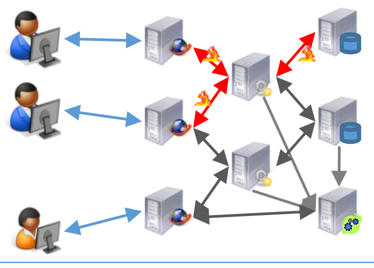

Verteilte Systeme/ Distributed Systems

Artur Andrzejak

7

Time and Clock Synchronization

Following contents are based on the slides of Lecture 09 in the course:
Distributed Computing, Google Code University/ Rutgers University:
By Paul Krzyzanowski, pxk@cs.rutgers.edu, ds@pk.org

What’s it for?

- Temporal ordering of events produced by concurrent processes
- Synchronization between senders and receivers of messages
- Coordination of joint activity
- Serialization of concurrent access for shared objects

Physical Clocks in Computers

- Real-time Clock: CMOS clock (counter) circuit driven by a quartz oscillator
  - Battery backup to continue measuring time when power is off

- OS generally programs a timer circuit to generate an interrupt periodically
  - e.g., 60, 100, 250, 1000 interrupts per second
    (Linux 2.6+ adjustable up to 1000 Hz)
  - Programmable Interval Timer (PIT) – Intel 8253, 8254
  - Interrupt service procedure adds 1 to a counter in memory

Problems

- Getting two systems to agree on time
  - 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
  - **Clock Skew**

Dealing with Drift

Following contents are based on the slides of Lecture 09 in the course:
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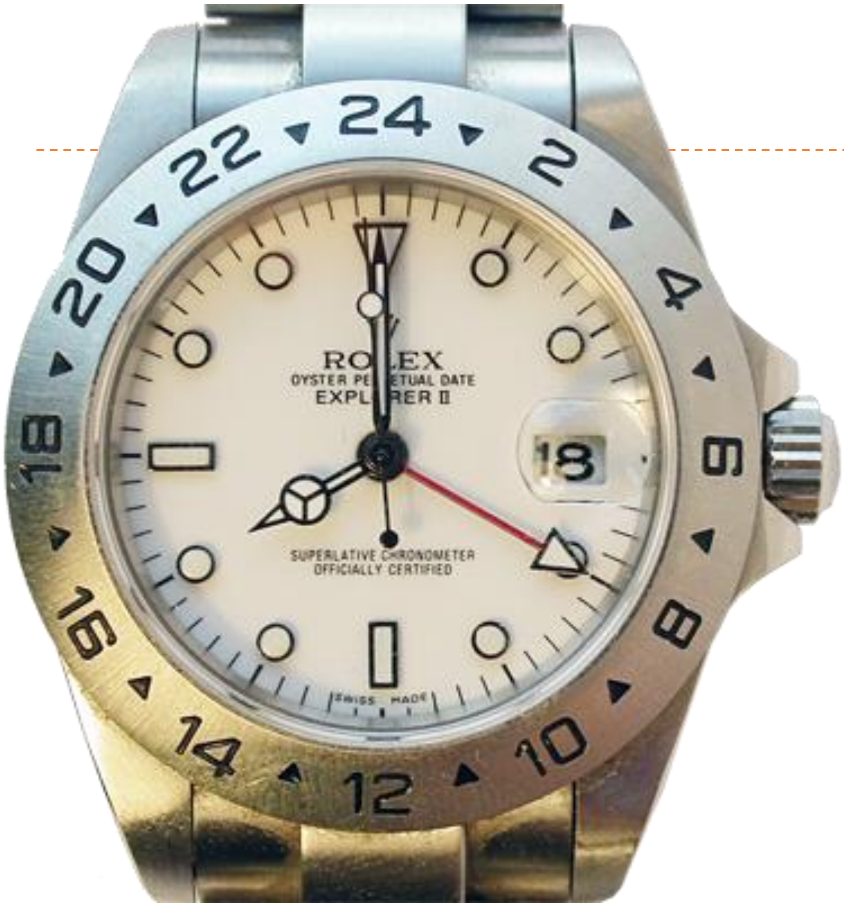
By Paul Krzyzanowski, pxk@cs.rutgers.edu, ds@pk.org



