MODERN OPERATING SYSTEMS

Third Edition

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Chapter 5
Input/Output

I/O Devices

Device	Data rate
Keyboard	10 bytes/sec
Mouse	100 bytes/sec
56K modem	7 KB/sec
Scanner	400 KB/sec
Digital camcorder	3.5 MB/sec
802.11g Wireless	6.75 MB/sec
52x CD-ROM	7.8 MB/sec
Fast Ethernet	12.5 MB/sec
Compact flash card	40 MB/sec
FireWire (IEEE 1394)	50 MB/sec
USB 2.0	60 MB/sec
SONET OC-12 network	78 MB/sec
SCSI Ultra 2 disk	80 MB/sec
Gigabit Ethernet	125 MB/sec
SATA disk drive	300 MB/sec
Ultrium tape	320 MB/sec
PCI bus	528 MB/sec

Figure 5-1. Some typical device, network, and bus data rates.

Memory-Mapped I/O (1)

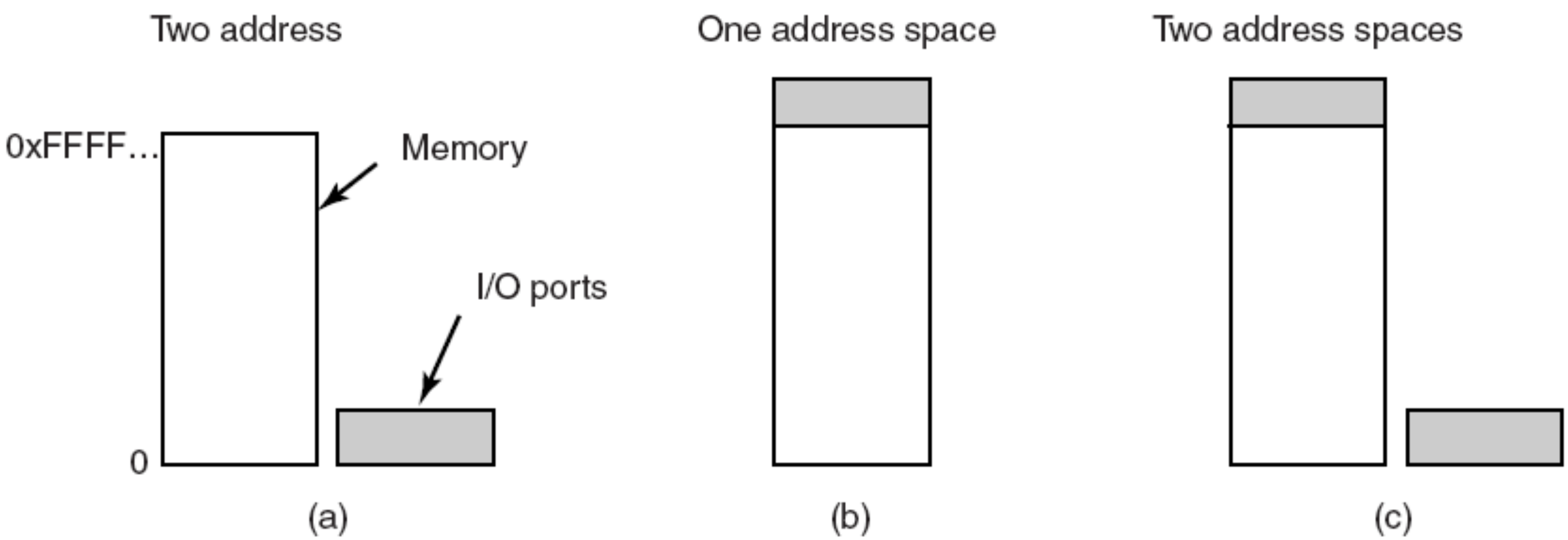


Figure 5-2. (a) Separate I/O and memory space. (b) Memory-mapped I/O. (c) Hybrid.

Memory-Mapped I/O (2)

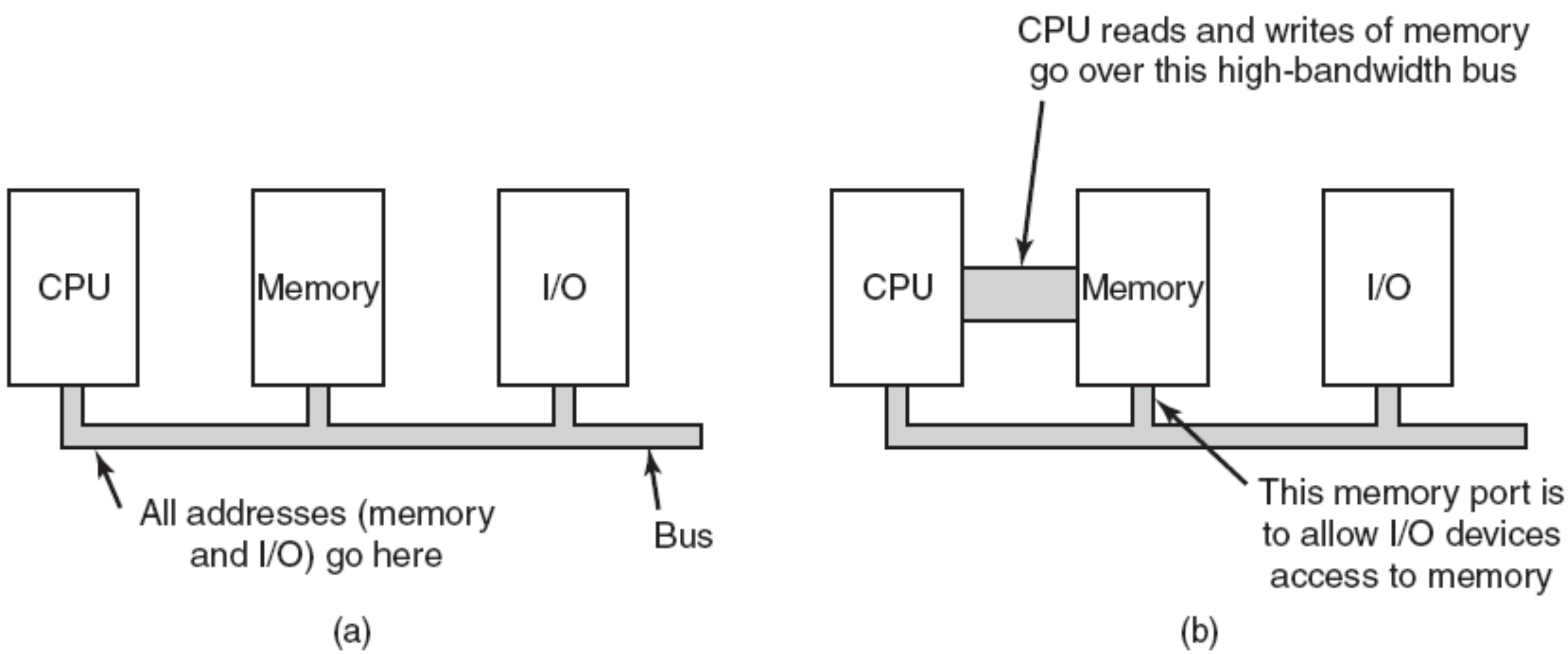


Figure 5-3. (a) A single-bus architecture.
(b) A dual-bus memory architecture.

Direct Memory Access (DMA)

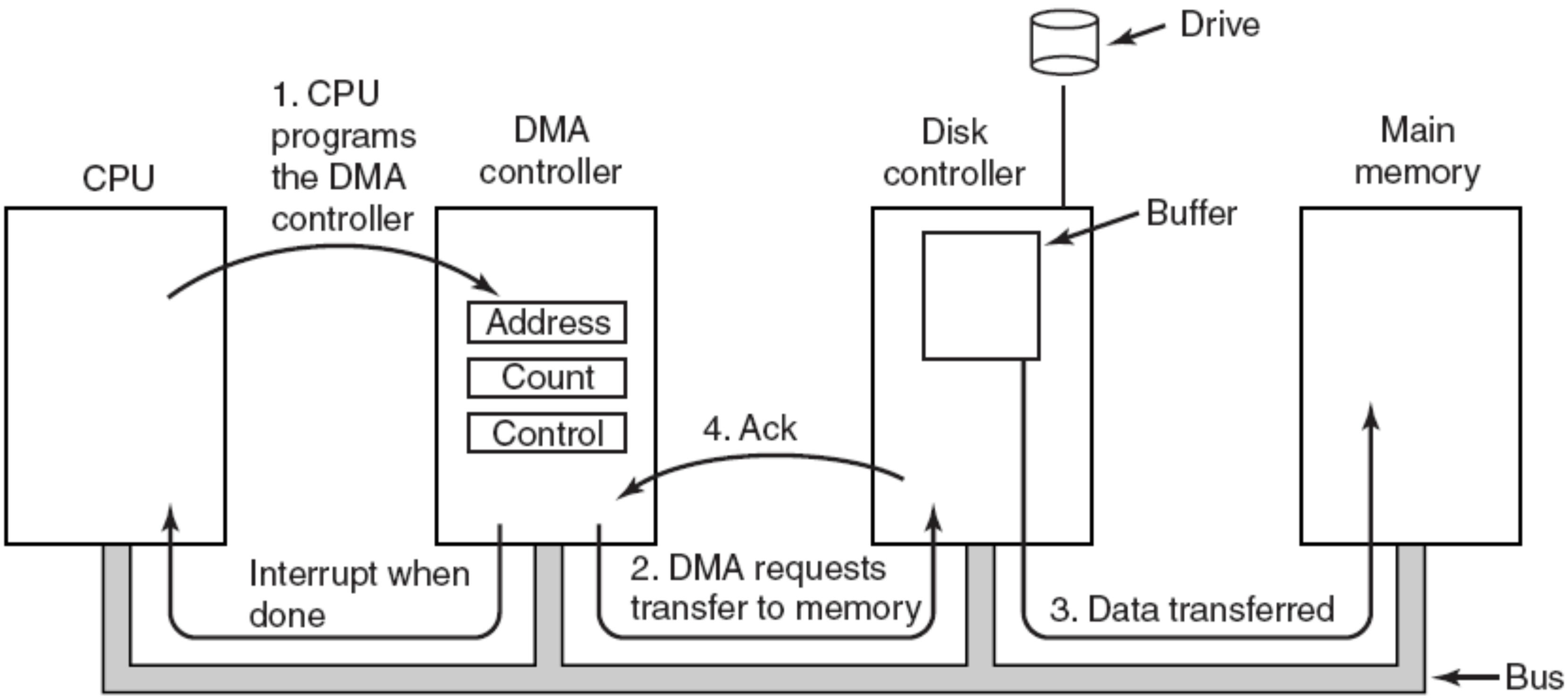


Figure 5-4. Operation of a DMA transfer.

Interrupts Revisited

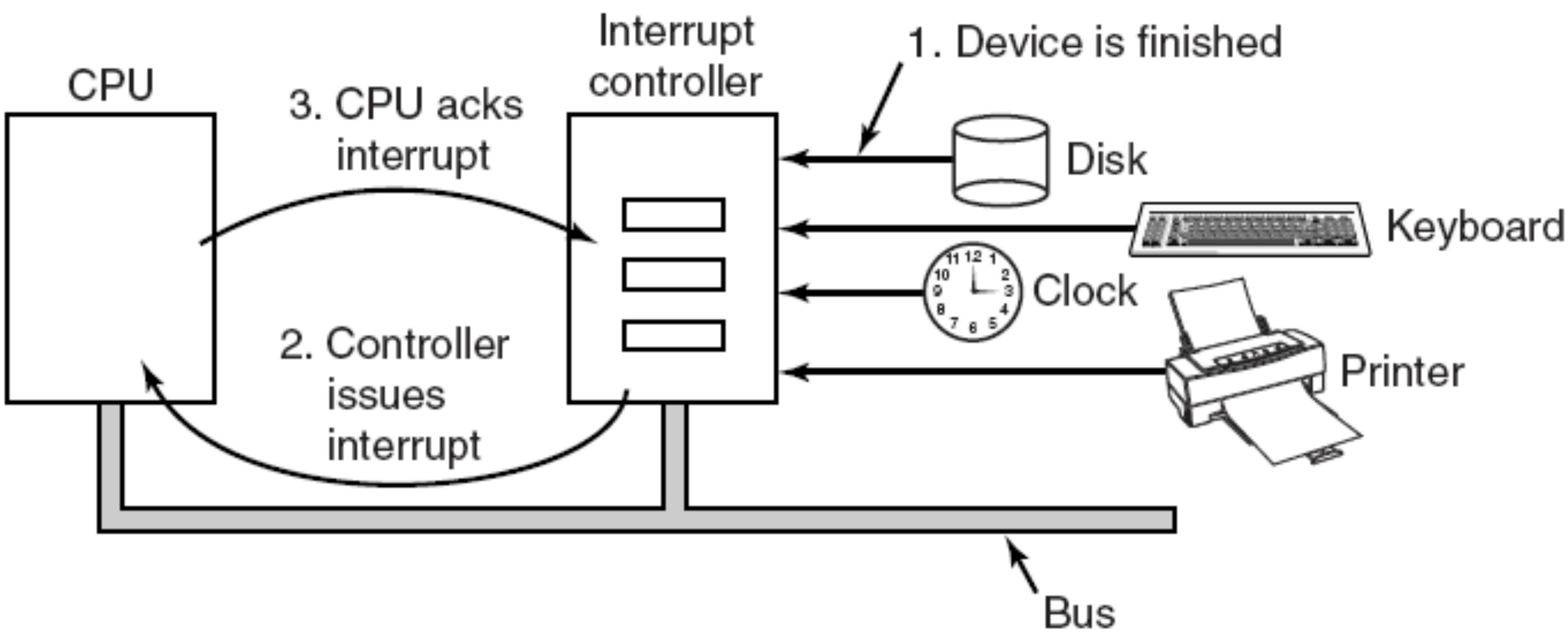


Figure 5-5. How an interrupt happens. The connections between the devices and the interrupt controller actually use interrupt lines on the bus rather than dedicated wires.

Precise and Imprecise Interrupts (1)

Properties of a *precise interrupt*

1. PC (Program Counter) is saved in a known place.
2. All instructions before the one pointed to by the PC have fully executed.
3. No instruction beyond the one pointed to by the PC has been executed.
4. Execution state of the instruction pointed to by the PC is known.

