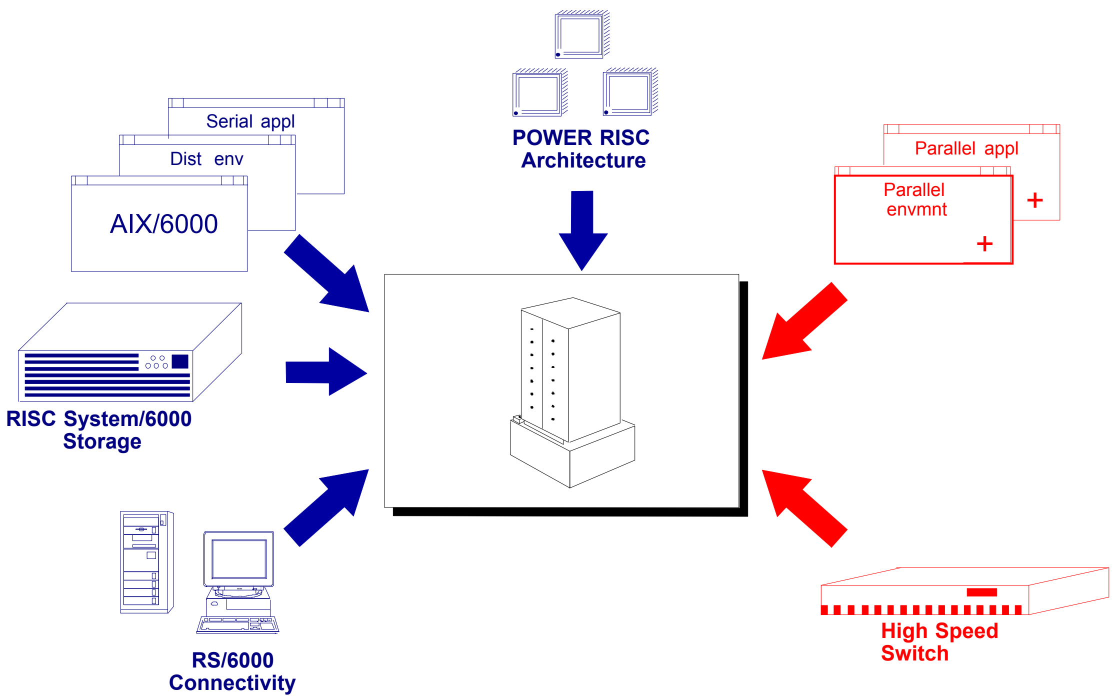
SP Architecture

- Uniprocessor node
  - Power 2 (peak 256 Mflop/s)
- Custom high-performance switch
  - 80 MB/s duplex, usec latency
- Distributed memory architecture
  - single Unix (AIX) kernel per node
- Scalable
  - 2 - 512 nodes
- Successful in the marketplace
  - more than 500 systems sold

Scalable Parallel Computer (a la SP) = Cluster of Workstations +

- Package
- High performance communication subsystem
  - h/w (switch, adapter)
  - s/w (user-space message passing)
- Single system image
  - single point of control (physical - console, and logical - config)
  - global services (system management, job management)
- Parallel operating environment
  - (parallel system interfaces, libraries, tools, compiler)
- High-availability framework
- Application subsystems
  - technical packages
  - commercial subsystems (DB, OLTP, monitor)
- Applications

Building on Workstation technology



Why Commodity Technology

+Necessary in relatively small, cost-conscious market.

+Leverage: lower development cost, time to the market.

+Support sequential loads with no modifications.

+Advantage of standard, open interfaces

+Easier integration of a parallel computer as a server in a network-centric environment, rather than a stand-alone, batch machine.

– Better parallel performance can be achieved by tighter coupling of microprocessor technology, interconnect technology. kernel technology, compiler technology, etc.

"Mostly commodity" approach has created a viable market for clusters and scalable computers today.

As market grows, there is more room for development of specific h/w and s/w

Q: What are the critical custom technologies for scalable computers today and tomorrow?

Scalable Parallel Computer = General Purpose High-End Server

Wide performance range (2w - 512w now)

Configuration flexibility

- Processor, memory, I/O, connectivity,...

Wide range of applications

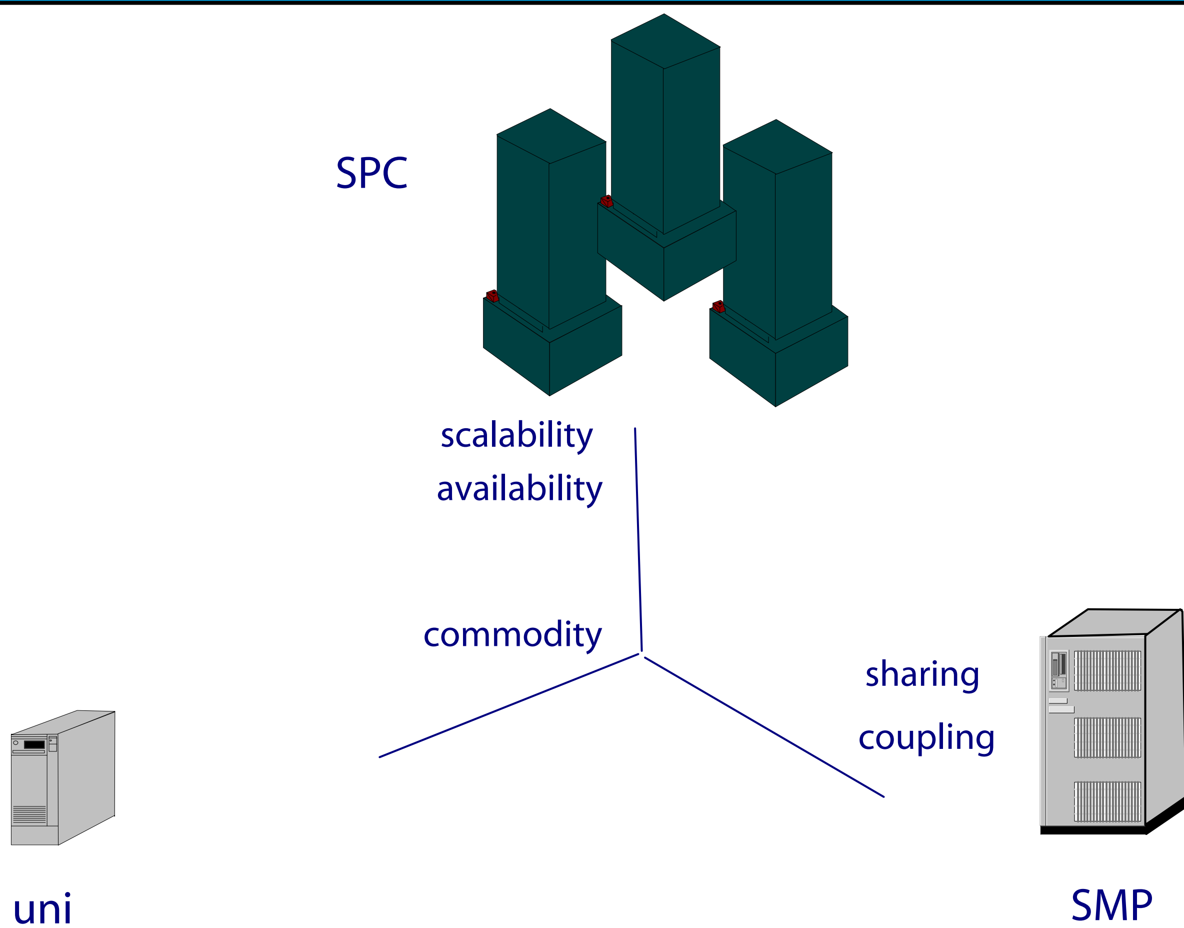
- I/O intensive ("commercial")
- Compute intensive ("technical")
- Communication intensive ("network centric")

Wide spectrum of requirements

- loosely/tightly coupled
  communication bandwidth. granularity
- low/high sharing
- low/high availability

One platform?