8:00:00

8:00:00

Sept 18, 2006
8:00:00

8:01:24

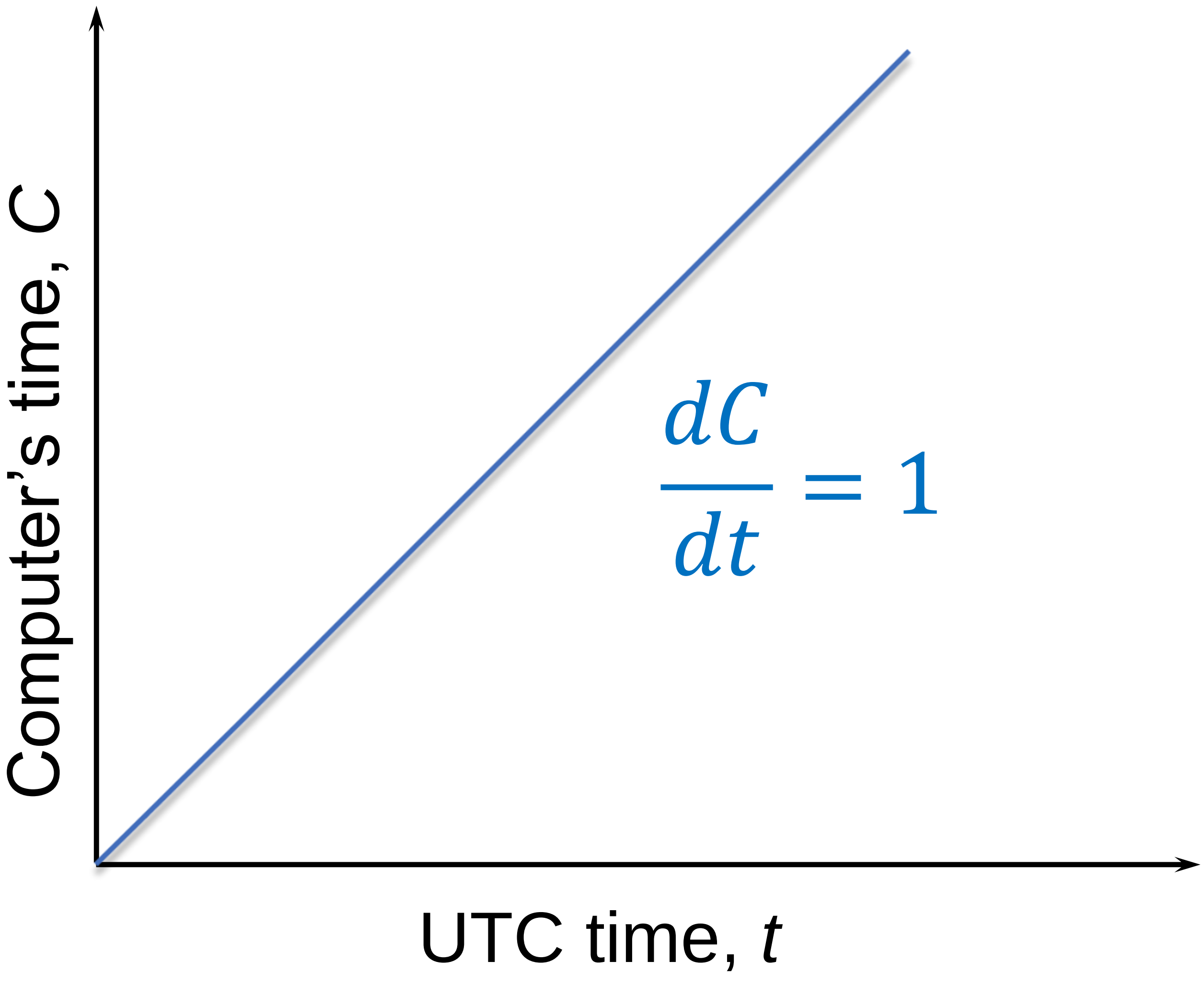
8:01:48

Skew = +84 seconds
+84 seconds/35 days
Drift = +2.4 sec/day

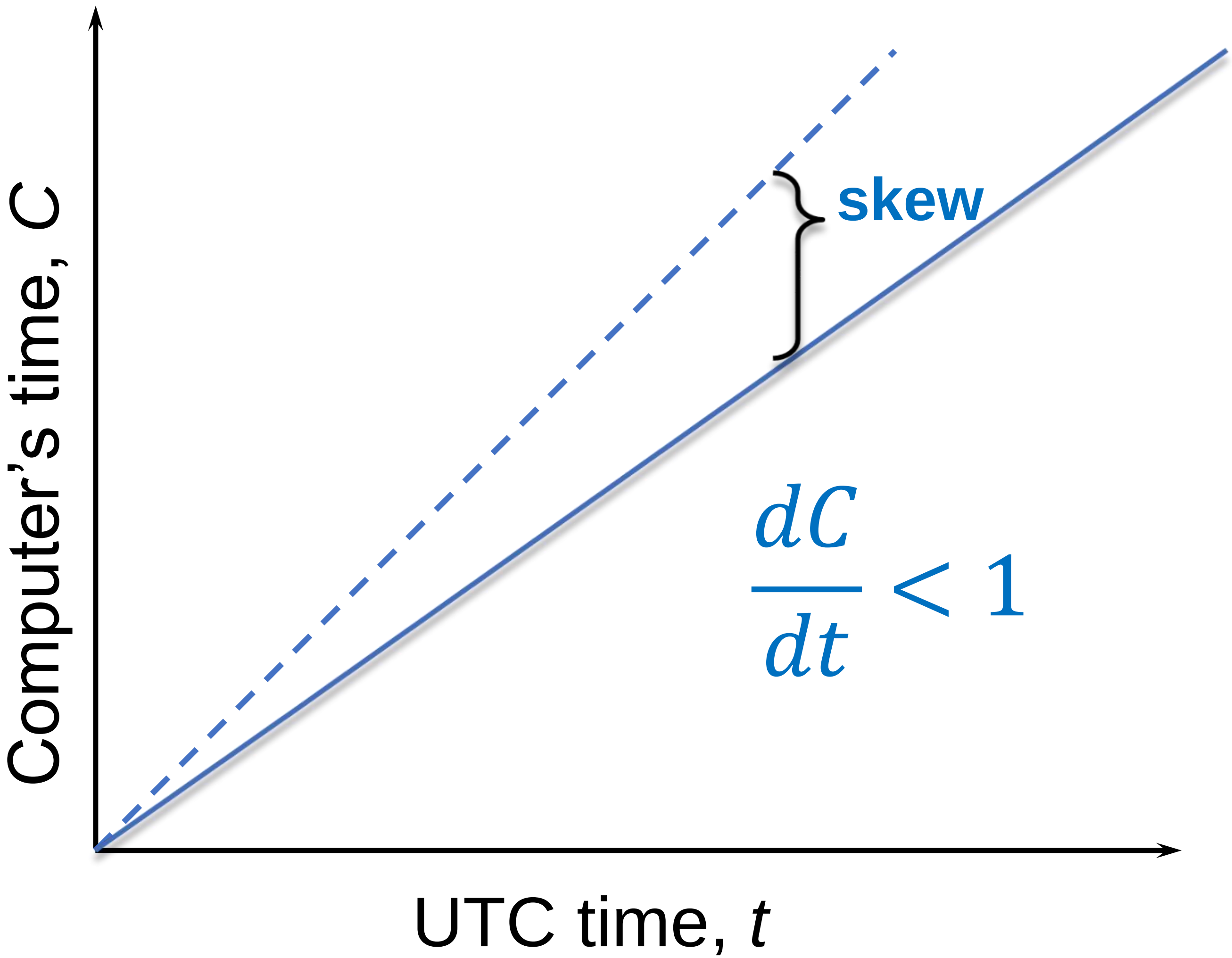
Oct 23, 2006
8:00:00

Skew = +108 seconds
+108 seconds/35 days
Drift = +3.1 sec/day

Perfect Clock



Drift with Slow Clock



Dealing With Drift

- Assume we set computer to true time
- Not good idea to set clock back
  - Illusion of time moving backwards can confuse message ordering and software development environments!

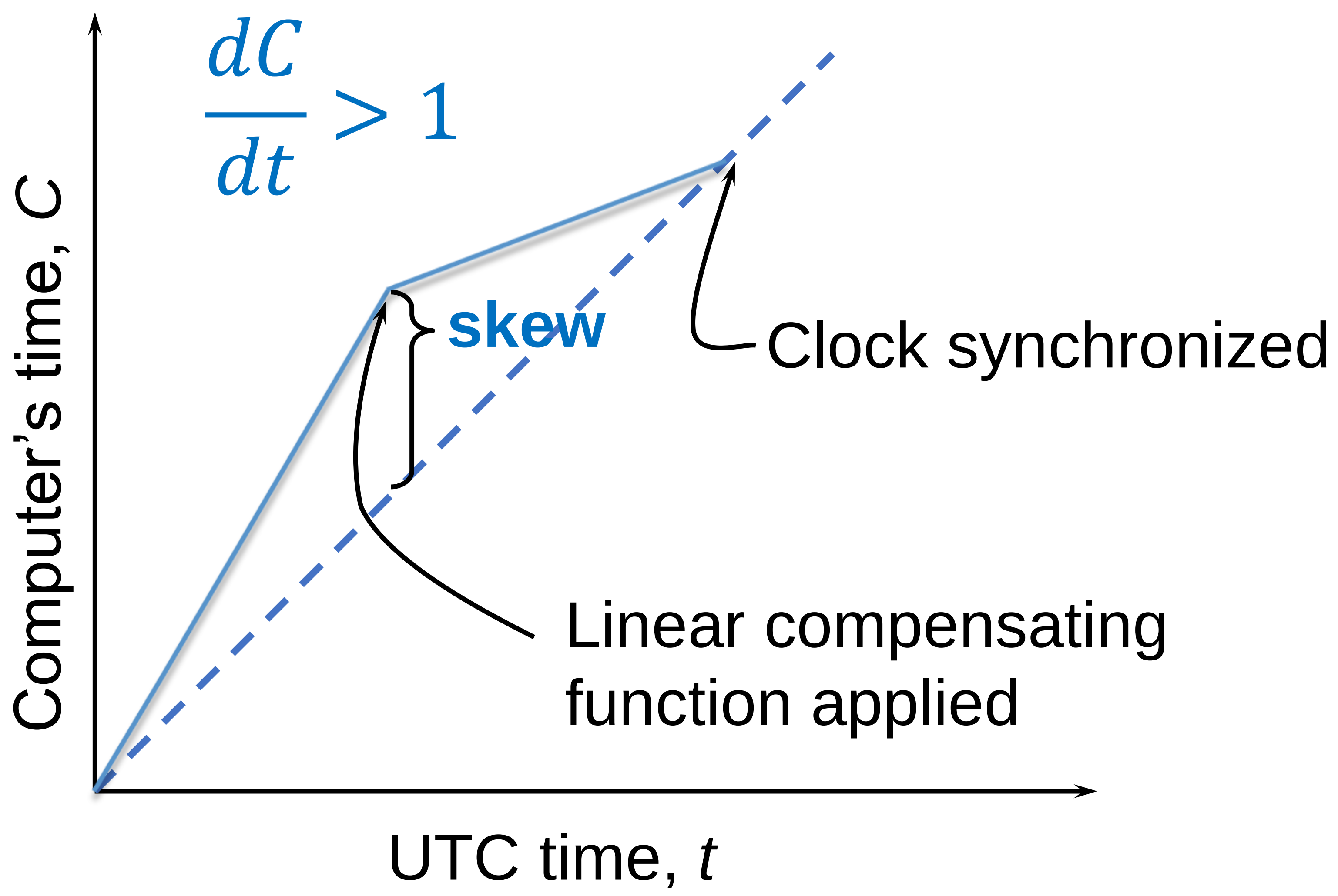
- How to do it better?
- Go for gradual clock correction
  - If fast: make clock run slower until it synchronizes
  - If slow: make clock run faster until it synchronizes

