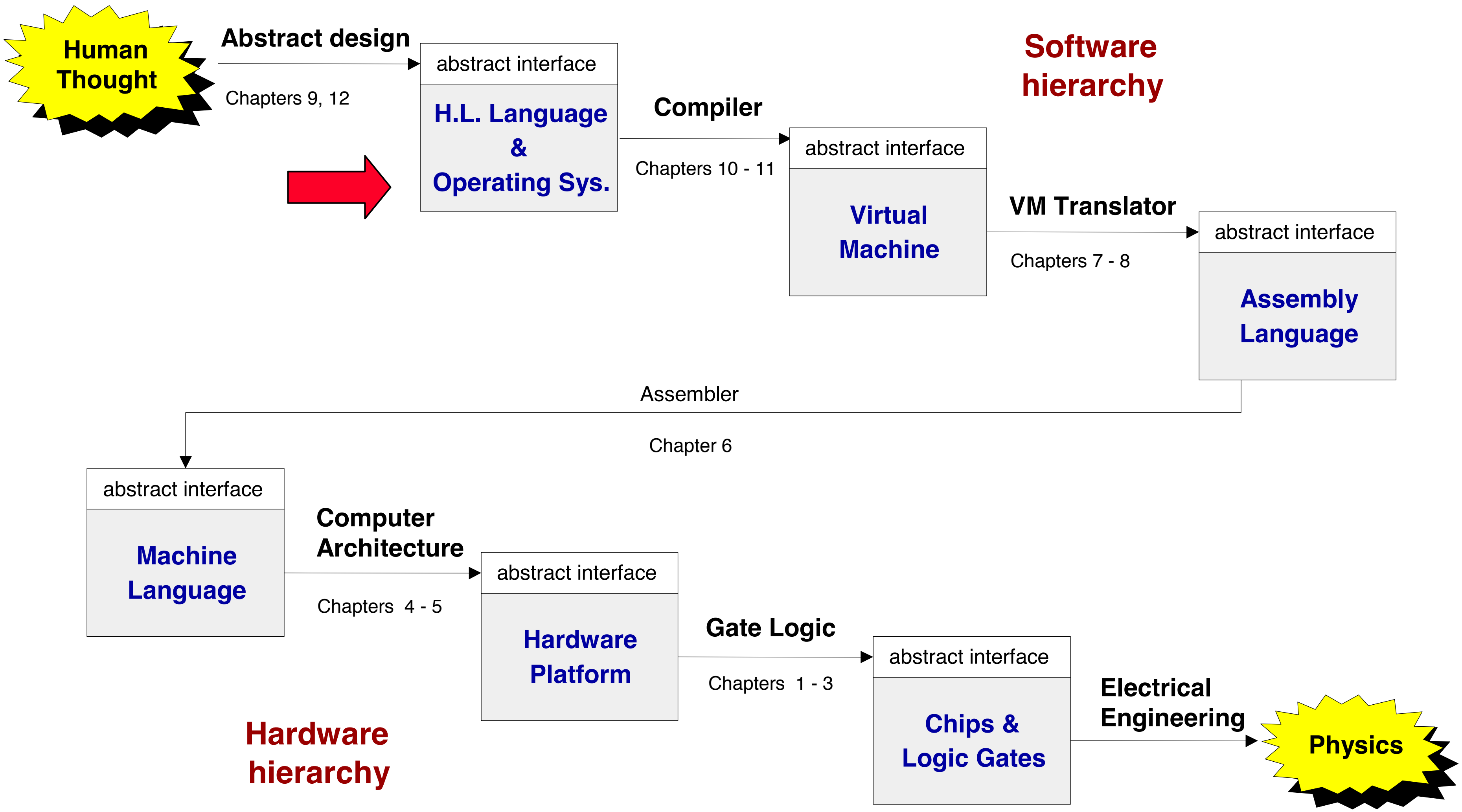
Operating Systems

Building a Modern Computer From First Principles

www.nand2tetris.org

Where we are at:



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

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/** Computes the average of a sequence of integers. */
class Main {
  function void main() {
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    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;
  }
}
```

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 ...

The Jack OS

- **`Math:`** Provides basic mathematical operations;
- **`String:`** Implements the **`String`** type and string-related operations;
- **`Array:`** Implements the **`Array`** type and array-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 {
}

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)
}
```

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

The "steps"

$$
\begin{array}{rrrrrrcrr}
 & & 1 & 0 & 1 & 1 & = & 1 & 1 \\
 & & & 1 & 0 & 1 & = & & 5 \\
\hline
 & & 1 & 0 & 1 & 1 & & & \\
 & 0 & 0 & 0 & 0 & & & & \\
1 & 0 & 1 & 1 & & & & & \\
\hline
1 & 1 & 0 & 1 & 1 & 1 & = & 5 & 5
\end{array}
$$

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

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

  $sum = sum + shiftedX$

 $shiftedX = shiftedX * 2$

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

Example II: square root

The square root function has two convenient properties:

- It's 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 $0 \ldots\ 2^{n/2} - 1$.

