# Unit OS5: Memory Management

## 5.2. Windows Memory Management Fundamentals

Windows Operating System Internals - by David A. Solomon and Mark E. Russinovich with Andreas Polze

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# Roadmap for Section 5.2.

- Memory Manager Features and Components
- Virtual Address Space Allocation
- Shared Memory and Memory-Mapped Files
- Physical Memory Limits
- Memory management APIs



# Windows Memory Management Fundamentals

- Classical virtual memory management
  - Flat virtual address space per process
  - Private process address space
  - Global system address space
  - Per session address space
- Object based
  - Section object and object-based security (ACLs…)
- Demand paged virtual memory
  - Pages are read in on demand & written out when necessary (to make room for other memory needs)
- Provides flat virtual address space
  - 32-bit: 4 GB, 64-bit: 16 Exabytes (theoretical)

# Windows Memory Management Fundamentals

- Lazy evaluation
  - Sharing – usage of prototype PTEs (page table entries)
  - Extensive usage of copy_on_write
  - ...whenever possible
- Shared memory with copy on write
- Mapped files (fundamental primitive)
  - Provides basic support for file system cache manager



# Memory Manager Components

- System services for allocating, deallocating, and managing virtual memory
- A access fault trap handler for resolving hardware-detected memory management exceptions and making virtual pages resident on behalf of a process
- Six system threads
  - *Working set manager* (priority 16) – drives overall memory management policies, such as working set trimming, aging, and modified page writing
  - *Process/stack swapper* (priority 23) -- performs both process and kernel thread stack inswapping and outswapping
  - *Modified page writer* (priority 17) – writes dirty pages on the modified list back to the appropriate paging files
  - *Mapped page writer* (priority 17) – writes dirty pages from mapped files to disk
  - *Dereference segment thread* (priority 18) is responsible for cache and page file growth and shrinkage
  - *Zero page thread* (priority 0) – zeros out pages on the free list

# MM: Process Support

- MmCreateProcessAddressSpace – 3 pages
  - The page directory
    - Points to itself
    - Map the page table of the hyperspace
    - Map system paged and nonpaged areas
    - Map system cache page table pages
  - The page table page for working set
  - The page for the working set list
- MmInitializeProcessAddressSpace
  - Initialize PFN for PD and hyperspace PDEs
  - MiInitializeWorkingSetList
  - Optional: MmMapViewOfSection for image file
- MmCleanProcessAddressSpace,
- MmDeleteProcess AddressSpace



# MM: Process Swap Support

- MmOutSwapProcess / MmInSwapProcess
- MmCreateKernelStack
  - MiReserveSystemPtes for stack and no-access page
- MmDeleteKernelStack
  - MiReleaseSystemPtes
- MmGrowKernelStack
- MmOutPageKernelStack
  - Signature (thread_id) written on top of stack before write
  - The page goes to transition list
- MmInPageKernelStack
  - Check signature after stack page is read / bugcheck

# MM: Working Sets

- Working Set:
  - The set of pages in memory at any time for a given process, or
  - All the pages the process can reference without incurring a page fault
  - Per process, private address space
  - WS limit: maximum amount of pages a process can own
  - Implemented as array of working set list entries (WSLE)
- Soft vs. Hard Page Faults:
  - Soft page faults resolved from memory (standby/modified page lis ts)
  - Hard page faults require disk access
- Working Set Dynamics:
  - Page replacement when WS limit is reached
  - NT 4.0: page replacement based on modified FIFO
  - Windows 2000: Least Recently Used algorithm (uniproc.)



# MM: Working Set Management

- Modified Page Writer thread
  - Created at system initialization
  - Writing modified pages to backing file
  - Optimization: min. I/Os, contigous pages on disk
  - Generally MPW is invoked before trimming
- Balance Set Manager thread
  - Created at system initialization
  - Wakes up every second
  - Executes MmWorkingSetManager
  - Trimming process WS when required: from current down to minimal WS for processes with lowest page fault rate
  - Aware of the system cache working set
  - Process can be out-swapped if all threads have pageable kernel stack

# MM: I/O Support

- I/O Support operations:
  - Locking/Unlocking pages in memory
  - Mapping/Unmapping Locked Pages into current address space
  - Mapping/Unmapping I/O space
  - Get physical address of a locked page
  - Probe page for access
- Memory Descriptor List
  - Starting VAD
  - Size in Bytes
  - Array of elements to be filled with physical page numbers
- Physically contiguous vs. Virtually contiguous



# MM: Cache Support

- System wide cache memory
  - Region of system paged area reserved at initialization time
  - Initial default: 512 MB (min. 64MB if /3GB, max 960 MB)
  - Managed as system wide working set
    - A valid cache page is valid in all address spaces
    - Lock the page in the cache to prevent WS removal
  - WS Manager trimming thread is aware of this special WS
  - Not accessible from user mode
  - Only views of mapped files may reside in the cache
- File Systems and Server interaction support
  - Map/Unmap view of section in system cache
  - Lock/Unlock pages in system cache
  - Read section file in system cache
  - Purge section

# Memory Manager: Services

- Caller can manipulate own/remote memory
  - Parent process can allocate/deallocate, read/write memory of child process
  - Subsystems manage memory of their client processes this way
- Most services are exposed through Windows API
  - Page granularity virtual memory functions (Virtualxxx...)
  - Memory-mapped file functions (CreateFileMapping, MapViewofFile)
  - Heap functions (Heapxxx, Localxxx (old), Globalxxx (old))
- Services for device drivers/kernel code (Mm...)



