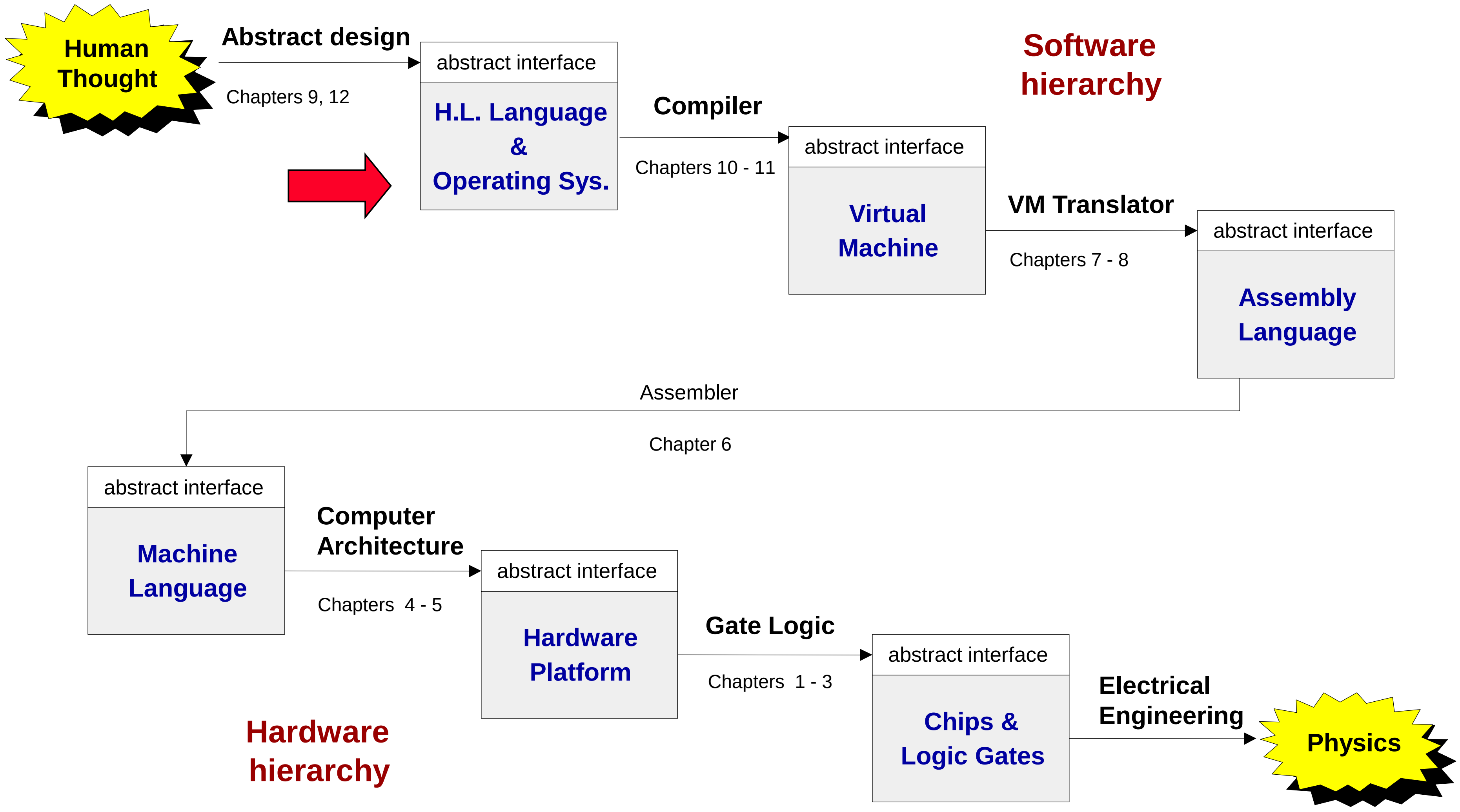
Operating Systems

Building a Modern Computer From First Principles

www.nand2tetris.org

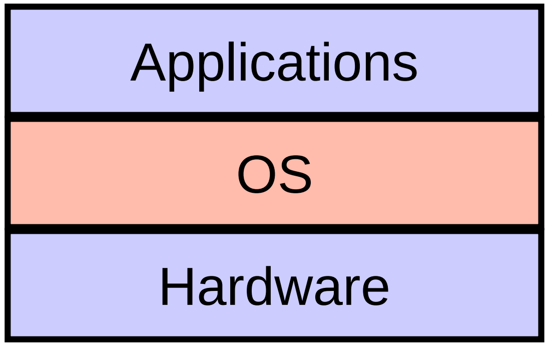
Where we are at:

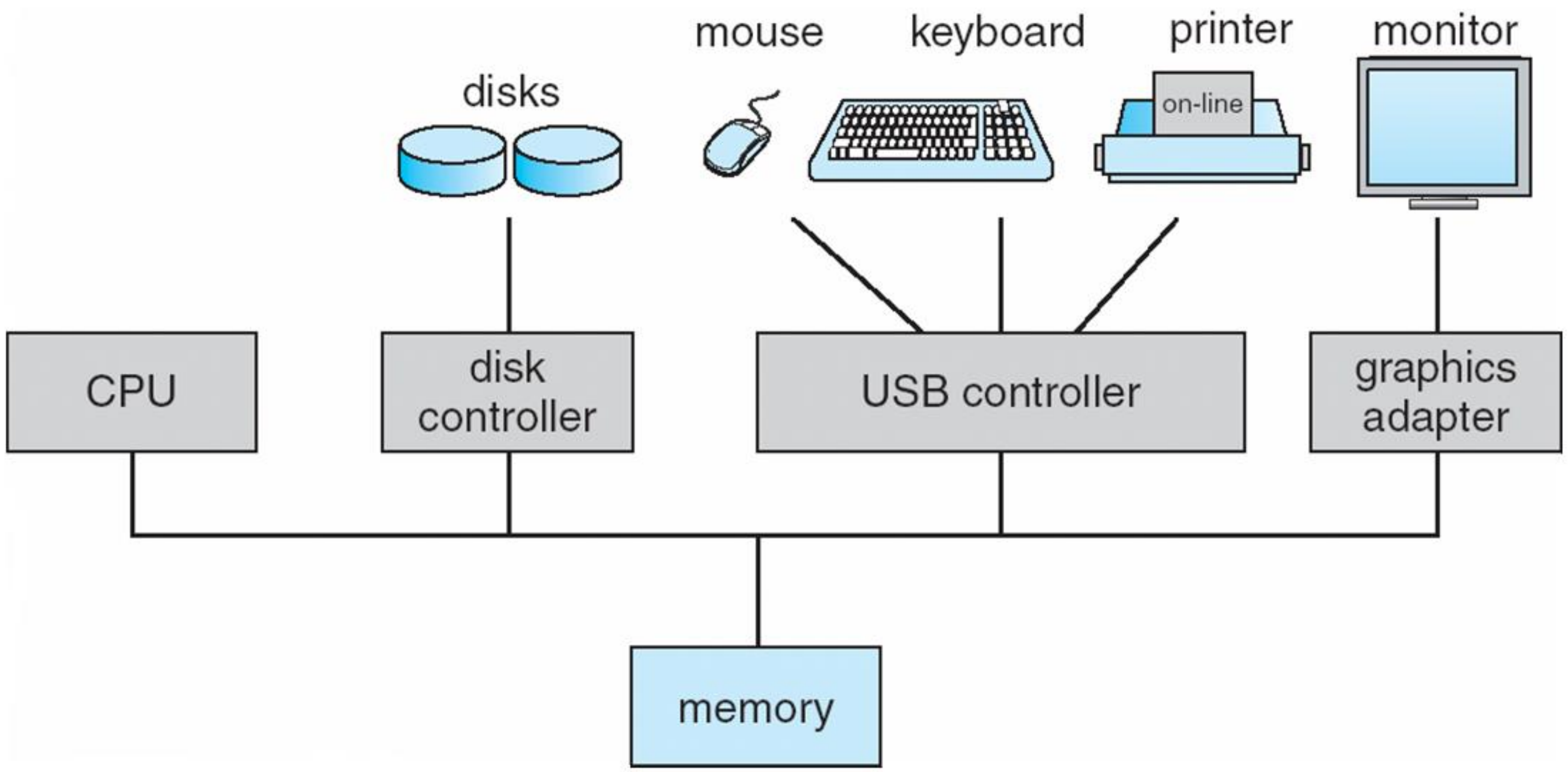


Operating system

A software layer to

- manage resources
- provide an abstract interface to application developers





Typical OS functions

Language extensions / standard library

- Mathematical operations (**abs**, **sqrt**, ...)
- Abstract data types (**String**, **Date**, ...)
- Output functions (**printChar**, **printString** ...)
- Input functions (**readChar**, **readLine** ...)
- Graphics functions (**drawPixel**, **drawCircle**, ...)
- And more ...

System-oriented services

- Memory management (objects, arrays, ...)
- I/O device drivers
- Mass storage
- File system
- Multi-tasking
- UI management (shell / windows)
- Security
- Communications
- And more ...

Jack revisited

```
/** Computes the average of a sequence of integers. */
class Main {
  function void main() {
    var Array a;
    var int length;
    var int i, sum;

    let length = Keyboard.readInt("How many numbers? ");
    let a = Array.new(length); // Constructs the array
    let i = 0;

    while (i < length) {
      let a[i] = Keyboard.readInt("Enter the next number: ");
      let sum = sum + a[i];
      let i = i + 1;
    }

    do Output.printString("The average is: ");
    do Output.printInt(sum / length);
    do Output.println();
    return;
  }
}
```

Jack revisited

```
/** Computes the average of a sequence of integers. */
class Main {
  function void main() {
    var Array a;
    var int length;
    var int i, sum;

    let length = Keyboard.readInt("How many numbers? ");
    let a = Array.new(length); // Constructs the array
    let i = 0;

    while (i < length) {
      let a[i] = Keyboard.readInt("Enter the next number: ");
      let sum = sum + a[i];
      let i = i + 1;
    }

    do Output.printString("The average is: ");
    do Output.printInt(sum / length);
    do Output.println();
    return;
  }
}
```

The Jack OS

`Math:`	Provides basic mathematical operations;
`String:`	Implements the **`String`** type and related operations;
`Array:`	Implements the **`Array`** type and related operations;
`Output:`	Handles text output to the screen;
`Screen:`	Handles graphic output to the screen;
`Keyboard:`	Handles user input from the keyboard;
`Memory:`	Handles memory operations;
`Sys:`	Provides some execution-related services.

Jack OS API

```
class Math {
   function void init()
   function int abs(int x)
   function int multiply(int x, int y)
   function int divide(int x, int y)
   function int min(int x, int y)
   function int max(int x, int y)
   function int sqrt(int x)
}
```

Jack OS API

```
Class String {
   constructor String new(int maxLength)
   method void   dispose()
   method int    length()
   method char   charAt(int j)
   method void   setCharAt(int j, char c)
   method String appendChar(char c)
   method void   eraseLastChar()
   method int    intValue()
   method void   setInt(int j)
   function char backSpace()
   function char doubleQuote()
   function char newLine()
}
```

Jack OS API

```
Class Array {

   function Array new(int size)

   method void dispose()

}
```

```
class Memory {

   function int peek(int address)

   function void poke(int address, int value)

   function Array alloc(int size)

   function void deAlloc(Array o)

}
```

Jack OS API

```
class Output {
    function void moveCursor(int i, int j)
    function void printChar(char c)
    function void printString(String s)
    function void printInt(int i)
    function void println()
    function void backSpace()
}
```

```
Class Screen {
    function void clearScreen()
    function void setColor(boolean b)
    function void drawPixel(int x, int y)
    function void drawLine(int x1, int y1, int x2, int y2)
    function void drawRectangle(int x1, int y1, int x2, int y2)
    function void drawCircle(int x, int y, int r)
}
```

Jack OS API

```
Class Keyboard {
   function char keyPressed()
   function char readChar()
   function String readLine(String message)
   function int readInt(String message)
}
```

```
Class Sys {
   function void halt():
   function void error(int errorCode)
   function void wait(int duration)
}
```

A typical OS:

- Is modular and scalable
- Empowers programmers (language extensions)
- Empowers users (file system, GUI, ...)
- Closes gaps between software and hardware
- Runs in "protected mode"
- Typically written in some high level language
- Typically grows gradually, assuming more and more functions
- Must be efficient.

Efficiency

We have to implement various operations on *n*-bit binary numbers (n = 16, 32, 64, ...).

For example, consider *multiplication*

- Naïve algorithm: to multiply x*y: { for i = 1 ... y do sum = sum + x }

  Run-time is proportional to *y*

  In a 64-bit system, *y* can be as large as 2^{64}.

  Multiplications can take years to complete

- Algorithms that operate on *n*-bit inputs can be either:
  - Naïve: run-time is proportional to the *value* of the *n*-bit inputs
  - Good: run-time is proportional to *n, the input's size.*

Example I: multiplication

Long multiplication

$$
\begin{array}{lcccccccccc}
x & & & & 1 & 0 & 1 & 1 & = & 1 & 1 \\
y & & * & & & 1 & 0 & 1 & = & & 5 \\
\hline
 & & & & 1 & 0 & 1 & 1 & & & \\
 & & & 0 & 0 & 0 & 0 & & & & \\
 & & 1 & 0 & 1 & 1 & & & & & \\
\hline
x \cdot y & & 1 & 1 & 0 & 1 & 1 & 1 & = & 5 & 5
\end{array}
$$

```
multiply(x, y):
    // Where $x, y \geq 0$
    $sum = 0$
    $shiftedX = x$
    for $j = 0 \ldots (n-1)$ do
        if ($j$-th bit of $y$) $= 1$ then
            $sum = sum + shiftedX$
        $shiftedX = shiftedX * 2$
```

The algorithm explained (first 4 of 16 iteration)

x:	0	0	0	1	0	1	1	
y:	0	0	0	0	1	0	1	j'th bit of y
	0	0	0	**1**	**0**	**1**	**1**	1
	0	0	**1**	**0**	**1**	**1**	0	0
	0	**1**	**0**	**1**	**1**	0	0	1
	1	**0**	**1**	**1**	0	0	0	0
$x \cdot y$:	0	1	1	0	1	1	1	sum

- Run-time: proportional to *n*
- Can be implemented in SW or HW
- Division: similar idea.