$y = 0$

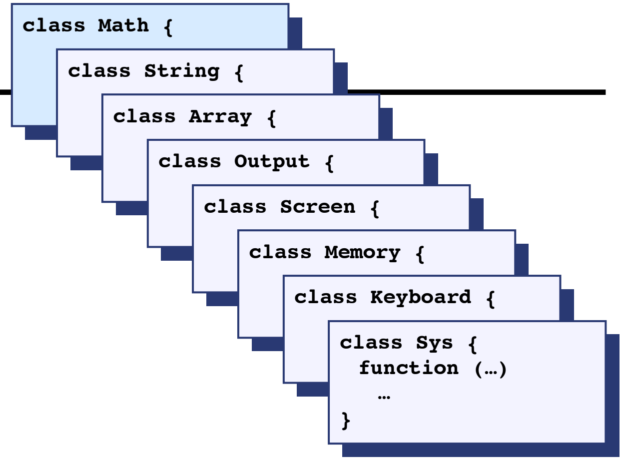
for $j = n/2 - 1 \ldots 0$ do

    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).

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)

}
```

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()

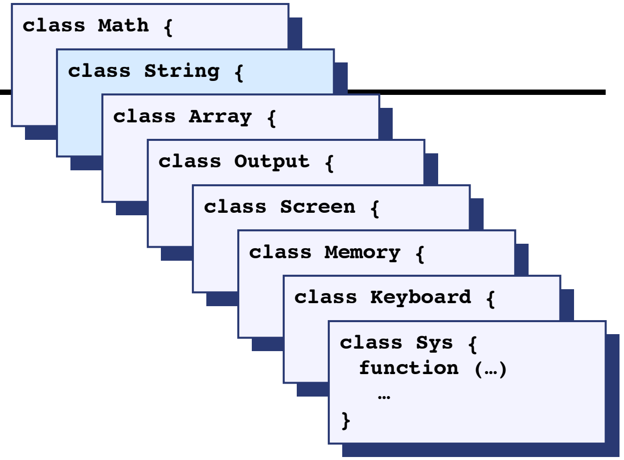
    method void   setInt(int j)

    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)
```

```
// Convert a string to a non-negative number
string2Int(s):
    v = 0
    for i = 1 ... 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 = 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*.