Dealing With Drift

- OS can do this:
  - Change rate at which it requests interrupts, e.g.:
  - if system requests interrupts every 17 msec but clock is too slow:
    - request interrupts at (e.g.) 15 msec
  - Or software correction: redefine the interval

- Adjustment changes slope of system time:
  - Linear compensating function

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
- Keep track of adjustments and apply continuously
  - e.g., UNIX ***adjtime*** system call

Getting Accurate Time

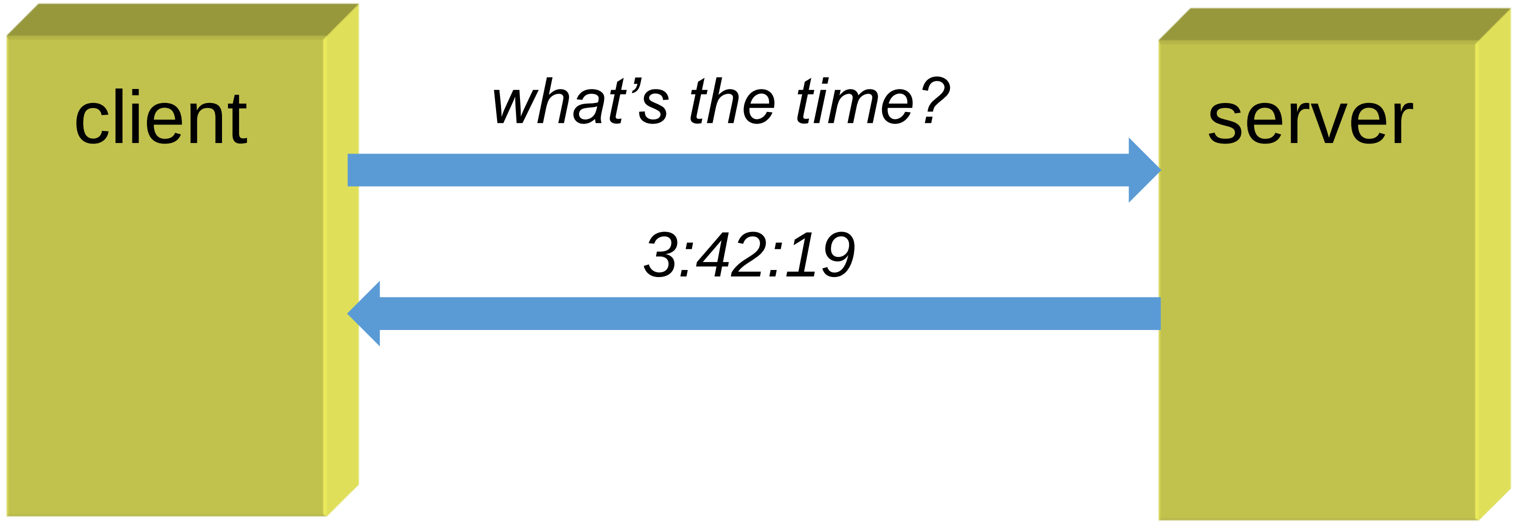
Getting Accurate time

- Attach GPS receiver to each computer
  - ± 1 msec of UTC
- Attach WWV radio receiver (link)
  - Obtain time broadcasts from Boulder or DC
  - ± 3 msec of UTC (depending on distance)
- Attach GOES receiver (link)
  - ± 0.1 msec of UTC
- Not practical solution for every machine – what else?
- Synchronize from another machine
  - One with a more accurate clock
- Machine/service that provides time information:
  - **Time server**

