Windows Kernel Internals
Cache Manager

David B. Probert, Ph.D.

Windows Kernel Development

Microsoft Corporation

What is the Cache Manager?

- Set of kernel-mode routines and asynchronous worker routines that form the interface between filesystems and the memory manager for Windows NT

Cache Manager Functionality

- Access methods for pages of file data on opened files
- Automatic asynchronous read ahead
- Automatic asynchronous write behind (lazy write)
- Supports “Fast I/O” – IRP bypass

Who Uses the Cache Manager?

- Disk File Systems (NTFS, FAT, CDFS, UDFS)
- Windows File Server(s)
- Windows Redirector
- Registry (as of Windows XP)

What Can Be Cached?

- User data streams
- File system metadata
  - directories
  - transaction logs
  - NTFS MFT
  - synthetic structures – FAT’s Virtual Volume File
- … anything that can be represented as a stream of bytes

Virtual Block vs Logical Block Cache

- More traditional approach is logical block cache (SmartDrive):
  - File+FileOffset translated by file system into one or more partition offsets
  - Each partition offset translated by cache manager to cache address
- In a virtual block cache:
  - File+FileOffset translated by cache manager to cache address, its memory mapping!

Advantages of Virtual Block Cache integrated with VM

- Single memory manager
  - the actual “cache” manager!
- Data cache is dynamically sized – just another working set
- Cache coherency with user mapped files is free

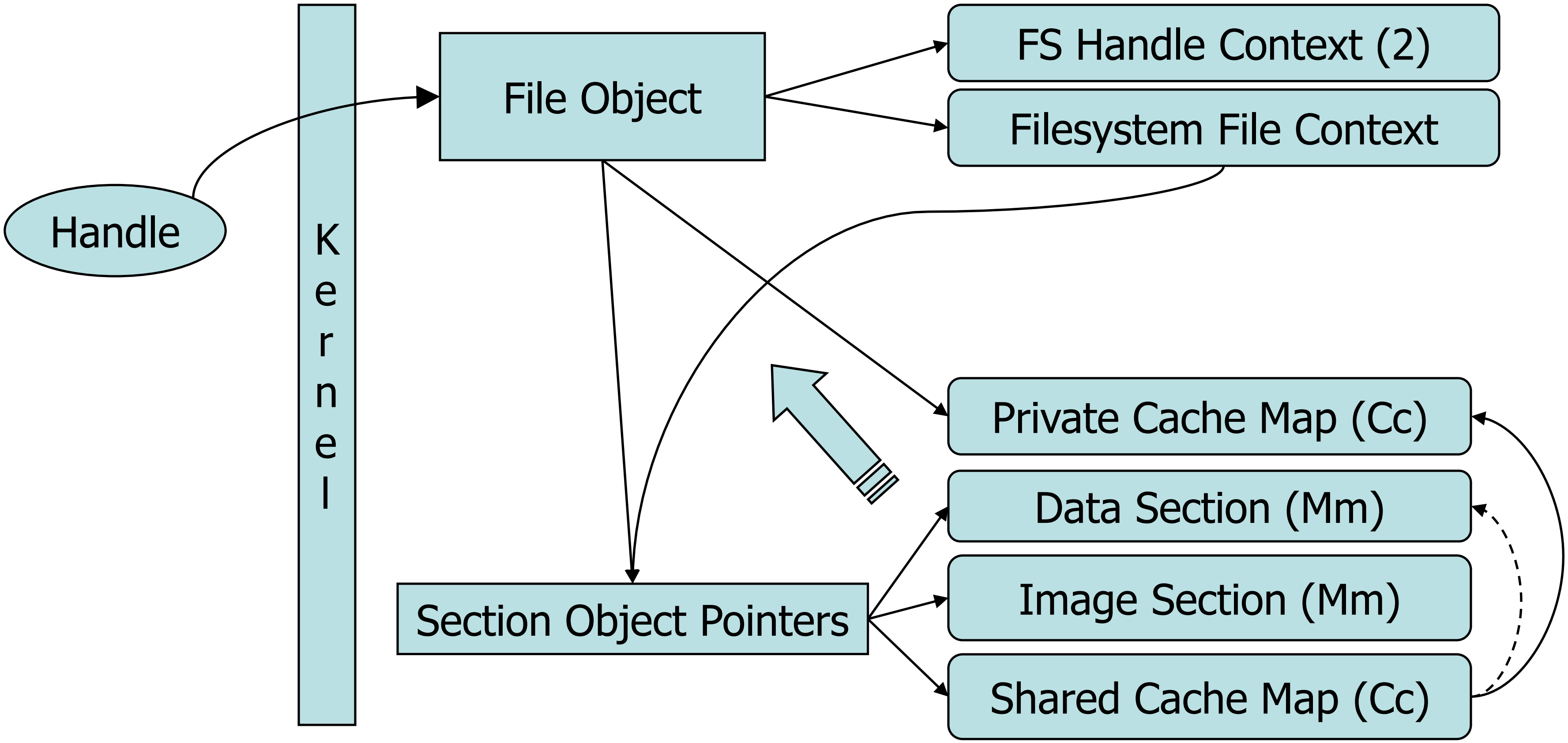
How Does It Work?

