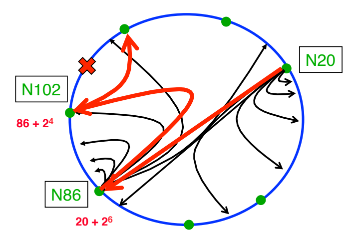
CSE 486/586 Distributed Systems
Consensus

Steve Ko
Computer Sciences and Engineering
University at Buffalo

Recap: Finger Table

- Finding a <key, value> using fingers



Let's Consider This…

Amazon EC2 Service Level Agreement

Effective Date: October 23, 2008
This Amazon EC2 Service Level Agreement ("SLA") is a policy governing the use of the Amazon Elastic Compute Cloud ("Amazon EC2") under the terms of the Amazon Web Services Customer Agreement (the "AWS Agreement") between Amazon Web Services, LLC ("AWS", "us" or "we") and users of AWS' services ("you"). This SLA applies separately to each account using Amazon EC2. Unless otherwise provided herein, this SLA is subject to the terms of the AWS Agreement and capitalized terms will have the meaning specified in the AWS Agreement. We reserve the right to change the terms of this SLA in accordance with the AWS Agreement.

Service Commitment
AWS will use commercially reasonable efforts to make Amazon EC2 available with an Annual Uptime Percentage (defined below) of at least 99.95% during the Service Year. In the event Amazon EC2 does not meet the Annual Uptime Percentage commitment, you will be eligible to receive a Service Credit as described below.

Definitions

- "Service Year" is the preceding 365 days from the date of an SLA claim.
- "Annual Uptime Percentage" is calculated by subtracting from 100% the percentage of 5 minute periods during the Service Year in which Amazon EC2 was in the state of "Region Unavailable." If you have been using Amazon EC2 for less than 365 days, your Service Year is still the preceding 365 days but any days prior to your use of the service will be deemed to have had 100% Region Availability. Any downtime occurring prior to a successful Service Credit claim cannot be used for future claims. Annual Uptime Percentage measurements exclude downtime resulting directly or indirectly from any Amazon EC2 SLA Exclusion (defined below).
- "Region Unavailable" and "Region Unavailability" means that more than one Availability Zone in which you are running an instance, within the same Region, is "Unavailable" to you.
- "Unavailable" means that all of your running instances have no external connectivity during a five minute

One Reason: Impossibility of Consensus

- Q: Should Steve give an A to everybody taking CSE 486/586?
- Input: everyone says either yes/no.
- Output: an agreement of yes or no.
- Bad news
  - Asynchronous systems cannot guarantee that they will reach consensus even with one faulty process.
- Many consensus problems
  - Reliable, totally-ordered multicast (what we saw already)
  - Mutual exclusion, leader election, etc. (what we will see)
  - Cannot reach consensus.

The Consensus Problem

- N processes
- Each process p has
  - input variable x_p : initially either 0 or 1
  - output variable y_p : initially b (b=undecided) – can be changed only once
- Consensus problem: Design a protocol so that either
  - all non-faulty processes set their output variables to 0
  - Or all non-faulty processes set their output variables to 1
  - There is at least one initial state that leads to each outcomes 1 and 2 above

Assumptions (System Model)

- Processes fail only by *crash-stop*ping
- Synchronous system: bounds on
  - Message delays
  - Max time for each process step
  - e.g., multiprocessor (common clock across processors)
- Asynchronous system: no such bounds
  - E.g., the Internet

Example: State Machine Replication

- Run multiple copies of a state machine
- For what?
  - Reliability
- All copies agree on the order of execution.
- Many mission-critical systems operate like this.
  - Air traffic control systems, Warship control systems, etc.

First: Synchronous Systems

- Every process starts with an initial input value (0 or 1).
- Every process keeps the history of values received so far.
- The protocol proceeds in *rounds*.
- At each round, everyone multicasts the history of values.
- After all the rounds are done, pick the minimum.

First: Synchronous Systems

- For a system with at most f processes crashing, the algorithm proceeds in f+1 rounds (with timeout), using basic multicast (B-multicast).
- $Values^r_i$: the set of proposed values known to process p=P_i at the beginning of round r.
- Initially $Values^0_i$ = {} ; $Values^1_i$ = {v_i=x_p}

```
for round r = 1 to f+1 do
      multicast (Values^r_i)
      Values^(r+1)_i ← Values^r_i
      for each V_j received
          Values^(r+1)_i = Values^(r+1)_i ∪ V_j
      end
end
y_p=d_i = minimum(Values^(f+1)_i)
```


Why Does It Work?

- Assume that two non-faulty processes differ in their final set of values → proof by contradiction
- Suppose p_i and p_j are these processes.
- Assume that p_i possesses a value v that p_j does not possess.
- Intuition: p_j must have consistently missed v in all rounds. Let's backtrack this.
  - → In the last round, some third process, p_k, sent v to p_i, and crashed before sending v to p_j.
  - → Any process sending v in the penultimate round must have crashed; otherwise, both p_k and p_j should have received v.
  - → Proceeding in this way, we infer at least one crash in each of the preceding rounds.
  - → But we have assumed at most f crashes can occur and there are f+1 rounds ==> contradiction.

Second: Asynchronous Systems

- Messages have arbitrary delay, processes arbitrarily slow
- Impossible to achieve consensus
  - even a single failed is enough to avoid the system from reaching agreement!
  - a slow process indistinguishable from a crashed process
- Impossibility applies to any protocol that claims to solve consensus
- Proved in a now-famous result by Fischer, Lynch and Patterson, 1983 (FLP)
  - Stopped many distributed system designers dead in their tracks
  - A lot of claims of "reliability" vanished overnight

Are We Doomed?