Precise and Imprecise Interrupts (2)

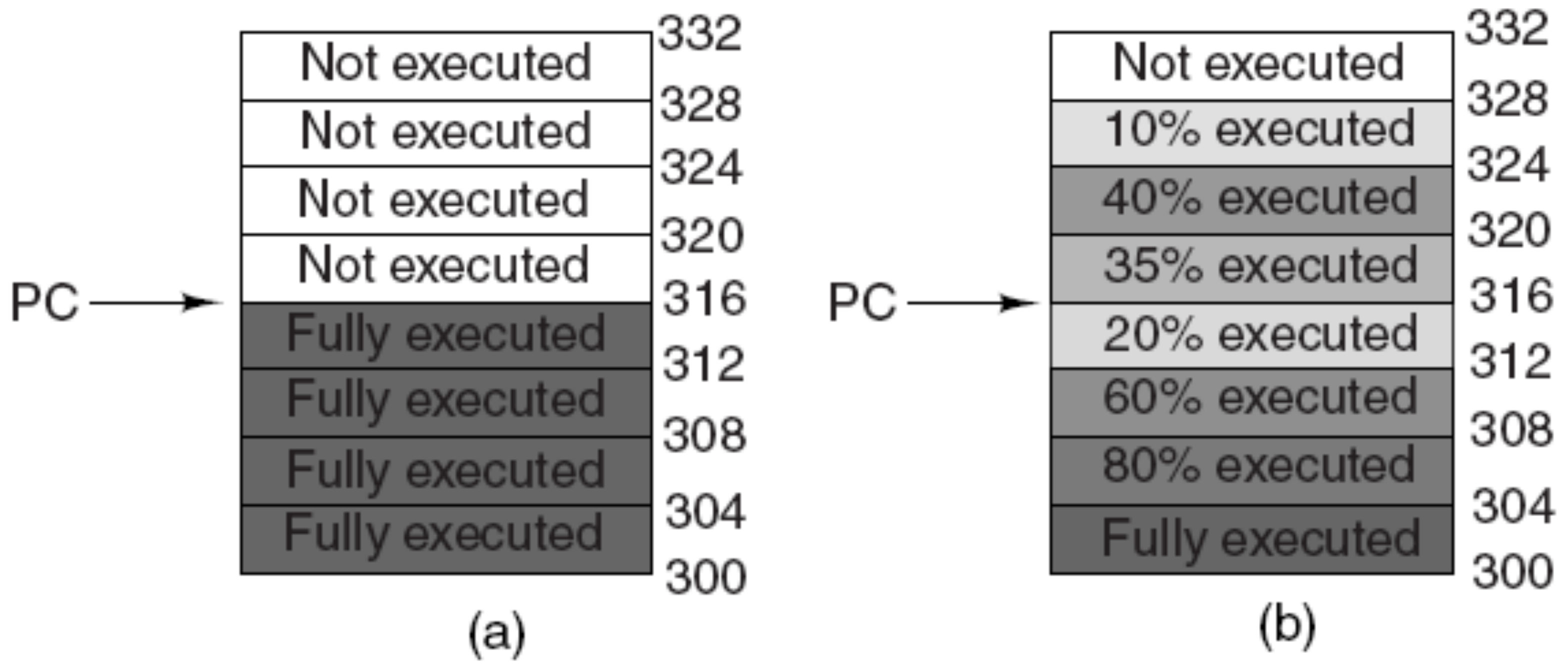


Figure 5-6. (a) A precise interrupt. (b) An imprecise interrupt.

Programmed I/O (1)

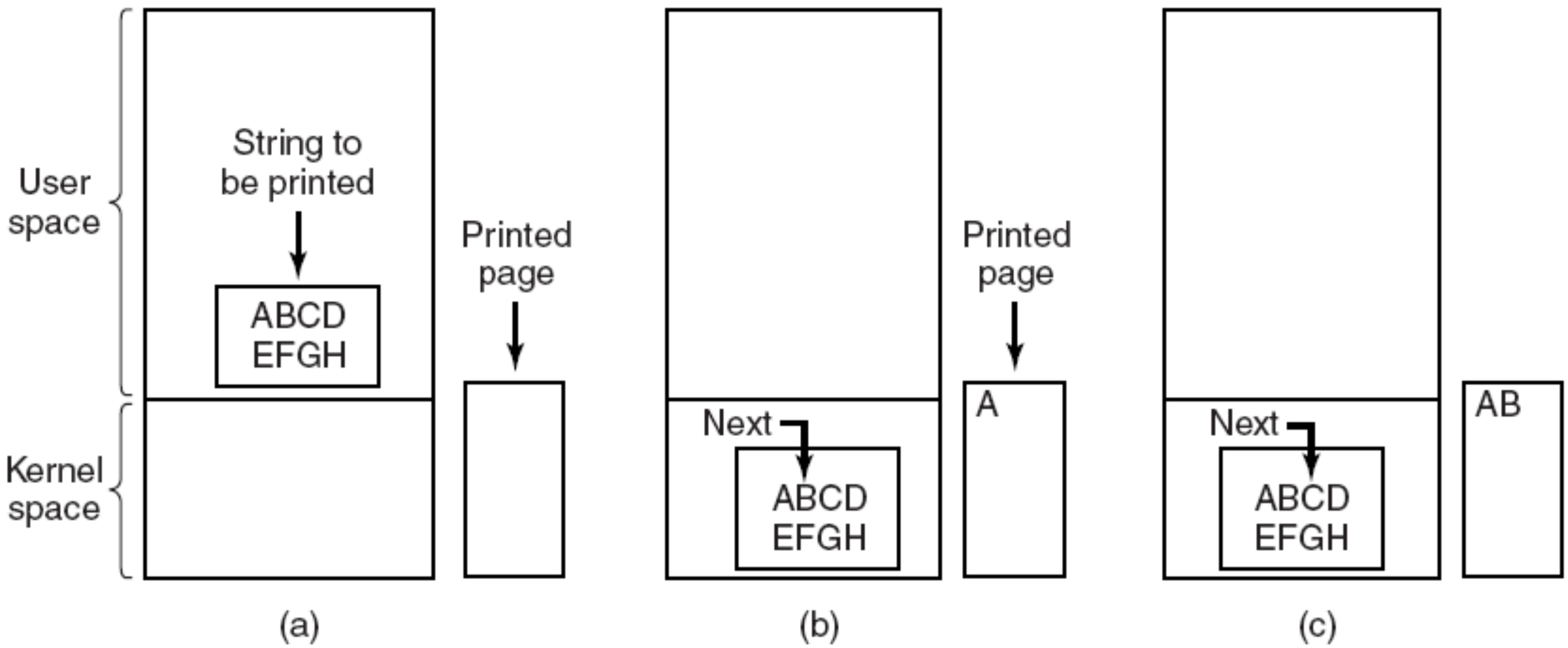


Figure 5-7. Steps in printing a string.

Programmed I/O (2)

```
copy_from_user(buffer, p, count);                    /* p is the kernel buffer */
for (i = 0; i < count; i++) {                        /* loop on every character */
      while (*printer_status_reg != READY) ;      /* loop until ready */
      *printer_data_register = p[i];                 /* output one character */
}
return_to_user();
```

Figure 5-8. Writing a string to the printer using programmed I/O.

Interrupt-Driven I/O

```
copy_from_user(buffer, p, count);
enable_interrupts( );
while (*printer_status_reg != READY) ;
*printer_data_register = p[0];
scheduler( );
```

(a)

```
if (count == 0) {
     unblock_user( );
} else {
     *printer_data_register = p[i];
     count = count − 1;
     i = i + 1;
}
acknowledge_interrupt( );
return_from_interrupt( );
```

(b)

Figure 5-9. Writing a string to the printer using interrupt-driven I/O. (a) Code executed at the time the print system call is made. (b) Interrupt service procedure for the printer.

I/O Using DMA

```
copy_from_user(buffer, p, count);
set_up_DMA_controller( );
scheduler( );
```

(a)

```
acknowledge_interrupt( );
unblock_user( );
return_from_interrupt( );
```

(b)

Figure 5-10. Printing a string using DMA. (a) Code executed when the print system call is made. (b) Interrupt service procedure.

I/O Software Layers

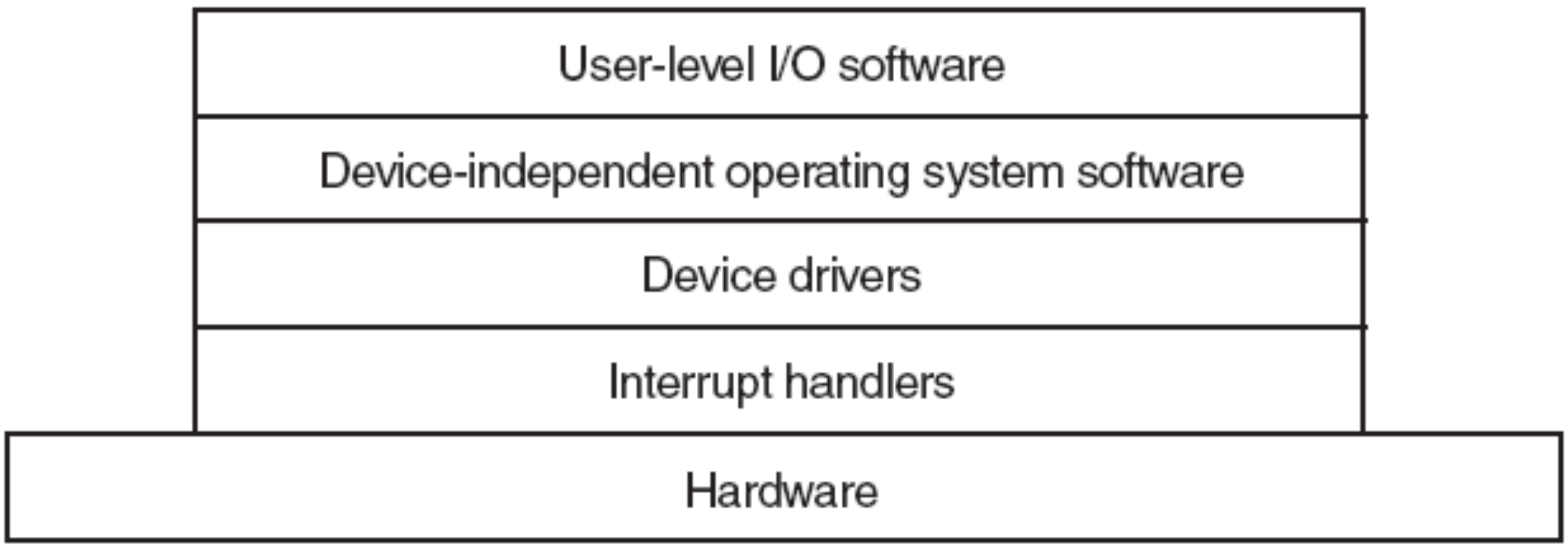


Figure 5-11. Layers of the I/O software system.

Interrupt Handlers (1)

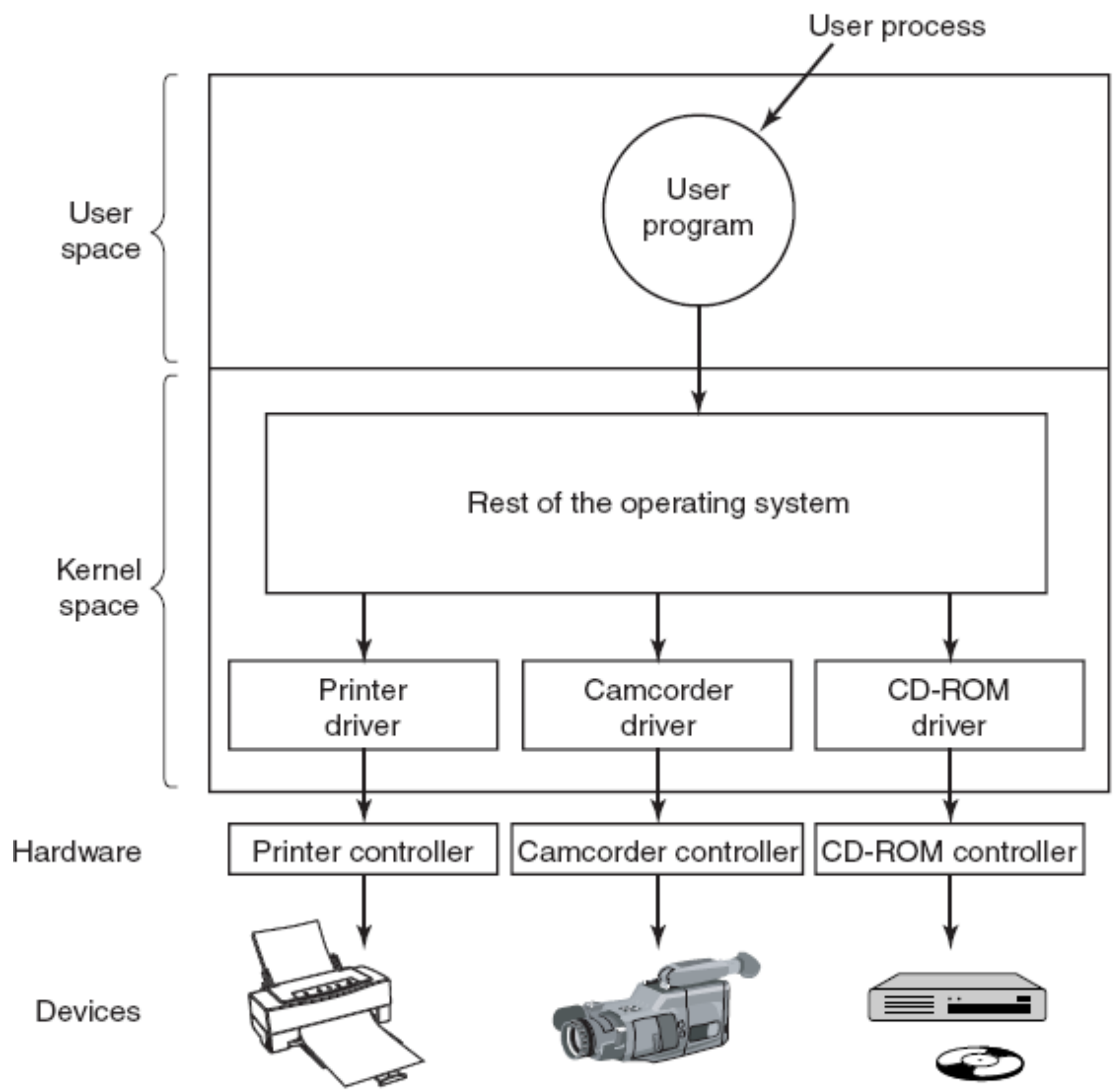
1. Save registers not already been saved by interrupt hardware.
2. Set up a context for the interrupt service procedure.
3. Set up a stack for the interrupt service procedure.
4. Acknowledge the interrupt controller. If there is no centralized interrupt controller, reenable interrupts.
5. Copy the registers from where they were saved to the process table.

Interrupt Handlers (2)

6. Run the interrupt service procedure.
7. Choose which process to run next.
8. Set up the MMU context for the process to run next.
9. Load the new process' registers, including its PSW.
10. Start running the new process.

Device Drivers

Figure 5-12. Logical positioning of device drivers. In reality all communication between drivers and device controllers goes over the bus.



