Global Time

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CIS 541, Spring 2010

Ordering in the Distributed Real-Time System

- The distributed computer system performs a multitude of different functions concurrently.
  - The monitoring of RT-entities
  - The detection of alarm conditions
  - The display of the observations
  - The execution of control algorithms
- All nodes process all events in the same consistent order.
  - To guarantee a consistent behavior of the entire distributed system ♪

Temporal Order

- A timeline consists of an infinite set {T} of ***instants*** with the following properties.
  - {T} is an ordered set, if p and q are any two instants, then either p is simultaneous with q, or p recedes q, or q recedes p, where these relations are mutually exclusive. We call the order of instants on the timeline the temporal order.
  - {T} is a dense set : There is at least one q between p and r iff p is not the same instance as r, where p, q and r are instants.
- A section of the time line is called a ***duration***.
- An ***event*** takes place at an instant of time.
- If two events occur at an identical instant, then the two events are said to occur ***simultaneously***.

Causal Order

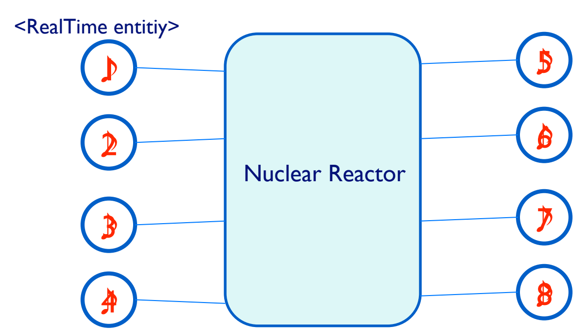
- In many real-time applications, the causal dependencies among events are of interests.
  - A nuclear reactor equipped with many sensors.
  - In case a pipe ruptures, what is the primary event that triggers the alarm shower?
  - The temporal order of two events is necessary, but not sufficient, for their ***causal*** order.
- Causal order is more than temporal order.

Delivery Order

- A weaker order relation than temporal or causal order is a consistent ***delivery order***.
- All host computers in the nodes see the sequence of events in the same delivery order.
- The delivery order is not necessarily related to the temporal order or the causal relationship between events.

Why need Temporal Order in Real-Time Systems?

- In case of sudden unexpected changes in the nuclear reactor, system causes an *alarm shower*.
- What is the primary event that triggers the alarm shower?
  - Knowledge of the exact temporal order is helpful to identify the primary event.

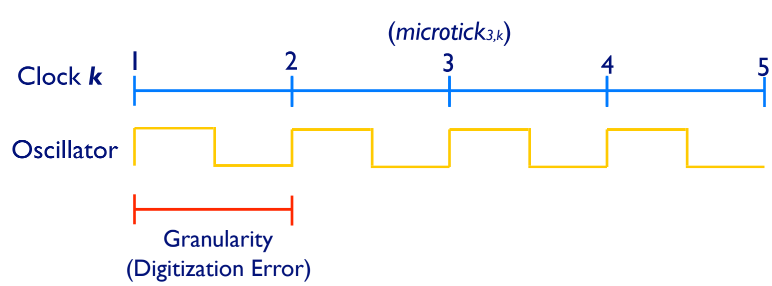


Issues in the Temporal Order

- What is the condition to reconstruct temporal order between two events?
- Need the following concepts
  - Clocks
    - Physical clock
    - Reference clock
    - Timestamp
    - Offset , Precision and Accuracy
  - Time measurement
    - Global Time
    - Reasonableness Condition of Global Time
    - Condition to reconstruct temporal order.

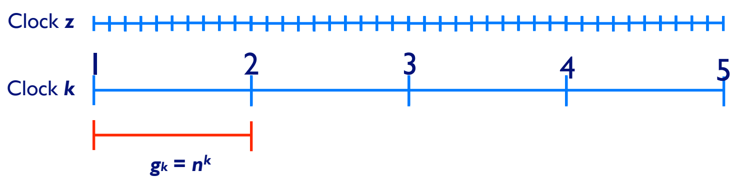
Clocks : Physical Clock

- Physical Clock
  - A device for measuring time with counter and a physical oscillation mechanism.
  - ***Microtick*** : The periodic event generated by a oscillation mechanism. (Denoted by $microtick_{i,k}$ for i th microtick of clock k)
  - ***Granularity*** : The duration between two consecutive microticks.



