Networking for Operating Systems and Distributed Systems
CS 111
Operating System Principles
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Outline

- Introduction to networking
- Networking implications for operating systems
- Networking and distributed systems

Networking Implications for the Operating System

- More and more computer activities require efficient networking support
- The operating system must be good at meetingthe special needs of networks
- The network is not just another peripheral device
- Instead, the key demand on future systems

Changing Paradigms

- Network connectivity becomes "a given"
  - New applications assume/exploit connectivity
  - New distributed programming paradigms emerge
  - New functionality depends on network services
- Thus, applications demand new services from the OS:
  - Location independent operations
  - Rendezvous between cooperating processes
  - WAN scale communication, synchronization
  - Support for splitting and migrating computations
  - Better virtualization services to safely share resources
  - Network performance becomes critical

The Old Networking Clients

- Old fashioned clients were basic networking applications
  - Implementations of higher level remote access protocols
    - telnet, FTP, SMTP, POP/IMAP, network printing
  - Occasionally run, to explicitly access remote systems
  - Applications specifically written to network services
- OS provided transport level services
  - TCP or UDP, IP, NIC drivers
- Little impact on OS APIs
  - OS objects were not expected to have network semantics
  - Network apps provided services, did not implement objects

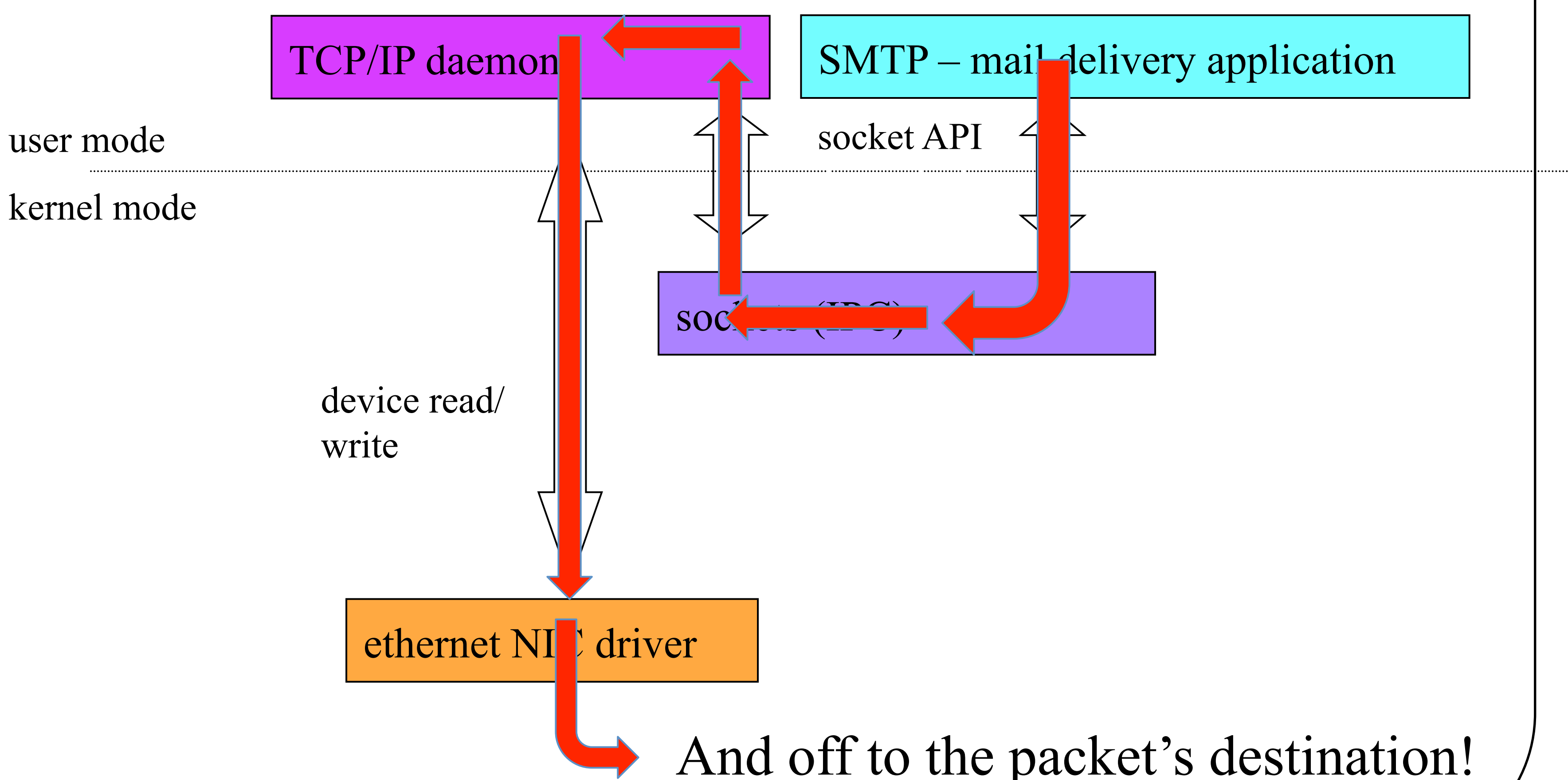
The New Networking Clients

- The OS itself is a client for network services
  - OS may depend on network services
    - netboot, DHCP, LDAP, Kerberos, etc.
  - OS-supported objects may be remote
    - Files may reside on remote file servers
    - Console device may be a remote X11 client
    - A cooperating process might be on another machine
- Implementations must become part of the OS
  - For both performance and security reasons
- Local resources may acquire new semantics
  - Remote objects may behave differently than local