Device-Independent I/O Software

Uniform interfacing for device drivers
Buffering
Error reporting
Allocating and releasing dedicated devices
Providing a device-independent block size

Figure 5-13. Functions of the device-independent I/O software.

Uniform Interfacing for Device Drivers

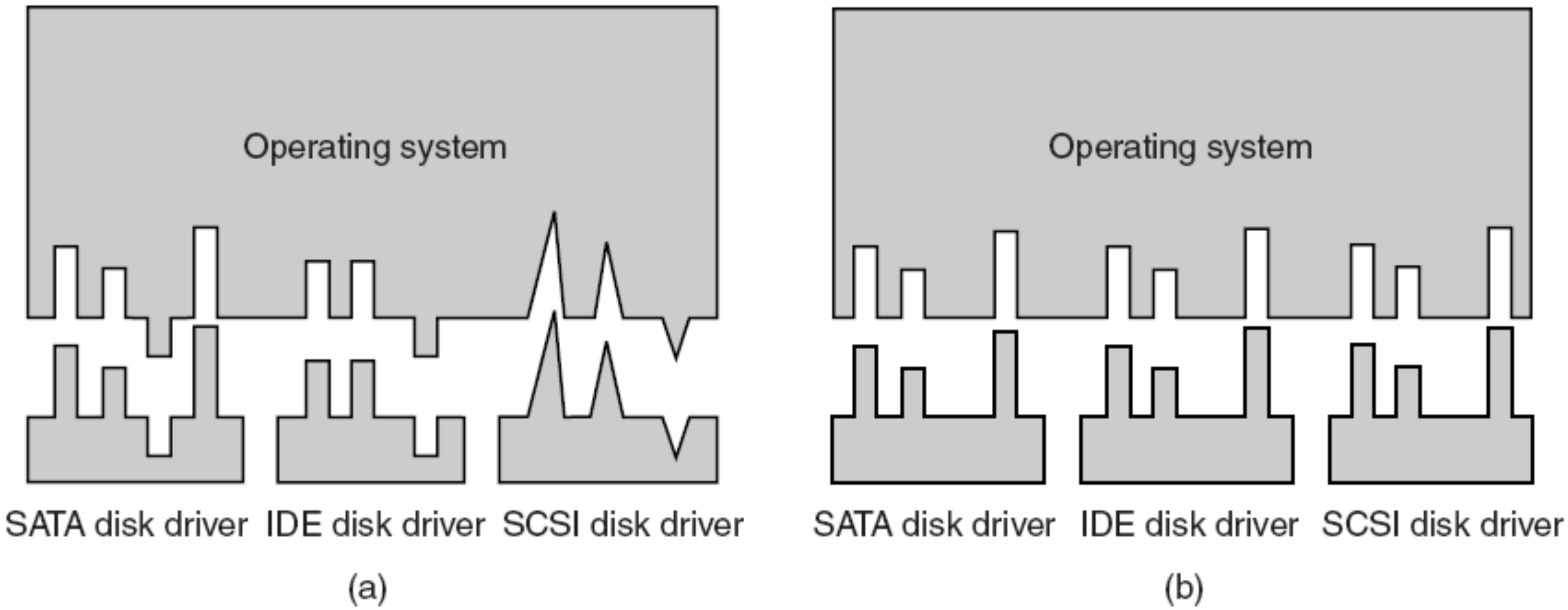


Figure 5-14. (a) Without a standard driver interface.
(b) With a standard driver interface.

Buffering (1)

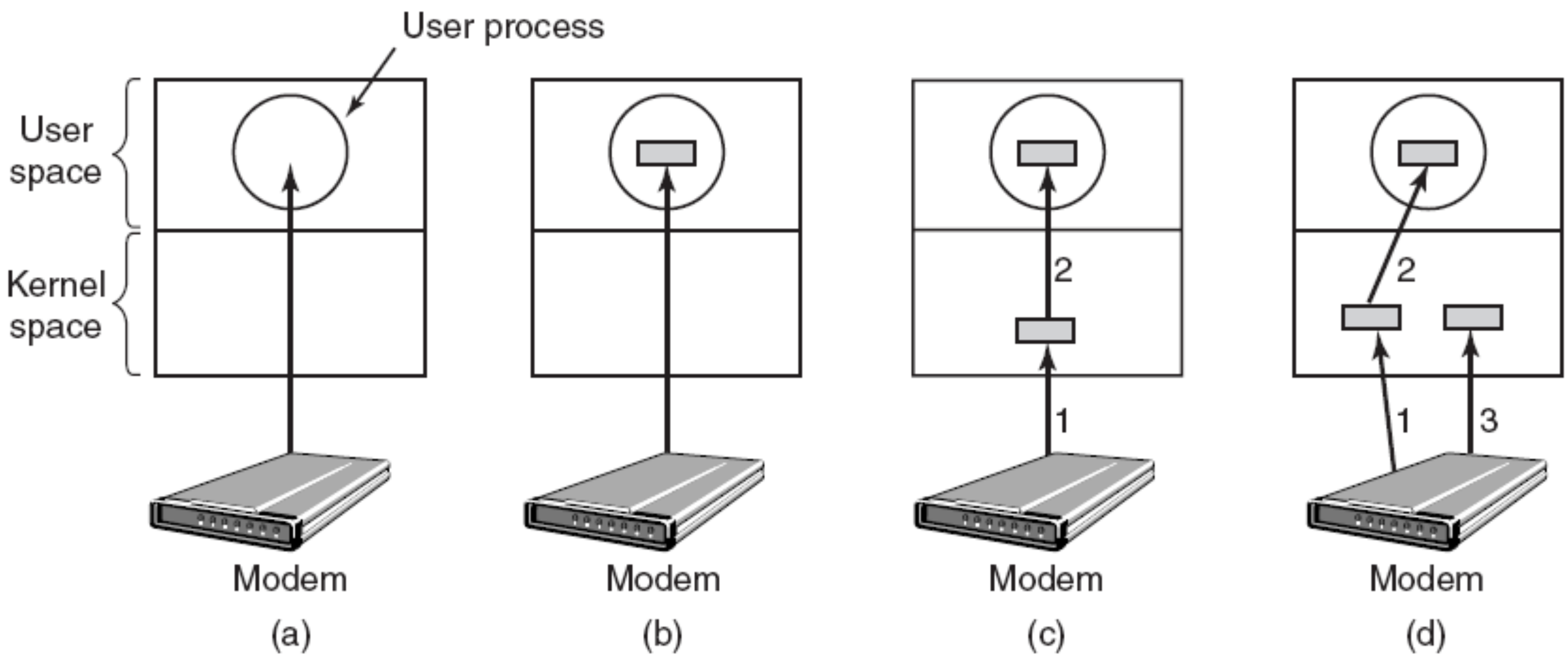


Figure 5-15. (a) Unbuffered input. (b) Buffering in user space. (c) Buffering in the kernel followed by copying to user space. (d) Double buffering in the kernel.

Buffering (2)

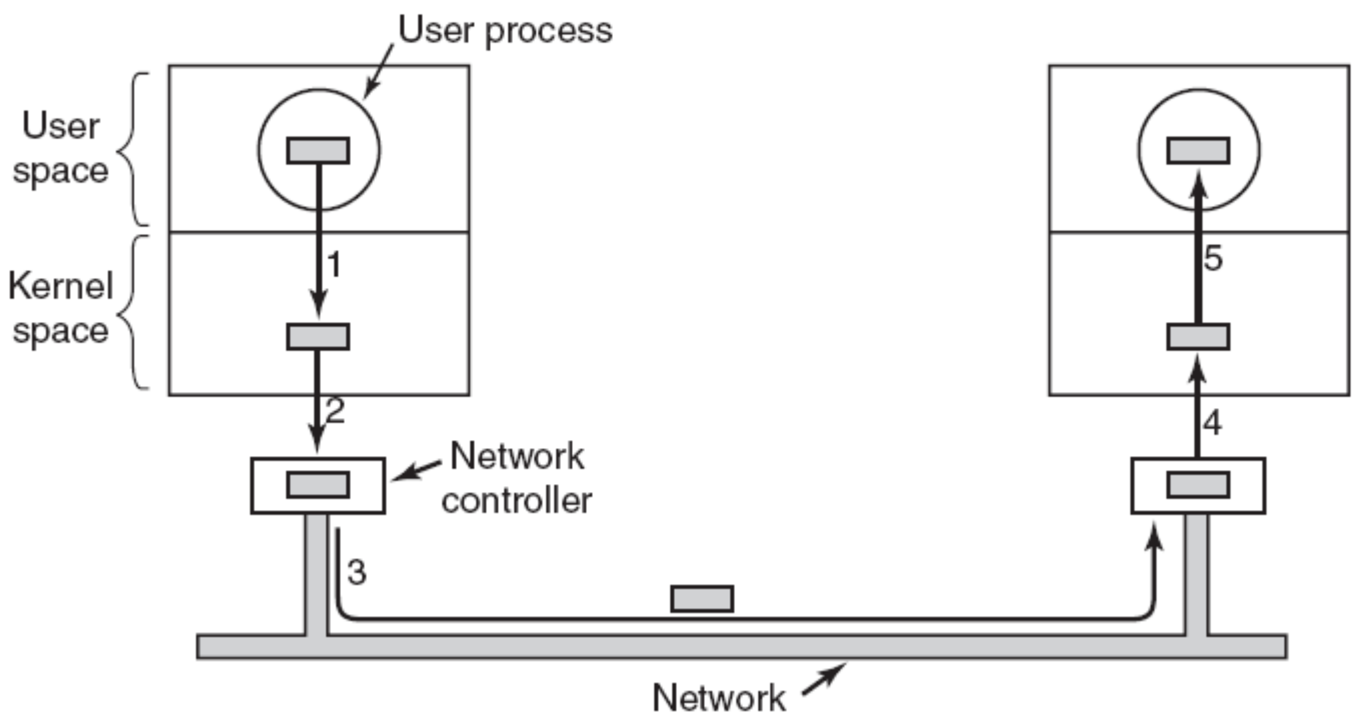


Figure 5-16. Networking may involve many copies of a packet.

User-Space I/O Software

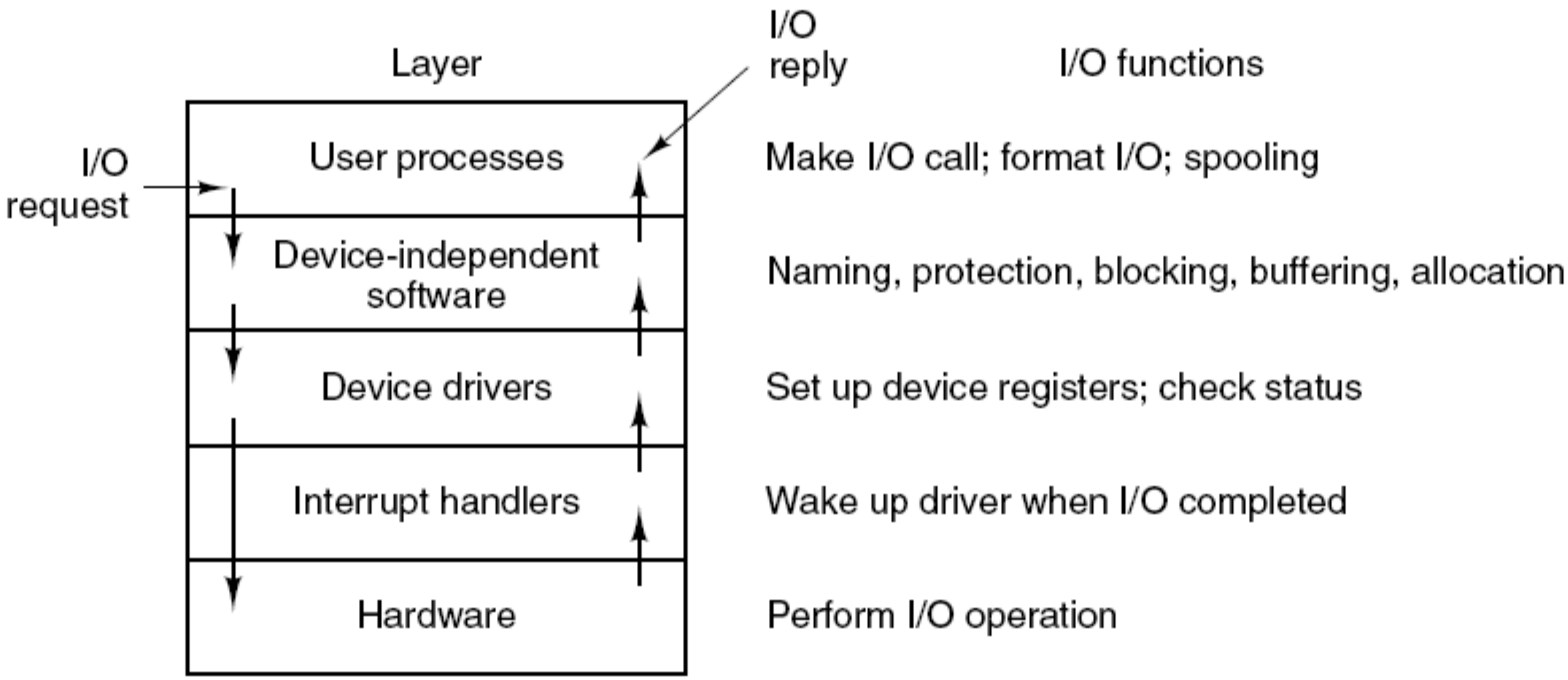


Figure 5-17. Layers of the I/O system and the main functions of each layer.

Magnetic Disks (1)

Parameter	IBM 360-KB floppy disk	WD 18300 hard disk
Number of cylinders	40	10601
Tracks per cylinder	2	12
Sectors per track	9	281 (avg)
Sectors per disk	720	35742000
Bytes per sector	512	512
Disk capacity	360 KB	18.3 GB
Seek time (adjacent cylinders)	6 msec	0.8 msec
Seek time (average case)	77 msec	6.9 msec
Rotation time	200 msec	8.33 msec
Motor stop/start time	250 msec	20 sec
Time to transfer 1 sector	22 msec	17 μsec

Figure 5-18. Disk parameters for the original IBM PC 360-KB floppy disk and a Western Digital WD 18300 hard disk.

