Operating Systems Principles

Advanced Architectures

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Advanced Architectures

Goals of Distributed Computing

- better services
  - scalability
    - apps too big to run on a single computer
    - grow system capacity to meet growing demand
  - improved reliability and availability
  - improved ease of use, reduced CapEx/OpEx
- new services
  - applications that span multiple system boundaries
  - global resource domains, services (vs. systems)
  - complete location transparency

Major Classes of Distributed Systems

- Symmetric Multi-Processors (SMP)
  - multiple CPUs, sharing memory and I/O devices
- Single-System Image (SSI) & Cluster Computing
  - a group of computers, acting like a single computer
- loosely coupled, horizontally scalable systems
  - coordinated, but relatively independent systems
- application level distributed computing
  - peer-to-peer, application level protocols
  - distributed middle-ware platforms

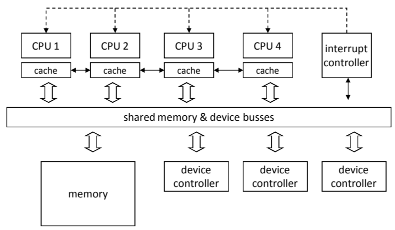
Evaluating Distributed Systems

- Performance
  - overhead, scalability, availability
- Functionality
  - adequacy and abstraction for target applications
- Transparency
  - compatibility with previous platforms
  - scope and degree of location independence
- Degree of Coupling
  - on how many things do distinct systems agree
  - how is that agreement achieved

SMP systems and goals

- Characterization:
  - multiple CPUs sharing memory and devices
- Motivations:
  - price performance (lower price per MIP)
  - scalability (economical way to build huge systems)
  - perfect application transparency
- Example:
  - single socket, multi-core Intel CPUs

Symmetric Multi-Processors



SMP Price/Performance

- a computer is much more than a CPU
  - mother-board, disks, controllers, power supplies, case
  - CPU might cost 10-15% of the cost of the computer
- adding CPUs to a computer is very cost-effective
  - a second CPU yields cost of 1.1x, performance 1.9x
  - a third CPU yields cost of 1.2x, performance 2.7x
- same argument also applies at the chip level
  - making a machine twice as fast is ever more difficult
  - adding more cores to the chip gets ever easier
- massive multi-processors are obvious direction

SMP Operating System Design

- one processor boots with power on
  - it controls the starting of all other processors
- same OS code runs in all processors
  - one physical copy in memory, shared by all CPUs
- Each CPU has its own registers, cache, MMU
  - they must cooperatively share memory and devices
- ALL kernel operations must be Multi-Thread-Safe
  - protected by appropriate locks/semaphores
  - very fine grained locking to avoid contention

SMP Parallelism

- scheduling and load sharing
  - each CPU can be running a different process
  - just take the next ready process off the run-queue
  - processes run in parallel
  - most processes don't interact (other than in kernel)
- serialization
  - mutual exclusion achieved by locks in shared memory
  - locks can be maintained with atomic instructions
  - spin locks acceptable for VERY short critical sections
  - if a process blocks, that CPU finds next ready process

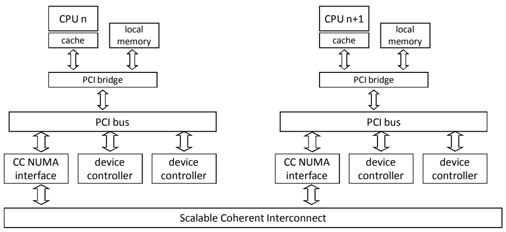
The Challenge of SMP Performance

- scalability depends on memory contention
  - memory bandwidth is limited, can't handle all CPUs
  - most references satisfied from per-core cache
  - if too many requests go to memory, CPUs slow down
- scalability depends on lock contention
  - waiting for spin-locks wastes time
  - context switches waiting for kernel locks waste time
- contention wastes cycles, reduces throughput
  - 2 CPUs might deliver only 1.9x performance
  - 3 CPUs might deliver only 2.7x performance