The Old Implementations

- Network protocol implemented in user-mode daemon
  - Daemon talks to network through device driver
- Client requests
  - Sent to daemon through IPC port
  - Daemon formats messages, sends them to driver
- Incoming packets
  - Daemon reads from driver and interprets them
  - Unpacks data, forward to client through IPC port
- Advantages – user mode code is easily changed
- Disadvantages – lack of generality, poor performance, weak security

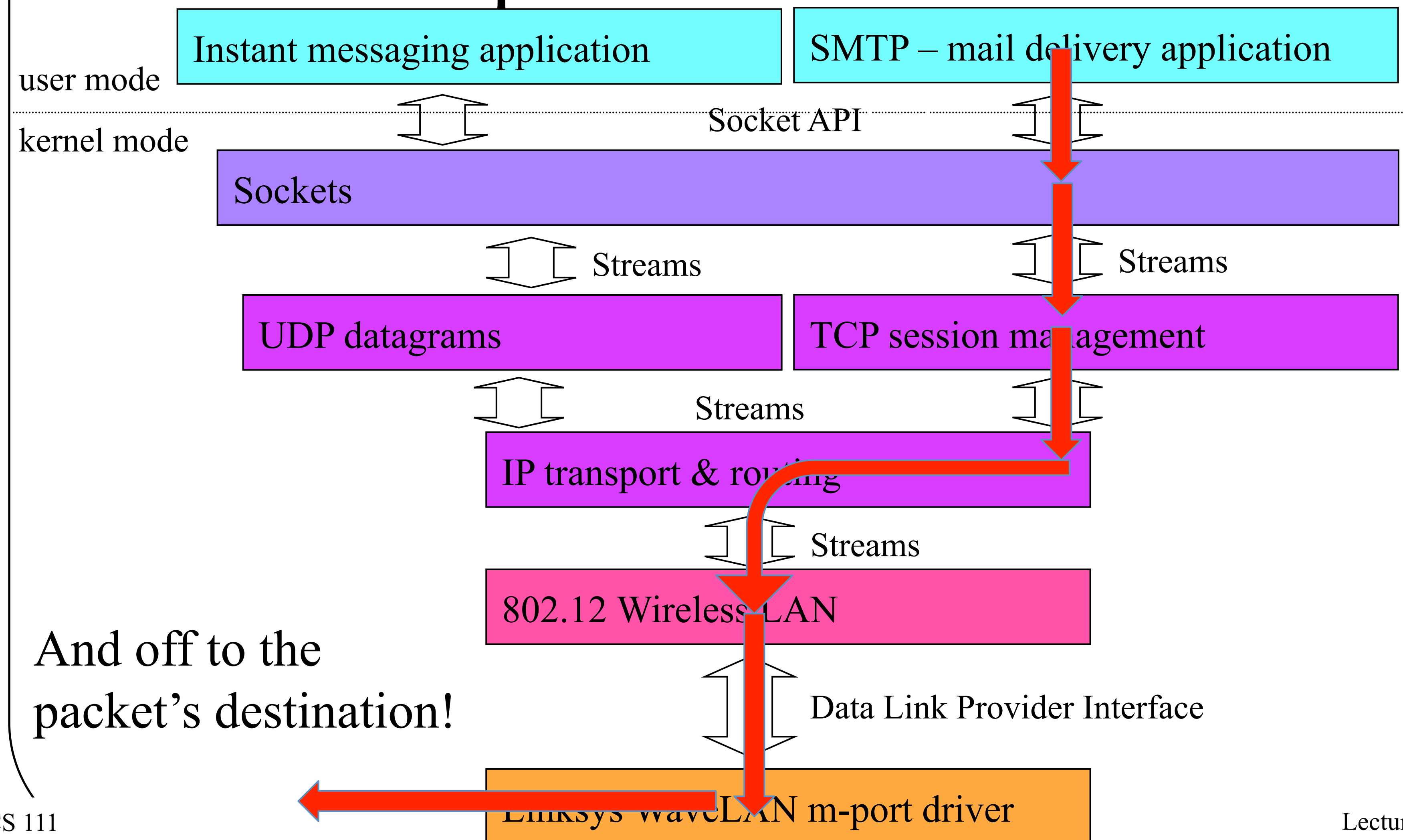
User-Mode Protocol Implementations



The New Implementations

- Basic protocols implemented as OS modules
  - Each protocol implemented in its own module
  - Protocol layering implemented with module plumbing
  - Layering and interconnections are configurable
- User-mode clients attach via IPC-ports
  - Which may map directly to internal networking plumbing
- Advantages
  - Modularity (enables more general layering)
  - Performance (less overhead from entering/leaving kernel)
  - Security (most networking functionality inside the kernel)
- A disadvantage – larger, more complex OS

In-Kernel Protocol Implementations



And off to the packet's destination!