Clocks : Reference Clock

- Reference Clock
  - Assume an *omniscient external observer* who can observe all events that are of interest in a given context.
  - A unique reference clock **z** with granularity g_z which is in perfect agreement with the international standard of time.
    - (Assume g_z is really really really small, say 10^{-15} second)
- The relationship between reference clock **z** and a given clock ***k***
  - n^k : a nominal number of microticks of clock z which occur between $microtick_{i,k}$ and $microtick_{i+1,k}$



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Clocks : Timestamp

- ***Clock***(***event***) : denotes the ***timestamp*** generated by the use of a given clock to timestamp an event.
  - Ex) ***z(e)*** : The timestamp of event e which is observed by clock z (the absolute timestamp)
- What if the interval of two events is less than g_z?
  - The temporal order of events that occur between any two consecutive microticks of the reference clock z cannot be reestablished from their absolute timestamps.
  - => *Limitation of this time measurement.*

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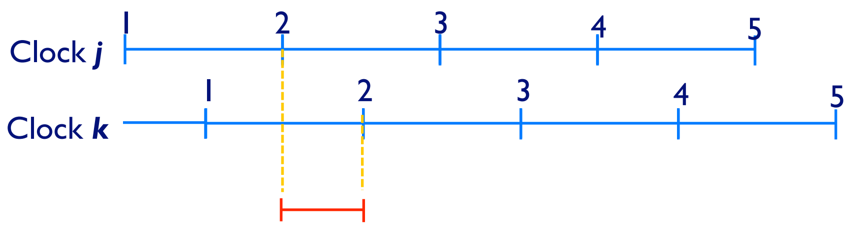
Clocks : Offset

- Offset
  - The offset at microtick ***i*** between two clocks ***j*** and ***k*** with the same granularity.
  - $Offset_{j,k}(i) = |z(\textit{\textbf{microtick}}_{i,j}) - z(\textit{\textbf{microtick}}_{i,k})|$



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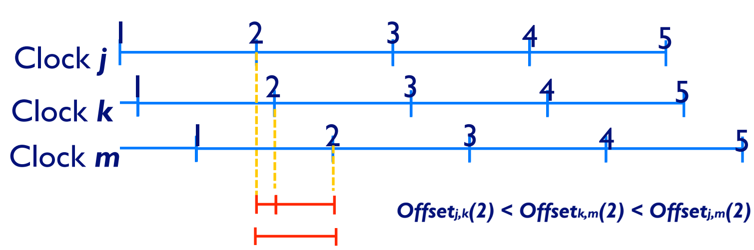
Clocks : Precision

- Precision
  - Given an ensemble of clocks {*1, 2, …, n*}, the maximum offset between any two clocks of the ensemble

    $\Pi_i = \max\{offset_{j,k}(i)\}$ **for all** $1 \le j, k \le n$
  - The precision of ensemble Π : the maximum Π_i of over an interval of interest.
- Internal synchronization
  - The process of mutual resynchronization of an ensemble of clocks ***to maintain a bounded precision***



