Distributed Systems

05. Clock Synchronization

Paul Krzyzanowski

Rutgers University

Fall 2017

Synchronization

Synchronization covers interactions among distributed processes

Clocks	Identifying *when* something happened
Mutual exclusion	Only one entity can do an operation at a time
Leader election	Who coordinates activity?
Message consistency	Does everyone have the same view of events?
Agreement	Can everyone agree on a proposed value?

All of these are trivial in non-distributed systems

All of these are tricky in distributed systems

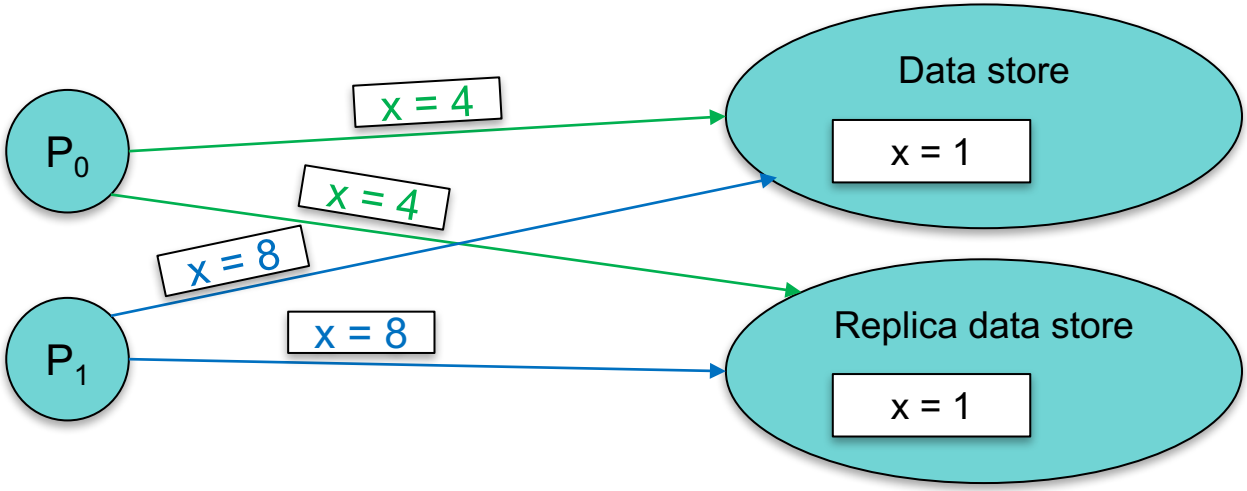
Clock Synchronization

Why?

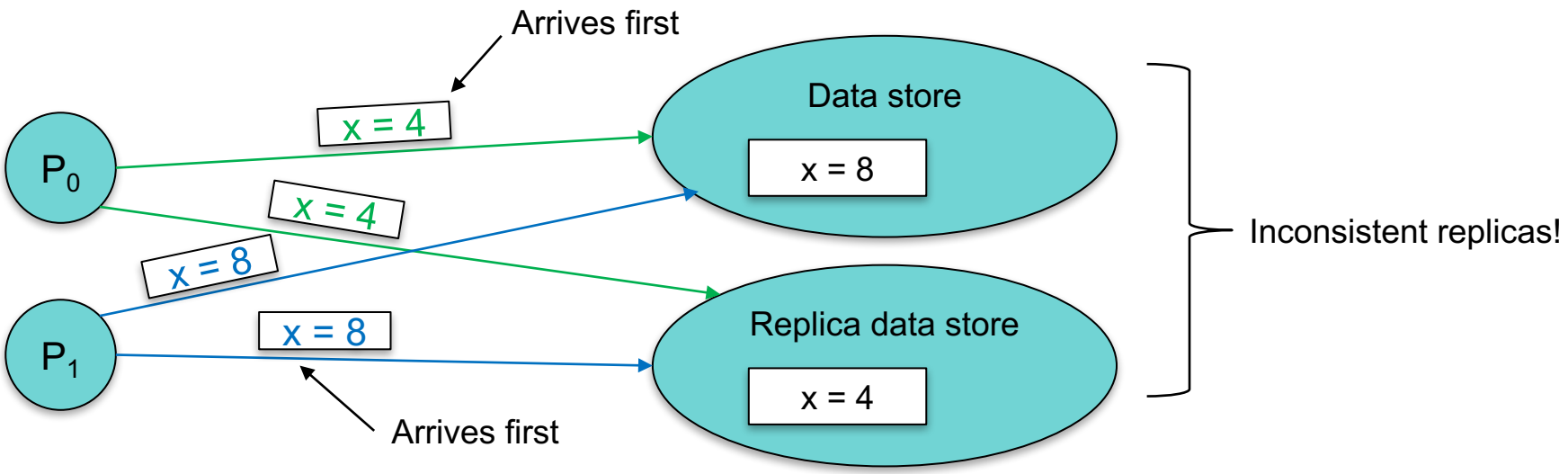
- Allow a process to identify "now" in a way that's consistent with other processes on other systems

- Temporal ordering of events from concurrent processes
  - Example: replication & identifying latest versions
    - *Last writer wins* or *latest version wins*

Simple approach to replication



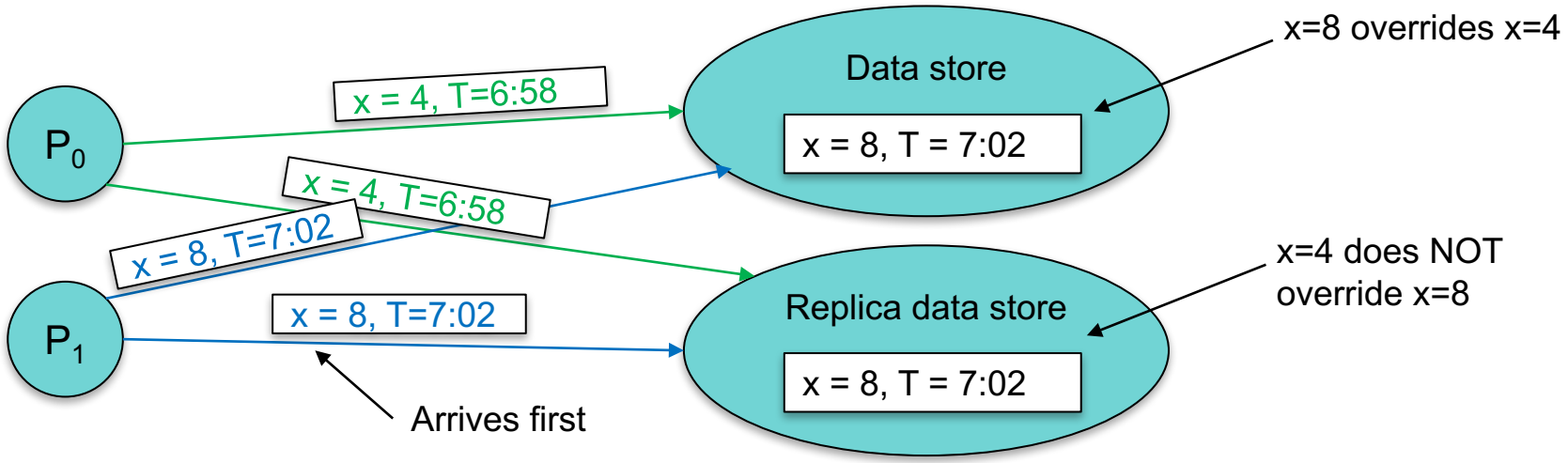
Simple approach to replication



Simple approach to replication

Send a time stamp with each modification request

Only newer timestamps can override older data



There are problems with this … but physical clocks help this work most of the time

