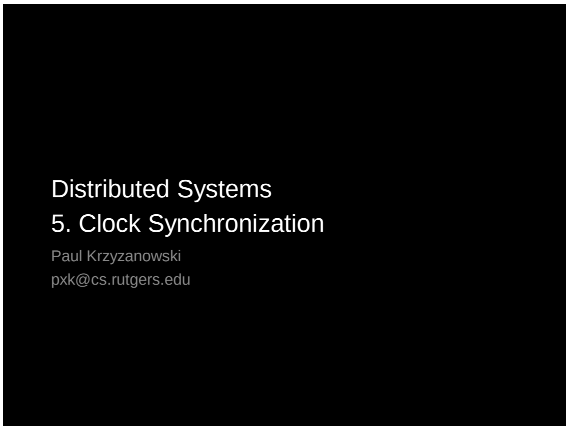

Distributed Systems
5. Clock Synchronization

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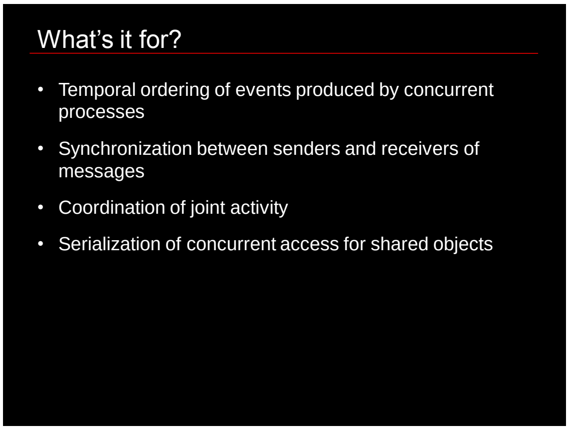
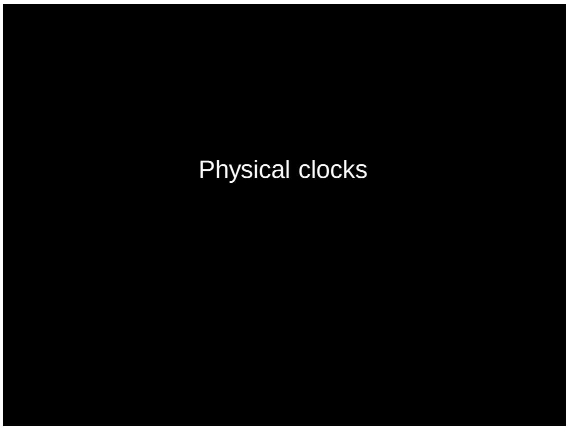
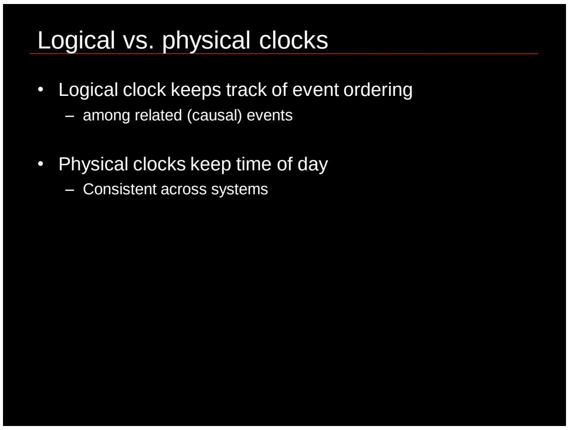


What’s it for?

