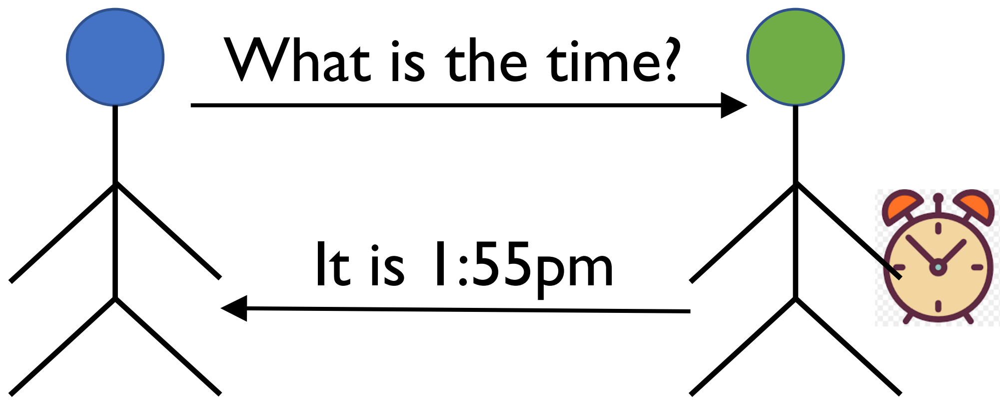
Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

While we wait…



Bluey does not own a clock, and wants to know the time.
He sends a message to Greeny asking the time, and Greeny sends a response as soon as he receives the request.
Bluey records that it took 6 minutes for him to receive Greeny's response after sending his request.

Given this information, what time should Bluey assume it actually is when he receives Greeny's message? Can he be totally accurate?

Logistics Related

- Make sure you are on CampusWire.
  - Email Sarthak (sm106) to get access if you are not already on it.
- Please fill up VM cluster form by tomorrow (Thursday).
- MP0 released today
  - Will discuss in more details at the end of the class.

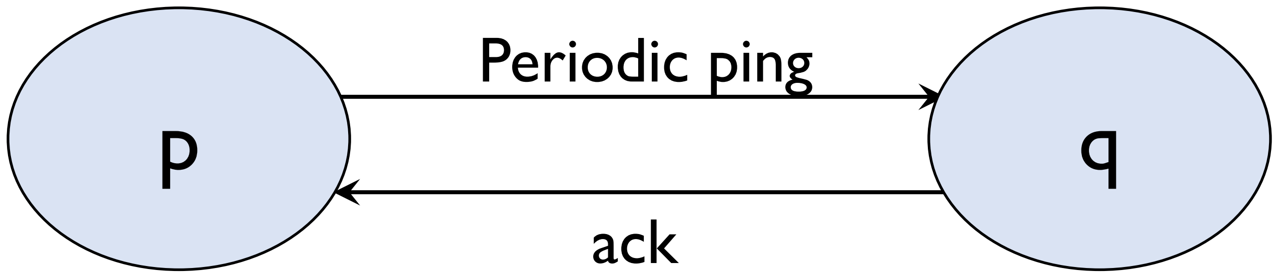
Today's agenda

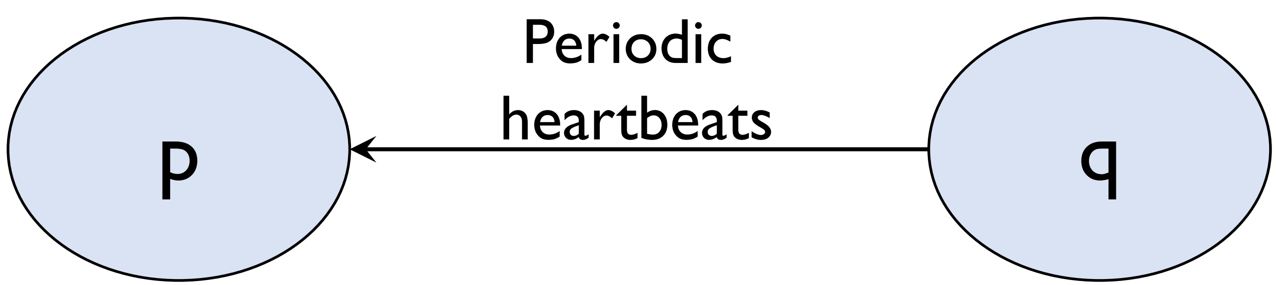
- Failure Detection
  - Chapter 15.1
- Time and Clocks
  - Chapter 14.1-14.3
- Logical Clocks and Timestamps (if time)
  - Chapter 14.4

Types of failure

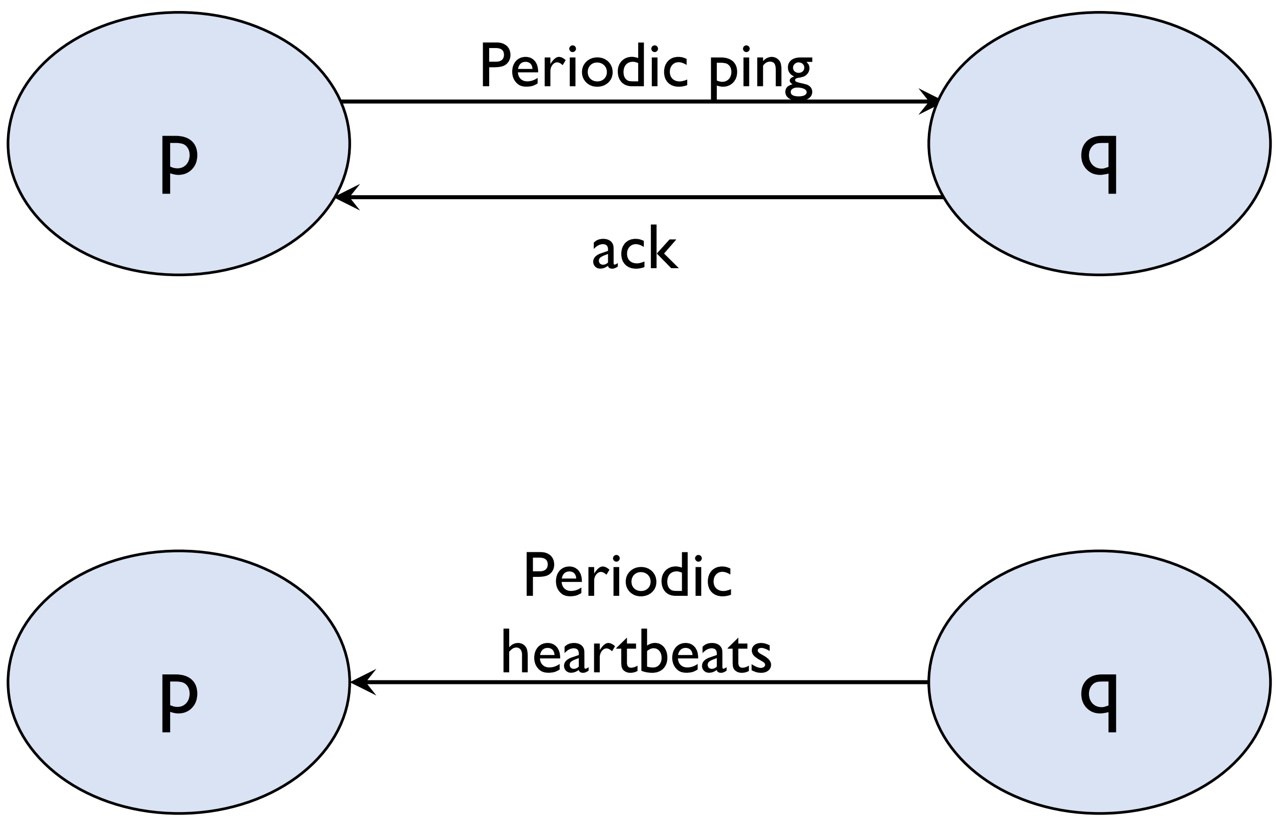
- **Omission:** when a process or a channel fails to perform actions that it is supposed to do.
  - Process may **crash**.
    - Detected using ping-ack or heartbeat failure detector.
    - Completeness and accuracy in synchronous and asynchronous systems.
    - Worst case failure detection time.
  - **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?





How to detect a crashed process?



