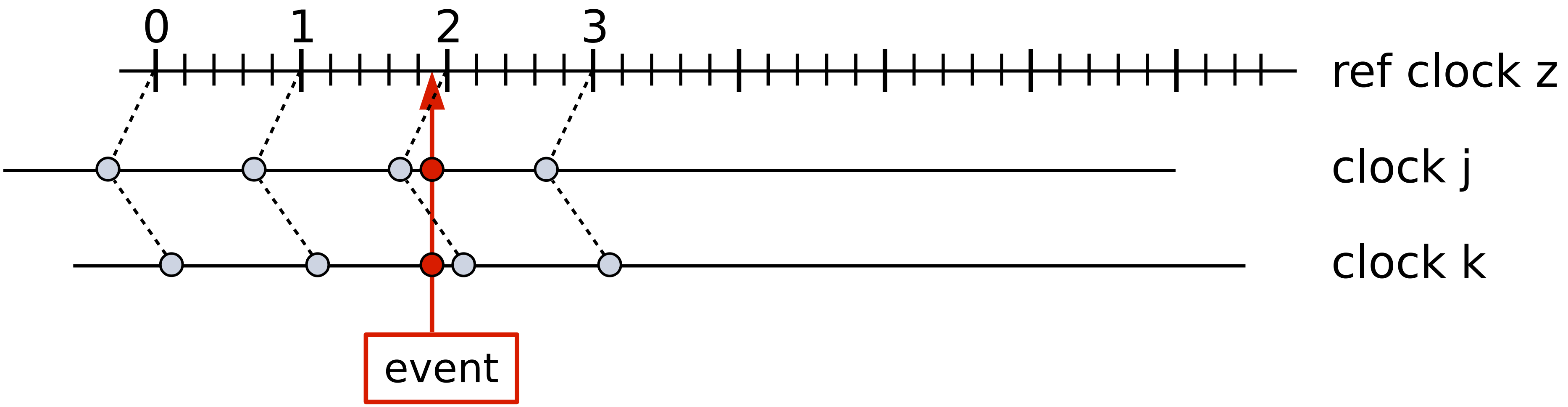
Internal Resynchronization

- mutual resynchronization of an ensemble to maintain a bounded precision

Global Time

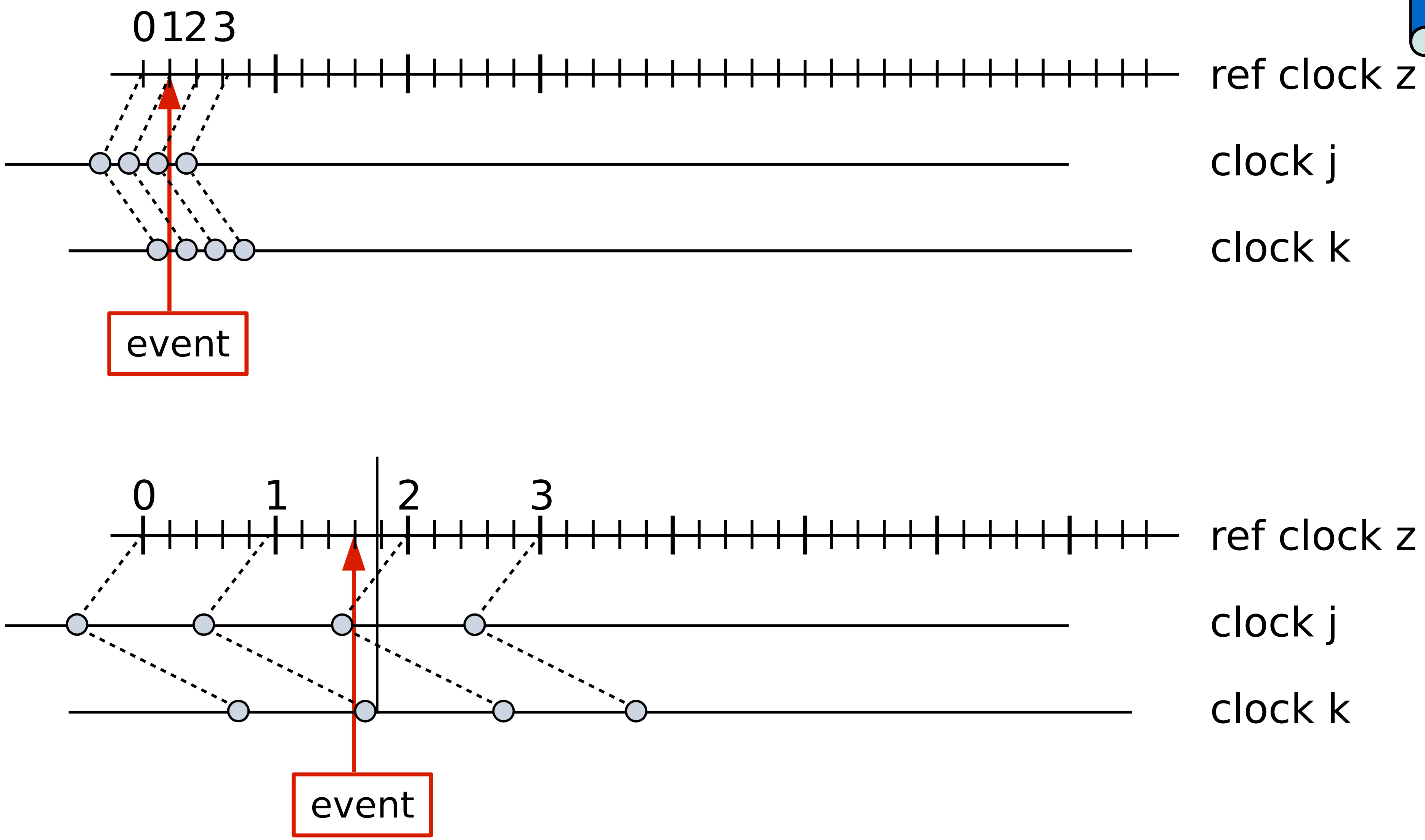


- Given an ensemble of clocks (internally) synchronized with precision π...
- For each clock select *macrotick* as local implementation of a global notion of time with granularity g^{global}
- We note ref clock time (real-time, UTC) in units of g^{global}