Logical vs. physical clocks

- Physical clocks keep time of day
  - Consistent across systems

- Logical clock keeps track of event ordering
  - among related (causal) events

Physical clocks

Problem: Get two systems to agree on time

- Why is it hard?
  - Two clocks hardly ever agree
  - Quartz oscillators oscillate at slightly different frequencies
- Clocks tick at different rates
  - Create ever-widening gap in perceived time
  - Clock Drift
- Difference between two clocks at one point in time
  - Relative offset
- Short-term variation in frequency
  - Jitter
- Also note: astronomical time vs. relative time
  - Time of day vs. count of seconds from epoch

Dealing with drift

Not good idea to set a clock back

- Illusion of time moving backwards can confuse message ordering and software development environments

Go for *gradual* clock correction

If fast:

Make the clock run slower until it synchronizes

If slow:

Make the clock run faster until it synchronizes

Dealing with drift

The OS can do this:

1. Redefine the rate at which system time is advanced with each interrupt

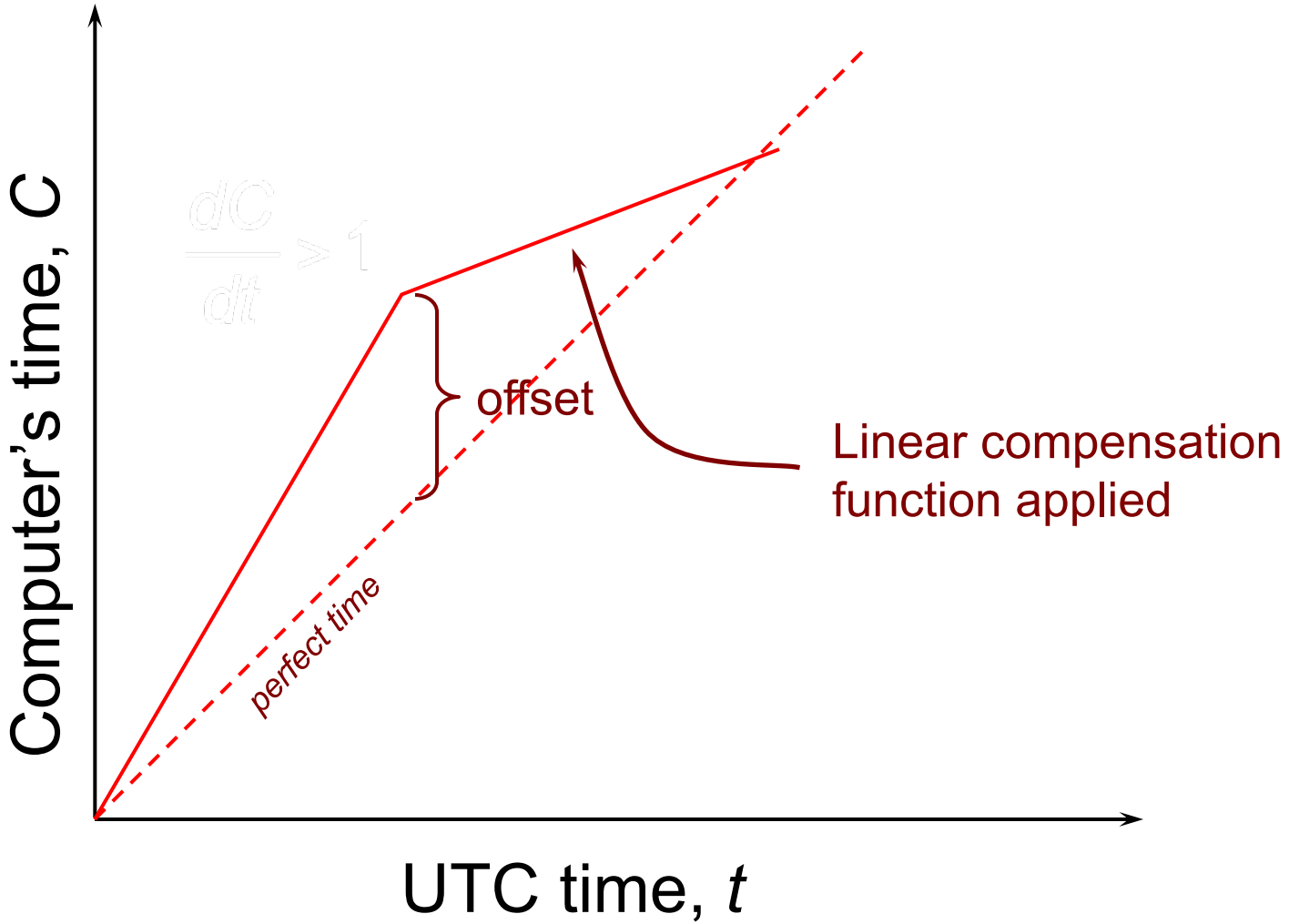
   or

2. Read the counter but compensate for drift

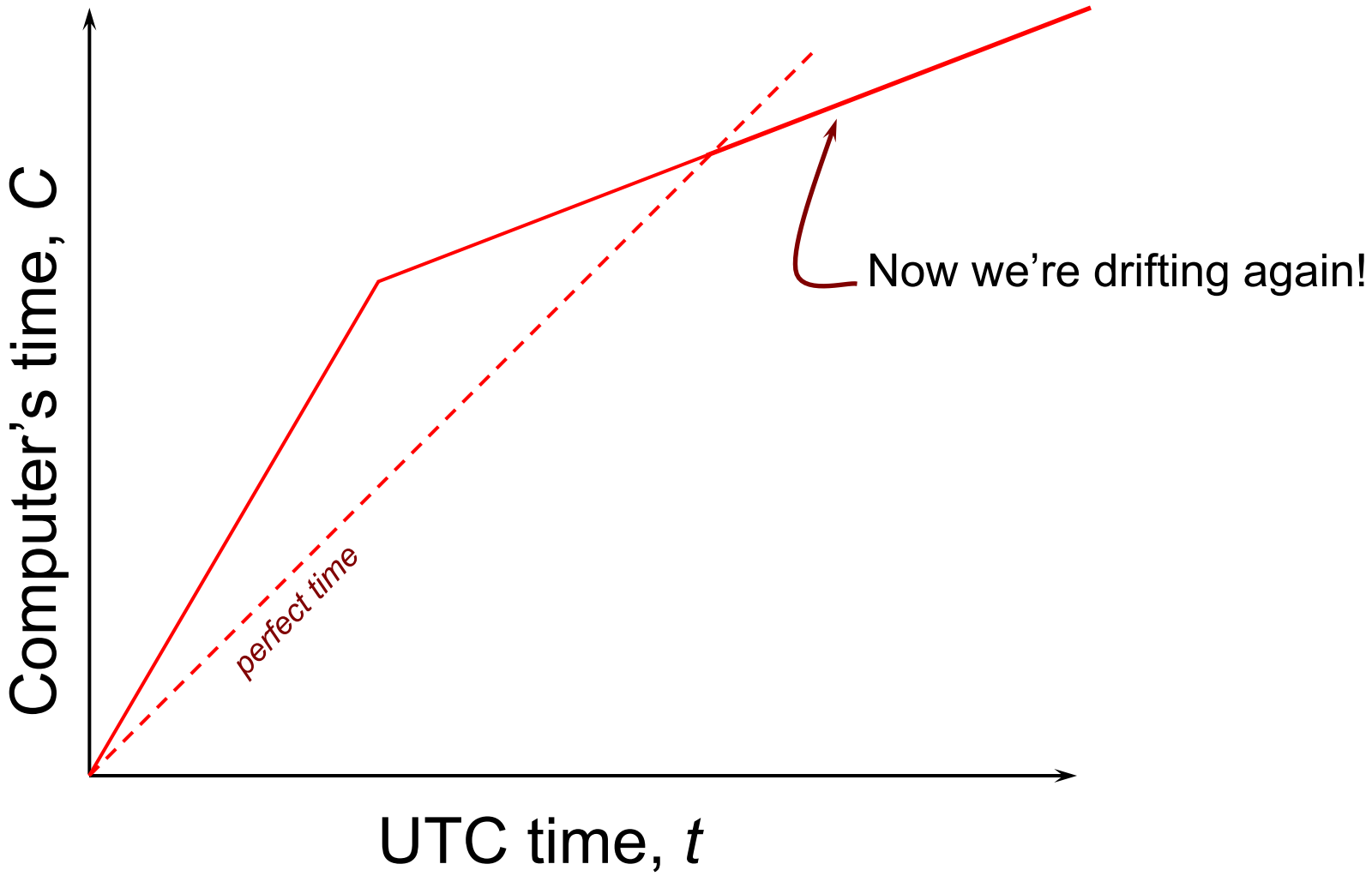
Adjustment changes slope of system time:

Linear compensation function

Compensating for a fast clock



Compensating for a fast clock



Resynchronizing

After synchronization period is reached

- Resynchronize periodically
- Successive application of a second linear compensating function can bring us closer to true slope

Long-term clock stability is not guaranteed

The system clock can still drift based on changes in temperature, pressure, humidity, and age of the crystal

Keep track of adjustments and apply continuously

- e.g., BSD *adjtimex* & Linux *adjtimex* system calls and *hwclock* command

Going to sleep

- RTC keeps on ticking when the system is off (or sleeping)
- OS cannot apply correction continually
- Estimate drift on wake-up and apply a correction factor

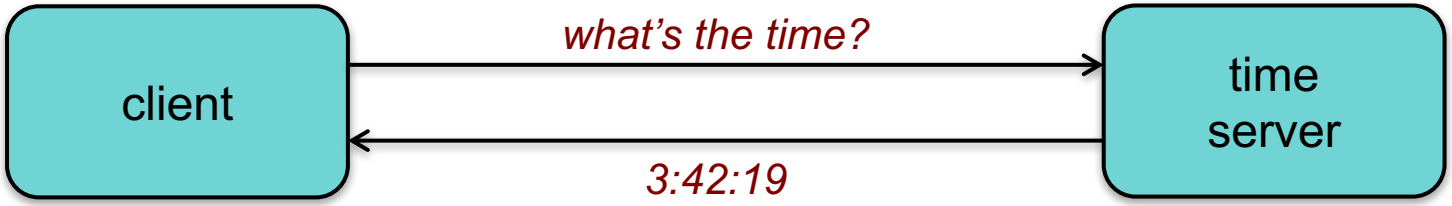
Getting accurate time

- Attach GPS receiver to each computer
  - Accurate to ~ 40 ns
- Not practical solution for every machine
  - Cost, power, convenience, environment
  - Accuracy gets worse near buildings, bridges, trees, …

Synchronize from a time server

Simplest synchronization technique

- Send a network request to obtain the time
- Set the time to the returned value

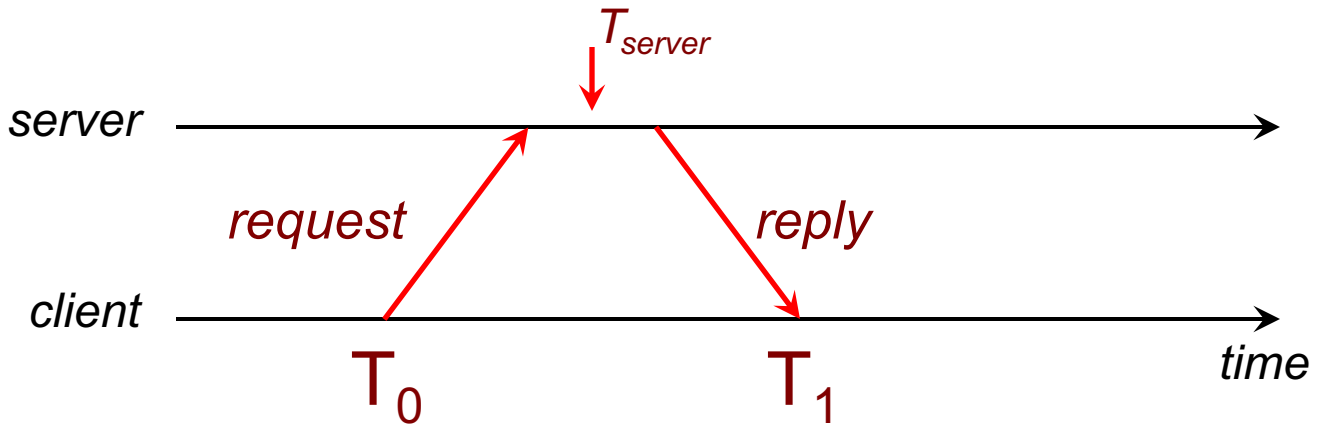


Does not account for network or processing latency

Cristian's algorithm

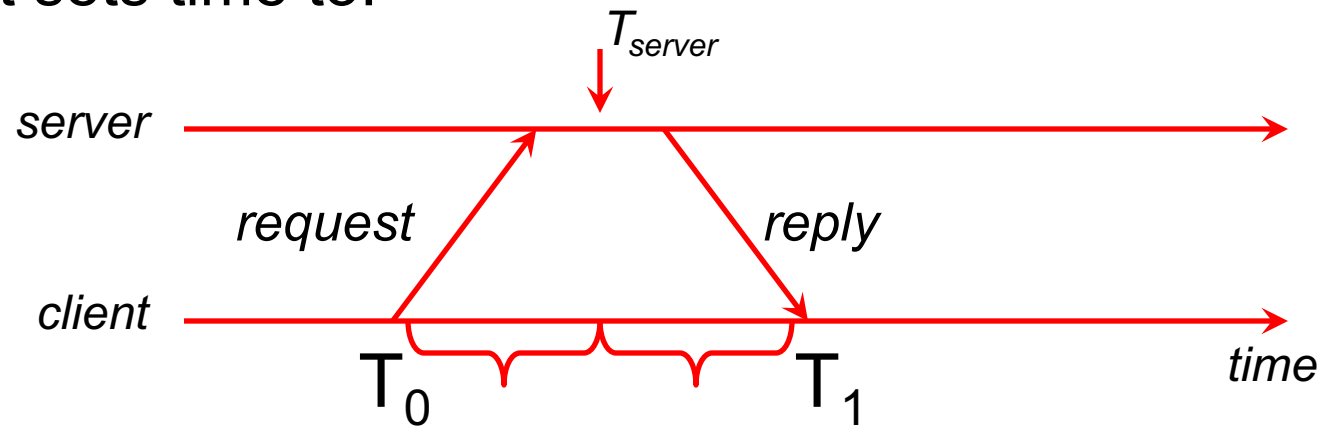
Compensate for delays

- Note times:
  - request sent: T_0
  - reply received: T_1
- Assume network delays are symmetric



