Chapter 12

Operating System

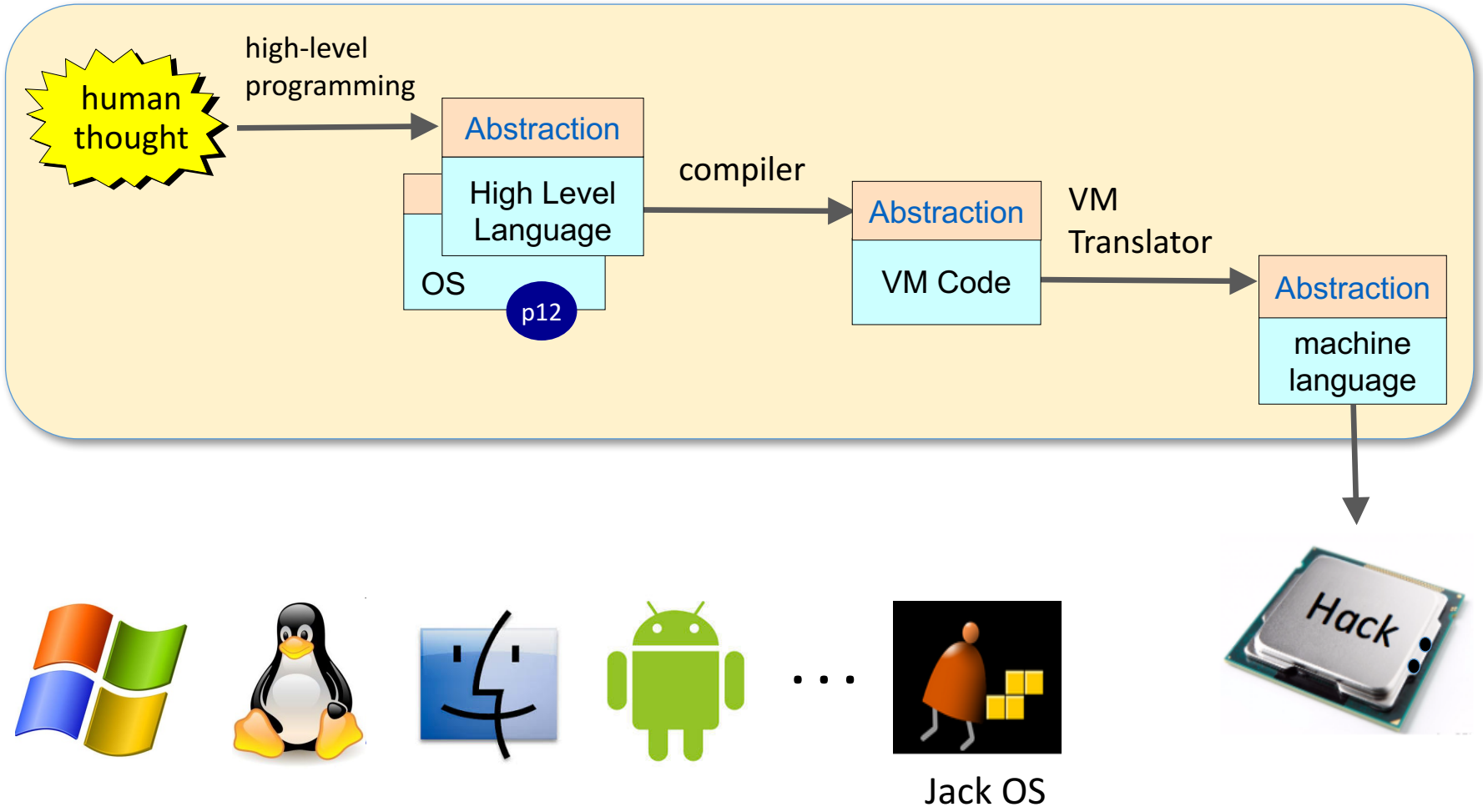
These slides support chapter 12 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

The big picture



High-level programming

```
/** Computes the length of the hypotenuse in a right triangle. */
class Main {
  function void main() {
     var int a;
     var int b;
     var int c;
     let a = Keyboard.readInt("Enter the length of side 1: ");
     let b = Keyboard.readInt("Enter the length of side 2: ");
     do Output.printString("The hypotenuse length is: ");
     do Output.printInt(Main.hypotenuseLength(a,b));
     return;
  }

  function int hypotenuseLength(int x, int y) {
     return Math.sqrt((x*x) + (y*y));
  }
}
```

OS services highlighted

Typical OS services

Language extensions

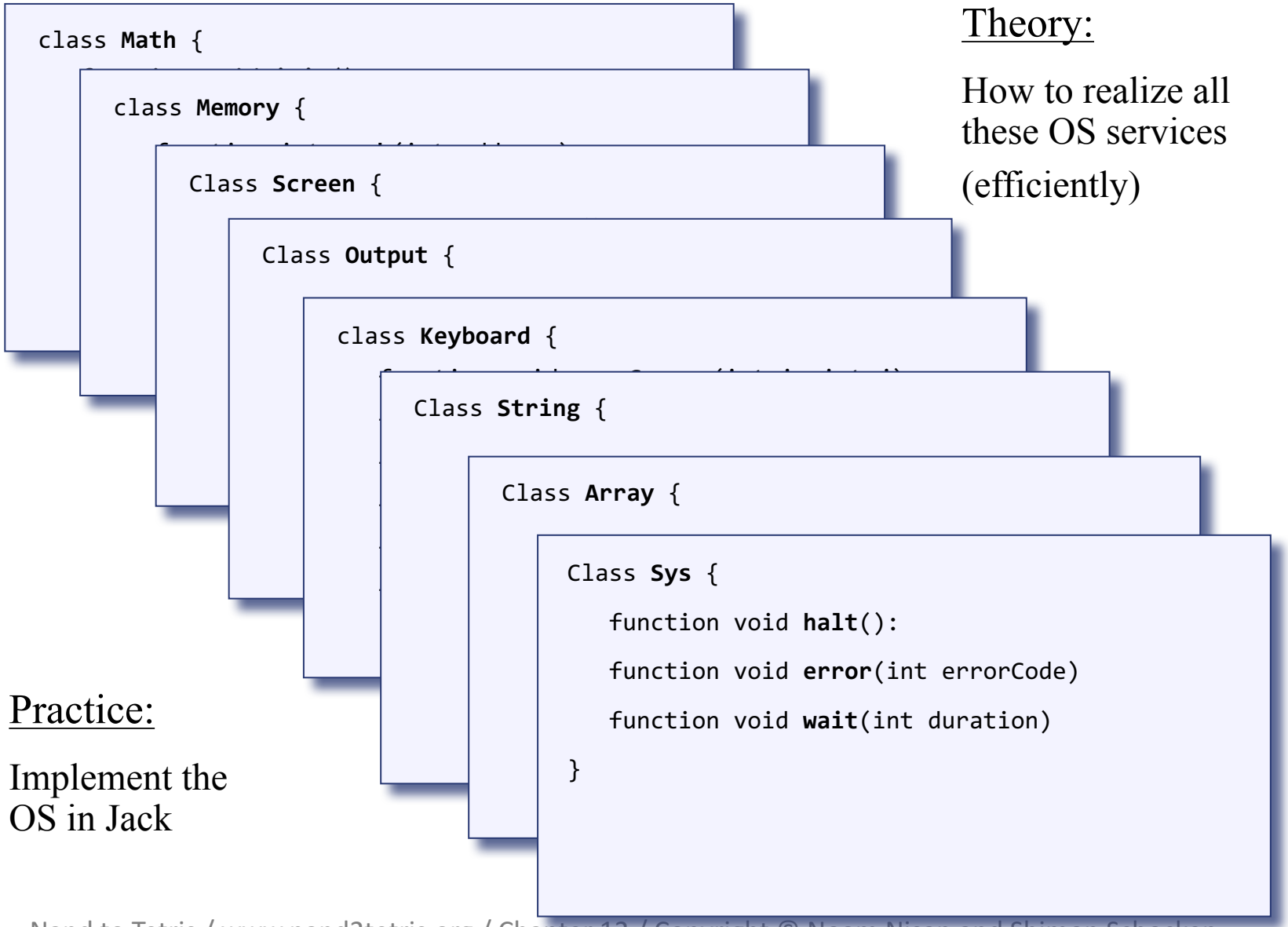
- ✓ mathematical operations (`abs`, `sqrt`, ...)
- ✓ abstract data types (`String`, `Array`, ...)
- ✓ input functions (`readChar`, `readLine` ...)
- ✓ textual output (`printChar`, `printString` ...)
- ✓ graphics output (`drawLine`, `drawCircle`, ...)
- ...

System oriented services

- ✓ memory management (objects, arrays, ...)
- ✓ I/O device drivers
- file system
- UI management (shell / windows)
- multi-tasking
- networking
- security
- ...

✓ : implemented in the Jack OS

Module 6: OS



Theory:

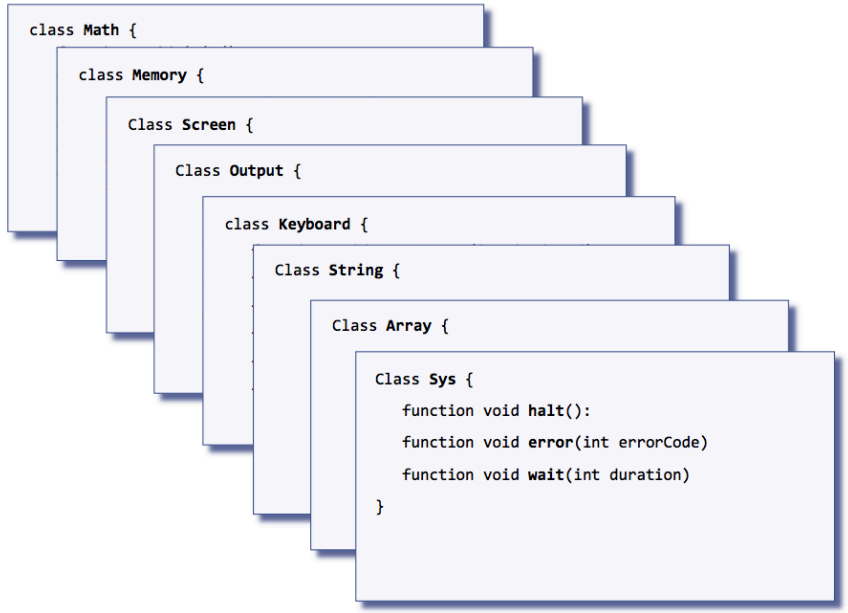
How to realize all these OS services (efficiently)

Practice:

Implement the OS in Jack

Take home lessons

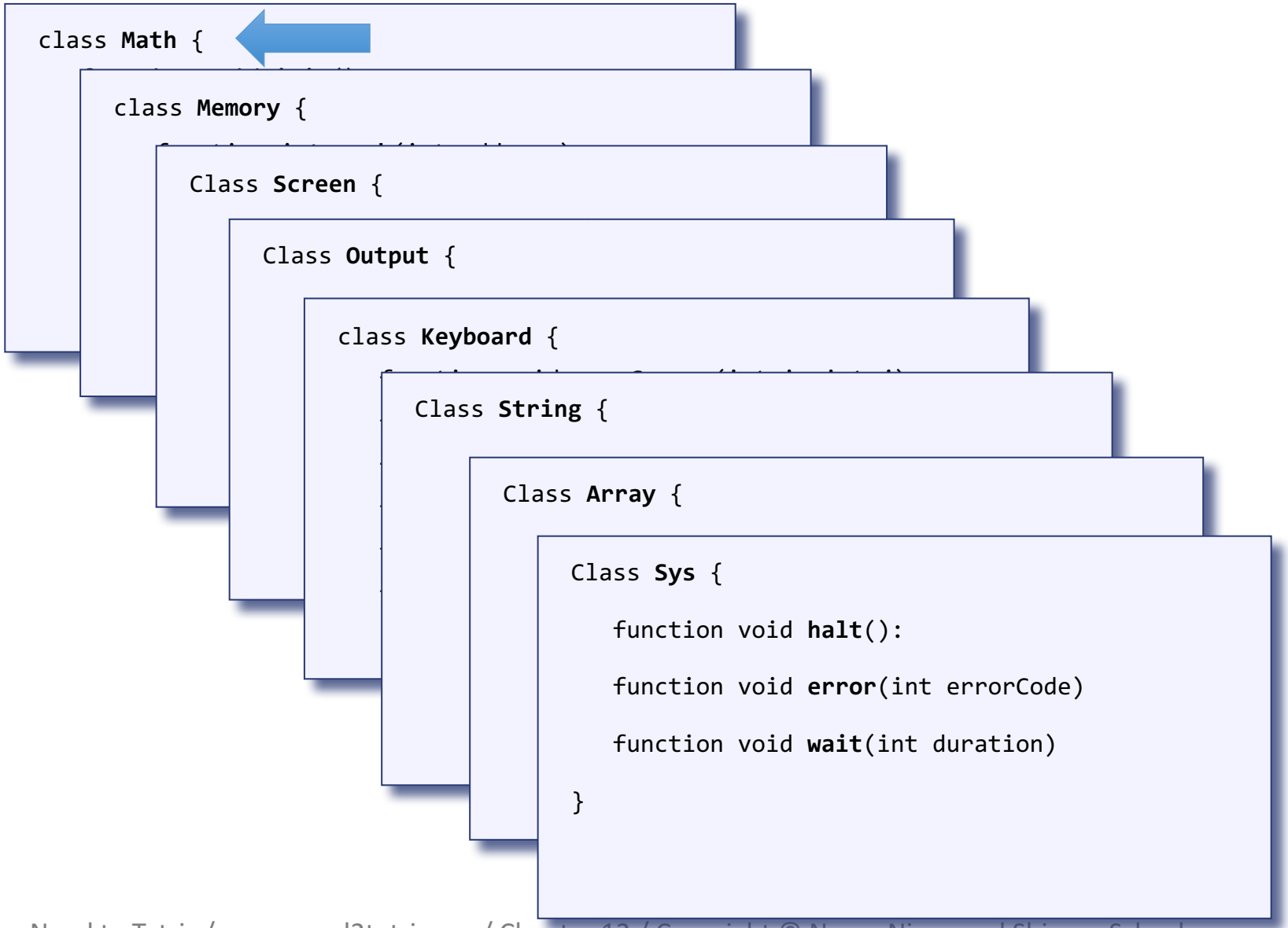
- Running-time analysis
- Resource allocation
- Input handling
- Output handling:
  - Vector graphics
  - Textual outputs
- Type conversions
- String processing
- ...



Methodology:

- Classical algorithms
- Ingenious hacks
- Trade-offs
- Implementation issues.

The Jack OS


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

OS `Math` class

```
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)
}
```

Efficiency matters!

