CS 455: Introduction To Distributed Systems
[Distributed Coordination/Mutual Exclusion]

Shrideep Pallickara
Computer Science
Colorado State University

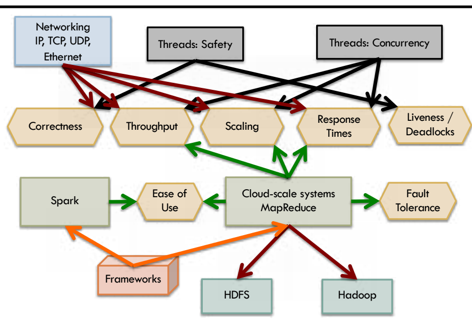
Frequently asked questions from the previous class survey

- Is the streaming data received and buffered on multiple nodes or just one?
- Does 1 batch = 1 RDD?
- Can you (would it be worth it to) call `persist()` on an RDD in Spark Streaming?

Topics covered in this lecture

- Distributed Coordination
- Distributed Mutual Exclusion

The Journey So Far



Distributed Coordination

What we will cover

- Collection of algorithms whose goals vary, but share an aim that is fundamental in distributed systems
  - For a set of processes to:
    - **Coordinate** their actions
    - **Agree** on one or more values

Communication styles

- Asynchronous communications
  - No timing assumptions
- Synchronous communications have bounds on
  - Maximum message transmission delay
  - Time to execute each step of a process
  - Clock drift rates

Allows us to use timeouts to detect process crashes

Coordination & Agreement

- A set of processes need to **coordinate** actions or **agree** on a set of values
- Must be able to do so even when *hierarchical* relationships do not exist
  - E.g.: Controller-Worker where a single point of failure exists

Example: Spaceship

- Multiple computers
- Computers that control spaceship must agree on several conditions
  - E.g., Status: Proceed or abort mission
- Coordinate access to shared resources
  - Sensors, actuators, etc.

Distributed Mutual Exclusion

Distributed processes often need to coordinate their activities

- If a collection of processes share a set of resources **mutual exclusion** is needed to:
  - Prevent interference
  - Ensure consistency
- This is the critical section problem in OS

Distributed mutual exclusion

- Extension to distributed systems of the familiar problem of avoiding race conditions
  - In kernels and multi-threaded applications
- Shared variables or facilities provided by a local kernel cannot be used to solve this
- Solution must be based *solely* on **message passing**

Distributed mutual exclusion

- Consider a set of N processes p_i $\text{i}=1, 2, \ldots, \text{N}$
  - These **do not share variables**
- Processes access common resources
  - They do so in a critical section

Summary of Approaches

Approaches to distributed mutual exclusion

- Token-based solutions
- Permission-based solutions

Token-based solutions

- Mutual exclusion is achieved by *passing* a special message (**token**) between the processes
- There is only one token
  - Whoever has that token is allowed to access shared resource
- When finished, token is passed to another process

Token-based solutions: Advantages

- Depending on how processes are organized, fairly easy to avoid starvation
- Deadlocks can also be avoided

Token-based solutions: Disadvantages

- When the token is **lost** – for *e.g.,* process holding the token crashes, complex actions need to be taken
- Intricate distributed process needs to be initiated
  - Ensure that a ***new*** token is created
  - But above all, make sure that that is the ***only*** token

Permission-based solutions

- Process wanting to access resource first requires **permission** of *other* processes
- Many different ways to granting this permission

Structural considerations for the solution

- With a central server
- Without a central server
  - Peer processes must coordinate their accesses to shared resources
  - Occurs routinely on Ethernets and IEEE 802.11 wireless
    - Network interfaces cooperate as peers so that only one node transmits at a time on the shared medium
    - Ethernet: Method of operation "Carrier Sensing, Multiple Access with Collision Detection" or CSMA/CD
    - Wireless: "Carrier Sensing, Multiple Access with Collision Avoidance" CSMA/CA

ASSUMPTION & REQUIREMENTS

Assumptions in our algorithms

- The system is asynchronous
- Processes do not fail
- Message delivery is reliable
  - Delivered eventually and exactly-once

Application level protocol for entering the critical section

- `enter()`
  - **Block** if necessary
- `resourceAccesses()`
  - **Access shared resources** in the critical section
- `exit()`
  - Allow other processes to enter

Requirements for distributed mutual exclusion

- **ME1:** *At most one* process may execute in the critical section at a time
  - **Safety**
- **ME2:** Requests to enter and exit the critical section *eventually succeed*
  - **Liveness:** Freedom from **deadlocks** and **starvation**
- **ME3:** If one request *happened-before* another, then entry to the CS is granted in that order

Evaluation of the algorithms

- **Bandwidth consumed**
  - Proportional to number of messages sent in each entry and exit operation
- **Client delay** incurred by process for each entry or exit operation
- Effect on **throughput** of the system
  - **Synchronization delay** between one process exiting critical section and next process entering it
  - Throughput is greater when synchronization delay is shorter

The Central Server Algorithm

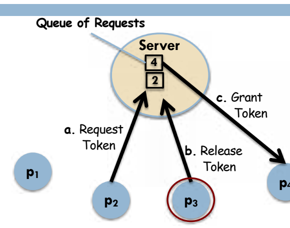
The central server algorithm

- Simplest way to achieve mutual exclusion
- Central server *grants authorization* to enter the critical section
- To enter a critical section, process sends request message to the server
  - Awaits reply from server
  - Reply constitutes **token** signifying authorization to enter critical section

Acquisition of token

- If no process holds the token?
  - Server replies immediately granting token
- If the token is held by another process?
  - Server does not reply, but *queues the request*
  - When that process exits the critical section, it sends a message giving server back the token
    - If the queue of waiting processes is non-empty, **server chooses oldest entry** in the queue and sends it the token

