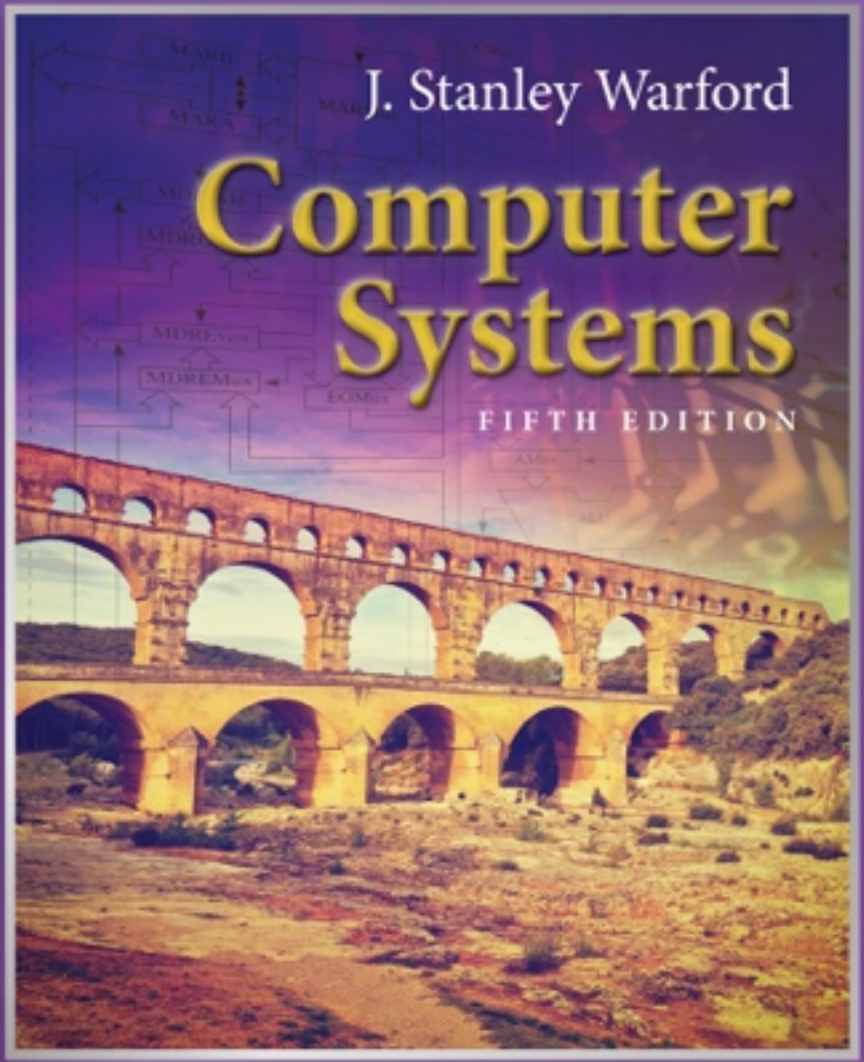
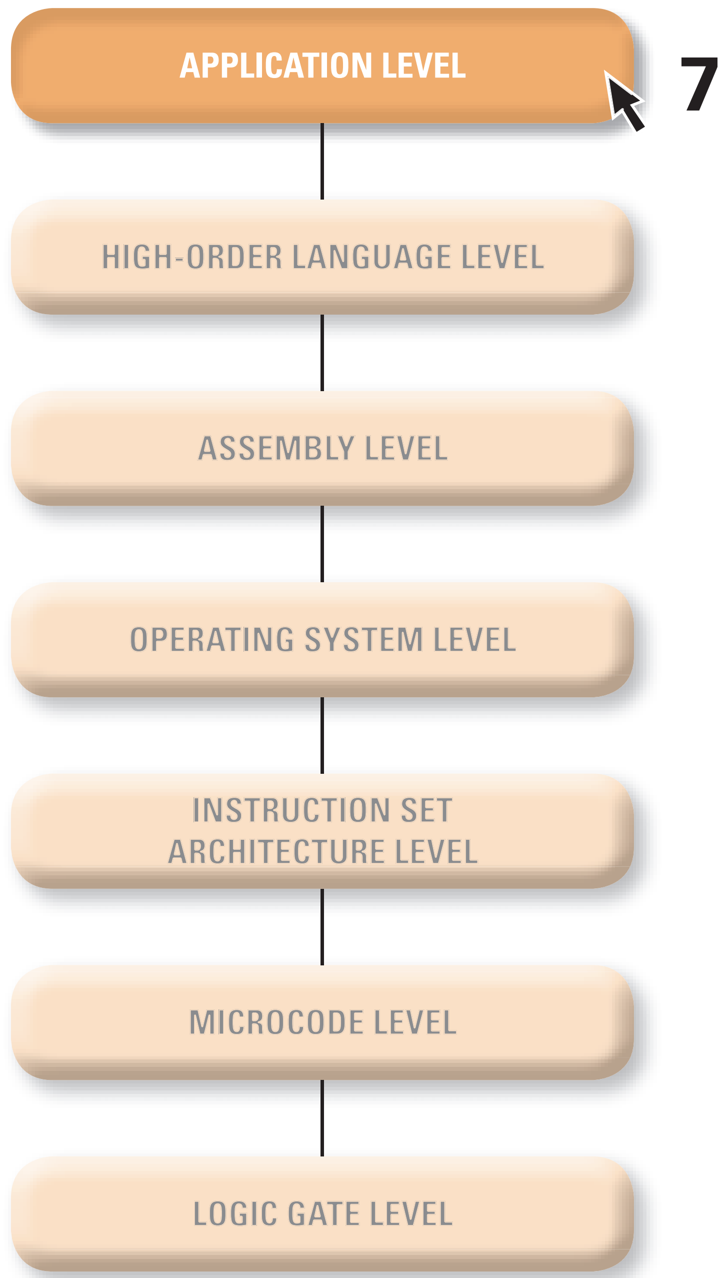
Chapter 1

Computer Systems

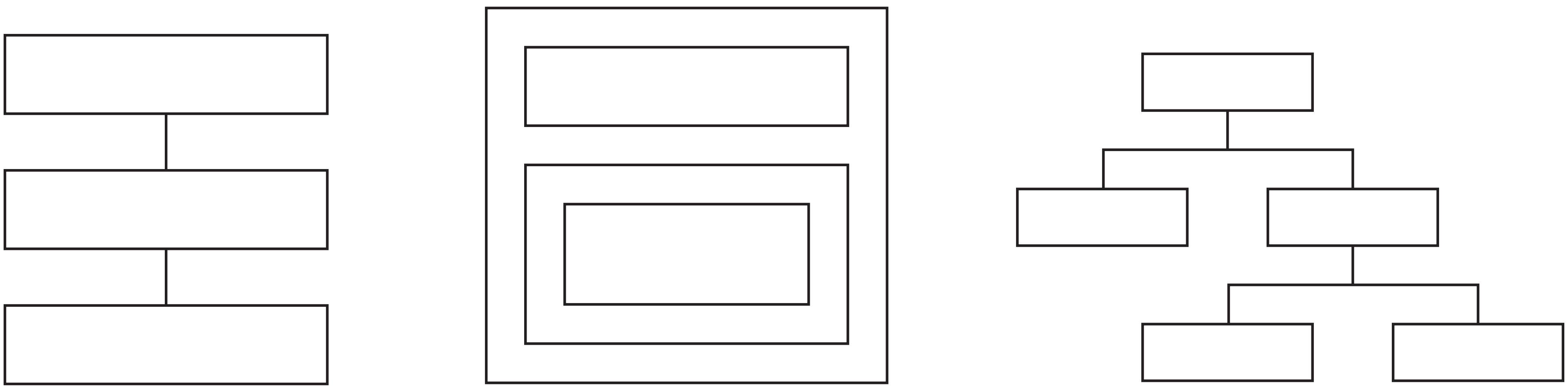


Application



Abstraction

- Suppression of detail to show the essence of the matter
- An outline structure
- Division of responsibility through a chain of command
- Subdivision of a system into smaller subsystems



(a) A level diagram. **(b)** A nesting diagram. **(c)** A hierarchy, or tree, diagram.

