Scale and Performance in a Distributed File System

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15-712 F15

Lecture 9

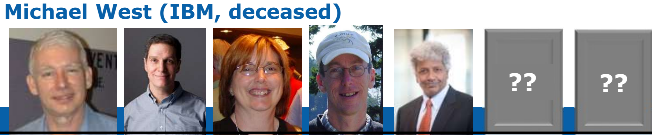
Today's Reminders

- **Office Hours**
  - TA Kevin Hsieh as office hours 2-4 Tues
- **Summaries**
  - Everyone should be able to see each other's summaries 2 days after
- **Projects**
  - Should be formed by Wed so can start brainstorming ideas
  - Week after that: we will post possible project ideas
  - OK (encouraged) to overlap project idea with current research under advisor

Scale and Performance in a Distributed File System

SigOps HoF paper [SOSP'87, TOCS 1988]

- **John Howard (Project Lead, retired from Sun)**
- **Michael Kazar (CTO Avere, IEEE Info Storage Sys Award)**
  Co-founded Transarc (commercial AFS, acquired by IBM)
- **Sherri Menees [Nichols] (community activist, Redmond WA)**
- **David Nichols (Microsoft, start-up became Live Meeting)**
- **M. Satyanarayanan (CMU, ACM & IEEE Fellow)**
- **Robert Sidebotham (Google, inventor of volumes)**
- **Michael West (IBM, deceased)**



Andrew v.1

- **Morris, Satyanarayanan, Conner, Howard, Rosenthal, Smith "Andrew: A Distributed Personal Computing Environment" [CACM 1986]**
  - started in 1983
- **Prototype had 400 users, 100 workstations, 6 servers**
- **Cache whole file locally: contact server (Vice) only on file open/close**
- **Each directory had a single server site for updates**
- **File location: Navigate server directory with stub directories pointing to other servers**

Why Whole File Caching

- **Workload locality makes caching attractive**
- **Servers only contacted on opens/closes**
- **Most files read in their entirety:**
  - Can use efficient bulk data transfer protocols
- **Disk caches retain contents across (frequent) reboots**
- **Simplifies cache management**

Qualitative Observations on v.1

- **Commands were noticeably slower than w/local files**

"The performance was so much better than that of the heavily loaded timesharing systems…that our users willingly suffered!"

- **Performance anomaly**
  - Apps used the "stat" primitives to test for presence of files or obtain status info before opening them – many client-server interactions
- **Difficult to operate & maintain**
  - Use of dedicated process per client on each server: excessive context switches, page faults, resource exhaustion
  - Kernel RPC support: network-related resource exhaustion
  - Stub directories: difficult to migrate directories between servers

Benchmark

"Although we do not demonstrate any statistical similarity between these file references and those observed in real systems,…"

MakeDir	Constructs a target subtree that is identical in structure to the source subtree.
Copy	Copies every file from the source subtree to the target subtree.
ScanDir	Recursively traverses the target subtree and examines the status of every file in it. It does not actually read the contents of any file.
ReadAll	Scans every byte of every file in the target subtree once.
Make	Compiles and links all the files in the target subtree.

70 files, 200 KB total

Table I. Stand-alone Benchmark Performance

Benchmark phase	Machine type: Sun2	IBM RT/25	Sun3/50
Overall	1054 (5)	798 (20)	482 (8)
MakeDir	16 (1)	13 (1)	10 (0)
Copy	40 (1)	37 (2)	31 (2)
ScanDir	70 (4)	51 (9)	44 (5)
ReadAll	106 (2)	132 (8)	51 (0)
Make	822 (2)	566 (11)	346 (1)

Performance Observations on v.1

- **Avg file-cache hit ratio 81%; status-cache hit ratio 82%**

Table II. Distribution of Vice Calls in Prototype

Server	Total calls	Call distribution: TestAuth (%)	GetFileStat (%)	Fetch (%)	Store (%)	SetFileStat (%)	ListDir (%)	All others (%)
cluster0	1,625,954	64.2	28.7	3.4	1.4	0.8	0.6	0.9
cluster1	564,981	64.5	22.7	3.1	3.5	2.8	1.3	2.1
cmu-0	281,482	50.7	33.5	6.6	1.9	1.5	3.6	2.2
cmu-1	1,527,960	61.1	29.6	3.8	1.1	1.4	1.8	1.2
cmu-2	318,610	68.2	19.7	3.3	2.7	2.3	1.6	2.2
Mean		61.7 (6.7)	26.8 (5.6)	4.0 (1.5)	2.1 (1.0)	1.8 (0.8)	1.8 (1.1)	1.7 (0.6)

- TestAuth: validates cache entries
- GetFileStat: status info about files not in cache

Performance Observations on v.1

Table III. Prototype Benchmark Performance

Load units	Overall benchmark time: Absolute (s)	Overall benchmark time: Relative (%)	Time per TestAuth call: Absolute (ms)	Time per TestAuth call: Relative (%)
1	1789 (3)	100	87 (0)	100
2	1894 (4)	106	118 (1)	136
5	2747 (48)	154	259 (16)	298
8	5129 (177)	287	670 (23)	770
10	7326 (69)	410	1050 (13)	1207