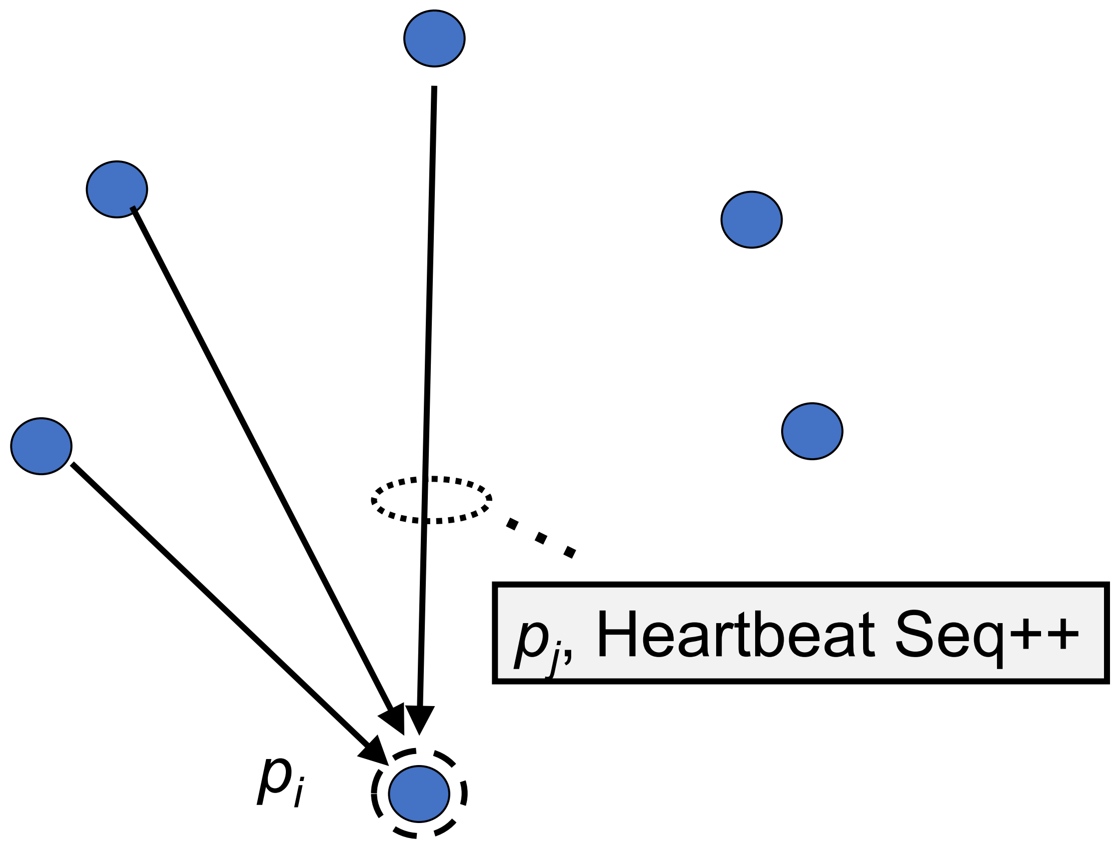
Extending heartbeats

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

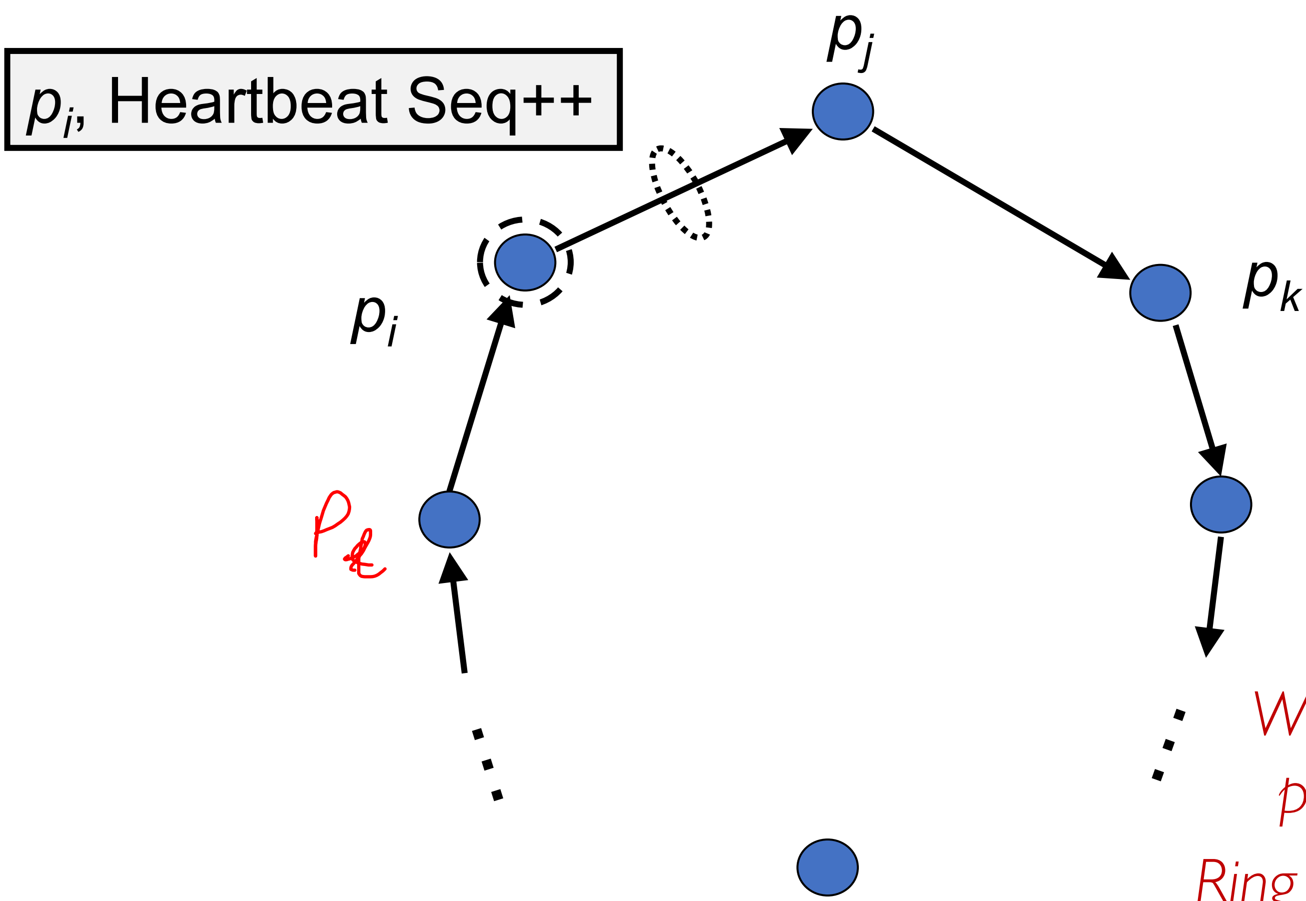
Centralized heartbeating

Downside:

What if p_i fails?



Ring heartbeating

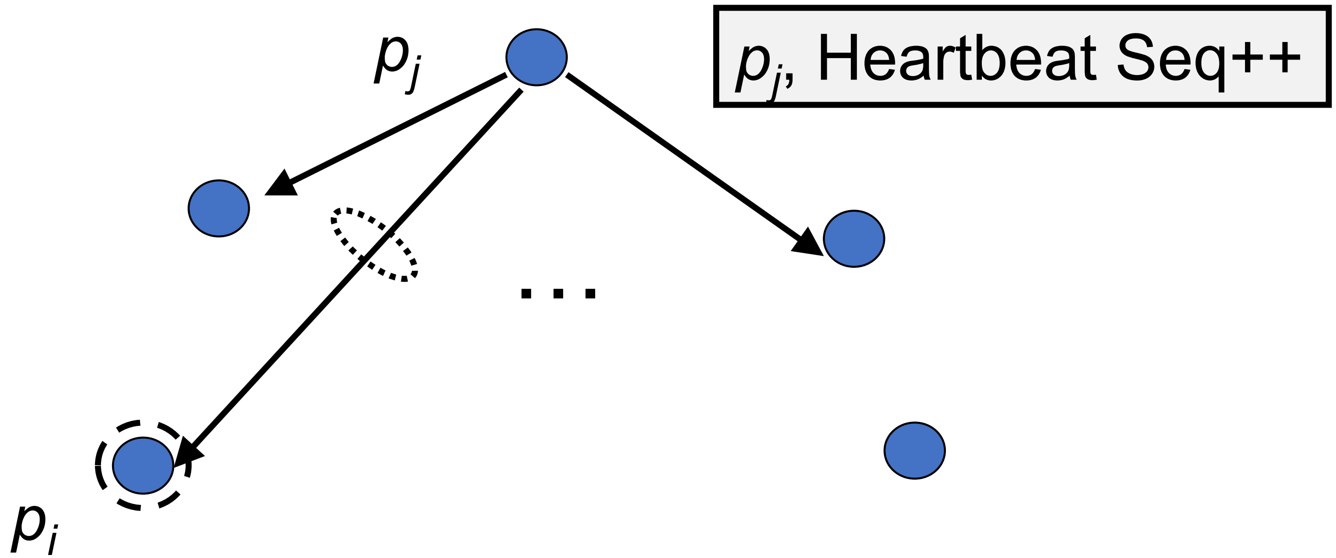


Downside:

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.*

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.