Cristian's algorithm

Client sets time to:



$\frac{T_1 - T_0}{2}$ = estimated overhead in each direction

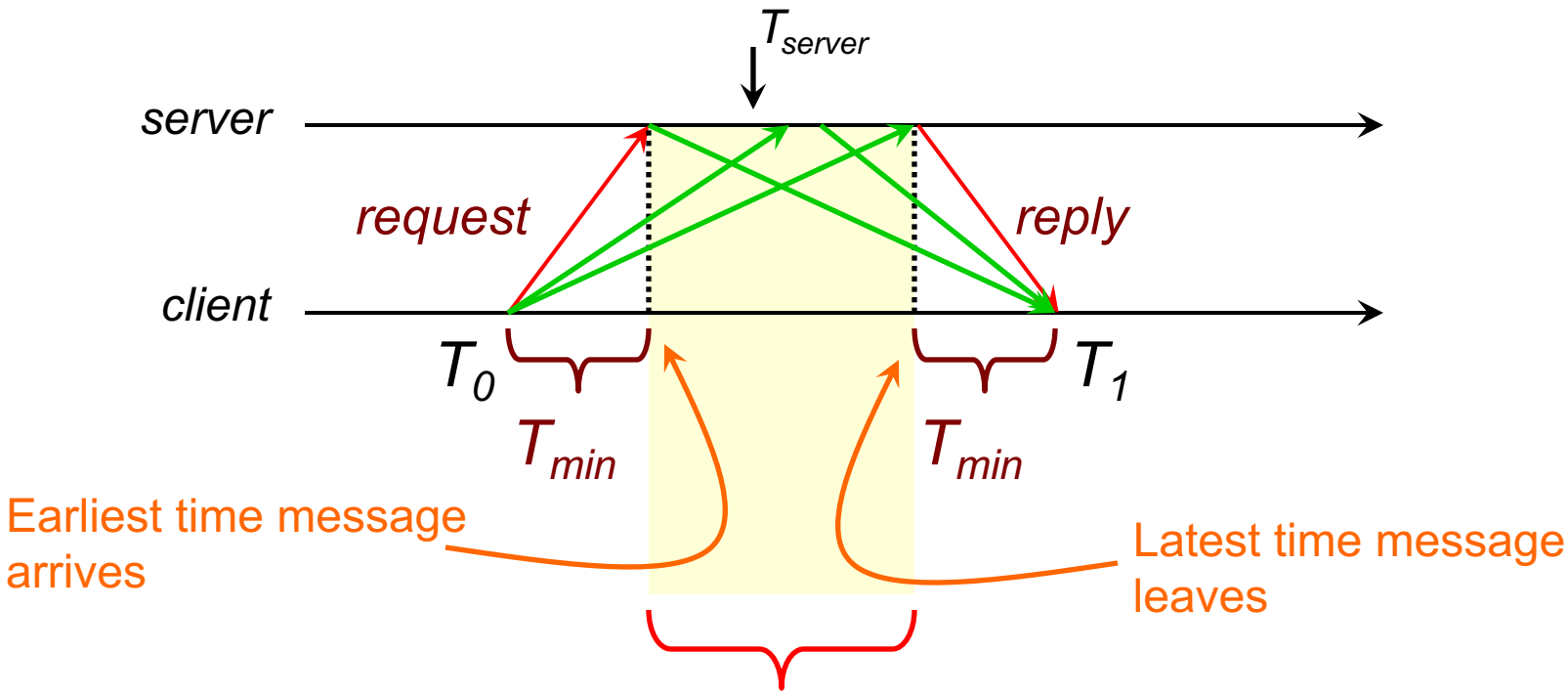
$$T_{new} = T_{server} + \frac{T_1 - T_0}{2}$$

Error bounds

If the minimum message transit time (T_{min}) is known:

Place bounds on accuracy of result

Error bounds



range = $T_1 - T_0 - 2T_{min}$

accuracy of result = $\pm \frac{T_1 - T_0}{2} - T_{min}$

Cristian's algorithm: example

- Send request at 5:08:15.100 (T_0)
- Receive response at 5:08:15.900 (T_1)
  - Response contains 5:09:25.300 (T_{server})
- Elapsed time is $T_1 - T_0$

  5:08:15.900 - 5:08:15.100 = 800 ms

Note:
1 000 ms = 1 s
1 000 000 µs = 1s

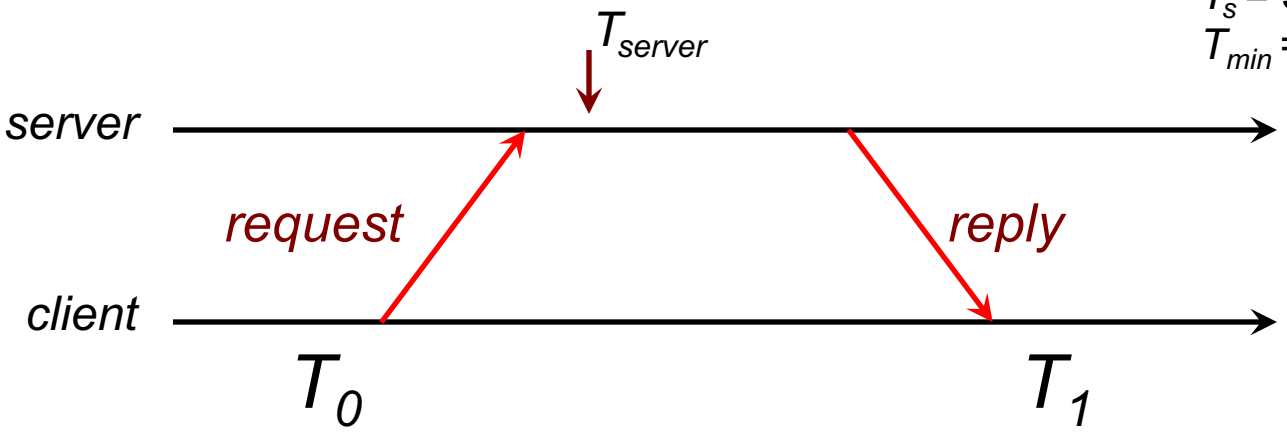
- Best guess: timestamp was generated 400 ms ago
- Set time to T_{server} + *elapsed time*

