Windows NT File System

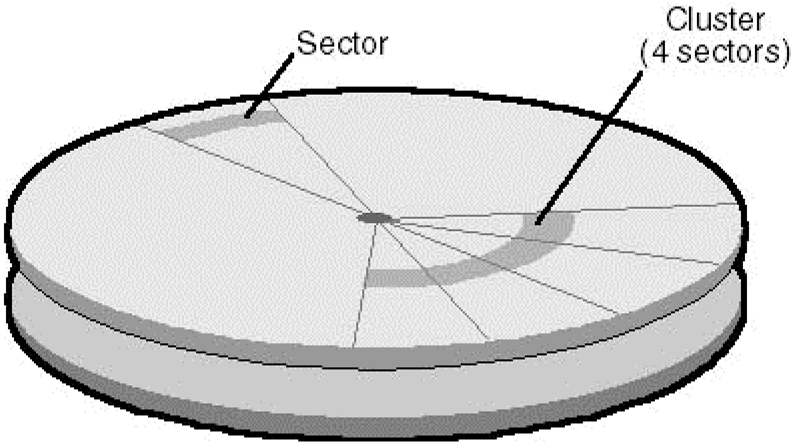
„Ausgewählte Betriebssysteme“
Institut Betriebssysteme
Fakultät Informatik

Outline

- NTFS
  - File System Formats
  - File System Driver Architecture
  - Advanced Features
  - NTFS Driver
  - On-Disk Structure (MFT, ...)
  - Compression
  - Recovery Support
  - Encryption Support

Hardware Basics

- Sector:
  - addressable block on storage medium
  - usually 512 bytes (x86 disks)
- Cluster:
  - addressable block of file system format
  - multiple of sector size



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Win2K File System Formats

- CDFS: ISO 9660 (old CD-ROM FS)
- UDF (Universal Disk Format):
  - ISO 13346 compliant (for optical disk/DVD)
  - Replaces CDFS
  - Filenames can be 255 character long
  - Max path length is 1023 character
  - Filenames can be upper and lower case
- FAT12, FAT16, FAT32
  - FAT12 for anything smaller 16MB
  - FAT16 if explicitly specified (format command)
  - FAT32 anything bigger than 4GB
- NTFS

NTFS

- For volumes larger than 2GB default cluster size of 4KB is used
- Can (theoretically) address up to 16 exabytes using 64-bit cluster indices
- Limited to address using 32-bit indices → up to 128 TB (using 64KB clusters)

NTFS Cluster Sizes

Volume Size	Default Cluster Size
512 MB or less	512 bytes
513 MB-1024 MB (1 GB)	1 KB
1025 MB-2048 MB (2 GB)	2 KB
Greater than 2048 MB	4 KB

- Default value can be overridden

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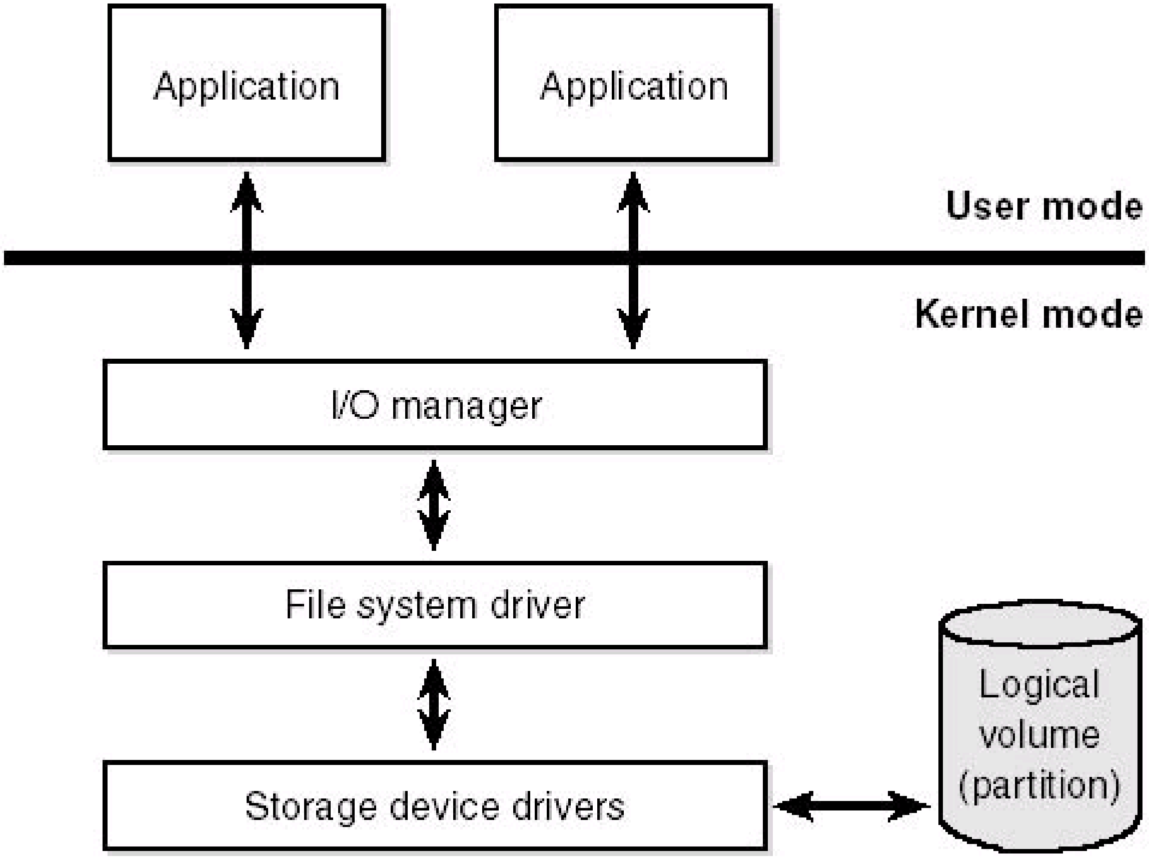
FS Driver Architecture

- Local FSDs:
  - Manage volumes directly connected to computer
  - Responsible for registering with I/O manager
  - First sector on volume identifies volume, its format and location of metadata
- Remote FSDs:
  - Allow access to volumes connected to remote computers
  - Consists of two components (client & sever)

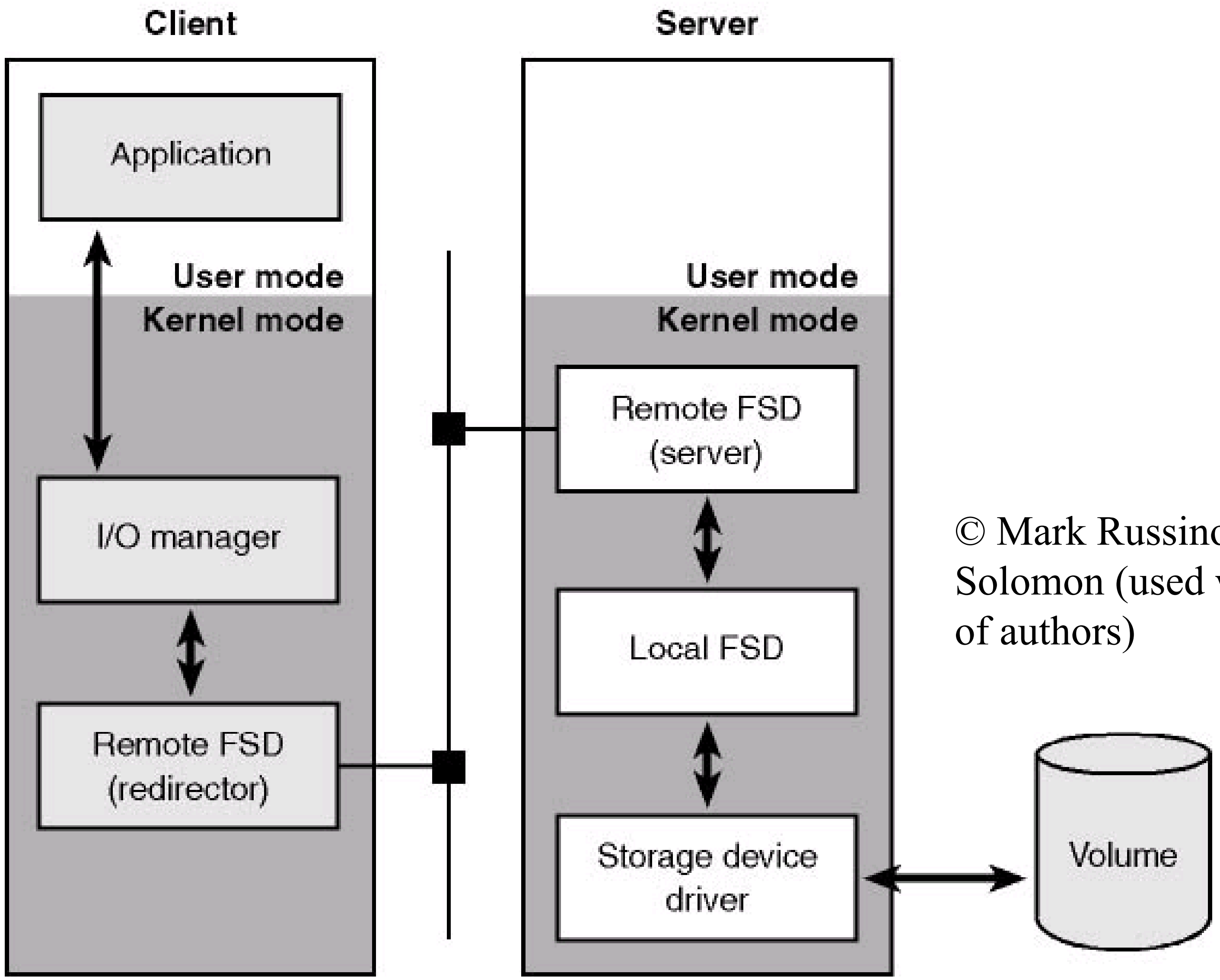
Local FSD


Application
Application
User mode
Kernel mode
I/O manager
File system driver
Storage device drivers
Logical
volume
(partition)

