Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Logistics Related

- Make sure you are on CampusWire.
  - Email Yu Li (yuli9) to get access if you are not already on it.
- Those registered for the course by Monday were added to Gradescope.
  - If you are newly registered, please email Yu Li (yuli9) to get added to Gradescope.
- Please fill up VM cluster form by tonight.
  - Form access changed – Google sign in no longer required.
- MP0 released today
  - Will discuss in more details at the end of the class.

Logistics Related

- *Every now and then, there's error with video recording.*
- Last class's audio wasn't recorded.
- Last year's lectures added to the Mediaspace.

Today's agenda

- Failure Detection
  - Chapter 15.1
- Time and Clocks
  - Chapter 14.1-14.3
- Logical Clocks and Timestamps (if time)
  - Chapter 14.4

Key aspects of a *distributed* system

- Processes must communicate with one another to coordinate actions. Communication time is variable.

- Different processes (on different computers) have different clocks!

- Processes and communication channels may fail.

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.

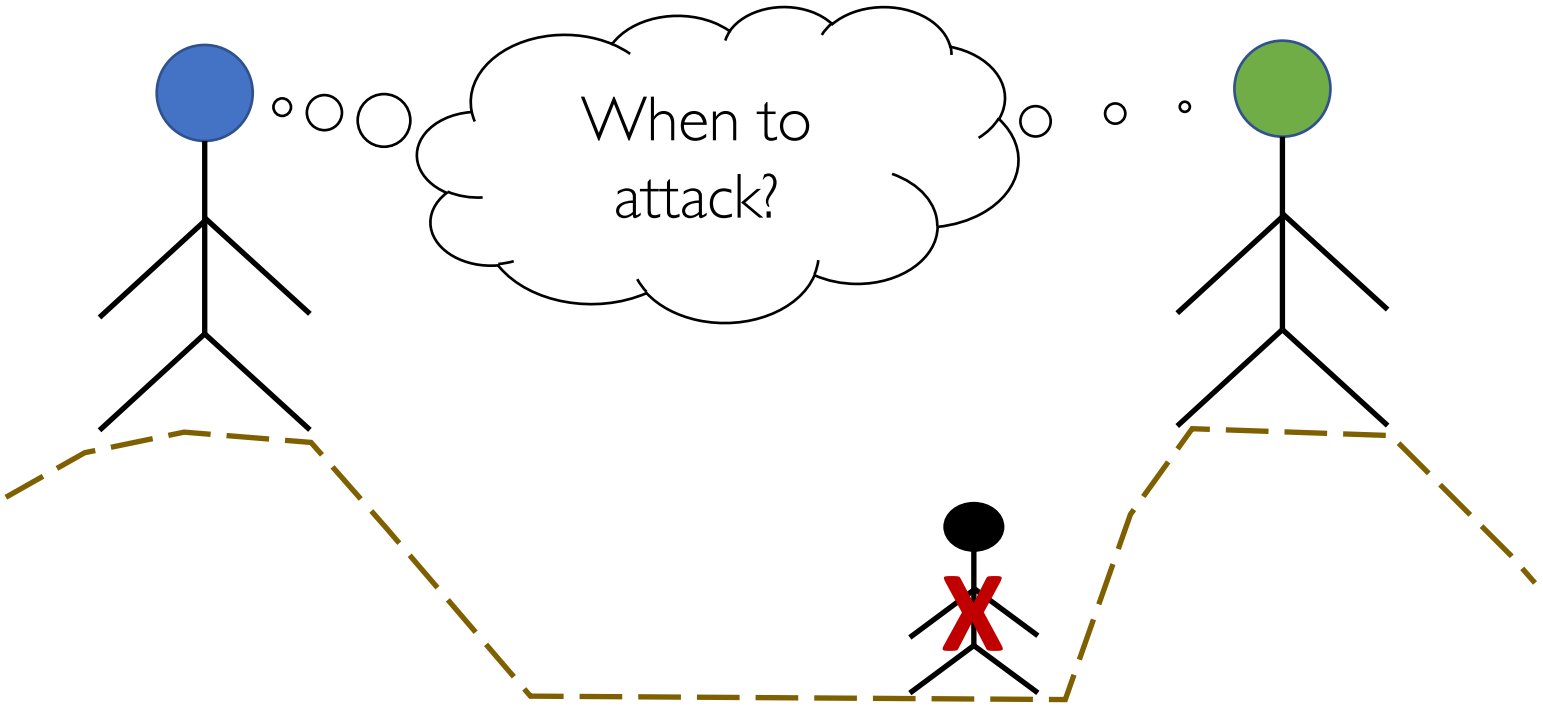
Types of failure

- **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.

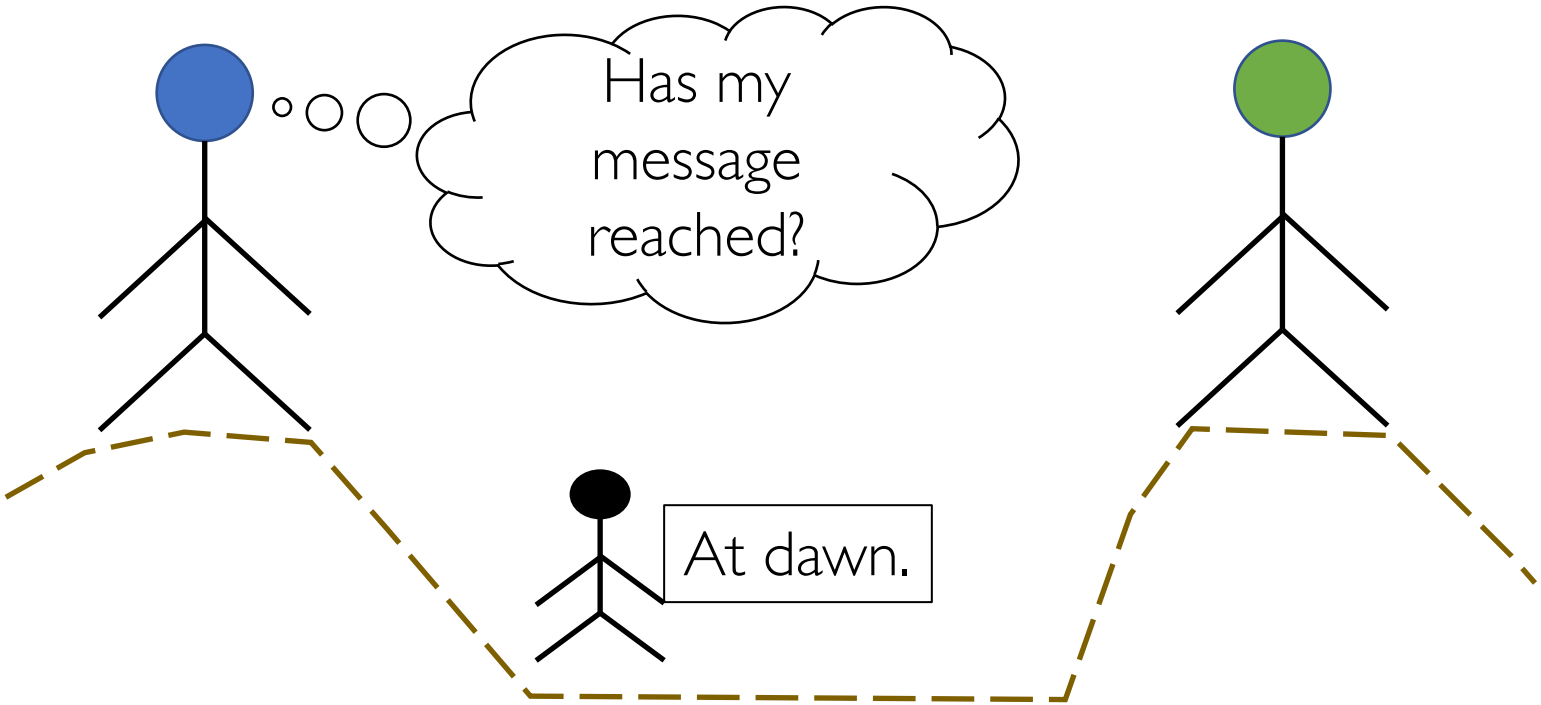
Types of failure

- **Omission:** when a process or a channel fails to perform actions that it is supposed to do.
  - Process may **crash**.
  - **Fail-stop**: if other processes can certainly detect the crash.
  - **Communication omission**: a message sent by process was not received by another.

