Time, Clocks, and the Ordering of Events in a Distributed System

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Fun facts:

1. With >13k citations, this is Lamport's most often cited paper
2. LaTeXoriginates from a set of macros created by Lamport for Donald Knuth's TeXtypesetting system

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Abstract

The concept of one event happening before another in a distributed system is examined, and is shown to define a partial ordering of the events. A distributed algorithm is given for synchronizing a system of logical clocks which can be used to totally order the events. The use of the total ordering is illustrated with a method for solving synchronization problems. The algorithm is then specialized for synchronizing physical clocks, and a bound is derived on how far out of synchrony the clocks can become.

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Key Words and Phrases: distributed systems, computer networks, clock synchronization, multiprocess systems

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The concept of the temporal ordering of events pervades our thinking about systems.

Machines Think Different™

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Problems often arise because people are not fully aware of this fact and its implications.

Intro to Partial Ordering

Recap: Most **people** would probably say that an event a happened before an event b if a happened at an earlier time than b. However, if a **system** is to meet a specification correctly, then that specification must be given in terms of events observable within the system.

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No worries! Lamport defined the "happened before" relation without using physical clocks.

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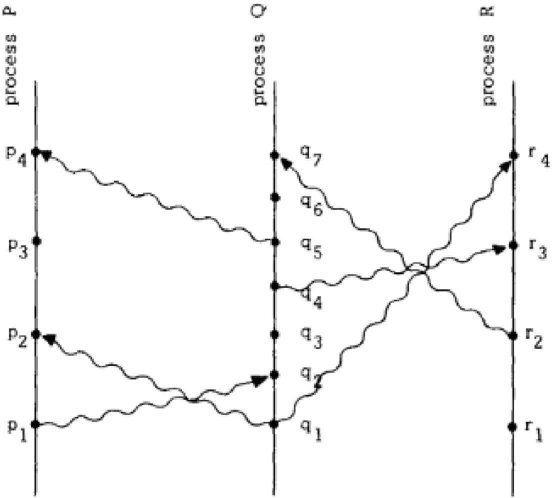
Another way to think about concurrency: $a \rightarrow b$ means it's possible for a to causally affect b. Concurrent events don't causally affect each other.

Figure 1

Space-time diagram

- horizontal direction represents space and the vertical direction represents time—later times are higher
- dots denote events
- vertical lines denote processes
- wavy lines denote messages



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What about correctness? Remember: no physical time! The strongest reasonable condition is that if an event a occurs before another event b, then a should happen at an earlier time than b.

Clock Condition

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- **C1** If a and b are events in process P_i, and a comes before b, then $C_i\langle a\rangle < C_i\langle b\rangle$
- **C2** If a is the sending of a message by process P_i and b is the receipt of that message by process P_j, then $C_i\langle a\rangle < C_j\langle b\rangle$

Figure 2

Space-time diagram

- dashed "tick line" through all the like-numbered ticks of the different processes.
- consider the tick lines to be the time coordinate lines of some Cartesian coordinate system on space-time

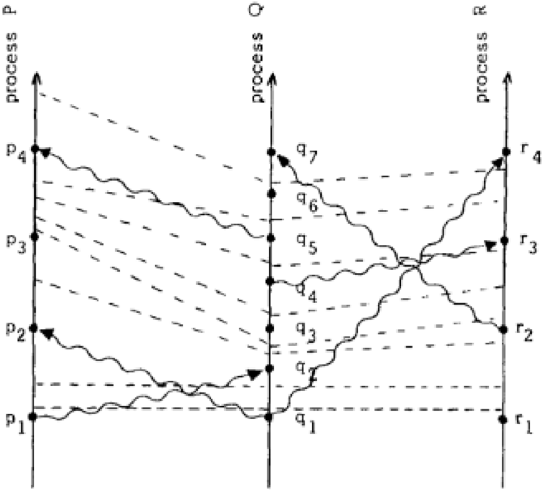

Figure 2

Figure 3

Space-time diagram

- Same as Figure 2 except we straightened the coordinate lines
- Which figure is a better representation? No right answer due to lack of physical time concept in system.

