A Case for Networks of Workstations (NOW)

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Outline

- **Background: Evolution of Computer Industry**
- **Opportunity for Large Scale Computing on NOW**
- **Why NOW now?**
- **The NOW Project at Berkeley**
- **Issues and Potential Solutions**
  - **Time Lag for NOW using fastest workstations**
  - **Network Overhead**
  - **Preserving Response Time for large and small jobs**
  - **I/O Bottleneck**
  - **NOW helps only parallel jobs?**
- **Conclusion**

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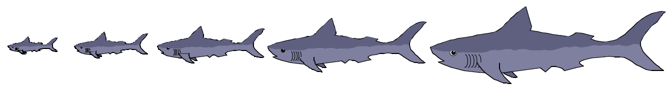
Original Food Chain Picture



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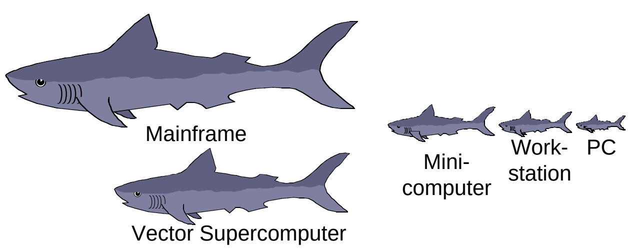
1984 Computer Food Chain



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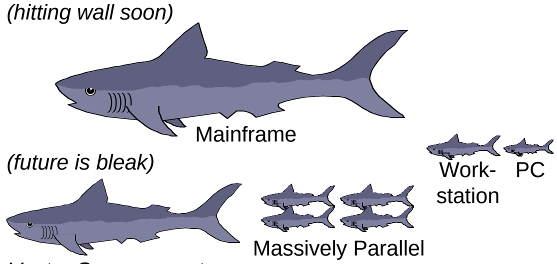
1994 Computer Food Chain



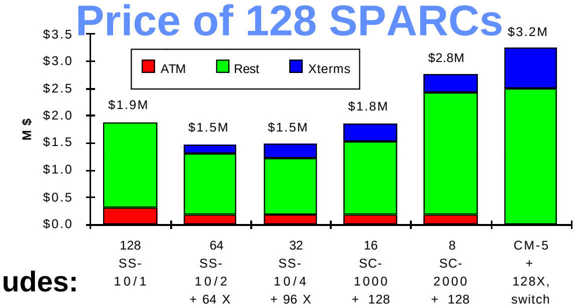
MPP: A Near Miss

- **"near commodity" μprocs,DRAMs, boards => delayed shipment:**

MPP	*Proc*	*Year*	*=WS*
T3D	150 MHz Alpha	'93/'94	'92/'93
Paragon	50 MHz i860	'92/'93	≈ '91
CM-5	32 MHz SS-2	'91/'92	'89/'90

- **μproc perf. improves 50% / yr (4%/month)**
  - **1 year lag:WS = 1.50 MPP node perf.**
  - **2 year lag:WS = 2.25 MPP node perf.**
- **No economy of scale in 100s => +$**
- **SW incompatibility (OS & apps) => +$$$$**

Price of 128 SPARCs



- **Includes:**
  - **128 50 MHz SuperSPARCs w. 1 MB external cache (3/94)**
  - **4 GB of DRAM (32 MB/processor)**
  - **134 GB of magnetic disk (128 1.05 GB magnetic disks)**
  - **128 screens (native or Xterms)**
  - **Switch (native or ATM: 1 interface/2 procs+ switch)**
    - **$700/node for interface + $70,000 per 64-way switch**
- **Cost Xterms for MPP > Cost ATM for NOWs**
- **≈ 2X MPP v. new NOW, ≈10X MPP v. old NOW**

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Volume vs. Cost

- **Rule of thumb on applying learning curve to Manufacturing:**

"When volume doubles, costs reduce 10%"

A DEC View of Computer Engineering **by C. G. Bell, J. C. Mudge, and J. E. McNamara, Digital Press, Bedford, MA., 1978.**

- **40 MPPs @ 200 nodes = 8,000 nodes/year vs. 100,000 Workstations/year**

$12.5X \approx 2^{3.6} \Rightarrow (0.9)^{3.6} = 0.68$

Cost should be 1/3 less for same components

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1990s Building Blocks

- There is no "near commodity" component
- Building block = complete computers (HW & SW) shipped in 100,000s: Killer micro, Killer DRAM, Killer disk, Killer OS, Killer packaging, Killer investment
  - Leverage billion $ per year investment
- Interconnecting Building Blocks => Killer Net
  - High Bandwidth
  - Low latency
  - Reliable
  - Commodity

  (ATM?)

