CHAPTER 4

Exploring Windows 2000 Memory

Memory management is one of the most important and most difficult duties of an operating system. This chapter presents a comprehensive overview of Windows 2000 memory management and the structure of the 4-GB linear address space. In this context, the virtual memory addressing and paging capabilities of the Intel i386 CPU family are explained, focusing on how the Windows 2000 kernel exploits them. To aid the exploration of memory, this chapter features a pair of sample programs: a kernel-mode device driver that collects information about the system, and a user-mode client application that queries this data from the driver via device I/O control and displays it in a console window. The "spy driver" module will be reused in the remaining chapters for several other interesting tasks that require execution of kernel-mode code. This chapter—especially the first section—is tough reading because it puts your hands directly on the CPU hardware. Nevertheless I hope you won't skip it, because virtual memory management is an exciting topic, and understanding how it works provides insight into the mechanics of a complex operating system such as Windows 2000.

INTEL i386 MEMORY MANAGEMENT

The Windows 2000 kernel makes heavy use of the protected-mode virtual memory management mechanisms of the Intel i386 CPU class. To get a better understanding of how Windows 2000 manages its main memory, it is important to be at least minimally familiar with some architectural issues of the i386 CPU. The term *i386* might look somewhat anachronistic because the 80386 CPU dates back to the early days of Windows computing. Windows 2000 is designed for Pentium CPUs and above. However, even these newer processors rely on the memory management model originally designed for the 80386 CPU, with some important enhancements, of course. Therefore, Microsoft usually labels the Windows NT and 2000 versions built for

Intel processors “i386” or even “x86.” Don’t be confused about that—whenever you read the numbers 86 or 386 in this book, keep in mind that the corresponding information refers to a specific CPU *architecture,* not a specific processor release.

BASIC MEMORY LAYOUT

Windows 2000 uses a very straightforward memory layout for application and system code. The 4-GB virtual memory space offered by the 32-bit Intel CPUs is divided into two equal parts. Memory addresses below *0x80000000* are assigned to user-mode modules, including the Win32 subsystem, and the remaining 2 GB are reserved for the kernel. Windows 2000 Advanced Server also supports an alternative memory model commonly called *4GT RAM Tuning,* which has been introduced with Windows NT 4.0 Server Enterprise Edition. This model features 3-GB address space for user processes, and 1-GB space for the kernel. It is enabled by adding the `/3GB` switch to the bootstrap command line in the boot manager configuration file `boot.ini`.

The Advanced Server and Datacenter variants of Windows 2000 support yet another memory option named *Physical Address Extension (PAE)* enabled by the `boot.ini` switch `/PAE`. This option exploits a feature of some Intel CPUs (e.g., the Pentium Pro processor) that allows physical memory larger than 4 GB to be mapped into the 32-bit address space. In this Chapter, I will ignore these special configurations. You can read more about them in Microsoft’s Knowledge Base article Q171793 (Microsoft 2000¢), Intel’s Pentium manuals (Intel 1999a, 1999b, 1999c), and the Windows 2000 Device Driver Kit (DDK) documentation (Microsoft 2000f).

MEMORY SEGMENTATION AND DEMAND PAGING

Before delving into the technical details of the i386 architecture, let’s travel back in time to the year 1978, when Intel released the mother of all PC processors: the 8086. I want to restrict this discussion to the most significant milestones. If you want to know more, Robert L. Hummel’s 80486 programmer’s reference is an excellent starting point (Hummel 1992). It is a bit outdated now because it doesn’t cover the new features of the Pentium family; however, this leaves more space for important information about the basic i386 architecture. Although the 8086 was able to address 1 MB of Random Access Memory (RAM), an application could never “see” the entire physical address space because of the restriction of the CPU’s address registers to 16 bits. This means that applications were able to access a contiguous linear address space of only 64 KB, but this memory window could be shifted up and down in the physical space with the help of a set of 16-bit segment registers. Each segment register defined a base address in 16-byte increments, and the linear addresses in the 64-KB logical space were added as offsets to this base, effectively resulting in 20-bit addresses. This archaic memory model is still supported even by the latest Pentium CPUs, and it is called *Real-Address Mode,* commonly referred to as *Real Mode.*

An alternative mode was introduced with the 80286 CPU, referred to as *Protected Virtual Address Mode,* or simply *Protected Mode.* It featured a memory model where physical addresses were not generated by simply adding a linear address to a segment base. To retain backward compatibility with the 8086 and 80186, the 80286 still used segment registers, but they did not contain physical segment addresses after the CPU had been switched to Protected Mode. Instead, they provided a selector, comprising an index into a descriptor table. The target entry defined a 24-bit physical base address, allowing access to 16 MB of RAM, which seemed like an incredible amount then. However, the 80286 was still a 16-bit CPU, so the limitation of the linear address space to 64 KB tiles still applied.

The breakthrough came in 1985 with the 80386 CPU. This chip finally cut the ties of 16-bit addressing, pushing up the linear address space to 4 GB by introducing 32-bit linear addresses while retaining the basic selector/descriptor architecture of its predecessor. Fortunately, the 80286 descriptor structure contained some spare bits that could be reclaimed. While moving from 16- to 32-bit addresses, the size of the CPU's data registers was doubled as well, and new powerful addressing modes were added. This radical shift to 32-bit data and addresses was a real benefit for programmers—at least theoretically. Practically, it took several years longer before the Microsoft Windows platform was ready to fully support the 32-bit model. The first version of Windows NT was released on July 26th, 1993, constituting the very first incarnation of the Win32 API. Whereas Windows 3.x programmers still had to deal with memory tiles of 64 KB with separate code and data segments, Windows NT provided a flat linear address space of 4 GB, where all code and data could be addressed by simple 32-bit pointers, without segmentation. Internally, of course, segmentation was still active, as I will show later in this chapter, but the entire responsibility for managing segments finally had been moved to the operating system.

Another essential new 80386 feature was the hardware support for paging, or, more precisely, demand-paged virtual memory. This is a technique that allows memory to be backed up by a storage medium other than RAM—a hard disk, for example. With paging enabled, the CPU can access more memory than physically available by swapping out the least recently accessed memory contents to backup storage, making space for new data. Theoretically, up to 4 GB of contiguous linear memory can be accessed this way, provided that the backup media is large enough—even if the installed physical RAM amounts to just a small fraction of the memory. Of course, paging is not the fastest way to access memory. It is always good to have as much physical RAM as possible. But it is an excellent way to work with large amounts of data that would otherwise exceed the available memory. For example, graphics and database applications require a large amount of working memory, and some wouldn't be able to run on a low-end PC system if paging weren't available.

In the paging scheme of the 80386, memory is subdivided into pages of 4-KB or 4-MB size. The operating system designer is free to choose between these two options, and it is even possible to mix pages of both sizes. Later I will show that Windows 2000 uses such a mixed page design, keeping the operating system in 4-MB pages and using 4-KB pages for the remaining code and data. The pages are managed by means of a hierarchically structured page-table tree that indicates for each page where it is currently located in physical memory. This management structure also contains information on whether the page is actually in physical memory in the first place. If a page has been swapped out to the hard disk, and some module touches an address within this page, the CPU generates a page fault, similar to an interrupt generated by a peripheral hardware device. Next, the page fault handler inside the operating system kernel will attempt to swap back this page to physical memory, possibly writing other memory contents to disk to make space. Usually, the system will apply a least-recently-used (LRU) schedule to decide which pages qualify to be swapped out. By now it should be clear why this procedure is sometimes referred to as *demand* paging: Physical memory contents are moved to the backup storage and back on software demand, based on statistics of the memory usage of the operating system and its applications.

The address indirection layer represented by the page-tables has two interesting implications. First, there is no predetermined relationship between the addresses used by a program and the addresses found on the physical address bus of the CPU chip. If you know that a data structure of your application is located at the address, say, `0x00140000`, you still don't know anything about the physical address of your data unless you examine the page-table tree. It is up to the operating system to decide what this address mapping looks like. Even more, the address translation currently in effect is unpredictable, in part because of the probabilistic nature of the paging mechanism. Fortunately, knowledge of physical addresses isn't required in most application cases. This is something left for developers of hardware drivers. The second implication of paging is that the address space is not necessarily contiguous. Depending on the page-table contents, the 4-GB space can comprise large "holes" where neither physical nor backup memory is mapped. If an application tries to read to or write from such an address, it will be aborted immediately by the system. Later in this chapter, I will show in detail how Windows 2000 spreads its available memory over the 4-GB address space.

The 80486 and Pentium CPUs use the very same i386 segmentation and paging mechanisms introduced with the 80386, except for some exotic addressing features such as the Physical Address Extension (PAE) of the Pentium Pro. Along with higher clock frequencies, these newer models contain optimizations in other areas. For example, the Pentium features a dual instruction pipeline that enables it to execute two operations at the same time, as long as these instructions don't depend on each other. For example, if instruction A modifies a register value, and the consecutive instruction B uses the modified value for a computation, B cannot be executed before A has finished. But if instruction B involves a different register, the CPU can execute A and B simultaneously without adverse effects. This and other Pentium optimizations have opened a wide field for compiler optimization. If this topic looks interesting, see Rick Booth's *Inner Loops* (Booth 1997).

In the context of i386 memory management, three sorts of addresses must be distinguished, termed *logical, linear,* and *physical* addresses in Intel's system programming manual for the Pentium (Intel 1999c).

1. *Logical addresses:* This is the most precise specification of a memory location, usually written in hexadecimal form as `XXXX:YYYYYYYY`, where `XXXX` is a selector, and `YYYYYYYY` is a linear offset into the segment addressed by the selector. Instead of a numeric `XXXX` value, it is also possible to specify the name of a segment register holding the selector, such as `CS` (code segment), `DS` (data segment), `ES` (extra segment), `FS` (additional data segment #1), `GS` (additional data segment #2), and `SS` (stack segment). This notation is borrowed from the old "segment:offset" style of specifying "far pointers" in 8086 Real-Mode.
2. *Linear addresses:* Most applications and many kernel-mode drivers disregard virtual addresses. More precisely, they are just interested in the offset part of a virtual address, which is referred to as a *linear address*. An address of this type assumes a default segmentation model, determined by the current values of the CPU's segment registers. Windows 2000 uses flat segmentation, with the `CS, DS, ES,` and `SS` registers pointing to the same linear address space; therefore, programs can safely assume that all code, data, and stack pointers can be cast among one another. For example, a stack location can be cast to a data pointer at any time without concern about the values of the corresponding segment registers.
3. *Physical addresses:* This address type is of interest only if the CPU works in paging mode. Basically, a physical address is the voltage pattern measurable at the address bus pins of the CPU chip. The operating system maps linear addresses to physical addresses by setting up page-tables. The layout of the Windows 2000 page-tables, which has some very interesting properties for debugging software developers, will be discussed later in this chapter.

The distinction between virtual and linear addresses is somewhat artificial, and some documentation uses both terms interchangeably. I will do my best to use this nomenclature consistently. It is important to note that Windows 2000 assumes physical addresses to be 64 bits wide. This might seem odd on Intel i386 systems, which usually have a 32-bit address bus. However, some Pentium systems can address more than 4 GB of physical memory. For example, the Physical Address Extension (PAE) mode of the Pentium Pro CPU extends the physical address space to 36 bits, allowing access to 64 GB of RAM (Intel 1999c). Therefore, the Windows 2000 API functions involving physical addresses usually rely on the data type `PHYSICAL_ADDRESS`, which is just an alias name for the `LARGE_INTEGER` structure, as shown in Listing 4-1. Both types are defined in the DDK header file `ntdef.h`. The `LARGE_INTEGER` is a structural representation of a 64-bit signed integer, allowing interpretation as a concatenation of two 32-bit quantities (`LowPart` and `HighPart`) or a single 64-bit number (`QuadPart`). The `LONGLONG` type is equivalent to the native Visual C/C++ type `__int64`. Its unsigned sibling is called `ULONGLONG` or `DWORDLONG` and is based on the native `unsigned __int64` type.

Figure 4-1 outlines the i386 memory segmentation model, showing the relationship between logical and linear addresses. For clarity, I have drawn the descriptor table and the segment as small, nonoverlapping boxes. However, this isn't a requirement. Actually, a 32-bit operating system usually applies a segmentation layout as shown in Figure 4-2. This so-called flat memory model is based on segments that span the entire 4-GB address space. As a side effect, the descriptor table becomes part of the segment and can be accessed by all code that has sufficient access rights.

```
typedef LARGE_INTEGER PHYSICAL_ADDRESS, *PPHYSICAL_ADDRESS;

typedef union _LARGE_INTEGER
    {
    struct
        {
        ULONG LowPart;
        LONG  HighPart;
        };
    LONGLONG QuadPart;
    }
    LARGE_INTEGER, *PLARGE_INTEGER;
```

LISTING 4-1. *Definition of* `PHYSICAL_ADDRESS` *and* `LARGE_INTEGER`

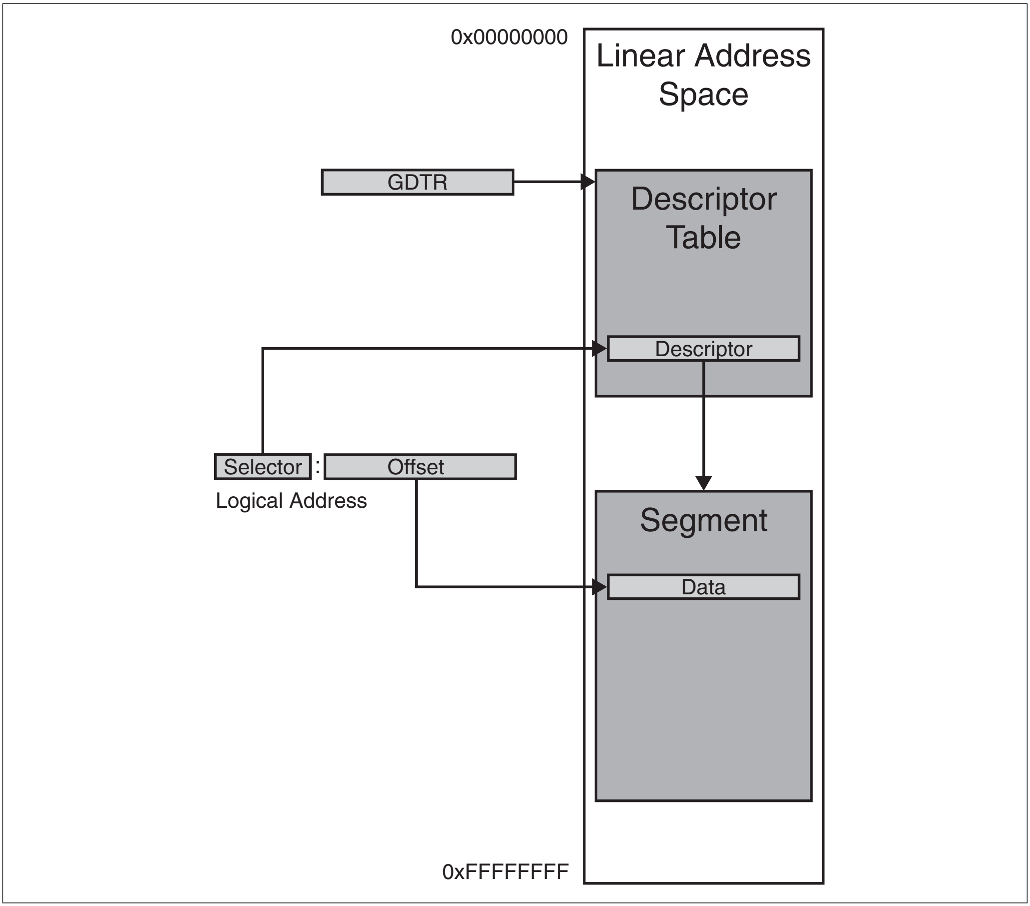


FIGURE 4-1. *i386 Memory Segmentation*

The memory model in Figure 4-2 is adopted by Windows 2000 for the standard code, data, and stack segments, that is, all logical addresses that involve the `CS`, `DS`, `ES`, and `SS` segment registers. The `FS` and `GS` segments are treated differently. `GS` is not used by Windows 2000, and `FS` addresses special system data areas inside the linear address space. Therefore, its base address is greater than zero and its size is less than 4 GB. Interestingly, Windows 2000 maintains different `FS` segments in user-mode and kernel-mode. More on this topic follows later in this chapter.

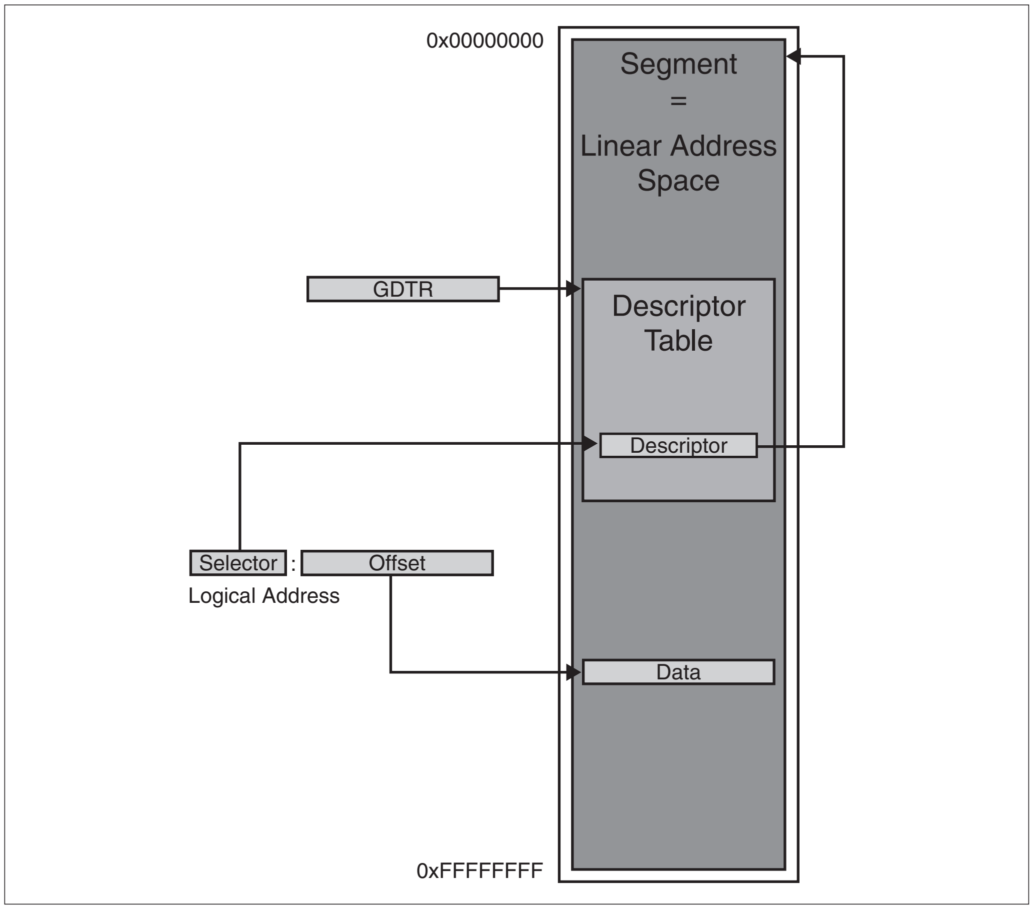


FIGURE 4-2. *Flat 4-GB Memory Segmentation*

In Figures 4-1 and 4-2, the selector portion of the logical address is shown to point into a descriptor table determined by a register termed `GDTR`. This is the CPU's Global Descriptor Table Register, which can be set by the operating system to any suitable linear address. The first entry of the Global Descriptor Table (GDT) is reserved, and the corresponding selector called "null segment selector" is intended as an initial value for unused segment registers. Windows 2000 keeps its GDT at address `0x80036000`. The GDT can hold up to 8,192 64-bit entries, resulting in a maximum size of 64 KB. Windows 2000 uses only the first 128 entries, restricting the GDT size to 1,024 bytes. Along with the GDT, the i386 CPU provides a Local Descriptor Table (LDT) and an Interrupt Descriptor Table (IDT), addressed by the `LDTR` and `IDTR` registers, respectively. Whereas the `GDTR` and `IDTR` values are unique and apply to all tasks executed by the CPU, the `LDTR` value is task-specific, and, if used, contains a 16-bit GDT selector.

Figure 4-3 demonstrates the complex mechanism of linear-to-physical address translation applied by the i386 memory management unit if demand paging is enabled in 4-KB page mode. The Page-Directory Base Register (PDBR) in the upper left corner contains the physical base address of the page-directory. The PDBR is identical to the i386 CR3 register. Only the upper 20 bits are used for addressing. Therefore, the page-directory is always located on a page boundary. The remaining PDBR bits are either flags or reserved for future extensions. The page-directory occupies exactly one 4-KB page, structured as an array of 1,024 32-bit page-directory entries (PDEs). Similar to the PDBR, each PDE can be divided into a 20-bit page-frame number (PFN) addressing a page-table, and an array of bit flags. Each page-table is page-aligned and spans 4 KB, comprising 1,024 page-table entries (PTEs). Again, the

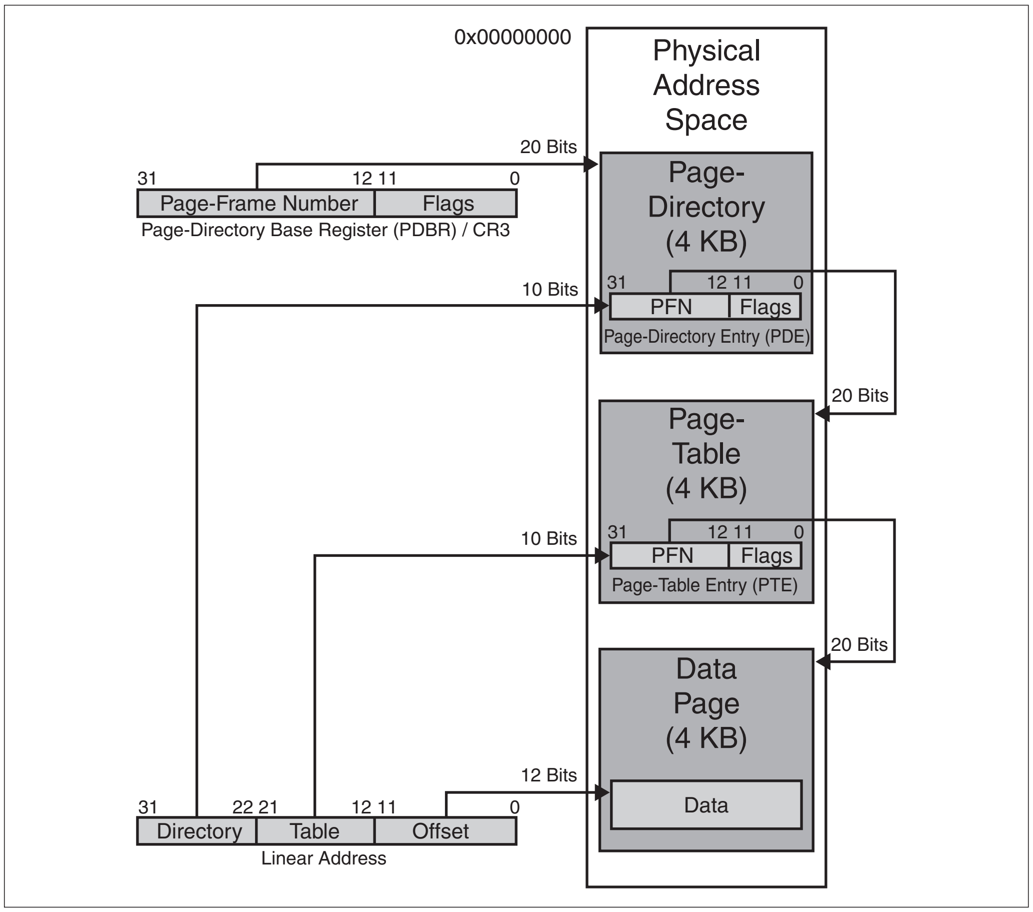


FIGURE 4-3. *Double-Layered Paging with 4-KB Pages*

upper 20 bits are extracted from a PTE to form a pointer to a 4-KB data page. Address translation takes place by breaking a linear address into three parts: The upper 10 bits select a PDE out of the page-directory, the next lower 10 bits select a PTE out of the page-table addressed by the PDE, and, finally, the lower 12 bits specify an offset into the data page addressed by the PTE.

In the 4-KB paging scheme, the 4-GB linear address space is addressable by means of a double-layered indirection mechanism. In the worst case, 1,048,576 PTEs are required to cover the entire range. Because each page-table holds 1,024 PTEs, this amounts to 1,024 page-tables, which is the number of PDEs the page-directory contains. With the page-directory and each page-table consuming 4 KB, the maximum memory management overhead in this paging model is 4 KB plus 4 MB, or 4,100 KB. That's a reasonable price for a subdivision of the entire 4-GB space into 4-KB tiles that can be mapped to any linear address.

In 4-MB paging mode, things are much simpler because one indirection layer is eliminated, as shown in Figure 4-4. Again, the PDBR points to the page-directory, but now only the upper 10 bits of the PDE are used, resulting in 4-MB alignment of the target address. Because no page-tables are used, this address is already the base address of a 4-MB data page. Consequently, the linear address now consists of two parts only: 10 bits for PDE selection and 22 offset bits. The 4-MB memory scheme requires no more than 4 KB overhead, because only the page-directory consumes additional memory. Each of its 1,024 PDEs can address one 4-MB page. This is just enough to cover the entire 4-GB address space. Thus, 4-MB pages have the advantage of keeping the memory management overhead low, but for the price of a more coarse addressing granularity.

Both the 4-KB and 4-MB paging modes have advantages and disadvantages. Fortunately, operating system designers don't have to decide for one of them, but can run the CPU in mixed mode. For example, Windows 2000 works with 4-MB pages in the memory range `0x80000000` to `0x9FFFFFFF`, where the kernel modules `hal.dll` and `ntoskrnl.exe` are loaded. The remaining linear address blocks are managed in 4-KB tiles. This mixed design is recommended by Intel for improved system performance, because 4-KB and 4-MB page entries are cached in different Translation Lookaside Buffers (TLBs) inside the i386 CPU (Intel 1999c, pp. 3-22f). The operating system kernel is usually large and is always resident in memory, so storing it in several 4-KB pages would permanently use up valuable TLB space.