Local FSD (2)

- Device object is created for volume by FSD representing FS format
- I/O Manager connects FSD’s device object to volume’s device object
- Use cache manager to cache FS data (including metadata)
- Cooperate with memory manager:
  - Mapped file cannot be truncated or deleted
- Volume can be dismounted (for raw access)
  - First “normal” access remounts volume

Remote FSD



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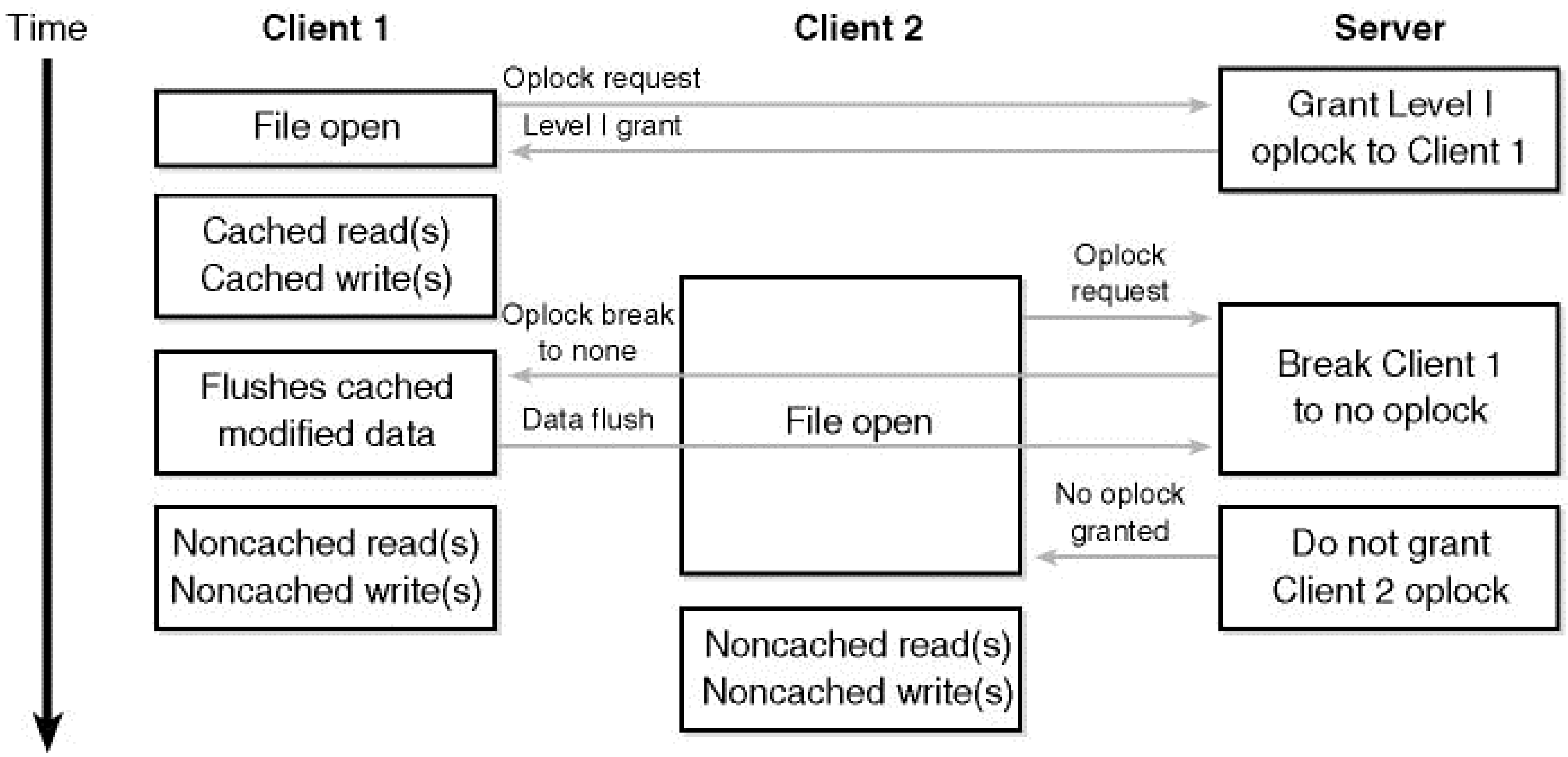
Remote FSD (2)

- Win2K uses Common Internet File System (CIFS) protocol (enhanced version of SMB)
- Client side FSD caches data (to synchronize *oplock protocol* is used)
- File and printer sharing built on it

Oplock Protocol

- „Opportunistic lock“
- Level I oplock granted for exclusive access (cached read and write)
- Level II oplock granted for shared access (cached read)
- Batch lock is Level I for multiple accesses with close operation in between (no additional oplock when reopening file)

Oplock Example



Time

Client 1

Client 2

Server

File open

Oplock request

Level I grant

Grant Level I oplock to Client 1

Cached read(s)
Cached write(s)

File open

Oplock request

Break Client 1 to no oplock

Oplock break to none

Flushes cached modified data

Data flush

No oplock granted

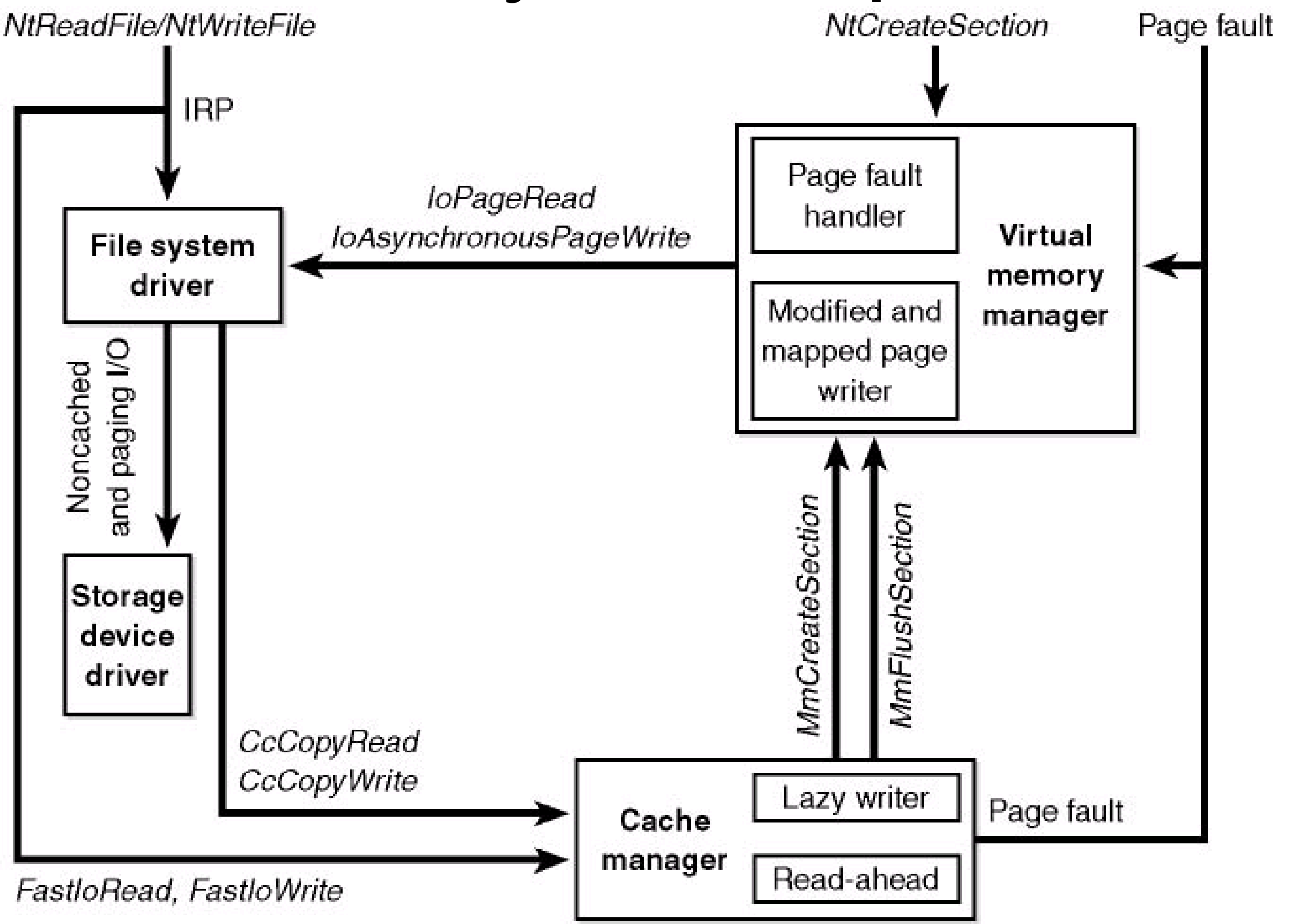
Do not grant Client 2 oplock

Noncached read(s)
Noncached write(s)

Noncached read(s)
Noncached write(s)