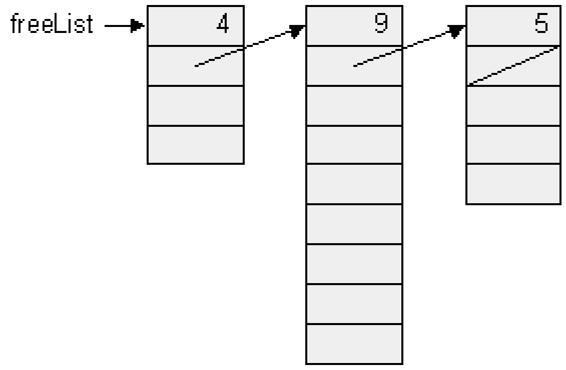
deAlloc(*object*):

segment = *object* - 1

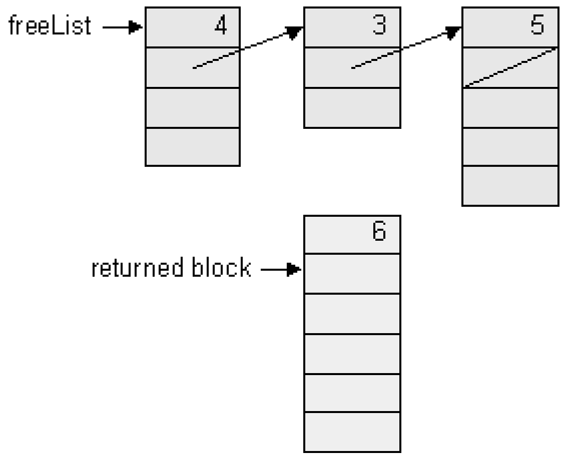
segment.length = *object*[-1]

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)

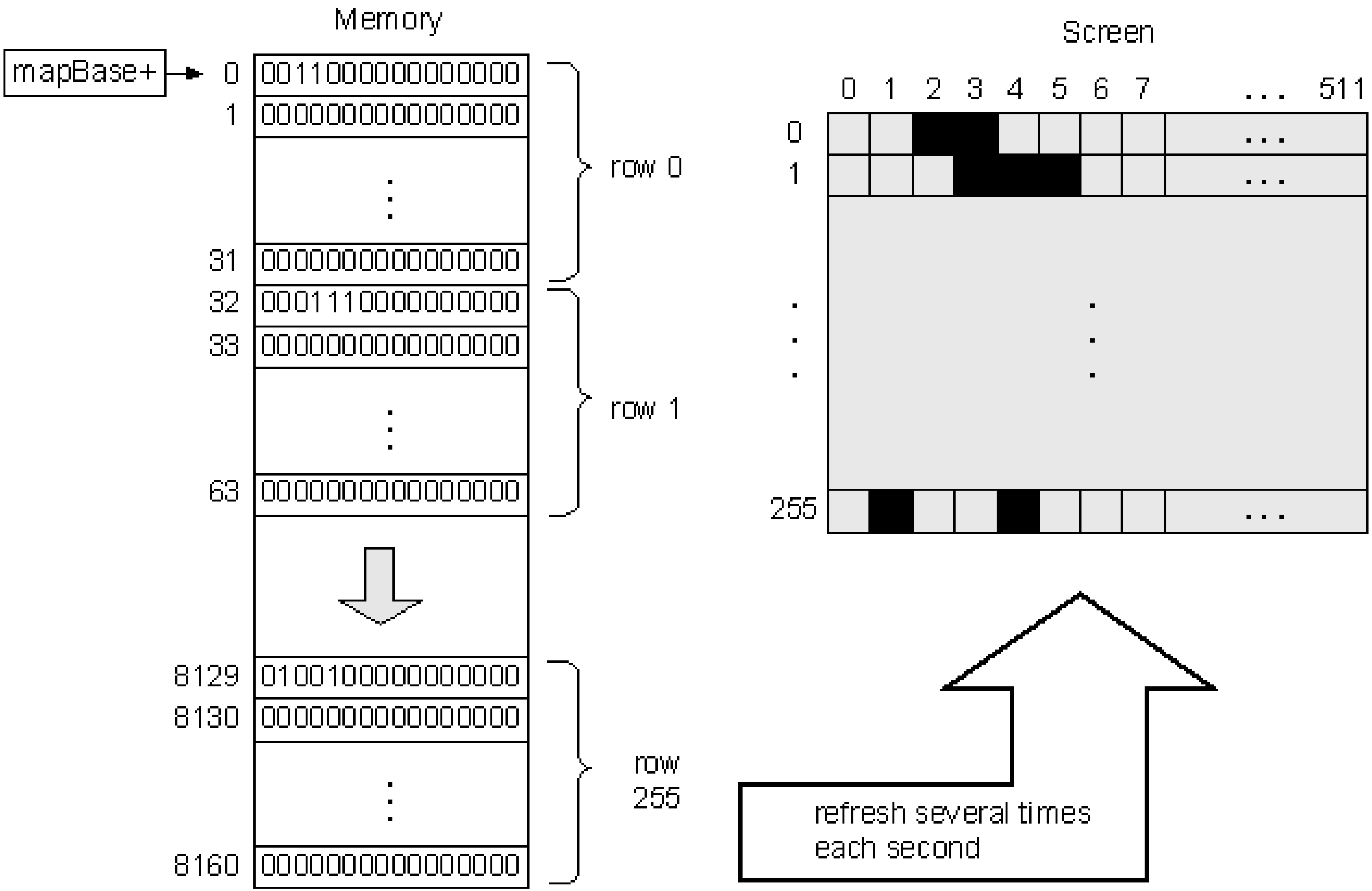
   function void drawLine(int x1, int y1, int x2, int y2)

   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)

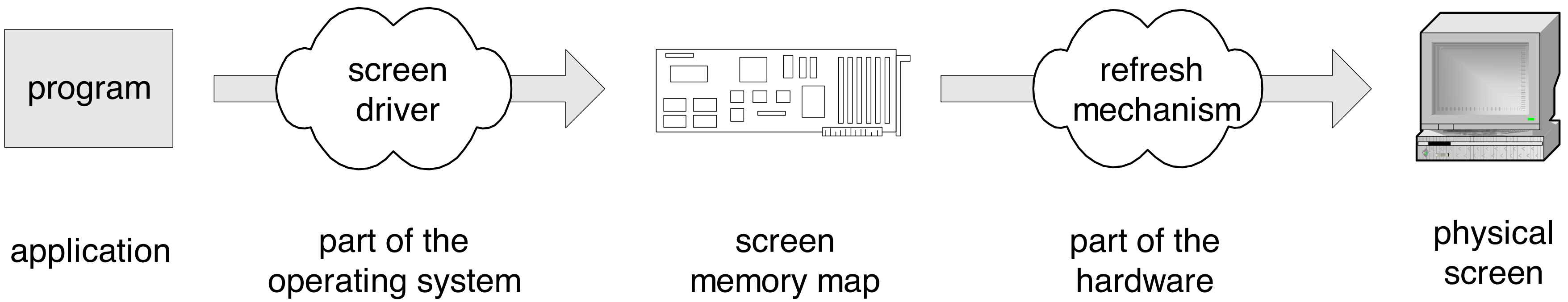
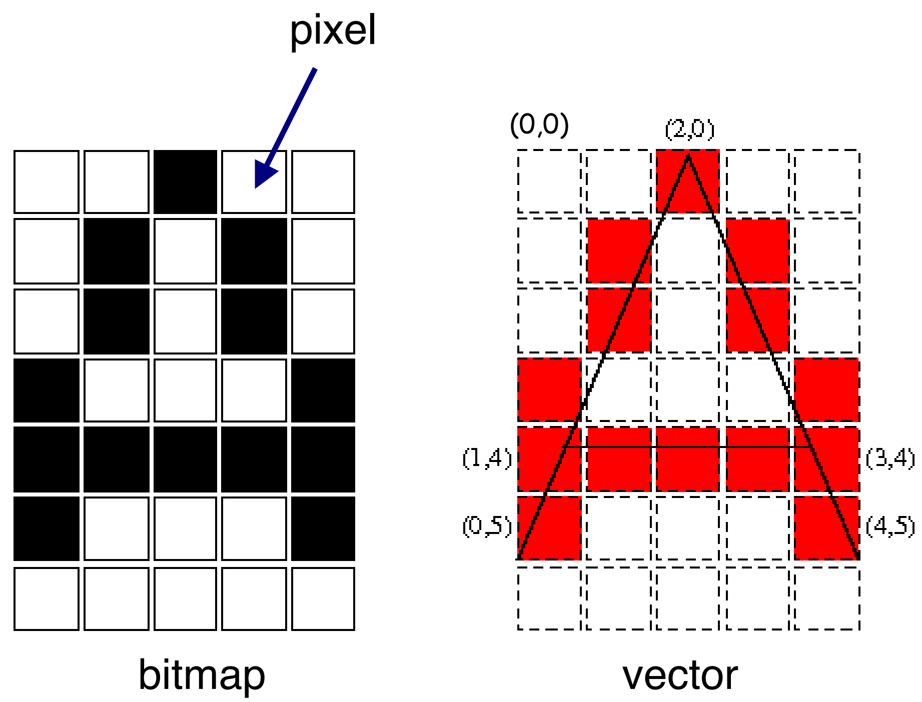
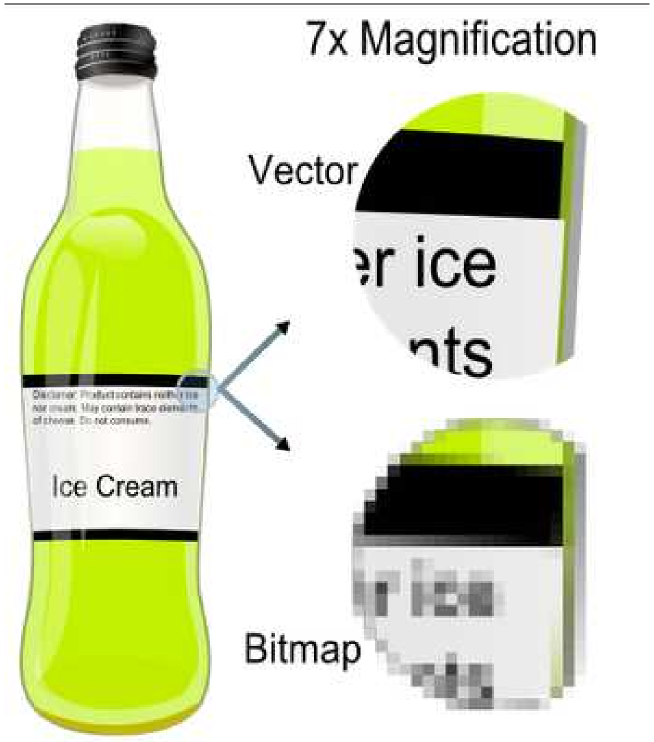


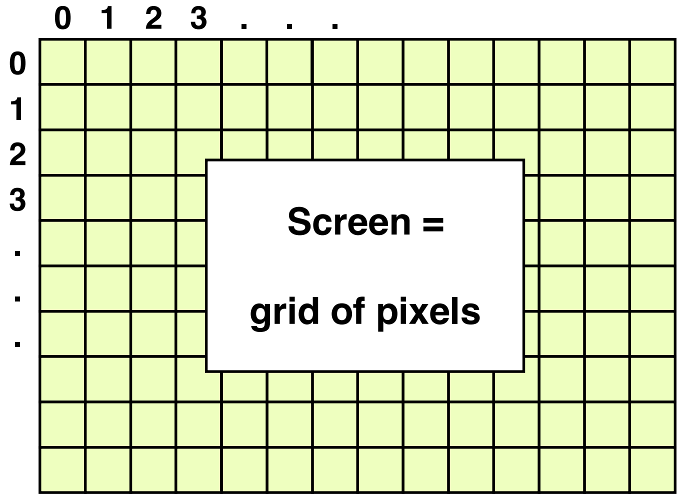
Image representation: bitmap versus vector graphics



