Windows Kernel Architecture Internals

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NT Timeline: the first 20 years

2/1989	**Design/Coding Begins**
7/1993	NT 3.1
9/1994	NT 3.5
5/1995	NT 3.51
7/1996	NT 4.0
12/1999	NT 5.0 Windows 2000
8/2001	***NT 5.1 Windows XP – ends Windows 95/98***
3/2003	NT 5.2 Windows Server 2003
8/2004	NT 5.2 Windows XP SP2
4/2005	NT 5.2 Windows XP 64 Bit Edition (& WS03SP1)
10/2006	NT 6.0 Windows Vista (client)
2/2008	NT 6.0 Windows Server 2008 (Vista SP1)
10/2009	NT 6.1 Windows 7 & Windows Server 2008 R2

Windows Academic Program

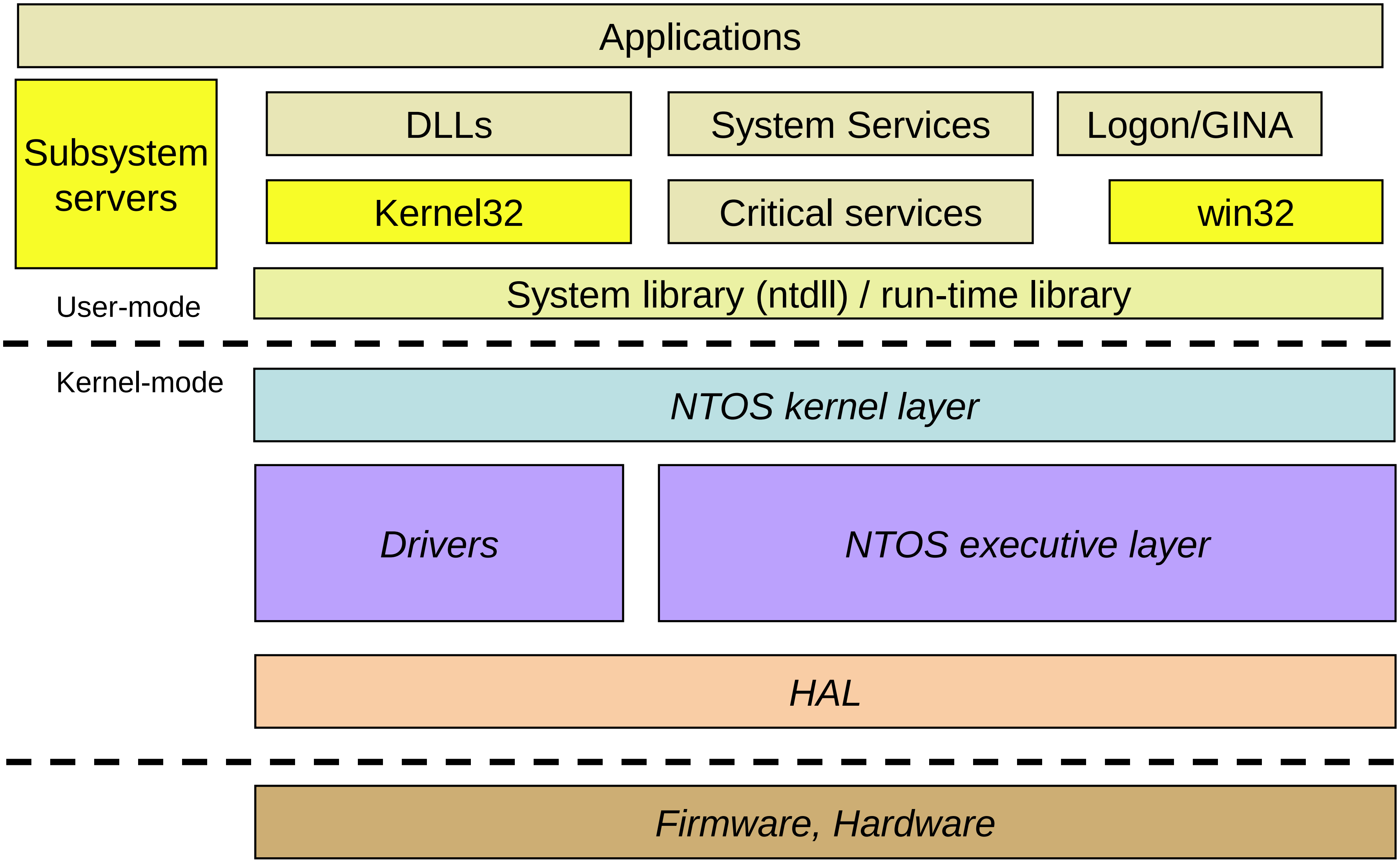
Historically little information on NT available

- Microsoft focus was end-users and Win9x
- Source code for universities was too encumbered

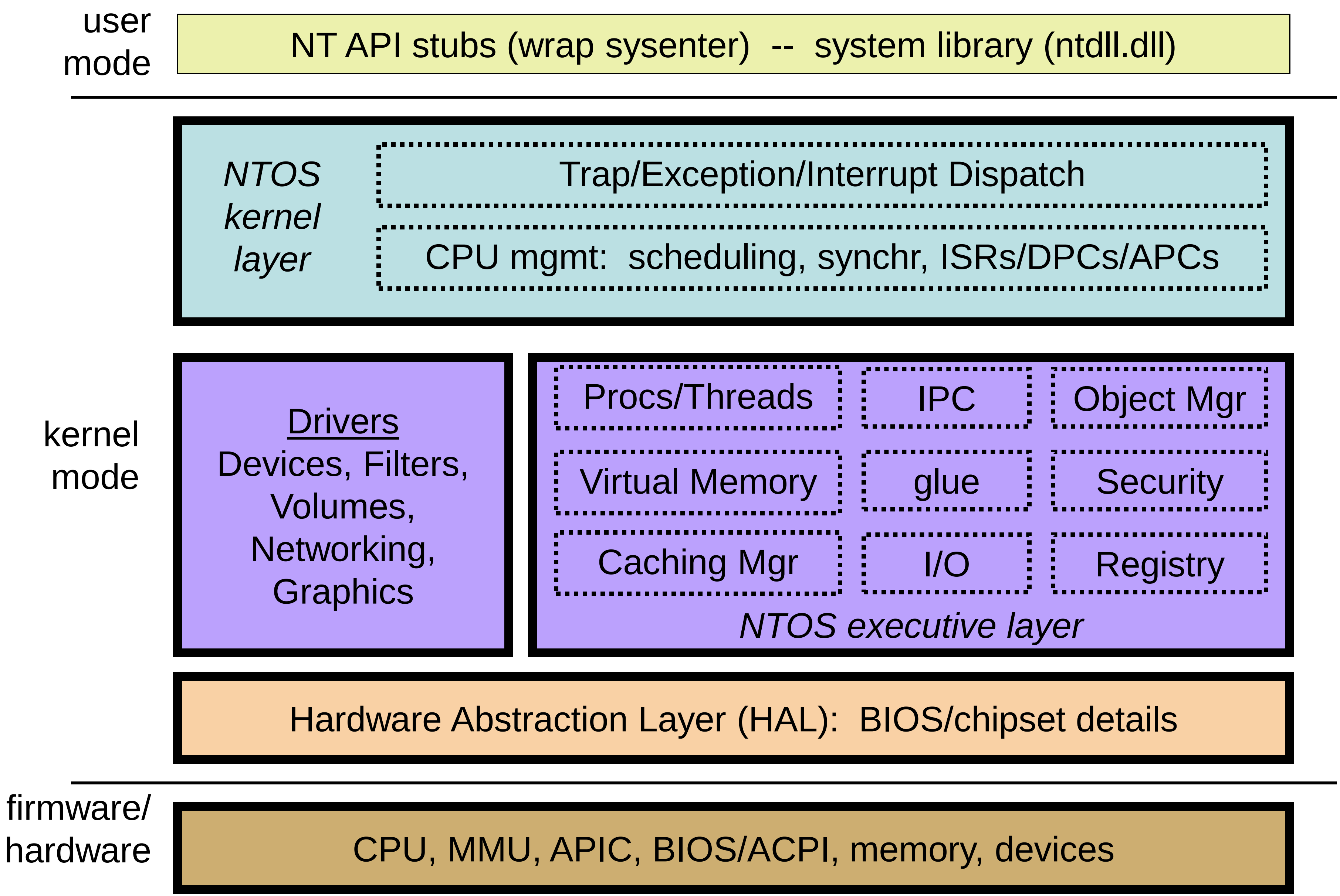
Much better internals information today

- Windows Internals, 4^{th} Ed., Russinovich & Solomon
- Windows Academic Program (universities only):
  - CRK: Curriculum Resource Kit (NT kernel in PowerPoint)
  - WRK: Windows Research Kernel (NT kernel in source)
- Chapters in leading OS textbooks (Tanenbaum, Silberschatz, Stallings)

Windows Architecture



Windows Kernel-mode Architecture



NT (Native) API examples

NtCreateProcess (&ProcHandle, Access, SectionHandle, DebugPort, ExceptionPort, …)

NtCreateThread (&ThreadHandle, ProcHandle, Access, ThreadContext, bCreateSuspended, …)

NtAllocateVirtualMemory (ProcHandle, Addr, Size, Type, Protection, …)

NtMapViewOfSection (SectHandle, ProcHandle, Addr, Size, Protection, …)

NtReadVirtualMemory (ProcHandle, Addr, Size, …)

NtDuplicateObject (srcProcHandle, srcObjHandle, dstProcHandle, dstHandle, Access, Attributes, Options)

Object Manager

NT Object Manager

Provides unified management of:

- kernel data structures
- kernel references
- user references (handles)
- namespace
- synchronization objects
- resource charging
- cross-process sharing
- central ACL-based security reference monitor
- configuration (registry)

\ObjectTypes

Object Manager: Directory, SymbolicLink, Type

Processes/Threads: DebugObject, Job, Process, Profile, Section, Session, Thread, Token

Synchronization:

Event, EventPair, KeyedEvent, Mutant, Semaphore, ALPC Port, IoCompletion, Timer, TpWorkerFactory

