Loosely Coupled Systems

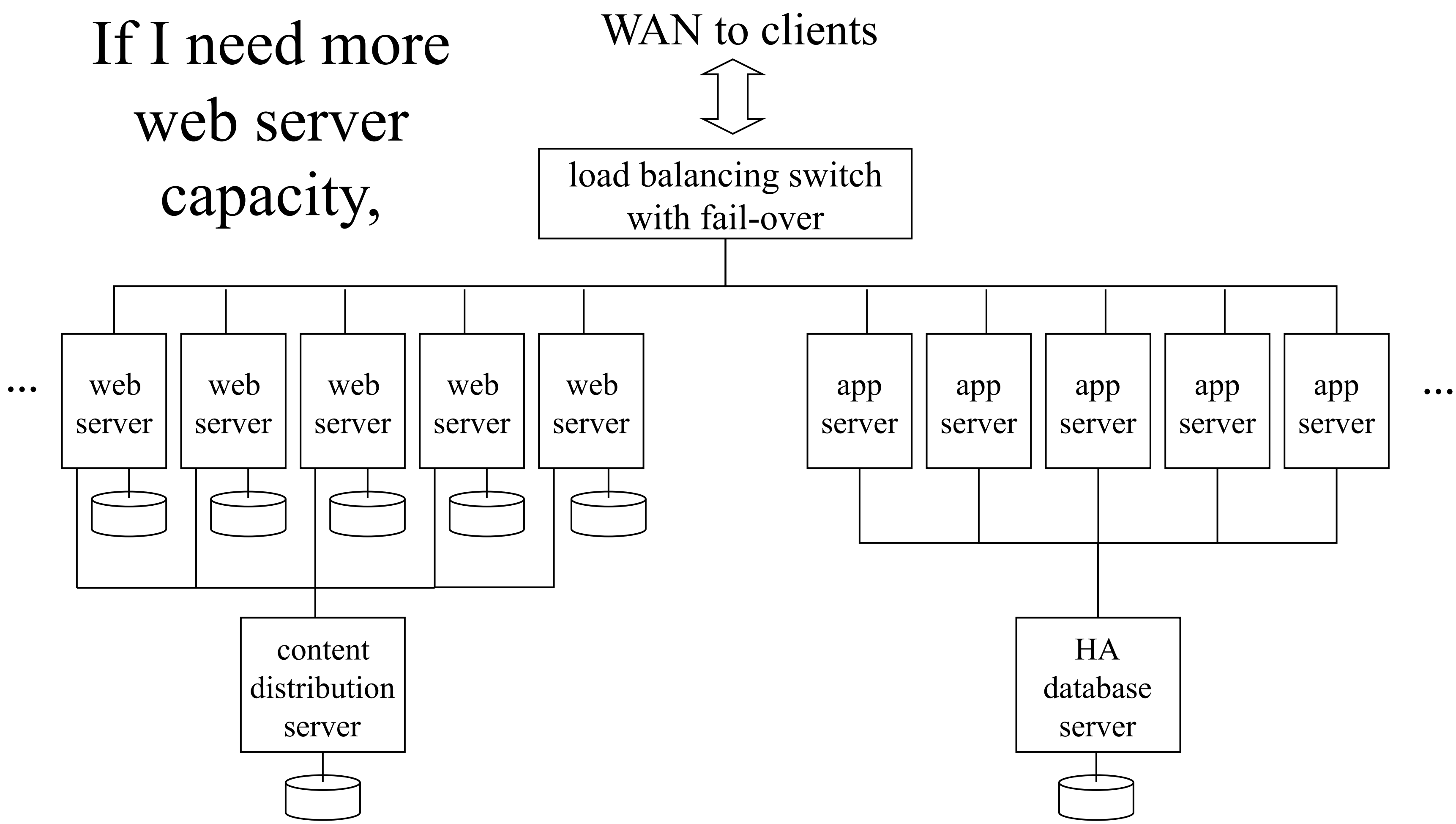
- Characterization:
  - A parallel group of independent computers
  - Serving similar but independent requests
  - Minimal coordination and cooperation required
- Motivation:
  - Scalability and price performance
  - Availability – if protocol permits stateless servers
  - Ease of management, reconfigurable capacity
- Examples:
  - Web servers, app servers

Horizontal Scalability

- Each node largely independent
- So you can add capacity just by adding a node "on the side"
- Scalability can be limited by network, instead of hardware or algorithms
  - Or, perhaps, by a load balancer
- Reliability is high
  - Failure of one of N nodes just reduces capacity