Two Generals Problem



Two Generals Problem



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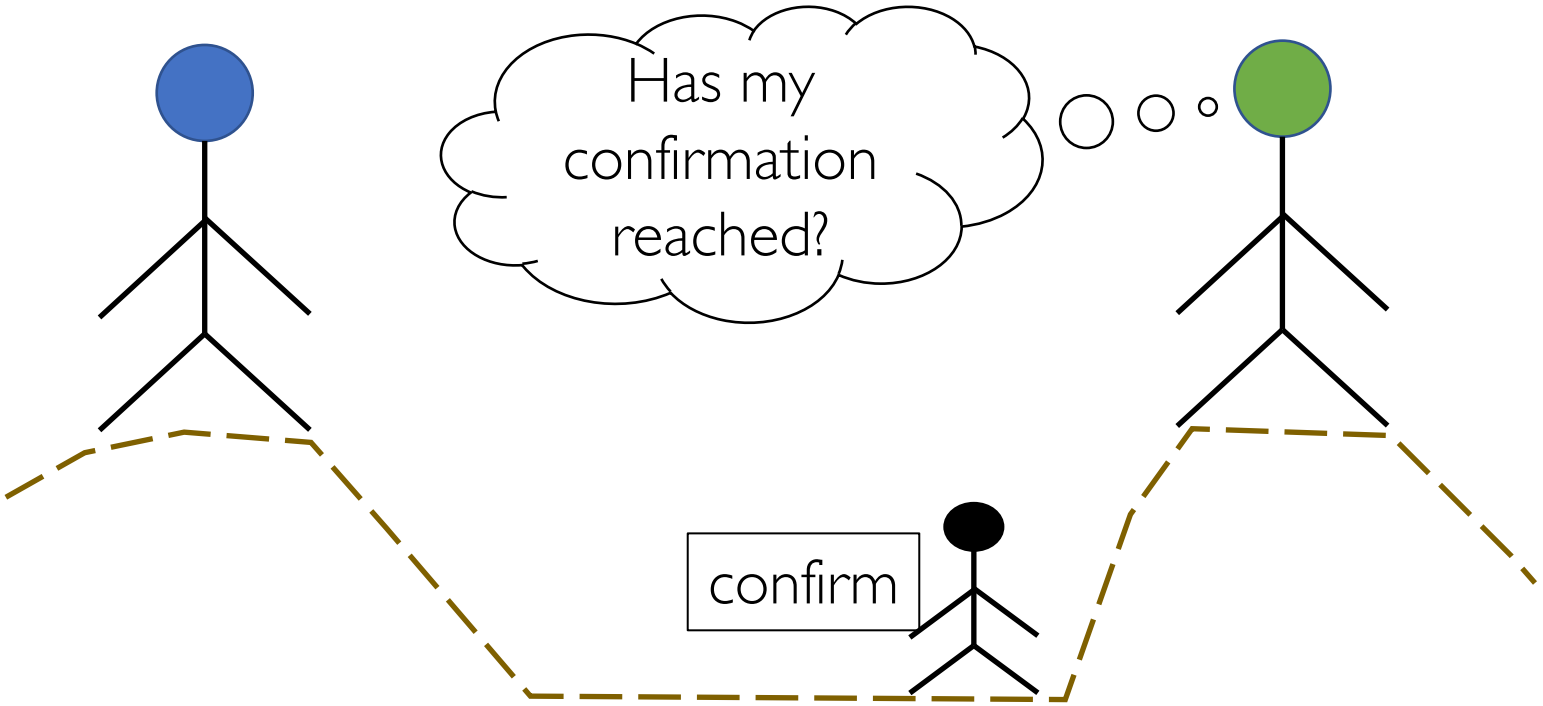
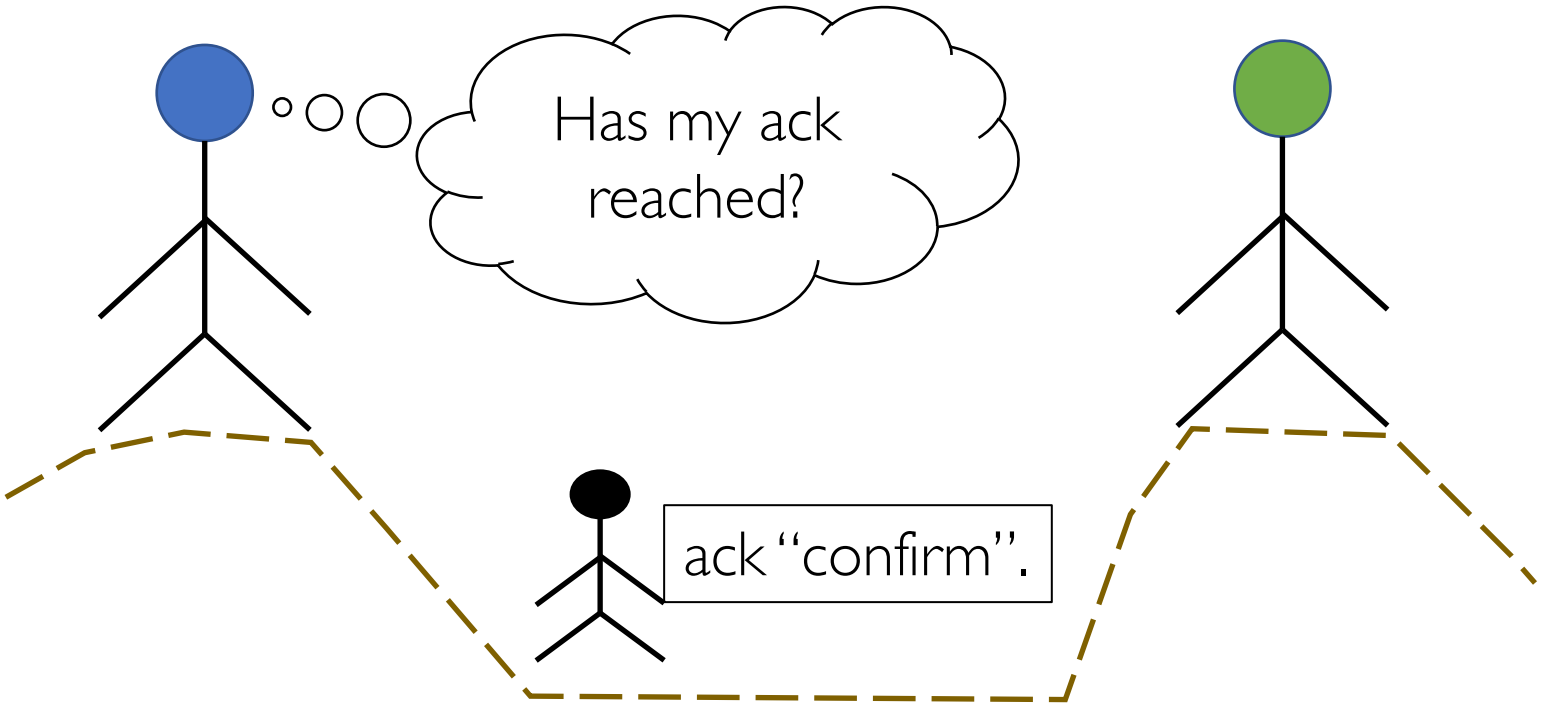
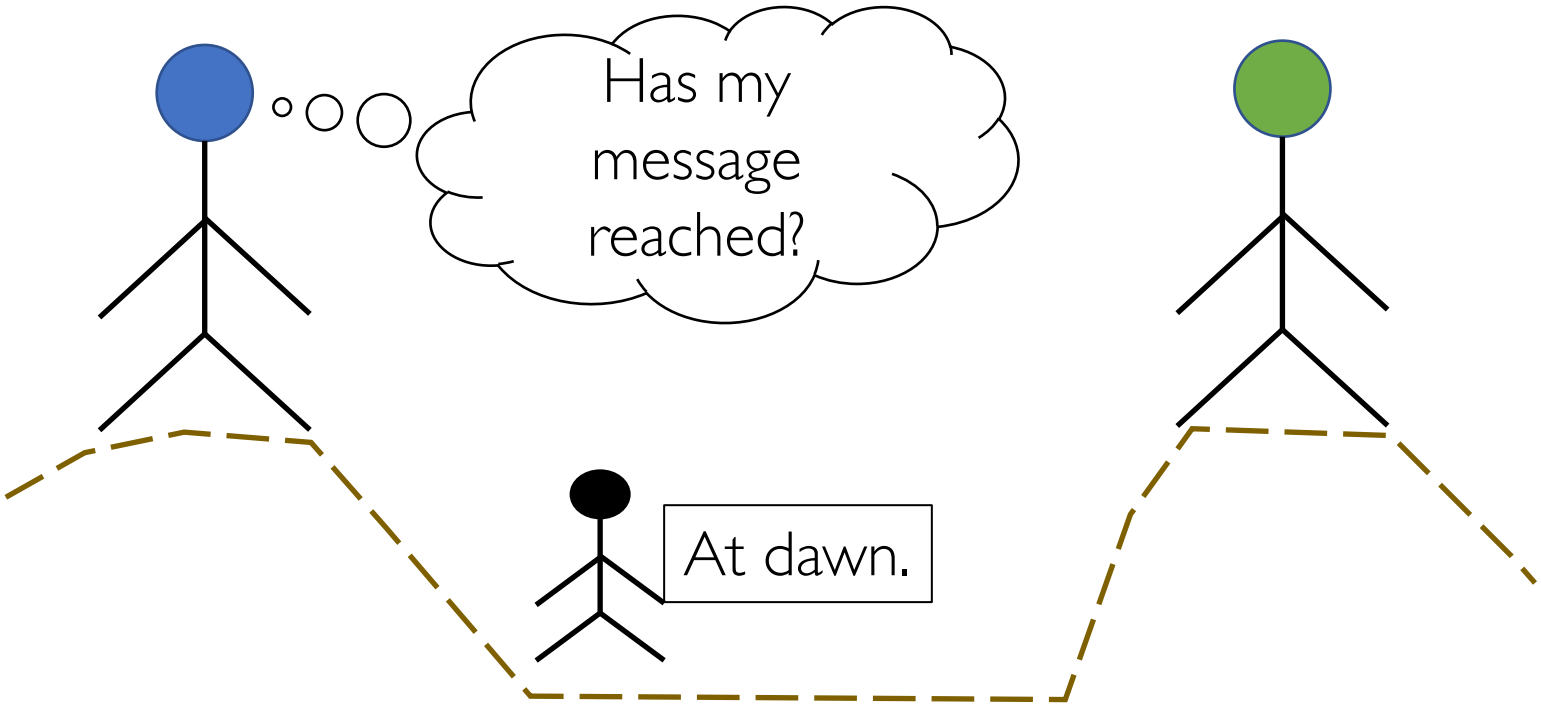