IO: Adapter, Controller, Device, Driver, File, Filter*Port

Kernel Transactions: TmEn, TmRm, TmTm, TmTx

Win32 GUI: Callback, Desktop, WindowStation

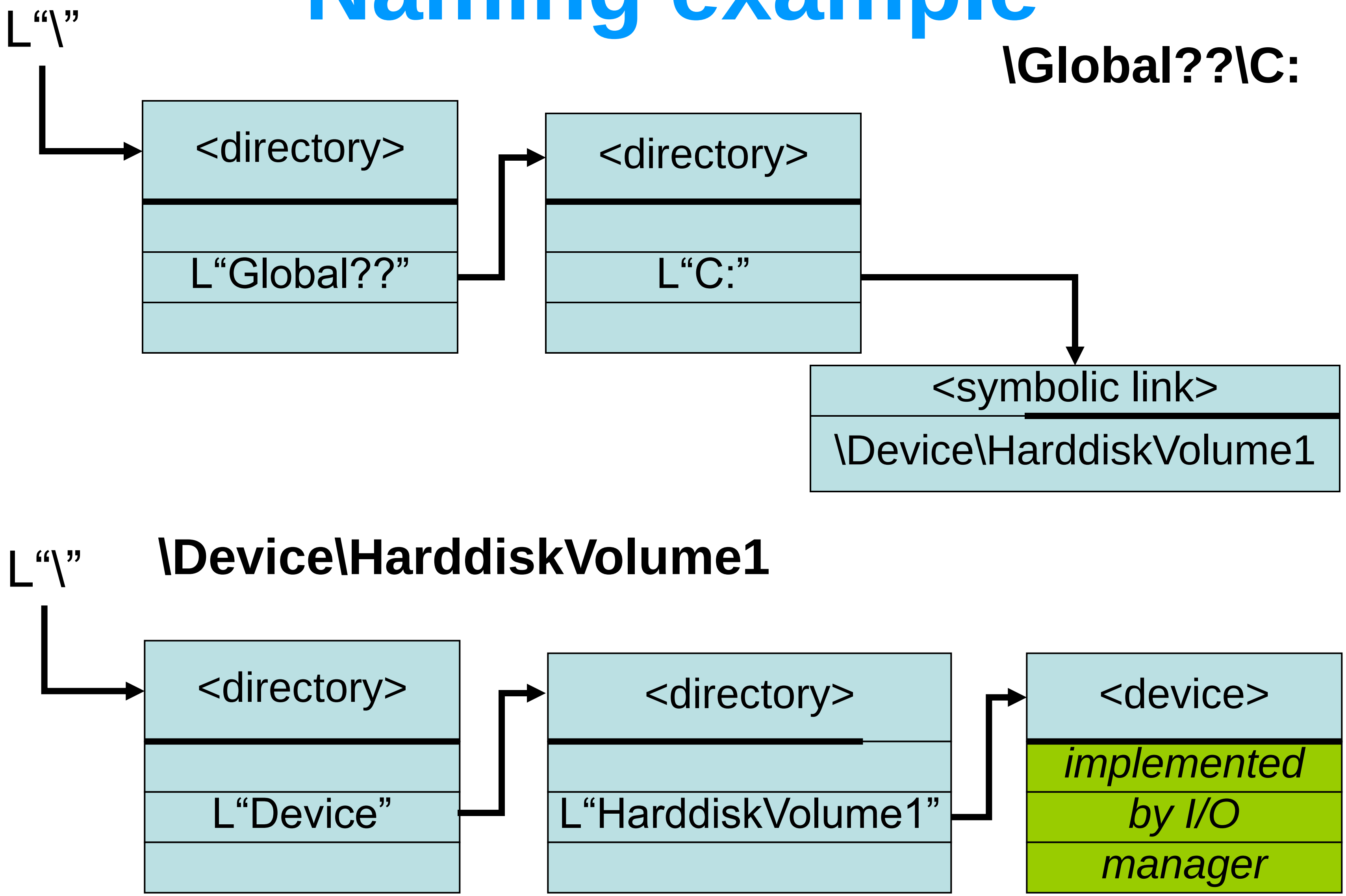
System: EtwRegistration, WmiGuid

Implementation: Object Methods

Note that the methods are unrelated to actual operations on the underlying objects:

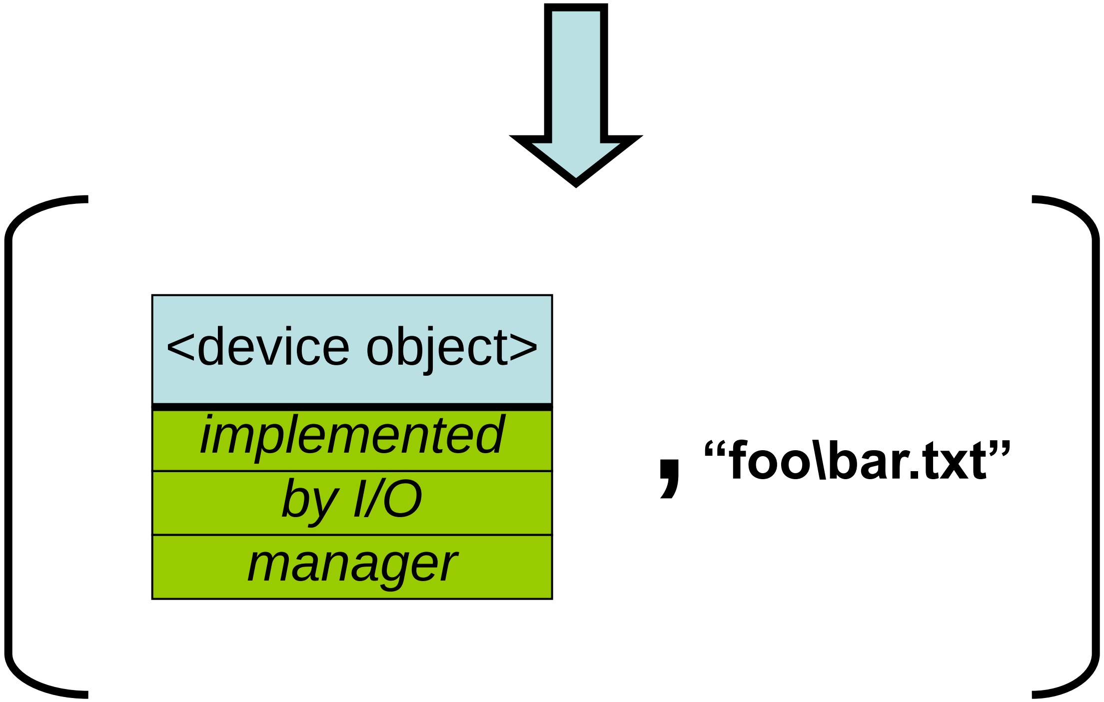
OPEN:	Create/Open/Dup/Inherit handle
CLOSE:	Called when each handle closed
DELETE:	Called on last dereference
PARSE:	Called looking up objects by name
SECURITY:	Usually *SeDefaultObjectMethod*
QUERYNAME:	Return object-specific name