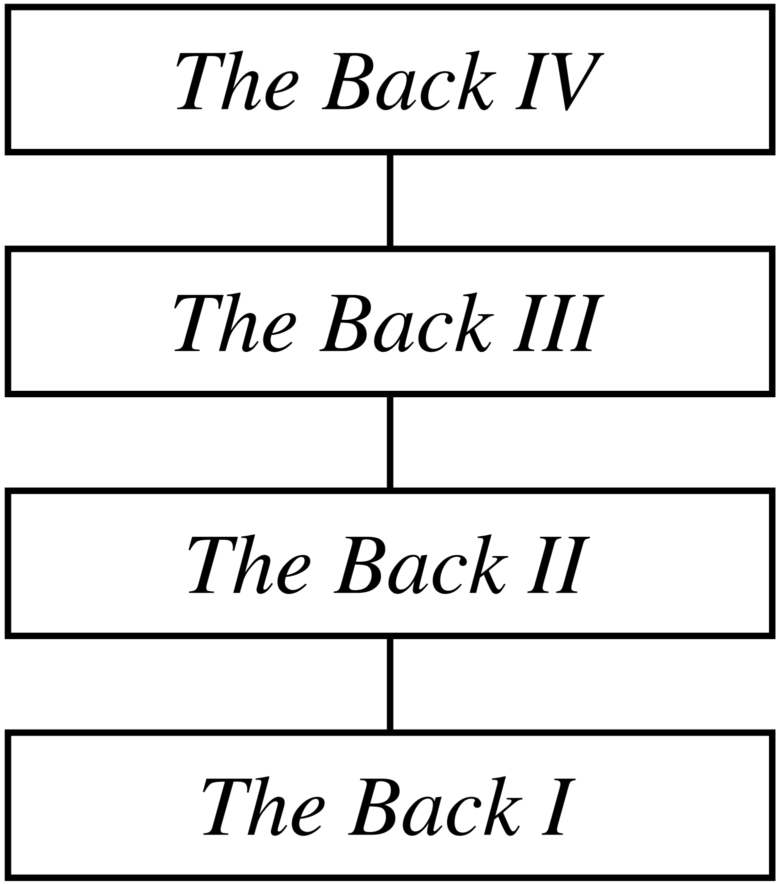
Henri Matisse

The Back I
1909

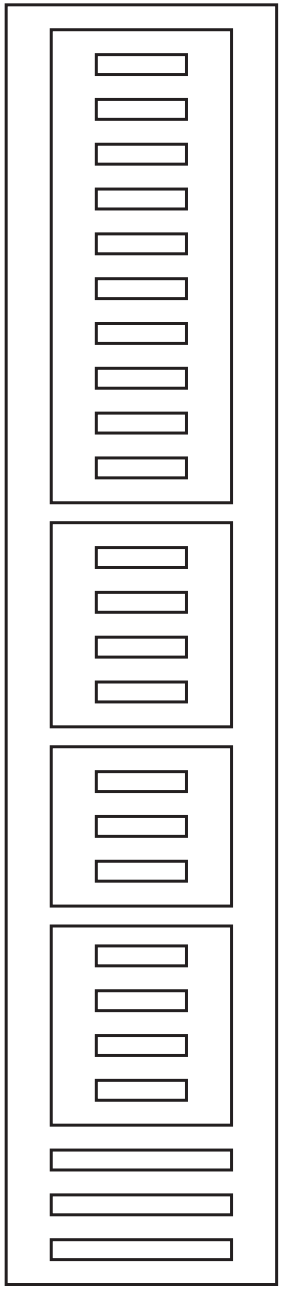
The Back II
1913

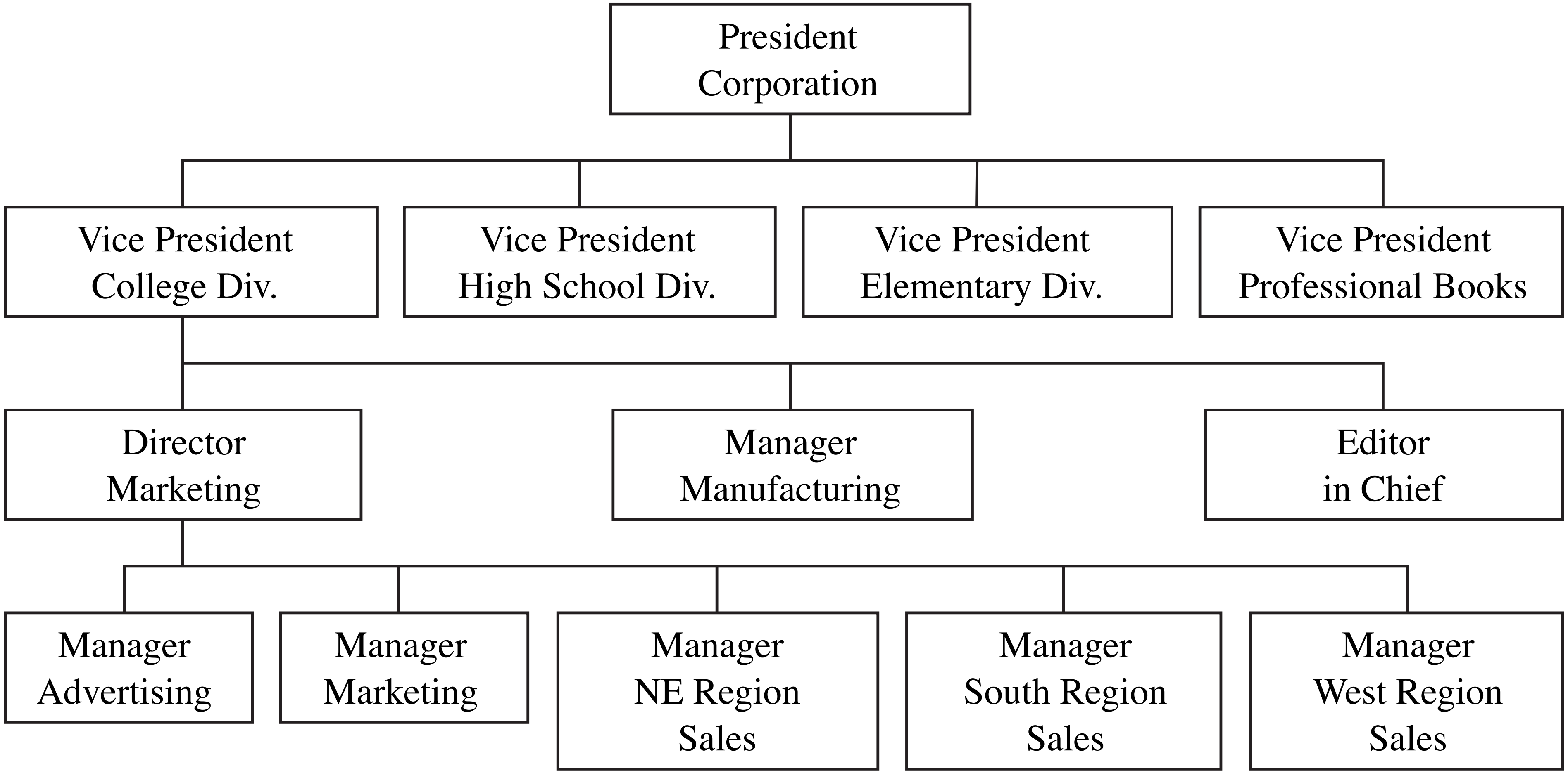
The Back III
1917

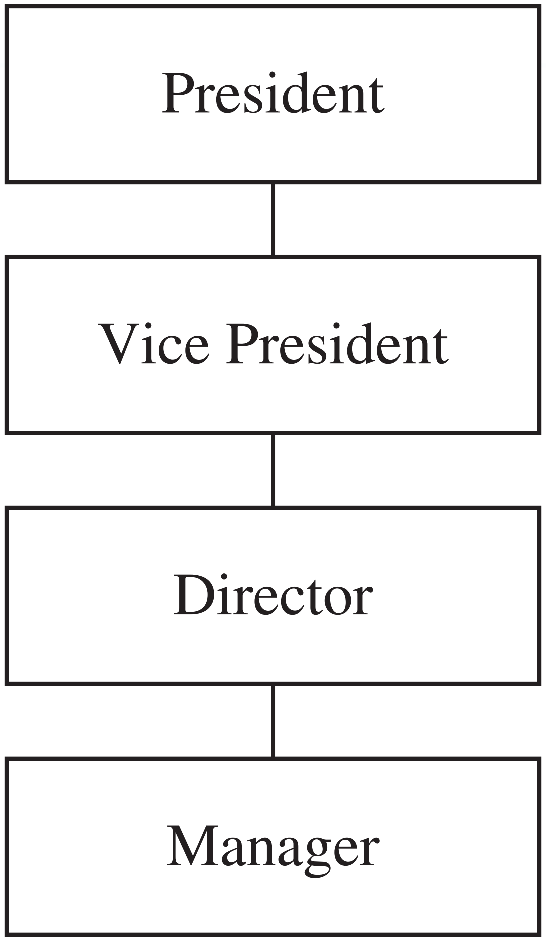
The Back IV
1930

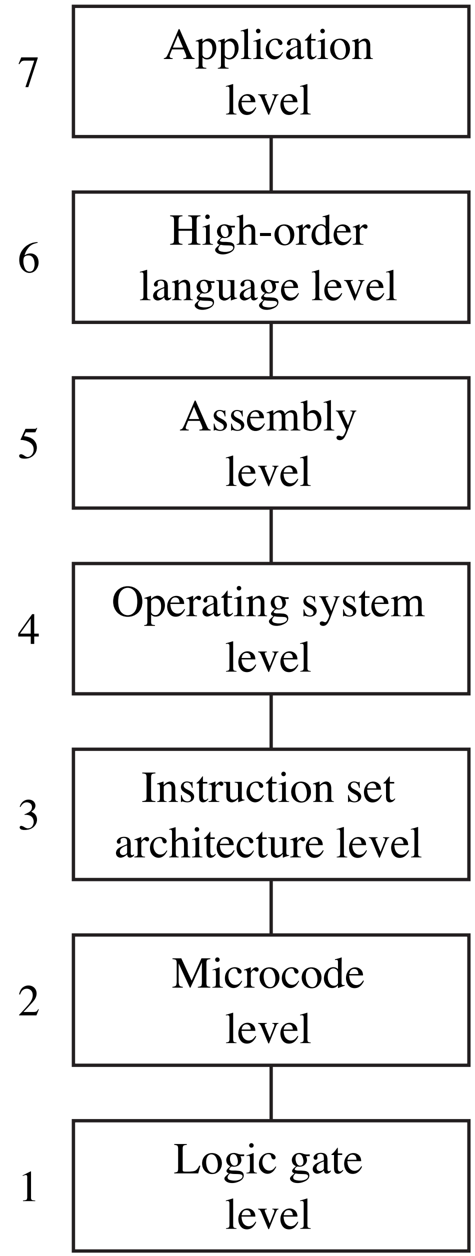

The Back IV
The Back III
The Back II
The Back I

United States Constitution
- Article I. Legislative Department
  - Section 1. Congress
  - ...
  - Section 10. Powers Prohibited to States
- Article II. Executive Department
  - ...
- Article III. Judicial Department
- Article IV. The States and the Federal Government
- Article V. Amendments
- Article VI. General Provisions
- Article VII. Ratification of the Constitution




President
Corporation
Vice President
College Div.
Vice President
High School Div.
Vice President
Elementary Div.
Vice President
Professional Books
Director
Marketing
Manager
Manufacturing
Editor
in Chief
Manager
Advertising
Manager
Marketing
Manager
NE Region
Sales
Manager
South Region
Sales
Manager
West Region
Sales