- If Client 1 only reads → both get Level II oplock

File System Operation



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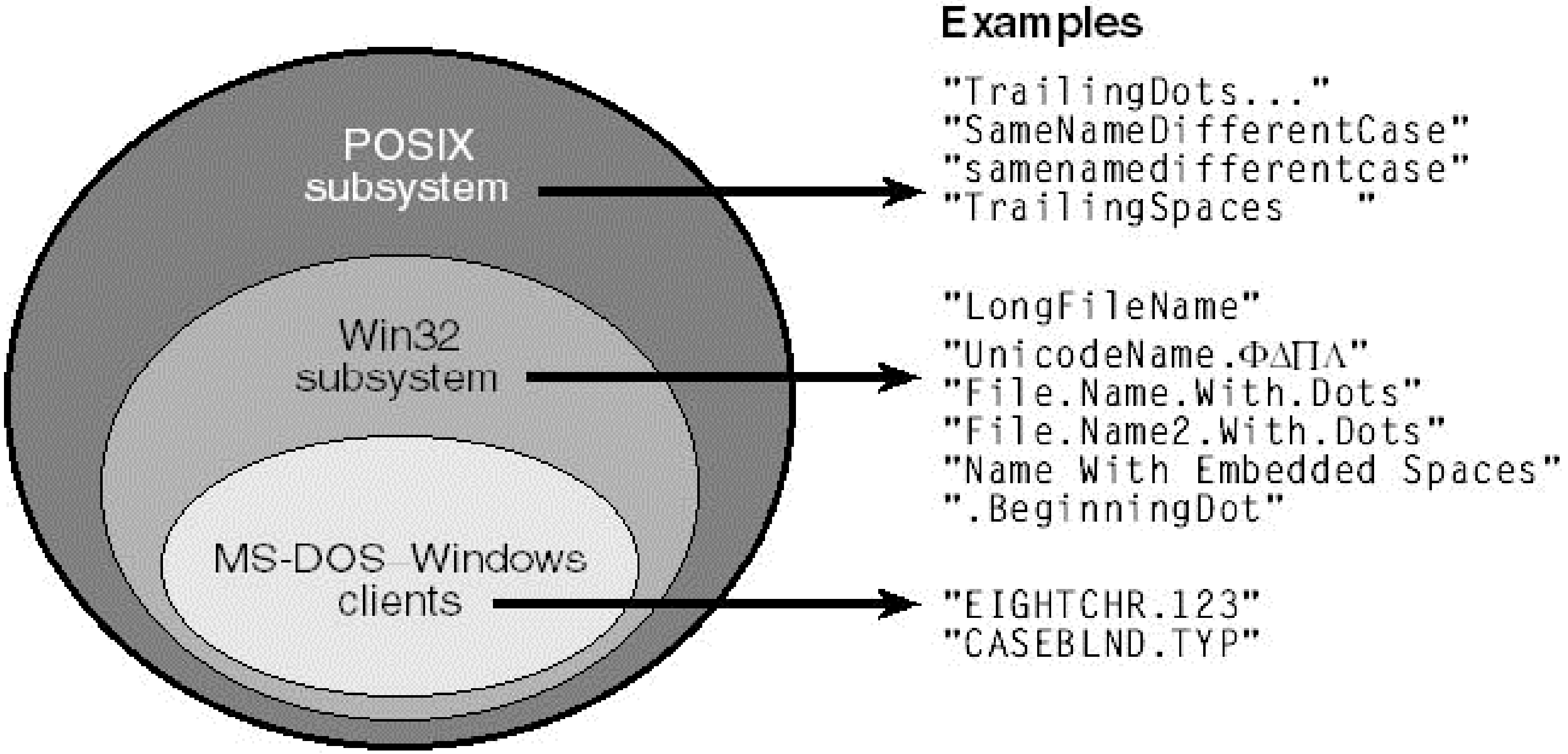
Advanced Features

- Multiple data streams
- Unicode-based names
- General indexing facility
- Dynamic bad-cluster remapping
- Hard links and junctions (soft-links)
- Link tracking
- Per-user volume quotas
- De-fragmentation
- Compression and sparse files (see later section)
- Change logging (see later section)
- Encryption (see later section)

Multiple Data Streams

- A file consists of streams
- One unnamed, default stream
- Stream name added to file name with colon (`stream.txt:longer`)
- Each stream has separate allocation size
- Each stream has separate file lock

Unicode Filenames



Examples

"TrailingDots..."
"SameNameDifferentCase"
"samenamedifferentcase"
"TrailingSpaces   "

"LongFileName"
"UnicodeName.ΦΔΠΛ"
"File.Name.With.Dots"
"File.Name2.With.Dots"
"Name With Embedded Spaces"
".BeginningDot"

"EIGHTCHR.123"
"CASEBLND.TYP"

Hard Links and Junctions

- Hard links can be created with *CreateHardLink* and *ln*
  - Different names link to same file on disk
  - One file contains multiple $FILE_NAME attributes
- Junctions are soft links, based on reparse points
  - Reparse point has reparse tag, which allows to identify owner, and reparse data
  - Owner can alter pathname and reissue I/O or
  - Owner can remove reparse point, alter file and reissue I/O (archive and restore file automatically)

Link Tracking

- Links (e.g. shell shortcuts or OLE links) are another mechanism to “soft-link” files
- Link points to unique Object ID, which is stored in $OBJECT_ID attribute of file
- Target file can be allocated by querying for the Object ID
- Link tracking service implements the „link following“
- Mapping of Object IDs to filenames stored in file „$Extend:$O“ (see slide 29/30)

Quotas

- Files are tagged with security ID (SID) of user
- Logical size of files counts against quota (not compressed size)
- Attempted violations and reached warning thresholds are logged in event log (and administrator can be notified)

Defragmentation

- NTFS does not automatically de-fragment disks
- NTFS provides de-fragmentation API
- Can be used to move file data, and obtain cluster information of file
- Win2K includes de-fragmentation tool

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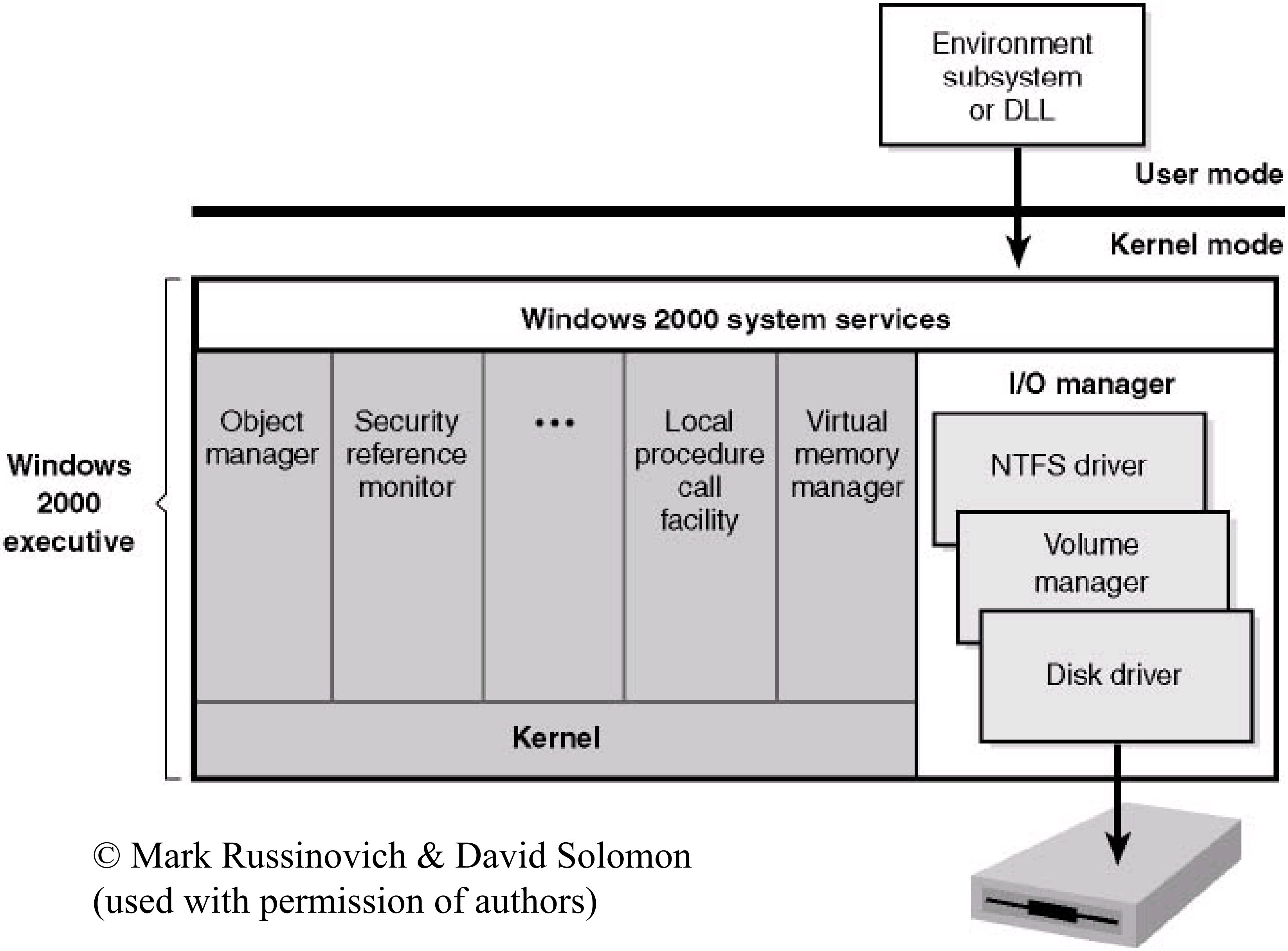
NTFS Driver