Naming example



Object Manager Parsing example

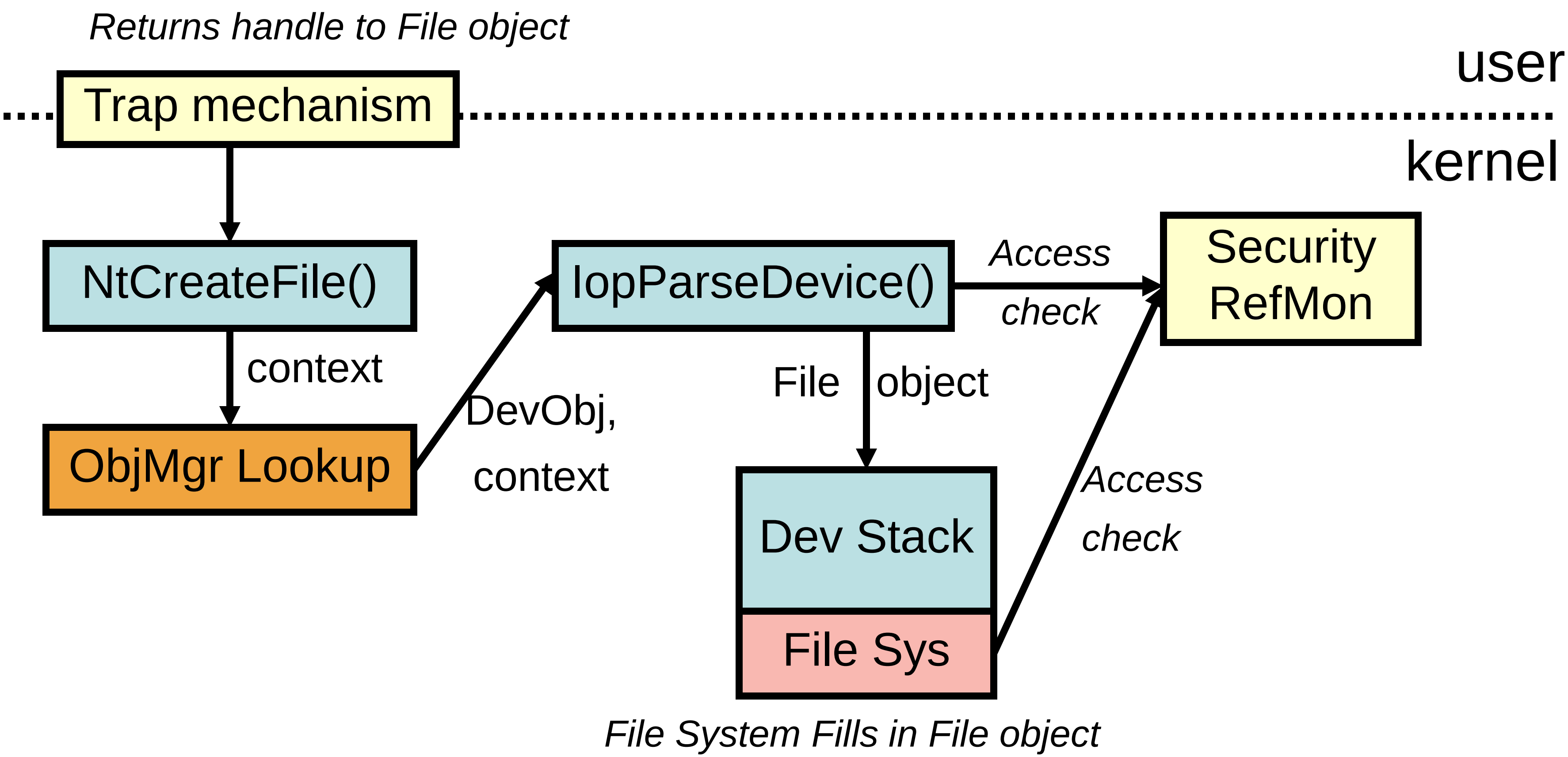
\Global??\C:\foo\bar.txt



deviceobject->ParseRoutine == IopParseDevice

Note: namespace rooted in object manager, not FS

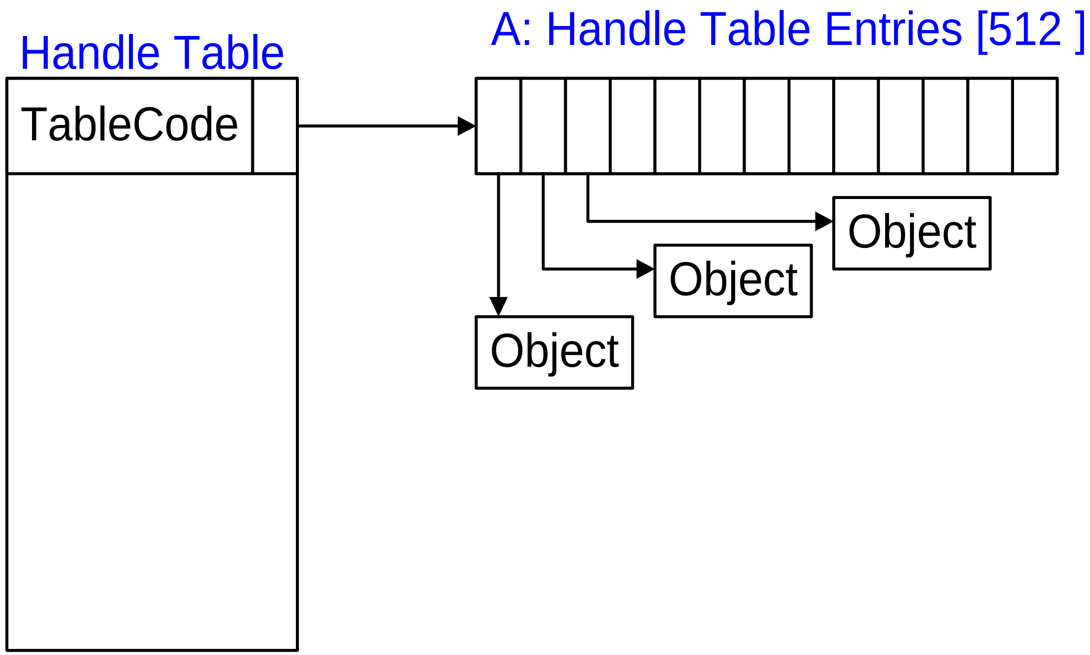
I/O Support: IopParseDevice



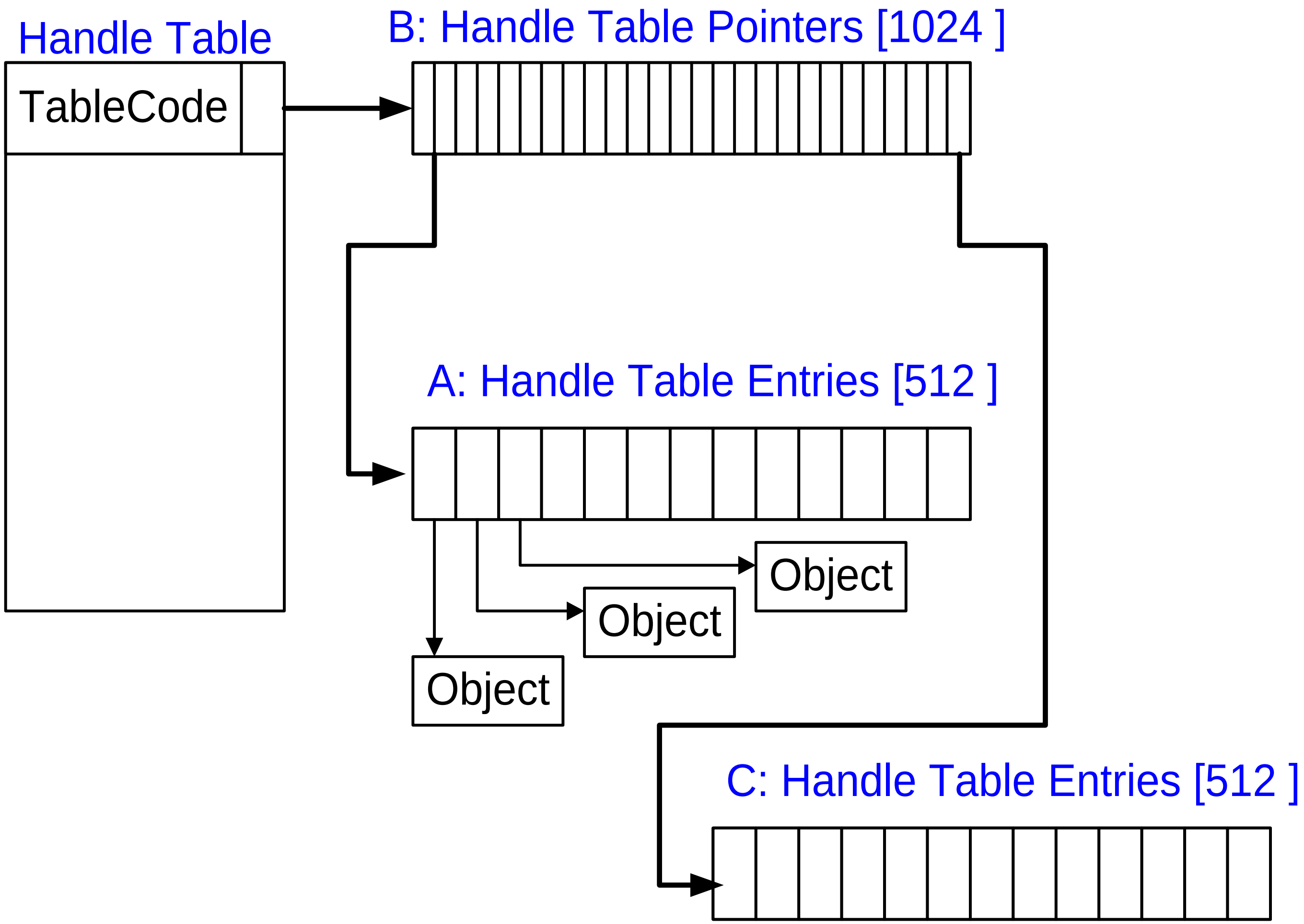
Handle Table

- Every process has a handle table
  - System Process (kernel) has global handle table
  - Data structure also used to allocate/map process/thread IDs
- NT handles reference kernel data structures
  - Mostly used from user-mode
  - Kernel mode uses handles or referenced pointers
- NT APIs use explicit handles to refer to objects
  - Simplifies cross-process operations
  - Handles can be restricted and duplicated cross-process
- Handles can be used for synchronization
  - Any *dispatcher object* can be waited on
  - Multiple objects can be waited by single thread

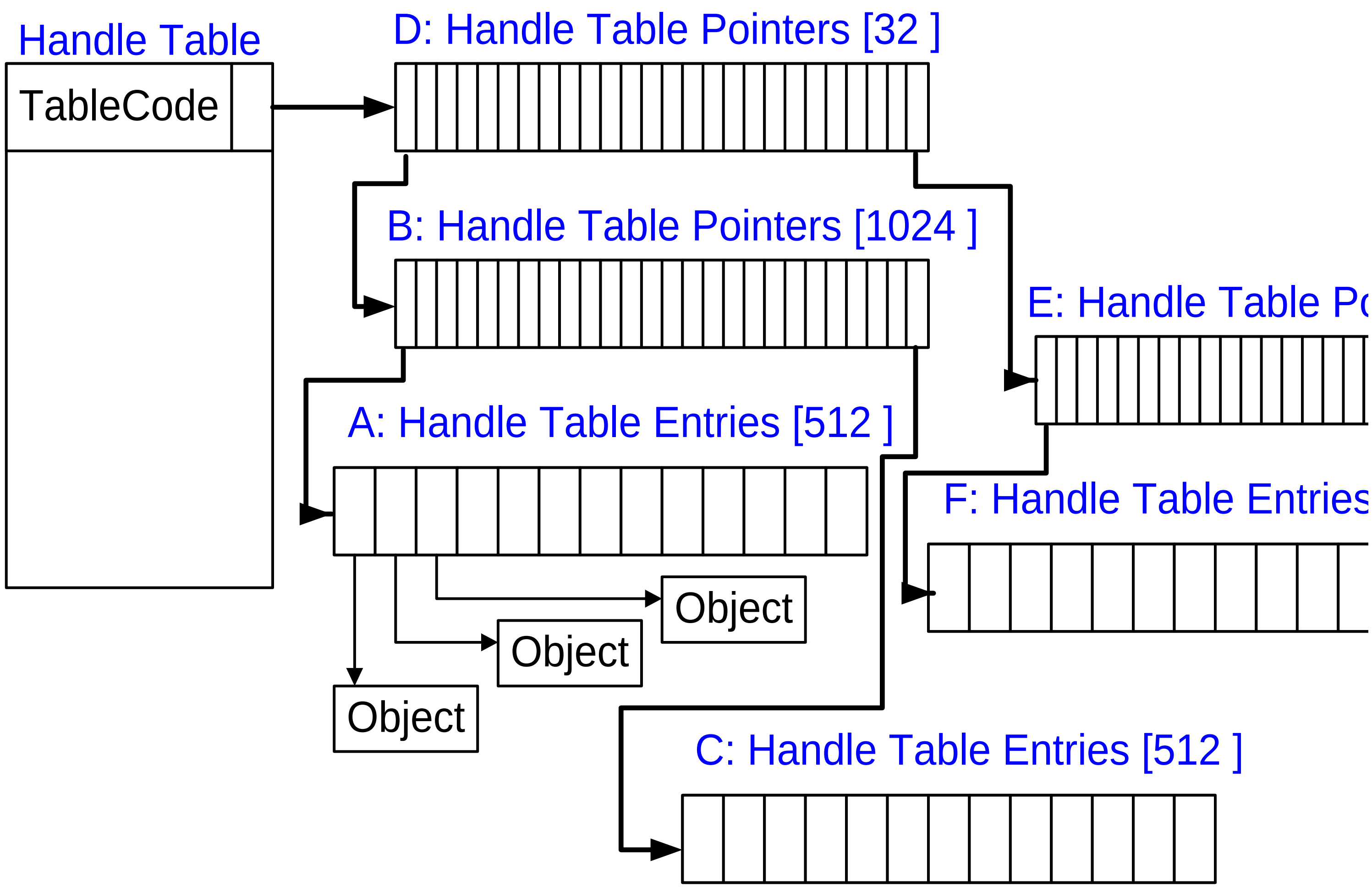
One level: (to 512 handles)