# Protecting Memory

| Attribute | Description |
| --- | --- |
| PAGE_NOACCESS | Read/write/execute causes access violation |
| PAGE_READONLY | Write/execute causes access violation; read permitted |
| PAGE_READWRITE | Read/write accesses permitted |
| PAGE_EXECUTE | Any read/write causes access violation; execution of code is permitted (relies on special processor support) |
| PAGE_EXECUTE_ READ | Read/execute access permitted (relies on special processor support) |
| PAGE_EXECUTE_ READWRITE | All accesses permitted (relies on special processor support) |
| PAGE_WRITECOPY | Write access causes the system to give process a private copy of this page; attempts to execute code cause access violation |
| PAGE_EXECUTE_ WRITECOPY | Write access causes creation of private copy of pg. |
| PAGE_GUARD | Any read/write attempt raises EXCEPTION_GUARD_PAGE and turns off guard page status |

# Reserving & Committing Memory

- Optional 2-phase approach to memory allocation:
  1. Reserve address space (in multiples of page size)
  2. Commit storage in that address space
  - Can be combined in one call (VirtualAlloc, VirtualAllocEx)
- Reserved memory:
  - Range of virtual addresses reserved for future use (contiguous buffer)
  - Accessing reserved memory results in access violation
  - Fast, inexpensive
- Committed memory:
  - Has backing store (pagefile.sys, memory-mapped file)
  - Either private or mapped into a view of a section
  - Decommit via VirtualFree, VirtualFreeEx

A thread's user-mode stack is constructed using this 2-phase approach: initial reserved size is 1MB, only 2 pages are committed: stack & guard page



# Features new to Windows 2000 Memory Management

- Support of 64 GB physical memory on Intel platform
  - PAE – physical address extension (36 bit, changes PDE/PTE structs)
  - New version of kernel (ntkrnlpa.exe, ntkrpamp.exe)
    - /PAE switch in boot.ini
- Integrated support for Terminal Server
  - HydraSpace : per session
  - In NT 4 Terminal Server had a specific kernel
- Driver Verifier: verifier.exe
  - Pool checking, IRQL checking
  - Low resources simulation, pool tracking, I/O verification

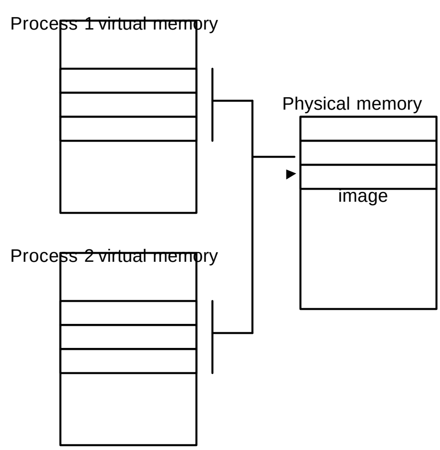
# Features new to Windows XP/2003 Memory Management

- 64-bit support
- Up to 1024 Gbytes physical memory supported
- Support for Data Execution Prevention (DEP)
  - Memory manager supports HW no-execute protection
- Performance & Scalability enhancements



# Shared Memory & Mapped Files

- Shared memory + copy-on-write per default
- Executables are mapped as read-only
- Memory manager uses section objects to implement shared memory
(file mapping objects in Windows API)



# Virtual Address Space Allocation

- Virtual address space is sparse
  - Address spaces contain reserved, committed, and unused regions
- Unit of protection and usage is one page
  - On x86, default page size is 4 KB (x86 supports 4KB or 4MB)
    - In PAE mode, large pages are 2 MB
  - On x64, default page size is 4 KB (large pages are 4 MB)
  - On Itanium, default page size is 8 KB
    (Itanium supports 4k, 8k, 16k, 64k, 256k, 1mb, 4mb, 16mb, 64mb, or 256mb) – large is 16MB



# Large Pages

- Large pages allow a single page directory entry to map a larger region
  - x86, x64: 4 MB, IA64: 16 MB
  - Advantage: improves performance
    - Single TLB entry used to map larger area
- Large pages are used to map NTOSKRNL, HAL, nonpaged pool, and the PFN database if a “large memory system”
  - Windows 2000: more than 127 MB
  - Windows XP/2003: more than 255 MB
  - In other words, most systems…
- Disadvantage: disables kernel write protection
  - With small pages, OS/driver code pages are mapped as read only; with large pages, entire area must be mapped read/write
    - Drivers can then modify/corrupt system & driver code without immediately crashing system
  - Driver Verifier turns large pages off
  - Can also override by changing HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Control\Session Manager\Memory Management\LargePageMinimum to FFFFFFFF

# Large Pages: Server 2003 Enhancements

- Can specify other drivers to map with large pages:
  - HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Control\Session Manager\Memory Management\LargePageDrivers (multi-string)
- Applications can use large pages for process memory
  - VirtualAlloc with MEM_LARGE_PAGE flag
  - Can query if system supports large pages with GetLargePageMinimum



# Data Execution Prevention

- Windows XP SP2 and Windows Server 2003 SP1 support Data Execution Prevention (DEP)
  - Prevents code from executing in a memory page not specifically marked as executable
  - Stops exploits that rely on getting code executed in data areas
- Relies on hardware ability to mark pages as non executable
  - AMD calls it NX ("No Execute")
  - Intel calls it XD ("Execute Disable")
- Processor support:
  - Intel Itanium had this in 2001, but Windows didn't support it until now
  - AMD64 was the next to support it
  - Then, AMD added Sempron (32-bit processor with NX support)
  - Intel added it first with their 64-bit extension chips (Xeon/Pentium 4s with EM64T)
  - More recently, Intel added it to their 32-bit processor line (anything ending in "J")

# Data Execution Prevention

- Attempts to execute code in a page marked no execute result in:
  - User mode: access violation exception
  - Kernel mode: ATTEMPTED_EXECUTE_OF_NOEXECUTE_MEMORY bugcheck (blue screen)
- Memory that needs to be executable must be marked as such using page protection bits on VirtualAlloc and VirtualProtect APIs:
  - PAGE_EXECUTE, PAGE_EXECUTE_READ, PAGE_EXECUTE_READWRITE, PAGE_EXECUTE_WRITECOPY

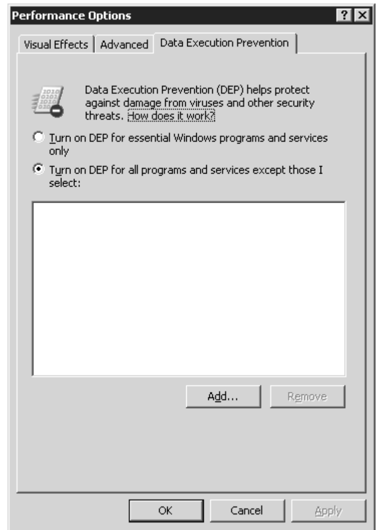


# Controlling DEP

- New Boot.ini switch /NOEXECUTE
  - /NOEXECUTE=ALWAYSON – enables DEP for all applications
  - /NOEXECUTE=ALWAYSOFF – disables DEP
- Two qualifiers apply only to 32-bit applications:
  - /NOEXECUTE=OPTIN – enables DEP for core Windows programs
    - Default for Windows XP (32-bit and 64-bit editions)
  - /NOEXECUTE=OPTOUT – enables DEP for all applications except those excluded
    - Default for Windows Server 2003 (32-bit and 64-bit editions)