RPC

Simplest synchronization technique

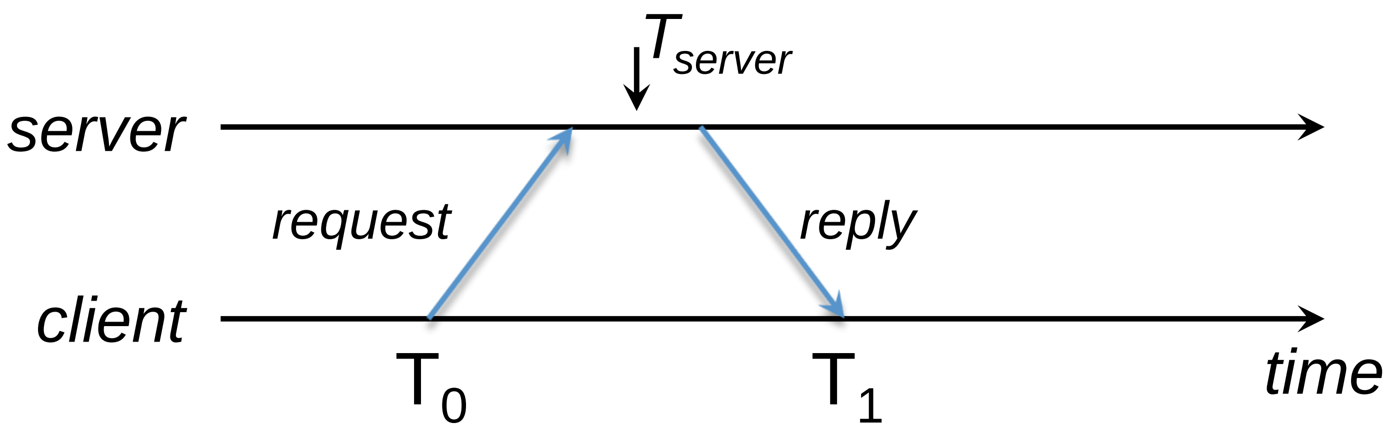
- Issue RPC to obtain time
- Set time



- Problems?
- Does not account for network or processing latency

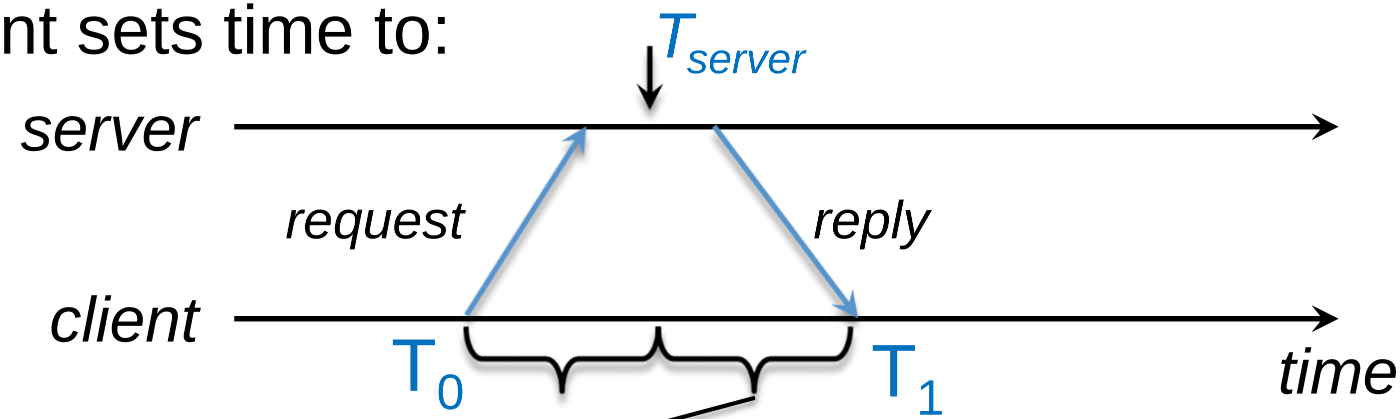
Cristian's algorithm

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



Cristian's Algorithm

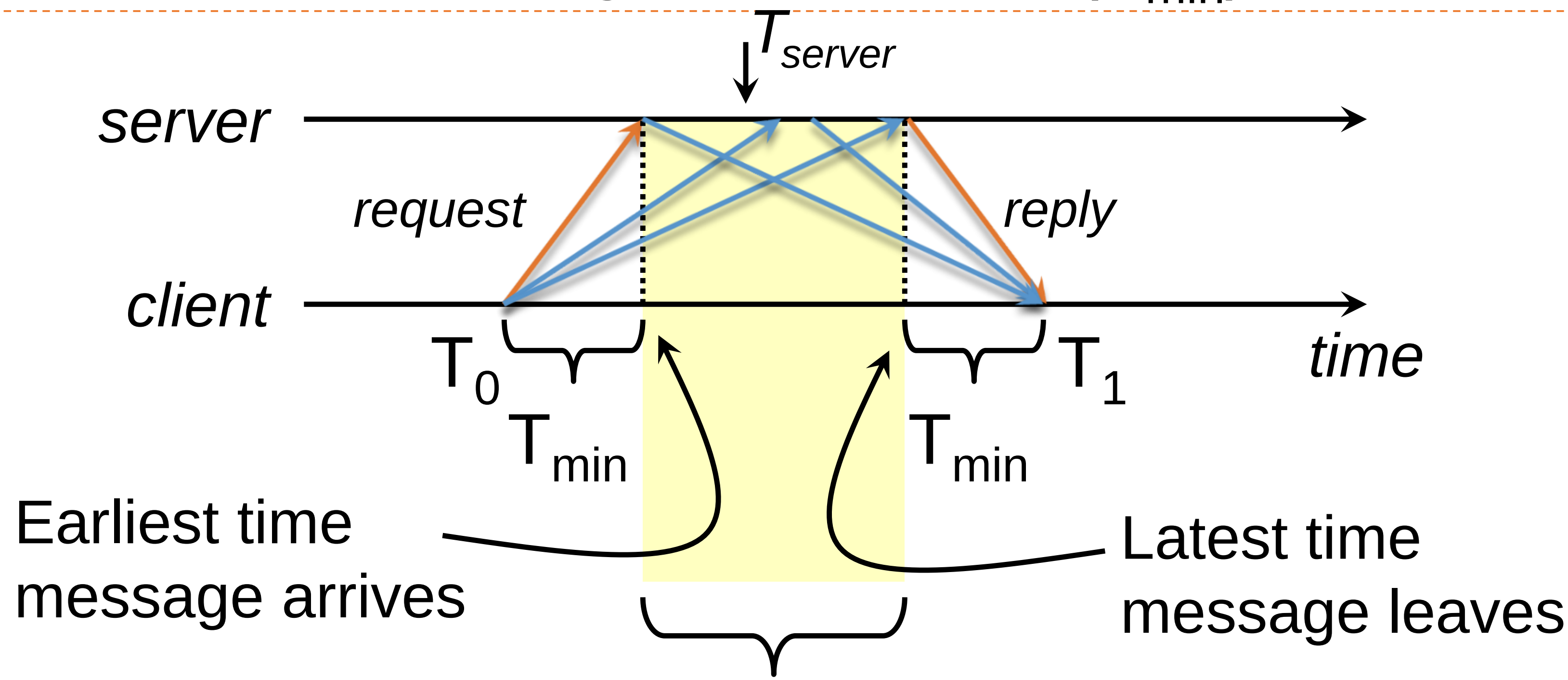
- Client sets time to:



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

$$\boxed{T_{new} = Tser_{ver} + \frac{T_1 - T_0}{2}}$$

Cristian's Algorithm - Error Bounds: If minimum message transit time (T_{min}) is known



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

accuracy of result = $\boxed{\pm \frac{T_1 - T_0}{2} - Tmin}$

Berkeley Algorithm

- Gusella & Zatti, 1989
- Assumes no machine has an accurate time source
- Obtains average from participating computers
- Synchronizes all clocks to average

- Machines run **time dæmon**
  - Process that implements protocol
- One machine is elected (or designated) as the server (**master**)
  - Others are **slaves**

Berkeley Algorithm

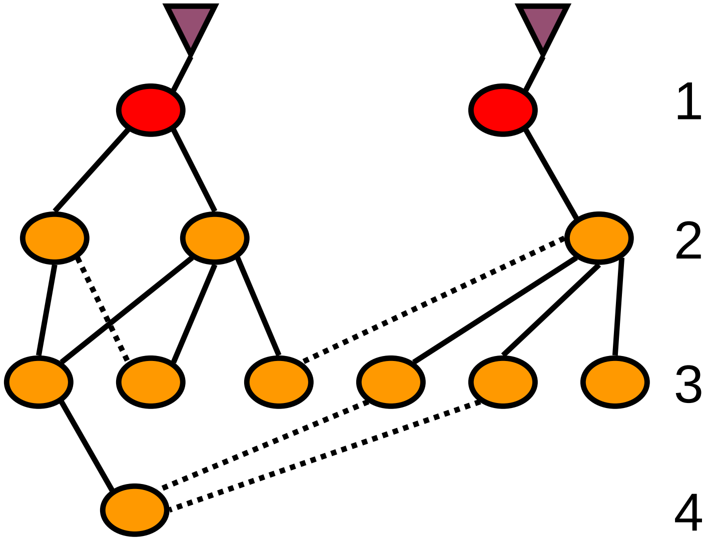
- Master polls each machine periodically, i.e. ask each machine for time
  - Can use Cristian's algorithm to compensate for network latency
- When results are in, compute average, including master's
- Hope: average cancels out individual clock's tendencies to run fast or slow
- Improvements:
  - Send offset by which each clock needs adjustment to each slave
    - Avoids problems with network delays if we send a time stamp
  - Algorithm has provisions for ignoring readings from clocks whose skew is too great
    - Compute a fault-tolerant average
  - If master fails: Any slave can take over

Network Time Protocol, **NTP**

- 1991, 1992: Internet Standard, version 3: RFC 1305
- 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
- Enable clients to synchronize frequently
  - Offset effects of clock drift
- Provide protection against interference
  - Authenticate source of data

NTP Servers

- … Arranged in **strata**
  - 1st stratum: machines connected directly to accurate time source
  - 2nd stratum: machines synchronized from 1st stratum machines
  - …



SYNCHRONIZATION SUBNET

NTP Synchronization Modes

- Multicast mode
  - for high speed LANS
  - Lower accuracy but efficient
- Procedure call mode
  - Similar to Cristian's algorithm
- Symmetric mode
  - Intended for master servers
  - Pair of servers exchange messages and retain data to improve synchronization over time

All messages delivered unreliably with UDP

NTP Messages

- Procedure call and symmetric mode
  - Messages exchanged in pairs
- NTP calculates:
  - **Offset** for each pair of messages
    - Estimate of offset between two clocks
  - **Delay**
    - Transmit time between two messages
  - **Filter Dispersion**
    - Estimate of error – quality of results
    - Based on accuracy of server's clock and consistency of network transit time
- Use this data to find preferred server:
  - Lower stratum & lowest total dispersion