- Mapped stream model integrated with memory management
- Cached streams are mapped with fixed-size views (256KB)
- Pages are faulted into memory via MM
- Pages may be modified in memory and written back
- MM manages global memory policy

Cache Addresses

- MM allocated kernel VA range (512MB +)
  - common: 0xc1000000 – 0xe0000000
- Visible in all kernel-mode contexts
- Member of the System Cache working set (includes paged pool and code)
  - this is what Task Manager shows you!
  - not just the "file" cache, though it does frequently dominate
- Competes for physical memory
- "Owned" by Cache Manager

Datastructure Layout



- File Object == Handle (U or K), *not one per file*
- Section Object Pointers and FS File Context are the same for all file objects for the same stream

Datastructures

- File Object
  - FsContext – per physical stream context
  - FsContext2 – per user handle stream context, not all streams have handle context (metadata)
  - SectionObjectPointers – the point of “single instancing”
    - DataSection – exists if the stream has had a mapped section created (for use by Cc or user)
    - SharedCacheMap – exists if the stream has been set up for the cache manager
    - ImageSection – exists for executables
  - PrivateCacheMap – per handle Cc context (readahead) that also serves as reference from this file object to the shared cache map

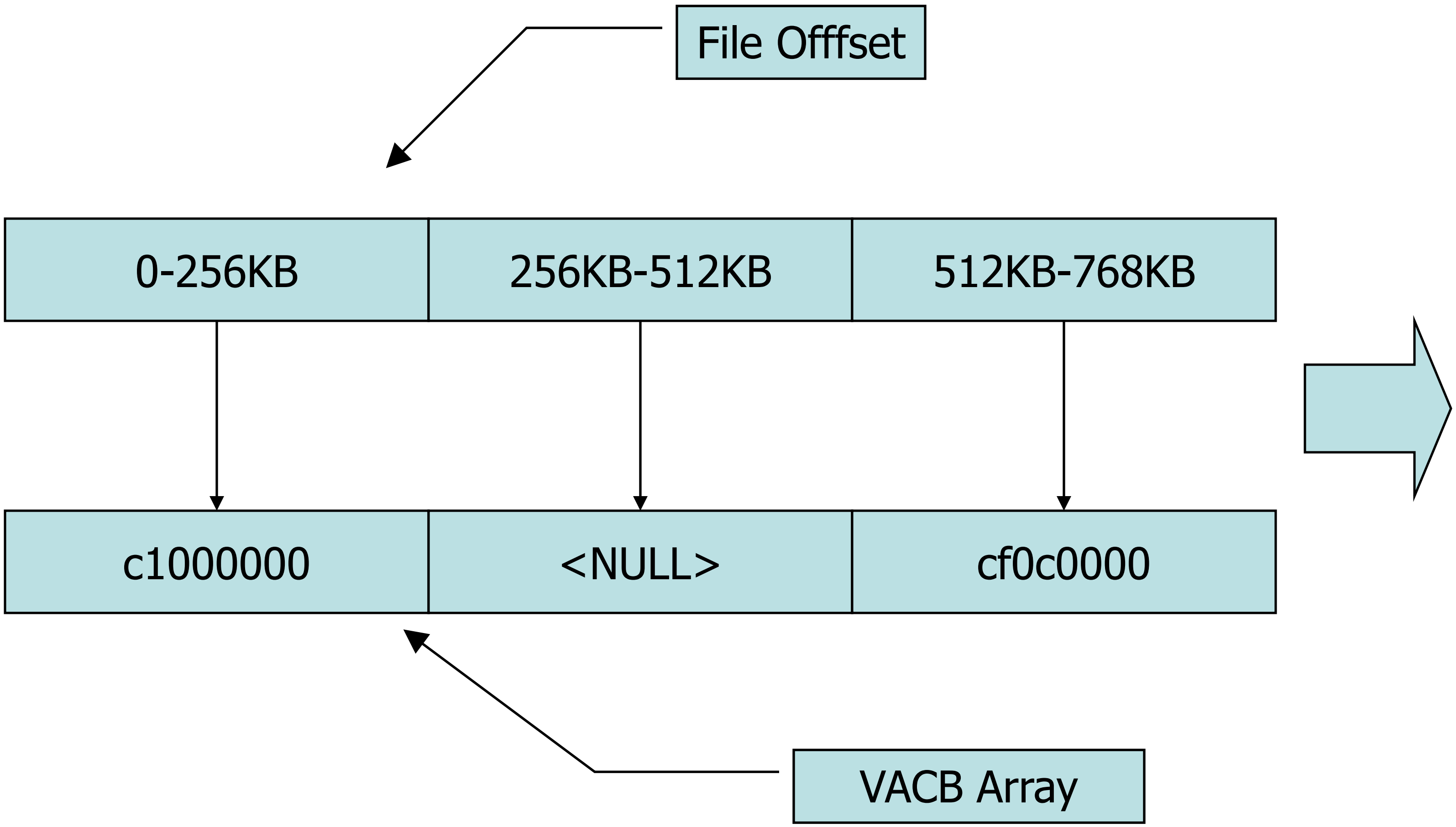
Single Instancing & Metadata

- Although filesystems represent metadata as streams, they are not exported to user mode
- Directories require a level of indirection to escape single instancing exposing the data
- Filesystems create a second internal “stream” fileobject
  - user’s fileobject has NULL members in its Section Object Pointers
  - stream fileobjects have no FsContext2 (user handle context)
- All metadata streams are built like this (MFTs, FATs, etc.)
- FsContext2 == NULL plays an important role in how Cc treats these streams, which we’ll discuss later.

View Management

- A Shared Cache Map has an array of View Access Control Block (VACB) pointers which record the base cache address of each view
  - promoted to a sparse form for files > 32MB
- Access interfaces map File+FileOffset to a cache address
- Taking a view miss results in a new mapping, possibly unmapping an unreferenced view in another file (views are recycled LRU)
- Since a view is fixed size, mapping across a view is impossible – Cc returns one address
- Fixed size means no fragmentation …

