Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Acknowledgements: Indy Gupta and Nikita Borisov

Midterm 1 next week Wed-Fri

- Detailed instructions shared on CampusWire (post #98).
  - Go over them again.
  - Reserve a slot if you haven't already.
  - Submit your Letters of Accommodations to CBTF, if required.
  - Syllabus: everything covered in class upto and including Global State.
  - Closed-book exam: cannot refer to any materials.
    - We will provide a cheatsheet over PrairieLearn.
    - Shared in post #98
  - CBTF will provide calculator and scratch paper.
  - *Dummy Quiz has been released on PrairieLearn.*

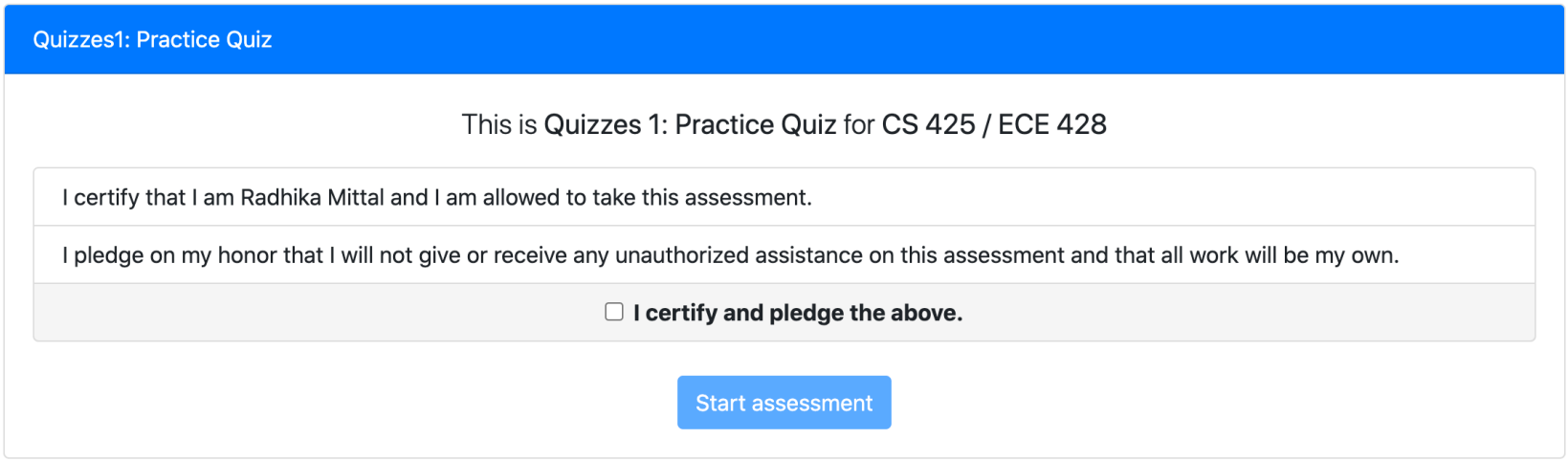
Midterm exam

- Syllabus:
  - everything up to and including Global State.
- Exam duration: 50mins
  - Extra time to check-in and settle in.

PrairieLearn

- Exam format:
  - Multiple choice questions:
    - Single answer correct; True/False
    - Multiple answers may be correct.
  - Numerical questions
    - No step marking!
  - Ensure all your responses are "saved" and none are "invalid".

PrairieLearn: interface example



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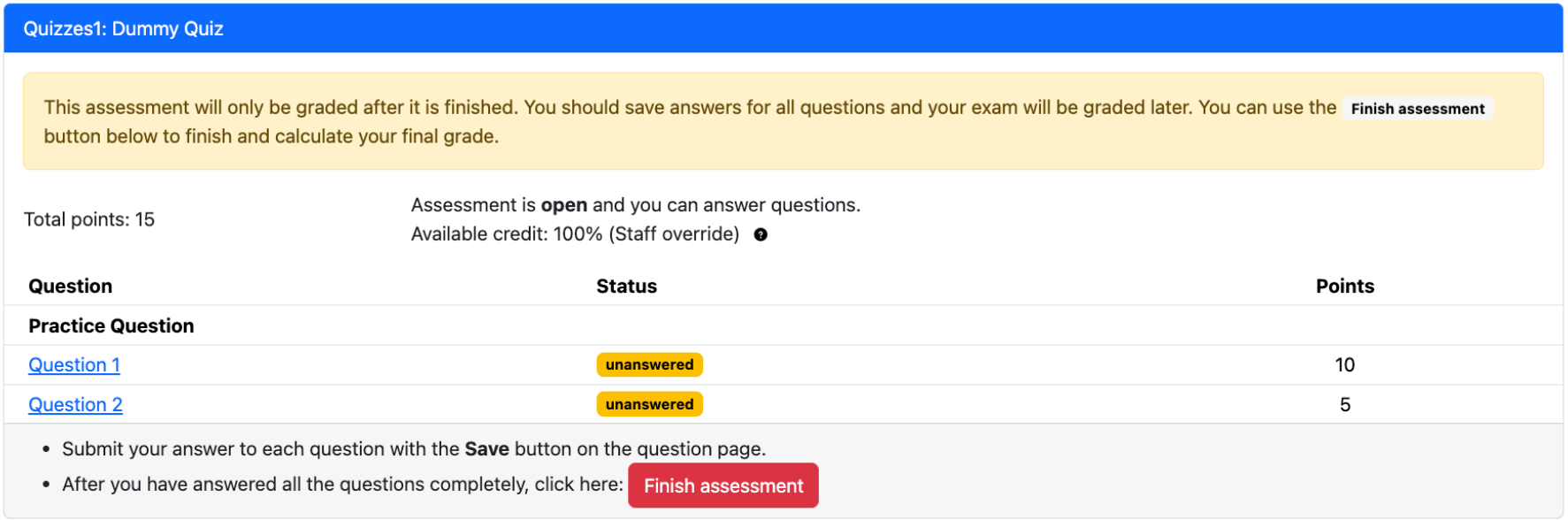
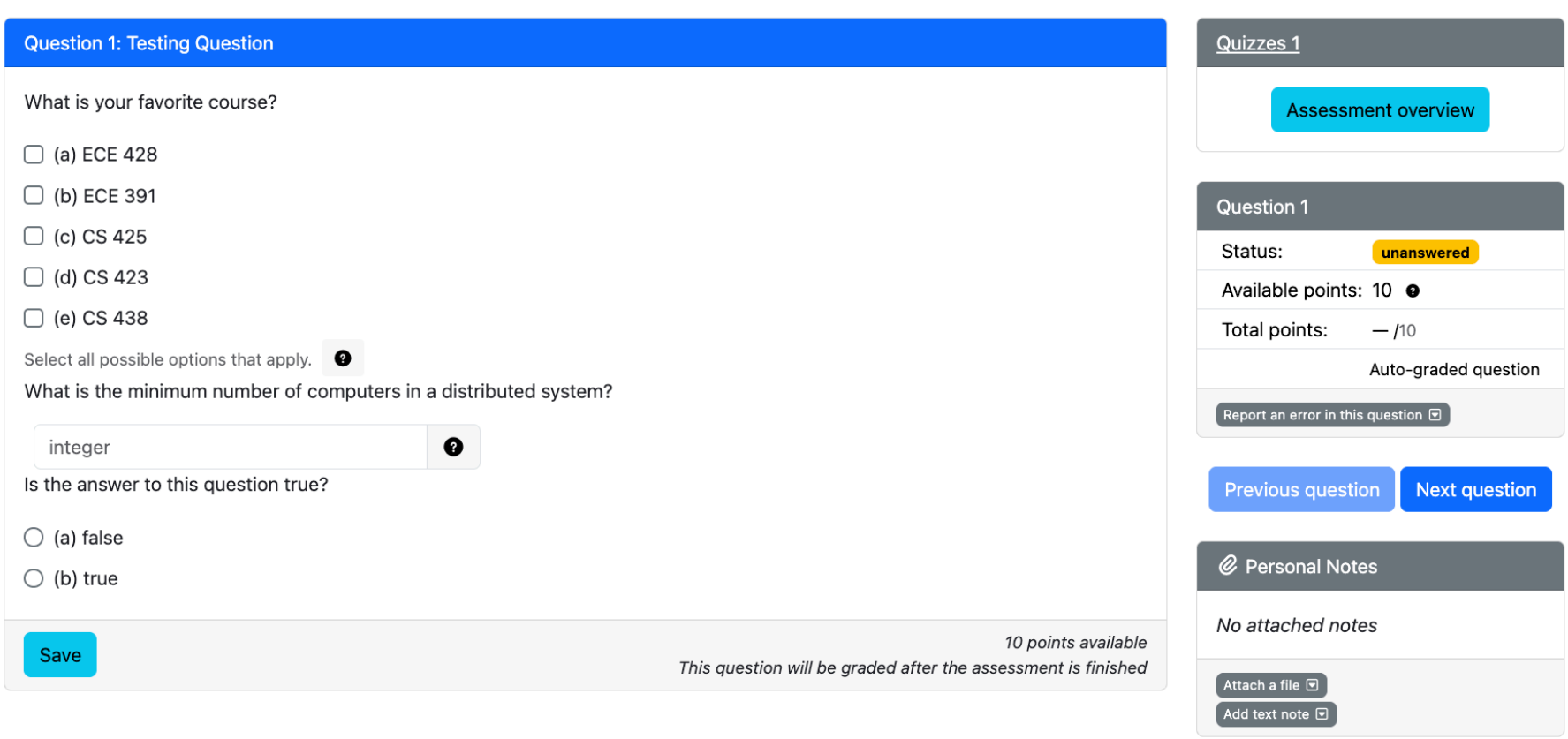


This demo has only two questions. Your midterm will display more questions.

PrairieLearn: interface example



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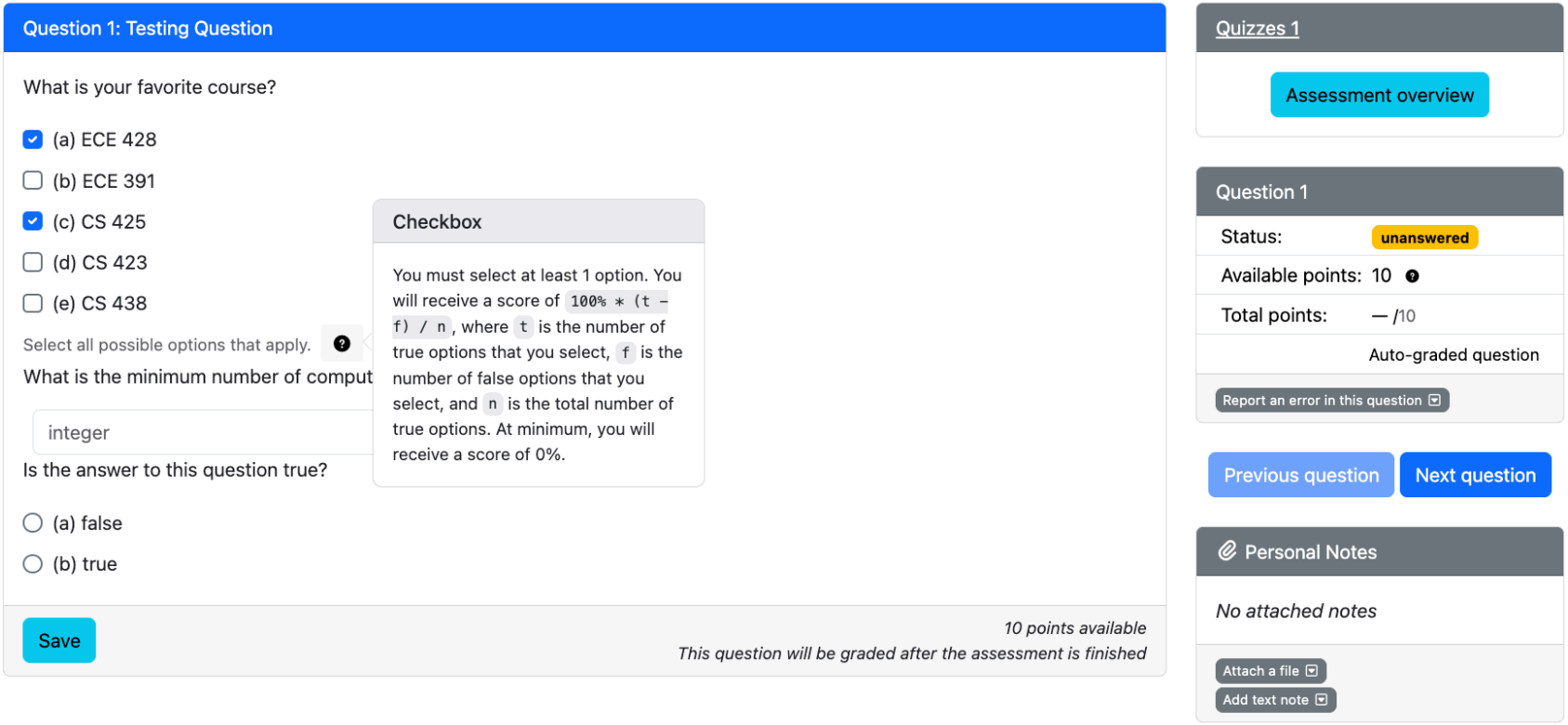