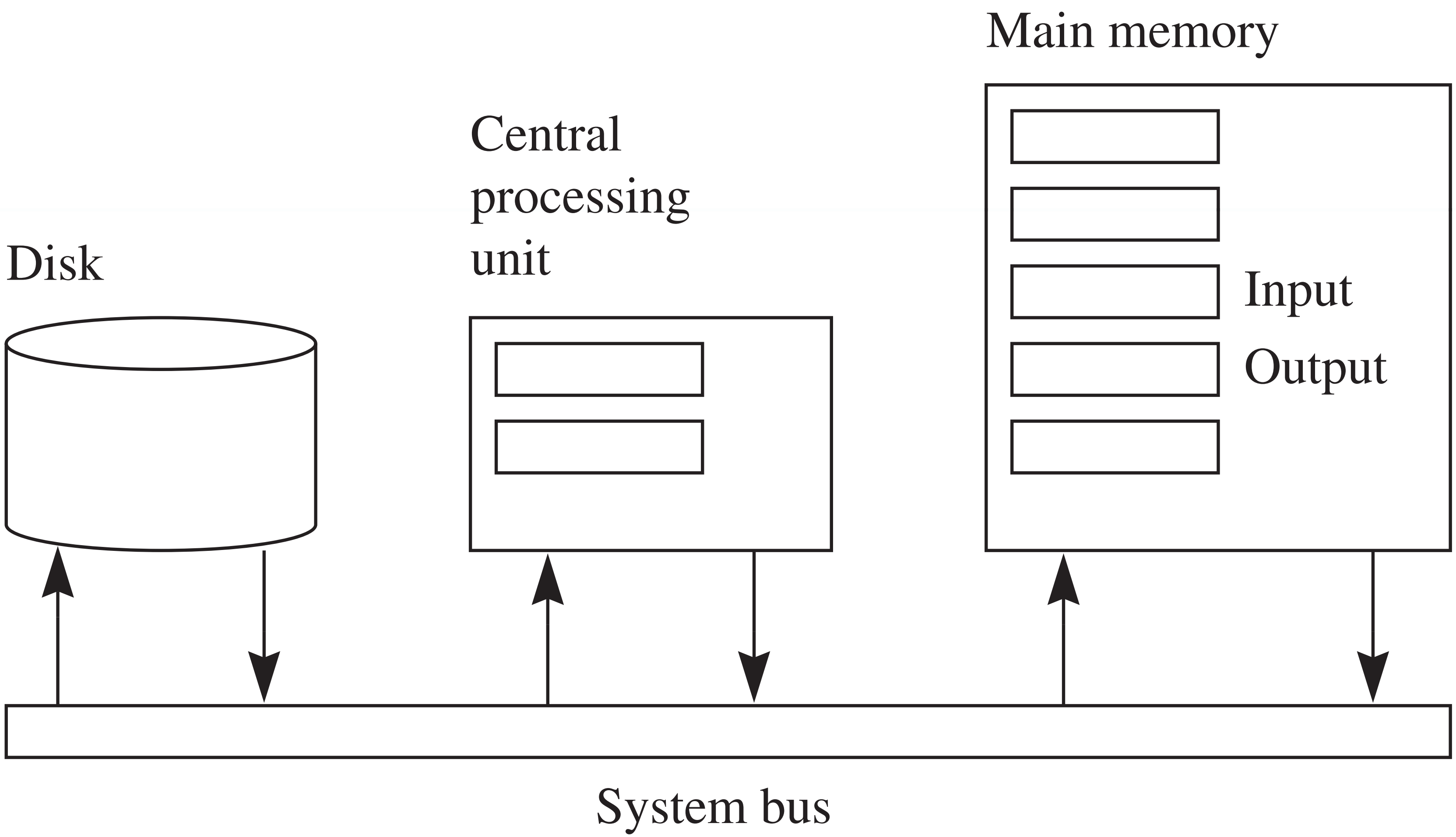

President
Vice President
Director
Manager


7
Application level
6
High-order language level
5
Assembly level
4
Operating system level
3
Instruction set architecture level
2
Microcode level
1
Logic gate level

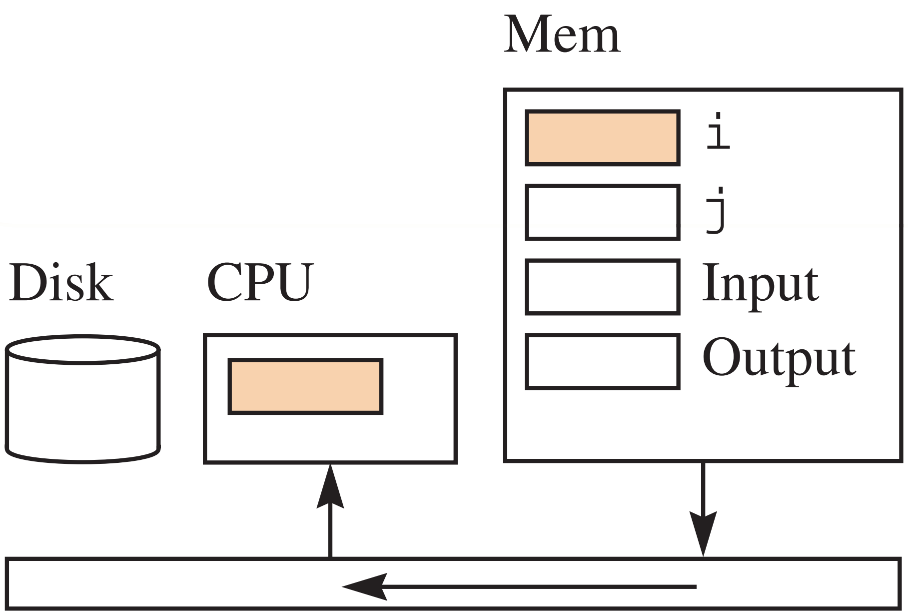
Some HOL6 languages

- *C* For programming operating systems
- *C++* For general applications; C with added object-oriented features
- *Python* A scripting language for web applications
- *Java* For general-purpose and web applications

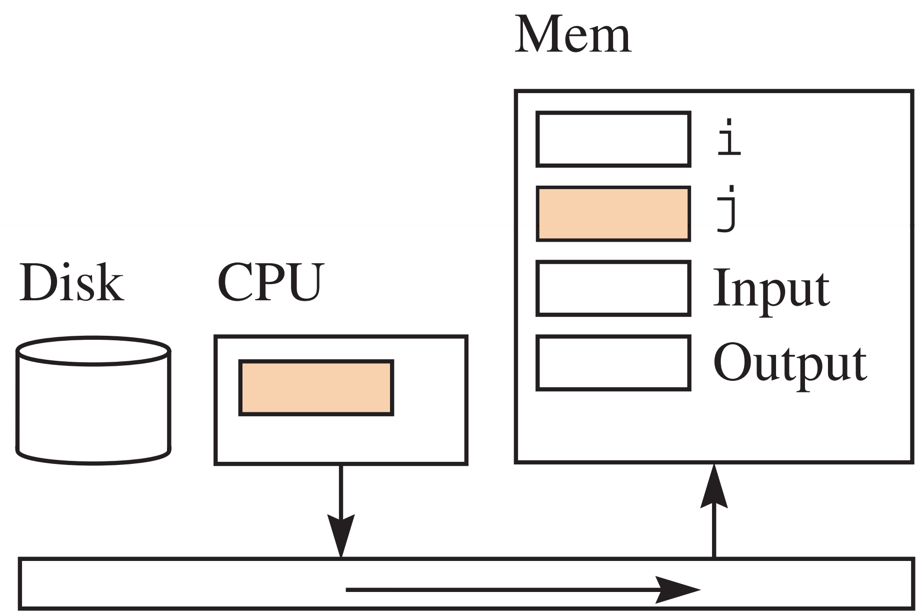
Activities of a computer system


Main memory
Central
processing
unit
Disk
Input
Output
System bus

`j = i + 1`

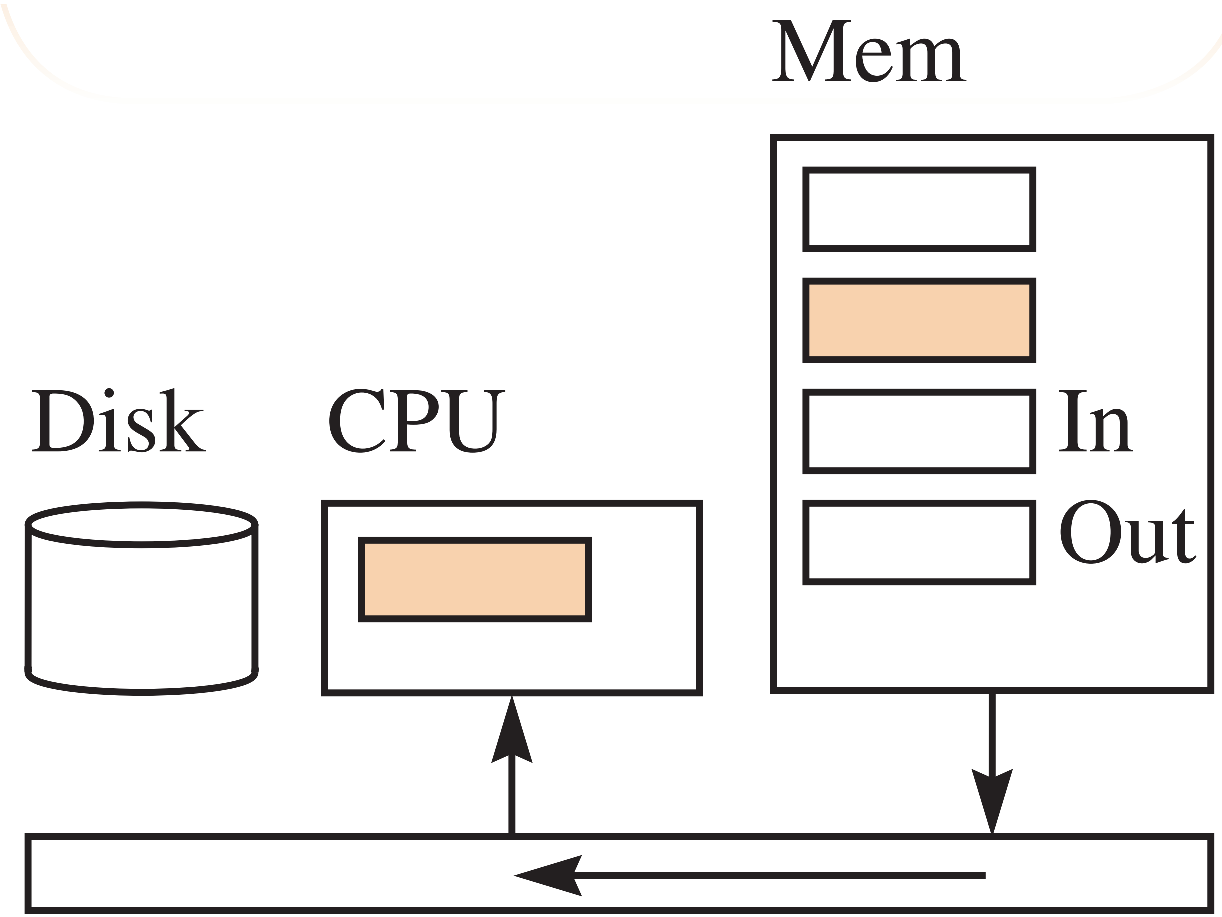


(a) The first Level ISA3 instruction: fetch the value of `i`.