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 (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.

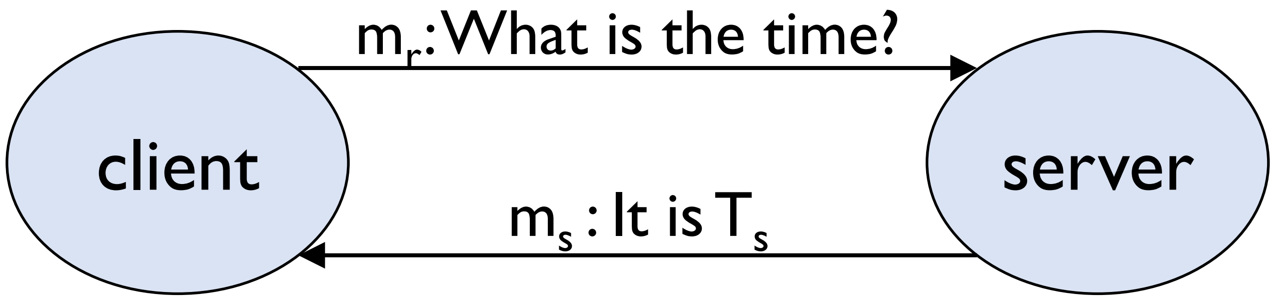
Synchronization Bound

- 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?*

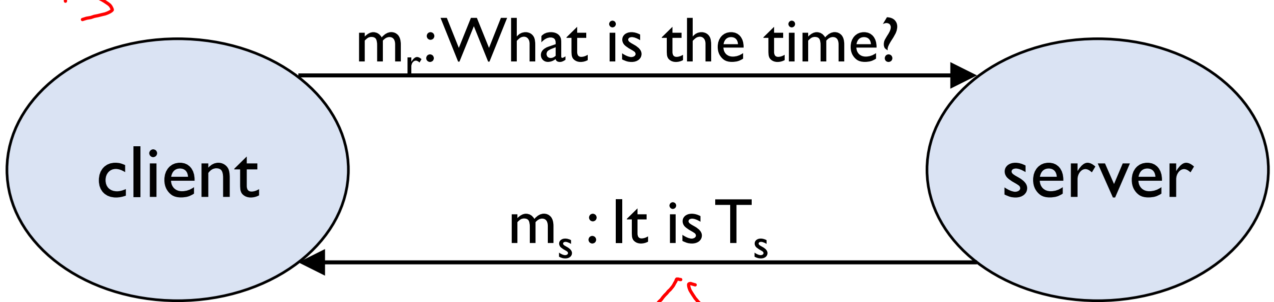
A: 2D. So the clocks are internally synchronized within a bound of 2D.

Synchronization in synchronous systems



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

Synchronization in synchronous systems



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.

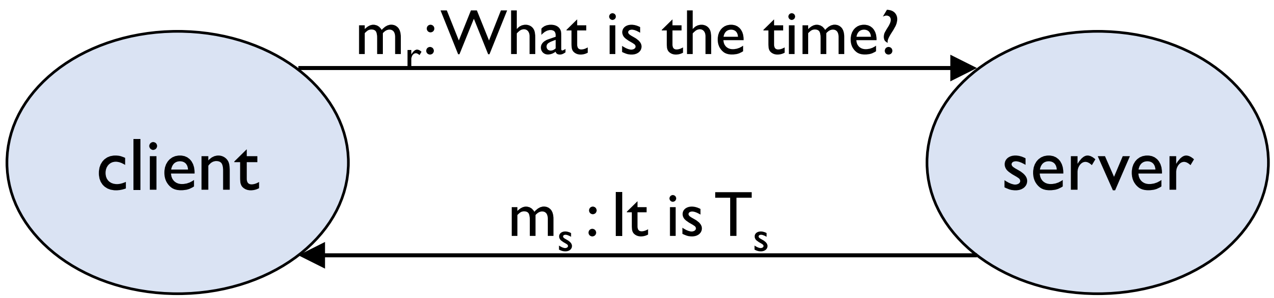
- If $T_c = T_s$, skew(client, server) ≤
- If $T_c = (T_s + max)$, skew(client, server) ≤
- If $T_c = (T_s + min)$, skew(client, server) ≤
- If $T_c = (T_s + (min + max)/2)$, skew(client,server) ≤

Provably the best you can do!

Synchronization in asynchronous systems

- Cristian Algorithm
- Berkeley Algorithm
- Network Time Protocol

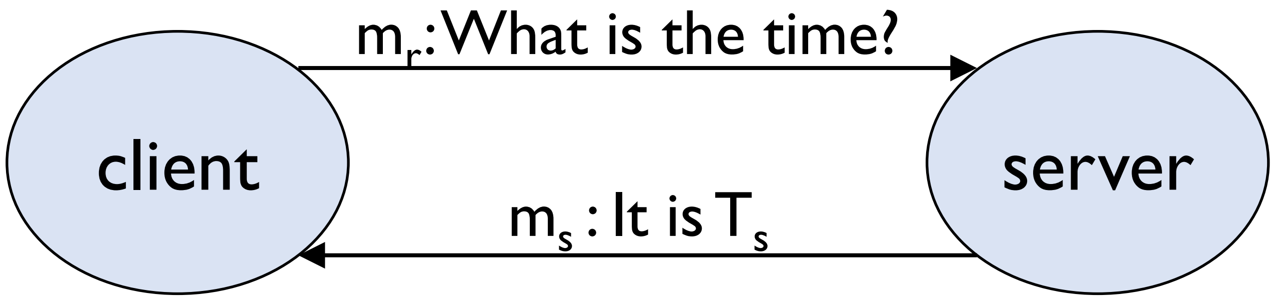
Cristian Algorithm



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

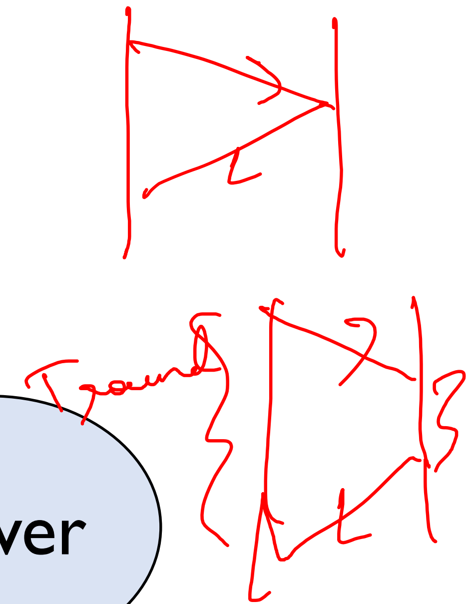
$\leq (T_{round} / 2)$

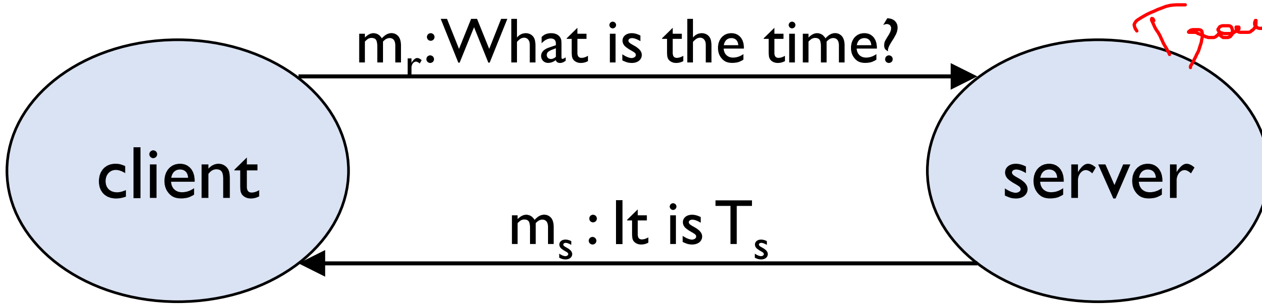
(*min* is minimum one way network delay which is atleast zero).

Try deriving the worst case skew!