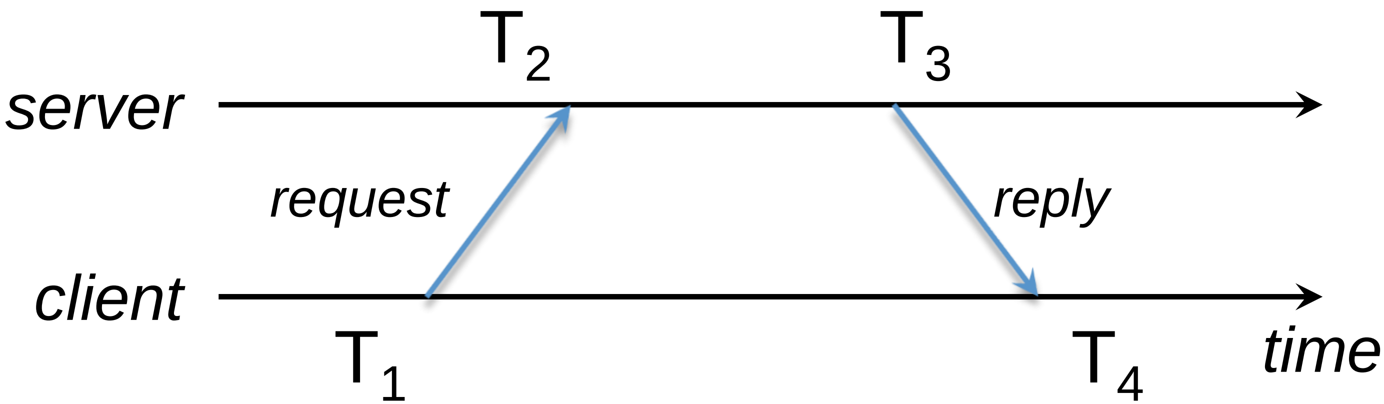
SNTP

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

- RFC 2030, October 1996

SNTP



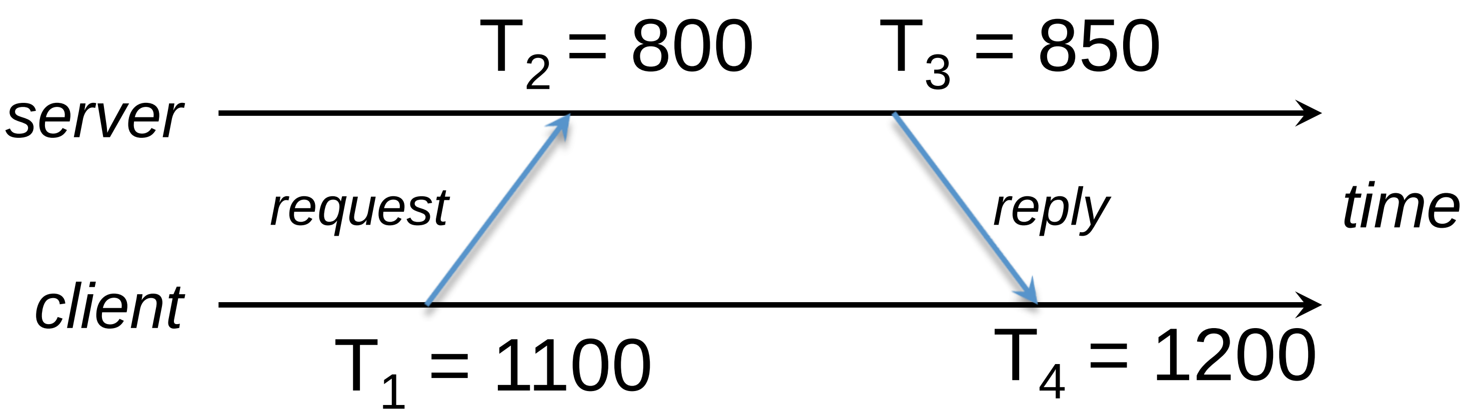
Roundtrip delay:

$$d = (T_4 - T_1) - (T_2 - T_3)$$

Time offset:

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

SNTP Example



Offset =

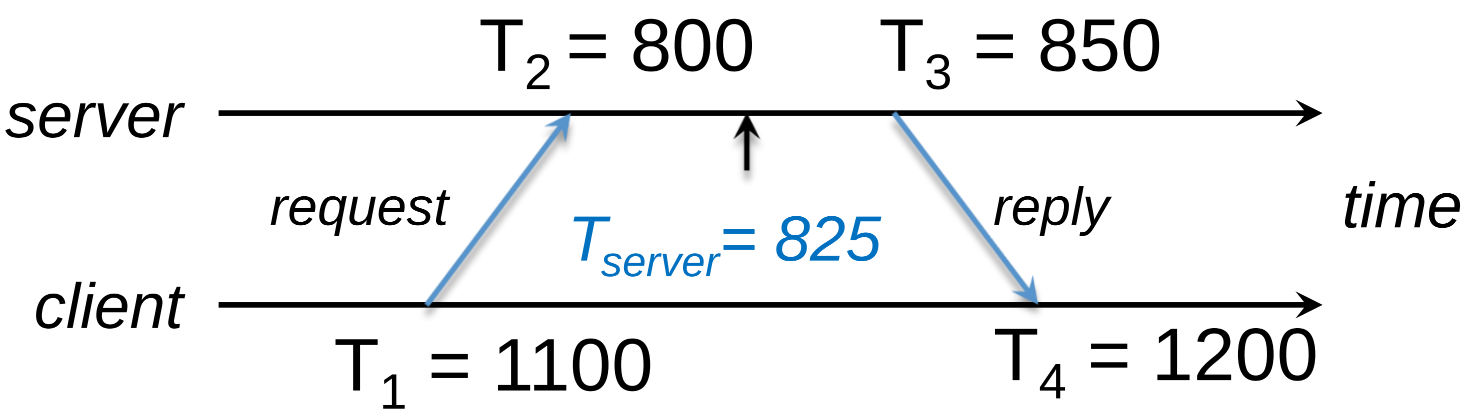
$((800 - 1100) + (850 - 1200))/2$
$=((-300) + (-350))/2$
$= -650/2 = -325$

Set time to T4 + t
= 1200 - 325 = 875

Time offset:

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

Compare to Christian's Algorithm



Offset =

(1200 - 1100)/2 = **50**

Time offset:

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

Set time to T_{server} + offset

= 825 + 50 = **875**

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
    ± 10 msec and ± 20 msec = ± 30 msec.
- Adjust for local clock skew
  - Linear compensating function