# DEP on 64-bit Windows

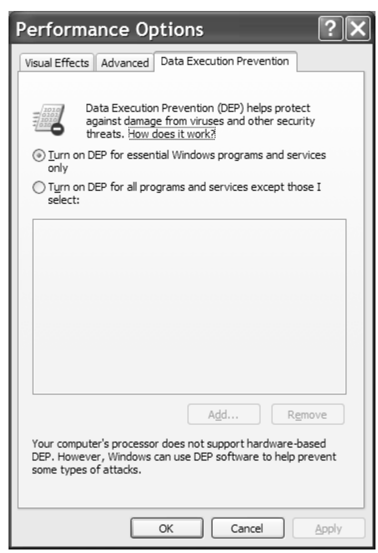
- Always applied to all 64-bit processes and device drivers
  - Protects user and kernel stacks, paged pool, session pool
- 32-bit processes depend on configuration settings






# DEP on 32-bit Windows

- Hardware DEP used when running 32-bit Windows on systems that support it
- When enabled, system boots PAE kernel (Ntkrnlpa.exe)
- Kernel mode: applied to kernel stacks, but not paged/session pool
- User mode: depends on system configuration
- Even on processors without hardware DEP, some limited protection implemented for exception handlers



# Mapped Files

- A way to take part of a file and map it to a range of virtual addresses

  (address space is 2 GB, but files can be much larger)
- Called “file mapping objects” in Windows API
- Bytes in the file then correspond one-for-one with bytes in the region of virtual address space
  - Read from the “memory” fetches data from the file
  - Pages are kept in physical memory as needed
  - Changes to the memory are eventually written back to the file (can request explicit flush)
- Initial mapped files in a process include:
  - The executable image (EXE)
  - One or more Dynamically Linked Libraries (DLLs)
- Processes can map additional files as desired (data files or additional DLLs)



# Section Objects (mapped files)

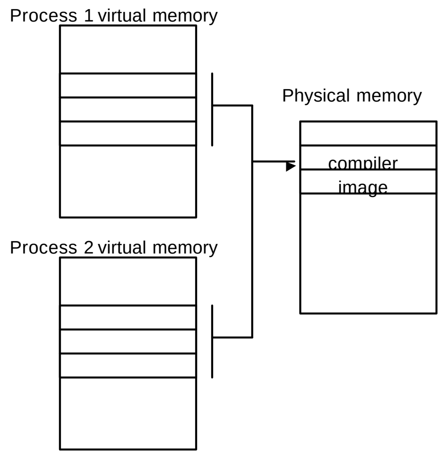
- Called “file mapping objects” in Windows API
- ~~Files may be mapped into v.a.s.~~

```
// first, do EITHER ...
hMapObj = CreateFileMapping (hFile, security, protection,sizeHigh, sizeLow,
   mapname);
// … OR …
hMapObj = OpenFileMapping (accessMode, inheritflag, mapname);
// … then, pass the resulting handle to a mapping object (section) to ...
lpvoid = MapViewOfFile (hMapObj, accessMode,
      offsetHigh, offsetLow, cbMap);
```

- Bytes in the file then correspond one-for-one with bytes in the region of virtual address space
  - Read from the “memory” fetches data from the file
  - Changes to the memory are written back to the file
  - Pages are kept in physical memory as needed
  - If desired, can map to only a part of the file at a time

# Shared Memory

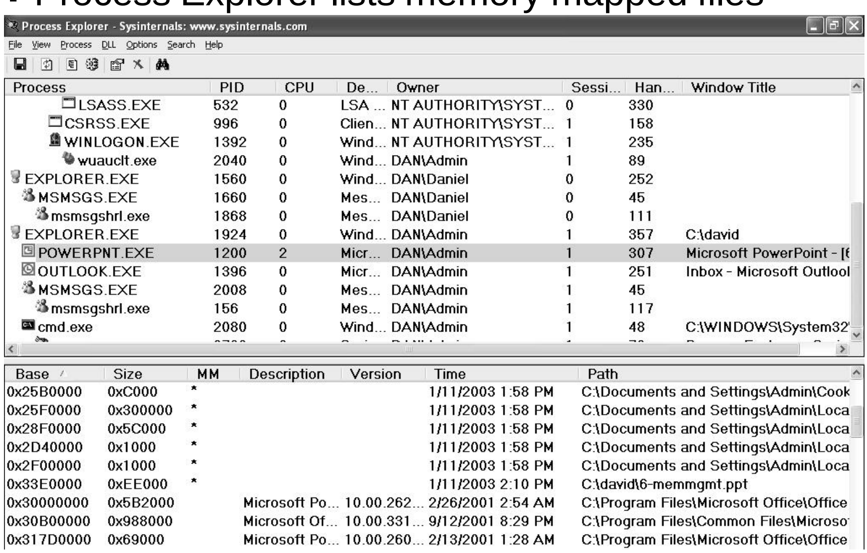
- Like most modern OS's, Windows provides a way for processes to share memory
  - High speed IPC (used by LPC, which is used by RPC)
  - Threads share address space, but applications may be divided into multiple processes for stability reasons
- It does this automatically for shareable pages
  - E.g. code pages in an EXE or DLL
- Processes can also create shared memory sections
  - Called page file backed file mapping objects
  - Full Windows security