IPC Implications

- IPC used to be occasionally used for pipes
  - Now it is used for all types of services
    - Demanding richer semantics, and better performance
- Used to interconnect local processes
  - Now it interconnects agents all over the world
    - Need naming service to register & find partners
    - Must interoperate with other OSes IPC mechanisms
- Used to be simple and fast inside the OS
  - We can no longer depend on shared memory
  - We must be prepared for new modes of failure

Improving Our OS Plumbing

- Protocol stack performance becomes critical
  - To support file access, network servers
- High performance plumbing: UNIX Streams
  - General bi-directional in-kernel communications
    - Can interconnect any two modules in kernel
    - Can be created automatically or manually
  - Message based communication
    - Put (to stream head) and service (queued messages)
    - Accessible via read/write/putmsg/getmsg system calls

Network Protocol Performance

- Layered implementation is flexible and modular
  - But all those layers add overhead
    - Calls, context switches and queuing between layers
    - Potential data recopy at boundary of <u>each</u> layer
  - Protocol stack plumbing must also be high performance
    - High bandwidth, low overhead
- Copies can be avoided by clever data structures
  - Messages can be assembled from multiple buffers
    - Pass buffer pointers rather than copying messages
- Increasingly more of the protocol stack is in the NIC

Implications of Networking for Operating Systems

- Centralized system management
- Centralized services and servers
- The end of “self-contained” systems
- A new view of architecture
- Performance, scalability, and availability
- The rise of middleware

Centralized System Management

- For all computers in one local network, manage them as a single type of resource
  - Ensure consistent service configuration
  - Eliminate problems with mis-configured clients
- Have all management done across the network
  - To a large extent, in an automated fashion
  - E.g., automatically apply software upgrades to all machines at one time
- Possibly from one central machine
  - For high scale, maybe more distributed

Benefits of Central Management

- Zero client-side administration
  - Plug in a new client, and it should just work
    - Since everything it needs to get going will be automatically delivered over the network
  - Reduced (per client) costs of support
    - Since all management info is centralized, rarely have to manually examine a client machine
- Uniform & ubiquitous computer services
  - All data and services available from all clients
  - Global authentication and resource domain
- Security benefits
  - All important security patches get applied with certainty
  - Individual users can't screw up their machine's security

Dangers of Central Management

- Screw-ups become ubiquitous
- Loss of local autonomy for users
- Administrators gain extreme power
  - So you'd better be sure they're trustworthy and competent
- Security disadvantages
  - All machines are arbitrarily reconfigurable from remote sites
  - Encourages monocultures, which are susceptible to malware

Centralized Services and Servers

- Networking encourages tendency to move services from all machines to one machine
  - E.g. file servers, web servers, authentication servers
- Other machines can access and use the services remotely
  - So they don't need local versions
  - Or perhaps only simplified local versions

Benefits of Service Centralization

- Quality and reliability of service
  - "Guaranteed" to be up 24x7
  - Performance monitored, software kept up-to-date
  - Regular back-ups taken
- Price performance
  - Powerful servers amortized over many clients
- Ease of use
  - No need to install and configure per client services
  - Services are available from any client
- Allows thinner, cheaper clients
  - Or allows existing clients to devote resources to their users

Dangers of Centralized Services

- Forces reliance on networking
  - Which is “almost always” available, but . . .
  - Makes network congestion more likely
- Makes per-user customization harder
  - Sometimes that’s a good thing, though
- From a security perspective, one big fat target
  - As opposed to lots of little skinny targets
  - But automation of attacks makes this less important
- Can lead to huge privacy breaches

The End of Self Contained Systems

- Years ago, each computer was nearly totally self-sufficient
- Maybe you got some data from some other machine
- Or used some specialized hardware on one machine
- Or shared a printer over the network
- But your computer could do almost all of what you wanted to do, on its own

Now Vital Services Provided Over the Network

- Authentication
  - Active Directory, LDAP, Kerberos, …
- Configuration and control
  - Active Directory, LDAP, DHCP, CIM/WBEM, SNMP, …
- External data services
  - CIFS, NFS, Andrew, Amazon S3, …
- Remote devices
  - X11, web user interfaces, network printers
- Even power management, bootstrap, installation
  - vPro, PXE boot, bootp, live CDs, automatic s/w updates

Benefits of Losing Self-Sufficiency

- Remote specialized servers often do the job better
- Your machine doesn't need to pay the costs of doing the work itself
- Advantages of centralized administration
- Generally possible if any networking available
  - And, for modern use, relatively little is possible when networking isn't available, anyway

Dangers of Losing Self Sufficiency

- Your device is a brick without connectivity
- Your security depends on the security of many others
- Worse, your privacy is dependent on a bunch of service providers
  - In many cases, their business model is using your private information . . .
- Harder, maybe impossible, to customize services to your needs

A New View of System Architecture

- Old view is that we build systems
  - Which are capable of running programs that their owners want executed
  - Each system is largely self-contained and only worries about its own concerns and needs
- New view is that system is only a conduit for services
  - Which are largely provided over the network