Division

```
**divide (x, y):**
    // Integer part of $x/y$, where $x \geq 0$ and $y > 0$
    if $y > x$ return 0
    $q = \text{divide}(x, 2 * y)$
    if $(x - 2 * q * y) < y$
        return $2 * q$
    else
        return $2 * q + 1$
```

- Run-time: proportional to *n* instead of y

Example II: square root

The square root function has two convenient properties:

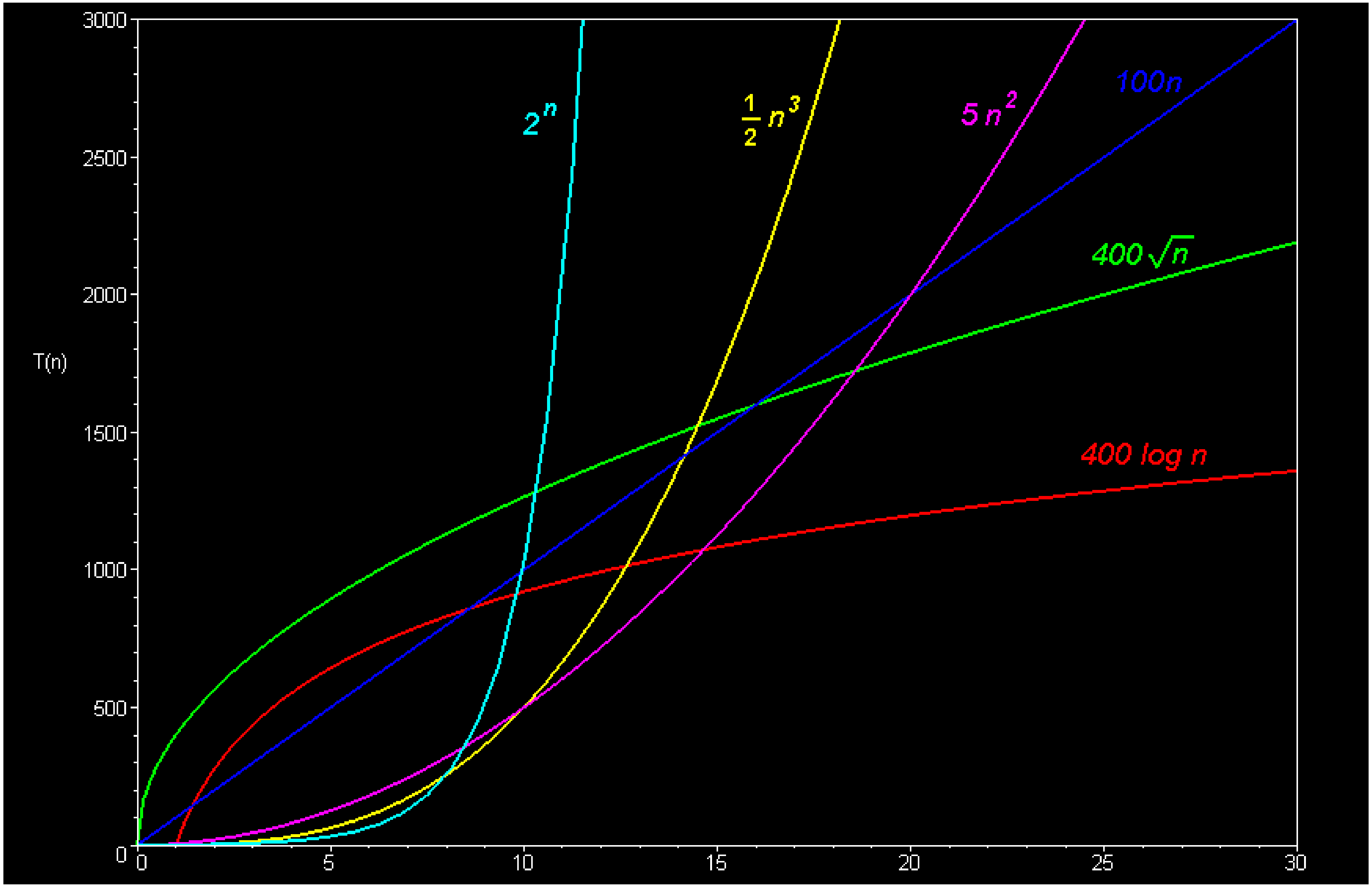
- Its inverse function is computed easily
- Monotonically increasing

Functions that have these two properties can be computed by binary search:

```
sqrt($x$):
    // Compute the integer part of $y = \sqrt{x}$. Strategy:
    // Find an integer $y$ such that $y^2 \le x < (y+1)^2$ (for $0 \le x < 2^n$)
    // By performing a binary search in the range $0 \dots 2^{n/2} - 1$.
    $y = 0$
    for $j = n/2 - 1 \dots 0$ do
        if $(y + 2^j)^2 \le x$ then $y = y + 2^j$
    return $y$
```

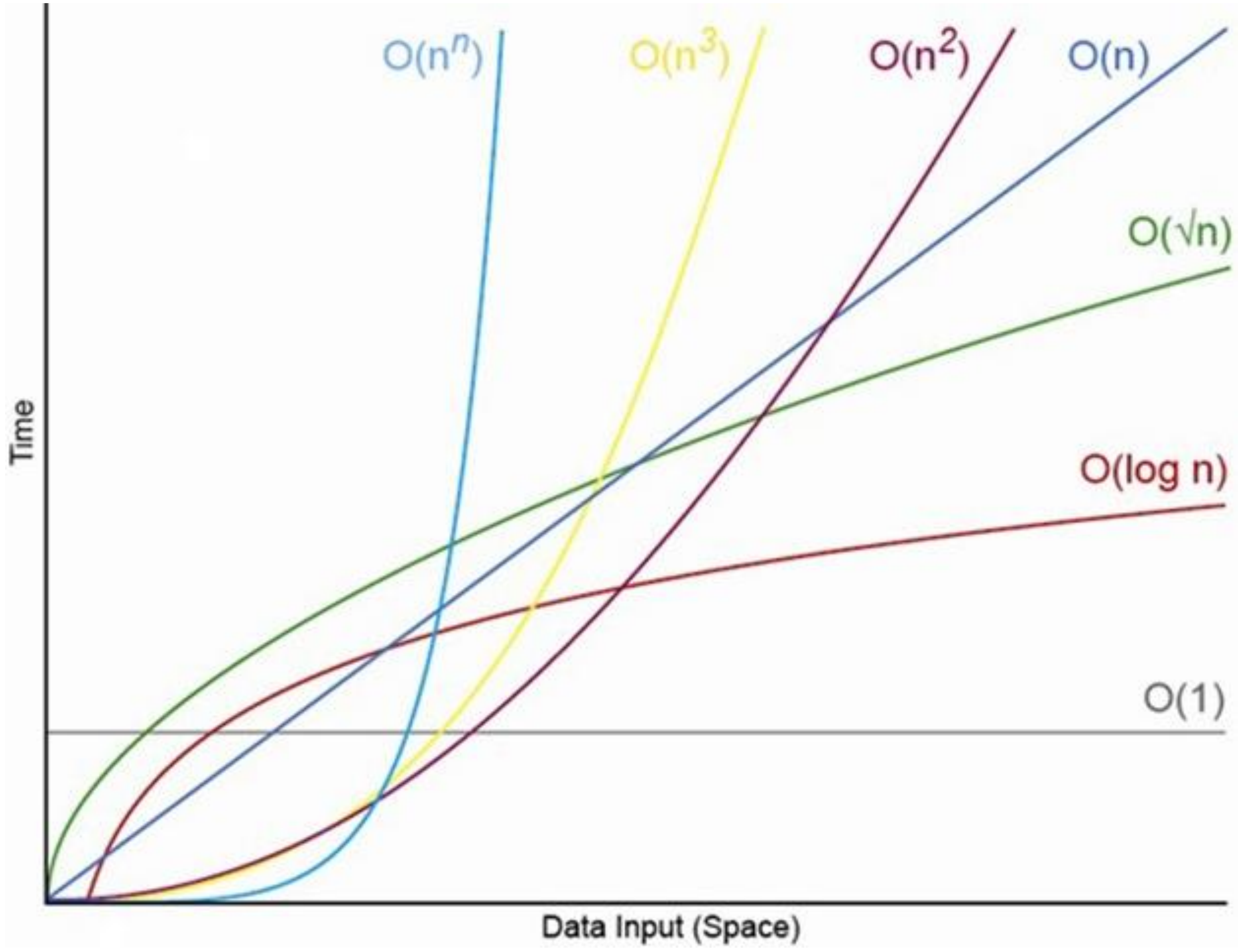
Number of loop iterations is bounded by n/2, thus the run-time is O(n).

Complexity



3000
2500
2000
1500
1000
500
0
T(n)
0
5
10
15
20
25
30
2^n
$\frac{1}{2}n^3$
$5n^2$
$100n$
$400\sqrt{n}$
$400 \log n$

Complexity



Donald Knuth 高德納

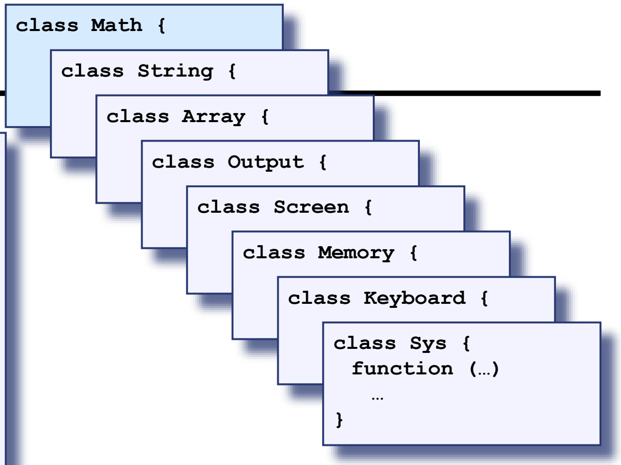
- Born in 1938
- Author of "The Art of Computer Programming"

《美國科學家》（American Scientist）雜誌曾將該書與愛因斯坦的《相對論》、狄拉克的《量子力學》、理查·費曼的《量子電動力學》等書並列為20世紀最重要的12本物理科學類專論書之一。

- Creator of Tex and metafont
- Turing Award, 1974
- $2.56 check
- Sorting animation 1 2

Math operations (in the Jack OS)

```
class Math {

    function void init()

    function int abs(int x)

✓   function int multiply(int x, int y)

✓   function int divide(int x, int y)

    function int min(int x, int y)

    function int max(int x, int y)

✓   function int sqrt(int x)

}
```

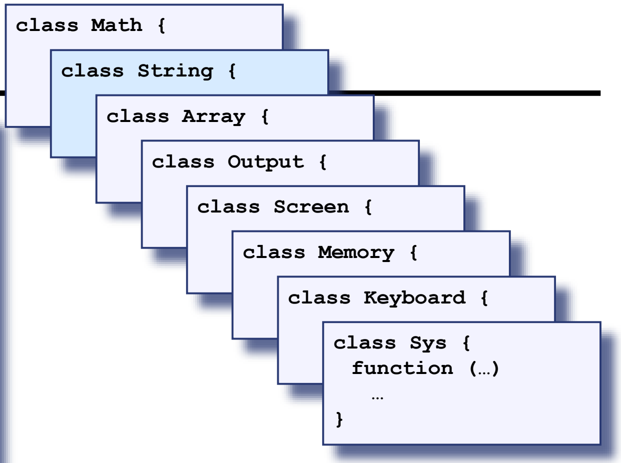


```
class Math {
class String {
class Array {
class Output {
class Screen {
class Memory {
class Keyboard {
class Sys {
  function (…)
    …
}
```

The remaining functions are simple to implement.

String processing (in the Jack OS)

```
Class String {
    constructor String new(int maxLength)
    method void   dispose()
    method int    length()
    method char   charAt(int j)
    method void   setCharAt(int j, char c)
    method String appendChar(char c)
    method void   eraseLastChar()
    method int    intValue()
    method void   setInt(int j)
    function char backSpace()
    function char doubleQuote()
    function char newLine()
}
```



Single digit ASCII conversions

Character:	'0'	'1'	'2'	'3'	'4'	'5'	'6'	'7'	'8'	'9'
ASCII code:	48	49	50	51	52	53	54	55	56	57

- asciiCode(digit) == digit + 48
- digit(asciiCode) == asciiCode - 48

Converting a number to a string

- SingleDigit-to-character conversions: done
- Number-to-string conversions:

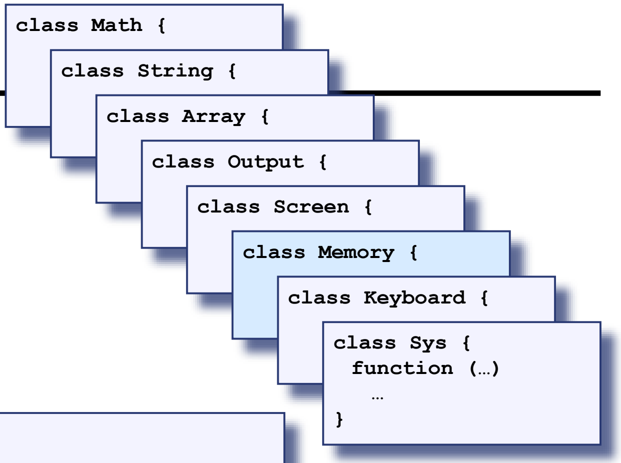
```
// Convert a non-negative number to a string
int2String(n):
    $lastDigit = n \% 10$
    $c$ = character representing $lastDigit$
    if $n < 10$
        return $c$ (as a string)
    else
        return int2String($n/10$).append($c$)
```

Converting a number to a string

- SingleDigit-to-character conversions: done
- Number-to-string conversions:

```
// Convert a string to a non-negative number
string2Int(s):
    $v = 0$
    for $i = 1 \ldots$ length of $s$ do
        $d$ = integer value of the digit $s[i]$
        $v = v * 10 + d$
    return $v$
    // (Assuming that $s[1]$ is the most
    //  significant digit character of $s$.)
```

Memory management (in the Jack OS)



```
class Math {
class String {
class Array {
class Output {
class Screen {
class Memory {
class Keyboard {
class Sys {
  function (…)
    …
}
```

```
class Memory {

    function int peek(int address)

    function void poke(int address, int value)

    function Array alloc(int size)

    function void deAlloc(Array o)

}
```

Memory management (naive)

- When a program constructs (destructs) an object, the OS has to allocate (de-allocate) a RAM block on the heap:
  - `alloc(size)`: returns a reference to a free RAM block of size `size`
  - `deAlloc(object)`: recycles the RAM block that `object` refers to

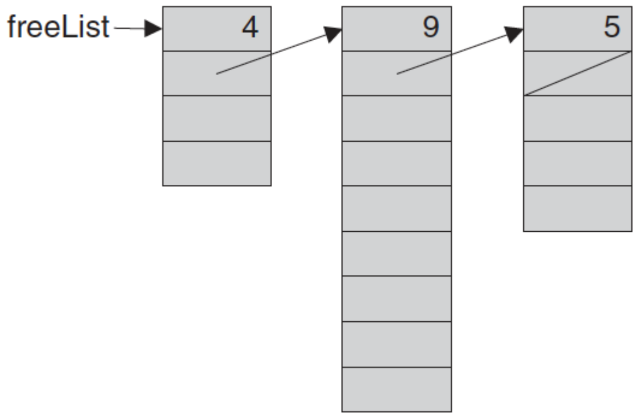
```
Initialization: $free = heapBase$

// Allocate a memory block of $size$ words.
alloc($size$):
    $pointer = free$
    $free = free + size$
    return $pointer$

// De-allocate the memory space of a given $object$.
deAlloc($object$):
    do nothing
```

- The data structure that this algorithm manages is a single pointer: free.

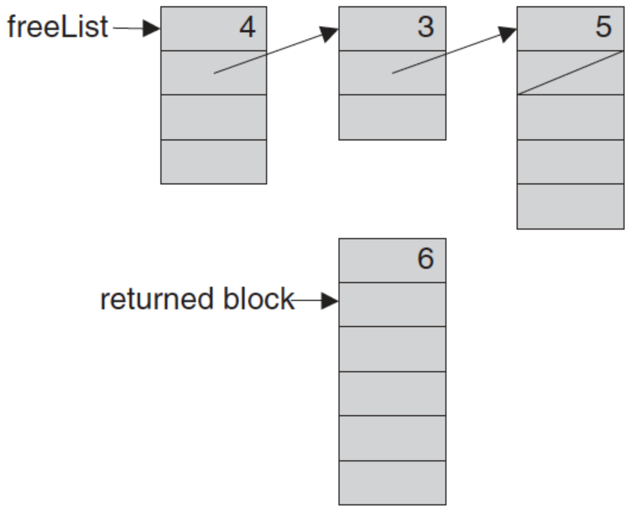
Memory management (improved)

```
Initialization:
  $freeList = heapBase$
  $freeList.length = heapLength$
  $freeList.next = \text{null}$

// Allocate a memory space of size words.
alloc(size):
  Search freeList using best-fit or first-fit heuristics
    to obtain a segment with $segment.length > size$
  If no such segment is found, return failure
    (or attempt defragmentation)
  block = needed part of the found segment
    (or all of it, if the segment remainder is too small)
  Update freeList to reflect the allocation
  $block[-1] = size + 1$   // Remember block size, for de-allocation
  Return block

// Deallocate a decommissioned object.
deAlloc(object):
  $segment = object - 1$
  $segment.length = object[-1]$
  Insert segment into the freeList
```

Data structure



After alloc(5)



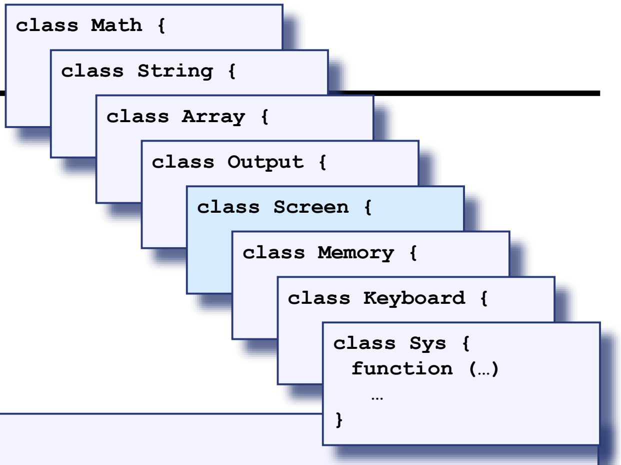
Peek and poke

```
class Memory {

    function int peek(int address)

    function void poke(int address, int value)

    function Array alloc(int size)

    function void deAlloc(Array o)

}
```

- Implementation: based on our ability to exploit exotic casting in Jack:

```
// To create a Jack-level "proxy" of the RAM:
var Array memory;
let memory = 0;
// From this point on we can use code like:
let x = memory[j]   // Where j is any RAM address
let memory[j] = y   // Where j is any RAM address
```