Horizontal Scalability Architecture

If I need more web server capacity,



Elements of Loosely Coupled Architecture

- Farm of independent servers
  - Servers run same software, serve different requests
  - May share a common back-end database
- Front-end switch
  - Distributes incoming requests among available servers
  - Can do both load balancing and fail-over
- Service protocol
  - Stateless servers and idempotent operations
  - Successive requests may be sent to different servers

Horizontally Scaled Performance

- Individual servers are very inexpensive
  - Blade servers may be only $100-$200 each
- Scalability is excellent
  - 100 servers deliver approximately 100x performance
- Service availability is excellent
  - Front-end automatically bypasses failed servers
  - Stateless servers and client retries fail-over easily
- The challenge is managing thousands of servers
  - Automated installation, global configuration services
  - Self monitoring, self-healing systems
  - Scaling limited by management, not HW or algorithms

What About the Centralized Resources?

- The load balancer appears to be centralized
- And what about the back-end databases?
- Are these single points of failure for this architecture?
- And also limits on performance?
- Yes, but . . .

Handling the Limiting Factors

- The centralized pieces can be special hardware
  - There are very few of them
  - So they can use aggressive hardware redundancy
    - Expensive, but only for a limited set
  - They can also be high performance machines
- Some of them have very simple functionality
  - Like the load balancer
- With proper design, their roles can be minimized, decreasing performance problems

