# Synchronization

## Physical Clocks, Logical Clocks

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# Outline

1. Synchronous Systems
   - Physical Clocks
     - Quartz Clocks
     - Atomic Clocks
     - GPS
   - Network Time Protocol
   - Totally Ordered Multicast
2. Asynchronous Systems
   - Happens-Before Relationship
   - Totally Ordered Mutual Exclusion

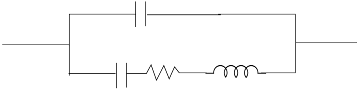
# Outline

# Quartz Based Clock

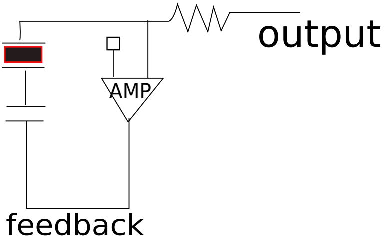
## Quartz Oscillator

- Computers clock use a quartz crystal to generate a clock signal.
- Quartz is a piezoelectric material – generates a voltage, when subjected to mechanical stress.
- Resistant to temperature fluctuations.


quartz oscillator


equivalent circuit

# Quartz Clock II



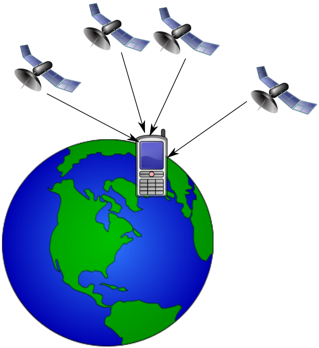

- The quartz oscillator is a part of a self-feedback loop.
- It typically oscillates at 32 KHz.
- Processors generate a higher frequency by dividing this clock.
- The clock drift is $\pm 15$ seconds per month (6 ppm).
- A regular quartz clock is not suitable for large distributed systems.

# Atomic Clock

## Atomic Clock

- Uses a Caesium-133 atom as an oscillator.
- Uses a similar feedback based circuit as the quartz clock.
- Accuracy : $10^{-8}$ ppm

# Use of Atomic Clock: GPS



- Each satellite broadcasts its position $(x_i, y_i, z_i)$ and time $t_i$
- The time is obtained through an atomic clock.

# Finding the Position through GPS

- Current position: $(x, y, z)$
- The drift between the receiver clock and the atomic clocks is $d$.
- The time at which the receiver receives the message is $t_r$.
- Setup equation:

$$\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} = (t_r - t_i + d) \times c$$

- $c$ is the speed of light
- For four unknowns $x, y, z, d$, we need at least four equations

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Hence, we need at least four satellites.

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# Network Time Protocol

- There are a set of network time servers that have accurate clocks (stratum 1).
- These servers might in turn synchronize with servers that have even more accurate clocks (stratum 0).
- A client machine needs to contact a NTP time server and find the drift between the clocks.
- There are different clock synchronization algorithms.

# Cristian's Algorithm

1. Client sends a request to the server at its local time $t_1$.
2. Server receives it at its local time $t_2$.
3. Server sends a reply at its local time $t_3$.
4. Client receives the reply at $t_4$.

## Calculating the Drift - $\Delta$

If we assume that the jitter in the network is 0, then the request and response take the same amount of time. We have

$$\begin{aligned} t_2 - (t_1 + \Delta) &= t_4 + \Delta - t_3 \\ \Rightarrow \Delta &= \frac{(t_2 - t_1) + (t_3 - t_4)}{2} \end{aligned} \tag{1}$$

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**Shift the clock of the client by $\Delta$**

# Berkeley Algorithm

- A master is chosen by some method among a group of nodes.
- The master uses Cristian's algorithm to find the clock drift with each slave.
- The master computes the mean value of the drift.
- The master sends an update to each slave regarding the amount that the slave needs to shift its clock.
- This ensures that the clocks of most slaves are relatively synchronized with each other.
- The algorithm also aims to minimize the amount by which each slave needs to adjust its clock.

# Outline

# Totally Order Multicast with Synchronized Clocks

## Problem

Nodes randomly send messages to a subset of other nodes. The network has a non-deterministic delay. It is bounded by $\Delta$. Ensure that all the messages are delivered in the same order at all nodes.

## Solution

Sender: Timestamp every message with the local time.
Receiver:

1. For a message with timestamp $t$, transfer it to the receive queue at time $t + \Delta$.
2. Deliver the messages in the receive queue in the order of their timestamps.

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# Definitions

- Our distributed system does not have a notion of global time.
- It contains a set of processes.
- Each process issues its own set of events.
- A process can send a message to another process.