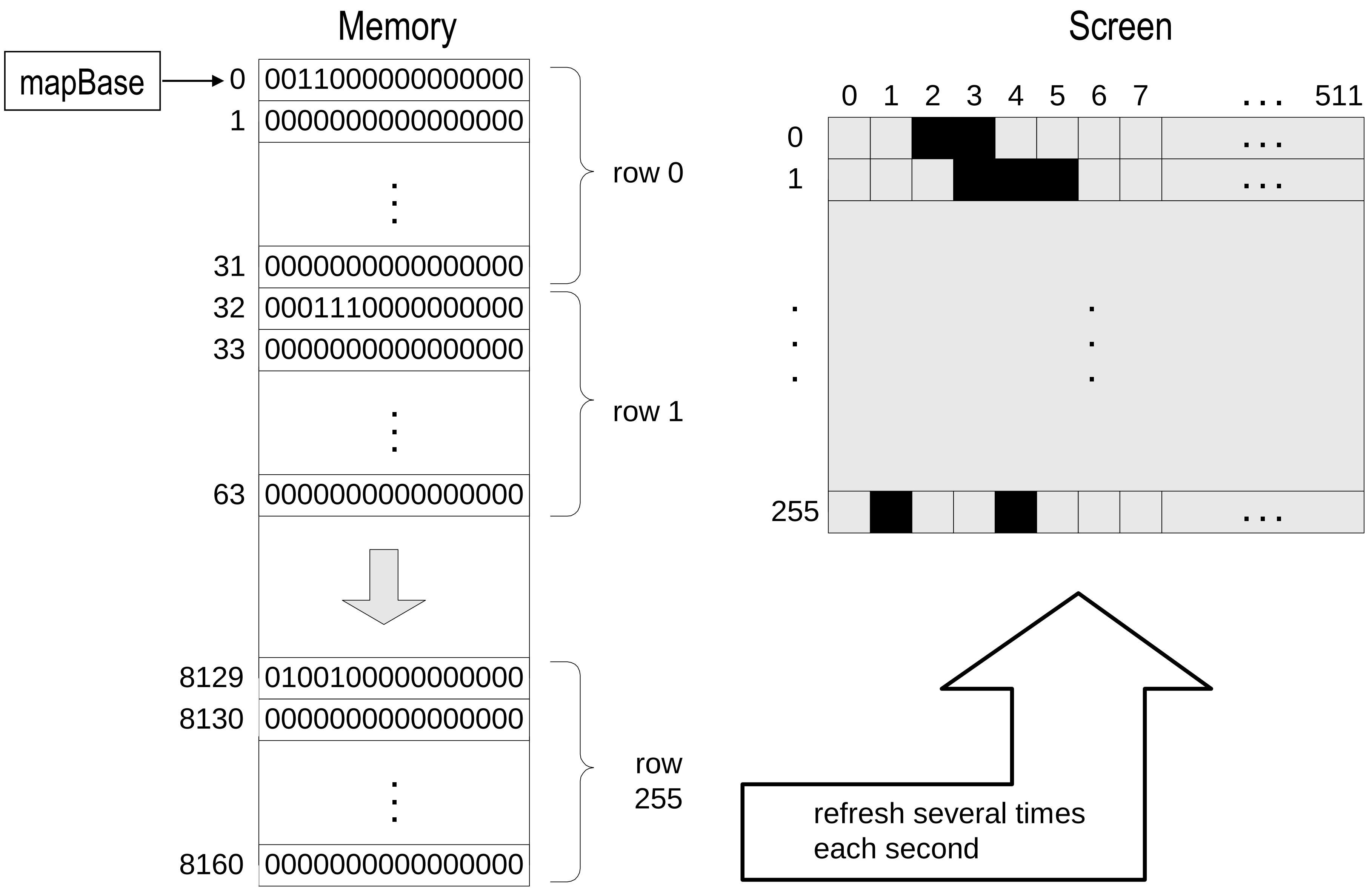
Graphics primitives (in the Jack OS)



```
class Math {
class String {
class Array {
class Output {
class Screen {
class Memory {
class Keyboard {
class Sys {
  function (…)
    …
}
```

```
Class Screen {

    function void clearScreen()

    function void setColor(boolean b)

    function void drawPixel(int x, int y)

    function void drawLine(int x1, int y1, int x2, int y2)

    function void drawRectangle(int x1, int y1,int x2, int y2)

    function void drawCircle(int x, int y, int r)

}
```

Memory-mapped screen



Pixel drawing

```
drawPixel (x, y):
    // Hardware-specific.
    // Assuming a memory mapped screen:
    Write a predetermined value in the RAM location corresponding to screen
    location (x, y).
```

- Implementation: using poke(address,value)

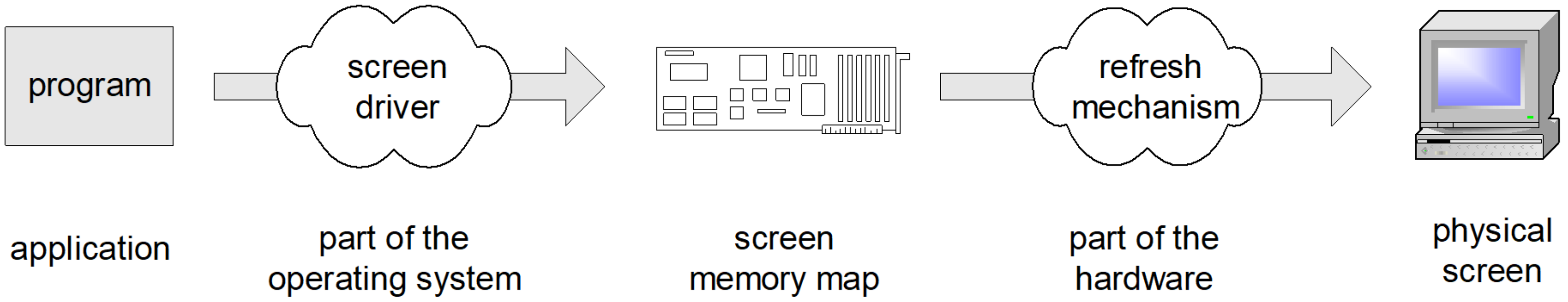
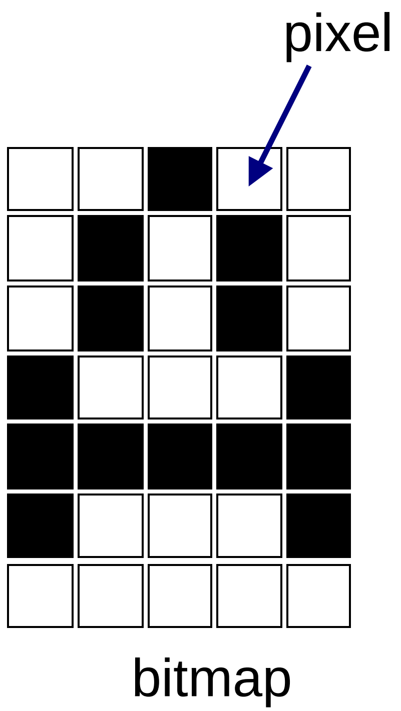
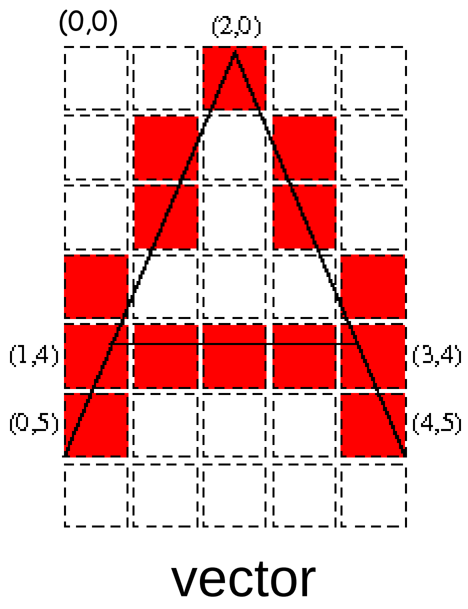
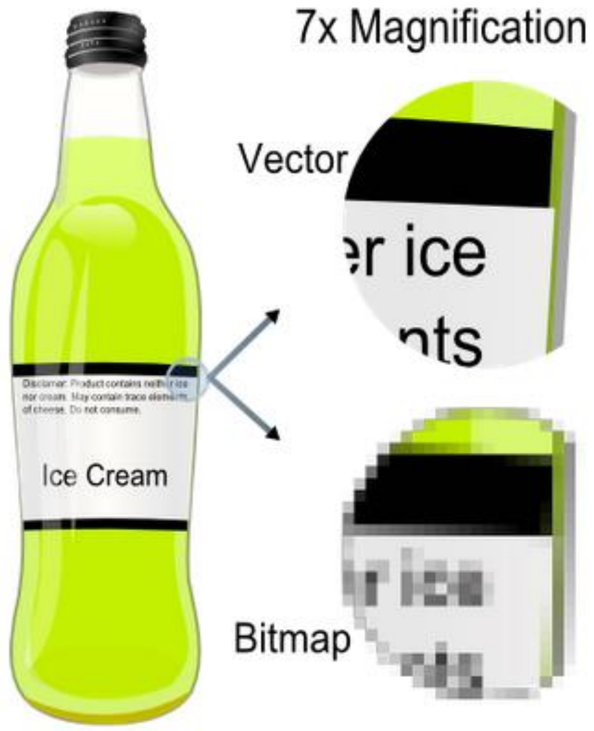


Image representation: bitmap versus vector graphics

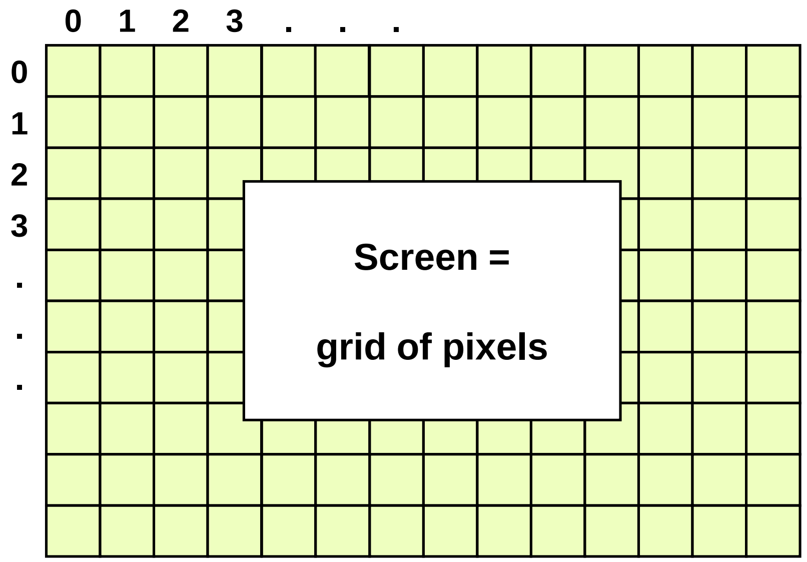


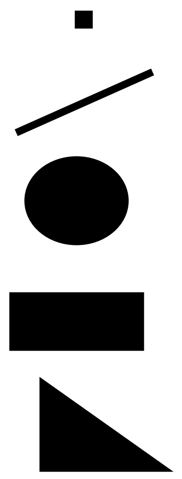




- Bitmap file: 00100, 01010,01010,10001,11111,10001,00000, . . .
- Vector graphics file: drawLine(2,0,0,5), drawLine(2,0,4,5), drawLine(1,4,3,4)
- Pros and cons of each method.

Vector graphics: basic operations





drawPixel(x,y) (Primitive operation)

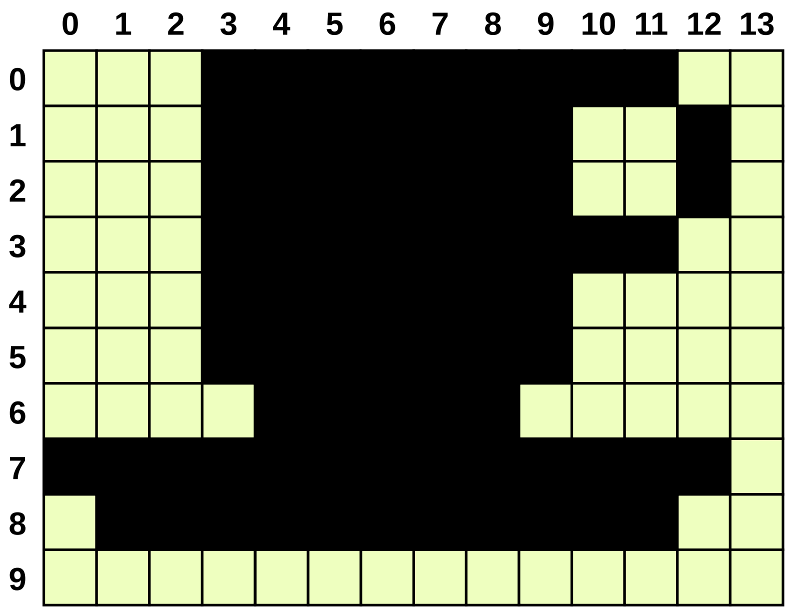
drawLine(x1,y1,x2,y2)

drawCircle(x,y,r)

drawRectangle(x1,y1,x2,y2)

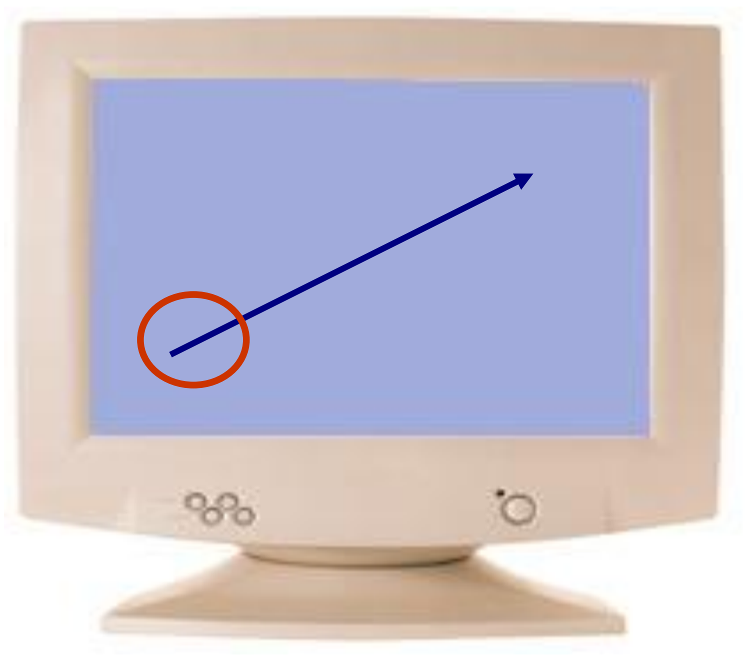
drawTriangle(x1,y1,x2,y2,x3,y3)

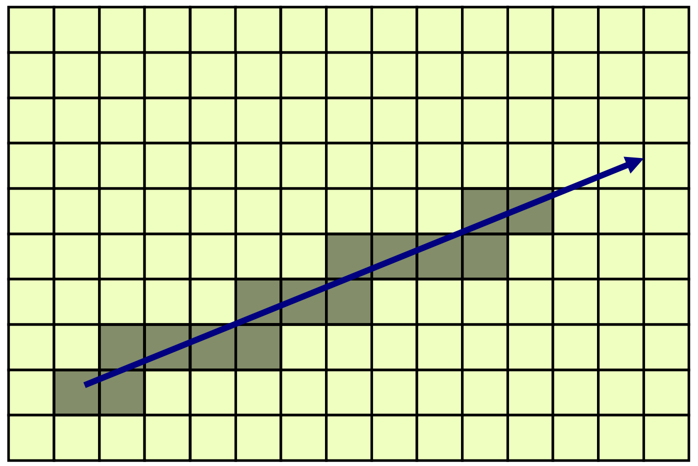
etc. (a few more similar operations)



```
drawLine(0,3,0,11)
drawRectangle(1,3,5,9)
drawLine(1,12,2,12)
drawLine(3,10,3,11)
drawLine(6,4,6,9)
drawLine(7,0,7,12)
drawLine(8,1,8,12)
```

How to draw a line?