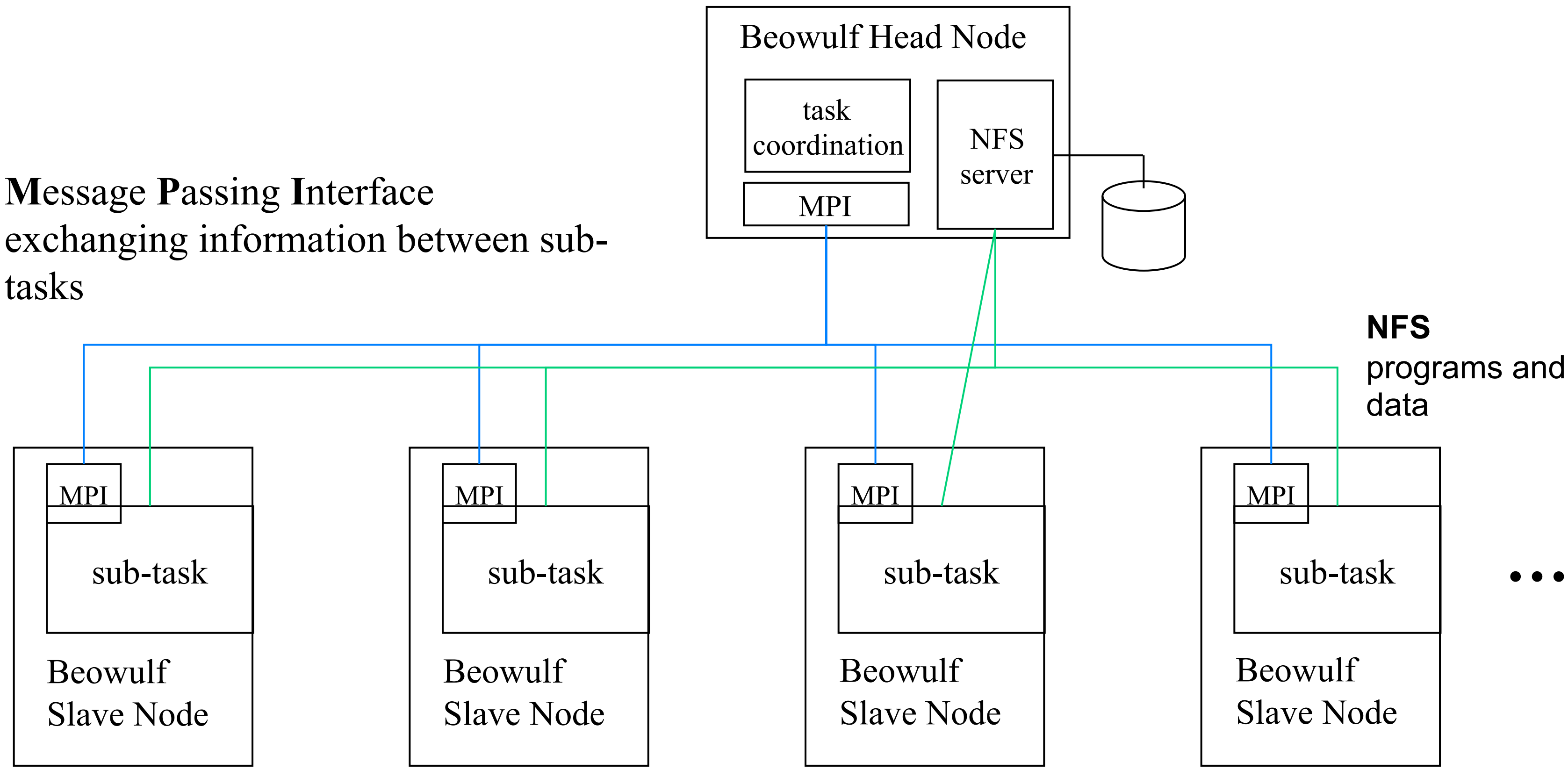
Limited Transparency Clusters

- Single System Image clusters had problems
  - All nodes had to agree on state of all objects
  - Lots of messages, lots of complexity, poor scalability
- What if they only had to agree on a few objects?
  - Like cluster membership and global locks
  - Fewer objects, fewer operations, much less traffic
  - Objects could be designed for distributed use
    - Leases, commitment transactions, dynamic server binding
- Simpler, better performance, better scalability
  - Combines best features of SSI and horizontally scaled loosely coupled systems

Example: Beowulf Clusters

- A technology for building high performance parallel machines out of commodity parts
- One server machine controlling things
- Lots of pretty dumb client machines handling processing
- A LAN technology connecting them
  - Standard message passing between machines
- Applications must be written for parallelization

Beowulf High Performance Computing Cluster



There is no effort at transparency here. Applications are specifically written for a parallel execution platform and use a Message Passing Interface to mediate exchanges between cooperating computations.

Cloud Computing

- The most recent twist on distributed computing
- Set up a large number of machines all identically configured
- Connect them to a high speed LAN
  - And to the Internet
- Accept arbitrary jobs from remote users
- Run each job on one or more nodes
- Entire facility probably running mix of single machine and distributed jobs, simultaneously

Distributed Computing and Cloud Computing

- In one sense, these are orthogonal
- Each job submitted might or might not be distributed
- Many of the hard problems of the distributed ones are the user's problem, not the system's
  - E.g., proper synchronization and locking
- But the cloud facility must make communications easy

What Runs in a Cloud?

- In principle, anything
- But general distributed computing is hard
- So much of the work is run using special tools
- These tools support particular kinds of parallel/distributed processing
- Either embarrassingly parallel jobs
- Or those using a method like map-reduce
- Things where the user need not be a distributed systems expert

Embarrassingly Parallel Jobs

- Problems where it's really, really easy to parallelize them
- Probably because the data sets are easily divisible
- And exactly the same things are done on each piece
- So you just parcel them out among the nodes and let each go independently
- Everyone finishes at more or less same time

The Most Embarrassing of Embarrassingly Parallel Jobs

- Say you have a large computation
- You need to perform it N times, with slightly different inputs each time
- Each iteration is expected to take the same time
- If you have N cloud machines, write a script to send one of the N jobs to each
- You get something like N times speedup

Map-Reduce

- A computational technique for performing operations on large quantities of data
- Basically:
  - Divide the data into pieces
  - Farm each piece out to a machine
  - Collect the results and combine them
- For example, searching a large data set for occurrences of a phrase
- Originally developed by Google

Map-Reduce in Cloud Computing

- A master node divides the problem among N cloud machines
- Each cloud machine performs the map operation on its data set
- When all complete, the master performs the reduce operation on each node's results
- Can be divided further
  - E.g., a node given a piece of a problem can divide it into smaller pieces and farm those out
  - Then it does a reduce before returning to its master

Do-It-Yourself Distributed Computing in the Cloud

- Generally, you can submit any job you want to the cloud
- If you want to run a SSI or horizontally scaled loosely coupled system, be their guest
  - Assuming you pay, of course
- They'll offer basic system tools
- You'll do the distributed system heavy lifting
- Wouldn't it be nice if you had some middleware to help . . . ?

Distribution at the Application Level

- This course has focused on the OS as a "platform"
  - OS services have evolved to meet application needs
  - SMP creates a scalable distributed OS platform
  - SSI clusters are a robust distributed OS platform
- There are limitations to such a platform
  - Architectural limitations on scalability
  - A legacy of single-system semantics
  - Heterogeneity is a fundamental fact of life
- Who said "applications must be written to an OS?"
  - Perhaps there are other, more suitable, platforms

A Different Paradigm

- We tried to make remote services appear local
  - This failed for the reasons that Deutch laid out
- We don't want to distinguish local from remote
  - Doing so is awkward, constraining, and poor abstraction
- What's our other option?
- What if we made all services seem remote?