Multiple Platforms

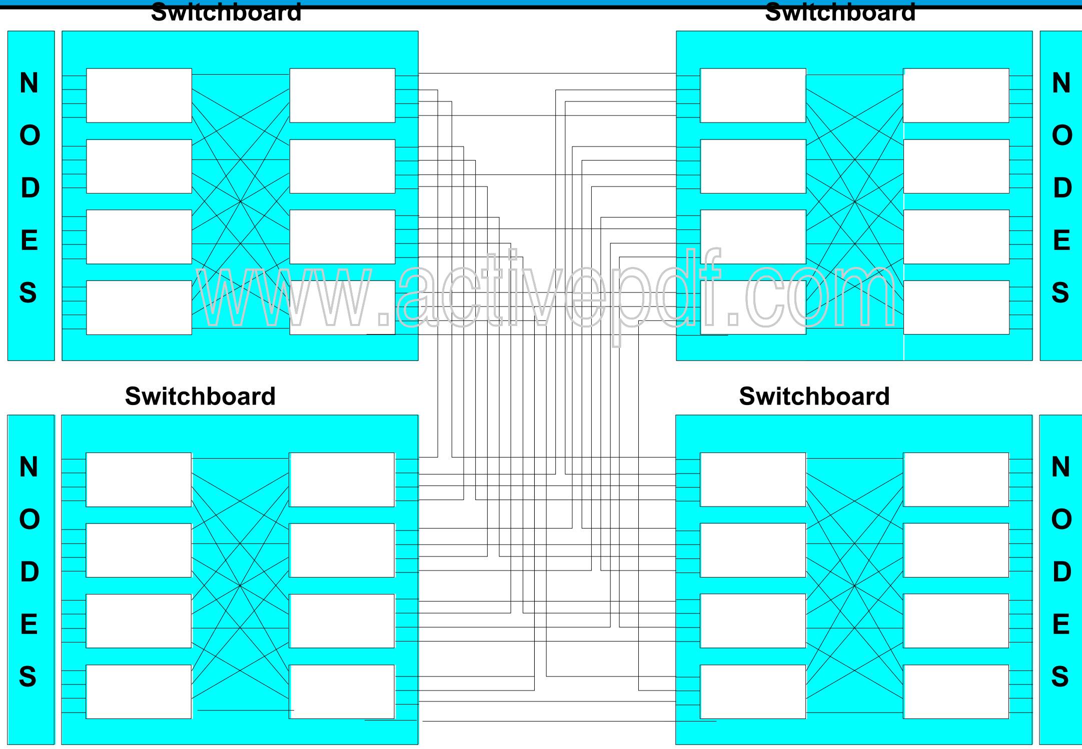


SP Evolution

- Faster node
  - increased single node performance
  - SMP node (package efficiency)
    - uniform access shared memory
- Distributed O/S
  - single kernel per node (scalability problem)
- No single point of failure
- Wider application spectrum
  - possibilities: data mining, unstructured search engine, web server, mail server, video server, ...

What else?

SP Switch (64 way)



Multiple Paths between any two nodes
Network Scales with each added Node
80 MB/s duplex, 0.5 usec latency per board now
B/w can be scaled with node performance for 2 generations, with no major change in technology

Custom vs Commodity Switch

Increased similarity in function
- switched (not shared)
- Packet-switching, small packets

2-3 years gap in performance
- Performance gated by cost, not by physics

Different requirements
- b/w, reliability, package, distance, protocols

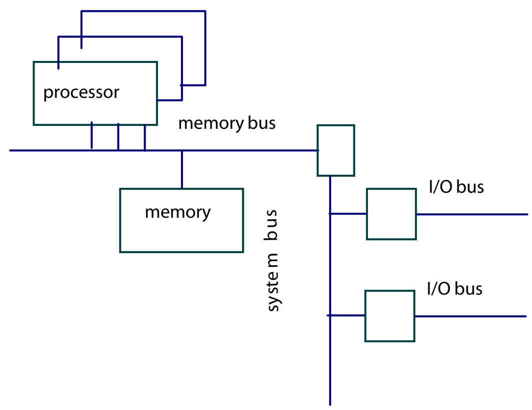
Custom switch can and will maintain performance differential

Custom switch may use components of commodity (ATM ?) technology

I/O Bus vs Memory Bus

I/O bus is
- standard, stable interface
- supports many loads
- built for lower performance
- built for long DMA transfers in non paged memory

Memory bus
- proprietary, and changing
- built for high performance
- supports few loads
- built for short cache line transfers and cache coherence protocols



Direct connection to memory bus will differentiate SPC's from clusters.

Standard W/S I/O slots will not be fast enough for SPC and will not have right functional interface for smart, deep adapter

Scheduling and Communication

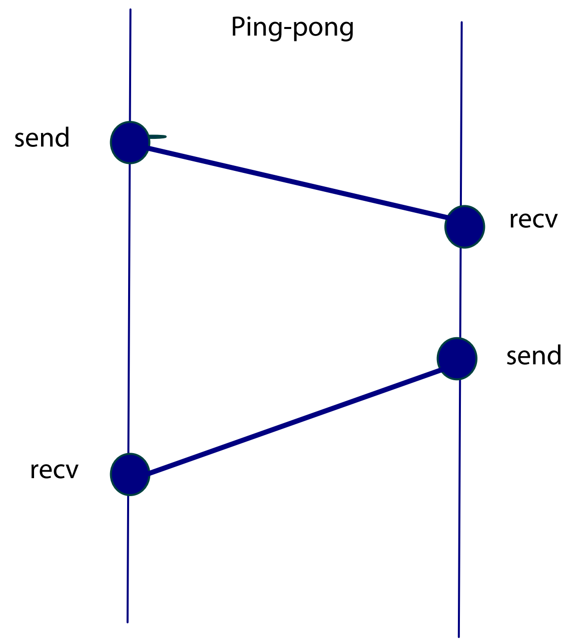
Effective communication time
= communication latency+ scheduling_time x Prob[recv is not running]

Effective broadcast time
= broadcast latency+ scheduling_time x Prob[some recv is not running]

Up to 40% performance loss on a 128 node system, if not taken care of!

Solutions:

0. Gang scheduling + nonblocking communication; or
1. efficient message-driven thread scheduling



Communication Architecture Now

User and kernel paths

Message-passing library

- MPI, MPL, PVMe

35-48 MB/s, 40 usec

Protocol stack executed by main compute engine

One copy protocol

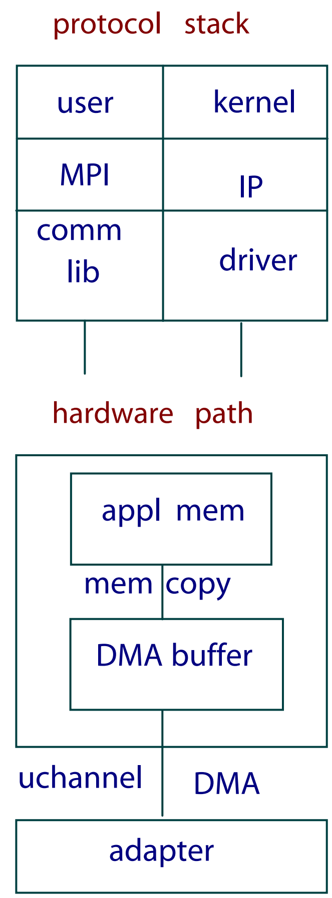
(no cache coherent DMA)

Bandwidth bottlenecks:

- switch (< 80 MB/s)
- uchannel (< 160 MB/s)
- s/w (<255B packet)

Latency bottlenecks:

- uchannel
- no autonomous comm coprocessor



IBM

Evolution - Message Passing

Higher bandwidth, lower latency, increased overlap
- direct memory connection
- higher link b/w
- larger packets
- h/w comm assist (CRC, packaging, flow control,...)
- dedicated comm proc (?)

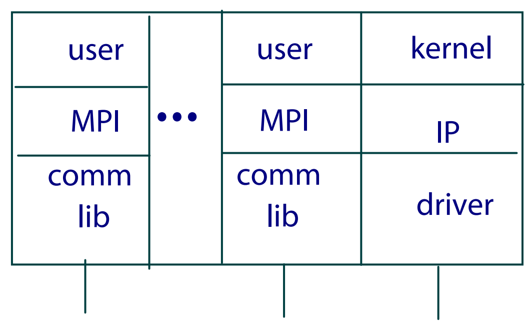
Zero copy protocol

Multiple protection domains

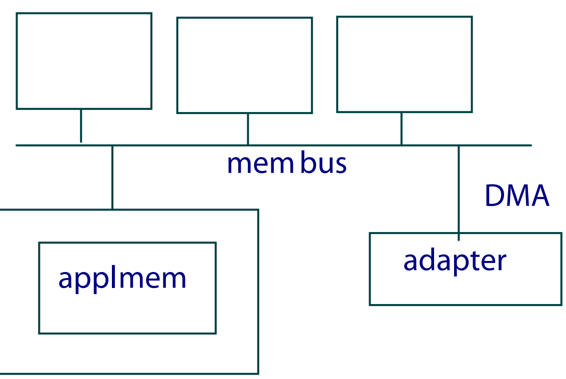
Thread compatibility

Virtual DMA support

protocol stack



hardware path



Evolution -- Communication Paradigms

Integration of communication and process/thread scheduling

- message-driven thread scheduling
- remote thread spawn
- active message paradigm

Impediments:

heavy thread context
error isolation
protection

Integration of internal and external communication

Support to shared memory programming models

Shared Memory Programming Model (1)