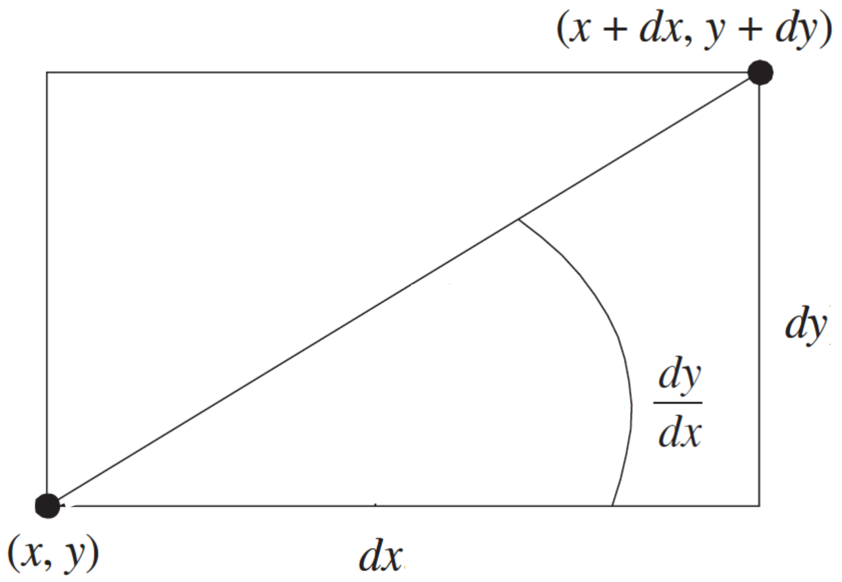


drawLine(x1,y1,x2,y2)

- Basic idea: drawLine is implemented through a sequence of drawPixel operations
- Challenge 1: which pixels should be drawn ?
- Challenge 2: how to draw the line *fast* ?
- Simplifying assumption: the line that we are asked to draw goes north-east.

Line Drawing

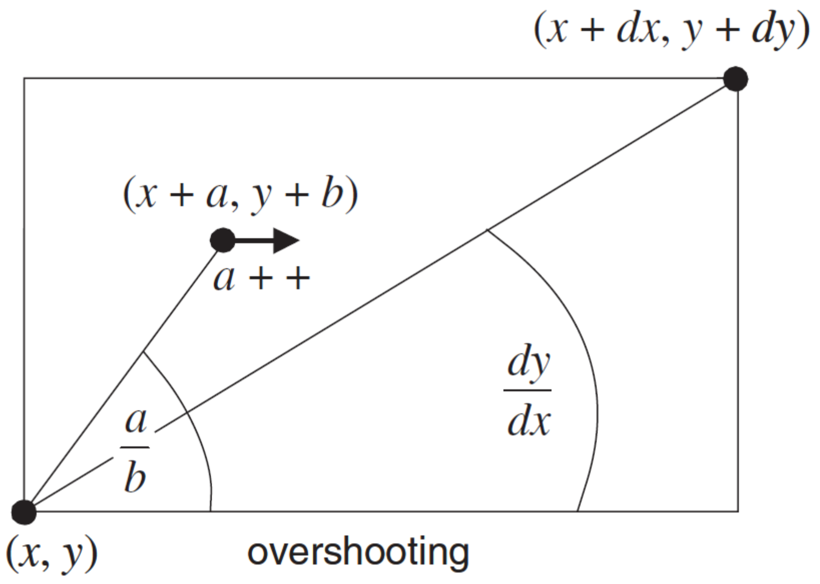
- Given: drawLine(x1,y1,x2,y2)
- Notation: x=x1, y=y1, dx=x2-x1, dy=y2-y1
- Using the new notation:
  We are asked to draw a line between (x,y) and (x+dx,y+dy)

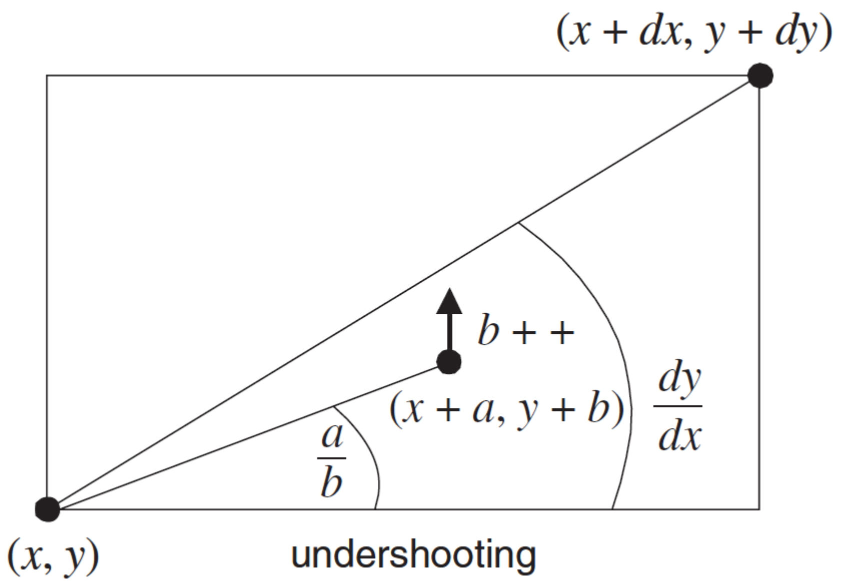


```
set (a,b) = (0,0)
while there is more work to do
    drawPixel(x+a,y+b)
    decide if you want to go right, or up
    if you decide to go right, set a=a+1;
    if you decide to go up, set b=b+1
```

```
set (a,b) = (0,0)
while (a ≤ dx) and (b ≤ dy)
    drawPixel(x+a,y+b)
    decide if you want to go right, or up
    if you decide to go right, set a=a+1;
    if you decide to go up, set b=b+1
```

Line Drawing algorithm





```
drawLine(x,y,x+dx,y+dy)
set (a,b) = (0,0)
while (a ≤ dx) and (b ≤ dy)
    drawPixel(x+a,y+b)
    decide if you want to go right, or up
    if you decide to go right, set a=a+1;
    if you decide to go up, set b=b+1
```

```
drawLine(x,y,x+dx,y+dy)
set (a,b) = (0,0)
while (a ≤ dx) and (b ≤ dy)
    drawPixel(x+a,y+b)
    if b/a > dy/dx set a=a+1
    else           set b=b+1
```

costy

Line Drawing algorithm, optimized

```
drawLine(x,y,x+dx,y+dy)

set (a,b) = (0,0)

while (a ≤ dx) and (b ≤ dy)

    drawPixel(x+a,y+b)

    if b/a > dy/dx set a=a+1
    else           set b=b+1
```

Motivation

- When you draw polygons, e.g. in animation or video, you need to draw millions of lines
- Therefore, drawLine must be ultra fast
- Division is a very slow operation
- Addition is ultra fast (hardware based)

```
drawLine(x,y,x+dx,y+dy)

set (a,b) = (0,0),  diff = 0

while (a ≤ dx) and (b ≤ dy)

    drawPixel(x+a,y+b)

    if diff < 0 set a=a+1,  diff = diff + dy
    else        set b=b+1, diff = diff - dx
```

b/a > dy/dx   is the same as   a*dy < b*dx

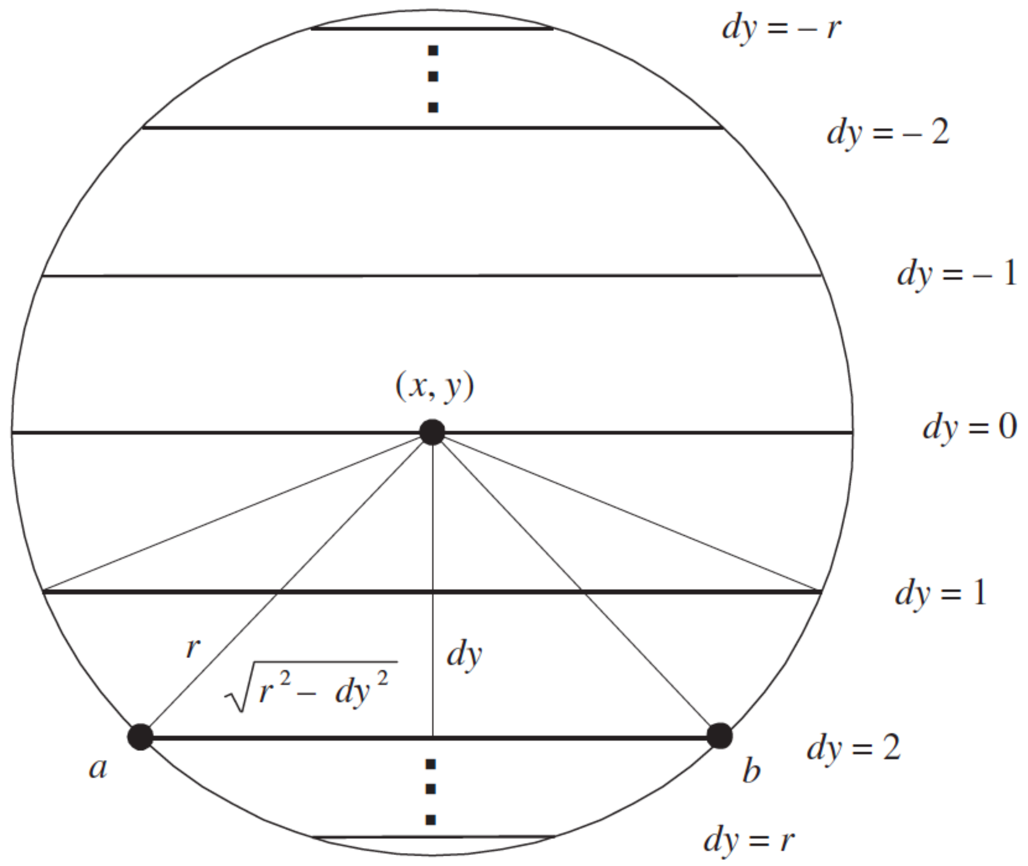
Define diff = a*dy – b*dx

Let's take a close look at this diff:

1. b/a > dy/dx is the same as diff < 0
2. When we set (a,b)=(0,0), diff = 0
3. When we set a=a+1, diff goes up by dy
4. When we set b=b+1, diff goes down by dx

Circle drawing

The screen origin (0,0) is at the top left.

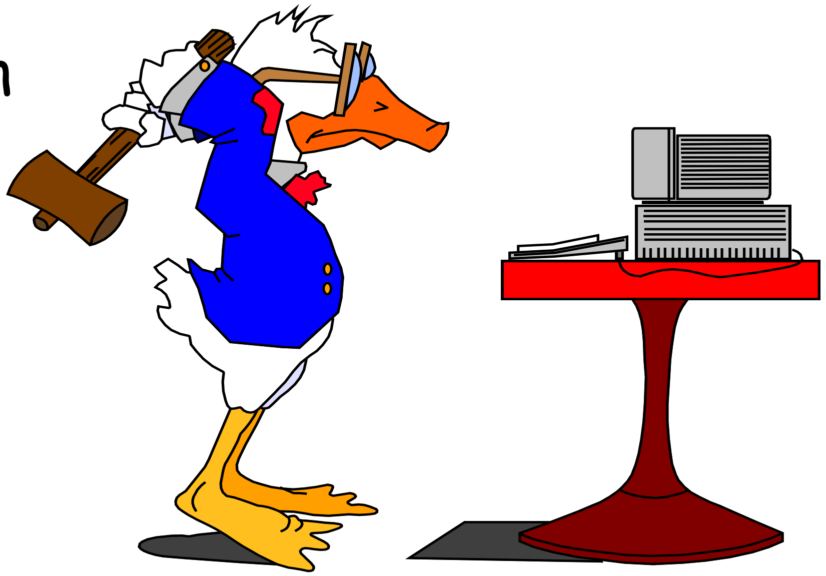


point $a = (x - \sqrt{r^2 - dy^2}, y + dy)$ point $b = (x + \sqrt{r^2 - dy^2}, y + dy)$

```
drawCircle(x, y, r):
    for each $dy \in -r \ldots r$ do
        drawLine from $(x - \sqrt{r^2 - dy^2}, y + dy)$ to $(x + \sqrt{r^2 - dy^2}, y + dy)$
```

To sum up (vector graphics)…

- To do vector graphics (e.g. display a PPT file), you have to draw polygons
- To draw polygons, you need to draw lines
- To draw lines, you need to divide
- Division can be re-expressed as multiplication
- Multiplication can be reduced to addition
- Addition is easy.

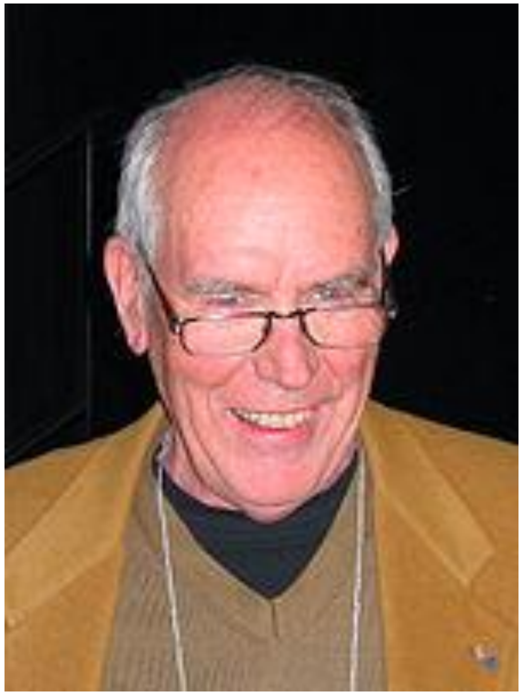


Ivan Sutherland

- Born in 1938
- PhD dissertation on Sketchpad (3D demo), 1963

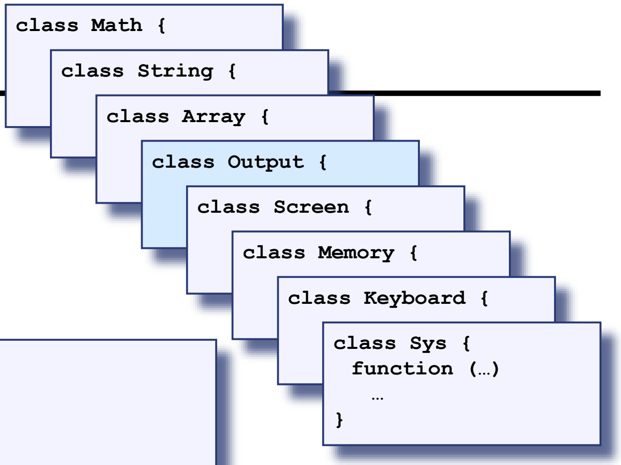
one of the most influential computer programs ever written. This work was seminal in Human-Computer Interaction, Graphics and Graphical User Interfaces (GUIs), Computer Aided Design (CAD), and contraint/object-oriented programming.

TX-2 computer (built circa 1958) on which the software ran was built from discrete transistors (not integrated circuits -it was room-sized) and contained just 64K of 36-bit words (~272k bytes).



- PhD advisor: Claude Shannon
- Father of computer graphics
- Turing Award, 1988

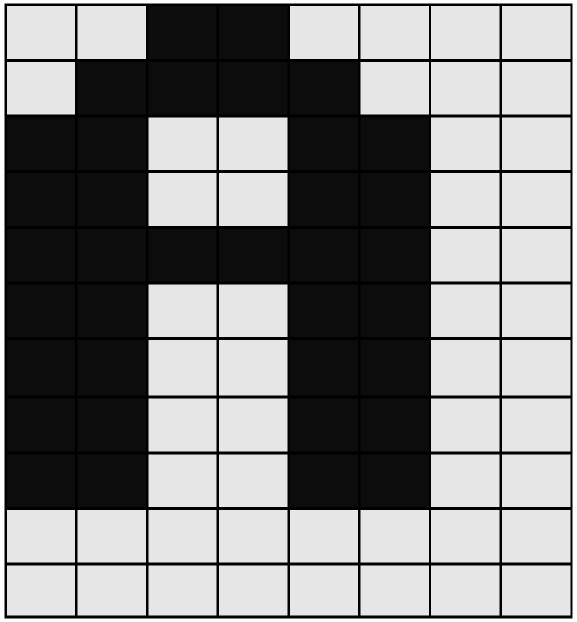
Character output primitives (in the Jack OS)



```
class Output {

    function void moveCursor(int i, int j)

    function void printChar(char c)

    function void printString(String s)

    function void printInt(int i)

    function void println()

    function void backSpace()

}
```

Character output

- Given display: a physical screen, say 256 rows by 512 columns
- We can allocate an 11 by 8 grid for each character
- Hence, our output package should manage a 23 lines by 64 characters screen
- Font: each displayable character must have an agreed-upon bitmap
- In addition, we have to manage a "cursor".