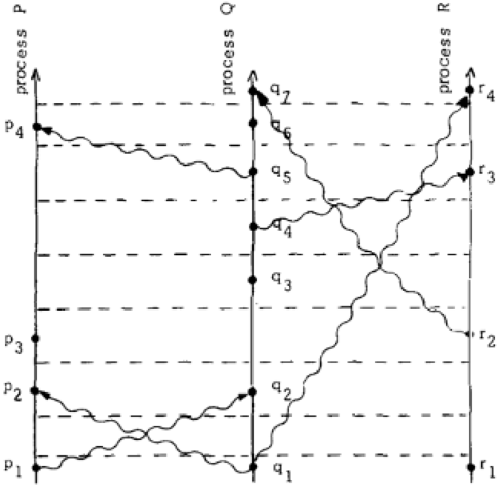

Figure 3

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Let's make things less abstract! Assume now that processes are algorithms, and the events represent certain actions during their execution. How do we introduce these clocks we've been talking about into processes?

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IR2 (a) If event a is the sending of a message m by process P_i, then the message m contains a timestamp $T_m = C_i\langle a\rangle$. (b) Upon receiving a message m, process P_j sets C_j greater than or equal to its present value and greater than T_m.

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- Tiebreaker: use any arbitrary total ordering $\prec$ of the processes

But How? Now, Lamport-Style

We define a relation $\Rightarrow$ as follows: if a is an event in process P_i and b is an event in process P_j, then $a \Rightarrow b$ if and only if either:

(i) $C_i\langle a\rangle < C_j\langle b\rangle$, or

(ii) $C_i\langle a\rangle = C_j\langle b\rangle$ and $P_i \prec P_j$

♩ In other words, please be true ♩, in other words, the relation $\Rightarrow$ is a way of completing the "happened before" partial ordering to a total ordering.

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- Given any total ordering relation $\Rightarrow$ which extends $\rightarrow$, there is a system of clocks satisfying the Clock Condition which yields that relation. It is only the partial ordering $\rightarrow$ which is uniquely determined by the system of events

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Mutual exclusion problem: in a system consisting of many processes and one resource, we wish to find an algorithm for granting the resource to a process which satisfies the following three conditions:

1. A process which has been granted the resource must release it before it can be granted to another process.
2. Different requests for the resource must be granted in the order in which they are made.
3. If every process which is granted the resource eventually releases it, then every request is eventually granted.

Assume that the resource is initially granted to exactly one process.

Algorithm: Rule #1 (out of 5)

1. To request the resource, process P_i sends the message $T_m : P_i$ *requests resource* to every other process, and puts that message on its request queue, where T_m is the timestamp of the message.

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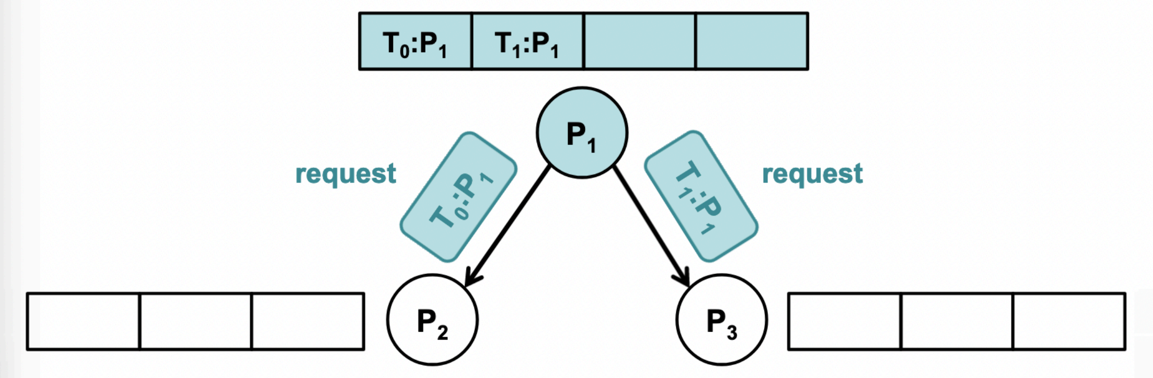

Source: Nicole Caruso, Cornell CS

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2. When process P_j receives the message $T_m : P_i$ *requests resource*, it places it on its request queue and sends a (timestamped) acknowledgment message to P_i.

