CSC 36000:
Modern Distributed Computing *with AI Agents*

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Today's Lecture

Timing in Distributed Systems

Coordination with Mutual Exclusion

Distributed Computing with JAX

Timing in Distributed Systems

Recall: Asynchronous Systems

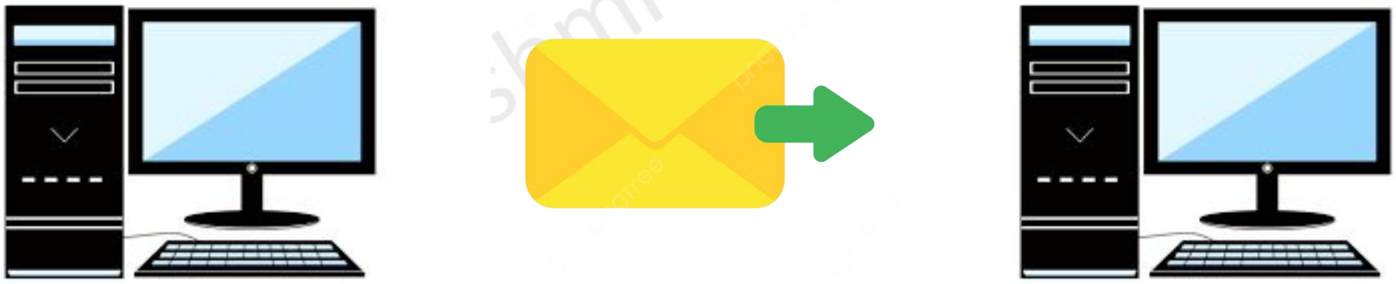
In the vast majority of real-world distributed systems, we don't have access to a **global** clock, only a system-level clock for each process.

Sometimes the time it takes for a message to pass is quite significant

This is a fundamental problem in distributed systems that we need to address!

The Problem with Physical Clocks

- Physical clocks can record the time for a single computer, but cannot be relied upon to maintain the order of messages. This is especially important for applications like banking.



Message Sent: 10:00:00.123

Message Sent: 10:00:00.122

These messages didn't travel back in time, the clocks were out of sync!

The Ordering of Events

- Leslie Lamport - “Time, Clocks, and the Ordering of Events in a Distributed System”
- For many problems, we don’t need to agree on the physical time of an event!
- We only need to agree on the *order*.

The "Happens-Before" Relation (cont.)

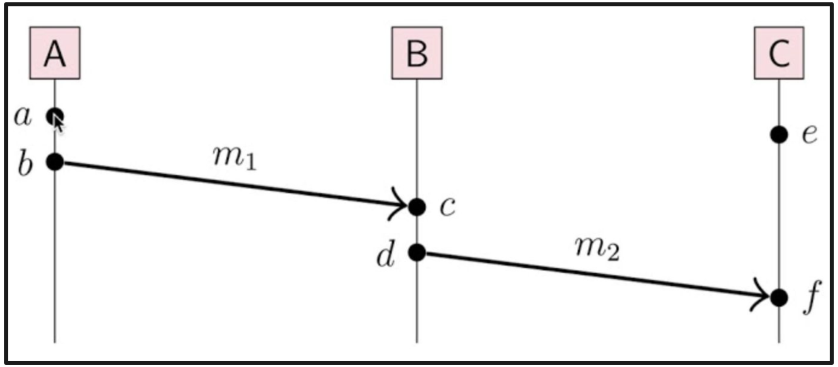
The "happens-before" relation is denoted by an arrow. It's defined by three rules:

1. If two events happen on the same machine, we know their order
2. The act of sending a message must happen before the act of receiving that same message
3. The relation is transitive: if A causes B, and B causes C, then A causes C.

Consider three processes A, B, C and six distinct events a, b, c, d, e, f. In this example:

- a -> b
- b -> c
- b -> f

What else can we say about the order of events in this example?

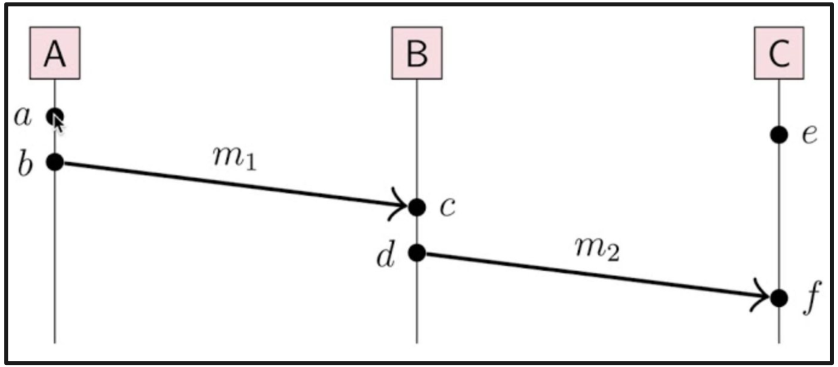


Lamport Timestamps

- Instead of relying on a physical clock, we use a *logical clock*
- Assign a number to each event in the order in which it occurs
    - We call this the *Lamport Timestamp*
- If A -> B (meaning A happens before B) then TS(A) < TS(B)

- In the previous example, we would have:

    TS(a) = 1 TS(b) = 2
    TS(c) = 3 TS(d) = 4
    TS(e) = 1 TS(f) = 5

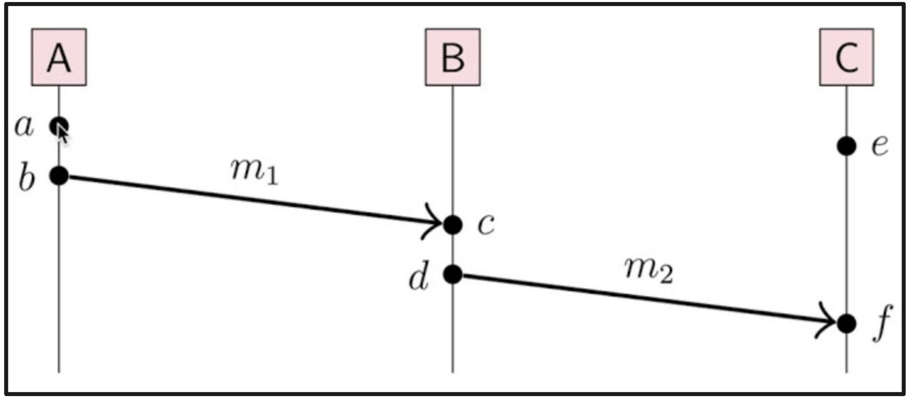


Lamport Clocks

When a process (e.g. A) starts, it's clock is 0
When an event happens, the clock is incremented
When a message is received, the process timestamp becomes the max of its current timestamp and the timestamp of the received message + 1

In the previous example, we would have:

TS(a) = 1
TS(b) = 2
TS(c) = 3
TS(d) = 4
TS(e) = 1
TS(f) = 5



Partial Order vs Total Order

- The "happens-before" relation is a *partial order*, which means concurrent events can have identical timestamps

- Many distributed algorithms require a *total order* to deterministically sequence every event in the system for consistent coordination.

- We can extend the partial order into a total order by using a tie-breaking rule. The standard approach is to use the process ID for events with the same timestamp:

1. If TS(a) < TS(b), event a comes before event b
2. If TS(a) = TS(b) and ID(a) < ID(b), event a comes before event b

Coordination via Mutual Exclusion

Mutual Exclusion

- A "critical section" is a block of code accessing a shared resource (e.g., a file) that cannot be safely executed by multiple processes at the same time.
- We want to enforce *mutual exclusion*: a property that guarantees only one process can enter its critical section at any given time, preventing data corruption.
- On a single computer, this is solved with OS tools like mutexes that rely on shared memory.
  - In most distributed systems, there is no shared memory!
- The only mechanism available for processes to coordinate and solve the mutual exclusion problem is by passing messages to one another.

Approach #1: Centralized

- Designate a single process as a coordinator to manage all access to the critical section.
- A process sends a REQUEST to the coordinator and waits for a GRANT message before entering. When finished, it sends a RELEASE message, allowing the coordinator to grant access to the next process in its queue.
- This is a simple approach, and enforces mutual exclusion
- However, the coordinator represents a critical weakness:
    - If it crashes, the system can no longer access the resource.
    - All requests must be routed through it, creating a bottleneck

Approach #2: Distributed Mutual Exclusion

- A fully distributed, permission-based algorithm with no central coordinator
- Uses the total order of Lamport timestamps to determine who enters the critical section next
- All processes agree to grant access to the request with the earliest timestamp
- Avoids a single point of failure but requires more messages

Distributed Computing with JAX

Introduction to JAX

- JAX is an accelerated Python extension that allows for fast distributed computing
- It looks much the same as NumPy, a very popular Python library for mathematical operations on large arrays of numbers

Example: Numpy to JAX

```
import numpy as np
import jax.numpy as jnp

# JAX arrays look and feel like NumPy arrays
x_np = np.linspace(0, 10, 100)
x_jnp = jnp.linspace(0, 10, 100)

# We can run familiar operations
y_jnp = jnp.sin(x_jnp) * 2.0

print(f"Created a JAX array of shape: {y_jnp.shape}")
print(f"Data type: {y_jnp.dtype}")
```

Recall: Four Key JAX Functions

- `jit`: Just-in-time compilation for speed
- `grad`: Automatic differentiation for training models.
- `vmap`: Automatic vectorization for batching
- `pmap`: Parallel execution across multiple devices

Code Example: `jit`

```
import jax
import jax.numpy as jnp
from jax import jit
import numpy as np

# A function with multiple element-wise
operations
def f(x):
    return jnp.sin(x) + 2 * jnp.cos(x) *
jnp.tanh(x)

# Create a JIT-compiled version using a
decorator
@jit
def f_jit(x):
    return jnp.sin(x) + 2 * jnp.cos(x) *
jnp.tanh(x)
```

```
x = jnp.ones((5000, 5000))

# The first call to f_jit will be
slower due to compilation.
# Subsequent calls will be much
faster than the pure Python version.
print("Running JIT-compiled
version...")
%timeit f_jit(x).block_until_ready()

print("\nRunning pure
Python-dispatched version...")
%timeit f(x).block_until_ready()
```

Code Example: `grad`

```
import jax
import jax.numpy as jnp
from jax import grad

# Define a simple scalar function f(x) = x^3 + 2x
def f(x):
    return x**3 + 2.0 * x

# Use grad to get a new function that computes the derivative, f'(x)
df_dx = grad(f)

# f'(x) = 3x^2 + 2
# Evaluate the derivative at x = 4.0. Expected: 3 * (4^2) + 2 = 50
gradient_value = df_dx(4.0)

print(f"The original function f(4.0) is: {f(4.0)}")
print(f"The gradient df/dx at x=4.0 is: {gradient_value}")
```

Questions?