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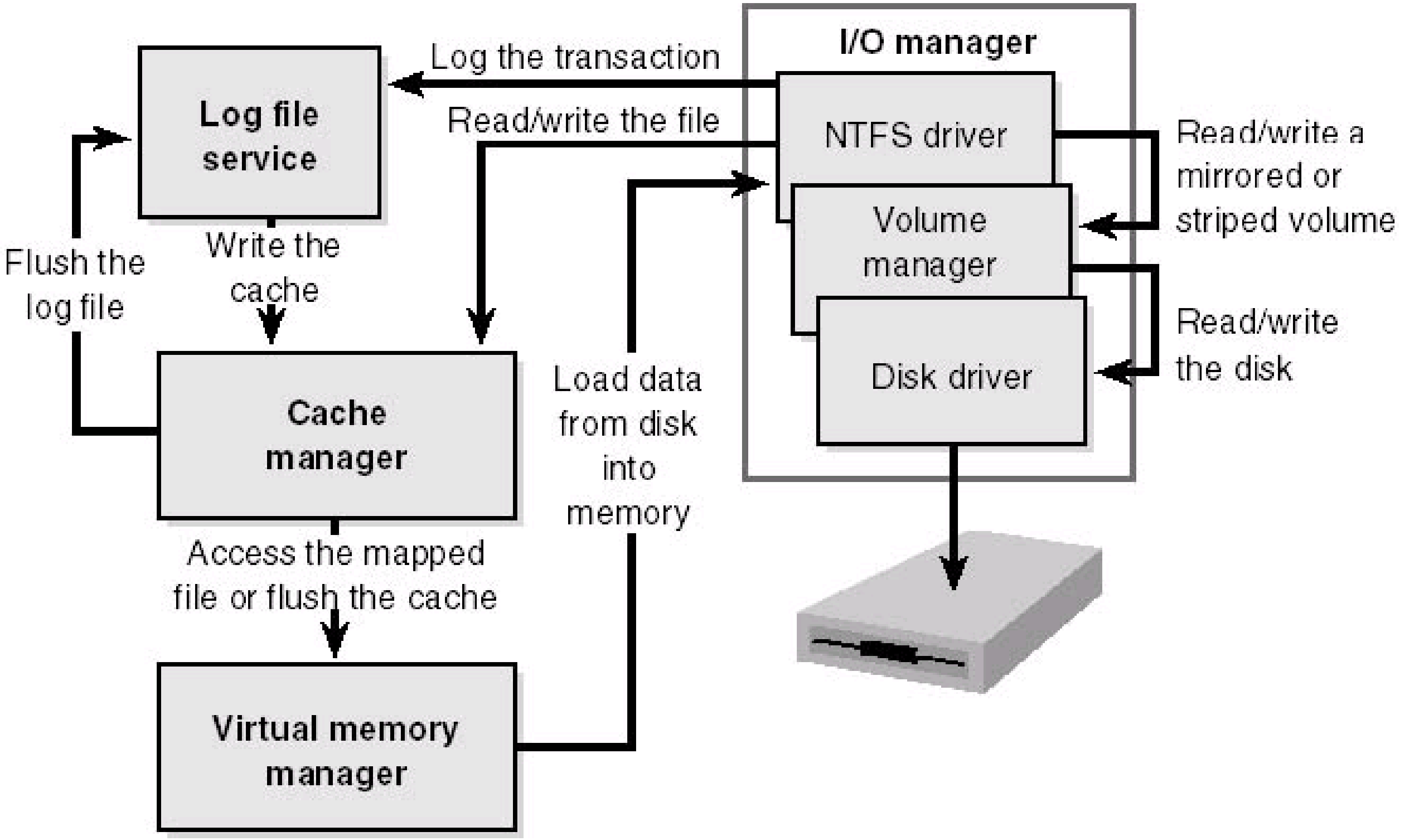
NTFS and Related Components



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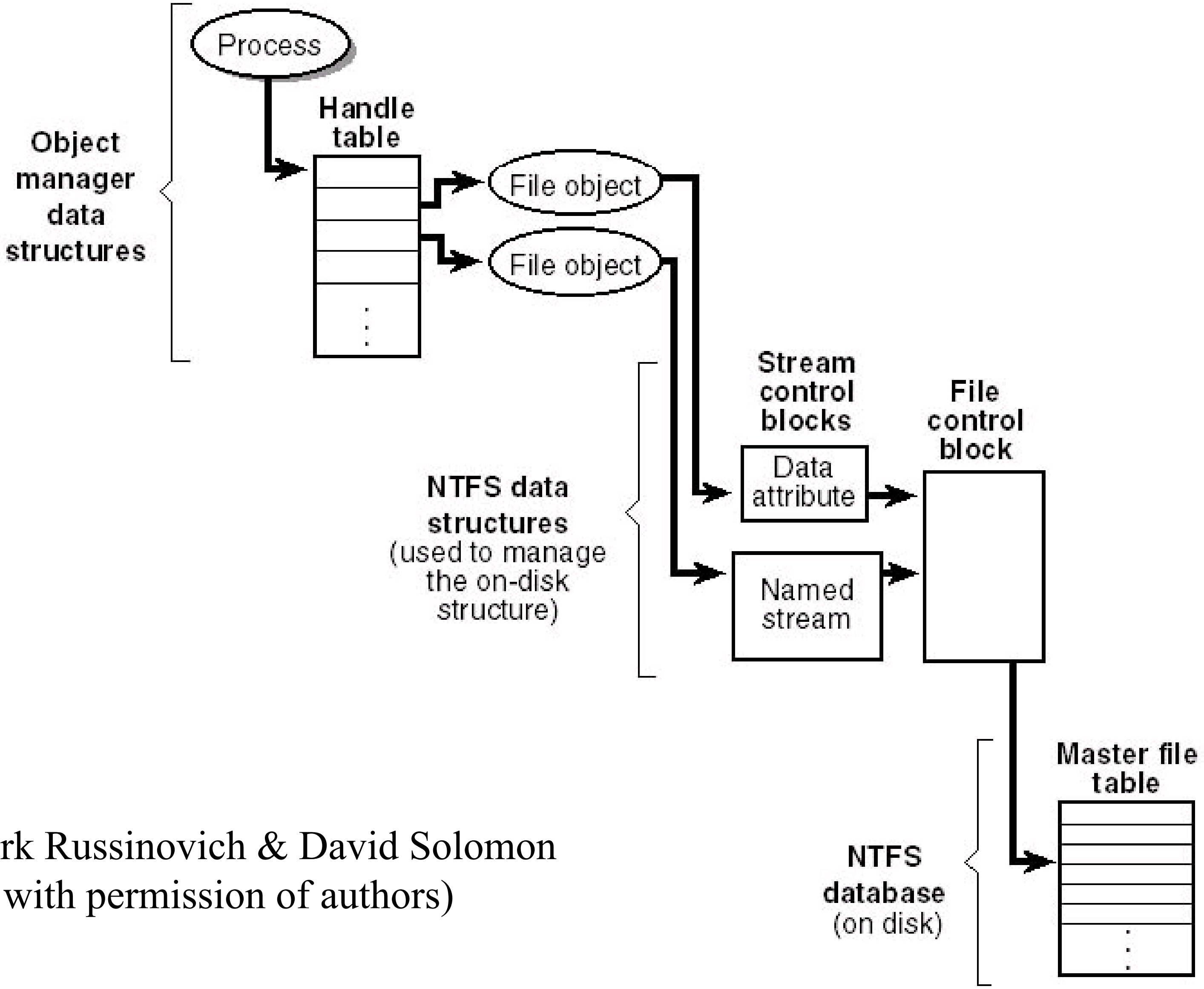
NTFS Data Structures



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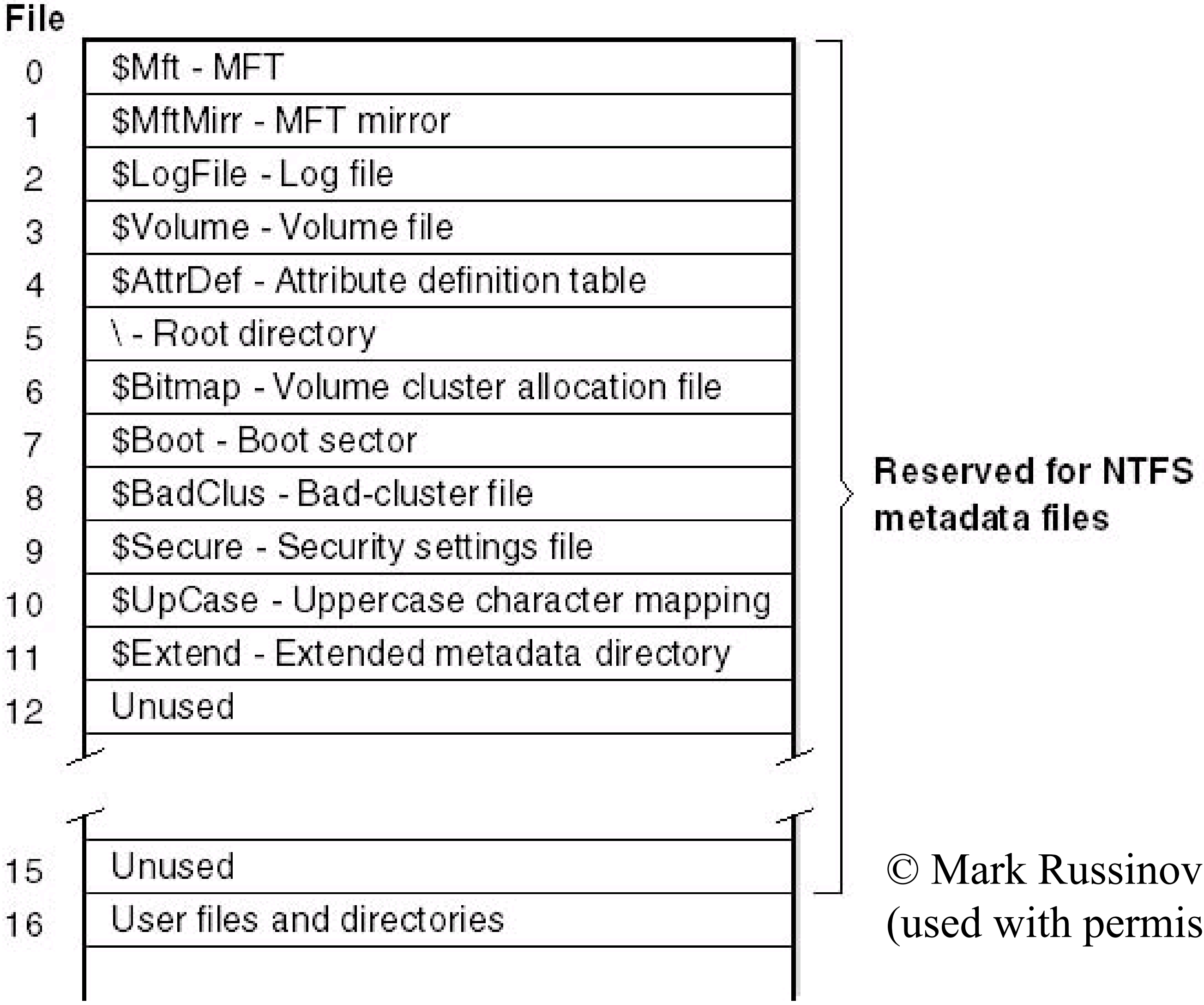
NTFS On-Disk Structure