Note that all address translation steps are carried out in physical memory. The PDBR and all PDEs and PTEs contain physical address pointers. The only linear address found in Figures 4-3 and 4-4 is the box in the lower left corner specifying the address to be converted to an offset inside a physical page. On the other hand, applications must work with linear addresses and are ignorant of physical addresses. However, it is possible to fill this gap by mapping the page-directory and all of its subordinate page-tables into the linear address space. On Windows 2000 and Windows NT 4.0, all

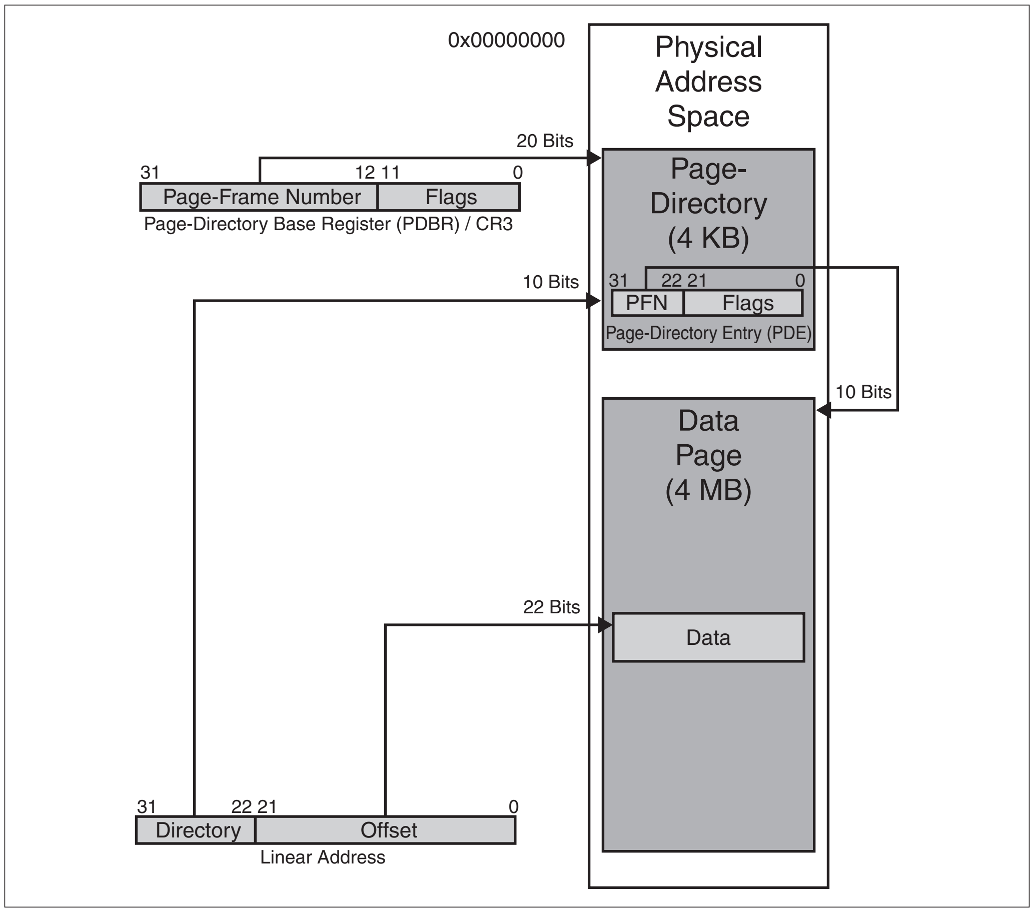


FIGURE 4-4. *Single-Layered Paging with 4-MB Pages*

PDEs and PTEs are accessible in the address range `0xC0000000` to `0xC03FFFFF`. This is a linear memory area of 4-MB size. This is obviously the maximum amount of memory consumed by the page-table layer in 4-KB paging mode. The PTE associated to a linear address can be looked up by simply using its most significant 20 bits as an index into the array of 32-bit PTEs starting at `0xC0000000`. For example, the PTE of address `0x00000000` is located at `0xC0000000`. The PTE index of address `0x80000000` is computed by shifting it right by 12 bits to get at the upper 20 bits, yielding `0x80000`. Because each PTE takes four bytes, the target PTE is found at `0xC0000000 + (4 * 0x80000) = 0xC0200000`. This result looks interesting—obviously, the address that divides the 4-GB address space in two equal halves is mapped to a PTE address that divides the PTE array in two equal halves.

Now let's go one more step ahead and compute the entry address of the PTE array itself. The general mapping formula is `((LinearAddress >> 12) * 4) + 0xC0000000`. Setting `LinearAddress` to `0xC0000000` yields `0xC0300000`. Let's pause for a moment: The entry at linear address `0xC0300000` points to the beginning of the PTE array in physical memory. Now look back to Figure 4-3. The 1,024 entries starting at address `0xC0300000` must be the page-directory! This special PDE and PTE arrangement is exploited by various memory management functions implemented in `ntoskrnl.exe`. For example, the (documented) API functions `MmIsAddressValid()` and `MmGetPhysicalAddress()` take a 32-bit linear address, look up its PDE and, if applicable, its PTE, and examine their contents. `MmIsAddressValid()` simply checks out whether the target page is currently present in physical memory. If the test fails, the linear address is either invalid or it refers to a page that has been flushed to backup storage, represented by the set of system pagefiles. `MmGetPhysicalAddress()` first extracts the page-frame number (PFN) corresponding to a linear address, which is the base address of its associated physical page divided by the page size. Next, it computes the offset into this page by extracting the least significant 12 bits of the linear address, and adds the offset to the physical base address determined by the PFN.

More thorough examination of the implementation of `MmGetPhysicalAddress()` reveals another interesting property of the Windows 2000 memory layout. Before anything else, the code tests whether the linear address is within the range `0x80000000` to `0x9FFFFFFF`. As already mentioned, this is the home of `hal.dll` and `ntoskrnl.exe`, and it is also the address block where Windows 2000 uses 4-MB pages. The interesting thing is that `MmGetPhysicalAddress()` doesn't care at all for PDEs or PTEs if the address is within this range. Instead, it simply sets the top three bits to zero, adds the byte offset, as usual, and returns the result as the physical address. This means that the physical address range `0x00000000` to `0x1FFFFFFF` is mapped 1:1 to the linear addresses `0x80000000` to `9FFFFFFF`! Knowing that `ntoskrnl.exe` is always loaded to the linear address `0x80400000`, this means that the Windows 2000 kernel is always found at physical address `0x00400000`, which happens to be the base address of the second 4-MB page in physical memory. In fact, examination of these memory regions proves that the above assumptions are correct. You will have the opportunity to see this with the memory spy presented in this chapter.

DATA STRUCTURES

Some portions of the sample code following in this chapter are concerned with low-level memory management and peek inside the mechanisms outlined above. For convenience, I have defined several C data structures that make this task easier. Because many data items inside the i386 CPU are concatenations of single bits or bit groups, C bit-fields come in handy. Bit-fields are an efficient way to access individual bits of or extract contiguous bit groups from larger data words. Microsoft Visual C/C++

generates quite clever code for bit-field operations. Listing 4-2 is part one of a series of CPU data type definitions, containing the following items:

- `X86_REGISTER` is a basic unsigned 32-bit integral type that can represent various CPU registers. This comprises all general-purpose, index, pointer, control, debug, and test registers.
- `X86_SELECTOR` represents a 16-bit segment selector, as stored in the segment registers `CS, DS, ES, FS, GS,` and `SS`. In Figures 4-1 and 4-2, selectors are depicted as the upper third of a logical 48-bit address, serving as an index into a descriptor table. For computational convenience, the 16-bit selector value is extended to 32 bits, with the upper half marked "reserved." Note that the `X86_SELECTOR` structure is a union of two structures. The first one specifies the selector value as a packed 16-bit `WORD` named `wValue,` and the second breaks it up into bit-fields. The `RPL` field specifies the Requested Privilege Level, which is either 0 (kernel-mode) or 3 (user-mode) on Windows 2000. The `TI` bit switches between the Global and Local Descriptor Tables (GDT/LDT).
- `X86_DESCRIPTOR` defines the format of a table entry pointed to by a selector. It is a 64-bit quantity with a very convoluted structure resulting from its historic evolution. The linear base address defining the start location of the associated segment is scattered among three bit-fields named `Base1, Base2,` and `Base3,` with `Base1` being the least significant part. The segment limit specifying the segment size minus one is divided into the pair `Limit1` and `Limit2,` with the former representing the least significant half. The remaining bit-fields store various segment properties (cf. Intel 1999c, pp. 3-11). For example, the `G` bit defines the segment granularity. If zero, the segment limit is specified in bytes; otherwise, the limit value has to be multiplied by 4 KB. Like `X86_SELECTOR,` the `X86_DESCRIPTOR` structure is composed of a union to allow different interpretations of its value. The `dValueLow` and `dValueHigh` members are helpful if you have to copy descriptors without regard to their internal structure.
- `X86_GATE` looks somewhat similar to `X86_DESCRIPTOR`. In fact, the structures are related: `X86_DESCRIPTOR` is a GDT entry and describes the memory properties of a segment, and `X86_GATE` is an entry inside the Interrupt Descriptor Table (IDT) and describes the memory properties of an interrupt handler. The IDT can contain task, interrupt, and trap gates. (No, Bill Gates is *not* stored in the IDT!) The `X86_GATE` structure matches all three types, with the Type bit-field determining the identity. Type 5

identifies a task gate; types 6 and 14, interrupt gates; and types 7 and 15, trap gates. The most significant type bit specifies the size of the gate: 16-bit gates have this bit set to zero; otherwise it is a 32-bit gate.

- X86_TABLE is a tricky structure that is used to read the values of the GDTR or IDTR by means of the assembly language instructions SGDT (store GDT register) and SIDT (store IDT register) respectively (cf. Intel 1999b, pp. 3-636). Both instructions require a 48-bit memory operand, where the limit and base address values will be stored. To maintain DWORD alignment for the 32-bit base address, X86_TABLE starts out with the 16-bit dummy member wReserved. Depending on whether the SGDT or SIDT instruction is applied, the base address must be interpreted as a descriptor or gate pointer, as suggested by the union of PX86_DESCRIPTOR and PX86_GATE types. The wLimit member is the same for both table types.

```
// =================================================================
// INTEL X86 STRUCTURES, PART 1 OF 3
// =================================================================

typedef DWORD X86_REGISTER, *PX86_REGISTER, **PPX86_REGISTER;

// -----------------------------------------------------------------

typedef struct _X86_SELECTOR
    {
    union
        {
        struct
            {
            WORD wValue;            // packed value
            WORD wReserved;
            };
        struct
            {
            unsigned RPL      :  2; // requested privilege level
            unsigned TI       :  1; // table indicator: 0=gdt, 1=ldt
            unsigned Index    : 13; // index into descriptor table
            unsigned Reserved : 16;
            };
        };
    }
    X86_SELECTOR, *PX86_SELECTOR, **PPX86_SELECTOR;
```

```
#define X86_SELECTOR_ sizeof (X86_SELECTOR)

// -----------------------------------------------------------------

typedef struct _X86_DESCRIPTOR
    {
    union
        {
        struct
            {
            DWORD dValueLow;        // packed value
            DWORD dValueHigh;
            };
        struct
            {
            unsigned Limit1   : 16; // bits 15..00
            unsigned Base1    : 16; // bits 15..00
            unsigned Base2    :  8; // bits 23..16
            unsigned Type     :  4; // segment type
            unsigned S        :  1; // type (0=system, 1=code/data)
            unsigned DPL      :  2; // descriptor privilege level
            unsigned P        :  1; // segment present
            unsigned Limit2   :  4; // bits 19..16
            unsigned AVL      :  1; // available to programmer
            unsigned Reserved :  1;
            unsigned DB       :  1; // 0=16-bit, 1=32-bit
            unsigned G        :  1; // granularity (1=4KB)
            unsigned Base3    :  8; // bits 31..24
            };
        };
    }
    X86_DESCRIPTOR, *PX86_DESCRIPTOR, **PPX86_DESCRIPTOR;

#define X86_DESCRIPTOR_ sizeof (X86_DESCRIPTOR)

// -----------------------------------------------------------------

typedef struct _X86_GATE
    {
    union
        {
        struct
            {
            DWORD dValueLow;          // packed value
            DWORD dValueHigh;
            };
        struct
            {
            unsigned Offset1    : 16; // bits 15..00
            unsigned Selector   : 16; // segment selector
            unsigned Parameters :  5; // parameters
            unsigned Reserved   :  3;
```

(continued)

```
            unsigned Type       :  4; // gate type and size
            unsigned S          :  1; // always 0
            unsigned DPL        :  2; // descriptor privilege level
            unsigned P          :  1; // segment present
            unsigned Offset2    : 16; // bits 31..16
            };
        };
    }
    X86_GATE, *PX86_GATE, **PPX86_GATE;

#define X86_GATE_ sizeof (X86_GATE)

// -----------------------------------------------------------------

typedef struct _X86_TABLE
    {
    WORD wReserved;                  // force 32-bit alignment
    WORD wLimit;                     // table limit
    union
        {
        PX86_DESCRIPTOR pDescriptors; // used by sgdt instruction
        PX86_GATE       pGates;       // used by sidt instruction
        };
    }
    X86_TABLE, *PX86_TABLE, **PPX86_TABLE;

#define X86_TABLE_ sizeof (X86_TABLE)

// =================================================================
```

LISTING 4-2. *i386 Registers, Selectors, Descriptors, Gates, and Tables*

The next set of i386 memory management structures, collected in Listing 4-3, relates to demand paging and contains several items illustrated in Figures 4-3 and 4-4:

- `X86_PDBR` is, of course, a structural representation of the CPU's `CR3` register, also known as the *page-directory base register (PDBR)*. The upper 20 bits contain the PFN, which is an index into the array of physical 4-KB pages. `PFN=0` corresponds to physical address `0x00000000`, `PFN=1` to `0x00001000`, and so forth. Twenty bits are just enough to cover the entire 4-GB address space. The PFN in the PDBR is the index of the physical page that holds the page-directory. Most of the remaining bits are reserved, except for bit #3, controlling page-level write-through (PWT), and bit #4, disabling page-level caching if set.

- `X86_PDE_4M` and `X86_PDE_4K` are alternative incarnations of page-directory entries (PDEs) for 4-MB and 4-KB pages, respectively. A page-directory contains a maximum of 1,024 PDEs. Again, PFN is the page-frame number, pointing to the subordinate page. For a 4-MB PDE, the PFN bit-field is only 10 bits wide, addressing a 4-MB data page. The 20-bit PFN of 4-KB PDE points to a page-table that ultimately selects the physical data pages. The remaining bits define various properties. The most interesting ones are the "Page Size" bit `PS,` controlling the page size (0 = 4-KB, 1 = 4-MB), and the "Present" bit `P,` indicating whether the subordinate data page (4-MB mode) or page-table (4-KB mode) is present in physical memory.
- `X86_PTE_4K` defines the internal structure of a page-table entry (PTE) contained in a page-table. Like a page-directory, a page-table can contain up to 1,024 entries. The only difference between `X86_PTE_4K` and `X86_PDE_4K` is that the former lacks the `PS` bit, which is not required because the page size must be 4-KB, as determined by the PDE's `PS` bit. Note that there is no such thing as a 4-MB PTE, because the 4-MB memory model doesn't require an intermediate page-table layer.
- `X86_PNPE` represents a "page-not-present entry" (PNPE), that is, a PDE or PTE in which the `P` bit is zero. According to the Intel manuals, the remaining 31 bits are "available to operating system or executive" (Intel 1999c, pp. 3-28). If a linear address maps to a PNPE, this means either that this address is unused or that it points to a page that is currently swapped out to one of the pagefiles. Windows 2000 uses the 31 unassigned bits of the PNPE to store status information of the page. The structure of this information is undocumented, but it seems that bit #10, named `PageFile` in Listing 4-3, is set if the page is swapped out. In this case, the `Reserved1` and `Reserved2` bit-fields contain values that enable the system to locate the page in the pagefiles, so it can be swapped in as soon as one of its linear addresses is touched by a memory read/write instruction.
- `X86_PE` is included for convenience. It is merely a union of all possible forms a page entry can take, comprising the PDBR contents, 4-MB and 4-KB PDEs, PTEs, and PNPEs.

```
// =================================================================
// INTEL X86 STRUCTURES, PART 2 OF 3
// =================================================================

typedef struct _X86_PDBR // page-directory base register (cr3)
    {
    union
        {
        struct
            {
            DWORD dValue;            // packed value
            };
        struct
            {
            unsigned Reserved1 :  3;
            unsigned PWT       :  1; // page-level write-through
            unsigned PCD       :  1; // page-level cache disabled
            unsigned Reserved2 :  7;
            unsigned PFN       : 20; // page-frame number
            };
        };
    }
    X86_PDBR, *PX86_PDBR, **PPX86_PDBR;

#define X86_PDBR_ sizeof (X86_PDBR)

// -----------------------------------------------------------------

typedef struct _X86_PDE_4M // page-directory entry (4-MB page)
    {
    union
        {
        struct
            {
            DWORD dValue;            // packed value
            };
        struct
            {
            unsigned P         :  1; // present (1 = present)
            unsigned RW        :  1; // read/write
            unsigned US        :  1; // user/supervisor
            unsigned PWT       :  1; // page-level write-through
            unsigned PCD       :  1; // page-level cache disabled
            unsigned A         :  1; // accessed
            unsigned D         :  1; // dirty
            unsigned PS        :  1; // page size (1 = 4-MB page)
            unsigned G         :  1; // global page
            unsigned Available :  3; // available to programmer
            unsigned Reserved  : 10;
            unsigned PFN       : 10; // page-frame number
            };
        };
    }
    X86_PDE_4M, *PX86_PDE_4M, **PPX86_PDE_4M;

#define X86_PDE_4M_ sizeof (X86_PDE_4M)

// -----------------------------------------------------------------

typedef struct _X86_PDE_4K // page-directory entry (4-KB page)
    {
    union
        {
        struct
            {
            DWORD dValue;            // packed value
            };
        struct
            {
            unsigned P         :  1; // present (1 = present)
            unsigned RW        :  1; // read/write
            unsigned US        :  1; // user/supervisor
            unsigned PWT       :  1; // page-level write-through
            unsigned PCD       :  1; // page-level cache disabled
            unsigned A         :  1; // accessed
            unsigned Reserved  :  1; // dirty
            unsigned PS        :  1; // page size (0 = 4-KB page)
            unsigned G         :  1; // global page
            unsigned Available :  3; // available to programmer
            unsigned PFN       : 20; // page-frame number
            };
        };
    }
    X86_PDE_4K, *PX86_PDE_4K, **PPX86_PDE_4K;

#define X86_PDE_4K_ sizeof (X86_PDE_4K)

// -----------------------------------------------------------------

typedef struct _X86_PTE_4K // page-table entry (4-KB page)
    {
    union
        {
        struct
            {
            DWORD dValue;            // packed value
            };
        struct
            {
            unsigned P         :  1; // present (1 = present)
            unsigned RW        :  1; // read/write
            unsigned US        :  1; // user/supervisor
```

(continued)

```
           unsigned PWT       :  1; // page-level write-through
            unsigned PCD       :  1; // page-level cache disabled
            unsigned A         :  1; // accessed
            unsigned D         :  1; // dirty
            unsigned Reserved  :  1;
            unsigned G         :  1; // global page
            unsigned Available :  3; // available to programmer
            unsigned PFN       : 20; // page-frame number
            };
        };
    }
    X86_PTE_4K, *PX86_PTE_4K, **PPX86_PTE_4K;

#define X86_PTE_4K_ sizeof (X86_PTE_4K)

// -----------------------------------------------------------------

typedef struct _X86_PNPE // page not present entry
    {
    union
        {
        struct
            {
            DWORD dValue;            // packed value
            };
        struct
            {
            unsigned P         :  1; // present (0 = not present)
            unsigned Reserved1 :  9;
            unsigned PageFile  :  1; // page swapped to pagefile
            unsigned Reserved2 : 21;
            };
        };
    }
    X86_PNPE, *PX86_PNPE, **PPX86_PNPE;

#define X86_PNPE_ sizeof (X86_PNPE)

// -----------------------------------------------------------------
typedef struct _X86_PE // general page entry
    {
    union
        {
        DWORD      dValue; // packed value
        X86_PDBR   pdbr;   // page-directory Base Register
        X86_PDE_4M pde4M;  // page-directory entry (4-MB page)
        X86_PDE_4K pde4K;  // page-directory entry (4-KB page)
        X86_PTE_4K pte4K;  // page-table entry (4-KB page)
        X86_PNPE   pnpe;   // page not present entry
        };
    }
    X86_PE, *PX86_PE, **PPX86_PE;

#define X86_PE_ sizeof (X86_PE)

// =================================================================
```

LISTING 4-3. *i386 PDBR, PDE, PTE, and PNPE Values*

In Listing 4-4, I have added structural representations of linear addresses. These structures are formal definitions of the "Linear Address" boxes in Figures 4-3 and 4-4:

- `X86_LINEAR_4M` is the format of linear addresses that point into a 4-MB data page, as shown in Figure 4-4. The page-directory index `PDI` is an index into the page-directory currently addressed by the PDBR, selecting one of its PDEs. The 22-bit `Offset` member points to the target address within the corresponding 4-MB physical page.
- `X86_LINEAR_4K` is the 4-KB variant of a linear address. As outlined in Figure 4-3, it is composed of three bit-fields: Like in a 4-MB address, the upper 10 `PDI` bits select a PDE. The page-table index `PTI` has a similar duty, pointing to a PTE inside the page-table addressed by this PDE. The remaining 12 bits are the offset into the resulting 4-KB physical page.
- `X86_LINEAR` is another convenience structure that simply unites `X86_LINEAR_4M` and `X86_LINEAR_4K` in a single data type.

MACROS AND CONSTANTS

The definitions in Listing 4-5 are supplements to the structures in Listings 4-2 to 4-4 and make the work with i386 memory management easier. They can be subdivided into three main groups. The first group handles linear addresses:

1. `X86_PAGE_MASK, X86_PDI_MASK,` and `X86_PTI_MASK` are bit masks that isolate the constituent parts of linear addresses. They are based on the constants `PAGE_SHIFT (12), PDI-SHIFT (22),` and `PTI-SHIFT (12),` defined in the Windows 2000 DDK header file `ntddk.h. X86_PAGE_MASK` evaluates to `0xFFFFF000,` effectively masking off the 4-KB offset part of a linear address (cf. `X86_LINEAR_4K`). `X86_PDI_MASK` is equal to `0xFFC00000` and obviously extracts the 10 topmost PDI bits of a linear address (cf. `X86_LINEAR_4M` and `X86_LINEAR_4K`). `X86_PTI_MASK` evaluates to `0x003FF0000` and masks off all bits except for the page-table index (PTI) bits of a linear address (cf. `X86_LINEAR_4K`).

```
// =================================================================
// INTEL X86 STRUCTURES, PART 3 OF 3
// =================================================================

typedef struct _X86_LINEAR_4M // linear address (4-MB page)
    {
    union
        {
        struct
            {
            PVOID pAddress;       // packed address
            };
        struct
            {
            unsigned Offset : 22; // offset into page
            unsigned PDI    : 10; // page-directory index
            };
        };
    }
    X86_LINEAR_4M, *PX86_LINEAR_4M, **PPX86_LINEAR_4M;

#define X86_LINEAR_4M_ sizeof (X86_LINEAR_4M)

// -----------------------------------------------------------------

typedef struct _X86_LINEAR_4K // linear address (4-KB page)
    {
    union
        {
        struct
            {
            PVOID pAddress;       // packed address
            };
        struct
            {
            unsigned Offset : 12; // offset into page
            unsigned PTI    : 10; // page-table index
            unsigned PDI    : 10; // page-directory index
            };
        };
    }
    X86_LINEAR_4K, *PX86_LINEAR_4K, **PPX86_LINEAR_4K;

#define X86_LINEAR_4K_ sizeof (X86_LINEAR_4K)

// -----------------------------------------------------------------

typedef struct _X86_LINEAR // general linear address
    {
    union
        {
```

```
        PVOID         pAddress; // packed address
        X86_LINEAR_4M linear4M; // linear address (4-MB page)
        X86_LINEAR_4K linear4K; // linear address (4-KB page)
        };
    }
    X86_LINEAR, *PX86_LINEAR, **PPX86_LINEAR;

#define X86_LINEAR_ sizeof (X86_LINEAR)

// =================================================================
```

LISTING 4-4. *i386 Linear Addresses*

2. `X86_PAGE()`, `X86_PDI()`, and `X86_PTI()` use the above constants to compute the page index, PDI, or PTI of a given linear address. `X86_PAGE()` is typically used to read a PTE from the Windows 2000 PTE array starting at address `0xC0000000`. `X86_PDI()` and `X86_PTI()` simply apply `X86_PDI_MASK` or `X86_PTI_ MASK` to the supplied pointer and shift the resulting index to the rightmost bit position.
3. `X86_OFFSET_4M()` and `X86_OFFSET_4K()` extract the offset portion of a 4-MB or 4-KB linear address, respectively.
4. `X86_PAGE_4M` and `X86_PAGE_4K` compute the sizes of 4-MB and 4-KB pages from the DDK constants `PDI_SHIFT` and `PTI_SHIFT`, resulting in `X86_PAGE_4M` = 4,194,304 and `X86_PAGE_4K` = 4,096. Note that `X86_PAGE_4K` is equivalent to the DDK constant `PAGE_SIZE`, also defined in `ntddk.h`.
5. `X86_PAGES_4M` and `X86_PAGES_4K` state the number of 4-MB or 4-KB pages fitting into the 4-GB linear address space. `X86_PAGES_4M` evaluates to 1,024, and `X86_PAGES_4K` to 1,048,576.

The second group of macros and constants relates to the Windows 2000 PDE and PTE arrays. Unlike several other system addresses, the base addresses of these arrays are not available as global variables set up at boot time, but are defined as constants. This can be proved easily by disassembling the memory manager API functions `MmGetPhysicalAddress()` or `MmIsAddressValid()`, where these addresses appear as "magic numbers." These constants are not included in the DDK header files, but Listing 4-5 shows how they might have been defined.

- `X86_PAGES` is a hard-coded address and points, of course, to `0xC0000000`, where the Windows 2000 PTE array starts.

- X86_PTE_ARRAY is equal to X86_PAGES, but typecasts the value to PX86_PE, that is, a pointer to an array of X86_PE page entry structures, as defined in Listing 4-2.
- X86_PDE_ARRAY is a tricky definition that computes the base address of the PDE array from the PTE array location, using the PTI_SHIFT constant. As explained earlier, the general formula for mapping a linear address to a PTE address is ((LinearAddress >> 12) * 4) + 0xC0000000, and the page-directory is located by setting LinearAddress to 0xC0000000. Nothing else is done by the definition of X86_PDE_ARRAY.

```
// =================================================================
// INTEL X86 MACROS & CONSTANTS
// =================================================================

#define X86_PAGE_MASK (0 - (1 << PAGE_SHIFT))
#define X86_PAGE(_p)  (((DWORD) (_p) & X86_PAGE_MASK) >> PAGE_SHIFT)

#define X86_PDI_MASK  (0 - (1 << PDI_SHIFT))
#define X86_PDI(_p)   (((DWORD) (_p) & X86_PDI_MASK) >> PDI_SHIFT)

#define X86_PTI_MASK  ((0 - (1 << PTI_SHIFT)) & ~X86_PDI_MASK)
#define X86_PTI(_p)   (((DWORD) (_p) & X86_PTI_MASK) >> PTI_SHIFT)

#define X86_OFFSET_4M(_p) ((_p) & ~(X86_PDI_MASK               ))
#define X86_OFFSET_4K(_p) ((_p) & ~(X86_PDI_MASK | X86_PTI_MASK))

#define X86_PAGE_4M   (1 << PDI_SHIFT)
#define X86_PAGE_4K   (1 << PTI_SHIFT)

#define X86_PAGES_4M  (1 << (32 - PDI_SHIFT))
#define X86_PAGES_4K  (1 << (32 - PTI_SHIFT))

// -----------------------------------------------------------------

#define X86_PAGES         0xC0000000
#define X86_PTE_ARRAY     ((PX86_PE) X86_PAGES)
#define X86_PDE_ARRAY     (X86_PTE_ARRAY + (X86_PAGES >> PTI_SHIFT))

// -----------------------------------------------------------------

#define X86_SELECTOR_RPL            0x0003
#define X86_SELECTOR_TI             0x0004
#define X86_SELECTOR_INDEX          0xFFF8
#define X86_SELECTOR_SHIFT          3
```

```
#define X86_SELECTOR_LIMIT          (X86_SELECTOR_INDEX >> \
                                     X86_SELECTOR_SHIFT)

// ----------------------------------------------------------------

#define X86_DESCRIPTOR_SYS_TSS16A       0x1
#define X86_DESCRIPTOR_SYS_LDT          0x2
#define X86_DESCRIPTOR_SYS_TSS16B       0x3
#define X86_DESCRIPTOR_SYS_CALL16       0x4
#define X86_DESCRIPTOR_SYS_TASK         0x5
#define X86_DESCRIPTOR_SYS_INT16        0x6
#define X86_DESCRIPTOR_SYS_TRAP16       0x7
#define X86_DESCRIPTOR_SYS_TSS32A       0x9
#define X86_DESCRIPTOR_SYS_TSS32B       0xB
#define X86_DESCRIPTOR_SYS_CALL32       0xC
#define X86_DESCRIPTOR_SYS_INT32        0xE
#define X86_DESCRIPTOR_SYS_TRAP32       0xF

// ----------------------------------------------------------------

#define X86_DESCRIPTOR_APP_ACCESSED     0x1
#define X86_DESCRIPTOR_APP_READ_WRITE   0x2
#define X86_DESCRIPTOR_APP_EXECUTE_READ 0x2
#define X86_DESCRIPTOR_APP_EXPAND_DOWN  0x4
#define X86_DESCRIPTOR_APP_CONFORMING   0x4
#define X86_DESCRIPTOR_APP_CODE         0x8

// ================================================================
```

LISTING 4-5. *Additional i386 Memory Management Definitions*

The last two sections of Listing 4-5 handle selectors and special types of descriptors, and are complementary to Listing 4-2:

- `X86_SELECTOR_RPL`, `X86_SELECTOR_TI`, and `X86_SELECTOR_INDEX` are bit masks corresponding to the `RPL`, `TI`, and `Index` members of the `X86_SELECTOR` structures defined in Listing 4-2.
- `X86_SELECTOR_SHIFT` is a right-shift factor that right-aligns the value of the selector's `Index` member.
- `X86_SELECTOR_LIMIT` defines the maximum index value a selector can hold and is equal to 8,191. This value determines the maximum size of a descriptor table. Each selector index points to a descriptor, and each descriptor consists of 64 bits or 8 bytes (cf. `X86_DESCRIPTOR` in Listing 4-2), so the maximum descriptor table size amounts to 8,192 * 8 = 64 KB.