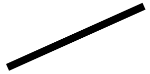


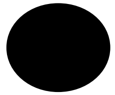
- Bitmap file: 00100, 01010,01010,10001,11111,10001,00000, . . .
- Vector graphics file: drawLine(2,0,0,5), drawLine(2,0,4,5), drawLine(1,4,3,4)
- Pros and cons of each method.

Vector graphics: basic operations



 drawPixel(x,y) (Primitive operation)

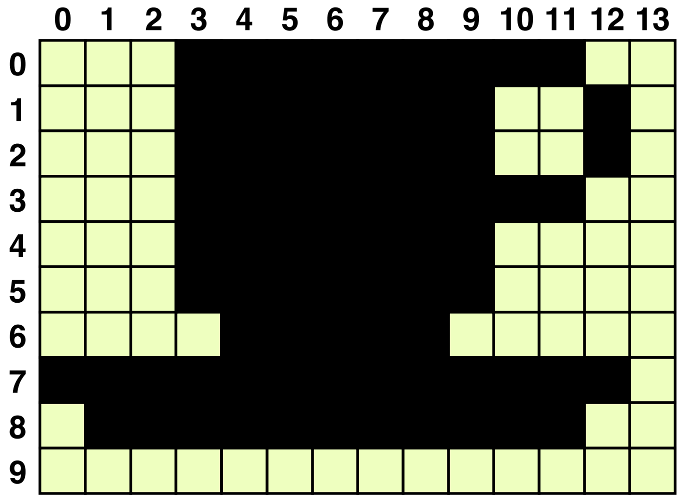
 drawLine(x1,y1,x2,y2)

 drawCircle(x,y,r)

 drawRectangle(x1,y1,x2,y2)

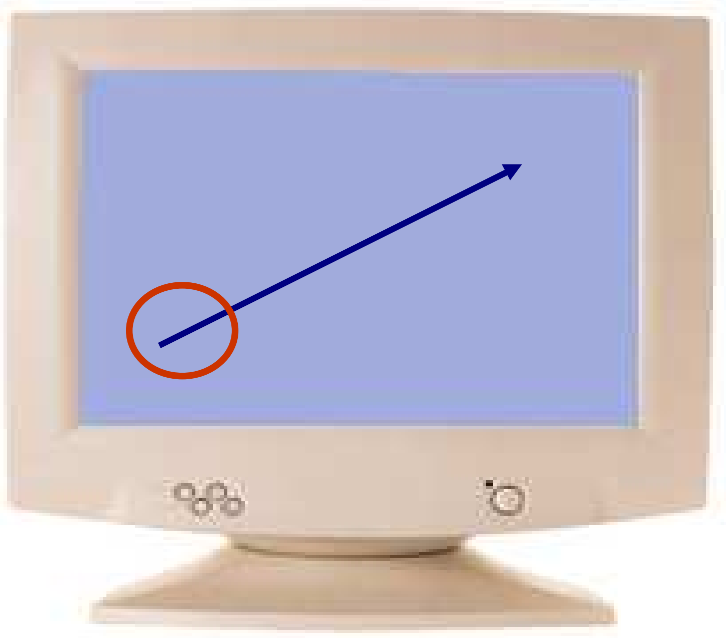
 drawTriangle(x1,y1,x2,y2,x3,y3)

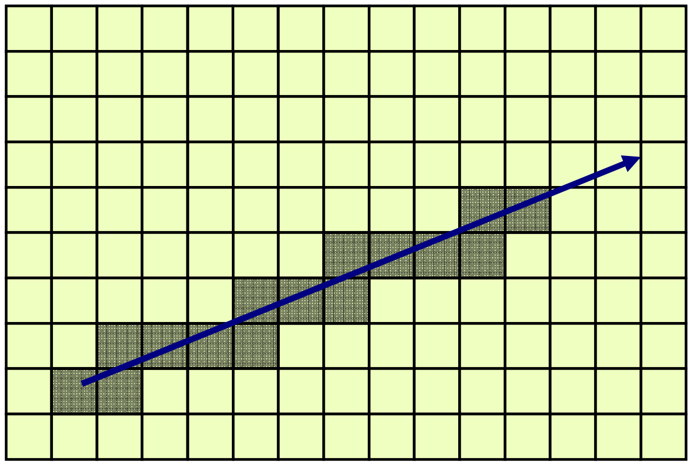
etc. (a few more similar operations)