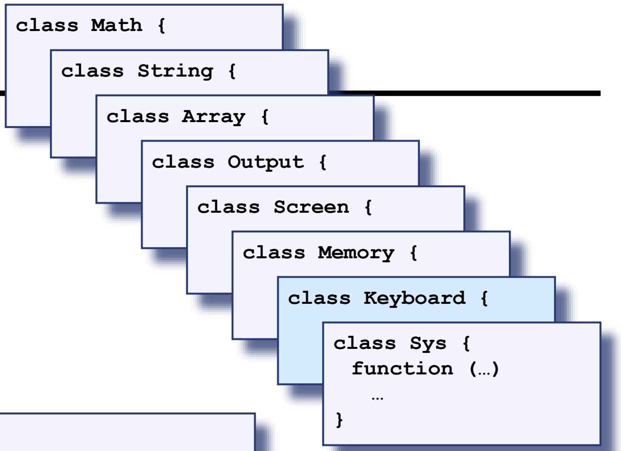
Font implementation (in the Jack OS)

```
class Output {
   static Array charMaps;
   function void initMap() {
     let charMaps = Array.new(127);
     // Assign a bitmap for each character
     do Output.create(32,0,0,0,0,0,0,0,0,0,0,0);           // space
     do Output.create(33,12,30,30,30,12,12,0,12,12,0,0);  // !
     do Output.create(34,54,54,20,0,0,0,0,0,0,0,0);        // "
     do Output.create(35,0,18,18,63,18,18,63,18,18,0,0);  // #
     ...
     do Output.create(48,12,30,51,51,51,51,51,30,12,0,0); // 0
     do Output.create(49,12,14,15,12,12,12,12,12,63,0,0); // 1
     do Output.create(50,30,51,48,24,12,6,3,51,63,0,0);   // 2
     .  .  .
     do Output.create(65,0,0,0,0,0,0,0,0,0,0,0);           // A **
    TO BE FILLED **
     do Output.create(66,31,51,51,51,31,51,51,51,31,0,0); // B
     do Output.create(67,28,54,35,3,3,3,35,54,28,0,0);    // C
     .  .  .
     return;
  }
```

Font implementation (in the Jack OS)

```
// Creates a character map array
function void create(int index, int a, int b, int c, int d, int e,
                     int f, int g, int h, int i, int j, int k) {
    var Array map;
    let map = Array.new(11);
    let charMaps[index] = map;
    let map[0] = a;
    let map[1] = b;
    let map[2] = c;
    ...
    let map[10] = k;
    return;
}
```

Keyboard primitives (in the Jack OS)



```
Class Keyboard {

    function char keyPressed()

    function char readChar()

    function String readLine(String message)

    function int readInt(String message)

}
```

Keyboard input

```
keyPressed( ):
    // Depends on the specifics of the keyboard interface
    if a key is presently pressed on the keyboard
        return the ASCII value of the key
    else
        return 0
```

- If the RAM address of the keyboard's memory map is known, the above logic can be implemented using a peek function
- Problem I: the elapsed time between a "key press" and key release" events is unpredictable
- Problem II: when pressing a key, the user should get some visible feedback (cursor, echo, ...).

A historic moment remembered

… Wozniak began writing the software that would get the microprocessor to display images on the screen. After a couple of month he was ready to test it. “I typed a few keys on the keyboard and I was shocked! The letters were displayed on the screen.”

It was Sunday, June 29, 1975, a milestone for the personal computer. “It was the first time in history,” Wozniak later said, “anyone had typed a character on a keyboard and seen it show up on their own computer’s screen right in front of them”

(*Steve Jobs*, by Walter Isaacson, 2012)

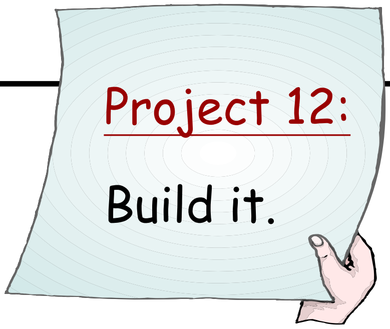
Keyboard input (cont.)

```
readChar( ):
    // Read and echo a single character
    display the cursor
    while no key is pressed on the keyboard
        do nothing // wait till a key is pressed
    $c$ = code of currently pressed key
    while a key is pressed
        do nothing // wait for the user to let go
    print $c$ at the current cursor location
    move the cursor one position to the right
    return $c$
```

Keyboard input (cont.)

```
readLine( ):
  // Read and echo a "line" (until newline)
  $s$ = empty string
  repeat
    $c$ = readChar( )
    if $c$ = newline character
      print newline
      return s
    else if $c$ = backspace character
      remove last character from $s$
      move the cursor 1 position back
    else
      $s = s.\text{append}(c)$
```

Jack OS recap



```
class Math {
Class String {
Class Array {
}
class Output {
Class Screen {
class Memory {
Class Keyboard {
Class Sys {
    function void halt():
    function void error(int errorCode)
    function void wait(int duration)
}
```

- Implementation: just like GNU Unix and Linux were built:
- Start with an existing system,
  and gradually replace it with a new system,
  one library at a time.

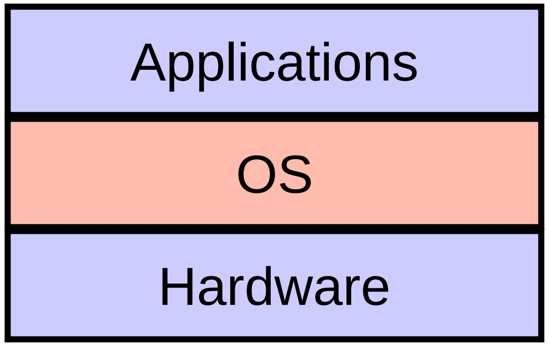
Perspective

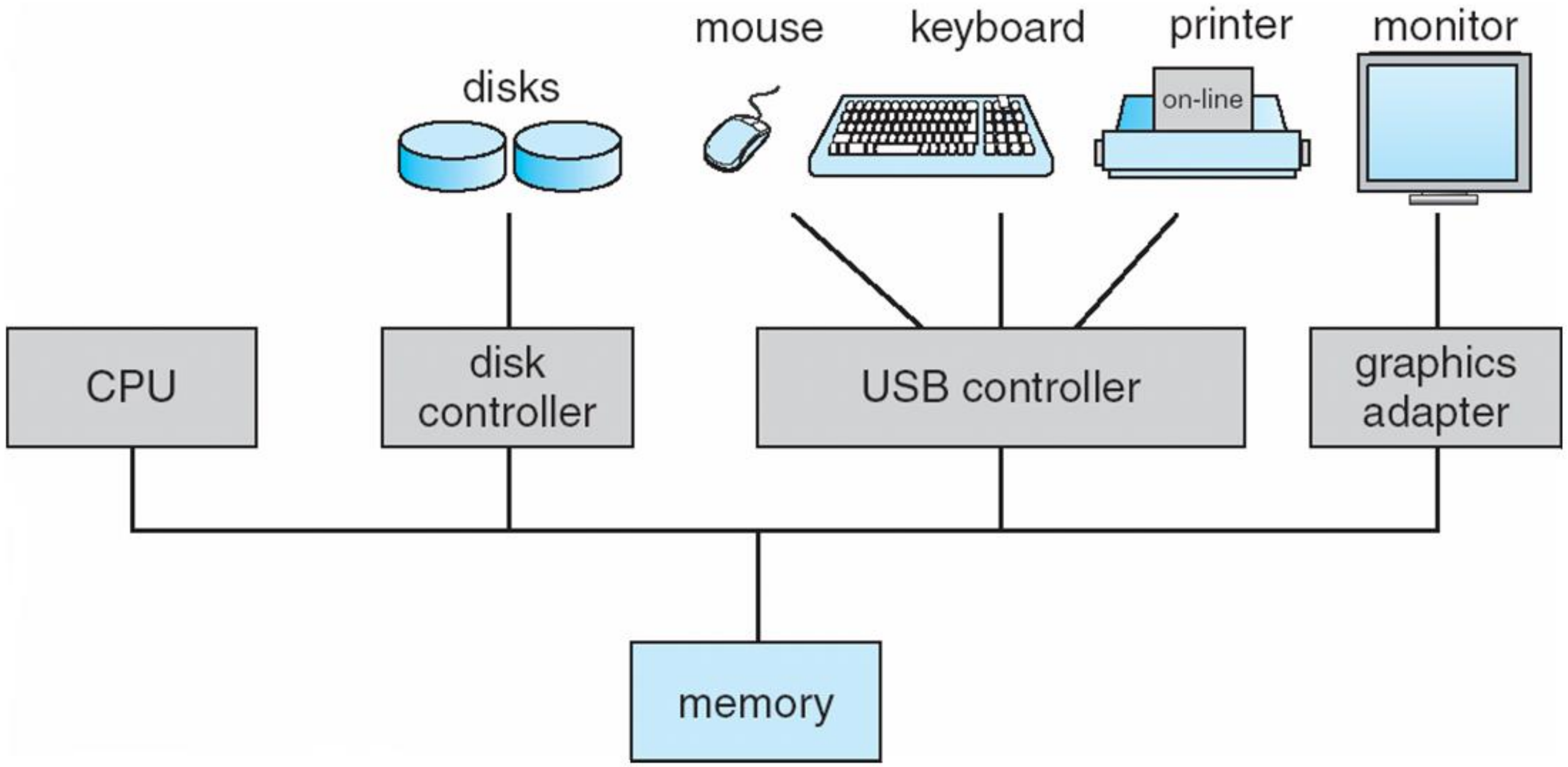
- What we presented can be described as a:
    - mini OS
    - Standard library
- Many classical OS functions are missing
- No separation between user mode and OS mode
- Some algorithms (e.g. multiplication and division) are standard
- Other algorithms (e.g. line- and circle-drawing) can be accelerated with special hardware
- And, by the way, we've just finished building the computer.

Operating system

A software layer to

- manage resources
- provide an abstract interface to application developers

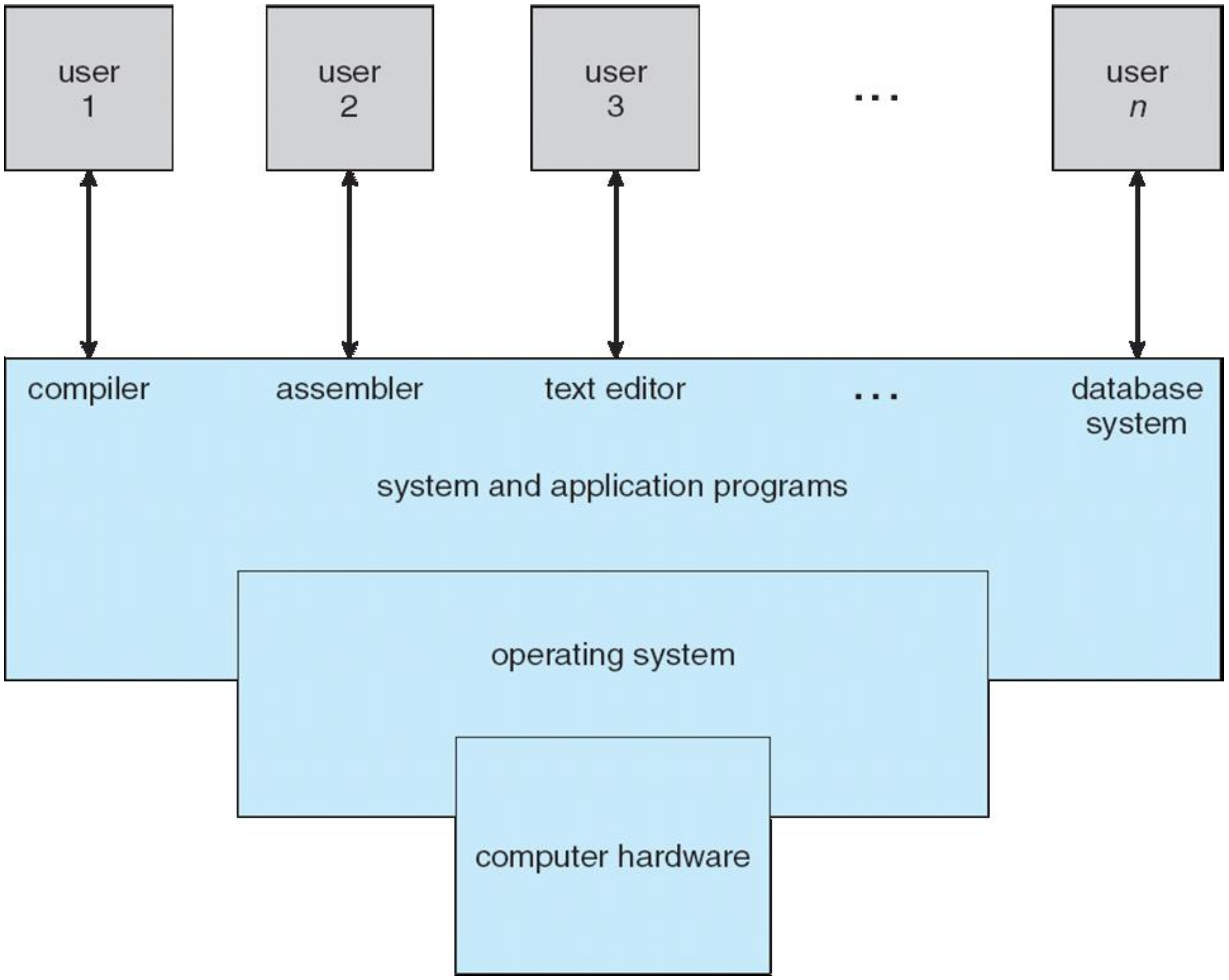




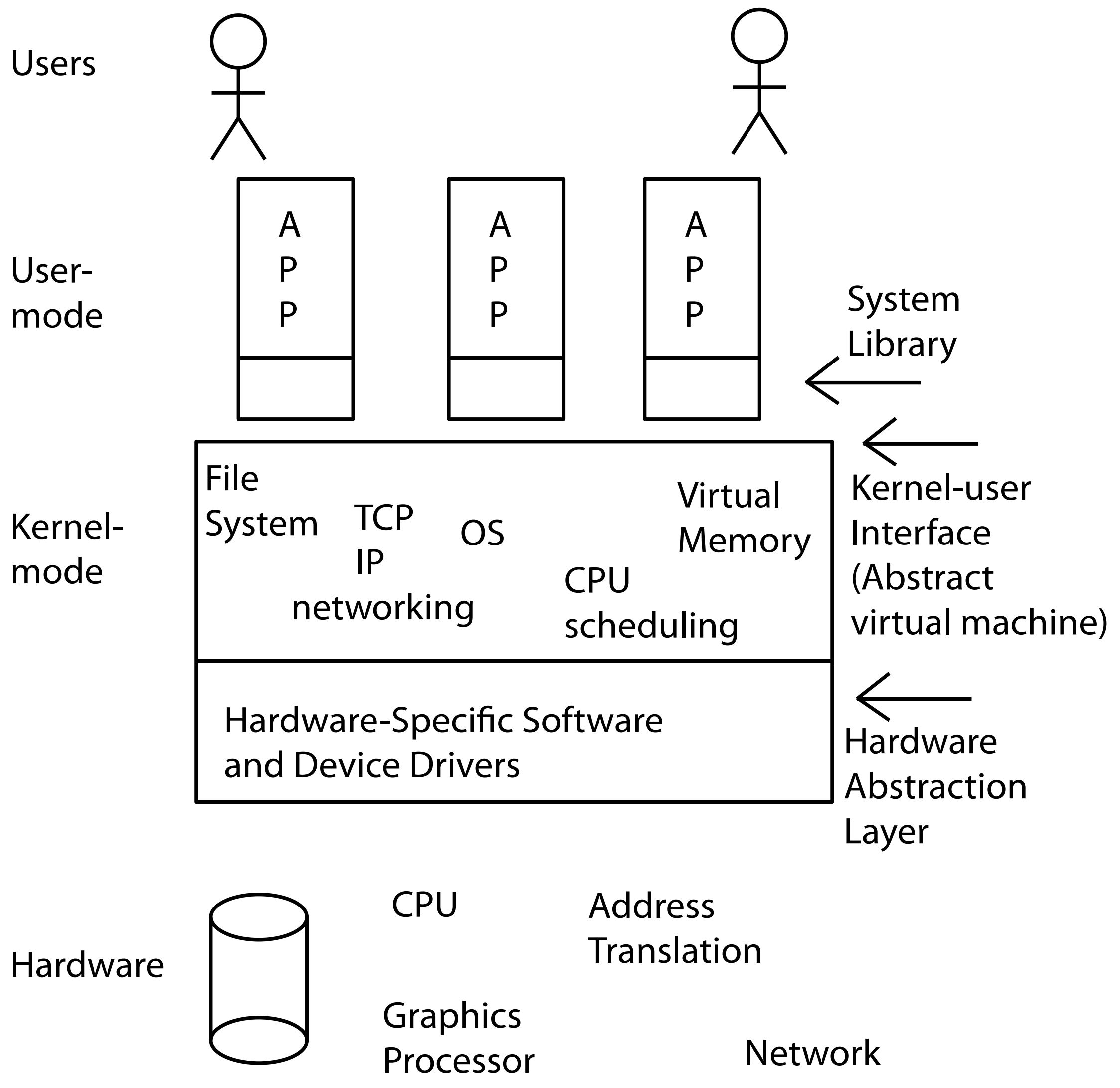
Operating system

- An OS mediates programs' access to hardware resources
  - Computation (CPU)
  - Volatile storage (memory) and persistent storage (disk, etc.)
  - Network communications (TCP/IP stacks, ethernet cards, etc.)
  - Input/output devices (keyboard, display, sound card, etc.)
- The OS abstracts hardware into logical resources and well-defined interfaces to those resources
  - processes (CPU, memory)
  - files (disk)
  - sockets (network)