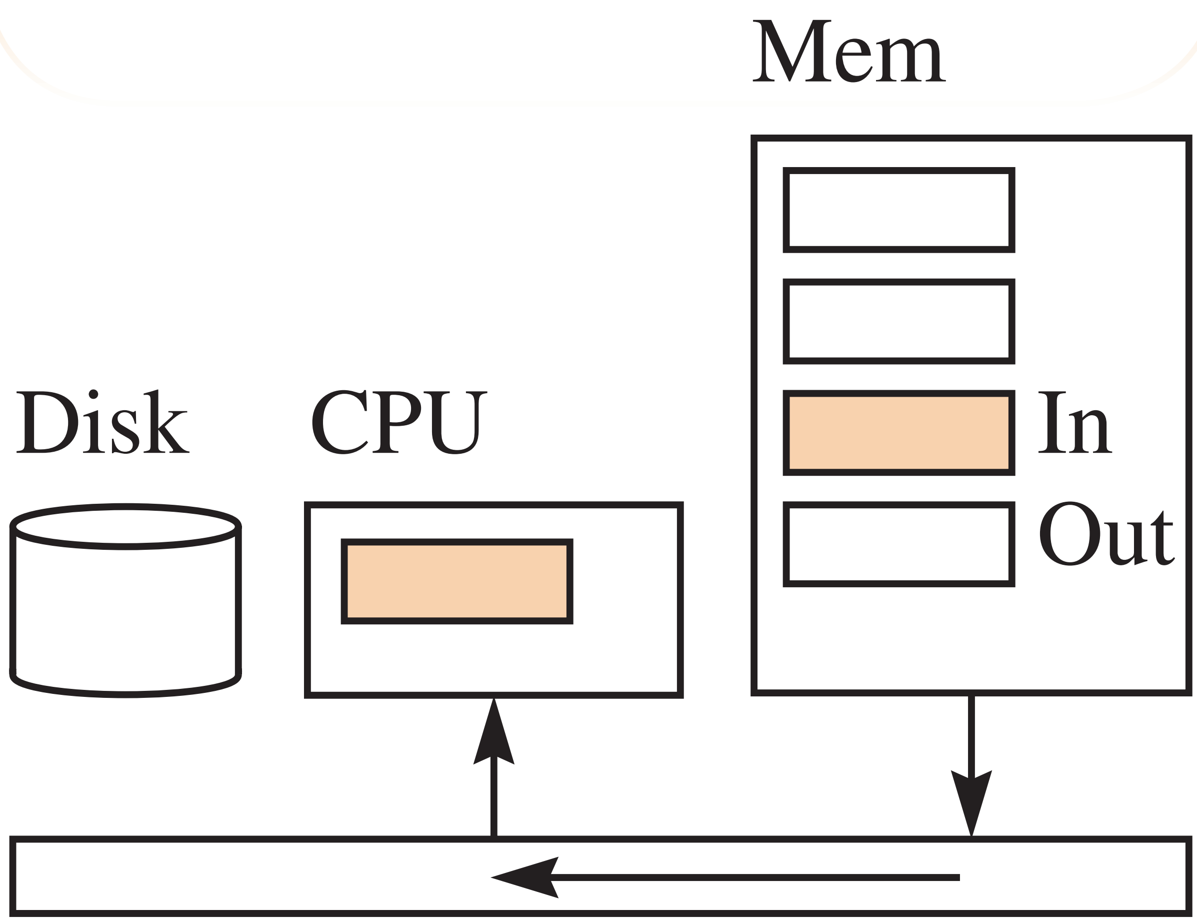


(b) The third Level ISA3 instruction: store the sum to `j`.

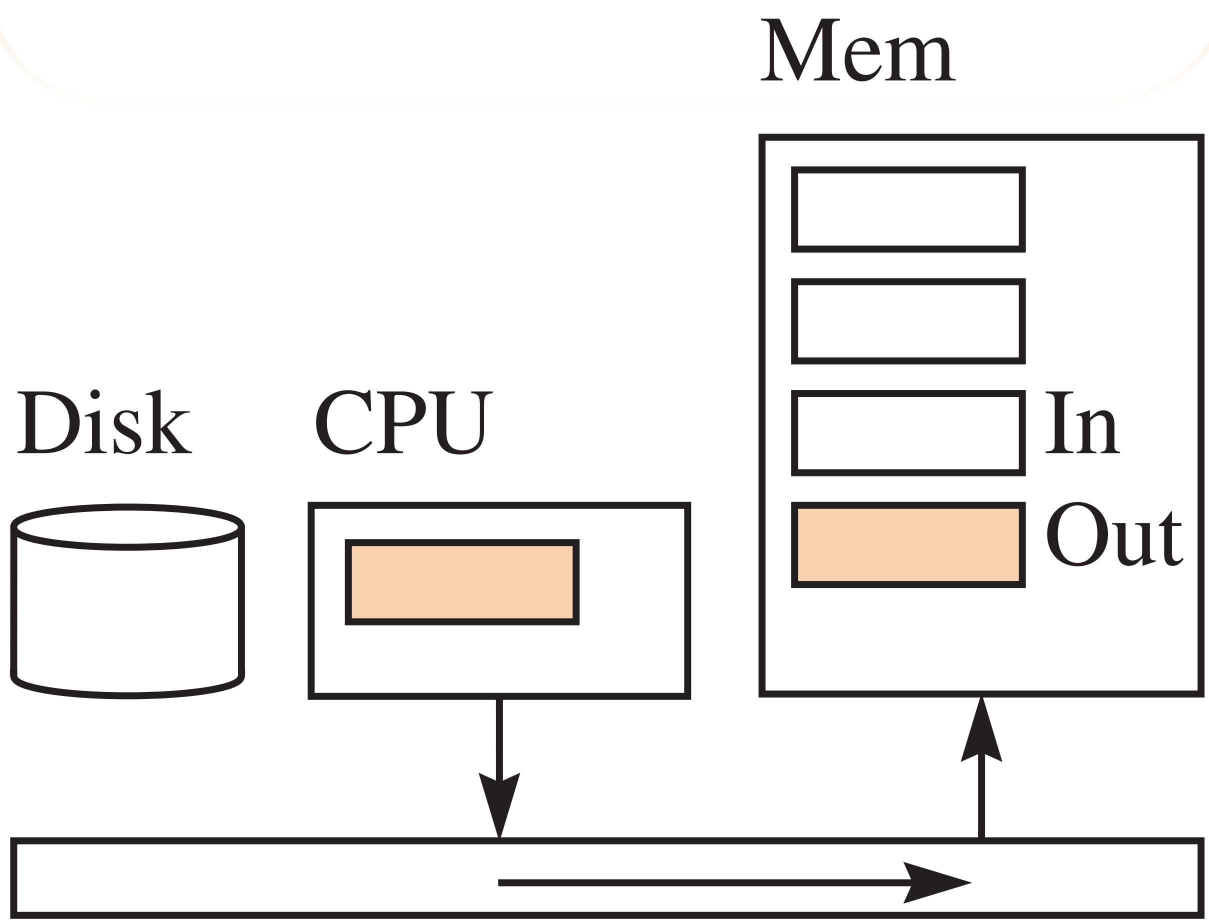
Fetch an instruction to be executed



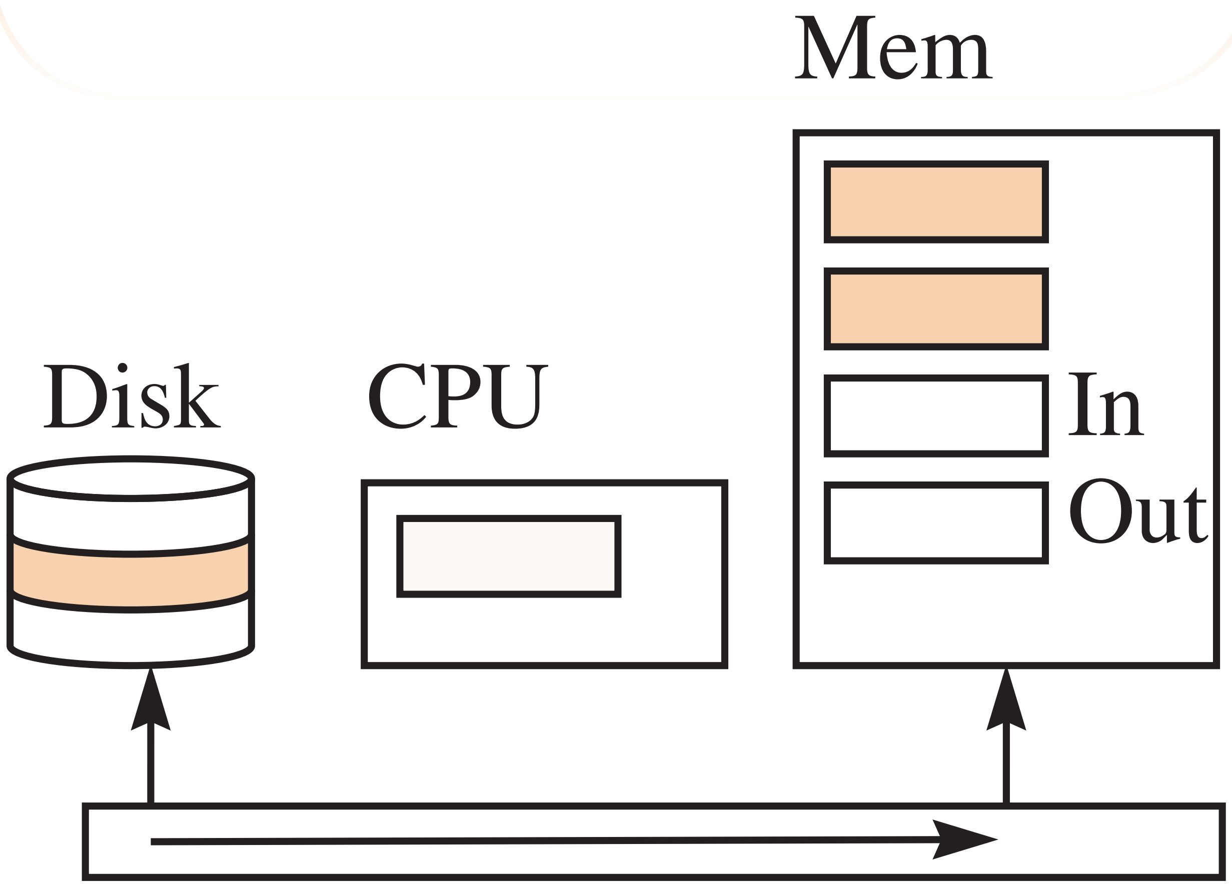
Receive a character from the keyboard



Send data to the output connection



Direct memory access



Software

- Algorithm
  - A set of instructions that, when carried out in the proper sequence, solves a problem in a finite amount of time
- Program
  - An algorithm written for execution on a computer

Ingredients

- 3 slightly beaten eggs
- ¼ cup sugar
- 2 cups milk, scalded
- ½ teaspoon vanilla