```
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?



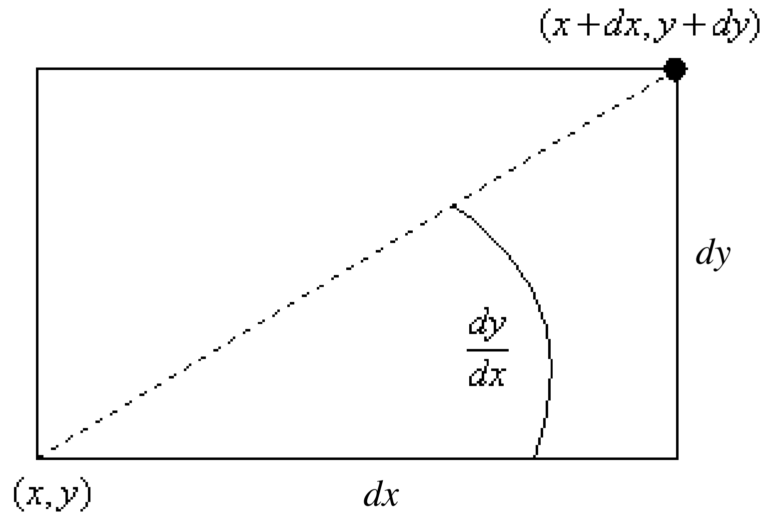


drawLine(x1,y1,x2,y2)

- 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

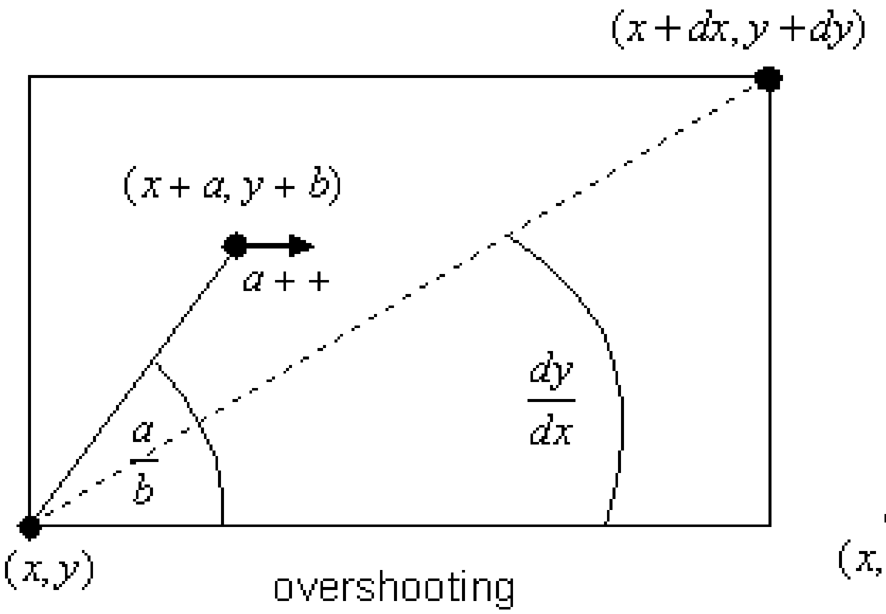
- Given: drawLine(x1,y1,x2,y2)
- Notation: x=x1, y=y1, dx=x2-x1, dy=y2-y1
- Using the new notation:
  We are asked to draw a line
  between (x,y) and (x+dx,y+dy)