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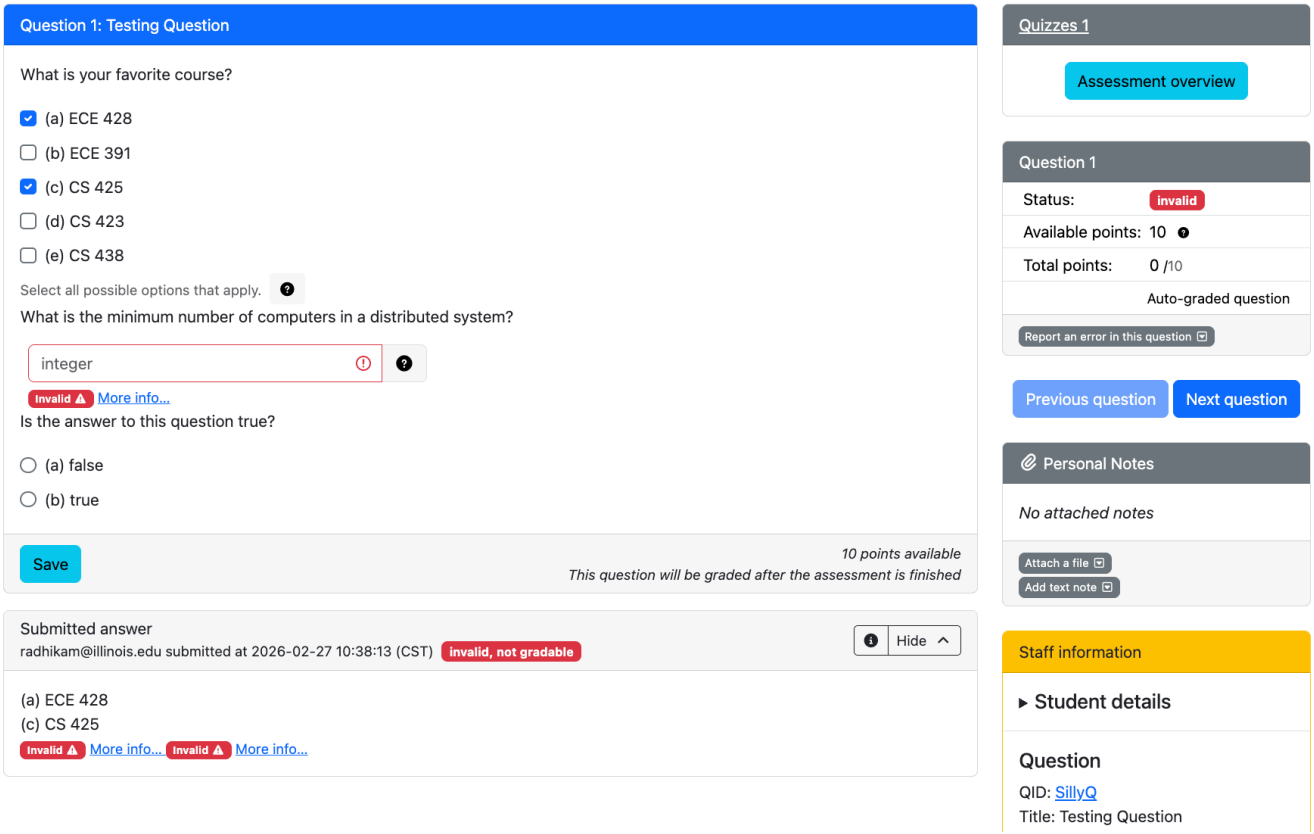
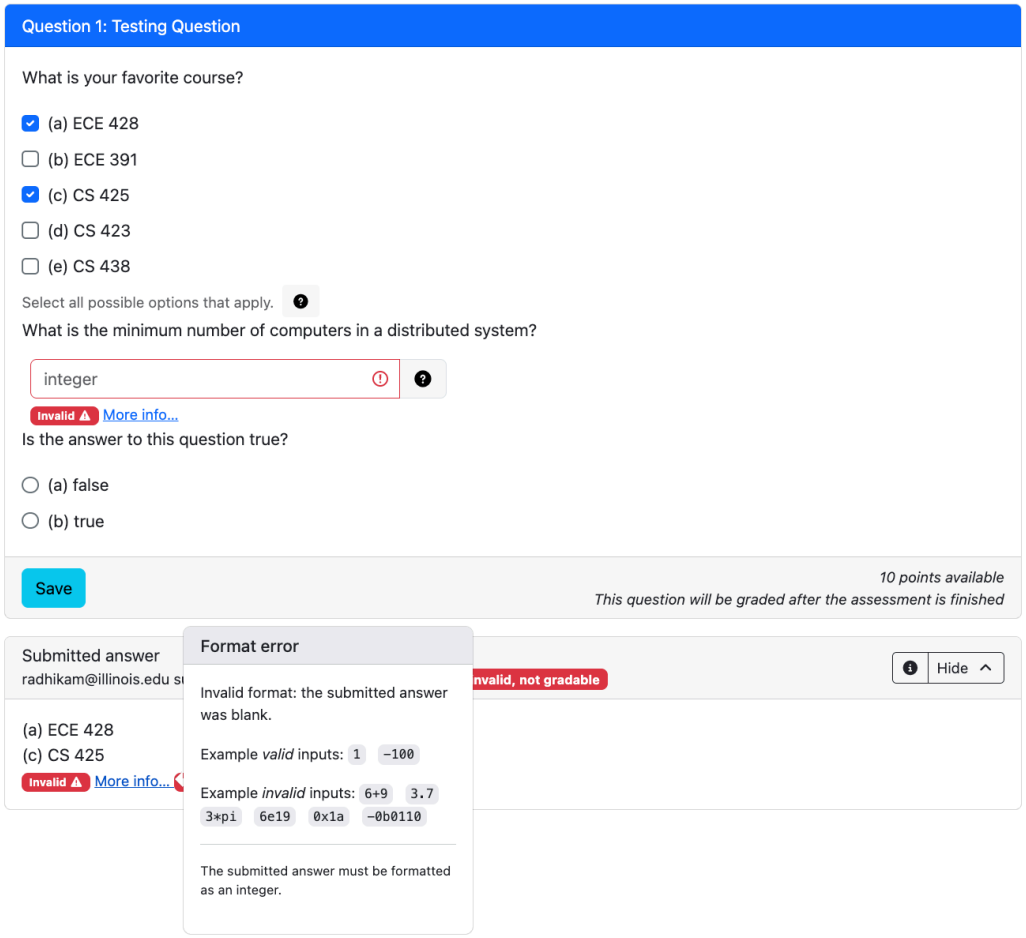


You must attempt all subparts of a given question for the question to be gradable.

PrairieLearn: interface example



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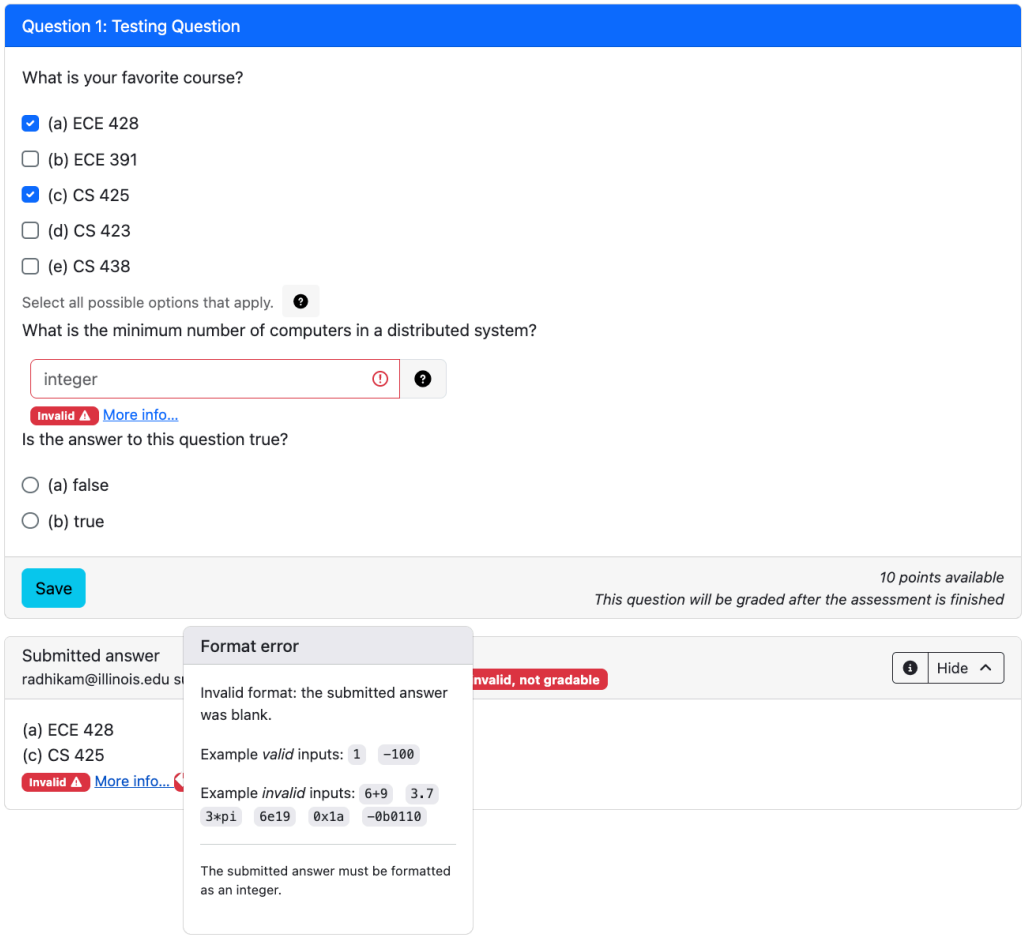

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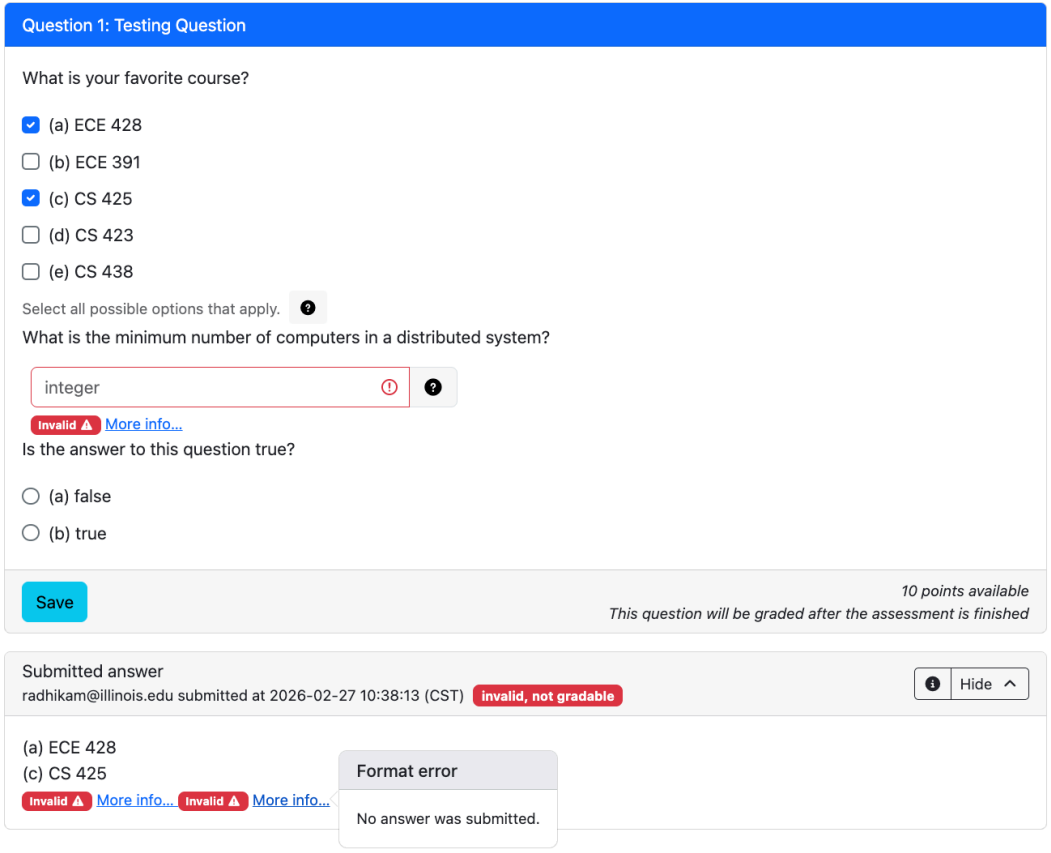