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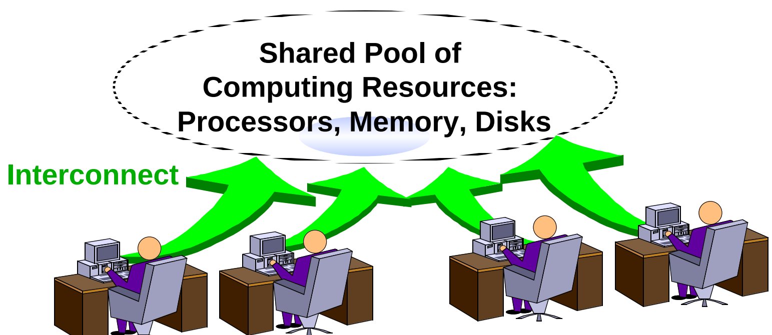
Opportunity of Large-scale Computing on NOW

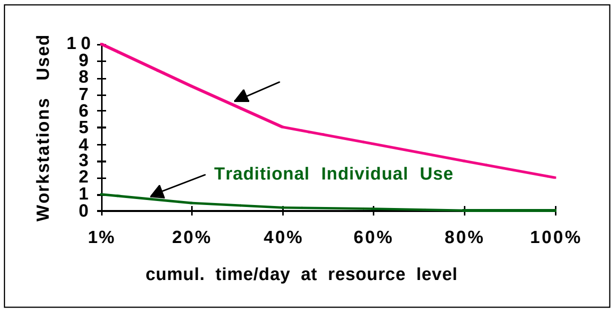


Guarantee at least one workstation to many individuals (when active)

Deliver large % of collective resources to few individuals at any one time

Current Utilization of Resources

- Out of 100 workstations, how are resources used by individual and by whole community?



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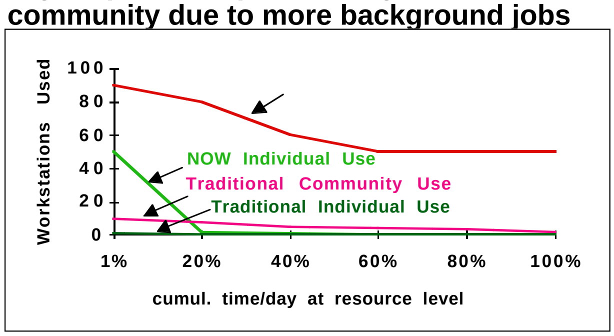
Using Available Resources means Better Performance

- Higher peak use/person; Higher tail for community due to more background jobs



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Why NOW now?
(Beyond technology and cost)

- Building block is big enough (v. Intel 8086)
- Networks are faster
  - Higher link bandwidth (v. 10 Mbit Ethernet)
  - Switch based networks coming (ATM)
  - Interfaces simple & fast (Active Msgs)
- Striped files preferred (RAID)
- Demise of mainframes, supercomputers, & MPPs

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NOW Benefits Parallel Programs: Example MPP Performance

Machine (no. processors)	*ODE*	*Transport*	*I/O*	*Total*
		(seconds)		
Cray C-90 (16)	7	4	25	38
Intel Paragon (256)	12	24	10	46
RS/6000 (256),Ether	4	23,340	4,030	27,374
+ ATM	4	192	2,015	2,211
+ Parallel FS	4	192	10	206
+ low net. overhead	4	11	10	25

(1 disk/processor, parallel FS for C-90, Paragon)

- Order of importance: ATM bandwidth, Parallel File System, low overhead ATM/SW=> 1000X