Algorithm

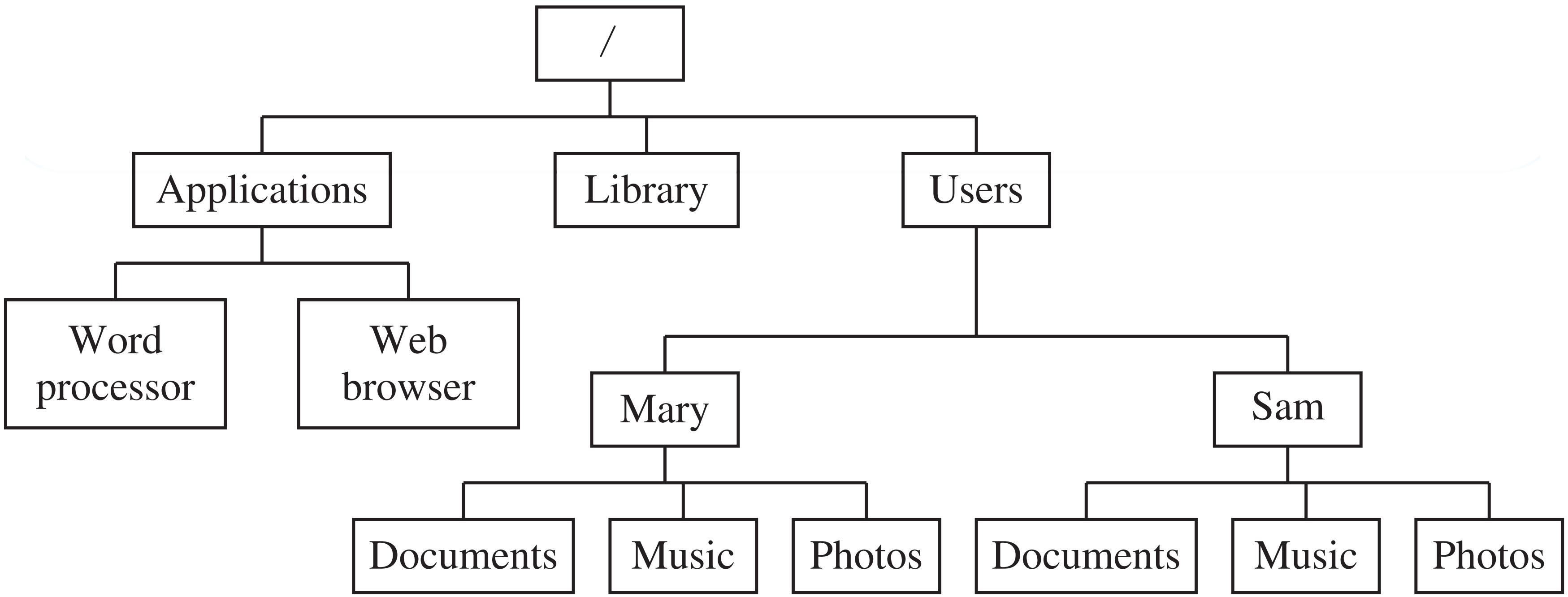
- Combine eggs, sugar, and ¼ teaspoon salt.
- Slowly stir in slightly cooled milk.
- Cook in double boiler over hot, not boiling, water, stirring constantly.
- As soon as custard coats metal spoon, remove from heat.
- Cool at once—place pan in cold water and stir a minute or two.
- Add vanilla.
- Chill.

Functions of an operating system

- File management
- Memory management
- Processor management

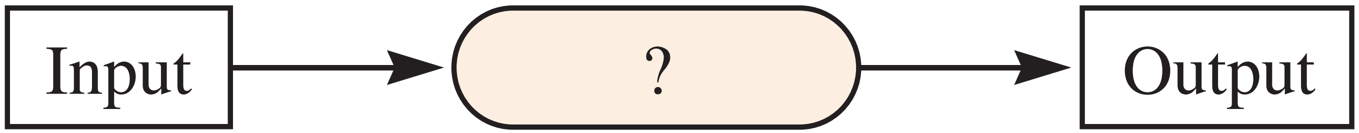
Types of information contained in files

- Documents
- Programs
- Data


/
Applications
Library
Users
Word processor
Web browser
Mary
Sam
Documents
Music
Photos
Documents
Music
Photos

(a) Analysis—The input and processing are given. The output is to be determined.

(a) Analysis—The input and processing are given. The output is to be determined.



(b) Design—The input and desired output are given. The processing is to be determined.

Quantifying space

- Bit – binary digit, 0 or 1
- Byte – 8 bits
- Character – 8 bits
    - Example: ‘q’ – 0111 0001
    - Example: ‘r’ – 0111 0010

Abbreviations

- Bit – b
- Byte – B

The number of values stored by a sequence of n bits is 2^n.

Decimal	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Multiple	Prefix	Prefix Letter
10^{-3}	milli-	m
10^{-6}	micro-	μ
10^{-9}	nano-	n
10^{-12}	pico-	p

Decimal Multiples	Decimal Prefix	Decimal Prefix Letter
$10^3 = 1000$	kilo-	K
$10^6 = 1000^2$	mega-	M
$10^9 = 1000^3$	giga-	G
$10^{12} = 1000^4$	tera-	T
$10^{15} = 1000^5$	peta-	P

(a) The decimal and binary prefixes.

Decimal Multiples	Decimal Prefix	Decimal Prefix Letter	Binary Multiples	Binary Prefix	Binary Prefix Letters
$10^3 = 1000$	kilo-	K	$2^{10} = 1024$	kibi-	Ki
$10^6 = 1000^2$	mega-	M	$2^{20} = 1024^2$	mebi-	Mi
$10^9 = 1000^3$	giga-	G	$2^{30} = 1024^3$	gibi-	Gi
$10^{12} = 1000^4$	tera-	T	$2^{40} = 1024^4$	tebi-	Ti
$10^{15} = 1000^5$	peta-	P	$2^{50} = 1024^5$	pebi-	Pi

(a) The decimal and binary prefixes.

Decimal Multiples	Binary Multiples	Percent Difference
$10^3 = 1000$	$2^{10} = 1024$	2.4%
$10^6 = 1,000,000$	$2^{20} = 1,048,576$	4.9%
$10^9 = 1,000,000,000$	$2^{30} = 1,073,741,824$	7.4%
$10^{12} = 1,000,000,000,000$	$2^{40} = 1,099,511,627,776$	10.0%
$10^{15} = 1,000,000,000,000,000$	$2^{50} = 1,125,899,906,842,624$	12.6%

(b) The differences between the decimal and binary values.

The system performance equation

$$\frac{\text{time}}{\text{program}} = \frac{\text{instructions}}{\text{program}} \times \frac{\text{cycles}}{\text{instruction}} \times \frac{\text{time}}{\text{cycle}}$$

The system performance equation

$$\frac{\text{time}}{\text{program}} = \frac{\text{instructions}}{\text{program}} \times \frac{\text{cycles}}{\text{instruction}} \times \frac{\text{time}}{\text{cycle}}$$

$$T = \frac{1}{f}$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

time/program

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
& \text{time/program} \\
= \quad & \langle \text{System performance equation} \rangle
\end{aligned}
$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
& \text{time/program} \\
= \quad & \langle \text{System performance equation} \rangle \\
& (\text{instructions/program}) \times (\text{cycles/instruction}) \times (\text{time/cycle})
\end{aligned}
$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
&\quad \text{time/program} \\
&= \quad \langle \text{System performance equation} \rangle \\
&\quad (\text{instructions/program}) \times (\text{cycles/instruction}) \times (\text{time/cycle}) \\
&= \quad \langle \text{Substitute values with } T = 1/f \text{ for the third term} \rangle
\end{aligned}
$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
& \text{time/program} \\
= \quad & \langle \text{System performance equation} \rangle \\
& (\text{instructions/program}) \times (\text{cycles/instruction}) \times (\text{time/cycle}) \\
= \quad & \langle \text{Substitute values with } T = 1/f \text{ for the third term} \rangle \\
& (16 \times 10^6) \times (3.7) \times (1/(2.5 \times 10^9))
\end{aligned}
$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
& \text{time/program} \\
= \quad & \langle \text{System performance equation} \rangle \\
& (\text{instructions/program}) \times (\text{cycles/instruction}) \times (\text{time/cycle}) \\
= \quad & \langle \text{Substitute values with } T = 1/f \text{ for the third term} \rangle \\
& (16 \times 10^6) \times (3.7) \times (1/(2.5 \times 10^9)) \\
= \quad & \langle \text{Math} \rangle
\end{aligned}
$$

Example 1.1 Suppose your CPU is rated at 2.5 GHz and you execute a program task on your app that requires the execution of 16 million ISA3 instructions. If each ISA3 instruction executes an average of 3.7 Mc2 instructions, what is the execution time of the program task?

$$
\begin{aligned}
& \text{time/program} \\
= \quad & \langle \text{System performance equation} \rangle \\
& (\text{instructions/program}) \times (\text{cycles/instruction}) \times (\text{time/cycle}) \\
= \quad & \langle \text{Substitute values with } T = 1/f \text{ for the third term} \rangle \\
& (16 \times 10^6) \times (3.7) \times (1/(2.5 \times 10^9)) \\
= \quad & \langle \text{Math} \rangle \\
& 23.7 \text{ ms}
\end{aligned}
$$

So, the time is 23.7×10^{-3} seconds, or about 0.024 seconds.

The bandwidth equation

$$\text{information} = \frac{\text{information}}{\text{time}} \times \text{time}$$

The bandwidth equation

$$\text{information} = \underbrace{\frac{\text{information}}{\text{time}}}_{\text{Bandwidth}} \times \text{time}$$

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute. 245

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute.

245

bandwidth

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute. 245

$$
\begin{aligned}
& \text{bandwidth} \\
= \quad & \langle \text{Definition of bandwidth} \rangle
\end{aligned}
$$

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute. 245

$$
\begin{aligned}
& \text{bandwidth} \\
= \quad & \langle \text{Definition of bandwidth} \rangle \\
& \text{information/time}
\end{aligned}
$$

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute.

245

bandwidth
$=$ ⟨Definition of bandwidth⟩
information/time
$=$ ⟨Substitute values⟩

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute.

245

$$
\begin{array}{ll}
& \text{bandwidth} \\
= & \langle \text{Definition of bandwidth} \rangle \\
& \text{information/time} \\
= & \langle \text{Substitute values} \rangle \\
& (8(\text{b/char}) \times \boxed{36\ \text{char}})/(1(\text{min}) \times 60(\text{s/min})) \qquad 245\ \text{char}
\end{array}
$$

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute. 245

$$
\begin{array}{ll}
 & \text{bandwidth} \\
= & \langle \text{Definition of bandwidth} \rangle \\
 & \text{information/time} \\
= & \langle \text{Substitute values} \rangle \\
 & (8(\text{b/char}) \times \boxed{36\ \text{char}})/(1(\text{min}) \times 60(\text{s/min})) \qquad \text{245 char} \\
= & \langle \text{Math} \rangle
\end{array}
$$

ERRATUM in text: Assume each word is six characters long on average.

Example 1.3 A typist is entering some text on a computer keyboard at the rate of 35 words per minute. How large must the bandwidth of the channel be to accommodate the information flow between the typist and the computer system? Assume that each word is followed by one space character, on average.