Processor to memory comm, rather than proc to proc

producer send recv consumer

vs

sync

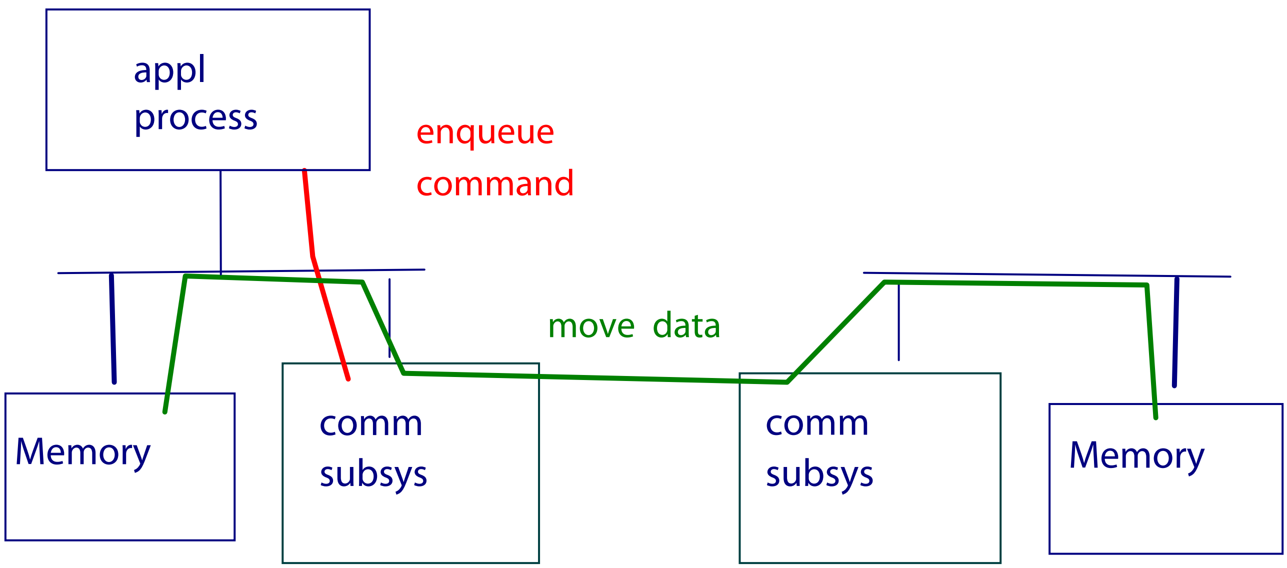
producer write mem read consumer

+Better fit to dynamic, irregular codes

+Can be implemented with less overhead (?)

–No buffering, no synchronization in communication

Memory to Memory Copy



Comm subsystem:

adapter + microcontroller (all h/w implementation)
or adapter + dedicated processor (polling)
or adapter + comm process (interrupt)

Basic Communication Mechanisms

- Put/get
  - put(local_address, remote_proc,remote_address, count, local_flag,remote_flag)
- Accumulate
  - same as put, specifies update operation (sum, max,...)
- Read_Modify_Write
  - same as accumulate, returns previous value
- Enqueue/dequeue
  - Enqueue(local_address, remote_proc,remote_queue, local_flag)

- nonblocking
- general data layouts (scatter/gather?)
- addressing (direct/indirect?)
- coordination mechanisms
- interrupt vs polling (enqueue/dequeue)

Shared Memory Support

0. Shared name space: data distribution does not "intrude" in data naming
1. Caching: a directory based scheme to keep track of local copies and their status
2. Communication occurs as side-effect of load/store: no need for special communication commands (still need synchronization commands)

(1) can be easily supported in s/w on top of put/get

(2) can be supported (with no preemption)-- requires active messages

(3) implemented via page exception (low performance) or requires h/w

Issue (for 3): H/w assis for shared memory that

- avoids use of page fault exception for comm
- does not require global virtual memory manager
- does not slow local memory accesses

How important is 3?

Parallel Programming Paradigms

Parallelism and communication have to be handled as part of algorithm design

Ideal situation:

- Implicit parallelism: user optimizes for coarse grain; system (compiler+run-time+h/w) map computations onto processors, with low synchronization cost.
- Implicit communication: user optimizes for (spatial, temporal) locality; system maps data onto processors with low communication cost.

Reality:

- Complex tradeoffs between total computation work, level of parallelism, granularity, and communication.
- Limited investments in compiler/run-time/hw technologies
- Large investments in existing programming languages

Implicit Parallelism

- Standard sequential program + compiler magic
  - far future (or science fiction)
- Standard sequential program + annotations
  - Program can compile and run on uniprocessor
  - Annotations specify mapping (of computation and data) to processors, but do not change program semantics
- Data parallelism:
  - User specifies data distribution; distribution of computation derived from data distribution
  - specification usually declarative, static, regular
- Control parallelism:
  - User specifies computation distribution: data migrates where needed
  - specification usually executable, dynamic
- The two approaches are equivalent if executable, dynamic distribution is allowed
- Dynamic redistribution requires shared-memory like communication for efficient support

Parallel FORTRAN

FORTRAN

- Support of High Performance FORTRAN
- Support for automatic data partition
- Support for control parallelism (loop parallelism/task parallelism)

HPF2 effort, "on" directive.

Same language supported on all (IBM) platforms (Uni, SMP, SP): FORTRAN 90 + directives

Easy port of "shared-memory" codes (Cray, SGI directives)

Performance on large-scale parallel computers will still require non-trivial algorithm development and tuning.

Remote memory copy and "shared memory" runtime solutions will improve performance and facilitate common shared-memory/distributed-memory compilation.

Compilation

```
$HPF  INDEPENDENT
DO I=1, N
  IF  COND(I)
    THEN   CALL  FOO1(I)
     ELSE   CALL  FOO2(I)
  END  IF
END  DO
```

Message passing compilation results in sequential execution (or wasteful communication)

Use of put/get results in shared-memory style compilation (access on demand)

Caching may further improve performance

Compilation (cont)

```
$HPF  INDEPENDENT
DO I=1, N
   A(I) = B(MAP1(I)) + B(MAP2(I))
END DO
```

Message passing compilation uses inspector/executor
- requires collective, expensive operation
- does not allow load balancing
- does not work if access pattern is dependent on data computed within same loop (e.g. N-body code)

Parallel C++

Ongoing efforts:

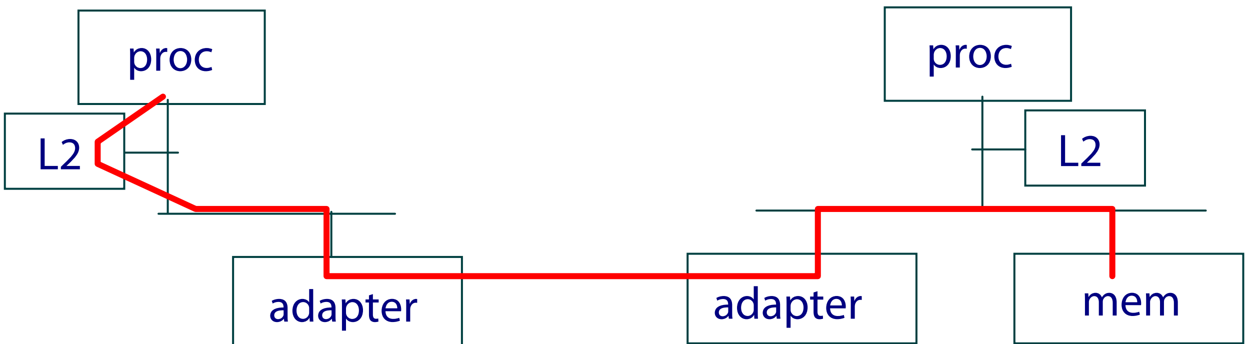
- ABC++
  - activeobjects (tasks)
  - futures
  - parametric regions
- Academic collaborations (CC++, pC++,...)

Please give us a standard

Ongoing research: SOM (Corba) encapsulation of parallel objects.

- interfacefor resource management
- high-performance SOM run-time
- IDL extensions (?)

Why not Conventional Shared Memory?