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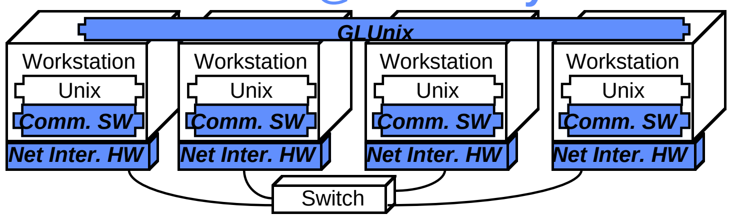
NOW @ Berkeley



- **Design & Implementation of higher-level system**
  - Global OS (Glunix)
  - Parallel File Systems (xFS)
  - Fast Communication (HW for Active Messages)
  - Application support
- **Overcoming technological shortcomings**
  - Fault tolerance
  - system management
- **NOW Goal: Faster for Parallel AND Sequential**

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NOW Issues and Potential Solutions

- **Network Overhead**
- **Preserving Response Time for large and small jobs**
  - Recruiting idle workstations
  - Gang scheduling for parallel tasks
  - Not annoying interactive users
- **I/O Bottleneck**
- **NOW helps only parallel jobs?**
  - NOW File System (xFS): large file cache
  - Network RAM: avoid I/O

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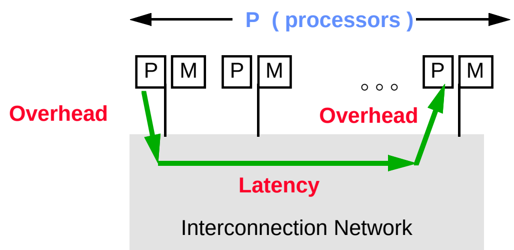
Communication Model: Beyond Bandwidth



- Network Latency incurred in sending message between nodes (1-way)
- Processor Overhead to send *or receive* a message (1-side)

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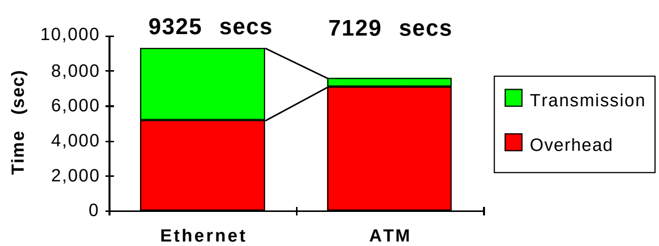
Importance of Overhead (and Latency)

- NFS trace over 1 week: 95% msgs < 200 bytes
- Ethernet: 9 Mb/s BW, 456 µsecs overhead
- ATM Synoptics: 78 Mbit/s BW, 626 µsecs ovhd.



- Bandwidth ≈ MIPS for processors; misleading?
(625 µsec overhead ATM vs. 155 Mb/s BW ATM)

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MPP/LAN Overhead & Latency

		Overhead	Latency
MPP	with A.M.	2 µs	5 µs
	w.o. A.M.	25 µs	
LAN	with A.M.	8 µs	5 - 50 µs
	w.o. A.M.	360 µs -625	

1996 Berkeley NOW Goal:
Overhead+Latency ≤ 10 µs for 100 WS

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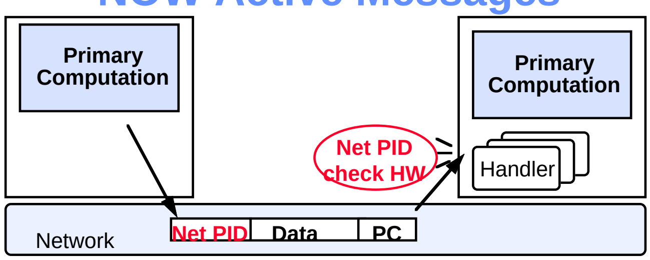
NOW Active Messages



- **Key Idea: Network Process ID attached to every message that HW checks upon receipt**
  - **Net PID match, as fast as before**
  - **Net PID mismatch, interrupt and invoke OS**
- **Can mix LAN messages and MPP messages; invoke OS & TCP/IP only when not cooperating (if everyone uses same physical layer format)**

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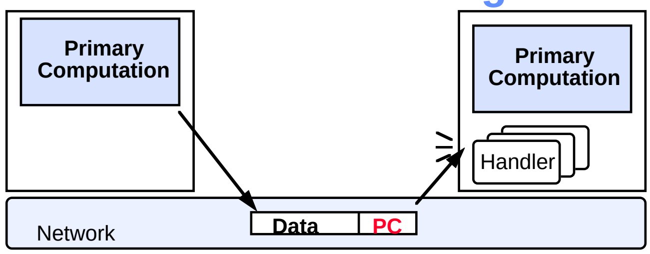
MPP Active Messages