Examples for Bad Choice for Global Time

Kopetz HRTS

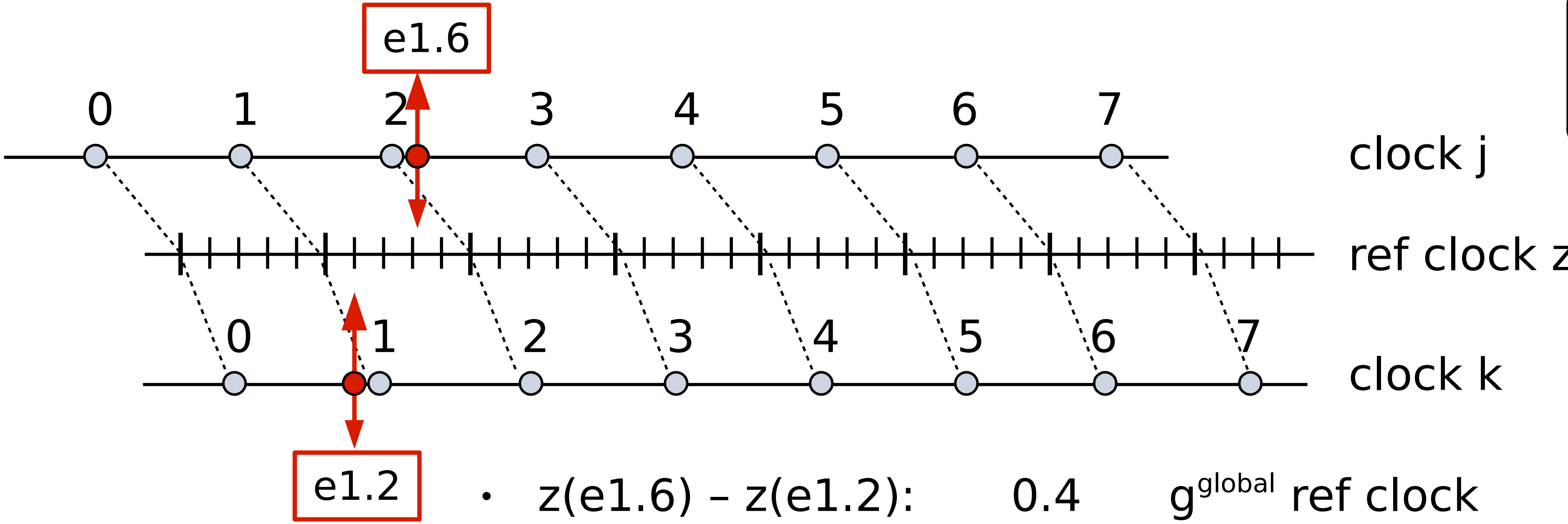


Reasonable => One Tick Difference

- Reasonableness Condition:
  - global time t is reasonable if $g^{global} > \pi$ holds for all local implementations
- t^j(event):
  - Denotes global time for the implementation at clock j
- Then: For any single event e, holds $|t^j(e) - t^k(e)| \leq 1$
- Global timestamps differ at most by one (macro-)tick.

  Best one can achieve!

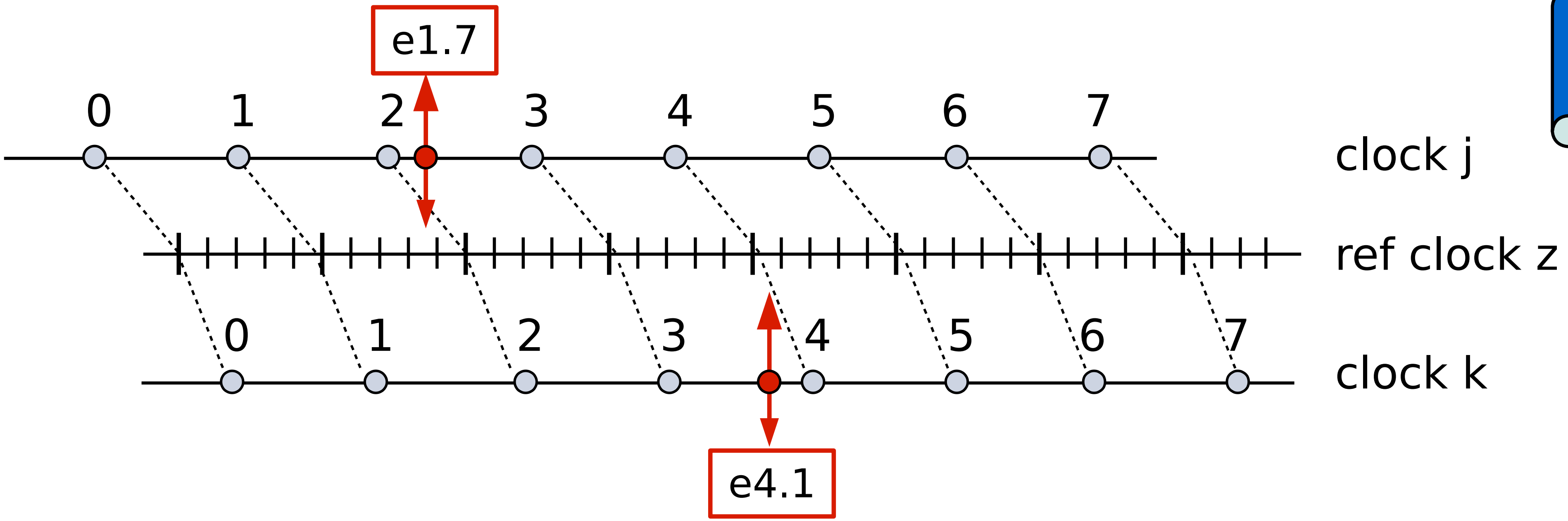
Interpretation for Temporal Order

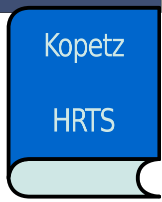


Kopetz HRTS

- z(e1.6) – z(e1.2): 0.4 g^{global} ref 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)
- Hence: If the (global) timestamps differ by two ticks, the temporal order can be established.

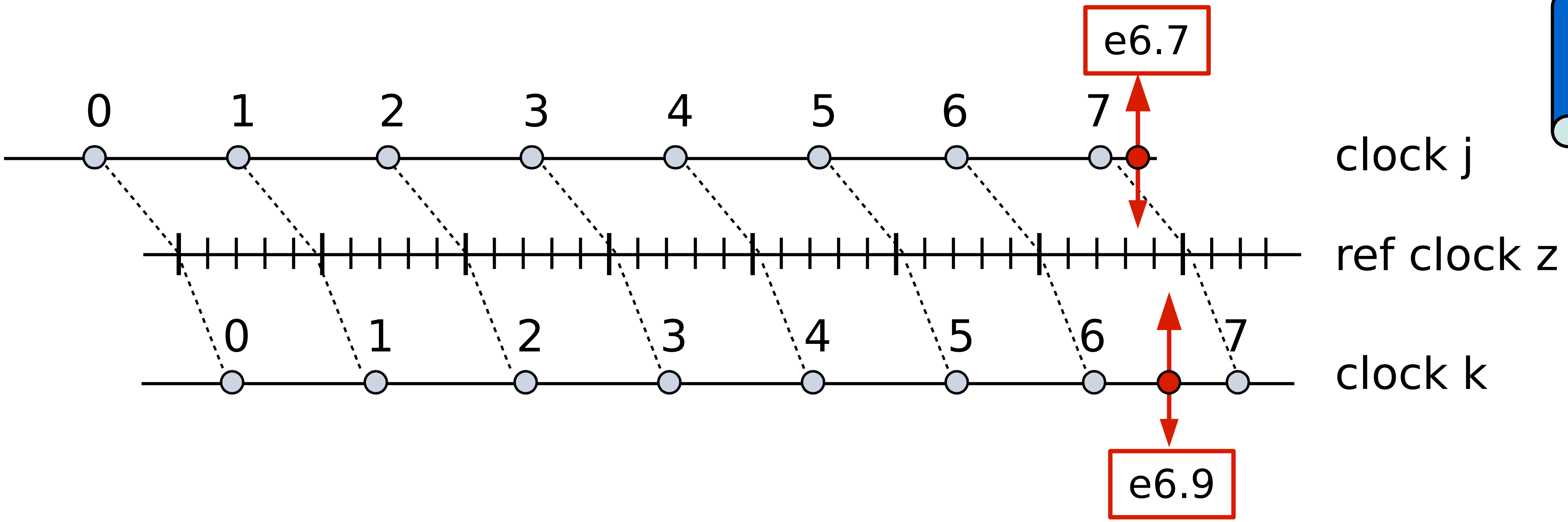
Caution: Example





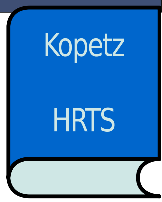
- z(e4.1) – z(e1.7): 2.4 g^{global} ref clock
- t^k(e4.1) - t^j(e1.7): 1 global tick
- A distance of 2*g^{global} between two events does not suffice to determine temporal order.