# Viewing DLLs & Memory Mapped Files

- Process Explorer lists memory mapped files




| Process | PID | CPU | De... | Owner | Sessi... | Han... | Window Title |
|---|---|---|---|---|---|---|---|
| LSASS.EXE | 532 | 0 | LSA ... | NT AUTHORITY\SYST... | 0 | 330 | |
| CSRSS.EXE | 996 | 0 | Clien... | NT AUTHORITY\SYST... | 1 | 158 | |
| WINLOGON.EXE | 1392 | 0 | Wind... | NT AUTHORITY\SYST... | 1 | 235 | |
| wuauclt.exe | 2040 | 0 | Wind... | DAN\Admin | 1 | 89 | |
| EXPLORER.EXE | 1560 | 0 | Wind... | DAN\Daniel | 0 | 252 | |
| MSMSGS.EXE | 1660 | 0 | Mes... | DAN\Daniel | 0 | 45 | |
| msmsgshrl.exe | 1868 | 0 | Mes... | DAN\Daniel | 0 | 111 | |
| EXPLORER.EXE | 1924 | 0 | Wind... | DAN\Admin | 1 | 357 | C:\david |
| POWERPNT.EXE | 1200 | 2 | Micr... | DAN\Admin | 1 | 307 | Microsoft PowerPoint - [6 |
| OUTLOOK.EXE | 1396 | 0 | Micr... | DAN\Admin | 1 | 251 | Inbox - Microsoft Outlool |
| MSMSGS.EXE | 2008 | 0 | Mes... | DAN\Admin | 1 | 45 | |
| msmsgshrl.exe | 156 | 0 | Mes... | DAN\Admin | 1 | 117 | |
| cmd.exe | 2080 | 0 | Wind... | DAN\Admin | 1 | 48 | C:\WINDOWS\System32' |

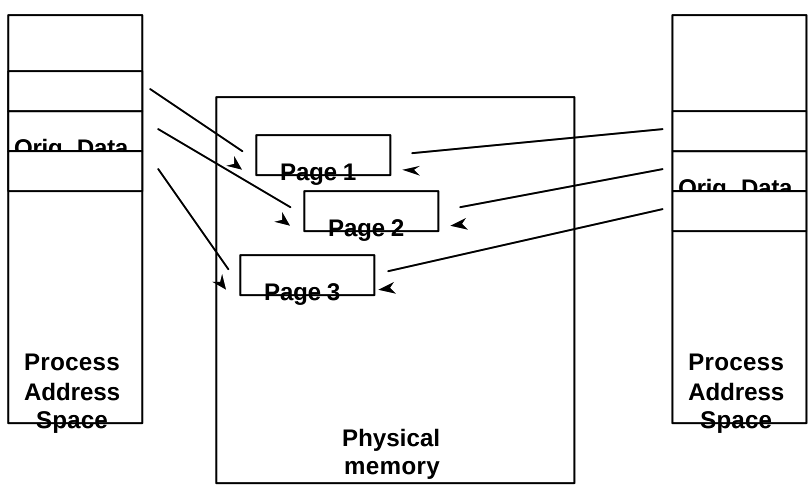
| Base | Size | MM | Description | Version | Time | Path |
|---|---|---|---|---|---|---|
| 0x25B0000 | 0xC000 | * | | | 1/11/2003 1:58 PM | C:\Documents and Settings\Admin\Cook |
| 0x25F0000 | 0x300000 | * | | | 1/11/2003 1:58 PM | C:\Documents and Settings\Admin\Loca |
| 0x28F0000 | 0x5C000 | * | | | 1/11/2003 1:58 PM | C:\Documents and Settings\Admin\Loca |
| 0x2D40000 | 0x1000 | * | | | 1/11/2003 1:58 PM | C:\Documents and Settings\Admin\Loca |
| 0x2F00000 | 0x1000 | * | | | 1/11/2003 1:58 PM | C:\Documents and Settings\Admin\Loca |
| 0x33E0000 | 0xEE000 | * | | | 1/11/2003 2:10 PM | C:\david\6-memmgmt.ppt |
| 0x30000000 | 0x5B2000 | | Microsoft Po... | 10.00.262... | 2/26/2001 2:54 AM | C:\Program Files\Microsoft Office\Office |
| 0x30B00000 | 0x988000 | | Microsoft Of... | 10.00.331... | 9/12/2001 8:29 PM | C:\Program Files\Common Files\Microso |
| 0x317D0000 | 0x69000 | | Microsoft Po... | 10.00.260... | 2/13/2001 1:28 AM | C:\Program Files\Microsoft Office\Office |

# Copy-On-Write Pages

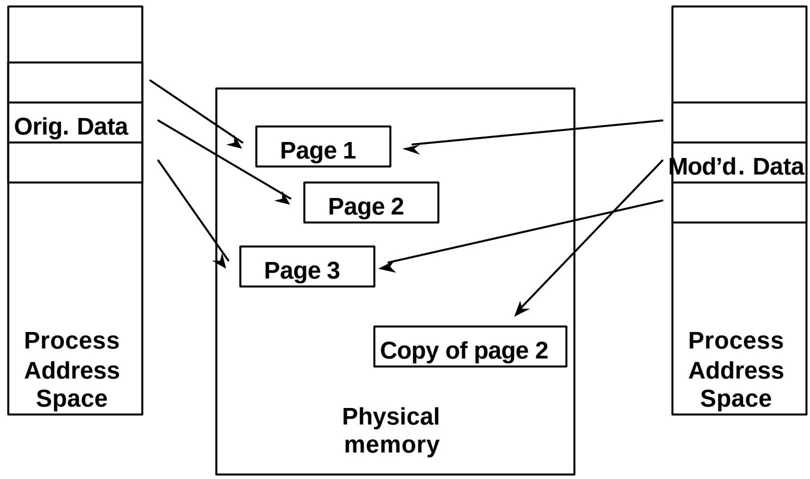
- Used for sharing between process address spaces
- Pages are originally set up as shared, read-only, faulted from the common file
  - Access violation on write attempt alerts pager
    - pager makes a copy of the page and allocates it privately to the process doing the write, backed to the paging file
  - So, only need unique copies for the pages in the shared region that are actually written (example of "lazy evaluation")
  - Original values of data are still shared
    - e.g. writeable data initialized with C initializers