- **Key Idea: associate a small user-level handler directly with each message**
  - Sender injects the message directly into the network
  - Handler executes immediately upon arrival
  - pulls the message out of the network and integrates it into the ongoing computation, or replies
  - No buffering (beyond transport), no parsing, no allocation, primitive scheduling

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Experiment running MPP workload on NOW running sequential workload

- **51 DECStation 5000s measured for 1 week, local disk and 64 MB memory; for IC design**
- **Measured CM-5 at Los Alamos National Labs 10/4/93 to 11/10/93 as prototype large program workload**
- **Simulated 32-node MPP workload on NOW with sequential workload (ignore network)**

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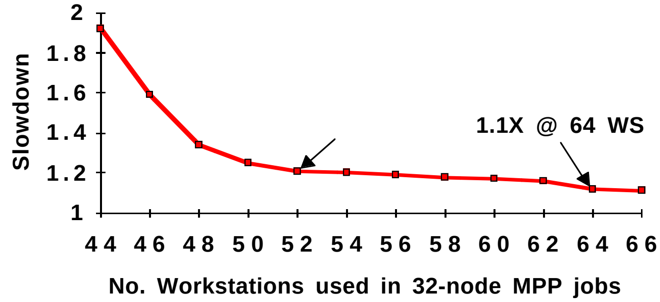
Sequential & Parallel on 1 System

- Sequential has priority
- Ratio MPP nodes:desktops 3:5=>1.2x slowdown



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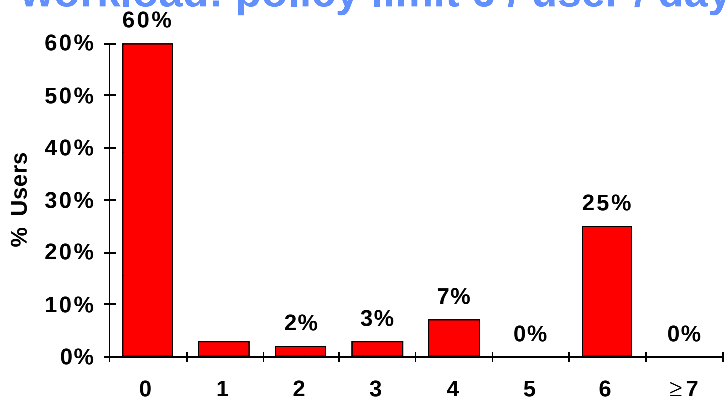
Annoyances per Day with MPP workload: policy limit 6 / user / day



User interactivity preserved with simple policy
(no policy some users annoyed > 20 times/day)

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Glunix Technical Challenge: Interactive Performance

- Must *gang schedule* parallel jobs to be as good as dedicated MPP for parallel jobs
- Must quickly restore state to be as good as dedicated workstation for uniprocessor jobs
- Focus on *memory state* as well as CPU cycles
  – Delay in restoring memory biggest roadblock to harvesting idle cycles
- Time to save or restore:
  – 64MB over Ethernet, single disk 60 seconds
  – 64MB over ATM, parallel file sys 2 seconds

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Issues and Potential Solutions

- Network Overhead
- Preserving Response Time for large and small jobs
  – Gang scheduling for parallel tasks
  – Recruiting idle workstations
  – Not annoying interactive users
- I/O Bottleneck
- NOW helps only parallel jobs?
  – NOW File System (xFS): large file cache
  – Network RAM: avoid I/O

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xFS: File System for NOW

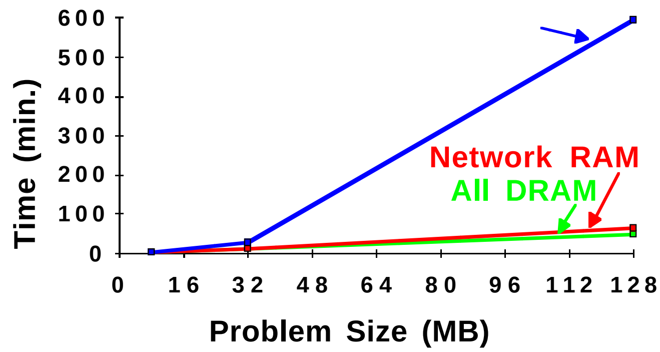
- Serverless File System: All data with clients
  - Use MP cache coherency to reduce traffic
- Files striped for parallel transfer
- Large file cache ("cooperative caching")