Magnetic Disks (2)

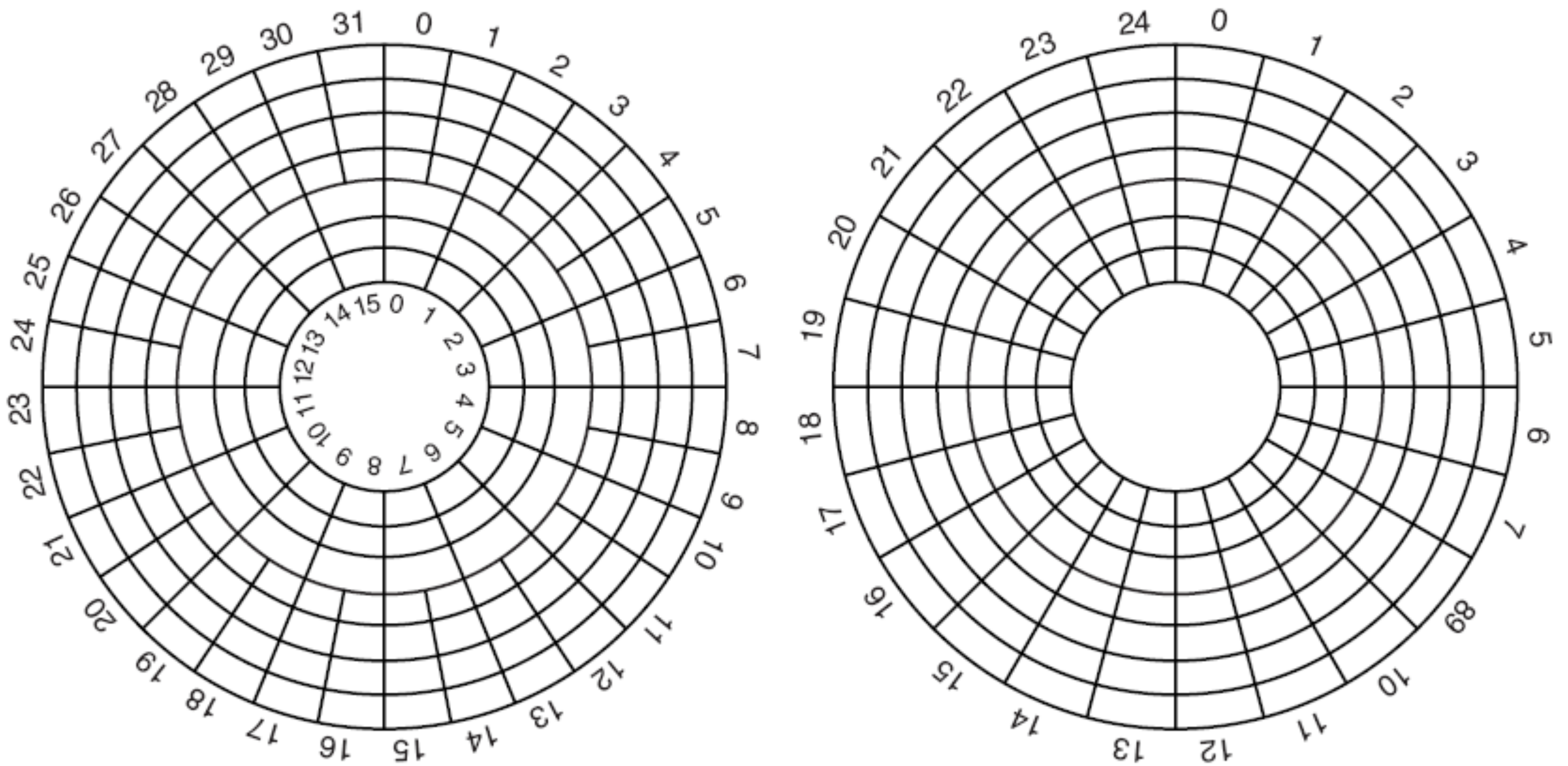


Figure 5-19. (a) Physical geometry of a disk with two zones.
(b) A possible virtual geometry for this disk.

RAID (1)

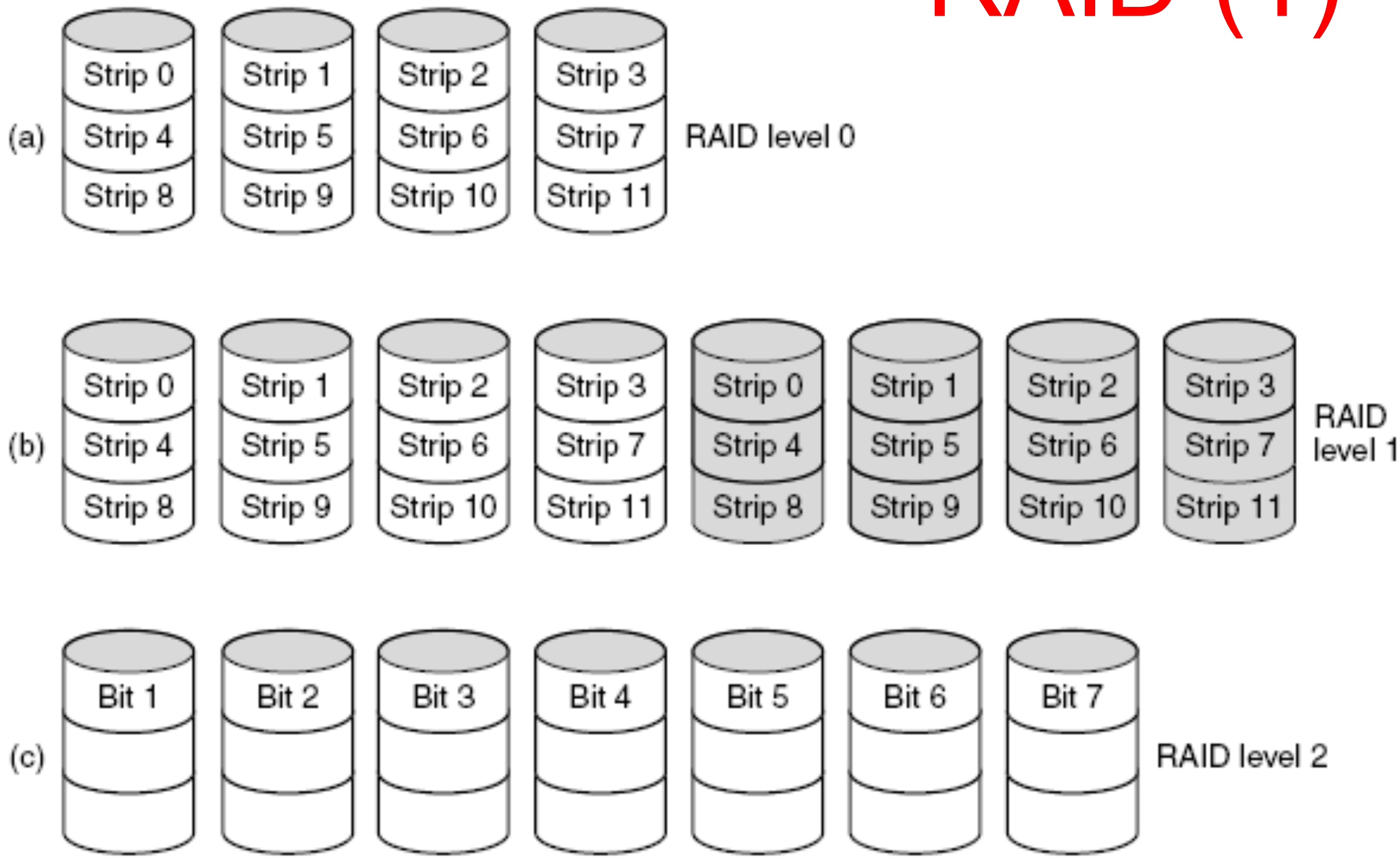


Figure 5-20. RAID levels 0 through 5.
Backup and parity drives are shown shaded.

RAID (2)

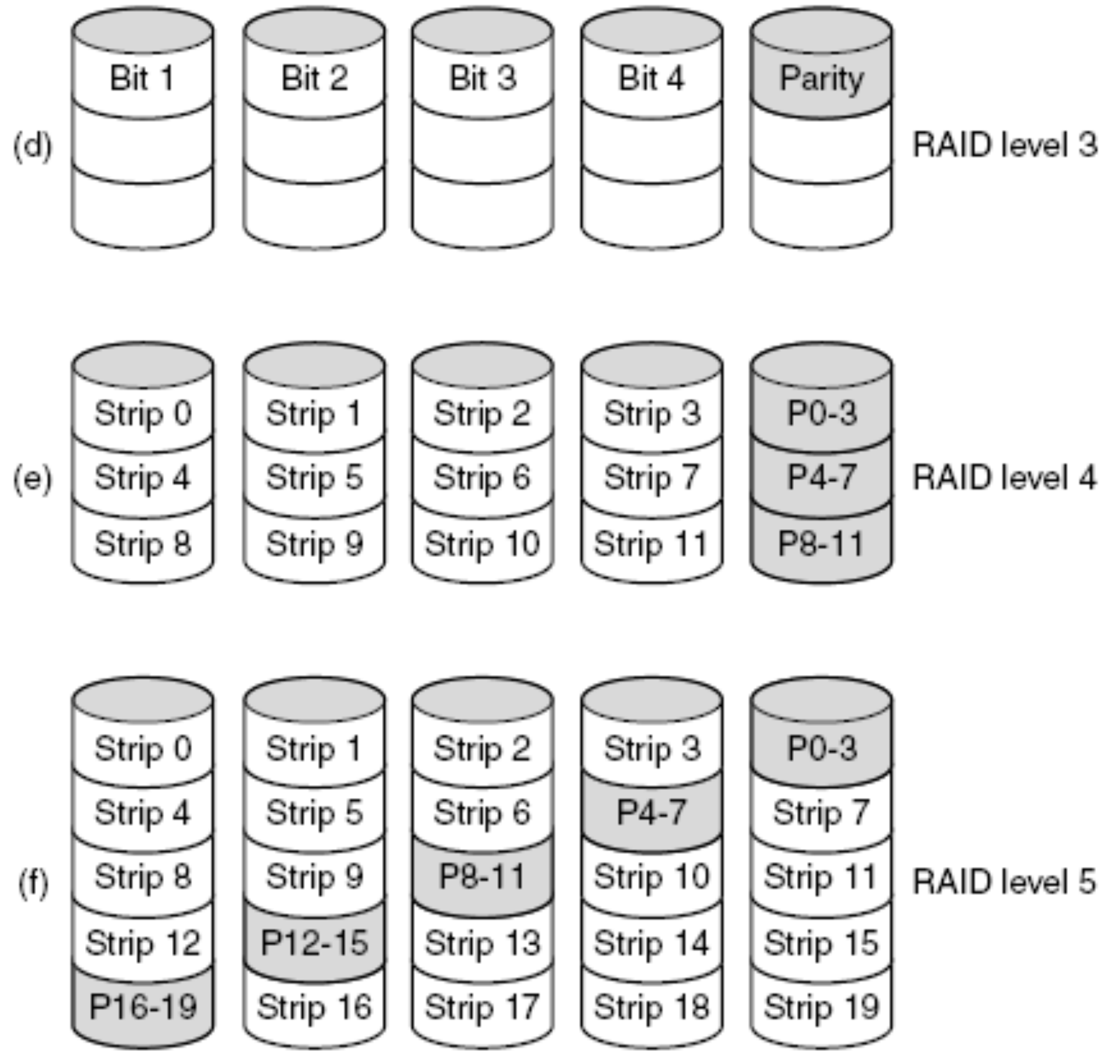


Figure 5-20. RAID levels 0 through 5.
Backup and parity drives are shown shaded.

CD-ROMs (1)

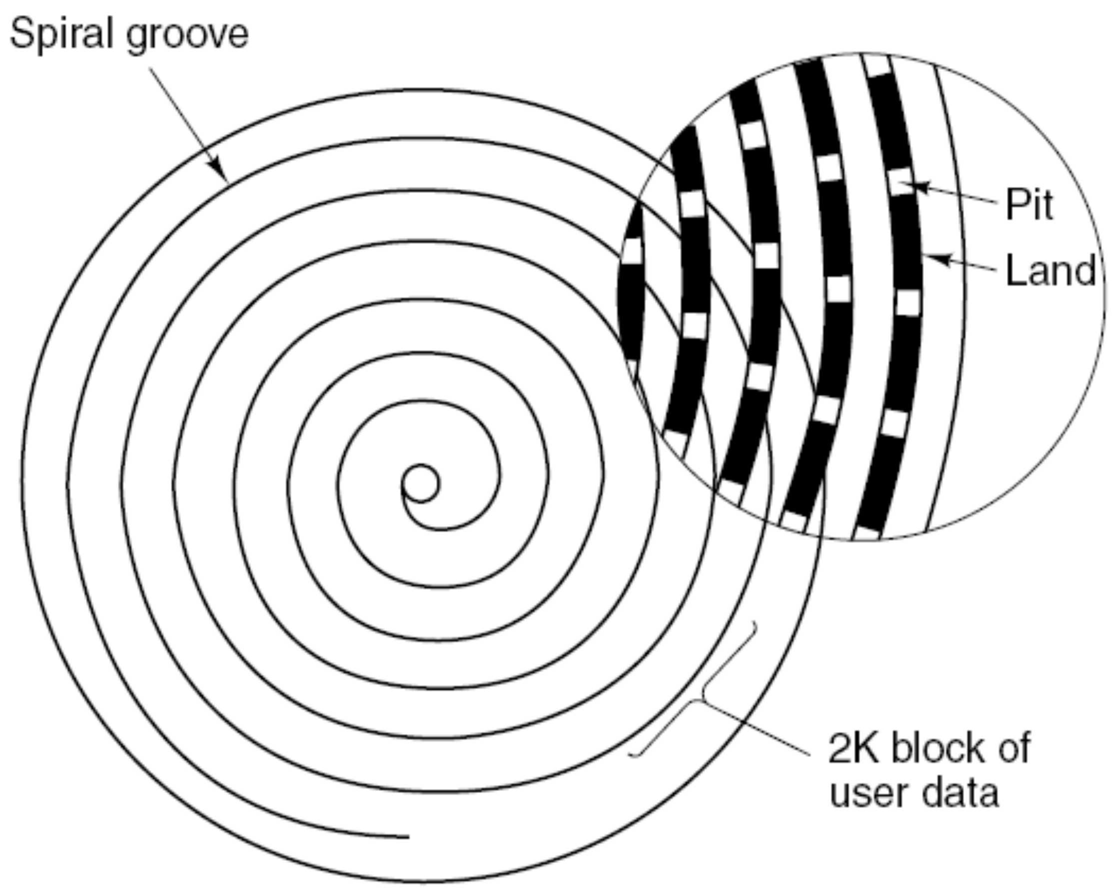


Figure 5-21. Recording structure of a compact disc or CD-ROM.