Recall: Absolute stand-alone = 1054 (s)

Significant performance gains possible if:

- Reduce the frequency of cache validity checks (TestAuth)
- Reduce the number of server processes
- Require clients rather than servers to do pathname traversals
- Balance server usage by reassigning users

Cache Management Changes

- **Cache contents of directories & symbolic links**
- **On open, assume cached entries are valid**
  - Server does Callback to client cache before allowing others to update the file
- **Pros:**
  - Reduces load on servers
  - Enables pathnames resolved locally
- **Cons:**
  - Client caches & Servers must maintain callback state
  - Such state may become inconsistent

Changes to Name Resolution & Low-Level Storage Representation

- **Each Vice file or directory identified by Fid**
  - (32-bit volume #, 32-bit vnode #, 32-bit uniquifier)
  - Vnode = BSD inode
- **Volume Location Directory replicated on each server**
- **Can migrate files between servers w/o invalidating locally cached directory contents**

Volume

- **Collection of files forming a partial subtree name space**
- **Glued together at Mount Points (invisible to name space)**
- **Resides within a single disk partition on a server**
- **On-the-fly (atomic) migration:**
  - Create a Clone (copy-on-write snapshot)
  - Construct machine-independent rep of Clone
  - Regenerate at remote site
  - Any updates during migration patched using incremental clone
- **User assigned a volume; each volume has a quota**
- **Read-only volume replicas improve availability & efficiency**

Volumes

- **Provide a level of operational transparency not supported by other file systems**
  - From an operation standpoint, system is a flat space of named volumes
- **Quite valuable: Volume quotas & Ease of migration**
- **Backup mechanism is simple, efficient, non-disruptive**
  - Read-only clone transferred in background to staging machine
  - 24 hours of backup in read-only subtree in user's home dir

Communication & Server Process Structure

- **Single server process to service all its clients**
  - ~5 Lightweight processes (LWPs) within a process
  - LWP bound to a client only for duration of a single server op
- **RPC code no longer in kernel**
  - Later argue that other AFS code SHOULD be in kernel

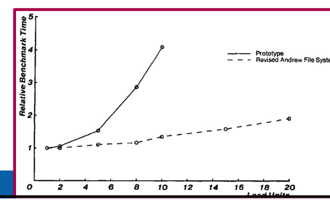
File Consistency

- **Writes to an open file by a client process are visible to all other local processes immediately but invisible non-locally**
- **Writes become visible on file close**
  - Changes visible to any new open, invisible to already open
- **All other file ops are visible everywhere on op completion**
- **No implicit locking: apps have to do own synchronization**

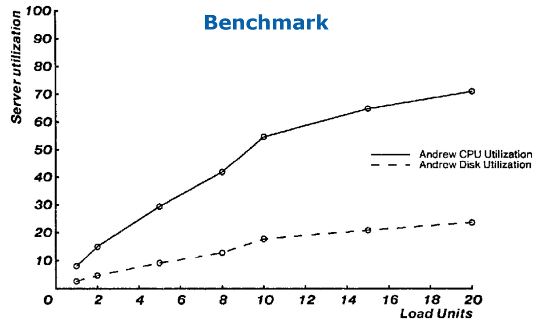
Scalability Improvements

Table VI. Andrew Benchmark Times

Load units	Overall time (in seconds)		Time for each phase (in seconds)				
	Absolute	Relative (%)	MakeDir	Copy	ScanDir	ReadAll	Make
1	949 (33)	100	14 (1)	85 (28)	64 (3)	179 (14)	608 (16)
2	948 (35)	100	14 (1)	82 (16)	65 (9)	176 (13)	611 (14)
5	1050 (19)	111	17 (1)	125 (30)	86 (0)	186 (17)	637 (1)
8	1107 (5)	117	22 (1)	159 (1)	78 (2)	206 (4)	641 (6)
10	1293 (70)	136	34 (9)	209 (13)	76 (5)	200 (7)	775 (81)
15	1518 (28)	160	45 (3)	304 (5)	81 (4)	192 (7)	896 (12)
20	1823 (42)	192	58 (1)	433 (45)	77 (4)	192 (6)	1063 (64)



Utilization Improvements

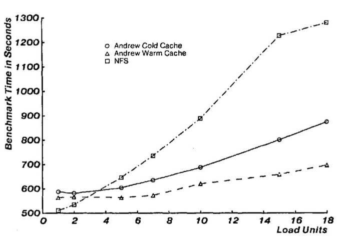


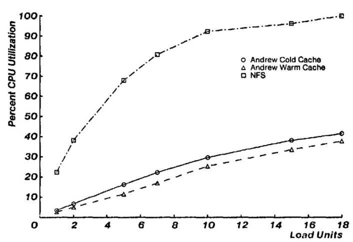
Also showed improved actual utilization during work hours

