Synchronization and Consistency

Content taken from the following:
"Distributed Systems: Principles and Paradigms" by Andrew S. Tanenbaum and Maarten Van Steen (Chapters 6, 7 and 11)
Various online sources
Synchronization

• In a shared-memory system:
  – Core mechanism: mutual exclusion
  – Conditions, semaphores, and barriers

• In a distributed-memory system:
  – Core mechanism: message passing
  – Coordinated clocks
    • Absolute vs. logical
  – Election and consensus algorithms
  – Consistency models and protocols
Clocks / Timers

• Measuring time
  – Movements of sun, moon, and stars
  – Unwinding of wound spring
  – Quartz crystal oscillating under tension
  – Energy transitions of a caesium 133 atom

• Synchronizing absolute clocks
  – Calendars and leap year/second adjustments
    • Coordinated Universal Time (UTC)
  – Clock skew
    • Network Time Protocol (NTP)
Network Time Protocol

- Reference clocks (hardware-based)
- Stratum 1-15 and 16 (unsynced)
- 64-bit time values (<1 ns resolution)

Time offset:
\[ \theta = \frac{(t_1 - t_0) + (t_2 - t_3)}{2} \]

Round-trip delay:
\[ \delta = (t_3 - t_0) - (t_2 - t_1) \]

Logical clocks

- Lamport clocks / timestamps
  - Invented by Leslie Lamport in 1978
  - Core notion: "happens-before" (total ordering)
    - Assigns clock value \( C(x) \) to any event \( x \)
    - Increment local clock before sending
    - Include local clock when sending
  - Adjust local clock after communications
    - Must preserve “happens-before” ordering
    - Always forwards—never backwards!
  - If \( a \) happened before \( b \), then \( C(a) < C(b) \)
    - Converse is not necessarily true!
    - Does not capture any notion of causality

For more info:
http://dl.acm.org/citation.cfm?id=359563
Logical clocks

• Which of the following is NOT true of Lamport clocks?
  - A. If a happened before b, then C(a) < C(b)
  - B. If b happened before a, then C(b) < C(a)
  - C. If C(a) >= C(b), then a did not happen before b
  - D. If C(a) < C(b), then a happened before b
  - E. All of the above are true
Vector clocks

- **Vector clocks** restore a notion of causality (partial ordering)
  - Keep a vector of clock values instead of only one
  - $VC_i$ is the logical clock at process $P_i$
  - $VC_j[k] = k$ means that $P_i$ knows that $k$ events have occurred at $P_j$ (i.e., $P_i$'s knowledge of $P_j$'s local time), any of which could have causality influence

from https://en.wikipedia.org/wiki/Vector_clock
If process A has vector clock \{(A:4), (B:2)\} and process B has vector clock \{(A:4), (B:6)\}, which of the following is true?

- A. A has seen all events that B has
- B. B has seen all events that A has
- C. A has seen more events in total than B
- D. B has seen fewer events in total than A
- E. None of the above are true
Vector clocks

If process A has vector clock \{(A:4), (B:2)\} and process B has vector clock \{(A:4), (B:6)\}, which of the following is true?

- A. The most recent event on A could have caused an event on B
- B. The most recent event on B could have caused an event on A
- C. No event on A could have caused an event on B
- D. No event on B could have caused an event on A
- E. None of the above are true
Distributed mutual exclusion

- Clocks provide *time*-based synchronization
- What about *task*-based synchronization?
- How can we implement mutual exclusion in a distributed system?
Distributed mutual exclusion

- **Token-based** (often used in ring networks)
  - Simple; slow; susceptible to lost tokens
- **Permission-based**
  - **Centralized** (single coordinator)
    - Easy to implement; single bottleneck and point of failure
  - **Decentralized** (multiple coordinators, need majority vote)
    - More resilient; can be slow; possibility of starvation
If a coordinator is needed, there are various election strategies available to choose one:

- **Bully algorithm**
  - Always defer to higher-numbered nodes

- **Ring algorithm**
  - Enforce one-way election traffic

- **Wireless algorithms**
  - Choose the best coordinator (e.g., CPU speed, battery life, etc.)
Distributed consensus

- Elections (and related auctions) are a specialized form of the general problem of determining consensus in a distributed system
- **Paxos** protocol: two-phase rounds
  - **Prepare / promise**: A proposer creates a proposal with value N larger than any value it has previously used and sends it to a quorum of acceptors, who respond with a promise to ignore future proposals with a value less than N
  - **Accept / accepted**: If a proposer receives enough promises, it sets a final value M for its proposal and sends it to a quorum of acceptors, who accept it if M is greater than any other proposals it has promised to
  - Real protocol has multiple ways to handle failures and lack of consensus