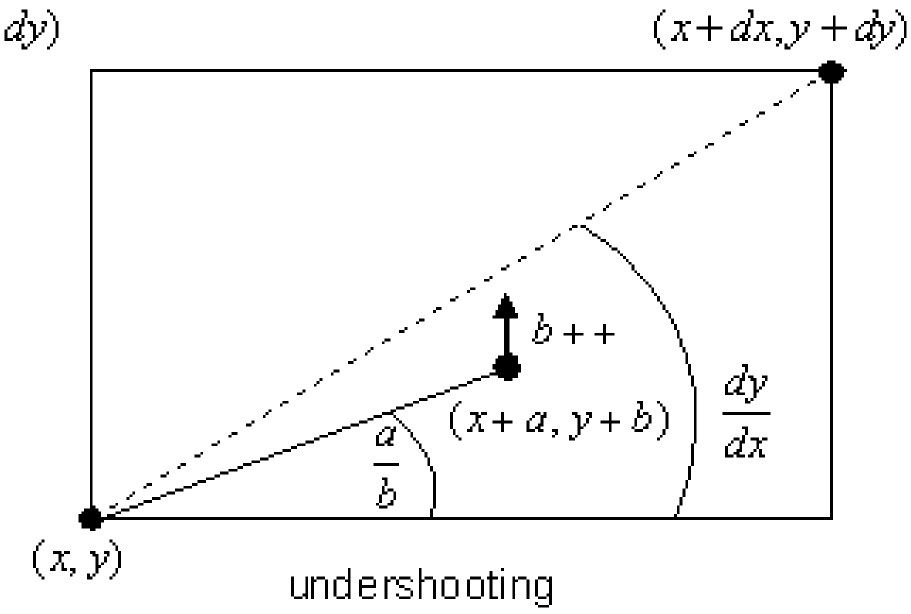



```
set (a,b) = (0,0)
while there is more work to do
    drawPixel(x+a,y+b)
    decide if you want to go right, or up
    if you decide to go right, set a=a+1;
     if you decide to go up, set b=b+1
```

```
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





<u>drawLine(x,y,x+dx,y+dy)</u>

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

Oy Vey

<u>drawLine(x,y,x+dx,y+dy)</u>

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

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
```

```
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 + dx
       else        set b=b+1, diff = diff - dy
```

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)

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

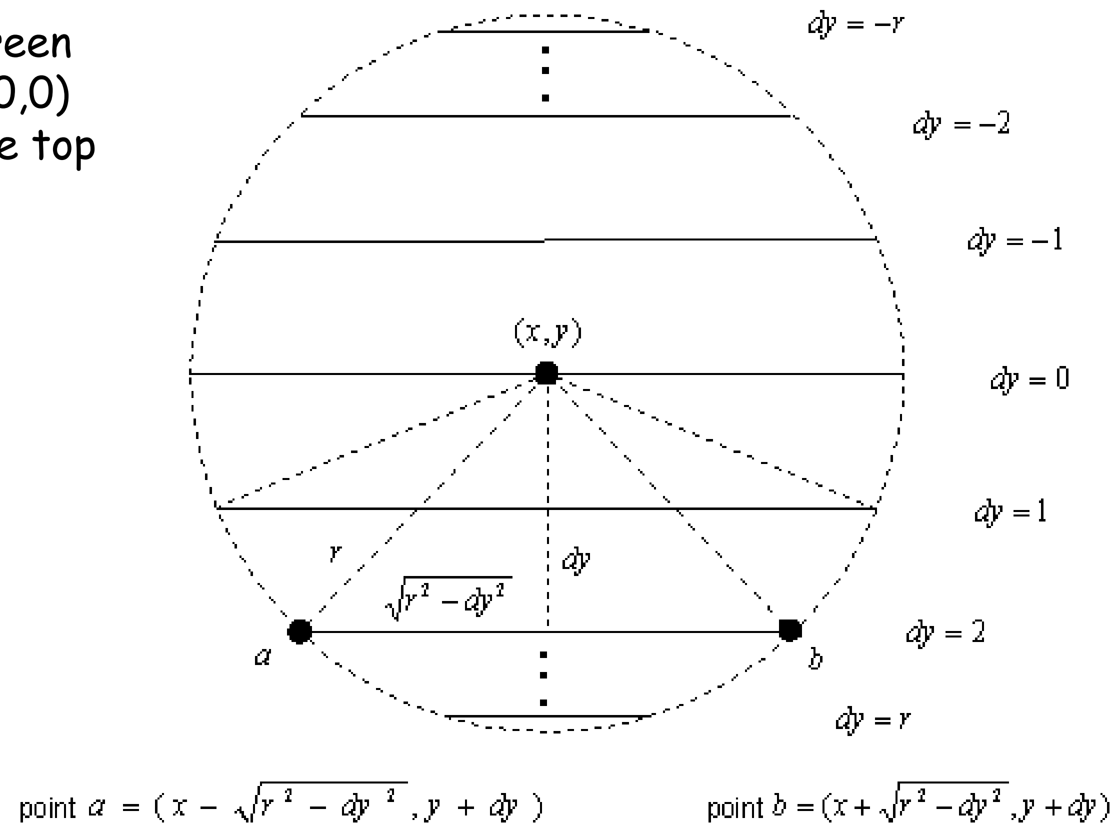
Define diff = a*dy – b*dx

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.