- The list of `X86_DESCRIPTOR_SYS_*` constants define values of a descriptor's `Type` member if its `S`-bit is zero, identifying it as a system descriptor. Please refer to Listing 4-2 for the bit-field layout of a descriptor, determined by the structure `X86_DESCRIPTOR`. The system descriptor types are described in detail in the Intel manuals (Intel 1999c, pp. 3-15f) and summarized in Table 4-1.

The `X86_DESCRIPTOR_APP_*` constants concluding Listing 4-5 apply to a descriptor's `Type` member if it is an application descriptor referring to a code or data segment, identified by a nonzero `S`-bit. Because application descriptor types can be characterized by independent properties reflected by the four type bits, the `X86_DESCRIPTOR_APP_*` constants are defined as single-bit masks, in which some bits are interpreted differently for data and code segments:

- `X86_DESCRIPTOR_APP_ACCESSED` is set if the segment has been accessed.
- `X86_DESCRIPTOR_APP_READ_WRITE` decides whether a data segment allows read-only or read/write access.
- `X86_DESCRIPTOR_APP_EXECUTE_READ` decides whether a code segment allows execute-only or execute/read access.
- `X86_DESCRIPTOR_APP_DOWN` is set for expand-down data segments, which is a property commonly exposed by stack segments.
- `X86_DESCRIPTOR_APP_CONFORMING` indicates whether a code segment is conforming, that is, whether it can be called by less privileged code (cf. Intel 1999c, pp. 4-13ff).
- `X86_DESCRIPTOR_APP_CODE` distinguishes code and data segments. Note that stack segments belong to the data segment category and must always be writable.

We will revisit system descriptors later when the memory spy application presented in the next sections is up and running. Table 4-1 also concludes a short introduction to i386 memory management. For more information on this topic, please refer to the original Intel Pentium manuals (Intel 1999a, 1999b, 1999c) or one of the secondary readings, such as Robert L. Hummel's great 80486 reference handbook (Hummel 1992).

TABLE 4-1. *System Descriptor Types*

NAME	VALUE	DESCRIPTION
X86_DESCRIPTOR_SYS_TSS16A	0x1	16-bit Task State Segment (Available)
X86_DESCRIPTOR_SYS_LDT	0x2	Local Descriptor Table
X86_DESCRIPTOR_SYS_TSS16B	0x3	16-bit Task State Segment (Busy)
X86_DESCRIPTOR_SYS_CALL16	0x4	16-bit Call Gate
X86_DESCRIPTOR_SYS_TASK	0x5	Task Gate
X86_DESCRIPTOR_SYS_INT16	0x6	16-bit Interrupt Gate
X86_DESCRIPTOR_SYS_TRAP16	0x7	16-bit Trap Gate
X86_DESCRIPTOR_SYS_TSS32A	0x9	32-bit Task State Segment (Available)
X86_DESCRIPTOR_SYS_TSS32B	0xB	32-bit Task State Segment (Busy)
X86_DESCRIPTOR_SYS_CALL32	0xC	32-bit Call Gate
X86_DESCRIPTOR_SYS_INT32	0xE	32-bit Interrupt Gate
X86_DESCRIPTOR_SYS_TRAP32	0xF	32-bit Trap Gate

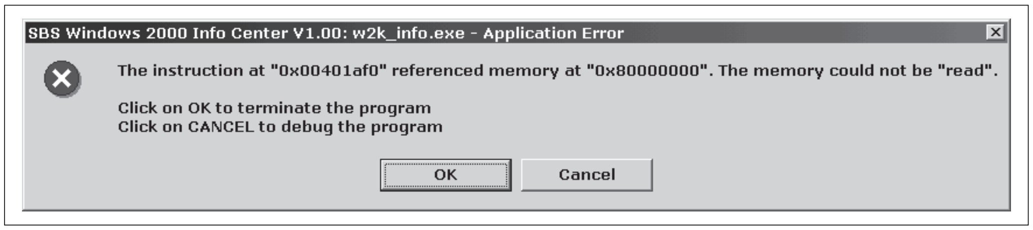
A SAMPLE MEMORY SPY DEVICE

One of the frequently recurring Microsoft statements about Windows NT and 2000 is that it is a *secure* operating system. Along with user authentication issues in networking environments, this also includes robustness against bad applications that might compromise the system's integrity by misusing pointers or writing outside the bounds of a memory data structure. This has always been a nasty problem on Windows 3.x, in which the system and all applications shared a single memory space. Windows NT has introduced a clear separation between system and application memory and between concurrent processes. Each process gets its own 4-GB address space, as depicted in Figure 4-2. Whenever a task switch occurs, the current address space is switched out and another one is mapped in by selecting different values for the segment registers, page tables, and other memory management data specific to a process. This design prevents applications from inadvertently tampering with memory of other applications. Each process also requires access to system resources, so the 4-GB space always contains some system code and data. To protect these memory regions from being overwritten by hostile application code, a different trick is employed.

WINDOWS 2000 MEMORY SEGMENTATION

Windows 2000 has inherited the basic memory segmentation scheme of Windows NT 4.0, which divides the 4-GB process address space in two equal parts by default. The lower half, comprising the range `0x00000000` to `0x7FFFFFFF`, contains application data and code running in user-mode, which is equivalent to Privilege Level 3 or "Ring 3" in Intel's terminology (Intel 1999a, pp. 4-8ff; Intel 1999c, pp. 4-8ff). The upper half, ranging from `0x80000000` to `0xFFFFFFFF`, is reserved for the system, which is running in kernel-mode, also known as Intel's Privilege Level 0 or "Ring 0." The privilege level determines what operations may be executed and which memory locations can be accessed by the code. Especially, this means that certain CPU instructions are forbidden and certain memory regions are inaccessible, for low-privileged code. For example, if a user-mode application touches any address in the upper half of the 4-GB address space, the system will throw an exception and terminate the application process without giving it another chance.

Figure 4-5 demonstrates what happens if an application attempts to read from address `0x80000000`. This strict access limitation is good for the integrity of the system but bad for debugging tools that should be able to show the contents of all valid memory regions. Fortunately, an easy workaround exists: Like the system itself, kernel-mode drivers run on the highest privilege level and therefore are allowed to execute all CPU instructions and to see all memory locations. The trick is to inject a spy driver into the system that reads the requested memory and sends the contents to a companion application waiting in user-mode. Of course, even a kernel-mode driver cannot read from virtual memory addresses that aren't backed up by physical or page file memory. Therefore, such a driver must check all addresses carefully before accessing them in order to avoid the dreaded Blue Screen Of Death (BSOD). Contrary to an application exception, which terminates the problem application only, a driver exception stops the entire system and forces a full reboot.


SBS Windows 2000 Info Center V1.00: w2k_info.exe - Application Error

The instruction at "0x00401af0" referenced memory at "0x80000000". The memory could not be "read".

Click on OK to terminate the program
Click on CANCEL to debug the program

FIGURE 4-5. *Addresses Starting at* 0x80000000 *Are Not Accessible in User-mode*

THE DEVICE I/O CONTROL DISPATCHER

The companion CD of this book contains the source code of a versatile spy device implemented as a kernel-mode driver, which can be found in the `\src\w2k_spy` directory tree. This device is based on a driver skeleton generated by the driver wizard introduced in Chapter 3. The user-mode interface of w2k_spy.sys is based on Win32 Device I/O Control (IOCTL), briefly described in the same chapter. The spy driver defines a device named \Device\w2k_spy and a symbolic link, \DosDevices\w2k_spy, required to make the device reachable from user-mode. It is funny that the namespace of symbolic links is called \DosDevices. We are certainly not working with DOS device drivers here. This name has historic roots and is now set in stone. With the symbolic link installed, the driver can be opened by any user-mode module via the standard Win32 API function CreateFile(), using the path \\.\w2k_spy. The character sequence \\.\ is a general escape for local devices. For example, \\.\C: refers to hard disk C: of the local system. See the CreateFile() documentation in the Microsoft Platform SDK for more details.

Parts of the driver's header file w2k_spy.h are included above as Listings 4-2 to 4-5. This file is somewhat similar to a DLL header file: It contains definitions required by the module itself during compilation, but it also provides enough information for a client application that needs to interface to it. Both the DLL/driver and the client application include the same header file, and each module picks out the definitions it needs for proper operation. However, this Janus-headed nature of the header file creates many more problems for a kernel-mode driver than for a DLL because of the special development environment Microsoft provides for drivers. Unfortunately, the header files contained in the DDK are not compatible with the Win32 files in the Platform SDK. The header files cannot be mixed, at least not in C language projects, resulting in a deadlocked situation in which the kernel-mode driver has access to constants, macros, and data types not available to the client application, and vice versa. Therefore, w2k_spy.c defines a flag constant named _W2K_SPY_SYS_, and w2k_spy.h checks the presence or absence of this constant to define items that are missing in one or the other environment, using #ifdef...#else...#endif clauses. This means that all definitions found in the #ifdef _W2K_SPY_SYS_ branch are "seen" by the driver code only, whereas the definitions in the #else branch are evaluated exclusively by the client application. All parts of w2k_spy.h outside these conditional clauses apply to both modules.

In Chapter 3, in the discussion of my driver wizard, I presented the driver skeleton code provided by the wizard in Listing 3-3. The starting point of any new driver project created by this wizard is usually the DeviceDispatcher() function. It receives a device context pointer and a pointer to the I/O Request Packet (IRP) that is to be dispatched. The wizard's boilerplate code already handles the basic I/O requests IRP_MJ_CREATE, IRP_MJ_CLEANUP, and IRP_MJ_CLOSE, sent to the device when it is opened or closed by a client. The DeviceDispatcher() simply returns STATUS_SUCCESS for these requests, so the device can be opened and closed without error. For some devices, this behavior is sufficient, but others require more or less complex initialization and cleanup code here. All remaining requests return STATUS_NOT_IMPLEMENTED. The first step in the extension of the code is to change this default behavior by handling more requests. As already noted, one of the main tasks of `w2k_spy.sys` is to send data unavailable in user-mode to a Win32 application by means of IOCTL calls, so the work starts with the addition of an `IRP_MJ_DEVICE_CONTROL` case to the `DeviceDispatcher()` function. Listing 4-6 shows the updated code, as it appears in `w2k_spy.c`.

```
NTSTATUS DeviceDispatcher (PDEVICE_CONTEXT pDeviceContext,
                           PIRP            pIrp)
    {
    PIO_STACK_LOCATION pisl;
    DWORD              dInfo = 0;
    NTSTATUS           ns    = STATUS_NOT_IMPLEMENTED;

    pisl = IoGetCurrentIrpStackLocation (pIrp);

    switch (pisl->MajorFunction)
        {
        case IRP_MJ_CREATE:
        case IRP_MJ_CLEANUP:
        case IRP_MJ_CLOSE:
            {
            ns = STATUS_SUCCESS;
            break;
            }
        case IRP_MJ_DEVICE_CONTROL:
            {
            ns = SpyDispatcher (pDeviceContext,

                                pisl->Parameters.DeviceIoControl
                                                .IoControlCode,

                                pIrp->AssociatedIrp.SystemBuffer,
                                pisl->Parameters.DeviceIoControl
                                                .InputBufferLength,

                                pIrp->AssociatedIrp.SystemBuffer,
                                pisl->Parameters.DeviceIoControl
                                                .OutputBufferLength,
                                &dInfo);
            break;
            }
        }
    pIrp->IoStatus.Status      = ns;
    pIrp->IoStatus.Information = dInfo;

    IoCompleteRequest (pIrp, IO_NO_INCREMENT);
    return ns;
    }
```

LISTING 4-6. *Adding an* `IRP_MJ_DEVICE_CONTROL` *Case to the Dispatcher*

The IOCTL handler in Listing 4-6 is fairly simple—it just calls `SpyDispatcher()` with parameters it extracts from the IRP structure and the current I/O stack location embedded in it. The `SpyDispatcher()`, shown in Listing 4-7, requires the following arguments:

- `pDeviceContext` is the driver's device context. The basic `Device_Context` structure provided by the driver wizard contains the driver and device object pointers only (see Listing 3-4). The spy driver adds a couple of members to it for private use.
- `dCode` specifies the IOCTL code that determines the command to be executed by the spy device. An IOCTL code is a 32-bit integer consisting of 4 bit-fields, as illustrated by Figure 4-6.
- `pInput` points to the buffer providing the IOCTL input data.
- `dInput` is the size of the input buffer.
- `pOutput` points to the buffer receiving the IOCTL output data.
- `dOutput` is the size of the output buffer.
- `pdInfo` points to a `DWORD` variable that should receive the number of bytes written to the output buffer.

Depending on the IOCTL method used, the input and output buffers are passed differently from the system to the driver. The spy device uses buffered I/O, directing the system to copy the input data to a safe buffer allocated automatically by the system, and to copy a specified amount of data from the same system buffer to the caller's output buffer on return. It is important to keep in mind that the input and output buffers overlap in this case, so the IOCTL handler must save any input data it might need later before it writes any output data to the buffer. The pointer to this I/O buffer is stored in the `SystemBuffer` member of the `AssociatedIrp` union inside the `IRP` structure (cf. `ntddk.h`). The input and output buffer sizes are stored in a completely different location of the `IRP`—they are part of the `DeviceIoControl` member of the `Parameters` union inside the `IRP's` current stack location, named `InputBufferLength` and `OutputBufferLength`, respectively. The `DeviceIoControl` substructure also provides the IOCTL code via its `IoControlCode` member. More information about the Windows NT/2000 IOCTL methods and how they pass data in and out can be found in my article "A Spy Filter Driver for Windows NT" in *Windows Developer's Journal* (Schreiber 1997).

```
NTSTATUS SpyDispatcher (PDEVICE_CONTEXT pDeviceContext,
                        DWORD           dCode,
                        PVOID           pInput,
                        DWORD           dInput,
                        PVOID           pOutput,
                        DWORD           dOutput,
                        PDWORD          pdInfo)
    {
    SPY_MEMORY_BLOCK smb;
    SPY_PAGE_ENTRY   spe;
    SPY_CALL_INPUT   sci;
    PHYSICAL_ADDRESS pa;
    DWORD            dValue, dCount;
    BOOL             fReset, fPause, fFilter, fLine;
    PVOID            pAddress;
    PBYTE            pbName;
    HANDLE           hObject;
    NTSTATUS         ns = STATUS_INVALID_PARAMETER;

    MUTEX_WAIT (pDeviceContext->kmDispatch);

    *pdInfo = 0;

    switch (dCode)
        {
        case SPY_IO_VERSION_INFO:
            {
            ns = SpyOutputVersionInfo (pOutput, dOutput, pdInfo);
            break;
            }
        case SPY_IO_OS_INFO:
            {
            ns = SpyOutputOsInfo (pOutput, dOutput, pdInfo);
            break;
            }
        case SPY_IO_SEGMENT:
            {
            if ((ns = SpyInputDword (&dValue,
                                     pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputSegment (dValue,
                                       pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_INTERRUPT:
            {
            if ((ns = SpyInputDword (&dValue,
                                     pInput, dInput))
                == STATUS_SUCCESS)
                {
```

```
            ns = SpyOutputInterrupt (dValue,
                                     pOutput, dOutput, pdInfo);
            }
        break;
        }
    case SPY_IO_PHYSICAL:
        {
        if ((ns = SpyInputPointer (&pAddress,
                                   pInput, dInput))
            == STATUS_SUCCESS)
            {
            pa = MmGetPhysicalAddress (pAddress);

            ns = SpyOutputBinary (&pa, PHYSICAL_ADDRESS_,
                                  pOutput, dOutput, pdInfo);
            }
        break;
        }
    case SPY_IO_CPU_INFO:
        {
        ns = SpyOutputCpuInfo (pOutput, dOutput, pdInfo);
        break;
        }
    case SPY_IO_PDE_ARRAY:
        {
        ns = SpyOutputBinary (X86_PDE_ARRAY, SPY_PDE_ARRAY_,
                              pOutput, dOutput, pdInfo);
        break;
        }
    case SPY_IO_PAGE_ENTRY:
        {
        if ((ns = SpyInputPointer (&pAddress,
                                   pInput, dInput))
            == STATUS_SUCCESS)
            {
            SpyMemoryPageEntry (pAddress, &spe);

            ns = SpyOutputBinary (&spe, SPY_PAGE_ENTRY_,
                                  pOutput, dOutput, pdInfo);
            }
        break;
        }
    case SPY_IO_MEMORY_DATA:
        {
        if ((ns = SpyInputMemory (&smb,
                                  pInput, dInput))
            == STATUS_SUCCESS)
            {
            ns = SpyOutputMemory (&smb,
                                  pOutput, dOutput, pdInfo);
            }
```

(continued)

```
            break;
            }
        case SPY_IO_MEMORY_BLOCK:
            {
            if ((ns = SpyInputMemory (&smb,
                                      pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputBlock (&smb,
                                     pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HANDLE_INFO:
            {
            if ((ns = SpyInputHandle (&hObject,
                                      pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputHandleInfo (hObject,
                                          pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_INFO:
            {
            ns = SpyOutputHookInfo (pOutput, dOutput, pdInfo);
            break;
            }
        case SPY_IO_HOOK_INSTALL:
            {
            if (((ns = SpyInputBool (&fReset,
                                     pInput, dInput))
                 == STATUS_SUCCESS)
                &&
                ((ns = SpyHookInstall (fReset, &dCount))
                 == STATUS_SUCCESS))
                {
                ns = SpyOutputDword (dCount,
                                     pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_REMOVE:
            {
            if (((ns = SpyInputBool (&fReset,
                                     pInput, dInput))
                 == STATUS_SUCCESS)
                &&
                ((ns = SpyHookRemove (fReset, &dCount))
                 == STATUS_SUCCESS))
                {
```

```
                ns = SpyOutputDword (dCount,
                                     pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_PAUSE:
            {
            if ((ns = SpyInputBool (&fPause,
                                    pInput, dInput))
                == STATUS_SUCCESS)
                {
                fPause = SpyHookPause (fPause);

                ns = SpyOutputBool (fPause,
                                    pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_FILTER:
            {
            if ((ns = SpyInputBool (&fFilter,
                                    pInput, dInput))
                == STATUS_SUCCESS)
                {
                fFilter = SpyHookFilter (fFilter);

                ns = SpyOutputBool (fFilter,
                                    pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_RESET:
            {
            SpyHookReset ();
            ns = STATUS_SUCCESS;
            break;
            }
        case SPY_IO_HOOK_READ:
            {
            if ((ns = SpyInputBool (&fLine,
                                    pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputHookRead (fLine,
                                        pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_HOOK_WRITE:
            {
            SpyHookWrite (pInput, dInput);
```

(continued)

```
            ns = STATUS_SUCCESS;
            break;
            }
        case SPY_IO_MODULE_INFO:
            {
            if ((ns = SpyInputPointer (&pbName,
                                       pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputModuleInfo (pbName,
                                          pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_PE_HEADER:
            {
            if ((ns = SpyInputPointer (&pAddress,
                                       pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputPeHeader (pAddress,
                                        pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_PE_EXPORT:
            {
            if ((ns = SpyInputPointer (&pAddress,
                                       pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputPeExport (pAddress,
                                        pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_PE_SYMBOL:
            {
            if ((ns = SpyInputPointer (&pbName,
                                       pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputPeSymbol (pbName,
                                        pOutput, dOutput, pdInfo);
                }
            break;
            }
        case SPY_IO_CALL:
            {
            if ((ns = SpyInputBinary (&sci, SPY_CALL_INPUT_,
                                      pInput, dInput))
                == STATUS_SUCCESS)
                {
                ns = SpyOutputCall (&sci,
                                    pOutput, dOutput, pdInfo);
                }
            break;
            }
        }
    MUTEX_RELEASE (pDeviceContext->kmDispatch);
    return ns;
    }
```

LISTING 4-7. *The Spy Driver's Internal Command Dispatcher*

The main DDK header file `ntddk.h`, as well as the Win32 file `winioctl.h` in the Platform SDK, define the simple but highly convenient `CTL_CODE()` macro shown in Listing 4-8 to build IOCTL codes according to the diagram in Figure 4-6. The four parts serve the following purposes:

1. `DeviceType` is a 16-bit device type ID. `ntddk.h` lists a couple of predefined types, symbolized by the constants `FILE_DEVICE_*`. Microsoft reserves the range `0x0000` to `0x7FFF` for internal use, while the range `0x8000` to `0xFFFF` is available to developers. The spy driver defines its own device ID `FILE_DEVICE_SPY` and sets it to `0x8000`.
2. `Access` specifies the 2-bit access check value determining the required access rights for the IOCTL operation. Possible values are `FILE_ANY_ACCESS` (0), `FILE_READ_ACCESS` (1), `FILE_WRITE_ACCESS` (2), and the combination of the latter two, `FILE_READ_ACCESS | FILE_WRITE_ACCESS` (3). See `ntddk.h` for more details.
3. `Function` is a 12-bit ID that selects the operation to be performed by the device. Microsoft reserves the values `0x000` to `0x7FF` for internal use, and leaves range `0x800` to `0xFFF` for developers. The IOCTL function IDs recognized by the spy device are drawn from the latter number pool.
4. `Method` consists of 2 bits, selecting one of four available I/O transfer methods named `METHOD_BUFFERED` (0), `METHOD_IN_DIRECT` (1), `METHOD_OUT_DIRECT` (2), and `METHOD_NEITHER` (3), found in `ntddk.h`. The spy device uses `METHOD_BUFFERED` for all requests, which is a highly secure but also somewhat sluggish method because of the data copying between the client and system buffers. Because the I/O of the memory spy is not time-critical, it is a good idea to opt for security. If you want to know more about the other methods, please refer to my spy filter article mentioned on p.191. (Schreiber 1997).

```
#define CTL_CODE (DeviceType, Function, Method, Access) \
        (((DeviceType) << 16) | ((Access) << 14) | ((Function) << 2) (Method))
```

LISTING 4-8. *The* `CTL_CODE()` *Macro Builds I/O Control Codes*

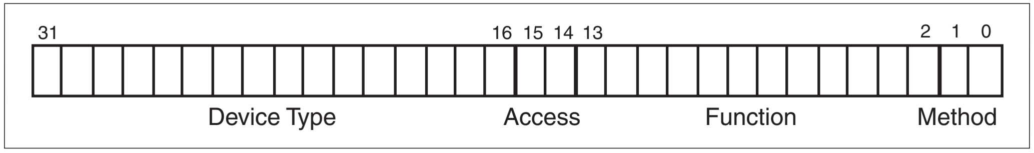


FIGURE 4-6. *Structure of a Device I/O Control Code*

Table 4-2 summarizes all IOCTL functions supported by `w2k_spy.sys`. The functions with IDs in the range 0 to 10 are memory exploration primitives that are sufficient to cover a wide range of tasks; they are discussed later in this chapter. The remaining functions with IDs of 11 and up belong to different IOCTL groups that will be described in detail in the next chapters, where Native API hooks and kernel calls from user-mode are discussed. Note that some IOCTL codes require the write access right, indicated by bit #15 being set (see Figure 4-6). That is, all IOCTL commands with a code of `0x80006nnn` can be issued via a read-only device handle, and a code of `0x8000Ennn` requires a read/write handle. The access rights are typically requested in the `CreateFile()` call that opens the device by specifying a combination of the `GENERIC_READ` and `GENERIC_WRITE` flags for the `dwDesiredAccess` argument.

The function names in the leftmost column of Table 4-2 also appear as cases of the large switch/case statement of the `SpyDispatcher()` function in Listing 4-7. This function first obtains the device's dispatcher mutex to guarantee that only a single request is executed at a time if more than one client or a multithreaded application communicates with the device. `MUTEX_WAIT()` is a wrapper macro for `KeWaitForMutexObject()`, which takes no less than five arguments. `KeWaitForMutexObject()` is a macro itself, forwarding its arguments to `KeWaitForSingleObject()`. `MUTEX_WAIT()`, along with its friends `MUTEX_RELEASE()` and `MUTEX_INITIALIZE()`, is shown in Listing 4-9. After the mutex object becomes signaled, `SpyDispatcher()` branches to various short code sequences, depending on the received IOCTL code. At the end, it releases the mutex and returns a status code to the caller.