Two Generals Problem

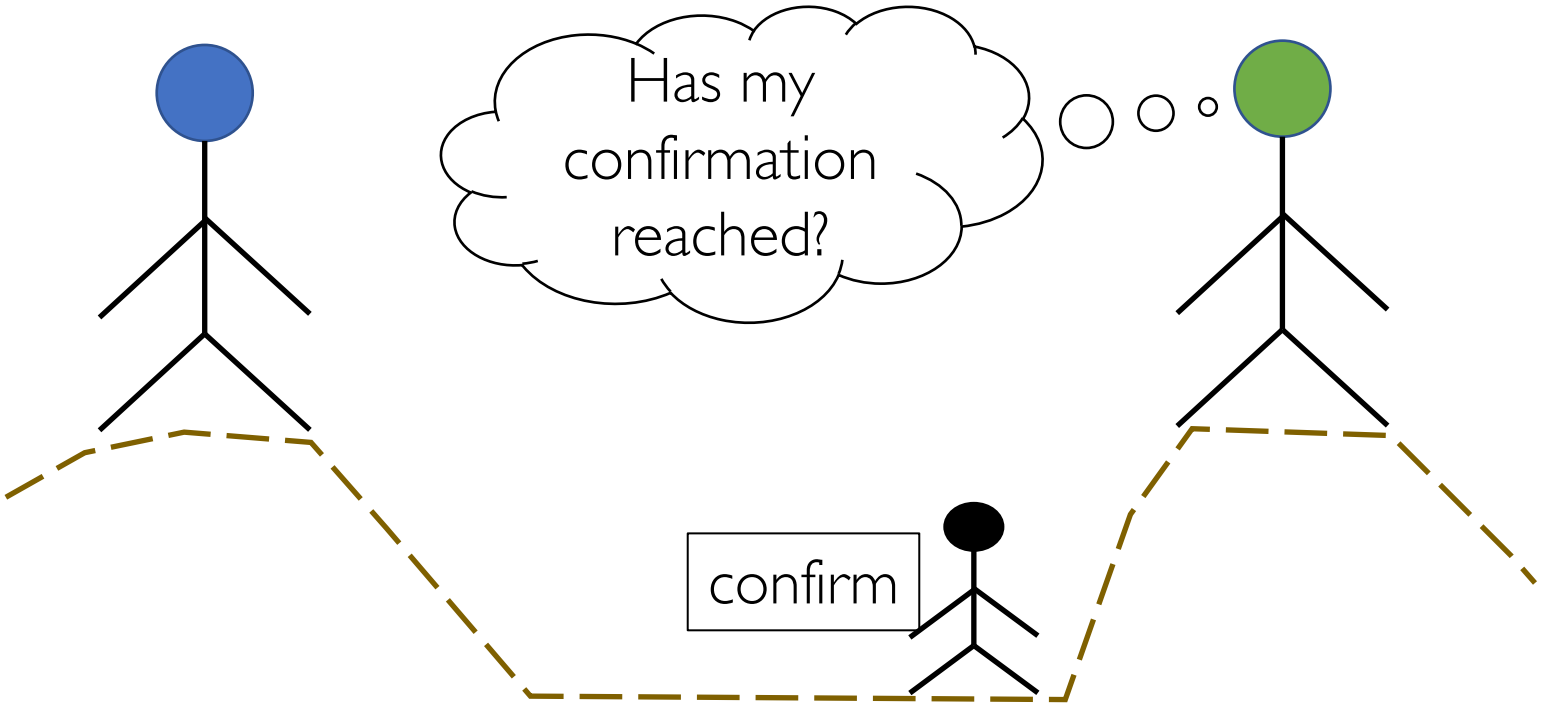


Two Generals Problem



Keep sending the message until confirmation arrives.

Two Generals Problem



Assume confirmation has reached in the absence of a repeated message.

Still no guarantees! But may be good enough in practice.

Types of failure

- **Omission:** when a process or a channel fails to perform actions that it is supposed to do.
  - Process may **crash**.
  - **Fail-stop**: if other processes can detect that the process has crashed.
  - **Communication omission**: a message sent by process was not received by another.

Message drops (or omissions) can be mitigated by network protocols.

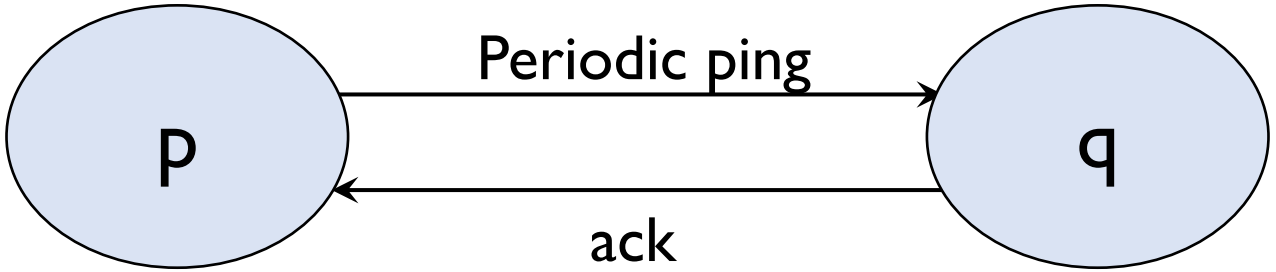
Types of failure

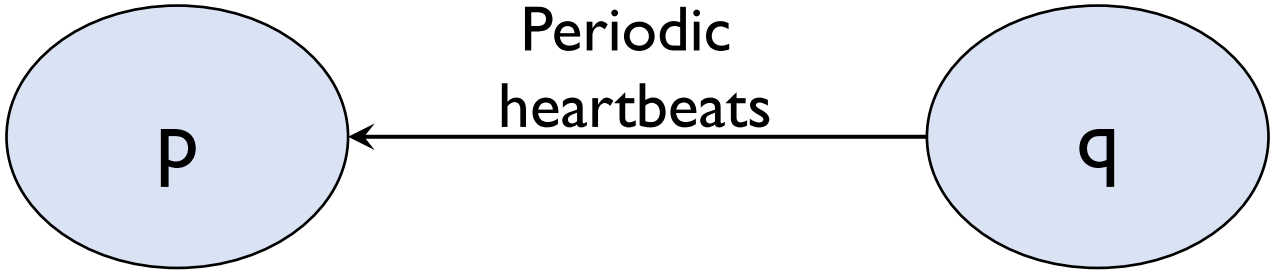
- **Omission:** when a process or a channel fails to perform actions that it is supposed to do, e.g. process crash and message drops.

- **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.

How to detect a crashed process?





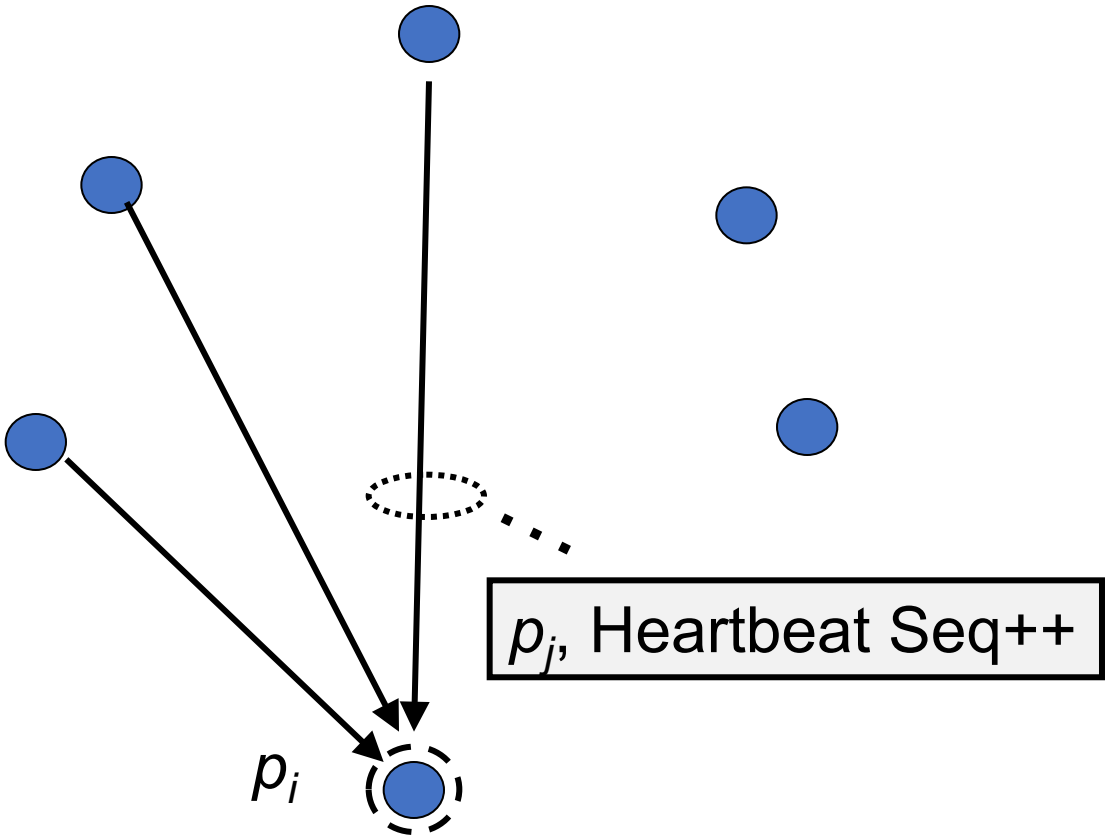
Extending heartbeats

- Looked at detecting failure between two processes.
- How do we extend to a system with multiple processes?