OS as a resource manager

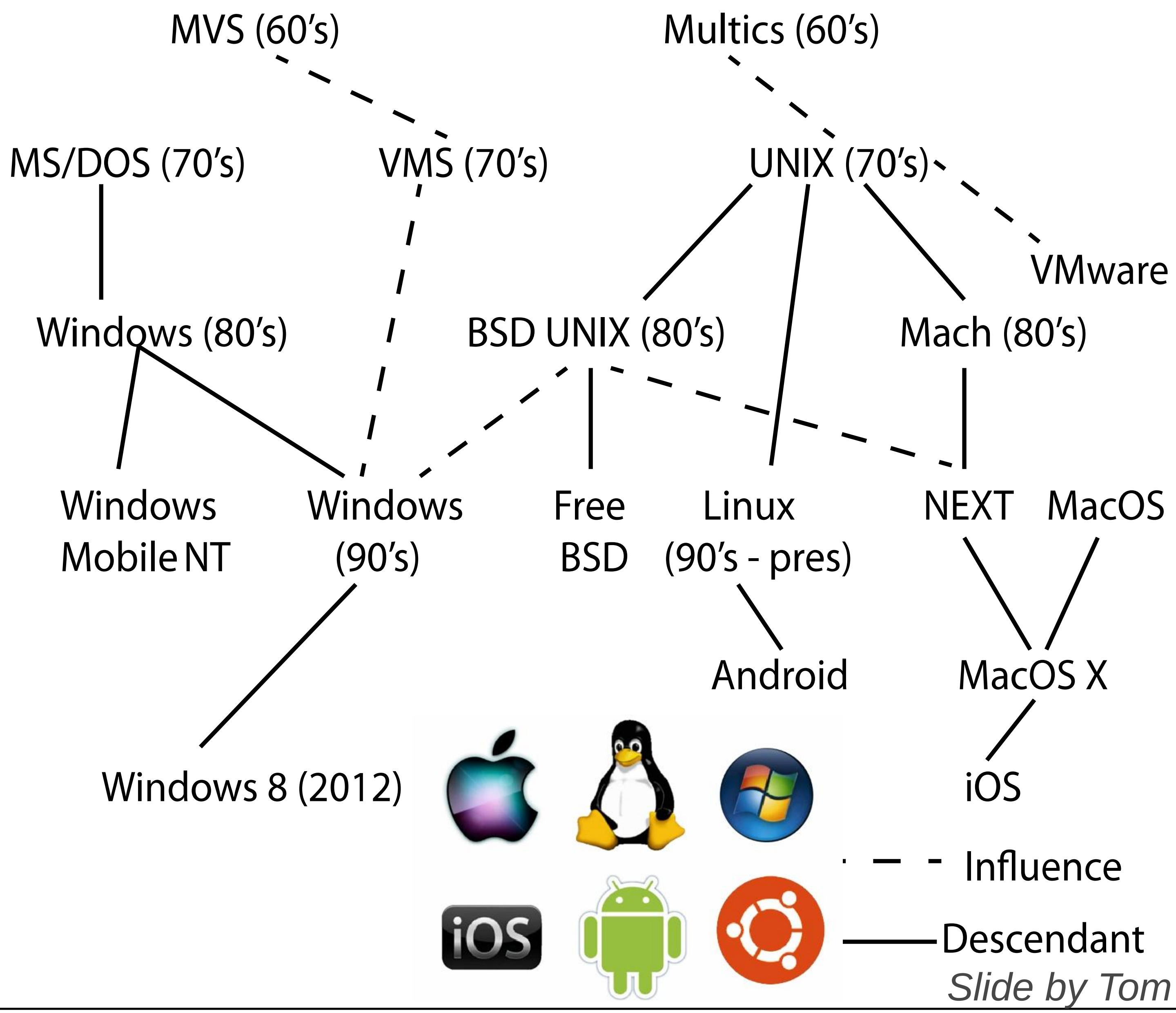


A detailed view of OS



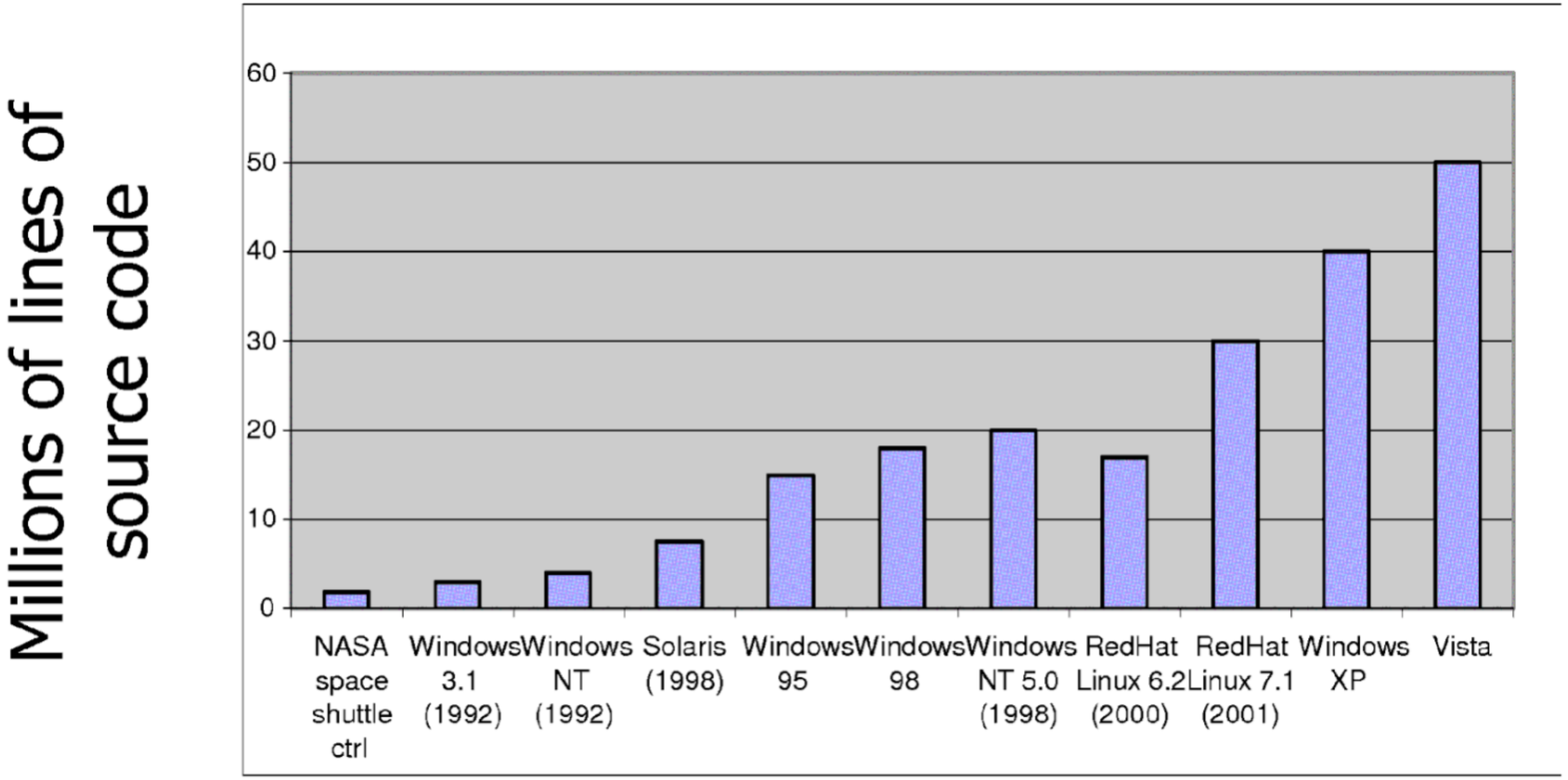
Slide by Tom Anderson

OS History



Slide by Tom Anderson

Increasing software complexity



Computer Performance Over Time

	1981	1996	2011	factor
MIPS	1	300	10000	10K
MIPS/$	$100K	$30	$0.50	200K
DRAM	128KB	128MB	10GB	100K
Disk	10MB	4GB	1TB	100K
Home Internet	9.6 Kbps	256 Kbps	5 Mbps	500
LAN network	3 Mbps (shared)	10 Mbps	1 Gbps	300
Users per machine	100	1	<< 1	100+

Slide by Tom Anderson

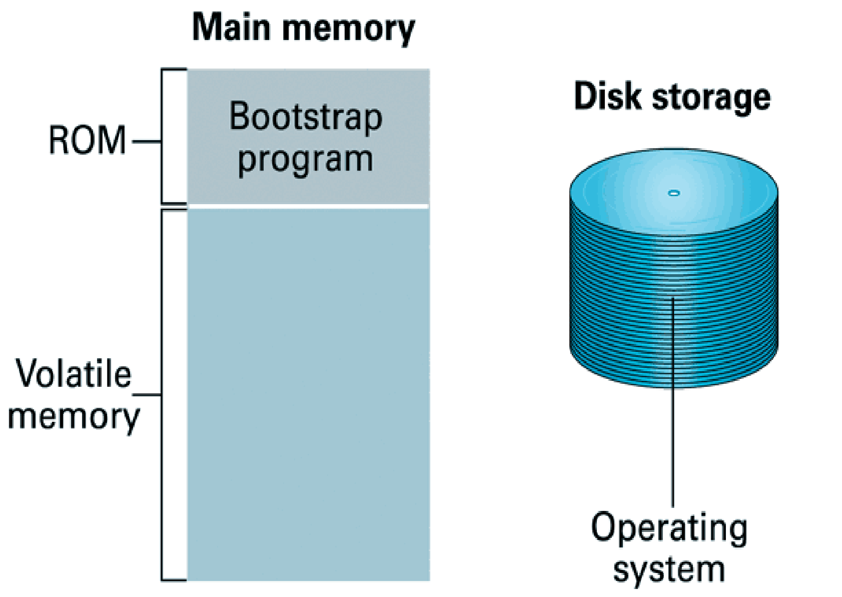
OS Challenges

- Performance
  - Latency/response time
    - How long does an operation take to complete?
  - Throughput
    - How many operations can be done per unit of time?
  - Overhead
    - How much extra work is done by the OS?
  - Fairness
    - How equal is the performance received by different users?
  - Predictability
    - How consistent is the performance over time?

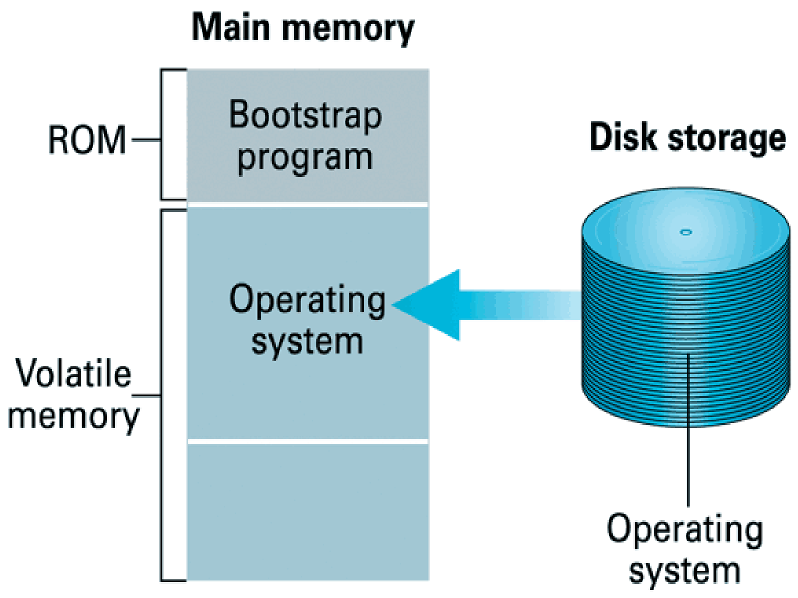
Slide by Tom Anderson

Booting

- The bootstrap program and other basic input/output functions are contained in a special ROM, called **BIOS** (basic input/output system)
- A program stored in ROM is called firmware.

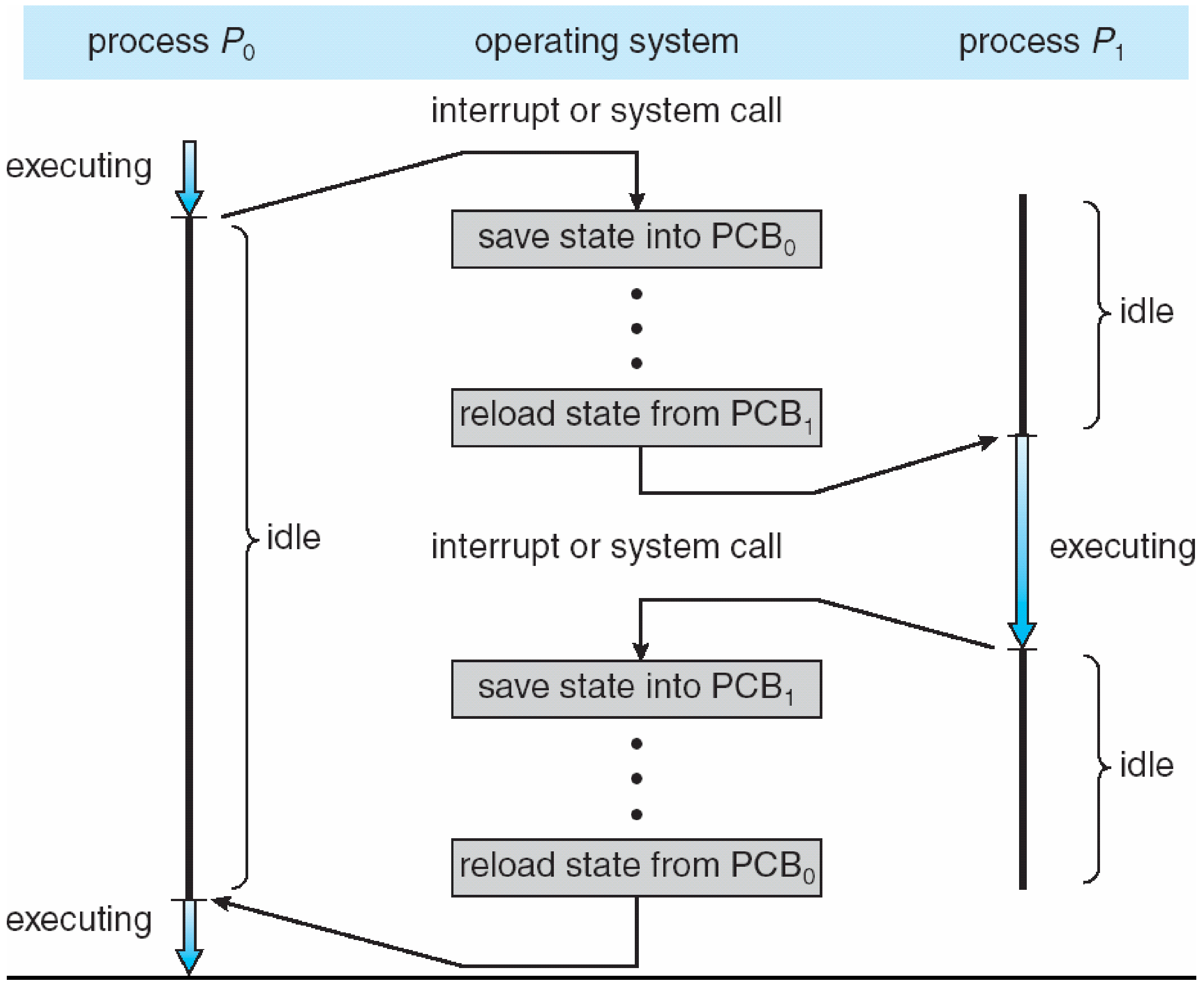


Step 1: Machine starts by executing the bootstrap program already in memory. Operating system is stored in mass storage.