The New Architectural Vision

- Customers want services, not systems
  - We design and build systems to provide services
- Services are built up from protocols
  - Service is delivered to customers via a network
  - Service is provided by collaborating servers
  - Which are run by remote providers, often as a business
- The fundamental unit of service is a node
  - Provides defined services over defined protocols
  - Language, OS, ISA are mere implementation details
- A node is not a single machine
  - It may be a collection of collaborating machines
  - Maybe widely distributed

Benefits of This View

- Moves away from computer users as computer experts
  - Which most of them aren't, and don't want to be
- A more realistic view of what modern machines are for
- Abstracts many of the ugly details of networks and distributed systems below human level
- Clarifies what we should really be concerned about

Dangers of This Vision

- Requires a lot of complex stuff under the covers
- Many problems we are expected to solve are difficult
  - Perhaps unsolvable, in some cases
- Higher degree of proper automated behavior is required

Performance, Availability, Scalability

- Used to be an easy answer for achieving these:
  - Moore’s law (and its friends)
- The CPUs (and everything else) got faster and cheaper
  - So performance got better
  - More people could afford machines that did particular things
  - Problems too big to solve today fell down when speeds got fast enough

The Old Way Vs. The New Way

- The old way – better components (4-40%/year)
  - Find and optimize all avoidable overhead
  - Get the OS to be as reliable as possible
  - Run on the fastest and newest hardware
- The new way – better systems (1000x)
  - Add more $150 blades and a bigger switch
  - Spreading the work over many nodes is a huge win
    - Performance – may be linear with the number of blades
    - Availability – service continues despite node failures

Benefits of the New Approach

- Allows us to leap past many hard problems
  - E.g., don’t worry about how to add the sixth nine of reliability to your machine
- Generally a lot cheaper
  - Adding more of something is just some dollars
  - Instead of having some brilliant folks create a new solution

Dangers of the New Solution

- Adds a different set of hard problems
  - Like solving distributed and parallel processing problems
- Your performance is largely out of your hands
  - E.g., will your service provider choose to spring for a bunch of new hardware?
- Behaviors of large scale systems not necessarily well understood
  - Especially in pathological conditions

The Rise of Middleware

- Traditionally, there was the OS and your application
  - With little or nothing between them
- Since your application was “obviously” written to run on your OS
- Now, the same application must run on many machines, with different OSes
- Enabled by powerful middleware
  - Which offer execution abstractions at higher levels than the OS
  - Essentially, powerful virtual machines that hide grubby physical machines and their OSes

The OS and Middleware

- Old model – the OS was the platform
  - Applications are written for an operating system
  - OS implements resources to enable applications
- New model – the OS enables the platform
  - Applications are written to a middleware layer
    - E.g., Enterprise Java Beans, Component Object Model, Ruby on Rails, etc.
  - OS APIs less relevant to applications developers
    - The network <u>is</u> the computer

Benefits of the Rise of Middleware

- Easy portability
  - Make the middleware run on whatever
  - Then the applications written to the middleware will run there
- Middleware interfaces offer better abstractions
  - Allowing quicker creation of more powerful programs

Dangers of the Rise of Middleware

- Not always easy to provide totally transparent portability
- The higher level abstractions can hide some of the power of simple machines
  - Particularly in performance

Networking and Distributed Systems

- Challenges of distributed computing
- Distributed synchronization
- Distributed consensus

What Is Distributed Computing?

- Having more than one computer work cooperatively on some task
- Implies the use of some form of communication
  - Usually networking
- Adding the second computer immensely complicates all problems
  - And adding a third makes it worse
- Ideally, with total *transparency*
  - Entirely hide the fact that the computation/service is being offered by a distributed system

Challenges of Distributed Computing

- Heterogeneity
  - Different CPUs have different data representations
  - Different OSes have different object semantics and operations
- Intermittent connectivity
  - Remote resources will not always be available
  - We must recover from failures in mid-computation
  - We must be prepared for conflicts when we reconnect
- Distributed object coherence
  - Object management is easy with one in-memory copy
  - How do we ensure multiple hosts agree on state of object?

Deutsch's "Seven Fallacies of Network Computing"

1. The network is reliable
2. There is no latency (instant response time)
3. The available bandwidth is infinite
4. The network is secure
5. The topology of the network does not change
6. There is one administrator for the whole network
7. The cost of transporting additional data is zero

Bottom Line: true transparency is not achievable

Distributed Synchronization

- As we’ve already seen, synchronization is crucial in proper computer system behavior
- When things don’t happen in the required order, we get bad results
- Distributed computing has all the synchronization problems of single machines
- Plus genuinely independent interpreters and memories

Why Is Distributed Synchronization Harder?