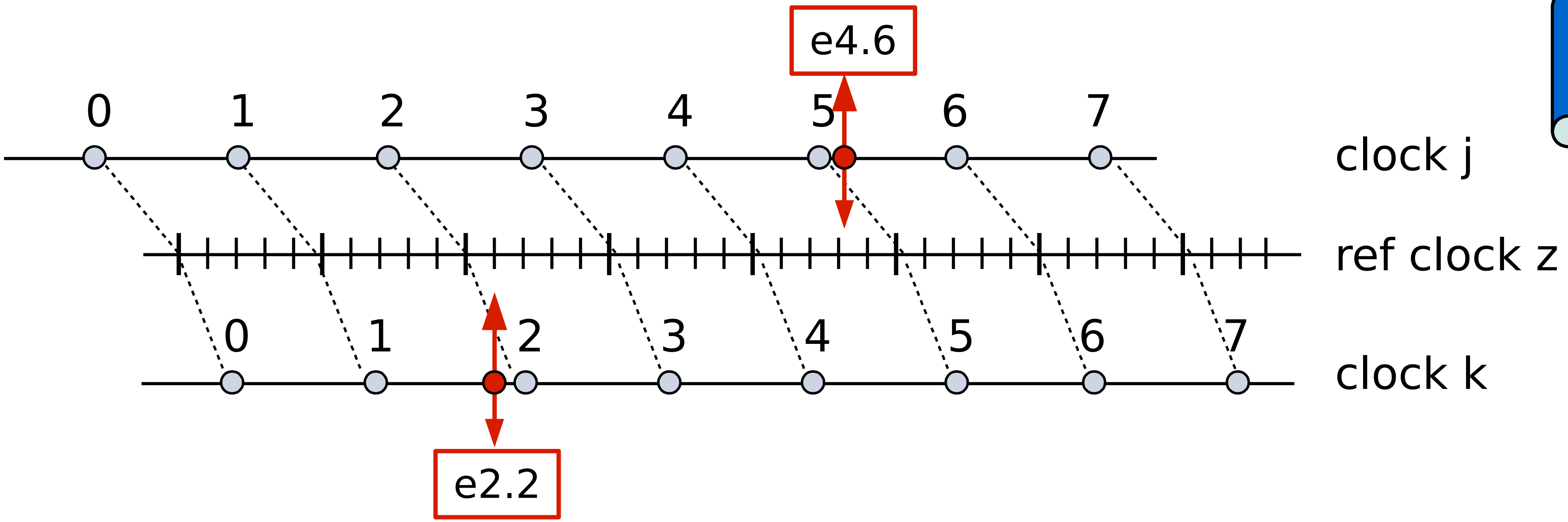
Another Example



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

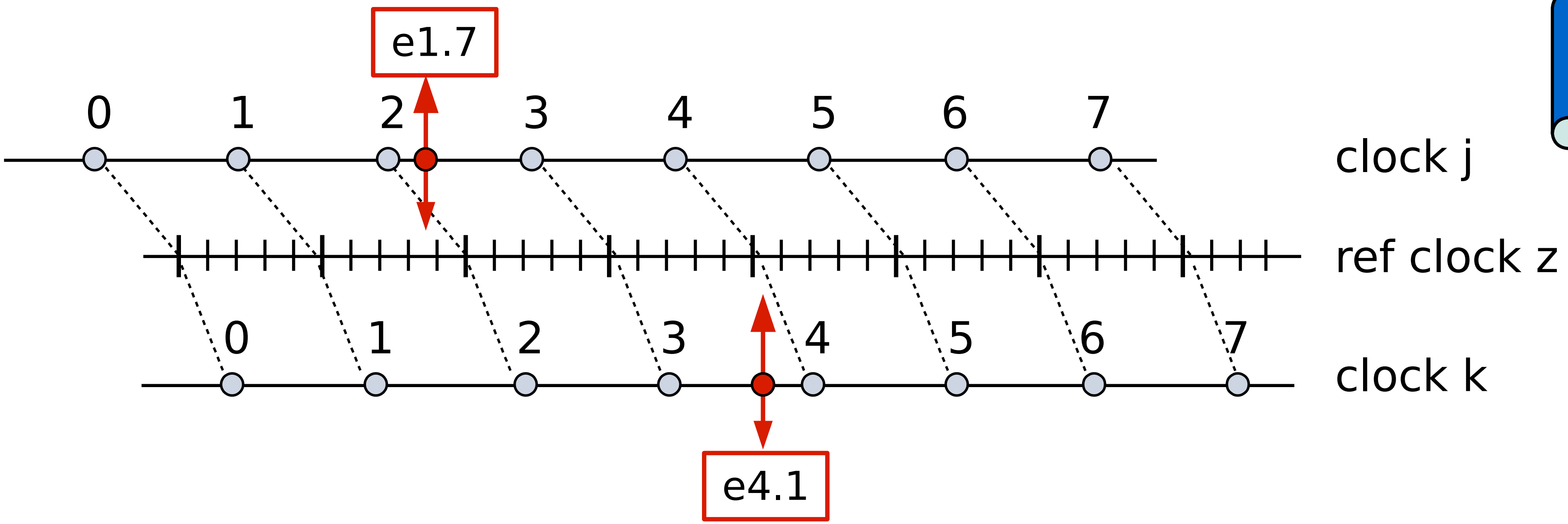
Interpretation for Durations





- True duration: 2.4
- Observed duration d: 5-1=4 ($t^j(e4.6) - t^k(e2.2)$)
- Can be driven to true duration: 2+ε for small ε
- $d^{obs} - 2*g^{global} \leq d^z$