The `SpyDispatcher()` uses a couple of helper functions to read input parameters, obtain the requested data, and write the data to the caller's output buffer. As already mentioned, a kernel-mode driver must be overly fussy with any user-mode

TABLE 4-2. *IOCTL Functions Supported by the Spy Device*

FUNCTION NAME	ID	IOCTL CODE	DESCRIPTION
SPY_IO_VERSION_INFO	0	0x80006000	Returns spy version information
SPY_IO_OS_INFO	1	0x80006004	Returns operating system information
SPY_IO_SEGMENT	2	0x80006008	Returns the properties of a segment
SPY_IO_INTERRUPT	3	0x8000600C	Returns the properties of an interrupt gate
SPY_IO_PHYSICAL	4	0x80006010	Linear-to-physical address translation
SPY_IO_CPU_INFO	5	0x80006014	Returns the values of special CPU registers
SPY_IO_PDE_ARRAY	6	0x80006018	Returns the PDE array at 0xC0300000
SPY_IO_PAGE_ENTRY	7	0x8000601C	Returns the PDE or PTE of a linear address
SPY_IO_MEMORY_DATA	8	0x80006020	Returns the contents of a memory block
SPY_IO_MEMORY_BLOCK	9	0x80006024	Returns the contents of a memory block
SPY_IO_HANDLE_INFO	10	0x80006028	Looks up object properties from a handle
SPY_IO_HOOK_INFO	11	0x8000602C	Returns info about Native API hooks
SPY_IO_HOOK_INSTALL	12	0x8000E030	Installs Native API hooks
SPY_IO_HOOK_REMOVE	13	0x8000E034	Removes Native API hooks
SPY_IO_HOOK_PAUSE	14	0x8000E038	Pauses/resumes the hook protocol
SPY_IO_HOOK_FILTER	15	0x8000E03C	Enables/disables the hook protocol filter
SPY_IO_HOOK_RESET	16	0x8000E040	Clears the hook protocol
SPY_IO_HOOK_READ	17	0x80006044	Reads data from the hook protocol
SPY_IO_HOOK_WRITE	18	0x8000E048	Writes data to the hook protocol
SPY_IO_MODULE_INFO	19	0x8000604C	Returns information about loaded system modules
SPY_IO_PE_HEADER	20	0x80006050	Returns `IMAGE_NT_HEADERS` data
SPY_IO_PE_EXPORT	21	0x80006054	Returns `IMAGE_EXPORT_DIRECTORY` data
SPY_IO_PE_SYMBOL	22	0x80006058	Returns the address of an exported system symbol
SPY_IO_CALL	23	0x8000E05C	Calls a function inside a loaded module

parameters it receives. From a driver's perspective, all user-mode code is evil and has no other thing on its mind but to trash the system. This somewhat paranoid view is not absurd—just the slightest slip brings the whole system to an immediate stop, with the appearance of a BlueScreen. So, if a client application says: "Here's my buffer—it can take up to 4,096 bytes," the driver does not accept it—neither that the buffer

```
#define MUTEX_INITIALIZE(_mutex) \
        KeInitializeMutex \
            (&(_mutex), 0)

#define MUTEX_WAIT(_mutex) \
        KeWaitForMutexObject \
            (&(_mutex), Executive, KernelMode, FALSE, NULL)

#define MUTEX_RELEASE(_mutex) \
        KeReleaseMutex \
            (&(_mutex), FALSE)
```

LISTING 4-9. *Kernel-Mutex Management Macros*

points to valid memory, nor that the buffer size is correct. In an IOCTL situation with buffered I/O (i.e., if the `Method` portion of the IOCTL code indicates `METHOD_ BUFFERED`), the system takes care of the sanity checks and allocates a buffer that is large enough to hold both the input and output data. However, the other I/O transfer methods, most notably `METHOD_NEITHER,` where the driver receives original user-mode buffer pointers, require more foresight.

Although the spy device uses buffered I/O, it has to check the input and output parameters for validity. It might be that the client application passes in less data than is required or provides an output buffer that is not large enough for the output data. The system cannot catch these semantic problems, because it doesn't know what kind of data is transferred in an IOCTL transaction. Therefore, `SpyDispatcher()` calls the `SpyInput*()` and `SpyOutput*()` helper functions to copy data from or to the I/O buffers. These functions execute the requested operation only if the buffer size matches the requirements of the operation. Listing 4-10 shows the basic input functions, and Listing 4-11 shows the basic output functions. `SpyInputBinary()` and `SpyOutputBinary()` are the workhorses. They test the buffer size, and, if it is OK, they copy the requested amount of data using the Windows 2000 Runtime Library function `RtlCopyMemory()`. The remaining functions are simple wrappers for the common data types `DWORD, BOOL, PVOID,` and `HANDLE`. Additionally, `SpyOutputBlock()` copies the data block specified by the caller in a `SPY_MEMORY_BLOCK` structure after verifying that all bytes in the indicated range are readable. The `SpyInput*()` functions return `STATUS_ INVALID_BUFFER_SIZE` if incomplete input data is passed in, and the `SpyOutput*()` functions return `STATUS_ BUFFER_TOO_SMALL` if the output buffer is smaller than required.

```
NTSTATUS SpyInputBinary (PVOID  pData,
                         DWORD  dData,
                         PVOID  pInput,
                         DWORD  dInput)
    {
    NTSTATUS ns = STATUS_OBJECT_TYPE_MISMATCH;

    if (dData <= dInput)
        {
        RtlCopyMemory (pData, pInput, dData);
        ns = STATUS_SUCCESS;
        }
    return ns;
    }

// -----------------------------------------------------------------
NTSTATUS SpyInputDword (PDWORD pdValue,
                        PVOID  pInput,
                        DWORD  dInput)
    {
    return SpyInputBinary (pdValue, DWORD_, pInput, dInput);
    }

// -----------------------------------------------------------------

NTSTATUS SpyInputBool (PBOOL  pfValue,
                       PVOID  pInput,
                       DWORD  dInput)
    {
    return SpyInputBinary (pfValue, BOOL_, pInput, dInput);
    }

// -----------------------------------------------------------------

NTSTATUS SpyInputPointer (PPVOID ppAddress,
                          PVOID  pInput,
                          DWORD  dInput)
    {
    return SpyInputBinary (ppAddress, PVOID_, pInput, dInput);
    }

// -----------------------------------------------------------------

NTSTATUS SpyInputHandle (PHANDLE phObject,
                         PVOID   pInput,
                         DWORD   dInput)
    {
    return SpyInputBinary (phObject, HANDLE_, pInput, dInput);
    }
```

LISTING 4-10. *Reading Input Data from an IOCTL Buffer*

```
NTSTATUS SpyOutputBinary (PVOID  pData,
                          DWORD  dData,
                          PVOID  pOutput,
                          DWORD  dOutput,
                          PDWORD pdInfo)
    {
    NTSTATUS ns = STATUS_BUFFER_TOO_SMALL;

    *pdInfo = 0;

    if (dData <= dOutput)
        {
        RtlCopyMemory (pOutput, pData, *pdInfo = dData);
        ns = STATUS_SUCCESS;
        }
    return ns;
    }

// -----------------------------------------------------------------

NTSTATUS SpyOutputBlock (PSPY_MEMORY_BLOCK psmb,
                         PVOID             pOutput,
                         DWORD             dOutput,
                         PDWORD            pdInfo)
    {
    NTSTATUS ns = STATUS_INVALID_PARAMETER;

    if (SpyMemoryTestBlock (psmb->pAddress, psmb->dBytes))
        {
        ns = SpyOutputBinary (psmb->pAddress, psmb->dBytes,
                              pOutput, dOutput, pdInfo);
        }
    return ns;
    }

// -----------------------------------------------------------------

NTSTATUS SpyOutputDword (DWORD  dValue,
                         PVOID  pOutput,
                         DWORD  dOutput,
                         PDWORD pdInfo)
    {
    return SpyOutputBinary (&dValue, DWORD_,
                            pOutput, dOutput, pdInfo);
    }

// -----------------------------------------------------------------

NTSTATUS SpyOutputBool (BOOL   fValue,
                        PVOID  pOutput,
                        DWORD  dOutput,
                        PDWORD pdInfo)
    {
```

```
    return SpyOutputBinary (&fValue, BOOL_,
                            pOutput, dOutput, pdInfo);
    }

// -----------------------------------------------------------------

NTSTATUS SpyOutputPointer (PVOID  pValue,
                           PVOID  pOutput,
                           DWORD  dOutput,
                           PDWORD pdInfo)
    {
    return SpyOutputBinary (&pValue, PVOID_,
                            pOutput, dOutput, pdInfo);
    }
```

LISTING 4-11. *Writing Output Data to an IOCTL Buffer*

You might have noticed that the `SpyDispatcher()` in Listing 4-7 contains references to a few more `SpyInput*()` and `SpyOutput*()` functions. Although ultimately based on `SpyInputBinary()` and `SpyOutputBinary()`, they are slightly more complex than the basic functions in Listings 4-10 and 4-11 and, therefore, are discussed separately a little later in this chapter. So let's start at the beginning of `SpyDispatcher()` and work through the switch/case statement step by step.

THE IOCTL FUNCTION SPY_IO_VERSION_INFO

The IOCTL `SPY_IO_VERSION_INFO` function fills a caller-supplied `SPY_VERSION_INFO` structure with data about the spy driver itself. It doesn't require input parameters and uses the `SpyOutputVersionInfo`() helper function. This function, included in Listing 4-12 together with the `SPY_VERSION_INFO` structure, is trivial. It sets the `dVersion` member to the constant `SPY_VERSION` (currently 100, indicating V1.00) defined in `w2k_spy.h`, and copies the driver's name symbolized by the string constant `DRV_NAME` ("SBS Windows 2000 Spy Device") to the `awName` member. The major version number is obtained by dividing `dVersion` by 100. The remainder yields the minor version number.

```
typedef struct _SPY_VERSION_INFO
    {
    DWORD dVersion;
    WORD  awName [SPY_NAME_];
    }
    SPY_VERSION_INFO, *PSPY_VERSION_INFO, **PPSPY_VERSION_INFO;
```

(continued)

```
#define SPY_VERSION_INFO_ sizeof (SPY_VERSION_INFO)

// -----------------------------------------------------------------

NTSTATUS SpyOutputVersionInfo (PVOID  pOutput,
                               DWORD  dOutput,
                               PDWORD pdInfo)
    {
    SPY_VERSION_INFO svi;

    svi.dVersion = SPY_VERSION;

    wcscpyn (svi.awName, USTRING (CSTRING (DRV_NAME)), SPY_NAME_);

    return SpyOutputBinary (&svi, SPY_VERSION_INFO_,
                            pOutput, dOutput, pdInfo);
    }
```

LISTING 4-12. *Obtaining Version Information About the Spy Driver*

THE IOCTL FUNCTION SPY_IO_OS_INFO

The IOCTL `SPY_IO_OS_INFO` function is much more interesting than the preceding one. It is another output-only function, expecting no input arguments and filling a caller-supplied `SPY_OS_INFO` structure with the values of several internal operating system parameters. Listing 4-13 shows the definition of this structure and the helper function `SpyOutputOsInfo()` called by the dispatcher. Some of the structure members are simply set to constants drawn from the DDK header files and `w2k_spy.h`; others receive "live" values read out from several internal kernel variables and structures. In Chapter 2, you became acquainted with the variables `NtBuildNumber` and `NtGlobalFlag`, exported by `ntoskrnl.exe` (see Table B-1 in Appendix B). Other than the other exported `Nt*` symbols, these don't point to API functions, but to variables in the kernel's `.data` section. In the Win32 world, it is quite uncommon to export variables. However, several Windows 2000 kernel modules make use of this technique. `ntoskrnl.exe` exports no fewer than 55 variables, `ntdll.dll` provides 4, and `hal.dll` provides 1. Of the set of `ntoskrnl.exe` variables, `SpyOutputOsInfo()` copies `MmHighestUserAddress`, `MmUserProbeAddress`, `MmSystemRangeStart`, `NtGlobalFlag`, `KeI386MachineType`, `KeNumberProcessors`, and `NtBuildNumber` to the output buffer.

When a module imports data from another module, it has to instruct the compiler and linker accordingly by using the `extern` keyword. This will cause the linker to generate an entry in the module's import section instead of trying to resolve the symbol to a fixed address. Some `extern` declarations are already included in `ntddk.h`. Those that are missing are included in Listing 4-13.

```
typedef struct _SPY_OS_INFO
    {
    DWORD   dPageSize;
    DWORD   dPageShift;
    DWORD   dPtiShift;
    DWORD   dPdiShift;
    DWORD   dPageMask;
    DWORD   dPtiMask;
    DWORD   dPdiMask;
    PX86_PE PteArray;
    PX86_PE PdeArray;
    PVOID   pLowestUserAddress;
    PVOID   pThreadEnvironmentBlock;
    PVOID   pHighestUserAddress;
    PVOID   pUserProbeAddress;
    PVOID   pSystemRangeStart;
    PVOID   pLowestSystemAddress;
    PVOID   pSharedUserData;
    PVOID   pProcessorControlRegion;
    PVOID   pProcessorControlBlock;
    DWORD   dGlobalFlag;
    DWORD   dI386MachineType;
    DWORD   dNumberProcessors;
    DWORD   dProductType;
    DWORD   dBuildNumber;
    DWORD   dNtMajorVersion;
    DWORD   dNtMinorVersion;
    WORD    awNtSystemRoot [MAX_PATH];
    }
    SPY_OS_INFO, *PSPY_OS_INFO, **PPSPY_OS_INFO;

#define SPY_OS_INFO_ sizeof (SPY_OS_INFO)

// -----------------------------------------------------------------
```

(continued)

```
extern PWORD  NlsAnsiCodePage;
extern PWORD  NlsOemCodePage;
extern PWORD  NtBuildNumber;
extern PDWORD NtGlobalFlag;
extern PDWORD KeI386MachineType;

// -----------------------------------------------------------------

NTSTATUS SpyOutputOsInfo (PVOID  pOutput,
                          DWORD  dOutput,
                          PDWORD pdInfo)
    {
    SPY_SEGMENT     ss;
    SPY_OS_INFO     soi;
    NT_PRODUCT_TYPE NtProductType;
    PKPCR           pkpcr;

    NtProductType = (SharedUserData->ProductTypeIsValid
                     ? SharedUserData->NtProductType
                     : 0);

    SpySegment (X86_SEGMENT_FS, 0, &ss);
    pkpcr = ss.pBase;

    soi.dPageSize               =  PAGE_SIZE;
    soi.dPageShift              =  PAGE_SHIFT;
    soi.dPtiShift               =  PTI_SHIFT;
    soi.dPdiShift               =  PDI_SHIFT;
    soi.dPageMask               =  X86_PAGE_MASK;
    soi.dPtiMask                =  X86_PTI_MASK;
    soi.dPdiMask                =  X86_PDI_MASK;
    soi.PteArray                =  X86_PTE_ARRAY;
    soi.PdeArray                =  X86_PDE_ARRAY;
    soi.pLowestUserAddress      =  MM_LOWEST_USER_ADDRESS;
    soi.pThreadEnvironmentBlock =  pkpcr->NtTib.Self;
    soi.pHighestUserAddress     = *MmHighestUserAddress;
    soi.pUserProbeAddress       =  (PVOID) *MmUserProbeAddress;
    soi.pSystemRangeStart       = *MmSystemRangeStart;
    soi.pLowestSystemAddress    =  MM_LOWEST_SYSTEM_ADDRESS;
    soi.pSharedUserData         =  SharedUserData;
    soi.pProcessorControlRegion =  pkpcr;
    soi.pProcessorControlBlock  =  pkpcr->Prcb;
    soi.dGlobalFlag             = *NtGlobalFlag;
    soi.dI386MachineType        = *KeI386MachineType;
    soi.dNumberProcessors       = *KeNumberProcessors;
    soi.dProductType            =  NtProductType;
    soi.dBuildNumber            = *NtBuildNumber;
    soi.dNtMajorVersion         =  SharedUserData->NtMajorVersion;
    soi.dNtMinorVersion         =  SharedUserData->NtMinorVersion;
    wcscpyn (soi.awNtSystemRoot, SharedUserData->NtSystemRoot,
             MAX_PATH);

    return SpyOutputBinary (&soi, SPY_OS_INFO_,
                            pOutput, dOutput, pdInfo);
    }
```

LISTING 4-13. *Obtaining Information About the Operating System*

The remaining members of the `SPY_OS_INFO` structure are filled with values from system data structures lying around in memory. For example, `SpyOutputOsInfo()` assigns the base address of the Kernel's Processor Control Region (`KPCR`) to the `pProcessorControlRegion` member. This is a very important data structure that contains lots of frequently used thread-specific data items, and therefore is placed in its own memory segment addressed by the CPU's `FS` register. Both Windows NT 4.0 and Windows 2000 set up `FS` to point to the linear address `0xFFDFF000` in kernel-mode. `SpyOutputOsInfo()` calls the `SpySegment()` function discussed later to query the base address of the `FS` segment in the linear address space. This segment also comprises the Kernel's Processor Control Block (KPRCB), pointed to by the `Prcb` member of the `KPCR`, immediately followed by a `CONTEXT` structure containing low-level CPU status information of the current thread. The definitions of the `KPCR`, `KPRCB`, and `CONTEXT` structures can be looked up in the `ntddk.h` header file. More on this topic follows later in this chapter.

Another internal data structure referenced in Listing 4-13 is `SharedUserData`. It is actually nothing but a "well-known address," typecast to a structure pointer. Listing 4-14 shows the definition as it appears in `ntddk.h`. Well-known addresses are locations within the linear address space that are set at compile time, and hence do not vary over time or with the configuration. Obviously, `SharedUserData` is a pointer to a `KUSER_SHARED_DATA` structure found at the fixed linear address `0xFFDF0000`. This memory area is shared by the user-mode application and the system, and it contains such interesting things as the operating system's version number, which `SpyOutputOsInfo()` copies to the `dNtMajorVersion` and `dNtMinorVersion` members of the caller's `SPY_OS_INFO` structure. As I will show later, the `KUSER_SHARED_DATA` structure is mirrored to address `0x7FFE0000`, where user-mode code can access it.

Following the explanation of the spy device's IOCTL functions is a demo application that displays the returned data on the screen.

```
#define KI_USER_SHARED_DATA 0xffdf0000
#define SharedUserData ((KUSER_SHARED_DATA * const) KI_USER_SHARED_DATA)
```

LISTING 4-14. *Definition of* `SharedUserData`

THE IOCTL FUNCTION SPY_IO_SEGMENT

Now this discussion becomes really interesting. The SPY_IO_SEGMENT function does some very-low-level operations to query the properties of a segment, given a selector. SpyDispatcher() first calls SpyInputDword() to get the selector value passed in by the calling application. You might recall that selectors are 16-bit quantities. However, I try to avoid 16-bit data types whenever possible because the native word size of the i386 CPUs in 32-bit mode is the 32-bit DWORD. Therefore, I have extended the selector argument to a DWORD where the upper 16 bits are always zero. If SpyInputDword() reports success, the SpyOutputSegment() function shown in Listing 4-15 is called. This function simply returns to the caller whatever the SpySegment() helper function, included in Listing 4-15, returns. Basically, SpySegment() fills a SPY_SEGMENT structure, defined at the top of Listing 4-15. It comprises the selector's value in the form of a X86_SELECTOR structure (see Listing 4-2), along with its 64-bit X86_DESCRIPTOR (Listing 4-2, again), the corresponding segment's linear base address, the segment limit (i.e., the segment size minus one), and a flag named fOk indicating whether the data in the SPY_SEGMENT structure is valid. The latter is required in the context of other functions (e.g., SPY_IO_CPU_INFO) that return the properties of several segments at once. In this case, the fOk member enables the caller to sort out any invalid segments contained in the output data.

```
typedef struct _SPY_SEGMENT
    {
    X86_SELECTOR   Selector;
    X86_DESCRIPTOR Descriptor;
    PVOID          pBase;
    DWORD          dLimit;
    BOOL           fOk;
    }
    SPY_SEGMENT, *PSPY_SEGMENT, **PPSPY_SEGMENT;

#define SPY_SEGMENT_ sizeof (SPY_SEGMENT)

// -----------------------------------------------------------------

NTSTATUS SpyOutputSegment (DWORD  dSelector,
                           PVOID  pOutput,
                           DWORD  dOutput,
                           PDWORD pdInfo)
    {
    SPY_SEGMENT ss;

    SpySegment (X86_SEGMENT_OTHER, dSelector, &ss);
    return SpyOutputBinary (&ss, SPY_SEGMENT_,
                            pOutput, dOutput, pdInfo);
    }

// -----------------------------------------------------------------

BOOL SpySegment (DWORD        dSegment,
                 DWORD        dSelector,
                 PSPY_SEGMENT pSegment)
    {
    BOOL fOk = FALSE;

    if (pSegment != NULL)
        {
        fOk = TRUE;

        if (!SpySelector   (dSegment, dSelector,
                            &pSegment->Selector))
            {
            fOk = FALSE;
            }
        if (!SpyDescriptor (&pSegment->Selector,
                            &pSegment->Descriptor))
            {
            fOk = FALSE;
            }
        pSegment->pBase  =
            SpyDescriptorBase  (&pSegment->Descriptor);

        pSegment->dLimit =
            SpyDescriptorLimit (&pSegment->Descriptor);

        pSegment->fOk = fOk;
        }
    return fOk;
    }
```

LISTING 4-15. *Querying Segment Properties*

`SpySegment()` relies on several other helper functions that provide the parts that make up the resulting `SPY_SEGMENT` structure. First, `SpySelector()` copies a selector value to the passed-in `X86_SELECTOR` structure (Listing 4-16). If the first argument, `dSegment,` is set to `X86_SEGMENT_OTHER,` the `dSelector` argument is assumed to specify a valid selector value, so this value is simply assigned to the `wValue` member of the output structure. Otherwise, `dSelector` is ignored, and `dSegment` is used in a switch/case construct that selects one of the CPU's segment registers or its task register `TR`. Note that this requires a little bit of inline assembly—the C language doesn't provide a standard means for accessing processor-specific features such as segment registers.

```
#define X86_SEGMENT_OTHER           0
#define X86_SEGMENT_CS              1
#define X86_SEGMENT_DS              2
#define X86_SEGMENT_ES              3
#define X86_SEGMENT_FS              4
#define X86_SEGMENT_GS              5
#define X86_SEGMENT_SS              6
#define X86_SEGMENT_TSS             7

// -----------------------------------------------------------------

BOOL SpySelector (DWORD         dSegment,
                  DWORD         dSelector,
                  PX86_SELECTOR pSelector)
    {
    X86_SELECTOR Selector = {0, 0};
    BOOL         fOk      = FALSE;

    if (pSelector != NULL)
        {
        fOk = TRUE;

        switch (dSegment)
            {
            case X86_SEGMENT_OTHER:
                {
                if (fOk = ((dSelector >> X86_SELECTOR_SHIFT)
                           <= X86_SELECTOR_LIMIT))
                    {
                    Selector.wValue = (WORD) dSelector;
                    }
                break;
                }
            case X86_SEGMENT_CS:
                {
                __asm mov Selector.wValue, cs
                break;
                }
            case X86_SEGMENT_DS:
                {
                __asm mov Selector.wValue, ds
                break;
                }
            case X86_SEGMENT_ES:
                {
                __asm mov Selector.wValue, es
                break;
                }
            case X86_SEGMENT_FS:
                {
                __asm mov Selector.wValue, fs
                break;
                }
            case X86_SEGMENT_GS:
                {
                __asm mov Selector.wValue, gs
                break;
                }
            case X86_SEGMENT_SS:
                {
                __asm mov Selector.wValue, ss
                break;
                }
            case X86_SEGMENT_TSS:
                {
                __asm str Selector.wValue
                break;
                }
            default:
                {
                fOk = FALSE;
                break;
                }
            }
        RtlCopyMemory (pSelector, &Selector, X86_SELECTOR_);
        }
    return fOk;
    }
```

Listing 4-16. *Obtaining Selector Values*

`SpyDescriptor()` reads in the 64-bit descriptor pointed to by the segment selector (Listing 4-17). As you might recall, all selectors contain a Table Indicator (`TI`) bit that decides whether the selector refers to a descriptor in the Global Descriptor Table (GDT, `TI`=0) or Local Descriptor Table (LDT, `TI`=1). The upper half of Listing 4-17 handles the LDT case. First, the assembly language instructions `SLDT` and `SGDT` are used to read the LDT selector value and the segment limit and base address of the GDT, respectively. Remember that the linear base address of the GDT is specified explicitly, whereas the LDT is referenced indirectly via a selector that points into the GDT. Therefore, `SpyDescriptor()` first validates the LDT selector value. If it is not the null segment selector and does not point beyond the GDT limit, the `SpyDescriptorType()`, `SpyDescriptorLimit()`, and `SpyDescriptorBase()` functions attached to the bottom of Listing 4-17 are called to obtain the basic properties of the LDT:

- `SpyDescriptorType()` returns the values of a descriptor's `Type` and *S* bit-fields (cf. Listing 4-2). The LDT selector must point to a system descriptor of type `X86_DESCRIPTOR_SYS_LDT` (2).

- `SpyDescriptorLimit()` compiles the segment limit from the `Limit1` and `Limit2` bit-fields of a descriptor. If its *G* flag indicates a granularity of 4-KB, the value is shifted left by 12 bits, shifting in 1-bits from the right end.
- `SpyDescriptorBase()` simply arranges the `Base1, Base2,` and `Base3` bit-fields of a descriptor properly to yield a 32-bit linear address.

```
BOOL SpyDescriptor (PX86_SELECTOR   pSelector,
                    PX86_DESCRIPTOR pDescriptor)
    {
    X86_SELECTOR    ldt;
    X86_TABLE       gdt;
    DWORD           dType, dLimit;
    BOOL            fSystem;
    PX86_DESCRIPTOR pDescriptors = NULL;
    BOOL            fOk          = FALSE;

    if (pDescriptor != NULL)
        {
        if (pSelector != NULL)
            {
            if (pSelector->TI) // ldt descriptor
                {
                __asm
                    {
                    sldt ldt.wValue
                    sgdt gdt.wLimit
                    }
                if ((!ldt.TI) && ldt.Index &&
                    ((ldt.wValue & X86_SELECTOR_INDEX)
                     <= gdt.wLimit))
                    {
                    dType  = SpyDescriptorType  (gdt.pDescriptors +
                                                 ldt.Index,
                                                 &fSystem);

                    dLimit = SpyDescriptorLimit (gdt.pDescriptors +
                                                 ldt.Index);

                    if ((dType == X86_DESCRIPTOR_SYS_LDT)
                        &&
                        ((DWORD) (pSelector->wValue
                                  & X86_SELECTOR_INDEX)
                         <= dLimit))
                        {
                        pDescriptors =
                            SpyDescriptorBase (gdt.pDescriptors +
                                               ldt.Index);
                        }
                    }
                }
            else // gdt descriptor
                {
                if (pSelector->Index)
                    {
                    __asm
                        {
                        sgdt gdt.wLimit
                        }
                    if ((pSelector->wValue & X86_SELECTOR_INDEX)
                        <= gdt.wLimit)
                        {
                        pDescriptors = gdt.pDescriptors;
                        }
                    }
                }
            }
        if (pDescriptors != NULL)
            {
            RtlCopyMemory (pDescriptor,
                           pDescriptors + pSelector->Index,
                           X86_DESCRIPTOR_);
            fOk = TRUE;
            }
        else
            {
            RtlZeroMemory (pDescriptor,
                           X86_DESCRIPTOR_);
            }
        }
    return fOk;
    }

// -----------------------------------------------------------------
PVOID SpyDescriptorBase (PX86_DESCRIPTOR pDescriptor)
    {
    return (PVOID) ((pDescriptor->Base1      ) |
                    (pDescriptor->Base2 << 16) |
                    (pDescriptor->Base3 << 24));
    }

// -----------------------------------------------------------------

DWORD SpyDescriptorLimit (PX86_DESCRIPTOR pDescriptor)
    {
    return (pDescriptor->G ? (pDescriptor->Limit1 << 12) |
                             (pDescriptor->Limit2 << 28) | 0xFFF
```

(continued)

```
                            : (pDescriptor->Limit1      ) |
                              (pDescriptor->Limit2 << 16));
    }

// -----------------------------------------------------------------

DWORD SpyDescriptorType (PX86_DESCRIPTOR pDescriptor,
                         PBOOL           pfSystem)
    {
    if (pfSystem != NULL) *pfSystem = !pDescriptor->S;
    return pDescriptor->Type;
    }
```

LISTING 4-17. *Obtaining Descriptor Values*

If the selector's `TI` bit indicates a GDT descriptor, things are much simpler. Again, the `SGDT` instruction is used to get the size and location of the GDT in linear memory, and if the descriptor index specified by the selector is within the proper range, the `pDescriptors` variable is set to point to the GDT base address. In both the LDT and GDT cases, the `pDescriptor` variable is non-NULL if the caller has passed in a valid selector. In this case, the 64-bit descriptor value is copied to the caller's `X86_DESCRIPTOR` structure. Otherwise, all members of this structure are set to zero with the kind help of `RtlZeroMemory()`.