Server managing a mutual exclusion token



Evaluating the central server algorithm [1/2]

- Entering critical section
  - Requires 2 messages: `Request` followed by `grant`
  - Delay at the requesting process?
    - Round trip delay
      - There is also the *queuing delay* for messages residing in the queue
- Exiting the critical section requires one *release* message
  - Assuming asynchronous communications means that this does not delay the exiting process

Evaluating the central server algorithm [2/2]

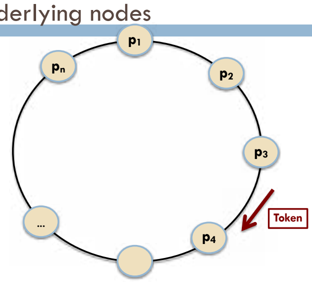
- Synchronization delay
  - `Release` message to server followed by `grant` to another process: Round trip time
- Server is a *performance bottleneck* for the system
  - Single point of failure as well

Ring based algorithm

Ring-based algorithm

- Arrange mutual exclusion between N processes **without** requiring an additional process
- Each process p_i has a communication channel to the next process in the ring, $p_{(i+1) mod N}$
- Exclusion is conferred by obtaining a token that is *passed from process to process* in a single direction around the ring
  - E.g. clockwise

Ring topology is unrelated to physical connections between underlying nodes



Acquisition of token

- When a process that does not need to enter critical section receives the token?
  - Immediately forwards token to its neighbor
- Process that requires token, **waits** until it receives it **and then retains it**
- To **exit** the critical section, process **sends token** to neighbor

Properties satisfied by the ring algorithm

- Satisfies **ME1** and **ME2**
- Token is not necessarily acquired in a happened-before manner (**ME3**)

Performance analysis [1/2]

- **Continuously** consumes network bandwidth (except when process is in critical section)
  - Processes send messages around ring even when no process requires critical section entry
- Delay experienced by process requesting entry to critical section?
  - 0: when it has just received the token
  - N messages when it has just passed on the token

Performance analysis [2/2]

- Exit from critical section
  - Requires only 1 message
- Synchronization delay between one process' exit and another process' entry into critical section
  - Anywhere between 1 and N message transmissions

Mutual Exclusion using Multicast and Logical Clocks Ricart & Agarwala's Algorithm}

Logical Clocks: If two processes do not interact with each other

- Their clocks need not be synchronized
- Lack of synchronization is not observable
  - Does not cause problems

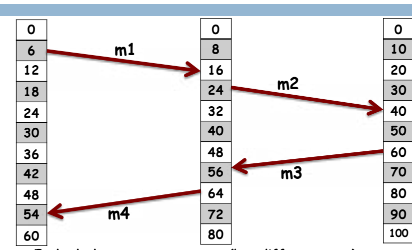
Lamport's logical clocks

- The **happens-before** relation ➔
- *a* and *b* are events in the process; and *a* occurs before *b*
  - Then *a* ➔ *b* is true
- *a* is event of message sent by one process;
  b is event of message being received in another process
  - Then *a* ➔ *b* is true

Some more things about the happens-before relation

- If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$
  - **Transitive**
- If events x and y occur in processes that do not exchange messages, then …
  - $x \rightarrow y$ is not true
  - But, neither is $y \rightarrow x$
  - These events are said to be **concurrent**

An example of Lamport's algorithm:



Each clock runs at a constant (but different rate)

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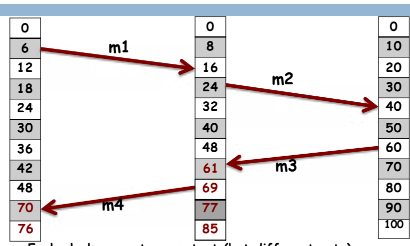
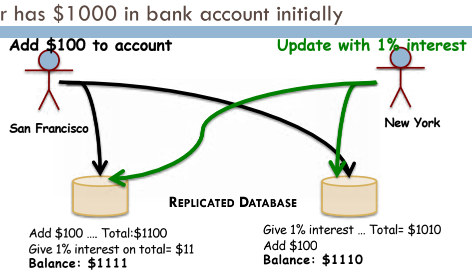


Each clock runs at a constant (but different rate)

Implementing Lamport'c clocks

1. Before executing an event; P_i executes
   $C_i \leftarrow C_i + 1$
2. When P_i sends a message m to P_j ; it sets m's timestamp $ts(m)$ to C_i in previous step
3. Upon receipt of message m, P_j adjusts its own local counter
   $C_j \leftarrow max\{C_j, ts(m)\}$
   do step (1) and deliver message

An application of Lamport's clock: User has $1000 in bank account initially



There is a difference when the orders are reversed

- Our objective for now is consistency
- Both copies must be exactly the same
- Situations like this require **totally-ordered multicast**
  - All messages are delivered in the same order to each receiver
  - Lamport's logical clocks allow us to accomplish this in a completely distributed fashion

Using Lamport's clock to order messages

- Process puts received messages into local queue
  - Ordered according to the message's timestamp
- Message can be delivered only if it is **acknowledged** by all the other processes
- If a message is at the head of the queue, and acknowledged by all processes
  - It is delivered and processed

Other types of logical clocks

- Vector clocks
- Matrix clocks

The contents of this slide set are based on the following references

- Distributed Systems: Concepts and Design. George Coulouris, Jean Dollimore, Tim Kindberg, Gordon Blair. 5th Edition. Addison Wesley. ISBN: 978-0132143011 [Chapter 15]