Managing Memory Contention

- Fast n-way memory is <u>very</u> expensive
  - without it, memory contention taxes performance
  - cost/complexity limits how many CPUs we can add
- Non-Uniform Memory Architectures (NUMA)
  - each CPU has its own memory
    - each CPU has fast path to its own memory
  - connected by a Scalable Coherent Interconnect
    - a <u>very fast</u>, <u>very local</u> network between memories
    - accessing memory over the SCI may be 3-20x slower
  - these interconnects can be highly scalable

Non-Uniform Memory Architecture Symmetric Multi-Processors



OS design for NUMA systems

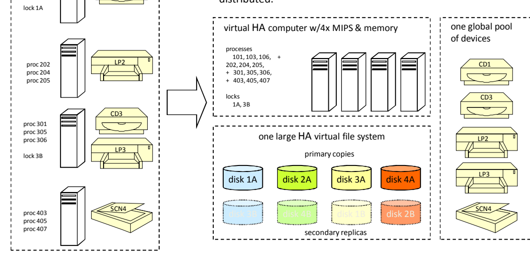
- it is all about local memory hit rates
  – every outside reference costs us 3-20x performance
  – we need 75-95% hit rate just to break even
- How can the OS ensure high hit-rates?
  – replicate shared code pages in each CPU's memory
  – assign processes to CPUs, allocate all memory there
  – migrate processes to achieve load balancing
  – spread kernel resources among all the CPUs
  – attempt to preferentially allocate local resources
  – migrate resource ownership to CPU that is using it

Single System Image (SSI) Clusters

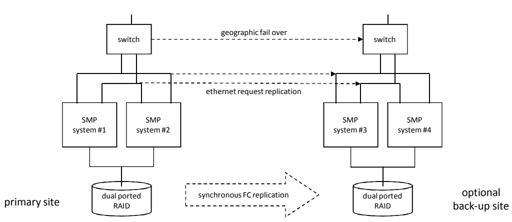
- Characterization:
  – a group of seemingly independent computers collaborating to provide SMP-like transparency
- Motivation:
  – higher reliability, availability than SMP/NUMA
  – more scalable than SMP/NUMA
  – excellent application transparency
- Examples:
  – Locus, Sun Clusters, MicroSoft Wolf-Pack, OpenSSI
  – enterprise database servers

The Dream

Programs don't run on hardware, they run atop operating systems. All the resources that processes see are already virtualized. Instead of merely virtualizing all the resources in a single system, virtualize all the resources in a cluster of systems. Applications that run in such a cluster are (automatically and transparently) distributed.

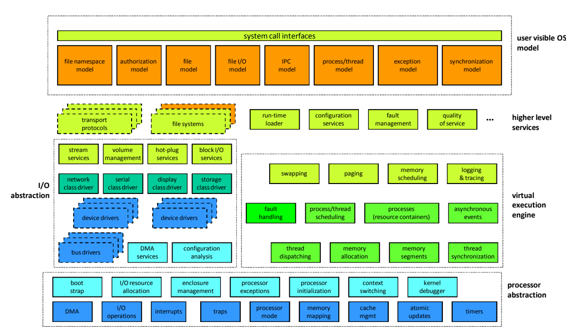


Modern Clustered Architecture



Active systems service independent requests in parallel. They cooperate to maintain shared global locks, and are prepared to take over partner's work in case of failure. State replication to a back-up site is handled by external mechanisms.

Structure of a Modern OS



OS design for SSI clustering

- all nodes agree on the state of all OS resources
  - file systems, processes, devices, locks IPC ports
  - any process can operate on any object, transparently
- they achieve this by exchanging messages
  - advising one-another of all changes to resources
    - each OS's internal state mirrors the global state
  - request execution of node-specific requests
    - node-specific requests are forwarded to owning node
- implementation is large, complex, difficult
- the exchange of messages can be very expensive

SSI Clustered Performance

- clever implementation can minimize overhead
  - 10-20% overall is not uncommon, can be much worse
- complete transparency
  - even very complex applications "just work"
  - they do not have to be made "network aware"
- good robustness
  - when one node fails, others notice and take-over
  - often, applications won't even notice the failure
- nice for application developers and customers
  - but they are complex, and not particularly scalable