We are still in the discussion of the `SpySegment()` function shown in Listing 4-15. The `SpySelector()` and `SpyDescriptor()` calls have been handled. Only the concluding `SpyDescriptorBase()` and `SpyDescriptorLimit()` invocations are left, but you already know what these functions do (see Listing 4-17). If `SpySelector()` and `SpyDescriptor()` succeed, the data returned in the `SPY_SEGMENT` structure is valid. `SpyDescriptorBase()` and `SpyDescriptorLimit()` don't return error flags because they cannot fail—they just might return meaningless data if the supplied descriptor is invalid.

THE IOCTL FUNCTION SPY_IO_INTERRUPT

`SPY_IO_INTERRUPT` is similar to `SPY_IO_SEGMENT`, except that this function works on interrupt descriptors stored in the system's Interrupt Descriptor Table (IDT), rather than on LDT or GDT descriptors. The IDT contains up to 256 descriptors that can represent task, interrupt, or trap gates (cf. Intel 1999c, pp. 5-11ff). By the way, interrupts and traps are quite similar in nature, differing in a tiny detail only: An interrupt handler is always entered with interrupts disabled, whereas the interrupt flag is left unchanged upon entering a trap handler. The `SPY_IO_INTERRUPT` caller supplies an interrupt number between 0 and 256 in its input buffer and a `SPY_INTERRUPT` structure as output buffer, which will contain the properties of the corresponding interrupt handler on successful return. The `SpyOutputInterrupt()` helper function invoked by the dispatcher is a simple wrapper that calls `SpyInterrupt()` and copies the returned data to the output buffer. Both functions, as well as the `SPY_INTERRUPT` structure they operate on, are shown in Listing 4-18. The latter is filled by `SpyInterrupt()` with the following items:

- `Selector` specifies the selector of a Task-State Segment (TSS, see Intel 1999c, pp. 6-4ff) or a code segment. A code segment selector determines the segment where an interrupt or trap handler is located.
- `Gate` is the 64-bit task, interrupt, or trap gate descriptor addressed by the selector.
- `Segment` contains the properties of the segment addressed by the gate.
- `pOffset` specifies the offset of the interrupt or trap handler's entry point relative to the base address of the surrounding code segment. Because task gates don't comprise an offset value, this member must be ignored if the input selector refers to a TSS.
- `fOk` is a flag that indicates whether the data in the `SPY_INTERRUPT` structure is valid.

A TSS is typically used to guarantee that an error situation is handled by a valid task. It is a special system segment type that holds 104 bytes of processor state information needed to restore a task after a task switch has occurred, as outlined in Table 4-3. The CPU always forces a task switch and saves all CPU registers to the TSS when an interrupt associated with a TSS occurs. Windows 2000 stores task gates in the interrupt slots `0x02` (Nonmaskable Interrupt [NMI]), `0x08` (Double Fault), and `0x12` (Stack-Segment Fault). The remaining entries point to interrupt handlers. Unused interrupts are handled by dummy routines named `KiUnexpectedInterruptNNN()`, where "`NNN`" is a decimal ordinal number. These handlers branch to the internal function `KiEndUnexpectedRange()`, which in turn branches to `KiUnexpected InterruptTail()`, passing in the number of the unhandled interrupt.

```
typedef struct _SPY_INTERRUPT
    {
    X86_SELECTOR Selector;
    X86_GATE     Gate;
    SPY_SEGMENT  Segment;
    PVOID        pOffset;
    BOOL         fOk;
    }
    SPY_INTERRUPT, *PSPY_INTERRUPT, **PPSPY_INTERRUPT;
```

(continued)

```
#define SPY_INTERRUPT_ sizeof (SPY_INTERRUPT)

// -----------------------------------------------------------------

NTSTATUS SpyOutputInterrupt (DWORD  dInterrupt,
                             PVOID  pOutput,
                             DWORD  dOutput,
                             PDWORD pdInfo)
    {
    SPY_INTERRUPT si;

    SpyInterrupt (dInterrupt, &si);

    return SpyOutputBinary (&si, SPY_INTERRUPT_,
                            pOutput, dOutput, pdInfo);
    }

// -----------------------------------------------------------------

BOOL SpyInterrupt (DWORD          dInterrupt,
                   PSPY_INTERRUPT pInterrupt)
    {
    BOOL fOk = FALSE;

    if (pInterrupt != NULL)
        {
        if (dInterrupt <= X86_SELECTOR_LIMIT)
            {
            fOk = TRUE;

            if (!SpySelector (X86_SEGMENT_OTHER,
                              dInterrupt << X86_SELECTOR_SHIFT,
                              &pInterrupt->Selector))
                {
                fOk = FALSE;
                }
            if (!SpyIdtGate  (&pInterrupt->Selector,
                              &pInterrupt->Gate))
                {
                fOk = FALSE;
                }
            if (!SpySegment  (X86_SEGMENT_OTHER,
                              pInterrupt->Gate.Selector,
                              &pInterrupt->Segment))
                {
                fOk = FALSE;
                }
            pInterrupt->pOffset = SpyGateOffset (&pInterrupt->Gate);
            }
        else
            {
```

```
            RtlZeroMemory (pInterrupt, SPY_INTERRUPT_);
            }
        pInterrupt->fOk = fOk;
        }
    return fOk;
    }

// -----------------------------------------------------------------

PVOID SpyGateOffset (PX86_GATE pGate)
    {
    return (PVOID) (pGate->Offset1 | (pGate->Offset2 << 16));
    }
```

LISTING 4-18. *Querying Interrupt Properties*

TABLE 4-3. *CPU Status Fields in the Task State Segment (TSS)*

OFFSET	BITS	ID	DESCRIPTION
0x00	16		Previous Task Link
0x04	32	ESP0	Stack Pointer Register for Privilege Level 0
0x08	16	SS0	Stack Segment Register for Privilege Level 0
0x0C	32	ESP1	Stack Pointer Register for Privilege Level 1
0x10	16	SS1	Stack Segment Register for Privilege Level 1
0x14	32	ESP2	Stack Pointer Register for Privilege Level 2
0x18	16	SS2	Stack Segment Register for Privilege Level 2
0x1C	32	CR3	Page-Directory Base Register (PDBR)
0x20	32	EIP	Instruction Pointer Register
0x24	32	EFLAGS	Processor Flags Register
0x28	32	EAX	General-Purpose Register EAX
0x2C	32	ECX	General-Purpose Register ECX
0x30	32	EDX	General-Purpose Register EDX
0x34	32	EBX	General-Purpose Register EDX
0x38	32	ESP	Stack Pointer Register
0x3C	32	EBP	Base Pointer Register
0x40	32	ESI	Source Index Register
0x44	32	EDI	Destination Index Register
0x48	16	ES	Extra Segment Register
0x4C	16	CS	Code Segment Register
0x50	16	SS	Stack Segment Register

(continued)

TABLE 4-3. *(continued)*

OFFSET	BITS	ID	DESCRIPTION
0x54	16	DS	Data Segment Register
0x58	16	FS	Additional Data Segment Register #1
0x5C	16	GS	Additional Data Segment Register #2
0x60	16	LDT	Local Descriptor Table Segment Selector
0x64	1	T	Debug Trap Flag
0x66	16		I/O Map Base Address
0x68	—		End of CPU State Information

The `SpySegment()` and `SpySelector()` functions called by `SpyInterrupt()` have already been presented in Listings 4-15 and 4-16. `SpyGateOffset()`, included at the end of Listing 4-18, works analogous to `SpyDescriptorBase()` and `SpyDescriptorLimit()`, picking up the `Offset1` and `Offset2` bit-fields of an `X86_GATE` structure and arranging them properly to yield a 32-bit address. `SpyIdtGate()` is defined in Listing 4-19. It bears a strong similarity to `SpyDescriptor()` in Listing 4-17 if the LDT clause would be omitted. The assembly language instruction `SIDT` stores the 48-bit contents of the CPU's IDT register, comprising the 16-bit table limit and the 32-bit linear base address of the IDT. The remaining code in Listing 4-19 compares the descriptor index of the supplied selector to the IDT limit, and, if it is valid, the corresponding interrupt descriptor is copied to the caller's `X86_GATE` structure. Otherwise, all gate structure members are set to zero.

```
BOOL SpyIdtGate (PX86_SELECTOR pSelector,
                 PX86_GATE     pGate)
    {
    X86_TABLE idt;
    PX86_GATE pGates = NULL;
    BOOL      fOk    = FALSE;

    if (pGate != NULL)
        {
        if (pSelector != NULL)
            {
            __asm
                {
                sidt idt.wLimit
                }
            if ((pSelector->wValue & X86_SELECTOR_INDEX)
                <= idt.wLimit)
                {
                pGates = idt.pGates;
                }
            }
        if (pGates != NULL)
            {
            RtlCopyMemory (pGate,
                           pGates + pSelector->Index,
                           X86_GATE_);
            fOk = TRUE;
            }
        else
            {
            RtlZeroMemory (pGate, X86_GATE_);
            }
        }
    return fOk;
    }
```

LISTING 4-19. *Obtaining IDT Gate Values*

THE IOCTL FUNCTION SPY_IO_PHYSICAL

The IOCTL `SPY_IO_PHYSICAL` function is simple, because it relies entirely on the `MmGetPhysicalAddress()` function exported by `ntoskrnl.exe`. The IOCTL function handler simply calls `SpyInputPointer()` (see Listing 4-10) to get the linear address to be converted, lets `MmGetPhysicalAddress()` look up the corresponding physical address, and returns the resulting `PHYSICAL_ADDRESS` value to the caller. Note that `PHYSICAL_ADDRESS` is a 64-bit `LARGE_INTEGER`. On most i386 systems, the upper 32 bits will be always zero. However, on systems with Physical Address Extension (PAE) enabled and more than 4 GB of memory installed, these bits can assume nonzero values.

`MmGetPhysicalAddress()` uses the PTE array starting at linear address `0xC0000000` to find out the physical address. The basic mechanism works as follows:

- If the linear address is within the range `0x80000000` to `0x9FFFFFFF`, the three most significant bits are set to zero, yielding a physical address in the range `0x00000000` to `0x1FFFFFFF`.
- Otherwise, the upper 20 bits are used as an index into the PTE array at address `0xC0000000`.

- If the P bit of the target PTE is set, indicating that the corresponding page is present in physical memory, all PTE bits except for the 20-bit PFN are stripped, and the least significant 12 bits of the linear address are added, resulting in a proper 32-bit physical address.
- If the physical page is not present, MmGetPhysicalAddress() returns zero.

It is interesting to see that MmGetPhysicalAddress() assumes 4-KB pages for all linear addresses outside the kernel memory range 0x80000000 to 0x9FFFFFFF. Other functions, such as MmIsAddressValid(), first load the PDE of the linear address and check its PS bit to find out whether the page size is 4 KB or 4 MB. This is a much more general approach that can cope with arbitrary memory configurations. Both functions return correct results, because Windows 2000 happens to use 4-MB pages in the 0x80000000 to 0x9FFFFFFF memory area only. Some kernel API functions, however, are apparently designed to be more flexible than others.

The IOCTL Function SPY_IO_CPU_INFO

Several CPU instructions are available only to code running on privilege level zero, which is the most privileged of the four available levels. In Windows 2000 terminology, this means kernel-mode. Among the forbidden instructions are those that read the contents of the control registers CR0, CR2, and CR3. Because these registers contain interesting information, an application might wish to find a way to access them, and the SPY_IO_CPU_INFO function is the solution. As Listing 4-20 shows, the SpyOutputCpuInfo() function invoked by the IOCTL handler uses some ASM inline code to read the control registers, along with other valuable information, such as the contents of the IDT, GDT, and LDT registers and the segment selectors stored in the registers CS, DS, ES, FS, GS, SS, and TR. The Task Register TR contains a selector that refers to the TSS of the current task.

```
typedef struct _SPY_CPU_INFO
    {
    X86_REGISTER cr0;
    X86_REGISTER cr2;
    X86_REGISTER cr3;
    SPY_SEGMENT  cs;
    SPY_SEGMENT  ds;
    SPY_SEGMENT  es;
    SPY_SEGMENT  fs;
    SPY_SEGMENT  gs;
    SPY_SEGMENT  ss;
    SPY_SEGMENT  tss;
    X86_TABLE    idt;
    X86_TABLE    gdt;
    X86_SELECTOR ldt;
    }
    SPY_CPU_INFO, *PSPY_CPU_INFO, **PPSPY_CPU_INFO;

#define SPY_CPU_INFO_ sizeof (SPY_CPU_INFO)

// -----------------------------------------------------------------

NTSTATUS SpyOutputCpuInfo (PVOID  pOutput,
                           DWORD  dOutput,
                           PDWORD pdInfo)
    {
    SPY_CPU_INFO  sci;
    PSPY_CPU_INFO psci = &sci;

    __asm
        {
        push    eax
        push    ebx
        mov     ebx, psci

        mov     eax, cr0
        mov     [ebx.cr0], eax

        mov     eax, cr2
        mov     [ebx.cr2], eax

        mov     eax, cr3
        mov     [ebx.cr3], eax

        sidt    [ebx.idt.wLimit]
        mov     [ebx.idt.wReserved], 0
        sgdt    [ebx.gdt.wLimit]
        mov     [ebx.gdt.wReserved], 0
        sldt    [ebx.ldt.wValue]
        mov     [ebx.ldt.wReserved], 0

        pop     ebx
        pop     eax
        }
    SpySegment (X86_SEGMENT_CS,  0, &sci.cs);
    SpySegment (X86_SEGMENT_DS,  0, &sci.ds);
    SpySegment (X86_SEGMENT_ES,  0, &sci.es);
    SpySegment (X86_SEGMENT_FS,  0, &sci.fs);
    SpySegment (X86_SEGMENT_GS,  0, &sci.gs);
    SpySegment (X86_SEGMENT_SS,  0, &sci.ss);
    SpySegment (X86_SEGMENT_TSS, 0, &sci.tss);

    return SpyOutputBinary (&sci, SPY_CPU_INFO_,
                            pOutput, dOutput, pdInfo);
    }
```

LISTING 4-20. *Querying CPU State Information*

The segment selectors are obtained with the help of the `SpySegment()` function discussed earlier. See Listing 4-15 for details.

THE IOCTL FUNCTION SPY_IO_PDE_ARRAY

`SPY_IO_PDE_ARRAY` is another trivial function that simply copies the entire page-directory from address `0xC0300000` to the caller's output buffer. This buffer has to take the form of a `SPY_PDE_ARRAY` structure shown in Listing 4-21. As you might have guessed, this structure's size is exactly 4 KB, and it comprises 1,024 32-bit PDE values. The `X86_PE` structure used here, which represents a generalized page entry, can be found in Listing 4-3, and the constant `X86_PAGES_4M` is defined in Listing 4-5. Because the items in a `SPY_PDE_ARRAY` are always page-directory entries, the embedded `X86_PE` structures are either of type `X86_PDE_4M` or `X86_PDE_4K`, depending on the value of the page size bit `PS`.

It usually is not a good idea to copy memory contents without ensuring that the source page is currently present in physical memory. However, the page-directory is one of the few exceptions. The page-directory of the current task is always present in physical memory while the task is running (Intel 1999c, pp. 3-23). It cannot be swapped out to a pagefile unless another task is switched in. That's why the CPU's Page-Directory Base Register (PDBR) doesn't have a *P* (present) bit, like the PDEs and PTEs. Please refer to the definition of the `X86_PDBR` structure in Listing 4-3 to verify this.

```
typedef struct _SPY_PDE_ARRAY
    {
    X86_PE apde [X86_PAGES_4M];
    }
    SPY_PDE_ARRAY, *PSPY_PDE_ARRAY, **PPSPY_PDE_ARRAY;

#define SPY_PDE_ARRAY_ sizeof (SPY_PDE_ARRAY)
```

LISTING 4-21. *Definition of* `SPY_PDE_ARRAY`

THE IOCTL FUNCTION SPY_IO_PAGE_ENTRY

If you are interested in the page entry of a given linear address, this is the function of choice. Listing 4-22 shows the internals of the `SpyMemoryPageEntry()` function that handles this IOCTL request. The `SPY_PAGE_ENTRY` structure it returns is basically a `X86_PE` page entry, as defined in Listing 4-3, plus two convenient additions: The `dSize` member indicates the page size in bytes, which is either `X86_PAGE_4K`

(4,096 bytes) or X86_PAGE_4M (4,194,304 bytes), and the fPresent member indicates whether the page is present in physical memory. This flag must be contrasted to the return value of SpyMemoryPageEntry() itself, which can be TRUE even if fPresent is FALSE. In this case, the supplied linear address is valid, but points to a page currently swapped out to a pagefile. This situation is indicated by bit #10 of the page entry—referred to as PageFile in Listing 4-22—being set while the *P* bit is clear. Please refer to the introduction to the X86_PNPE structure earlier in this chapter for details. X86_PNPE represents a page-not-present entry and is defined in Listing 4-3.

SpyMemoryPageEntry() first assumes that the target page is a 4-MB page, and, therefore, copies the PDE of the specified linear address from the system's PDE array at address 0xC0300000 to the pe member of the SPY_PAGE_ENTRY structure. If the *P* bit is set, the subordinate page or page-table is present, so the next test checks the *PS* bit for the page size. If it is set, the PDE addresses a 4-MB page, and the work is done—SpyMemoryPageEntry() returns TRUE, and the fPresent member of the SPY_PAGE_ENTRY structure is set to TRUE as well. If the PS bit is zero, the PDE refers to a PTE, so the code extracts this PTE from the array at address 0xC0000000 and checks its *P* bit. If set, the 4-KB page comprising the linear address is present, and both SpyMemoryPageEntry() and fPresent report TRUE. Otherwise, the retrieved value must be a page-not-present entry, so fPresent is FALSE, and SpyMemoryPageEntry() returns TRUE only if the PageFile bit of the page entry is set.

```
typedef struct _SPY_PAGE_ENTRY
    {
    X86_PE pe;
    DWORD  dSize;
    BOOL   fPresent;
    }
    SPY_PAGE_ENTRY, *PSPY_PAGE_ENTRY, **PPSPY_PAGE_ENTRY;

#define SPY_PAGE_ENTRY_ sizeof (SPY_PAGE_ENTRY)

// -----------------------------------------------------------------

BOOL SpyMemoryPageEntry (PVOID           pVirtual,
                         PSPY_PAGE_ENTRY pspe)
    {
    SPY_PAGE_ENTRY spe;
    BOOL           fOk = FALSE;

    spe.pe       = X86_PDE_ARRAY [X86_PDI (pVirtual)];
    spe.dSize    = X86_PAGE_4M;
    spe.fPresent = FALSE;
```

(continued)

```
    if (spe.pe.pde4M.P)
        {
        if (spe.pe.pde4M.PS)
            {
            fOk = spe.fPresent = TRUE;
            }
        else
            {
            spe.pe    = X86_PTE_ARRAY [X86_PAGE (pVirtual)];
            spe.dSize = X86_PAGE_4K;

            if (spe.pe.pte4K.P)
                {
                fOk = spe.fPresent = TRUE;
                }
            else
                {
                fOk = (spe.pe.pnpe.PageFile != 0);
                }
            }
        }
    if (pspe != NULL) *pspe = spe;
    return fOk;
    }
```

LISTING 4-22. *Querying PDEs and PTEs*

Note that `SpyMemoryPageEntry()` does not identify swapped-out 4-MB pages. If a 4-MB PDE refers to an absent page, there is no indication whether the linear address is invalid or the page is currently kept in a pagefile. 4-MB pages are used in the kernel memory range `0x80000000` to `0x9FFFFFFF` only. I have never seen one of these pages swapped out, even in extreme low-memory situations, so I was not able to examine any associated page-not-present entries.

THE IOCTL FUNCTION SPY_IO_MEMORY_DATA

The `SPY_IO_MEMORY_DATA` function is certainly one of the most important ones, because it copies arbitrary amounts of memory data to a buffer supplied by the caller. As you might recall, user-mode applications are readily passed in invalid addresses. Therefore, this function is very cautious and verifies the validity of all source addresses before touching them. Remember, the Blue Screen is lurking everywhere in kernel-mode.

The calling application requests the contents of a memory block by passing in a `SPY_MEMORY_BLOCK` structure—shown at the top of Listing 4-23—that specifies its address and size. For convenience, the address is defined as a union, allowing interpretation as a byte array `(PBYTE pbAddress)` or an arbitrary pointer `(PVOID pAddress)`.

The `SpyInputMemory()` function in Listing 4-23 copies this structure from the IOCTL input buffer. The companion function `SpyOutputMemory()`, concluding Listing 4-23, is a wrapper around `SpyMemoryReadBlock()`, which is shown in Listing 4-24. The main duty of `SpyOutputMemory()` is to return the appropriate `NTSTATUS` values while `SpyMemoryReadBlock()` provides the data.

`SpyMemoryReadBlock()` returns the memory contents in a `SPY_MEMORY_DATA` structure, defined in Listing 4-25. I have chosen a different approach than in the previous definitions because `SPY_MEMORY_DATA` is a data type of variable size. Essentially, it consists of a `SPY_MEMORY_BLOCK` structure named `smb`, followed by an array of `WORD`s called `awData[]`. The length of the array is determined by the `dBytes` member of `smb`. To allow easy definition of `SPY_MEMORY_DATA` instances as global or local variables of a predetermined size, this structure's definition is based on the macro `SPY_MEMORY_DATA_N()`. The single argument of this macro specifies the size of the `awData[]` array. The actual structure definition follows the macro definition, providing `SPY_MEMORY_DATA` with a zero-length `awData[]` array. The `SPY_MEMORY_DATA__()` macro computes the overall size of a `SPY_MEMORY_DATA` structure given the size of its data array, and the remaining definitions allow packing and unpacking the data `WORD`s in the array. Obviously, the lower half of each `WORD` contains the memory data byte and the upper half specifies flags. Currently, only bit #8 has a meaning, indicating whether the data byte in bits #0 to #7 is valid.

```
typedef struct _SPY_MEMORY_BLOCK
    {
    union
        {
        PBYTE pbAddress;
        PVOID pAddress;
        };
    DWORD dBytes;
    }
    SPY_MEMORY_BLOCK, *PSPY_MEMORY_BLOCK, **PPSPY_MEMORY_BLOCK;

#define SPY_MEMORY_BLOCK_ sizeof (SPY_MEMORY_BLOCK)

// -----------------------------------------------------------------

NTSTATUS SpyInputMemory (PSPY_MEMORY_BLOCK psmb,
                         PVOID             pInput,
                         DWORD             dInput)
    {
    return SpyInputBinary (psmb, SPY_MEMORY_BLOCK_, pInput, dInput);
    }
```

(continued)

```
// ----------------------------------------------------------------

NTSTATUS SpyOutputMemory (PSPY_MEMORY_BLOCK psmb,
                          PVOID             pOutput,
                          DWORD             dOutput,
                          PDWORD            pdInfo)
    {
    NTSTATUS ns = STATUS_BUFFER_TOO_SMALL;

    if (*pdInfo = SpyMemoryReadBlock (psmb, pOutput, dOutput))
        {
        ns = STATUS_SUCCESS;
        }
    return ns;
    }
```

LISTING 4-23. *Handling Memory Blocks*

```
DWORD SpyMemoryReadBlock (PSPY_MEMORY_BLOCK psmb,
                          PSPY_MEMORY_DATA  psmd,
                          DWORD             dSize)
    {
    DWORD i;
    DWORD n = SPY_MEMORY_DATA__ (psmb->dBytes);

    if (dSize >= n)
        {
        psmd->smb = *psmb;

        for (i = 0; i < psmb->dBytes; i++)
            {
            psmd->awData [i] =
                (SpyMemoryTestAddress (psmb->pbAddress + i)
                 ? SPY_MEMORY_DATA_VALUE (psmb->pbAddress [i], TRUE)
                 : SPY_MEMORY_DATA_VALUE (0, FALSE));
            }
        }
    else
        {
        if (dSize >= SPY_MEMORY_DATA_)
            {
            psmd->smb.pbAddress = NULL;
            psmd->smb.dBytes    = 0;
            }
        n = 0;
        }
    return n;
    }
```

```
// ----------------------------------------------------------------

BOOL SpyMemoryTestAddress (PVOID pVirtual)
    {
    return SpyMemoryPageEntry (pVirtual, NULL);

// ----------------------------------------------------------------

BOOL SpyMemoryTestBlock (PVOID pVirtual,
                         DWORD dBytes)
    {
    PBYTE pbData;
    DWORD dData;
    BOOL  fOk = TRUE;

    if (dBytes)
        {
        pbData = (PBYTE) ((DWORD_PTR) pVirtual & X86_PAGE_MASK);
        dData  = (((dBytes + X86_OFFSET_4K (pVirtual) - 1)
                   / PAGE_SIZE) + 1) * PAGE_SIZE;
        do  {
            fOk = SpyMemoryTestAddress (pbData);
            pbData += PAGE_SIZE;
            dData  -= PAGE_SIZE;
            }
        while (fOk && dData);
        }
    return fOk;
    }
```

LISTING 4-24. *Copying Memory Block Contents*

The validity of a data byte is determined by the function `SpyMemoryTestAddress()`, which is called by `SpyMemoryReadBlock()` for the address of each byte before it is copied to the buffer. `SpyMemoryTestAddress()`, included in the lower half of Listing 4-24, simply calls `SpyMemoryPageEntry()` with the second argument set to `NULL`. The latter function has just been introduced in the course of the discussion of the IOCTL function `SPY_IO_PAGE_ENTRY` (Listing 4-22). Setting its `PSPY_PAGE_ENTRY` pointer argument to `NULL` means that the caller is not interested in the page entry of the supplied linear address, so all that remains is the function's return value, which is `TRUE` if the linear address is valid. In the context of `SpyMemoryPageEntry()`, an address is valid if the page it is contained in is either present in physical memory or resident in one of the system's pagefiles. Note that this behavior is not compatible with the `ntoskrnl.exe` API function `MmIsAddressValid()`, which will always return `FALSE` if the page is not present, even if it is a valid page currently kept in a pagefile. Also included in Listing 4-24 is the function

```
#define SPY_MEMORY_DATA_N(_n) \
        struct _SPY_MEMORY_DATA_##_n \
            { \
            SPY_MEMORY_BLOCK smb; \
            WORD             awData [_n]; \
            }

typedef SPY_MEMORY_DATA_N (0)
        SPY_MEMORY_DATA, *PSPY_MEMORY_DATA, **PPSPY_MEMORY_DATA;

#define SPY_MEMORY_DATA_ sizeof (SPY_MEMORY_DATA)
#define SPY_MEMORY_DATA__(_n) (SPY_MEMORY_DATA_ + ((_n) * WORD_))

#define SPY_MEMORY_DATA_BYTE  0x00FF
#define SPY_MEMORY_DATA_VALID 0x0100

#define SPY_MEMORY_DATA_VALUE(_b,_v) \
        ((WORD) (((_b) & SPY_MEMORY_DATA_BYTE     ) | \
                 ((_v) ? SPY_MEMORY_DATA_VALID : 0)))
```

LISTING 4-25. *Definition of* `SPY_MEMORY_DATA`

`SpyMemoryTestBlock()`, which is an enhanced version of `SpyMemoryTestAddress()`. It tests a memory range for validity by walking across the specified block in 4,096-byte steps, testing whether all pages it spans are accessible.