Virtual Memory Management does not scale

Error isolation is hard

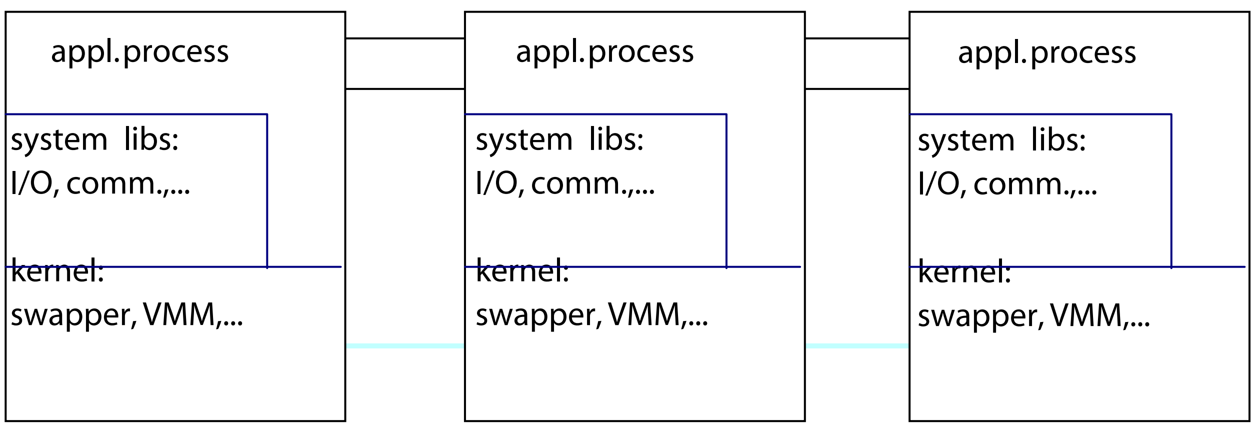
L2 interface does not scale

- small cache line
- small number of pending memory accesses
- small TLB
- expensive L2 and TLB coherence protocol
- small L2

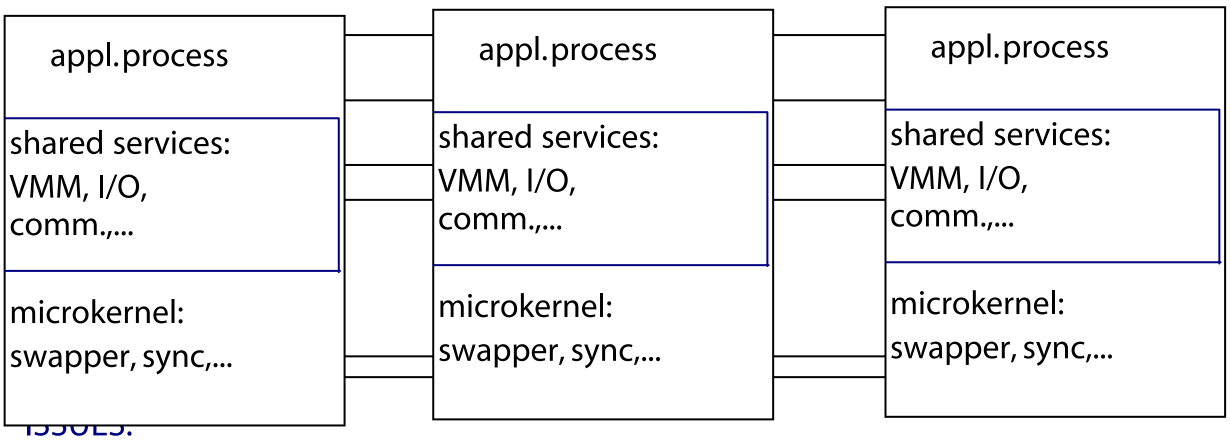
Need to use local memory as additional level in memory hierarchy (L3)

Parallel System Services

- Each node is controlled by separate kernel
- Application processes are tightly coupled
  - coordinated parallel computation
- Kernels and services are not coupled!
  - coordinated management of resources used by parallel application
  - parallel system interfaces



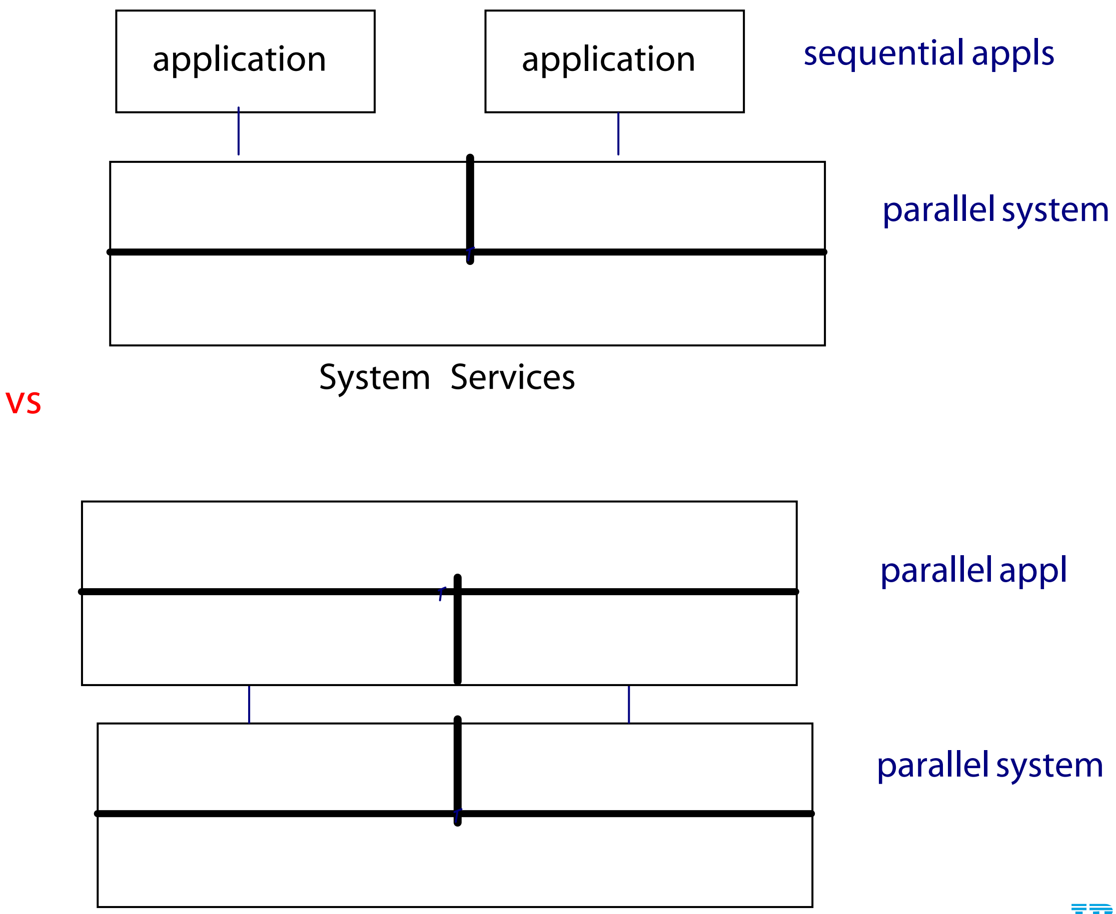
The Microkernel Approach



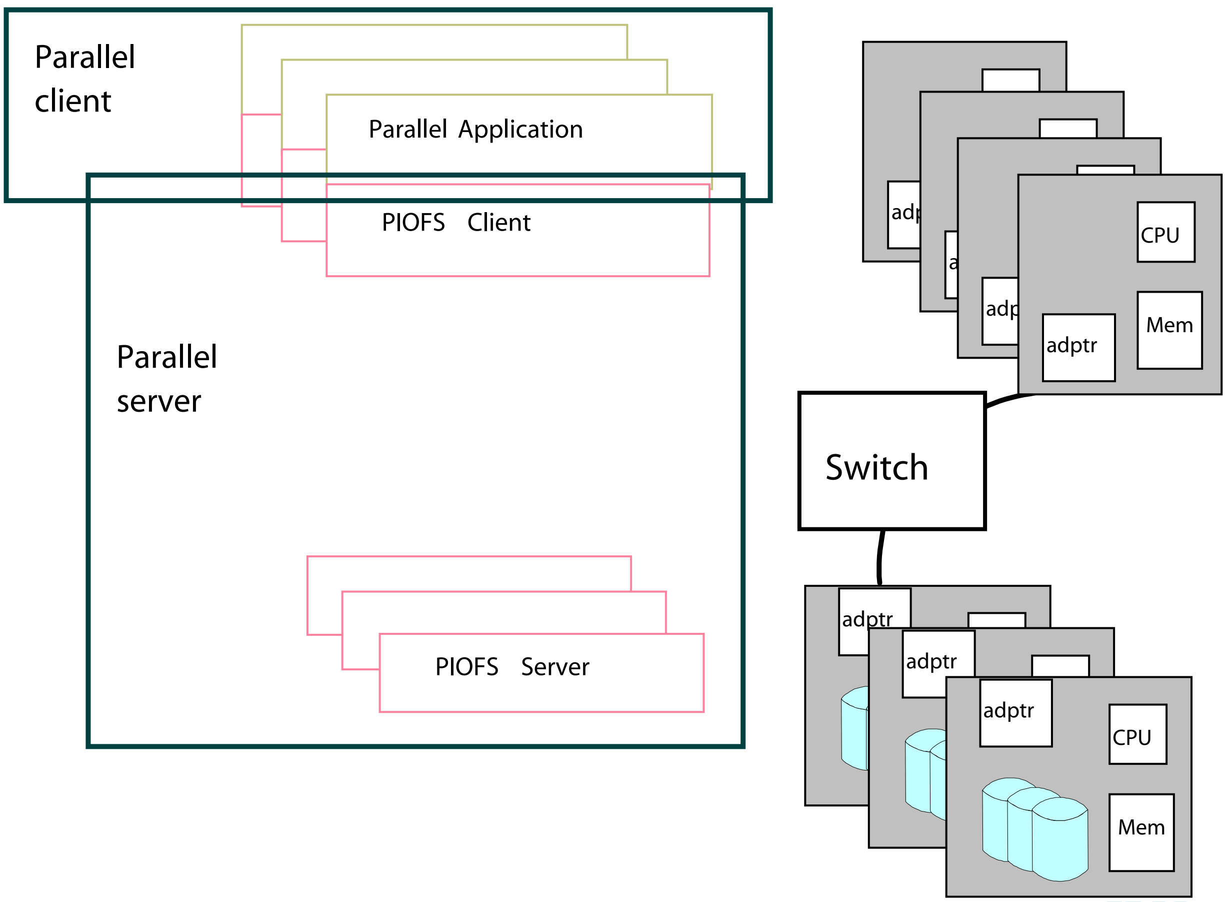
ISSUES:

- Parallelism within the kernel
  - Performance
  - Scalability
- Parallel interface to parallel application
  - Parallel system call interface
  - coordinated management of resources used by multiprocess parallel application

Serial vs Parallel System Interface



Parallel I/O Server



Conventional Invocation Model

- Conventional model - sequential server
  - each process invokes I/O server separately
  - all invocations are channeled to one server
- Conventional model - parallel server
  - each process invokes I/O server separately
  - I/O server is parallel subsystem
  - parallel synchronization code within parallel server enforces atomicity (kernel locks or monitors)

Parallel Invocation Models

Improved conventional model:

- server has policies that take advantage of correlation between requests of parallel client processes

  e.g. back-end caching vs front-end caching

Parallel model

- system call is a collective call, executed in a loosely synchronous manner by all clients in a group

  e.g. collective I/O: read-broadcast, read scatter, write-gather, etc.

Thesis: more efficient performance can be achieved by direct support for collective calls (true for message passing)

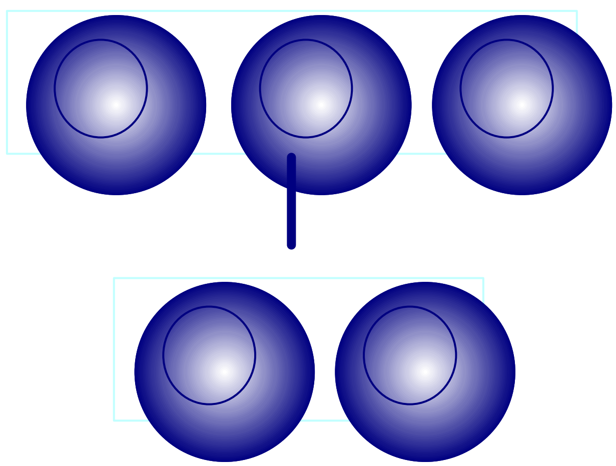
Third-party protocols required for efficient implementation of collective I/O

(a process requires a system service on behalf of another process)

Collective Method Invocation

What mechanisms are available for collective invocation of (local, remote) parallel procedures (objects, methods)?

Are these mechanisms compatible with distributed object frameworks such as CORBA (OLE, Java,...)



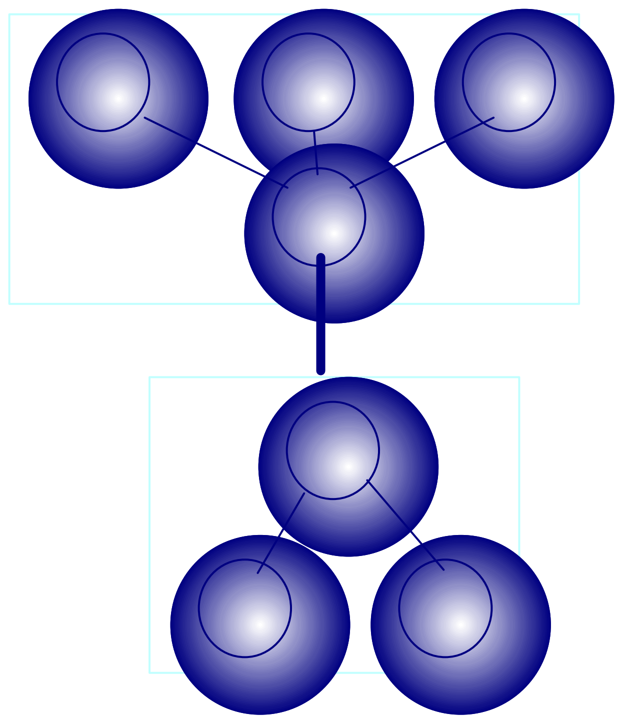
What information is available at the interface?

Sequential Interface

Best encapsulation
- "knowledge" about parallelism is internal to each module

Easy fit in existing object frameworks
- each parallel object is "represented" by a sequential stub
- sequential stub may negotiate for parallel resource allocation, if needed

Worst performance
- Each invocation is a serial bottleneck



Sequential Control - Parallel Data

Reasonable encapsulation

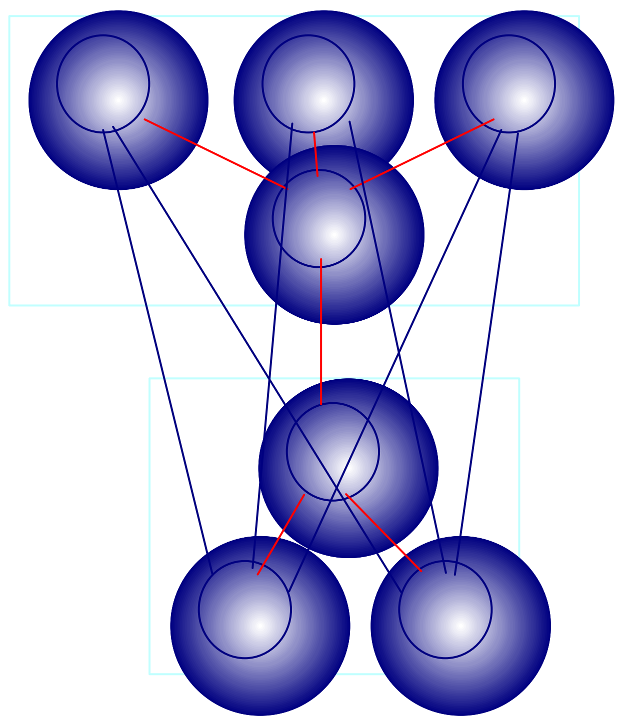
- data path can be negotiated at binding time
-

Fits existing object frameworks (?)

- may need extensions for dynamic data path binding

Good performance

- trivially so with shared memory

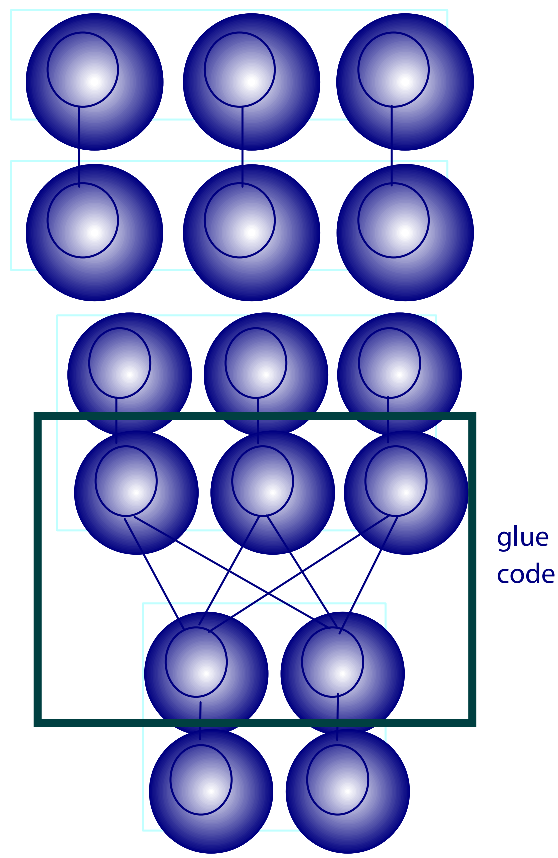


All Parallel Invocation

Important special case: parallel collective invocation resolves into multiple, loosely synchronous, local invocations

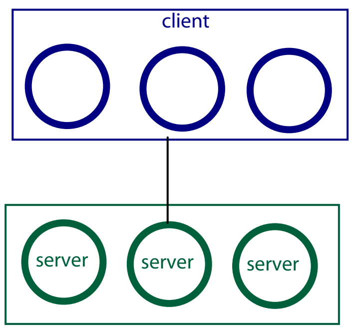
Generalization to remote invocation?