CD-ROMs (2)

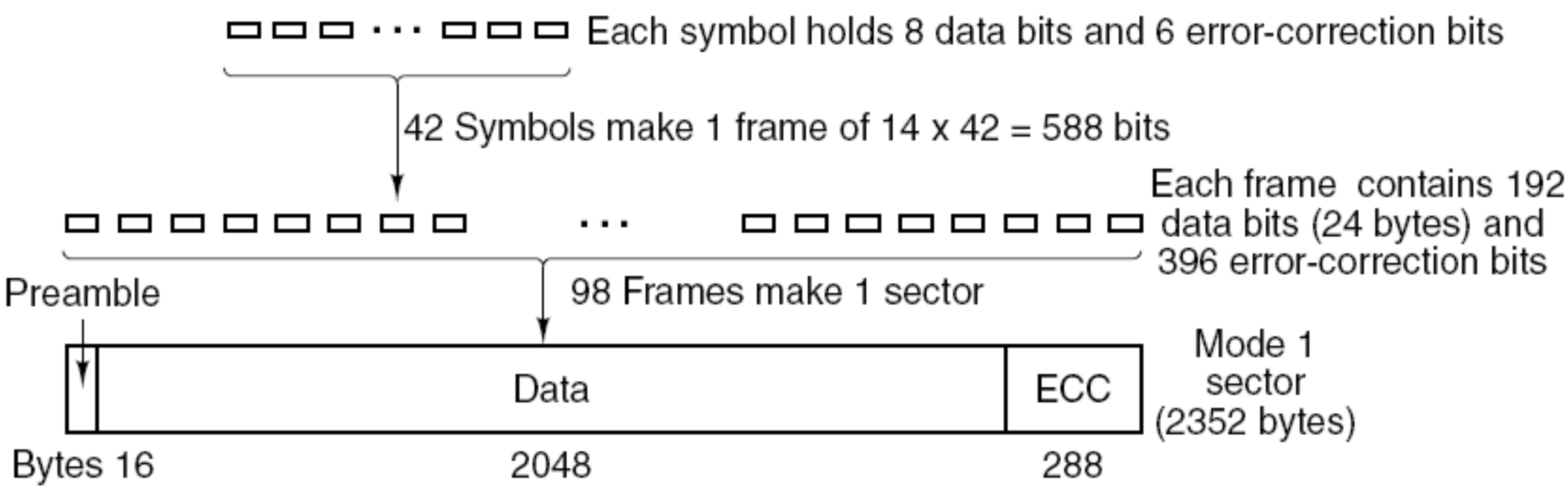


Figure 5-22. Logical data layout on a CD-ROM.

CD-Recordables (1)

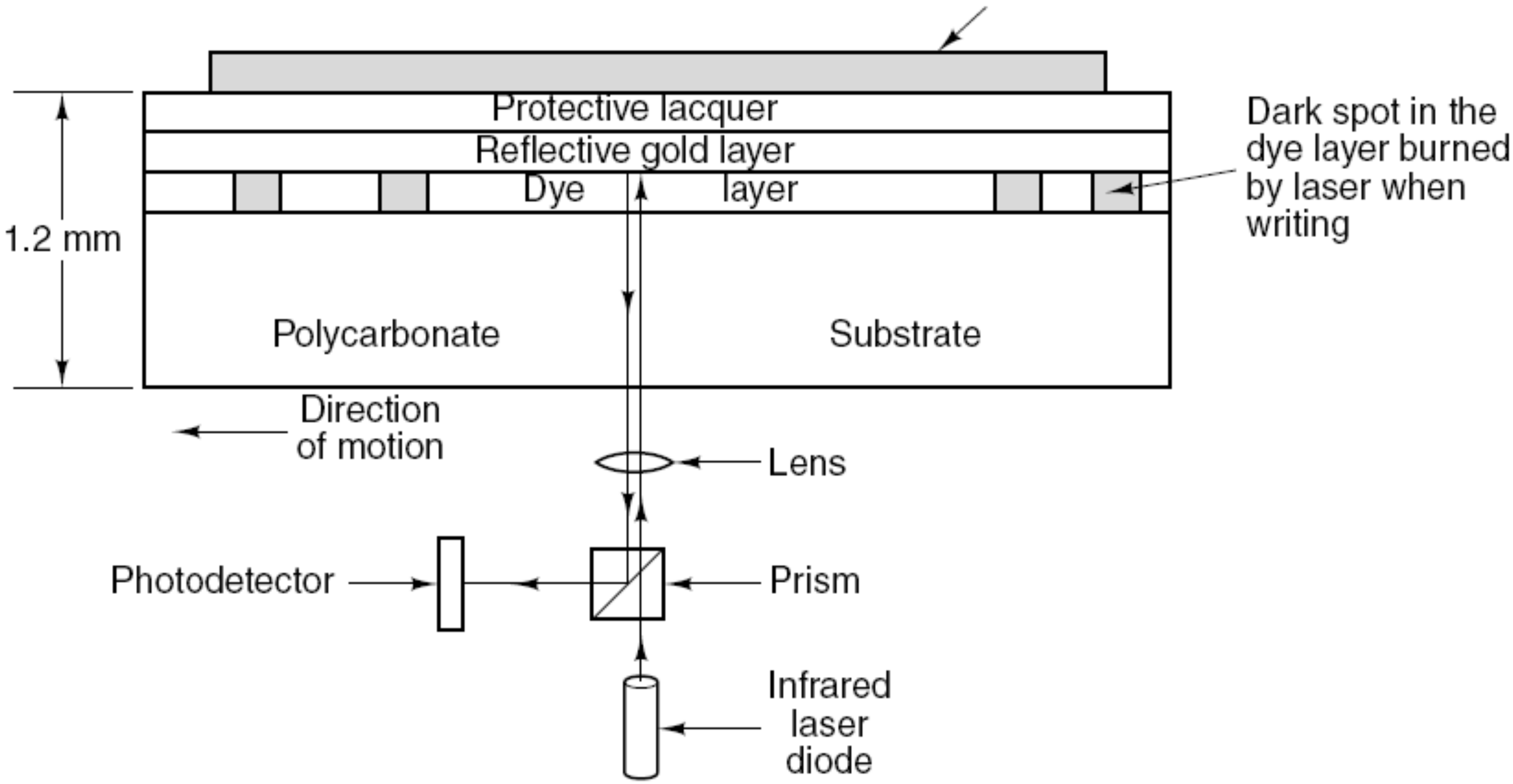


Figure 5-23. Cross section of a CD-R disk and laser. A silver CD-ROM has similar structure, except without dye layer and with pitted aluminum layer instead of gold layer.

DVD (1)

DVD Improvements on CDs

1. Smaller pits
(0.4 microns versus 0.8 microns for CDs).
2. A tighter spiral
(0.74 microns between tracks versus 1.6 microns for CDs).
3. A red laser
(at 0.65 microns versus 0.78 microns for CDs).

DVD (2)

DVD Formats

1. Single-sided, single-layer (4.7 GB).
2. Single-sided, dual-layer (8.5 GB).
3. Double-sided, single-layer (9.4 GB).
4. Double-sided, dual-layer (17 GB).

DVD (3)

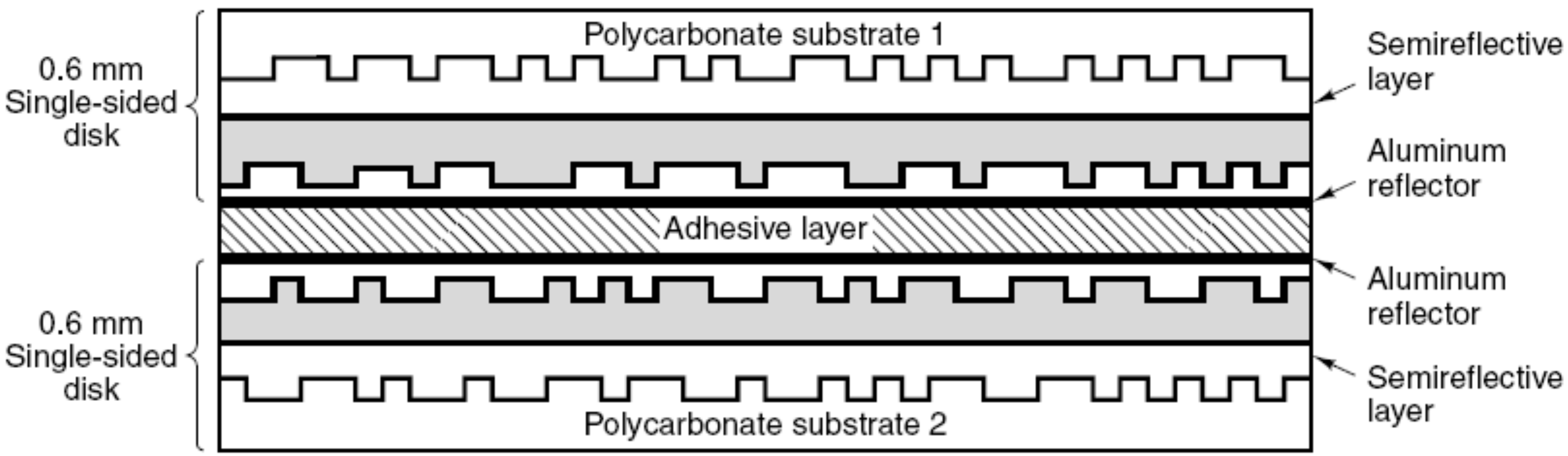


Figure 5-24. A double-sided, dual-layer DVD disk.

Disk Formatting (1)

Preamble	Data	ECC

Figure 5-25. A disk sector.

Disk Formatting (2)

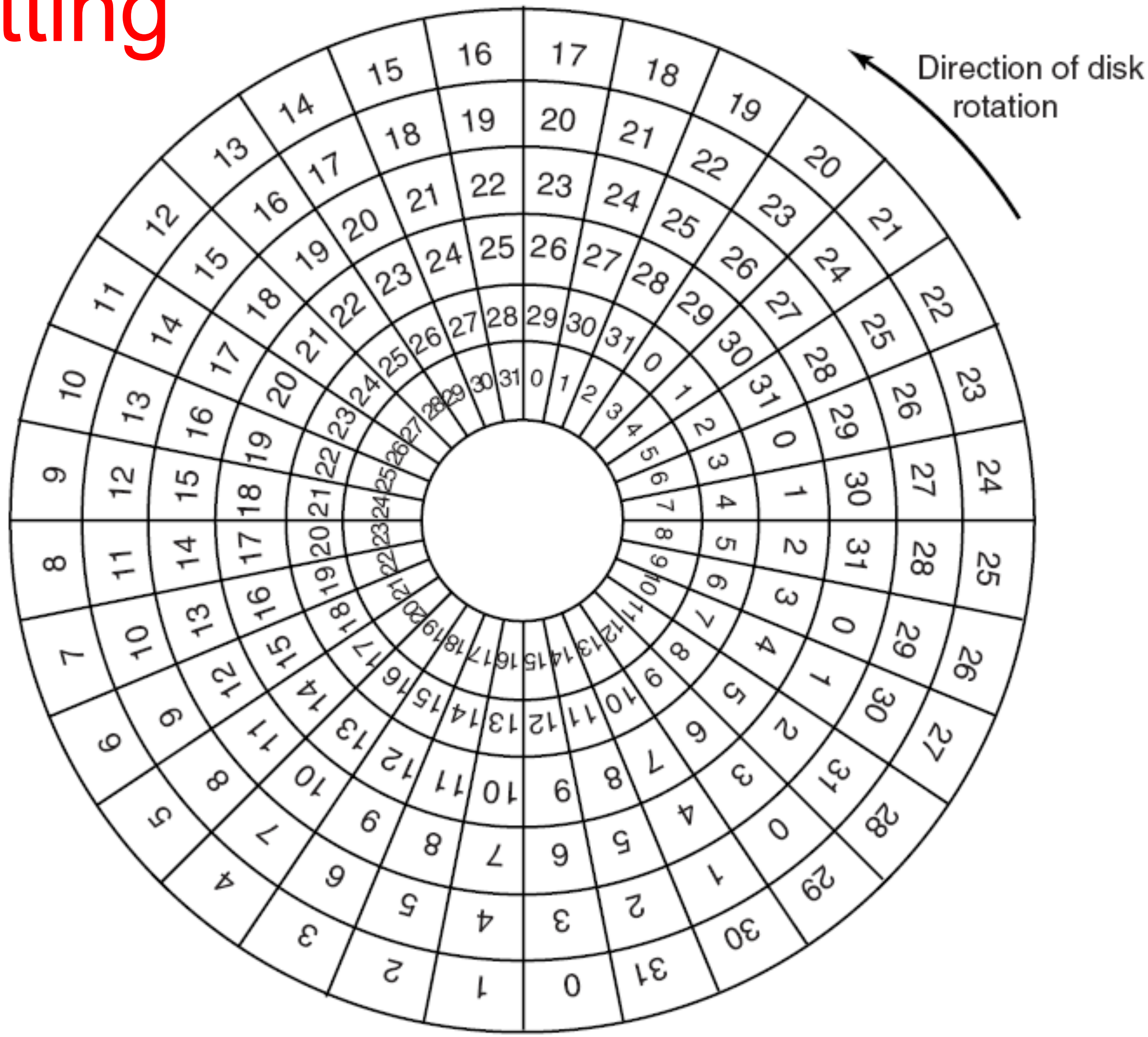


Figure 5-26. An illustration of cylinder skew.

Disk Formatting (3)

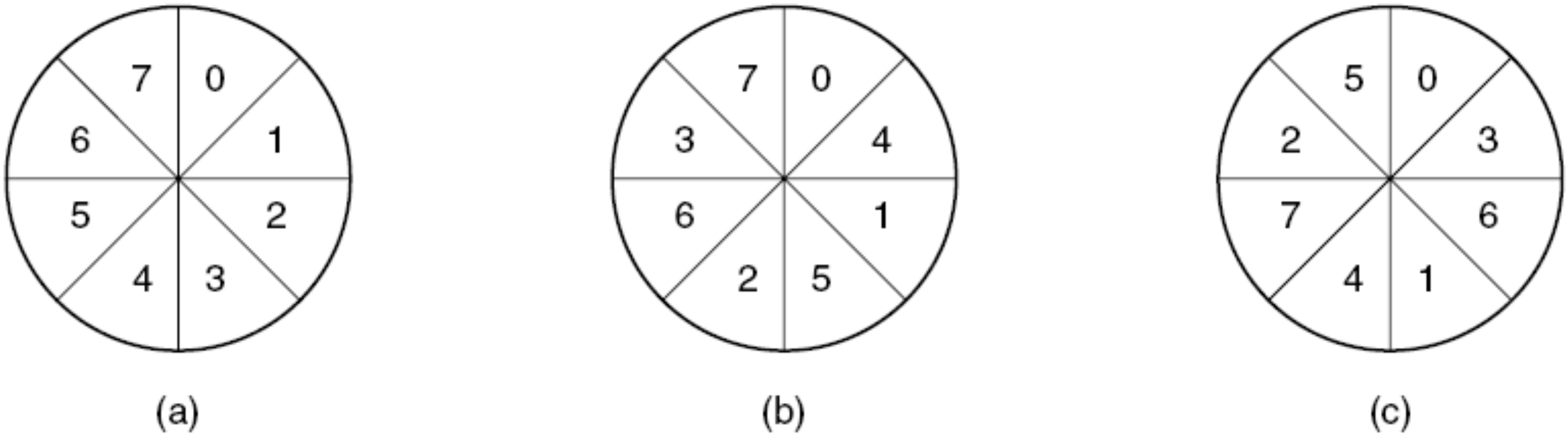


Figure 5-27. (a) No interleaving. (b) Single interleaving. (c) Double interleaving.