- Spatial separation
  - Different processes run on different systems
  - No shared memory for (atomic instruction) locks
  - They are controlled by different operating systems
- Temporal separation
  - Can't "totally order" spatially separated events
  - "Before/simultaneous/after" become fuzzy
- Independent modes of failure
  - One partner can die, while others continue

Dealing With Distributed Synchronization

- Two fundamental approaches:
  1. Avoid it
     - Work extra hard to avoid sharing data
     - Try to limit complexities of failures
  2. Use distributed analogs of single machine synchronization mechanisms

Avoidance Approaches

- Don't keep copies of data on different machines
- Usually implies avoidance of distributed state
  - E.g., servers don't keep track of what clients are up to
- Some examples:
  - NSF servers don't keep state on client operations
  - Web servers don't remember what their clients did previously
- Offload the burdens to the clients

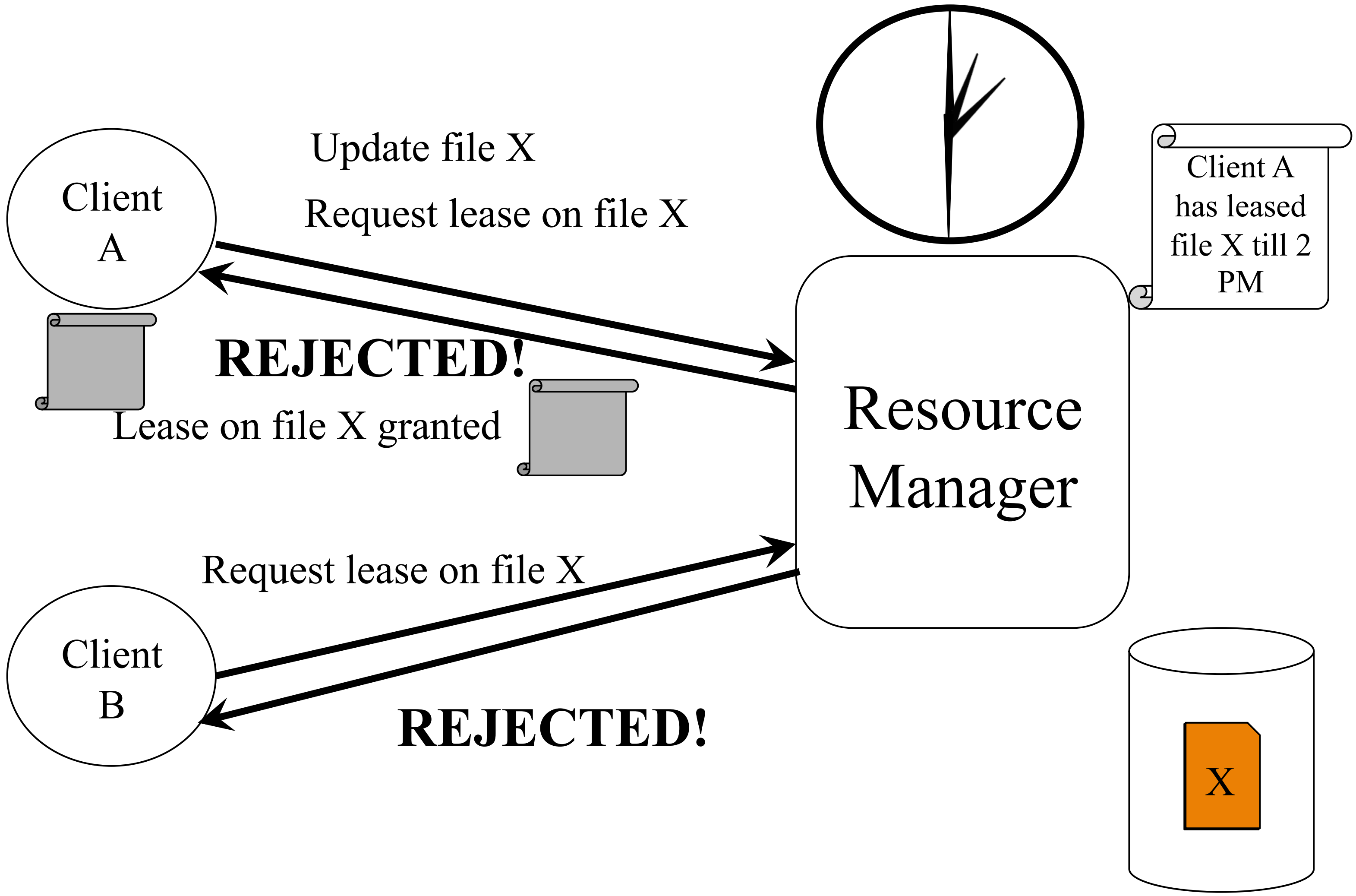
Distributed Synchronization Mechanisms

- Distributed analogs to what we do in a single machine
- But they are constrained by the fundamental differences of distributed environments
- They tend to be:
  - Less efficient
  - More fragile and error prone
  - More complex
  - Often all three

Leases

- A relative of locks
- Obtained from an entity that manages a resource
  - Gives client exclusive right to update the file
  - The lease "cookie" must be passed to server with an update
  - Lease can be released at end of critical section
- Only valid for a limited period of time
  - After which the lease cookie expires
    - Updates with stale cookies are not permitted
  - After which new leases can be granted
- Handles a wide range of failures
  - Process, node, network

A Lease Example



What Is This Lease?

- It's essentially a ticket that allows the leasee to do something
  - In our example, update file X
- In other words, it's a bunch of bits
- But proper synchronization requires that only the manager create one
- So it can't be forgeable
- How do we create an unforgeable bunch of bits?