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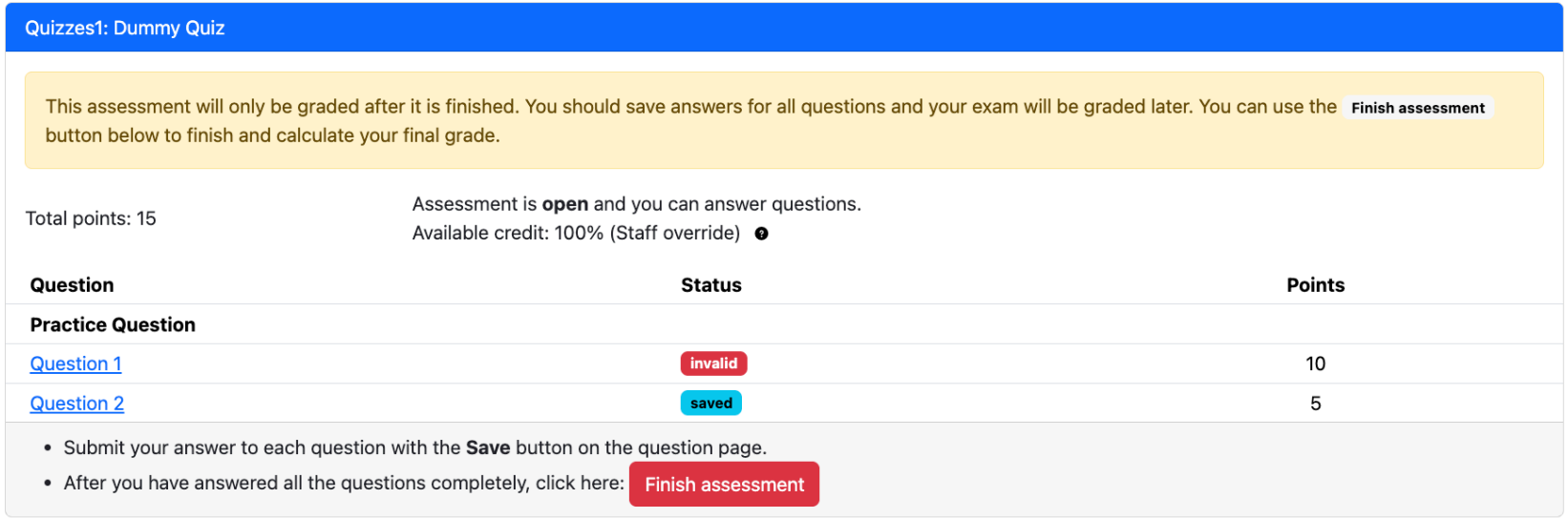
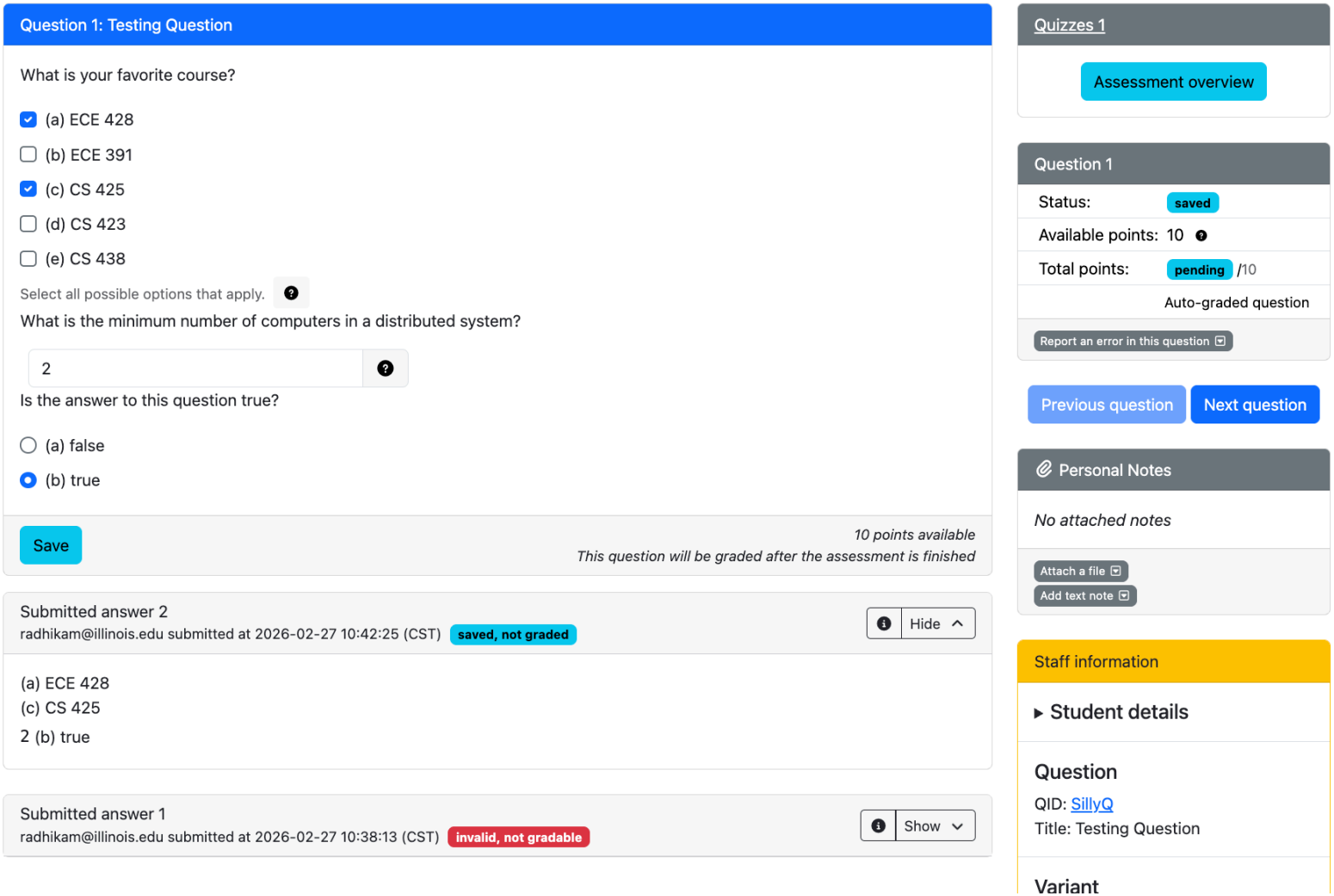


Valid responses saved for other questions will not be affected.

PrairieLearn: interface example



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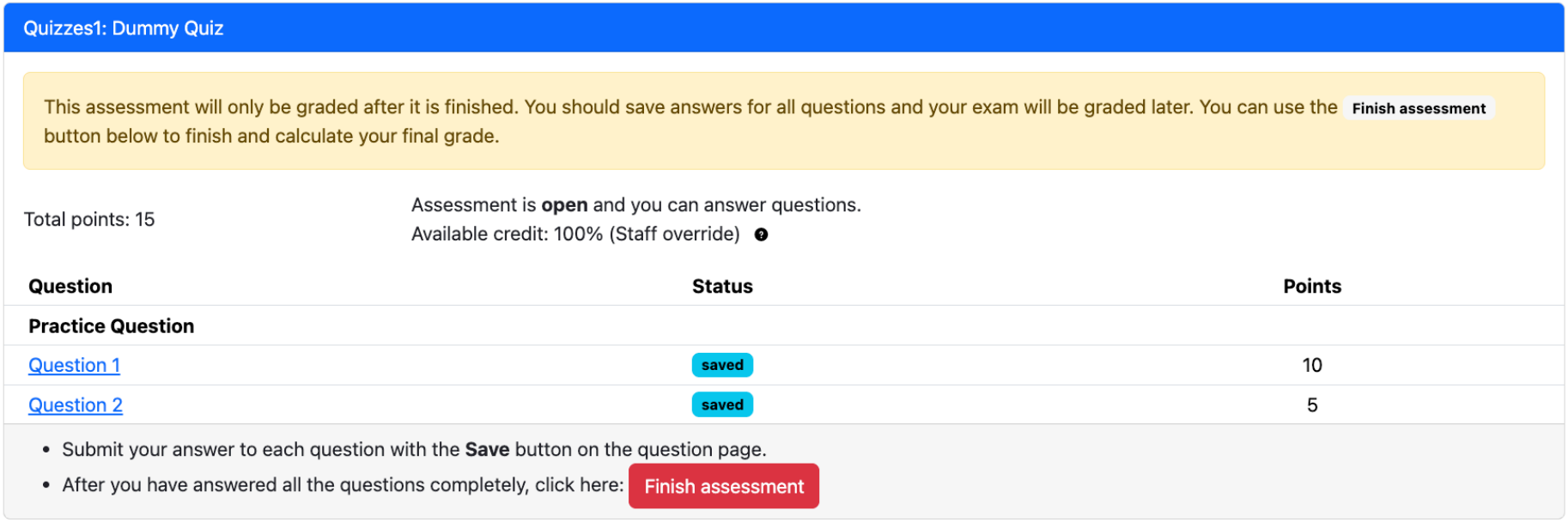


Today's agenda

- **Leader Election (contd)**
  - Chapter 15.3
- **Goal:**
  - What is leader election in distributed systems?
  - How do we elect a leader?
  - To what extent can we handle failures when electing a leader?
- **Exam Review**

Calling for an Election

- Any process can call for an election.
- A process can call for at most one election at a time.
- Multiple processes are allowed to call an election simultaneously.
  - All of them together must yield only a single leader
- The result of an election should not depend on which process calls for it.

Election Problem, Formally

- A run of the election algorithm must always guarantee:
  - **Safety**: For all non-faulty processes *p*:
    - *p* has elected:
      - (q: a particular non-faulty process with the *best attribute value*)
      - or Null
  - **Liveness**: For all election runs:
    - election run terminates
    - & for all non-faulty processes *p*: *p*'s elected is not Null
- At the end of the election protocol, the non-faulty process with the best (highest) election attribute value is elected.
  - Common attribute : leader has highest id
  - Other attribute examples: leader has fastest cpu, or most disk space, or most number of files, etc.

System Model

- *N* processes.
- Messages are eventually delivered.
- Failures may occur during the election protocol.
- **Each process has a unique id.**
  - Each process has a unique attribute (based on which Leader is elected).
  - If two processes have the same attribute, combine the attribute with the process id to break ties.

Classical Election Algorithms

- Ring election algorithm
- Bully algorithm

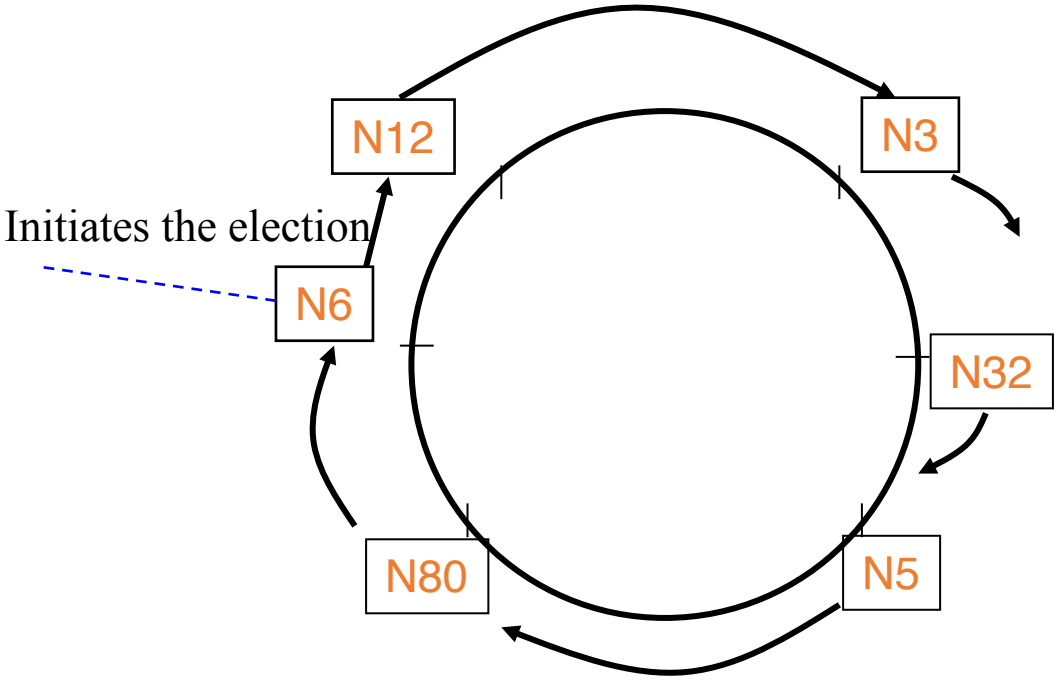
Ring Election Protocol [Chang & Roberts'79]

- When Pi start election
  - send election message with Pi's <$attr_i$, i> to ring successor.
  - set state to participating
- When Pj receives message (election, <$attr_x$, x>) from predecessor
  - If ($attr_x$, x) > ($attr_j$, j):
    - forward message (election, <$attr_x$, x>) to successor
    - set state to participating
  - If ($attr_x$, x) < ($attr_j$, j)
    - If (not participating):
      - send (election, <$attr_j$, j>) to successor
      - set state to participating
  - If ($attr_x$, x) = ($attr_j$, j) : Pj is the elected leader (why?)
    - send elected message containing Pj's id.
- elected message forwarded along the ring until it reaches the leader.
  - Set state to not participating when an elected message is received.