Accepting swapped-out pages as valid address ranges has the important advantage that the page will be pulled back into physical memory as soon as `SpyMemoryReadBlock()` tries to access one of its bytes. The sample memory dump utility presented later would not be quite useful if it relied on `MmIsAddressValid()`. It would sometimes refuse to display the contents of certain address ranges, even if it was able to display them 5 minutes before, because the underlying page recently would have been transferred to a pagefile.

THE IOCTL FUNCTION SPY_IO_MEMORY_BLOCK

The `SPY_IO_MEMORY_BLOCK` function is related to `SPY_IO_MEMORY_DATA` in that it also copies data blocks from arbitrary addresses to a caller-supplied buffer. The main difference is that `SPY_IO_MEMORY_DATA` attempts to copy all bytes that are accessible, whereas `SPY_IO_MEMORY_BLOCK` fails if the requested range comprises any invalid addresses. This function will be needed in Chapter 6 to deliver the contents of data structures living in kernel memory to a user-mode application. It is obvious that this function must be very restrictive. A structure that contains inaccessible bytes cannot be copied safely—the copy would be lacking parts of the data.

Like `SPY_IO_MEMORY_DATA`, the `SPY_IO_MEMORY_BLOCK` function expects input in the form of a `SPY_MEMORY_BLOCK` structure that specifies the base address and size of the memory range to be copied. The returned copy is a faithful 1:1 reproduction of the original data. The output buffer must be large enough to hold the entire copy. Otherwise, an error is reported, and no data is sent back.

THE IOCTL FUNCTION SPY_IO_HANDLE_INFO

Like the `SPY_IO_PHYSICAL` function introduced above, this function allows a user-mode application to call kernel-mode API functions that are otherwise unreachable. A kernel-mode driver can always get a pointer to an object represented by a handle by simply calling the `ntoskrnl.exe` function `ObReferenceObjectByHandle()`. There is no equivalent function in the Win32 API. However, the application can instruct the spy device to execute the function call on its behalf and to return the object pointer afterward. Listing 4-26 shows the `SpyOutputHandleInfo()` function called by the `SpyDispatcher()` after obtaining the input handle via `SpyInputHandle()`, defined in Listing 4-10.

The `SPY_HANDLE_INFO` structure at the beginning of Listing 4-26 receives the pointer to the body of the object associated with the handle and the handle attributes, both returned by `ObReferenceObjectByHandle()`. It is important to call `ObDereferenceObject()` if `ObReferenceObjectByHandle()` reports success to reset the object's pointer reference count to its previous value. Failing to do so constitutes an "object reference leak."

```
typedef struct _SPY_HANDLE_INFO
    {
    PVOID pObjectBody;
    DWORD dHandleAttributes;
    }
    SPY_HANDLE_INFO, *PSPY_HANDLE_INFO, **PPSPY_HANDLE_INFO;

#define SPY_HANDLE_INFO_ sizeof (SPY_HANDLE_INFO)

// -----------------------------------------------------------------

NTSTATUS SpyOutputHandleInfo (HANDLE hObject,
                              PVOID  pOutput,
                              DWORD  dOutput,
                              PDWORD pdInfo)
    {
    SPY_HANDLE_INFO           shi;
    OBJECT_HANDLE_INFORMATION ohi;
    NTSTATUS                  ns = STATUS_INVALID_PARAMETER;
```

(continued)

```
    if (hObject != NULL)
        {
        ns = ObReferenceObjectByHandle (hObject,
                                        STANDARD_RIGHTS_READ,
                                        NULL, KernelMode,
                                        &shi.pObjectBody, &ohi);
        }
    if (ns == STATUS_SUCCESS)
        {
        shi.dHandleAttributes = ohi.HandleAttributes;

        ns = SpyOutputBinary (&shi, SPY_HANDLE_INFO_,
                              pOutput, dOutput, pdInfo);

        ObDereferenceObject (shi.pObjectBody);
        }
    return ns;
    }
```

LISTING 4-26. *Referencing an Object by Its Handle*

A SAMPLE MEMORY DUMP UTILITY

Now that you have worked through the complex and possibly confusing IOCTL function handler code of the memory spy device driver, you probably want to see these functions in action. Therefore, I have created a sample console-mode utility named "SBS Windows 2000 Memory Spy" that loads the spy driver and calls various IOCTL functions, depending on the parameters passed in on the command line. This application resides in the executable file `w2k_mem.exe`, and its source code is included on the CD accompanying this book, in the directory `\src\w2k_mem`.

COMMAND LINE FORMAT

You can run the memory spy utility from the CD by invoking `d:\bin\w2k_mem.exe`, where `d:` should be replaced by the drive letter of your CD-ROM drive. If `w2k_mem.exe` is started without arguments, the lengthy command info screen shown in Example 4-1 is displayed. The basic command philosophy of `w2k_mem` is that a command consists of one or more data requests, each providing at least a linear base address where the memory dump should start. Optionally, the memory block size can be specified as well—otherwise, the default size 256 is used. The memory size must be prefixed by the "#" character. Several option switches may be added that modify the default behavior of the command. An option consists of a single-character option ID and a "+" or "–" prefix that determines whether the option is switched on or off. By default, all options are turned off.

```
// w2k_mem.exe
// SBS Windows 2000 Memory Spy V1.00
// 08-27-2000 Sven B. Schreiber
// sbs@orgon.com

Usage: w2k_mem { { [+option|-option] [/<path>] } [#[[0]x]<size>] [[0]x]<base> }

<path> specifies a module to be loaded into memory.
Use the +x/-x switch to enable/disable its startup code.
If <size> is missing, the default size is 256 bytes.

Display address options (mutually exclusive):
   +z -z   zero-based display         on / OFF
   +r -r   physical RAM addresses     on / OFF

Display mode options (mutually exclusive):

   +w -w   WORD  data formatting      on / OFF
   +d -d   DWORD data formatting      on / OFF
   +q -q   QWORD data formatting      on / OFF

Addressing options (mutually exclusive):

   +t -t   TEB-relative addressing    on / OFF
   +f -f   FS-relative  addressing    on / OFF
   +u -u   user-mode   FS:[<base>]    on / OFF
   +k -k   kernel-mode FS:[<base>]    on / OFF
   +h -h   handle/object resolution   on / OFF
   +a -a   add bias  to  last base    on / OFF
   +s -s   sub bias from last base    on / OFF
   +p -p   pointer  from last block   on / OFF

System status options (cumulative):

   +o -o   display OS  information    on / OFF
   +c -c   display CPU information    on / OFF
   +g -g   display GDT information    on / OFF
   +i -i   display IDT information    on / OFF
   +b -b   display contiguous blocks  on / OFF

Other options (cumulative):

   +x -x   execute DLL startup code   on / OFF

Example: The following command displays the first 64
bytes of the current Process Environment Block (PEB)
in zero-based DWORD format, assuming that a pointer to
the PEB is located at offset 0x30 inside the current
Thread Environment Block (TEB):

   w2k_mem +t #0 0 +pzd #64 0x30

Note: Specifying #0 after +t causes the TEB to be
addressed without displaying its contents.
```

EXAMPLE 4-1. *Help Screen of the Memory Spy Utility*

A data request is executed for each command line token that cannot be identified as an option, a data block size specification, a path, or any other command modifier. Each plain number on the command line is assumed to specify a linear address and triggers a hex dump, starting at this address. Numbers are interpreted as decimal by default or hexadecimal if prefixed by "0x" or simply "x."

Complex command line option models like the one employed by `w2k_mem.exe` are much easier to grasp if some simple examples are provided. Here is a short compilation:

- **`w2k_mem 0x80400000`** displays the first 256 bytes of memory at linear address `0x80400000`, yielding something that should look similar to Example 4-2. By the way, this is the DOS header of the `ntoskrnl.exe` module (note the "MZ" ID at the beginning).
- **`w2k_mem #0x40 0x80400000`** displays the same data block, but stops after 64 bytes, as demanded by the block size specification `#0x40`.
- **`w2k_mem +d #0x40 0x80400000`** is another variant, this time packing the bytes into 32-bit `DWORD` chunks because of the `+d` option. This option remains in effect until reset by `–d` or overridden by a competing option such as `+w` or `+q`.
- **`w2k_mem +wz #0x40 0x10000 +d –z 0x20000`** contains two data requests. First, the linear address range `0x10000` to `0x1003F` is shown in 16-bit `WORD` format, followed by the range `0x20000` to `0x2003F` in `DWORD` format (Example 4-3). The first request also includes the `+z` switch, which forces the numbers in the "Address" column to start at zero. In the second request, the zero-based display mode is turned off by adding a `–z` switch.
- **`w2k_mem +rd #4096 0xC0300000`** displays the system's page-directory at address `0xC0300000` in `DWORD` format. The `+r` option enables the display of physical RAM addresses in the "Address" column instead of linear ones.

By now, you should have a basic understanding of how the command line format works. In the following subsections, some of the more exotic options and features are discussed in more detail. Most of them alter the interpretation of the address parameter they precede. In default mode, the specified address is a linear base address where the memory dump starts. The options `+t`, `+f`, `+u`, `+k`, `+h`, `+a`, `+s`, and `+p` change this default interpretation in various ways.

```
E:\>w2k_mem 0x80400000

// w2k_mem.exe
// SBS Windows 2000 Memory Spy V1.00
// 08-27-2000 Sven B. Schreiber
// sbs@orgon.com

Loading “SBS Windows 2000 Spy Device” (w2k_spy) ...
Driver: “D:\Program Files\DevStudio\MyProjects\w2k_mem\Release\w2k_spy.sys”
Opening “\\.\w2k_spy” ...

SBS Windows 2000 Spy Device V1.00 ready

80400000..804000FF: 256 valid bytes

Address  | 00 01 02 03-04 05 06 07 : 08 09 0A 0B-0C 0D 0E 0F | 0123456789ABCDEF
---------|-------------------------:-------------------------|-----------------
80400000 | 4D 5A 90 00-03 00 00 00 : 04 00 00 00-FF FF 00 00 | MZ•.........ÿÿ..
80400010 | B8 00 00 00-00 00 00 00 : 40 00 00 00-00 00 00 00 | ¸.......@.......
80400020 | 00 00 00 00-00 00 00 00 : 00 00 00 00-00 00 00 00 | ................
80400030 | 00 00 00 00-00 00 00 00 : 00 00 00 00-C8 00 00 00 | ............È...
80400040 | 0E 1F BA 0E-00 B4 09 CD : 21 B8 01 4C-CD 21 54 68 | ..º..´.Í!¸.LÍ!Th
80400050 | 69 73 20 70-72 6F 67 72 : 61 6D 20 63-61 6E 6E 6F | is program canno
80400060 | 74 20 62 65-20 72 75 6E : 20 69 6E 20-44 4F 53 20 | t be run in DOS
80400070 | 6D 6F 64 65-2E 0D 0D 0A : 24 00 00 00-00 00 00 00 | mode....$.......
80400080 | 50 7A C4 CE-14 1B AA 9D : 14 1B AA 9D-14 1B AA 9D | PzÄÎ..ª•..ª•..ª•
80400090 | 14 1B AB 9D-53 1B AA 9D : 18 3B A4 9D-5B 1B AA 9D | ..«•S.ª•.;¤•[.ª•
804000A0 | 42 13 AC 9D-15 1B AA 9D : 14 1B AA 9D-1A 19 AA 9D | B.¬•..ª•..ª•..ª•
804000B0 | 4D 38 B9 9D-12 1B AA 9D : 52 69 63 68-14 1B AA 9D | M8¹•..ª•Rich..ª•
804000C0 | 00 00 00 00-00 00 00 00 : 50 45 00 00-4C 01 13 00 | ........PE..L...
804000D0 | 17 9B 4D 38-00 00 00 00 : 00 00 00 00-E0 00 0E 03 | .?M8........à...
804000E0 | 0B 01 05 0C-C0 2D 14 00 : 80 D6 04 00-00 00 00 00 | ....À-..?Ö......
804000F0 | 20 D1 00 00-C0 04 00 00 : 80 73 06 00-00 00 40 00 |  Ñ..À...?s....@.

       256 bytes requested
       256 bytes received

Closing the spy device ...
```

EXAMPLE 4-2. *A Sample Data Request*

```
E:\>w2k_mem +wz #0x40 0x10000 +d -z 0x20000

// w2k_mem.exe
// SBS Windows 2000 Memory Spy V1.00
// 08-27-2000 Sven B. Schreiber
// sbs@orgon.com

Loading “SBS Windows 2000 Spy Device” (w2k_spy) ...
```

(continued)

```
Driver: "D:\Program Files\DevStudio\MyProjects\w2k_mem\Release\ w2k_spy.sys"
Opening "\\.\w2k_spy" ...
SBS Windows 2000 Spy Device V1.00 ready

00010000..0001003F: 64 valid bytes

Address  | 0000 0002-0004 0006 : 0008 000A-000C 000E | 00 02 04 06 08 0A 0C 0E
---------|---------------------:---------------------|-----------------------
00000000 | 003D 0044-003A 003D : 0044 003A-005C 0050 | .= .D .: .= .D .: .\ .P
00000010 | 0072 006F-0067 0072 : 0061 006D-0020 0046 | .r .o .g .r .a .m .  .F
00000020 | 0069 006C-0065 0073 : 005C 0044-0065 0076 | .i .l .e .s .\ .D .e .v
00000030 | 0053 0074-0075 0064 : 0069 006F-005C 004D | .S .t .u .d .i .o .\ .M

00020000..0002003F: 64 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
00020000 | 00001000 - 00000880 : 00000001 - 00000000 | .... ...? .... ....
00020010 | 02B20001 - 00000000 : 00000003 - 00000007 | .².. .... .... ....
00020020 | 0000000B - 0208006C : 00020290 - 00000018 | .... ...l ...• ....
00020030 | 02A0029E - 00020498 : 00840082 - 00020738 | . .? ...? .?.? ...8

       128 bytes requested
       128 bytes received

Closing the spy device ...
```

EXAMPLE 4-3. *Displaying Data in Special Formats*

TEB-RELATIVE ADDRESSING

Each thread in a process has its own Thread Environment Block (`TEB`) where the system keeps frequently used thread-specific data. In user-mode, the `TEB` of the current thread is located in a separate 4-KB segment accessible via the processor's `FS` register. In kernel-mode, `FS` points to a different segment, as will be explained below. All `TEB`s of a process are stacked up in linear memory at linear address `0x7FFDE000`, expanding down in 4-KB steps as needed. That is, the `TEB` of the second thread is found at address `0x7FFDD000`, the `TEB` of the third thread at `0x7FFDC000`, and so on. The contents of the `TEB`s and the Process Environment Block (`PEB`) address `0x7FFDF000` will be discussed in more detail in Chapter 7 (see Listings 7-18 and 7-19). Here it should suffice to take note that `TEB`s exist and that they are addressed by the `FS` register.

If the `+t` switch precedes an address on the command line, `w2k_mem.exe` adds the base address of the `FS` segment to it, effectively applying a bias of `0x7FFDE000` bytes. Example 4-4 shows the output of the command **`w2k_mem +dt #0x38 0`** on my system. This time I have omitted the banner and status messages issued by `w2k_mem.exe`. The omissions are marked by [...].

```
E:\>w2k_mem +dt #0x38 0
[...]
7FFDE000..7FFDE037: 56 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
7FFDE000 | 0012FA58 - 00130000 : 0012E000 - 00000000 | ..úX .... ..à. ....
7FFDE010 | 00001E00 - 00000000 : 7FFDE000 - 00000000 | .... .... .ýà. ....
7FFDE020 | 000002C0 - 000002C8 : 00000000 - 00000000 | ...À ...È .... ....
7FFDE030 | 7FFDF000 - 00000000 :          -          | .ýô. ....
[...]
```

EXAMPLE 4-4. *Displaying the first Thread Environment Block* (TEB)

FS-RELATIVE ADDRESSING

I have already mentioned that the `FS` refers to different segments in user- and kernel-mode. Whereas the `+t` switch selects the user-mode `FS` address as the reference point, the `+f` switch uses the `FS` base address that is in effect in kernel-mode. Of course, a Win32 application has no way to get at this value, so once again the spy device is required. `w2k_mem.exe` calls the IOCTL function `SPY_IO_CPU_INFO`, introduced in the previous section, to read CPU status information that includes the kernel-mode values of all segment registers. From there, everything goes on just the same as with the `+t` switch.

The kernel-mode `FS` points to another thread-specific structure frequently accessed by the Windows 2000 kernel, named the Kernel's Processor Control Region (`KPCR`). This structure has already been mentioned in the course of the discussion of the IOCTL function `SPY_IO_OS_INFO` and will be revisited in Chapter 7 (see Listing 7-16). Again, suffice it to note for now that this structure exists at linear address `0xFFDFF000`, and that the `+f` switch gives easy access to it. In Example 4-5, I have issued the command **`w2k_mem +df #0x54 0`** to demonstrate that the `+f` switch in fact applies a bias of `0xFFDFF000` bytes to the specified memory address.

```
E:\>w2k_mem +df #0x54 0
[...]
FFDFF000..FFDFF053: 84 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
FFDFF000 | BECD9CF0 - BECD9DF0 : BECD6000 - 00000000 | ¾Í?Ô ¾Í•Õ ¾Í`. ....
FFDFF010 | 00000000 - 00000000 : 7FFDE000 - FFDFF000 | .... .... .ýà. ÿßÕ.
FFDFF020 | FFDFF120 - 00000000 : 00000000 - 00000000 | ÿßñ  .... .... ....
FFDFF030 | FFFF20C0 - 00000000 : 80036400 - 80036000 | ÿÿ À .... ?.d. ?.`.
FFDFF040 | 80244000 - 00010001 : 00000001 - 000000C9 | ?$@. .... .... ...É
FFDFF050 | 00000000 -          :          -          | ....
[...]
```

EXAMPLE 4-5. *Displaying the Kernel's Processor Control Region* (KPCR)

FS:[<BASE>] ADDRESSING

When examining Windows 2000 kernel code, you will frequently come across instructions such as `MOV EAX,` and `FS:[18h]`. These instructions retrieve member values of the `TEB`, `KPCR`, or other structures contained in the `FS` segment. Many of them are pointers to other internal structures. The command line switches `+u` and `+k` allow you to follow this indirection with ease. `+u` retrieves a pointer from the user-mode `FS` segment; `+k` does the same in kernel-mode. For example, the command **`w2k_mem +du #0x1E8 0x30`** (see Example 4-6) dumps 488 bytes of the memory block addressed by `FS:[30h]` in user-mode, which happens to be a pointer to the Process Environment Block `(PEB)` of `w2k_mem.exe`. The command **`w2k_mem +dk #0x1C 0x20`** (see Example 4-7) displays the first 28 bytes of memory pointed to by `FS:[20h]` in kernel-mode, which is a pointer to the Kernel's Processor Control Block `(KPRCB)`, briefly mentioned earlier in the discussion of the IOCTL function `SPY_IO_OS_INFO` and also discussed in Chapter 7 (see Listing 7-15). Don't worry if you don't know what a `PEB` or `KPRCB` is—you *will* know it after having read this book.

```
E:\>w2k_mem +du #0x1E8 0x30
[...]
7FFDF000..7FFDF1E7: 488 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
7FFDF000 | 00000000 - FFFFFFFF : 00400000 - 00131E90 | .... ÿÿÿÿ .@.. ...•
7FFDF010 | 00020000 - 00000000 : 00130000 - 77FCD170 | .... .... .... wüÑp
7FFDF020 | 77F8AA4C - 77F8AA7D : 00000001 - 77E33E58 | wøªL wøª} .... wã>X
7FFDF030 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF040 | 77FCD1A8 - 0000007F : 00000000 - 7F6F0000 | wüÑ¨ .... .... .o..
7FFDF050 | 7F6F0000 - 7F6F0688 : 7FFB0000 - 7FFC1000 | .o.. .o.? .û.. .ü..
7FFDF060 | 7FFD2000 - 00000001 : 00000000 - 00000000 | .ý . .... .... ....
7FFDF070 | 079B8000 - FFFFE86D : 00100000 - 00002000 | .??. ÿÿèm .... .. .
7FFDF080 | 00010000 - 00001000 : 00000003 - 00000010 | .... .... .... ....
7FFDF090 | 77FCE380 - 00410000 : 00000000 - 00000014 | wüã? .A.. .... ....
7FFDF0A0 | 77FCD348 - 00000005 : 00000000 - 00000893 | wüÓH .... .... ...?
7FFDF0B0 | 00000002 - 00000003 : 00000004 - 00000000 | .... .... .... ....
7FFDF0C0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF0D0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF0E0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF0F0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF100 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF110 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF120 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF130 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF140 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF150 | 77FCDCC0 - 00000000 : 00000000 - 00000000 | wüÜÀ .... .... ....
7FFDF160 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
```

```
7FFDF170 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF180 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF190 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF1A0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF1B0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF1C0 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
7FFDF1D0 | 00000000 - 00000000 : 00000000 - 00020000 | .... .... .... ....
7FFDF1E0 | 7F6F06C2 - 00000000 :          -          | .o.Â ....
[...]
```

EXAMPLE 4-6. *Displaying the Process Environment Block* (PEB)

```
E:\>w2k_mem +dk #0x1C 0x20
[...]
FFDFF120..FFDFF13B: 28 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
-----|-----------:-----------|----------
FFDFF120 | 00010001 - 86BBA820 : 00000000 - 8046BDF0 | .... ?»¨  .... ?F½ó
FFDFF130 | 00020000 - 00000001 : 05010106 -          | .... .... ....
[...]
```

EXAMPLE 4-7. *Displaying the Kernel's Processor Control Block* (KPRCB)

HANDLE/OBJECT RESOLUTION

Suppose you have an object `HANDLE` and want to see what the corresponding object looks like in memory. This is an almost trivial task if you use the `+h` switch, which simply calls the spy device's `SPY_IO_HANDLE_INFO` function (Listing 4-26) to look up the object body of the given handle. The world of Windows 2000 objects is an amazing topic that will be treated in depth in Chapter 7. So let's forget about it for now.

RELATIVE ADDRESSING

Sometimes it might be useful to display a series of memory blocks that are spaced out by the same number of bytes. This might be, for example, an array of structures, like the stack of `TEB`s in a multithreaded application. The `+a` and `+s` switches enable this kind of relative addressing by changing the interpretation of the specified address to an offset. The difference between these options is that `+a` ("add bias") yields a positive offset, whereas `+s` ("subtract bias") yields a negative one. Example 4-8 shows the output of the command **`w2k_mem +d #32 0xC0000000 +a 4096 4096`** on my system. It samples the first 32 bytes of three consecutive 4-KB pages, starting at address `0xC0000000`, where the system's page-tables are located. Note the `+a` switch near the end of the command. It causes the following "4096" tokens to be interpreted as offsets

```
E:\>w2k_mem +d #32 0xC0000000 +a 4096 4096
[...]
C0000000..C000001F: 32 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
C0000000 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....
C0000010 | 00000000 - 00000000 : 00000000 - 00000000 | .... .... .... ....

C0001000..C000101F: 32 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
C0001000 | 037D1025 - 03324025 : 0329D025 - 04DDE025 | .}.% .2@% .)Ð% .Ýà%
C0001010 | 06F17067 - 03297225 : 05115067 - 00000000 | .ñpg .)r% ..Pg ....

C0002000..C000201F: 0 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|-------------------
C0002000 |          -          :          -          |
C0002010 |          -          :          -          |

        96 bytes requested
        64 bytes received
[...]
```

EXAMPLE 4-8. *Sampling Page-Tables*

to be added to the previous base address. The +a and +s switches remain in effect until switched off explicitly by specifying –a or -s or overridden by any of the other switches that change the interpretation of the address parameter.

Example 4-8 also shows what happens if an invalid linear address is passed in. Obviously, the first pair of page-tables referring to the 4-MB address ranges 0x00000000 to 0x003F0000 and 0x00400000 to 0x007F0000 were valid, and the third one was not. w2k_mem.exe reflects this fact by displaying an empty hex dump table. The program knows which address ranges are valid because the spy device's SPY_IO_MEMORY_DATA function puts this information into the resulting SPY_MEMORY_DATA structure (cf. Listing 4-25).

INDIRECT ADDRESSING

One of my favorite command options is +p, because it saved a lot of typing while I was preparing this book. This option works similar to +u and +k, but doesn't use the FS segment as reference, but rather uses the previously displayed data block. This is a great feature if you want to chase down a linked list of objects, for example. Instead of displaying the first list member, reading out the address of the next member, typing a new command with this address, and so on, simply append `+p` to the command and a series of offsets that specify where the link to the next object is located in the previous hex dump panel.

In Example 4-9, I have used this option to walk down the list of active processes. First, I have asked the Kernel Debugger to give me the address of the internal variable `PsActiveProcessHead`, which is a `LIST_ENTRY` structure marking the beginning of the process list. A `LIST_ENTRY` consists of a `Flink` (forward link) member at offset 0 and a `Blink` (backward link) member at offset 4 (cf. Listing 2-7). The command **`w2k_mem #8 +d 0x8046a180 +p 0 0 0 0`** first dumps the `LIST_ENTRY` of `PsActiveProcessHead`, and then it switches to indirect addressing on behalf of the `+p` switch. The four zeros tell `w2k_mem.exe` to extract the value at offset zero of the previous data block, which is, of course, the `Flink` member of each `LIST_ENTRY`. Note that the `Blink` members in Example 4-9, located at offset 4, do in fact point back to the previous `LIST_ENTRY`, as expected.

If enough zero-valued parameters would be appended to the command, the hex dump would eventually return to `PsActiveProcessHead`, which marks the beginning *and* the end of the process list. As explained in Chapter 2, the doubly-linked lists maintained by Windows 2000 are usually circular; that is, the `Flink` of the last list member points to the first one, and the `Blink` of the first list member points to the last one.

```
E:\>w2k_mem #8 +d 0x8046a180 +p 0 0 0 0
[...]
8046A180..8046A187: 8 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
8046A180 | 8149D900 - 840D2BE0 :          -          | •IÙ.  ?.+à

8149D900..8149D907: 8 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
8149D900 | 8131A4A0 - 8046A180 :          -          |  •1¤  ?F¡?

8131A4A0..8131A4A7: 8 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
8131A4A0 | 812FFDE0 - 8149D900 :          -          | •/ýà •IÙ.

812FFDE0..812FFDE7: 8 valid bytes
```

(continued)

```
Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
812FFDE0 | 812FA460 - 8131A4A0 :          -          | •/¤ ` •1¤

812FA460..812FA467: 8 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
812FA460 | 812E30C0 - 812FFDE0 :          -          | •.0À •/ýà
[...]
```

EXAMPLE 4-9. *Walking Down the Active-Process List*

LOADING MODULES ON THE FLY

Sometimes you might want to dump the memory image of a module, but the module is not mapped into the linear address space of the `w2k_mem.exe` process. This problem can be solved by loading the module explicitly using the `/<path>` and `+x` command options. Every command token prefixed by a slash character is interpreted as a module path, and `w2k_mem.exe` attempts to load this module from this path using the Win32 API function `LoadLibraryEx()`. By default, the load option `DONT_RESOLVE_DLL_REFERENCES` is used, causing the module to be loaded without initializing it. For a DLL, this means that its `DllMain()` entry point is not called. Also, none of the dependent modules specified in the import section is loaded. However, if you specify the `+x` switch before the path, the module is loaded and fully initialized. Note that some modules might refuse initialization in the context of the `w2k_mem.exe` process. For example, kernel-mode device drivers should not be loaded with this option turned on.