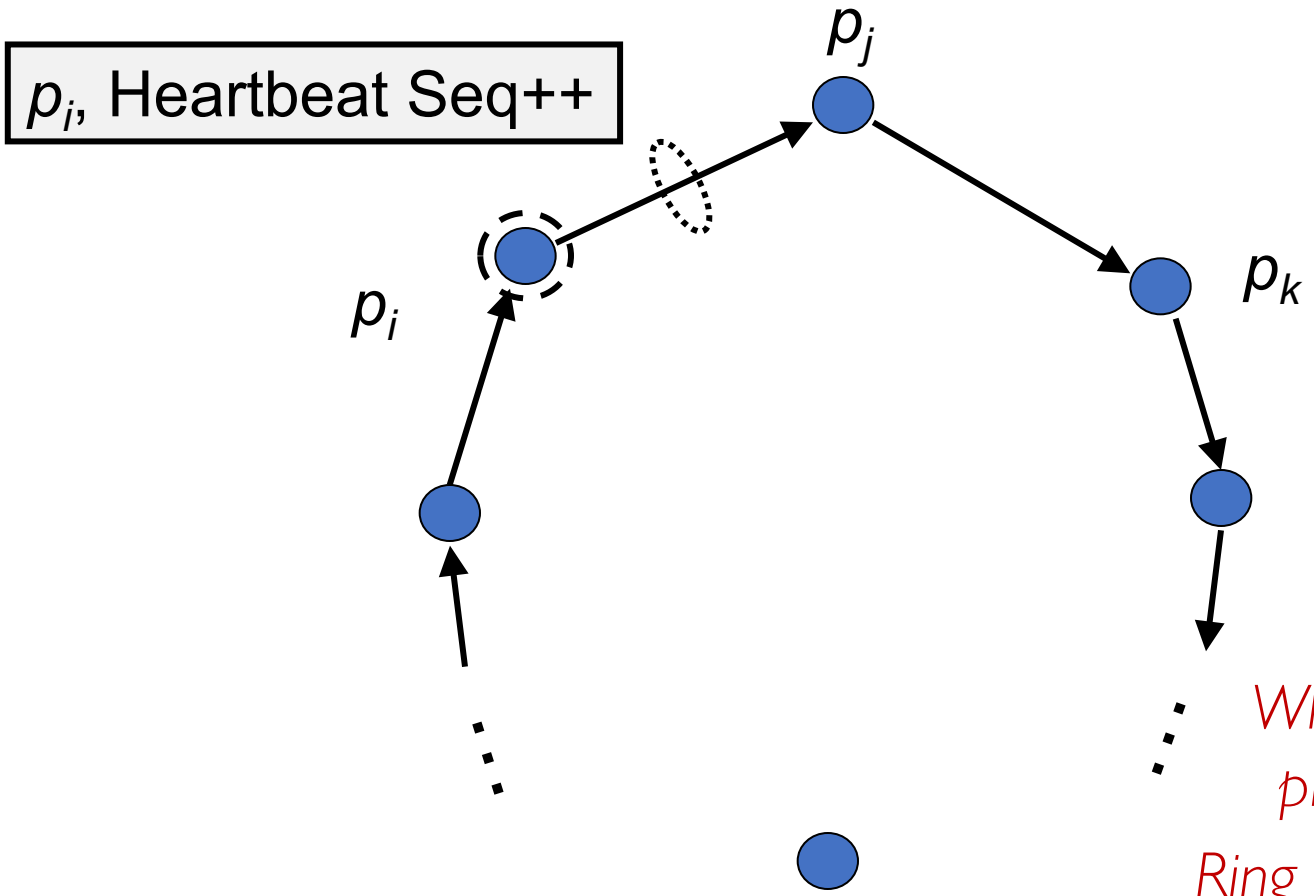
Centralized heartbeating

Downside:

What if p_i fails?



Ring heartbeating

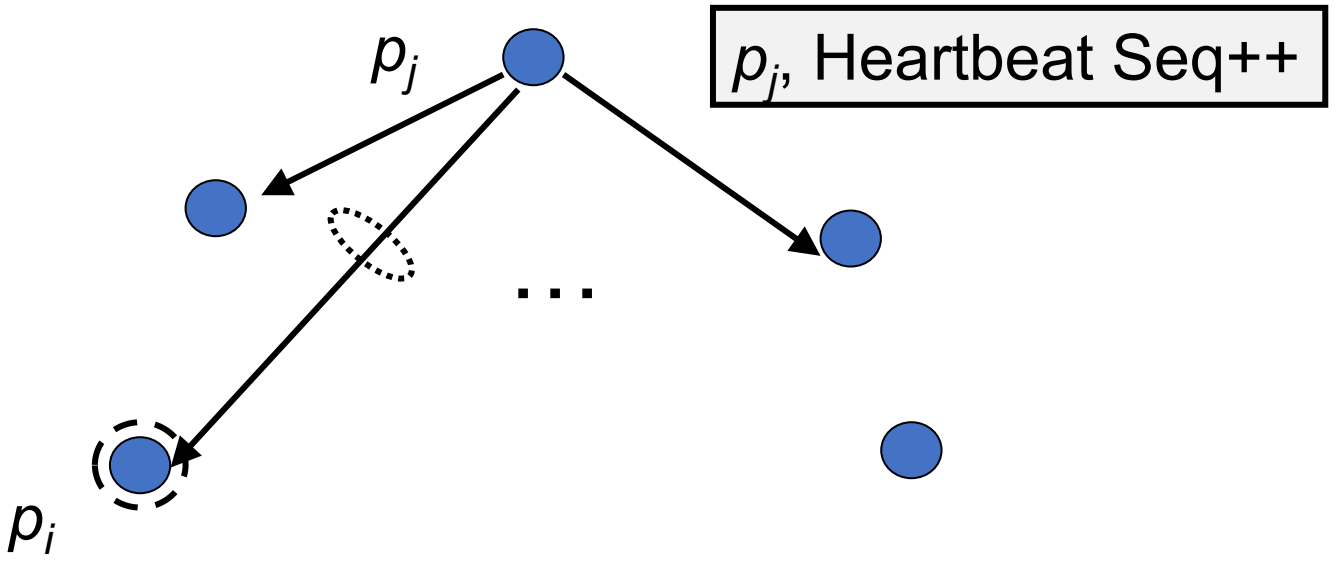


Downside:

What if multiple processes fail?

Ring repair overhead

All-to-all heartbeats



Everyone can keep track of everyone.

Downside:

Extending heartbeats

- Looked at detecting failure between two processes.
- How do we extend to a system with multiple processes?
  - Centralized heartbeating: *not complete.*
  - Ring heartbeating: *not entirely complete, ring repair overhead.*
  - All-to-all: *complete, but more bandwidth usage.*

Failures: Summary

- Three types
  - omission, arbitrary, timing.

- Failure detection (detecting a crashed process):
  - Send periodic ping-acks or heartbeats.
  - Report crash if no response until a timeout.
  - Timeout can be precisely computed for synchronous systems and estimated for asynchronous.
  - Metrics: *completeness, accuracy, failure detection time, bandwidth.*
  - Failure detection for a system with multiple processes:
    - Centralized, ring, all-to-all
    - Trade-off between completeness and bandwidth usage.

Today's agenda

- Failure Detection
  - Chapter 15.1
- Time and Clocks
  - Chapter 14.1-14.3
- Logical Clocks and Timestamps (if time)
  - Chapter 14.4

Why are clocks useful?

- How long did it take my search request to reach Google?
  - Requires my computer's clock to be *synchronized* with Google's server.

- Use timestamps to order events in a distributed system.
  - Requires the system clocks to be *synchronized* with one another.

- At what day and time did Alice transfer money to Bob?
  - Require *accurate* clocks (*synchronized* with a global authority).

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 (as 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.

Ordinary and Authoritative Clocks

- Ordinary quartz crystal clocks:
  - Drift rate is about 10^{-6} seconds/second.
  - Drift by 1 second every 11.6 days.
  - Skew of about 30minutes after 60 years.