Embracing Remote Services

- Design interactions for remote services
- Provide:
  - Discovery
  - Rendezvous
  - Leases
  - Rebinding
  - And other features to deal with Deutsch's fallacies
- And then provide efficient local implementations
  - Minimizing performance penalty for local resources

Alternatives to Distributed Operating Systems

- Network aware applications
  - That register themselves with network name services
  - Exchange services by sending messages
  - Monitor the comings and goings of their partners
- Distributed middleware
  - To provide convenient, distributed objects and services
  - Examples:
    - Platforms: RPC, COM/.NET, Java Beans
    - Environments: Erlang, Rational Rose, Ruby on Rails
    - Services: TIBCO pub/sub messaging

RPC As an Underlying Paradigm

- Procedure calls are already a fundamental paradigm
  - Primary unit of computation in most languages
  - Unit of information hiding in most methodologies
  - Primary level of interface specification
- RPC is a natural boundary between client and server
  - Turn procedure calls into message send/receives
- A few limitations
  - No implicit parameters/returns (e.g., global variables)
  - No call-by-reference parameters
  - Much slower than procedure calls (TANSTAAFL)
  - Partial failure far more likely than local procedure calls

Key Features of RPC

- Client application links against local procedures
  – Calls local procedures, gets results
- All RPC implementation is inside those procedures
- Client application does not know about RPC
  – Does not know about formats of messages
  – Does not worry about sends, timeouts, resents
  – Does not know about external data representation
- All of this is generated automatically by RPC tools
  – Canonical versions of converting calls to messages
- The key to the tools is the interface specification

Objects – Another Key Paradigm

- Not inherently distributed, but . . .
- A dominant application development paradigm
- Good interface/implementation separation
  - All we can know about object is through its methods
  - Implementation and private data opaquely encapsulated
- Powerful programming model
  - Polymorphism ... methods adapt themselves to clients
  - Inheritance ... build complex objects from simple ones
  - Instantiation ... trivial to create distinct object instances
- Objects are not intrinsically location sensitive
  - You don’t reference them, you call them

Local Objects and Distributed Computing

- Local objects are supported by compilers, inside an address space
  - Compiler generates code to instantiate new objects
  - Compiler generates calls for method invocations
- This doesn't work in a distributed environment
  - All objects are no longer in a single address space
  - Different machines use different binary representations
  - You can’t make a call across machine boundaries