Performance Analysis

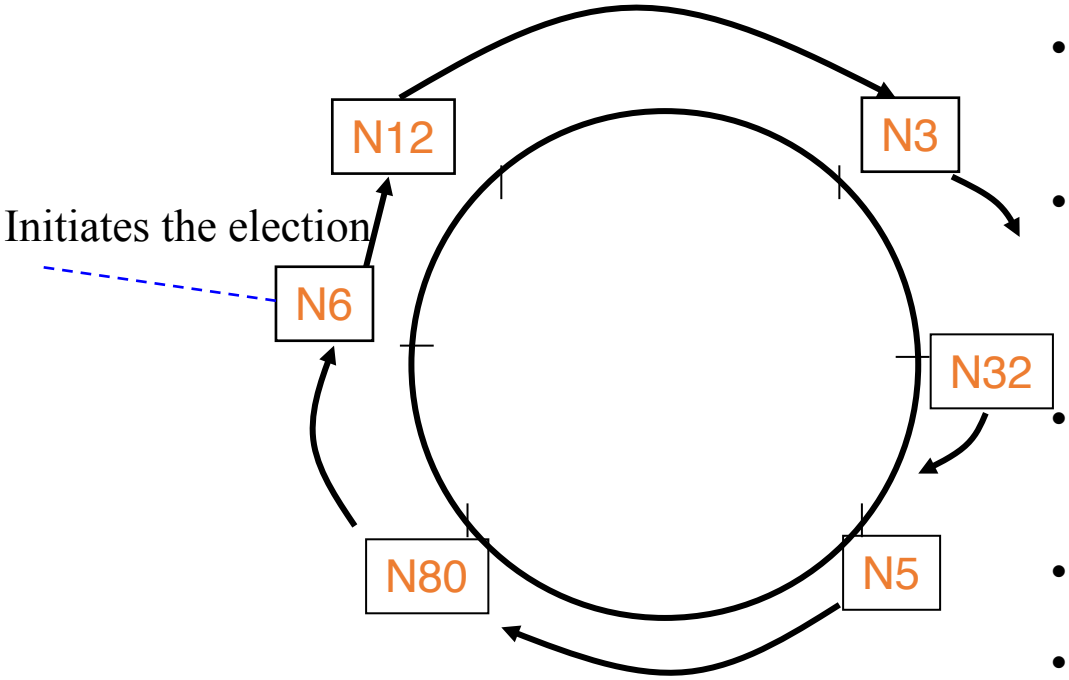
- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- Let's also assume that only one process initiates the algorithm
- **Bandwidth usage:** Total number of messages sent.
- **Turnaround time:** The number of serialized message transmission times between the initiation and termination of a single run of the algorithm.

Worst-case



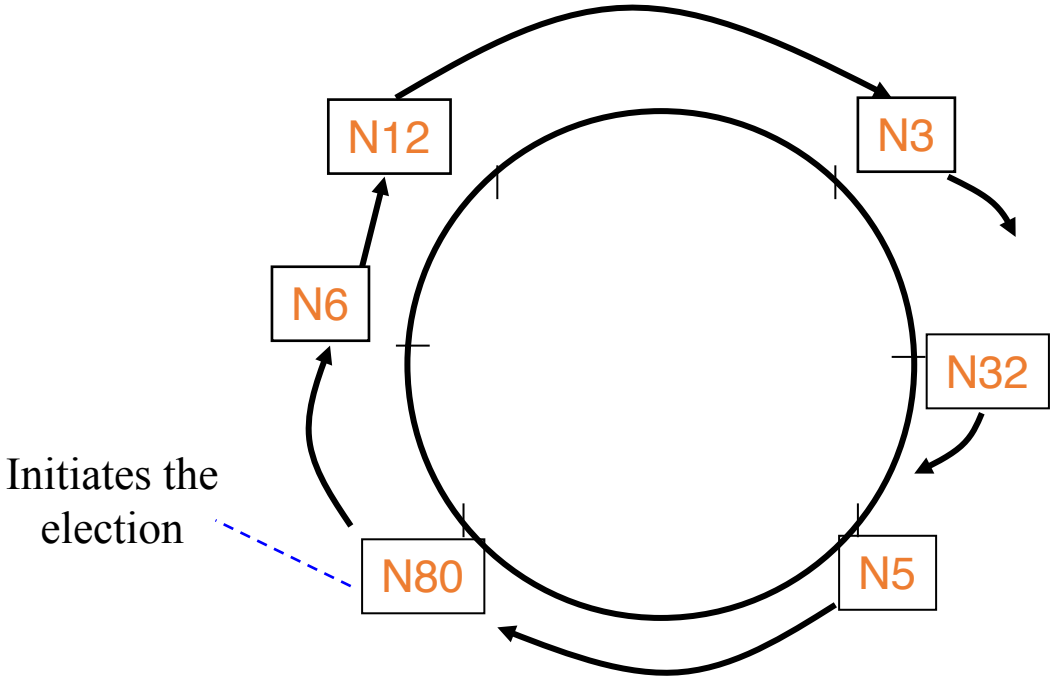
When the initiator is the ring successor of the would-be leader.

Worst-case



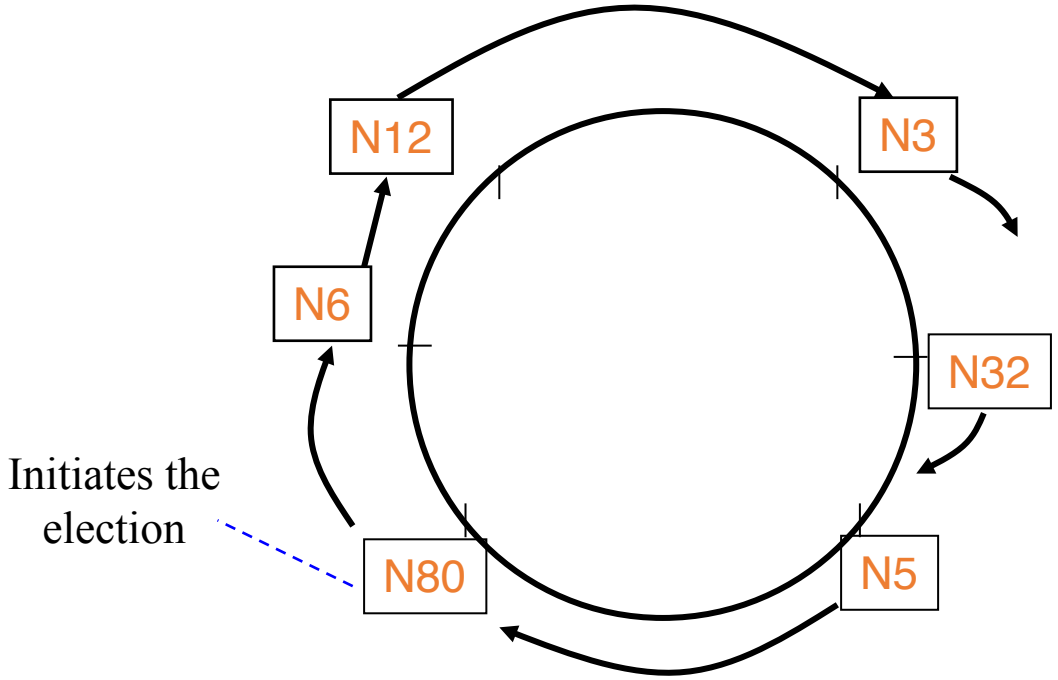
- (N-1) messages for Election message to get from N6 to N80.
- N messages for Election message to circulate around ring without message being changed.
- N messages for Elected message to circulate around the ring
- **No. of messages: (3N-1)**
- **Turnaround time: (3N-1) message transmission times**

Best-case



When the initiator is the would-be leader.

Best-case



When the initiator is the would-be leader.

No. of messages: 2N

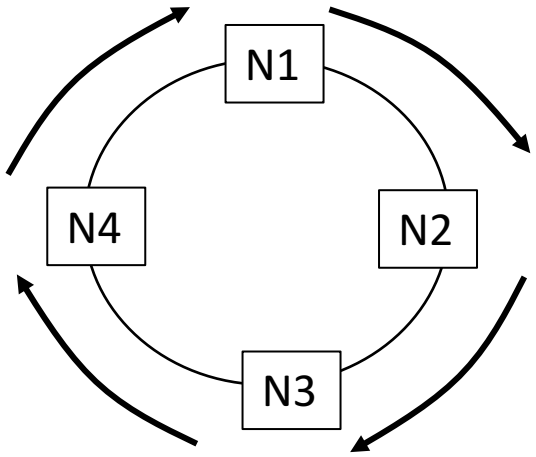
Turnaround time:
2N message transmission times

Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- Let's also assume that only one process initiates the algorithm
- Bandwidth usage (total number of messages)
  - O(N): Worst case = 3N - 1; Best case = 2N.
- O(N) turnaround time.

Performance Analysis

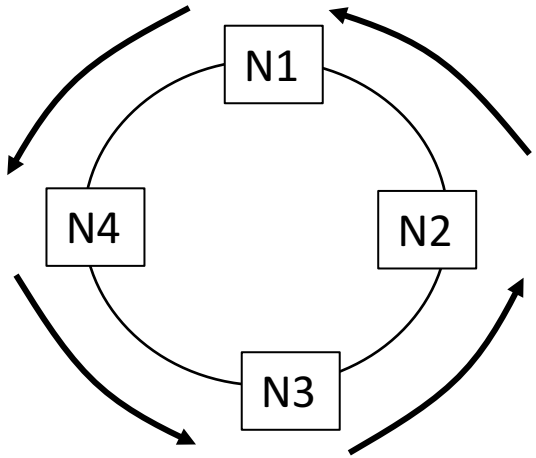
- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.



- N election messages generated at the start of algorithm.
- Only one survives, and completes a full round.
  - N-1 more messages.
- One round for the elected message
  - N messages.
- Total: 3N-1 messages

Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.
  - O(N^2) in worst-case.



- N election messages generates at the starts of algorithm.
- N - 1 survive the next time step.
- N – 2 survive the next time step.
- ….

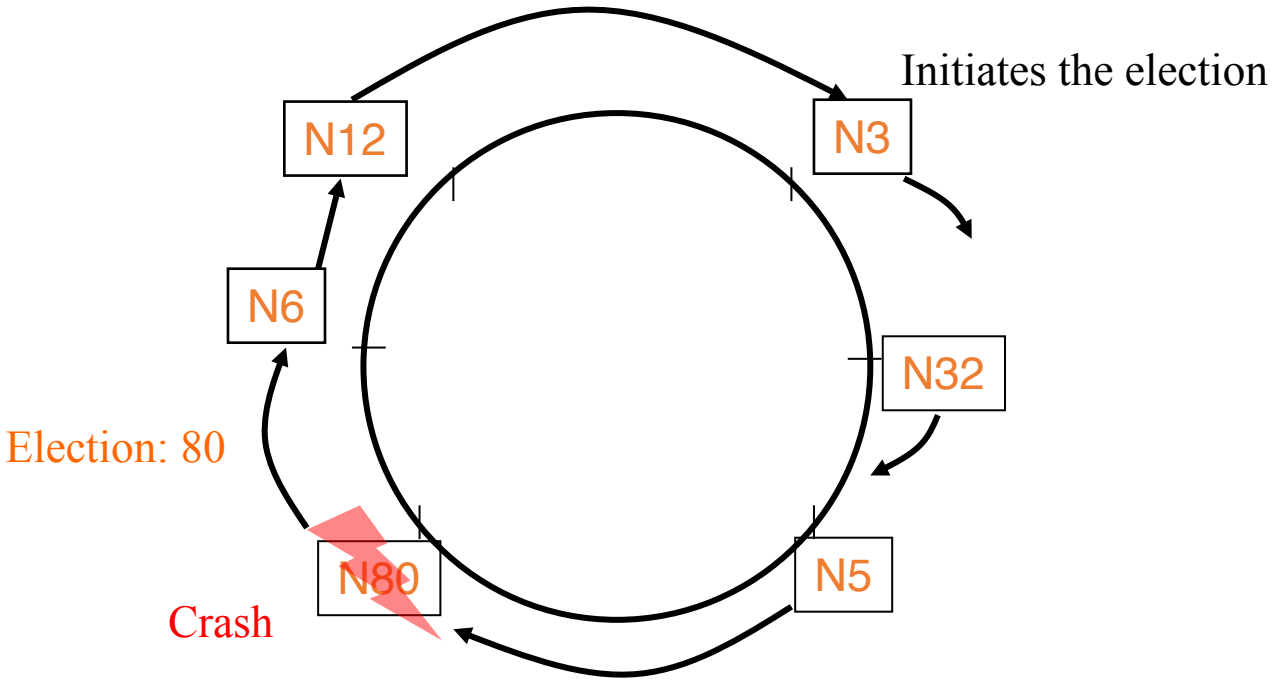
Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.
  - $O(N^2)$ messages in worst-case.
  - O(N) turnaround time.

Correctness

- Assuming no process fails.
- Safety:
  - Process with highest attribute elected by all nodes.
- Liveness:
  - Election completes within 3N – 1 message transmission times.

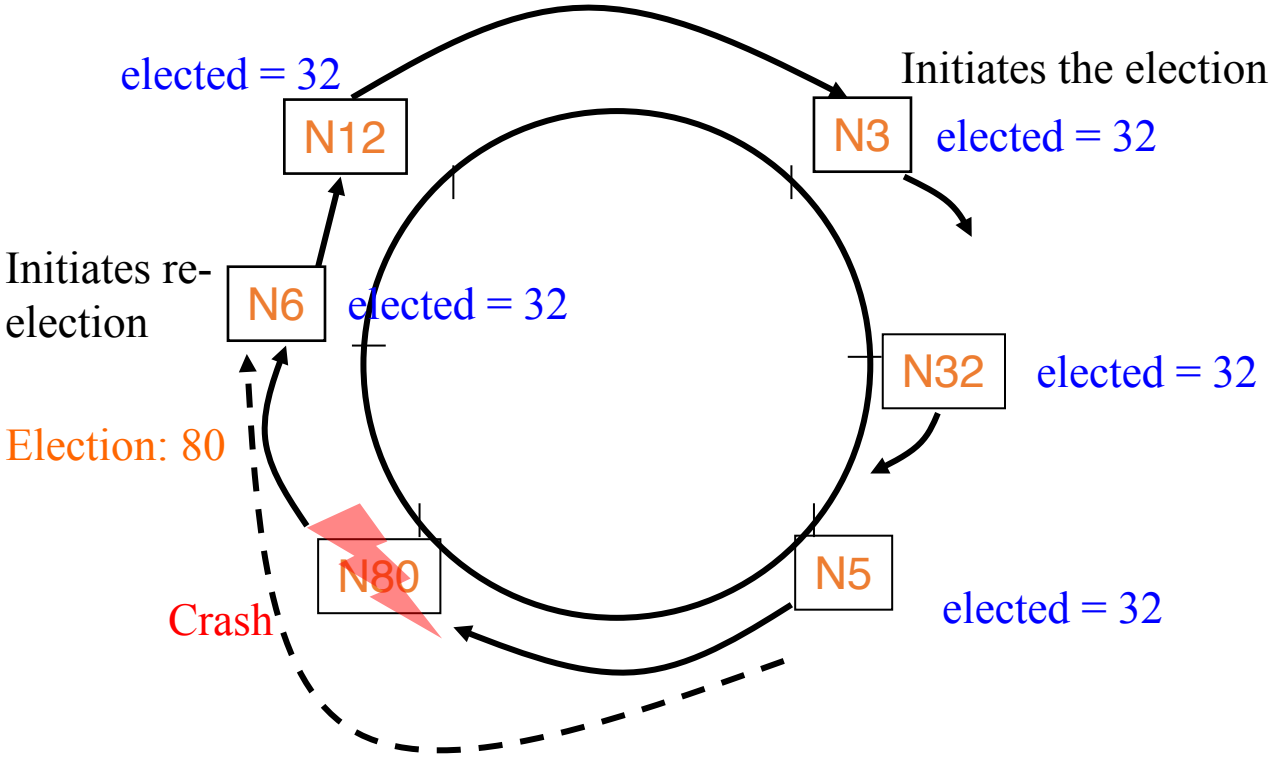
Handling Failures



Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.

