File System Design for an NFS File Server Appliance

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http://www.netapp.com/us/library/white-papers/wp_3002.html

(At WPI: http://www.wpi.edu/Academics/CCC/Help/Unix/snapshots.html)

Introduction

- In general, *appliance* is device designed to perform specific function
- Distributed systems trend has been to use appliances instead of general purpose computers. Examples:
  - *routers* from Cisco and Avici
  - network *terminals*
  - network *printers*
- For files, not just another computer with your files, but new type of network appliance
  → *Network File System (NFS) file server*

Introduction: NFS Appliance

- NFS File Server Appliances have different requirements than those of a general purpose file system
  - NFS access patterns are different than local file access patterns
  - Large client-side caches result in fewer reads than writes
- Network Appliance Corporation uses *Write Anywhere File Layout (WAFL)* file system

Introduction: WAFL

- WAFL has 4 requirements
  - Fast NFS service
  - Support large file systems (10s of GB) that can grow (can add disks later)
  - Provide high performance writes and support Redundant Arrays of Inexpensive Disks (RAID)
  - Restart quickly, even after unclean shutdown
- NFS and RAID both strain write performance:
  - NFS server must respond after data is written
  - RAID must write parity bits also

WPI File System

- CCC machines have central, Network File System (NSF)
  - Have same home directory for `cccwork1`, `cccwork2`…
  - `/home` has 9055 directories!
- Previously, Network File System support from NetApp WAFL
- Switched to EMC Celera NS-120
  → similar features and protocol support
- Provide notion of "snapshot" of file system (next)

Outline

- Introduction (done)
- Snapshots : User Level (next)
- WAFL Implementation
- Snapshots: System Level
- Performance
- Conclusions

Introduction to Snapshots

- *Snapshots* are copy of file system at given point in time
- WAFL creates and deletes snapshots automatically at preset times
  - Up to 255 snapshots stored at once
- Uses *copy-on-write* to avoid duplicating blocks in the active file system
- Snapshot uses:
  - Users can recover accidentally deleted files
  - Sys admins can create backups from running system
  - System can restart quickly after unclean shutdown
    - Roll back to previous snapshot

User Access to Snapshots

- Note! Paper uses `.snapshot`, but is `.ckpt`
- Example, suppose accidentally removed file named "`todo`":

```
CCCWORK1% ls -lut .ckpt/*/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.ckpt/2011_10_26_18.15.29_America_New_York/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.ckpt/2011_10_26_19.27.40_America_New_York/todo
-rw-rw---- 1 claypool claypool 4319 Oct 24 18:42
.ckpt/2011_10_26_19.37.10_America_New_York/todo
```

- Can then recover most recent version:

```
CCCWORK1% cp .ckpt/2011_10_26_19.37.10_America_New_York/todo todo
```

- Note, snapshot directories (`.ckpt`) are hidden in that they don't show up with `ls` unless specifically requested

Snapshot Administration

- WAFL server allows sys admins to create and delete snapshots, but usually automatic
- At WPI, snapshots of `/home`:
  - 3am, 6am, 9am, noon, 3pm, 6pm, 9pm, midnight
  - Nightly snapshot at midnight every day
  - Weekly snapshot is made on Saturday at midnight every week
- Thus, always have:
  - 6 hourly
  - 7 daily snapshots
  - 7 weekly snapshots

Snapshots at WPI (Linux)

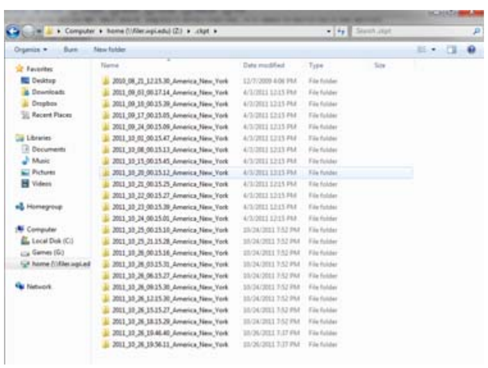
ckpt = "checkpoint"

```
claypool 32 CCCWORK1% pwd
/home/claypool/.ckpt
claypool 33 CCCWORK1% ls
2010_08_21_12.15.30_America_New_York/ 2014_03_23_00.39.23_America_New_York/
2014_02_01_00.34.45_America_New_York/ 2014_03_24_00.39.45_America_New_York/
2014_02_08_00.34.29_America_New_York/ 2014_03_24_09.39.26_America_New_York/
2014_02_15_00.35.58_America_New_York/ 2014_03_24_12.39.24_America_New_York/
2014_02_22_00.35.50_America_New_York/ 2014_03_24_15.39.33_America_New_York/
2014_03_01_00.37.14_America_New_York/ 2014_03_24_18.39.25_America_New_York/
2014_03_08_00.38.25_America_New_York/ 2014_03_24_21.39.35_America_New_York/
2014_03_15_00.38.11_America_New_York/ 2014_03_25_00.39.53_America_New_York/
2014_03_19_00.38.23_America_New_York/ 2014_03_25_03.39.11_America_New_York/
2014_03_20_00.38.47_America_New_York/ 2014_03_25_06.28.53_America_New_York/
2014_03_21_00.39.06_America_New_York/ 2014_03_25_06.38.33_America_New_York/
2014_03_22_00.39.45_America_New_York/ 2014_03_25_06.39.19_America_New_York/
```