View Mapping



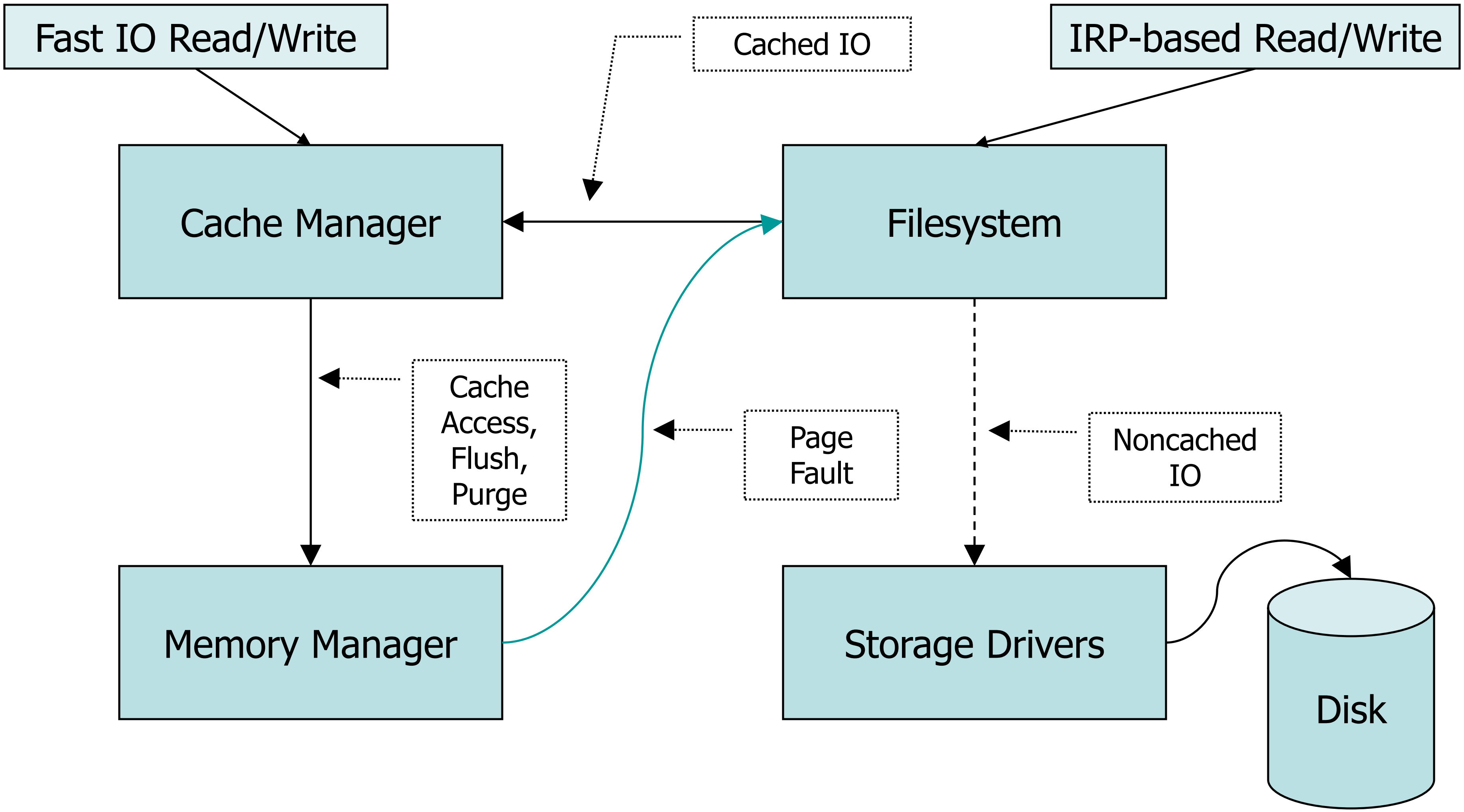
Interface Summary

- File objects start out unadorned
- CcInitializeCacheMap to initiate caching via Cc on a file object
  - setup the Shared/Private Cache Map & Mm if neccesary
- Access methods (Copy, Mdl, Mapping/Pinning)
- Maintenance Functions
- CcUninitializeCacheMap to terminate caching on a file object
  - teardown S/P Cache Maps
  - Mm lives on. *Its data section is the cache!*

The Cache Manager Doesn’t Stand Alone

- Cc is an extension of either Mm or the FS depending how you look at it
- Cc is intimately tied into the filesystem model
- Understanding Cc means we have to take a slight detour to mention some concepts filesystem folks think are interesting. Raise your hand if you’re a filesystem person :-)

The Big Block Diagram



The Slight Filesystem Digression

- Three basic types of IO on NT: cached, noncached and “paging”
- Paging IO is simply IO generated by Mm – flushing or faulting
  - the data section implies the file is big enough
  - can never extend a file
- A filesystem will re-enter itself on the same callstack as Mm dispatches cache pagefaults
- This makes things exciting! (ERESOURCEs)

The Three File Sizes

- FileSize – how big the file looks to the user
  – 1 byte, 102 bytes, 1040592 bytes
- AllocationSize – how much backing store is allocated on the volume
  – multiple of cluster size, which is 2^n * sector size
  – ... a more practical definition shortly
- ValidDataLength – how much of the file has been written by the user in cache, zeros seen beyond (some OS use sparse allocation)
- ValidDataLength <= FileSize <= AllocationSize

Valid Data Length

- The Win32 model expects full allocation of files (STATUS_DISK_FULL is uncool)
- Writing zeroes is expensive, but users tend to write files front to back
- Windows FS keep track of this as a high-water mark
- If the user reads beyond VDL, we may be able to get clever and not bother the filesystem at all.
- If a user writes beyond VDL, zeroing of a “hole” may be required
- Never SetEndOfFile and write at the end if you can help it!

How to get data *into* the cache

Fast IO – Who Needs an FS?