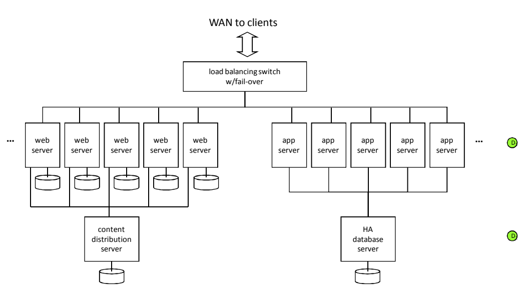
Lessons Learned

- consensus protocols are expensive
  - they converge slowly and scale poorly
- systems have a great many resources
  - resource change notifications are expensive
- location transparency encouraged non-locality
  - remote resource use is much more expensive
- a greatly complicated operating system
  - distributed objects are more complex to manage
  - complex optimizations to reduce the added overheads
  - new modes of failure w/complex recovery procedures

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, Google search farm, Hadoop

Horizontal Scalability w/HA



(elements of architecture)

- farm of independent servers
  - servers run same software, serve different requests
  - may share a common back-end database
- front-ending 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

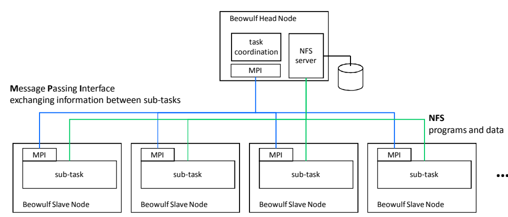
Limited Transparency Clusters

- 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

Limited LocationTransparency

- what things look the same as local?
  - remote file systems
  - remote terminal sessions, X sessions
  - remote procedure calls
- what things don't look the same as local?
  - primitive synchronization (e.g. mutexes)
  - basic Inter-Process Communication (e.g. signals)
  - process create, destroy, status, authorization
  - Accessing devices (e.g. tape drives)

Loosely Coupled Scalability
(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.

Distributed Systems – Summary

- 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
- performance vs. independence vs. robustness
  - cooperating redundant nodes offer higher availability
  - communication and coordination are expensive
  - mutual-dependency creates more modes of failure

Clouds: Applied Horizontal Scalability

- Many servers, continuous change
  - dramatic fluctuations in load volume and types
  - continuous node additions for increased load
  - nodes and devices are failing continuously
  - continuous and progressive s/w updates
- Most services delivered via switched HTTP
  - clients/server communication is over WAN links
  - large (whole file) transfers to optimize throughput
  - switches route requests to appropriate servers
  - heavy reliance on edge caching

Geographic Disaster Recovery

- Cloud reliability/availability are key
  - one data center serves many (10^3-10^7) clients
- Local redundancy can only provide 4-5 nines
  - fires, power and communications disruptions
  - regional scale (e.g. flood, earthquake) disasters
- Data Centers in distant Availability Zones
  - may be running active/active or active/stand-by
  - key data is replicated to multiple data centers
  - traffic can be redirected if a primary site fails

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WAN-Scale Replication

- WAN-scale mirroring is slow and expensive
  - much slower than local RAID or network mirroring
- Synchronous Mirroring
  - each write must be ACKed by remote servers
- Asynchronous Mirroring
  - write locally, queue for remote replication
- Mirrored Snapshots
  - writes are local, snapshots are mirrored
- Fundamental tradeoff: reliability vs. latency

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WAN-Scale Consistency

- CAP theorem - it is not possible to assure:
  - Consistency (all readers see the same result)
  - Availability (bounded response time)
  - Partition Tolerance (survive node failures)
- ACID databases sacrifice partition tolerance
- BASE semantics make a different trade-off
  - Basic Availability (most services most of the time)
  - Soft state (there is no global consistent state)
  - Eventual consistency (changes propagate, slowly)

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Dealing with Eventual Consistency