Logical Time: Introduction

Logical Time

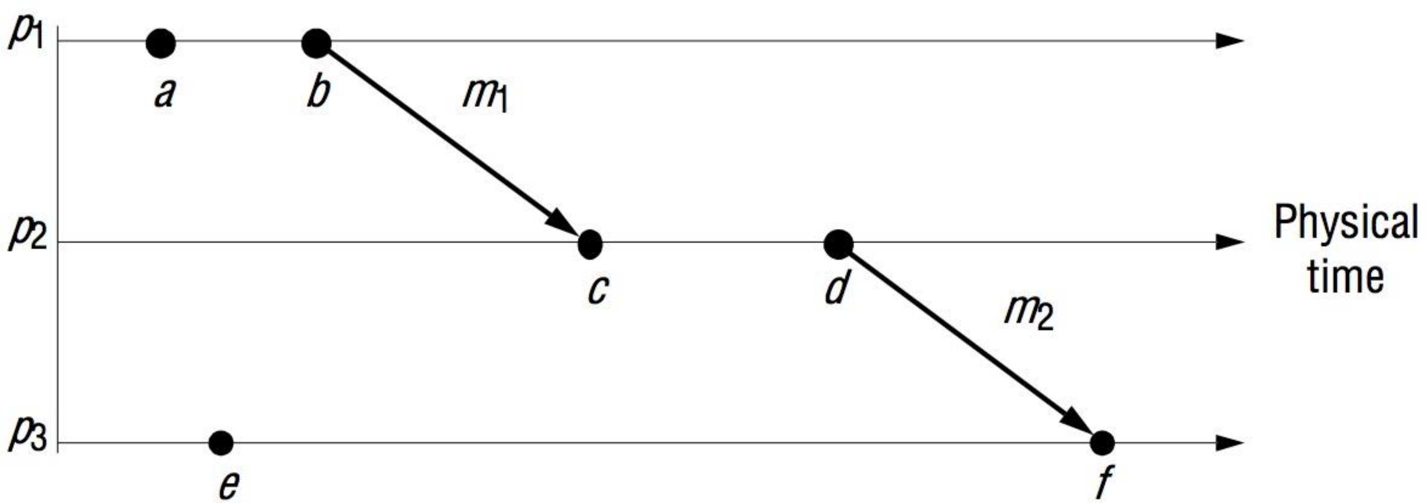
- Physical clocks can not be perfectly synchronized
- What we often only need is a unique sequence of events in a distributed system, not absolute time
  - But based on physical clocks we can not define a clear order
- Solution by Leslie Lamport: **logical time** (definition follows)
  - Paper: "Time, Clocks, and the Ordering of Events in a Distributed System," Commun. ACM, vol. 21, no. 7, pp. 558-565, 1978
- We first introduce the **temporal order** through two rules:
  - If two events take place in the same process P, then they have the order (order) that P has observed
  - When a message is sent, the event of transmission occurs before the event of reception

Happened-Before Relation

- Lamport defined from the two relationships the **Happened-Before** relation $\rightarrow$
  - It formalizes the temporal order

- Happened-Before-Relation $\rightarrow$ is defined by:
  - **HB1**: If there is a process p_i with $e \rightarrow_i e'$, then $e \rightarrow e'$
    - I.e. the "local" order $\rightarrow_i$ in p_i specifies $\rightarrow$ for e, e'
  - **HB2**: For each message m: send(m) $\rightarrow$ receive(m)
    - I.e. event send(m) is before event receive(m)
  - **HB3**: If for e, e', e'' we have: $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$ (transitivity)

Examples and Concurrent Events



- Example: a → b, b → c, a → f
- For some events the HB relation is not true - examples?
- Example: a↛e, e↛a
- Events x, y that are not ordered with → are called **concurrent**, denoted as x **||** y

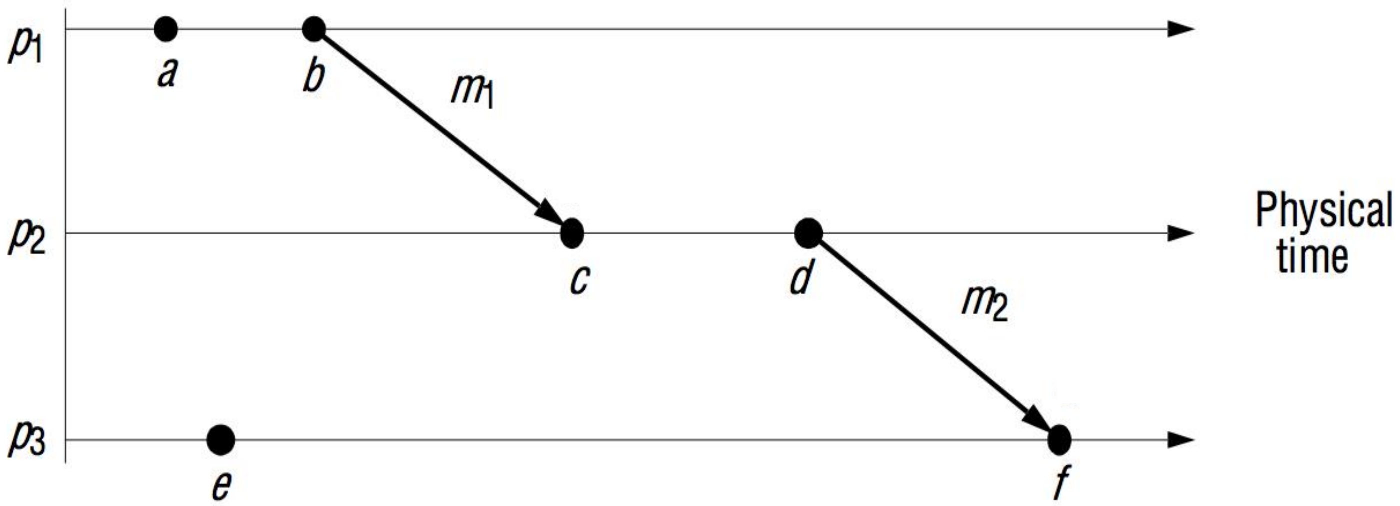
Lamport Clock

- Lamport (1978) developed a simple method to numerically express Happened-Before-Relation: **Lamport clock** (logical clock)
- Lamport clock is a monotonously increasing (software) counter
  - No relationship to the physical time needed
- Each process p_i has its own logical clock L_i
- Process p_i assigns timestamps to events by:
  - Timestamp of the clock L_i (L_i local for p_i) for event e is the Lamport timestamp $\mathbf{L_i(e)}$ (note: index i in L_i)
- $\mathbf{L(e)}$ (without index i) is the Lamport timestamp of an event, regardless of where it occurred

Lamport Clock and Happened-Before

- To comply with the Happened-Before relationship, processes change their logical clock as follows:
- **LC1**:
  - L_i is incremented just before an event occurs on p_i, i.e. $L_i := L_i + 1$
- **LC2**:
  - a) When a process p_i sends a message m, it also sends with m the actual value **t** of its own logical clock L_i
  - b) When other process p_j receives the values (m, **t**)
    - b1. Calculate max(L_j, **t**), and set its new L_j to this value, i.e $L_j := \max(L_j, t)$
    - b2. Executes LC1 (i.e., increments L_j)
    - b3. Then assign to receive(m) the timestamp computed in b2

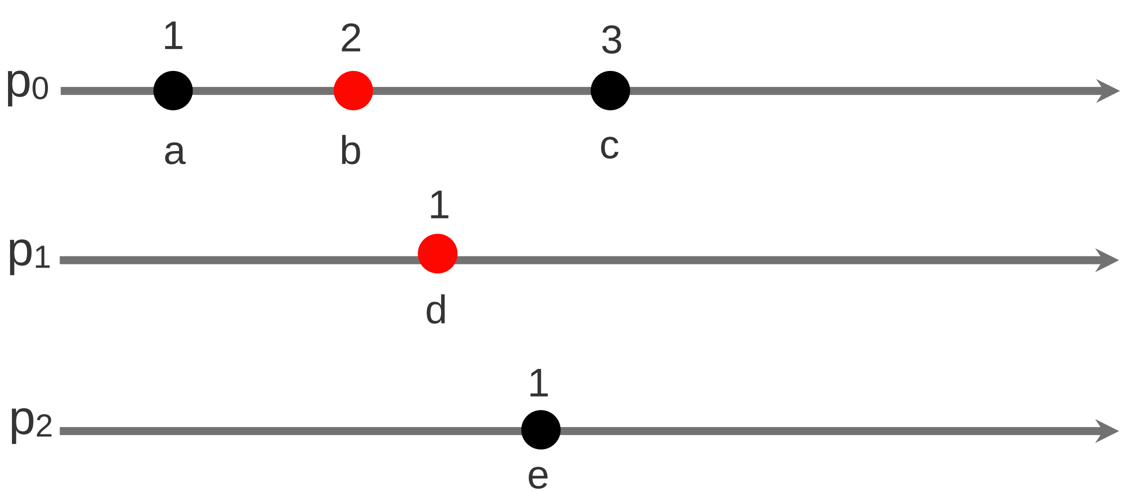
Lamport Clock: Quiz and a Surprise



- Each process has its own logical clock, initialized with 0
- What are L (a), L (b), ..., L (f)?
- Note the following: L(b) **>** L(e), but b **||** e

Lamport Clock: Problems

- Lamport clock ensures that …
  - For two events a and b with a → b (a happened-before b) we have: L(a) < L(b)
- But the converse does not apply!
  - From L(a) < L(b) it does not follow that a → b holds
- Therefore, in general we cannot conclude about the causality of two events based on the Lamport time only



We have L(d) < L(b),
but not d → b
(it holds: d || b)

Thank you.