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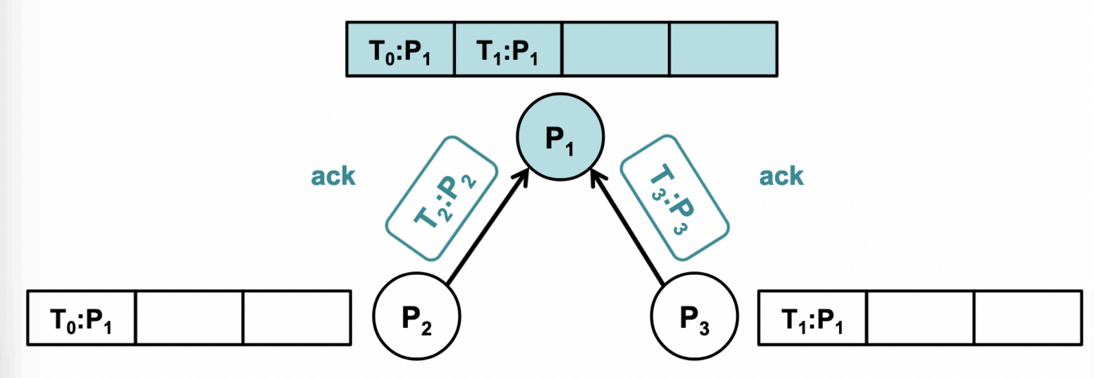

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Algorithm: Rule #3 (out of 5)

3. To release the resource, process P_i removes any $T_m : P_i$ *requests resource* message from its request queue and sends a (timestamped) P_i *releases resource* message to every other process.

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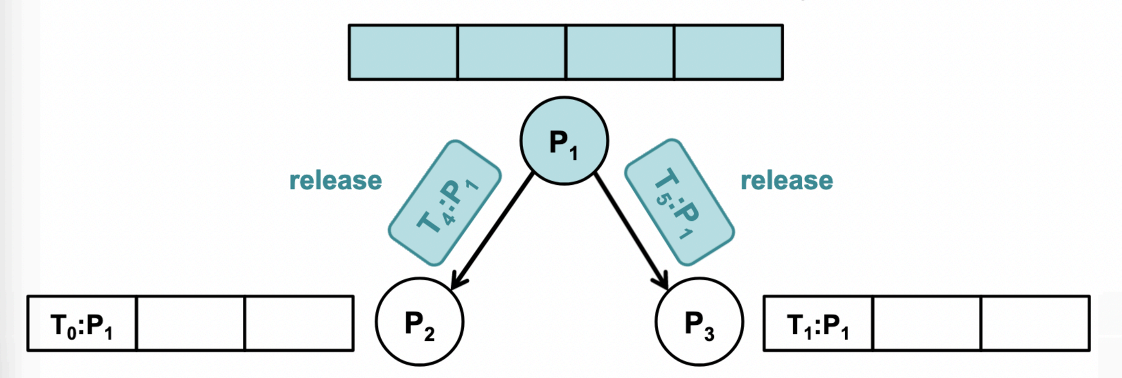

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Algorithm: Rule #4 (out of 5)

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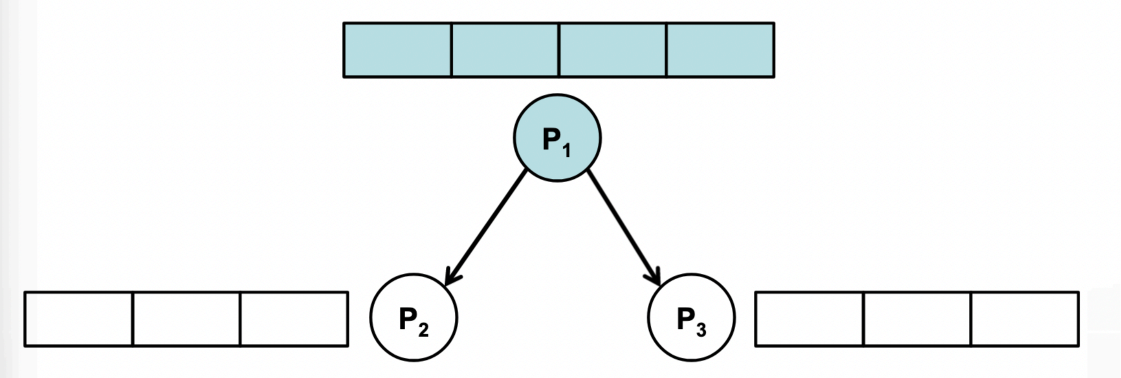