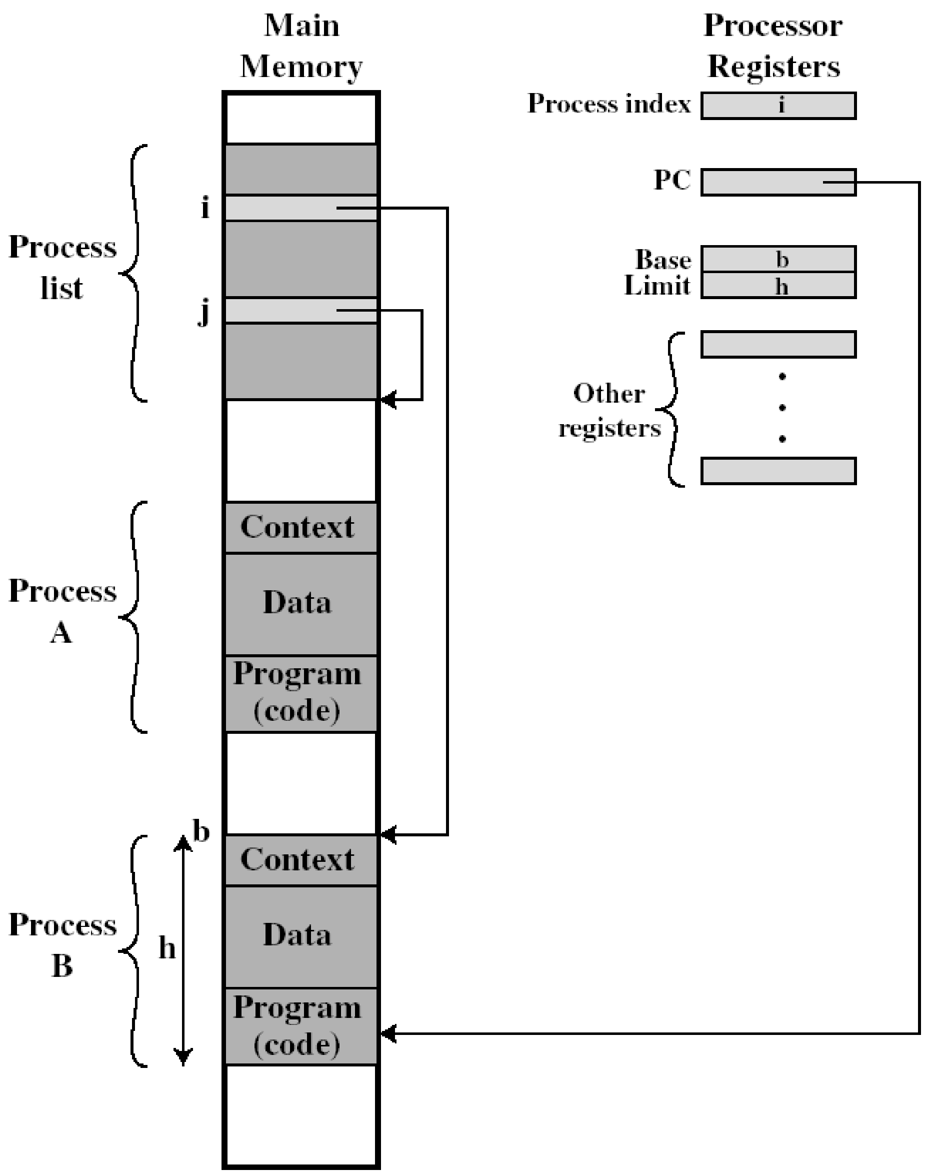


Step 2: Bootstrap program directs the transfer of the operating system into main memory and then transfers control to it.

Process switching

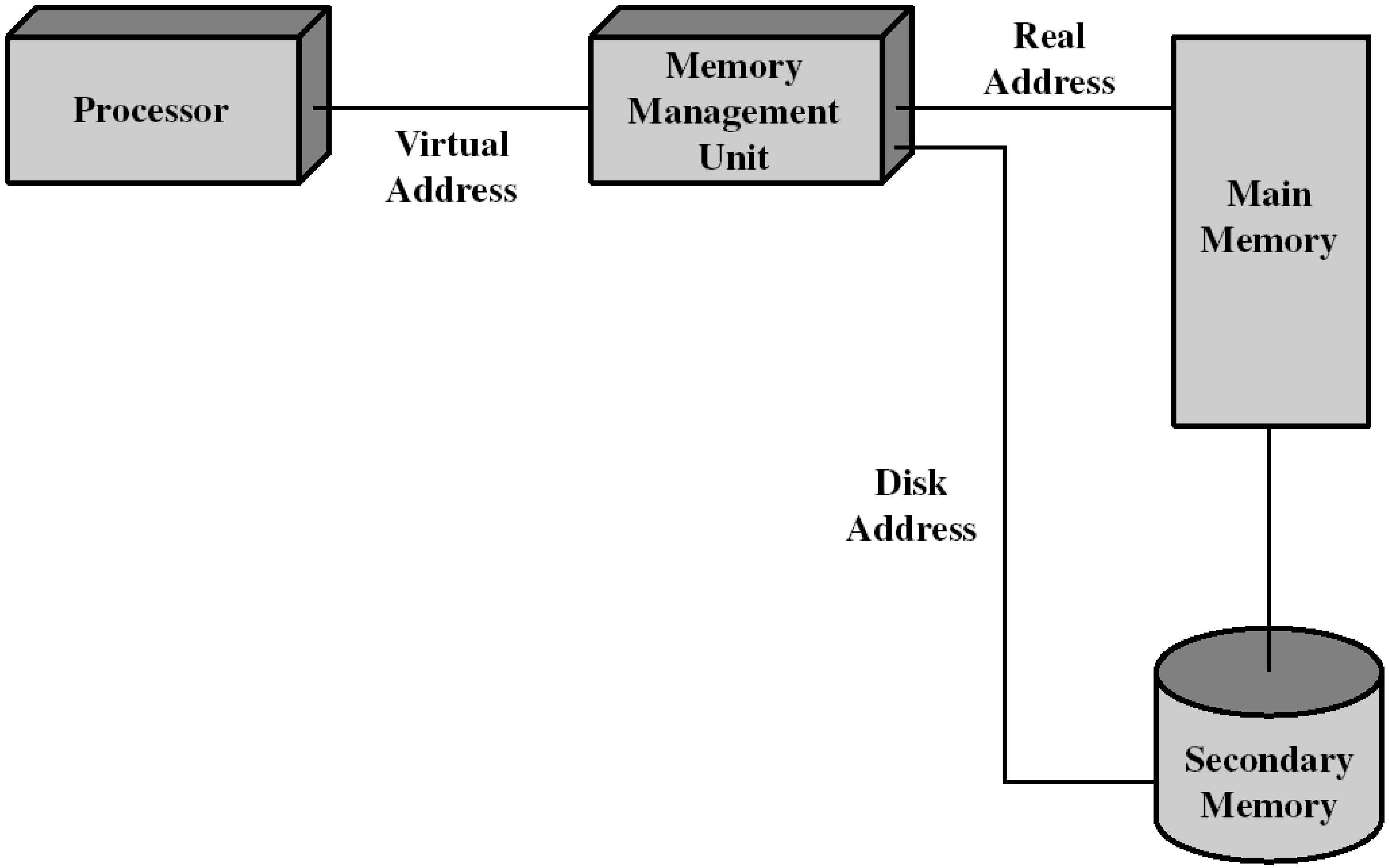


Process and context switching



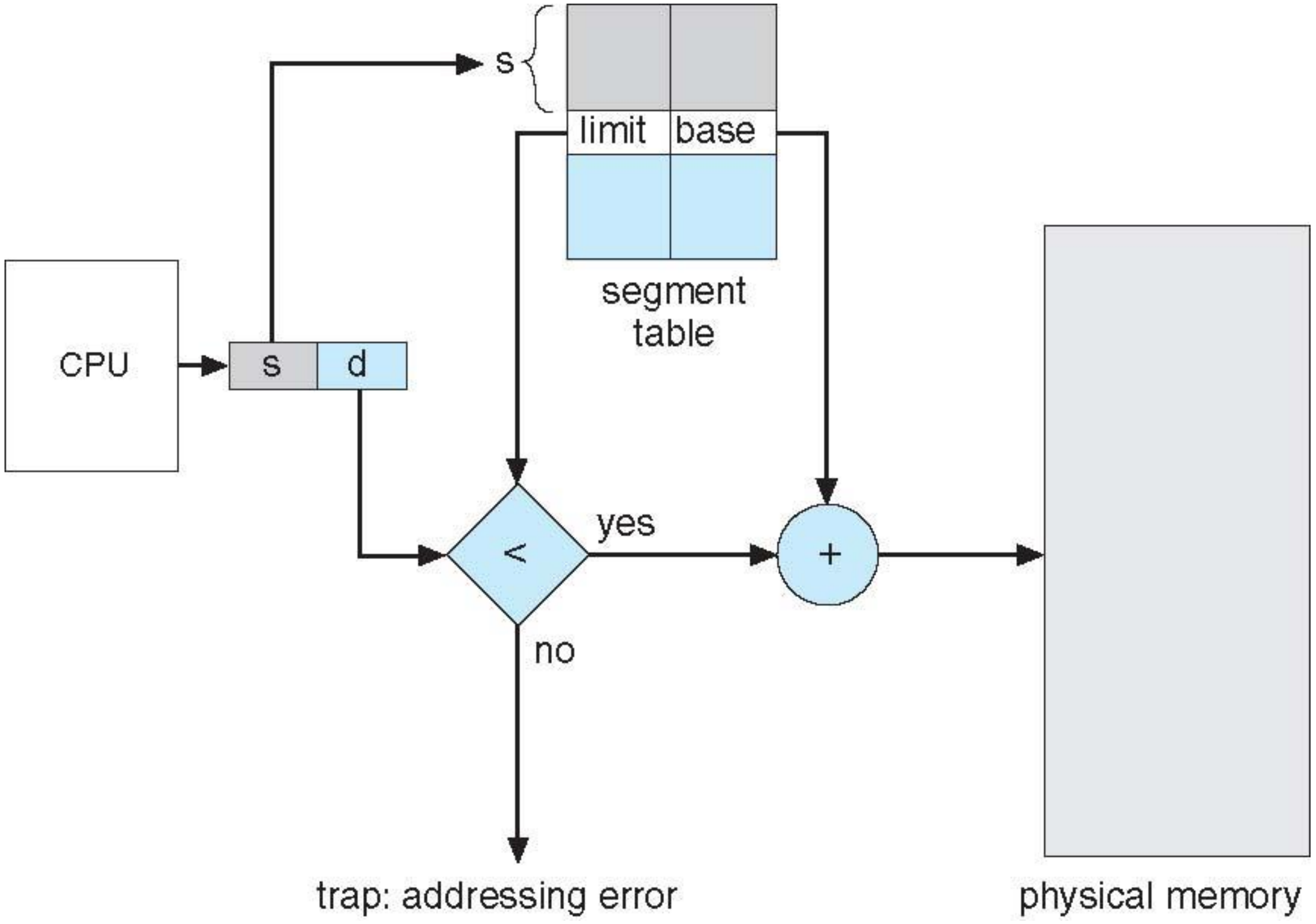
- When to switch?
  - Call system service
  - Interrupts (e.g. time slice)
- Switch to which process?
  - Scheduling: first-com-first-serve, shortest job first, round robin …
- What to store/restore?
  - Basically registers
- Competition to resource
  - Semaphore
  - Critical section

Memory management

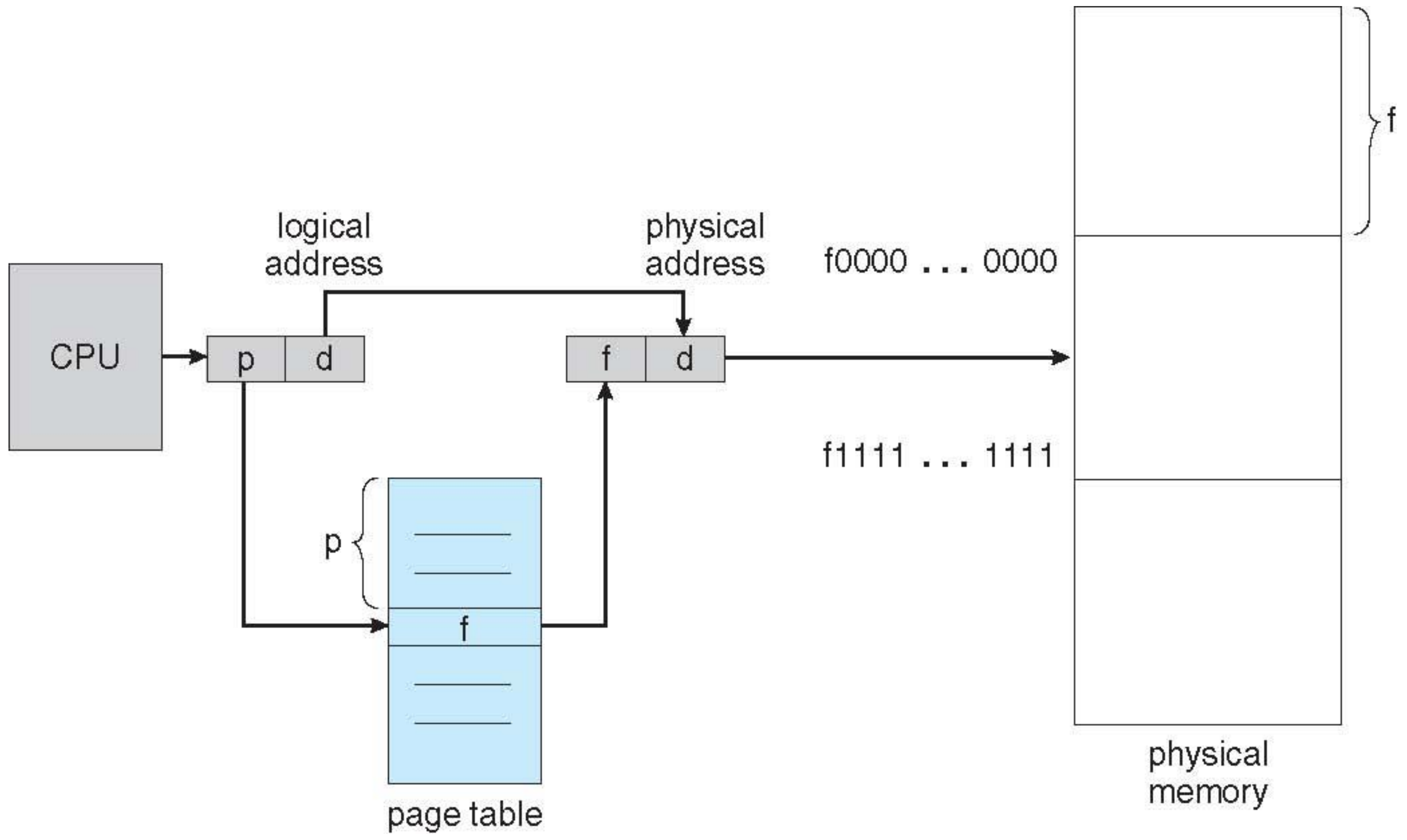


Segmentation hardware

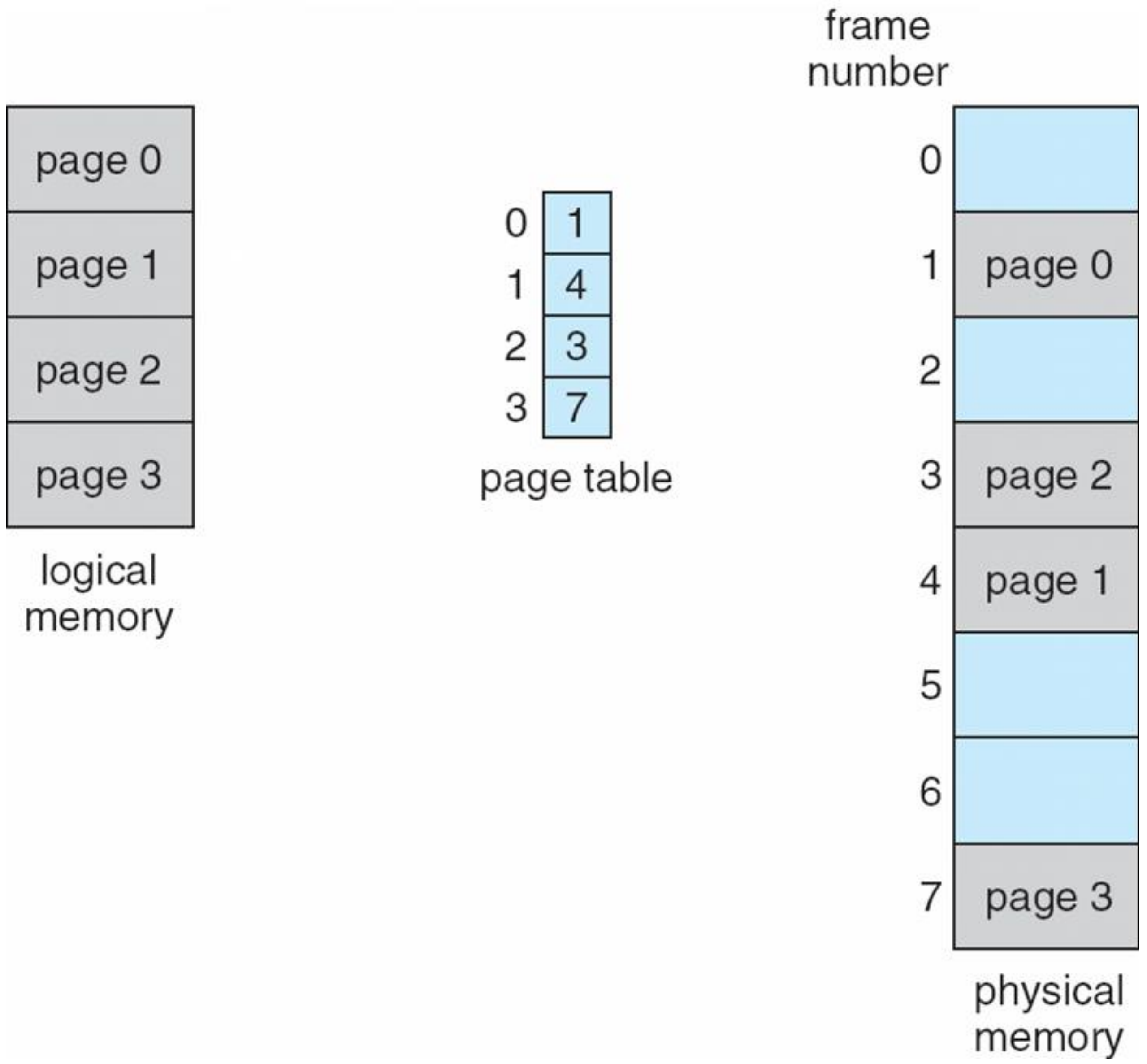
- Each process has its own segment table managed by OS.