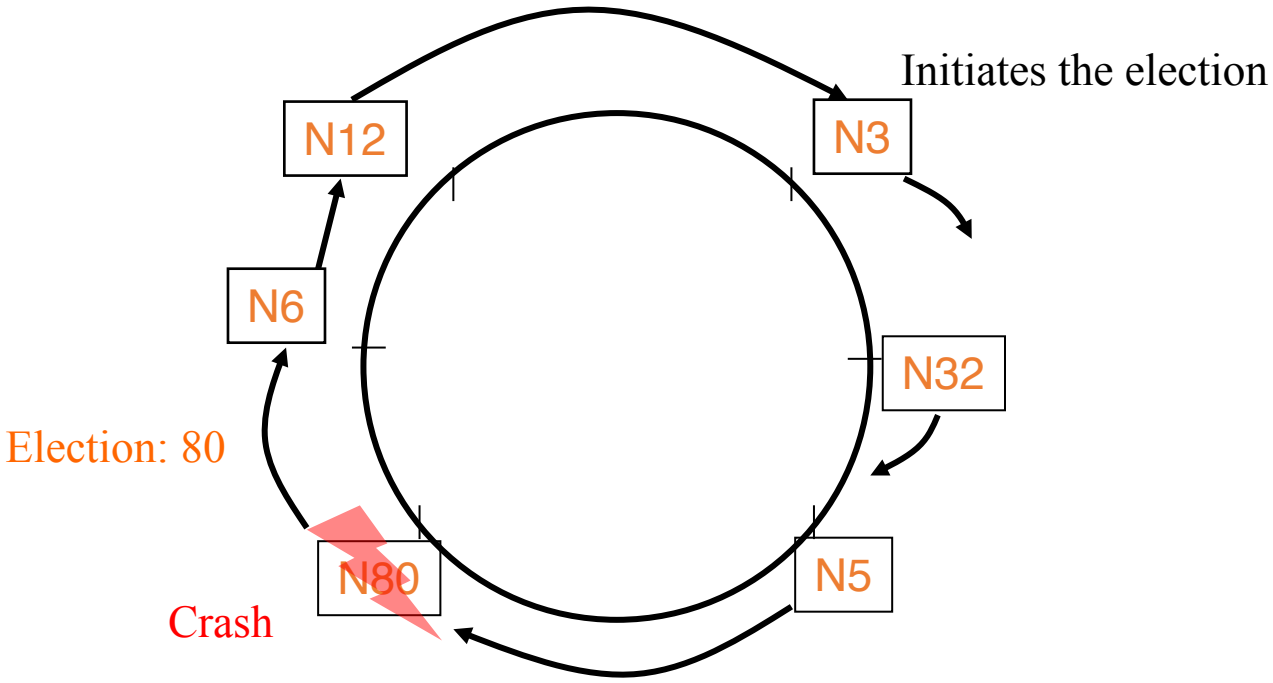
Handling Failures



Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed .

What happens if a process failure is undetected?



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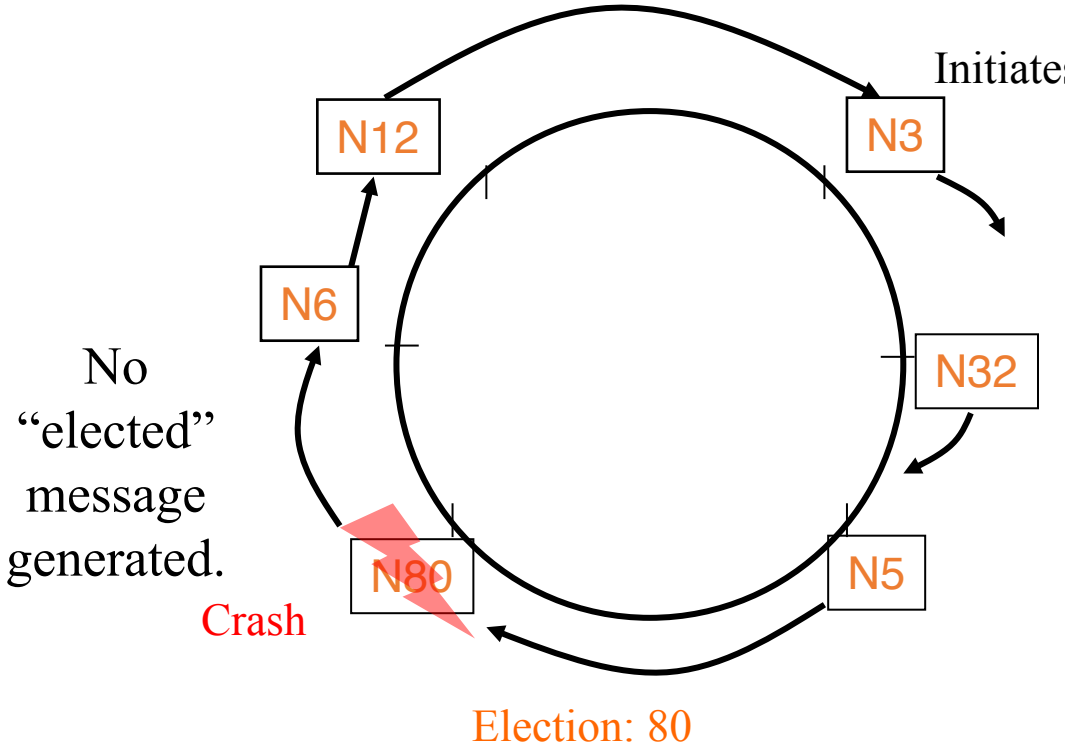


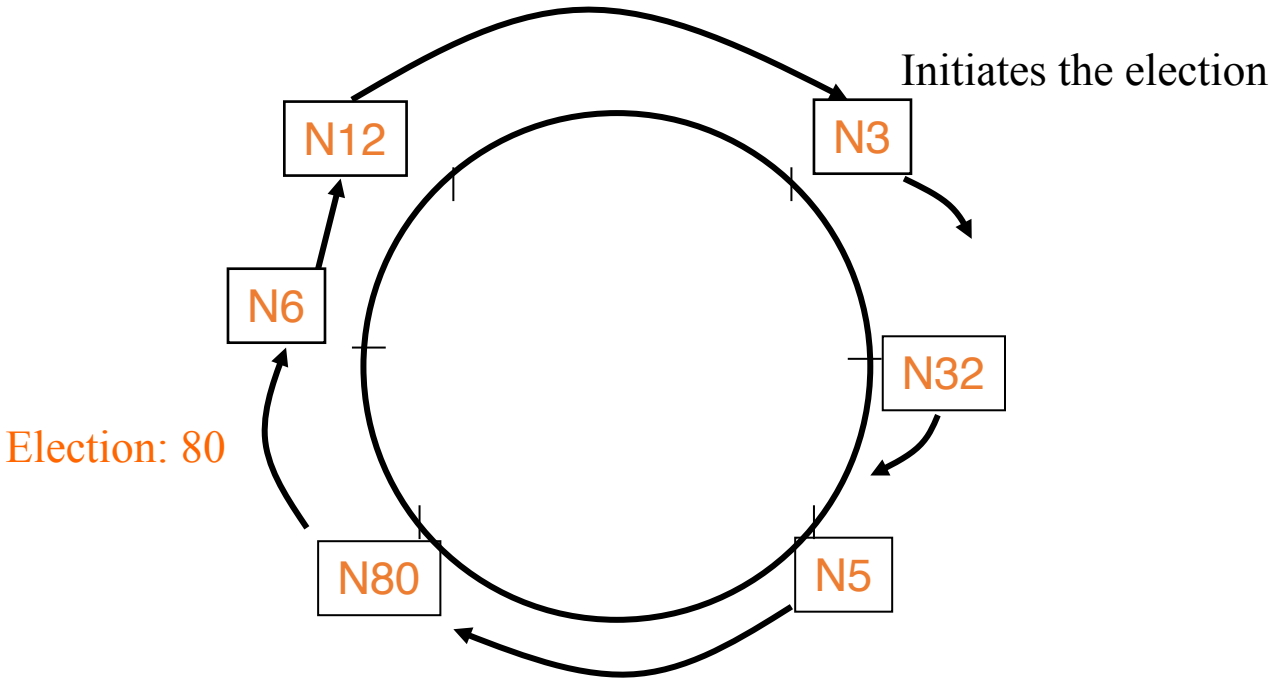
Algorithm does not terminate.

Liveness violated.

Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed
    - violation of liveness.
  - Inaccurate FD => N80 mistakenly detected as failed

What can happen if an alive process is detected as failed?



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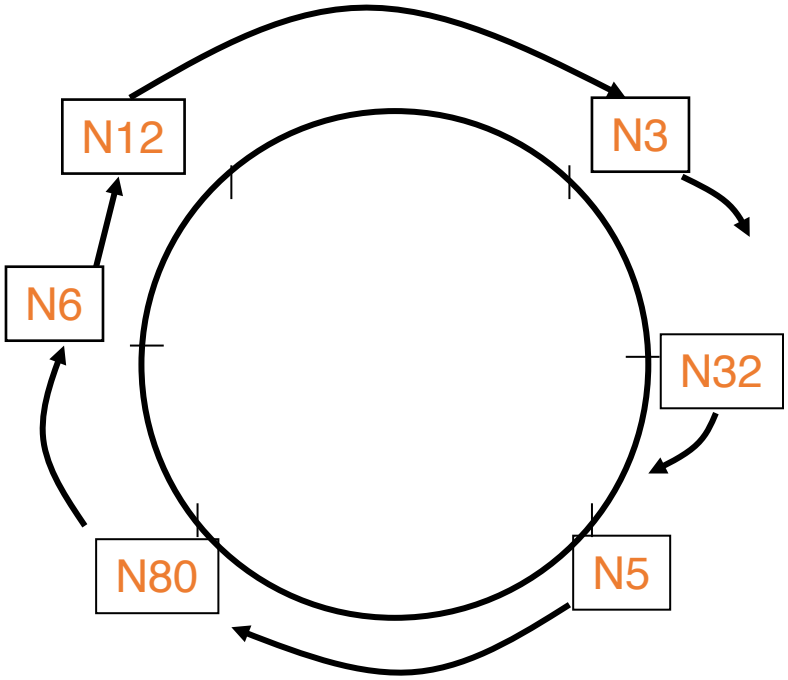
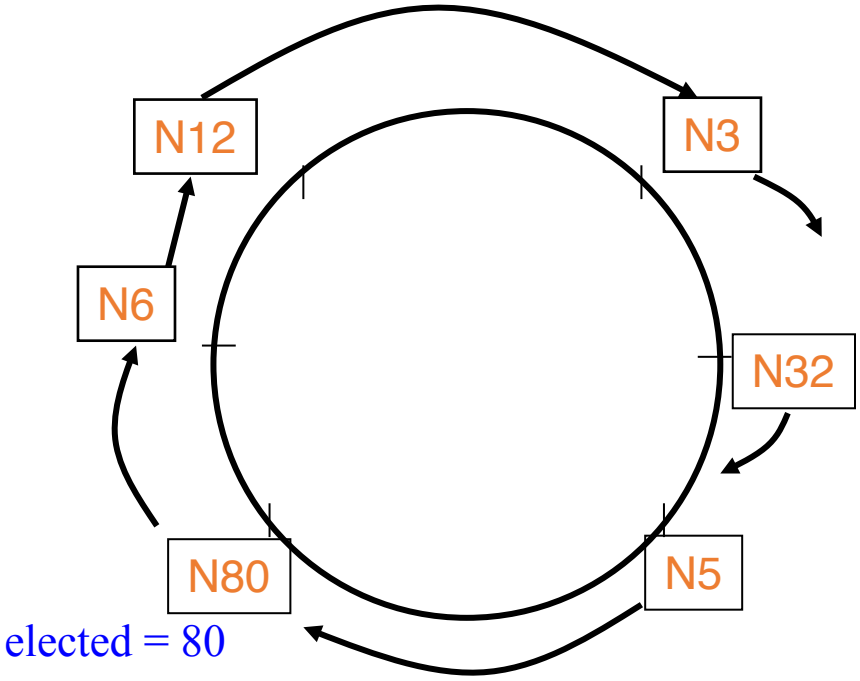


Election: 80

What can happen if an alive process is detected as failed?