Two levels: (to 512K handles)



Three levels: (to 16M handles)



Thread Manager Kernel Layer

CPU Control-flow

Normal threads are composed of kernel-threads and user-threads, each with stack, and scheduling/environmental info

APCs (Asynchronous Procedure Calls) interrupt the execution of a thread, not a processor

DPCs (Deferred Procedure Calls) interrupt the execution of a processor, not a thread

Thread Pools and Worker threads used to spawn work as tasks and reducing thread create/delete overhead

Threads

- Unit of concurrency (abstracts the CPU)
- Threads created within processes
- System threads created within system process (kernel)
- System thread examples:
  - Dedicated threads
    - Lazy writer, modified page writer, balance set manager, mapped pager writer, other housekeeping functions
  - General worker threads
    - Used to move work out of context of user thread
    - Must be freed before drivers unload
    - Sometimes used to avoid kernel stack overflows
  - Driver worker threads
    - Extends pool of worker threads for heavy hitters, like file server

Thread elements

user-mode

- user-mode stack
- Thread Environment Block (TEB)
  - most interesting: *thread local storage*

kernel-mode

- kernel-mode stack
- KTHREAD: scheduling, synchronization, timers, APCs
- ETHREAD: timestamps, I/O list, exec locks, process link
- thread ID
- impersonation token

Context-switching Kernel VM

Three regions of kernel VM are switched

- Page tables and page directory self-map
- Hyperspace (working set lists)
- Session space

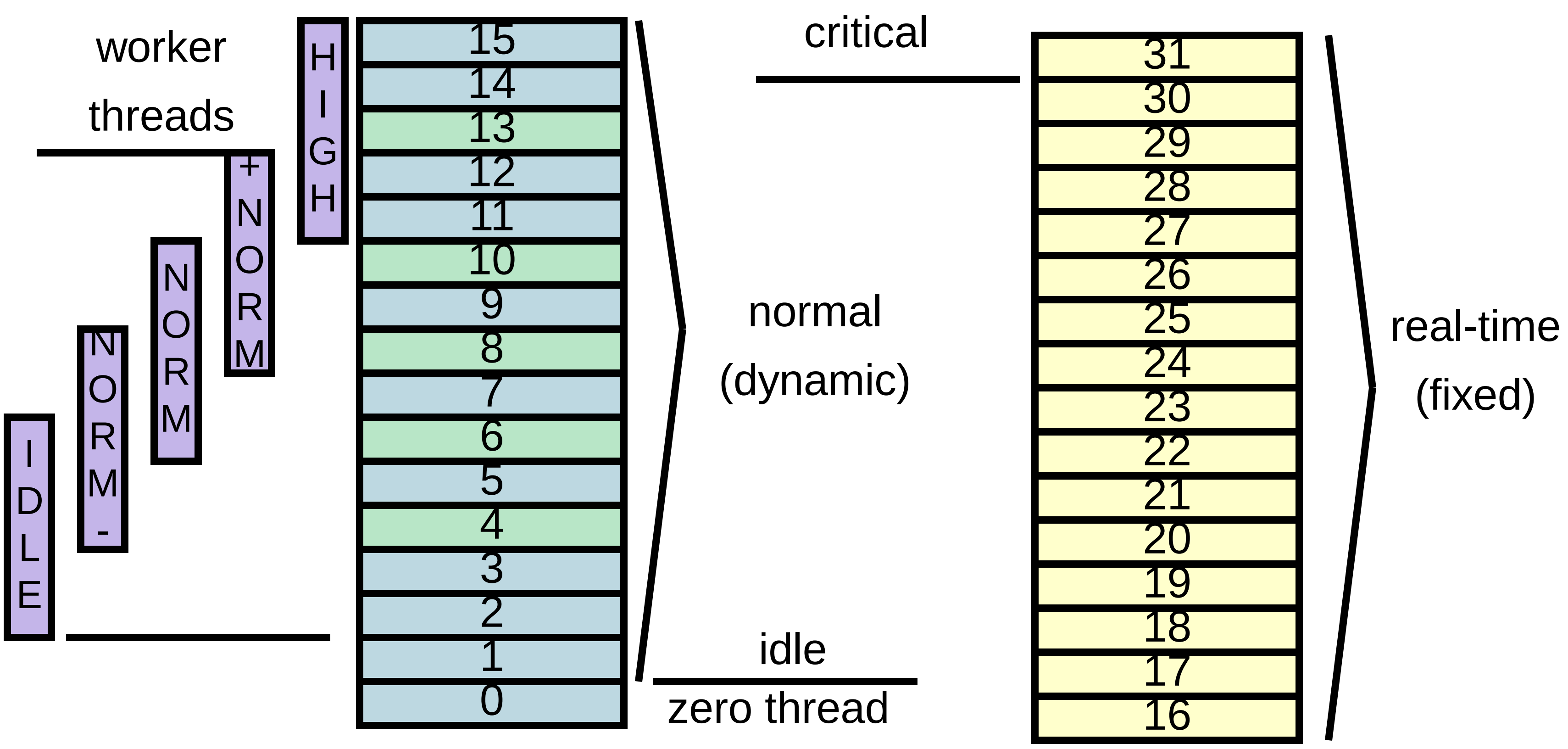
- Session space
  - 'Session' is a terminal services session
  - Contains data structures for kernel-level GUI
  - Only switched when processes in different TS session
- Switched kernel regions not usually needed in other processes
  - *Thread attach* is used to temporary context switch when they are
  - Savings in KVA is substantial, as these are very large data structures

Kernel Thread Attach

Allows a thread in the kernel to temporarily move to a different process' address space

- Used heavily in Mm and Ps, e.g.
  - Used to access process page tables, working set descriptors, etc
  - PspProcessDelete() attaches before calling ObKillProcess() to close/delete handles in proper process context
- Used to access the TEB/PEB in user-mode
  - (Thread/Process Environment Blocks)

NT thread priorities



Scheduling

Windows schedules threads, not processes

- Scheduling is preemptive, priority-based, and round-robin at the highest-priority
- 16 real-time priorities above 16 normal priorities
- Scheduler tries to keep a thread on its ideal processor/node to avoid perf degradation of cache/NUMA-memory
- Threads can specify affinity mask to run only on certain processors

Each thread has a current & base priority

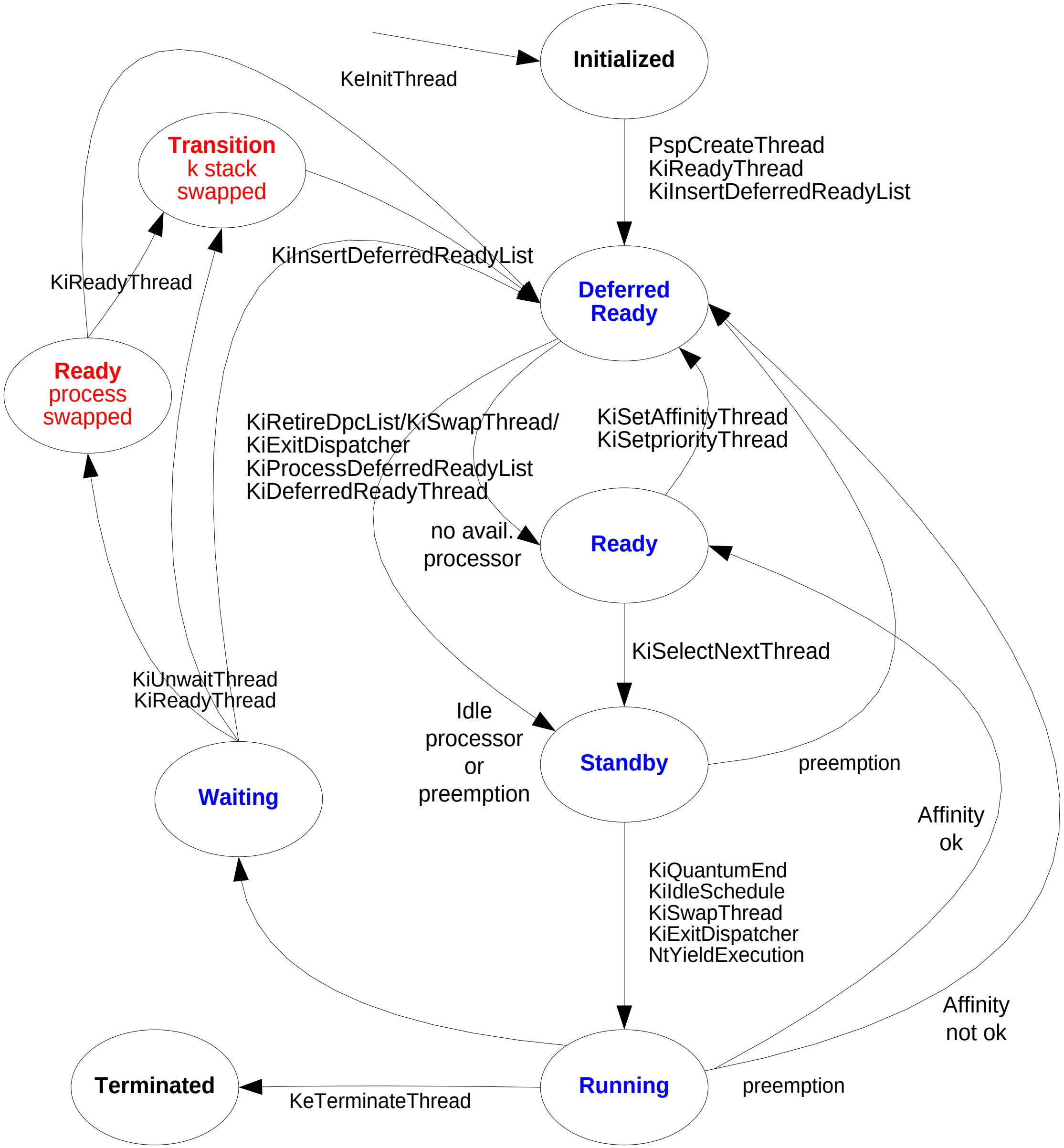
- Base priority initialized from process
- Non-realtime threads have priority boost/decay from base
- Boosts for GUI foreground, waking for event
- Priority decays, particularly if thread is CPU bound (running at quantum end)