# How Copy-On-Write Works <u>Before</u>

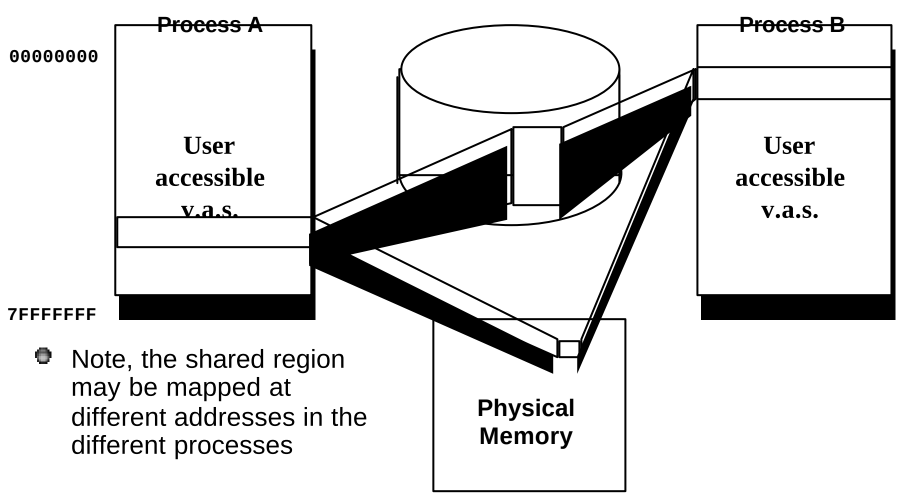


## How Copy-On-Write Works After





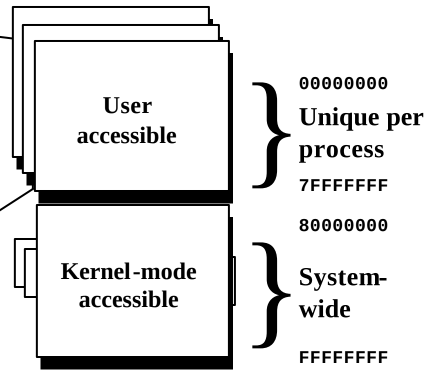

## Shared Memory = File Mapped by Multiple Processes




- Note, the shared region may be mapped at different addresses in the different processes

# Virtual Address Space (V.A.S.)

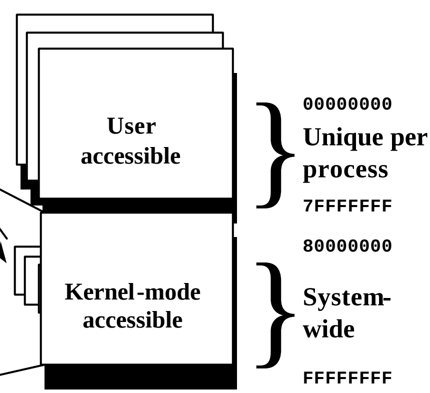
- Process space contains:
  - The application you're running (.EXE and .DLLs)
  - A user-mode stack for each thread (automatic storage)
  - All static storage defined by the application






# Virtual Address Space (V.A.S.)

- System space contains:
  - Executive, kernel, and HAL
  - Statically-allocated system-wide data cells
  - Page tables (remapped for each process)
  - Executive heaps (pools)
  - Kernel-mode device drivers (in nonpaged pool)
  - File system cache
  - A kernel-mode stack for every thread in every process

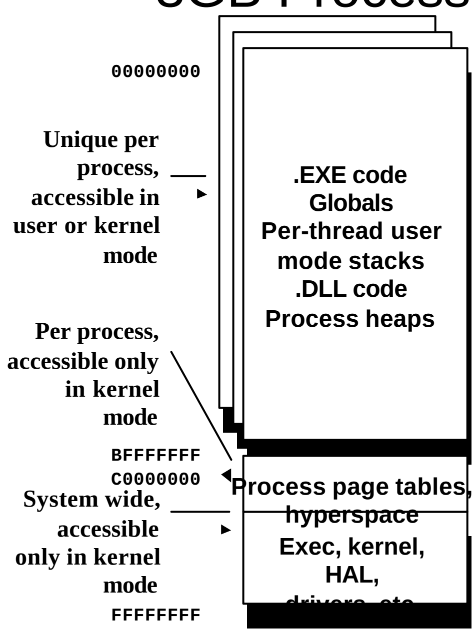


# Windows User Process Address Space Layout

| Range | Size | Function |
|---|---|---|
| 0x0 – 0xFFFF | 64 KB | No-access region to catch incorrect pointer ref. |
| 0x10000 - 07FFEFFFF | 2 GB minus at least 192kb | The private process address space |
| 0x7FFDE000 - 0x7FFDEFFF | 4 KB | Thread Environment Block (TEB) for first thread, more TEBs are created at the page prior to that page |
| 0x7FFDF000 - 0x7FFDFFFF | 4 KB | Process Environment Block (PEB) |
| 0x7FFE0000 - 0x7FFE0FFF | 4 KB | Shared user data page – read-only, mapped to system space, contains system time, clock tick count, version number (avoid kernel-mode transition) |
| 0x7FFE1000 – 0x7FFEFFFF | 60 KB | No-access region |
| 0x7FFF0000 – 0x7FFFFFFF | 64 KB | No-access region to prevent threads from passing buffers that straddle user/system space boundary |



# 3GB Process Space Option




- Only available on:
  - Windows 2003 Server, Enterprise Edition & Windows 2000 Advanced Server, XP SP2
    - Limits phys memory to 16 GB
  - /3GB option in BOOT.INI
  - Windows Server 2003 and XP SP2 supports variations from 2GB to 3GB (/USERVA=)
- Provides 3 GB per-process address space
  - Commonly used by database servers (for file mapping)
  - .EXE must have "large address space aware" flag in image header, or they're limited to 2 GB (specify at link time or with imagecfg.exe from ResKit)
  - Chief "loser" in system space is file system cache
  - Better solution: address windowing extensions
  - Even better: 64-bit Windows

# Large Address Space Aware Images

- Images marked as “large address space aware”:
  - Lsass.exe – Security Server
  - Inetinfo.exe—Internet Information Server
  - Chkdsk.exe – Check Disk utility
  - Dllhst3g.exe – special version of Dllhost.exe (for COM+ applications)
  - Esentutl.exe - jet database repair tool
- To see this type:

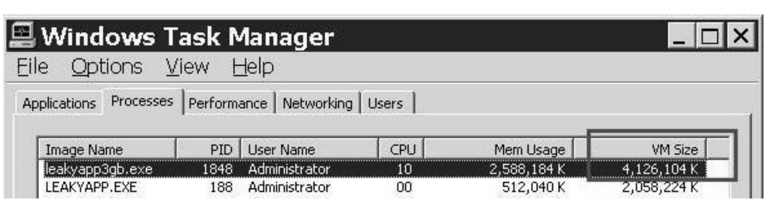
```
Imagecfg \windows\system32\*.exe > large_images.txt
```