Disk Arm Scheduling Algorithms (1)

Read/write time factors

1. Seek time (the time to move the arm to the proper cylinder).
2. Rotational delay (the time for the proper sector to rotate under the head).
3. Actual data transfer time.

Disk Arm Scheduling Algorithms (2)

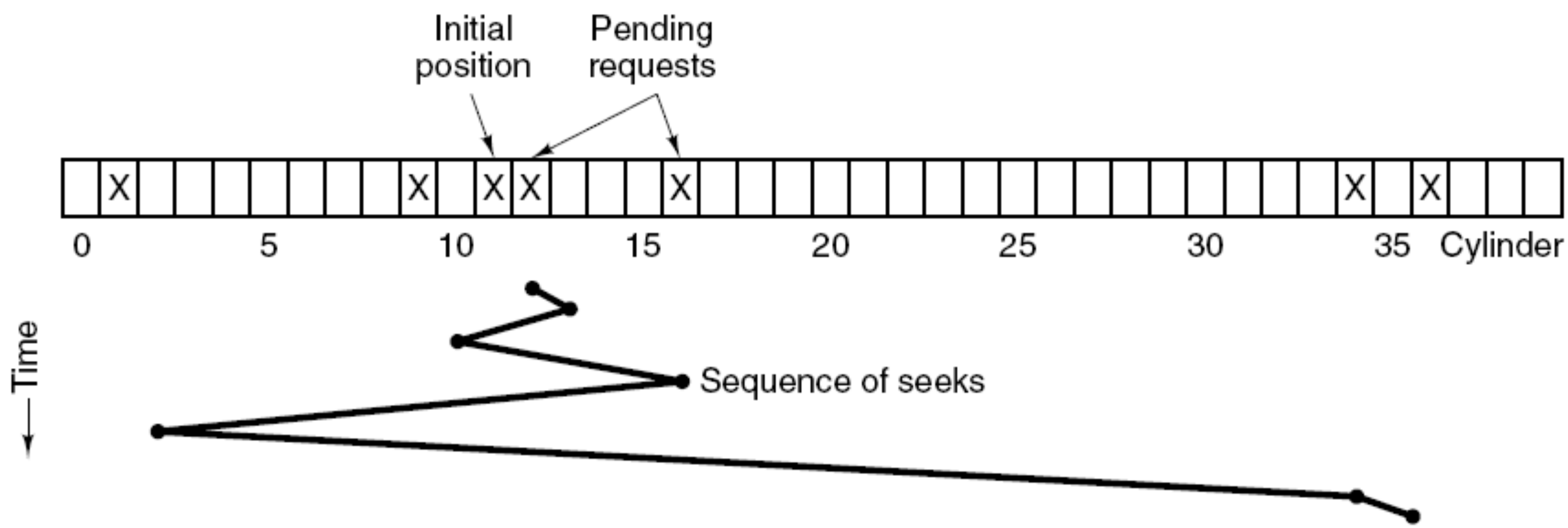


Figure 5-28. Shortest Seek First (SSF) disk scheduling algorithm.

Disk Arm Scheduling Algorithms (3)

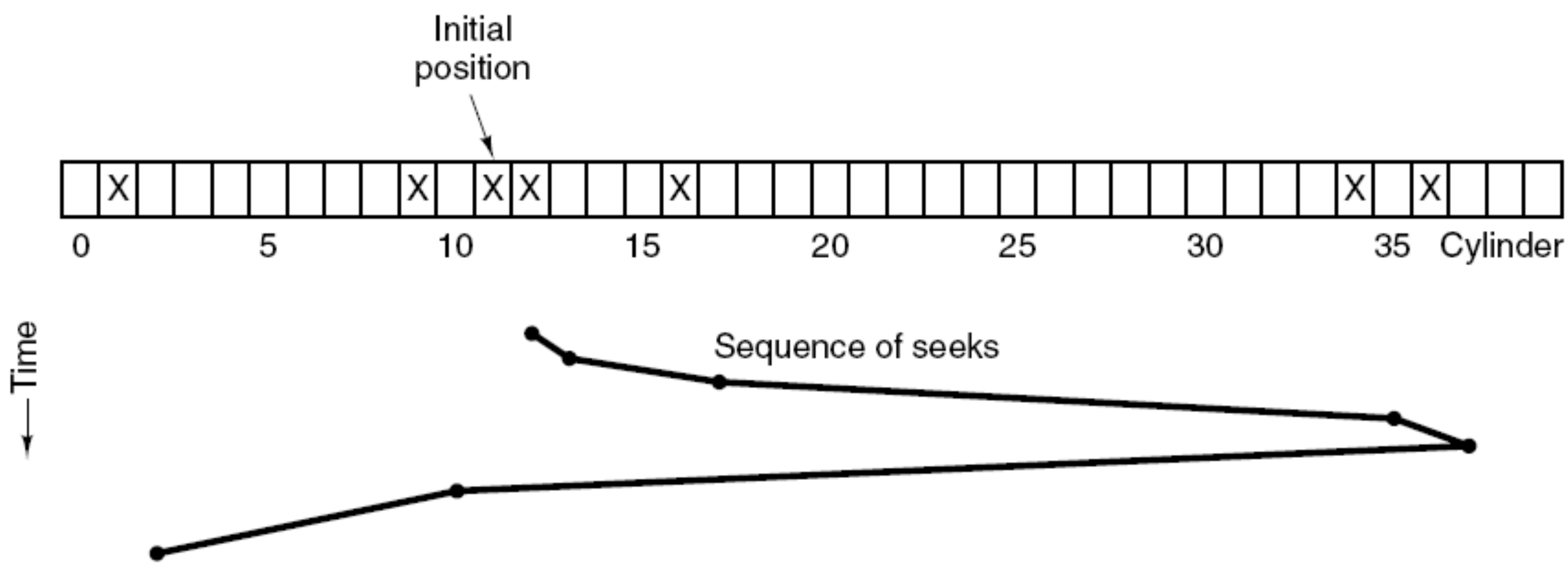


Figure 5-29. The elevator algorithm for scheduling disk requests.

Error Handling

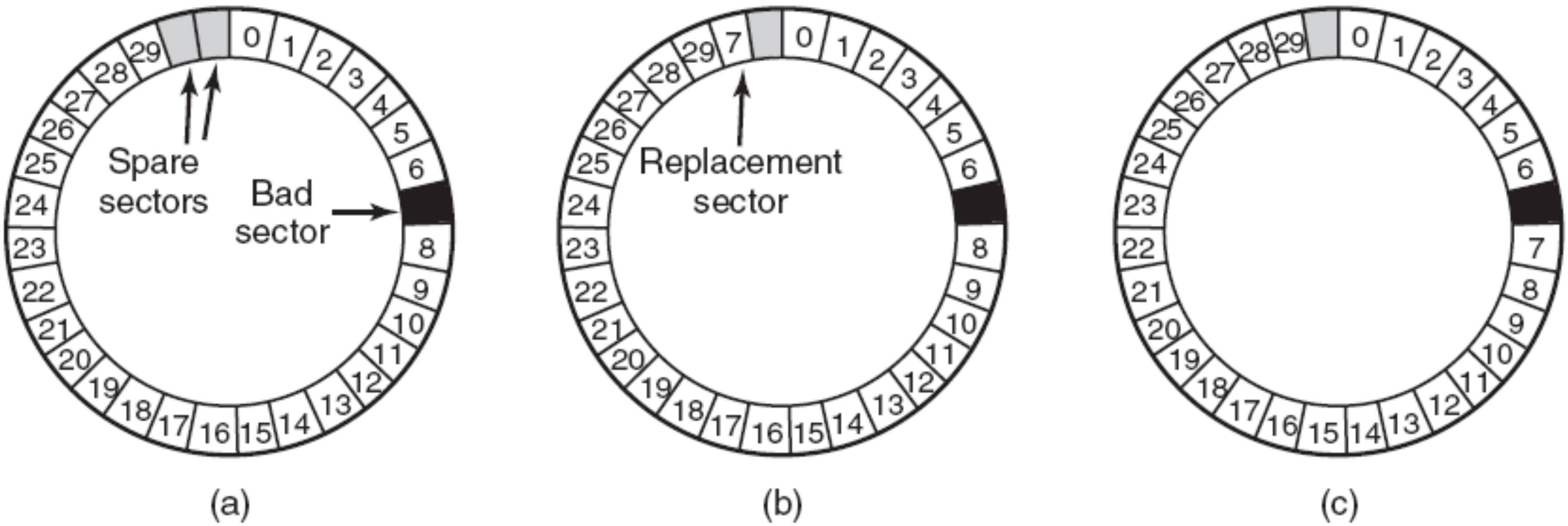


Figure 5-30. (a) A disk track with a bad sector.
(b) Substituting a spare for the bad sector.
(c) Shifting all the sectors to bypass the bad one.

Stable Storage (1)

Operations for stable storage using identical disks:

1. Stable writes
2. Stable reads
3. Crash recovery

Stable Storage (2)

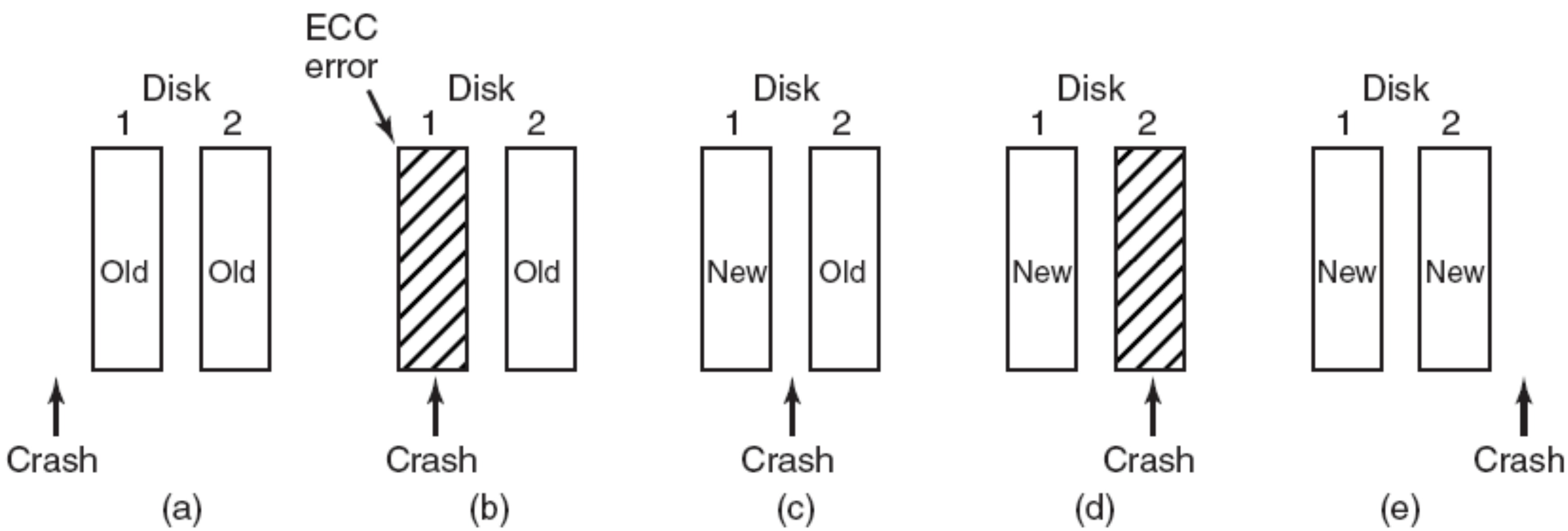


Figure 5-31. Analysis of the influence of crashes on stable writes.

Clock Hardware

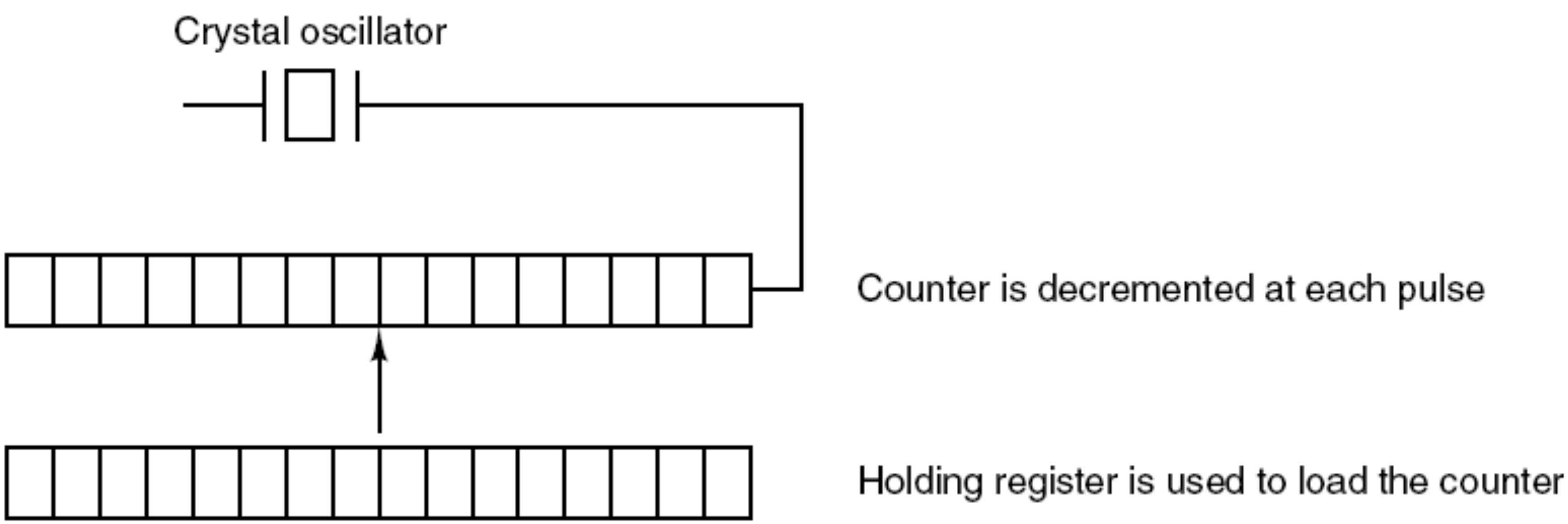


Figure 5-32. A programmable clock.

Clock Software (1)

Typical duties of a clock driver

1. Maintaining the time of day.
2. Preventing processes from running longer than they are allowed to.
3. Accounting for CPU usage.
4. Handling alarm system call made by user processes.
5. Providing watchdog timers for parts of the system itself.
6. Doing profiling, monitoring, statistics gathering.