- Volumes: logical partitions (can span multiple partitions)
- Cluster: multiple of sector (always power of 2, e.g. 1,2,4,8 sectors)
- NTFS refers to physical locations on disk by logical cluster numbers (LCNs)
- NTFS refers to the data within a file by virtual cluster numbers (VCNs)

Master File Table

- All data stored on volume is contained in files:
  - MFT, bootstrap data, allocation bitmap
  - Can relocate metadata
- MFT is array of file records
- File record has fixed size of 1KB
- MFT contains one record for each file on volume
- Metadata files have name starting with $
- On boot, volume is mounted by reading MFT and constructing internal data structures

MFT (2)



File	
0	$Mft - MFT
1	$MftMirr - MFT mirror
2	$LogFile - Log file
3	$Volume - Volume file
4	$AttrDef - Attribute definition table
5	\ - Root directory
6	$Bitmap - Volume cluster allocation file
7	$Boot - Boot sector
8	$BadClus - Bad-cluster file
9	$Secure - Security settings file
10	$UpCase - Uppercase character mapping
11	$Extend - Extended metadata directory
12	Unused
15	Unused
16	User files and directories

Reserved for NTFS metadata files

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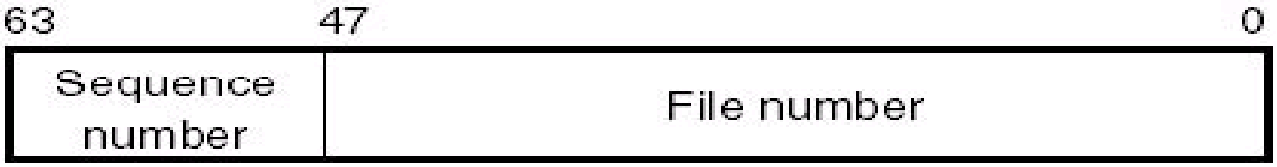
MFT (3)

- $Mft and $MftMirr contain information about MFT (which blocks it occupies, ...)
- $LogFile contains recovery information
- NTFS starts searching for a file in Root directory
- $Bitmap shows free clusters
- $Secure volume wide security descriptor database
- $Boot – bootstrap code must be allocated at specific position on volume, but a file table entry is created, so inform can be read like file
- $Volume contains volume name, NTFS version, disk-corruption bit
- $Extend contains metadata, like quota, object ID file, ...

File Reference Number

- A file is identified by 64-bit value, called file reference
- Consists of file number and sequence number
- File number corresponds to index in MFT
- Sequence number is incremented if file record in MFT is reused



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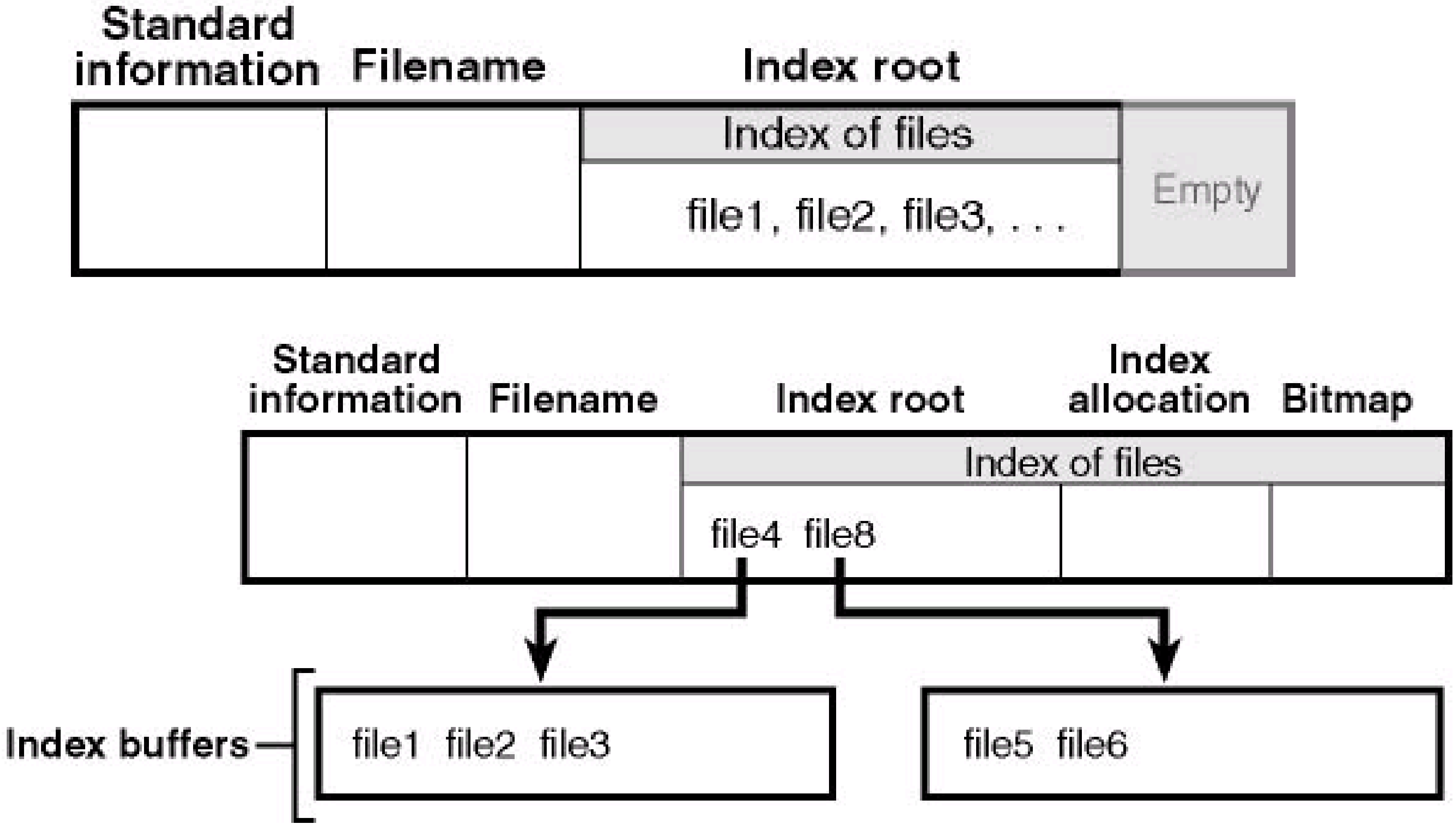
File Record

- Strictly speaking: consists of attribute streams
- Each attribute:
  - Is identified by its attribute code
  - Has a value
  - Has an optional name (used to distinguish attributes of same type)
- E.g.:
  - $FILE_NAME attribute stores file name
  - $DATA attribute stores content of file

File Record (2)

- Small files fit into record
- Attributes with values stored in record are called resident attribute (standard information is always resident)
- Attribute header contains information if it is resident
- For big attributes clusters are allocated (so-called runs) and referenced from record
- These attributes are called non-resident

Resident/Non-Resident Attributes



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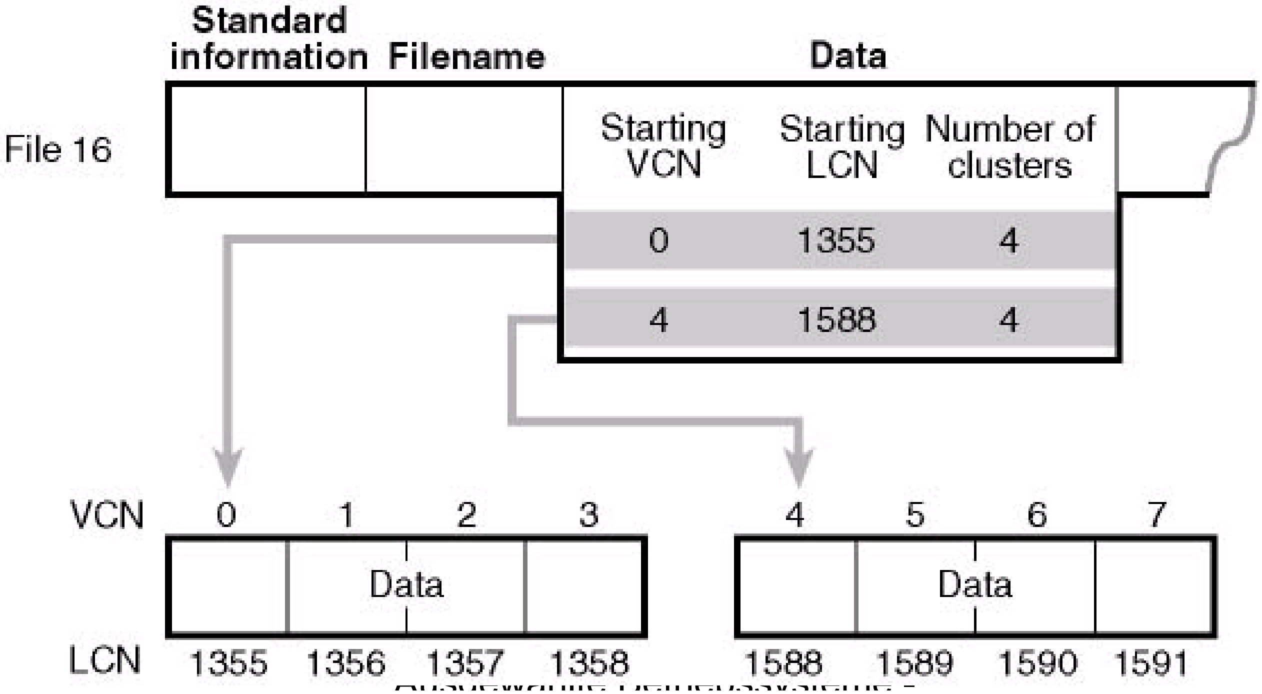
Non-Resident Attributes