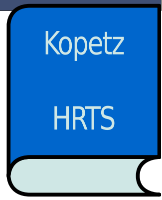
Interpretation for Durations

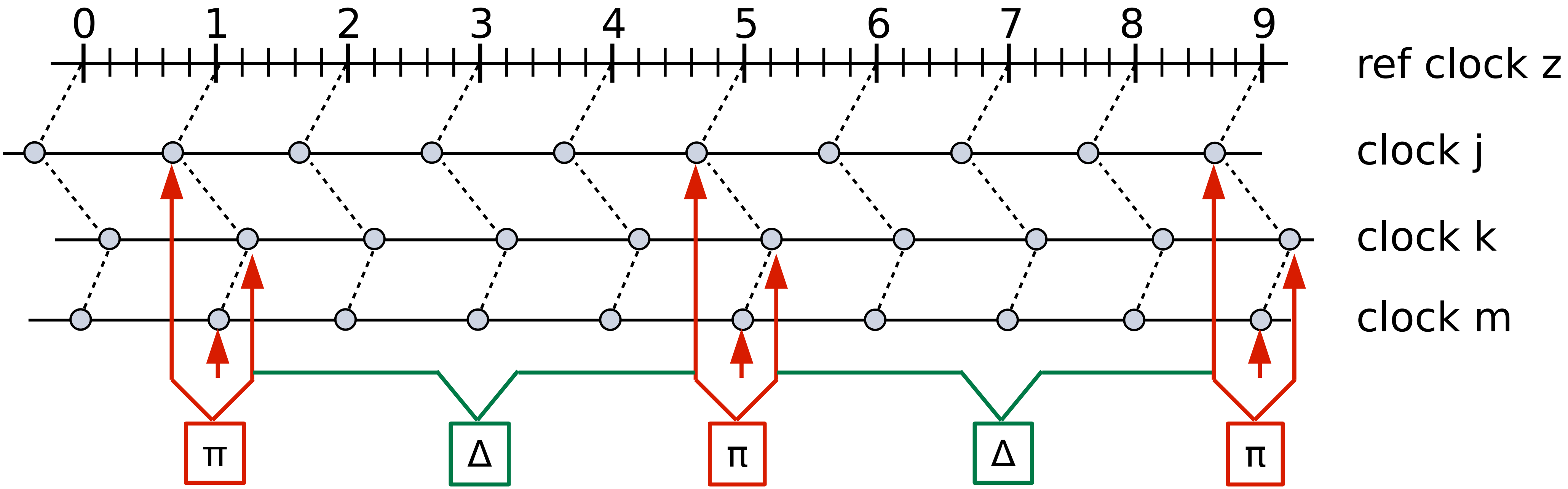


- True duration: 2.4
- Observed duration d: 3-2=1 ($t^k(e4.1) - t^j(e1.7)$)
- Can be driven to true duration: 3 - ε for small ε
- $D^{obs} - 2*g^{global} < d^z < d^{obs} + 2*g^{global}$

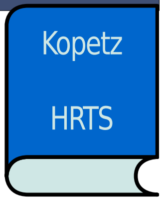
Generated Events

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





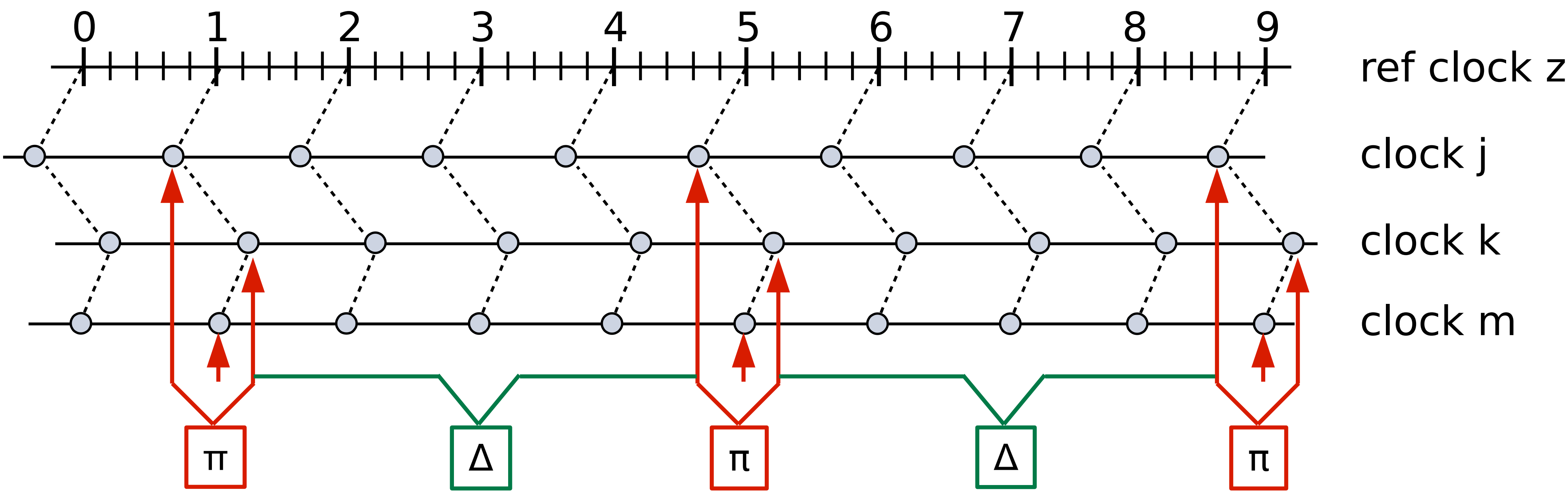
π/Δ-Precedence of Sets of Events



- Properties of sets of events:
  - How far apart (number of granules) must events be to enable reconstruction of order ....

- A set of events is called π/Δ-precedent, if:

$$[|z(e_i)-z(e_j)| \leqslant \pi] \vee [|z(e_i)-z(e_j)| > \Delta]$$



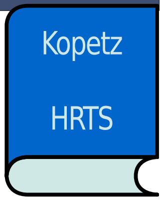
Temporal Order

Kopetz

HRTS

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	$\lvert t^j(e_1)-t^k(e_2)\rvert \geqslant 0$	no
0/2g precendent	$\lvert t^j(e_1)-t^k(e_2)\rvert \geqslant 1$	no
0/3g precendent	$\lvert t^j(e_1)-t^k(e_2)\rvert \geqslant 2$	yes
0/4g precendent	$\lvert t^j(e_1)-t^k(e_2)\rvert \geqslant 3$	yes

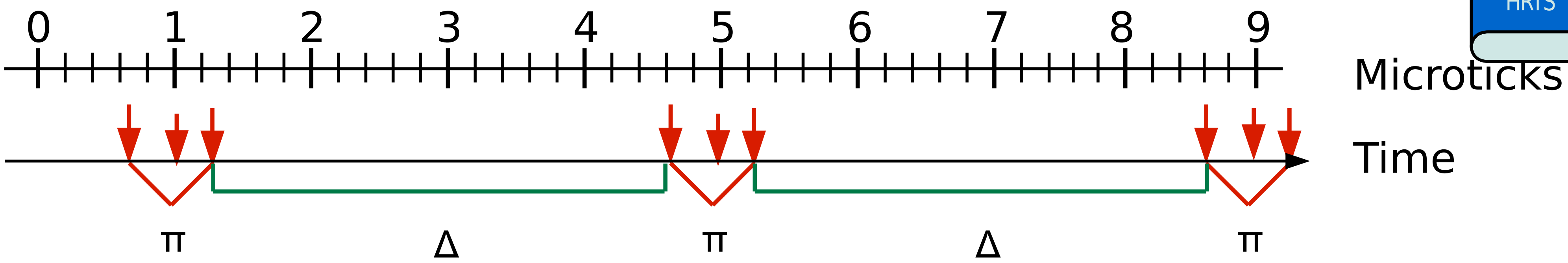
Fundamental Results in Time Measurement



- A single event observed at different nodes may have timestamps differing by one; not sufficient to establish temporal order
- Duration: $d^{obs} - 2*g^{global} < d_z < d_{obs} + 2*g^{global}$
- 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