Including one space character after each word, the typist enters $\boxed{36}$ characters per minute. 245

bandwidth

$=$ ⟨Definition of bandwidth⟩

information/time

$=$ ⟨Substitute values⟩

$(8(\text{b/char}) \times \boxed{36\ \text{char}})/(1(\text{min}) \times 60(\text{s/min}))$ 245 char

$=$ ⟨Math⟩

$\boxed{4.8\ \text{b/s}}$ 32.7 b/s

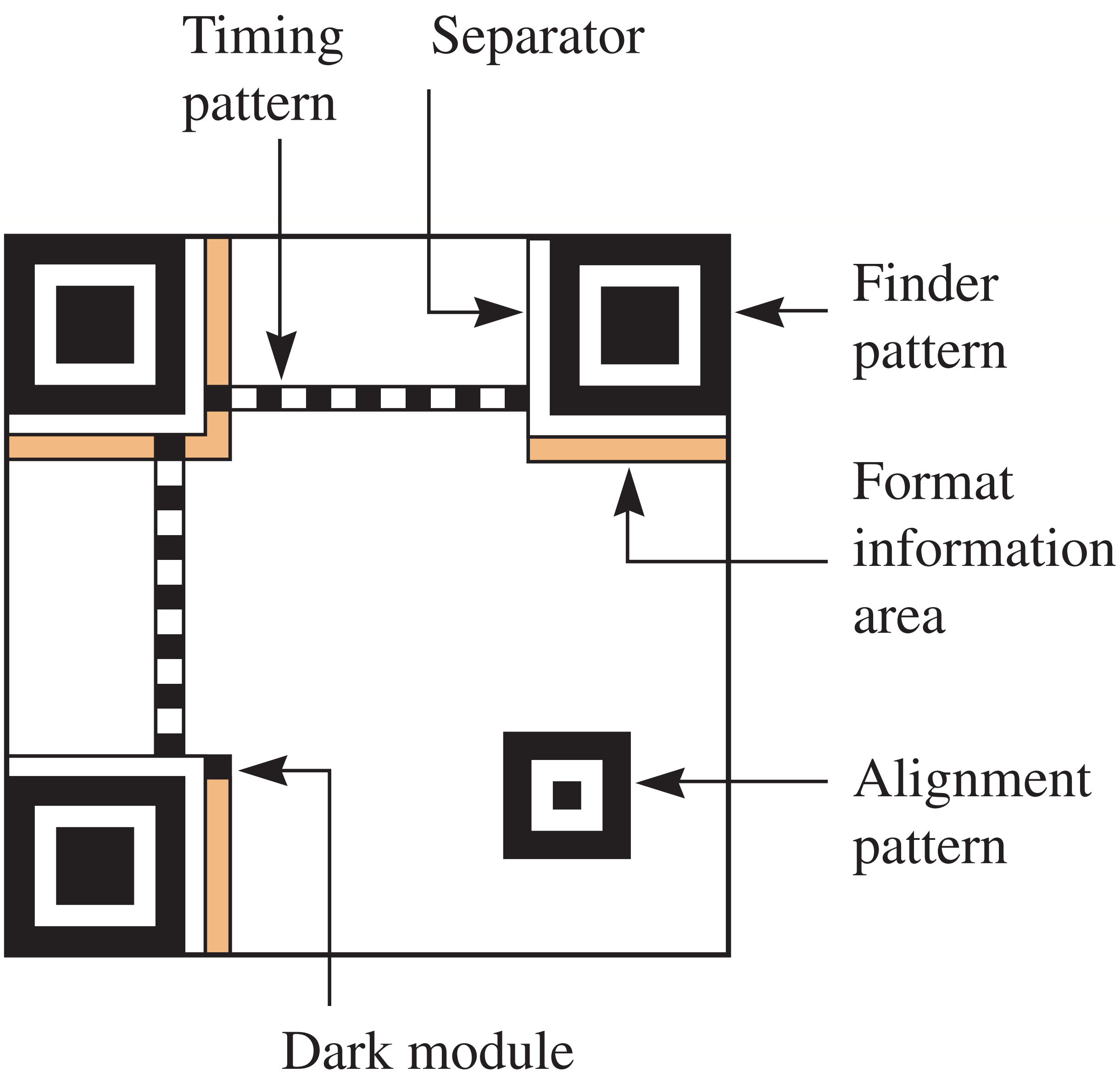
QR codes

(a) The QR code for a web URL.

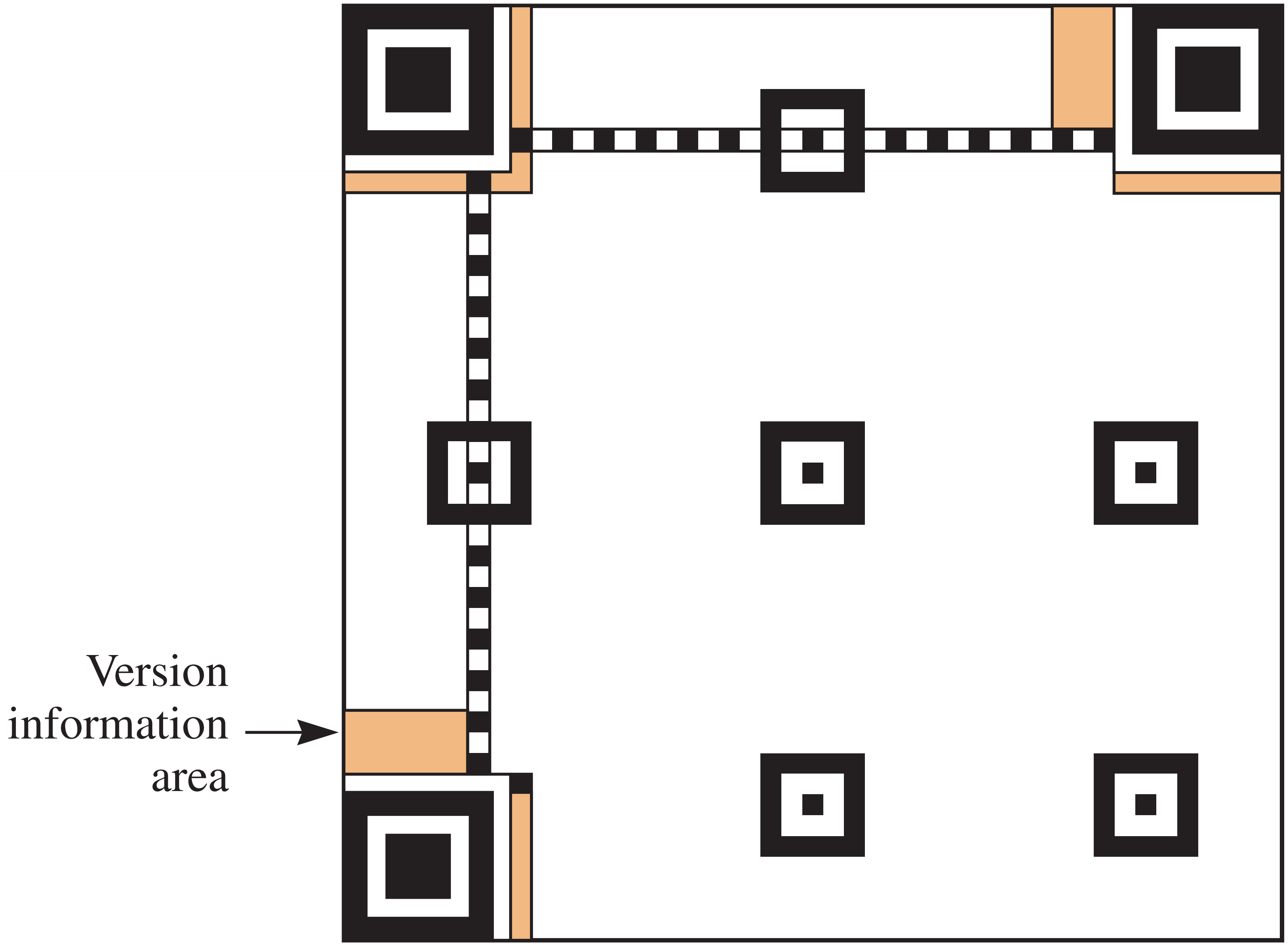
(b) The QR code for the text of the first paragraph of this chapter.

QR code format regions

- Finder patterns
- Separators
- The dark module
- The format information area
- Timing patterns
- Alignment patterns (for Version 2 and higher)
- The version information area (for Version 7 and higher)



(a) The regions in the Version 3 QR code of Figure 1.21(a).



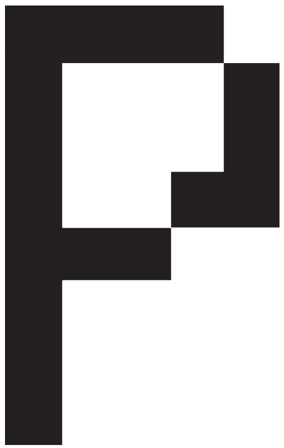
(b) The regions in a Version 7 code.

QR code information bits

- The mode indicator
- The character count indicator
- The redundant bits for error correction
- The data bits

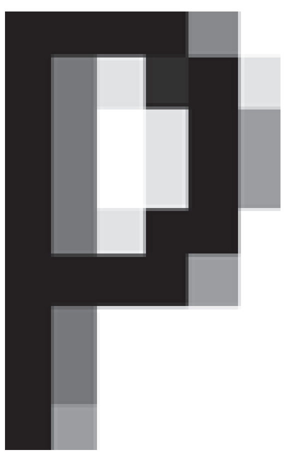
Correction at Level	Will Correct the Data With
L	7% damaged.
M	15% damaged.
Q	25% damaged.
H	30% damaged.

Images

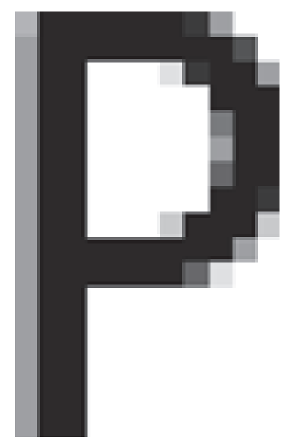


(a) Black and white, 5 × 8.

(b) Black and white, 11 × 16.

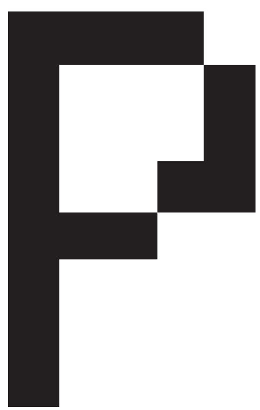


(c) Grayscale, 6 × 9.



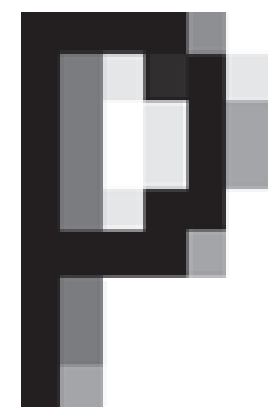
(d) Grayscale, 11 × 17.

1	1	1	1	0
1	0	0	0	1
1	0	0	0	1
1	0	0	1	1
1	1	1	0	0
1	0	0	0	0
1	0	0	0	0
1	0	0	0	0



(a) Storage for the image in Figure 1.24(a).