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

Cristian Algorithm





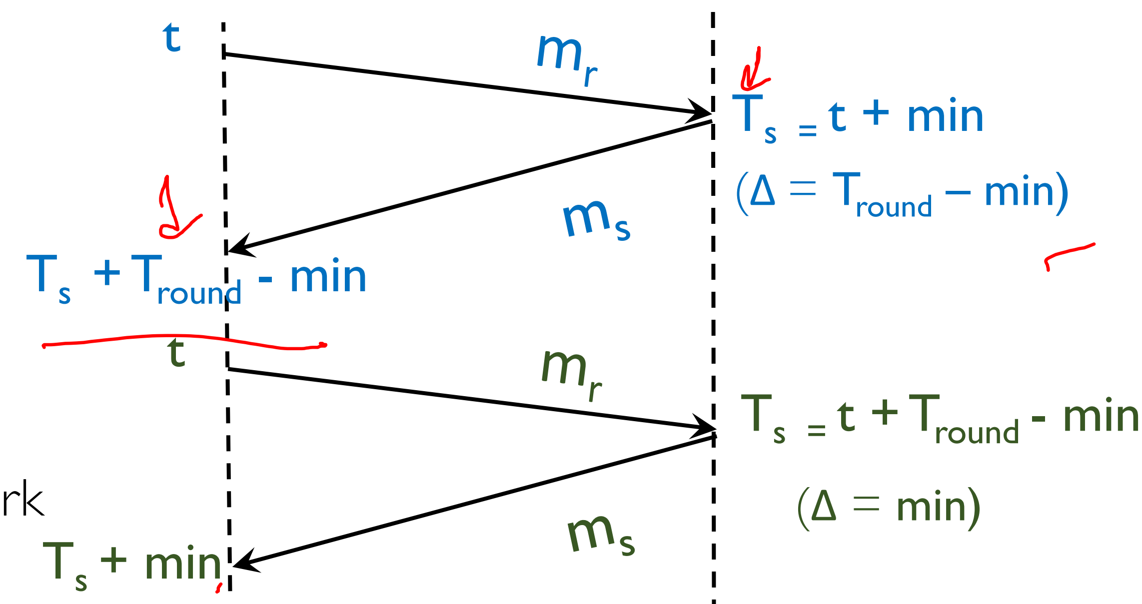
What time T_c should client adjust its local clock to after receiving m_s ?

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

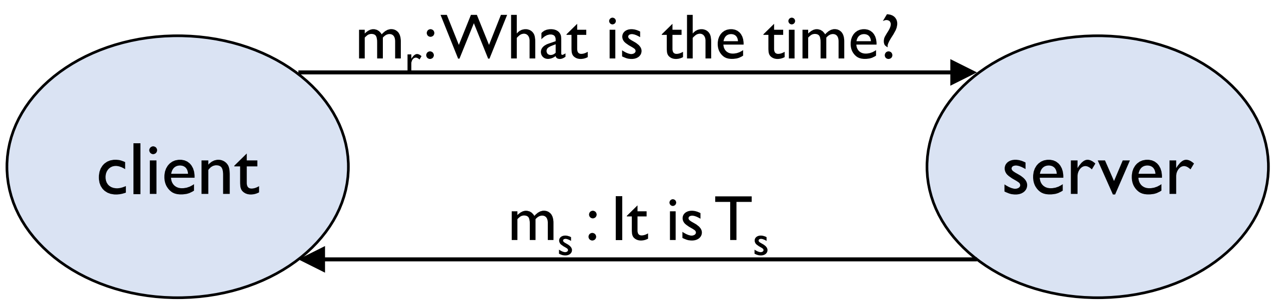
$T_c = T_s + (T_{round} / 2)$

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

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



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}).

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

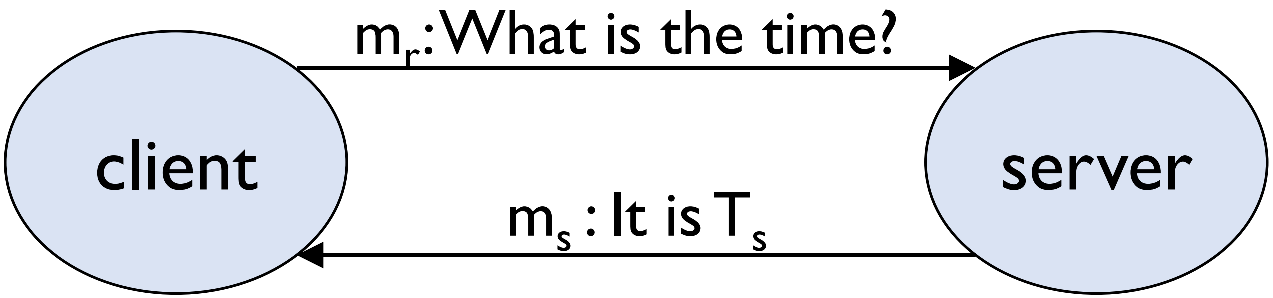
skew $\leq (T_{round} / 2) - min$
$\leq (T_{round} / 2)$

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

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

Server failure: Use multiple synchronized time servers.

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

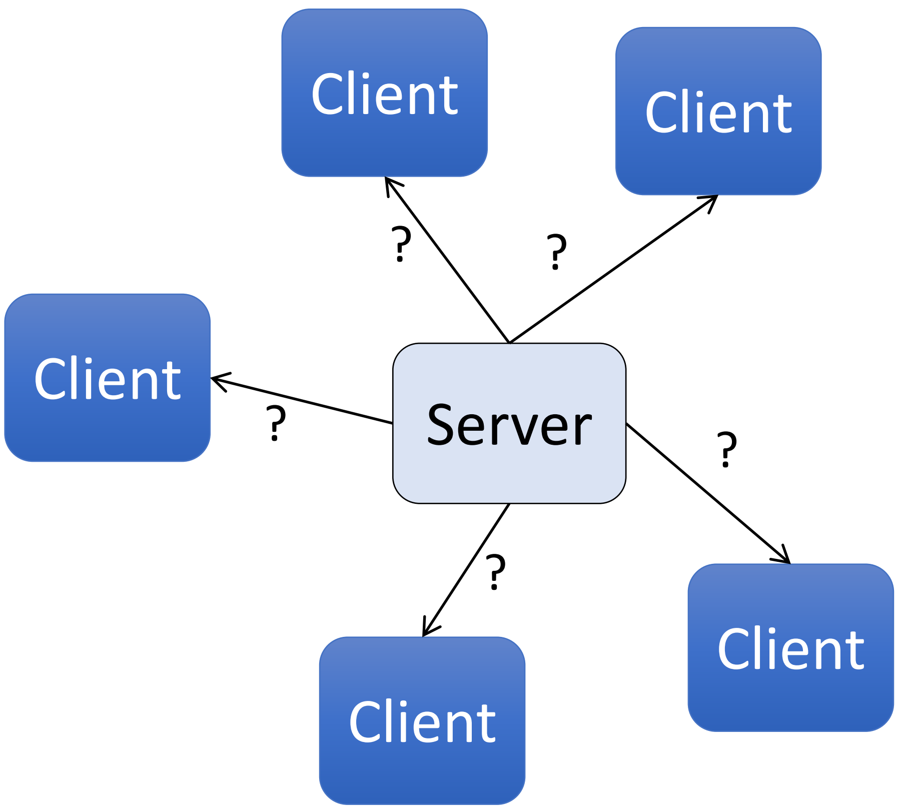
$\leq (T_{round} / 2)$

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

Cannot handle faulty time servers.

Berkeley Algorithm

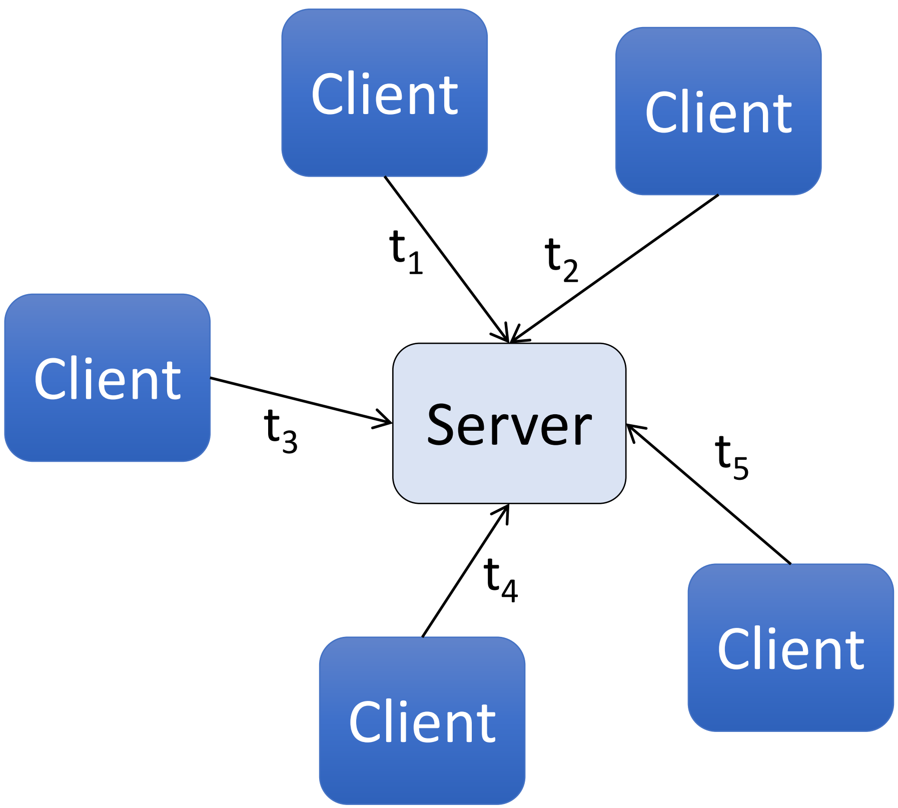
Only supports internal synchronization.