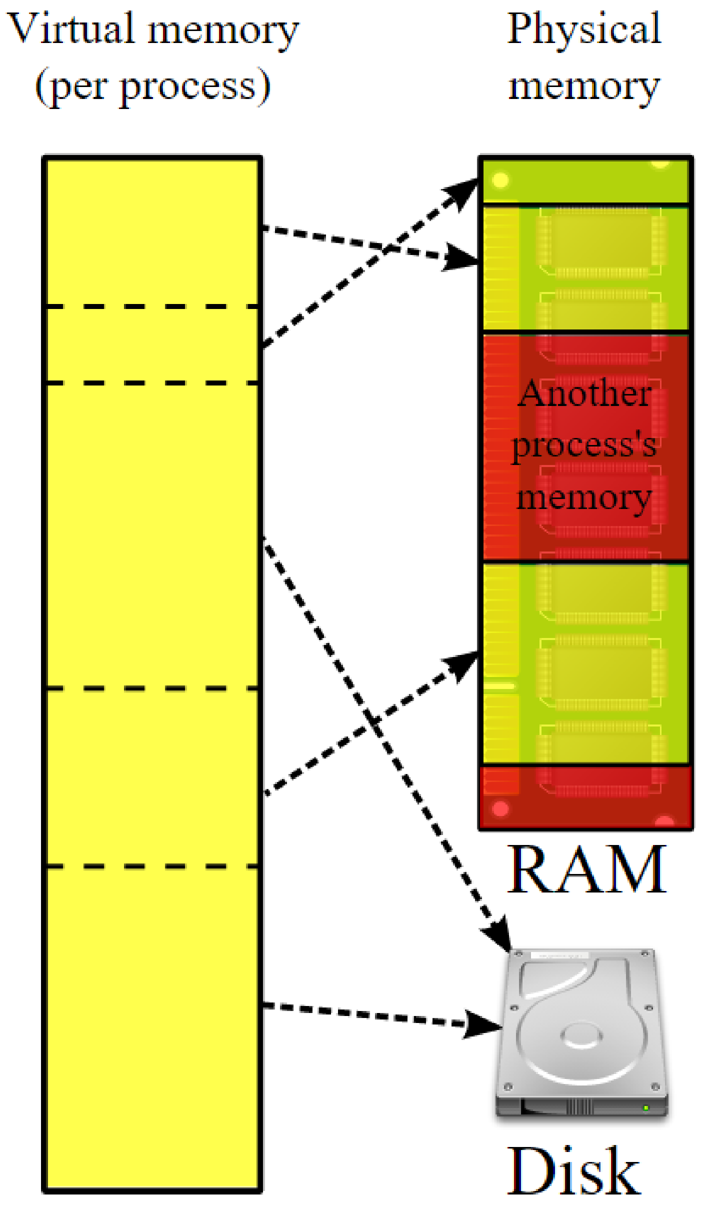
Paging hardware



Paging example

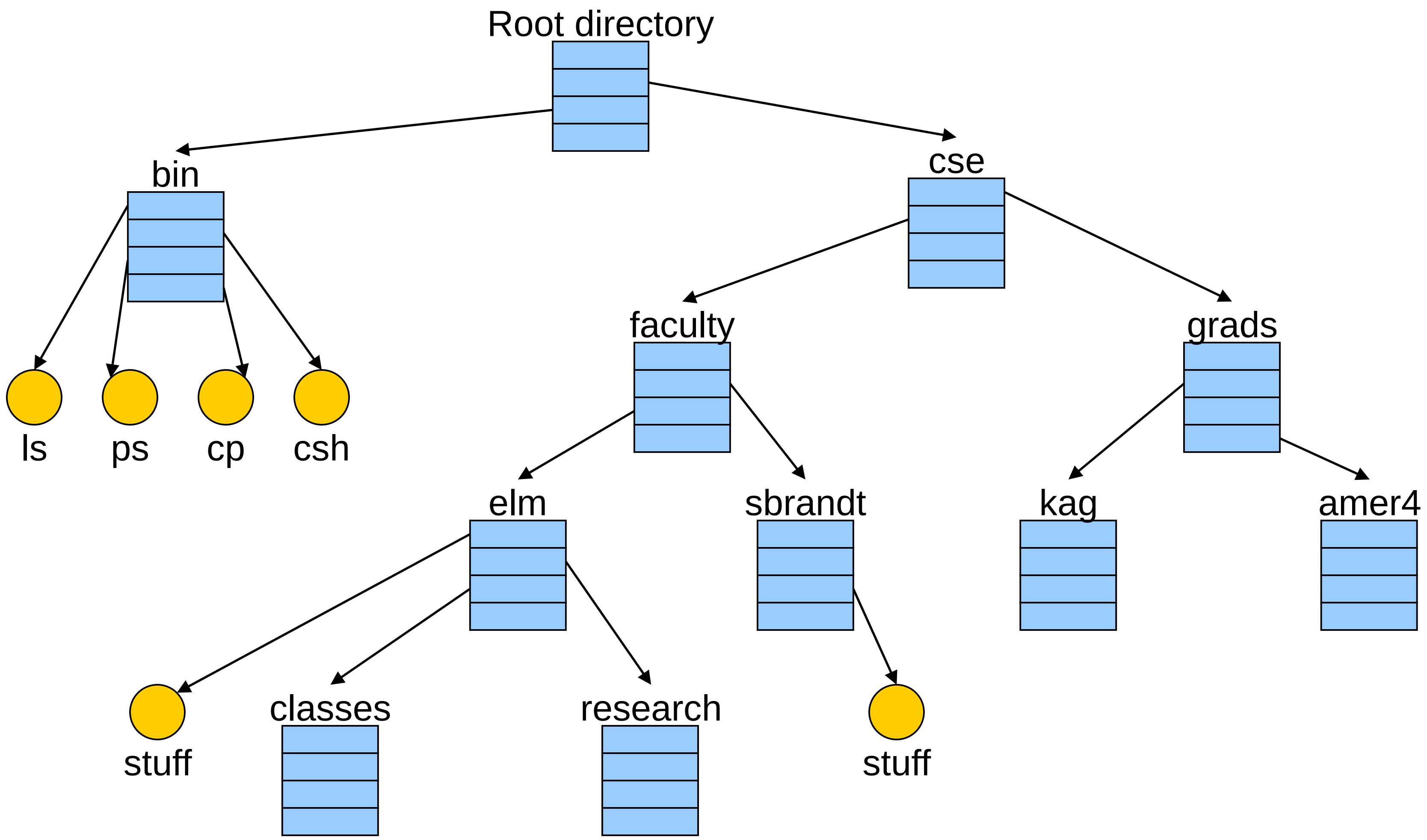


Virtual memory

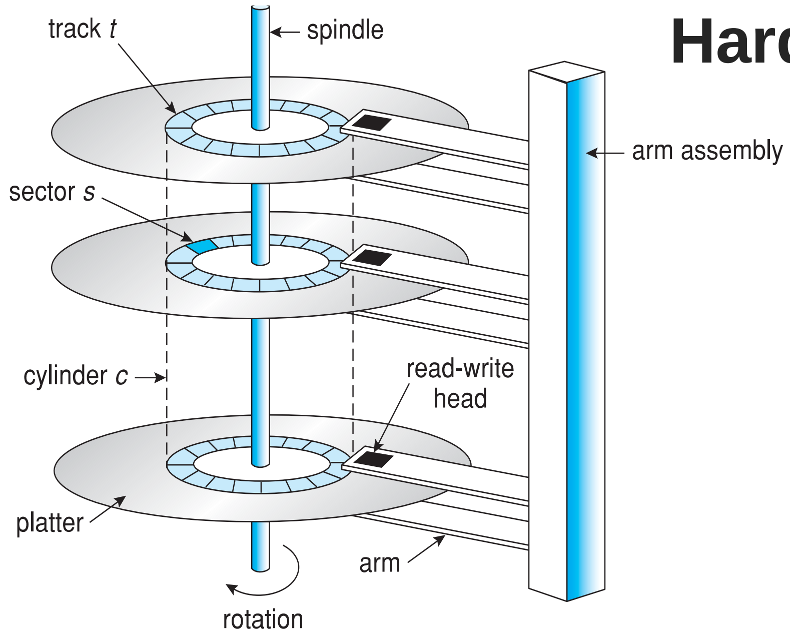


- The page could locate on the disk => virtual memory

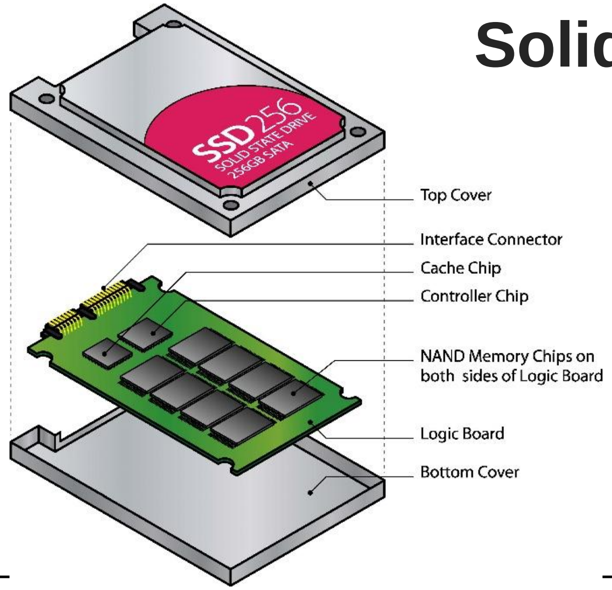
Hierarchical file systems



Storage



Hard Disk



Solid State Disk

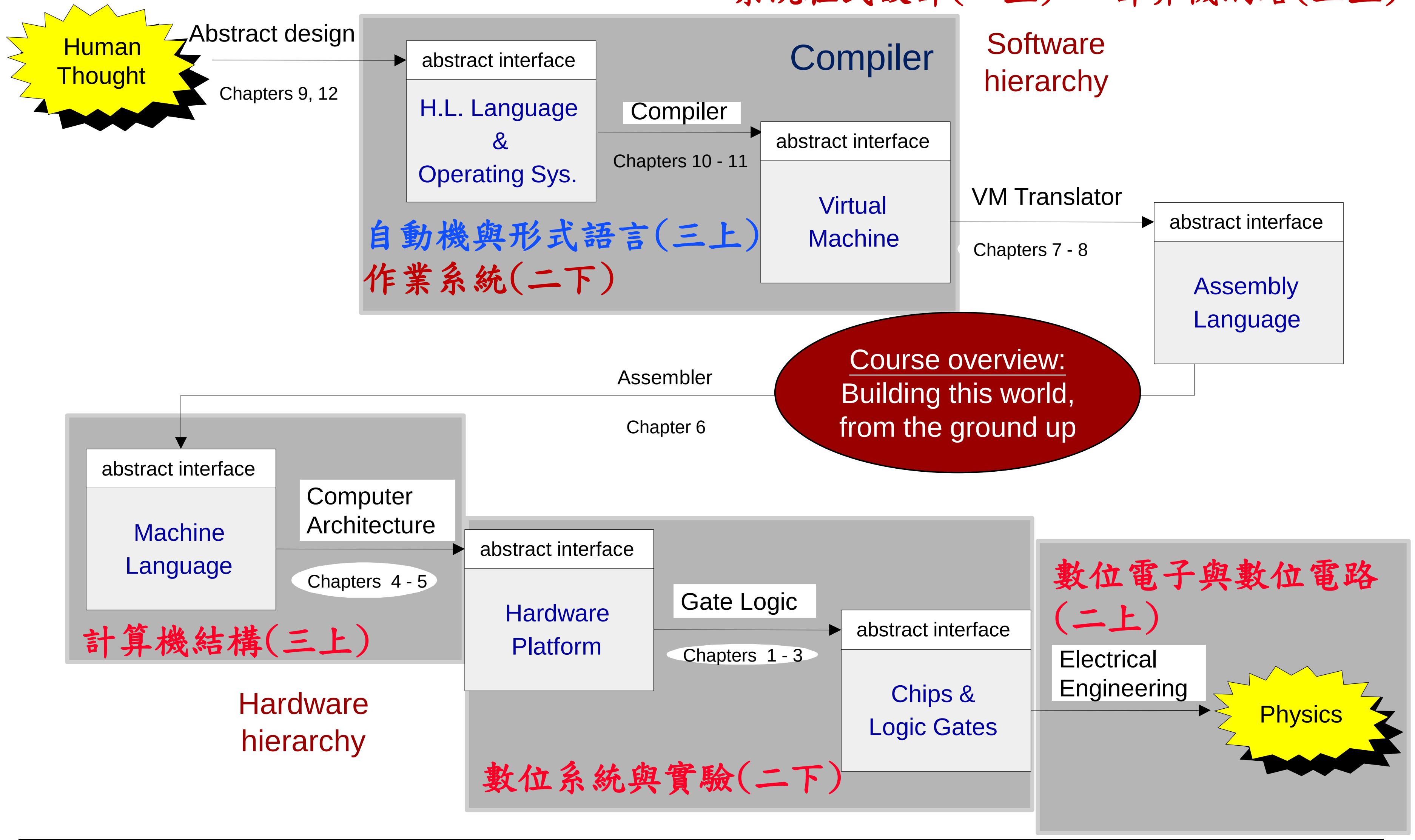
1956 IBM RAMDAC computer included the IBM Model 350 disk storage system (5M)

The tour map

線性代數（二上），機率（二下）

資料結構與演算法(一下)，演算法設計與分析(二上)

系統程式設計(二上) ，計算機網路(三上)


Human Thought
Abstract design
Chapters 9, 12
abstract interface
H.L. Language & Operating Sys.
Compiler
Compiler
Chapters 10 - 11
abstract interface
Virtual Machine
Software hierarchy
自動機與形式語言(三上)
作業系統(二下)
VM Translator
Chapters 7 - 8
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Assembly Language
Course overview:
Building this world, from the ground up
Assembler
Chapter 6
abstract interface
Machine Language
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計算機結構(三上)
abstract interface
Hardware Platform
Gate Logic
Chapters 1 - 3
abstract interface
Chips & Logic Gates
數位電子與數位電路(二上)
Electrical Engineering
Physics
Hardware hierarchy
數位系統與實驗(二下)