## Happens-before relationship( $\rightarrow$)

1. If a process issues event $a$ before $b$, then $a \rightarrow b$.
2. If event $a$ is the sending of a message by one process and $b$ is its receipt by another process. Then $a \rightarrow b$.
3. If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$

# Definitions - II

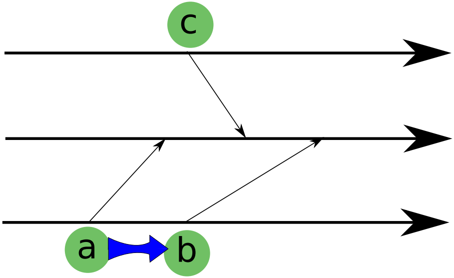
- If $a \nrightarrow b$ and $b \nrightarrow a$, then $a \bowtie b$(concurrent)
- If $a$ happens before $b$, then we say that $a$ causally affects $b$
- Let us assign a number to each event: $\tau(a)$
- We want it to satisfy some conditions
  - Clock Condition : $(a \rightarrow b) \Rightarrow \tau(a) < \tau(b)$
  - C1: If $a \rightarrow b$ and they belong to the same process, then $\tau(a) < \tau(b)$
  - C2: If $a$ represents a send, and $b$ is its receipt, then $\tau(a) < \tau(b)$

# Enforcing the Clock Condition

- Every process keeps a clock that is initialized to 0. Process $i$'s clock is $\tau_i$.
- Each process increments $\tau_i$ between two successive events.
- If event $a$ is the sending of a message by process $i$, then this process embeds $\tau_i(a)$ in the message.
  - $\tau(a) = \tau_i(a)$
- Let $b$ be the receive event at process $j$.
  - $\tau_j = \tau_j(b) = max(\tau_j, \tau_i(a)) + 1$
  - $\tau(b) = \tau_j(b)$
- This method provides a partial ordering.

# Vector Clocks: Motivation

- Clock Condition: $a \rightarrow b$ implies $\tau(a) < \tau(b)$
- Is it true that: $\tau(a) < \tau(b)$ implies $a \rightarrow b$
  - This would mean that $a \bowtie b$ implies $\tau(a) = \tau(b)$
  - Not True



# Vector Clocks: Design

## Vector Clock

- If there are $n$ processes, every process maintains an $n$-element array $\mathcal{V}_i$
- Process $i$ increments $\mathcal{V}_i(i)$ before sending or receiving a message, and on every internal event.
- Every message is timestamped with the vector clock of the sender
- The receiver merges the clocks:
  - Assume: $i$ sends a message to $j$
  - $\forall k, \mathcal{V}_j(k) = max(\mathcal{V}_i(k), \mathcal{V}_j(k))$
- $\mathcal{V}_i < \mathcal{V}_j \Rightarrow (\forall k, \mathcal{V}_i(k) \leq \mathcal{V}_j(k)) \wedge (\exists k, \mathcal{V}_i(k) < \mathcal{V}_j(k))$

## Additional Properties

1. $\mathcal{V}_a < \mathcal{V}_b \Leftrightarrow a \rightarrow b$
2. $(\mathcal{V}_a \not\leq \mathcal{V}_b) \wedge (\mathcal{V}_a \not\geq \mathcal{V}_b) \Leftrightarrow a \bowtie b$

# Outline

# Total Ordering $\Rightarrow$

- Let us consider two events $a$ and $b$ belonging to processes $i$ and $j$
  - $a \Rightarrow b$, if $\tau_i(a) < \tau_j(b)$
  - $a \Rightarrow b$, if $\tau_i(a) = \tau_j(b)$, and $i \prec j$

## Ordered Mutual Exclusion Problem

- A certain resource can be owned by only one process. It must be explicitly granted and released.
- Different requests must be granted in the order in which they were made.
- If no process hangs forever after taking the resource, every request is ultimately granted.

# Lamport's Algorithm for the Mutual Exclusion Problem

## Resource Request

1. To request a resource, $P_i$ sends a message: $(T_M, i)$ to all nodes, and also puts the message in its request queue. $T_M = \tau_i$ (Lamport clocks with FIFO channels)
2. When $P_j$ receives $(T_M, i)$, it places it in its request queue, and sends a timestamped acknowledgement.

## Resource Access

Access the resource when both these conditions are met:

1. $(T_M, i)$ is the earliest message in the queue.
2. The process has received a message with timestamp greater than $T_M$ from every other process.

# Algorithm - II

## Resource Release

1. $P_i$ removes any $(T_M, i)$ messages in its queue, and sends a timestamped $P_i$ releases message to all other processes.
2. When process $P_j$ receives a release message from process $i$, it removes any request message from process $i$ in its request queue.

# Proof – Main Idea

## Objectives

1. If the resource is free, then some process will get it.
2. No two processes can get the resource at the same time.
3. Processes get the resource in the order of the requests.

## Discussion

- If a process is getting a resource, then there are two possibilities
  1. It has seen requests by all other processes.
  2. It has not seen the request of some set of processes, but it has seen messages that precede them.

# Proof – Details

- Assume that two processes *i* and *j* are accessing the resource at the same time.
- Let $\tau_i < \tau_j$ (break ties by the process id).
- This means that *j* must have gotten a message from *i* with timestamp $> \tau_j$ before acquiring the resource.
- This means that *i* must have sent its request before sending this message, else $\tau_i > \tau_j$. *i*'s message would have been in *j*'s queue, when it accessed the resource.
- Given that $\tau_i < \tau_j$, *j* could not have accessed the resource without *i* releasing it first. Contradiction
- Total: 3 (N-1) messages

Time, clocks, and the ordering of events in a distributed system by Leslie Lamport, Communications of the ACM, 1978