Scheduler is state-driven by timer, setting thread priority, thread block/exit, etc

Priority inversions can lead to starvation

- balance manager periodically boosts non-running runnable threads

Scheduler



Kernel Thread Transition Diagram
DavePr@Microsoft.com
2003/04/06 v0.4b

Asynchronous Procedure Calls

APCs execute routine in thread context

- not as general as UNIX signals
- user-mode APCs run when blocked & alertable
- kernel-mode APCs used extensively: timers, notifications, swapping stacks, debugging, set thread ctx, I/O completion, error reporting, creating & destroying processes & threads, …

APCs generally blocked in critical sections

- e.g. don’t want thread to exit holding resources

Asynchronous Procedure Calls

APCs execute code in context of a particular thread

APCs run only at PASSIVE or APC LEVEL (0 or 1)

- Interrupted by DPCs and ISRs

Three kinds of APCs

- **User-mode:** deliver notifications, such as I/O done
- **Kernel-mode:** perform O/S work in context of a process/thread, such as completing IRPs
- **Special kernel-mode:** used for process termination

Process Manager
Memory Manager
Cache Manager

Processes

- An environment for program execution
  - Namespaces (access to files & kernel objects)
  - virtual address mappings
  - ports (debug, exceptions)
  - threads
  - user authentication (token)
  - virtual memory data structures
  - PEB (Process Environment Block) in user-mode
- In Windows, a process abstracts the MMU, not the CPU

Process Lifetime

- Process created as an empty shell
- Address space created with only system DLL and the main image (including linked DLLs)
- Handle table created empty or populated via duplication of inheritable handles from parent
- Add environment, threads, map executable image sections (EXE and DLLs)

- Process partially destroyed (“rundown”) at last thread exit
- Process totally destroyed on last dereference

System DLL

Core user-mode functionality in the system dynamic link library (DLL) *ntdll.dll*

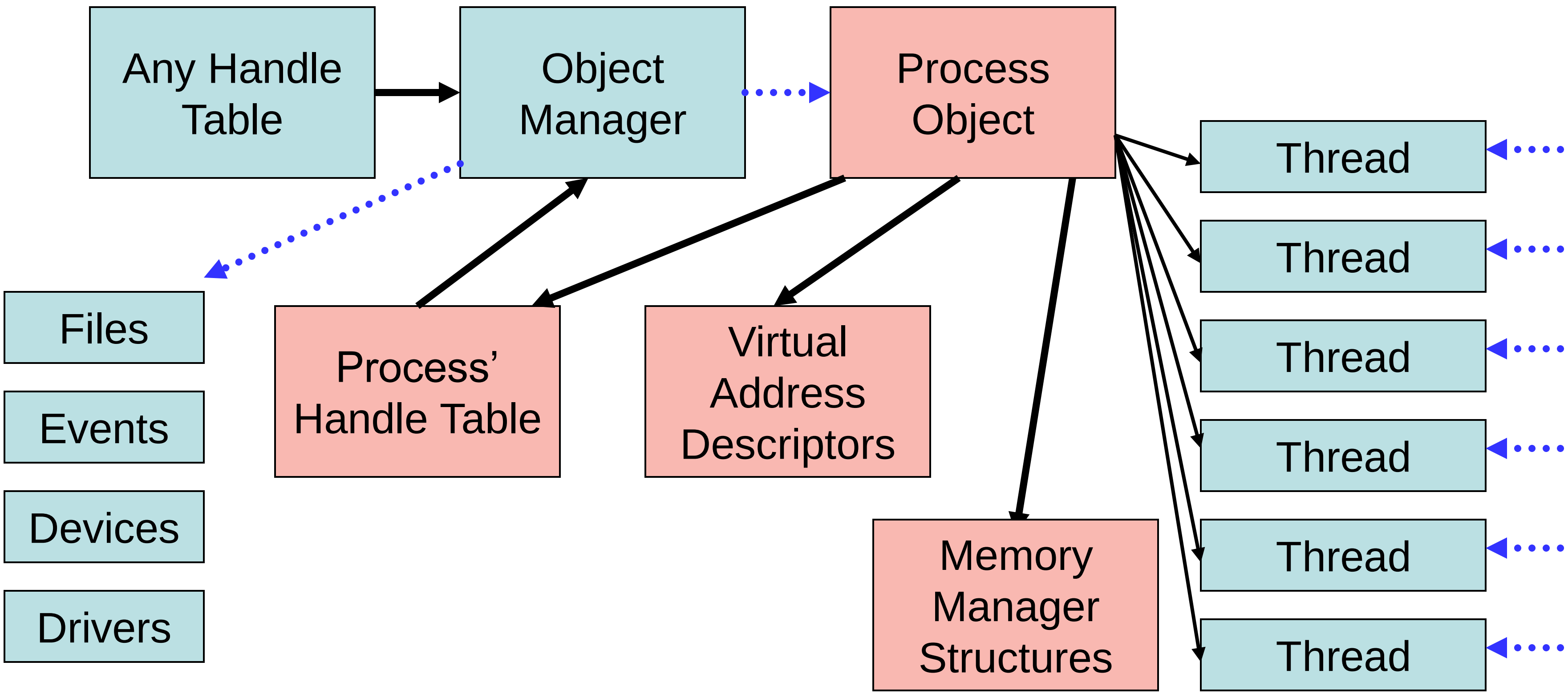
Mapped during process address space setup by the kernel

Contains all core system service entry points

User-mode trampoline points for:

- Process/thread startup
- Exception dispatch
- User APC dispatch
- Kernel-user callouts