Multiplication

In some class:

```
...
let x = 419 * 5003;
...
let x = Math.multiply(419,5003);
...
```

OS `Math` class

```
...
// Returns x*y, where x, y ≥ 0
// Strategy: repetitive addition
multiply(x, y):
    sum = 0
    for i = 0 ... y - 1   do
        sum = sum + x
    return sum
...
```

Let N be the largest number that we may be asked to multiply

Algorithm's run-time:

Proportional to N

Multiplication

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

= 27
= 9
= 243

x :	...	0	0	0	**1**	**1**	**0**	**1**	**1**	
y :	...	0	0	0	0	**1**	**0**	**0**	**1**	*i*'th bit of *y*
	...	0	0	0	**1**	**1**	**0**	**1**	**1**	1
	...	0	0	**1**	**1**	**0**	**1**	**1**	0	0
	...	0	**1**	**1**	**0**	**1**	**1**	0	0	0
...	...	**1**	**1**	**0**	**1**	**1**	0	0	0	1
x*y :	...	1	1	1	1	0	0	1	1	sum

Multiplication of *w*-bit numbers:

```
// Returns x*y, where x, y ≥ 0
multiply(x, y):
  sum = 0
  shiftedX = x
  for  i = 0 ... w - 1   do
     if  ((i'th bit of y) == 1)
        sum = sum + shiftedX
     shiftedX = shiftedX * 2
  return sum
```

Let *N* be the largest number that we may be asked to multiply

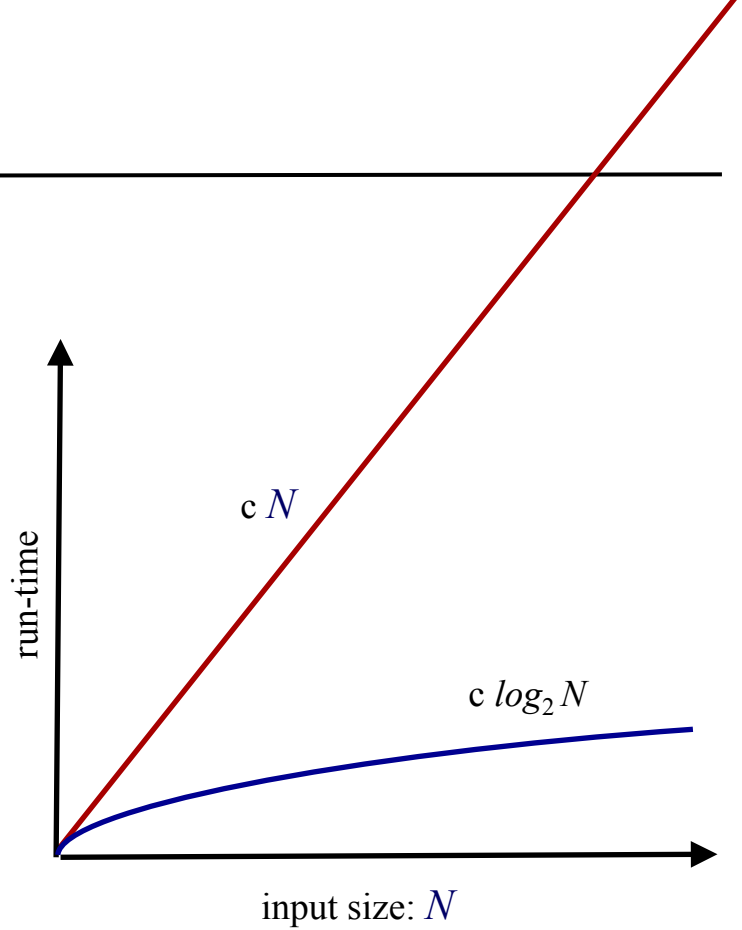
Run-time: proportional to *w*, the number of bits required to represent *N*

$w = log_2 N$

- The algorithm involves only addition operations
- Can be implemented efficiently in either software or hardware

Running time

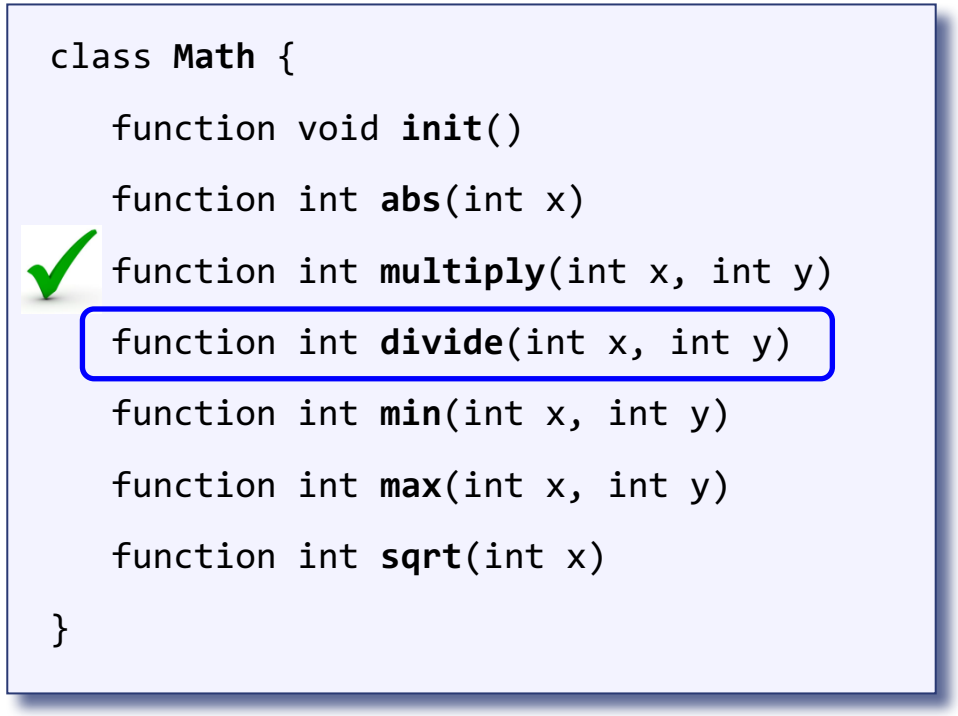
input size: N	linear run-time: c N	log. run-time: c $log_2(N)$
8	(c = 10) 80	(c = 10) 30
16	160	40
32	320	50
64	640	60
100	1000	70
1,000	10,000	100
1,000,000	10,000,000	200
1,000,000,000	10,000,000,000	300



Why is log_2N attractive?

- Because $log_2(2N) = log_2N + 1$
- As the size of the input doubles, an algorithm with logarithmic running-time requires 1 additional step

Recap



```
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)
}
```

Division

In some class:

```
...
let x = 17873 / 219;
...
let x = Math.divide(17873,219);
...
```

OS `Math` class

```
// Returns the integer part of x / y,
// where x ≥ 0 and y > 0
// Strategy: repetitive subtraction

divide (x , y) :
   div = 0
   rem = x
   while rem  ≤  x
        rem = rem – y
        div = div + 1
   return div
```

Algorithm's run-time:

Proportional to N

Division

```
      5   8
    ------------
1   7   5 | 3
1   5   0
-------------
    2   5
    2   4
    -------
        1
```

Algorithm's run-time:

proportional to the number of digits representing N, which is $log_2 N$

What is the largest number $x = (90, 80, 70, 60, 50, 40, 30, 20, 10)$, so that $3*x \leq 175$?

Answer: *div* = at least 50,
and we still have to divide the remainder 25 by 3

What is the largest number $x = (9, 8, 7, 6, 5, 4, 3, 2, 1)$, so that $3*x \leq 25$?

Answer: *div* = at least 50 + 8,
and we still have to divide the remainder 1 by 3

1 is less than 3, so we're done: *div* = 58 with a remainder of 1.

Running time

72347234723484938492340493 48 / 3 = ?

Division by repetitive subtraction :

```
divide (x, y):
  let div = 0
  let rem = x
  while rem ≤ x
      let rem = rem – y
      let div = div + 1
  return div
```

Running time:

depends on the *input's size*: ~241157000000000000000000000

By the long division method:

```
      5   8
  ---------
1   7   5 | 3
1   5   0
  -------
      2   5
      2   4
    -----
          1
```

Running time:

depends on the *number of digits*: 27

Division

Another efficient algorithm:

```
// Returns the integer part of x / y,
// where x ≥ 0 and y > 0
divide (x, y):
    if  (y > x) return 0
    q = divide (x, 2 * y)
    if ((x – 2 * q * y) < y)
        return 2 * q
    else
        return 2 * q + 1
```

Run-time:

proportional to $log_2 N$

- The algorithm involves only addition operations
- Can be implemented efficiently in either software or hardware

Recap

```
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)
}
```

Square root

The square root function $\sqrt{x}$ has two appealing properties:

- its inverse function (x^2) can be easily computed
- it is a monotonically increasing function

Therefore:

- square roots can be computed using *binary search*
- and the running-time of binary search is logarithmic.

```
// Compute the integer part of y = √x
// Strategy: find an integer y such that y^2 ≤ x < (y+1)^2  ( for 0 ≤ x < 2^n )
// by performing a binary search in the range 0 ... 2^(n/2) − 1

sqrt (x) :
   y = 0
   for  j = n/2 - 1 ... 0  do
      if  (y + 2^j)^2 ≤ x  then  y = y + 2^j
   return y
```

Recap

```
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)
}
```

Implementation notes: multiplication

Issues:

- how to handle negative numbers?
- how to handle overflow?
- how to implement (*i*'th bit of *y*) quickly?

```
// Returns x*y, where x, y ≥ 0
multiply(x, y):
  sum = 0
  shiftedX = x
  for  i = 0 ... w - 1   do
     if  ((i'th bit of y) == 1)
          sum = sum + shiftedX
     shiftedX = shiftedX * 2
  return sum
```

Implementation notes: multiplication

Handling negative numbers

- If the inputs are two's complement values, the algorithm works fine as-is

Handling overflow

- this algorithm always returns the correct answer modulu 2^{16}

```
// Returns x*y, where x, y ≥ 0
multiply(x, y):
  sum = 0
  shiftedX = x
  for  i = 0 ... w - 1   do
     if  ((i'th bit of y) == 1)
         sum = sum + shiftedX
     shiftedX = shiftedX * 2
  return sum
```

Implementation notes: multiplication

Implementing (*i*'th bit of *y*)

We suggest encapsulating this operation in the following function:

```
// Returns true if the i-th bit of x is 1, false otherwise
function boolean bit(int x, int i)
```

```
// Returns x*y, where x, y ≥ 0
multiply(x, y):
  sum = 0
  shiftedX = x
  for i = 0 ... w - 1  do
    if ((i'th bit of y) == 1)
      sum = sum + shiftedX
    shiftedX = shiftedX * 2
  return sum
```

The `bit(x,i)` function can be implemented using bit shifting operations, which Jack does not have.

Instead, we can use an array that holds the 16 values 2^i, $i = 0,...,15$

- a fixed array, say `twoToThe[i]`
- declared as a static, class variable of `Math`, constructed by `Math.init`
- can support the imeplementation of `bit(x,i)`

Implementation notes: division

Issues:

- Handling negative numbers

  Solution: divide $|x|$ by $|y|$, then set the result's sign

- Handling overflow (of y)

  Solution: the overflow can be detected when y becomes negative

  We can change the function's first statement to:

  if $(y > x)$ or $(y < 0)$ return 0

```
// Returns the integer part of x / y,
// where x ≥ 0 and y > 0
divide (x, y):
    if  (y > x) return 0
    q = divide (x, 2 * y)
    if ((x – 2 * q * y) < y)
        return 2 * q
    else
        return 2 * q + 1
```

Implementation notes: square root

Issue:

the calculation of $(y+2^j)^2$ can overflow

// 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 $0 \ldots 2^{n/2}-1$

sqrt (x) :

$y = 0$

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

if $(y+2^j)^2 \le x$ then $y = y+2^j$

return y

Solution:

Change the condition $(y+2^j)^2 \le x$ to:

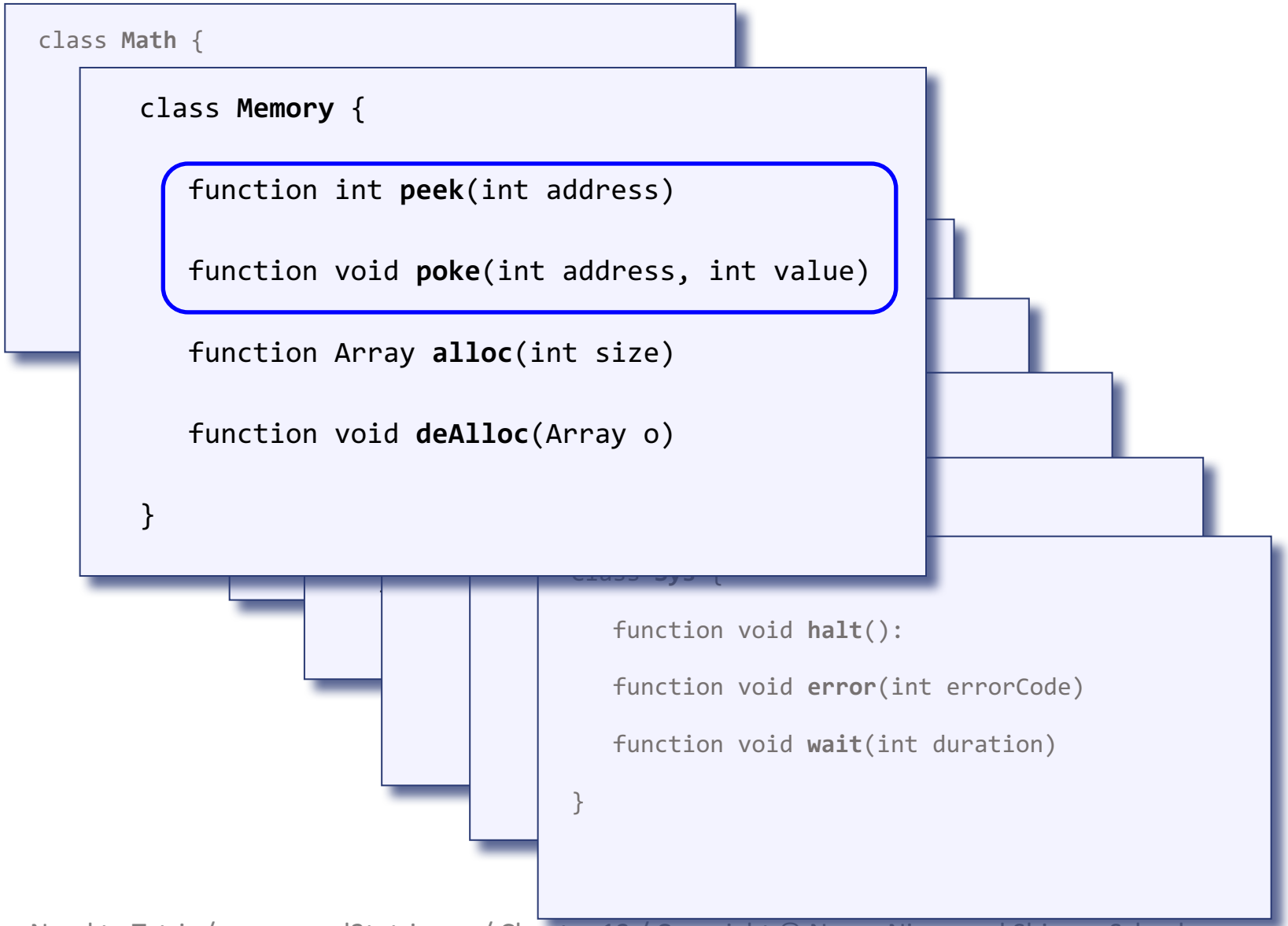
$(y+2^j)^2 \le x$ and $(y+2^j)^2 > 0$

Recap

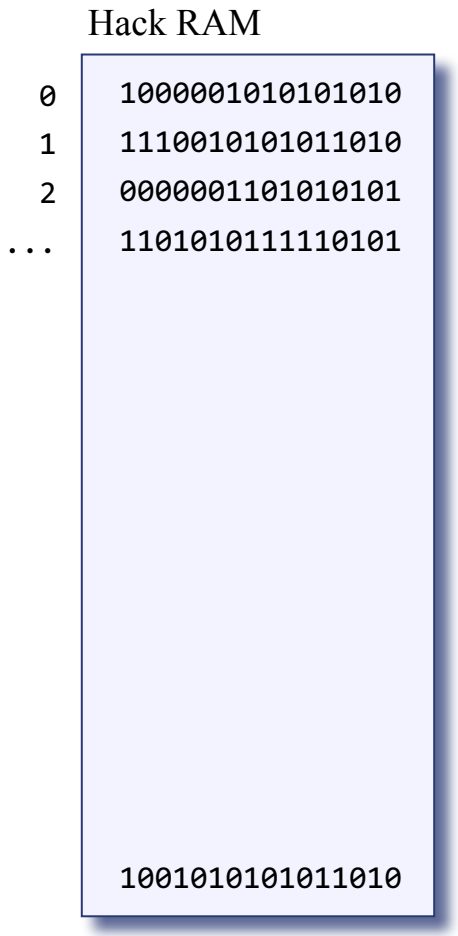
```
class Math {
   function void init()
   function int abs(int x)
   function int multiply(int x, int y)
   function int divide(int x, int y)
   function int min(int x, int y)
   function int max(int x, int y)
   function int sqrt(int x)
}
```

The implementation of the remaining `Math` functions is simple.

Recap


class Math {
class Memory {
function int peek(int address)
function void poke(int address, int value)
function Array alloc(int size)
function void deAlloc(Array o)
}
function void halt():
function void error(int errorCode)
function void wait(int duration)
}

The need



Application programs

- access the RAM via abstractions: variables, objects, arrays, ...
- access I/O devices via abstractions:

  `readInt()`, `printInt(x)`, `...`

How to implement these abstractions?

- The OS provides low-level services that facilitate direct RAM access
- Based on these low-level services, the OS features higher-level memory and I/O management services.