Additional Slides

Additional Slides: Time and Clock Synchronization

Following contents are based on the slides of Lecture 09 in the course:
Distributed Computing, Google Code University/ Rutgers University:
By Paul Krzyzanowski, pxk@cs.rutgers.edu, ds@pk.org

What's it for?

- Temporal ordering of events produced by concurrent processes
- Synchronization between senders and receivers of messages
- Coordination of joint activity
- Serialization of concurrent access for shared objects

Quartz clocks

- 1880: Piezoelectric effect
  - Curie brothers
  - Squeeze a quartz crystal & it generates an electric field
  - Apply an electric field and it bends
- 1929: Quartz crystal clock
  - Resonator shaped like tuning fork
  - Laser-trimmed to vibrate at 32,768 Hz
  - Standard resonators accurate to 6 parts per million at 31° C
  - Watch will gain/lose < ½ sec/day
  - Stability > accuracy: stable to 2 sec/month
  - Good resonator <u>can</u> have accuracy of 1 second in 10 years
    - Frequency changes with age, temperature, and acceleration

Atomic clocks

- Second is defined as 9,192,631,770 periods of radiation corresponding to the transition between two hyperfine levels of cesium-133
- Accuracy:
  better than 1 second in six million years
- NIST standard since 1960

UTC

- UT0
  - Mean solar time on Greenwich meridian
  - Obtained from astronomical observation
- UT1
  - UT0 corrected for polar motion
- UT2
  - UT1 corrected for seasonal variations in Earth's rotation
- UTC
  - Civil time measured on an atomic time scale

UTC

- Coordinated Universal Time
- Temps Universel Coordonné
  - Kept within 0.9 seconds of UT1
  - Atomic clocks cannot keep mean time
    - Mean time is a measure of Earth’s rotation

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 msec
- Best guess: timestamp was generated

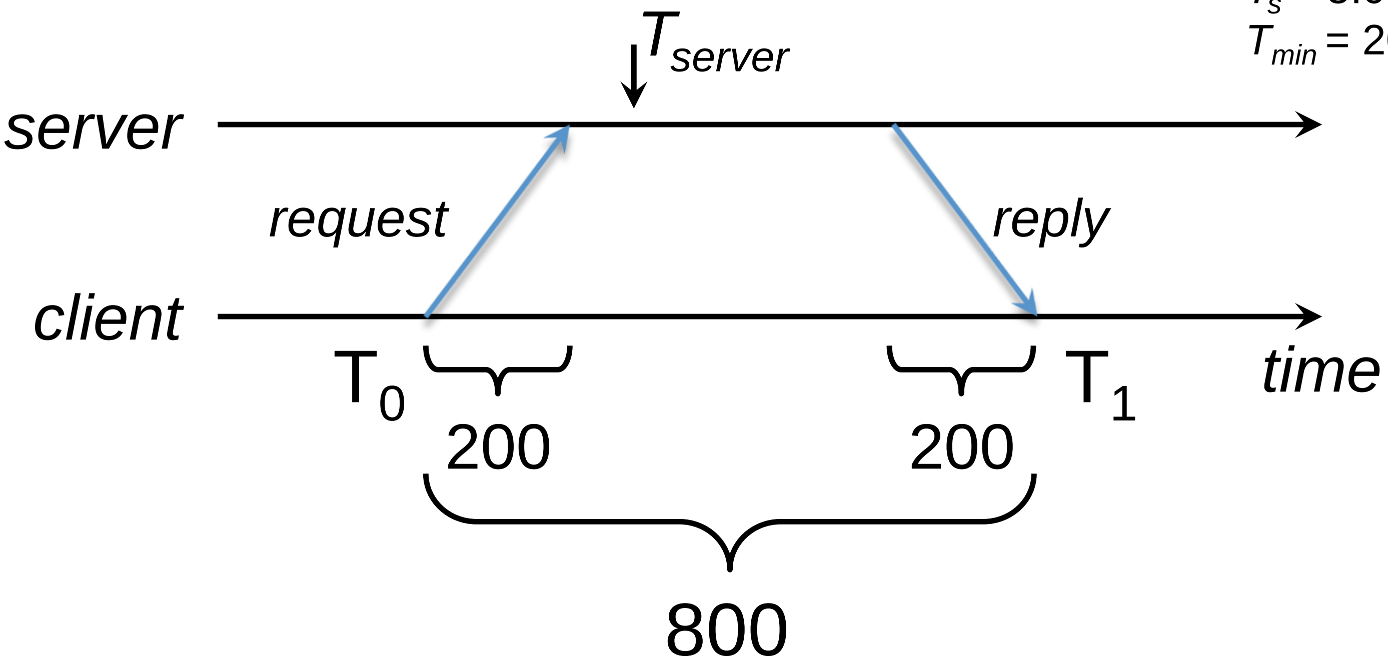
  400 msec ago
- Set time to T_{server} + *elapsed time*

  5:09:25.300 + 400 = 5:09.25.700

Cristian's algorithm: example

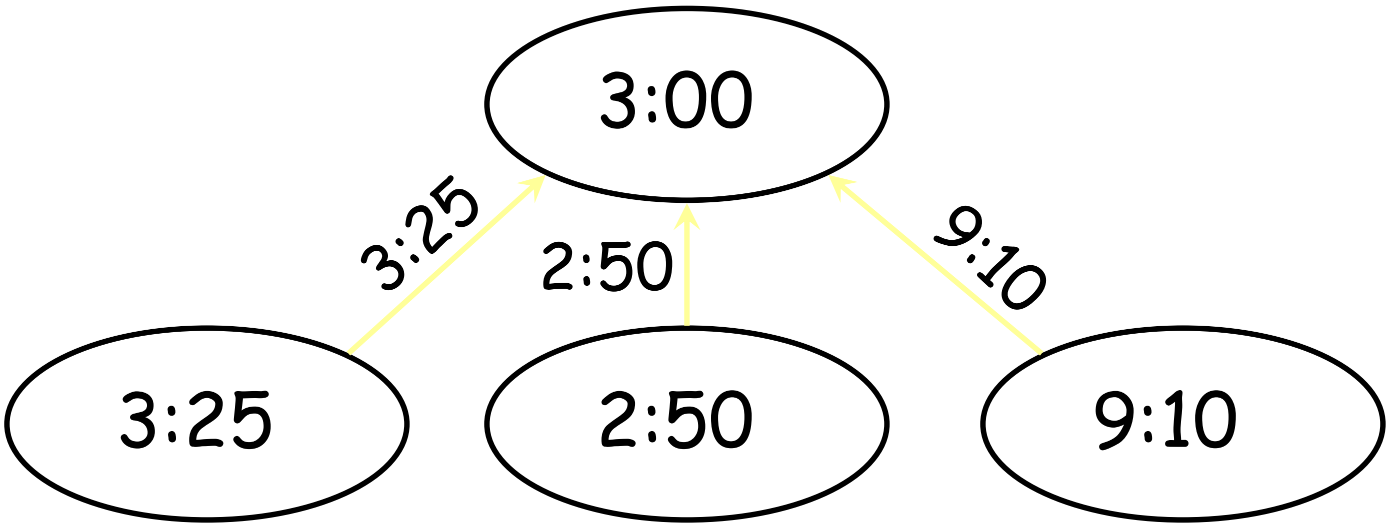
T_0 = 5:08:15.100
T_1 = 5:08:15.900
T_s = 5:09:25:300
T_{min} = 200msec