  - Then search for “large” in large_images.txt



# Large Address Space Aware on 64-bits

- Images marked large address space aware get a full 4 GB process virtual address space
  - OS isn’t mapped there, so space is available for process



# Physical Memory

- Maximum on Windows NT 4.0 was 4 GB for x86 (8 GB for Alpha AXP)
  - This is fixed by page table entry (PTE) format
- What about x86 systems with > 4 GB?
  - Pentium Pro and Xeon systems can support up to 64 GB physical memory
    - Four more bits of physical address in PTEs = 36 bits = 64 GB
- NT4: Intel provides a driver that allows use of RAM beyond 4 GB as a RAM disk
- Windows 2000 added proper support for PAE
  - Requires booting /PAE to select the PAE kernel
- Actual physical memory usable varies by Windows package…



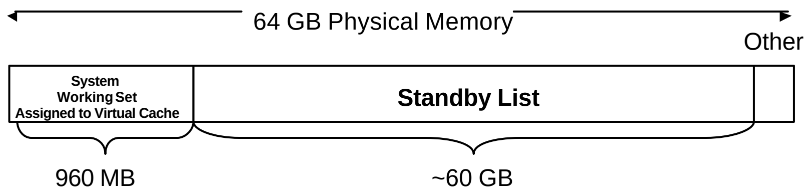
# Physical Memory Limits (in GB)

| | x86 | x64 32-bit | x64 64-bit | IA-64 64-bit |
|---|---|---|---|---|
| XP Home | 4 | 4 | n/a | n/a |
| XP Professional | 4 | 4 | 16 | n/a |
| Server 2003 Web Edition | 2 | 2 | n/a | n/a |
| Server 2003 Standard | 4 | 4 | 16 | n/a |
| Server 2003 Enterprise | 32 | 32 | 64 | 64 |
| Server 2003 Datacenter | 64 | 128 | 1024 | 1024 |

# Physical Memory Usage on Systems in PAE Mode

- Virtual address space is still 4 GB, so how can you “use” > 4 GB of memory?

1. Although each process can only address 2 GB, many may be in memory at the same time (e.g. 5 * 2 GB processes = 10 GB)
2. Files in system cache remain in physical memory
   - Although file cache doesn’t know it, memory manager keeps unmapped data in physical memory

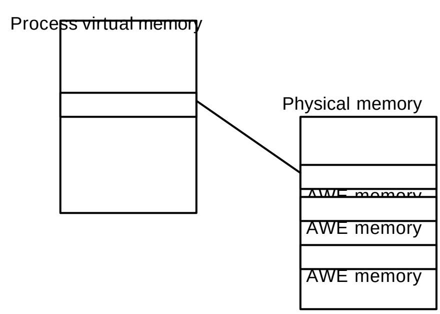



3. New Address Windowing Extensions allow Windows processes to use more than 2 GB of memory



# Address Windowing Extensions

- AWE functions allow Windows processes to allocate large amounts of physical memory and then map “windows” into that memory
- Applications: database servers can cache large databases
- Up to programmer to control
  - Like DOS enhanced memory (EMS) with more bits…
- 64-bits removes this need

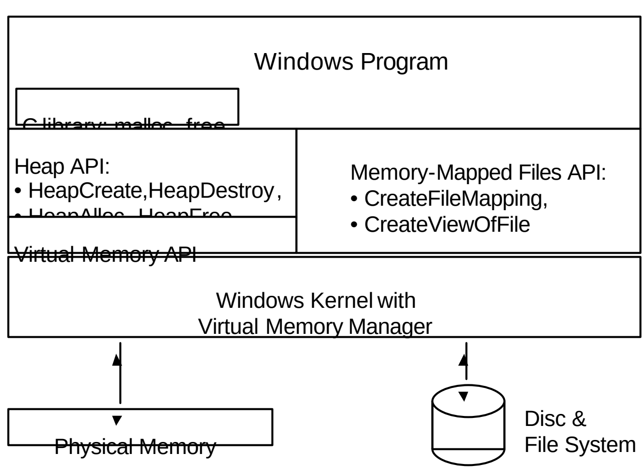


# Windows Memory Allocation APIs

- HeapCreate, Alloc, etc. (process heap APIs)
  - Windows equivalent of malloc(), free(), etc.
- VirtualAlloc( MEM_RESERVE )
- VirtualAlloc( MEM_COMMIT )
- VirtualFree
- VirtualQuery



# Windows API Memory Management Architecture



# Windows Memory Management

- Windows maintains pools of memory in heaps
- A process can contain several heaps
  - C library functions manage default heap: malloc, free, calloc
- Heaps are Windows objects – have handle
  - Each process has own default heap
  - Return value of NULL indicates failure (instead of INVALID_HANDLE_VALUE)

```
HANDLE GetProcessHeap( VOID );
HANDLE HeapCreate (DWORD floptions,
            DWORD dwInitialSize,
            DWORD dwMaximumSize);
BOOL HeapDestroy( HANDLE hHeap );
```



# Managing Heap Memory

```
LPVOID HeapAlloc( HANDLE hHeap,
            DWORD dwFlags,
            DWORD dwBytes );
```

- dwFlags:
  - HEAP_GENERATE_EXCEPTION,
    - raise SEH on memory allocation failure
    - STATUS_NO_MEMORY, STATUS_ACCESS_VIOLATION
  - HEAP_NO_SERIALIZE:
    - no serialization of concurrent (multithreaded) requests
  - HEAP_ZEROC_MEMORY: initialize allocated memory to zero
- dwSize:
  - Block of memory to allocate
  - For non-growable heaps: 0x7FFF8 (0.5 MB)
- HeapFree(), HeapReAlloc(),
- HeapCompact(), HeapValidate()

HeapLock(), HeapUnlock(): Manage concurrent accesses to heap

# Excerpt:
# Sorting with Binary Search Tree

```
#define NODE_HEAP_ISIZE 0x8000
__try {
        /* Open the input file. */
        hIn = CreateFile (fname, GENERIC_READ, 0, NULL,
                OPEN_EXISTING, 0, NULL);
        if (hIn == INVALID_HANDLE_VALUE)
                fprintf(stderr, "Failed to open input file"), exit(1);
        /* Allocate the two heaps. */
        hNode = HeapCreate (
                HEAP_GENERATE_EXCEPTIONS | HEAP_NO_SERIALIZE,
                NODE_HEAP_ISIZE, 0);
        hData = HeapCreate (
                HEAP_GENERATE_EXCEPTIONS | HEAP_NO_SERIALIZE,
                DATA_HEAP_ISIZE, 0);
        /* Process the input file, creating the tree, actual search. */
        pRoot = FillTree (hIn, hNode, hData);
```