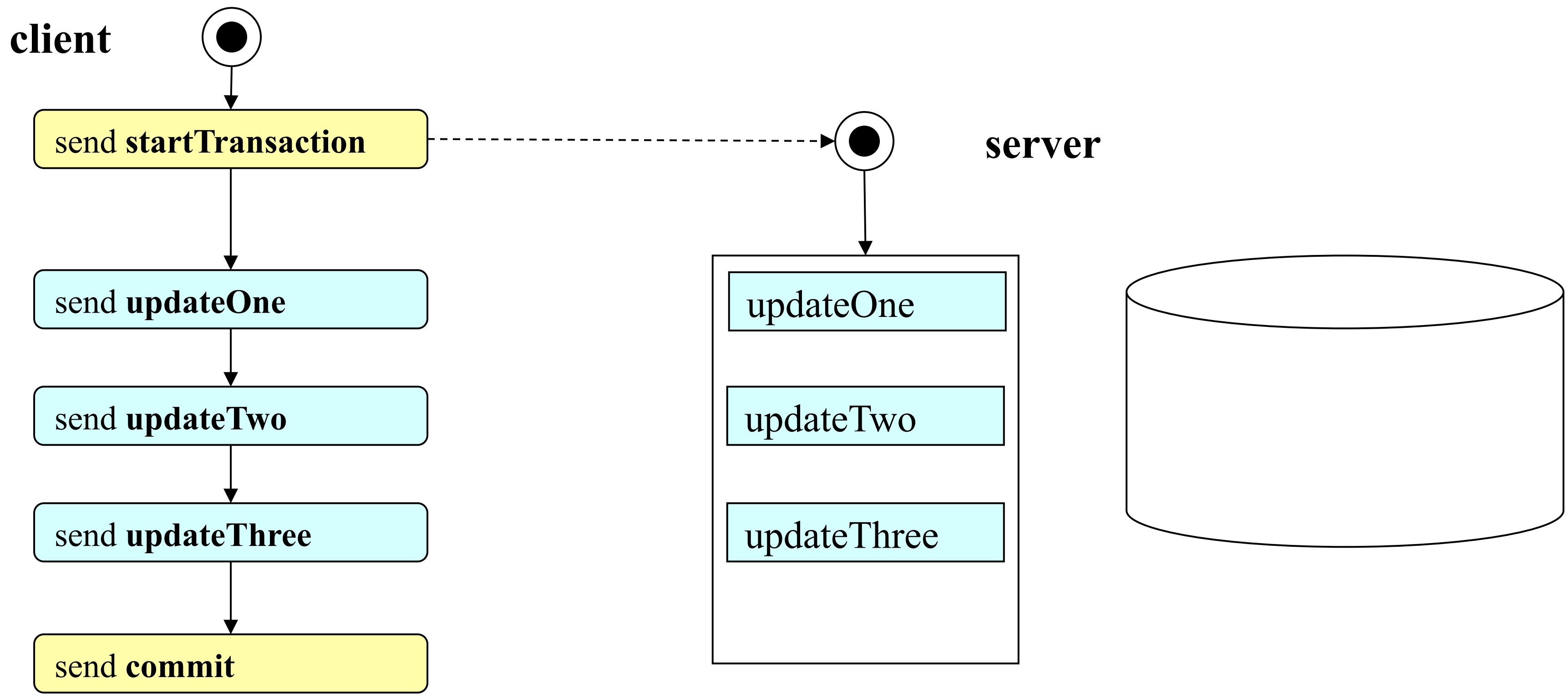
What’s Good About Leases?

- The resource manager controls access centrally
  - So we don’t need to keep multiple copies of a lock up to date
  - Remember, easiest to synchronize updates to data if only one party can write it
- The manager uses his own clock for leases
  - So we don’t need to synchronize clocks
- What if a lease holder dies, losing its lease?
  - No big deal, the lease would expire eventually