- If multiple runs are needed to store an attribute, a mapping table of VCN is needed
- VCN (location in file), LCN (location on disk and size



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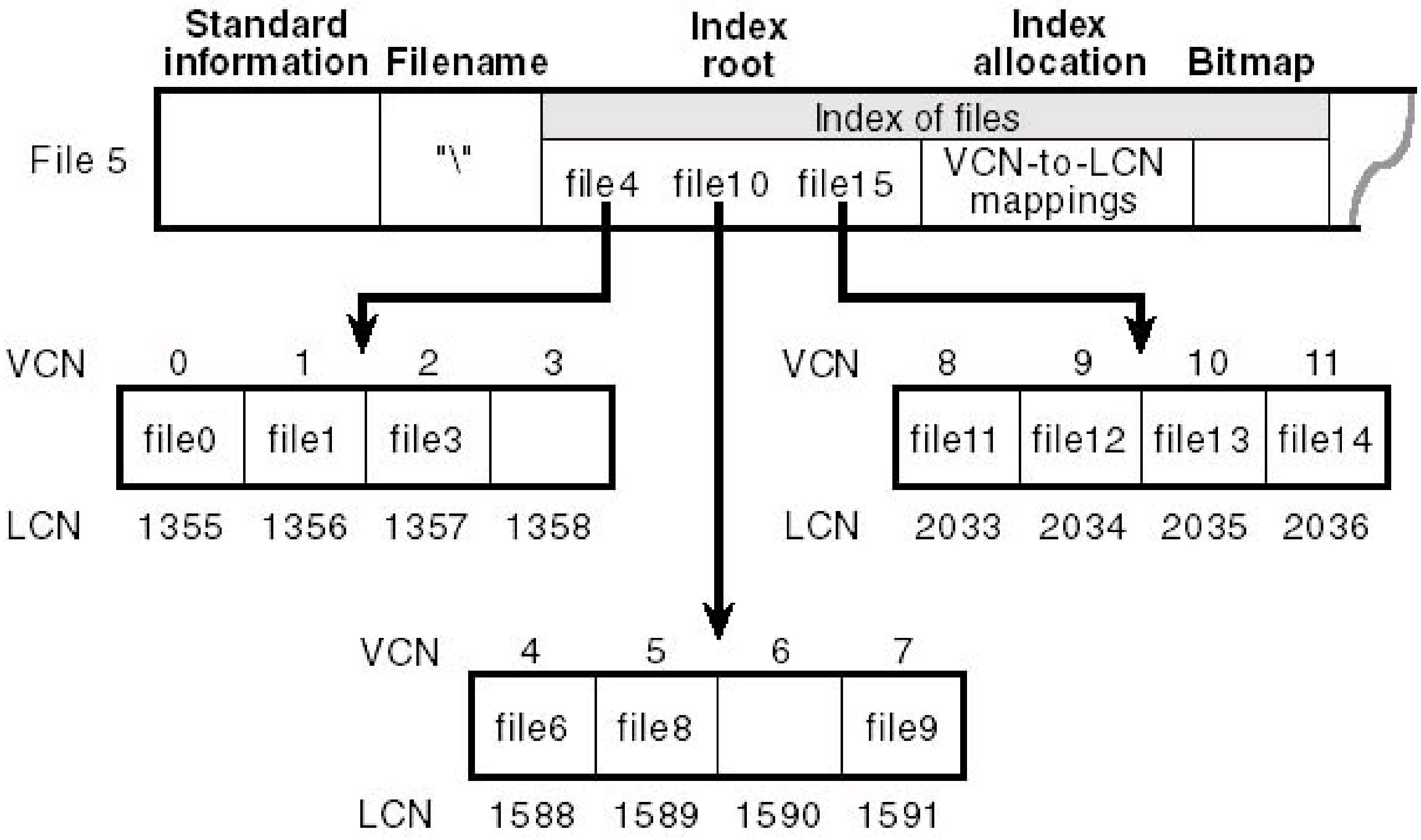
Directory Lookup

- For fast directory lookup an index tree is maintained
- Tree is B+ tree
- Each entry in tree contains information on file name, size, time stamp → directory information can be displayed without touching the file
- Requires this information to be updated in two places
- Each 4KB index buffer can contain 20-30 filenames

Directory Lookup (2)



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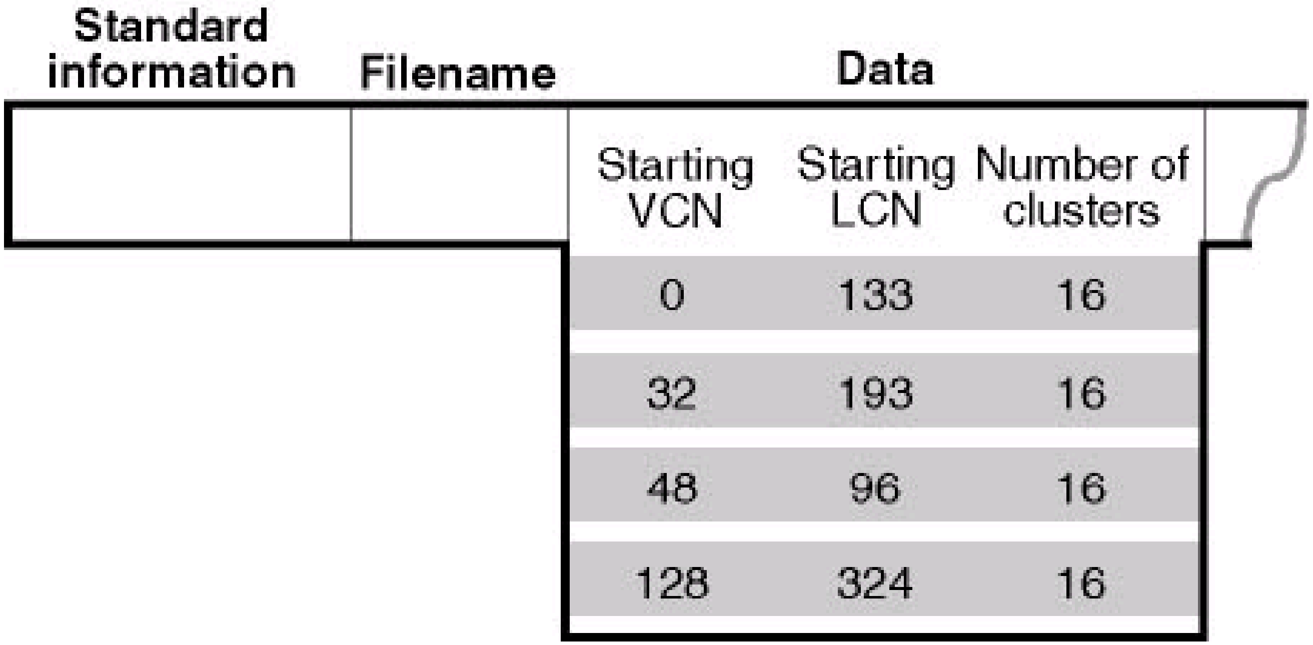
Compression

- Compress sparse files (with holes), by not allocating runs for the holes (zeros)

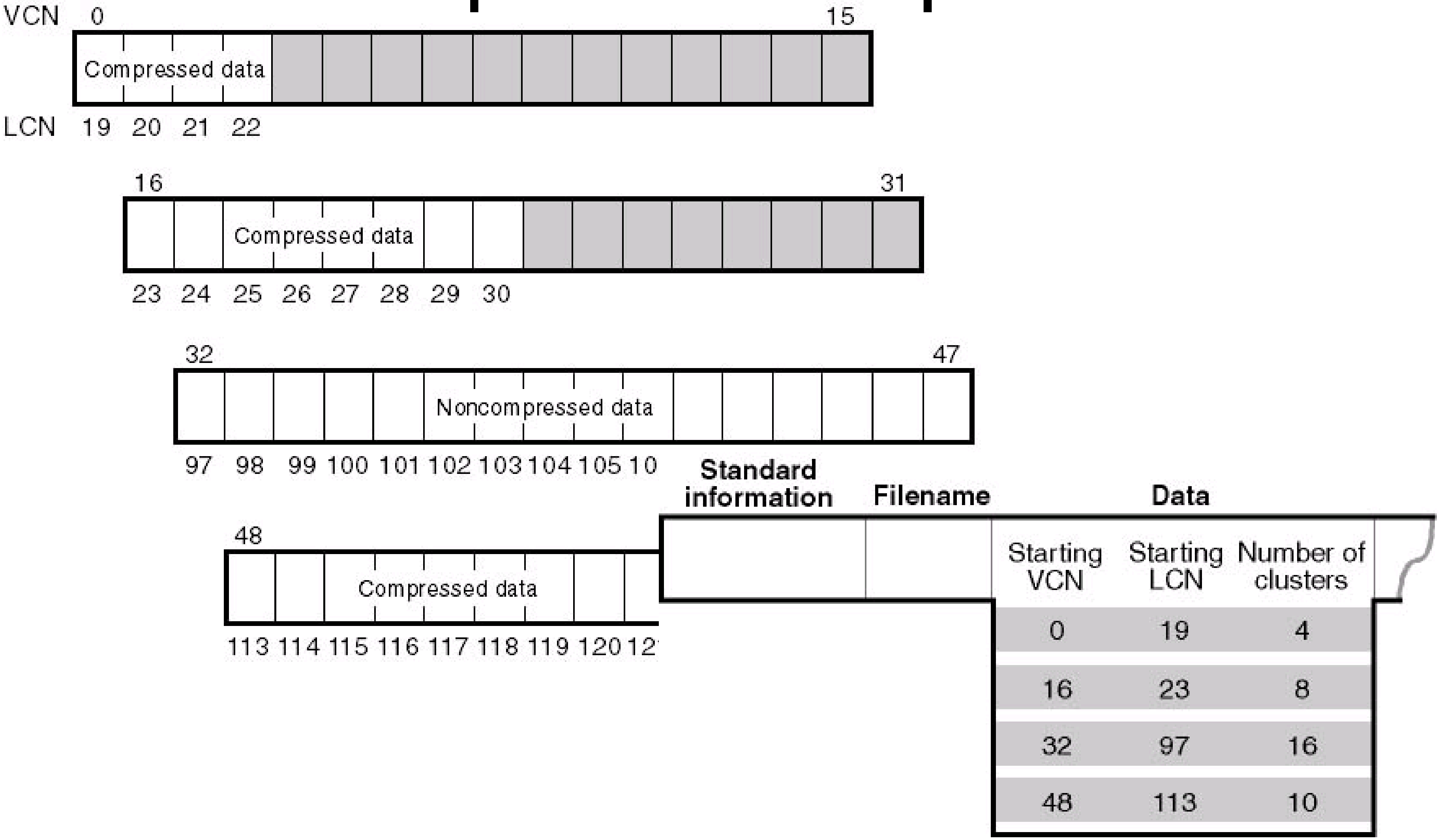


Starting VCN	Starting LCN	Number of clusters
0	133	16
32	193	16
48	96	16
128	324	16

