Inherent Limitations of a Distributed System

- A distributed system is a set of computers that communicate over a network, and do not share a common memory or a common clock
- Absence of a common (global) clock
  - No concept of global time
  - It's difficult to reason about the temporal ordering of events
    - Cooperation between processes (e.g., producer/consumer, client/server)
    - Arrival of requests to the OS (e.g., for resources)
    - Collecting up-to-date global state
  - It's difficult to design and debug algorithms in a distributed system
    - Mutual exclusion
    - Synchronization
    - Deadlock

Inherent Limitations of a Distributed System (cont.)

- Absence of shared memory means "state" is distributed throughout system
- One process can get either:
    - a **coherent** but **partial** view of the system,
    - or an **incoherent** but **complete** (**global**) view of the system
  - where *coherent* means:
    - all processes make their observations at the same time
  - where *complete* (or **global**) includes:
    - all local views of the state, plus
    - any messages that are in transit

➥ It is very difficult for every process to get a complete and coherent view of the global state

- Example: one person has two bank accounts, and is in process of transferring $50 between the accounts

Why Do We Care About "Time" in a Distributed System?

- May need to know the time of day some event happened on a specific computer
  - Synchronize that computer's clock with some external authoritative source of time (*external* clock synchronization)
- May need to know the time interval, or relative order, between two events that happened on different computers
  - Synchronize the clocks on those computers to each other to some known degree of accuracy (called *internal* clock synchronization), and then measure time relative to a local clock
- Can we synchronize this way?
  - Will the clocks stay synchronized?
  - Network delay is unpredictable
  - Is this synchronization sufficient?

Physical Clocks

- Every computer contains a physical clock
  - A *clock* (also called a *timer*) is an electronic device that counts oscillations in a crystal at a particular frequency
    - Count is typically divided and stored in a counter register
  - Clock can be programmed to generate interrupts at regular intervals (e.g., at time interval required by a CPU scheduler)
- Counter can be scaled to get time of day
  - This value can be used to *timestamp* an event on that computer
    - Two events will have different timestamps only if *clock resolution* is sufficiently small
  - Many applications are interested only in the **<u>order</u>** of the events, not the exact time of day at which they occurred, so this scaling is often not necessary

Physical Clocks in a Distributed System

- Does this work?
  - Synchronize all the clocks to some known high degree of accuracy, and then
  - measure time relative to each local clock to determine order between two events
- Well, there are some problems…
  - It's difficult to synchronize the clocks
  - Crystal-based clocks tend to *drift* over time — count time at different rates, and diverge from each other
    - Physical variations in the crystals, temperature variations, etc.
    - Drift is small, but adds up over time
    - For quartz crystal clocks, typical drift rate is about one second every 10^6 seconds =11.6 days
    - Best atomic clocks have drift rate of one second in 10^{13} seconds = 300,000 years

Coordinated Universal Time

- The output of the atomic clocks is called *International Atomic Time*
  - *Coordinated Universal Time* (UTC) is an international standard based on atomic time, with an occasional *leap second* added or deleted
- UTC signals are broadcast regularly by various radio stations (e.g., WWV in Ft. Collins, CO) and satellites (e.g., GEOS — used by GPS receivers)
  - Have propagation delay due to speed of light, distance from broadcast source, atmospheric conditions, etc.
  - Received value is only accurate to 0.1–10 milliseconds
- Unfortunately, most workstations and PCs don't have UTC receivers

Synchronizing Physical Clocks

- Centralized algorithms
  - Use a time server with a UTC receiver, and synchronize everyone to this time
  - Client sets time to $T_{server} + D_{trans}$
    - T_{server} = server's time
    - D_{trans} = transmission delay
      - Unpredictable due to network traffic
  - Cristian's algorithm (1989):
    - Nodes send request to time server, measure time D_{trans} to receive reply T_{server}
    - Nodes set local time to $T_{server} + (D_{trans} / 2)$
      - Accuracy is $\pm$ ($(D_{trans} / 2) - D_{min}$)
      - Improvement: make several requests, take average T_{server} value
    - Assumptions:
      - Network delay is fairly consistent
      - Request & reply take equal amount of time
    - Problems:
      - Doesn't work if time server fails
      - Not secure against malfunctioning time server, or malicious impostor time server

Synchronizing Physical Clocks (cont.)

- Centralized algorithms (cont.)
  - Berkeley (Gusella & Zatti) algorithm (1989):
    - Choose a coordinator computer to act as the *master*
    - Master periodically polls the *slaves* — the other computers whose clocks should be synchronized to the master
      - Slaves send their clock value to master
    - Master observes transmission delays, and estimates their local clock times
      - Master averages everyone's clock times (including its own)
        - » Master takes a *fault-tolerant average* — it ignores readings from clocks that have drifted badly, or that have failed and are producing readings far outside the range of the other clocks
      - Master sends to each slave the amount (positive or negative) by which it should adjust its clock

Synchronizing Physical Clocks (cont.)

- Distributed algorithms
  - All nodes have a UTC receiver, but internal synchronization may still be desirable
  - Global averaging:
    - Each node periodically broadcasts its time
    - Each node collects times broadcast by other nodes, recording when it received each broadcast and the difference between its clock and theirs
      - Then it takes a fault-tolerant average of the differences, and sets its local clock accordingly
    - Problem:
      - A lot of network traffic
  - Localized averaging:
    - Structure the nodes in some way (ring, tree, etc.) such that each node only averages values with a small subset of the total number of nodes

Synchronizing Physical Clocks — Network Time Protocol (NTP)

- Provides time service on the Internet
- Hierarchical network of servers:
  - Primary servers (100s) — connected directly to a time source
  - Secondary servers (1000s) — connected to primary servers in hierarchical fashion
  - Servers at higher levels are presumed to be more accurate than at lower levels
- Several synchronization modes:
  - Multicast — for LANs, low accuracy
  - Procedure call — similar to Cristian's algorithm, higher accuracy (file servers)
  - Symmetric mode — exchange detailed messages, maintain history
- All built on top of UDP (connectionless)

Compensating for Clock Drift

- Compare time T_s provided by time server to time T_c at computer C
- If $T_s > T_c$ (e.g., 9:07am vs 9:05am)
  - Could advance C's time to T_s
  - May miss some clock ticks; probably OK
- If $T_s < T_c$ (e.g., 9:07am vs 9:10am)
  - Can't roll back C's time to T_s
    - Many applications (e.g., make) assume that time always advances!
  - Can cause C's clock to run slowly until it resynchronizes with the time server
    - Can't change the clock oscillator rate, so have to change the software interpreting the clock's counter register
    - $T_{software} = a\, T_{hardware} + b$
    - Can determine constants *a* and *b*

Is It Enough to Synchronize Physical Clocks?

- Summary:
  - In a distributed system, there is no common clock, so we have to:
    - Use atomic clocks to minimize clock drift
    - Synchronize with time servers that have UTC receivers, trying to compensate for unpredictable network delay
- Is this sufficient?
  - Value received from UTC receiver is only accurate to within 0.1–10 milliseconds
    - At best, we can synchronize clocks to within 10–30 milliseconds of each other
    - We have to synchronize frequently, to avoid local clock drift
  - In 10 ms, modern CPU can execute millions of instructions
    - Accurate enough as time-of-day
    - ➥ ***Not sufficiently accurate*** to determine the relative order of events on different computers in a distributed system