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<tr>
<th>Client</th>
<th>Proposer</th>
<th>Acceptors</th>
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<tbody>
<tr>
<td>1</td>
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Distributed consensus

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</tbody>
</table>
| 3      |          | X-------->|->|->|   Request
| 4      |          | <-------X-X-X   |   Prepare(N) |
| 5      |          | X-------->|->|->|   Promise(N) |
| 6      |          | <-------X-X-X   |   Accept(M) |
| 7      |<--------X   |          |  |  |   Response

Graph:
- Client sends [Request]
- Proposer:
  - Sends [Prepare] (n) to Request
  - Sends [Promise] (n/2+1) to Accept
- Acceptors:
  - Sends [Promise] to Promise
  - Sends [Accept] (n) to Accept
  - Sends [Accepted] (n/2+1) to Accepted
  - Sends [Response] to Response
- Winning Proposer:
  - Sends [Accept] (n) to Accept
  - Sends [Accepted] (n/2+1) to Accepted
  - Sends [Response] to Response
What is the maximum number of unique states (include “idle”) for a single participant during the Paxos protocol?

- A. 1
- B. 2
- C. 3
- D. 4
- E. 5
Replication

- All of these protocols require a lot of communication
  - Communication is expensive!

- Alternative: keep redundant data
  - **Replica**: a copy of data
  - In a distributed system, every process could be a separate replica
  - Goal: improved availability/locality and therefore performance
    - Related concepts: **mirroring** and **caching**
    - Relieve single-node access bottlenecks
Replicas

- **Server-initiated (e.g., mirroring)**
  - Updates are pushed to other replicas
- **Client-initiated (e.g., caching)**
  - Updates are pulled from other replicas
  - **Write-through vs. write-back**
- **Peer-to-peer**
  - Nodes have symmetric roles
  - Requires well-defined protocol for enforcing consistency
- **Issue: keeping replicas consistent**
  - Propagating updates
  - Events (reads/writes) will arrive at different times
  - But maybe we’re ok with some inconsistency
• Theme: **loosen consistency constraints** to *decrease communication overhead*
  - Tradeoff: performance vs. consistency
Replication and consistency

• CS 374 pop quiz: What does ACID stand for in the context of database consistency?
  - A. Accessible, Continuous, Integral Data
  - B. Atomic, Consistent, Isolated, Durable
  - C. Atomic, Constant, Integrated, Data-agnostic
  - D. Agnostic, Continuous, Isolated, Durable
  - E. Accessible, Consistent, Integrated Database
Replication and consistency

- Theme: **loosen consistency constraints** to *decrease communication overhead*
  - Tradeoff: performance vs. consistency

Traditional databases:
  - **ACID** - Atomic, Consistent, Isolated, Durable

Distributed systems:
  - **BASE** - Basically Available, Soft-state, Eventually consistent
Replication

- **Consistency model**: contract between entities and data stores
  - If the entities follow the rules, the data store will be consistent

- **Data-centric models (global view)**
  - Strict / continuous consistency (absolute time)
  - Sequential consistency (logical time)
  - Causal consistency (logical causality)

- **Client-centric models (local view)**
  - Monotonic reads
  - Monotonic writes
  - Read-your-writes
  - Writes-follow-reads
Strict / continuous consistency

- All events are seen instantaneously by all nodes
  - Issue: speed of light (~$3 \times 10^8$ m/s) prevents instantaneous updates, especially in large-scale distributed systems
  - To be practical, designate an interval of allowable deviation

(interval)

$\text{speed of light} \cdot \text{distance traveled}$

$1\text{ms} \quad 1\text{s} \quad 1\text{min} \quad 24\text{hr}$

(not to scale)
Sequential consistency

- Every node sees events in the same order
  - Events must have a total order (i.e., they must be linearizable)
  - Important: a particular node need not see ALL events
    - But the order of the ones it sees must not violate the total order
  - Notation: "W(x)a" means "write value a to item x"
    - (corresponding notation for reads)

```
P0: W(x)a
P1: W(x)b
P2: R(x)b   R(x)a
P3: R(x)b   R(x)a
```

Sequentially-consistent

```
P0: W(x)a
P1: W(x)b
P2: R(x)b   R(x)a
P3: R(x)a   R(x)b
```