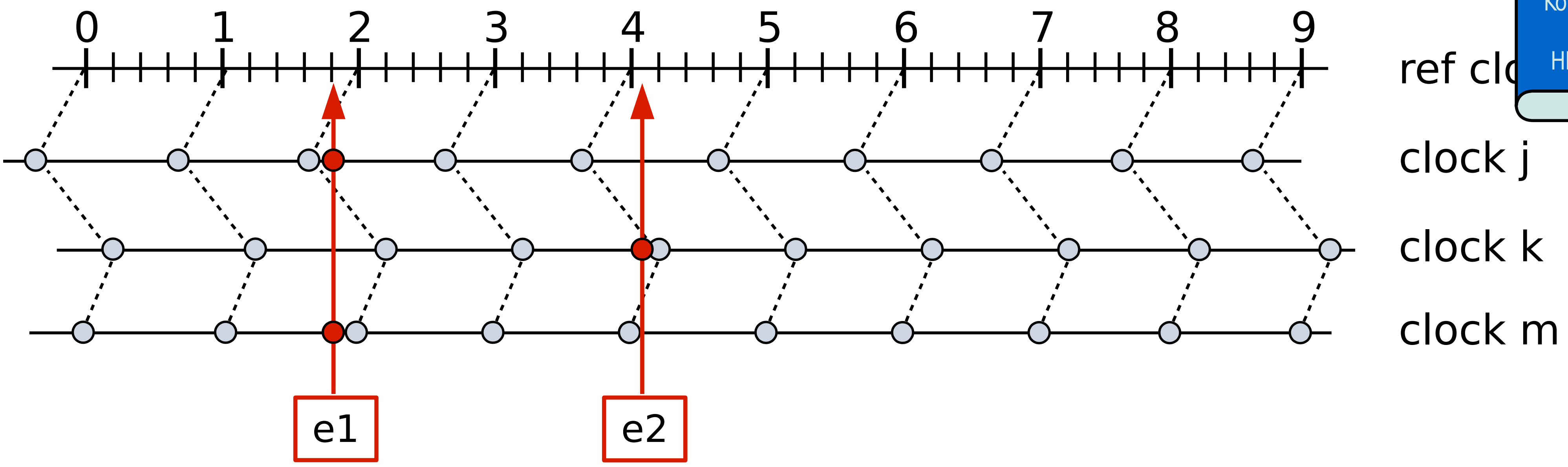
Dense Time vs. Sparse Time

Kopetz HRTS



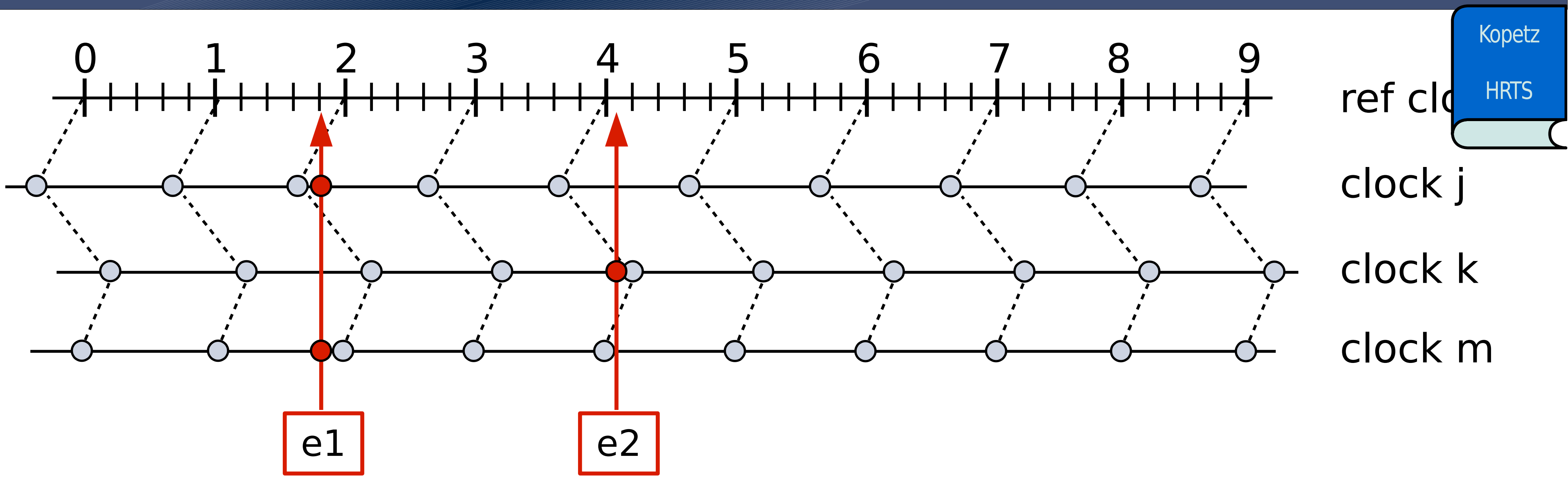
- **dense time**: events are allowed at any time
- **sparse time**: events are only allowed within *active* time intervals π
- sparse time only possible for computer controlled events

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

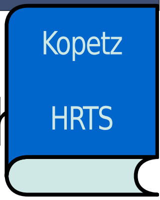
- information interchange:

  each node acquires local views from all other nodes

- deterministic algorithm that lead to same result on all nodes

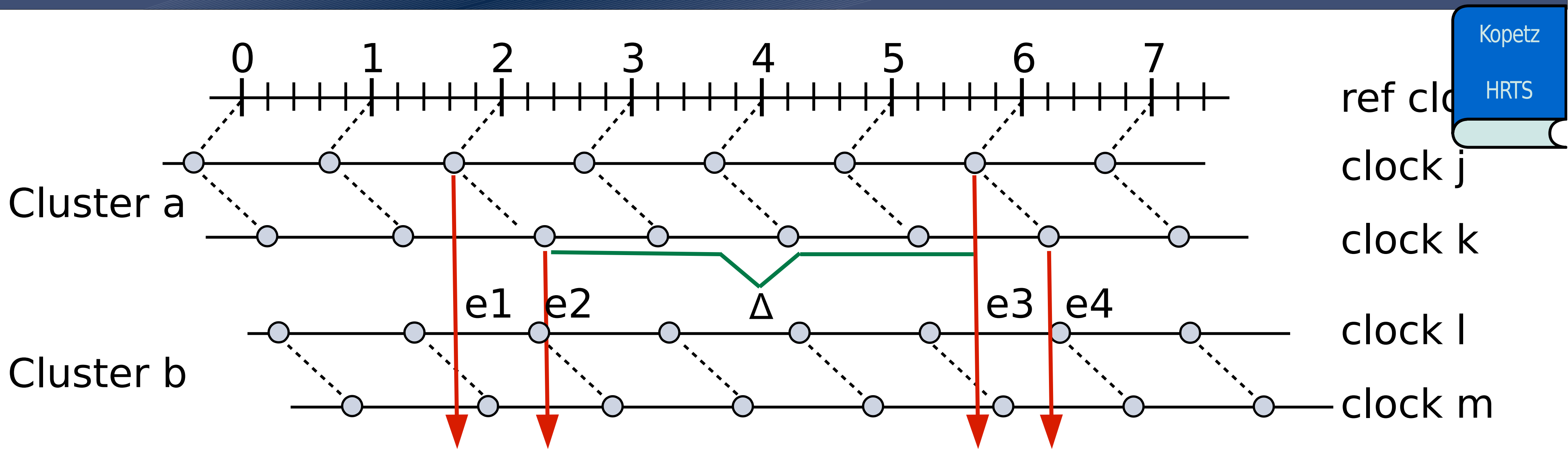
- expansive !!