drawCircle(x, y, r):

for each $dy \in -r \ldots r$ do

drawLine from $(x - \sqrt{r^2 - dy^2}, y + dy)$ to $(x + \sqrt{r^2 - dy^2}, y + dy)$

An anecdote about efficiency and design

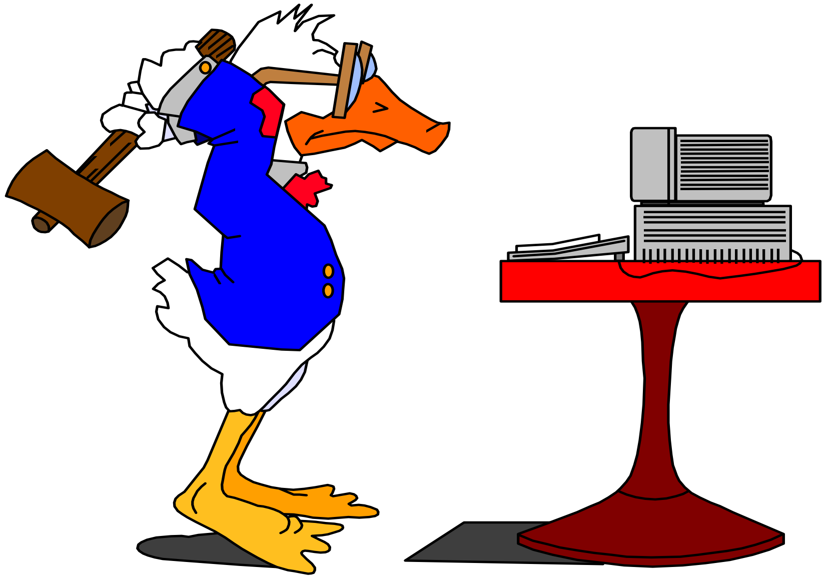
… Jobs obsessed about the look of what would appear on the screen. One day Bill Atkinson burst into his office all excited. He had just come up with a brilliant algorithm that could draw circles onscreen quickly. The math for making circles usually required calculating square roots, which the Motorola 68000 microprocessor didn’t support. But Atkinson did a workaround based on the fact that the sum of a sequence of odd numbers produces a sequence of perfect squares (e.g. 1 + 3 = 4, 1 + 3 + 5 = 9, etc.)

When Atkinson fired up his demo, everyone was impressed except Jobs. “Well, circles are nice,” he said, “but how about drawing rectangles with rounded corners?”

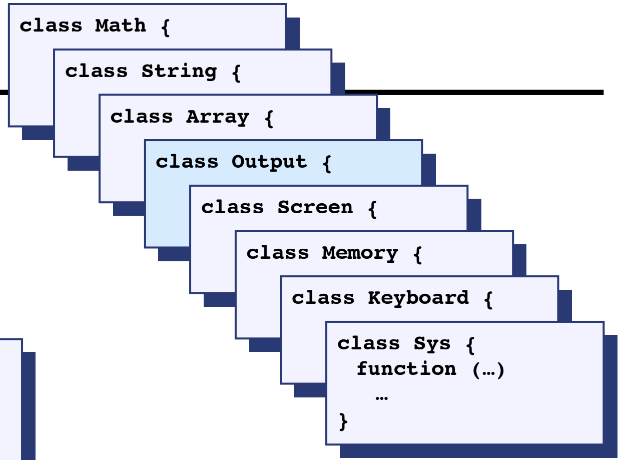
(*Steve Jobs*, by Walter Isaacson, 2012)

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.



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)

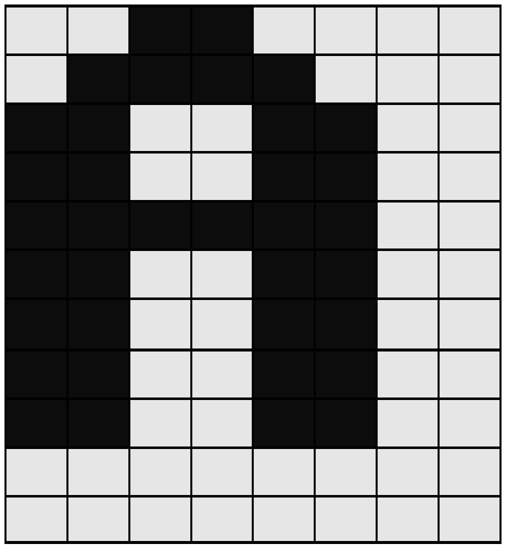
    function void println()

    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".