- High precision atomic clocks:
  - Drift rate is about 10^{-13} seconds/second.
  - Skew of about 0.18ms after 60 years.
  - Used as standard for real time.
  - Universal Coordinated Time (UTC) obtained from such clocks.

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.

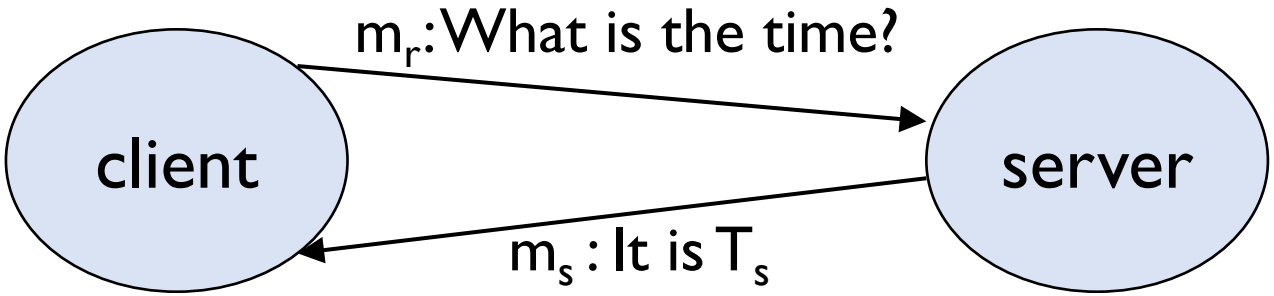
Synchronization Bound

- 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

Q: *If all clocks in a system are externally synchronized within a bound of D, what is the bound on their skew relative to one another?*

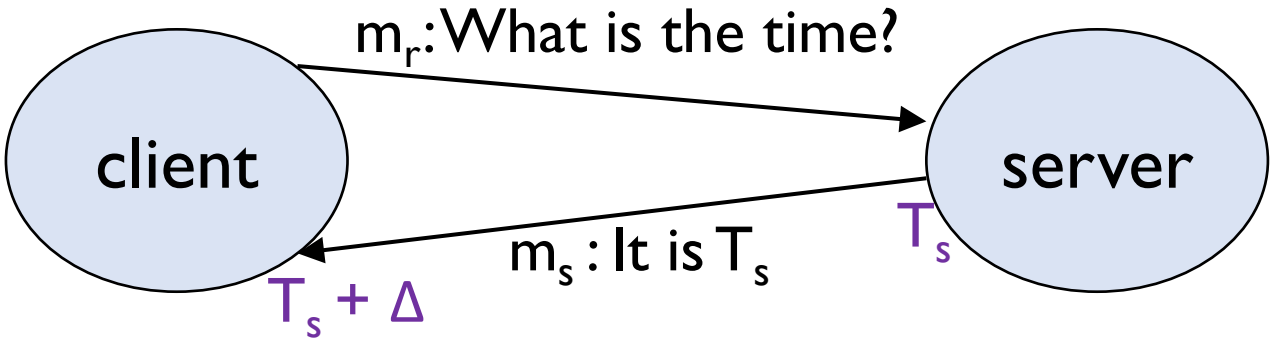
A: 2D. So the clocks are internally synchronized within a bound of 2D.

Synchronization in synchronous systems



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

Synchronization in synchronous systems



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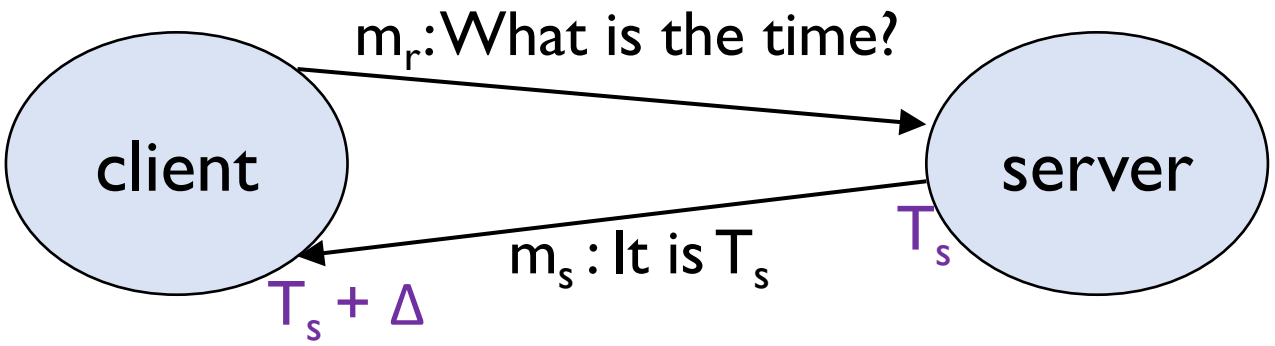


What time T_c should client adjust its local clock to after receiving m_s ?

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

If $T_c = T_s$, skew(client, server) ≤

If $T_c = (T_s + \mathbf{max})$, skew(client, server) ≤

If $T_c = (T_s + \mathbf{min})$, skew(client, server) ≤

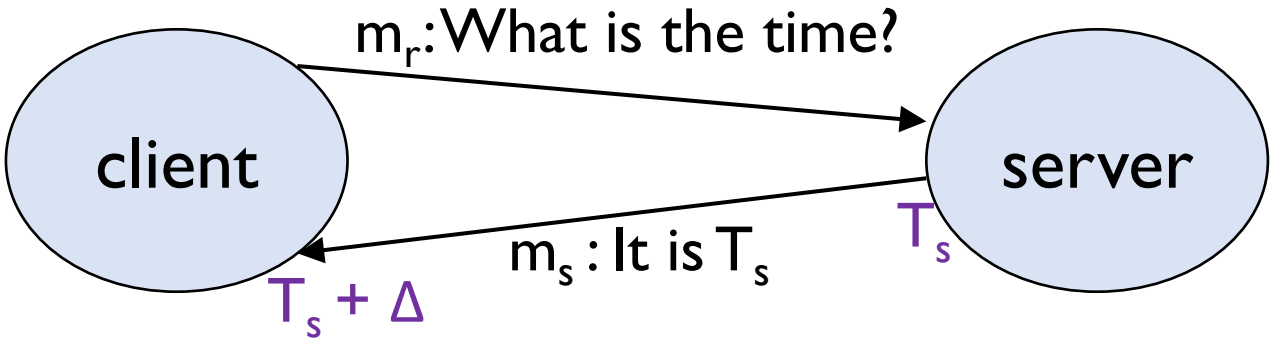
If $T_c = (T_s + \mathbf{(min + max)/2})$, skew(client,server) ≤

Provably the best you can do!

Synchronization in asynchronous systems

- Cristian Algorithm
- Berkeley Algorithm
- Network Time Protocol

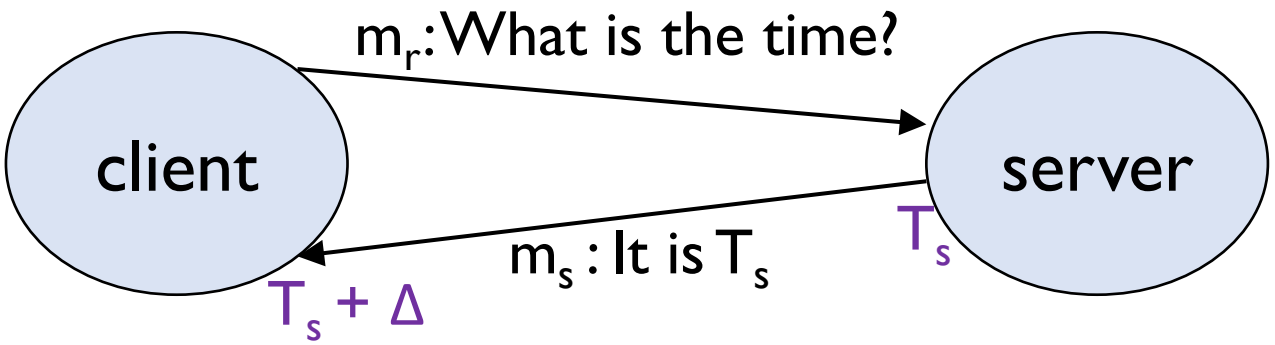
Cristian Algorithm



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

Client measures the round trip time (T_{round})
= time difference between when client sends m_r and receives m_s.

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})

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

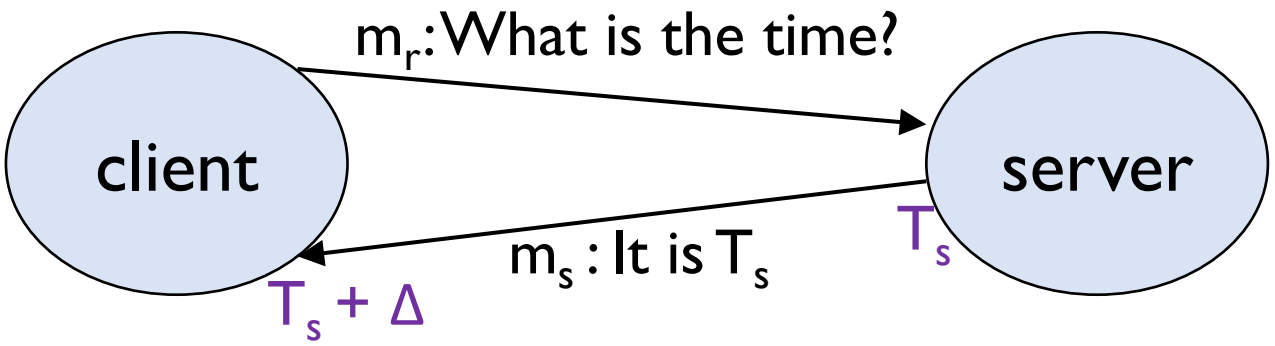
skew $\leq (T_{round} / 2) - min$
$\leq (T_{round} / 2)$

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

Try deriving the worst case skew!