  5:09:25.300 + 400 = 5:09.25.700

Cristian's algorithm: example

If best-case message time=200 ms

T_0 = 5:08:15.100
T_1 = 5:08:15.900
T_s = 5:09:25:300
T_{min} = 200 ms



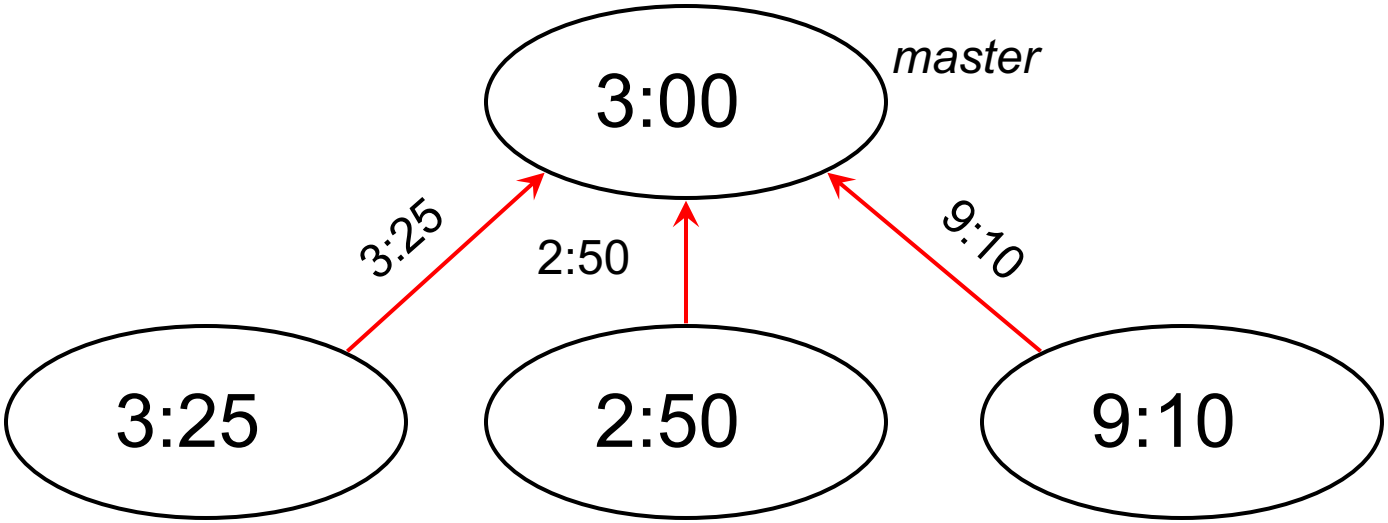
$$\text{Error} = \pm\frac{900-100}{2} - 200 = \pm\frac{800}{2} - 200 = \pm 200$$

Berkeley Algorithm

- Gusella & Zatti, 1989

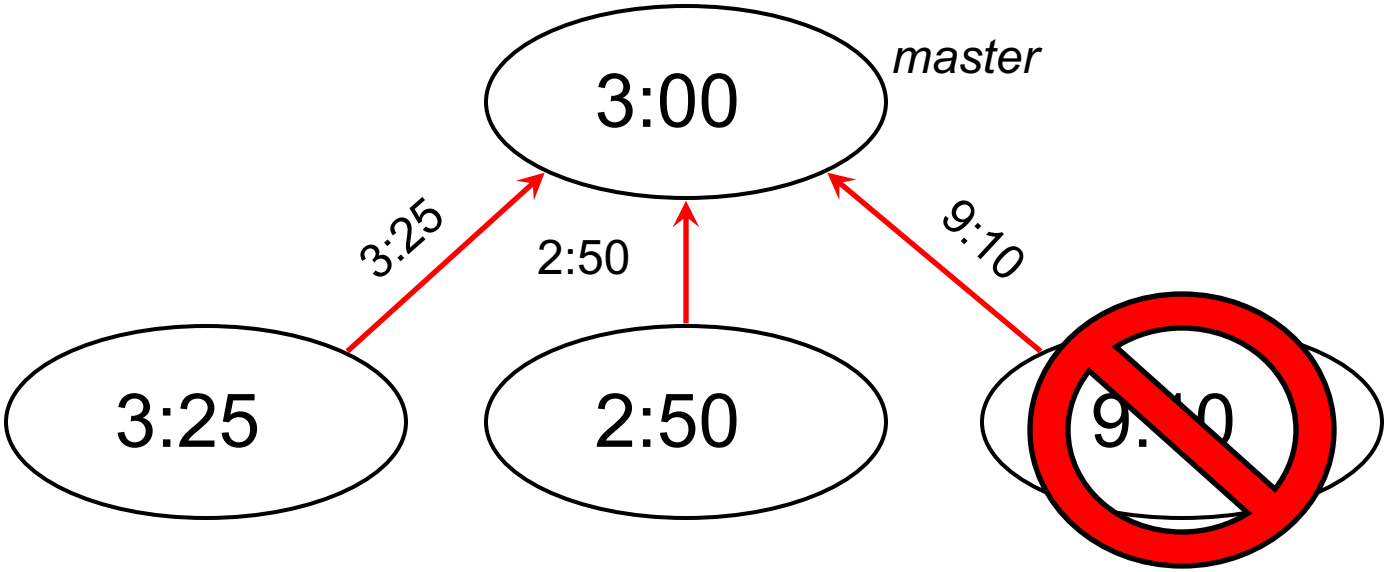
- Assumes no machine has an accurate time source
- Obtains average from participating computers
- Synchronizes all clocks to a fault-tolerant average

Berkeley Algorithm: example



1. Request timestamps from all slaves

Berkeley Algorithm: example

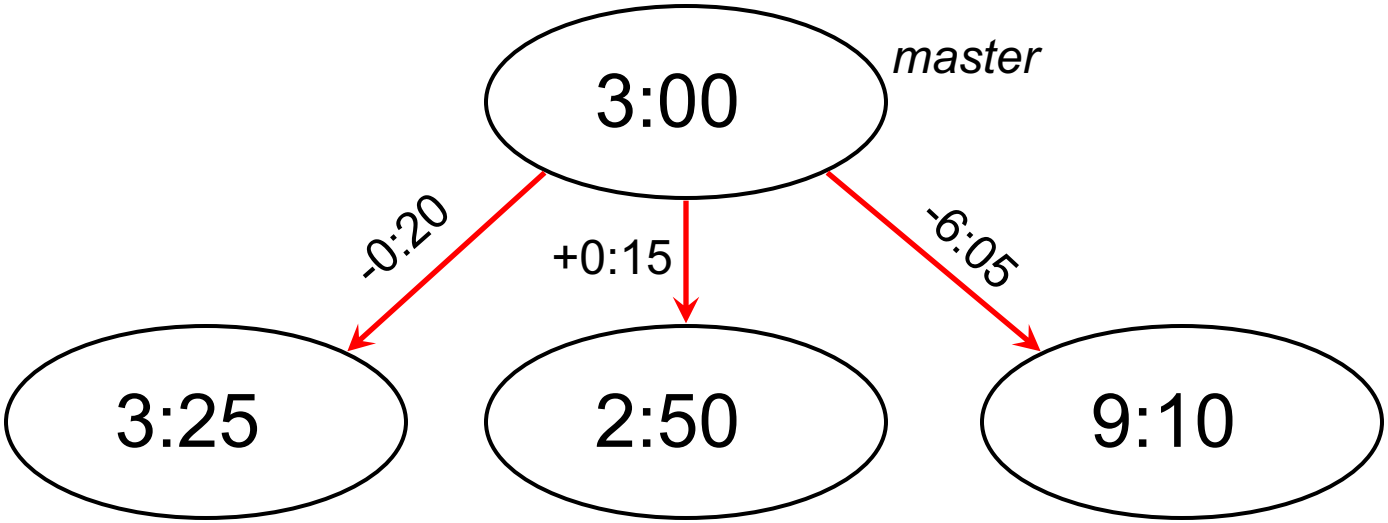


2. Compute fault-tolerant average:

Suppose max ∂=0:45

$$\frac{3:25 + 2:50 + 3:00}{3} = 3:05$$

Berkeley Algorithm: example



3. Send offset to each client

Network Time Protocol, NTP

- 1991, 1992
  - Internet Standard, version 3: RFC 1305
- June 2010
  - Internet Standard, version 4: RFC 5905-5908
  - IPv6 support
  - Improve accuracy to tens of microseconds
  - Dynamic server discovery