- distributed system has no single, global state
  - state updates are not globally serialized events
  - different nodes may have different opinions
- expose the inconsistencies to the applications
  - ask the cloud, receive multiple answers
  - let each application reconcile the inconsistencies
- BASE semantics are neither simple nor pretty
  - they embrace parallelism and independence
  - they reflect the complexity of distributed systems

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Distributed Computing Reformation

- systems must be more loosely coupled
  - tight coupling is complex, slow, and error-prone
  - move towards coordinated independent systems
- move away from old single system APIs
  - local objects and services don't generalize
  - services are obtained through messages (or RPCs)
  - in-memory objects, local calls are a special case
- embrace the brave new (distributed) world
  - topology and partnerships are ever-changing
  - failure-aware services (commits, leases, rebinds)
  - accept distributed (e.g. BASE) semantics

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Changing Architectural Paradigms

- a "System" is a collection of services
  - interacting via stable and standardized protocols
  - implemented by app software deployed on nodes
- Operating Systems
  - manage the hardware on which the apps run
  - implement the services/ABIs the apps need
- The operating system is a platform
  - upon which higher level software can be built
  - goodness is measured by how well it does that job

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What Operating Systems Do

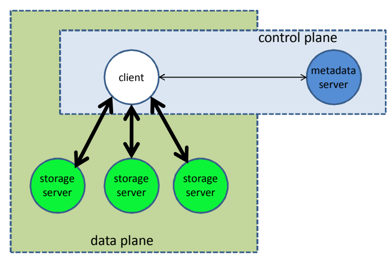
- Originally (and at the start of this course)
  - abstract heterogeneous hardware into useful services
  - manage system resources for user-mode processes
  - ensure resource integrity and trusted resource sharing
  - provide a powerful platform for developers
- None of this has changed, but …
  - notion of a self-contained system becoming obsolete
  - hardware and OS heterogeneity is a given
  - most important interfaces are higher level protocols
- Operating Systems continue to evolve as
  - new applications demand new services
  - new hardware must be integrated and exploited

Final Exam (Mon 6/6)

- Location: Humanities A51
- Part 1: 11:30-13:00
  - 10 questions, similar to mid-term
  - covering weeks 6-10
- Part 2: 13:00-14:30
  - 6 hard questions, choose any 3 to answer
    - real problems: analyze, explain, propose approach
    - questions not answered in reading or lecture
  - covering the entire course

Supplementary Slides

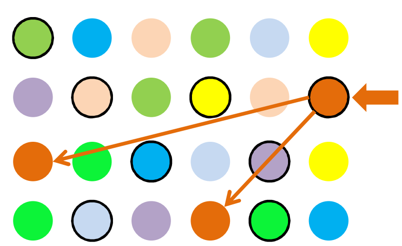
Control and Data Planes



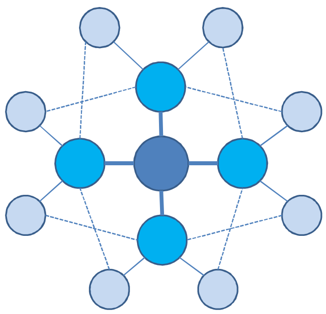
Scalability: Cluster Protocols

- Consensus protocols do not scale well
  - they only work for small numbers of nodes
- Minimize number of consensus operations
  - elect a single master who makes decisions
  - partitioned and delegated responsibility
- Avoid large-consensus/transaction groups
  - partition work among numerous small groups
- Avoid high communications fan-in/fan-out
  - hierarchical information gathering/distribution

Small Transaction Clusters



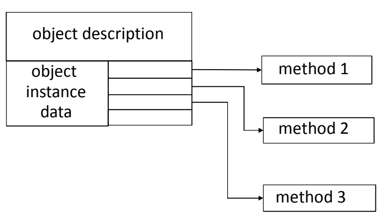
Hierarchical Communication Structure



Paradigm – Objects

- dominant application development paradigm
- good interface/implementation separation
  - all we can know about object is through its methods
  - implementation and private data opquely 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