OS `Memory` class

Hack RAM

```
    0   1000001010101010
    1   1110010101011010
    2   0000001101010101
  ...   1101010111110101

19003   0000000000000111

        1001010101011010
```

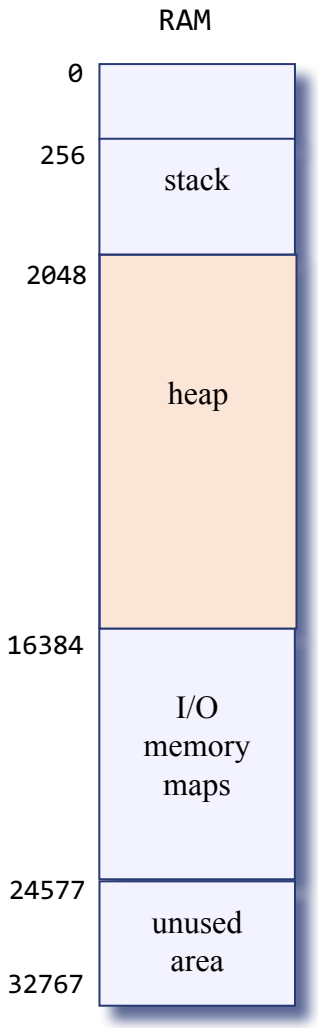
OS `Memory` class API

```
/** OS Memory operations  */
class Memory {

    /** Returns the value of the given RAM address */
    function int peek(int address) {}

    /** Sets the value of the given RAM address to the given value */
    function void poke(int address, int value) {}

    ...
}
```

Usage:

```
...
let x = Memory.peek(19003)   // x becomes 7
...
do Memory.poke(19003,-1)     // RAM[19003] becomes 11..1
...
```

Implementation notes



The challenge

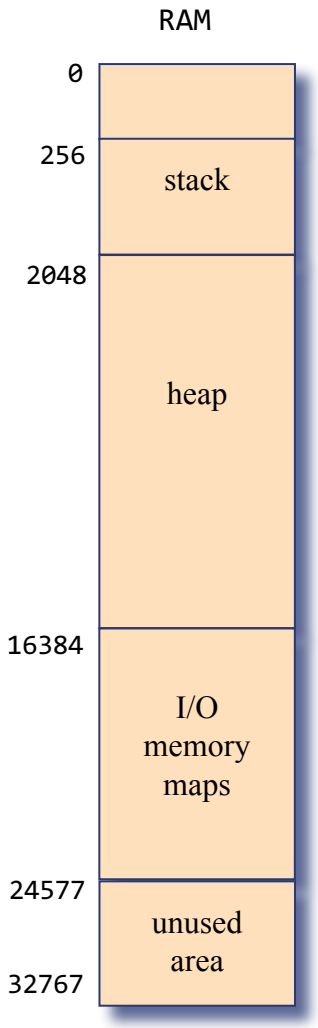
The OS is written in Jack; how can we access the RAM?

Conventional access

```
var Array ram;
let ram = Array.new(32768);
...
```

the compiler will attempt to allocate the array in the heap

Implementation notes



The challenge

The OS is written in Jack; how can we access the RAM?

Conventional access

```
var Array ram;
let ram = Array.new(32768);
...
```

Alternatively:

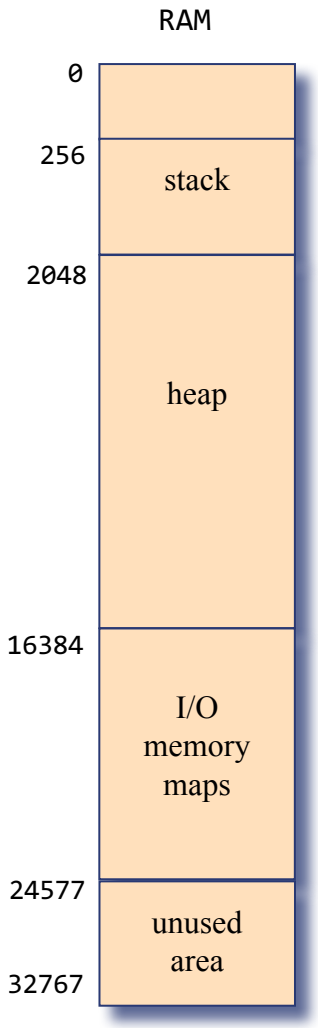
```
class Memory {
   ...
   static array ram;
   ...
   function void init() {
      let ram = 0;
      ...
   }
   ...
   // To set RAM[addr] to val:
   let ram[addr] = val;
   ...
```

accessing `ram[`*i*`]` results in accessing the word whose address is `0` + *i* in the RAM

The hack works because...

Jack is weakly typed, so `let ram = 0` does not cause the compiler to complain

Implementation notes

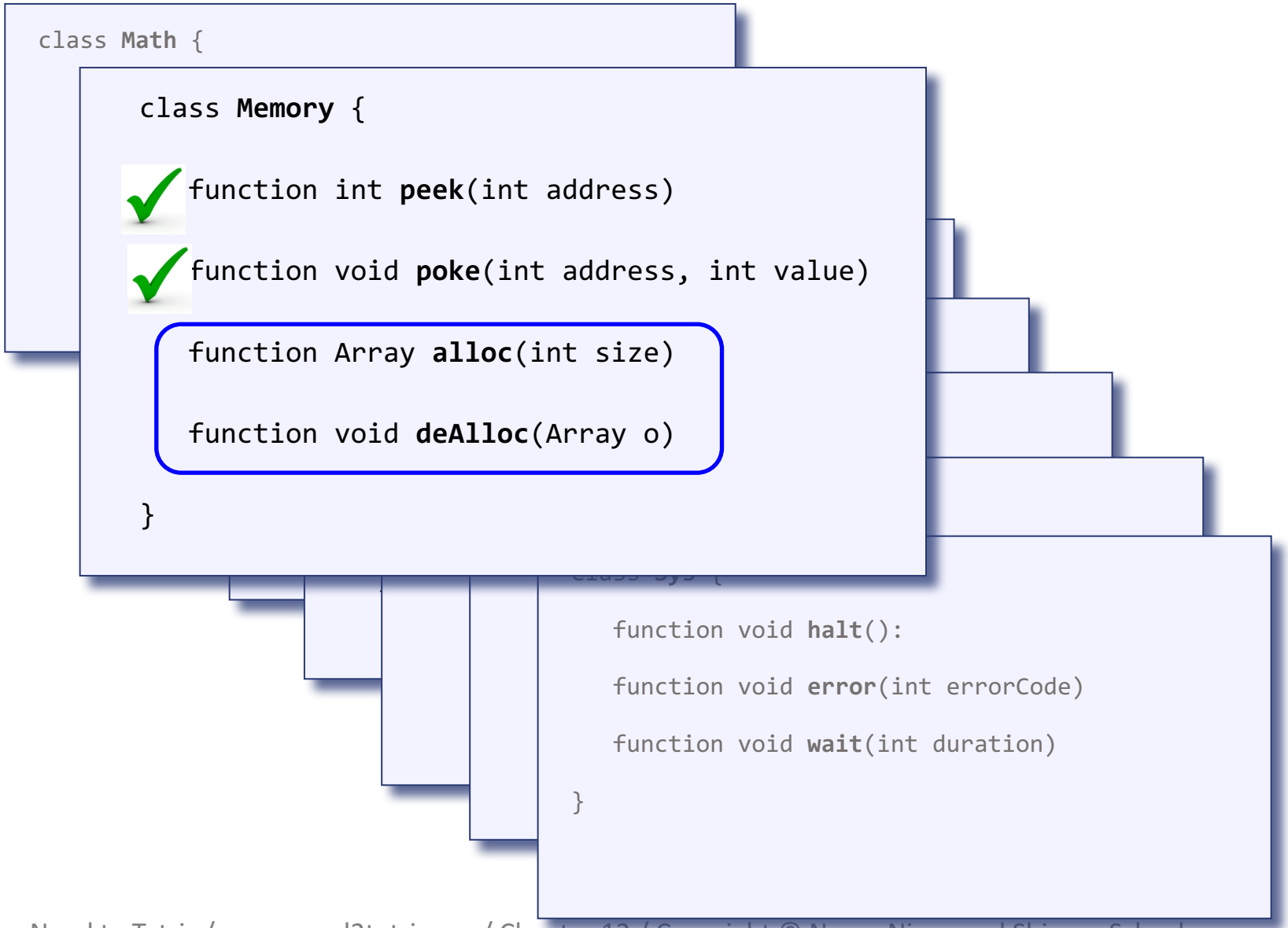



```
/** OS Memory operations  */
class Memory {
    ...
   static array ram;
   ...
   function void init() {
      let ram = 0;
      ...
   }

   /** Returns the value of the given RAM address */
   function int peek(int address) {}

   /** Sets the value of the given RAM address to the given value */
   function void poke(int address, int value) {}

   ...
}
```

Implementing `peek` and `poke`:

Manipulate the `ram` array.

Recap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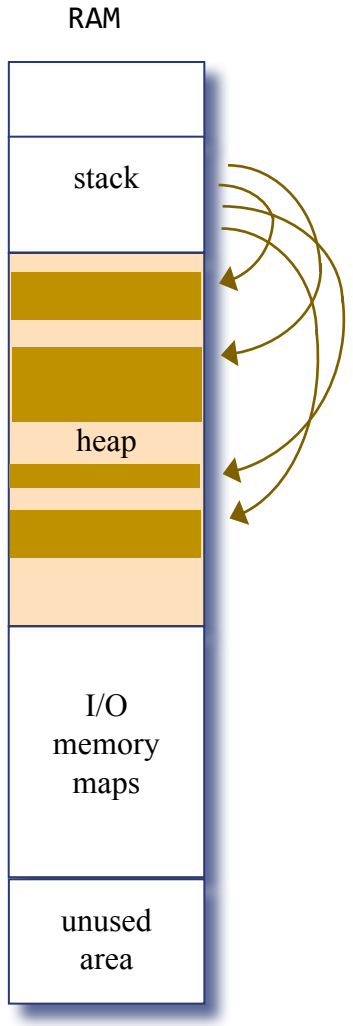
class Memory {
function int peek(int address)
function void poke(int address, int value)
function Array alloc(int size)
function void deAlloc(Array o)
}
function void halt():
function void error(int errorCode)
function void wait(int duration)
}

The need

During run-time, programs typically create (possibly many) objects and arrays

Objects and arrays are implemented using

- reference variables,
- pointing at actual data blocks (in the heap)



<u>The challenge:</u>

- Allocating memory for new objects / arrays
- Recycling memory of disposed objects / arrays

OS `Memory` class API

```
class Memory {
   ...
   /** Finds and allocates from the heap a memory block of the
   *  specified size and returns a reference to its base address */
   function int alloc(int size) {}
   /** De-allocates the given object and frees its space */
   function void deAlloc(int object) {}
}
```

The need: object construction

```
// In some class:
var Point p;
...
let p = Point.new(7,5);
```

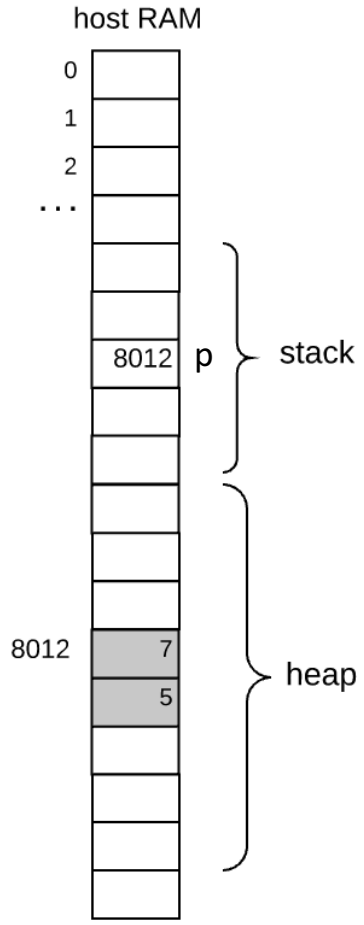
```
class Point {
   field int x,y;
   ...
   constructor Point new(int ax, int ay) {
      let x = ax;
      ley y = ay
      return this
   }
   ...
```

The constructor's compiled code includes (among other things) low-level code affecting:

```
this = Memory.alloc(2)
```

OS `Memory` class API

```
class Memory {
   ...
   /** Finds and allocates from the heap a memory block of the
   *  specified size and returns a reference to its base address */
   function int alloc(int size) {}
   /** De-allocates the given object and frees its space */
   function void deAlloc(int object) {}
}
```

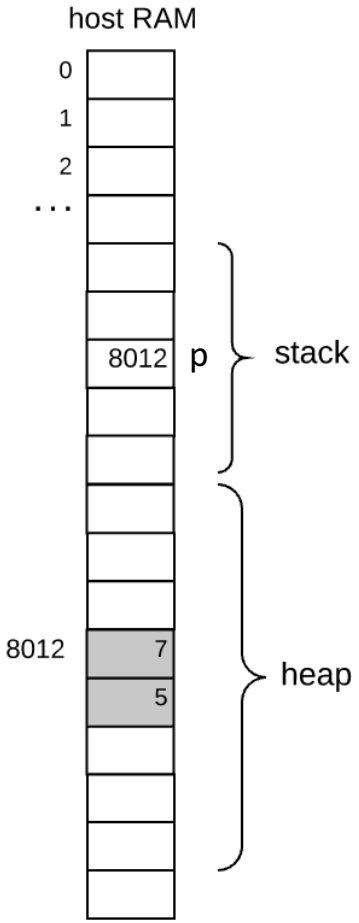


The need: object destruction

```
// In some class:
...
do p.dispose();
```

```
class Point {
   ...
   /** Disposes this square. */
   method void dispose() {
      do Memory.deAlloc(this);
      return;
   }
...
```

In languages that have *garbage collection*, there is no need to dispose objects explicitly



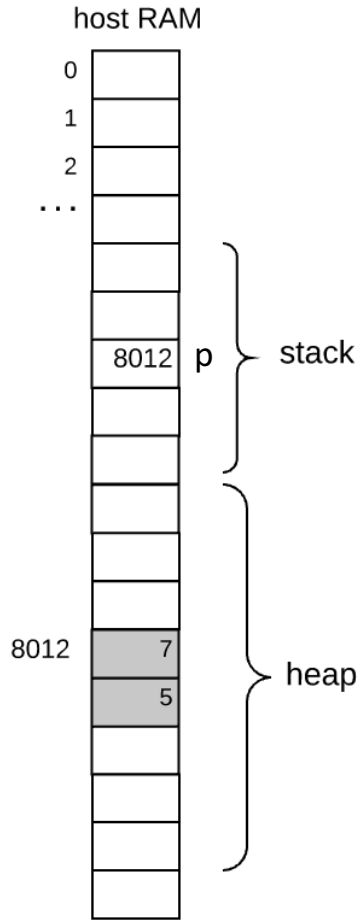
OS `Memory` class API

```
class Memory {
   ...
   /** Finds and allocates from the heap a memory block of the
   *  specified size and returns a reference to its base address */
   function int alloc(int size) {}
   /** De-allocates the given object and frees its space */
   function void deAlloc(int object) {}
}
```

Object construction and destruction

The challenge:
Implementing `alloc` and `deAlloc`

The solution:
Heap management.



OS `Memory` class API

```
class Memory {
   ...
   /** Finds and allocates from the heap a memory block of the
   *  specified size and returns a reference to its base address */
   function int alloc(int size) {}
   /** De-allocates the given object and frees its space */
   function void deAlloc(int object) {}
}
```

Heap management (simple)

Heap management

init:

free = heapBase

// allocates a memory block of *size* words

alloc (*size*):

block = free

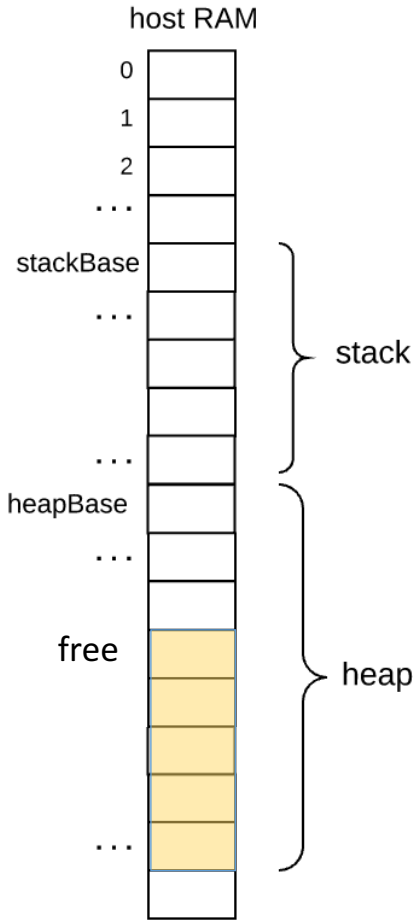
free = free + size

return *block*

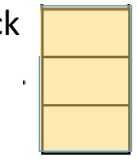
// de-allocates the memory space of the given object

deAlloc (*object*):

do nothing

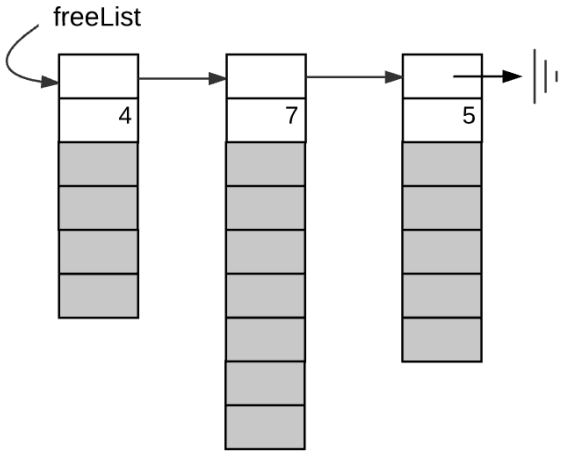


`deAlloc(block)`:



Heap management

Use a linked list to keep track of available heap segments



alloc(*size*):

find a block of size *size* in one of the segments, remove it from the segment, and give it to the client

dealloc(*object*):

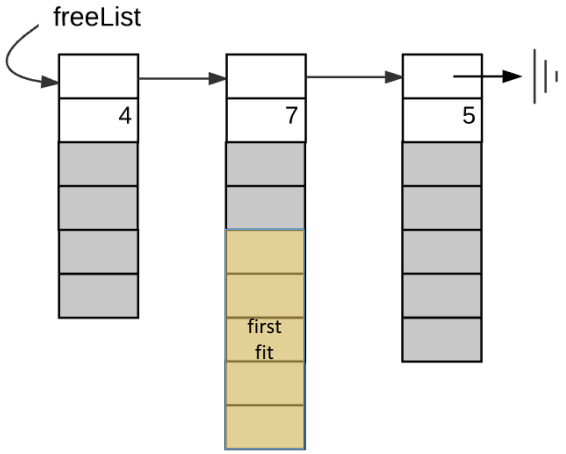
append the object/block to the *freeList*

Heap management (detailed)

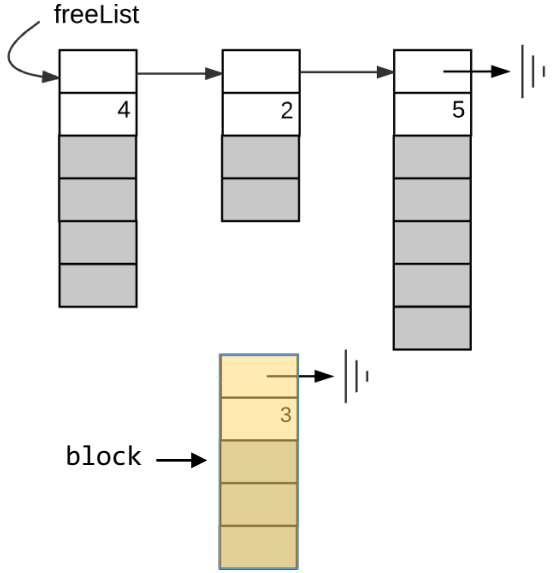
alloc(*size*):

Terminology: if *segment.size* ≥ *size*+2
we say that the segment is *possible*

- search the *freeList* for:
  - the first possible segment (*first fit*) , or
  - the smallest possible segments (*best fit*)
- carve a block of size *size*+2 from this segment
- return the base address of the block's data part

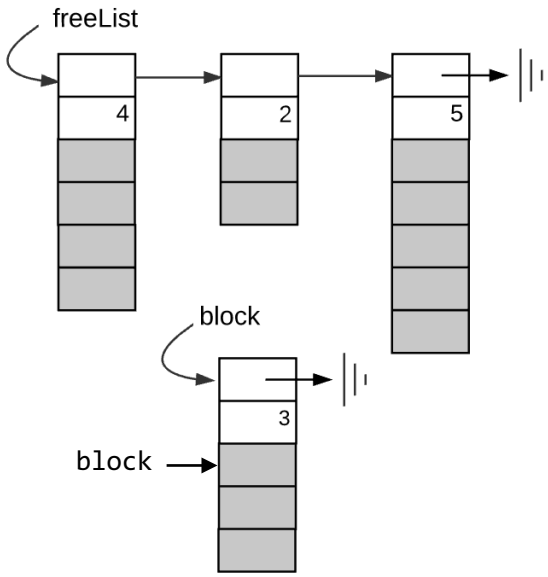


`alloc(3)`:



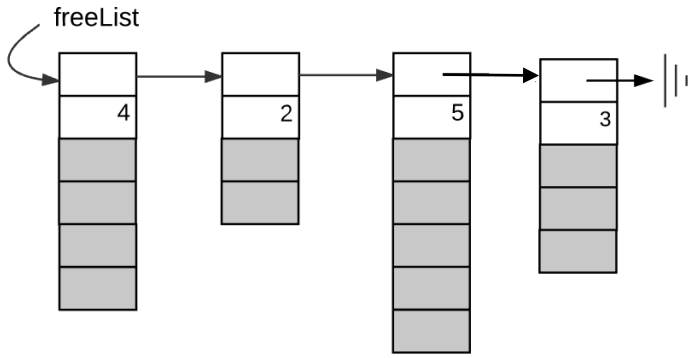
Heap management (detailed)

deAlloc(*object*):
append *object* to the end of the *freeList*



`deAlloc(block)`:

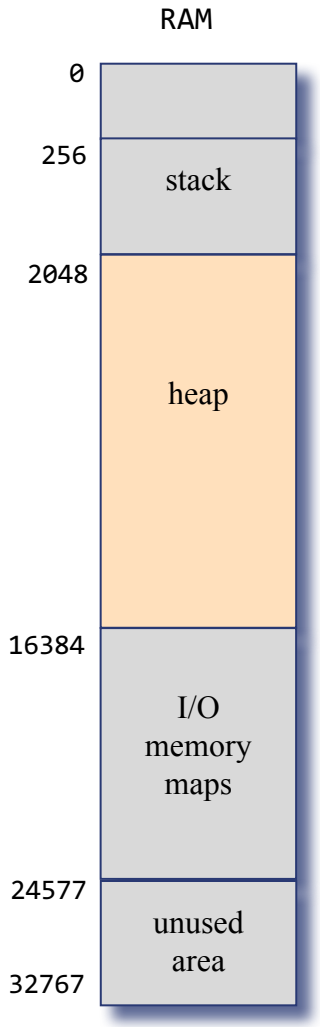
The more we recycle (`deAlloc`), the more the freeeList becomes fragmented



Implementation notes

Implementing the heap / *freeList* (on the Hack platform):

```
class Memory {
   ...
   static Array heap;
   ...

   // In Memory.init:
   ...
   let heap = 2048; // heapBase
   let freeList = heap;
   let heap[0] = 0;       // next
   let heap[1] = 14334;   // length
   ...
```



Implementation notes

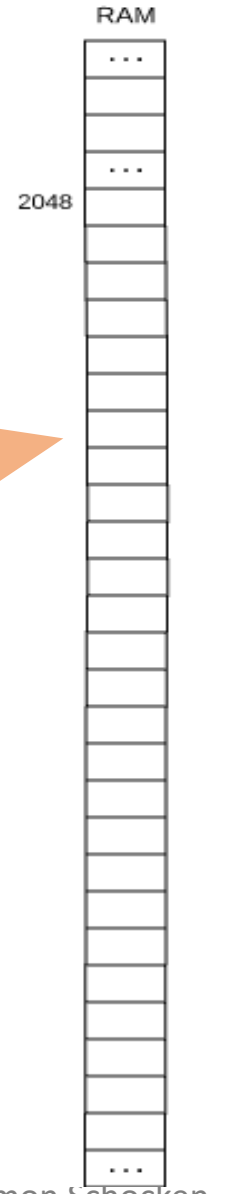
Implementing the heap

```
class Memory {
   ...
   static Array heap;
   ...

   // In Memory.init:
   ...
   let heap = 2048; // heapBase
   let freeList = heap;
   let heap[0] = 0;       // next
   let heap[1] = 14334;   // length
   ...
```

Initial state:

the entire heap is available

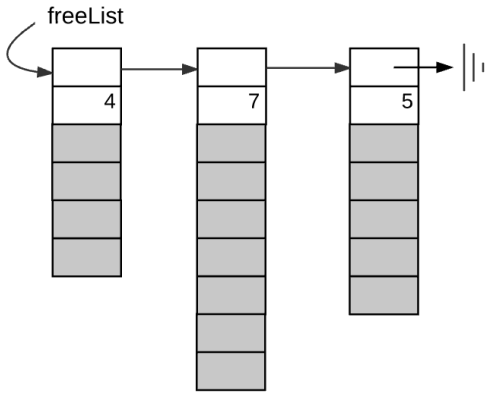
(*freeList* contains one long segment)

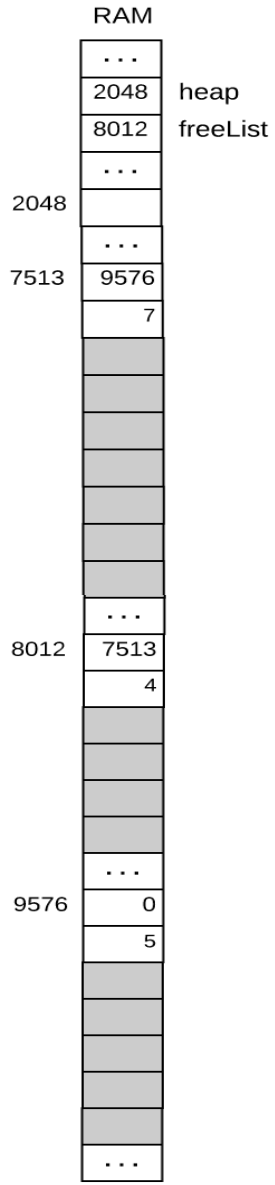


Implementation notes

Implementing the heap

```
class Memory {
   ...
   static Array heap;
   ...

   // In Memory.init:
   ...
   let heap = 2048;

   ...
```



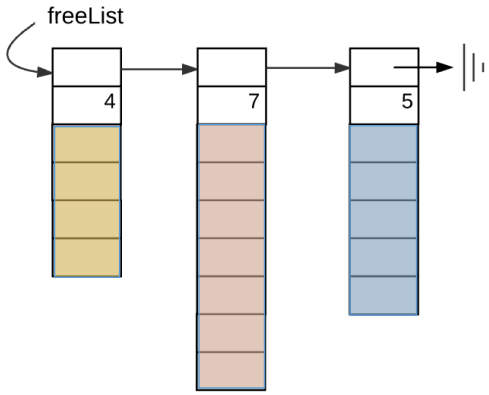


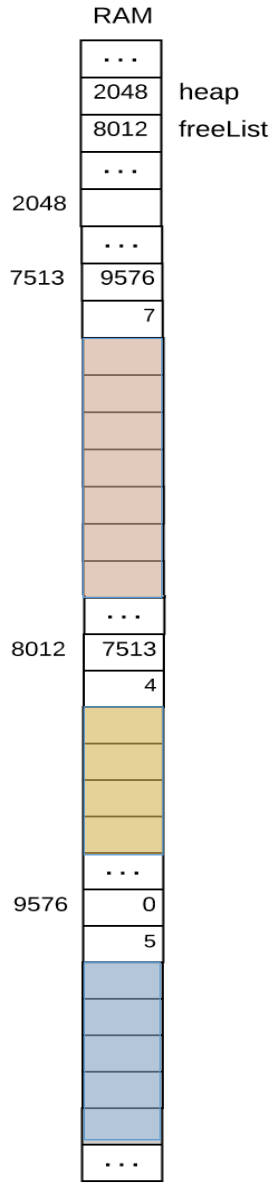
Heap state after several `alloc` and `deAlloc` operations:

Implementation notes

Implementing the heap

```
class Memory {
   ...
   static Array heap;
   ...

   // In Memory.init:
   ...
   let heap = 2048;

   ...
```





- The `freeList` can be realized using the `heap` array
- The `next` and `size` properties of the memory segment beginning in address `addr` can be realized by `heap[addr-1]` and `heap[addr-2]`
- `alloc`, `deAlloc`, and `deFrag` can be realized as operations on the `heap` array.

Implementation notes (recap)

init:

freeList = *heapBase*
freeList.*size* = *heapSize*
freeList.*next* = `0`

// Allocate a memory block of *size* words
alloc(*size*):

search *freeList* using best-fit or first-fit heuristics
to obtain a segment with *segment.size* ≥ *size* + 2

if no such segment is found, return failure
(or attempt defragmentation)

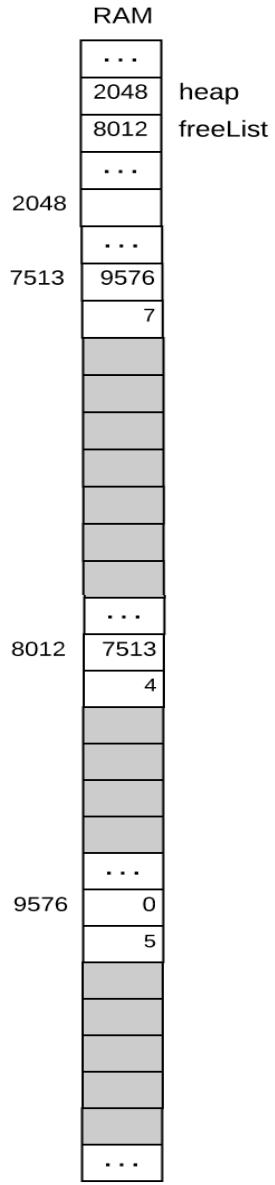
block = base address of the found space

update the *freeList* and the fields of *block*
to account for the allocation

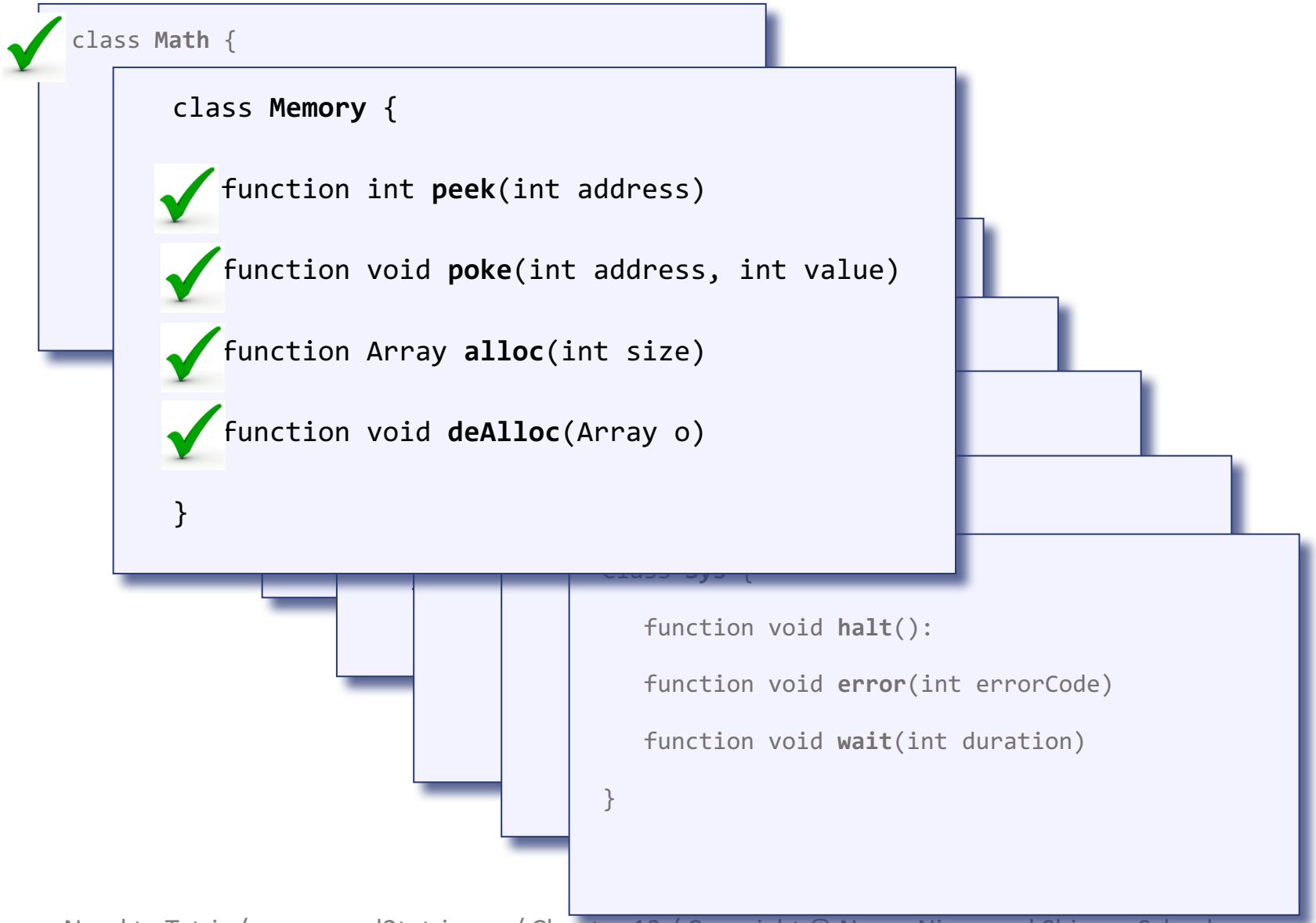
return *block*

// de-allocate the memory space of the given object
deAlloc(*object*):