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
- Goal:
  - if at cluster A events are generated at same cluster wide tick never should temporal order be concluded
  - always establish temporal order otherwise
- sufficient for A to generate 1g/3g precedent event
  set ??

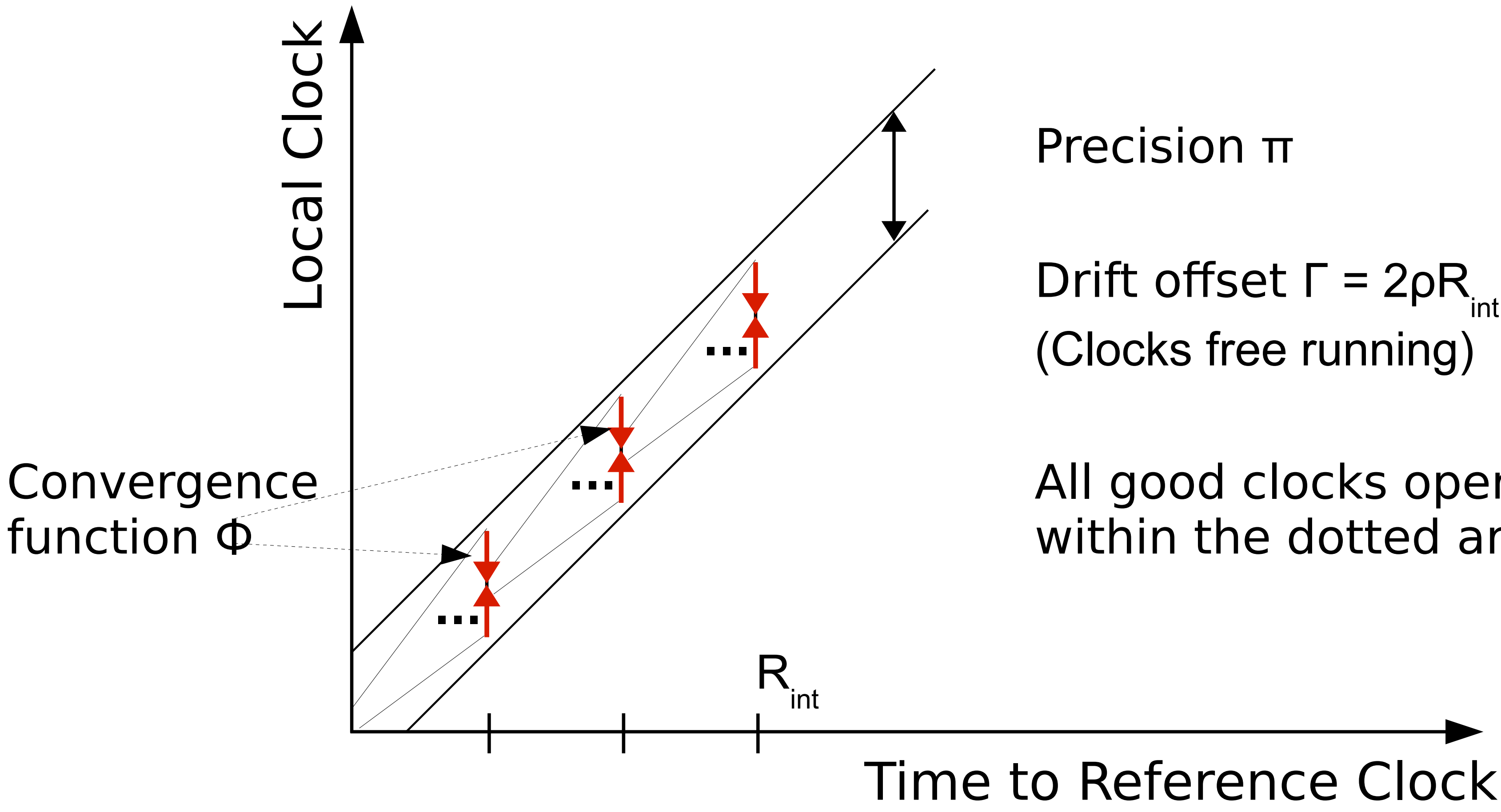
Example for 1g/3g



- $t^l(e2) - t^m(e1) = 2$:
  - BUT: should not derive order because events were intended by cluster A for the same time
- $t^m(e4) - t^l(e2) > 2$ BUT: $t^m(e3) - t^l(e2) = 2$:
  - BUT: temporal order is intended (Δ = 3g)

=> 1g/3g precedence not sufficient => 1g/4g

Internal Clock Synchronisation



Precision π

Drift offset $\Gamma = 2\rho R_{int}$
(Clocks free running)

All good clocks operate within the dotted area

$$\Phi + \Gamma \leq \Pi$$

Synchronisation Condition

Kopetz HRTS

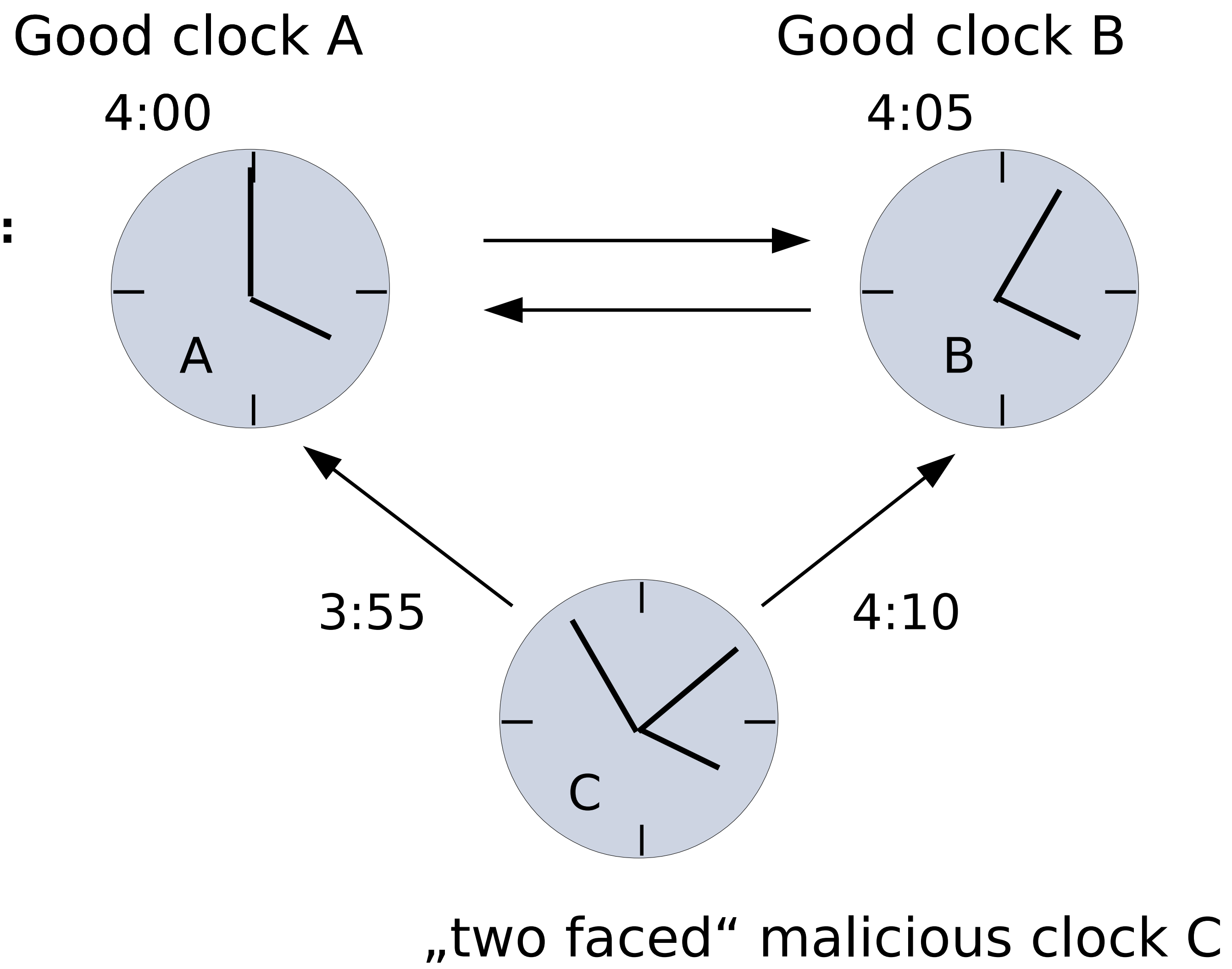
- resynchronization interval: R_{int}
- convergence function : Φ offset after resynch.
- drift offset: Γ