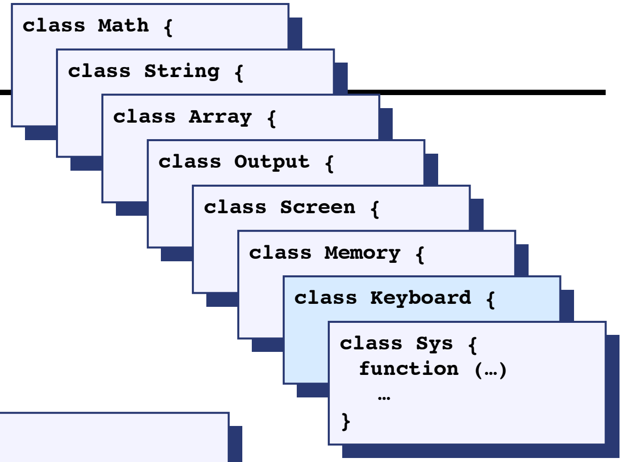


Font implementation (in the Jack OS)

```
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;
 }
```

```
// 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"

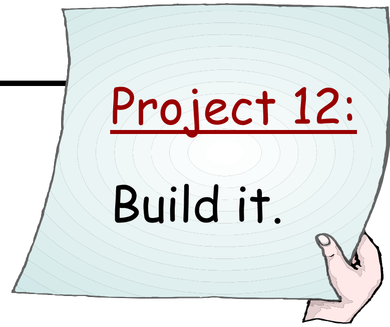
(*Steve Jobs*, by Walter Isaacson, 2012)

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 the user presses a key
   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
```

```
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.append(c)
   return s
```

Jack OS recap




```
class Math {

Class String {

Class Array {

}

class Output {

Class Screen {

class Memory {

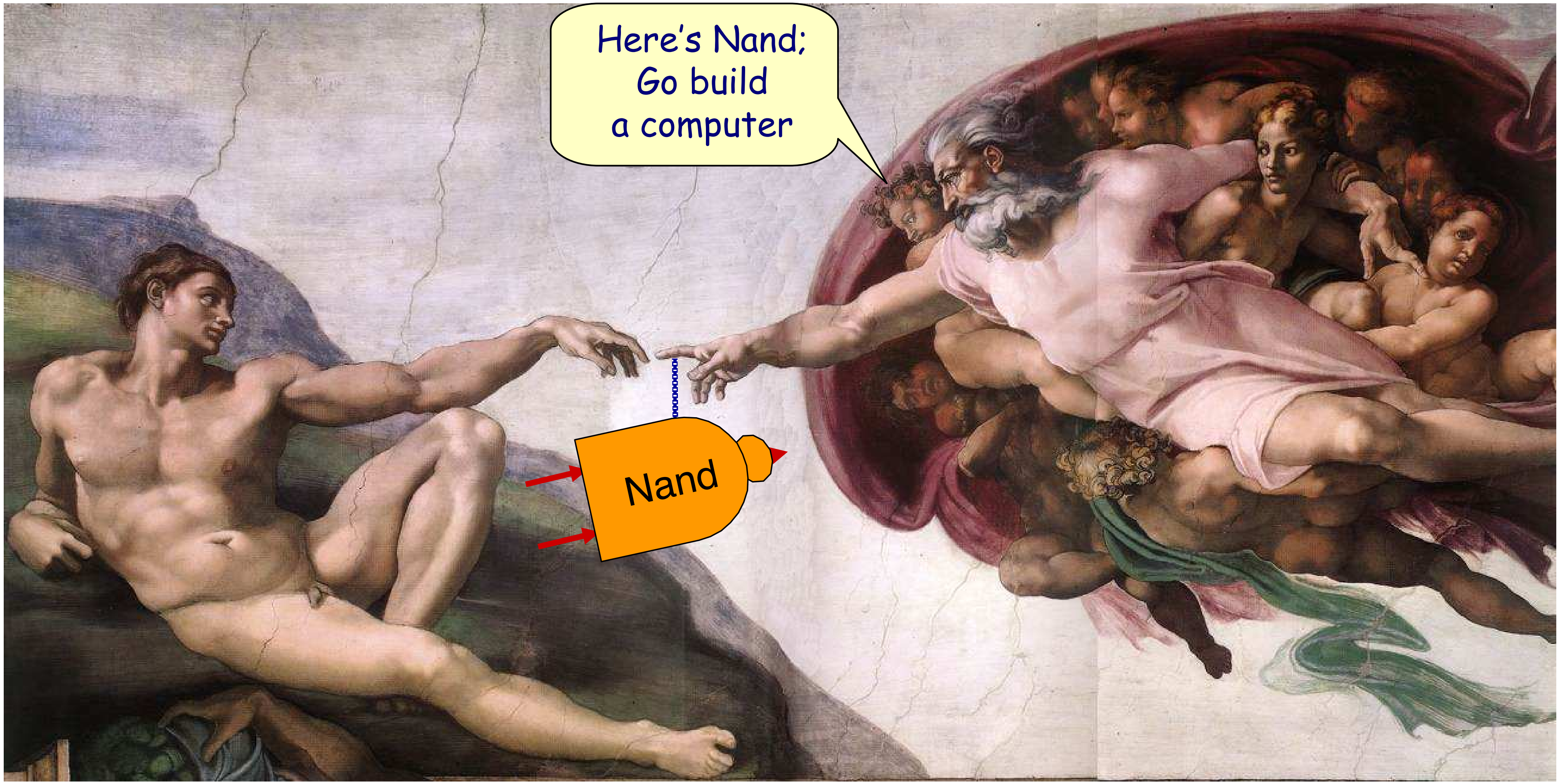
Class Keyboard {

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.



In CS, God gave us Nand

Everything else was done by humans.

Some Final notes

- CS is a science
- What is science?
- Reductionism
- Life science: From Aristo (millions of rules) to Darwin (3 rules) to Watson and Crick (1 rule)
- Computer science: We *knew* in advance that we could build a computer from almost nothing. In this course we actually did it.
- Key lessons:
  - Elegance
  - Clarity
  - Simplicity
  - Playfulness.

a	b	Out
0	0	1
0	1	1
1	0	1
1	1	0