- remote collective invocation has same interface as local collective invocation
- efficient
- requires extensions to existing object frameworks

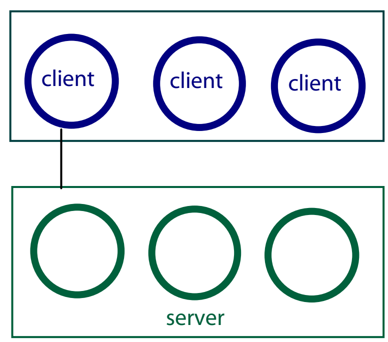


Parallel Server Models

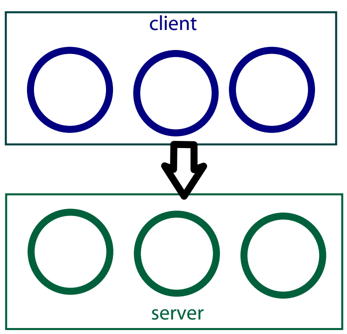
parallel-sequential



sequential - parallel



parallell - parallel



Collective I/O Library

- Most useful with (loosely) synchronous programming model
- Takes advantage of correlations btw system activities at processes of parallel application

Vesta Design

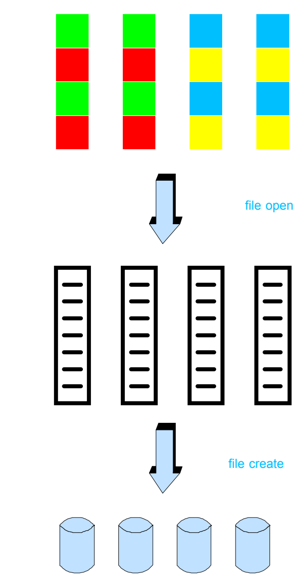
- Support parallel I/O to one file from multiple compute nodes to multiple storage nodes
  - Flexible allocation of I/O bandwidth to jobs
  - Flexibility in h/w configuration
  - Need not collocate files and processes
  - Can offload system calls
- Scalable design
  - No single point of access for metadata
  - No locking for atomicity control
  - 2^64 byte per file, 2^54 files
- User control of data layout
  - control of physical layout at creation time
  - access to user defined subfiles
- Support for shared offset
- Support of Posix interfaces
- Support for import/export functions

Vesta - Salient Features

User control of layout
- file is 2D array of records
  - cols are mapped round-robin
  - file struct and map specified at creation
- subfile is a rectilinear file decomposition
  - different processes can access same or different subfiles of same file;
  - subfile defined when opened

Accesses are atomic and serializable
- even if they span multiple store nodes

Minimal number of accesses
- comm occurs only between client and servers that hold data
- Client has full knowledge of data distribution after file is opened
- atomicity contrl done by com btw servers



Vesta - Future Activities

- Evolution to product (95)
  - Posix compatibility
  - protection, recovery
- MPI-IO -- MPI library for parallel IO
  - Jointly defined and implemented with NASA Ames
- Scalable IO Initiative
  - IO benchmarks and performance analysis
    - Performance tools for IO
  - Enhanced system support for parallel IO
  - Compiler support for parallel IO
    - Integration with HPF
- Optimizations and function enhancements
  - Collective IO
  - Checkpoint/restart

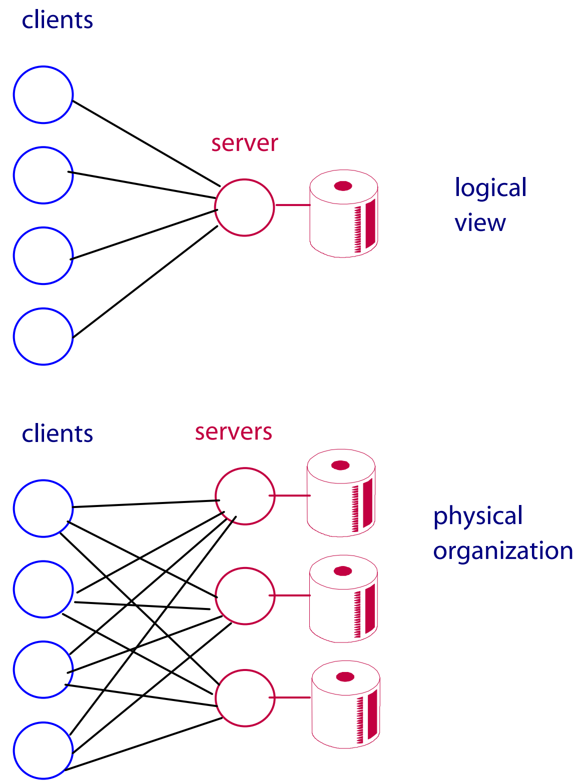
MPI-IO

IO = communication with (logical) IO server
- point-to-point
- collective
- blocking/nonblocking

Use of MPI datatypes
- for layout of data at client memory
- for layout of data on file

superset of vesta partitions

Use of MPI communicators
- file access group
- error handling



Scheduling

Problem: processes in parallel partition need be coscheduled

- up to 40% performance deterioration on 128 node benchmark, due to <3% random system background activity!

Current solution

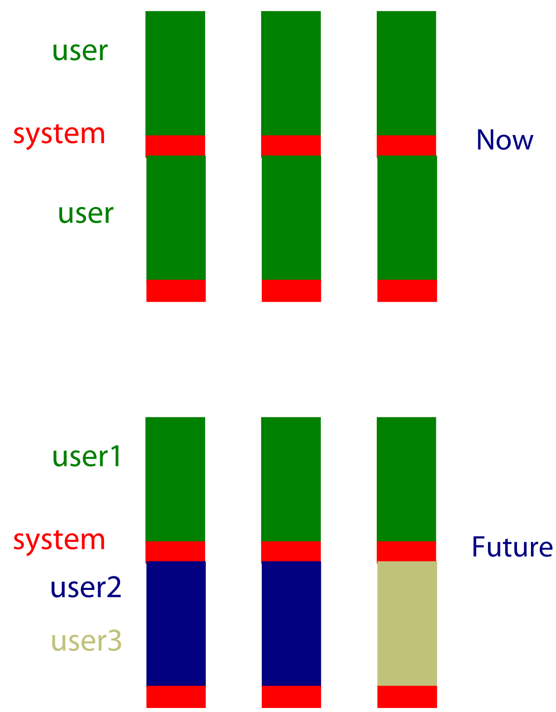
- dedicated fixed partition
- synchronization of scheduling slots for background processing

Future:

- gangscheduling

time sharing of virtual "dedicated" partitions

- variable size partition



Scheduling and Communication Infrastructure

Infrastructure

- control network

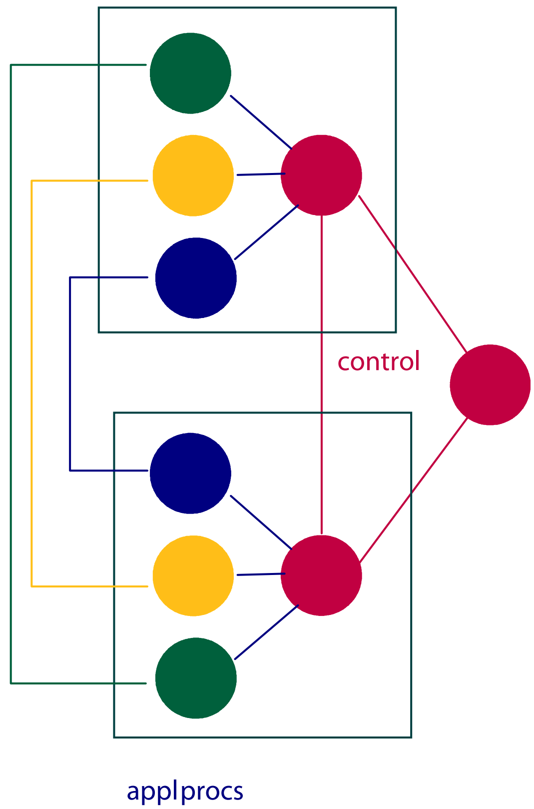
coordinate global changes in commstate (global swap, addition/deletion)

Policy

- parallel job time sharing policy
- application driven scheduling
- event-driven scheduling

Issues

- Need "parallel events" (collective calls) for event-driven scheduling
- Need more information on system overheads
- Interaction with memory management