Hint: *client is assuming its one-way delay from server is* $\Delta = (T_{round}/2)$. *How off can it be?*

Cristian Algorithm



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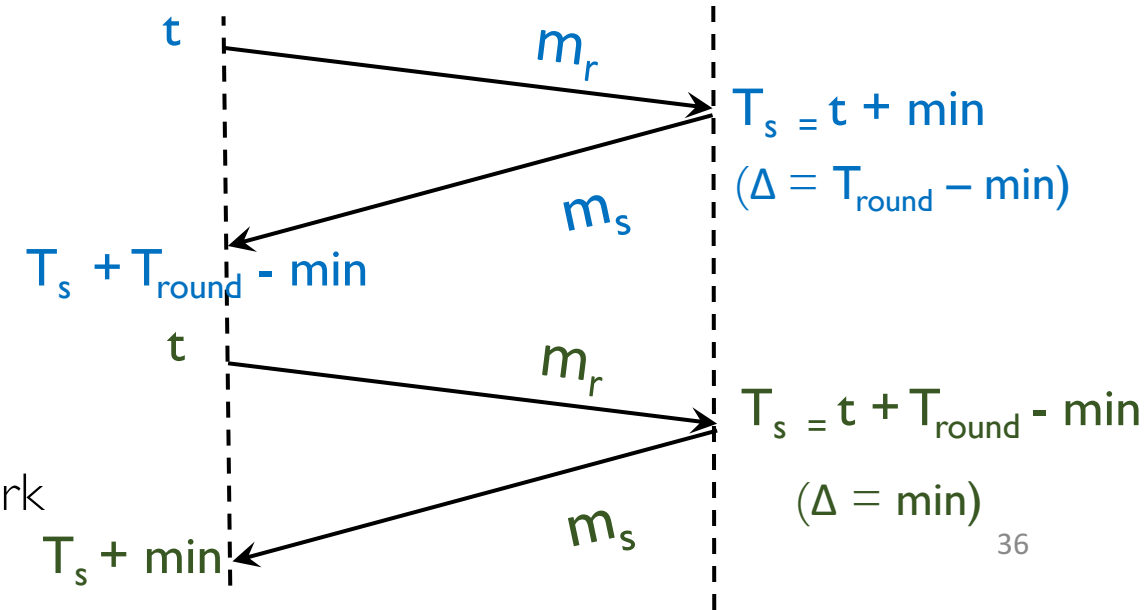
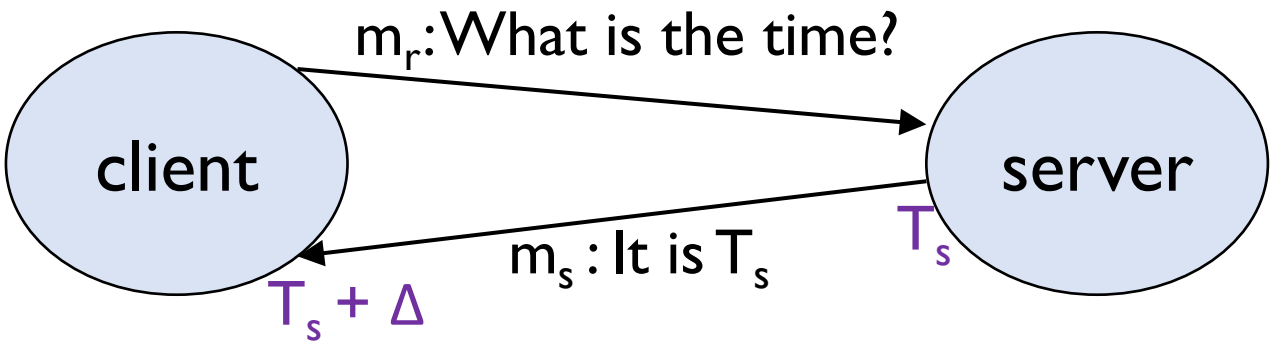


Cristian Algorithm



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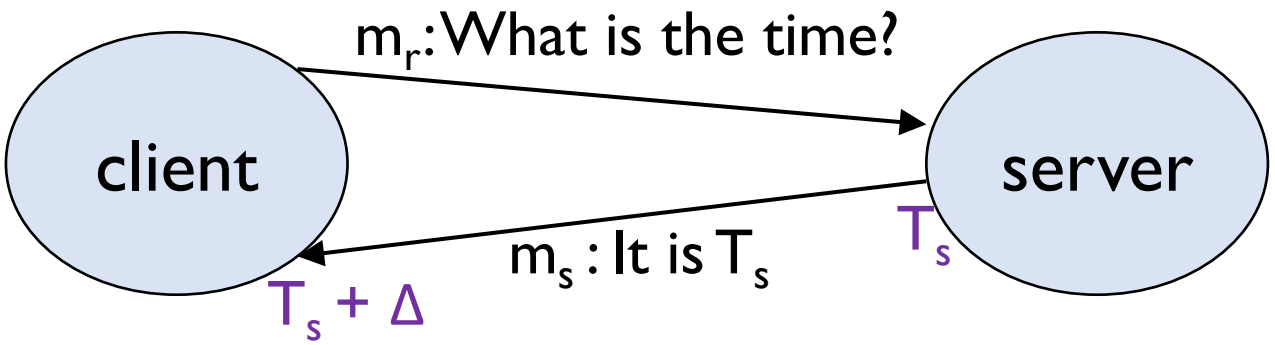
(*min* is minimum one way network delay which is atleast zero).

Improve accuracy by sending multiple spaced requests and using response with smallest T_{round}.

Server failure: Use multiple synchronized time servers.

Cristian Algorithm



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

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

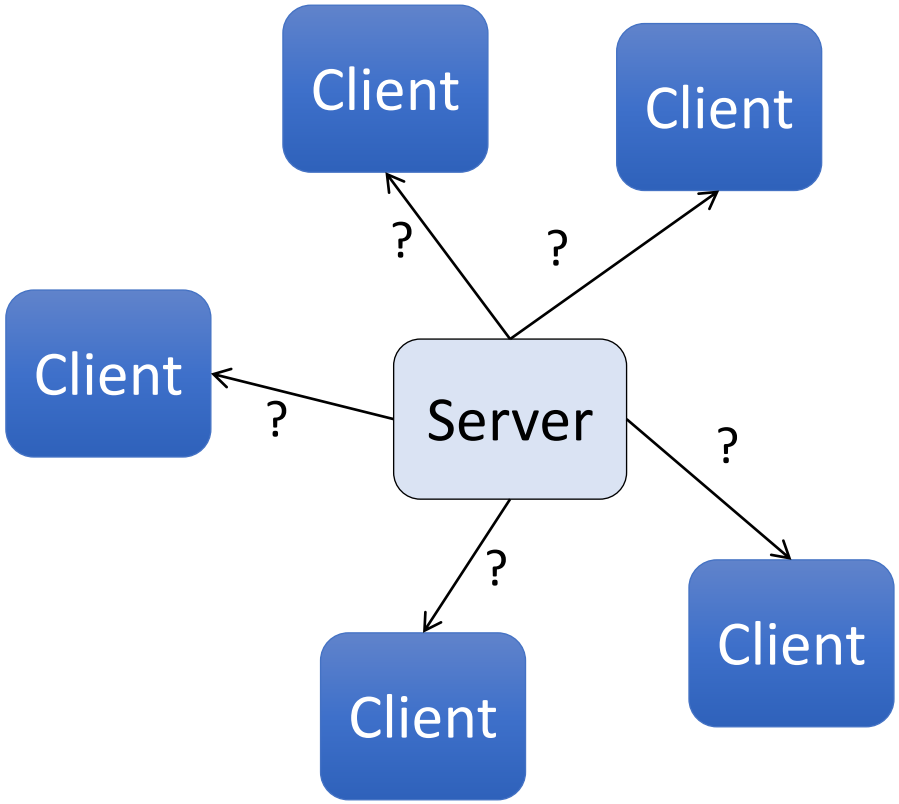
skew $\leq (T_{round} / 2) - min$
$\leq (T_{round} / 2)$

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

Cannot handle faulty time servers.