- 24? Not sure of times …

Snapshots at WPI (Windows)

- Mount UNIX space, add `.ckpt` to end



- Can also right-click on file and choose "restore previous version"

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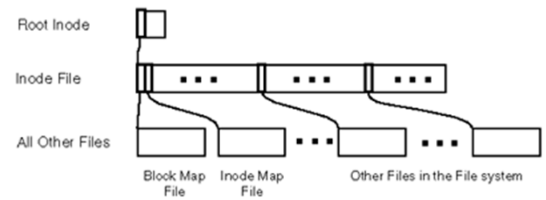
WAFL File Descriptors

- I-node based system with 4 KB blocks
- I-node has 16 pointers, which vary in type depending upon file size
  - For files smaller than 64 KB:
    - Each pointer points to data block
  - For files larger than 64 KB:
    - Each pointer points to indirect block
  - For really large files:
    - Each pointer points to doubly-indirect block
- For very small files (less than 64 bytes), data kept in i-node instead of pointers

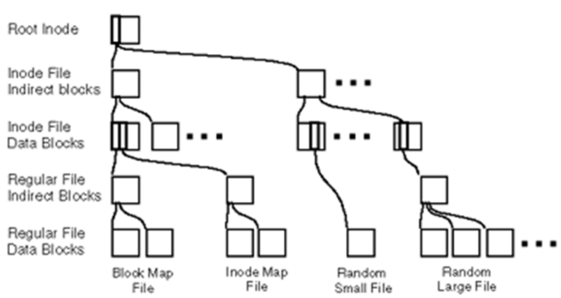
WAFL Meta-Data

- Meta-data stored in files
  - I-node file – stores i-nodes
  - Block-map file – stores free blocks
  - I-node-map file – identifies free i-nodes



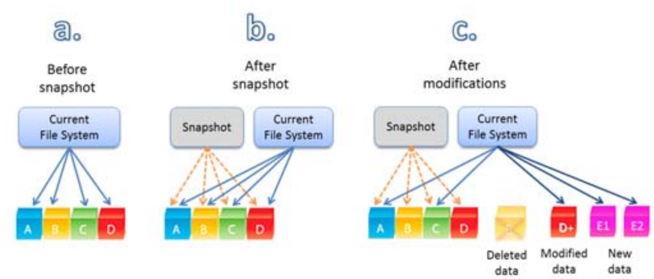
Zoom of WAFL Meta-Data (Tree of Blocks)

- Root i-node must be in fixed location
- Other blocks can be written anywhere



Snapshots (1 of 2)

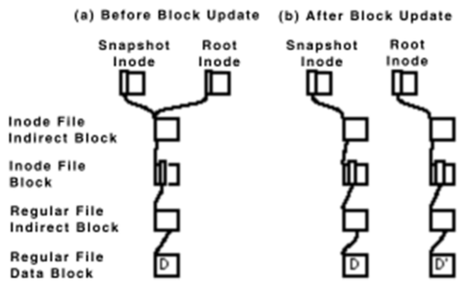
- Copy root i-node only, copy on write for changed data blocks



- Over time, old snapshot references more and more data blocks that are not used
- Rate of file change determines how many snapshots can be stored on system

Snapshots (2 of 2)

- When disk block modified, must modify meta-data (indirect pointers) as well



- Batch, to improve I/O performance

Consistency Points (1 of 2)

- In order to avoid consistency checks after unclean shutdown, WAFL creates special snapshot called *consistency point* every few seconds
  - Not accessible via NFS
- Batched operations are written to disk each consistency point
- In between consistency points, data only written to RAM

Consistency Points (2 of 2)

- WAFL uses NVRAM (NV = Non-Volatile):
  - (NVRAM is DRAM with batteries to avoid losing during unexpected poweroff, some servers now just solid-state or hybrid)
  - NFS requests are logged to NVRAM
  - Upon unclean shutdown, re-apply NFS requests to last consistency point
  - Upon clean shutdown, create consistency point and turnoff NVRAM until needed (to save power/batteries)
- Note, typical FS uses NVRAM for metadata write cache instead of just logs
  - Uses more NVRAM space (WAFL logs are smaller)
    - Ex: "rename" needs 32 KB, WAFL needs 150 bytes
    - Ex: write 8 KB needs 3 blocks (data, i-node, indirect pointer), WAFL needs 1 block (data) plus 120 bytes for log
  - Slower response time for typical FS than for WAFL (although WAFL may be a bit slower upon restart)