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

Berkeley Algorithm

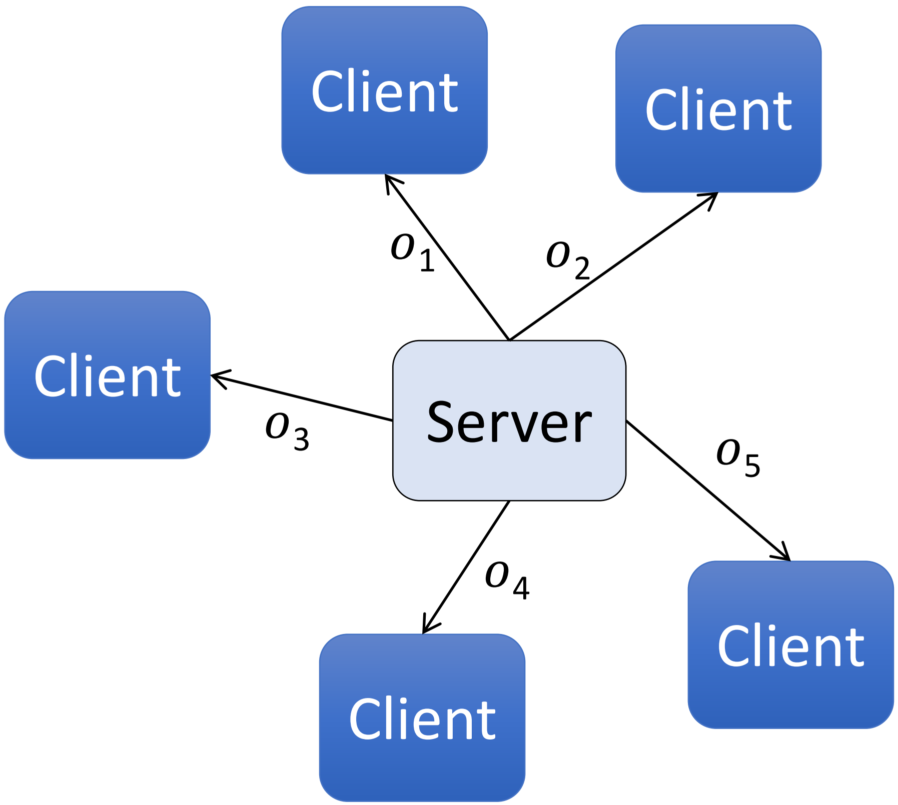
Only supports internal synchronization.



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

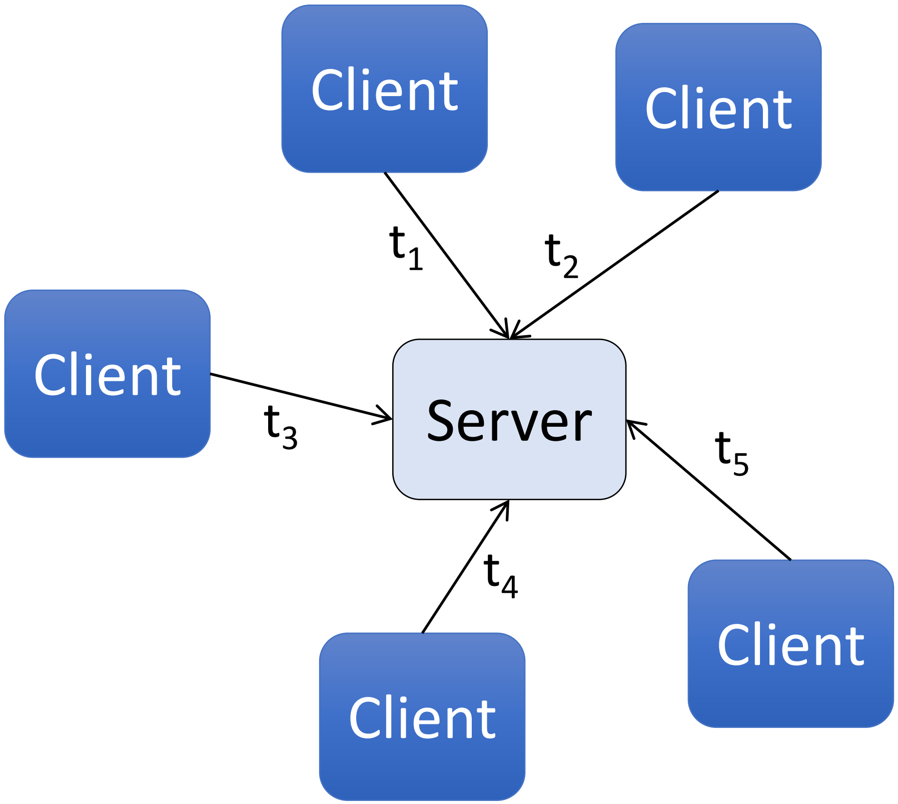
Only supports internal synchronization.



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.

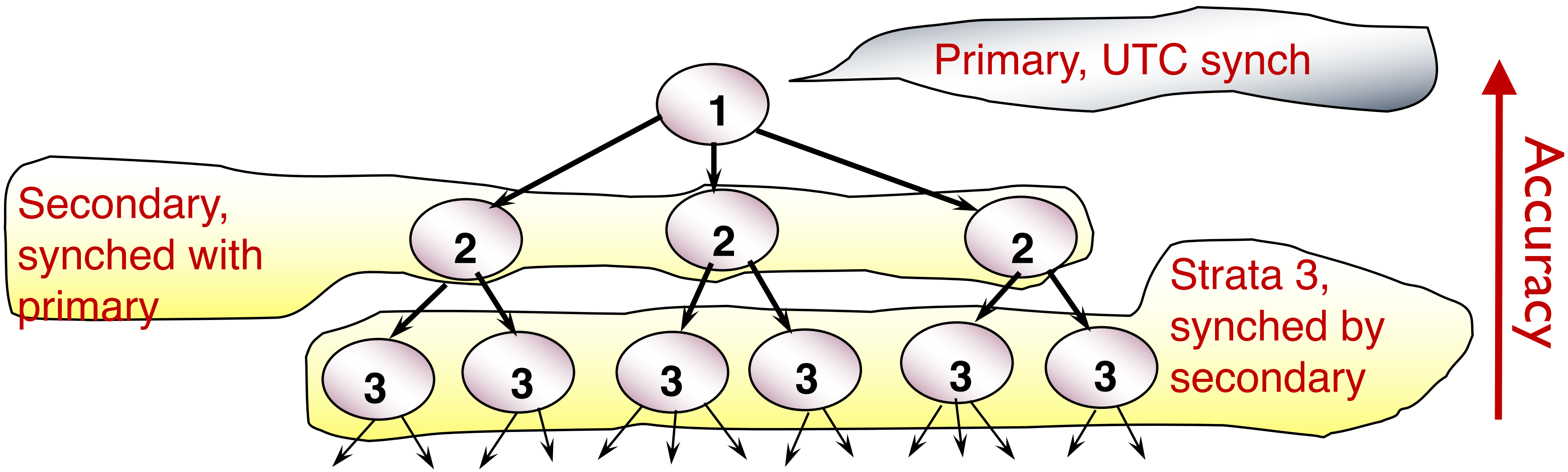


Handling faulty processes:
Only use timestamps within some threshold of each other.

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

Network Time Protocol

Time service over the Internet for synchronizing to UTC.