- 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

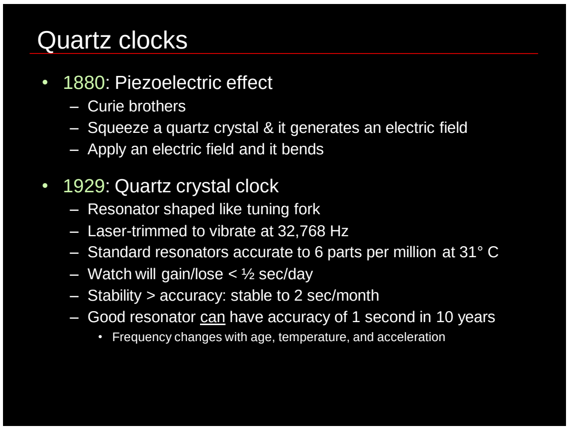


Physical clocks



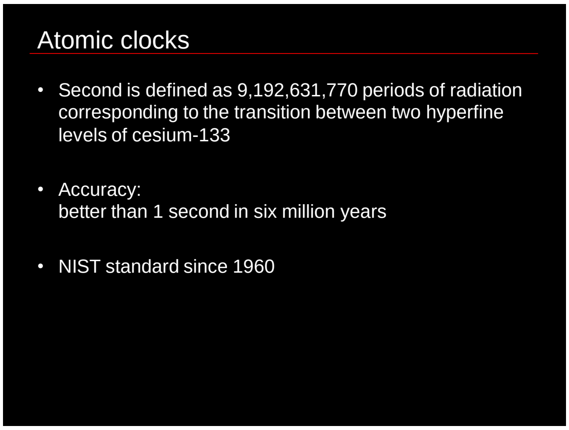
Logical vs. physical clocks

- Logical clock keeps track of event ordering
  - among related (causal) events
- Physical clocks keep time of day
  - Consistent across systems



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 can 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

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 increments a counter in memory

Problem

- 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

8:00:00

Sept 18 8:00:00

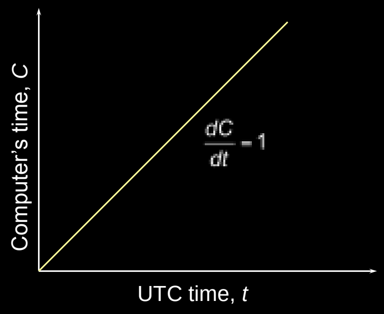
8:00:00

8:01:24
Skew = +84 seconds
+84 seconds/35 days
Drift = +2.4 sec/day

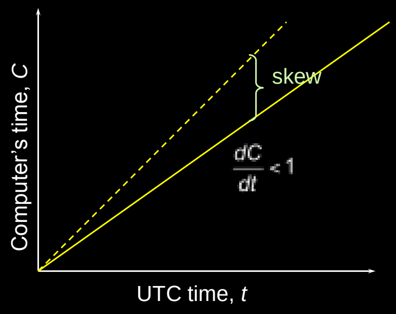
Oct 23 8:00:00

8:01:48
Skew = +108 seconds
+108 seconds/35 days
Drift = +3.1 sec/day

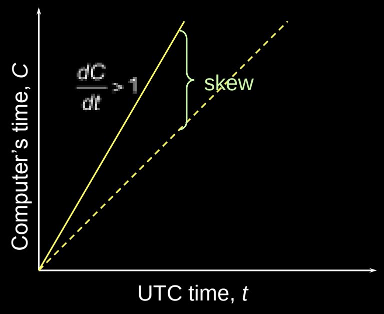
Perfect clock



Drift with slow clock



Drift with fast clock



Dealing with drift

We want to set the computer to the time of day

Not good idea to set clock back

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

Dealing with drift

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:

- Change the 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
- Not always practical: we may not have enough precision
- Easier (software-only) solution
  - adjust the rate at which the system time is advanced

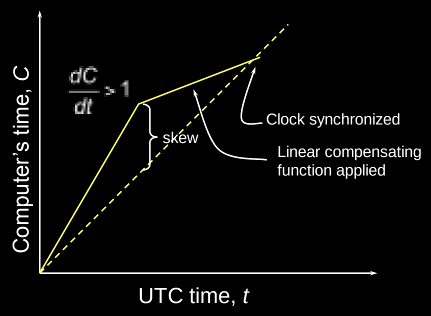
Adjustment changes slope of system time:

Linear compensating function

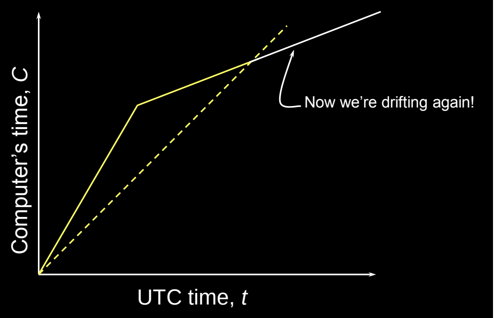
Dealing with drift

- 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

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

Keep track of adjustments and apply continuously

- e.g., UNIX *adjtime* system call

Getting accurate time

- Attach GPS receiver to each computer
  - ± 1 msec of UTC
- Attach WWV radio receiver
  - Obtain time broadcasts from Boulder or DC
  - ± 3 msec of UTC (depending on distance)
- Not practical solution for every machine
  - Cost, power, convenience, environment

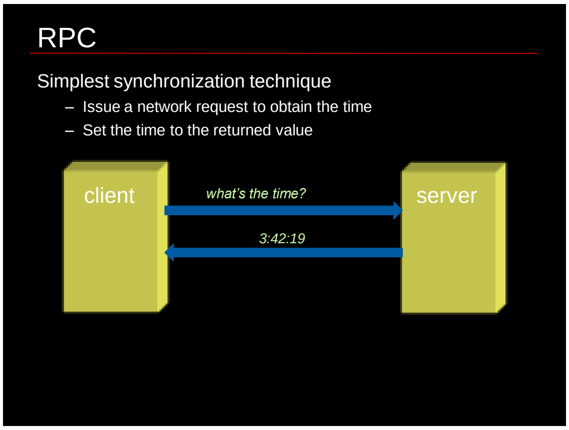
Getting accurate time

Synchronize from another machine

- One with a more accurate clock

Machine/service that provides time information:

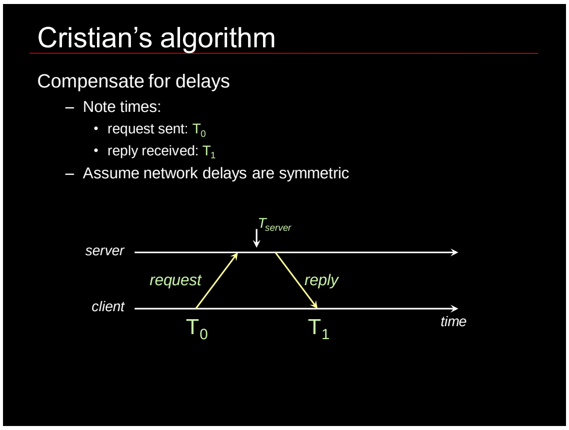
Time server



RPC

Simplest synchronization technique

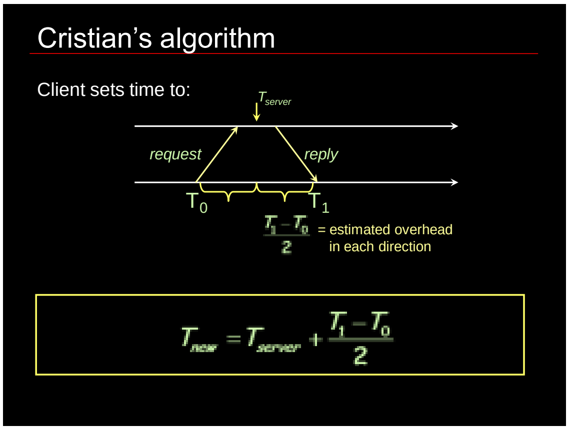
- Issue a network request to obtain the time
- Set the time to the returned value