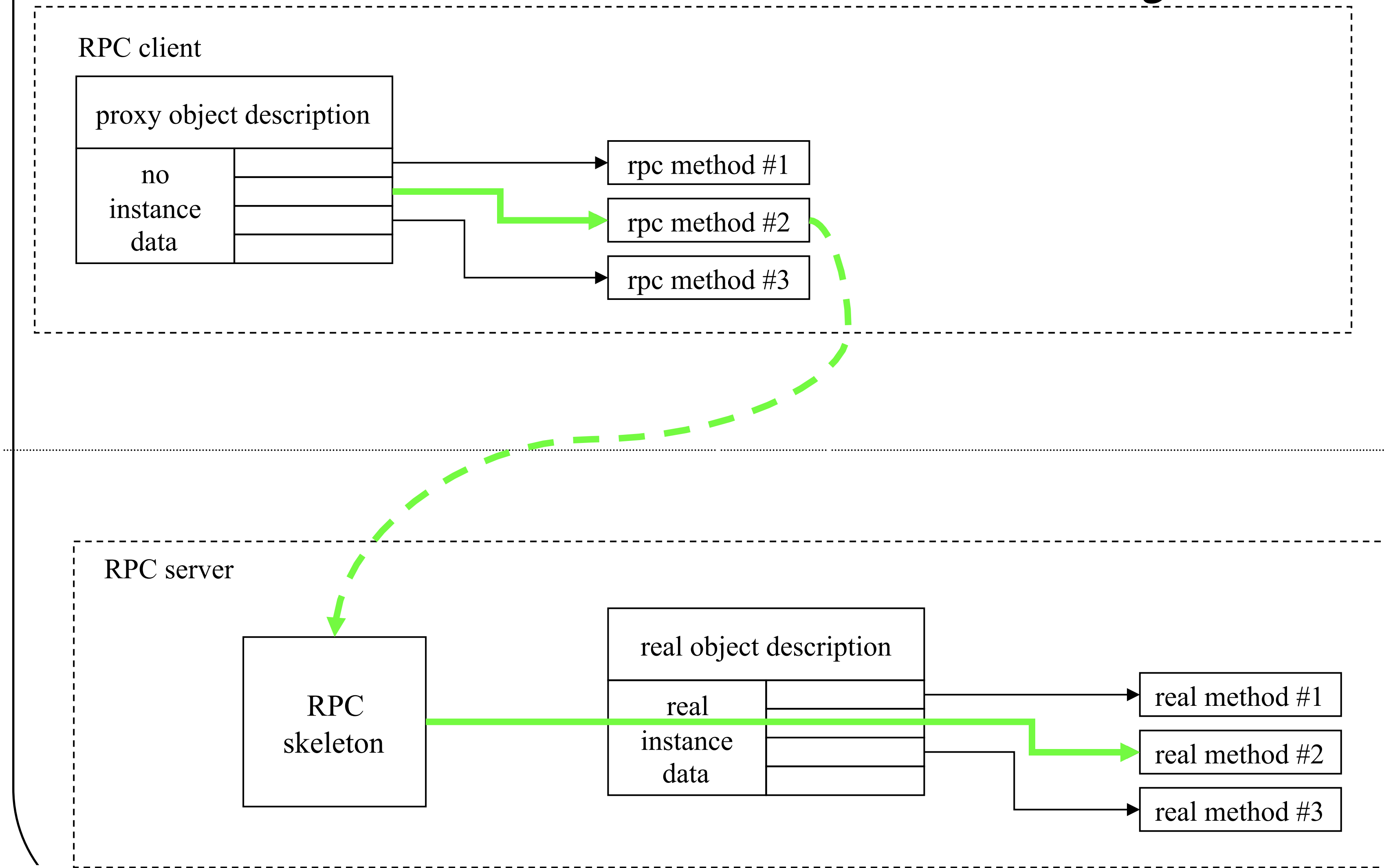
Merging the Paradigms

- Implement method calls with RPC, instead of local procedure calls
- The concept of an object hides what's inside, anyway
  - You shouldn't use global variables and calls by reference with them, anyway
- The mechanics are a bit more complicated than simply RPC, though

Invoking Remote Object Methods

- Compile OO program with proxy object implementation
  - Defines the same interface (methods and properties)
  - All method invocations go through the local proxy
- Local implementation is proxy for remote server
  - Translate parameters into a standard representation
  - Send request message to remote object server
  - Get response and translate it to local representation
  - Return result to caller
- Client cannot tell that object is not local

Proxies for Distributed Objects



Dynamic Object Binding

- How can we compile to a binary when some of the objects (and their implementations) are remote?
- Local objects are compiled into an application and are fully known at compile time
- Distributed objects must be bound at some later time
- These objects are provided by servers
  - The available servers change from minute to minute
  - New object classes can be created in real time
  - So the "later time" is run time
- We need a run-time object "match-maker"
  - Like DLLs on steroids

Object Request Brokers (ORBs)

- ORBs are the matchmakers
- A local portal to the domain of available objects
- A registry for available object implementations
  - Object implementers register with the broker
- Meeting place for object clients and implementers
  - Clients go to broker to obtain services of new objects
- A local interface to remote object components
  - Clients reference all remote objects through local ORB
- A router between local and remote requests
  - ORBs pass messages between clients and servers
- A repository for object interface definitions

But Still TANSTAAFL

- Moving distribution out of OS doesn't change the fact that distributed computing is complex
- It avoids having to ensure that everything local is invisibly distributed
- But those remote application-level objects still:
  - Need synchronization
  - Need to reach consensus
  - Need to handle partial failures
- Advantage is you can customize it to your needs

Evolution of System Services

- Operating systems started out on single computers
  - This biased the definition of system services
- Networking was added on afterwards
  - Some system services are still networking-naïve
  - New APIs were required to exploit networking
  - Many applications remained networking-impaired
- New programming paradigms embrace the network
  - Focus on services and interfaces, not implementations
  - Goal is to make distributed applications easier to write
- Increasingly, system services offered by the network

The Changing Role of Operating Systems

- Traditionally, operating systems:
  - Abstracted heterogeneous hardware into useful services
  - Managed system resources for user-mode processes
  - Ensured resource integrity and trusted resource sharing
  - Provided a powerful platform for application developers
- Now,
  - The notion of a self-contained system is fading
  - New programming platforms:
    - Are instruction set and operating system independent
    - Encompass and embrace distributed computing
    - Provide much higher level objects and services
- But they still depend on powerful underlying operating systems

Distributed Systems - Summary

- Different distributed system models support:
  - Different degrees of transparency
    - Do applications see a network or single system image?
  - Different degrees of coupling
    - Making multiple computers cooperate is difficult
    - Doing it without shared memory is even worse
- Distributed systems always face a trade-off between performance, independence, and robustness
  - Cooperating redundant nodes offer higher availability
  - Communication and coordination are expensive
  - Mutual dependency creates more modes of failure