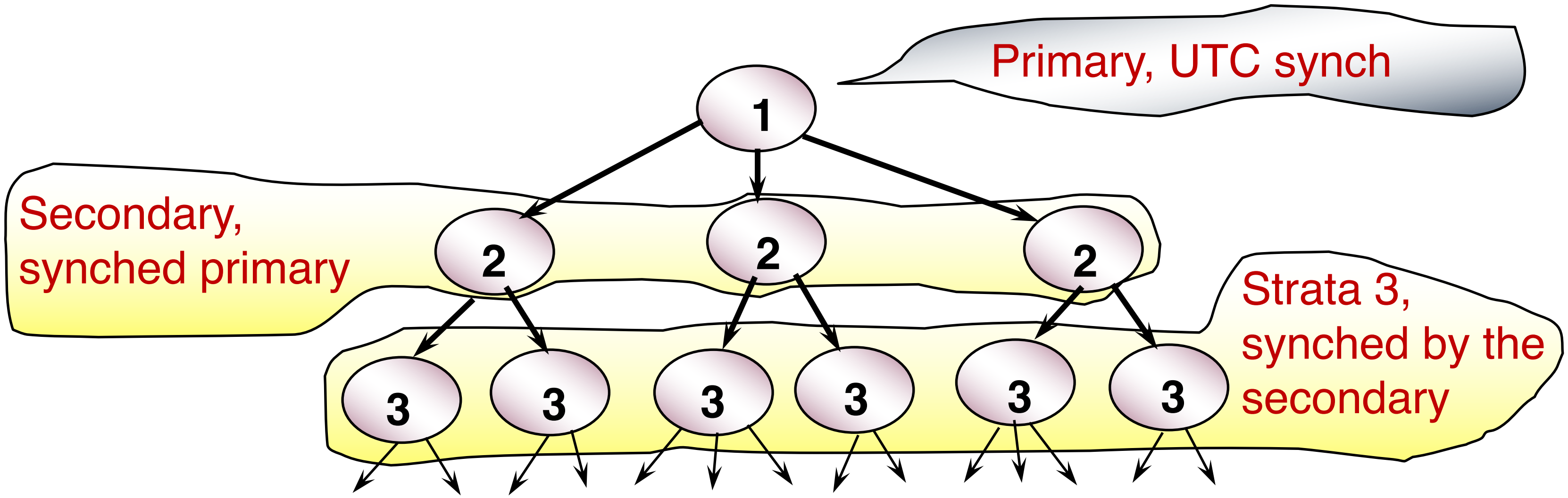
Hierarchical structure for *scalability*.

Multiple lower strata servers for *robustness*.

Authentication mechanisms for *security*.

Statistical techniques for better *accuracy*.

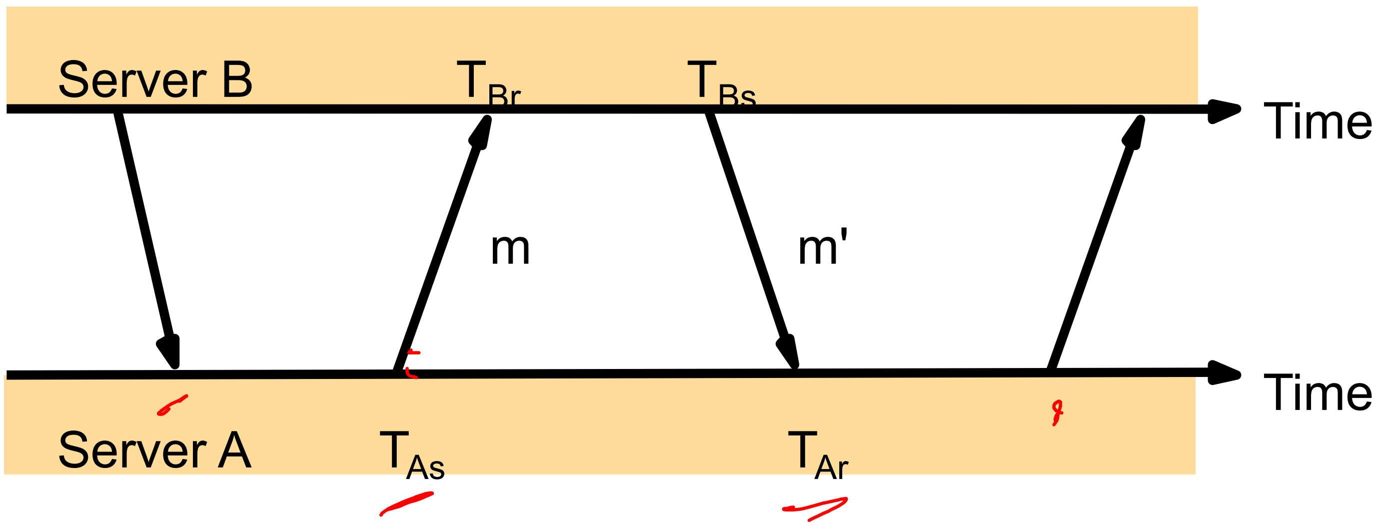
Network Time Protocol



How clocks get synchronized:

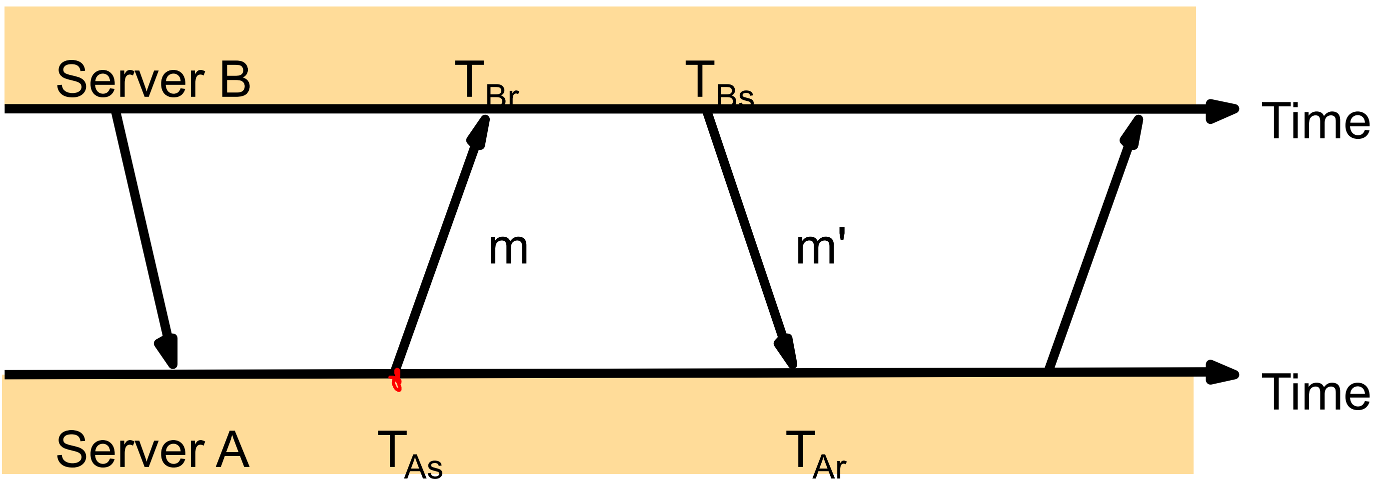
- Servers may *multicast* timestamps within a LAN. Clients adjust time assuming a small delay. *Low accuracy*.
- *Procedure-call* (Cristian algorithm). *Higher accuracy*.
- *Symmetric mode* used to synchronize lower strata servers. *Highest accuracy*.