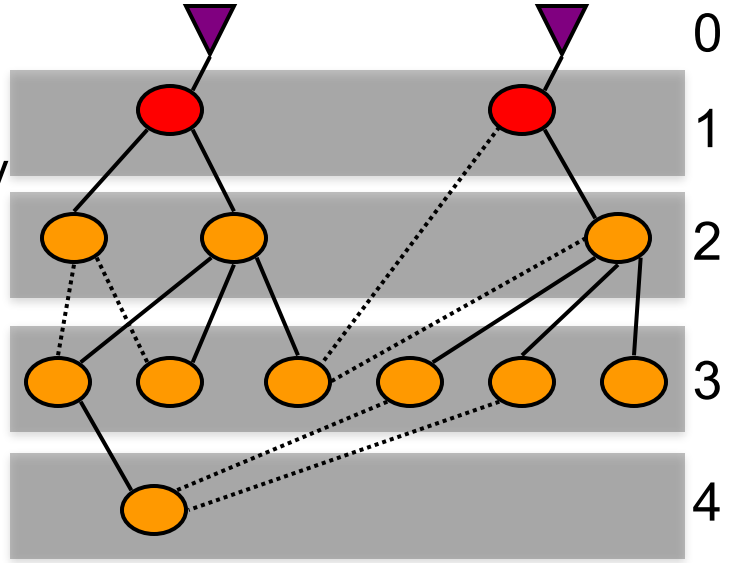
NTP Goals

- Enable clients across Internet to be accurately synchronized to UTC despite message delays
  - Use statistical techniques to filter data and gauge quality of results
- Provide reliable service
  - Survive lengthy losses of connectivity
  - Redundant paths
  - Redundant servers
- Provide scalable service
  - Enable huge numbers of clients to synchronize frequently
  - Offset effects of clock drift
- Provide protection against interference
  - Authenticate source of data

NTP servers

Arranged in strata

- Stratum 0 = master clock
- 1st stratum: systems connected directly to accurate time source
- 2nd stratum: systems synchronized from 1st stratum systems
- …
- 15th stratum: systems synchronized from 14th stratum systems



Synchronization Subnet

NTP Synchronization Modes

Multicast mode

- for high speed LANs
- Lower accuracy but efficient

Procedure call mode

- Cristian's algorithm

Symmetric mode

- Peer servers can synchronize with each other to provide mutual backup
  - Usually used with stratum 1 & 2 servers
  - Pair of servers retain data to improve synchronization over time

All messages are delivered unreliably with UDP (port 123)

NTP Clock Quality

- Precision
  - Smallest increase of time that can be read from the clock
- Jitter
  - Difference in successive measurements
  - Due to network delays, OS delays, and clock oscillator instability
- Accuracy
  - How close is the clock to UTC?

NTP messages

- Procedure call and symmetric mode
  - Messages exchanged in pairs: request & response
- Time encoded as a 64 bit value:
  - Divide by 2^{32} to get the number of seconds since Jan 1 1900 UTC
- NTP calculates:
  - Offset for each pair of messages (θ)
    - Estimate of time offset between two clocks
  - Delay (δ)
    - Travel time: ½ of total delay minus remote processing time
  - Dispersion
    - Maximum offset error relative to reference clock
- Use this data to find preferred server:
  - Probe multiple servers – each several times
  - *Pick lowest dispersion … at the lowest stratum if tied*

SNTP

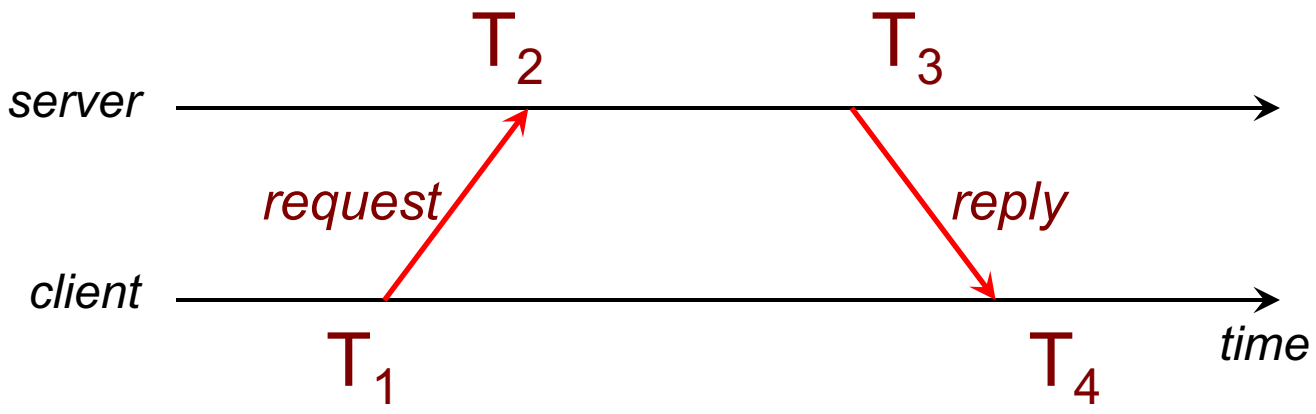
Simple Network Time Protocol

- Based on Unicast mode of NTP – subset of NTP, not new protocol
- Operates in multicast or procedure call mode
- Recommended for environments where server is root node and client is leaf of synchronization subnet
- Root delay, root dispersion, reference timestamp ignored

v3 RFC 2030, October 1996

v4 RFC 5905, June 2010

SNTP Example



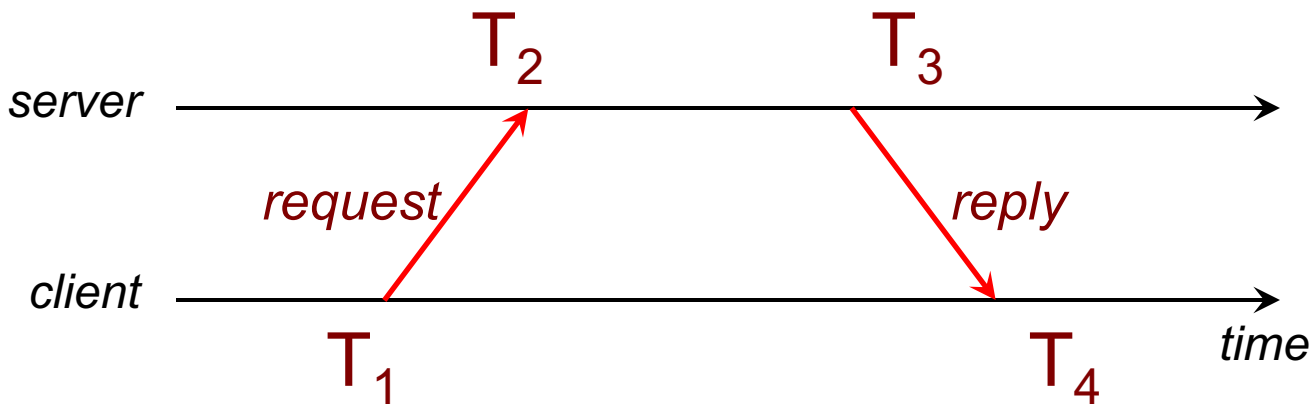
Round-trip network delay:

$$\partial = (T_4 - T_1) - (T_3 - T_2)$$

Time offset:

$$t = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

SNTP Example



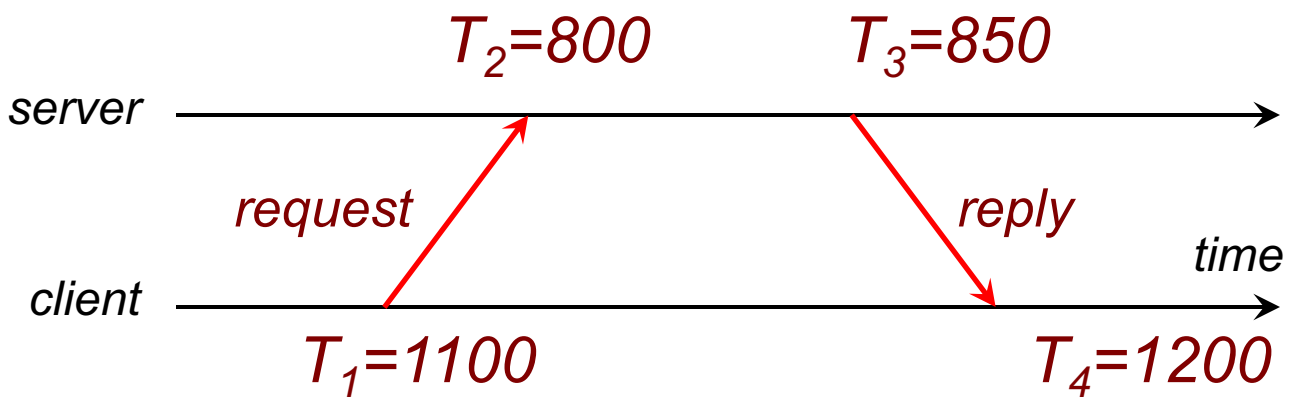
Round-trip network delay:

$$\partial = (T_4 - T_1) - (T_3 - T_2)$$

Time offset:

$$t = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

SNTP example



Offset =

((800 - 1100) + (850 - 1200)) / 2

= ((-300) + (-350)) / 2

= -650 / 2 = -325

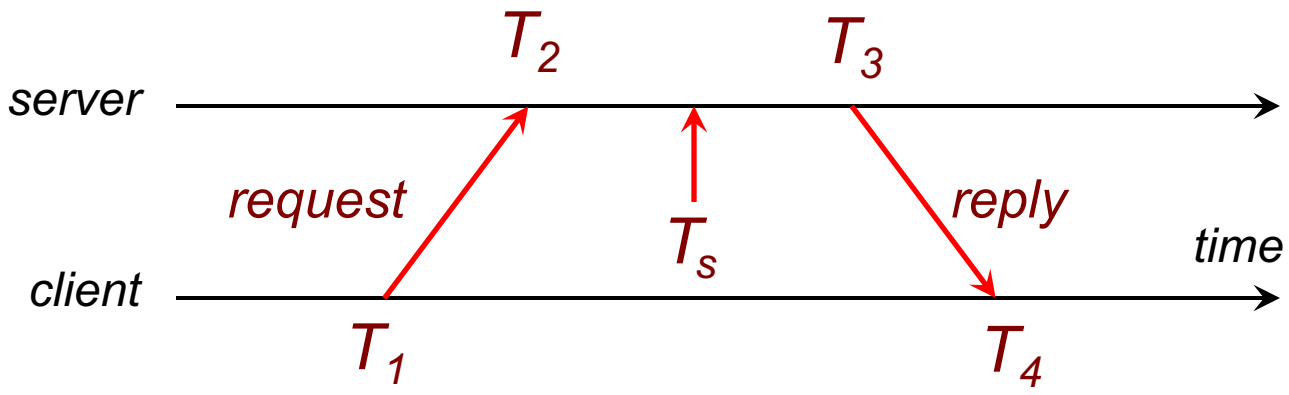
Time offset:

$$t = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

Set time to $T_4 + t$

= 1200 - 325 = 875

SNTP = Cristian's algorithm



Just define $T_s = \frac{T_2 + T_3}{2}$

Key Points: Physical Clocks

- Cristian's algorithm & SNTP
  - Set clock from server
  - But account for network delays
  - Error: uncertainty due to network/processor latency
    - Errors are additive
    - Example: ±10 ms and ±20 ms = ±30 ms
- Adjust for local clock drift
  - Linear compensating function

Precision Time Protocol

PTP: IEEE 1588 Precision Time Protocol

- Designed to synchronize clocks on a LAN to sub-microsecond precision
  - Designed for LANs, not global: low jitter, low latency
  - Timestamps ideally generated at the MAC or PHY layers to minimize delay and jitter
- Determine master clock
  - Use a Best Master Clock algorithm to determine which clock in the network is most precise
  - Other clocks become slaves
- Two phases in synchronization
  1. Offset correction
  2. Delay correction

PTP: Choose the “best” clock

Best Master Clock

- Distributed election based on properties of clocks
- Criteria from highest to lowest:
  - Priority 1 (admin-defined hint)
  - Clock class
  - Clock accuracy
  - Clock variance: estimate of stability based on past syncs
  - Priority 2 (admin-defined hint #2)
  - Unique ID (tie-breaker)