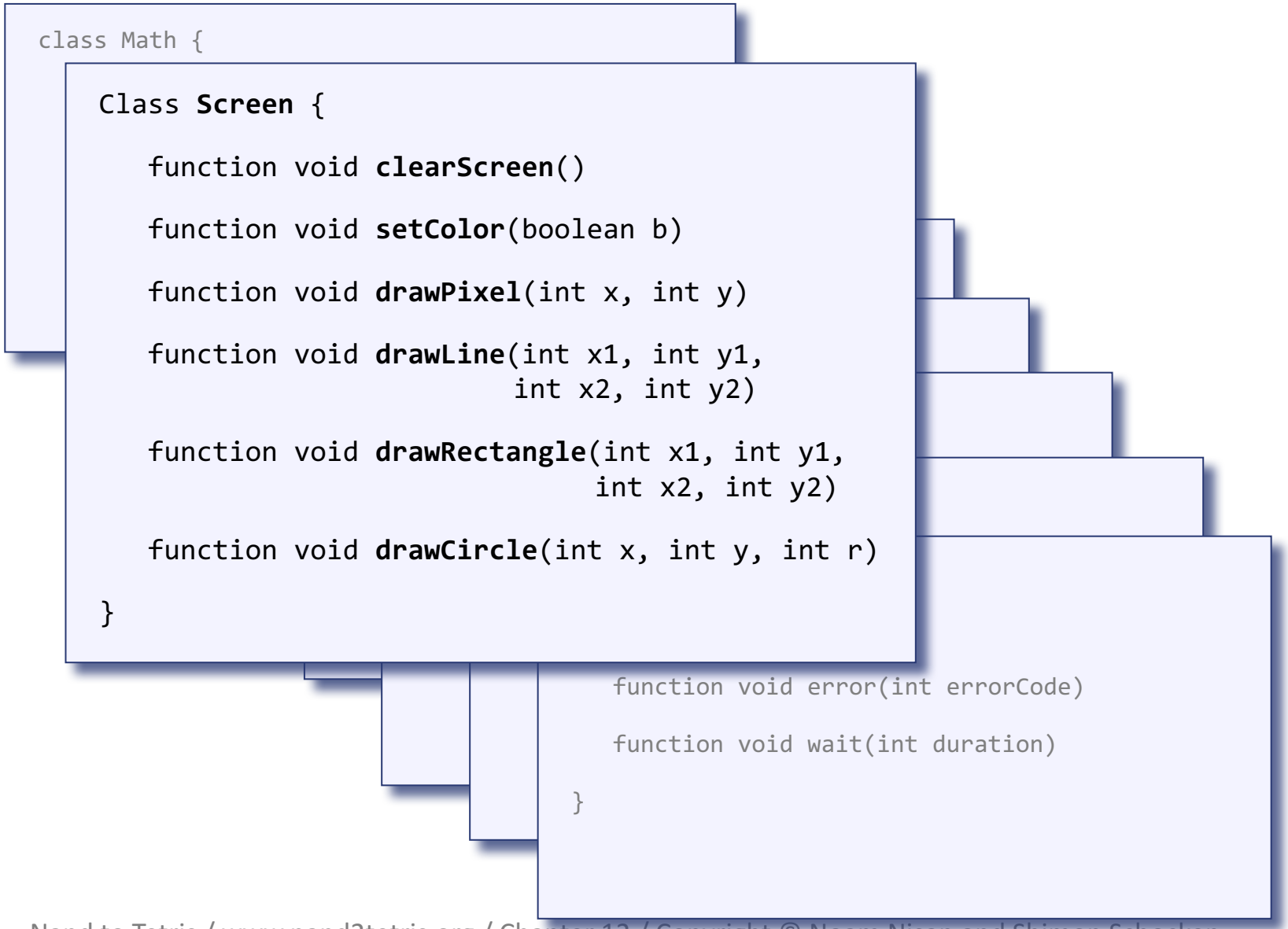
append *object* to the end of the *freeList*



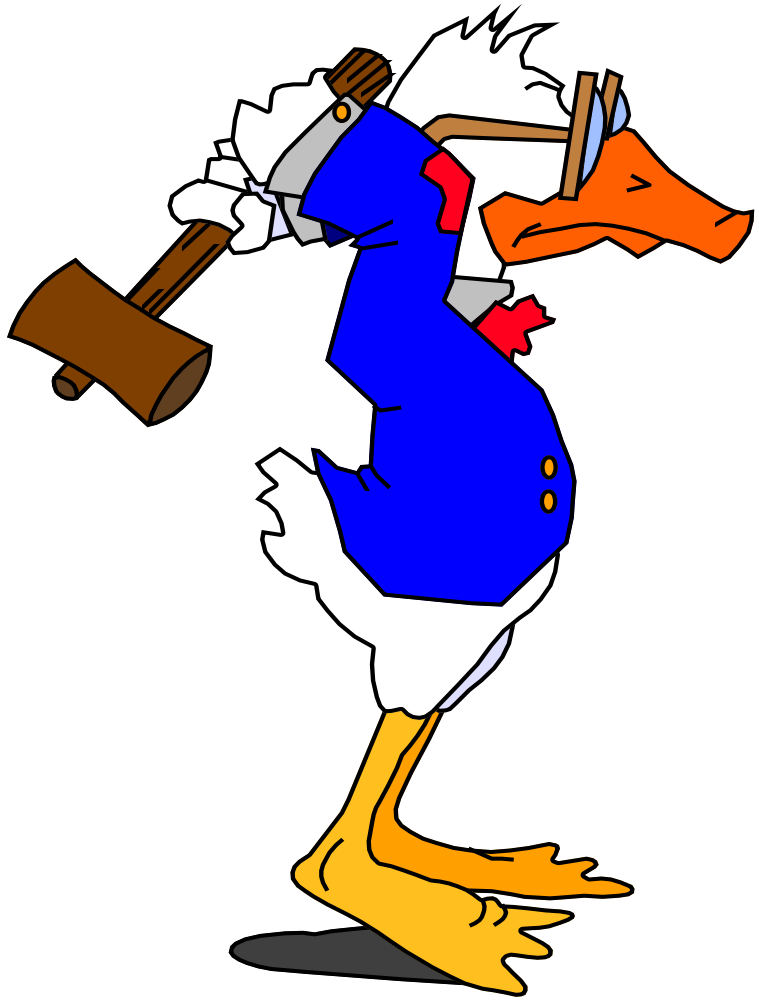
Recap


class Math {
class Memory {
function int peek(int address)
function void poke(int address, int value)
function Array alloc(int size)
function void deAlloc(Array o)
}
function void halt():
function void error(int errorCode)
function void wait(int duration)
}

The Jack OS


class Math {
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)
}
function void error(int errorCode)
function void wait(int duration)
}

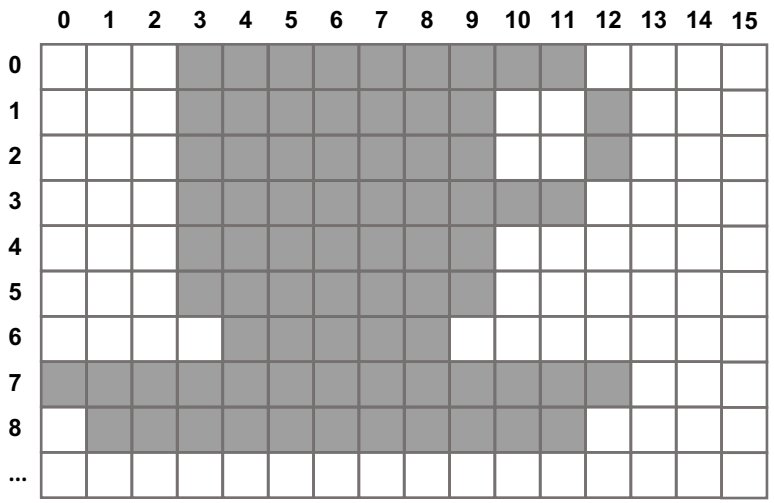
Graphics



vector graphics

bitmap graphics

Graphics



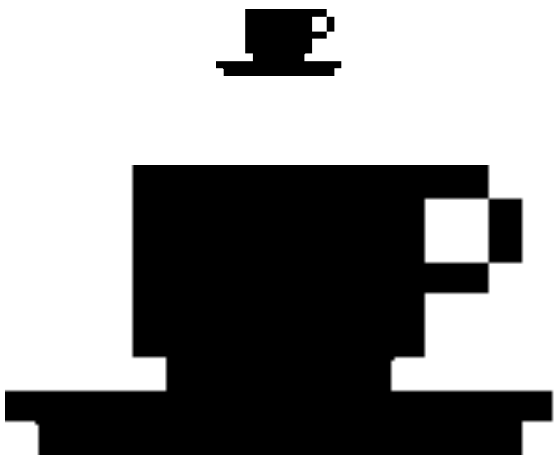
vector graphics file

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

bitmap graphics file

```
0001111111100000
0001111111010000
0001111111010000
0001111111100000
0001111111000000
0001111111000000
...
```

Graphics



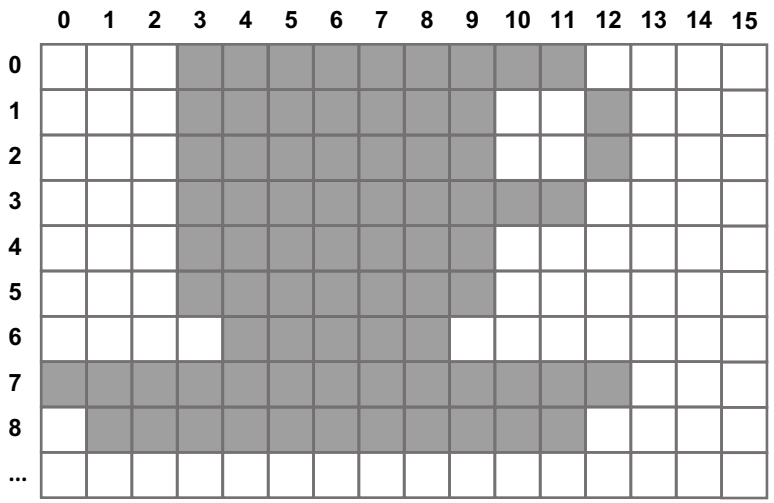
vector graphics file

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

bitmap graphics file

```
0001111111100000
0001111111010000
0001111111010000
0001111111100000
0001111111000000
0001111111000000
...
```

Graphics



vector graphics file

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

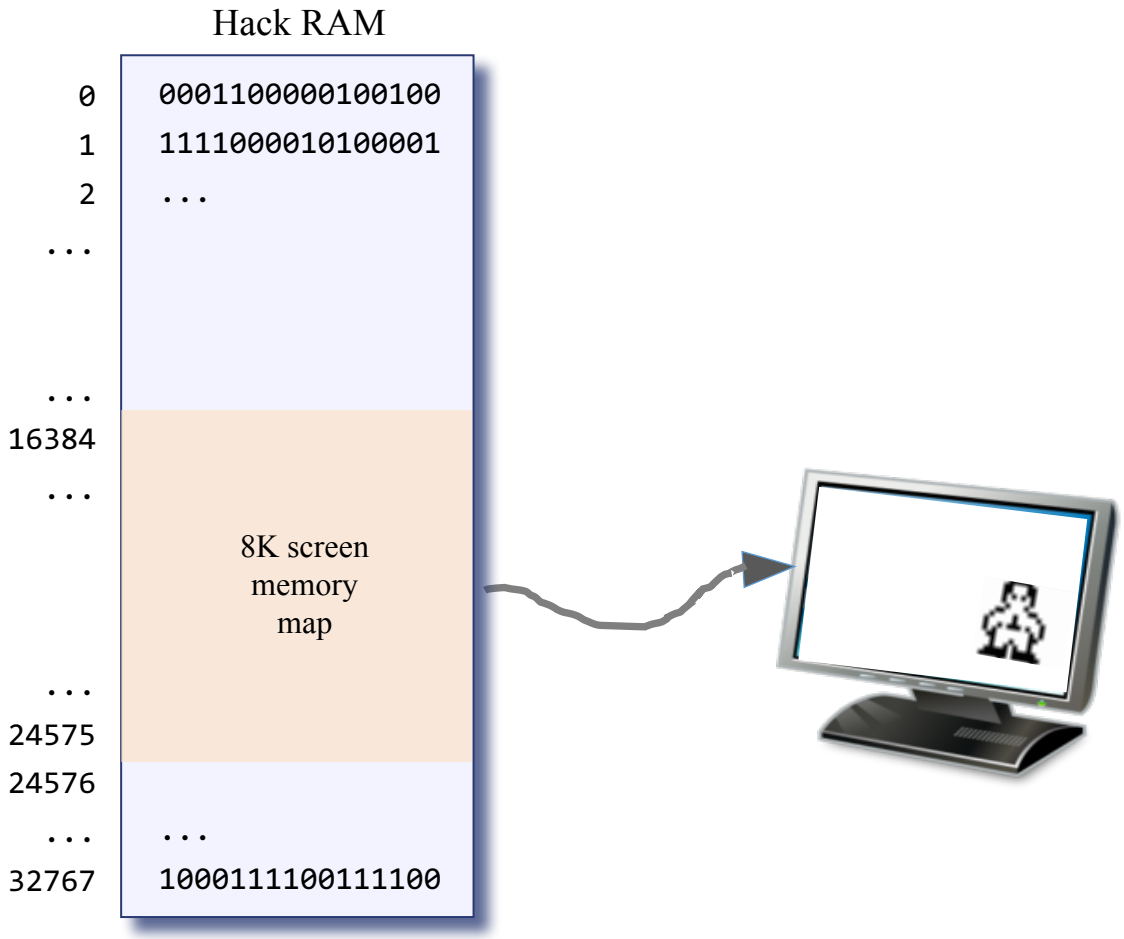
Vector graphics images can be easily:

- stored
- transmitted
- scaled
- turned into bitmap

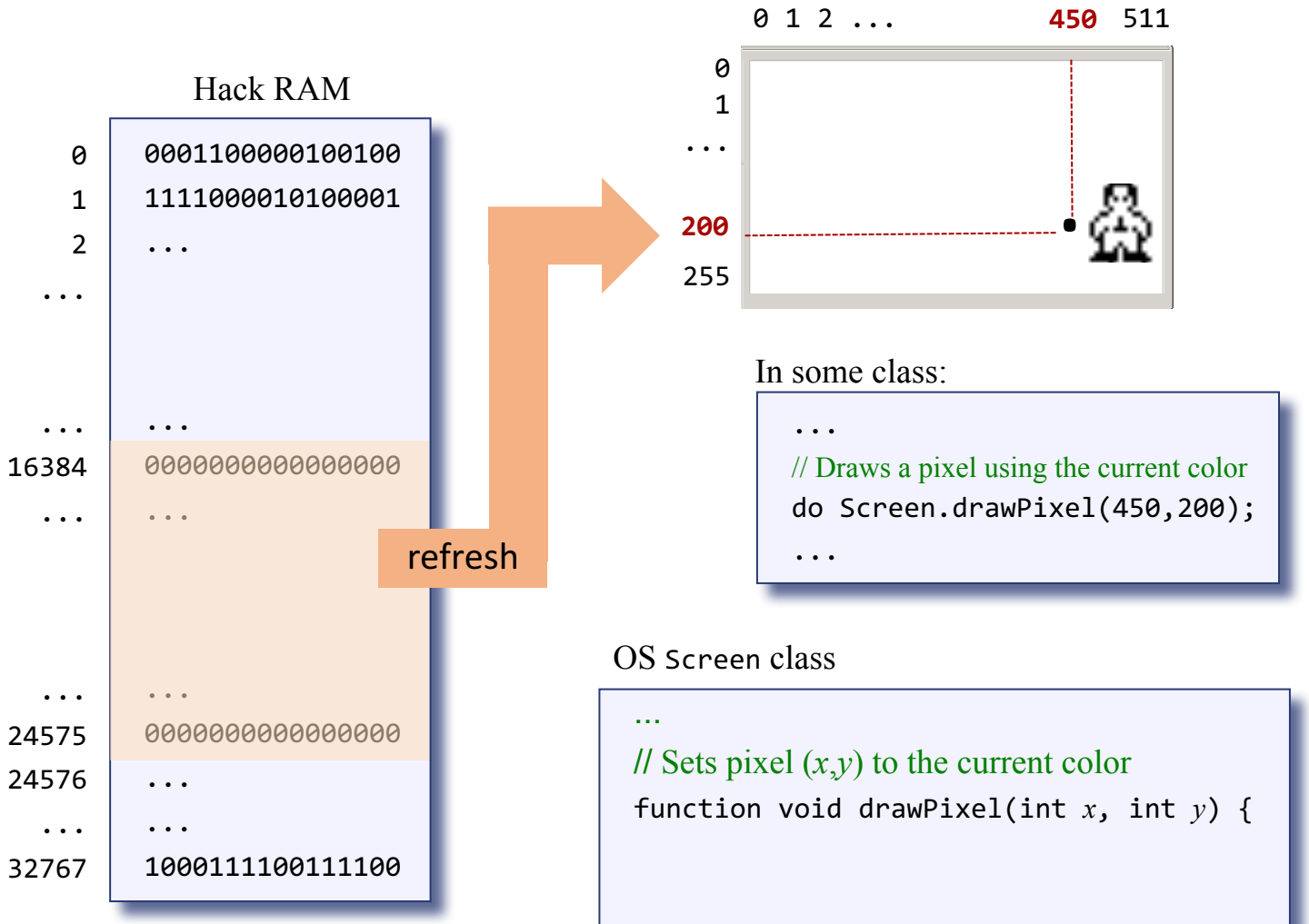
Vector graphics primitives

- `drawPixel` (x, y)
- `drawLine` (x_1, y_1, x_2, y_2)
- `drawCircle` (x, y, r)