	Miss Rate	Response Time
Client/Server	10%	1.8 ms
xFS	4%	1.0 ms

(42 WS, 32 MB/WS, 512 MB/server, 8 KB/access)

- Paper at SIGMETRICS '94
  - Tech. Report: UCB/CSD-94-798
  - anon FTP: cs-tr@cs.berkeley.edu

Network RAM simulation



- 1.1X to 1.3X slower v. all DRAM
- 4X to 9X faster v. DRAM+disk

3 Paths for Applications on NOW?

- **Revolutionary (MPP Style): write new programs from scratch using MPP languages, compilers, libraries, …**
- **Porting: port programs from mainframes, supercomputers, MPPs, …**
- **Evolutionary: take sequential program & use**

increasing programming difficulty ↓

1) **Network RAM: first use memory of many computers to reduce disk accesses; if not fast enough, then:**
2) **Parallel I/O: use many disks in parallel for accesses not in file cache; if not fast enough, then:**
3) **Parallel program: change program until it uses enough processors that it is fast**

=> Large speedup without fine grain parallel program

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Pitfalls for NOWs

- **Invoking operating system when communicate**
  - 100s µsec overhead added to low latency communication
- **Rewrite/Modify WS operating system to include features for NOW**
  - Limited to single brand of desktop computer
  - Can't leverage of OS improvements by vendor
  - New HW useless until OS port => lower performance
- **Design NOW to only help large programs that are parallel**
  - Few applications are parallel => hard to justify fast NOW
  - Many large programs just need memory and disk BW
- **Serial file system**
  - can't take advantage of 100s of parallel disks

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Pitfalls for NOWs (cont'd)

- **Design custom network interface HW &SW for single model of desktop computer**
  - New HW useless until new NI HW, SW port
    => lag time and lower performance
- **Custom proprietary network as new LAN**
  - LAN market demands standardization => multiple suppliers & add new products to network ASAP
  - Too important to rely on a single supplier
- **Scaling WS OS kernel beyond 32 processors**
  - Kernel locks are bottleneck as well as shared bus
- **Parallel tasks don't run at same time**
  - Parallel program communication much slower if nothing to consume messages from other parallel tasks

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Research Focus at New Level

- **"Higher Order" Systems Research: building on top of other systems vs. bottom-up**
  - Must avoid time lag: neither HW nor OS can delay putting new machines to use
- **Advantages:**
  + easier to track technological advances
  + less development time
  + easier to transfer technology (reduce lag)
- **New challenges:**
  - maintaining performance goals
  - system is changing underneath you
  - underlying system has other people's bugs
  - underlying system is poorly documented

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Conclusion

- **1990s building block is desktop HW&SW**
- **Need higher-level system research use building blocks: stand on shoulders, not toes**
- **NOWs underutilized => add large programs**
  - **Sequential apps use memories & disks (Network RAM)**
  - **MPP apps use CPUs, memories, & disks**
- **Technologies aligned to exploit NOW now**
  - **32-bit µprocessors, switch based LANs, active messages, striped files, file caches, process migration**
- **Challenges for NOW: Leveraging technology yet add low overhead user communication, global OS, parallel file system**

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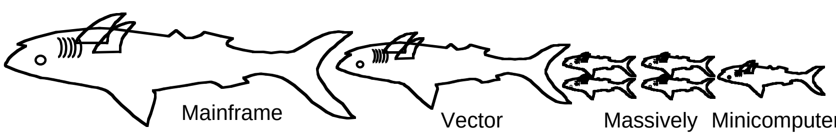
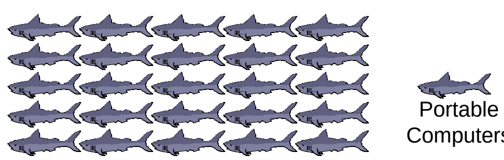


2004 Computer Food Chain



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Backup Slides

- (The following slides are only used to answer questions)

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Other NOW projects

- Shrimp at Princeton (Li, Clark):
  PCs with Intel Paragon switch
- FLASH at Stanford (Gupta, Hennessy)
  SGI workstations with shared address space
  with Intel Paragon Switch
- COW at Wisconsin (Hill, Wood):
  SPARCstations with shared address space
- Related projects at MIT, Rice, UCLA, ...