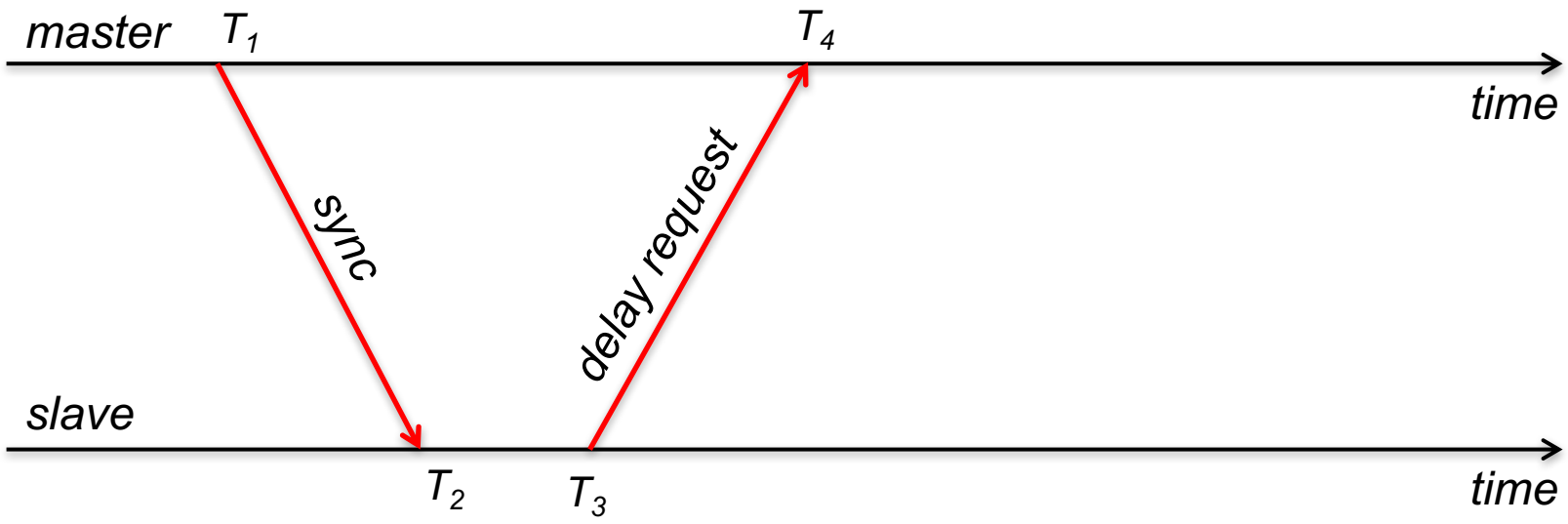
PTP: Master initiates sync

Master initiates the protocol by sending a *sync* message containing a timestamp

Slave timestamps arrival with a timestamp from its local clock

Offset + Delay = T_2 - T_1

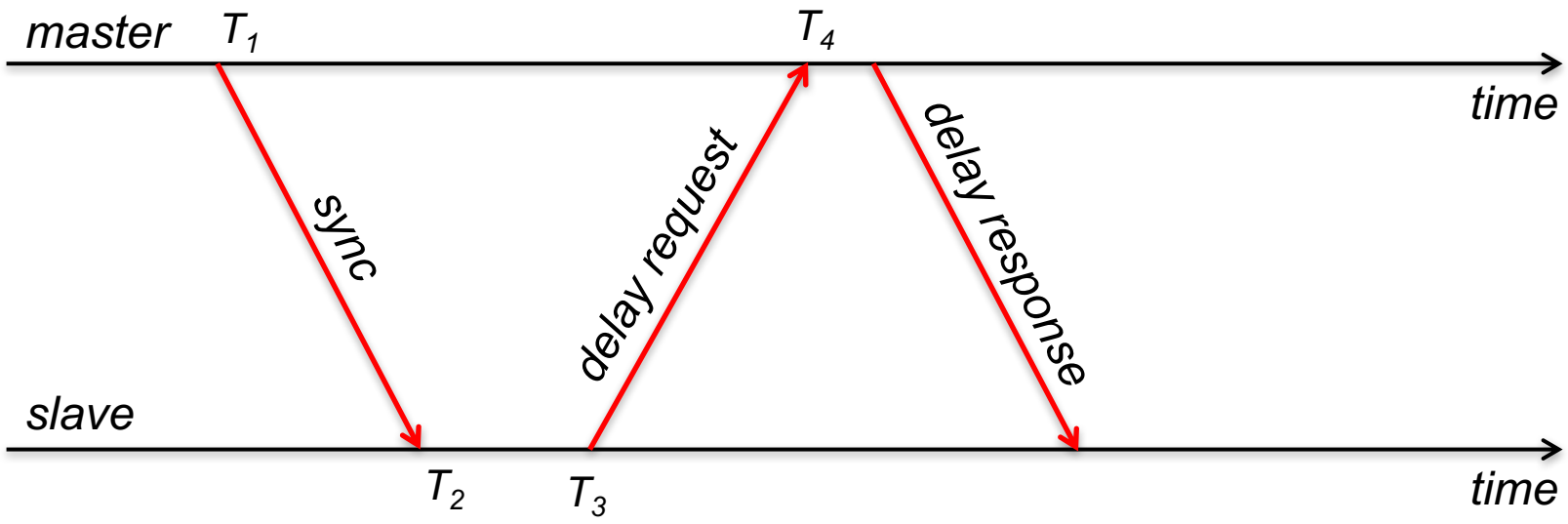
PTP: Send delay request



Slave needs to figure out the network delay. Send a *delay request*

Note the time it was sent.

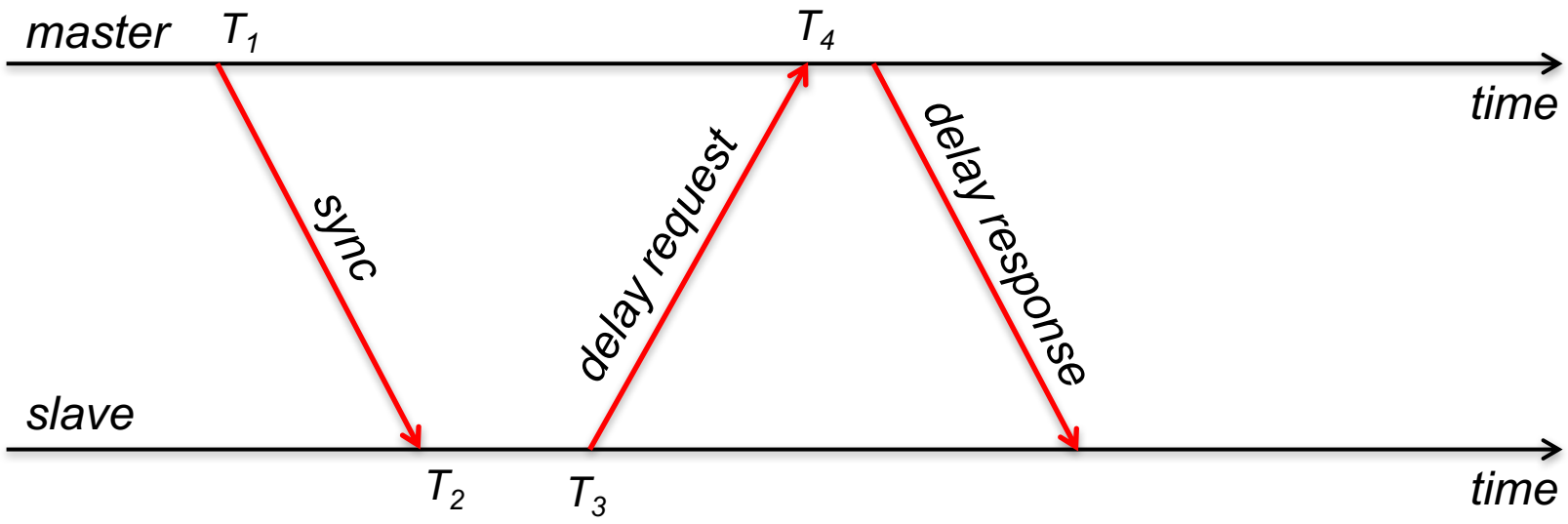
PTP: Receive delay response



Master marks the time of arrival and returns it in a *delay response*

Delay response = Delay - Offset = $T_4 - T_3$

PTP: Slave computes offset



$master\_slave\_difference = T_2 - T_1 = delay + offset$

$slave\_master\_difference = T_4 - T_3 = delay - offset$

$master\_slave\_difference - slave\_master\_difference = 2(offset)$

$T_2 - T_1 - T_4 + T_3 = 2\ (offset)$

$offset = (T_2 - T_1 - T_4 + T_3) / 2$

NTP vs. PTP

- Range
  - NTP: nodes widely spread out on the Internet
  - PTP: local area networks

- Accuracy
  - NTP usually several milliseconds on WAN
  - PTP usually sub-microsecond on LAN

The end