Pixel drawing



Pixel drawing



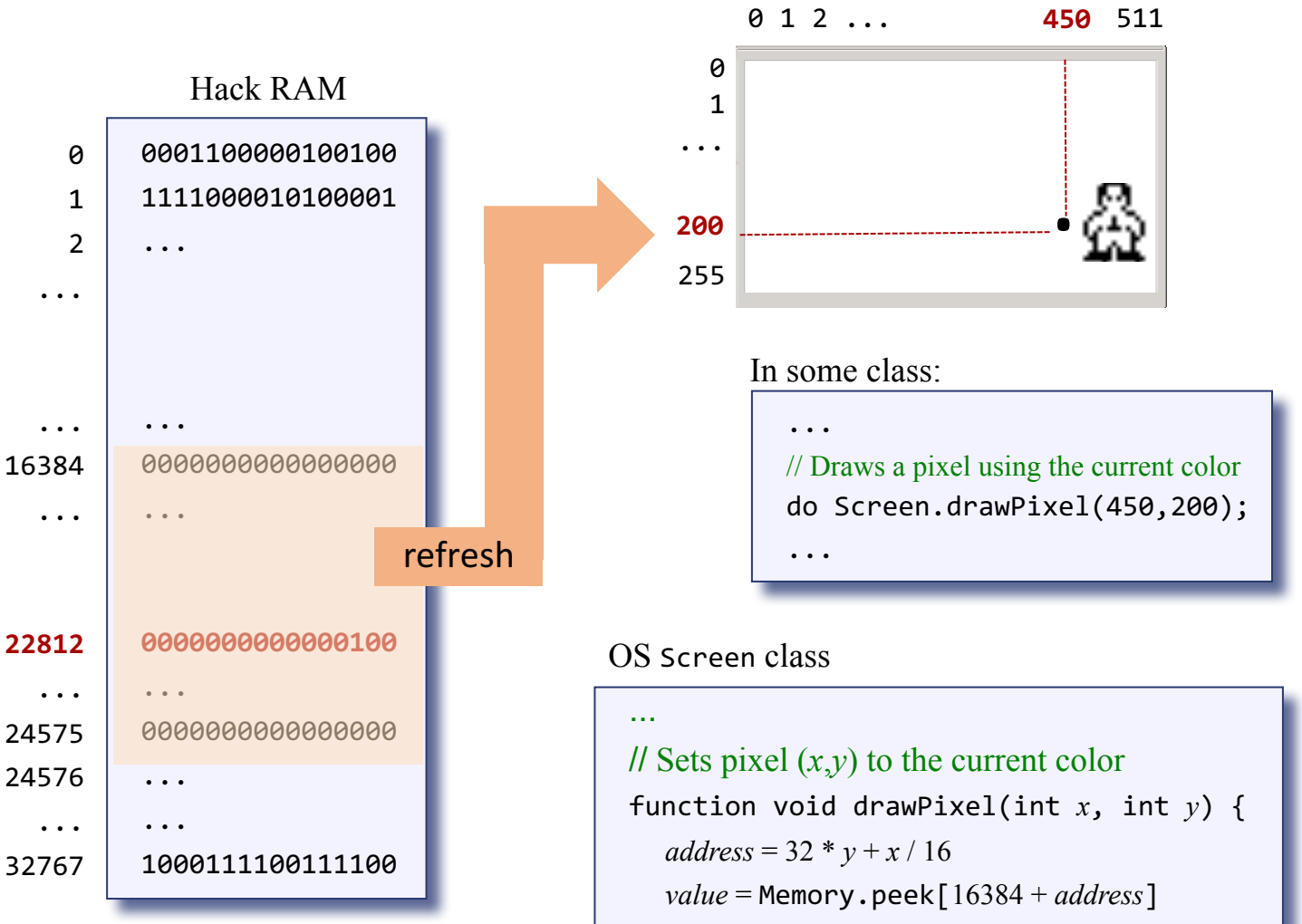
In some class:

```
...
// Draws a pixel using the current color
do Screen.drawPixel(450,200);
...
```

OS `Screen` class

```
...
// Sets pixel (x,y) to the current color
function void drawPixel(int x, int y) {
```

Pixel drawing



In some class:

```
...
// Draws a pixel using the current color
do Screen.drawPixel(450,200);
...
```

OS `Screen` class

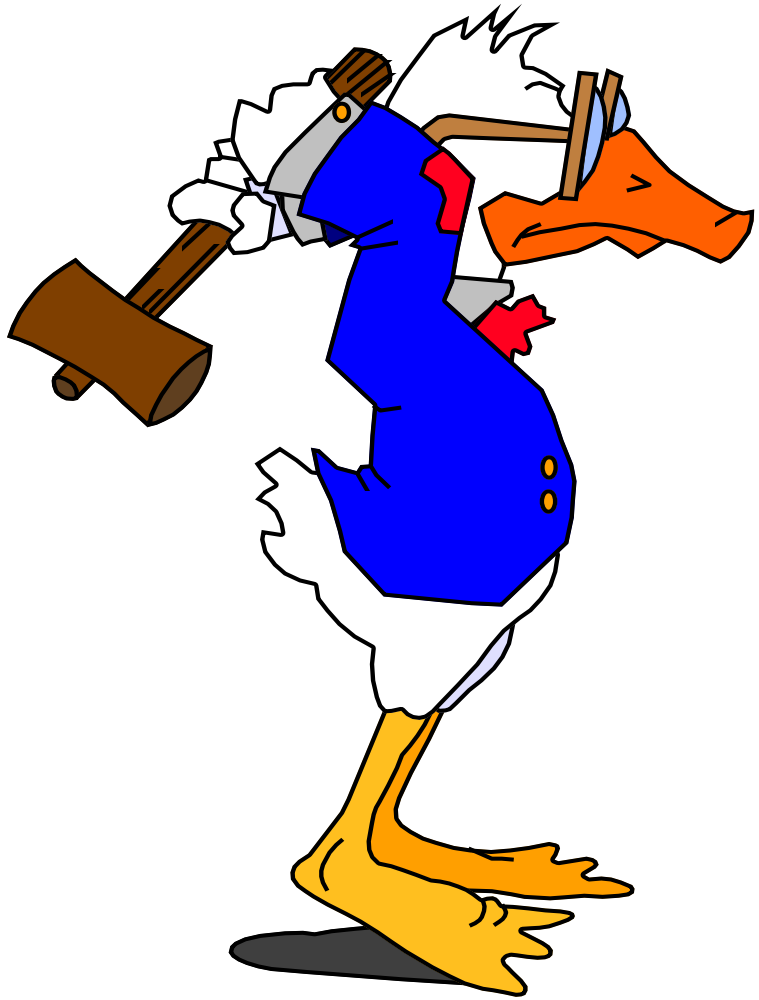
```
...
// Sets pixel (x,y) to the current color
function void drawPixel(int x, int y) {
    address = 32 * y + x / 16
    value = Memory.peek[16384 + address]
    set the (x % 16)th bit of value to the current color
    do Memory.poke(address,value)
}
```

`Memory.peek` and `Memory.poke` are implemented in the OS `Memory` class

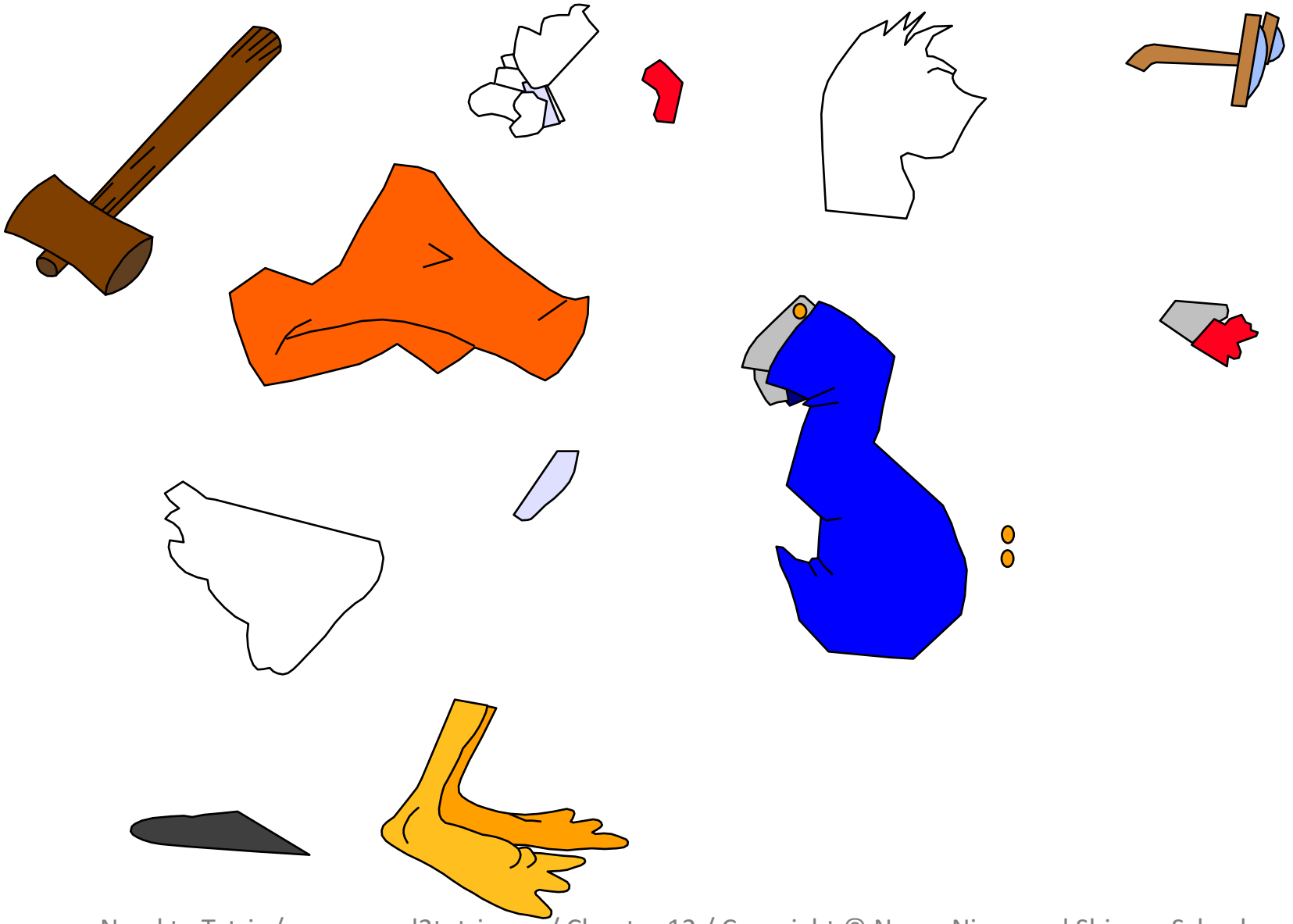
Recap

```
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)

}
```

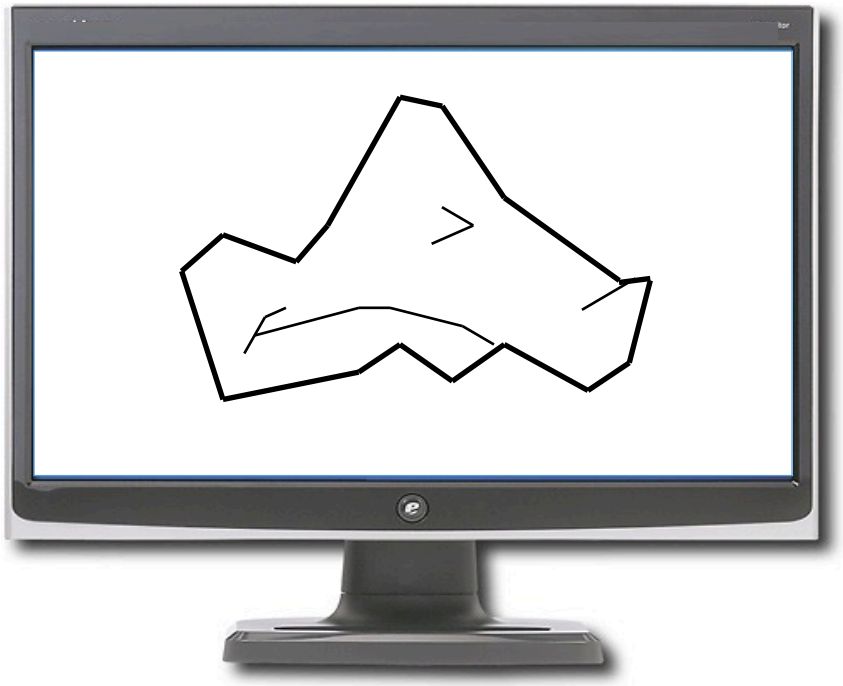
Vector graphics



Vector graphics



Vector graphics

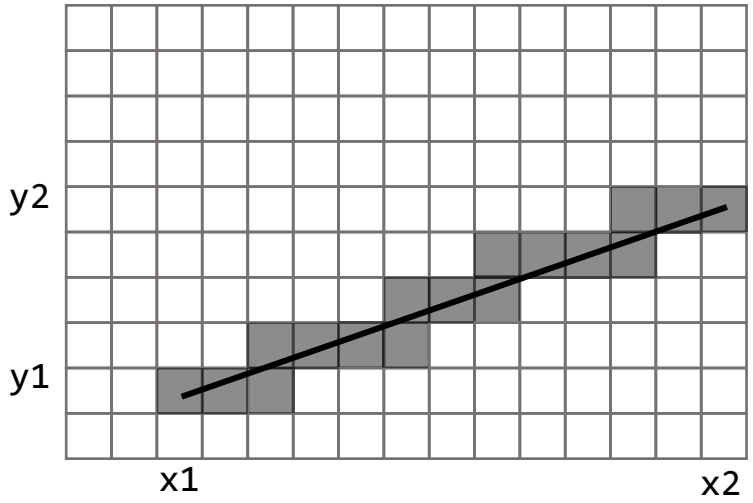


Basic idea: image drawing is implemented through a sequence of `drawLine` operations

Challenge: draw lines *fast*.

Line drawing

`drawLine(x1,y1,x2,y2)`



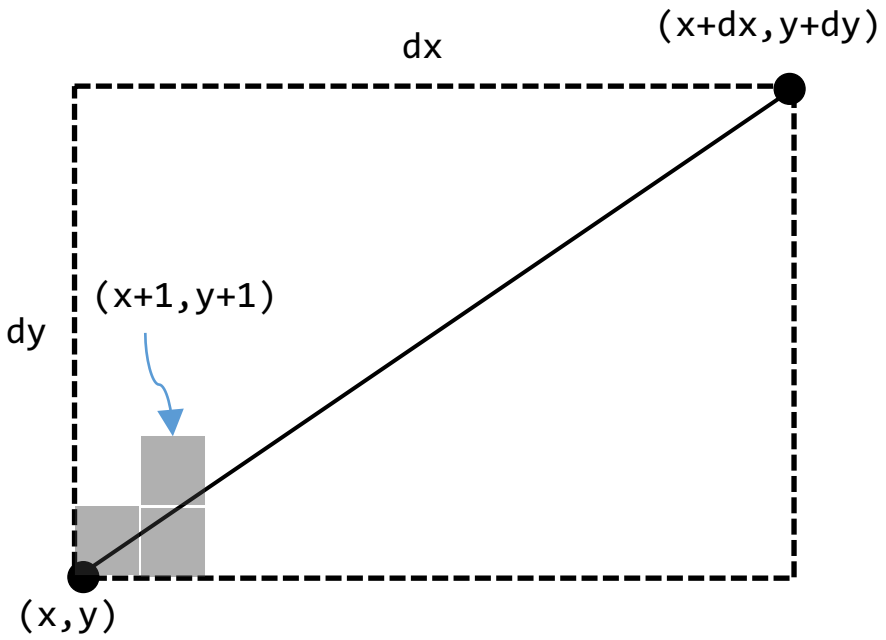
Simplifying assumption:

Let us focus on lines that go *north-east*

- `drawLine` is implemented through a sequence of `drawPixel` operations;
- In each stage we have to decide if we have to go *right*, or *up*

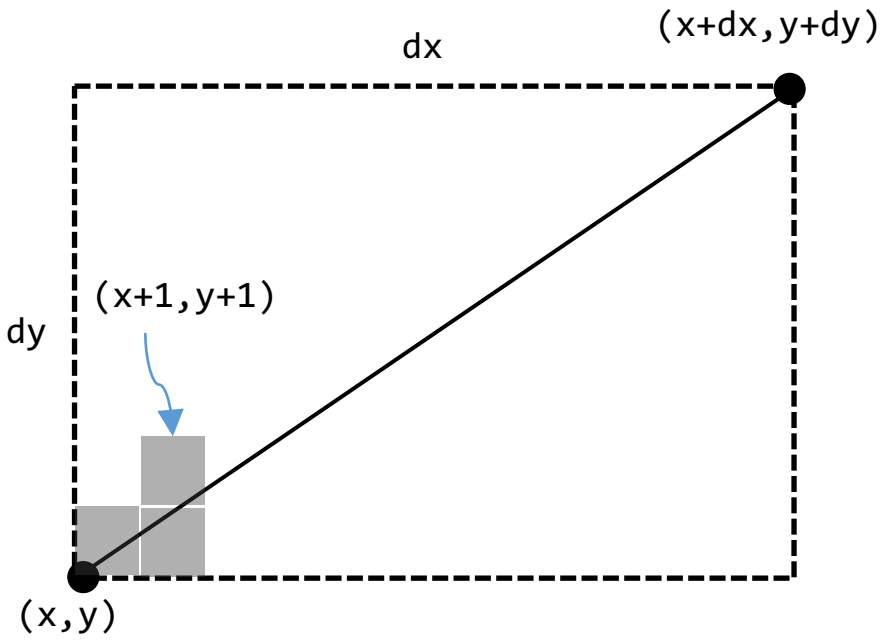
Challenge: how can we make these decisions ***fast*** ?