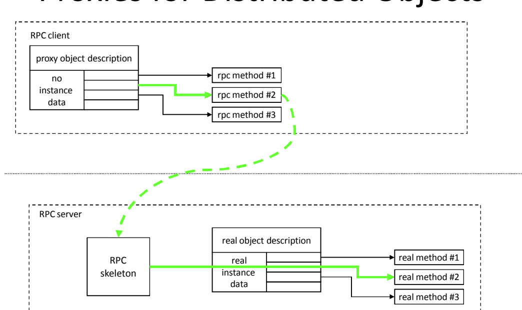
Simple Local Objects



Objects – Local vs. Distributed

- local objects
  - 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
  - method invocation is done via message exchange

Proxies for Distributed Objects



(invoking remote object methods)

- program compiles 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

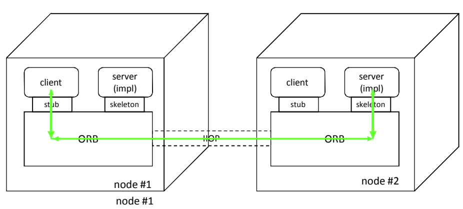
Dynamic Object Binding

- local objects are compiled into an application
  - the compiler "knows" about all available objects
  - there is no need to "discover" their implementations
- distributed objects are provided by servers
  - the available servers change from minute to minute
  - new object classes can be created in real time
- we need a run-time object "match-maker"
  - tracks object servers and classes as they come and go
  - matches clients' object requests with available servers (like DLLs on steroids)

Object Request Brokers (ORBs)

- 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

ORBs and Distributed Objects



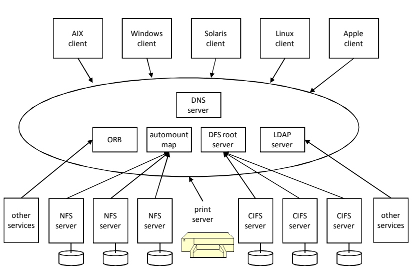
Distributed Applications

- Operating Systems started on single computer
  - this biased the definition of system services
- Networking was added on afterwards
  - some system services are still networking-naive
  - new APIs were required to exploit networking
  - many applications remained networking-impaired
- New programming paradigms embrace network
  - focus on services and interfaces, not implementations
  - goal is to make distributed applications easier to write

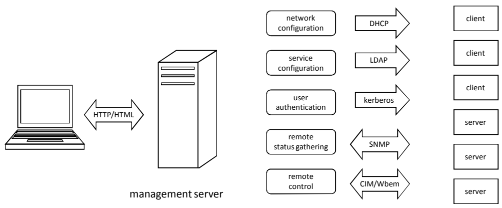
SMP Device I/O

- all processors can access all memory/devices
  - any processor can initiate an I/O operation
    - initiating processor need not be one that requested the I/O
  - any processor can service an I/O interrupt
    - servicing processor need not be one that initiated I/O
- interrupt controller picks which CPU to interrupt
  - dynamic priorities, always interrupt lowest priority CPU
  - fixed binding of some or all interrupts to one CPU
  - automatic round-robin delivery

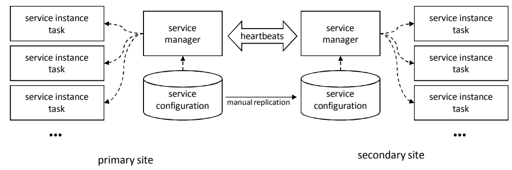
Global Resource View (heterogeneous systems &resources)



Single Point of Management
(for heterogeneous systems)



Loosely Coupled Availability
(Kimberlite HA Linux platforms)



There is global resource view or synchronization of resource state. The systems are completely Independently of one-another, but agree on the division of tasks, and are prepared to take over the partner's work load if he fails.

Internet Inter-ORB Protocol

- different ORBs may have very different goals
  - hard real time, small footprint, very fast local IPC
  - huge numbers of clients, high-availability
- Common Object Request Broker Architecture
  - define standard model for objects and services
- IIOP
  - the common inter-ORB language
  - enable different ORBs to exchange objects/services
  - machine, language, operating system independent