Cristian's algorithm

Compensate for delays

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

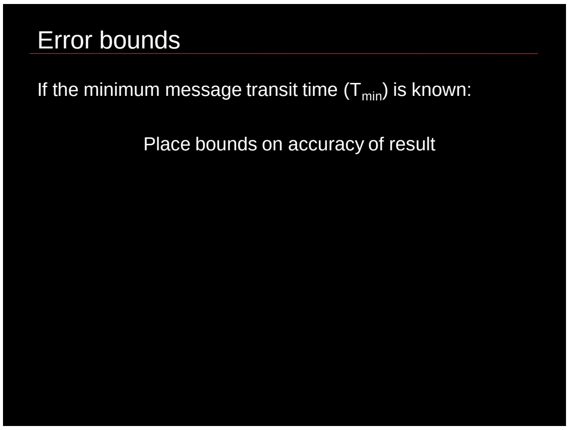


Cristian's algorithm

Client sets time to:

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

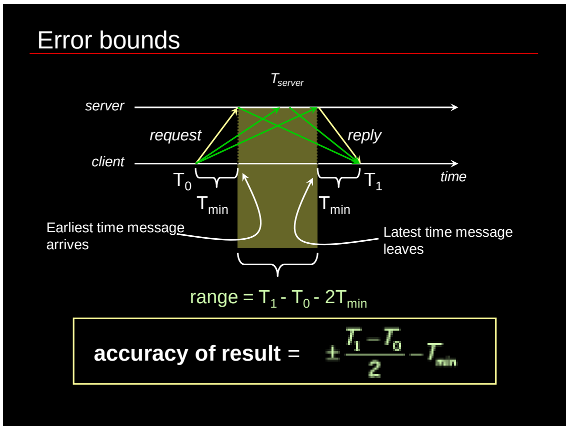
$$\boxed{T_{new} = T_{server} + \frac{T_1 - T_0}{2}}$$



Error bounds

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

Place bounds on accuracy of result



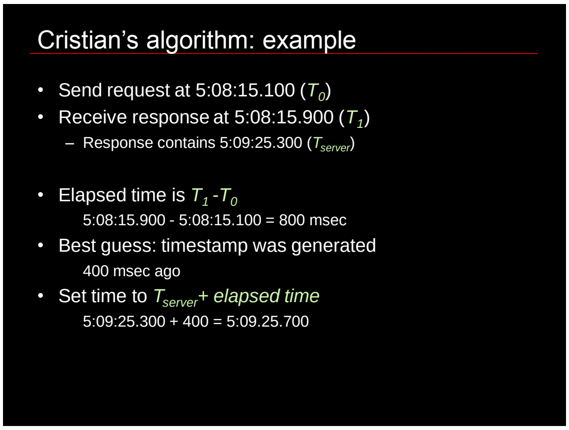
Error bounds

Earliest time message arrives

Latest time message leaves

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

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



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 msec
- Best guess: timestamp was generated

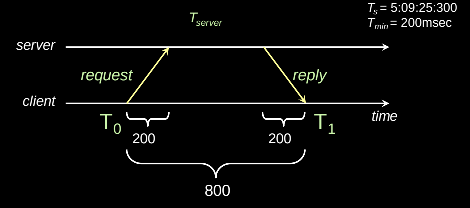
  400 msec ago
- Set time to T_{server}+ *elapsed time*

  5:09:25.300 + 400 = 5:09.25.700

Cristian's algorithm: example

If best-case message time=200 msec

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



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 average

Berkeley Algorithm

- 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
  - Ask each machine for time
    - Can use Cristian's algorithm to compensate for network latency
- When results are in, compute average
  - Including master's time
- *Hope: an average cancels out individual clock's tendencies to run fast or slow*
- Send offset by which each clock needs adjustment to each slave
  - Avoids problems with network delays if we send a time stamp

Berkeley Algorithm

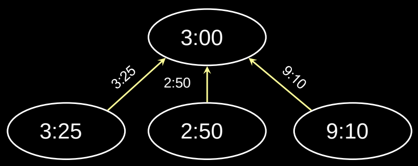
Algorithm has provisions for ignoring readings from clocks whose skew is too great