NOT sequentially-consistent
Causal consistency

- **Causally-related** events must be seen in order
  - Reads are causally-related to corresponding writes
  - Writes are causally-related to previous operations on the same node
  - Can be implemented using vector clocks
  - To verify, build global causality chain and check each process’s view

![Causal consistency diagram](image)
Sequential / causal consistency

- Is this sequence sequentially-consistent, causally-consistent, both, or neither?
  - A. Sequentially-consistent only
  - B. Causally-consistent only
  - C. Both
  - D. Neither

P0: W(x)a
P1: R(x)a W(x)b
P2: R(x)a R(x)c R(x)b
P3: R(x)a R(x)b R(x)c

Causally-consistent, but NOT sequentially-consistent
Partial vs. total ordering

- **Ordering**: definition of “<” operator
  - Usually over pairs of entities (for us, messages)
  - **Total ordering**: definition of “<” for **all** pairs (w/ transitivity)
    - Depicted graphically using a line
  - **Partial ordering**: definition of “<” for **some** pairs (also w/ transitivity)
    - Depicted graphically using a **graph** or **lattice**

“<” ≡ “less-than” (total ordering)

“<” ≡ “happens-before” (partial ordering)
Partial vs. total ordering

- Which of the following is NOT true of the following happens-before relationship?
  - A. D < E
  - B. D < F
  - C. D < C
  - D. C < F
  - E. C < B

“<” ≡ “happens-before” (partial ordering)
Implication

- Sequential consistency implies causal consistency
  - There is no way for the partial ordering of causal consistency to contradict the total ordering implied by sequential consistency
    - Both properties (writes before reads on same data & strict ordering for events on single processes) used to build the partial ordering are already enforced by any valid total ordering
  - Thus, every sequentially-consistent sequence must also be causally-consistent
  - Colloquially: causal consistency is *looser* than sequential consistency
Client-centric consistency

• Previous models focused on a **global** view of data
  – Sometimes called **data-centric** consistency models

• In a distributed system, we may only be interested in the **local** view at any given node
  – This motivates **client-centric** consistency models
Client-centric consistency

- Original application: Bayou database system for mobile computing
  - Developed in mid-1990s
  - Massive number of replicas
  - Multiple networks and unreliable connectivity
  - Data-centric, global consistency models are infeasible
  - Theme: loosen the constraints!
  - Four different consistency models (not mutually exclusive)

For more info:
http://dl.acm.org/citation.cfm?id=504497
Monotonic reads / writes

- **Monotonic reads**: if a process reads X, any successive read to X will see the same value or a more recent one
  - I.e., the process will never see an older version
  - E.g., distributed email database (messages shouldn’t disappear when viewing a thread on the same client)

- **Monotonic writes**: if a process writes X, any successive write to X will see the effect of the first write
  - I.e., newer writes must wait for older ones to finish
  - E.g., local wiki edits (should never edit an older version than the most recent the client has) – may introduce merge conflicts with respect to other clients’ changes!
Read-your-writes / Writes-follow-reads

- **Read-your-writes**: if a process writes X, any successive read to X will see the effect of the write
  - I.e., reads will never see old versions
  - Closely related to monotonic reads
  - Systems that often temporarily lack this consistency:
    - Retrieving websites
    - Updating passwords

- **Writes-follow-reads**: if a process reads X, any successive write to X will see the same value or a more recent one
  - I.e., writes will never see old versions
  - E.g., posts to an email list
Suppose a distributed news service guarantees nothing about consistency except that every news story posted will have a link to the most recent posted story. However, they will not necessarily be received by end users in the same order they are posted. Which client-centric consistency model most closely matches this description?

- A. Monotonic reads
- B. Monotonic writes
- C. Read-your-writes
- D. Writes-follow-reads
- E. None of the above
Consistency protocols

- Continuous consistency protocols
  - Bounding numerical deviation (# of updates)
  - Bounding staleness deviation (time of updates)

- Primary-based protocols
  - Primary: one replica that coordinates all writes for a data item
  - Remote-write: forward all writes to primary (similar to write-through)
  - Local-write: periodic updates sent to primary (similar to write-back)

- Replicated-write protocols
  - Active replication: multicast updates to all replicas
    - Need a reliable and efficient multicast protocol
  - Quorum-based voting: replicas vote on updates to replicas
    - Need a distributed voting/consensus protocol
Distributed version control