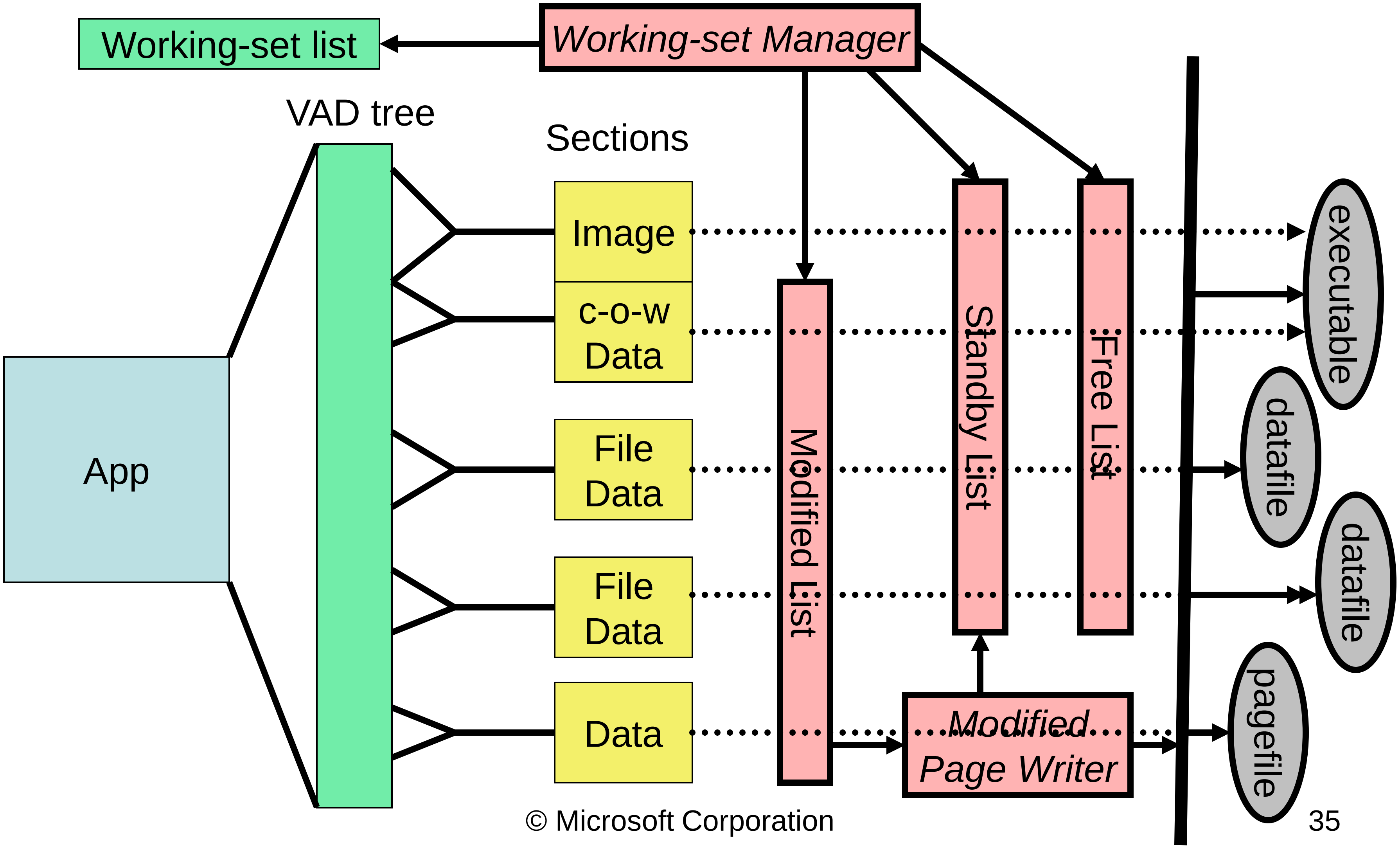
Process/Thread structure



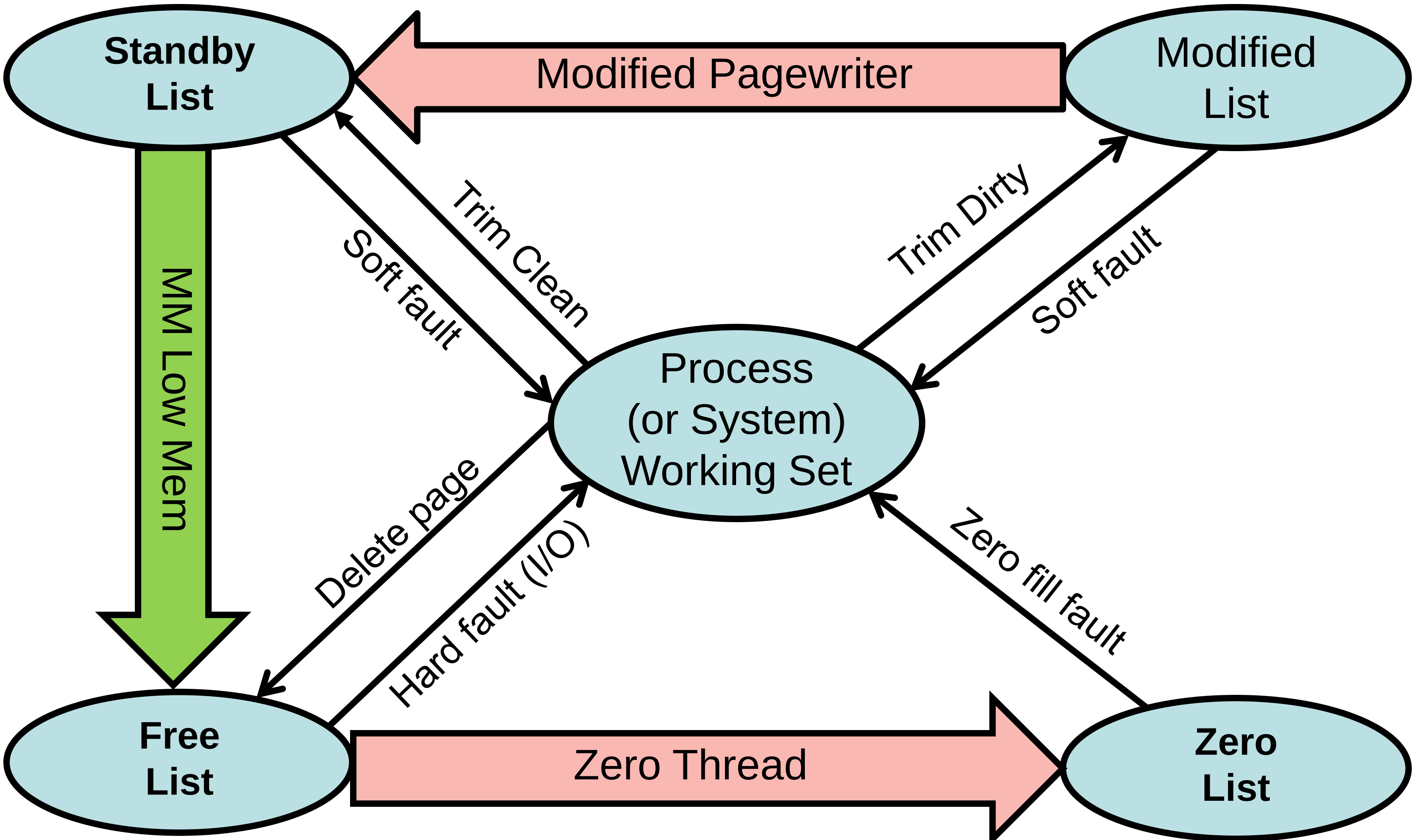
Physical Frame Management

- Table of PFN (Physical Frame Number) data structures
  - Represent all pageable pages
  - Synchronize page-ins
  - Linked to management lists
- Page Tables
  - Hierarchical index of page directories and tables
  - Leaf-node is *page table entry* (PTE)
  - PTE states:
    - Active/valid
    - Transition
    - Modified-no-write
    - Demand zero
    - Page file
    - Mapped file

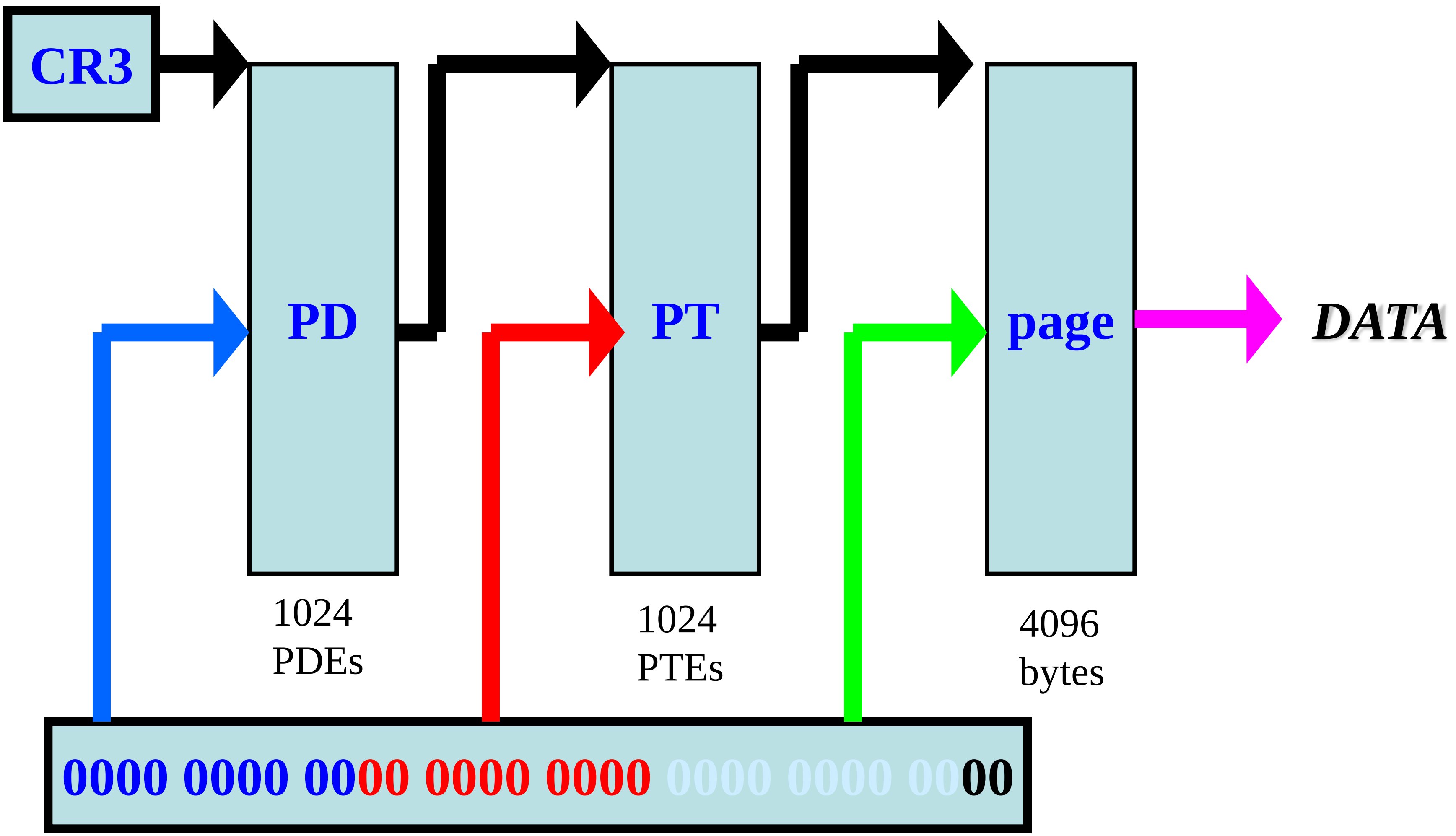
Virtual Memory Management



Physical Frame State Changes

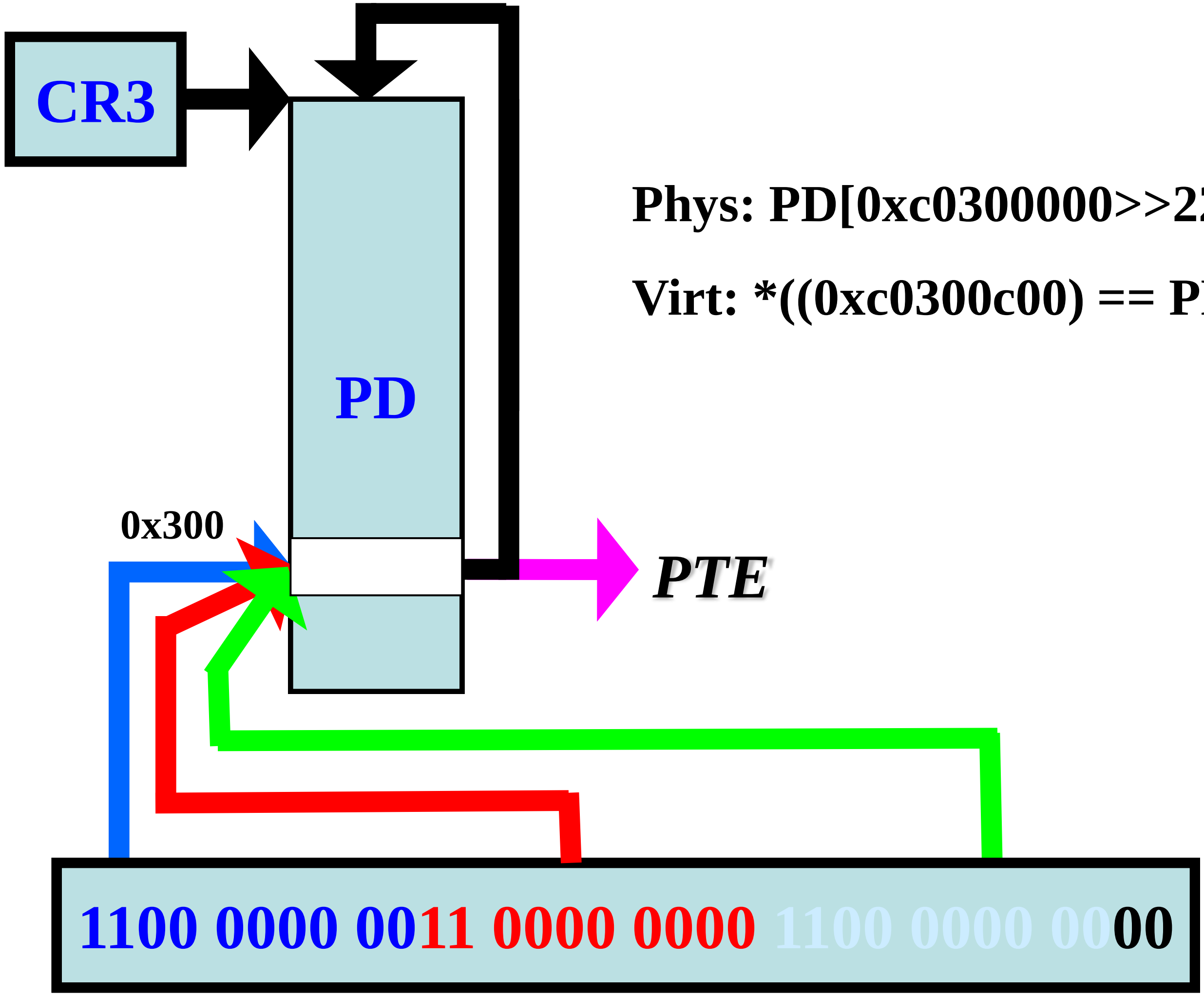


32b Virtual Address Translation



Self-mapping page tables

Virtual Access to PageDirectory[0x300]