Berkeley Algorithm

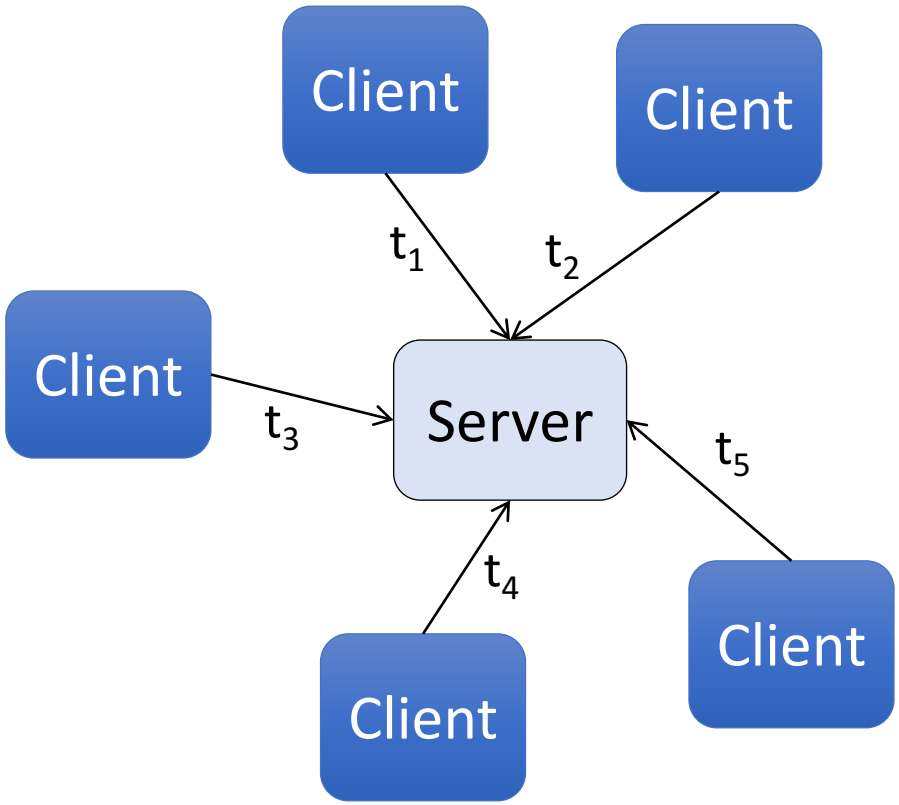
Only supports internal synchronization.



1. Server periodically polls clients:
   "what time do you think it is?"

Berkeley Algorithm

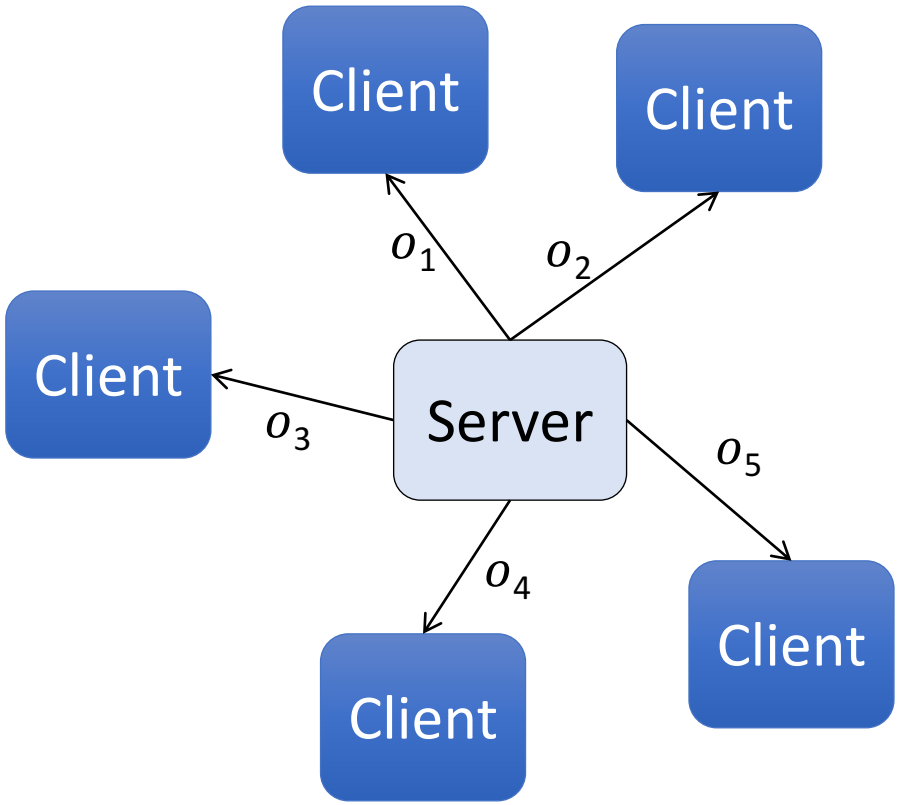
Only supports internal synchronization.



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.

Berkeley Algorithm

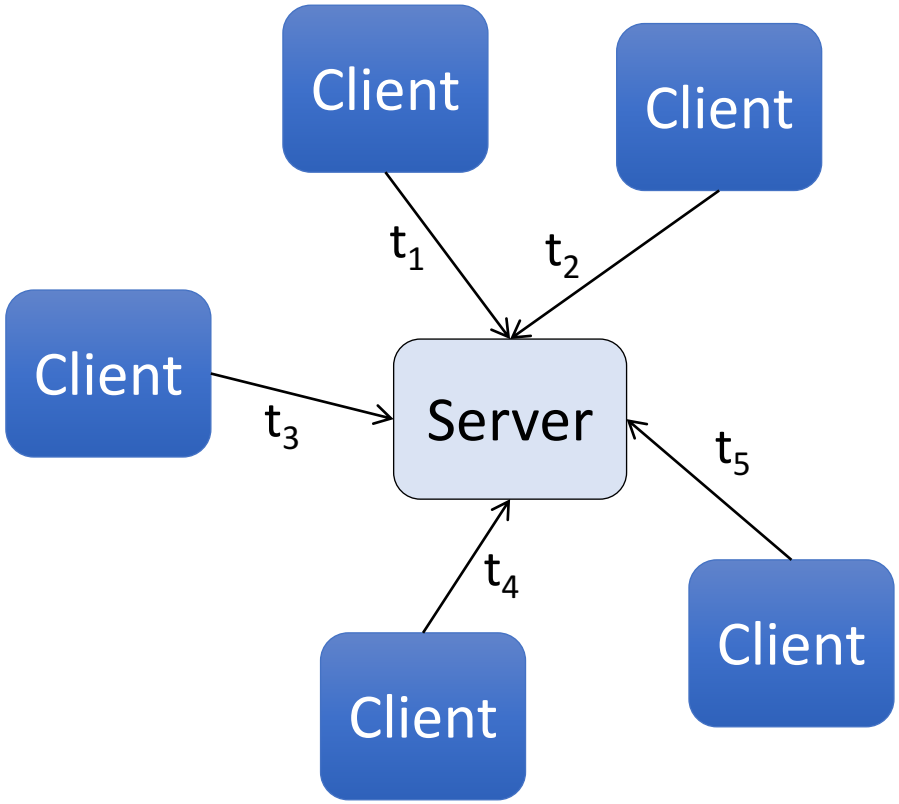
Only supports internal synchronization.



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).

Berkeley Algorithm

Only supports internal synchronization.



Handling faulty processes:
Only use timestamps within some threshold of each other.

Handling server failure:
Detect the failure and elect a new leader.

Network Time Protocol

To be continued next class….

MP0: Event Logging

- https://courses.grainger.illinois.edu/ece428/sp2026/mps/mp0.html
- Lead TA: Naman Raina

- Task:
  - Collect events from distributed nodes.
  - Aggregate them into a single log at a centralized logger.

- Objective:
  - Familiarize yourself with the cluster development environment.
  - Practice distributed experiments and performance analysis.
  - Build infrastructure that might be useful in future MPs.