111	111	111	111	010	000
111	101	001	101	111	001
111	101	000	001	111	010
111	101	000	001	111	010
111	101	001	101	111	000
111	111	111	110	010	000
111	101	000	000	000	000
111	101	000	000	000	000
111	010	000	000	000	000

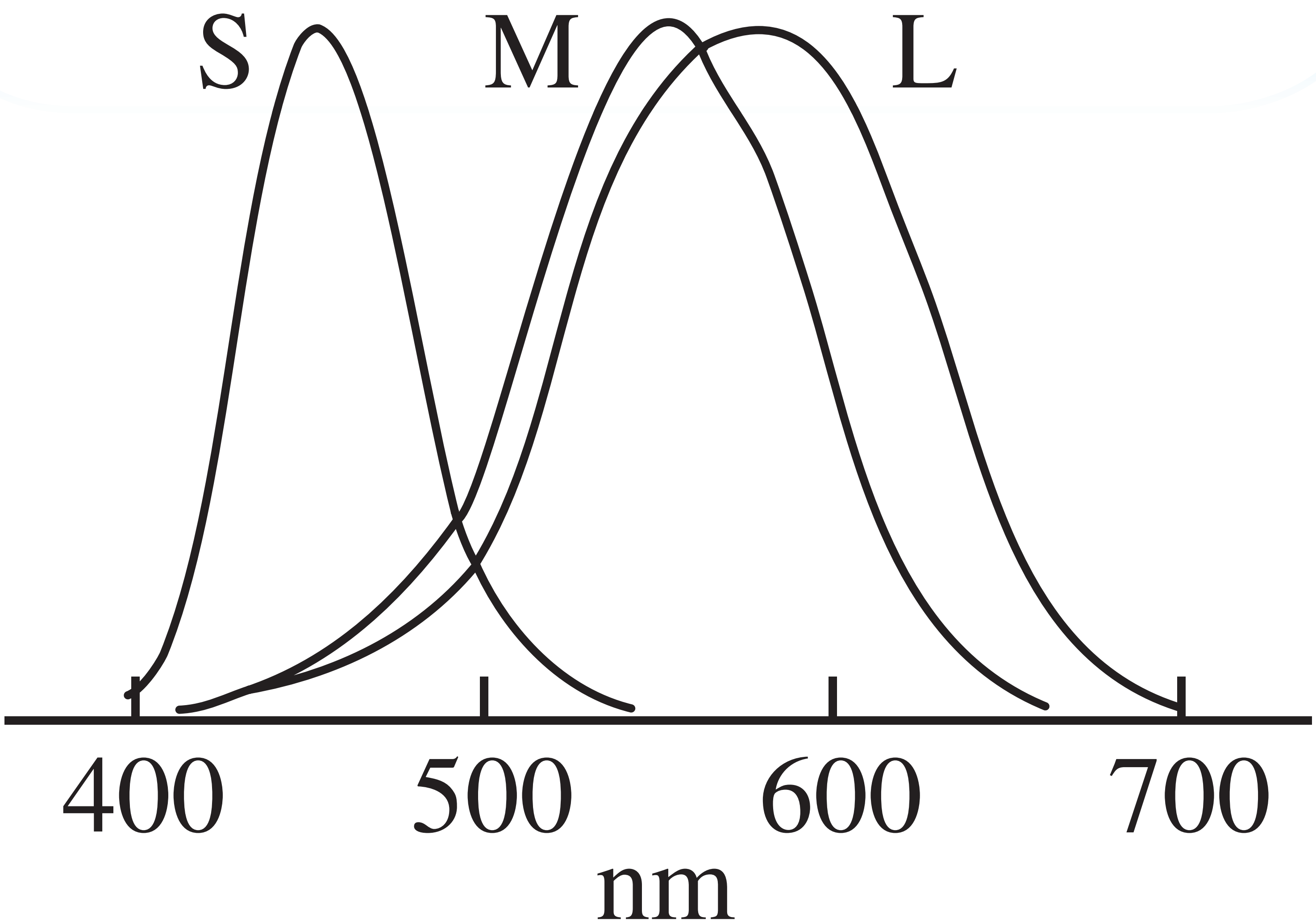


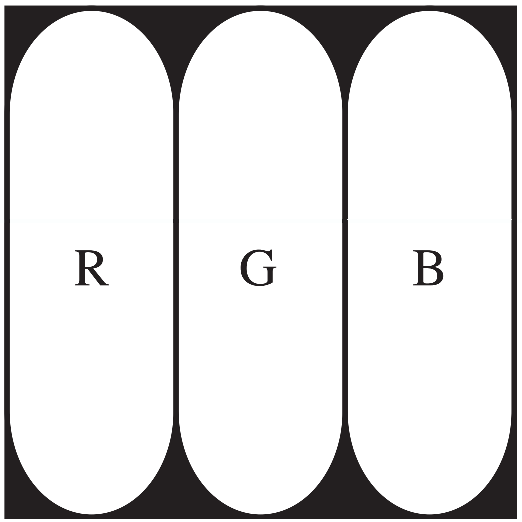
(b) Storage for the image in Figure 1.24(c).

Color images

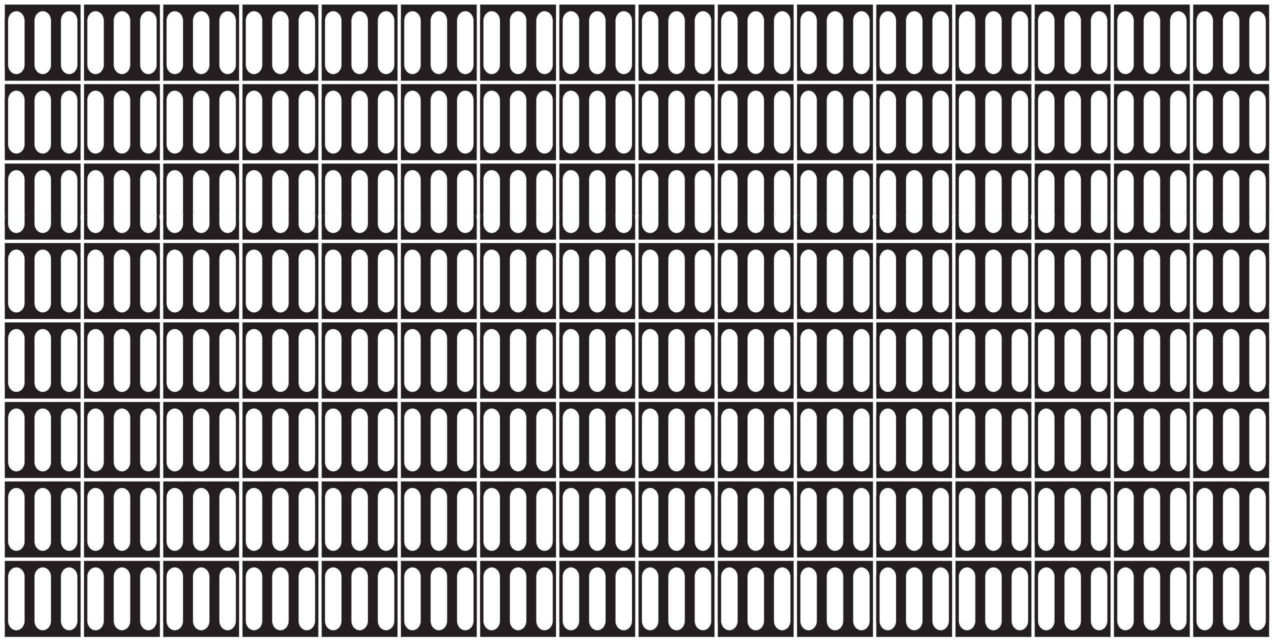
Figure 1.26

Color	Wavelength
Violet	400–450 nm
Blue	450–495 nm
Green	495–570 nm
Yellow	570–590 nm
Orange	590–620 nm
Red	620–700 nm


S
M
L
400
500
600
700
nm



(a) A single-color pixel with three subpixels.



(b) A 16- × 8-pixel portion of a color display.

Figure 1.29

Color	Red	Green	Blue
White	255	255	255
Silver	192	192	192
Gray	128	128	128
Black	0	0	0
Red	255	0	0
Maroon	128	0	0
Yellow	255	255	0
Olive	128	128	0
Lime	0	255	0
Green	0	128	0
Aqua	0	255	255
Teal	0	128	128
Blue	0	0	255
Navy	0	0	128
Fuchsia	255	0	255
Purple	128	0	128

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

number of pixels

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
&\text{number of pixels} \\
= \quad &\langle \text{Product} \rangle
\end{aligned}
$$

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
& \text{number of pixels} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number in width}) \times (\text{number in height})
\end{aligned}
$$

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
& \text{number of pixels} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number in width}) \times (\text{number in height}) \\
= \quad & \langle \text{Substitute values} \rangle
\end{aligned}
$$

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
& \text{number of pixels} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number in width}) \times (\text{number in height}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (4.5\text{ in.} \times 120\text{ pixels/in.}) \times (2.5\text{ in.} \times 120\text{ pixels/in.})
\end{aligned}
$$

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
& \text{number of pixels} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number in width}) \times (\text{number in height}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (4.5 \text{ in.} \times 120 \text{ pixels/in.}) \times (2.5 \text{ in.} \times 120 \text{ pixels/in.}) \\
= \quad & \langle \text{Math} \rangle
\end{aligned}
$$

Example 1.7 A GPS system in an automobile has a 4.5- × 2.5-inch screen with 120 color pixels per inch. Each subpixel color can display 64 levels of brightness. What is the KiB size of the display memory?