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Why Higher Price for Same Components in SBMPs?

- SparcStation-10 (1 to 4 processor desktop) vs.SparcCenter-2000 (2 to 20 proc. server)
  - Same processor and cache as building block
- ASIC Costs/Proc SS-10 SC-2000 Ratio

ASIC Costs/Proc	SS-10	SC-2000	Ratio
Number ASICs	5	8	1.6
Total Gates	90k	235k	2.6
Person Months	145	305	2.1
People Costs	$1.5M	$3.0M	2

- Sales (9/93-12/93) ≈33,000 ≈1,000 33
- Higher development spread over fewer sales => customer pays more for same processor
- Worse for MPPs since even smaller volume

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Hidden Costs of Large Systems

- Spares/Self maintenance for NOW vs. 5% to 10% purchase/ year for SBMP/MPP
- Upgrade components of NOW vs. discard for SBMP/MPP
  - SBMP limited processor upgrade (discard?), can't upgrade bus
  - MPP limited processor upgrade (discard?), can't upgrade network
  - LAN enables individual upgrades of workstations and/or switch
- NOW cheaper at purchase and cheaper to own

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Latency & Overhead for ATM

- **Latency: worse than MPP**
  - Links latency basically speed of light (1000 ft = 1 µsec)
  - Per-hop latencies:
    - » SynOptics 50 µsec
    - » Fore 10 µsec
    - » AN2 ≈ 2 µsec
  - Store and Forward vs. Cut through routing
  - Bigger switches so fewer hops (1/3): 6 to 150 µsec
- **Overhead: comparable to MPP**
  - HP WS UDP (OS) 360 µsec
  - HP WS w. A.M. 8 µsec (if can avoid OS)

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Heterogeneity of Workstations

	SPARC	D/MIPS	HP PA	RS/6000	Misc.
Berkeley	100	85	23	5	50
Cornell	150	0	11	1	50
Duke	110	0	0	1	29
Washing.	33	65	2	0	21
Wisconsin	48	228	47	0	99

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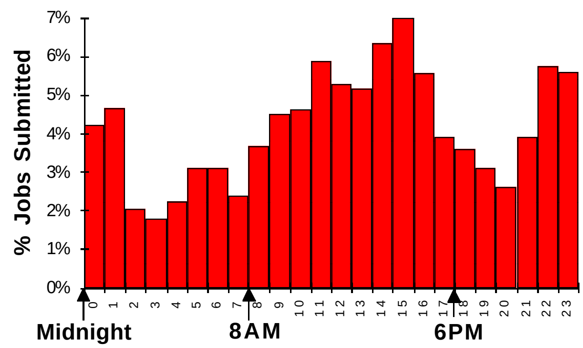
Time of day submit MPP jobs



24% 12am-8am, 52% 8am-6pm => need daytime MPP!

User's View of GLUnix

- **User's workstation + aggregate CPUs, DRAMs, & disks of entire network**
  - **sequential apps run as if on standard UNIX**
  - **parallel apps: *network process***
    - **coordinated scheduling**
    - **single system view of OS services**
- **System must survive node failures, migrate activity away from interactive use**

GLUnix Tradeoffs

If build kernel from scratch:

- **clean, elegant design possible**
- **hard to keep pace with commercial OS development**

If layer on top of unmodified commercial OS:

- **struggle with existing interfaces**
- **work-arounds may exist for common cases**

Goal: look for minimal set of changes to commercial OS that provide most leverage for demanding apps.