If best-case message time=200 msec



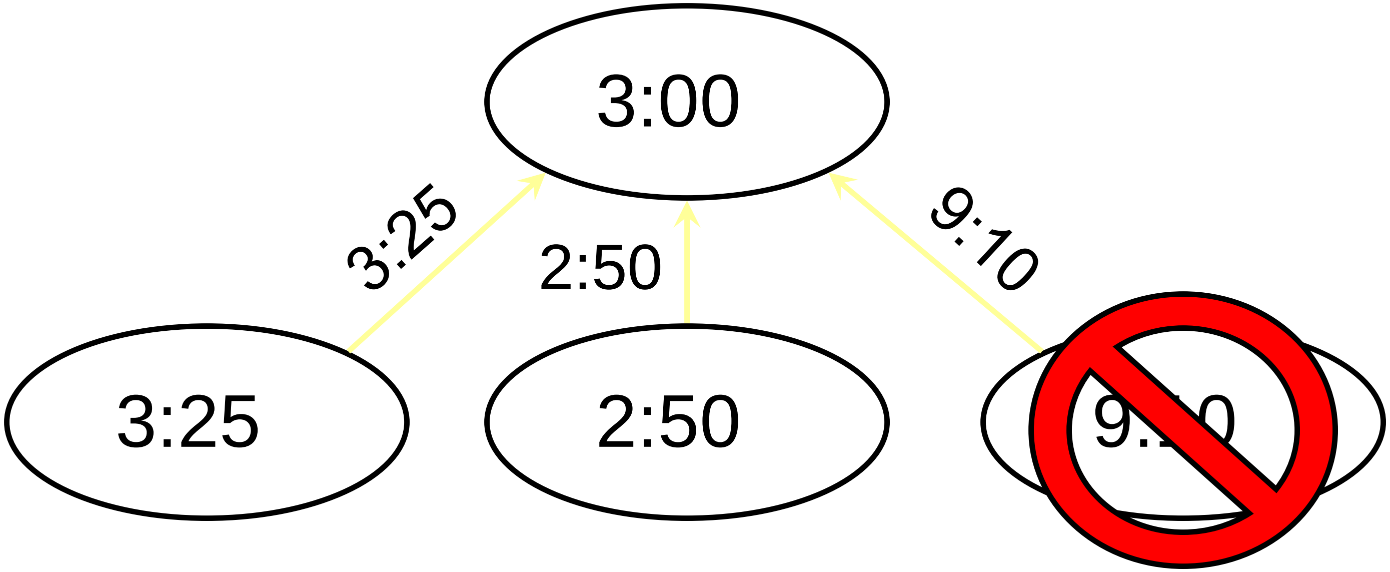
Error = $\pm\frac{900-100}{2} - 200 = \pm\frac{800}{2} - 200 = \pm 200$

Berkeley Algorithm: example



1. Request timestamps from all slaves

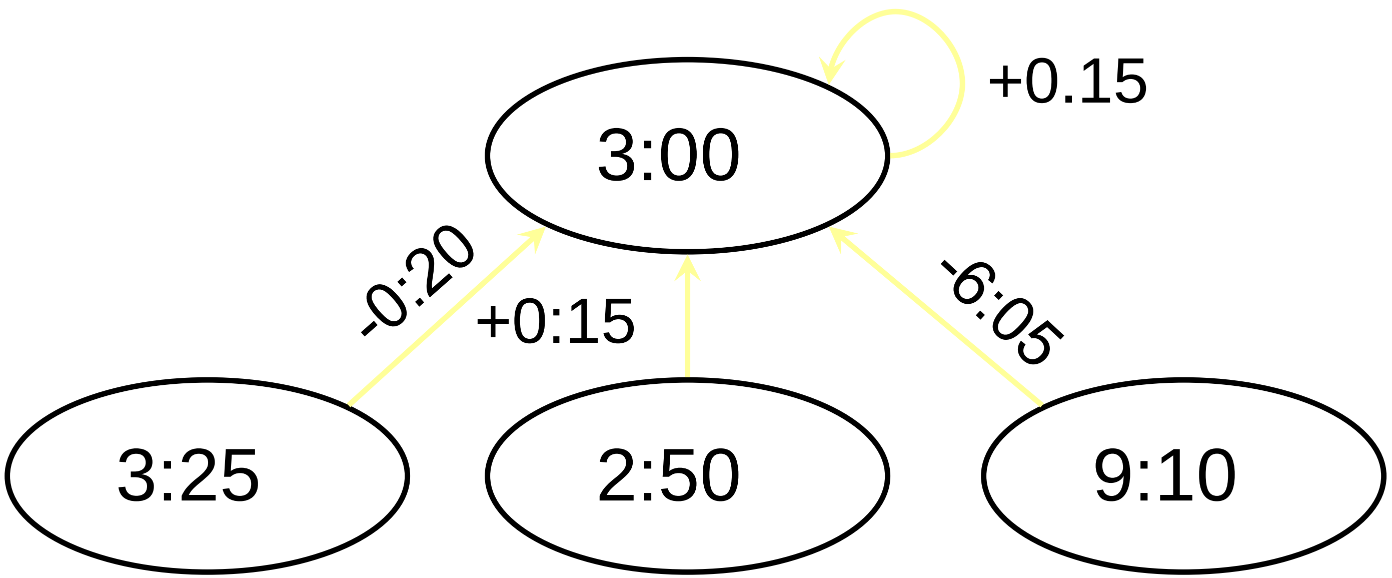
Berkeley Algorithm: example



2. Compute fault-tolerant average:

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

Berkeley Algorithm: example



3. Send offset to each client

NTP Message Structure

- Leap second indicator
  - Last minute has 59, 60, 61 seconds
- Version number
- Mode (symmetric, unicast, broadcast)
- Stratum (1=primary reference, 2-15)
- Poll interval
  - Maximum interval between 2 successive messages, nearest power of 2
- Precision of local clock
  - Nearest power of 2

NTP Message Structure

- Root delay
  - Total roundtrip delay to primary source
  - (16 bits seconds, 16 bits decimal)
- Root dispersion
  - Nominal error relative to primary source
- Reference clock ID
  - Atomic, NIST dial-up, radio, LORAN-C navigation system, GOES, GPS, …
- Reference timestamp
  - Time at which clock was last set (64 bit)
- Authenticator (key ID, digest)
  - Signature (ignored in SNTP)

NTP Message Structure

- T_1: originate timestamp
  - Time request departed client (client's time)
- T_2: receive timestamp
  - Time request arrived at server (server's time)
- T_3: transmit timestamp
  - Time request left server (server's time)

NTP's Validation Tests

- Timestamp provided ≠ last timestamp received
  - duplicate message?
- Originating timestamp in message consistent with sent data
  - Messages arriving in order?
- Timestamp within range?
- Originating and received timestamps ≠ 0?
- Authentication disabled? Else authenticate
- Peer clock is synchronized?
- Don't sync with clock of higher stratum #
- Reasonable data for delay & dispersion

Logical Time: Backup Slides

Following contents are based on the slides and book:
Ajay Kshemkalyani and Mukesh Singhal,
Distributed Computing: Principles, Algorithms, and Systems,
Cambridge University Press, 2011, [link]

Causality and Time

- The concept of **causality** between events is fundamental to the design and analysis of parallel and distributed computing and operating systems
- Usually causality is tracked using **physical time**
  - In distributed systems, it is not possible to have a (correct) global physical time
- Asynchronous distributed computations make progress in spurts …
- .. So the so-called **logical time** is sufficient to capture the fundamental monotonicity property associated with causality in distributed systems