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: <u>true</u> offset of clock at B relative to clock at A (unknown)
- o_i: <u>estimate</u> of actual offset between the two clocks
- d_i: estimate of <u>accuracy</u> of o_i ; total transmission times for m and m'. d_i=t+t'

$$T_{Br} = T_{As} + t + o \quad 1$$
$$T_{Ar} = T_{Bs} + t' - o \quad 2$$

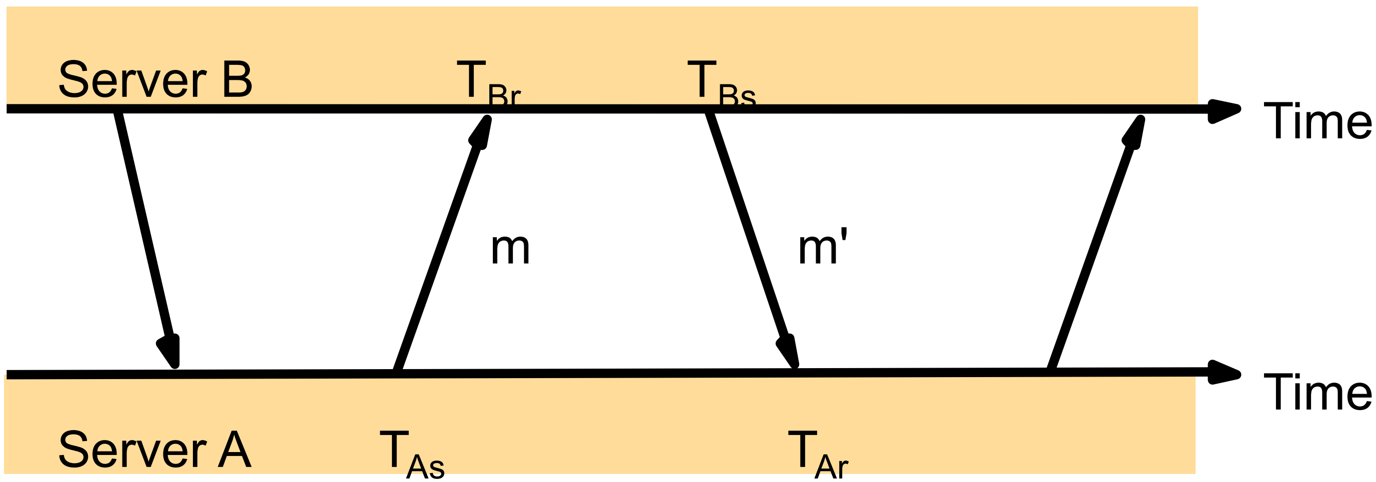
$$o = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}) + (t' - t))/2$$

$$\mathbf{o_i = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}))/2}$$

$$o = o_i + (t' - t)/2$$

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

NTP Symmetric Mode



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

$$T_{Br} = T_{As} + t + o$$

$$T_{Ar} = T_{Bs} + t' - o$$

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

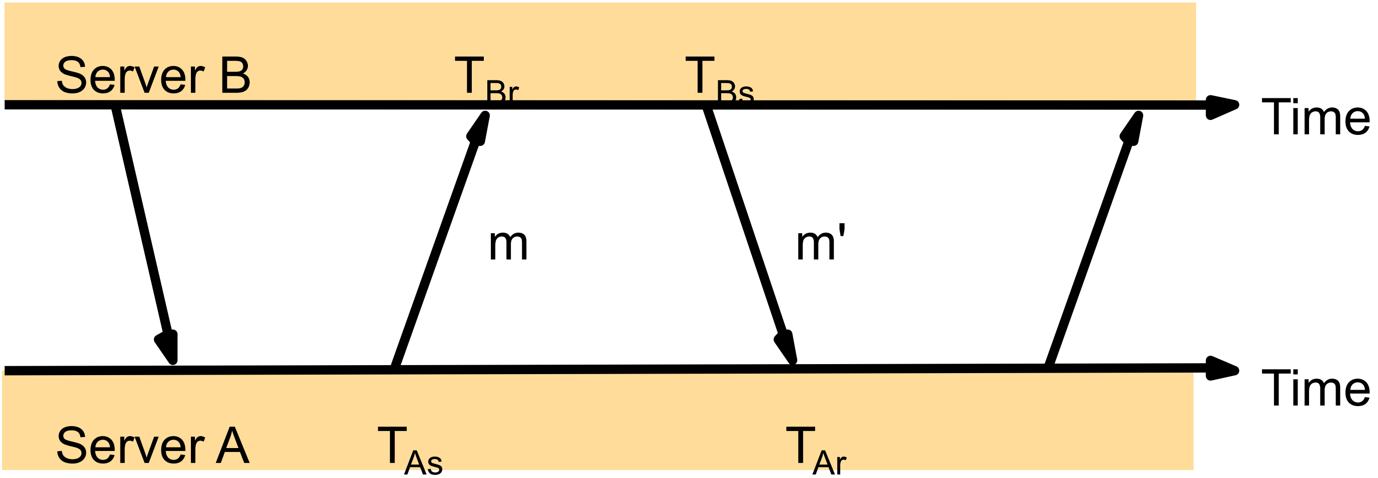
$$\mathbf{o_i = ((T_{Br} - T_{As}) - (T_{Ar} - T_{Bs}))/2}$$

$$o = o_i + (t' - t)/2$$

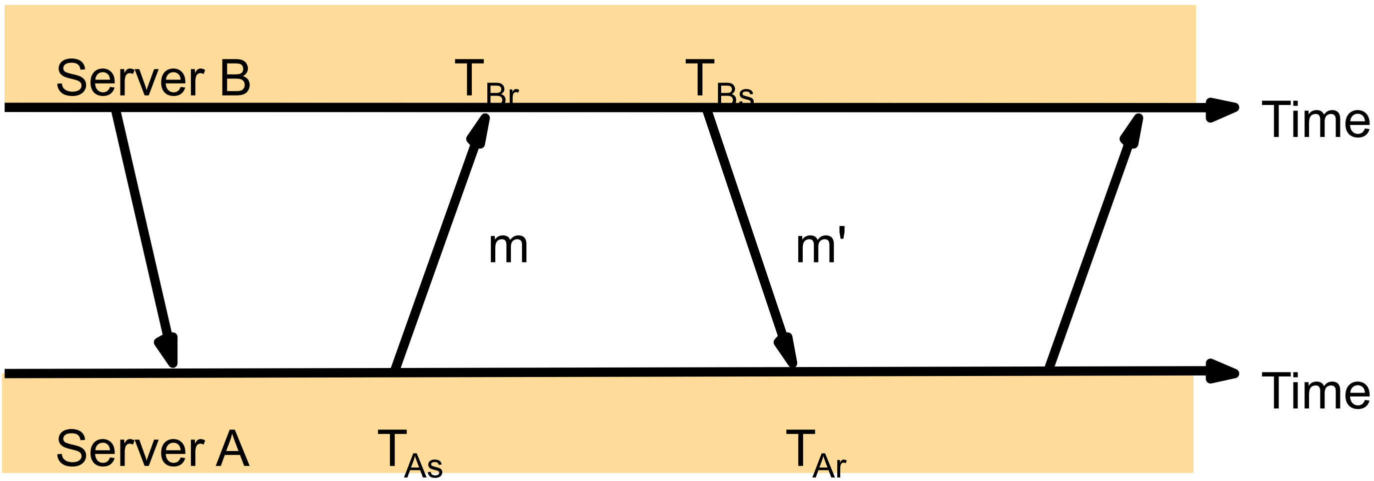
$$\mathbf{d_i = t + t' = (T_{Br} - T_{As}) + (T_{Ar} - T_{Bs})}$$

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

NTP Symmetric Mode



NTP Symmetric Mode



A and B exchange messages and record the send and receive timestamps.

Use these timestamps to compute offset with respect to one another ($\mathbf{o}_i$).

A server computes its offset from multiple different sources and adjust its local time accordingly.

Synchronization in asynchronous systems

- Cristian Algorithm
  - Synchronization between a client and a server.
  - Synchronization bound = $(T_{round} / 2) - min \leq T_{round} / 2$
- Berkeley Algorithm
  - Internal synchronization between clocks.
  - A central server picks the average time and disseminates offsets.
- Network Time Protocol
  - Hierarchical time synchronization over the Internet.

Event Ordering

- A usecase of synchronized clocks:
  - Reasoning about order of events.
- Why is it useful?
  - Debugging distributed applications
  - Reconciling updates made to an object in a distributed datastore.
  - Rollback recovery during failures:
    1. *Checkpoint state of the system; 2. Log events (with timestamps); 3. Rollback to checkpoint and replay events in order if system crashes.*
  - ….
- Can we reason about order of events without synchronized clocks?

Process, state, events

- Consider a system with **n** processes: $<p_1, p_2, p_3, \ldots., p_n>$
- Each process $\mathbf{p_i}$ is described by its *state* $\mathbf{s_i}$ that gets transformed over time.
  - State includes values of all local variables, affected files, etc.
- $\mathbf{s_i}$ gets transformed when an *event* occurs.
- Three types of events:
  - Local computation.
  - Sending a message.
  - Receiving a message.

Event Ordering

- Easy to order events within a single process $\mathbf{p_i}$, based on their time of occurrence.

- How do we reason about events across processes?
  - A message must be *sent* before it gets *received* at another process.

- These two notions help define *happened-before* (HB) relationship denoted by $\rightarrow$.
  - $\mathbf{e} \rightarrow \mathbf{e'}$ means **e** *happened before* **e'**.