- Fast IO paths short circuit the IO to a common FsRtl routine or filesystem-provided call
- This is just memory mapped IO, synchronizing with the FS for …
- Extending FileSize up to AllocationSize!
  - VDL zeroing means the cache data is already good
  - Hint set in fileobject so FS will update directory
- Extending ValidDataLength up to FileSize

Regular Cached IO

- Filesystems also implement a cached path
- Basically the same logic as the Fast IO path (or vice versa, depending)
- Reuses the same Cc functions
- Why not use Fast IO all the time?
  - file locks
  - oplocks
  - extending files (and so forth)

Copy Method

- Used for user cached IO, both fast and IRP based
- CcCopyRead maps and copies a mapped cache byte range into a buffer
- CcCopyWrite copies a buffer into a mapped cache byte range and marks the range for writing
- "Fast" versions of each are really the same code, but only taking 32bit fileoffsets
  – NT used to run on 386s! :-)

Mdl (DMA) Method

- Used by network transport layers
- CcMdlRead returns an Mdl describing specified byte range
- CcMdlReadComplete frees the Mdl
- CcPrepareMdlWrite returns an Mdl describing specified byte range (may contain “smart” zeros with respect to VDL)
- CcMdlWriteComplete frees the Mdl and marks range for writing

Pagefault Cluster Hints

- Taking a pagefault can result in Mm opportunistically bringing surrounding pages in (up 7/15 depending)
- Since Cc takes pagefaults on streams, but knows a lot about which pages are useful, Mm provides a hinting mechanism in the TLS
  - MmSetPageFaultReadAhead()
- Not exposed to usermode …

Readahead

- CcScheduleReadAhead detects patterns on a handle and schedules readahead into the next suspected ranges
  - Regular motion, backwards and forwards, with gaps
  - Private Cache Map contains the per-handle info
  - Called by CcCopyRead and CcMdlRead
- Readahead granularity (64KB) controls the scheduling trigger points and length
  - Small IOs – don't want readahead every 4KB
  - Large IOs – ya get what ya need (up to 8MB, thanks to Jim Gray)
- CcPerformReadAhead maps and touch-faults pages in a Cc worker thread, will use the new Mm prefetch APIs in a future release

Unmap Behind

- Recall how views are managed (misses)
- On view miss, Cc will unmap two views behind the current (missed) view before mapping
- Unmapped valid pages go to the standby list in LRU order and can be soft-faulted. In practice, this is where much of the actual cache is as of Windows 2000.
- Unmap behind logic is default due to large file read/write operations causing huge swings in working set. Mm's working set trim falls down at the speed a disk can produce pages, Cc must help.

Cache Hints

- Cache hints affect both read ahead and unmap behind
- Two flags specifiable at Win32 CreateFile()
- FILE_FLAG_SEQUENTIAL_SCAN
  – doubles readahead unit on handle, unmaps to the *front* of the standby list (MRU order) if all handles are SEQUENTIAL
- FILE_FLAG_RANDOM_ACCESS
  – turns off readahead on handle, turns off unmap behind logic if any handle is RANDOM
- Unfortunately, there is no way to split the effect

Write Throttling

- Avoids out of memory problems by delaying writes to the cache
  - Filling memory faster than writeback speed is not useful, we may as well run into it sooner
- Throttle limit is twofold
  - CcDirtyPageThreshold – dynamic, but ~1500 on all current machines (small, but see above)
  - MmAvailablePages & pagefile page backlog
- CcCanIWrite sees if write is ok, optionally blocking, also serving as the restart test
- CcDeferWrite sets up for callback when write should be allowed (async case)
- !defwrites debugger extension triages and shows the state of the throttle

Writing Cached Data

- There are three basic sets of threads involved, only one of which is Cc's
  - Mm's modified page writer
    - the paging file
  - Mm's mapped page writer
    - almost anything else
  - Cc's lazy writer pool
    - executing in the kernel critical work queue
    - writes data produced through Cc interfaces

The Lazy Writer

- Name is misleading, its really *delayed*
- All files with dirty data have been queued onto CcDirtySharedCacheMapList
- Work queueing – CcLazyWriteScan()
  - Once per second, queues work to arrive at writing 1/8th of dirty data given current dirty and production rates
  - Fairness considerations are interesting
- CcLazyWriterCursor rotated around the list, pointing at the next file to operate on (fairness)
  - 16th pass rule for user and metadata streams
- Work issuing – CcWriteBehind()
  - Uses a special mode of CcFlushCache() which flushes front to back (HotSpots – fairness again)

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Valid Data Length Calls

- Cache Manager knows highest offset successfully written to disk – via the lazy writer
- File system is informed by special FileEndOfFileInformation call after each write which extends/maintains VDL
- FS which persist VDL to disk (NTFS) push that down here
- FS use it as a hint to update directory entries (recall Fast IO extension, one among several)
- CcFlushCache() flushing front to back is important so we move VDL on disk as soon as possible.