Compression (2)

- Non-Sparse Data compressed by combining 16 consecutive clusters to *compression units*
- Compress unit and if at least one cluster is saved, store compressed data.
- Distinguish compressed from uncompressed by length of run (number of clusters < 16)
- (runs with less than 16 clusters can be compressed too, but mapping becomes complicated and when stored again, stored in consecutive 16 cluster run)

Non-Sparse Compression



Starting VCN	Starting LCN	Number of clusters
0	19	4
16	23	8
32	97	16
48	113	10

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Recovery Support

- NTFS uses transaction-processing scheme to implement recoverability
- Recovery Procedures limited to file system data – user data never guaranteed to be fully updated after crash
- Sub-operation of transactions that alter file system data are logged before being carried through on disk
- Logging done by Log File Service (LFS)

Log File Service (LFS)

- Log file divided into *restart area*:
  - 2 copies
  - Contains context information, such as location of start of recovery
- And *logging area*:
  - Treated as infinite (logs are written looping through area)
- Logical Sequence Numbers (LSN) used to identify records (64bit)
- Provides services to NTFS to open/close log file, read/write records

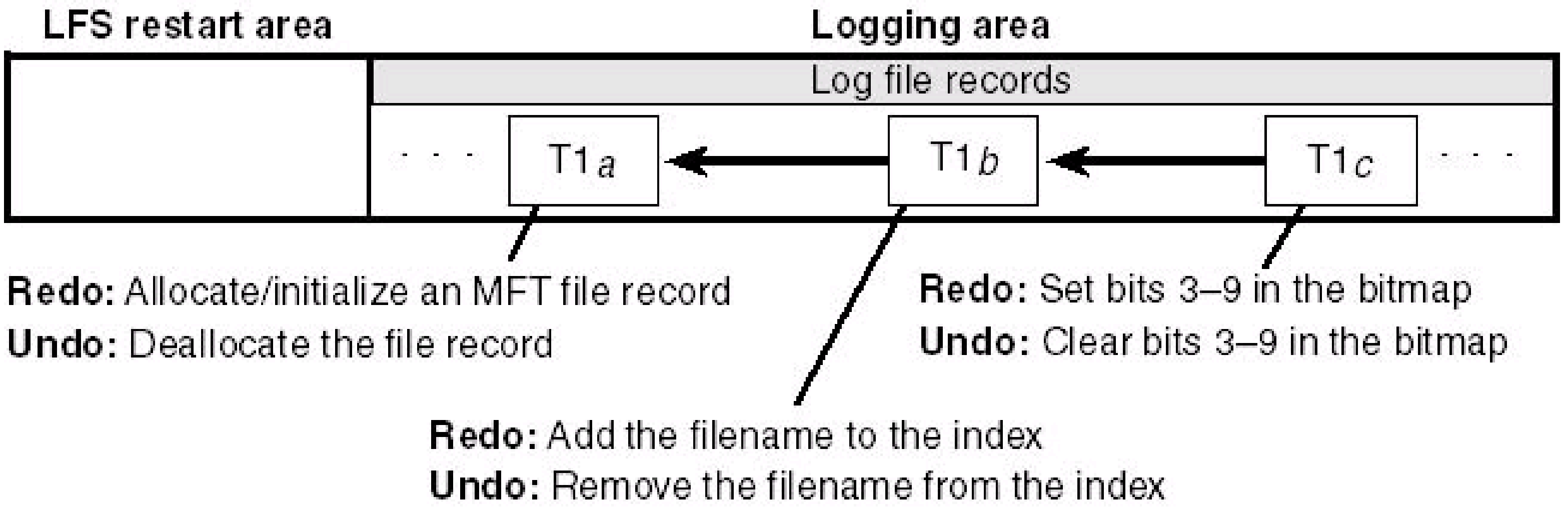
Transaction sequence

- Steps to ensure recoverability:
  1. NTFS calls LFS to record modification
  2. NTFS modifies volume
  3. Cache manager prompts LFS to flush Log to disk
  4. Cache manager flushes the volume changes
- Log file is also cached

Log Record Types

- Update Records
  - Redo information: how to reapply one sub-operation
  - Undo information: how to reverse one sub-operation
  - Contain physical state of data
- Checkpoint record
  - Written, when data has been updated in file as well

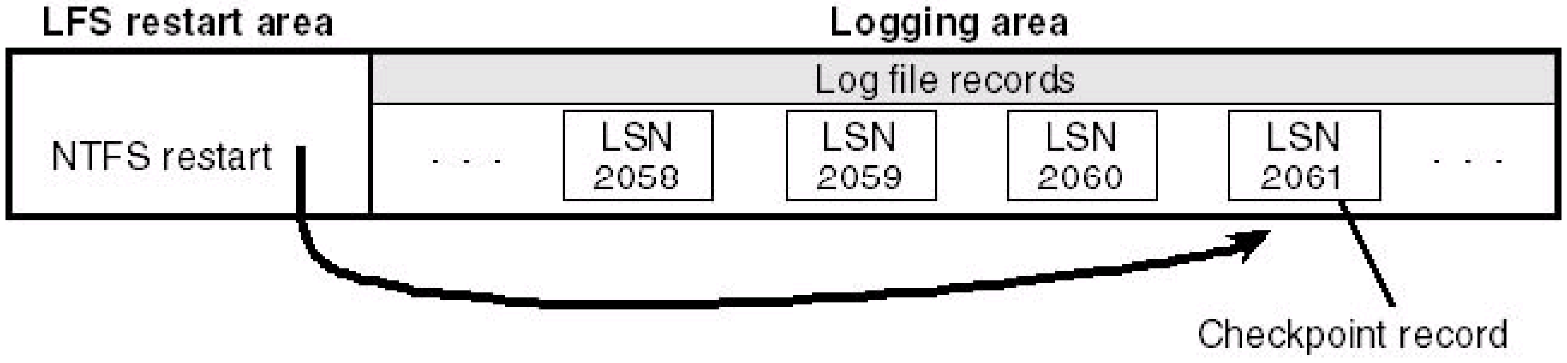
Log Record Types (2)



Redo: Allocate/initialize an MFT file record
Undo: Deallocate the file record

Redo: Add the filename to the index
Undo: Remove the filename from the index

Redo: Set bits 3–9 in the bitmap
Undo: Clear bits 3–9 in the bitmap



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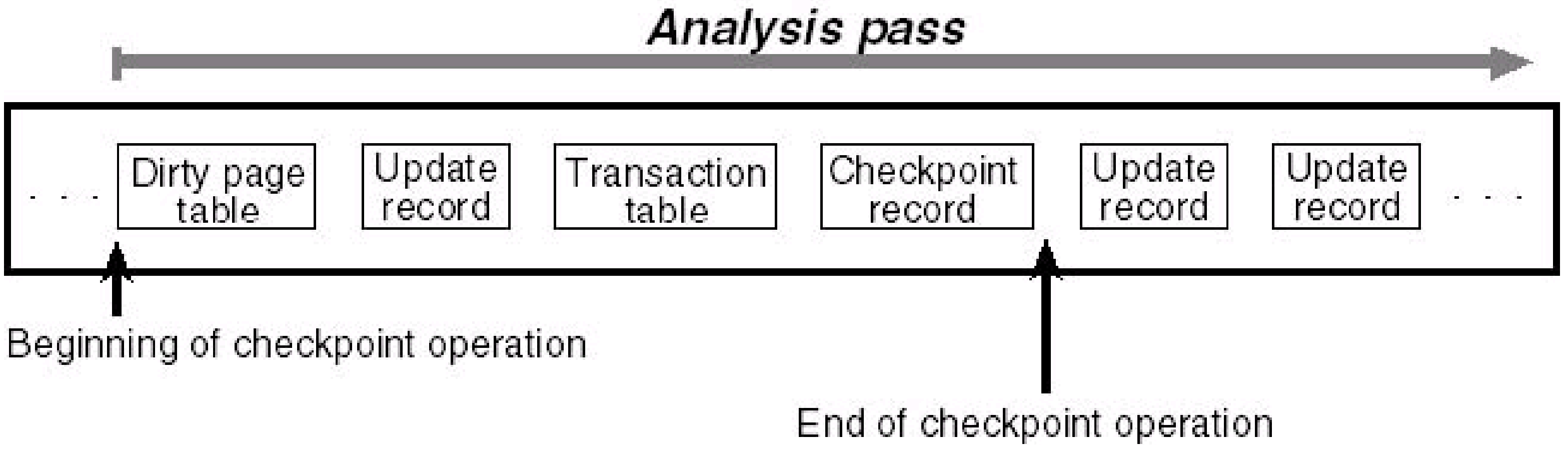
Recovery

- Depends on two tables
  - Transaction table: keeps track of unfinished transactions
  - Dirty page table: contains modified pages, which contain file system structures
- Once every 5 seconds:
  - Transaction table and dirty page table written to log
  - Checkpoint written to log
- On recovery log-file is scanned three times
  - Analysis
  - Redo transactions
  - Undo transactions