- Compute a fault-tolerant average

If master fails

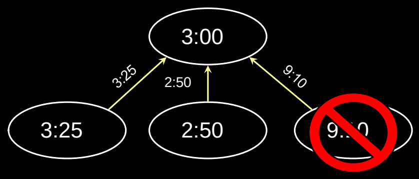
- Any slave can take over via an election algorithm

Berkeley Algorithm: example



1. Request timestamps from all slaves

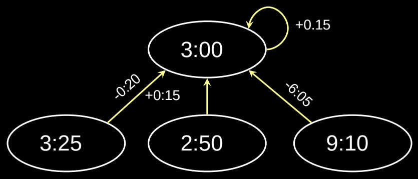
Berkeley Algorithm: example



2. Compute fault-tolerant average:

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

Berkeley Algorithm: example



3. Send offset to each client

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

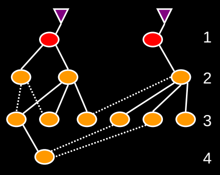
NTP Goals

- 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
- 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

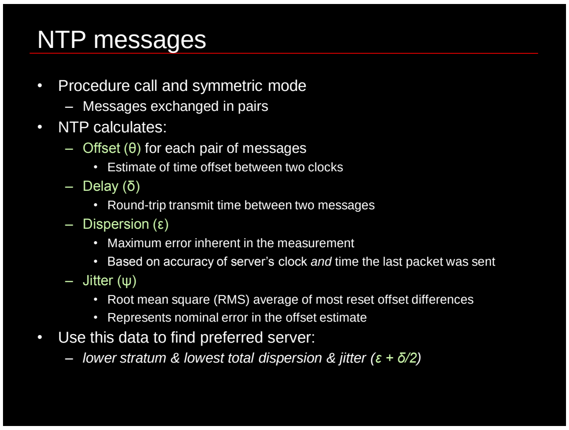
Procedure call mode

- Similar to Cristian's algorithm

Symmetric mode

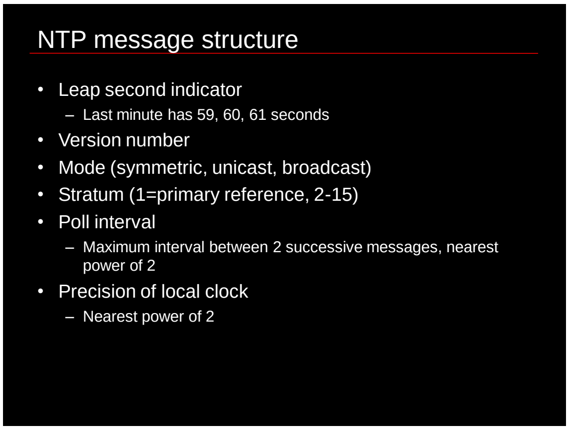
- Intended for master servers
- Pair of servers exchange messages and retain data to improve synchronization over time

All messages delivered unreliably with UDP



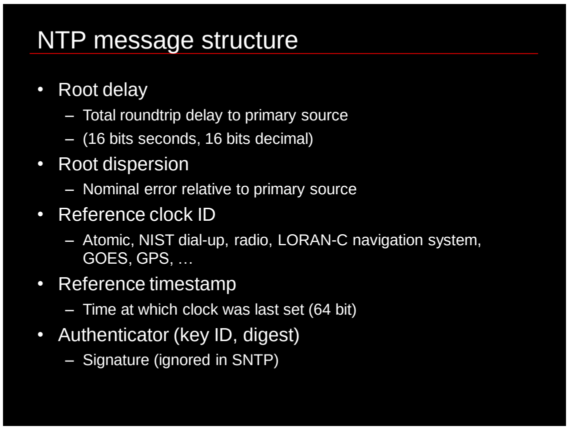
NTP messages

- Procedure call and symmetric mode
  - Messages exchanged in pairs
- NTP calculates:
  - Offset (θ) for each pair of messages
    - Estimate of time offset between two clocks
  - Delay (δ)
    - Round-trip transmit time between two messages
  - Dispersion (ε)
    - Maximum error inherent in the measurement
    - Based on accuracy of server's clock *and* time the last packet was sent
  - Jitter (ψ)
    - Root mean square (RMS) average of most reset offset differences
    - Represents nominal error in the offset estimate
- Use this data to find preferred server:
  - *lower stratum & lowest total dispersion & jitter* $(\varepsilon + \delta/2)$