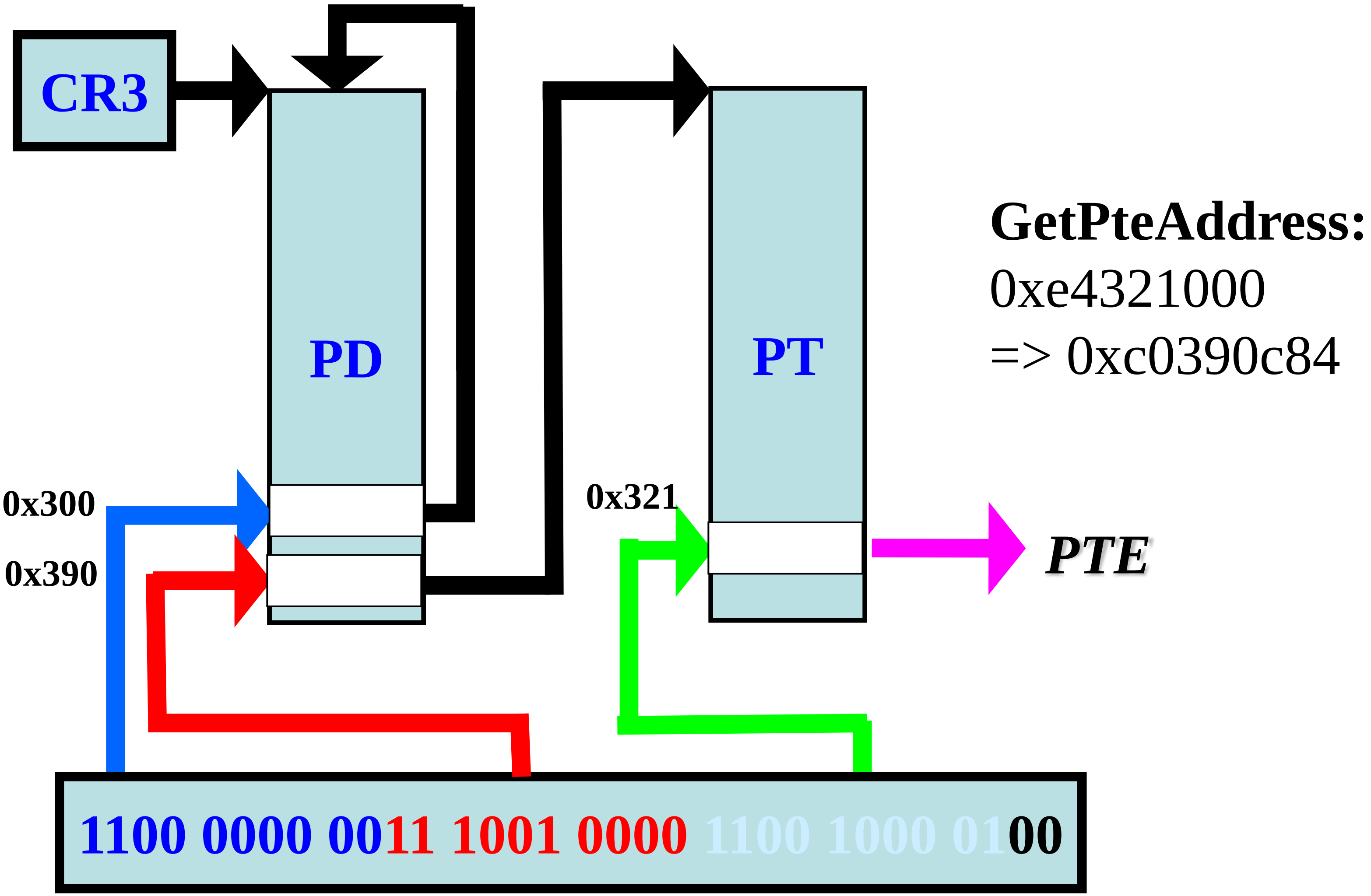


Phys: PD[0xc0300000>>22] = PD

Virt: *((0xc0300c00) == PD

Self-mapping page tables

Virtual Access to PTE for va 0xe4321000

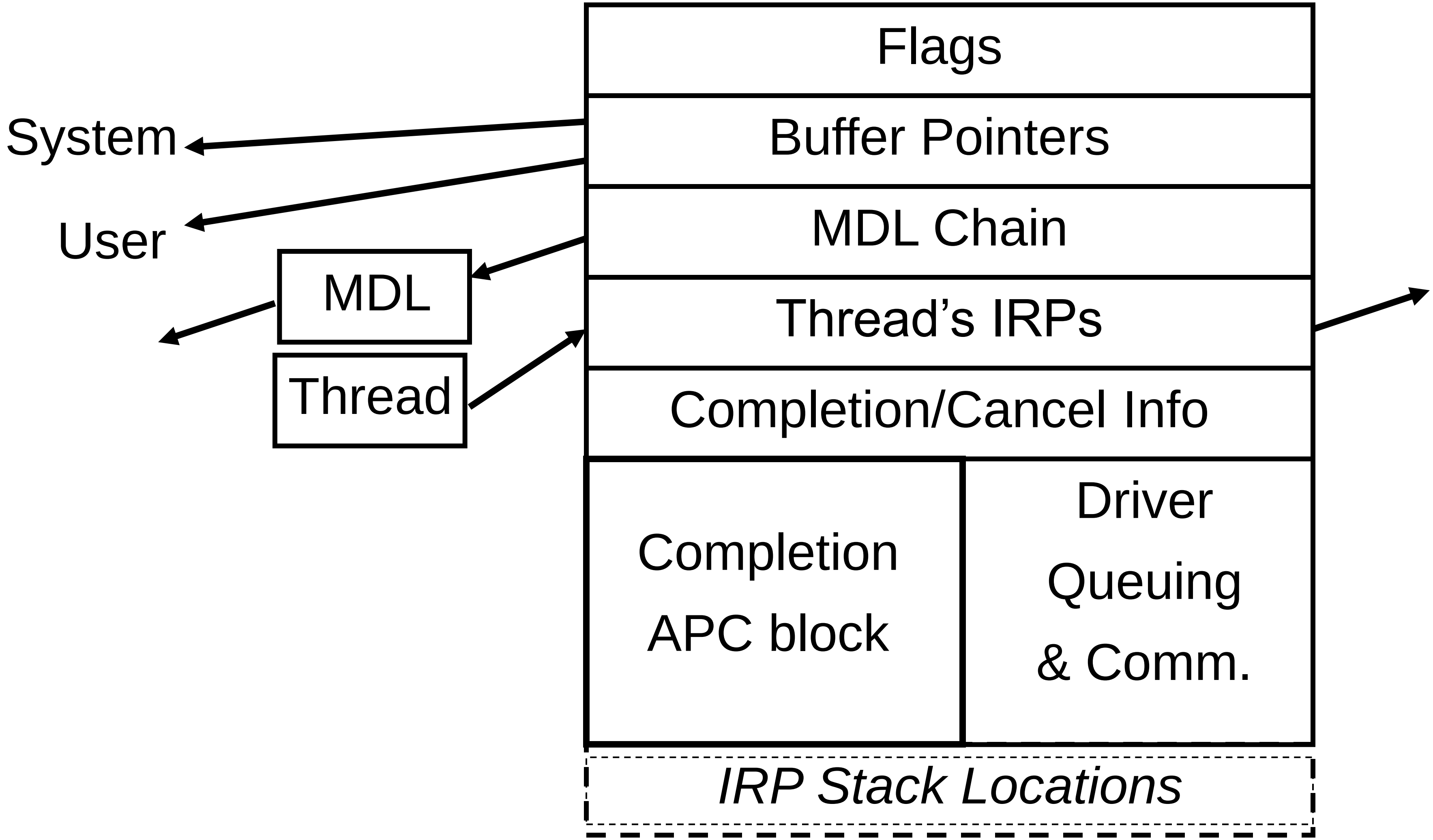


I/O

I/O Model

– Extensible filter-based I/O model with driver layering
– Standard device models for common device classes
– Support for notifications, tracing, journaling
– Configuration store
– File caching is virtual, based on memory mapping
– Completely asynchronous model (with cancellation)

I/O Request Packet (IRP)