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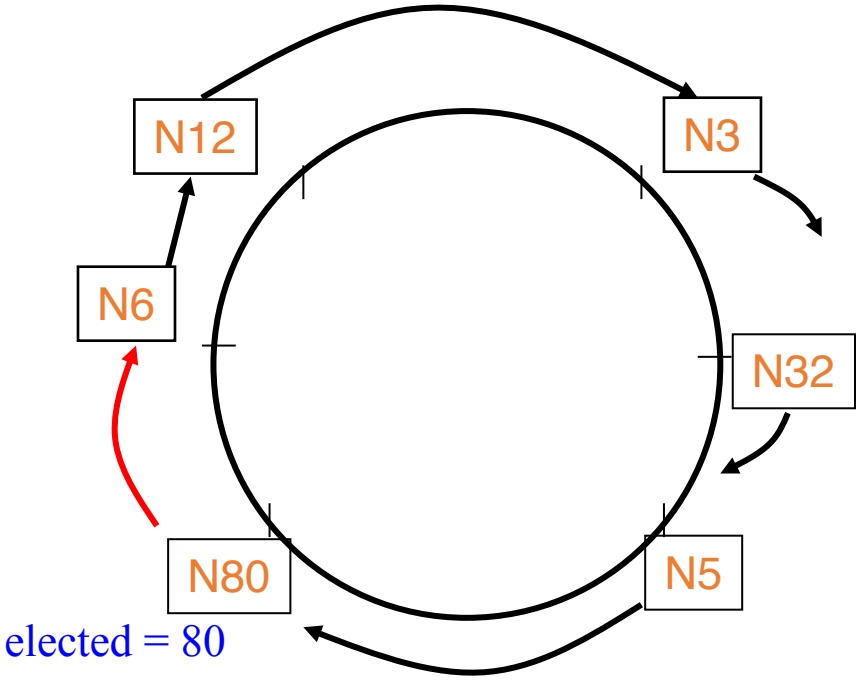

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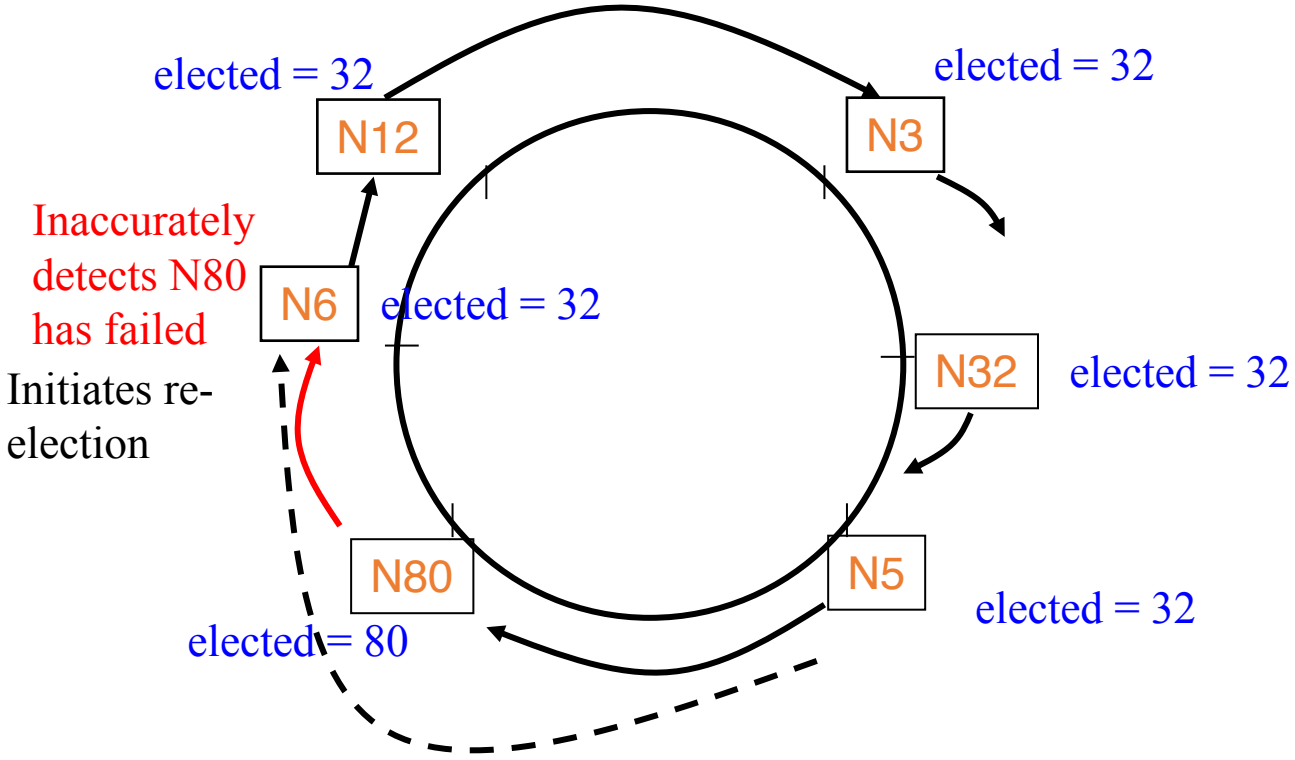


Safety has been violated.

Fixing for failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed
    - violation of liveness.
  - Inaccurate FD => N80 mistakenly detected as failed
    - new ring will be constructed without N80.
    - a process with lower attribute will be selected.
    - different processes end up with different elected leaders.
    - violation of safety.

Classical Election Algorithms

- Ring election algorithm
- **Bully algorithm**

Bully algorithm

- Faster turnaround time than ring election.
- Explicitly build in the notion of timeouts into the algorithm.
- Let's assume (for simplicity of exposition) that the attribute based on which leader is elected is the process id.
- Before discussing Bully algorithm, let's first discuss a simpler (related) algorithm…..

Multicast-based algorithm

- Start an election
  - Multicast <election, my ID> to all processes
  - If receive <agree> from all processes, then elected
    - Multicast <coordinator, my ID>
  - If receive <disagree> from any process
    - Give up election

- Receive <election, *ID*> from process *p*
  - If ID > my ID
    - Send <agree> to *p* (unicast)
  - If ID < my ID
    - Send <disagree> to *p*
    - Start election (if not already running)

- What about failures?

Multicast-based algorithm

- Start an election
  - Multicast <election, my ID> to all processes
  - If receive <agree> from all processes or timeout, then elected
    - Multicast <coordinator, my ID>
  - If receive <disagree> from any process
    - Give up election
- Receive <election, *ID*> from process *p*
  - If ID > my ID
    - Send <agree> to *p* (unicast)
  - If ID < my ID
    - Send <disagree> to *p*
    - Start election (if not already running)
- Can we improve on this?

Multicast-based algorithm

- Start an election
  - Multicast <election, my ID> to all processes
  - If ~~receive <agree> from all processes or~~ timeout, then elected
    - Multicast <coordinator, my ID>
  - If receive <disagree> from any process
    - Give up election
- Receive <election, *ID*> from process *p*
  - ~~If ID > my ID~~
    - ~~Send <agree> to *p* (unicast)~~
  - If ID < my ID
    - Send <disagree> to *p*
    - Start election (if not already running)
- Can we improve on this?

Bully Algorithm

- All processes know other process' ids.
- Do not need to multicast election to all processes.
- Only to processes with higher id.

Bully Algorithm

- When a process wants to initiate an election
  - **if** it knows its id is the highest
    - it elects itself as coordinator, then sends a *Coordinator* message to all processes with lower identifiers. Election is completed.
  - **else**
    - it initiates an election by sending an *Election* message
    - (contd.)

Bully Algorithm (2)

- **else** it initiates an election by sending an *Election* message
  - Sends it to only processes that have a *higher id than itself*.
  - **if** receives no answer within timeout, calls itself leader and sends *Coordinator* message to all lower id processes. Election completed.
  - **if** an answer received however, then there is some non-faulty higher process => so, wait for coordinator message. If none received after another timeout, start a new election run.
- A process that receives an *Election* message replies with *disagree* message, and starts its own leader election protocol (unless it has already done so).

Today's agenda

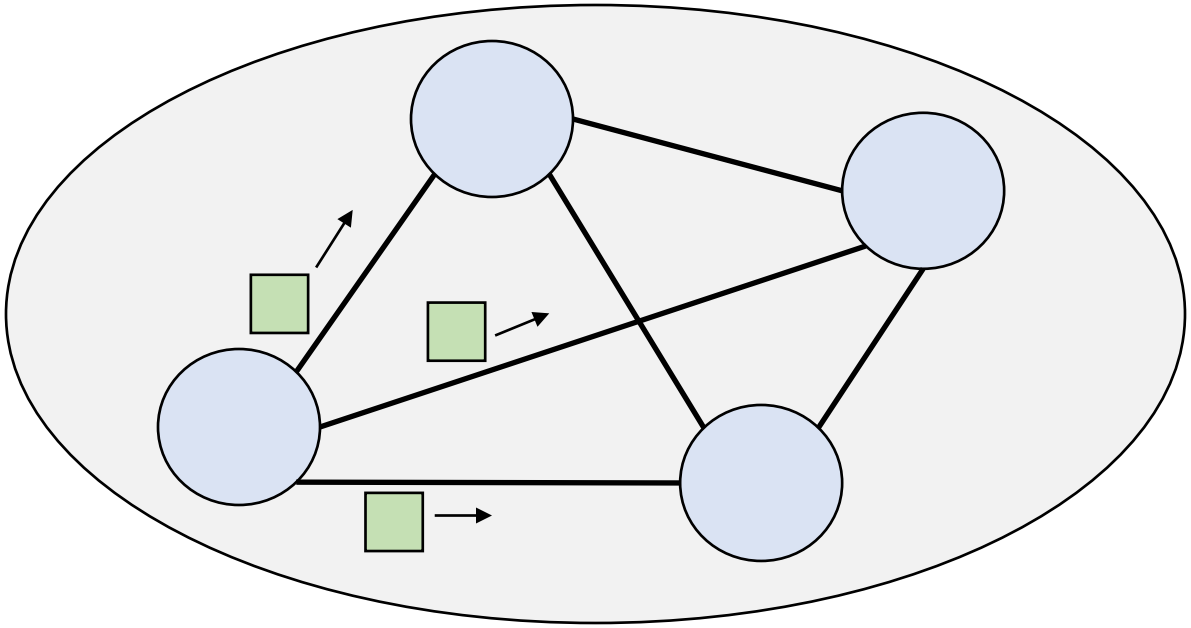
- Leader Election (contd)
  - Chapter 15.3
- Goal:
  - What is leader election in distributed systems?
  - How do we elect a leader?
  - To what extent can we handle failures when electing a leader?
- Exam Review

Disclaimer for our agenda today

- Quick reminder of the relevant topics we covered in class, that are included in your midterm.
- Not meant to be an exhaustive review!
- Go over the slides for each class.
  - Refer to lecture videos and textbook to fill in gaps in understanding.

- System Model
- Failure Detection
- Time and Clocks
- Logical Clocks and Timestamps
- Global State

What is a distributed system?



Independent components or elements that are **connected by a network** and communicate by **passing messages** to achieve a **common goal**, appearing as a single coherent system.

Relationship between processes

- Two main categories:
  - Client-server
  - Peer-to-peer

Two ways to model

- Synchronous distributed systems:
  - Known upper and lower bounds on time taken by each step in a process.
  - Known bounds on message passing delays.
  - Known bounds on clock drift rates.

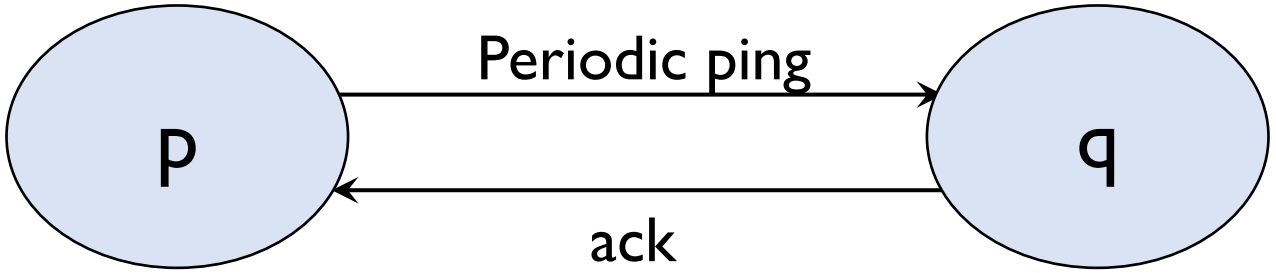
- Asynchronous distributed systems:
  - No bounds on process execution speeds.
  - No bounds on message passing delays.
  - No bounds on clock drift rates.

- System Model
- Failure Detection
- Time and Clocks
- Logical Clocks and Timestamps
- Global State

Types of failure

- **Omission:** when a process or a channel fails to perform actions that it is supposed to do.
  - Process may **crash**.
    - Detected using ping-ack or heartbeat failure detector.
    - Completeness and accuracy in synchronous and asynchronous systems.
    - Worst case failure detection time.
  - **Communication omission**: a message sent by process was not received by another.
    - Message drops (or omissions) can be mitigated by network protocols.

How to detect a crashed process?



p sends pings to q every T seconds.