$$\Gamma = 2\,\rho\,R_{int}$$

- Required: $\Gamma + \Phi \leq \Pi$

Byzantine Error

View at A:
B: 4:05
A: 4:00
C: 3:55



View at B:
A: 4:00
B: 4:05
C: 4:10

Central (Master) Synchronisation

- master sends time, slaves correct
- message latency jitter
  - ε, difference between fastest and slowest message
- $\pi_{central} = \varepsilon + \Gamma$

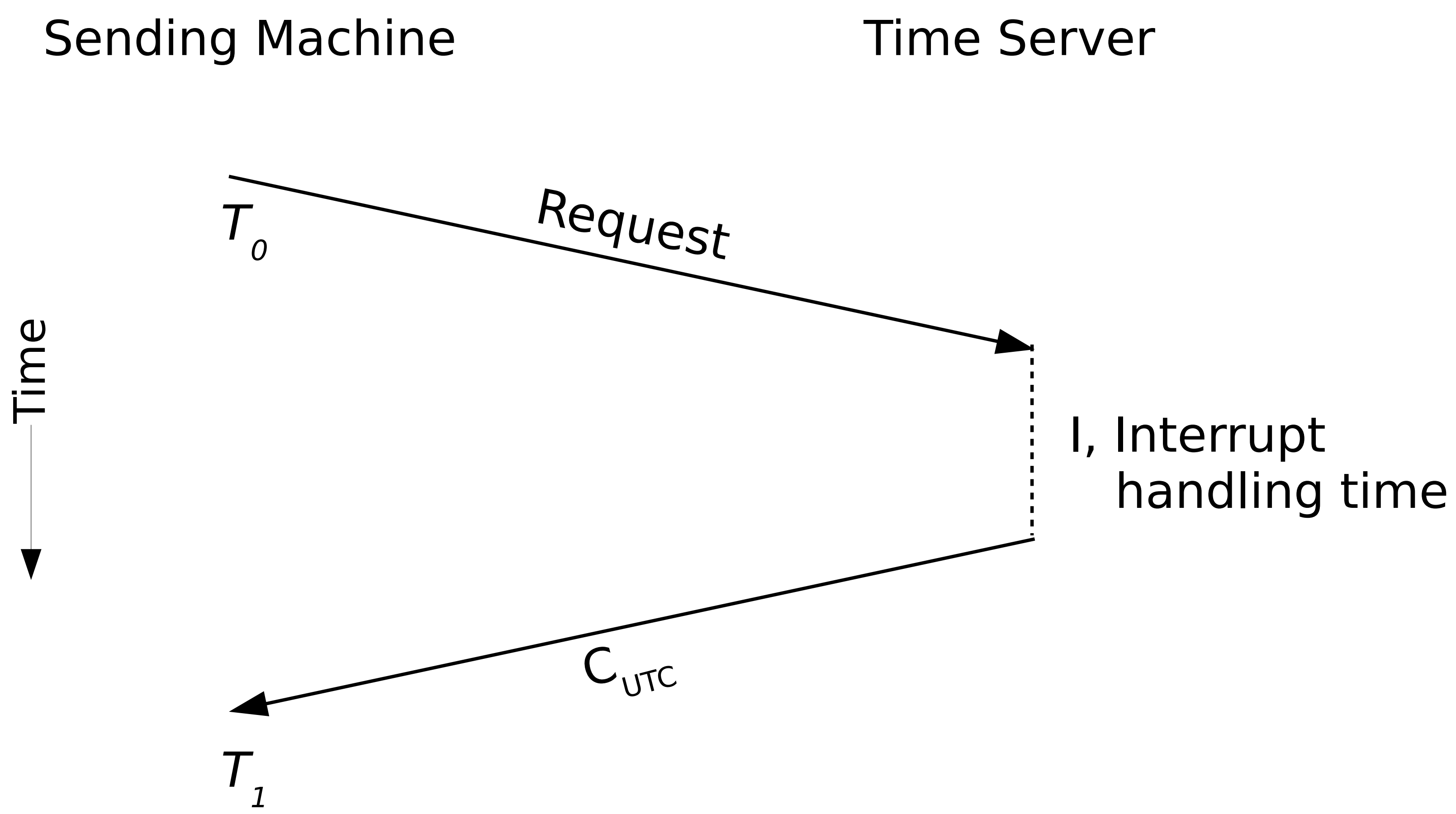
Impossibility Result

Kopetz HRTS

$$\pi = \varepsilon \left(1 - \frac{1}{N} \right)$$

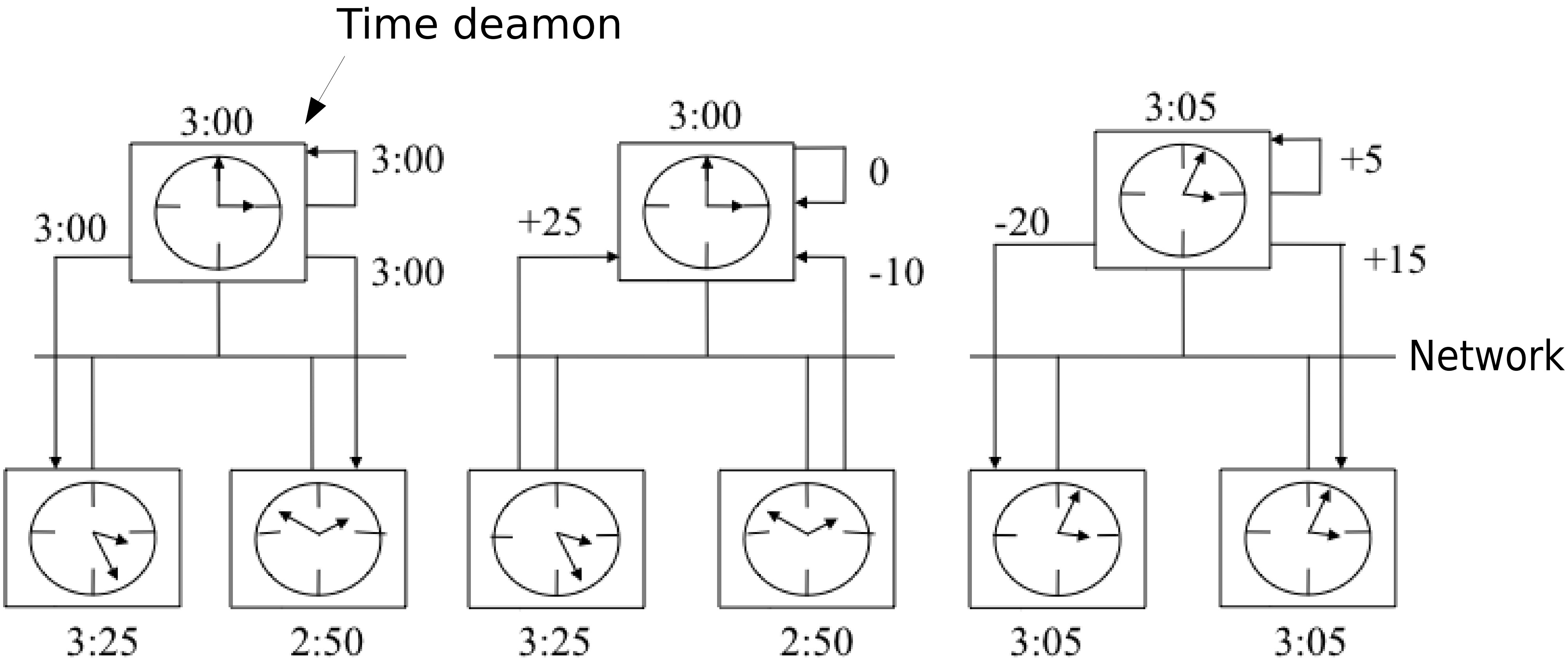
- No better precision can be achieved even with perfect clocks in all nodes (N number of nodes).

Distributed Synchronisation: Cristian



Both T_0 and T_1 are measured with the same clock

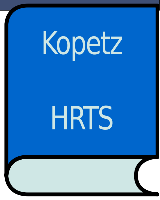
Distributed Synchronisation: Berkeley



Distributed Synchronisation: Kopetz' Tabelle