MP0: Event Logging

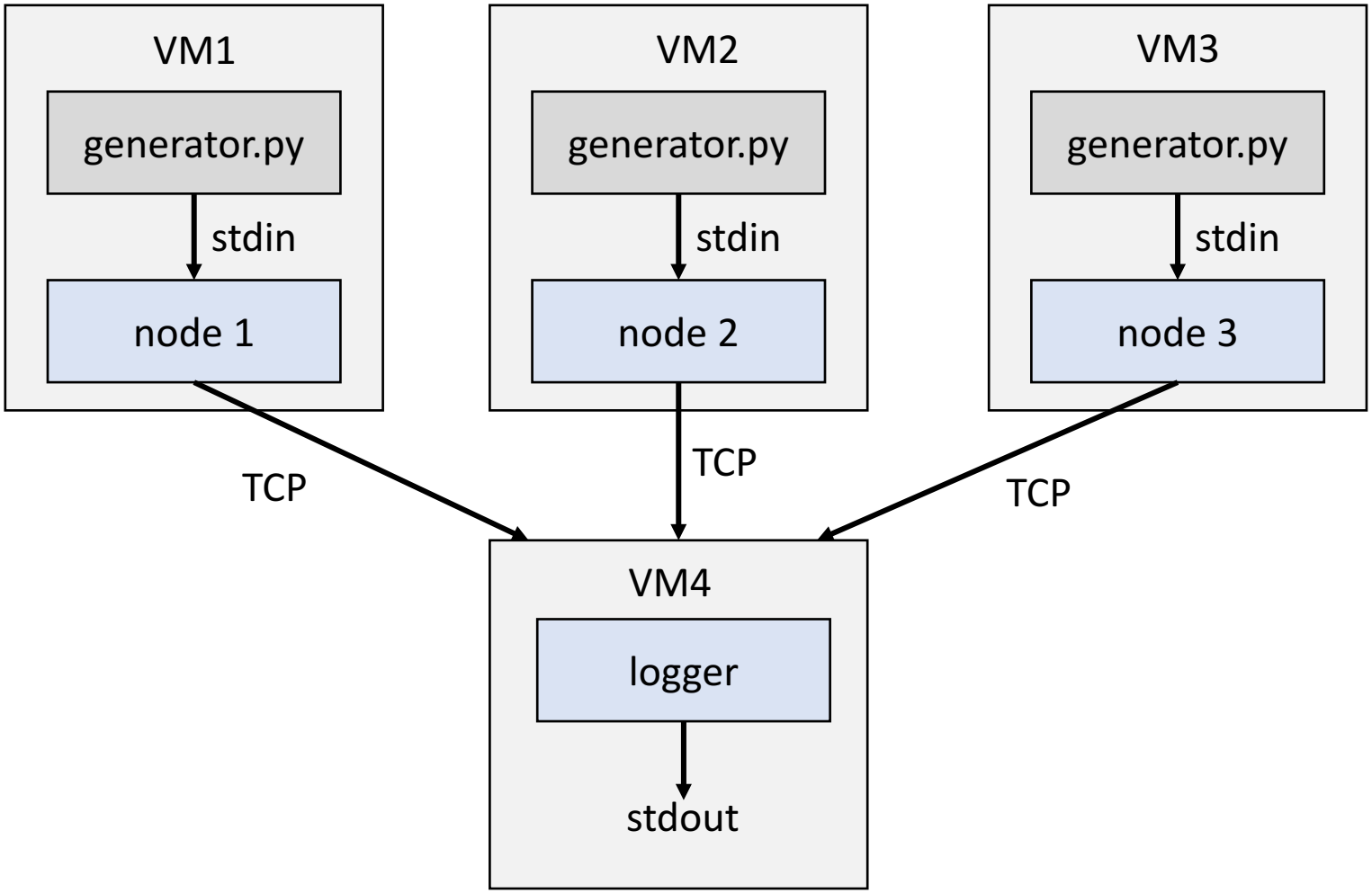
- We provide you with a script that generates logs **generator.py**

Timestamp

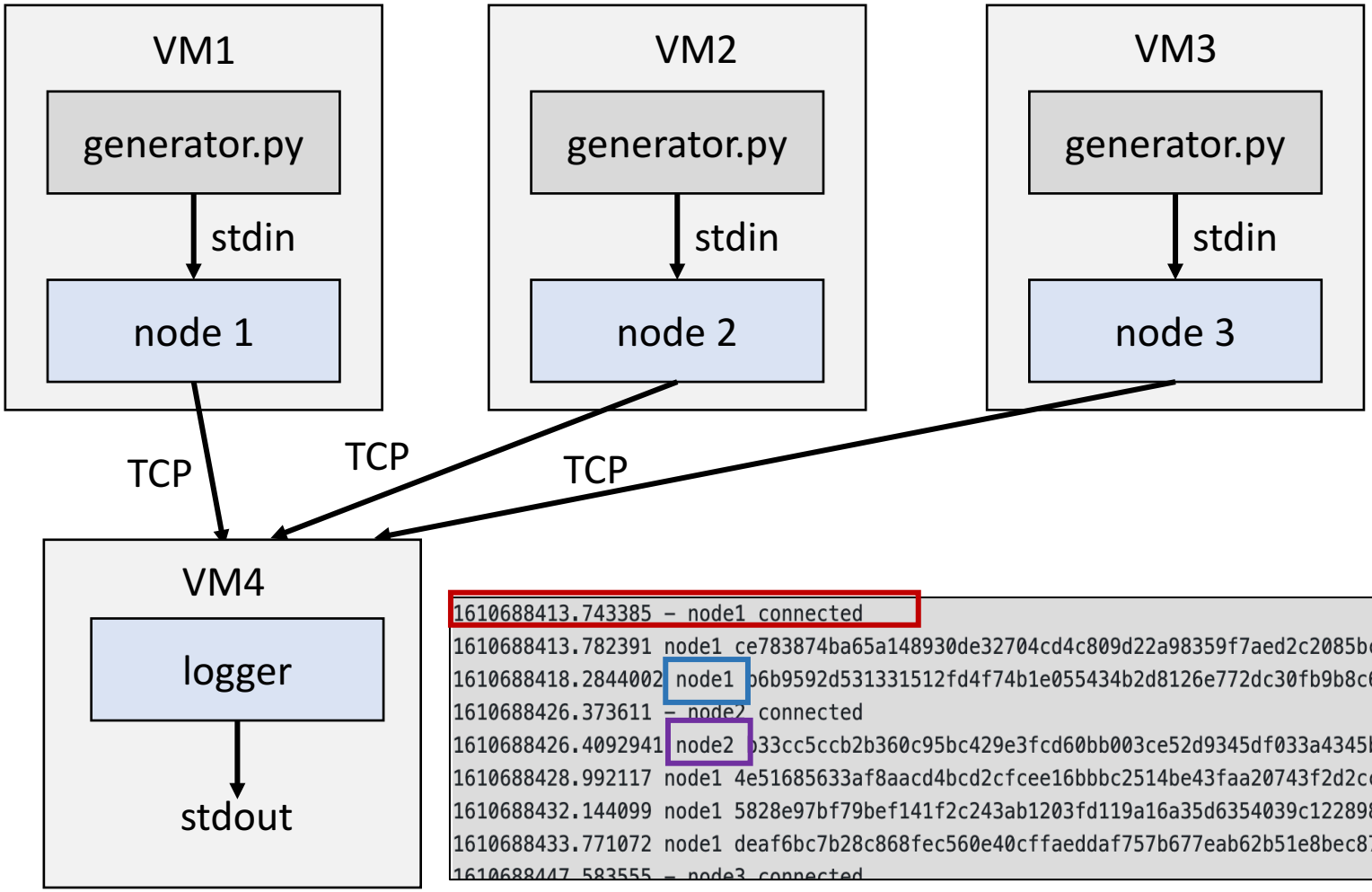
Event name (random)

```
% python3 generator.py 0.1
1610688413.782391 ce783874ba65a148930de32704cd4c809d22a98359f7aed2c2085bc1bd10f096
1610688418.2844002 b6b9592d531331512fd4f74b1e055434b2d8126e772dc30fb9b8c65298696517
1610688428.992117 4e51685633af8aacd4bcd2cfcee16bbbc2514be43faa20743f2d2cc4de853162
1610688432.144099 5828e97bf79bef141f2c243ab1203fd119a16a35d6354039c12289841bc33608
1610688433.771072 deaf6bc7b28c868fec560e40cffaeddaf757b677eab62b51e8bec87955ca3274
1610688449.1301062 ca6e5225e2ea02c1174701dd0320954fbfffb51dbcd9d15717e11d7e40556efb
1610688455.484428 ed4b1eb8a7bd980a1f0da41f5d6513e919e2bf201ba9ec9f9c05201bd777af94
1610688455.813278 3b014179e1cc1d2cc9cf553441492ad4f054634d2f0f0b66d0185c60fc4355da
1610688463.543133 8110f0cc37404a10989bfe14ae83224a73e642bb676ded625b08ed7d3e439706
```

MP0: Event Logging



MP0: Event Logging




```
1610688413.743385 - node1 connected
1610688413.782391 node1 ce783874ba65a148930de32704cd4c809d22a98359f7aed2c2085bc1bd10f096
1610688418.2844002 node1 b6b9592d531331512fd4f74b1e055434b2d8126e772dc30fb9b8c65298696517
1610688426.373611 - node2 connected
1610688426.4092941 node2 b33cc5ccb2b360c95bc429e3fcd60bb003ce52d9345df033a4345bde49f5da2c
1610688428.992117 node1 4e51685633af8aacd4bcd2cfcee16bbbc2514be43faa20743f2d2cc4de853162
1610688432.144099 node1 5828e97bf79bef141f2c243ab1203fd119a16a35d6354039c12289841bc33608
1610688433.771072 node1 deaf6bc7b28c868fec560e40cffaeddaf757b677eab62b51e8bec87955ca3274
1610688447.583555 - node3 connected
```

MP0: Event Logging

- Run two experiments
  - 3 nodes, 2 events/s each
  - 8 nodes, 5 events/s each

- Collect graphs of two metrics:
  - Delay between event generation at the node and it appearing in the centralized log.
  - Amount of bandwidth used by the central logger.
  - Need to add instrumentation to your code to track these metrics.

MP0: Event Logging

- Due on Feb 11, 11:59pm
  - Late policy: Can use part of your 168hours of grace period accounted per student over the entire semester.
- Carried out in groups of 1-2
  - Same expectations regardless of group size.
  - Fill out form on CampusWire to get access to cluster.
    - Getting cluster access may take some time.
    - But you can start coding now!
- Can use any language.
  - Supported languages are C/C++, Go, Java, Python.
  - Remember that MP2 must be in Go.