- Asynchronous systems (i.e., systems with arbitrary delay) cannot guarantee that they will reach consensus even with one faulty process.
- Key word: "guarantee"
  - *Does not* mean that processes can *never* reach a consensus if one is faulty
  - Allows room for reaching agreement with some probability greater than zero
  - In practice many systems reach consensus.
- How to get around this?
  - Two key things in the result: one faulty process & arbitrary delay

Techniques to Overcome Impossibility

- Technique 1: masking faults (crash-stop)
  - For example, use persistent storage and keep local checkpoints
  - Then upon a failure, restart the process and recover from the last checkpoint.
  - This masks fault, but may introduce arbitrary delays.
- Technique 2: using failure detectors
  - For example, if a process is slow, mark it as a failed process.
  - Then actually kill it somehow, or discard all the messages from that point on (fail-silent)
  - This effectively turns an asynchronous system into a synchronous system
  - Failure detectors might not be 100% accurate and requires a long timeout value to be reasonably accurate.

CSE 486/586 Administrivia

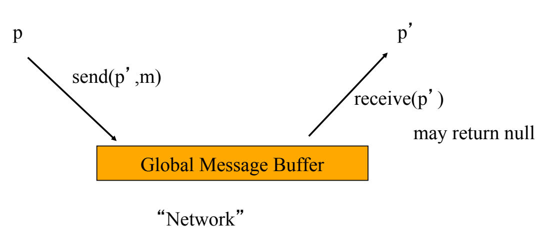
- PA2-B due on Friday (3/11)
  - Please do not use someone else's code!
- Midterm on Wednesday (3/9)
  - Cheat sheet allowed (letter-sized, front-and-back)
- Recitations this Friday and next Monday for undergrads

Recall

- Each process p has a state
  - program counter, registers, stack, local variables
  - input register xp : initially either 0 or 1
  - output register yp : initially b (b=undecided)
- Consensus Problem: Design a protocol so that either
  - all non-faulty processes set their output variables to 0
  - Or non-faulty all processes set their output variables to 1
  - (No trivial solutions allowed)

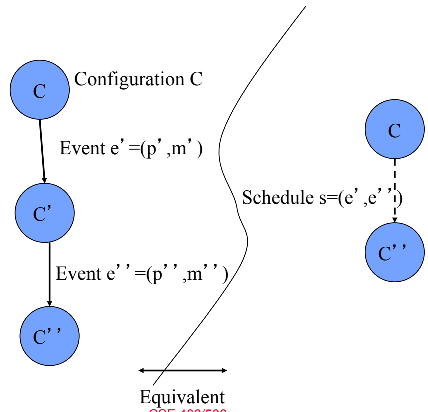
Proof of Impossibility: Reminder

- State machine
  - Forget real time, everything is in steps & state transitions.
  - Equally applicable to a single process as well as distributed processes
- A state (S1) is reachable from another state (S0) if there is a sequence of events from S0 to S1.
- There an initial state with an initial set of input values.



Different Definition of "State"

- State of a process
- Configuration: = Global state. Collection of states, one per process; and state of the global buffer
- Each Event consists atomically of three sub-steps:
  - receipt of a message by a process (say p), and
  - processing of message, and
  - sending out of all necessary messages by p (into the global message buffer)
- Note: this event is different from the Lamport events
- Schedule: sequence of events



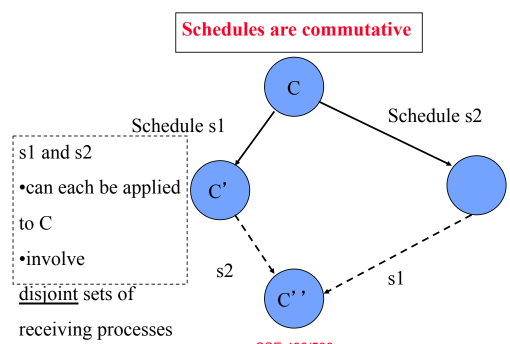
State Valencies

- Let config. C have a set of decision values V reachable from it
  - If |V| = 2, config. C is bivalent
  - If |V| = 1, config. C is said to be 0-valent or 1-valent, as is the case
- Bivalent means that the outcome is unpredictable (but still doesn’t mean that consensus is not guaranteed). Three possibilities:
  - Unanimous 0
  - Unanimous 1
  - 0’s and 1’s

Guaranteeing Consensus

- If we want to say that a protocol guarantees consensus (with one faulty process & arbitrary delays), we should be able to say the following:
- Consider all possible input sets (i.e., all initial configurations).
- For each input set (i.e., for each initial configuration), the protocol should produce either 0 or 1 even with one failure for all possible execution paths (runs).
  - I.e., no “0’s and 1’s”
- The impossibility result: We can’t do that.
  - I.e., there is always a run that will produce “0’s and 1’s”.

Lemma 1



The Theorem

- Lemma 2: There exists an initial configuration that is bivalent
- Lemma 3: Starting from a bivalent config., there is always another bivalent config. that is reachable
- Insight: It is not possible to distinguish a faulty node from a slow node.
- Theorem (Impossibility of Consensus): There is always a run of events in an asynchronous distributed system (given any algorithm) such that the group of processes never reaches consensus (i.e., always stays bivalent)

Summary

- Consensus: reaching an agreement
- Possible in synchronous systems
- Asynchronous systems cannot guarantee.
  - Asynchronous systems cannot guarantee that they will reach consensus even with one faulty process.

Acknowledgements

- These slides contain material developed and copyrighted by Indranil Gupta (UIUC).