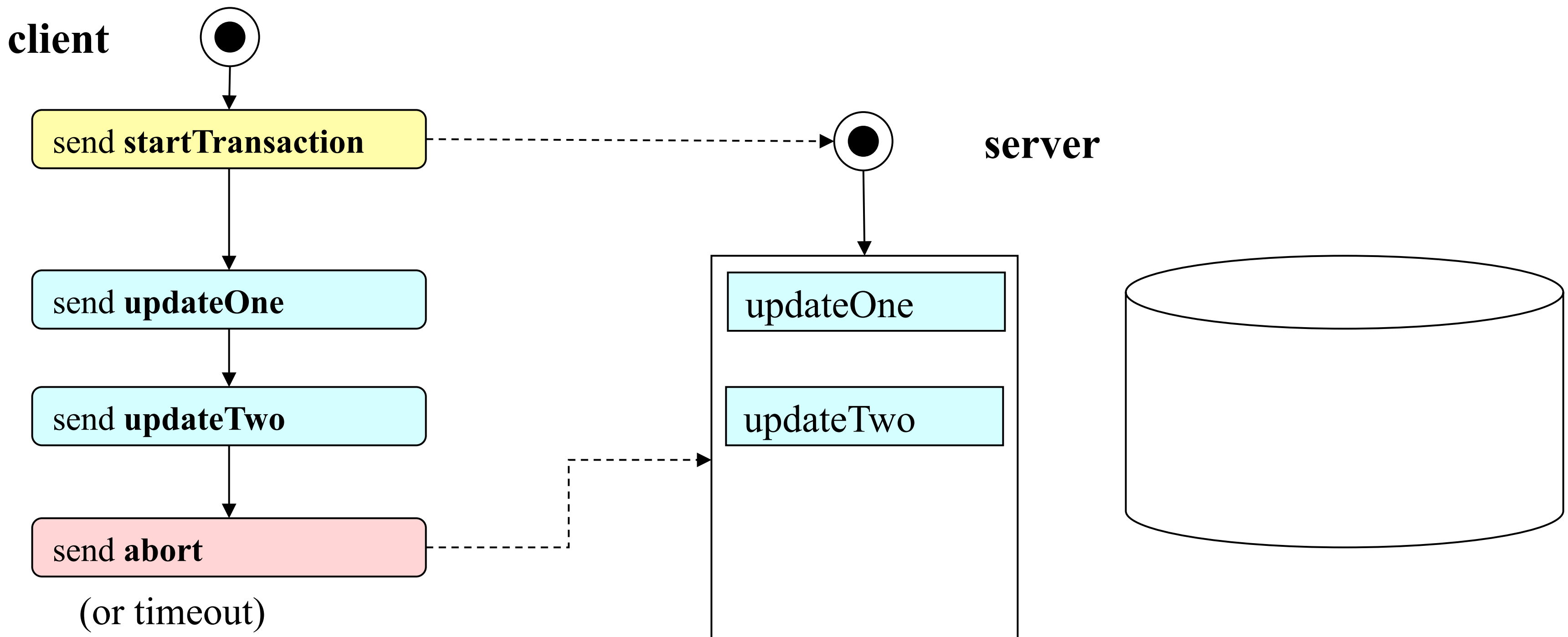
Atomic Transactions

- What if we want guaranteed uninterrupted, all-or-none execution?
- That requires true atomic transactions
- Solves multiple-update race conditions
  - All updates are made part of a transaction
    - Updates are accumulated, but not actually made
  - After all updates are made, transaction is committed
  - Otherwise the transaction is aborted
    - E.g., if client, server, or network fails before the commit
- Resource manager guarantees "all-or-none"
  - Even if it crashes in the middle of the updates

Atomic Transaction Example



What If There's a Failure?



Providing Transactions

- Basic mechanism is a *journal*
- Don't actually perform operations as they are submitted
- Instead, save them in a journal
- On commit, first write the journal to persistent storage
  - This is true commit action
- Then run through journal and make updates
- Some obvious complexities