Loading and displaying a module is typically a two-step operation, as shown in Example 4-10. First you should load the module without displaying any data, to find out the base address assigned to it by the system. Fortunately, load addresses are deterministic as long as no other modules are added to the process in the meantime, so the next attempt to load the module will yield the same base address. In Example 4-10, I have loaded the kernel-mode device driver `nwrdr.sys,` which is the Microsoft's NetWare redirector. I'm not using IPX/SPX on my machine, so this driver is not yet loaded. Obviously, `LoadLibraryEx()` succeeds, and the hex dumps of the reported load address `0x007A0000` preceding and following this API call prove that this memory region is initially unused but contains a DOS header afterward.

```
E:\>w2k_mem /e:\winnt\system32\drivers\nwrdr.sys
[...]
You didn't request any data!
```

```
LoadLibrary (e:\winnt\system32\drivers\nwrdr.sys) = 0x007A0000
[...]
E:\>w2k_mem 0x007A0000 /e:\winnt\system32\drivers\nwrdr.sys 0x007A0000
[...]
007A0000..007A00FF: 0 valid bytes

Address  | 00 01 02 03-04 05 06 07 : 08 09 0A 0B-0C 0D 0E 0F | 0123456789ABCDEF
---------|-------------------------:-------------------------|-----------------
007A0000 |            -            :            -            |
007A0010 |            -            :            -            |
007A0020 |            -            :            -            |
007A0030 |            -            :            -            |
007A0040 |            -            :            -            |
007A0050 |            -            :            -            |
007A0060 |            -            :            -            |
007A0070 |            -            :            -            |
007A0080 |            -            :            -            |
007A0090 |            -            :            -            |
007A00A0 |            -            :            -            |
007A00B0 |            -            :            -            |
007A00C0 |            -            :            -            |
007A00D0 |            -            :            -            |
007A00E0 |            -            :            -            |
007A00F0 |            -            :            -            |

LoadLibrary (e:\winnt\system32\drivers\nwrdr.sys) = 0x007A0000

007A0000..007A00FF: 256 valid bytes

Address  | 00 01 02 03-04 05 06 07 : 08 09 0A 0B-0C 0D 0E 0F | 0123456789ABCDEF
---------|-------------------------:-------------------------|-----------------
007A0000 | 4D 5A 90 00-03 00 00 00 : 04 00 00 00-FF FF 00 00 | MZ•.........ÿÿ..
007A0010 | B8 00 00 00-00 00 00 00 : 40 00 00 00-00 00 00 00 | ¸.......@.......
007A0020 | 00 00 00 00-00 00 00 00 : 00 00 00 00-00 00 00 00 | ................
007A0030 | 00 00 00 00-00 00 00 00 : 00 00 00 00-D0 00 00 00 | ............Ð...
007A0040 | 0E 1F BA 0E-00 B4 09 CD : 21 B8 01 4C-CD 21 54 68 | ..º..´.Í!¸.LÍ!Th
007A0050 | 69 73 20 70-72 6F 67 72 : 61 6D 20 63-61 6E 6E 6F | is program canno
007A0060 | 74 20 62 65-20 72 75 6E : 20 69 6E 20-44 4F 53 20 | t be run in DOS
007A0070 | 6D 6F 64 65-2E 0D 0D 0A : 24 00 00 00-00 00 00 00 | mode....$.......
007A0080 | 61 14 4B C1-25 75 25 92 : 25 75 25 92-25 75 25 92 | a.KÁ%u%?%u%?%u%?
007A0090 | 29 55 2B 92-27 75 25 92 : 7C 56 36 92-22 75 25 92 | )U+?’u%?|V6?”u%?
007A00A0 | 25 75 24 92-BF 75 25 92 : 0F 7D 23 92-24 75 25 92 | %u$?¿u%?.}#?$u%?
007A00B0 | 25 75 25 92-14 75 25 92 : 52 69 63 68-25 75 25 92 | %u%?.u%?Rich%u%?
007A00C0 | 00 00 00 00-00 00 00 00 : 00 00 00 00-00 00 00 00 | ................
007A00D0 | 50 45 00 00-4C 01 09 00 : 66 EC 08 38-00 00 00 00 | PE..L...fì.8....
007A00E0 | 00 00 00 00-E0 00 0E 03 : 0B 01 05 0C-00 2D 02 00 | ....à........-..
007A00F0 | 40 3A 00 00-00 00 00 00 : 3E 14 01 00-40 03 00 00 | @:......>...@...
[...]
```

EXAMPLE 4-10. *Loading and Displaying a Module Image*

Oddly, you can even load the `.exe` file of another application into memory using the `/<path>` option. However, this module probably will be loaded to an unusual address, because its preferred load address is usually occupied by `w2k_mem.exe`. Moreover, you cannot get the loaded application to run—the `+x` switch applies to DLLs only and has no effect on other module types.

Demand-Paging in Action

In the discussion of the spy device function `SPY_IO_MEMORY_DATA`, I mentioned that this function is able to read the contents of memory pages that are flushed out to a pagefile. Now is the time to prove this claim. First, it is necessary to maneuver the system into a severe low-memory situation, forcing it to swap to the pagefiles anything that isn't urgently needed. My favorite method goes as follows:

1. Copy the Windows 2000 desktop to the clipboard by pressing the `Print` key.
2. Paste this bitmap into a graphics application.
3. Inflate the bitmap to an enormous size.

Now watch out what the command **`w2k_mem +d #16 0xC0280000 0xA0000000 0xA0001000 0xA0002000 0xC0280000`** yields on the screen. You might wonder what this command is supposed to do. Well, it simply takes a snapshot of some PTEs before and after touching the pages they refer to. The four PTEs found at address `0xC0280000` are associated with the linear address range `0xA0000000` to `0xA0003FFF`, which is part of the image of the kernel module `win32k.sys`. As Example 4-11 shows, this address range has been swapped out because of the bitmap operation I had performed just before. How do I know? Because the four `DWORD`s at address `0xC0280000` are even numbers, meaning that their least significant bit—the `P` bit of a PTE—is zero, indicating a nonpresent page. The next three hex dump panels belong to the command parameters `0xA0000000`, `0xA0001000`, and `0xA0002000`, requesting data from three of the four pages currently under examination. As it turns out, `w2k_mem.exe` has no problems accessing these pages—the system simply swaps them in on demand. However, the final test is still to come: What do the four PTEs look like afterward? The answer is given by the last panel of Example 4-11: The first three PTEs have the `P` bit set, and the fourth still indicates "not present."

```
E:\>w2k_mem +d #16 0xC0280000 0xA0000000 0xA0001000 0xA0002000 0xC0280000
[...]
C0280000..C028000F: 16 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
C0280000 | 056A14E0 - 056A14E2 : 056A14E4 - 056A14E6 | .j.à .j.â .j.ä .j.æ

A0000000..A000000F: 16 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
A0000000 | 00905A4D - 00000003 : 00000004 - 0000FFFF | .•ZM .... .... ..ÿÿ

A0001000..A000100F: 16 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
A0001000 | 000000A6 - FF0C75FF : 1738B415 - F8458BA0 | ...¦ ÿ.uÿ .8´. øE?

A0002000..A000200F: 16 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
A0002000 | 89A018E0 - F685D875 : 468D1A74 - 458D5020 | ? .à ö?Øu F•.t E•P

C0280000..C028000F: 16 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
C0280000 | 0556B123 - 028C2121 : 05AD1121 - 056A14E6 | .V±# .?!! .-.! .j.æ
[...]
```

EXAMPLE 4-11. *Watching PTEs Change Their States*

Before stepping to the next section, please study the first hex dump panel of Example 4-11 once more. The four PTEs at address `0xC0280000` all look quite similar. In fact, they differ only in the three least-significant bits. If you examine more of these PNPES that refer to pages in the pagefiles, you find that they all have bit #10 set. That's why I assigned the name `PageFile` to this bit in Listing 4-3. If it is set, the remaining bits—except for the `P` flag, of course—apparently specify the location of this page in the pagefiles.

More Command Options

Some of the most interesting command options listed in Example 4-1 have not yet been explained. For example the "System status options" `+o`, `+c`, `+g`, `+i`, and `+b` are missing, although they sound promising. I will return to them in the last section of this chapter, where several secrets of the Windows 2000 memory system will be revealed.

INTERFACING TO THE SPY DEVICE

Now that you know how `w2k_mem.exe` is used, it's time to see how it works. Rather than discuss command line parsing and dispatching, let's see how this application communicates with the spy device inside `w2k_spy.sys`.

Device I/O Control Revisited

The kernel-mode side of IOCTL communication has already been shown in Listings 4-6 and 4-7. The spy device simply sits waiting for I/O Request Packets (IRPs) and handles some of them, especially those tagged `IRP_MJ_DEVICE_CONTROL`, which request some forbidden actions to be executed, at least forbidden in the context of the user-mode application that sends these requests. It does so by calling the Win32 API function `DeviceIoControl()`, prototyped in Listing 4-27. The `dwIoControlCode`, `lpInBuffer`, `nInBufferSize`, `lpOutBuffer`, `nOutBufferSize`, and `lpBytesReturned` arguments should look familiar to you. In fact, they correspond 1:1 to the `dCode`, `pInput`, `dInput`, `pOutput`, `dOutput`, and `pdInfo` arguments of the `SpyDispatcher()` function in Listing 4-7. The remaining arguments are explained quickly. `hDevice` is the handle to the spy device, and `lpOverlapped` optionally points to an `OVERLAPPED` structure required for asynchronous IOCTL. We are not going to send asynchronous requests, so this argument will always be `NULL`.

Listing 4-28 is a collection of wrapper functions that perform basic IOCTL operations. The most basic function is `IoControl()`, which calls `DeviceIoControl()` and tests the reported output data size. Because `w2k_mem.exe` sizes its output buffers accurately, the number of output bytes should always be equal to the buffer size. `ReadBinary()` is a simplified version of `IoControl()` for IOCTL functions that don't require input data. `ReadCpuInfo()`, `ReadSegment()`, and `ReadPhysical()` are specifically tailored to the spy functions `SPY_IO_CPU_INFO`, `SPY_IO_SEGMENT`, and `SPY_IO_PHYSICAL`, because these are the most frequently used IOCTL functions. Encapsulating them in C functions makes the code much more readable.

```
BOOL WINAPI DeviceIoControl (HANDLE      hDevice,
                             DWORD       dwIoControlCode,
                             PVOID       lpInBuffer,
                             DWORD       nInBufferSize,
                             PVOID       lpOutBuffer,
                             DWORD       nOutBufferSize,
                             PDWORD      lpBytesReturned,
                             POVERLAPPED lpOverlapped);
```

LISTING 4-27. *Prototype of* `DeviceIoControl()`

```
BOOL WINAPI IoControl (HANDLE hDevice,
                       DWORD  dCode,
                       PVOID  pInput,
                       DWORD  dInput,
                       PVOID  pOutput,
                       DWORD  dOutput)
    {
    DWORD dData = 0;

    return DeviceIoControl (hDevice, dCode,
                            pInput,  dInput,
                            pOutput, dOutput,
                            &dData,  NULL)
           &&
           (dData == dOutput);
    }

// -----------------------------------------------------------------

BOOL WINAPI ReadBinary (HANDLE hDevice,
                        DWORD  dCode,
                        PVOID  pOutput,
                        DWORD  dOutput)
    {
    return IoControl (hDevice, dCode, NULL, 0, pOutput, dOutput);
    }

// -----------------------------------------------------------------

BOOL WINAPI ReadCpuInfo (HANDLE        hDevice,
                         PSPY_CPU_INFO psci)
    {
    return IoControl (hDevice, SPY_IO_CPU_INFO,
                      NULL,    0,
                      psci,    SPY_CPU_INFO_);
    }
```

(continued)

```
// -----------------------------------------------------------------

BOOL WINAPI ReadSegment (HANDLE       hDevice,
                         DWORD        dSelector,
                         PSPY_SEGMENT pss)
    {
    return IoControl (hDevice,    SPY_IO_SEGMENT,
                      &dSelector, DWORD_,
                      pss,        SPY_SEGMENT_);
    }
// -----------------------------------------------------------------

BOOL WINAPI ReadPhysical (HANDLE            hDevice,
                          PVOID             pLinear,
                          PPHYSICAL_ADDRESS ppa)
    {
    return IoControl (hDevice,  SPY_IO_PHYSICAL,
                      &pLinear, PVOID_,
                      ppa,      PHYSICAL_ADDRESS_)
           &&
           (ppa->LowPart || ppa->HighPart);
    }
```

LISTING 4-28. *Various IOCTL Wrappers*

All functions shown so far in this section require a spy device handle. It's time that I show how to obtain it. It is actually a quite simple Win32 operation, similar to opening a file. Listing 4-29 shows the implementation of the command handler inside `w2k_mem.exe`. This code uses the API functions `w2kFilePath(), w2kServiceLoad()`, and `w2kServiceUnload()`, exported by the "SBS Windows 2000 Utility Library" `w2k_lib.dll`, included on the companion CD of this book. If you have read the section about the Windows 2000 Service Control Manager in Chapter 3, you already know `w2kServiceLoad()` and `w2kServiceUnload()` from Listing 3-8. These powerful functions load and unload kernel-mode device drivers on the fly and handle benign error situations, such as gracefully loading a driver that is already loaded. `w2kFilePath()` is a helpful utility function that derives a file path from a base path, given a file name or file extension. `w2k_mem.exe` calls it to obtain a fully qualified path to the spy driver executable that matches its own path.

```
WORD awSpyFile      [] = SW(DRV_FILENAME);
WORD awSpyDevice    [] = SW(DRV_MODULE);
WORD awSpyDisplay   [] = SW(DRV_NAME);
WORD awSpyPath      [] = SW(DRV_PATH);
```

```
// -----------------------------------------------------------------

void WINAPI Execute (PPWORD ppwArguments,
                     DWORD  dArguments)
    {
    SPY_VERSION_INFO svi;
    DWORD            dOptions, dRequest, dReceive;
    WORD             awPath [MAX_PATH] = L"?";
    SC_HANDLE        hControl          = NULL;
    HANDLE           hDevice           = NULL;
    _printf (L"\r\nLoading \"%s\" (%s) ...\r\n",
             awSpyDisplay, awSpyDevice);

    if (w2kFilePath (NULL, awSpyFile, awPath, MAX_PATH))
        {
        _printf (L"Driver: \"%s\"\r\n",
                 awPath);

        hControl = w2kServiceLoad (awSpyDevice, awSpyDisplay,
                                   awPath, TRUE);
        }
    if (hControl != NULL)
        {
        _printf (L"Opening \"%s\" ...\r\n",
                 awSpyPath);

        hDevice = CreateFile (awSpyPath, GENERIC_READ,
                              FILE_SHARE_READ | FILE_SHARE_WRITE,
                              NULL, OPEN_EXISTING,
                              FILE_ATTRIBUTE_NORMAL, NULL);
        }
    if (hDevice != INVALID_HANDLE_VALUE)
        {
        if (ReadBinary (hDevice, SPY_IO_VERSION_INFO,
                        &svi, SPY_VERSION_INFO_))
            {
            _printf (L"\r\n%s V%lu.%02lu ready\r\n",
                     svi.awName,
                     svi.dVersion / 100, svi.dVersion % 100);
            }
        dOptions = COMMAND_OPTION_NONE;
        dRequest = CommandParse (hDevice, ppwArguments, dArguments,
                                 TRUE, &dOptions);

        dOptions = COMMAND_OPTION_NONE;
        dReceive = CommandParse (hDevice, ppwArguments, dArguments,
                                 FALSE, &dOptions);
        if (dRequest)
            {
            _printf (awSummary,
                     dRequest, (dRequest == 1 ? awByte : awBytes),
```

(continued)

```
                    dReceive, (dReceive == 1 ? awByte : awBytes));
                }
            _printf (L"\r\nClosing the spy device ...\r\n");
            CloseHandle (hDevice);
            }
        else
            {
            _printf (L"Spy device not available.\r\n");
            }
        if ((hControl != NULL) && gfSpyUnload)
            {
            _printf (L"Unloading the spy device ...\r\n");
            w2kServiceUnload (hControl, awSpyDevice);
            }
        return;
        }
```

LISTING 4-29. *Controlling the Spy Device*

Please note the four global string definitions at the top of Listing 4-29. The constants `DRV_FILENAME`, `DRV_MODULE`, `DRV_NAME`, and `DRV_PATH` are drawn from the header file of the spy device driver, `w2k_spy.h`. Table 4-4 lists their current values. You will not find device-specific definitions in the source files of `w2k_mem.exe`. `w2k_spy.h` provides everything a client application needs. This is very important: If any device-specific definitions change in the future, there is no need to update any application files. Just rebuild the application with the updated spy header file, and everything will fall into place.

The `w2kFilePath()` call near the beginning of Listing 4-29 guarantees that the `w2k_spy.sys` file specified by the global string `awSpyFile` (cf. Table 4-4) is always loaded from the directory where `w2k_mem.exe` resides. Next, the code in Listing 4-29 passes the global strings `awSpyDevice` and `awSpyDisplay` (cf. Table 4-4) to `w2kServiceLoad()`, attempting to load and start the spy device driver. If the driver was not loaded yet, these strings will be stored in the driver's property list and can be retrieved by other applications; otherwise, the current property settings are retained. Although the `w2kServiceLoad()` call in Listing 4-29 returns a handle, this is *not* a handle that can be used in any IOCTL calls. To get a handle to the spy device, the Win32 multipurpose function `CreateFile()` must be used. This function opens or creates almost anything that can be opened or created on Windows 2000. You certainly have called this function a million times to get a file handle. `CreateFile()` can also open kernel-mode devices if the symbolic link name of the device is supplied in the format `\\.\<SymbolicLink>` for the `lpFileName` argument. The symbolic link of the spy device is named `w2k_spy`, so the first `CreateFile()` argument must be `\\.\w2k_spy`, which is the value of the global string variable `awSpyPath` according to Table 4-4.

TABLE 4-4. *Device-Specific String Definitions*

w2k_spy CONSTANT	`w2k_mem` VARIABLE	VALUE
DRV_FILENAME	awSpyFile	w2k_spy.sys
DRV_MODULE	awSpyDevice	w2k_spy
DRV_NAME	awSpyDisplay	SBS Windows 2000 Spy Device
DRV_PATH	awSpyPath	\\.\w2k_spy

If `CreateFile()` succeeds, it returns a device handle that can be passed to `DeviceIoControl()`. The `Execute()` function in Listing 4-29 uses this handle immediately to query the version information of the spy device, which it displays on the screen if the IOCTL call succeeds. Next, the `CommandParse()` function is invoked twice with a different `BOOL` value for the fourth argument. The first call simply checks the command line for invalid parameters and displays any errors, and the second call actually executes all commands. I do not want to discuss in detail the command parser. The remaining code in Listing 4-29 is cleanup code that closes handles and optionally unloads the spy drives. The source code of `w2k_mem.exe` contains other interesting code snippets, but I will not discuss them here. Please see the files `w2k_mem.c` and `w2k_mem.h` in the `\src\w2k_mem` directory on the sample CD for further details.

The only notable thing left is the `gfSpyUnload` flag tested before unloading the spy driver. I have set this global flag to `FALSE`, so the driver will not be unloaded automatically. This enhances the performance of `w2k_mem.exe` and other `w2k_spy.sys` clients because loading a driver takes some time. The first client has to take the loading overhead, but all successors will benefit from having the driver already in memory. This setting also avoids conflict situations involving competitive clients, in which one client attempts to unload the driver while another one is still using it. Of course, Windows 2000 will not unload the driver unless all handles to its devices are closed, but it will put it into a `STOP_PENDING` state that will not allow new clients to access the device. However, if you don't run `w2k_spy.sys` in a multiclient environment, and you are updating the device driver frequently, you should probably set the `gfSpyUnload` flag to `TRUE`.

WINDOWS 2000 MEMORY INTERNALS

Along with the global separation of the 4-GB address space into user-mode and kernel-mode portions, these two halves are subdivided into various smaller blocks. As you might have guessed, most of them contain undocumented structures that serve undocumented purposes. It would be easy to forget about them if they were uninteresting. However, that's not the case—some of them are a real gold mine for anyone developing system diagnosis or debugging software.

Basic Operating System Information

Now the time has come to introduce one of the postponed command line options of the memory spy application `w2k_mem.exe`. If you take a look at the lower half of the program's help screen in Example 4-1, you will see a section titled "System Status Options." Let's try the option `+o`, named "display OS information." Example 4-12 shows a sample run on my machine. The data displayed here are the contents of the `SPY_OS_INFO` structure, defined in Listing 4-13 and set up by the spy device function `SpyOutputOsInfo()`, also included in Listing 4-13. In Example 4-12, you can already see some characteristic addresses within the 4-GB linear memory space of a process. For example, the valid user address range is reported to be `0x00010000` to `0x7FFEFFFF`. You have probably read in other programming books about Windows NT or Windows 2000 that the first and last 64 KB of the user-mode half of linear memory are "no-access regions" that are there to catch wild pointers produced by common programming errors (cf. Solomon 1998, Chapter 5). The output of `w2k_mem.exe` proves that this is correct.

```
E:\>w2k_mem +o
[...]
OS information:
———————-

Memory page size          : 4096 bytes
Memory page shift         : 12 bits
Memory PTI  shift         : 12 bits
Memory PDI  shift         : 22 bits
Memory page mask          : 0xFFFFF000
Memory PTI  mask          : 0x003FF000
Memory PDI  mask          : 0xFFC00000
Memory PTE  array         : 0xC0000000
Memory PDE  array         : 0xC0300000

Lowest user address       : 0x00010000
Thread environment block : 0x7FFDE000
Highest user address      : 0x7FFEFFFF
User probe address        : 0x7FFF0000
System range start        : 0x80000000
Lowest system address     : 0xC0800000
Shared user data          : 0xFFDF0000
Processor control region : 0xFFDFF000
Processor control block  : 0xFFDFF120
```

```
Global flag              : 0x00000000
i386 machine type        : 0
Number of processors     : 1
Product type             : Windows NT Workstation (1)
Version & Build number   : 5.00.2195
System root              : "E:\WINNT"
[...]
```

EXAMPLE 4-12. *Displaying Operating System Information*

The last three lines of Example 4-12 contain interesting information about the system, mostly extracted from the `SharedUserData` area at address `0xFFDF0000`. The data structure maintained there by the system is called `KUSER_SHARED_DATA` and is defined in the DDK header file `ntddk.h`.

WINDOWS 2000 SEGMENTS AND DESCRIPTORS

Another fine option of `w2k_mem.exe` is `+c`, which displays and interprets the contents of the processor's segment registers and descriptor tables. Example 4-13 shows the typical output. The contents of the `CS`, `DS`, and `ES` segment registers clearly demonstrate that Windows 2000 provides each process with a flat 4-GB address space: These basic segments start at offset `0x00000000` and have a limit of `0xFFFFFFFF`.

The flag characters in the rightmost column indicate the segment type as defined by its descriptor's Type member. The type attributes of code and data segments are symbolized by combinations of the characters "cra" and "ewa," respectively. A dash means that the corresponding attribute is not set. A Task State Segment (TSS) can have the attributes "a" (available) and "b" (busy) only. All applicable attributes are summarized in Table 4-5. Example 4-13 shows that the Windows 2000 `CS` segments are nonconforming and allow execute/read access, whereas the `DS`, `ES`, `FS`, and `SS` segments are of expand-up type and allow read/write access. Another inconspicuous but important detail is the different DPL of the `CS`, `FS`, and `SS` segments in user- and kernel-mode. DPL is the Descriptor Privilege Level. For nonconforming code segments, the DPL specifies the privilege level a caller must be on in order to be able to call into this segment (cf. Intel 1999c, pp. 4-8f). In user-mode, the required level is three; in kernel-mode, it is zero. For data segments, the DPL is the lowest privilege level required to be able to access the segment. This means that the `FS` and `SS` segments are accessible from all privilege levels in user-mode, whereas only level-0 accesses are allowed in kernel-mode.

```
E:\>w2k_mem +c
[...]
CPU information:
————————

User mode segments:

CS  : Selector = 001B, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = CODE -ra
DS  : Selector = 0023, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
ES  : Selector = 0023, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
FS  : Selector = 0038, Base = 7FFDE000, Limit = 00000FFF, DPL3, Type = DATA -wa
SS  : Selector = 0023, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
TSS : Selector = 0028, Base = 80244000, Limit = 000020AB, DPL0, Type = TSS32 b

Kernel mode segments:

CS  : Selector = 0008, Base = 00000000, Limit = FFFFFFFF, DPL0, Type = CODE -ra
DS  : Selector = 0023, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
ES  : Selector = 0023, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
FS  : Selector = 0030, Base = FFDFF000, Limit = 00001FFF, DPL0, Type = DATA -wa
SS  : Selector = 0010, Base = 00000000, Limit = FFFFFFFF, DPL0, Type = DATA -wa
TSS : Selector = 0028, Base = 80244000, Limit = 000020AB, DPL0, Type = TSS32 b

IDT : Limit    = 07FF, Base = 80036400
GDT : Limit    = 03FF, Base = 80036000
LDT : Selector = 0000

CR0 : Contents = 8001003B
CR2 : Contents = 00401050
CR3 : Contents = 06F70000
[...]
```

EXAMPLE 4-13. *Displaying CPU Information*

The contents of the IDT and GDT registers show that the GDT spans from linear address `0x80036000` to `800363FF`, immediately followed by the IDT, occupying the address range `0x80036400` to `0x80036BFF`. With each descriptor taking 64 bits, the GDT and IDT contain 128 and 256 entries, respectively. Note that the GDT could comprise as many as 8,192 entries, but Windows 2000 uses only a small fraction of them.