Offset*j,k***(2) < Offset****k,m***(2) < Offset****j,m***(2)***

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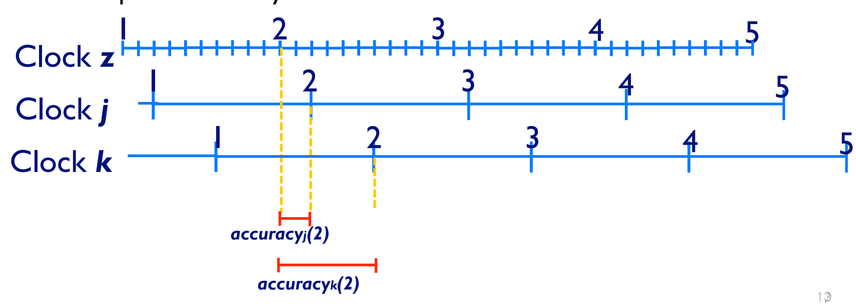
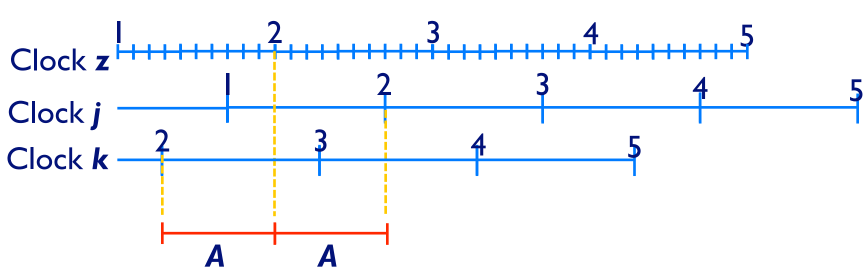
Clocks : Accuracy

- Accuracy
  - ***accuracy$_k$(i)*** : The offset of clock ***k*** with respect to the reference clock **z** at microtick ***i***
  - ***accuracy$_k$*** : The maximum offset over ***all microticks i*** that are of interest in clock ***k***
- External synchronization
  - The process of resynchronization of a clock with the reference clock



Clocks : Precision and Accuracy

- Relationship between Precision and Accuracy
  - If all clocks are ***externally*** synchronized with an ***accuracy A***, then the clocks are also ***internally*** synchronized with a ***precision*** of ***at most 2A***.
  - *The converse is not true*



Time Measurement

- Easiest way to achieve temporal order of every event
  - Having a perfect synchronization with a single reference clock ***z*** among all real-time clocks of nodes
- Challenge
  - In loosely coupled distributed system, every node has its own local clock.
  - A tight synchronization of clocks is not possible.
- The concept of ***global time***
  - A weaker notion of a universal time reference
  - With local clock, achieve ***local implementation of a global notion of time***.

Global Time(1/2)

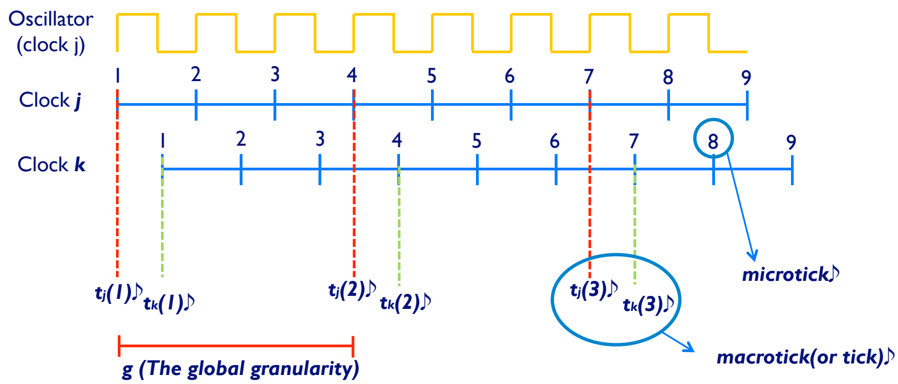
- How to achieve the local implementation of a global notion of time?
- Assumption
  - Each node has its own local physical clock c_k with granularity g_k.
  - All local clocks are internally synchronized with a precision Π.

    $$|z(microtick_j(i)) - z(microtick_k(i))| < \Pi$$

    for any two clocks j, k and all microticks i
- Macrotick
  - A subset of the ***microticks*** of each local clock.
  - The local implementation of a global notion of time.
  - Ex) Every tenth microtick of a local clock ***k*** may be interpreted as the global tick, the macrotick $t_k(i)$.♪

Global Time(2/2)

- Illustration of the relationship between microtick and macrotick.