synchronisation message assembled and interpreted	approximate range of jitter
at the application software level	500 µs to 5 ms
in the kernel of the operating system	10 µs to 100 µs
in the hardware of the communication controller	Obsolete (less than 10 µs)

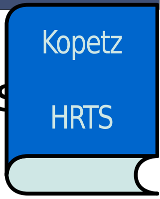
Correction: State vs. Rate

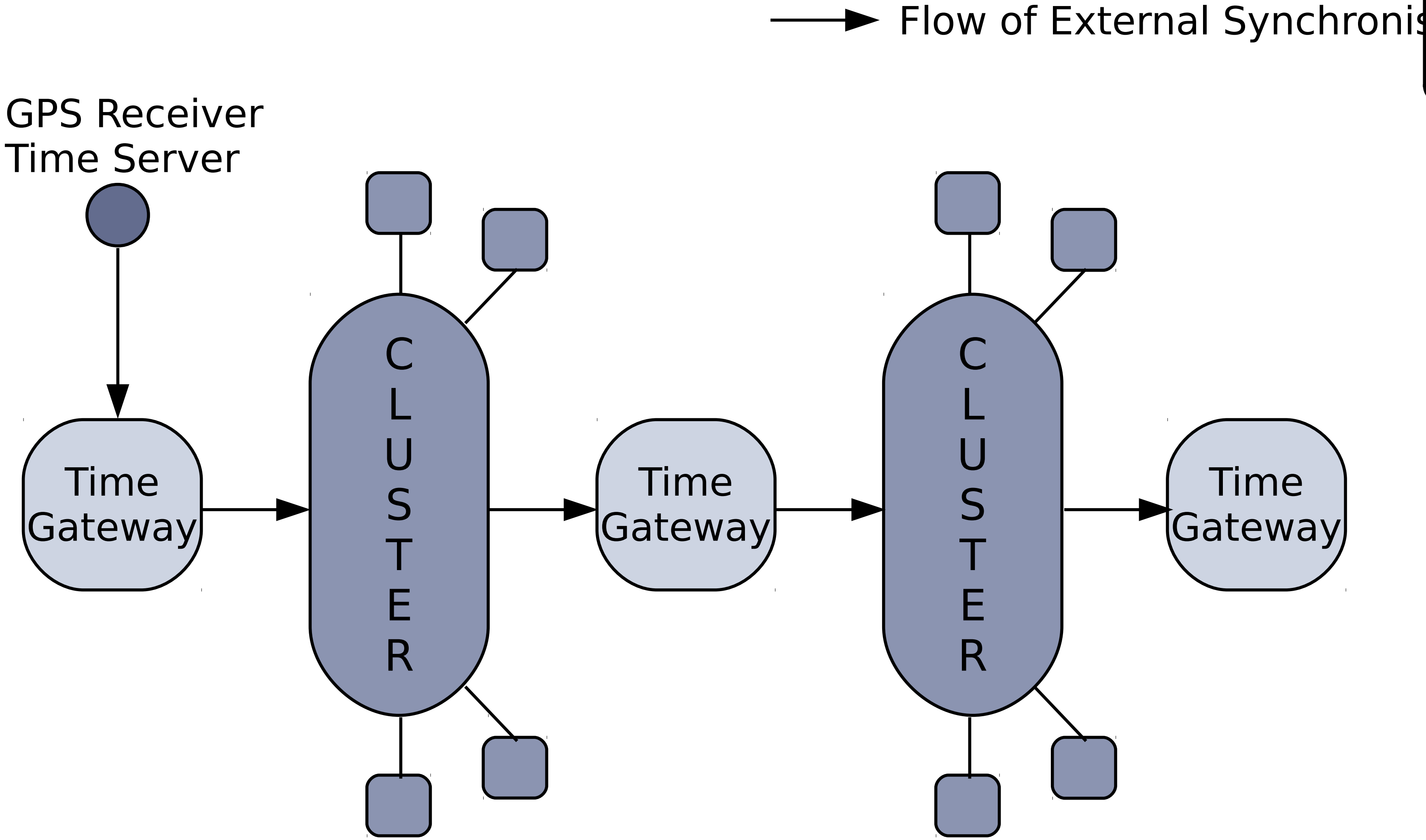


- State: reset local clock
- Rate: reset speed of clock

which should be used?

External Clock Synchronisation

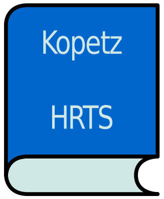




Literature

- Logical Clocks ...
  Standard text books: Coulouris, Tanenbaum, ...

- Physical Clocks ...
  This lecture followed strictly
  Hermann Kopetz, Distr. RT-Systems



- David Mills: Internet Time Synchronisation: the Network Time Protokol, IEEE Transactions Communic. 39,10 (Oktober 1991)