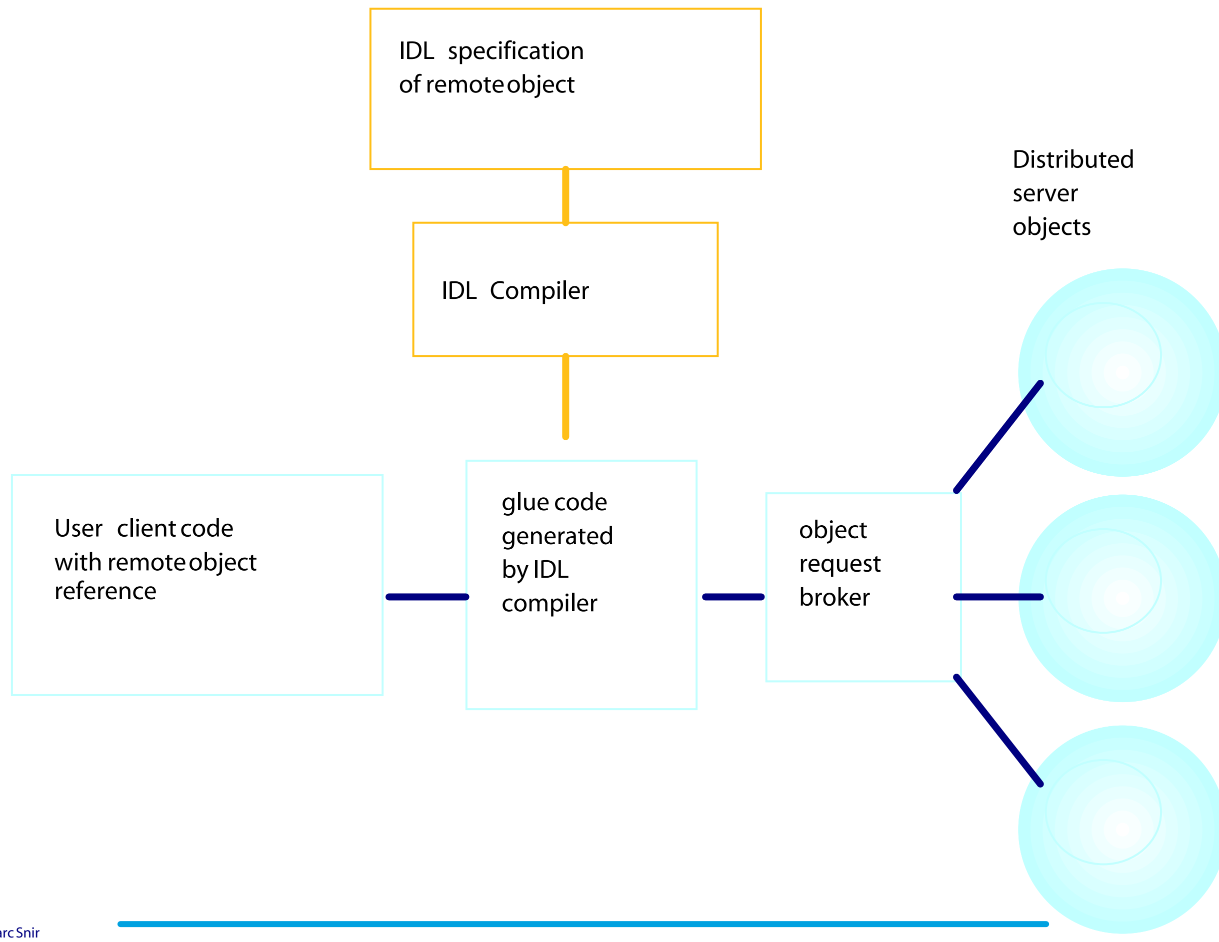
Problem

- Parallel code does not mix easily with sequential code.
  - cannot integrate parallel code modules in existing software systems
  - cannot integrate parallel servers into existing distributed systems
- No good parallel interfaces between parallel modules
  - E.g., from DB2 to Quest
- Parallel code runs efficiently only in batch.
  - no interactive, real-time, embedded, ..., parallelism

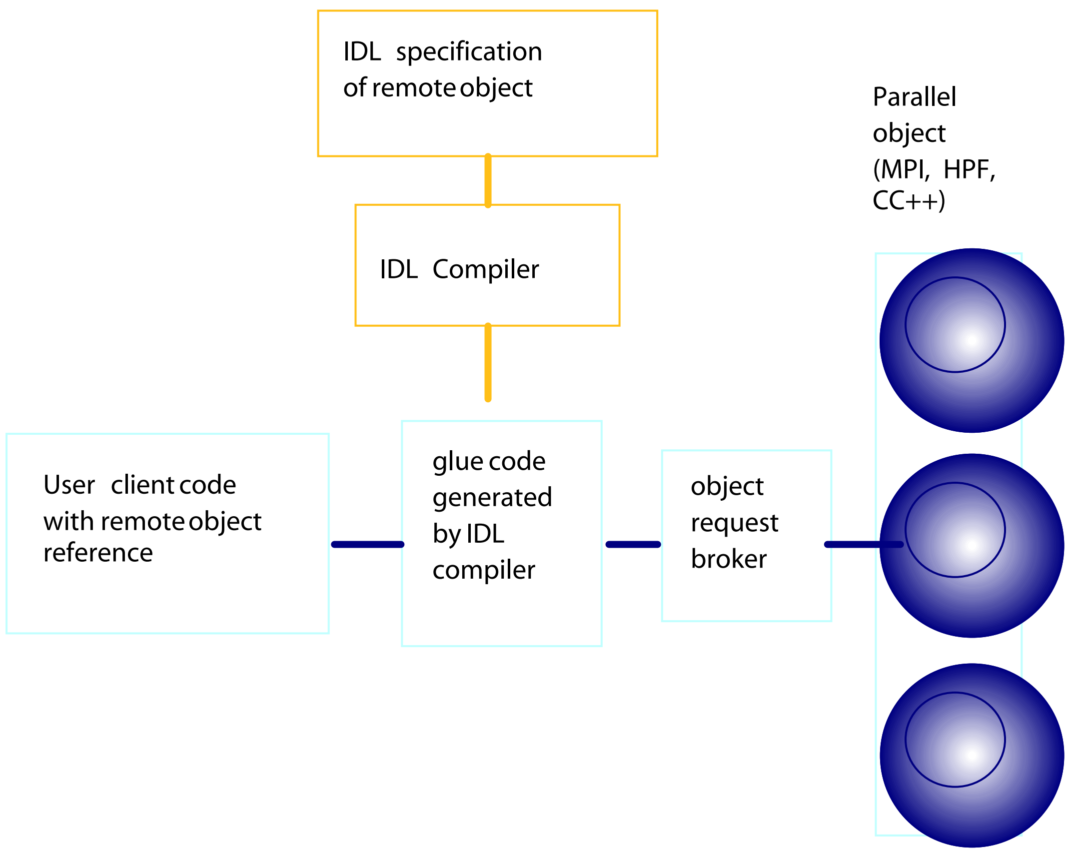
- Possible solution:
  - Encapsulate parallelism within objects
  - Provide SOM support for parallel objects

- Develop system where
  - Sequential objects can be replaced with parallel objects, with no change in the remaining system.
  - Parallel objects interact with parallel objects, with no sequential bottlenecks

DSOM (aka CORBA)



PARSOM



IDL specification
of remote object
IDL Compiler
User client code
with remote object
reference
glue code
generated
by IDL
compiler
object
request
broker
Parallel
object
(MPI, HPF,
CC++)

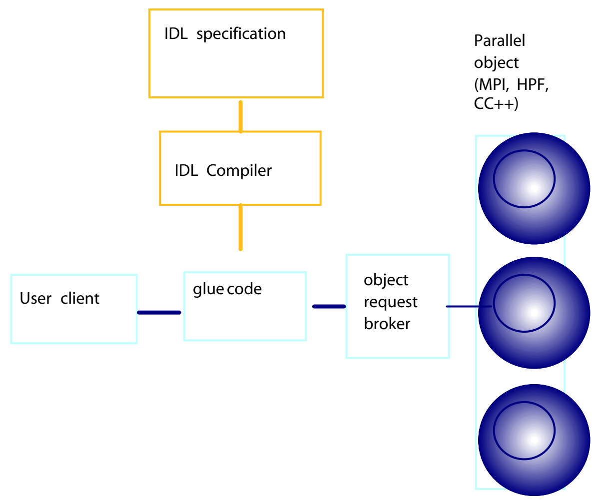
Some Technical Issues

Data needs to be distributed
- IDL: specification of distribution
- run-time for data (re)distribution