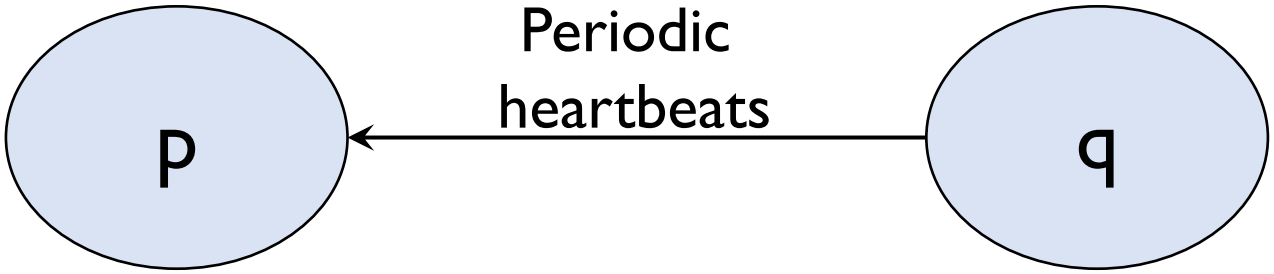
Δ_1 is the *timeout* value at p.

If Δ_1 time elapsed after sending ping, and no ack, report q crashed.

If synchronous, Δ_1 = 2(max network delay)

If asynchronous, Δ_1 = k(max observed round trip time); k >= 1

How to detect a crashed process?



q sends heartbeats to p every T seconds.

($T + \Delta_2$) is the *timeout* value at p.

If ($T + \Delta_2$) time elapsed since last heartbeat, report q crashed.

If synchronous, Δ_2 = max network delay – min network delay

If asynchronous, Δ_2 = k(observed delay); k>=1

Correctness of failure detection

- **Completeness**
  - Every failed process is *eventually* detected.
- **Accuracy**
  - Every detected failure corresponds to a crashed process (no mistakes).

Metrics for failure detection

- Worst case failure detection time
  - Ping-ack: $T + \Delta_1 - \Delta$ (where Δ is time taken for previous ping from p to reach q)
  - Heartbeat: $T + \Delta_2 + \Delta$ (where Δ is time taken for last heartbeat from q to reach p)
- Bandwidth usage:
  - Ping-ack: 2 messages every T units
  - Heartbeat: 1 message every T units.

Types of failure

- **Omission:** when a process or a channel fails to perform actions that it is supposed to do, e.g. process crash and message drops.

- **Arbitrary (Byzantine) Failures:** any type of error, e.g. a process executing incorrectly, sending a wrong message, etc.

- **Timing Failures:** Timing guarantees are not met.
  - Applicable only in synchronous systems.

- System Model
- Failure Detection
- Time and Clocks
- Logical Clocks and Timestamps
- Global State

Clock Skew and Drift Rates

- Each process has an internal clock.
- Clocks between processes on different computers differ:
  - Clock skew: relative difference between two clock values.
  - Clock drift rate: change in skew from a perfect reference clock per unit time (measured by the reference clock).
    - Depends on change in the frequency of oscillation of a crystal in the hardware clock.
- Synchronous systems have bound on maximum drift rate.

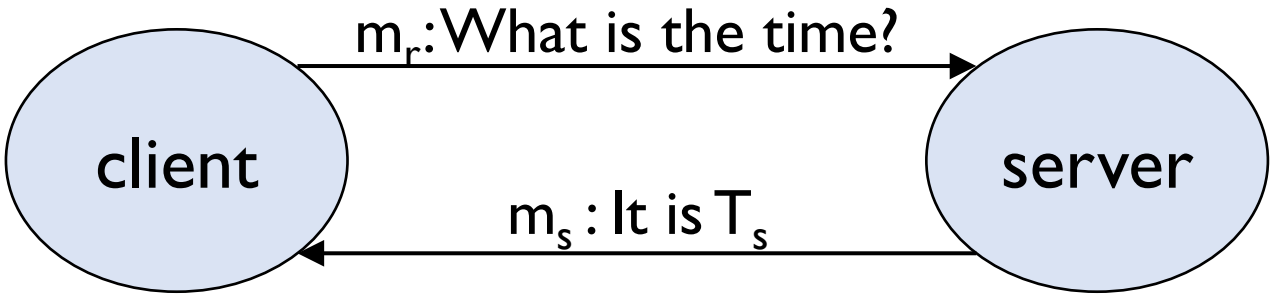
Two forms of synchronization

- External synchronization
  - Synchronize time with an authoritative clock.
  - When accurate timestamps are required.
- Internal synchronization
  - Synchronize time internally between all processes in a distributed system.
  - When internally comparable timestamps are required.
- If all clocks in a system are externally synchronized, they are also internally synchronized.

Synchronization Bound

- Synchronization bound (D) between two clocks A and B over a real time interval I.
  - $|A(t) - B(t)| < D$, for all t in the real time interval I.
    - Skew(A, B) < D during the time interval I.
    - A and B *agree* within a bound *D*.
  - If A is authoritative, D can also be called *accuracy bound*.
    - B is *accurate* within a bound of *D*.
- Synchronization/accuracy bound (D) at time 't'
  - worst-case skew between two clocks at time 't'
    - Skew(A, B) < D at time t

Synchronization in synchronous systems

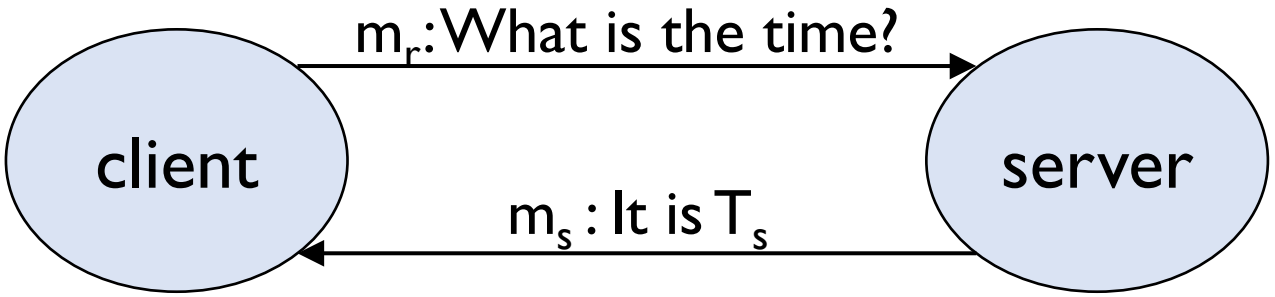


What time T_c should client adjust its local clock to after receiving m_s ?

Let *max* and *min* be maximum and minimum network delay.

If $T_c = (T_s + (min + max)/2)$, skew(client,server) $\leq$ *(max – min)/2*

Cristian Algorithm



What time T_c should client adjust its local clock to after receiving m_s ?

Client measures the round trip time (T_{round}).

$T_c = T_s + (T_{round} / 2)$

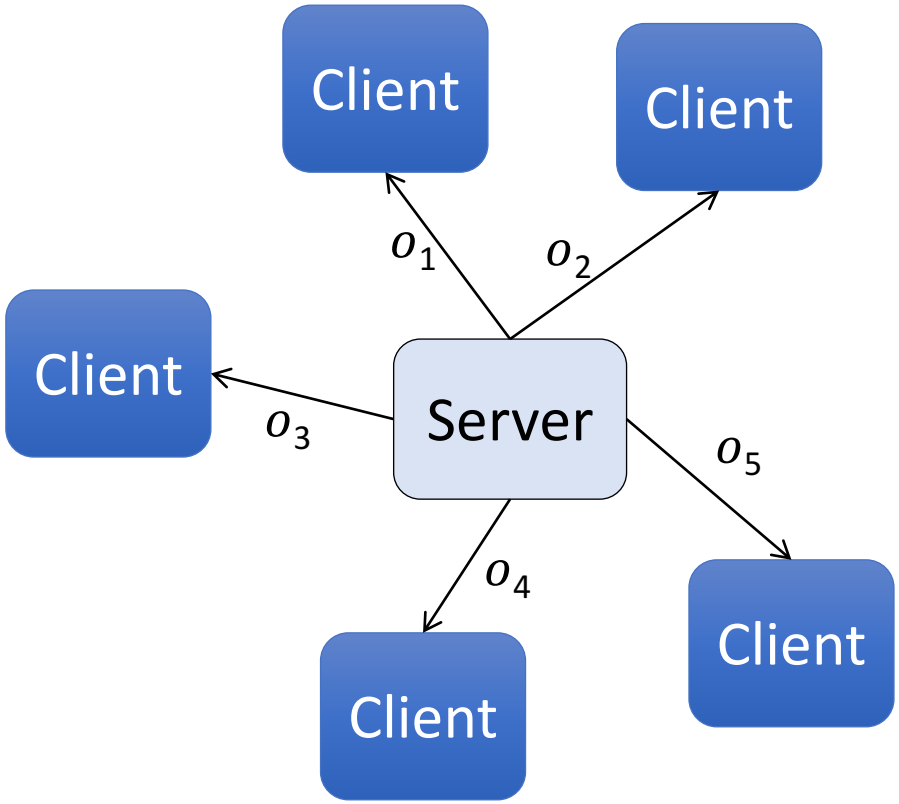
skew $\leq (T_{round} / 2) - min$

$\leq (T_{round} / 2)$

(*min* is minimum one way network delay which is atleast zero).

Berkeley Algorithm

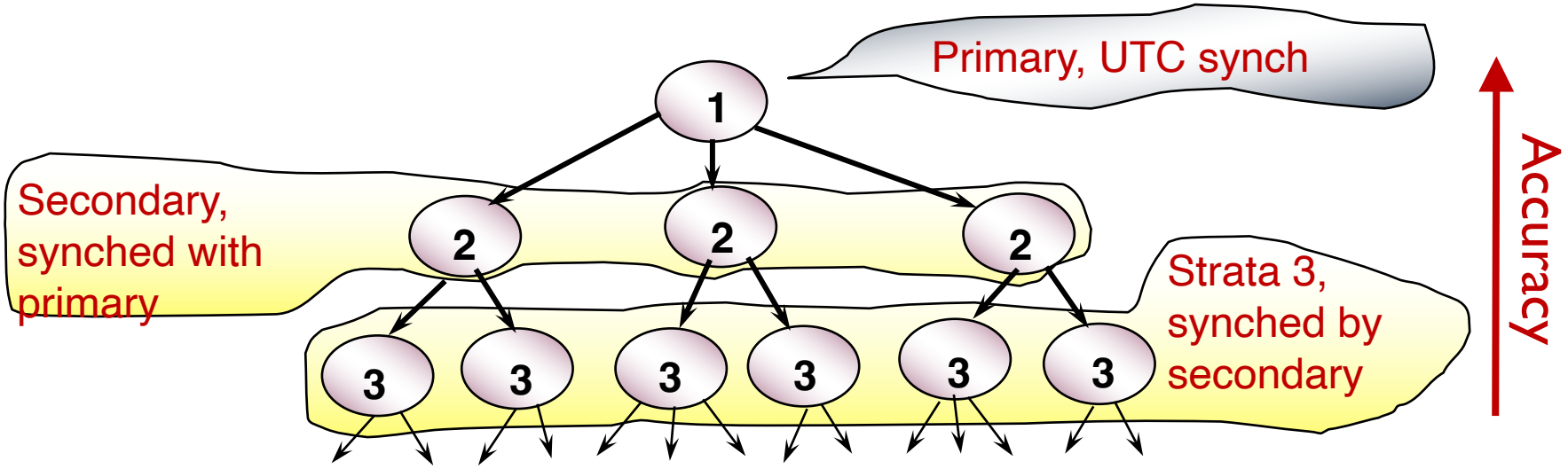
Only supports internal synchronization.



1. Server periodically polls clients: *"what time do you think it is?"*
2. Each client responds with its local time.
3. Server uses Cristian algorithm to estimate local time at each client.
4. Average all local times (including its own) – use as updated time.
5. Send the offset (amount by which each clock needs adjustment).

Network Time Protocol

Time service over the Internet for synchronizing to UTC.



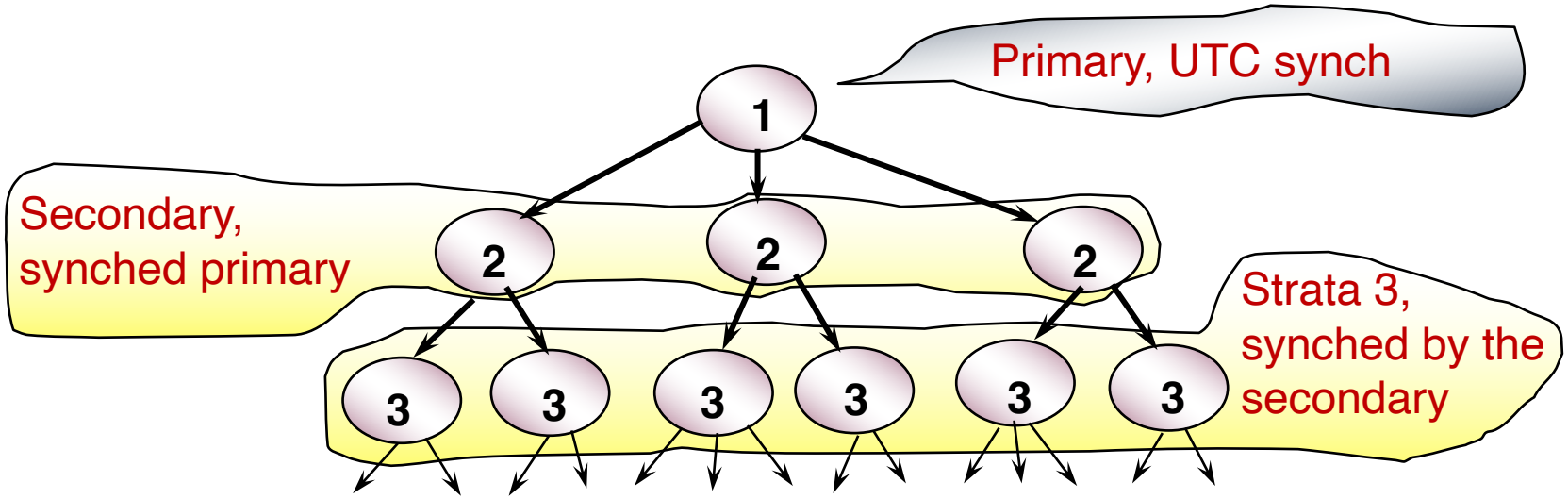
Hierarchical structure for *scalability*.