Clock Software (2)

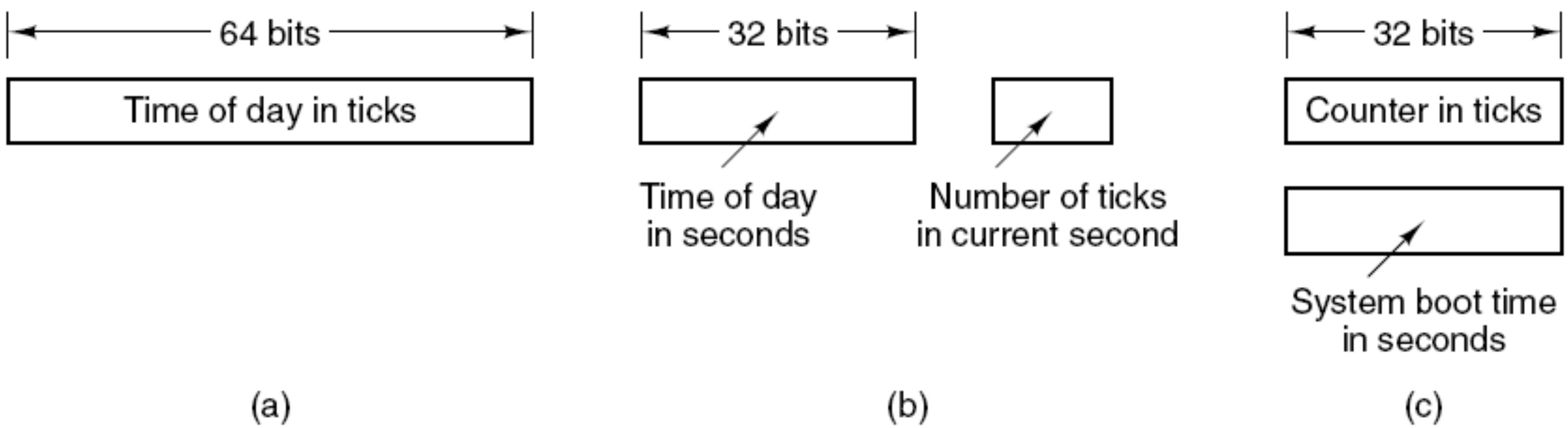


Figure 5-33. Three ways to maintain the time of day.

Clock Software (3)

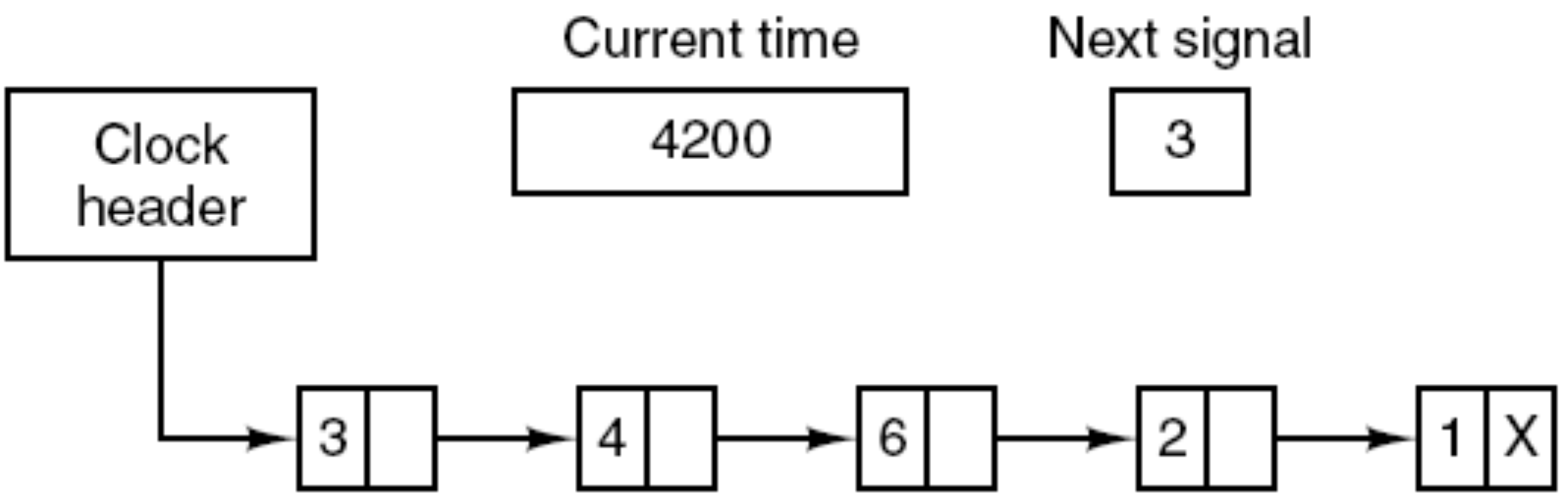


Figure 5-34. Simulating multiple timers with a single clock.

Soft Timers

Soft timers succeed according to rate at which kernel entries are made because of:

1. System calls.
2. TLB misses.
3. Page faults.
4. I/O interrupts.
5. The CPU going idle.

Keyboard Software

Character	POSIX name	Comment
CTRL-H	ERASE	Backspace one character
CTRL-U	KILL	Erase entire line being typed
CTRL-V	LNEXT	Interpret next character literally
CTRL-S	STOP	Stop output
CTRL-Q	START	Start output
DEL	INTR	Interrupt process (SIGINT)
CTRL-\	QUIT	Force core dump (SIGQUIT)
CTRL-D	EOF	End of file
CTRL-M	CR	Carriage return (unchangeable)
CTRL-J	NL	Linefeed (unchangeable)

Figure 5-35. Characters that are handled specially in canonical mode.

The X Window System (1)

Escape sequence	Meaning
ESC [*n* A	Move up *n* lines
ESC [*n* B	Move down *n* lines
ESC [*n* C	Move right *n* spaces
ESC [*n* D	Move left *n* spaces
ESC [*m* ; *n* H	Move cursor to (*m*,*n*)
ESC [*s* J	Clear screen from cursor (0 to end, 1 1from start, 2 all)
ESC [*s* K	Clear line from cursor (0 to end, 1 from start, 2 all)
ESC [*n* L	Insert *n* lines at cursor
ESC [*n* M	Delete *n* lines at cursor
ESC [*n* P	Delete *n* chars at cursor
ESC [*n* @	Insert *n* chars at cursor
ESC [*n* m	Enable rendition *n* (0=normal, 4=bold, 5=blinking, 7=reverse)
ESC M	Scroll the screen backward if the cursor is on the top line

Figure 5-36. The ANSI escape sequences accepted by the terminal driver on output. ESC denotes the ASCII escape character (0x1B), and *n*, *m*, and *s* are optional numeric parameters.

The X Window System (2)

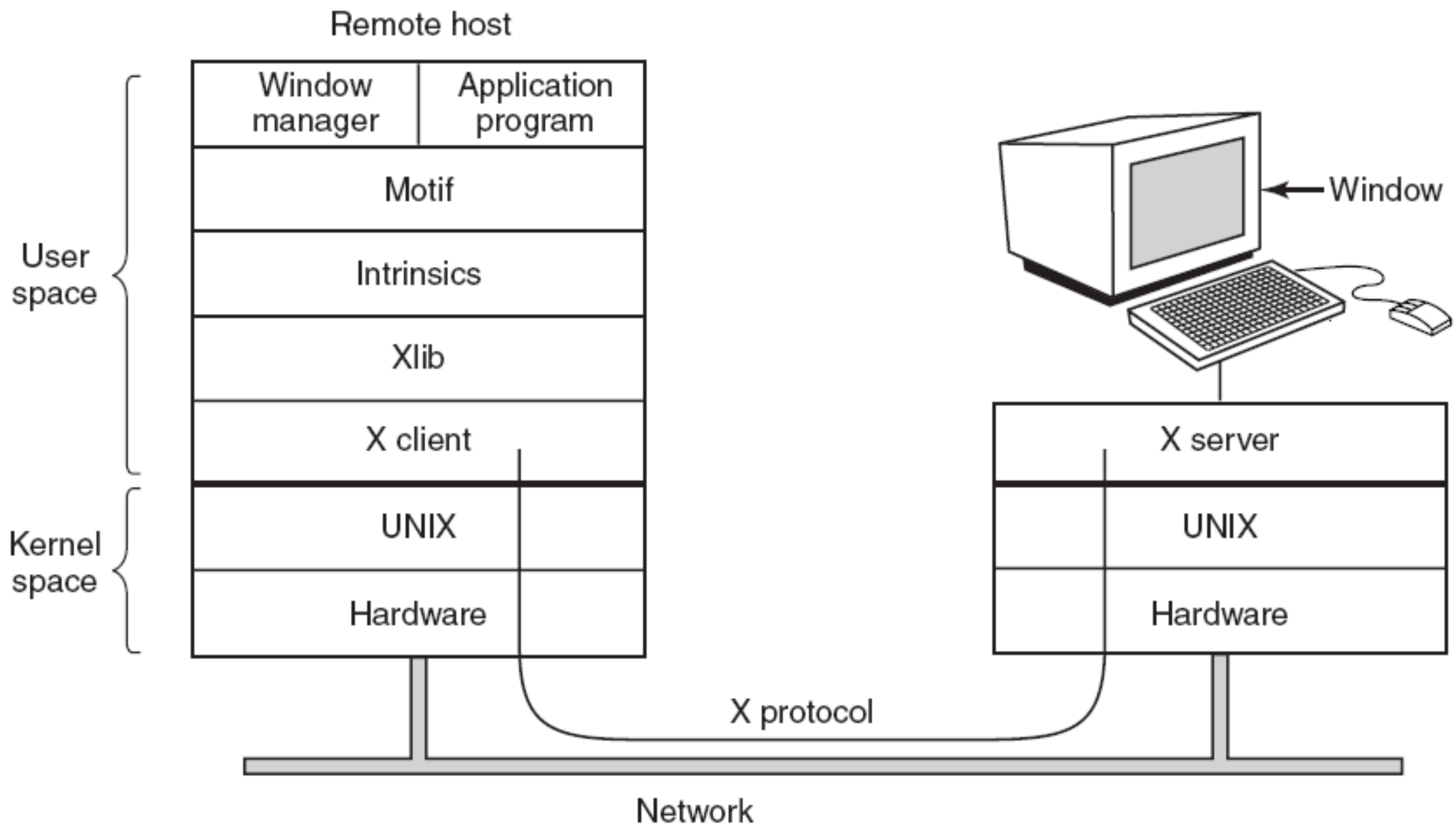


Figure 5-37. Clients and servers in the M.I.T. X Window System.

The X Window System (3)

Types of messages between client and server:

1. Drawing commands from the program to the workstation.
2. Replies by the workstation to program queries.
3. Keyboard, mouse, and other event announcements.
4. Error messages.

Graphical User Interfaces (1)

```
#include <X11/Xlib.h>
#include <X11/Xutil.h>

main(int argc, char *argv[])
{
        Display disp;                                           /* server identifier */
        Window win;                                             /* window identifier */
        GC gc;                                                  /* graphic context identifier */
        XEvent event;                                           /* storage for one event */
        int running = 1;

        disp = XOpenDisplay("display_name");                    /* connect to the X server */
        win = XCreateSimpleWindow(disp, ... );                  /* allocate memory for new window */
        XSetStandardProperties(disp, ...);              /* announces window to window mgr */
        gc = XCreateGC(disp, win, 0, 0);                /* create graphic context */
        XSelectInput(disp, win, ButtonPressMask | KeyPressMask | ExposureMask);
        XMapRaised(disp, win);                          /* display window; send Expose event */

        . . .
```

Figure 5-38. A skeleton of an X Window application program.

Graphical User Interfaces (2)

```
    . . .

    while (running) {
        XNextEvent(disp, &event);          /* get next event */
        switch (event.type) {
            case Expose:       ...;  break;      /* repaint window */
            case ButtonPress:  ...;  break;      /* process mouse click */
            case Keypress:     ...;  break;      /* process keyboard input */
        }
    }

    XFreeGC(disp, gc);                     /* release graphic context */
    XDestroyWindow(disp, win);             /* deallocate window's memory space */
    XCloseDisplay(disp);                   /* tear down network connection */
}
```

Figure 5-38. A skeleton of an X Window application program.

Graphical User Interfaces (3)

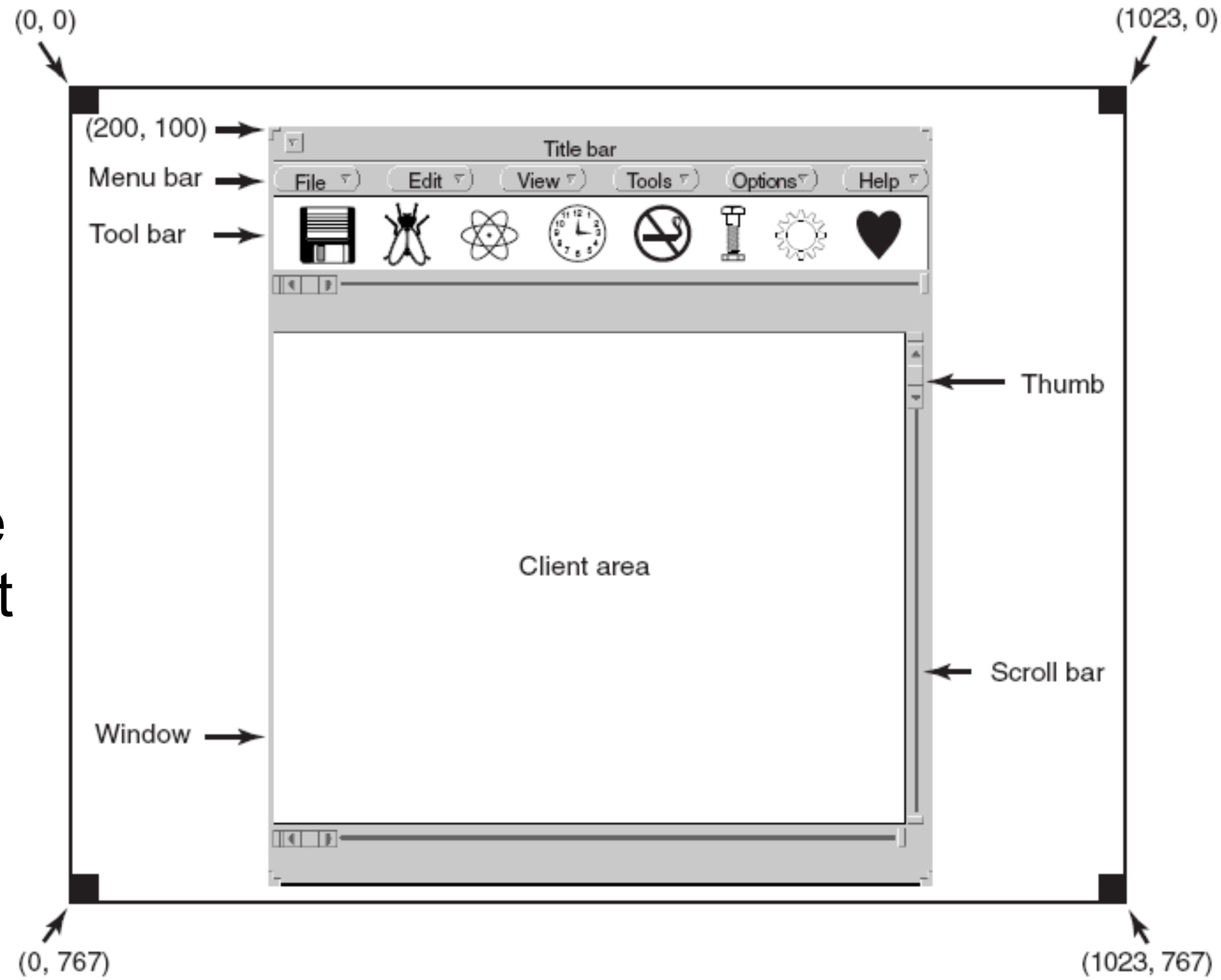


Figure 5-39. A sample window located at (200, 100) on an XGA display.