Layering Drivers

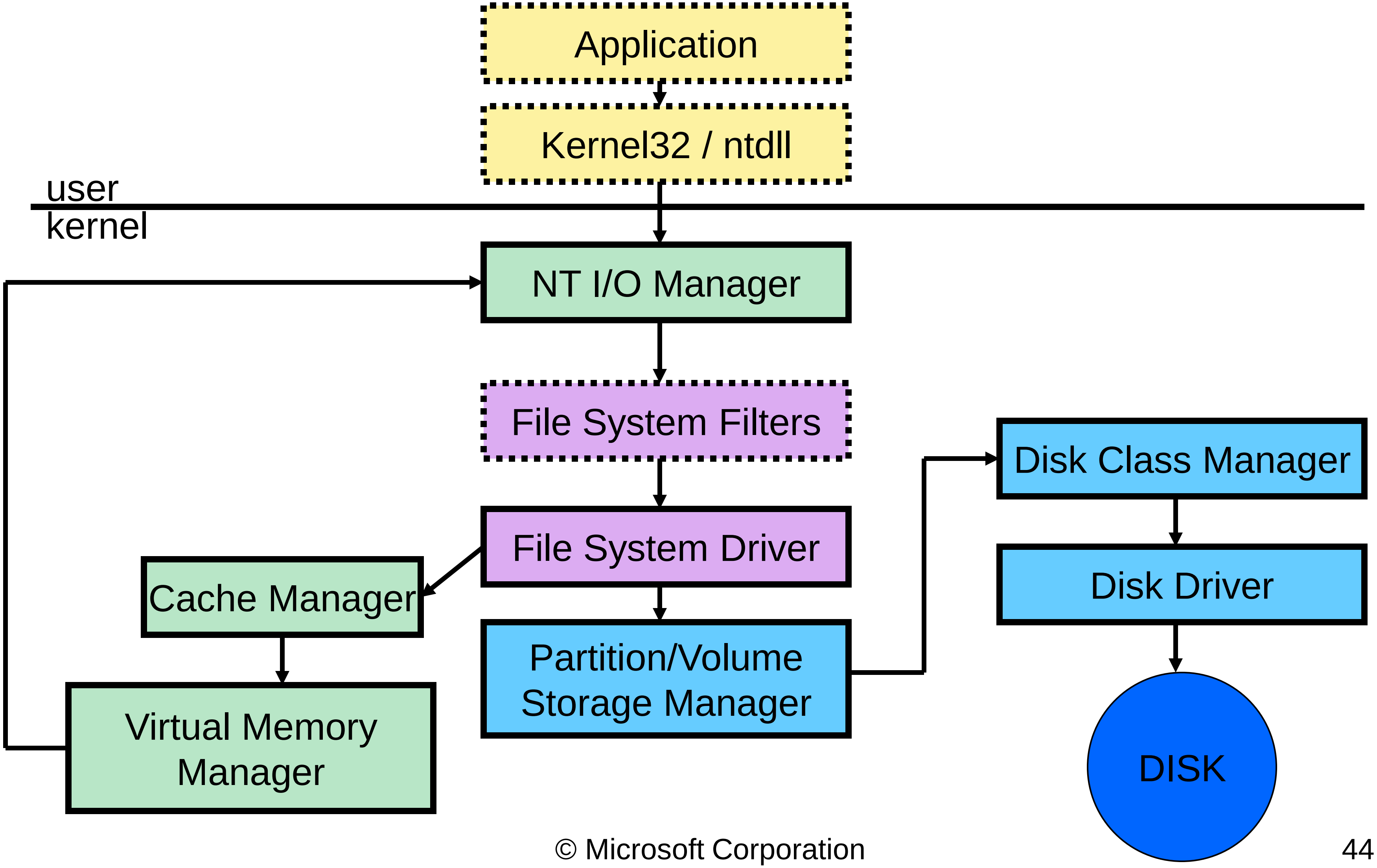
Device objects attach one on top of another using IoAttachDevice* APIs creating device stacks

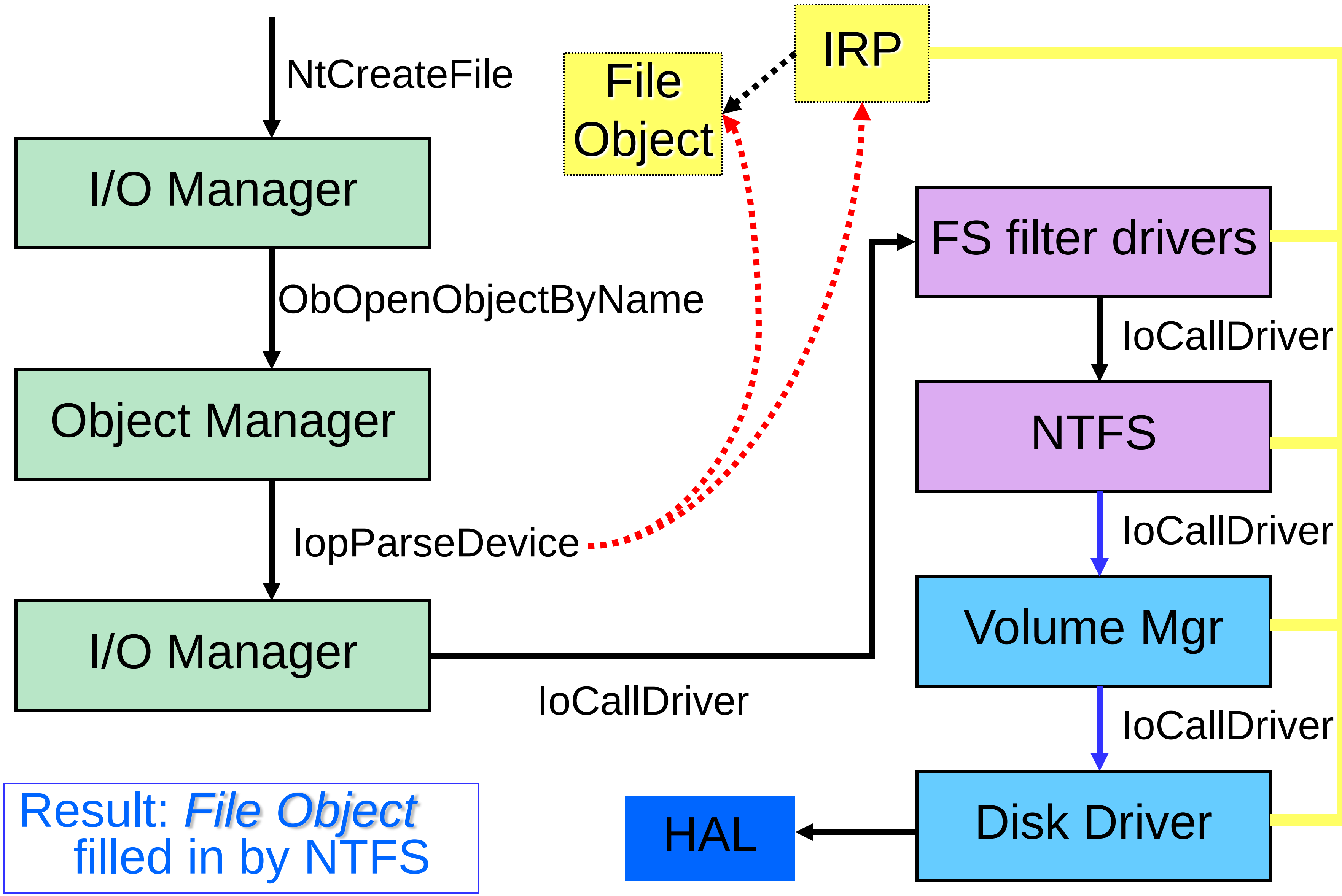
- I/O manager sends IRP to top of the stack
- Drivers store next lower device object in their private data structure
- Stack tear down done using IoDetachDevice and IoDeleteDevice

Device objects point to driver objects

- Driver represent driver state, including dispatch table

File System Device Stack



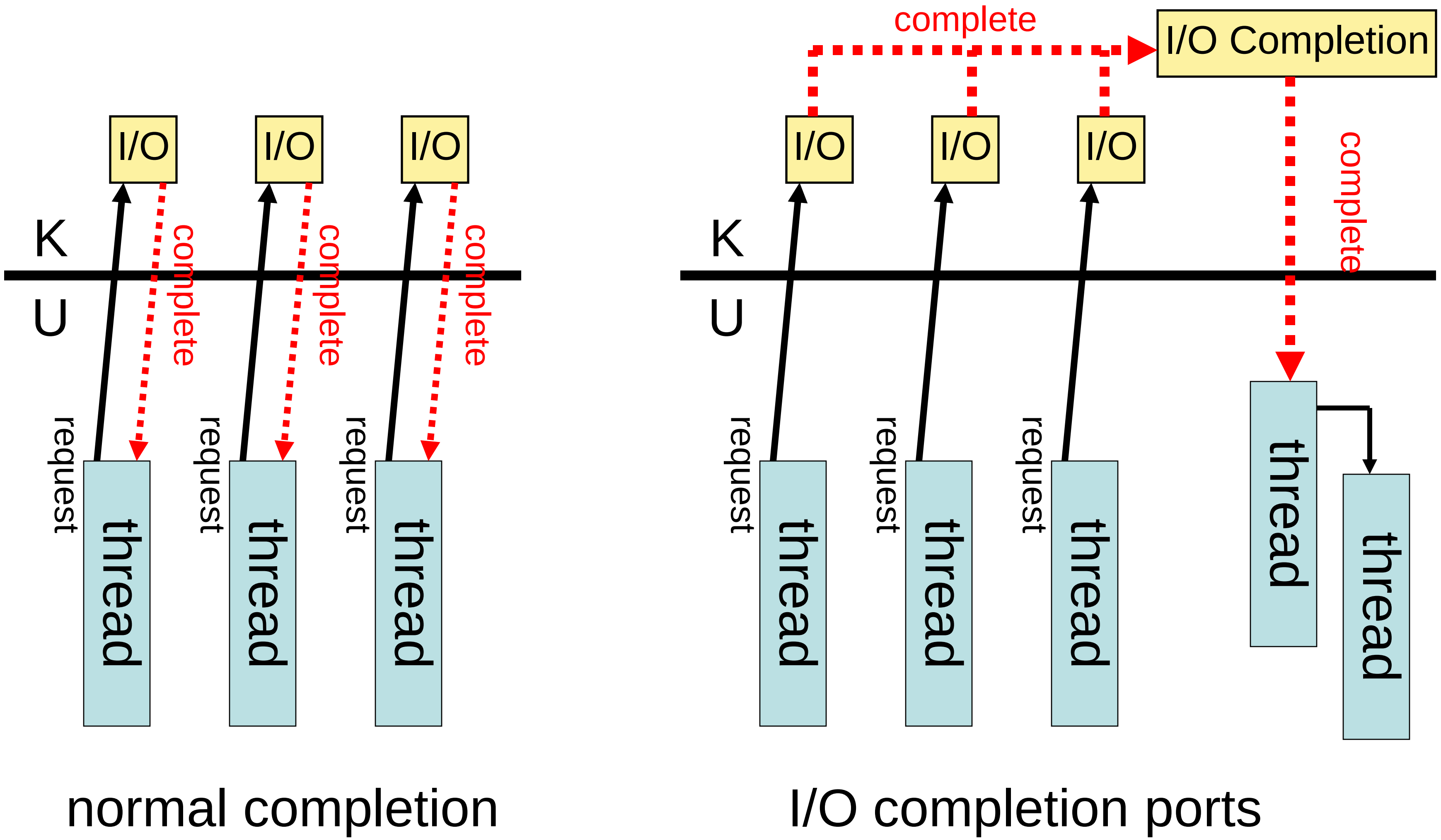


Result: *File Object*
filled in by NTFS

I/O Completions

- Receiving notification for asynchronous I/O completion:
  - poll status variable
  - wait for the file handle to be signalled
  - wait for an explicitly passed event to be signalled
  - specify a routine to be called on the originating ports
  - use an I/O completion port

I/O Completion Ports



Questions