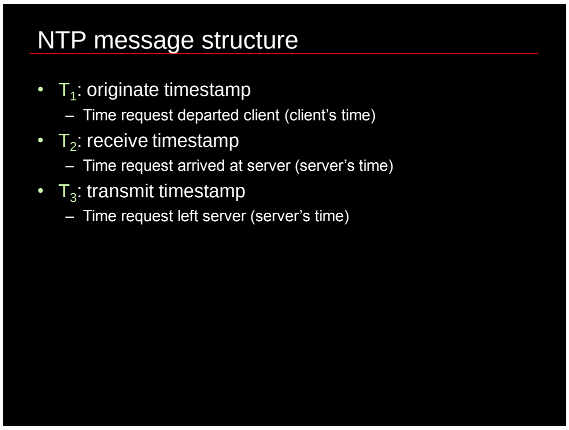
NTP message structure

- 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



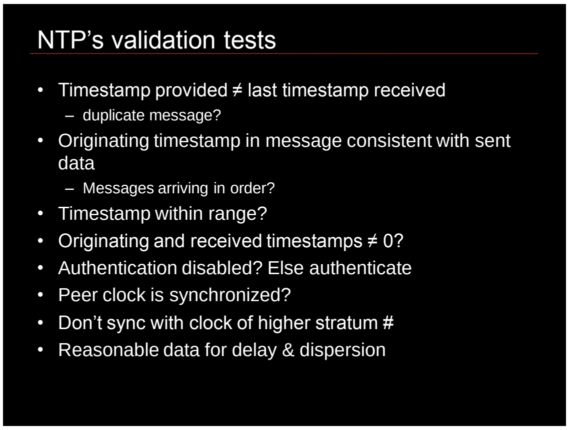
NTP message structure

- 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)



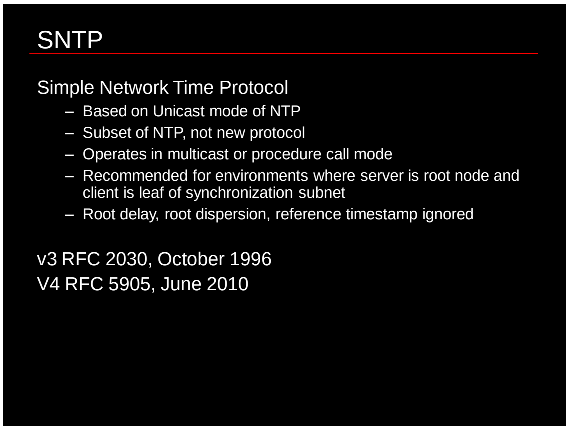
NTP message structure

- 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

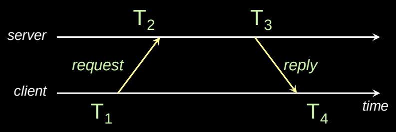


SNTP

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

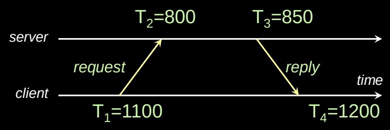


Roundtrip delay:

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

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

SNTP example



Offset =

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

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

= -650/2 = -325

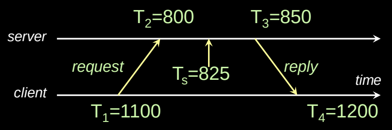
Time offset:

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

Set time to $T_4 + t$

= 1200 - 325 = 875

Cristian's algorithm



Offset = (1200 - 1100)/2 = 50

Set time to T_s + *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

The End