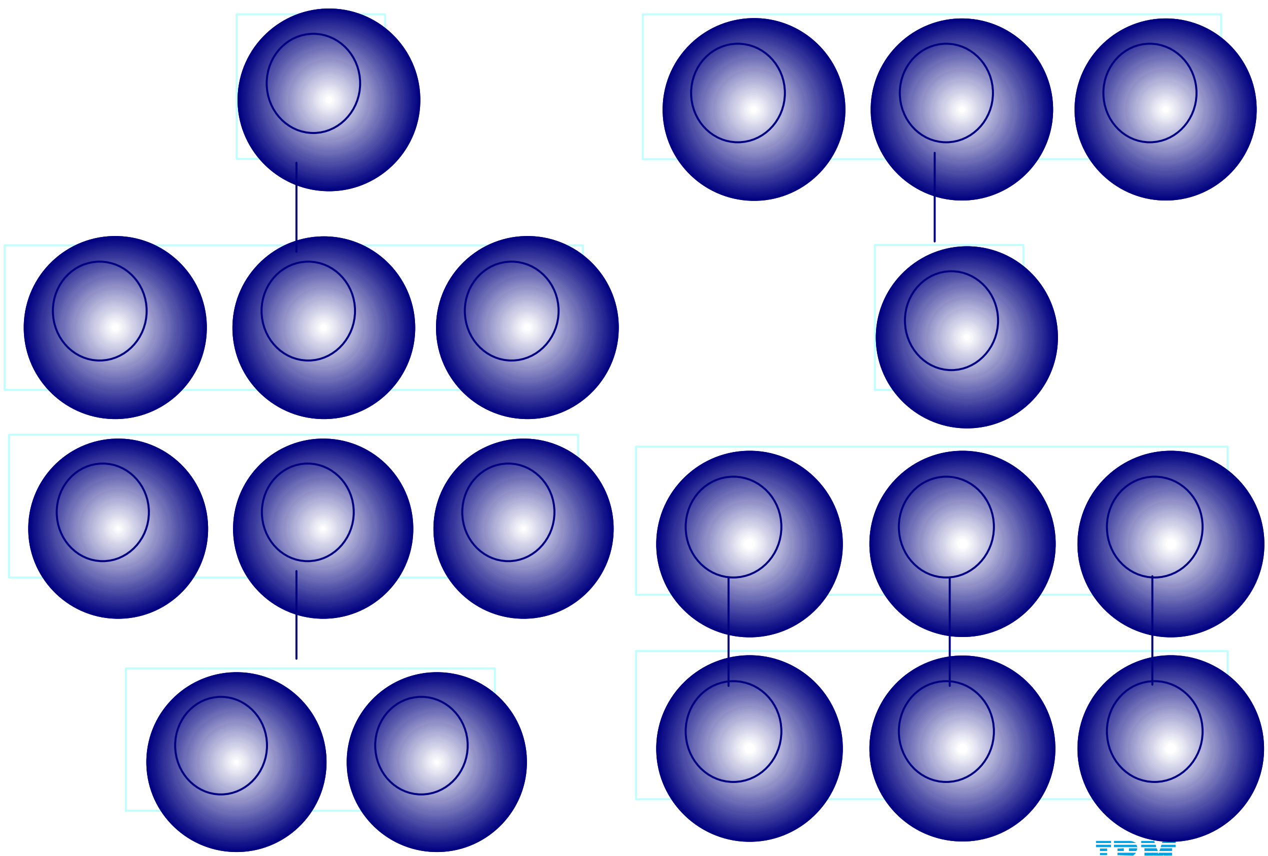
extension of activity on run-time for parallel languages

Parallel object may need to be instantiated
- Need dynamic partition allocation and protocol between ORB and resource manager

(rather then local ORB deamon)



Invocation Mechanisms



Relevant Activities

IBM
- SOM, DSOM

IBM Research (my area)
- Dynamic process group scheduling
- Persistent object storage
- Milliways

Pasadena II Workshop:

"A research program should be established to investigate and shape the interaction between distributed processing and HPC. This should take the form of. research into, and implementation of, an extended CORBA-like infrastructure that supports parallel processing."

Ongoing (starting) efforts by CRPC members (with my lobbying)

Providing CORBA interfaces from CC++ (Chandi/Kesselman, Caltech)

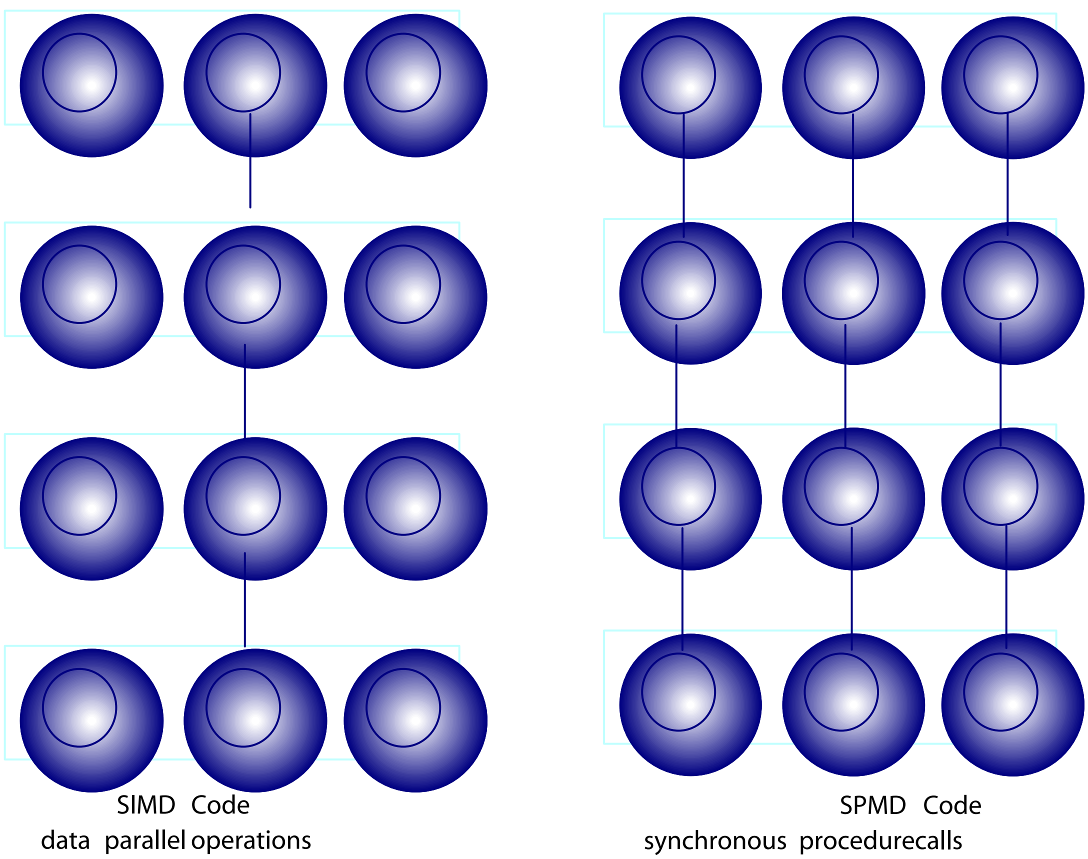
IDL specification for data parallelism (Gannon, Indiana)

Common interface and run-time support for parallel objects (Saltz, Maryland)

Use common object interfaces to link
- sequential client to parallel server (e.g., computational server, EOS server)
- multiple parallel modules (e.g. multidisciplinary applications)

Also, interest at LANL, NRL,...

SIMD and SPMD Model



SPMD Scientific Libraries

Parallel C++ libraries for matrix operations (A++/P++), linear algebra (Scalapack++), irregular data structures (Chaos++), adaptive grid (LPARX),..

Parallel code is identical to sequential code

- All processes executesame sequential code (including library calls)
- All communication is buried into library code
- Information on data distribution is buried in object descriptor.

Good match to HPF

Extendible approach (hook your own library with your messy message-passing code)

In need of standardization

Needs many additions (file I/O, graphics,...)

Pasadena II workshop:

"We recommend to convene within few months a forum for implementers of OO scientific libraries in view of standardizing the interfaces for these libraries... It will aim at defining within less than a year portable descriptions for distributed dense and sparse arrays, grids, etc...

Infrastructure for Parallel Objects

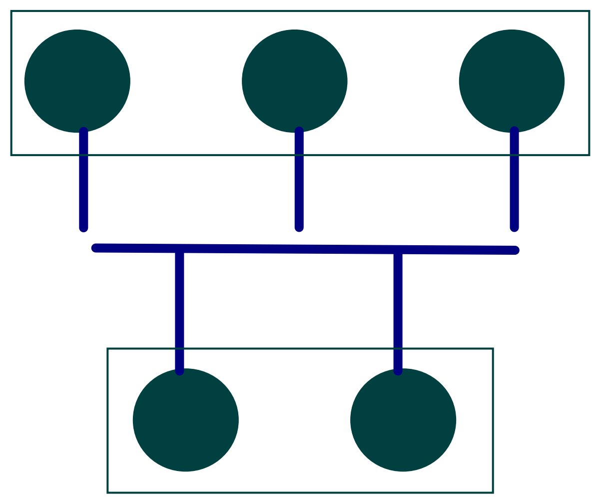
Mechanisms for dynamic parallel object instantiation

- 1-n, n-1, n-m
- same or distinct processes

Mechanisms for redistribution of data

- HPF rectilinear distributions
- user-defined distributions

Parallel persistent object repository (aka PIOFS)



Conclusion

- Scalable parallel servers are here to stay
  - intermediate level of integration between clusters and tightly coupled, single kernel SMPs.
  - significant reuse of commodity technology
- A reasonable path can be outlined for h/w evolution
  - including support for shared memory programming model
- Much thinking still needed on system structure
  - What is a scalable Operating System?
  - What should be system interfaces to parallel applications?
  - How does one build hierarchical resource management services?
- Much ground for useful and interesting research
  - But designing beautiful, nicely integrated solutions from scratch is an exercise in futility