# Heap Management Example (contd.)

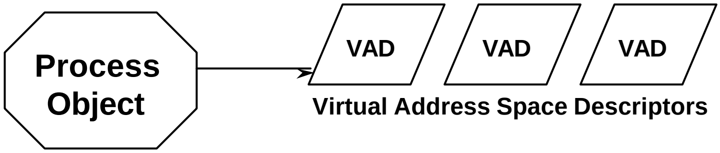
```
        /* Display the tree in Key order. */
        printf ("Sorted file: %s"), fname); Scan (pRoot);

        /* Destroy the two heaps and data structures. */
        HeapDestroy (hNode); hNode = NULL;
        HeapDestroy (hData); hData = NULL;
        CloseHandle (hIn);
} /* End of main file processing and try block. */

__except (EXCEPTION_EXECUTE_HANDLER) {
        if (hNode != NULL) HeapDestroy (hNode);
        if (hData != NULL) HeapDestroy (hData);
        if (hIn != INVALID_HANDLE_VALUE) CloseHandle (hIn);
}
return 0;
```

- UNIX C library uses only a single heap
- UNIX sbrk() can create a Process' address space – no general-purpose MM
- UNIX does not generate signals on memory alloc.

# Virtual Address Space Descriptors (VADs)



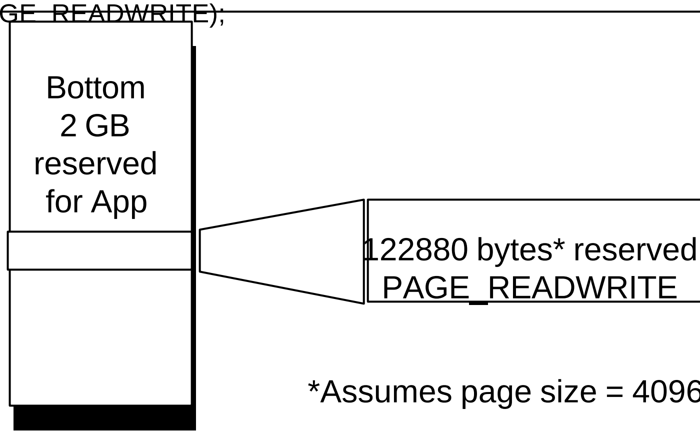

- VADs describe layout of virtual address space
  - Not the page mappings
- Used by memory manager to interpret access faults
  - Assists in “lazy evaluation”

**See kernel debugger command:**
**!vad**



# Example: Reserving Address Space

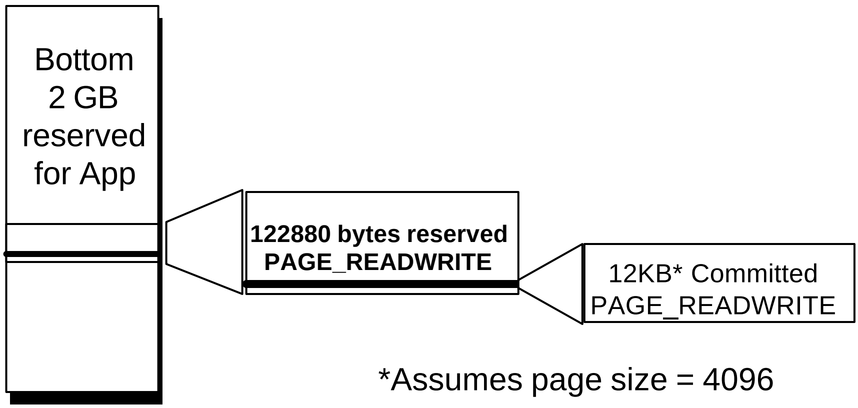
```
LPVOID lpMem = VirtualAlloc(NULL, 120000, MEM_RESERVE,
    PAGE_READWRITE);
```




*Assumes page size = 4096

# Example: Committing Address Space

```
VirtualAlloc(lpMem + 6 * 1024, 7 * 1024, MEM_COMMIT,
    PAGE_READWRITE);
```




*Assumes page size = 4096



# Memory-Mapped Files

- No need to perform direct file I/O (read/write)
- Data structures will be saved – be careful with pointers
- Convenient & efficient in-memory algorithms:
  - Can process data much larger than physical memory
- Improved performance for file processing
- No need to manage buffers and file data
  - OS does the hard work: efficient & reliable
- Multiple processes can share memory
- No need to consume space in paging file

# File Mapping Object

```
HANDLE CreateFileMapping (HANDLE hFile,
            LPSECURITY_ATTRIBUTES lpsa,
            DWORD fdwProtect,
            DWORD dwMaximumSizeHigh,
            DWORD dwMaximumSizeLow,
            LPCTSTR lpszMapName );
```

Parameters:

- hFile:
  - hFile: handle to open file with compatible access rights (fdwProtect)
  - hFile == 0xFFFFFFFF: paging file, no need to create separate file
- fdwProtect:
  - PAGE_READONLY, PAGE_READWRITE, PAGE_WRITECOPY
- dwMaximumSizeHigh, dwMaximumSizeLow:
  - Zero: current file size is used
- lpszMapName:
  - Name of mapping object for sharing between processes or NULL



# Shared Memory

```
HANDLE OpenFileMapping (HANDLE hFile,
            DWORD dwDesiredAccess,
            BOOL bInheritHandle,
            LPCTSTR lpName );
```

- Open an existing mapping object
  - Name comes from previous CreateFileMapping() call
  - First process creates mapping, subsequent processes open mapping
- dwDesiredAccess: same as fdwProtect
- lpName: name created with CreateFileMapping()
- CloseHandle() destroys mapping handles

# Mapping Process Address Space to Mapping Objects

UNIX:
4.3BSD/SysV.4
have mmap() call;