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GLUnix Technical Challenges

- **Implementing co-scheduling on top of UNIX kernel**
- **Preserving interactive performance**
- **Fault tolerance – surviving node failures, software upgrades, hardware expansion**
- **Free RAM**
- **Parallel file systems on workstation platforms**

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Technical Challenge: File systems

Technology push to re-think network file systems:

- **Aggregate ATM bandwidth > single disk**
- **workstations cheaper than server machines**
- **tertiary storage to provide infinite capacity**
- **wide area access is slow, expensive and unreliable**

Application pull:

- **high availability is a necessity**
- **peak demand >> average demand**
- **parallel program I/O**

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OS Features for Large Programs

- **Desirable characteristics for Sequential Tasks**
  - reliability
  - use processors for sequential tasks
  - low-overhead user level communication
  - standard services of WS: virtual memory/paging
  - parallel file system for fast I/O
  - system survives node crash
- **Added characteristics for Parallel Tasks**
  - network process
    - » single view of system services (files, sockets, ...)
  - co-ordinatred scheduling of logical program on all nodes
  - effective multiprogramming of sequential interactive programs with parallel programs
  - protected communication

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OS Assessment

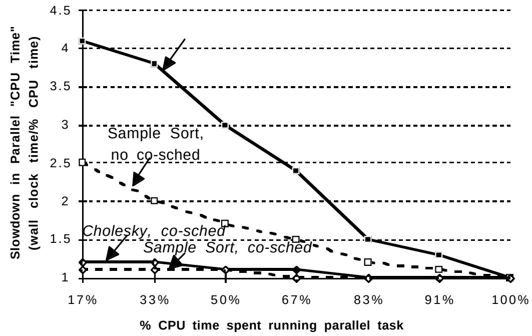
	SBMP	MPP	NOW
reliability	Yes	No	Yes
sequential tasks	Yes	No	Yes
low-overhead comm.	Yes	Yes	No
virtual memory/paging	Yes	No	Yes
parallel file system	No	Yes	No
node crash survival	No	No	Yes
network process	No	Yes	No
co-ordinatred scheduling	No	Yes	No
S/P multiprogramming	No	No	No
protected communication	Yes	No	Yes

- All OS have weaknesses for large, parallel programs!

Co-scheduling Experiment

- How important is co-scheduling to performance on MPP programs?
- Measured on CM-5 inserting random process to vary the amount of time processor runs parallel task vs. an independent serial task
- Two programs: Cholesky and Sample sort, with and without co-scheduling: 2.5 to 4X vs. 1.1 to 1.2 with
- Third program, EM3D, goes off the chart without co-scheduling at 17% parallel task (35X slower) vs. 1.2 with co-scheduling
- But skew in time slices not critical

Co-Schedulilng Value



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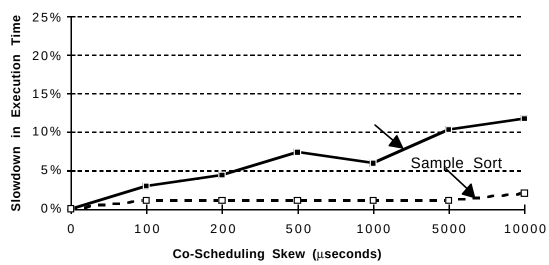
Value of exact start times of process co-scheduling



- **Large skews in synchronization of process start times make little difference in run time**
- **Expect real skews < 1000 µsecs (5% impact)**
- **Conclusion: Effective co-scheduling plausible for NOWs**

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How About Reliability of WS HW/OS?

- Do workstations fail so frequently that can't handle MPP workload? (all parallel machines stall until dead system reboots)
- 58 DECstation 5000s measured for > 1 year
  - Only 1 time/year all machines unavailable (power failure)
  - 632 reboots: 345 Shutdowns + 1 power failure for 58 machines + 229 surprises
  - Virtually every time run in degraded mode

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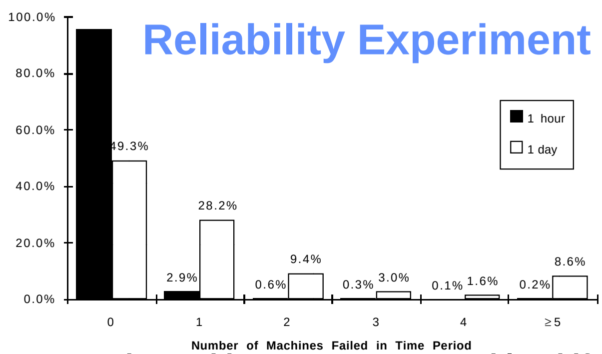
Reliability Experiment