Happened-Before Relationship

- *Happened-before* (HB) relationship denoted by $\rightarrow$.
  - **e** $\rightarrow$ **e'** means **e** *happened before* **e'**.
  - **e** $\rightarrow_i$ **e'** means **e** *happened before* **e'**, as observed by $\mathbf{p_i}$.
- HB rules:
  - If $\exists$ $\mathbf{p_i}$, **e** $\rightarrow_i$ **e'** then **e** $\rightarrow$ **e'**.
  - For any message m, **send(m)** $\rightarrow$ **receive(m)**
  - If **e** $\rightarrow$ **e'** and **e'** $\rightarrow$ **e''** then **e** $\rightarrow$ **e''**
- Also called *"causal" or "potentially causal"* ordering.
- *To be continued in next class…..*

MP0: Event Logging

- https://courses.grainger.illinois.edu/ece428/sp2024/mps/mp0.html
- Lead TA: Sanjit Kumar

- 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

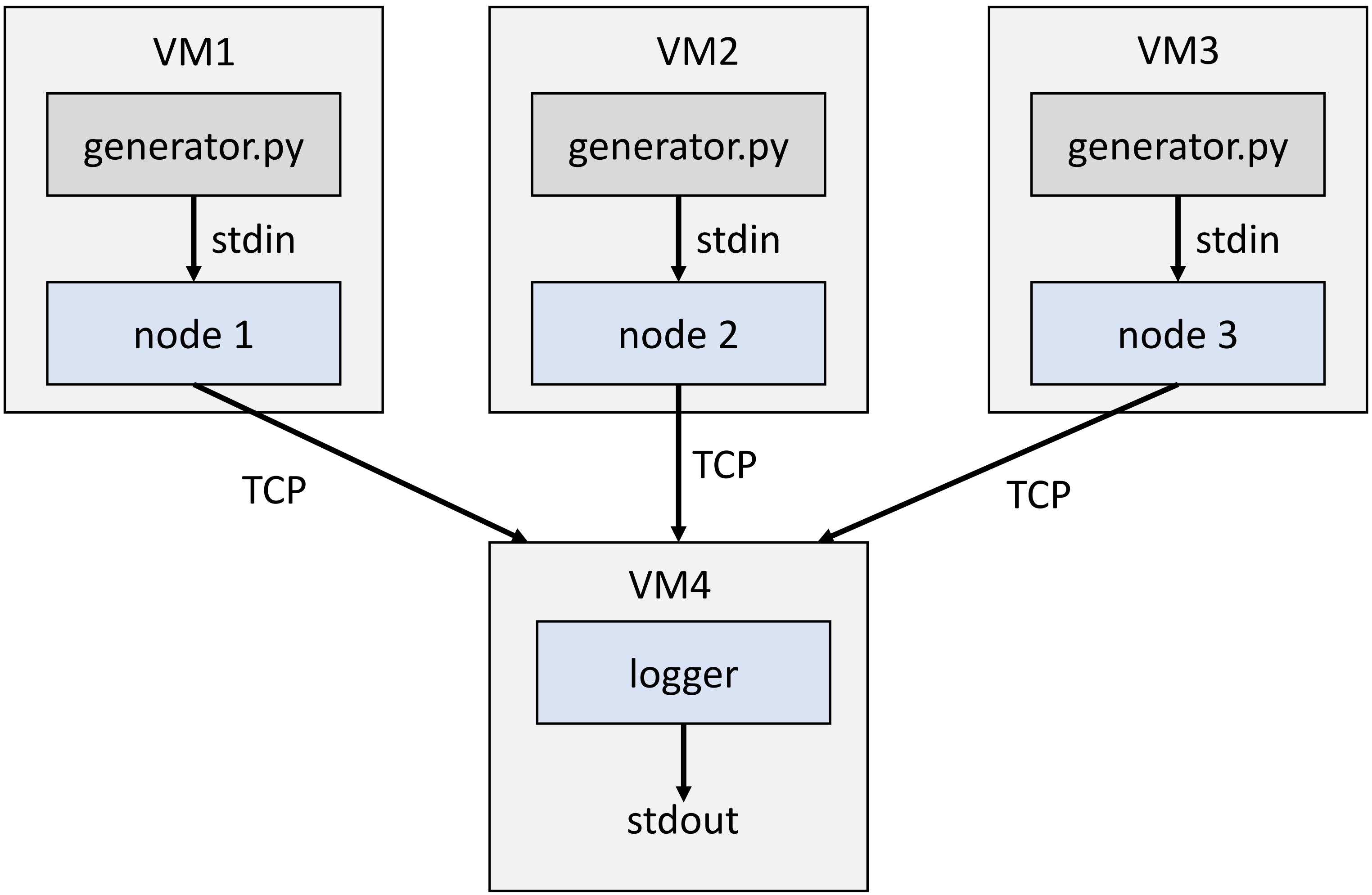
generator.py

Timestamp

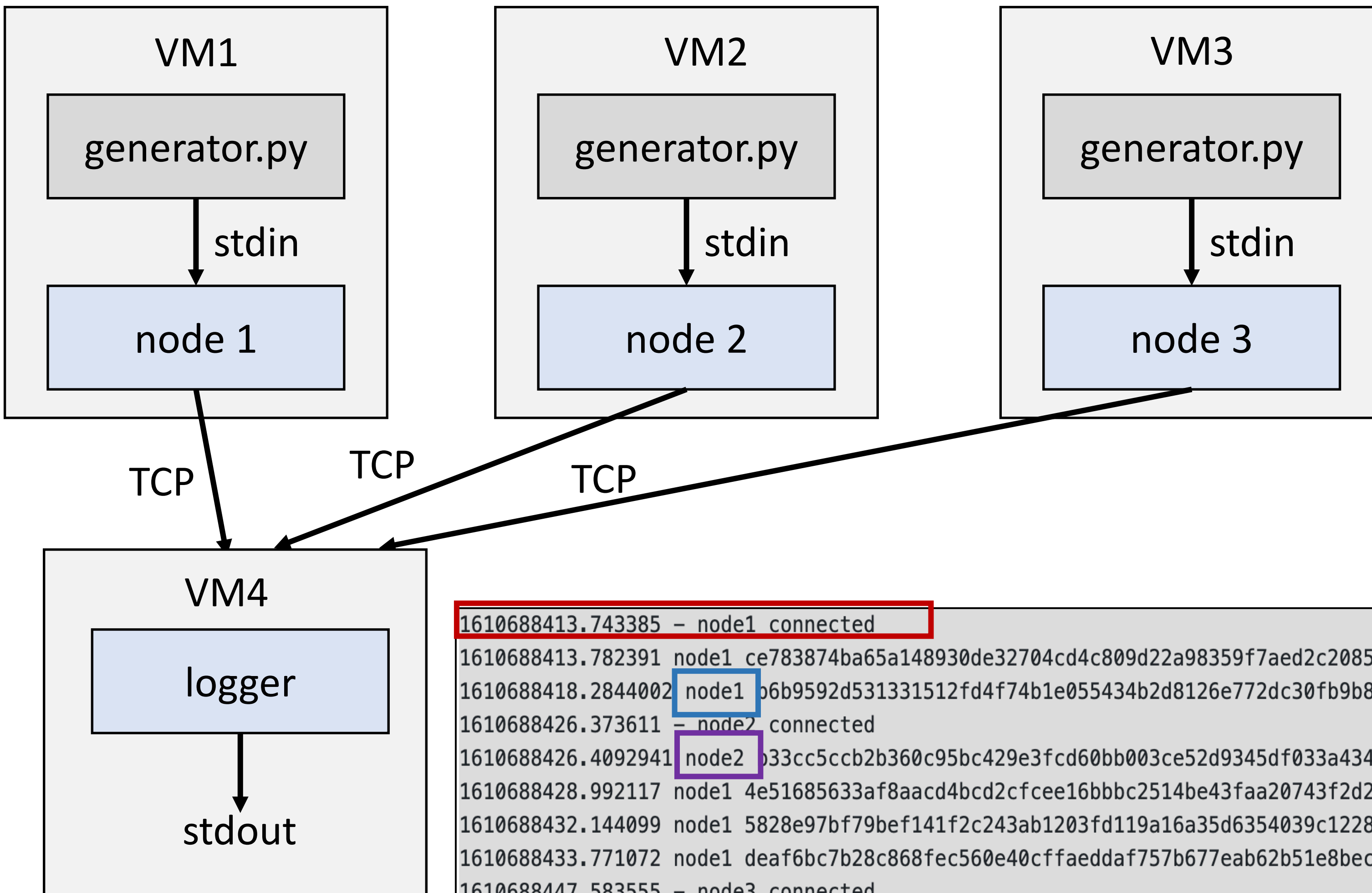
Event name (random)

```
% 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 7, 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.