Letting the Filesystem Into The Cache

- Two distinct access interfaces
  - Map – given File+FileOffset, return a cache address
  - Pin – same, but acquires synchronization – this is a range lock on the stream
    - Lazy writer acquires synchronization, allowing it to serialize metadata production with metadata writing
- Pinning also allows setting of a log sequence number (LSN) on the update, for transactional FS
  - FS receives an LSN callback from the lazy writer prior to range flush

Remember FsContext2?

- Synchronization on Pin interfaces requires that Cc be the writer of the data
- Mm provides a method to turn off the mapped page writer for a stream, MmDisableModifiedWriteOfSection()
  - confusing name, I know (modified writer is not involved)
- Serves as the trigger for Cc to perform synchronization on write

Mapping/Pinning Method

- CcMapData to map byte range for read access
- CcPinRead to map byte range for read/write access
- CcPreparePinWrite
- CcPinMappedData
- CcSetDirtyPinnedData
- CcUnpinData

BCBs and Lies Thereof

- Mapping and Pinning interfaces return opaque Buffer Control Block (BCB) pointers
- Unpin receives BCBs to indicate regions
- BCBs for Map interfaces are usually VACB pointers
- BCBs for Pin interfaces are pointers to a real BCB structure in Cc, which references a VACB for the cache address

Basic Maintenance Functions

- CcSetFileSizes
  - used by FS to tell Cc/Mm when it changes file sizes
  - updates VDL goal for the callback
  - extends data sections, purges on truncate
- CcFlushCache
- CcPurgeCacheSection
- CcZeroData
  - used during VDL zeroing for MDL hack
- ... and a few others, of course

Cc Grab Bag

- Every component has them, lets take a short tour of some of the more interesting ones
- This is the R-rated portion of today's presentation :-)

We Can’t Use That 16GB

- It takes on the order of 2-3KB pool (minimum) to cache a single stream once the handle has been closed
- Cc structures are torn down at handle close
- File object, Filesystem contexts (FCB, CCB, MCB) Mm section structures, PTEs, etc. remain, and add up.
- If cache is dominated by small files, pool limits dominate ability to cache. Mm must trim files from the cache if pool fills.
- This dramatically limits the effective cache size on large machines in reasonable scenarios
- Motivates thinking about a large-machine cache at the volume level (block cache!), much to our chagrin – lower overhead per page of data

Single Instancing is Security Context Insensitive

- What is single instancing and why does it matter?
- Recall the datastructures – Mm and Cc need a fileobject to reference. They choose the first fileobject seen for the file.
- Terminal Server creates an unanticipated case – multiple security contexts – a lot more often
- If multiple security contexts reference a file, page faults and flushes still only occur in the context of that first fileobject
- User logs out or SMB connection backing user's fileobject is torn down – oops!

Single Instancing is Security Context Insensitive

- Windows XP SMB RDR must break single instancing down to the security context level to solve.
- This means that each TS session will have a unique data section, and thus cache, for each file that otherwise could be shared between sessions.
- Non optimal. An optimal solution will require a lot of work that isn't well understood yet.

Mapping Is An Expense

- Requires Mm to pick up spinlocks
  - easy case – MP scale problem
- Cc MDL functions have to map part of the cache to build MDLs (and then unmap)
- Mm may provide an API which does not need a virtual address
  - recall comment about readahead and mapping

Views Are Large

- Mm provides views at a fixed size, 256KB
- Many files are smaller, some are larger
- If we had a pool of views at 64KB, we may avoid view misses under heavy load
- Mediating factors
  - Once misses start, they'll happen as fast with small as large
  - Can't be used for large files or mapping cost will skyrocket
  - As a result, benefit depends on file size mix
  - Overallocation of small views would eat into VA for large views
- An area to be investigated

Flushes Are Synchronous

- Mm only has a synchronous flush API
- An asynchronous paging IO flush would require FS rework as well
- There are only so many critical worker threads, and so many workers Cc can schedule
- As a result, effective bandwidth of the mapped and lazy writers is limited

Cache Manager Summary

- Virtual block cache for files not logical block cache for disks
- Memory manager is the ACTUAL cache manager
- Cache Manager context integrated into FileObjects
- Cache Manager manages views on files in kernel virtual address space
- I/O has special fast path for cached accesses
- The Lazy Writer periodically flushes dirty data to disk
- Filesystems need two interfaces to CC: map and pin

Discussion