Reasonableness Condition(1/3)

- The global time t is called ***reasonable***.
  - If all local implementations of the global time satisfy the condition

$$g > \Pi$$

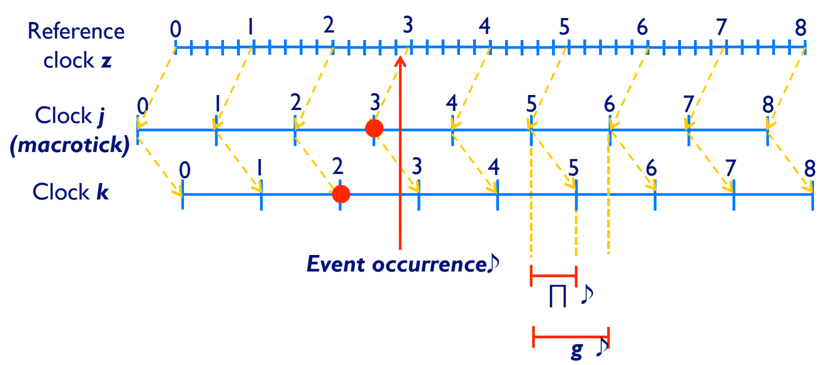
- The impact of reasonable condition
  - The synchronization error is bounded to less than ***one macrogranule g***.
  - For a single event **e**, that is observed by any two different clocks which satisfy the reasonable condition

$$|t_j(e) - t_k(e)| \leq 1$$

  - i.e. the global timestamps for a single event can differ by at most one tick. ***This is the best we can achieve***.

Reasonableness Condition(2/3)

- Illustration of the reasonableness condition (**g > ∏**)
  - Timestamp of a single event, $|t_j(e) - t_k(e)| \le 1$



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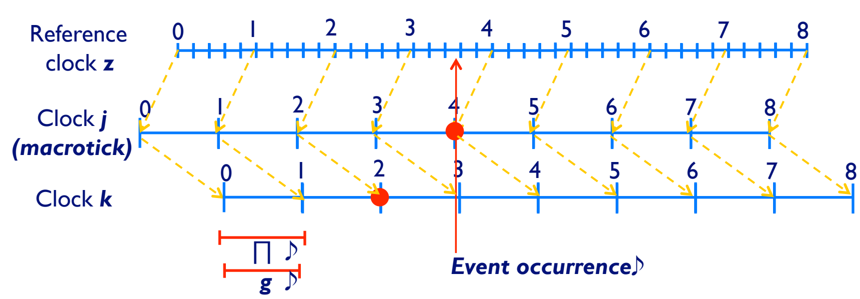
Reasonableness Condition(3/3)

- Illustration of the impact unless the reasonableness condition meets.
  - Timestamp of a single event $|t_j(e) - t_k(e)| > 1$ at some point. (not all points.)



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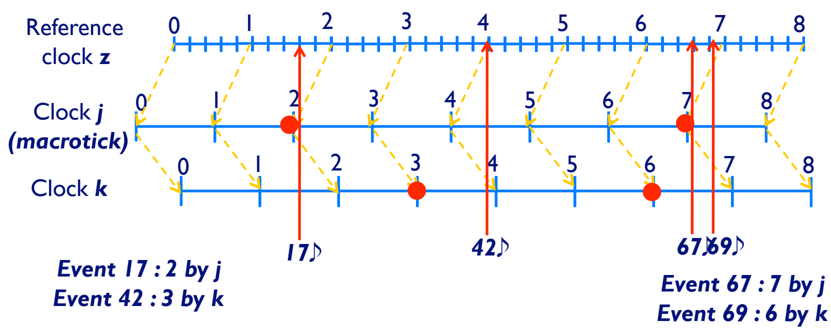
The meaning of one tick difference

- Both duration (17, 42), (67, 69) observed by clock ***j*** and ***k*** have one tick difference.
- Problem ? z(67) < z(69), but $t_k(67) > t_k(69)$
  - Because of the accumulation of the synchronization error and the digitalization error.