Graphical User Interfaces (4)

```
#include <windows.h>

int WINAPI WinMain(HINSTANCE h, HINSTANCE, hprev, char *szCmd, int iCmdShow)
{
     WNDCLASS wndclass;                   /* class object for this window */
     MSG msg;                             /* incoming messages are stored here */
     HWND hwnd;                           /* handle (pointer) to the window object */

     /* Initialize wndclass */
     wndclass.lpfnWndProc = WndProc;      /* tells which procedure to call */
     wndclass.lpszClassName = "Program name";     /* Text for title bar */
     wndclass.hIcon = LoadIcon(NULL, IDI_APPLICATION);     /* load program icon */
     wndclass.hCursor = LoadCursor(NULL, IDC_ARROW);       /* load mouse cursor */

     RegisterClass(&wndclass);            /* tell Windows about wndclass */
     hwnd = CreateWindow ( ... )          /* allocate storage for the window */
     ShowWindow(hwnd, iCmdShow);          /* display the window on the screen */
     UpdateWindow(hwnd);                  /* tell the window to paint itself */
   . . .
```

Figure 5-40. A skeleton of a Windows main program.

Graphical User Interfaces (5)

```
. . .
    while (GetMessage(&msg, NULL, 0, 0)) {          /* get message from queue */
        TranslateMessage(&msg);        /* translate the message */
        DispatchMessage(&msg);         /* send msg to the appropriate procedure */
    }
    return(msg.wParam);
}

long CALLBACK WndProc(HWND hwnd, UINT message, UINT wParam, long lParam)
{
    /* Declarations go here. */

    switch (message) {
        case WM_CREATE:     ... ;   return ... ;    /* create window */
        case WM_PAINT:      ... ;   return ... ;    /* repaint contents of window */
        case WM_DESTROY:    ... ;   return ... ;    /* destroy window */
    }
    return(DefWindowProc(hwnd, message, wParam, lParam));       /* default */
}
```

Figure 5-40. A skeleton of a Windows main program.

Bitmaps (1)

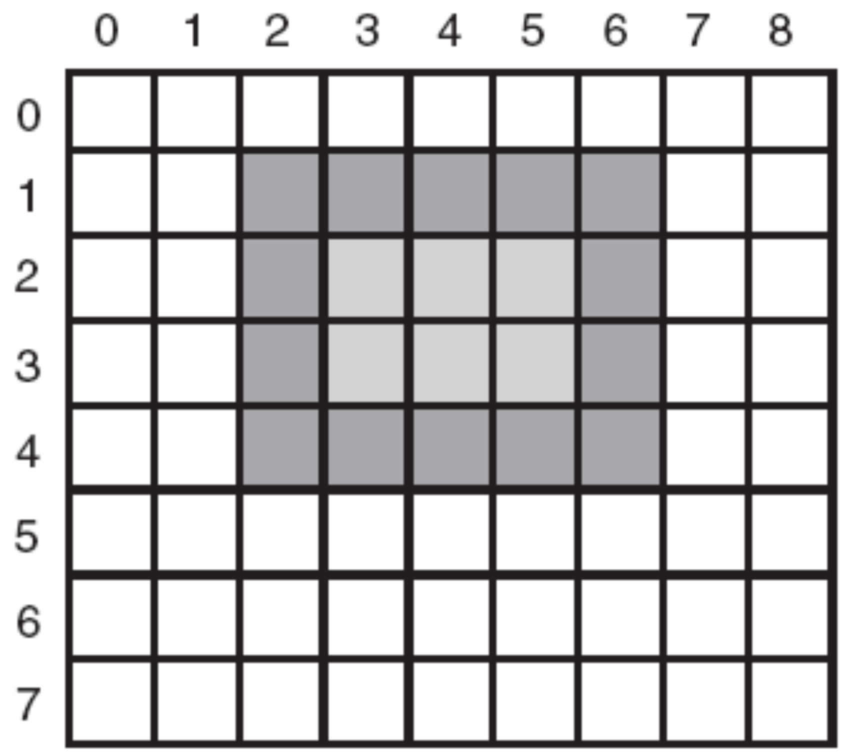


Figure 5-41. An example rectangle drawn using Rectangle. Each box represents one pixel.

Bitmaps (2)

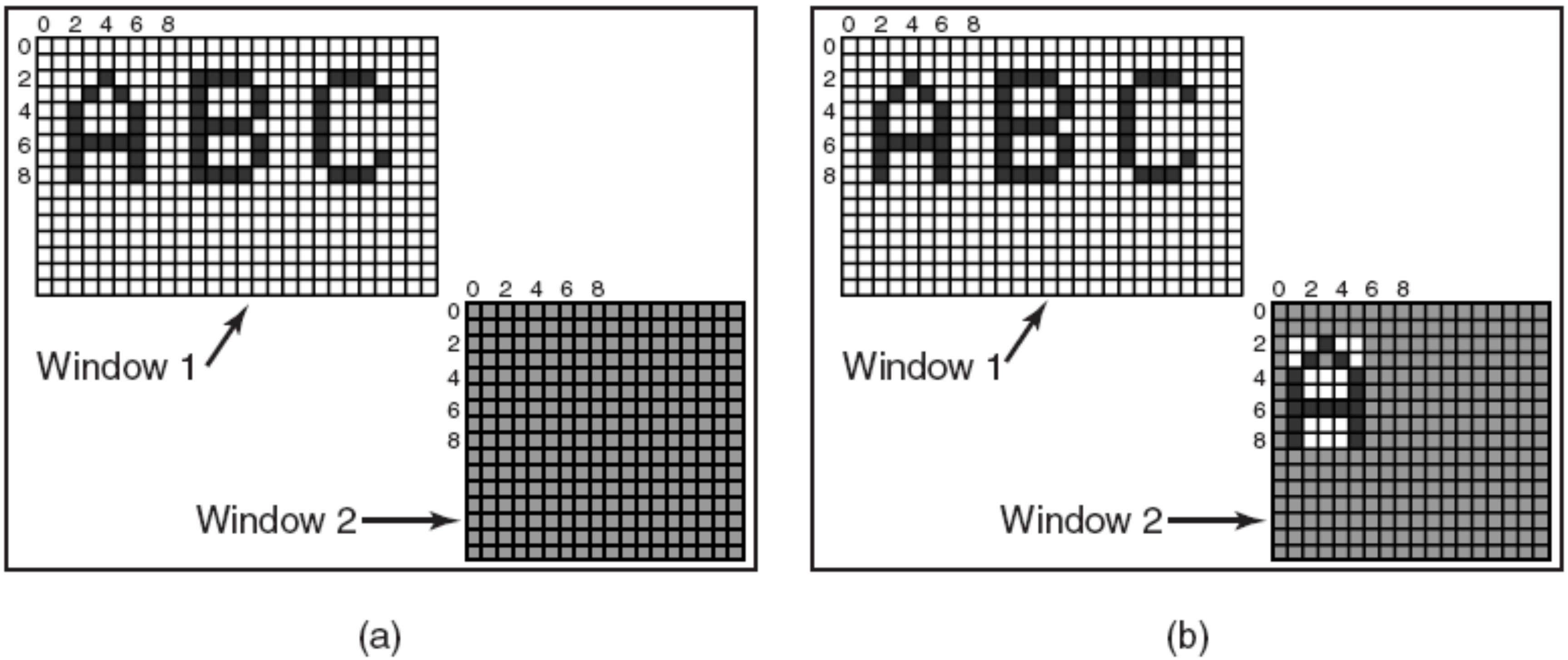


Figure 5-42. Copying bitmaps using *BitBlt*. (a) Before. (b) After.

Fonts

Figure 5-43. Some examples of character outlines at different point sizes.

Thin Clients

Command	Description
Raw	Display raw pixel data at a given location
Copy	Copy frame buffer area to specified coordinates
Sfill	Fill an area with a given pixel color value
Pfill	Fill an area with a given pixel pattern
Bitmap	Fill a region using a bitmap image

Figure 5-44. The THINC protocol display commands.

Power Management Hardware Issues

Device	Li et al. (1994)	Lorch and Smith (1998)
Display	68%	39%
CPU	12%	18%
Hard disk	20%	12%
Modem		6%
Sound		2%
Memory	0.5%	1%
Other		22%

Figure 5-45. Power consumption of various parts of a notebook computer.

Power Management
The Display

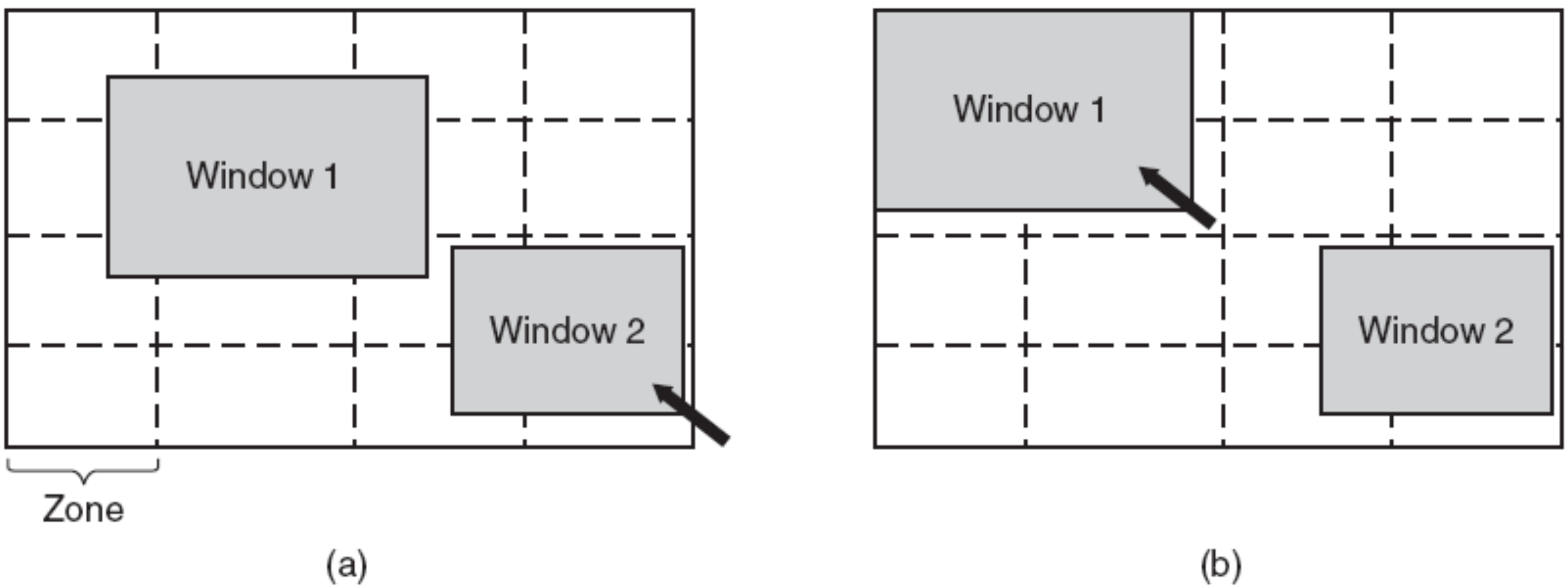


Figure 5-46. The use of zones for backlighting the display. (a) When window 2 is selected it is not moved. (b) When window 1 is selected, it moves to reduce the number of zones illuminated.

Power Management
The CPU

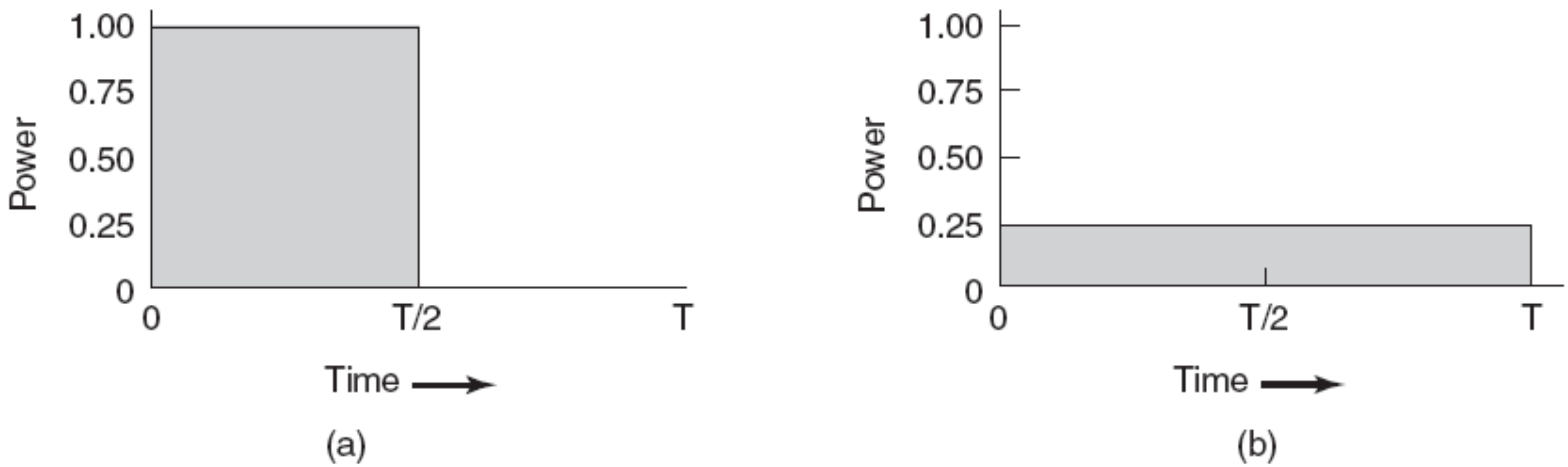


Figure 5-47. (a) Running at full clock speed. (b) Cutting voltage by two cuts clock speed by two and power consumption by four.