Analysis Pass

- Scan forward in log-file from beginning of last checkpoint operation to find update records to restore transaction and dirty page table
- Oldest update record, which‘s operation hasn‘t been carried out on disk, is determined (compared with dirty page table)
- If last checkpoint is older, Redo starts there



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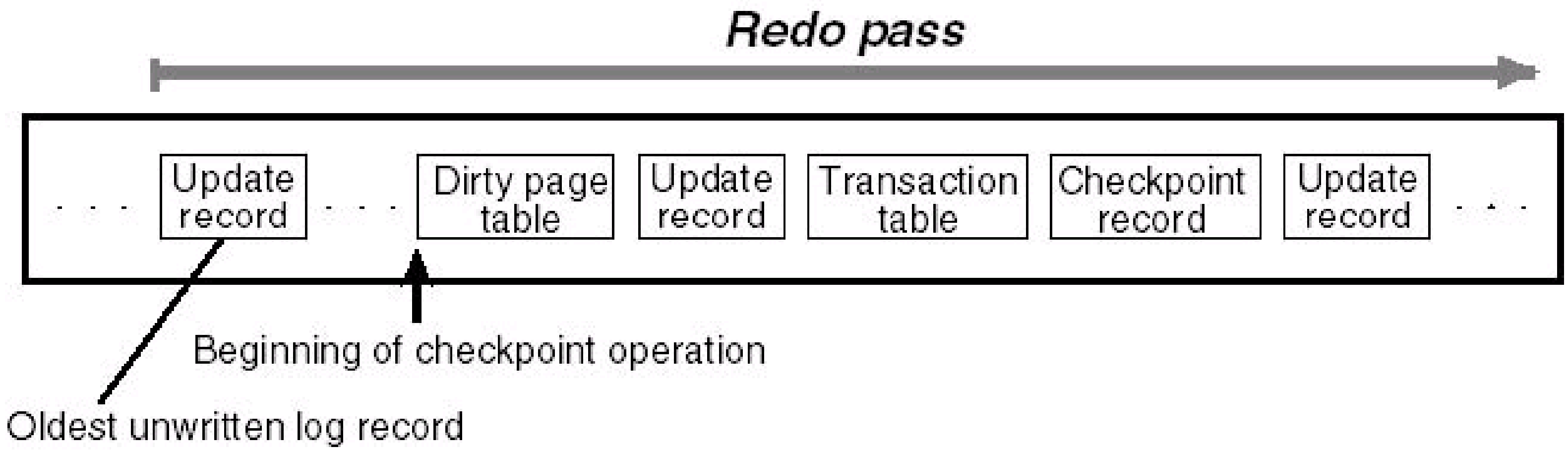
Redo Pass

- Looks for „page update“ records
  - Which contain volume modification written before crash
  - But have not been flushed to disk
  - These updates are redone
  - After pass completed cache updates finished



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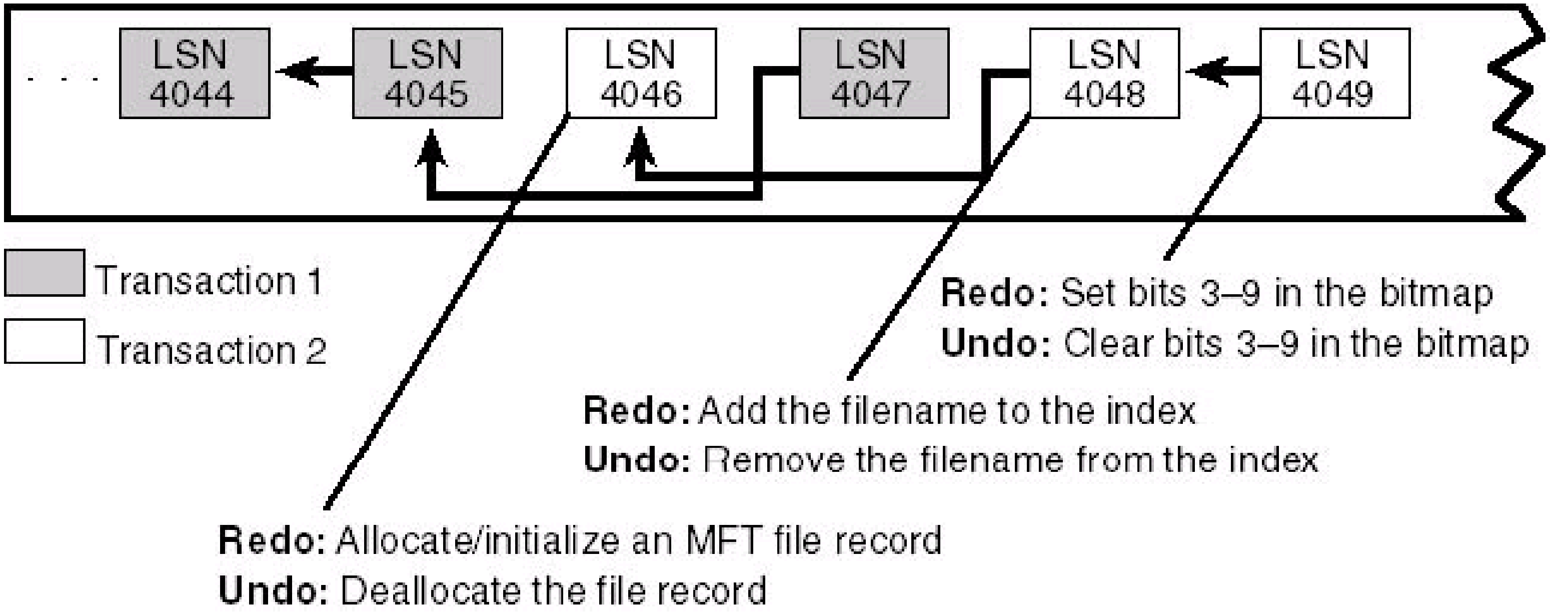
Undo Pass

- Roll back any transactions that weren‘t committed
- Undo operations are logged (in case of another power down)
- After Undo Pass is complete an „empty“ LFS restart area is written



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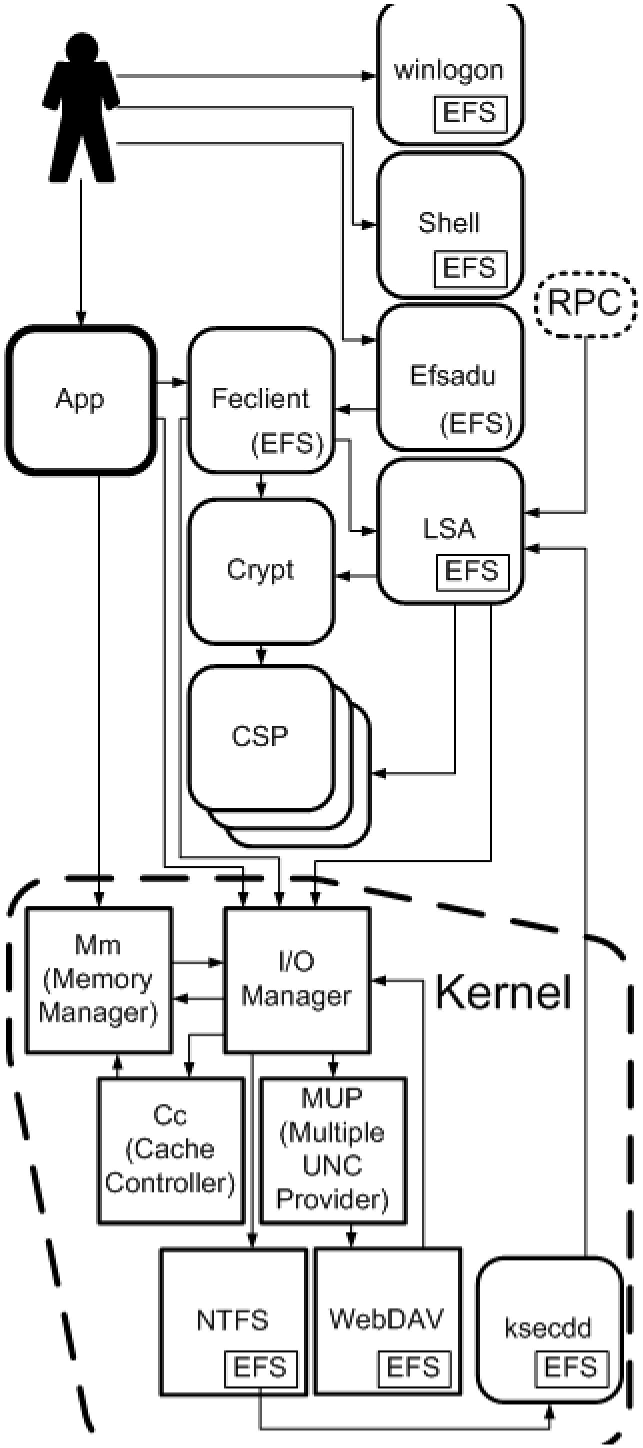
Encryption

- User is assigned a private/public key pair (when he/she first encrypts a file)
- When file is encrypted:
  - content is encrypted using random number called file encryption key (FEK) and DESX (stronger version of DES)
  - FEK is encrypted using public key of user and RSA and attached to file
  - For each user FEK is encrypted respectively

Encryption (2)

- Private Key is stored in Registry (on disk “in a safe place”) or smart card
- EFK is also encrypted for each Recovery Agent if recovery policy is defined
- Usage of private key:
  - CryptGetUserKey to tell crypto provider to subsequently use this user’s key
  - CryptDecrypt is called to decrypt EFK


winlogon
EFS
Shell
EFS
RPC
Efsadu
(EFS)
App
Feclient
(EFS)
LSA
EFS
Crypt
CSP
Kernel
Mm
(Memory
Manager)
I/O
Manager
Cc
(Cache
Controller)
MUP
(Multiple
UNC
Provider)
NTFS
EFS
WebDAV
EFS
ksecdd
EFS