- Estimated impact on MPP workload if this sample generalizes
  - Chance of ≥1 machine of 58 reboot in 1 hour is 4%
  - Chance of ≥1 machine of 58 reboot in 1 day is 50%
  - Chance of non-user directed reboot in 1 hour is<2%
  - Chance of non-user directed reboot in 1 day is <25%
- Not a problem if jobs << 1 hour

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MPP Workload & NOW Reliability

- Automatically checkpoint jobs that run longer than 30 minutes every 30 minutes
- Restart if crash
- If checkpoint takes 1 minute & lose 2% jobs taking >30 minutes, total extra time for long jobs:

  $\approx$ 4 x 1 min + 2% x (30/2) = 4.6 minutes
- <5% overhead to make it very likely to finish very long jobs

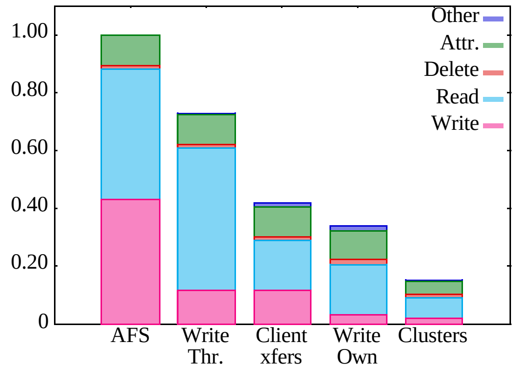
xFS vs. AFS: Server Load

- Simulation using Berkeley Auspex NFS Traces: 4 Networks, 237 Clients, 6 Days (+1 Day of Cache Warming)
  - Networks, CPUs, In-Memory File Caches, Disks

	Server Messages	Server Data	Server Load
AFS	1.4 M	15.2 GB	100%
xFS	0.4 M	0.0 GB	15%

- 6:1 Reduction in Server Load
- Network Bytes Through Server Reduced More Than 99%

xFS vs. AFS: Server Graph



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Example: Global Climate Model

- GCM program Gator
  - For a 4° by 5° section of Earth (L.A. Basin)
  - 20 vertical layers and 92 chemical species
  - 2 part computation: ODE + Transport
- Simulated time: 12 hours => 36 B FLOPS
- Input from disk=> 3.9 GB over run (1 byte every 8 FLOPS); 51 MB output to disk
- Want 10 to 50 years of simulated climate
- Single IBM RS/6000 over network to disk:
  - 2 hours on machine /12 simulated hours!
  - 8 years to simulate 50 years!
  - >50% time in I/O

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NOW Benefits Sequential Programs: “Network DRAM, Network Disk”

- **New Level of the Memory Hierarchy:**

	Latency (µsec)	BW (MB/s)	Size (MB)	Cost	Cost/ MB ($/MB)
Cache	0.032	500	0.25	$500	$2000
DRAM	0.32	50	64	$2500	$40
Network RAM	20*	15	6400	$2000	$0.30
Disk	10,000	2	1000	$1000	$1.00
Network Disk	10,250*	15	100000	$2000	$0.02

(* provided have low overhead network interface that avoids OS)

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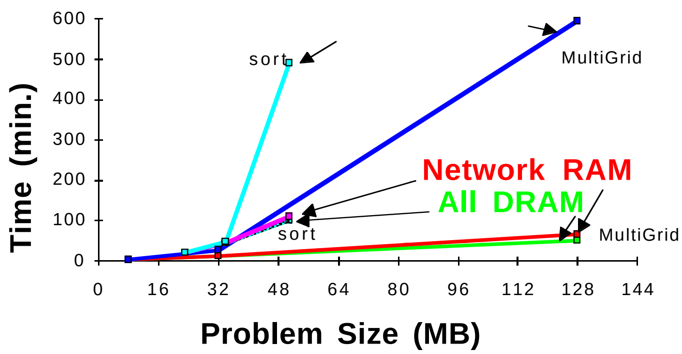
Network RAM simulations:



1.1 to 1.3X slower v. all DRAM; 4X to 9X faster v. disk

NOW 58