Line drawing



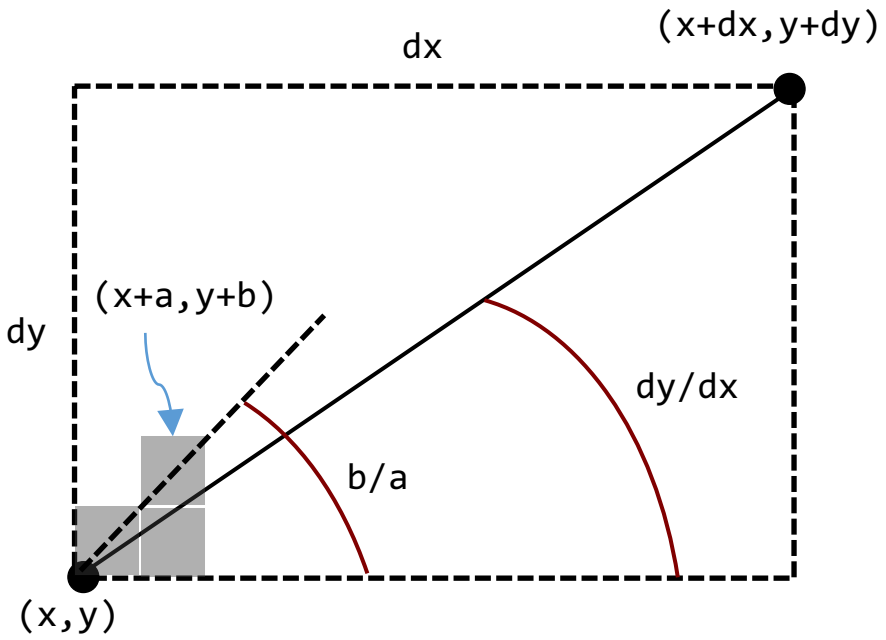

```
a = 0; b = 0;
while ... // there is more work to do
   drawPixel(x+a, y+b);
   // decide if to go right, or up;
   if going right, { a = a+1;}
   else            { b = b+1;}
```

Line drawing



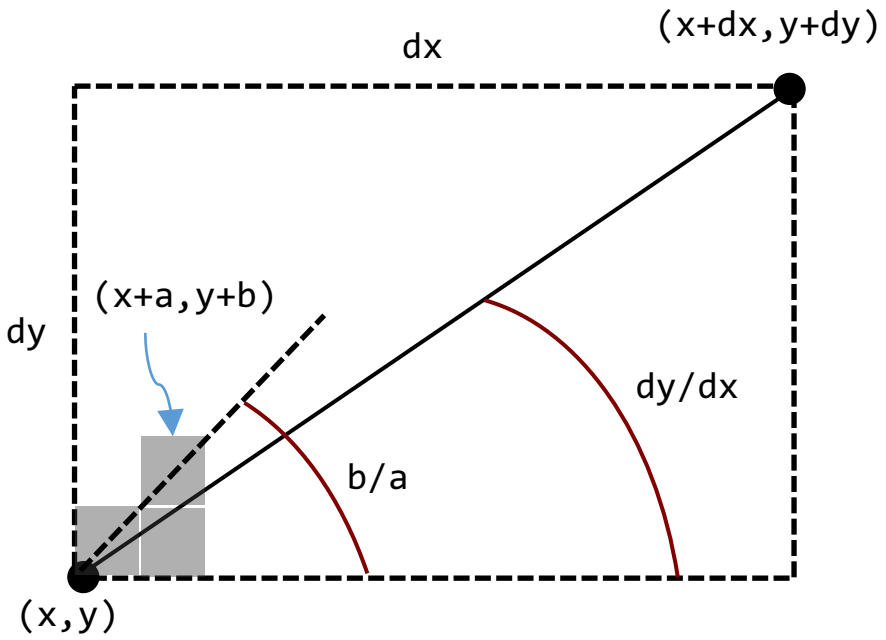

```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if going right, { a = a + 1;}
   else            { b = b + 1;}
```

Line drawing



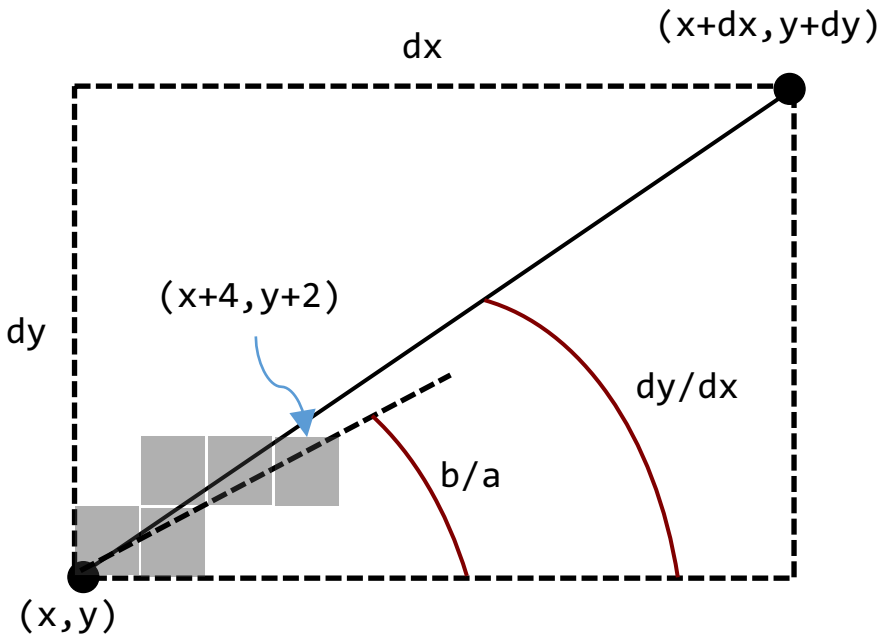

```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if going right,  { a = a + 1;}
   else             { b = b + 1;}
```

Line drawing



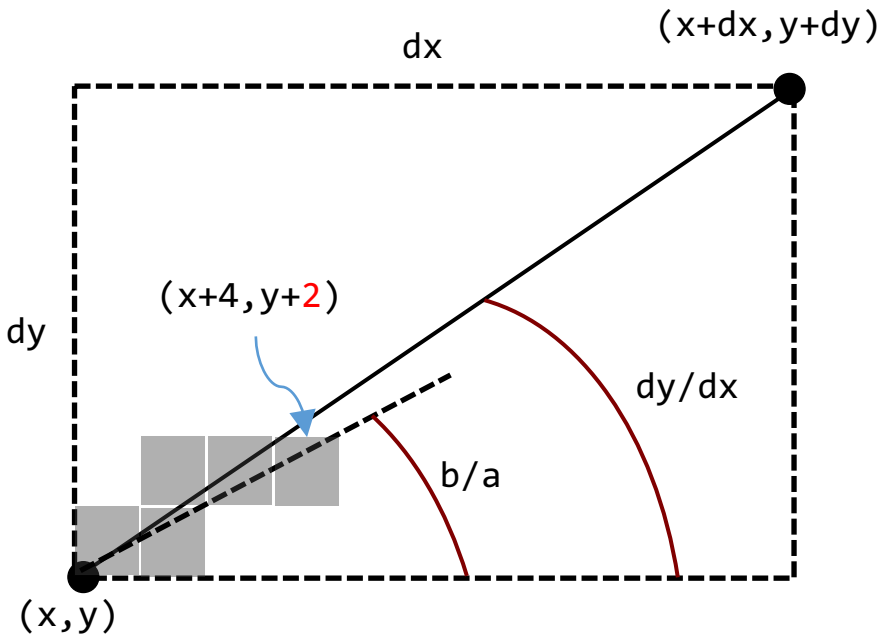

```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if (b/a > dy/dx)  { a = a + 1;}
   else              { b = b + 1;}
```

Line drawing



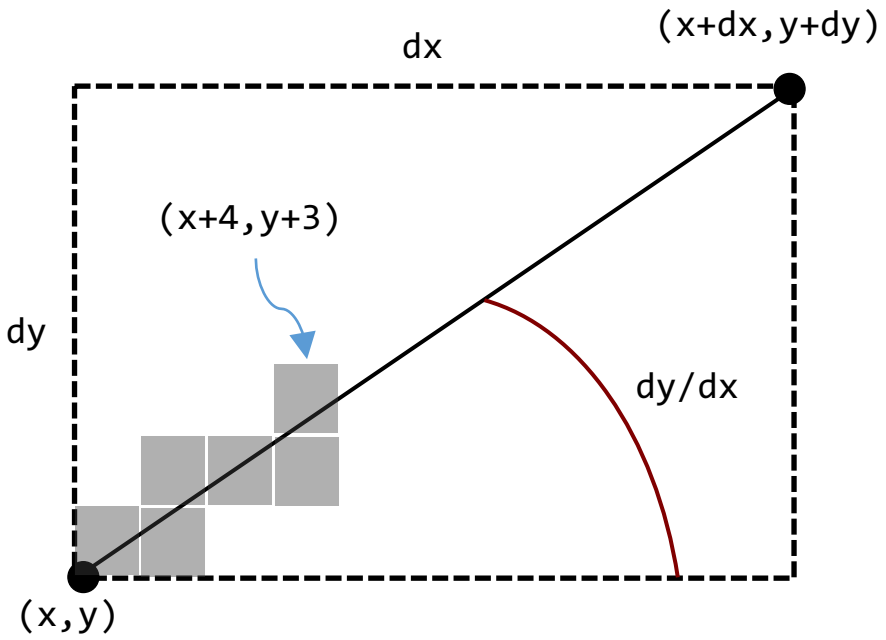

```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if (b/a > dy/dx)  { a = a + 1;}
   else              { b = b + 1;}
```

Line drawing



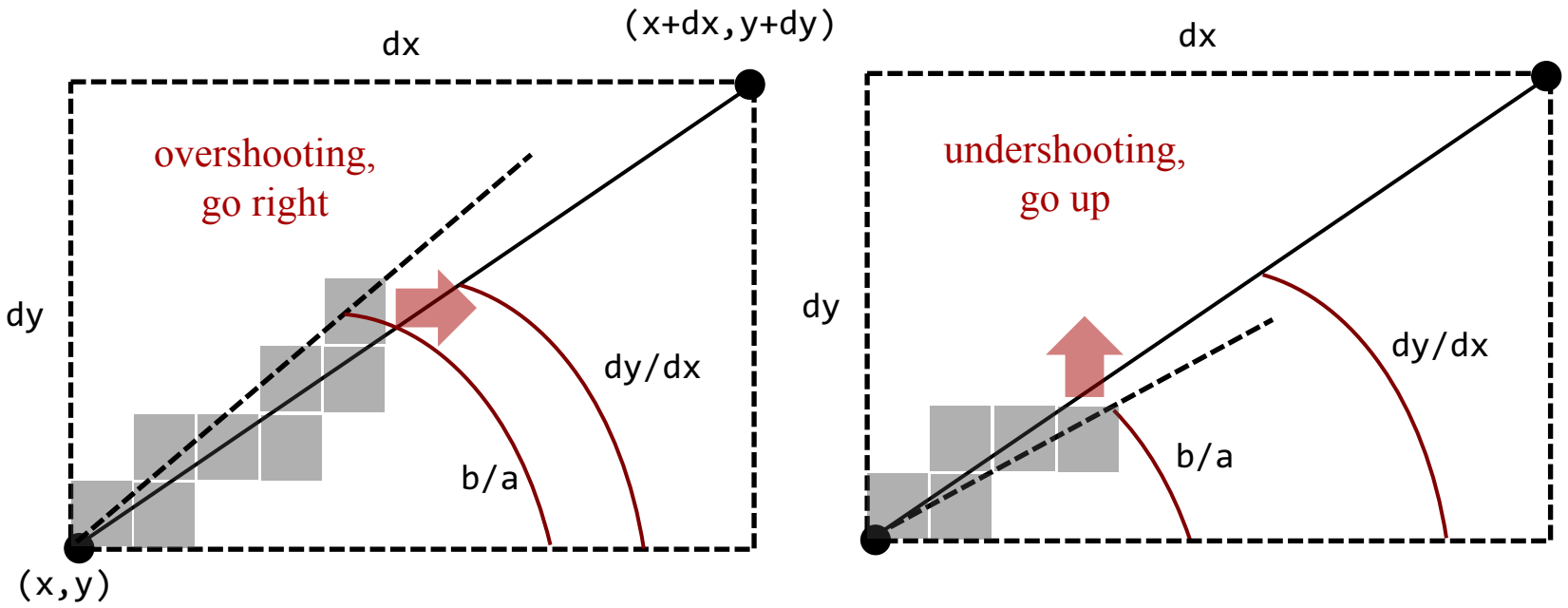

```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if (b/a > dy/dx)  { a = a + 1;}
   else              { b = b + 1;}
```

Line drawing




```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x + a, y + b);
   // decide if to go right, or up;
   if (b/a > dy/dx)  { a = a + 1;}
   else              { b = b + 1;}
```

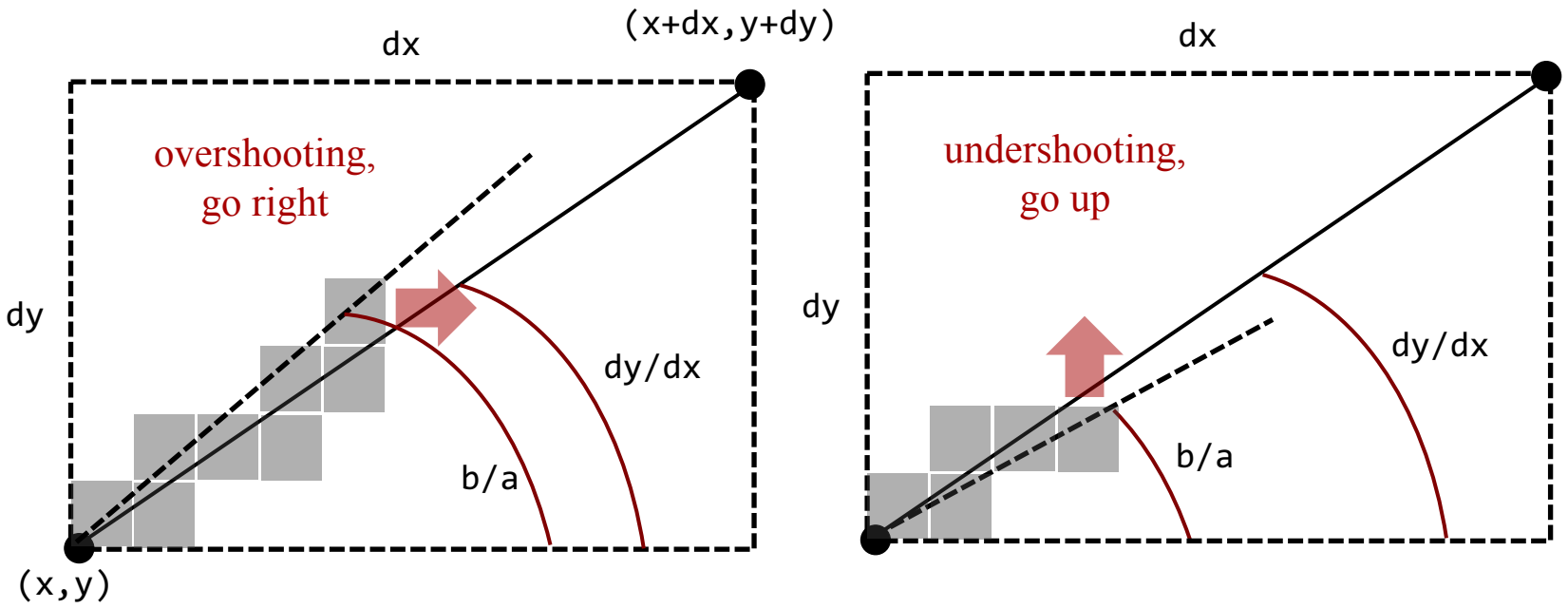
Line drawing




```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x+a, y+b);
   // decide if to go right, or up;
   if (b/a > dy/dx) { a = a+1;}
   else             { b = b+1;}
```

Oy Vey!