Write Allocation

- Write times dominate NFS performance
  - Read caches at client are large
  - Up to 5*x* as many write operations as read operations at server
- WAFL batches write requests (e.g., at consistency points)
- WAFL allows "write anywhere", enabling i-node next to data for better perf
  - Typical FS has i-node information and free blocks at fixed location
- WAFL allows writes in any order since uses consistency points
  - Typical FS writes in fixed order to allow `fsck` to work if unclean shutdown

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The Block-Map File

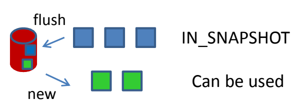
- Typical FS uses bit for each free block, 1 is allocated and 0 is free
  - Ineffective for WAFL since may be other snapshots that point to block
- WAFL uses 32 bits for each block
  - For each block, copy "active" bit over to snapshot bit

Time	Block-Map Entry	Description
t1	00000000	Block is unused
t2	00000001	Block is allocated for active FS
t3	00000011	Snapshot #1 is created
t4	00000111	Snapshot #2 is created
t5	00000110	Block is deleted from active FS
t6	00000110	Snapshot #3 is created
t7	00000100	Snapshot #1 is deleted
t8	00000000	Snapshot #2 is deleted; block is unused

bit 0: set for active file system
bit 1: set for Snapshot #1
bit 2: set for Snapshot #2
bit 3: set for Snapshot #3

Creating Snapshots

- Could suspend NFS, create snapshot, resume NFS
  - But can take up to 1 second
- Challenge: avoid locking out NFS requests
- WAFL marks all dirty cache data as IN_SNAPSHOT. Then:
  - NFS requests can read system data, write data not IN_SNAPSHOT
  - Data not IN_SNAPSHOT not flushed to disk
- Must flush IN_SNAPSHOT data as quickly as possible



Flushing IN_SNAPSHOT Data

- Flush i-node data first
  - Keeps two caches for i-node data, so can copy system cache to i-node data file, unblocking most NFS requests
    - Quick, since requires no I/O since i-node file flushed later
- Update block-map file
  - Copy active bit to snapshot bit
- Write all IN_SNAPSHOT data
  - Restart any blocked requests as soon as particular buffer flushed (don't wait for all to be flushed)
- Duplicate root i-node and turn off IN_SNAPSHOT bit

- All done in less than 1 second, first step done in 100s of ms

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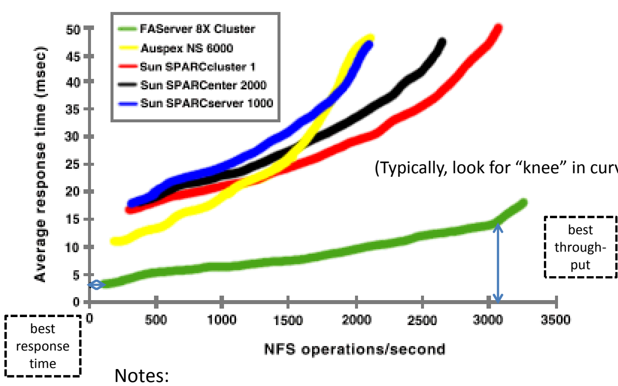
Performance (1 of 2)

- Compare against other NFS systems
- How to measure NFS performance?
  - Best is SPEC NFS
    - LADDIS: Legato, Auspex, Digital, Data General, Interphase and Sun
- Measure response times versus throughput
  - Typically, servers quick at low throughput then response time increases as throughput requests increase
- (Me: System Specifications?!)

Performance (2 of 2)

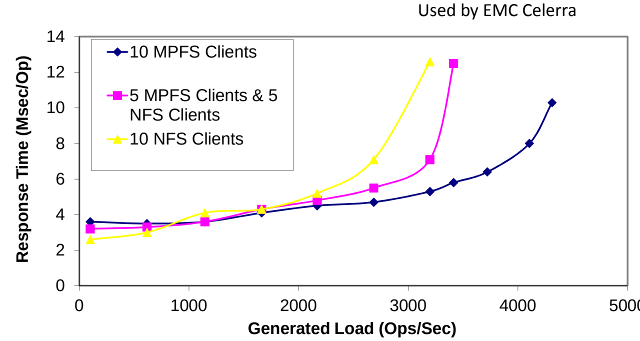


(Typically, look for "knee" in curve)

Notes:
+ FAS has only 8 file systems, and others have dozens
- FAS tuned to NFS, others are general purpose

NFS vs. Newer File Systems

MPFS = multi-path file system
Used by EMC Celerra



- Remove NFS server as bottleneck
- Clients write directly to device

Conclusion

- NetApp (with WAFL) works and is stable
  - Consistency points simple, reducing bugs in code
  - Easier to develop stable code for network appliance than for general system
    - Few NFS client implementations and limited set of operations so can test thoroughly
- WPI bought one ☺