The `w2k_mem.exe` utility features two more options—`+g` and `+i`—that display more details about the GDT and IDT. Example 4-14 demonstrates the output of the `+g` option. It is similar to the "kernel-mode segments:" section of Example 4-13, but lists all segment selectors available in kernel-mode, not just those that are stored in segment registers. `w2k_mem.exe` compiles this list by looping through the entire GDT,

TABLE 4-5. *Code and Data Segment Type Attributes*

SEGMENT	ATTRIBUTE	DESCRIPTION
CODE	c	Conforming segment (may be entered by less privileged code)
CODE	r	Read-access allowed (as opposed to execute-only access)
CODE	a	Segment has been accessed
DATA	e	Expand-down segment (typical attribute for stack segments)
DATA	w	Write-access allowed (as opposed to read-only access)
DATA	a	Segment has been accessed
TSS32	a	Task State Segment is available
TSS32	b	Task State Segment is busy

querying the spy device for segment information by means of the IOCTL function `SPY_IO_SEGMENT`. Only valid selectors are displayed. It is interesting to compare Examples 4-13 and 4-14 with the GDT selector definitions in `ntddk.h`, summarized in Table 4-6. Obviously, they are in accordance with the details reported by `w2k_mem.exe`.

```
E:\>w2k_mem +g
[...]
GDT information:
————————

001 : Selector = 0008, Base = 00000000, Limit = FFFFFFFF, DPL0, Type = CODE -ra
002 : Selector = 0010, Base = 00000000, Limit = FFFFFFFF, DPL0, Type = DATA -wa
003 : Selector = 0018, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = CODE -ra
004 : Selector = 0020, Base = 00000000, Limit = FFFFFFFF, DPL3, Type = DATA -wa
005 : Selector = 0028, Base = 80244000, Limit = 000020AB, DPL0, Type = TSS32 b
006 : Selector = 0030, Base = FFDFF000, Limit = 00001FFF, DPL0, Type = DATA -wa
007 : Selector = 0038, Base = 7FFDE000, Limit = 00000FFF, DPL3, Type = DATA -wa
008 : Selector = 0040, Base = 00000400, Limit = 0000FFFF, DPL3, Type = DATA -wa
009 : Selector = 0048, Base = E2E6A000, Limit = 00000177, DPL0, Type = LDT
00A : Selector = 0050, Base = 80470040, Limit = 00000068, DPL0, Type = TSS32 a
00B : Selector = 0058, Base = 804700A8, Limit = 00000068, DPL0, Type = TSS32 a
00C : Selector = 0060, Base = 00022AB0, Limit = 0000FFFF, DPL0, Type = DATA -wa
00D : Selector = 0068, Base = 000B8000, Limit = 00003FFF, DPL0, Type = DATA -w-
00E : Selector = 0070, Base = FFFF7000, Limit = 000003FF, DPL0, Type = DATA -w-
00F : Selector = 0078, Base = 80400000, Limit = 0000FFFF, DPL0, Type = CODE -r-
010 : Selector = 0080, Base = 80400000, Limit = 0000FFFF, DPL0, Type = DATA -w-
011 : Selector = 0088, Base = 00000000, Limit = 00000000, DPL0, Type = DATA -w-
```

(continued)

```
014 : Selector = 00A0, Base = 814985A8, Limit = 00000068, DPL0, Type = TSS32 a
01C : Selector = 00E0, Base = F0430000, Limit = 0000FFFF, DPL0, Type = CODE cra
01D : Selector = 00E8, Base = 00000000, Limit = 0000FFFF, DPL0, Type = DATA -w-
01E : Selector = 00F0, Base = 8042DCE8, Limit = 000003B7, DPL0, Type = CODE --
01F : Selector = 00F8, Base = 00000000, Limit = 0000FFFF, DPL0, Type = DATA -w-
020 : Selector = 0100, Base = F0440000, Limit = 0000FFFF, DPL0, Type = DATA -wa
021 : Selector = 0108, Base = F0440000, Limit = 0000FFFF, DPL0, Type = DATA -wa
022 : Selector = 0110, Base = F0440000, Limit = 0000FFFF, DPL0, Type = DATA -wa
[...]
```

Example 4-14. *Displaying GDT Descriptors*

Table 4-6. *GDT Selectors Defined in* ntddk.h

SYMBOL	VALUE	COMMENTS
KGDT_NULL	0x0000	Null segment selector (invalid)
KGDT_R0_CODE	0x0008	*CS* register in kernel-mode
KGDT_R0_DATA	0x0010	*SS* register in kernel-mode
KGDT_R3_CODE	0x0018	*CS* register in user-mode
KGDT_R3_DATA	0x0020	*DS, ES,* and *SS* register in user-mode, *DS* and *ES* register in kernel-mode
KGDT_TSS	0x0028	Task State Segment in user- and kernel-mode
KGDT_R0_PCR	0x0030	*FS* register in kernel-mode (Processor Control Region)
KGDT_R3_TEB	0x0038	*FS* register in user-mode (Thread Environment Block)
KGDT_VDM_TILE	0x0040	Base 0x00000400, limit 0x0000FFFF (Virtual DOS Machine)
KGDT_LDT	0x0048	Local Descriptor Table
KGDT_DF_TSS	0x0050	*ntoskrnl.exe* variable *KiDoubleFaultTSS*
KGDT_NMI_TSS	0x0058	*ntoskrnl.exe* variable *KiNMITSS*

The selectors in Example 4-14 that are not listed in Table 4-6 can in part be identified by looking for familiar base addresses or memory contents, and by using the Kernel Debugger to look up the symbols for some of the base addresses. Table 4-7 comprises the selectors that I have identified so far.

The `+i` option of `w2k_mem.exe` dumps the gate descriptors stored in the IDT. Example 4-15 is an excerpt from this rather long list, comprising only the first 20 entries that have a predefined meaning assigned by Intel (Intel 1999c, pp. 5-6). Interrupts `0x14` to `0x1F` are reserved for Intel; the remaining range `0x20` to `0xFF` is available to the operating system.

In Table 4-8, I have summarized all interrupts that refer to identifiable and non-trivial interrupt, trap, and task gates. Most of the user defined interrupts point to dummy handlers named `KiUnexpectedInterruptNNN()`, as explained earlier in this chapter. Some interrupt handlers are located at addresses that can't be resolved to symbols by the Kernel Debugger.

TABLE 4-7. *More GDT Selectors*

VALUE	BASE	DESCRIPTION
0x0078	0x80400000	*ntoskrnl.exe* code segment
0x0080	0x80400000	*ntoskrnl.exe* data segment
0x00A0	0x814985A8	TSS (EIP member points to *HalpMcaExceptionHandlerWrapper*)
0x00E0	0xF0430000	ROM BIOS code segment
0x00F0	0x8042DCE8	*ntoskrnl.exe* function *KiI386CallAbios*
0x0100	0xF0440000	ROM BIOS data segment
0x0108	0xF0440000	ROM BIOS data segment
0x0110	0xF0440000	ROM BIOS data segment

```
E:\>w2k_mem +i
[...]
IDT information:
________

00 : Pointer = 0008:804625E6, Base = 00000000, Limit = FFFFFFFF, Type = INT32
01 : Pointer = 0008:80462736, Base = 00000000, Limit = FFFFFFFF, Type = INT32
02 : TSS     = 0058,          Base = 804700A8, Limit = 00000068, Type = TASK
03 : Pointer = 0008:80462A0E, Base = 00000000, Limit = FFFFFFFF, Type = INT32
04 : Pointer = 0008:80462B72, Base = 00000000, Limit = FFFFFFFF, Type = INT32
05 : Pointer = 0008:80462CB6, Base = 00000000, Limit = FFFFFFFF, Type = INT32
06 : Pointer = 0008:80462E1A, Base = 00000000, Limit = FFFFFFFF, Type = INT32
07 : Pointer = 0008:80463350, Base = 00000000, Limit = FFFFFFFF, Type = INT32
08 : TSS     = 0050,          Base = 80470040, Limit = 00000068, Type = TASK
09 : Pointer = 0008:8046370C, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0A : Pointer = 0008:80463814, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0B : Pointer = 0008:80463940, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0C : Pointer = 0008:80463C44, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0D : Pointer = 0008:80463E50, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0E : Pointer = 0008:804648A4, Base = 00000000, Limit = FFFFFFFF, Type = INT32
0F : Pointer = 0008:80464C3F, Base = 00000000, Limit = FFFFFFFF, Type = INT32
10 : Pointer = 0008:80464D47, Base = 00000000, Limit = FFFFFFFF, Type = INT32
11 : Pointer = 0008:80464E6B, Base = 00000000, Limit = FFFFFFFF, Type = INT32
12 : TSS     = 00A0,          Base = 814985A8, Limit = 00000068, Type = TASK
13 : Pointer = 0008:80464C3F, Base = 00000000, Limit = FFFFFFFF, Type = INT32
[...]
```

EXAMPLE 4-15. *Displaying IDT Gate Descriptors*

TABLE 4-8. *Windows 2000 Interrupt, Trap, and Task Gates*

INT	INTEL DESCRIPTION	OWNER	HANDLER/TSS
0x00	Divide Error (DE)	ntoskrnl.exe	KiTrap00
0x01	Debug (DB)	ntoskrnl.exe	KiTrap01
0x02	NMI Interrupt	ntoskrnl.exe	KiNMITSS
0x03	Breakpoint (BP)	ntoskrnl.exe	KiTrap03
0x04	Overflow (OF)	ntoskrnl.exe	KiTrap04
0x05	BOUND Range Exceeded (BR)	ntoskrnl.exe	KiTrap05
0x06	Undefined Opcode (UD)	ntoskrnl.exe	KiTrap06
0x07	No Math Coprocessor (NM)	ntoskrnl.exe	KiTrap07
0x08	Double Fault (DF)	ntoskrnl.exe	KiDouble
0x09	Coprocessor Segment Overrun	ntoskrnl.exe	KiTrap09
0x0A	Invalid TSS (TS)	ntoskrnl.exe	KiTrap0A
0x0B	Segment Not Present (NP)	ntoskrnl.exe	KiTrap0B
0x0C	Stack-Segment Fault (SS)	ntoskrnl.exe	KiTrap0C
0x0D	General Protection (GP)	ntoskrnl.exe	KiTrap0D
0x0E	Page Fault (PF)	ntoskrnl.exe	KiTrap0E
0x0F	(Intel reserved)	ntoskrnl.exe	KiTrap0F
0x10	Math Fault (MF)	ntoskrnl.exe	KiTrap10
0x11	Alignment Check (AC)	ntoskrnl.exe	KiTrap11
0x12	Machine Check (MC)	?	?
0x13	Streaming SIMD Extensions	ntoskrnl.exe	KiTrap0F
0x14-0x1F	(Intel reserved)	ntoskrnl.exe	KiTrap0F
0x2A	User Defined	ntoskrnl.exe	KiGetTickCount
0x2B	User Defined	ntoskrnl.exe	KiCallbackReturn
0x2C	User Defined	ntoskrnl.exe	KiSetLowWaitHighThread
0x2D	User Defined	ntoskrnl.exe	KiDebugService
0x2E	User Defined	ntoskrnl.exe	KiSystemService
0x2F	User Defined	ntoskrnl.exe	KiTrap0F
0x30	User Defined	hal.dll	HalpClockInterrupt
0x38	User Defined	hal.dll	HalpProfileInterrupt

WINDOWS 2000 MEMORY AREAS

The last `w2k_mem.exe` option that remains to be discussed is the `+b` switch. It generates an enormously long list of contiguous memory regions within the 4-GB linear address space. `w2k_mem.exe` builds this list by walking through the entire PTE array at address `0xC0000000`, using the spy device's IOCTL function `SPY_IO_PAGE_ENTRY`.

The `dSize` member contained in each resulting `SPY_PAGE_ENTRY` structure is added to the linear address associated with the PTE to get the linear address of the next PTE to be retrieved. Listing 4-30 shows the implementation of this option.

```
DWORD WINAPI DisplayMemoryBlocks (HANDLE hDevice)
    {
    SPY_PAGE_ENTRY spe;
    PBYTE          pbPage, pbBase;
    DWORD          dBlock, dPresent, dTotal;
    DWORD          n = 0;

    pbPage   = 0;
    pbBase   = INVALID_ADDRESS;
    dBlock   = 0;
    dPresent = 0;
    dTotal   = 0;

    n += _printf (L"\r\nContiguous memory blocks:"
                  L"\r\n-------------\r\n\r\n");

    do  {
        if (!IoControl (hDevice, SPY_IO_PAGE_ENTRY,
                        &pbPage, PVOID_,
                        &spe,    SPY_PAGE_ENTRY_))
            {
            n += _printf (L" !!! Device I/O error !!!\r\n");
            break;
            }
        if (spe.fPresent)
            {
            dPresent += spe.dSize;
            }
        if (spe.pe.dValue)
            {
            dTotal += spe.dSize;

            if (pbBase == INVALID_ADDRESS)
                {
                n += _printf (L"%5lu : 0x%08lX ->",
                              ++dBlock, pbPage);

                pbBase = pbPage;
                }
            }
        else
            {
            if (pbBase != INVALID_ADDRESS)
                {
                n += _printf (L" 0x%08lX (0x%08lX bytes)\r\n",
                              pbPage-1, pbPage-pbBase);
```

(continued)

```
                pbBase = INVALID_ADDRESS;
                }
            }
        }
    while (pbPage += spe.Size);

    if (pbBase != INVALID_ADDRESS)
        {
        n += _printf (L"0x%08lX\r\n", pbPage-1);
        }
    n += _printf (L"\r\n"
                  L" Present bytes: 0x%08lX\r\n"
                  L" Total   bytes: 0x%08lX\r\n",
                  dPresent, dTotal);
    return n;
    }
```

LISTING 4-30. *Finding Contiguous Linear Memory Blocks*

Example 4-16 is an excerpt from a sample run on my machine, showing some of the more interesting regions. Some very obvious addresses are `0x00400000`, where the image of `w2k_mem.exe` starts (block #13), and `0x10000000`, where the image of `w2k_lib.dll` is located (block #23). The TEB and PEB pages also are clearly discernible (block #104), as are the `hal.dll`, `ntoskrnl.exe`, and `win32k.sys` areas (blocks #105 and 106). Blocks #340 to 350 are, of course, the valid fragments of the system's PTE array, featuring the page-directory as part of block #347. Block #2122 contains the `SharedUserData` area, and #2123 comprises the `KPCR`, `KPRCB`, and `CONTEXT` structures containing thread and processor status information.

```
E:\>w2k_mem +b
[...]
Contiguous memory blocks:
-------------------------

    1 : 0x00010000 -> 0x00010FFF (0x00001000 bytes)
    2 : 0x00020000 -> 0x00020FFF (0x00001000 bytes)
    3 : 0x0012D000 -> 0x00138FFF (0x0000C000 bytes)
    4 : 0x00230000 -> 0x00230FFF (0x00001000 bytes)
    5 : 0x00240000 -> 0x00241FFF (0x00002000 bytes)
    6 : 0x00247000 -> 0x00247FFF (0x00001000 bytes)
    7 : 0x0024F000 -> 0x00250FFF (0x00002000 bytes)
```

```
     8 : 0x00260000 -> 0x00260FFF (0x00001000 bytes)
     9 : 0x00290000 -> 0x00290FFF (0x00001000 bytes)
    10 : 0x002E0000 -> 0x002E0FFF (0x00001000 bytes)
    11 : 0x002E2000 -> 0x002E3FFF (0x00002000 bytes)
    12 : 0x003B0000 -> 0x003B1FFF (0x00002000 bytes)
    13 : 0x00400000 -> 0x00404FFF (0x00005000 bytes)
    14 : 0x00406000 -> 0x00406FFF (0x00001000 bytes)
    15 : 0x00410000 -> 0x00410FFF (0x00001000 bytes)
    16 : 0x00419000 -> 0x00419FFF (0x00001000 bytes)
    17 : 0x0041B000 -> 0x0041BFFF (0x00001000 bytes)
    18 : 0x00450000 -> 0x00450FFF (0x00001000 bytes)
    19 : 0x00760000 -> 0x00760FFF (0x00001000 bytes)
    20 : 0x00770000 -> 0x00770FFF (0x00001000 bytes)
    21 : 0x00780000 -> 0x00783FFF (0x00004000 bytes)
    22 : 0x00790000 -> 0x00791FFF (0x00002000 bytes)
    23 : 0x10000000 -> 0x10003FFF (0x00004000 bytes)
    24 : 0x10005000 -> 0x10005FFF (0x00001000 bytes)
    25 : 0x1000E000 -> 0x10016FFF (0x00009000 bytes)
    26 : 0x759B0000 -> 0x759B1FFF (0x00002000 bytes)
[...]
   103 : 0x7FFD2000 -> 0x7FFD3FFF (0x00002000 bytes)
   104 : 0x7FFDE000 -> 0x7FFE0FFF (0x00003000 bytes)
   105 : 0x80000000 -> 0xA01A5FFF (0x201A6000 bytes)
   106 : 0xA01B0000 -> 0xA01F2FFF (0x00043000 bytes)
   107 : 0xA0200000 -> 0xA02C7FFF (0x000C8000 bytes)
   108 : 0xA02F0000 -> 0xA03FFFFF (0x00110000 bytes)
   109 : 0xA4000000 -> 0xA4001FFF (0x00002000 bytes)
   110 : 0xBE63B000 -> 0xBE63CFFF (0x00002000 bytes)
[...]
   340 : 0xC0000000 -> 0xC0001FFF (0x00002000 bytes)
   341 : 0xC0040000 -> 0xC0040FFF (0x00001000 bytes)
   342 : 0xC01D6000 -> 0xC01D6FFF (0x00001000 bytes)
   343 : 0xC01DA000 -> 0xC01DAFFF (0x00001000 bytes)
   344 : 0xC01DD000 -> 0xC01E0FFF (0x00004000 bytes)
   345 : 0xC01FD000 -> 0xC01FDFFF (0x00001000 bytes)
   346 : 0xC01FF000 -> 0xC0280FFF (0x00082000 bytes)
   347 : 0xC0290000 -> 0xC0301FFF (0x00072000 bytes)
   348 : 0xC0303000 -> 0xC0386FFF (0x00084000 bytes)
   349 : 0xC0389000 -> 0xC038CFFF (0x00004000 bytes)
   350 : 0xC039E000 -> 0xC03FFFFF (0x00062000 bytes)
[...]
  2121 : 0xFFC00000 -> 0xFFD0FFFF (0x00110000 bytes)
  2122 : 0xFFDF0000 -> 0xFFDF0FFF (0x00001000 bytes)
  2123 : 0xFFDFF000 -> 0xFFDFFFFF (0x00001000 bytes)
[...]
 Present bytes: 0x22AA9000
 Total   bytes: 0x2B8BA000
[...]
```

EXAMPLE 4-16. *A Sample List of Contiguous Memory Blocks*

The odd thing about the +b option of w2k_mem.exe is that it reports an amount of used memory that is far beyond any reasonable value. Note the summary lines at the end of Example 4-16. Am I really using 700 MB of memory now? The Windows 2000 Task Manager indicates 150 MB—so what's going on here? This strange effect comes from memory block #105, which is reported to range from 0x80000000 to 0xA01A5FFF, spanning 0x201A6000 bytes, which equals *538,599,424* bytes. This is obviously nonsense. The problem is that the entire linear address range from 0x80000000 to 0x9FFFFFFF is mapped to the physical address range 0x00000000 to 0x1FFFFFFF, as already noted earlier in this chapter. All 4-MB pages in this range have valid PDEs in the page-directory at address 0xC0300000, which can be proved by issuing the command **w2k_mem +d #0x200 0xC0300800** (Example 4-17). Because all PDEs in the resulting list are odd numbers, the corresponding pages must be present; however, they are not necessarily backed up by physical memory. In fact, large portions of this memory range are really "holes" and seem to be filled with 0xFF bytes if copied to a buffer. Therefore, you shouldn't take the memory usage summary displayed by w2k_mem.exe too seriously.

```
E:\>w2k_mem +d #0x200 0xC0300800
[...]
C0300800..C03009FF: 512 valid bytes

Address  | 00000000 - 00000004 : 00000008 - 0000000C | 0000 0004 0008 000C
---------|---------------------:---------------------|--------------------
C0300800 | 000001E3 - 004001E3 : 008001E3 - 00C001E3 | ...ã .@.ã .?.ã .À.ã
C0300810 | 010001E3 - 014001E3 : 018001E3 - 01C001E3 | ...ã .@.ã .?.ã .À.ã
C0300820 | 020001E3 - 024001E3 : 028001E3 - 02C001E3 | ...ã .@.ã .?.ã .À.ã
C0300830 | 030001E3 - 034001E3 : 038001E3 - 03C001E3 | ...ã .@.ã .?.ã .À.ã
C0300840 | 040001E3 - 044001E3 : 048001E3 - 04C001E3 | ...ã .@.ã .?.ã .À.ã
C0300850 | 050001E3 - 054001E3 : 058001E3 - 05C001E3 | ...ã .@.ã .?.ã .À.ã
C0300860 | 060001E3 - 064001E3 : 068001E3 - 06C001E3 | ...ã .@.ã .?.ã .À.ã
C0300870 | 070001E3 - 074001E3 : 078001E3 - 07C001E3 | ...ã .@.ã .?.ã .À.ã
C0300880 | 080001E3 - 084001E3 : 088001E3 - 08C001E3 | ...ã .@.ã .?.ã .À.ã
C0300890 | 090001E3 - 094001E3 : 098001E3 - 09C001E3 | ...ã .@.ã .?.ã .À.ã
C03008A0 | 0A0001E3 - 0A4001E3 : 0A8001E3 - 0AC001E3 | ...ã .@.ã .?.ã .À.ã
C03008B0 | 0B0001E3 - 0B4001E3 : 0B8001E3 - 0BC001E3 | ...ã .@.ã .?.ã .À.ã
C03008C0 | 0C0001E3 - 0C4001E3 : 0C8001E3 - 0CC001E3 | ...ã .@.ã .?.ã .À.ã
C03008D0 | 0D0001E3 - 0D4001E3 : 0D8001E3 - 0DC001E3 | ...ã .@.ã .?.ã .À.ã
C03008E0 | 0E0001E3 - 0E4001E3 : 0E8001E3 - 0EC001E3 | ...ã .@.ã .?.ã .À.ã
C03008F0 | 0F0001E3 - 0F4001E3 : 0F8001E3 - 0FC001E3 | ...ã .@.ã .?.ã .À.ã
C0300900 | 100001E3 - 104001E3 : 108001E3 - 10C001E3 | ...ã .@.ã .?.ã .À.ã
```

```
C0300910 | 110001E3 - 114001E3 : 118001E3 - 11C001E3 | ...ã .@.ã .?.ã .À.ã
C0300920 | 120001E3 - 124001E3 : 128001E3 - 12C001E3 | ...ã .@.ã .?.ã .À.ã
C0300930 | 130001E3 - 134001E3 : 138001E3 - 13C001E3 | ...ã .@.ã .?.ã .À.ã
C0300940 | 140001E3 - 144001E3 : 148001E3 - 14C001E3 | ...ã .@.ã .?.ã .À.ã
C0300950 | 150001E3 - 154001E3 : 158001E3 - 15C001E3 | ...ã .@.ã .?.ã .À.ã
C0300960 | 160001E3 - 164001E3 : 168001E3 - 16C001E3 | ...ã .@.ã .?.ã .À.ã
C0300970 | 170001E3 - 174001E3 : 178001E3 - 17C001E3 | ...ã .@.ã .?.ã .À.ã
C0300980 | 180001E3 - 184001E3 : 188001E3 - 18C001E3 | ...ã .@.ã .?.ã .À.ã
C0300990 | 190001E3 - 194001E3 : 198001E3 - 19C001E3 | ...ã .@.ã .?.ã .À.ã
C03009A0 | 1A0001E3 - 1A4001E3 : 1A8001E3 - 1AC001E3 | ...ã .@.ã .?.ã .À.ã
C03009B0 | 1B0001E3 - 1B4001E3 : 1B8001E3 - 1BC001E3 | ...ã .@.ã .?.ã .À.ã
C03009C0 | 1C0001E3 - 1C4001E3 : 1C8001E3 - 1CC001E3 | ...ã .@.ã .?.ã .À.ã
C03009D0 | 1D0001E3 - 1D4001E3 : 1D8001E3 - 1DC001E3 | ...ã .@.ã .?.ã .À.ã
C03009E0 | 1E0001E3 - 1E4001E3 : 1E8001E3 - 1EC001E3 | ...ã .@.ã .?.ã .À.ã
C03009F0 | 1F0001E3 - 1F4001E3 : 1F8001E3 - 1FC001E3 | ...ã .@.ã .?.ã .À.ã
[...]
```

EXAMPLE 4-17. *The PDEs of the Address Range* `0x80000000` *to* `0x9FFFFFFF`

THE WINDOWS 2000 MEMORY MAP

The last part of this chapter is dedicated to the general layout of the 4-GB linear address space as it is "seen" by a Windows 2000 process. Table 4-9 lists the address ranges of various essential data structures. The big holes between them are used for several purposes, such as load areas for process modules and device drivers, memory pools, working set lists, and the like. Note that some addresses and block sizes might vary considerably from system to system, depending on the memory and hardware configuration, the process properties, and several other variables. Therefore, use this list only as a rough sketch, not as an accurate roadmap.

Some physical memory blocks appear twice or more in the linear address space. For example, the `SharedUserData` area at linear address `0xFFDF0000` is mirrored at address `0x7FFE0000`. Both refer to the same page in physical memory—writing a byte to `0xFFDF0000+n` mysteriously changes the value of the byte at `0x7FFE0000+n`. This is the world of virtual memory—a physical address can be mapped anywhere into the linear address space, even to several addresses at the same time. It's just a matter of setting up the page-directory and page-tables appropriately. Please recall Figures 4-3 and 4-4, which clearly show that linear addresses are fake. Their `Directory` and `Table` bit fields are just pointers to structures that determine the real location of the data. And if the PFNs of two PTEs happen to be identical, the corresponding linear addresses refer to the same physical memory location.

TABLE 4-9. *Identifiable Memory Regions in the Address Space of a Process*

START	END	HEX SIZE	TYPE/DESCRIPTION
0x00000000	0x0000FFFF	10000	Lower guard block
0x00010000	0x0001FFFF	10000	WCHAR[]/Environment strings, allocated in 4-KB pages
0x00020000	0x0002FFFF	10000	PROCESS_PARAMETERS/allocated in 4-KB pages
0x00030000	0x0012FFFF	100000	DWORD [4000]/Process stack (default: 1 MB)
0x7FFDD000	0x7FFDDFFF	1000	TEB/Thread Environment Block of thread #2
0x7FFDE000	0x7FFDEFFF	1000	TEB/Thread Environment Block of thread #1
0x7FFDF000	0x7FFDFFFF	1000	PEB/Process Environment Block
0x7FFE0000	0x7FFE02D7	2D8	KUSER_SHARED_DATA/SharedUserData in user-mode
0x7FFF0000	0x7FFFFFFF	10000	Upper guard block
0x80000000	0x800003FF	400	IVT/Interrupt Vector Table
0x80036000	0x800363FF	400	KGDTENTRY[80]/Global Descriptor Table
0x80036400	0x80036BFF	800	KIDTENTRY[100]/Interrupt Descriptor Table
0x800C0000	0x800FFFFF	40000	VGA/ROM BIOS
0x80244000	0x802460AA	20AB	KTSS/user/kernel Task State Segment (busy)
0x8046AB80	0x8046ABBF	40	KeServiceDescriptorTable
0x8046ABC0	0x8046ABFF	40	KeServiceDescriptorTableShadow
0x80470040	0x804700A7	68	KTSS/KiDoubleFaultTSS
0x804700A8	0x8047010F	68	KTSS/KiNMITSS
0x804704D8	0x804708B7	3E0	PROC[F8]/KiServiceTable
0x804708B8	0x804708BB	4	DWORD/KiServiceLimit
0x804708BC	0x804709B3	F8	BYTE[F8]/KiArgumentTable
0x814C6000	0x82CC5FFF	1800000	PFN[100000]/MmPfnDatabase (max. for 4 GB)
0xA01859F0	0xA01863EB	9FC	PROC[27F]/W32pServiceTable
0xA0186670	0xA01868EE	27F	BYTE[27F]/W32pArgumentTable
0xC0000000	0xC03FFFFF	400000	X86_PE[100000]/page-directory and page-tables
0xC1000000	0xE0FFFFFF	20000000	System Cache (MmSystemCacheStart, MmSystemCacheEnd)
0xE1000000	0xE77FFFFF	6800000	Paged Pool (MmPagedPoolStart, MmPagedPoolEnd)
0xF0430000	0xF043FFFF	10000	ROM BIOS code segment
0xF0440000	0xF044FFFF	10000	ROM BIOS data segment

TABLE 4-9. *(continued)*

START	END	HEX SIZE	TYPE/DESCRIPTION
0xFFDF0000	0xFFDF02D7	2D8	KUSER_SHARED_DATA/SharedUserData in kernel-mode
0xFFDFF000	0xFFDFF053	54	KPCR/Processor Control Region (kernel-mode FS segment)
0xFFDFF120	0xFFDFF13B	1C	KPRCB/Processor Control Block
0xFFDFF13C	0xFFDFF407	2CC	CONTEXT/Thread Context (CPU state)
0xFFDFF620	0xFFDFF71F	100	Lookaside list directories