Global Time

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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\textsubscript{k,i} for i\textsuperscript{th} microtick of clock k)
  ▪ Granularity: The duration between two consecutive microticks.}

![Diagram of Clocks and Granularity](image-url)
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 $i+1,k$

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.
Clocks : Offset

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

Clock $j$

Clock $k$

Clocks : Precision

- Precision
  - Given an ensemble of clocks $\{1, 2, \ldots, n\}$, the maximum offset between any two clocks of the ensemble.

\[ |\| = \max\{\text{offset}_{j,k}(i)\} \text{ for all } 1 \leq j, k \leq n \]
  - The precision of ensemble $\|$ : the maximum $|$ of over an interval of interest.

- Internal synchronization
  - The process of mutual resynchronization of an ensemble of clocks to maintain a bounded precision.

Clock $j$

Clock $k$

Clock $m$

$\text{Offset}_{j,k}(2) < \text{Offset}_{k,m}(2) < \text{Offset}_{j,m}(2)$
Clocks : Accuracy

- **Accuracy**
  - \textit{accuracy}_(i) \(k\): The offset of clock \(k\) with respect to the reference clock \(z\) at microtick \(i\)
  - \textit{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

\[
\begin{align*}
\text{Clock } z & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{Clock } j & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{Clock } k & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5
\end{align*}
\]

Clocks : Precision and Accuracy

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

\[
\begin{align*}
\text{Clock } z & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{Clock } j & \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{Clock } k & \quad 2 \quad 3 \quad 4 \quad 5
\end{align*}
\]
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 \( \pi \).

\[
|z(microtick(i)) - z(microtick(i))| < \pi
\]

- 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
    $$g > \prod$$
  - 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
      $$|t_{e} - t_{e}| \leq 1$$
    - 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 \((g > \prod)\)
  - Timestamp of a single event, \(|t_j(e) - t_k(e)| \leq 1\)

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.)
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.

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? \(The\ sum\ of\ the\ synchronization\ and\ digitalization\ error\ is\ always\ less\ than\ 2\ granules.\)
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 : $\rho$
The Synchronization Condition

- The synchronization condition
  - \( \Phi + \Gamma \leq \prod \)
  - => 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
  - A unique node, the central master, periodically sends the value of its time counter in synchronization messages to all other nodes, the slave nodes.
  - 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 close to each other