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Algorithm: Rule #5 (out of 5)

5. Process P_i is granted the resource when the following two conditions are satisfied:
   i. There is a $T_m : P_i$ *requests resource* message in its request queue which is ordered before any other request in its queue by the relation $\Rightarrow$. (To define the relation "$\Rightarrow$" for messages, we identify a message with the event of sending it.)
   ii. P_i has received a message from every other process timestamped later than T_m.

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Total ordering still permits the following type of anomalous behavior:

- 2 computers in a network can try to obtain a shared resource at the *same time* causing a conflict. This can happen despite the fact that a request a may have been made on computer A before a request b may have been made on computer B because b comes before a on computer B.

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Thoughts?

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One of the mysteries of the universe is that it is possible to construct a system of physical clocks which, running quite independently of one another, will satisfy the Strong Clock Condition.

Physical Clock Conditions

Let's introduce a physical time coordinate t! Let $C_i(t)$ denote the reading of the clock C_i at physical time t and $\frac{dC_i(t)}{dt}$ represent the rate at which the clock runs at t. In order for C_i to be a true physical clock, it must run at the correct rate, *i.e.*, $\frac{dC_i(t)}{dt} \approx 1$.

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More precisely,

PC1 There exists a constant $\kappa \ll 1$ such that for all $i : |\frac{dC_i(t)}{dt} - 1| < \kappa$, where $\kappa \leq 10^{-6}$ for quartz clocks. (Clocks individually run at approximately the correct rate) "drift"
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PC2 For all $i, j : |C_i(t) - C_j(t)| < \epsilon$. (Clocks must be synchronized so that $C_i(t) \approx C_j(t)$ for all i, j, and t) "skew"

Important Physical Clock Concepts

Keep in mind the following

- Clocks are never perfectly accurate, a term that refers to **“truth”**
- Any clock will also **drift** over time, causing **skew** between two clocks
- **Accuracy** relates to skew relative to a perfectly truthful clock
- **Precision** relates to skew between pairs of correct clocks in the system.

Ken Birman. *(Lecture Notes) CS5412 / Time-Related Content (Enrichment/Review).* https://www.cs.cornell.edu/courses/cs5412/2022fa/videos/lecture-9-enrichment.mp4. [Online; accessed 09-October-2022]. 2022

Specialized Rules IR1′ and IR2′

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- Purpose of IR1′ and IR2′: to guarantee PC2 is satisfied by the system of physical clocks
- IR1′ states clock readings change with physical time
- IR2′ states how clocks synchronize with each other. P_j's clock is set to max(current time, time at which message is received + expected minimum transmission delay)

Theorem

What does it do?

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- Bounds the time it takes for clocks to sync up at system startup time

Skipping detail due to time constraints. Also, very math intensive, so good luck! PS: Even Lamport thinks the proof of this theorem is difficult.

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- We discussed an algorithm for extending that partial ordering to a somewhat arbitrary total ordering
- Anomalous behavior arises when total ordering defined by algorithm disagrees with ordering perceived by system's users
  - Using properly synchronized clocks can prevent this

Conclusion

- Concept of "happening before" defines an invariant partial ordering of the events in a distributed multiprocess system
- We discussed an algorithm for extending that partial ordering to a somewhat arbitrary total ordering
- Anomalous behavior arises when total ordering defined by algorithm disagrees with ordering perceived by system's users
  - Using properly synchronized clocks can prevent this
- In a distributed system, it is important to realize that the order in which events occur is only a partial ordering

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- Discuss: Why not just use a centralized scheduler to deal with the mutex problem?

Questions?

Thank you for attending