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The Condition to Reconstruct Temporal Order

- One tick difference between two events
  - Not possible to reconstruct the temporal order.
  - (We are not sure : Some of them can be reconstructed, but some cannot be.)
- Two tick difference between two events
  - The temporal order can be reconstructed.
  - (Guaranteed : All such events can be reconstructed.)
  - WHY? ***The sum of the synchronization and digitalization error is always less than 2 granules.***

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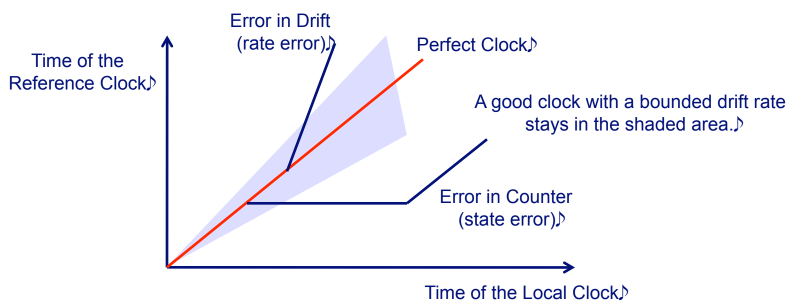
Why need Clock Synchronization?

- Failure modes of a clock
  - Error in Counter (state error)
  - Error in Drift (rate error)♪



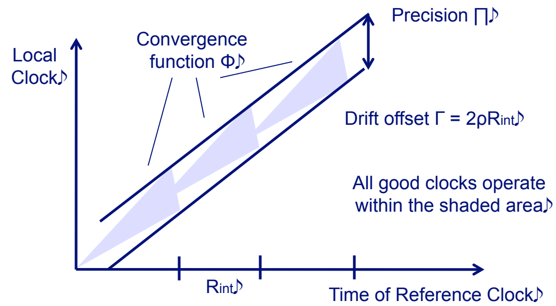
Internal Clock Synchronization

- The parameters for synchronization condition
  - Resynchronization interval : R_{int}
  - Convergence function : the offset of the time values immediately after the resynchronization.
  - Drift offset : the maximum divergence of any two good clocks from each other during R_{int}.
  - The maximum specified drift rate : ρ♪

The Synchronization Condition

- The synchronization condition
  - o $\Phi + \Gamma \leq \Pi$

  =>The synchronization algorithm must bring the clocks so close together that the amount of divergence during the next resynchronization interval will not cause a clock to leave the precision interval



Synchronization Algorithms (1)

- The goal is to achieve the synchronization condition.
- Central Master Synchronization
  - o A unique node, the central master, periodically sends the value of its time counter in synchronization messages to all other nodes, the slave nodes.
  - o The slave node corrects the clock based on the master's time and the latency of the message.

Synchronization Algorithms (2)

- Distributed Synchronization Algorithms
  - Step 1) Every node acquires knowledge about the state of the global time counters in all the other nodes.
  - Step 2) Every node analyzes the collected information to detect errors, and calculate a correction value for the local global time counter.
  - Step 3) The local time counter of the node is adjusted by the calculated correction value.

External Clock Synchronization

- External synchronization links the global time of a cluster to an external standard of time.
  - Time server
  - GPS
- Internal and external synchronization
  - Internal sync. : a cooperative activity among all the members of a cluster.
  - External sync. : an authoritarian process (the time server forces its view of external time on all its subordinates.) ♪

Clock Synchronization

- State correction
- Rate correction

Event-Triggered versus Time-Triggered

- Chap 4.4 (pp. 82-86)
- Event-triggered (ET) system – the control signal derived from state change, an event, in the environment or within the computer system
- Time-triggered (TT) system – the control signal derived from the progression of time
- Example in Elevator
  - Two buttons pushed repeatedly, very closed to each other