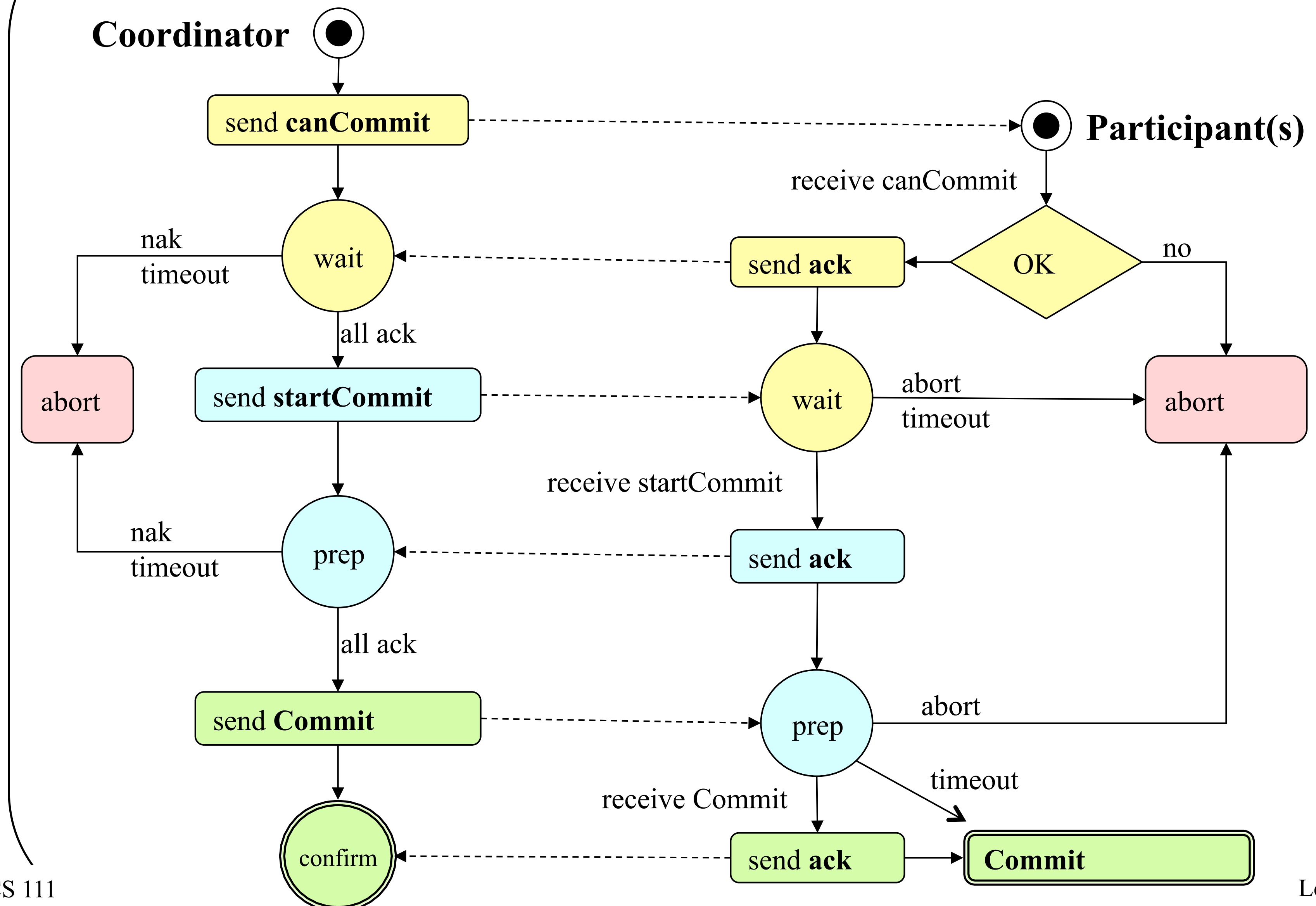
Transactions Spanning Multiple Machines

- Journals are fine if the data is all on one resource manager
- What if we need to atomically update data on multiple machines?
- Just keeping a journal on one machine is not enough
- How do we achieve the all-or-nothing effect when each machine acts asynchronously?
  - And can fail at any moment?

Commitment Protocols

- Used to implement distributed commitment
  - Provide for atomic all-or-none transactions
  - Simultaneous commitment on multiple hosts
- Challenges
  - Asynchronous conflicts from other hosts
  - Nodes fail in the middle of the commitment process
- Multi-phase commitment protocol:
  - Confirm no conflicts from any participating host
  - All participating hosts are told to prepare for commit
  - All participating hosts are told to “make it so”

Three Phase Commit



Why Three Phases?

- There's a two phase commit protocol, too
- Why two phases to prepare to commit?
  - The first phase asks whether there are conflicts or other problems that would prevent a commitment
  - If problems exist, we won't even attempt commit
  - The second phase is only entered if all nodes agree that commitment is possible
  - It is the actual "prepare to commit"
  - Acknowledgement of which means that all nodes are really ready to commit

Distributed Consensus

- Achieving simultaneous, unanimous agreement
  – Even in the presence of node & network failures
  – Requires agreement, termination, validity, integrity
  – Desired: bounded time
- Consensus algorithms tend to be complex
  – And may take a long time to converge
- So they tend to be used sparingly
  – E.g., use consensus to elect a leader
  – Who makes all subsequent decisions by fiat

A Typical Election Algorithm

1. Each interested member broadcasts his nomination
2. All parties evaluate the received proposals according to a fixed and well known rule
   – E.g., largest ID number wins
3. After a reasonable time for proposals, each voter acknowledges the best proposal it has seen
4. If a proposal has a majority of the votes, the proposing member broadcasts a resolution claim
5. Each party that agrees with the winner's claim acknowledges the announced resolution
6. Election is over when a quorum acknowledges the result

Cluster Membership

- A *cluster* is a group of nodes …
  - All of whom are in communication with one another
  - All of whom agree on an elected cluster master
  - All of whom abide by the cluster master’s decisions
    - He may (centrally) arbitrate all issues directly
    - He may designate other nodes to make some decisions
- Useful idea because it formalizes set of parties who are working together
- Highly available service clusters
  - Cluster master assigns work to all of the other nodes
  - If a node falls out of the cluster, its work is reassigned

Maintaining Cluster Membership

- Primarily through *heartbeats*
- "I'm still alive" messages, exchanged in cluster
- Cluster master monitors the other nodes
  - Regularly confirm each node is working properly
  - Promptly detect any node falling out of the cluster
  - Promptly reassign work to surviving nodes
- Some nodes must monitor the cluster master
  - To detect the failure of the cluster master
  - To trigger the election of a new cluster master

The Split Brain Problem

- What if the participating nodes are partitioned?
- One set can talk to each other, and another set can also
  - But the two sets can’t exchange messages
- We then have two separate clusters providing the same service
  - Which can lead to big problems, depending on the situation

Quorums

- The simplest solution to the split-brain problem is to require a *quorum*
  – In a cluster that has been provisioned for N nodes, becoming the cluster master requires (N/2)+1 votes
  – This completely prevents split-brain
    - It also prevents recovering from the loss of N/2 nodes
- Some systems use a "quorum device"
  – E.g., a shared (multi-ported) disk
    - Cluster master must be able to reserve/lock this device
    - Device won't allow simultaneous locking by two different nodes
  – Failure of this device takes down whole system
- Some systems use special election hardware

Conclusion

- Networking has become a vital service for most machines
- The operating system is increasingly involved in networking
  - From providing mere access to a network device
  - To supporting sophisticated distributed systems
- An increasing trend
- Future OSes might be primarily all about networking