First, determine the total number of pixels in the display.

$$
\begin{aligned}
& \text{number of pixels} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number in width}) \times (\text{number in height}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (4.5 \text{ in.} \times 120 \text{ pixels/in.}) \times (2.5 \text{ in.} \times 120 \text{ pixels/in.}) \\
= \quad & \langle \text{Math} \rangle \\
& 162{,}000 \text{ pixels}
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

size of display memory

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$\begin{aligned} & \text{size of display memory} \\ = \quad & \langle \text{Product} \rangle \end{aligned}$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels})
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{array}{ll}
 & \text{size of display memory} \\
= & \langle \text{Product} \rangle \\
 & (\text{number of pixels}) \times (\text{bit pixels}) \\
= & \langle \text{Substitute values} \rangle
\end{array}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (162{,}000 \text{ pixels}) \times 18(\text{b/pixel})
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (162{,}000 \text{ pixels}) \times 18(\text{b/pixel}) \\
= \quad & \langle \text{Math} \rangle
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (162{,}000 \text{ pixels}) \times 18(\text{b/pixel}) \\
= \quad & \langle \text{Math} \rangle \\
& 2{,}916{,}000 \text{ b}
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (162{,}000 \text{ pixels}) \times 18(\text{b/pixel}) \\
= \quad & \langle \text{Math} \rangle \\
& 2{,}916{,}000 \text{ b} \\
= \quad & \langle \text{Convert to KiB} \rangle
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{aligned}
& \text{size of display memory} \\
= \quad & \langle \text{Product} \rangle \\
& (\text{number of pixels}) \times (\text{bit pixels}) \\
= \quad & \langle \text{Substitute values} \rangle \\
& (162{,}000 \text{ pixels}) \times 18(\text{b/pixel}) \\
= \quad & \langle \text{Math} \rangle \\
& 2{,}916{,}000 \text{ b} \\
= \quad & \langle \text{Convert to KiB} \rangle \\
& (2{,}916{,}000 \text{ b}) \times (1 \text{ B}/8 \text{ b}) \times (1 \text{ KiB}/1024 \text{ B})
\end{aligned}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

$$
\begin{array}{ll}
 & \text{size of display memory} \\
= & \langle \text{Product} \rangle \\
 & (\text{number of pixels}) \times (\text{bit pixels}) \\
= & \langle \text{Substitute values} \rangle \\
 & (162{,}000 \text{ pixels}) \times 18(\text{b/pixel}) \\
= & \langle \text{Math} \rangle \\
 & 2{,}916{,}000 \text{ b} \\
= & \langle \text{Convert to KiB} \rangle \\
 & (2{,}916{,}000 \text{ b}) \times (1 \text{ B}/8 \text{ b}) \times (1 \text{ KiB}/1024 \text{ B}) \\
= & \langle \text{Math} \rangle
\end{array}
$$

Because each subpixel can display 64 levels of brightness, and $2^6 = 64$, the number of bits for each subpixel is 6. Because there are 3 subpixels per pixel, the bit depth is 3×6, which is 18. Compute the size of the display memory as follows:

size of display memory

= ⟨Product⟩

(number of pixels) × (bit pixels)

= ⟨Substitute values⟩

(162,000 pixels) × 18(b/pixel)

= ⟨Math⟩

2,916,000 b

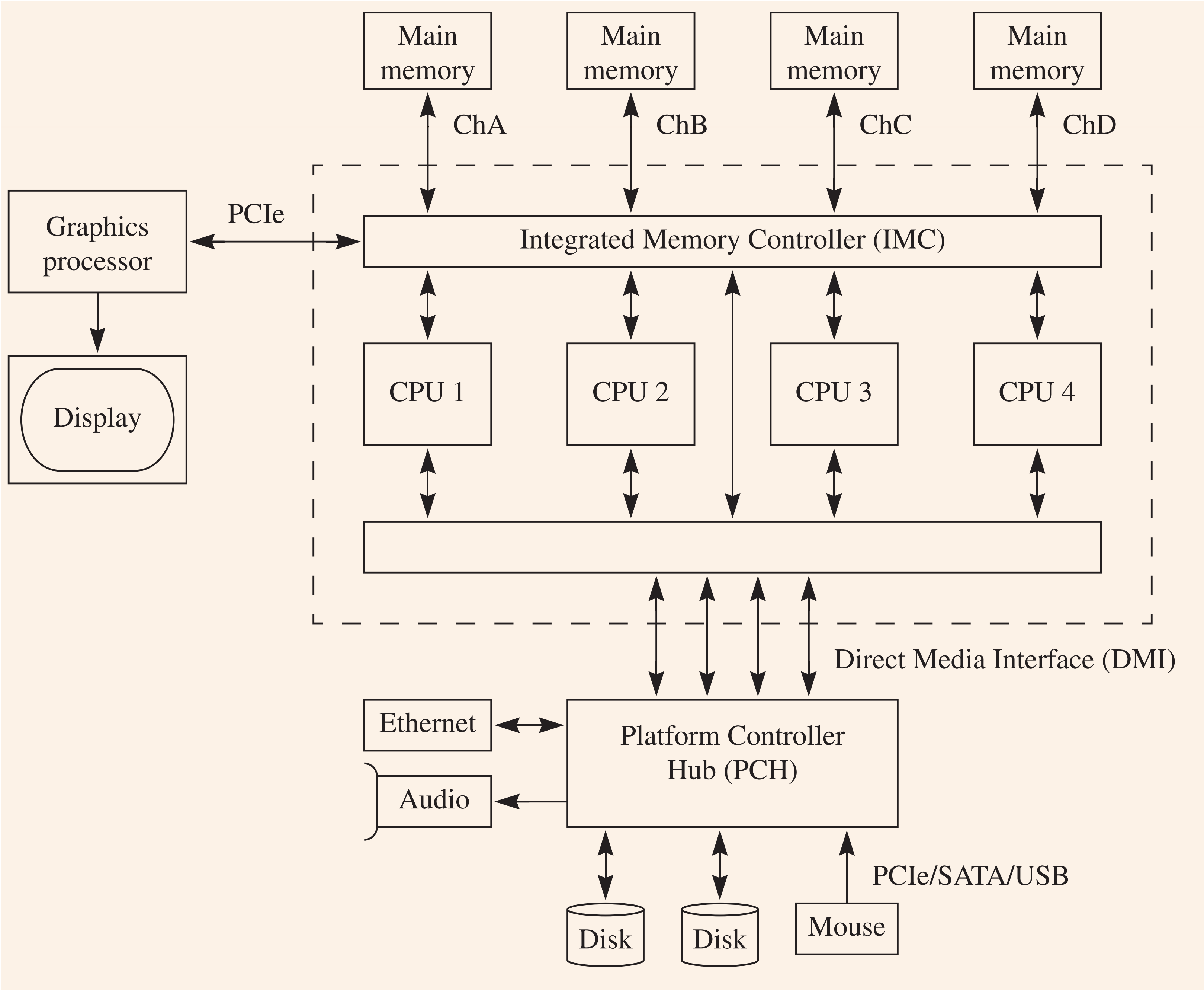
= ⟨Convert to KiB⟩

(2,916,000 b) × (1 B/8 b) × (1 KiB/1024 B)

= ⟨Math⟩

356 KiB

Intel x-86 systems


Main memory
Main memory
Main memory
Main memory
ChA
ChB
ChC
ChD
Graphics processor
PCIe
Integrated Memory Controller (IMC)
Display
CPU 1
CPU 2
CPU 3
CPU 4
Direct Media Interface (DMI)
Ethernet
Audio
Platform Controller Hub (PCH)
PCIe/SATA/USB
Disk
Disk
Mouse

Relational database systems

- *Relation* A table
- *Attribute* A column
- *Tuple* A row
- *Domain* The set of all possible values of an attribute

Sor

S.Name	S.Class	S.Major	S.State
Beth	Soph	Hist	TX
Nancy	Jr	Math	NY
Robin	Sr	Hist	CA
Allison	Soph	Math	AZ
Lulwa	Sr	CompSci	CA

Frat

F.Name	F.Major	F.State
Emile	PolySci	CA
Sam	CompSci	WA
Ron	Math	OR
Mehdi	Math	CA
David	English	AZ
Jeff	Hist	TX
Craig	English	CA
Gary	CompSci	CA

Query

- List Ron's home state

Result1

F.State
OR

Query

- List all the sophomores in the sorority

Result2

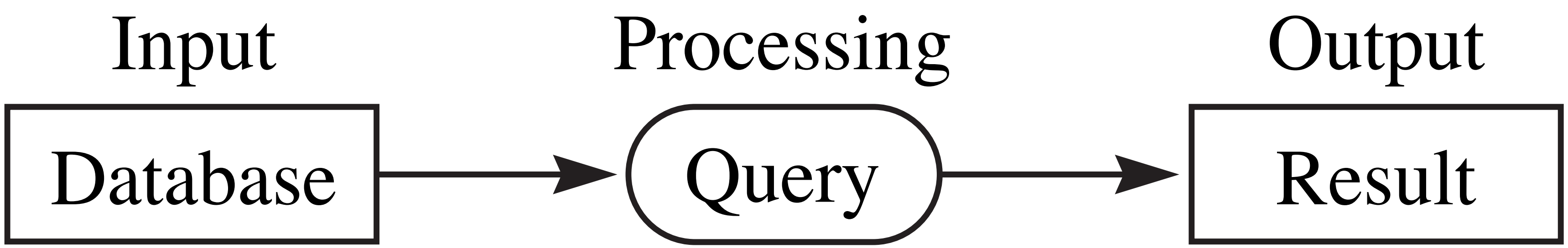
S.Name
Beth
Allison

Query

- List those sorority and fraternity members who have the same major, and what that common major is

Result3

S.Name	F.Name	Major
Beth	Jeff	Hist
Nancy	Ron	Math
Nancy	Mehdi	Math
Robin	Jeff	Hist
Allison	Ron	Math
Allison	Mehdi	Math
Lulwa	Sam	CompSci
Lulwa	Gary	CompSci


Input
Processing
Output
Database
Query
Result

Database operators

- `select` Takes a set of rows
- `project` Takes a set of columns
- `join` Combines tuples from two tables with a common column

- `select Frat where F.Major = English giving Temp1`

Temp1

F.Name	F.Major	F.State
David	English	AZ
Craig	English	CA

- `project Sor over S.Name giving Temp2`

Temp2

F.Name
David
Craig

- `project Sor over (S.Class, S.State) giving Temp3`

Temp3

S.Class	S.State
Soph	TX
Jr	NY
Sr	CA
Soph	AZ

- `join Sor and Frat over Major giving Temp4`

Temp4

S.Name	S.Class	S.State	Major	F.Name	F.State
Beth	Soph	TX	Hist	Jeff	TX
Nancy	Jr	NY	Math	Ron	OR
Nancy	Jr	NY	Math	Mehdi	CA
Robin	Sr	CA	Hist	Jeff	TX
Allison	Soph	AZ	Math	Ron	OR
Allison	Soph	AZ	Math	Mehdi	CA
Lulwa	Sr	CA	CompSci	Sam	WA
Lulwa	Sr	CA	CompSci	Gary	CA

Query

- List Ron's home state

Result1

F.State
OR

Query

- List Ron’s home state

```
select Frat where F.Name = Ron
giving Temp5

project Temp5 over F.State
giving Result1
```

Query

- List all the sophomores in the sorority

Result2

S.Name
Beth
Allison

Query

- List all the sophomores in the sorority

```
select Sor where S.Class = Soph
giving Temp6

project Temp6 over S.Name
giving Result2
```

Query

- List those sorority and fraternity members who have the same major, and what that common major is

Result3

S.Name	F.Name	Major
Beth	Jeff	Hist
Nancy	Ron	Math
Nancy	Mehdi	Math
Robin	Jeff	Hist
Allison	Ron	Math
Allison	Mehdi	Math
Lulwa	Sam	CompSci
Lulwa	Gary	CompSci

See Figure 1.32

Query

- List those sorority and fraternity members who have the same major, and what that common major is

```
join Sor and Frat over Major
giving Temp4

project Temp4 over (S.Name,
F.Name, Major)giving Result3
```