NFS

- **Once file open, remote site treated like local disk**
  - Return to server for each new page accessed (does prefetch)
  - Caches file pages locally in memory
- **No transparent file location facility; mounted individually**
- **Client & server components are in kernel**
- **Caches inodes locally in memory**
  - Performs validity check on file open
  - Suppressed for directory inodes if checked in last 30 seconds
- **File consistency is messier**

AFS vs. NFS





- **Single server experiments**
- **Some NFS clients terminated prematurely in final phase**
  - Lost RPC reply packets at high network load
- **ReadAll at load 15 & 18: NFS=211-215 vs. AFS=48**

AFS vs. NFS Latency

Table XIV. Latency of NFS and Andrew

File size (bytes)	Time (milliseconds)			
	Andrew cold	Andrew warm	NFS	Stand-alone
3	160.0 (34.6)	16.1 (0.5)	15.7 (0.1)	5.1 (0.1)
1,113	148.0 (17.9)			
4,334	202.9 (29.3)			
10,278	310.0 (53.5)			
24,576	515.0 (142.0)		15.9 (0.9)	

"Low latency is an obvious advantage of remote-open FS"

- **SMALL file sizes studied**
  - Benchmark: avg size is 3 KBs
- **Network Traffic: At load 1, NFS is 3x AFS**

AFS vs. NFS: By Workload

Workload	NFS	AFS	AFS/NFS
1. Small file, sequential read	$N_s \cdot L_{net}$	$N_s \cdot L_{net}$	1
2. Small file, sequential re-read	$N_s \cdot L_{mem}$	$N_s \cdot L_{mem}$	1
3. Medium file, sequential read	$N_m \cdot L_{net}$	$N_m \cdot L_{net}$	1
4. Medium file, sequential re-read	$N_m \cdot L_{mem}$	$N_m \cdot L_{mem}$	1
5. Large file, sequential read	$N_L \cdot L_{net}$	$N_L \cdot L_{net}$	1
6. Large file, sequential re-read	$N_L \cdot L_{net}$	$N_L \cdot L_{disk}$	$\frac{L_{disk}}{L_{net}}$
7. Large file, single read	L_{net}	$N_L \cdot L_{net}$	N_L
8. Small file, sequential write	$N_s \cdot L_{net}$	$N_s \cdot L_{net}$	1
9. Large file, sequential write	$N_L \cdot L_{net}$	$N_L \cdot L_{net}$	1
10. Large file, sequential overwrite	$N_L \cdot L_{net}$	$2 \cdot N_L \cdot L_{net}$	2
11. Large file, single write	L_{net}	$2 \cdot N_L \cdot L_{net}$	$2 \cdot N_L$

- **File sizes N_s, N_m, N_L ; N_L > Local memory**
- **Cold Cache; Latencies: $L_{net} > L_{disk} > L_{mem}$**

From [Operating Systems: Three Easy Pieces]

Performance Conclusions

- **Scales much better than NFS**
  - Claim: Scales to 500-700 clients
  - "We are certain that further growth will stress our skill, patience, and ingenuity."
- **Small-scale performance is nearly on par**
- **NFS in kernel, AFS was not**
  - "There is thus untapped potential for improved performance in Andrew, whereas we see no similar potential in NFS."
- **Supports well-defined consistency semantics, security, operability**

Jim Morris Reflects in AFS at 25

Why WWW beat Global AFS

- Kernel mods were deadly.
  - Forgot Window Manager Lesson
- Consistency was overrated.
  - "Read-only" Web was useful.
  - File close is arbitrary check-point.
- URL was obvious, but crucial.
- HTTP & Browser blindsided us.
- WWW was a paradigm shift. AFS was incremental.

Carnegie Mellon SILICON VALLEY

Leases: An Efficient Fault-Tolerant Mechanism for Distributed File Cache Consistency

Cary Gray & David Cheriton
[SOSP'89]

"This paper pioneered through its analysis of the Leases mechanism, which has become one of the most widely-used mechanisms for managing distributed caches. The paper is particularly striking for its careful analysis of the semantics of leases, its detailed experiments, and its thoughtful discussion of fault-tolerance issues."
– *SigOps HoF citation*

Leases

- **Time-based mechanism that provides efficient consistent access to cached data in distributed systems**
  - Lease grants holder control over writes to the covered data until lease expires
  - Leaseholder can approve request from server to give up lease
- **Non-Byzantine failures affect performance, not correctness**
  - If can't communicate, wait for its leases to expire
  - On recovery, honor leases granted before crash
- **Assumes write-through caches**
- **Leases of short duration (10s) provide good performance**
  - Longer term if accessed repeatedly with little write-sharing
  - AFS went from lease term=0 to effectively a lease term=infinity

Wednesday's Paper

The Design and Implementation of a Log-Structured File System

Mendel Rosenblum & John Ousterhout
[TOCS 1992]

SigOps Hall of Fame paper