See also
shmget(),shmctl(),
shmat(),shmdt()

```
LPVOID MapViewOfFile(   HANDLE hMapObject,
            DWORD fdwAccess, DWORD dwOffsetHigh,
            DWORD dwOffsetLow, DWORD cbMap );
BOOL UnmapViewOfFile ( LPVOID lpBaseAddress );
```

- Allocate virtual memory space and map it to a file through a mapping object
  - Similar to HeapAlloc – much coarser granularity
  - Pointer to allocated block is returned (file view)
- Parameters:
  - FILE_MAP_WRITE, FILE_MAP_READ, FILE_MAP_ALL_ACCESS flag bits for fdwAccess
  - cbMap: size; entire file if zero
- FlushViewOfFile(): create consistent view

Limitation:
2GB virtual
Address space



# Example: File Conversion with Memory Mapping (Excerpt)

```
            /* Open the input file. */
hIn = CreateFile (fIn, GENERIC_READ, 0, NULL,
            OPEN_EXISTING, FILE_ATTRIBUTE_NORMAL, NULL);
if (hIn == INVALID_HANDLE_VALUE)  fprintf(stderr, "Failure opening input file."), exit(1);
            /* Create a file mapping object on the input file. Use the file size. */
hInMap = CreateFileMapping (hIn, NULL, PAGE_READONLY, 0, 0, NULL);
if (hInMap == INVALID_HANDLE_VALUE) fprintf(stderr, "Failure Creating input map."),  exit(2);

pInFile = MapViewOfFile (hInMap, FILE_MAP_READ, 0, 0, 0);
if (pInFile == NULL) fprintf(stderr, "Failure Mapping input file."), exit(3);
            /* The output file MUST have Read/Write access for the mapping to succeed. */
hOut = CreateFile (fOut, GENERIC_READ | GENERIC_WRITE,
                0, NULL, CREATE_ALWAYS, FILE_ATTRIBUTE_NORMAL, NULL);
if (hOut == INVALID_HANDLE_VALUE) fprintf(stderr, "Failure Opening output file."), exit(4);
hOutMap = CreateFileMapping (hOut, NULL, PAGE_READWRITE, 0, 2 * FsLow, NULL);
if (hOutMap == INVALID_HANDLE_VALUE) fprintf(stderr, "Failure creating output map."), exit(5);

pOutFile = MapViewOfFile (hOutMap, FILE_MAP_WRITE, 0, 0, 2 * FsLow);
if (pOutFile == NULL) fprintf(stderr, "Failure mapping output file."), exit(6);
```

# Example (contd.)

```
        pIn = pInFile;                              /* actual file conversion */
        pOut = pOutFile;
        while (pIn < pInFile + FsLow) {
                *pOut = (WCHAR) *pIn; pIn++; pOut++;
        }

        /* Close all views and handles. */
        UnmapViewOfFile (pOutFile); UnmapViewOfFile (pInFile);
        CloseHandle(hOutMap); CloseHandle (hInMap);
        CloseHandle(hIn); CloseHandle ( hOut);
        Complete = TRUE; return TRUE;
}

_except (EXCEPTION_EXECUTE_HANDLER) {
                /* Delete the output file if the operation did not complete successfully. */
        if (!Complete)
                DeleteFile (fOut);
        return FALSE;
}
```



# Memory Management APIs

- Memory protection may be changed
  - per-page basis

```
status = VirtualProtect(baseAddress, size, newProtect, pOldprotect);
```

- Page protection choices:

| | |
|---|---|
| PAGE_NOACCESS | PAGE_EXECUTE |
| PAGE_READONLY | PAGE_EXECUTE_READ |
| PAGE_READWRITE | PAGE_EXECUTE_READWRITE |
| PAGE_WRITECOPY | PAGE_EXECUTE_WRITECOPY |

PAGE_GUARD

PAGE_NOCACHE

# Memory Management Information

```
VOID GetSystemInfo(LPSYSTEM_INFO lpSystemInfo);

typedef struct _SYSTEM_INFO {
    DWORD      dwOemId;
    DWORD      dwPageSize;
    LPVOID lpMinimumApplicationAddress;
    LPVOID lpMaximumApplicationAddress;
    DWORD      dwActiveProcessorMask;
    DWORD      dwNumberOfProcessors;
    DWORD      dwProcessorType;
    DWORD      dwAllocationGranularity;
    DWORD      dwReserved;
} SYSTEM_INFO;
```



# Querying Address Space

```
DWORD VirtualQuery(LPVOID lpAddress,
    PMEMORY_BASIC_INFORMATION lpBuffer, DWORD dwLength);
```

Returns:

```
typedef struct _MEMORY_BASIC_INFORMATION {
    PVOID BaseAddress;              // Block base
    PVOID AllocationBase;      // Region base
    DWORD AllocationProtect;// Region prot
    DWORD RegionSize;               // # bytes in block
    DWORD State;                    // State of block:
            // MEM_RESERVE, MEM_COMMIT, MEM_FREE
    DWORD Protect;             // Pages prot
    DWORD Type;                     // Type:
            // MEM_IMAGE, MEM_MAPPED, MEM_PRIVATE
} MEMORY_BASIC_INFORMATION;
```

# Memory Management Information

```
VOID GlobalMemoryStatus(LPMEMORYSTATUS lpms);

    typedef struct _MEMORYSTATUS {
    DWORD dwLength;                     // sizeof(MEMORYSTATUS)
    DWORD dwMemoryLoad;
    DWORD dwTotalPhys;
    DWORD dwAvailPhys;
    DWORD dwTotalPageFile;
    DWORD dwAvailPageFile;
    DWORD dwTotalVirtual;       // Process specific
    DWORD dwAvailVirtual;       // Process specific
} MEMORYSTATUS, *LPMEMORYSTATUS;
```

Note: much more available via Registry Performance counters



# Further Reading

- Mark E. Russinovich and David A. Solomon, Microsoft Windows Internals, 4th Edition, Microsoft Press, 2004.
  - Chapter 7 - Memory Management
  - Memory Manager (from pp.375)
  - Services the Memory Manager Provides (from pp. 382)
- Jeffrey Richter, Programming Applications for Microsoft Windows, 4th Edition, Microsoft Press, September 1999.
  - Chapter 5 - Windows API Memory Architecture
  - Chapter 7 - Using Virtual Memory
  - Chapter 8 - Memory-Mapped Files
  - Chapter 9 - Heaps