Multiple lower strata servers for *robustness*.

Authentication mechanisms for *security*.

Statistical techniques for better *accuracy*.

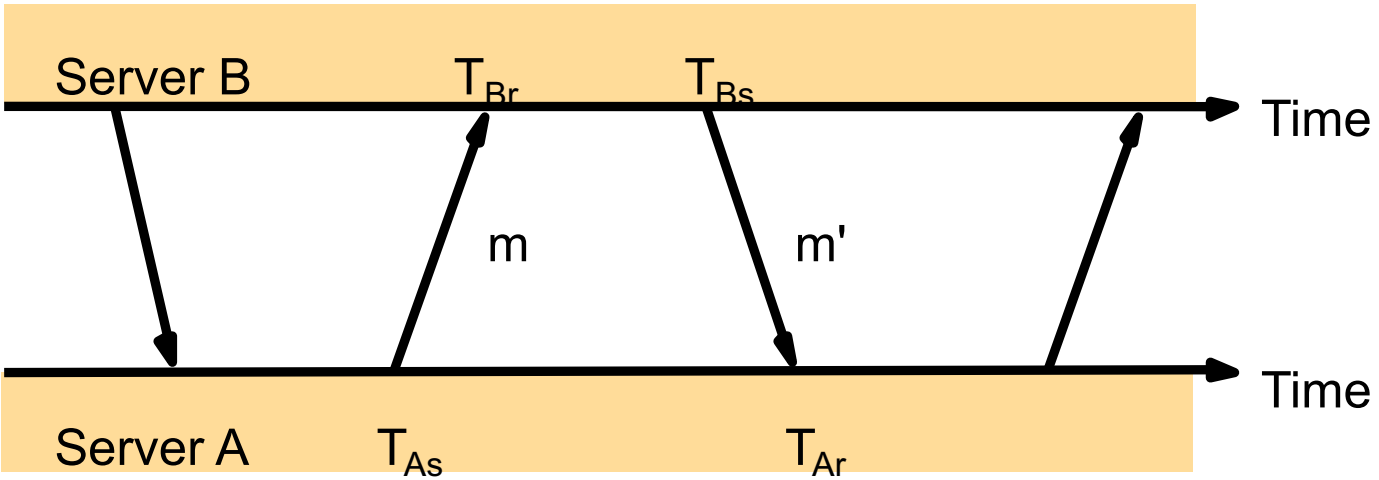
Network Time Protocol



How clocks get synchronized:

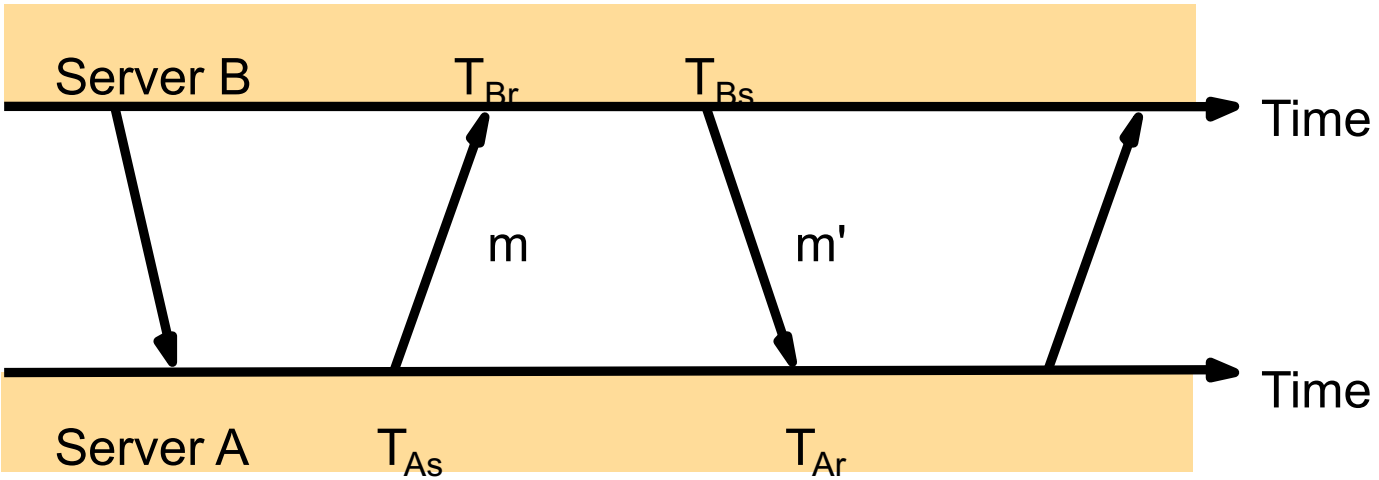
- Servers may *multicast* timestamps within a LAN. Clients adjust time assuming a small delay. *Low accuracy*.
- *Procedure-call* (Cristian algorithm). *Higher accuracy.*
- *Symmetric mode* used to synchronize lower strata servers. *Highest accuracy*.

NTP Symmetric Mode



- A and B exchange messages and record the send and receive timestamps.
  - T_{Br} and T_{Bs} are local timestamps at B.
  - T_{Ar} and T_{As} are local timestamps at A.
  - A and B exchange their local timestamp with eachother.
- Use these timestamps to compute offset with respect to one another.

NTP Symmetric Mode



- t and t': actual transmission times for m and m' (unknown)
- o: true offset of clock at B relative to clock at A (unknown)
- o_i: estimate of actual offset between the two clocks
- d_i: estimate of accuracy of o_i ; $d_i = t + t'$
- $d_i/2$: synchronization bound

$$T_{Br} = T_{As} + t + o$$
$$T_{Ar} = T_{Bs} + t' - o$$
$$o = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}) + (t' - t))/2$$
$$\mathbf{o_i = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}))/2}$$
$$o = o_i + (t' - t)/2$$
$$\mathbf{d_i = t + t' = (T_{Br} - T_{As}) + (T_{Ar} - T_{Bs})}$$

$(o_i - d_i / 2) \leq o \leq (o_i + d_i / 2)$ given $t, t' \geq 0$

- System Model
- Failure Detection
- Time and Clocks
- Logical Clocks and Timestamps
- Global State

Happened-Before Relationship

- *Happened-before* (HB) relationship denoted by →.
  - **e** → **e'** means **e** *happened before* **e'**.
  - **e** $\rightarrow_i$ **e'** means **e** *happened before* **e'**, as observed by $\mathbf{p_i}$.

- HB rules:
  - If ∃ $\mathbf{p_i}$, **e** $\rightarrow_i$ **e'** then **e** → **e'**.
  - For any message m, **send(m)** → **receive(m)**
  - If **e** → **e'** and **e'** → **e"** then **e** → **e"**

- Also called *"causal" or "potentially causal"* ordering.

Lamport's Logical Clock

- Logical timestamp for each event that captures the *happened-before* relationship.

- *Algorithm:* Each process $\mathbf{p_i}$
  1. initializes local clock $\mathbf{L_i = 0}$.
  2. increments $\mathbf{L_i}$ before timestamping each event.
  3. piggybacks $\mathbf{L_i}$ when sending a message.
  4. upon receiving a message with clock value $\mathbf{t}$
     - sets $\mathbf{L_i = max(t, L_i)}$
     - increments $\mathbf{L_i}$ before timestamping the receive event (as per step 2).

Vector Clocks

- Each event associated with a vector timestamp.
- Each process p_i maintains vector of clocks V_i
- The size of this vector is the same as the no. of processes.
  - $V_i[j]$ is the clock for process p_j as maintained by p_i
- Algorithm: each process p_i:
  1. initializes local clock $V_i[j] = 0$
  2. increments $V_i[i]$ before timestamping each event.
  3. piggybacks V_i when sending a message.
  4. upon receiving a message with vector clock value v
     - sets $V_i[j] = \max(V_i[j], v[j])$ for all $j = 1 \ldots n$.
     - increments $V_i[i]$ before timestamping receive event (as per step 2).

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Some more notations and definitions

- For a process p_i , where events $e_i^1, \ldots$ occur:

  history(p_i) = $h_i = \langle e_i^1, \ldots \rangle$

  prefix history(p_i^k) = $h_i^k = \langle e_i^1, \ldots, e_i^k \rangle$

  s_i^k : p_i's state immediately after k^{th} event.

- For a set of processes $\langle p_1, p_2, p_3, \ldots, p_n \rangle$:

  global history: $H = \cup_i (h_i)$

  global state: $S = \cup_i (s_i^{c_i})$

  a cut $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_n}$

  the frontier of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

Consistent cuts and snapshots

- A cut **C** is **consistent** if and only if

$$\forall \mathbf{e} \in \mathbf{C} \text{ (if } \mathbf{f} \rightarrow \mathbf{e} \text{ then } \mathbf{f} \in \mathbf{C})$$

- A global state **S** is consistent if and only if it corresponds to a consistent cut.

Chandy-Lamport Algorithm

- Goal:
  - Record a global snapshot
    - Process state (and channel state) for a set of processes.
  - The recorded global state is consistent.
- Identifies a consistent cut.
- Records corresponding state locally at each process.

Chandy-Lamport Algorithm

- *System model and assumptions:*
  - System of **n** processes: $\langle p_1, p_2, p_3, \ldots, p_n \rangle$.
  - There are two uni-directional communication channels between each ordered process pair : p_j to p_i and p_i to p_j.
  - Communication channels are FIFO-ordered (first in first out).
  - All messages arrive intact, and are not duplicated.
  - No failures: neither channel nor processes fail.

- *Requirements:*
  - Snapshot should not interfere with normal application actions, and it should not require application to stop sending messages.
  - Any process may initiate algorithm.

Chandy-Lamport Algorithm

- First, initiator $\mathbf{p_i}$:
  - records its own state.
  - creates a special **marker** message.
  - for *j= 1 to n* except *i*
    - $\mathbf{p_i}$ sends a **marker** message on outgoing channel $\mathbf{c_{ij}}$
    - starts recording the incoming messages on each of the incoming channels at $\mathbf{p_i}$: $\mathbf{c_{ji}}$ (for *j= 1 to n* except *i*).

Chandy-Lamport Algorithm

Whenever a process p_i receives a **marker** message on an incoming channel c_{ki}

- if (this is the first **marker** p_i is seeing)
  - p_i records its own state first
  - marks the state of channel c_{ki} as "empty"
  - for j=1 to n except i
    - p_i sends out a **marker** message on outgoing channel c_{ij}
  - starts recording the incoming messages on each of the incoming channels at p_i : c_{ji} (for *j=1 to n* except *i and k*).
- else // already seen a **marker** message
  - mark the state of channel c_{ki} as all the messages that have arrived on it since recording was turned on for c_{ki}

Chandy-Lamport Algorithm

The algorithm terminates when

- All processes have received a **marker**
  - To record their own state
- All processes have received a **marker** on all the (*n*-*1*) incoming channels
  - To record the state of all channels

More notations and definitions

- A **run** is a total ordering of events in H that is consistent with each $\mathbf{h}_i$'s ordering.
- A **linearization** is a run consistent with happens-before ($\rightarrow$) relation in H.

Global State Predicates

- A global-state-predicate is a property that is *true* or *false* for a global state.
  - Is there a deadlock?
  - Has the distributed algorithm terminated?

- Two ways of reasoning about predicates (or system properties) as global state gets transformed by events.
  - Liveness
  - Safety

Liveness

- Liveness = guarantee that something good will happen, eventually

- **Examples:**
  - Guarantee that a distributed computation will terminate.
  - "Completeness" in failure detectors.
  - All processes eventually decide on a value.

- A global state S_0 satisfies a **liveness** property P iff:
  - liveness($P(S_0)$) ≡ $\forall L \in$ linearizations from S_0, L passes through a S_L & $P(S_L)$ = true
  - For any linearization starting from S_0, P is true for some state S_L reachable from S_0.

Safety

- Safety = guarantee that something bad will never happen.

- Examples:
  - There is no deadlock in a distributed transaction system.
  - "Accuracy" in failure detectors.
  - No two processes decide on different values.

- A global state S_0 satisfies a **safety** property P iff:
  - safety($P(S_0)$) ≡ $\forall S$ reachable from S_0, $P(S)$ = true.
  - For all states S reachable from S_0, P(S) is true.

Stable Global Predicates

- once true for a state S, stays true for all states reachable from S (for stable liveness)
- once false for a state S, stays false for all states reachable from S (for stable non-safety)
- Stable liveness examples (once true, always true)
  - Computation has terminated.
- Stable non-safety examples (once false, always false)
  - There is no deadlock.
  - An object is not orphaned.
- *All stable global properties can be detected using the Chandy-Lamport algorithm.*

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Good luck!