Line drawing




```
a = 0; b = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x+a, y+b);
   // decide if to go right, or up;
   if (b/a > dy/dx) { a = a+1;}
   else             { b = b+1;}
```

diff = 0

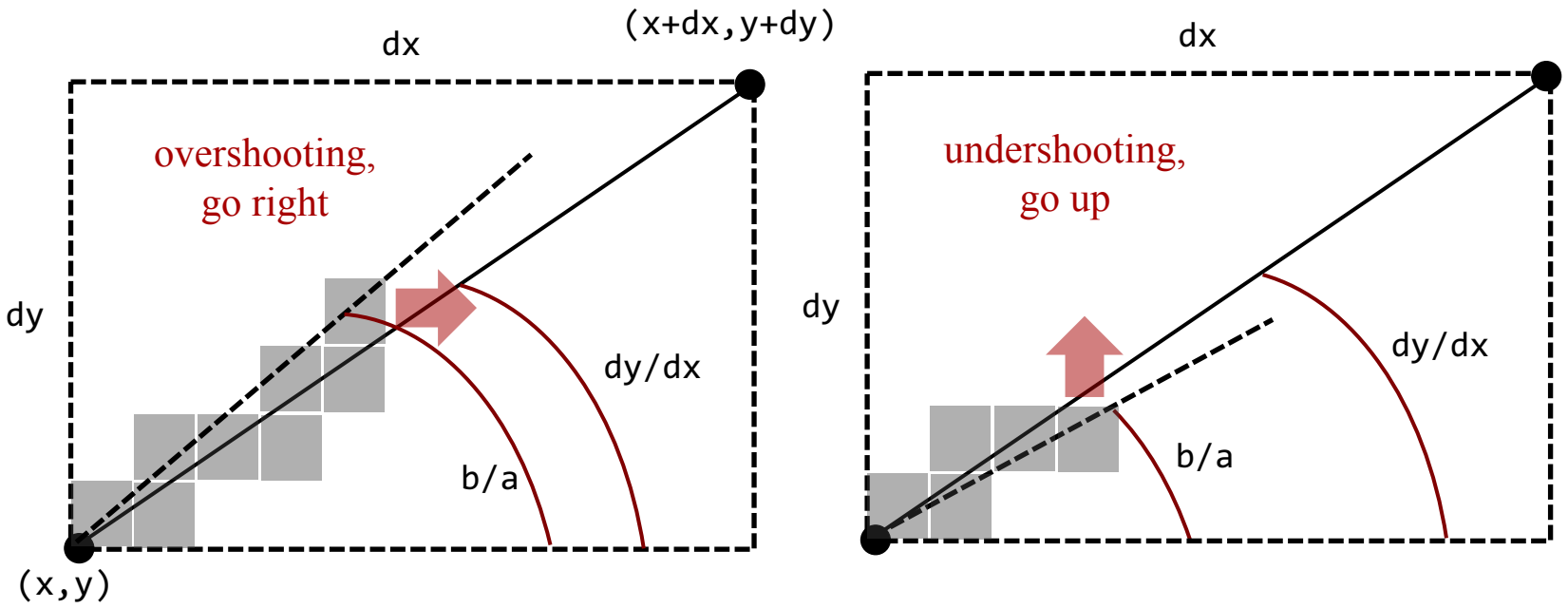
diff < 0

- (b/a > dy/dx) has the same value as (a*dy < b*dx)
- let diff = a*dy – b*dx

How do a++ and b++ impact diff?

- when we set a=a+1, diff goes up by dy
- when we set b=b+1, diff goes down by dx

Line drawing



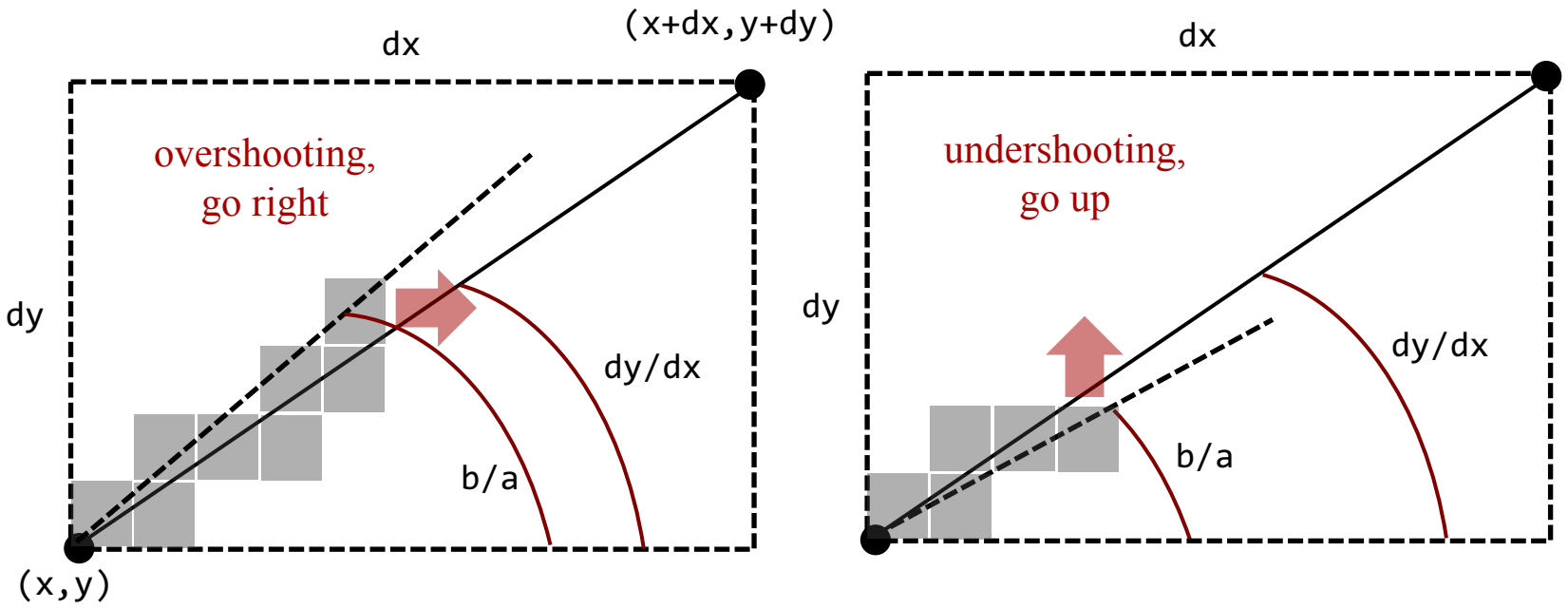

```
a = 0; b = 0; diff = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x+a, y+b);
   // decide if to go right, or up;
   if (diff < 0) { a = a+1; diff = diff+dy;}
   else          { b = b+1; diff = diff-dx;}
```

- `(b/a > dy/dx)` has the same value as `(a*dy < b*dx)`
- let `diff = a*dy – b*dx`

How do `a++` and `b++` impact `diff`?

- when we set `a=a+1`, `diff` goes up by `dy`
- when we set `b=b+1`, `diff` goes down by `dx`

Line drawing



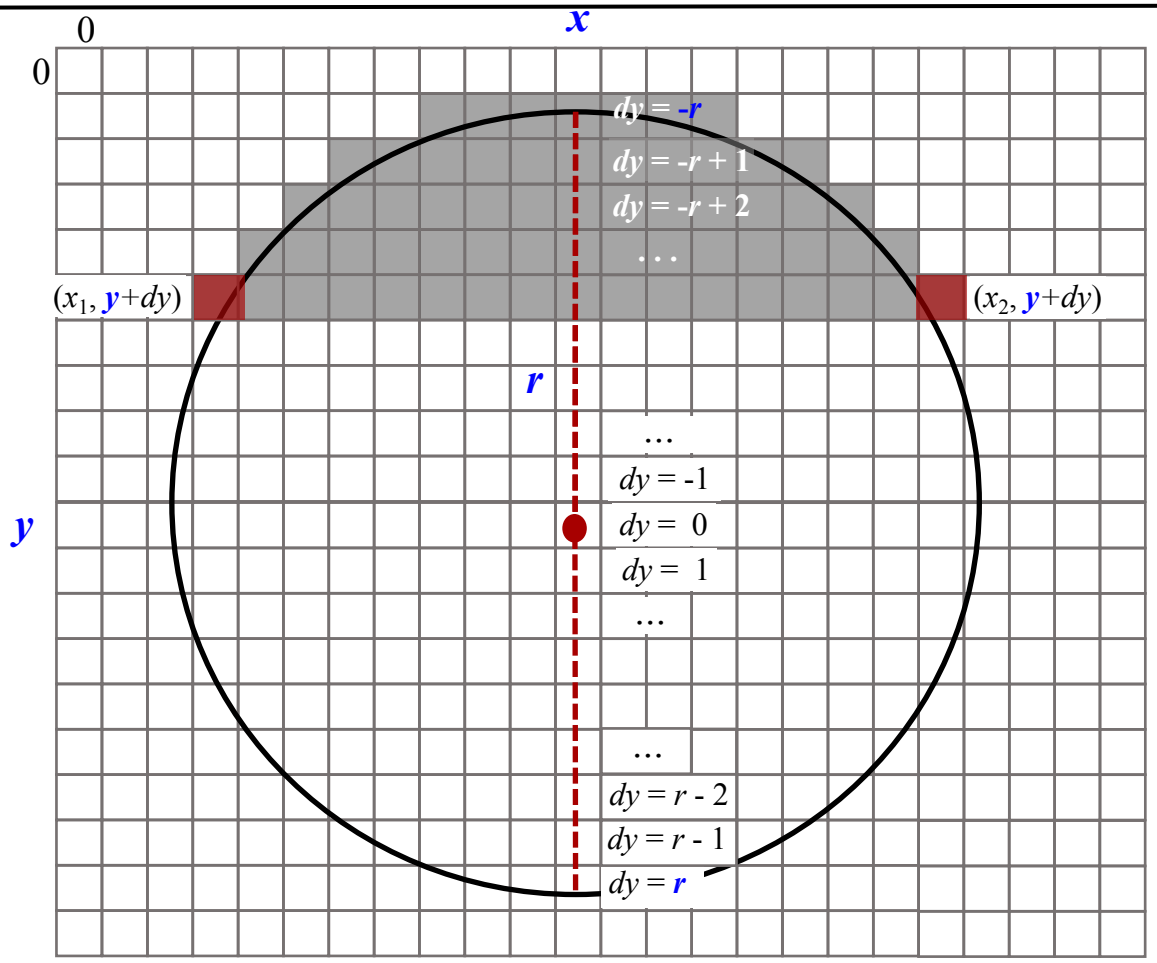

```
a = 0; b = 0; diff = 0;
while ((a ≤ dx) and (b ≤ dy))
   drawPixel(x+a, y+b);
   // decide if to go right, or up;
   if (diff < 0) { a = a+1; diff = diff+dy;}
   else          { b = b+1; diff = diff-dx;}
```

- involves only addition and subtraction operations
- can be implemented either in software or hardware.

Recap

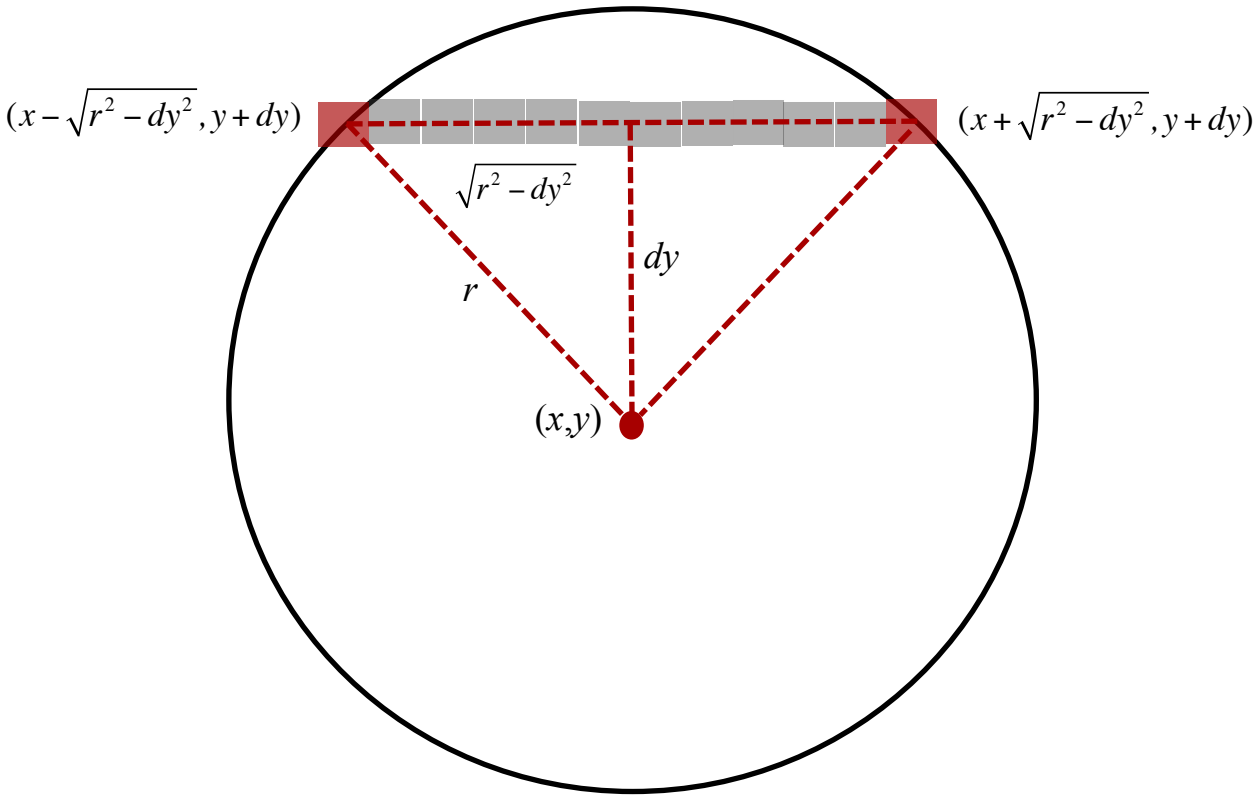
```
Class Screen {

   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)

}
```

Circle drawing




```
drawCircle (x, y, r)
    for each dy = –r  to  r  do:
        drawLine ( x1, y+dy,   x2, y+dy )
```

Circle drawing



drawCircle (x, y, r)

for each $dy = -r$ to r do:

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

Recap

```
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)

}
```

Implementation notes: `drawPixel`

```
// Sets pixel (x,y) to the current color
function void drawPixel(int x, int y) {
   address = 32 * y + x / 16
   value = Memory.peek[16384 + address]
   set the (x % 16)th bit of value to the current color
   do Memory.poke(address,value)
}
```

Issues

- Uses the services of the OS Memory class:
  - `Memory.peek`
  - `Memory.poke`
- Setting a single bit in a 16-bit value can be done using logical 16-bit operations

Implementation notes: `drawLine`

```
// Draws a line from (x1,y1) to (x2,y2)
function void drawLine(int x1, int y1, int x2, int y2)
   dx = x2 - x1; dy = y2 – y1;
   a = 0; b = 0; diff = 0;
   while ((a <= dx) and (b <= dy))
      drawPixel(x + a, y + b);
      // decide which way to go (up, or right)
      if (diff < 0) { a++; diff += dy; }
      else          { b++; diff -= dx; }
```

Issues

- modify the algorithm for a screen origin (0,0) at the screen's top-left corner
- generalize the algorithm to draw lines that go in any direction
- drawing horizontal and vertical lines should probably be handled as special cases.

Implementation notes: `drawCircle`

/** Draws a filled circle of radius *r* around (*cx*, *cy*). */

function void drawCircle(int *cx*, int *cy*, int *r*) {

for each $dy = -r$ to r do:

drawLine ($cx - \sqrt{r^2 - dy^2}, cy + dy$, $cx + \sqrt{r^2 - dy^2}, cy + dy$)

Issues

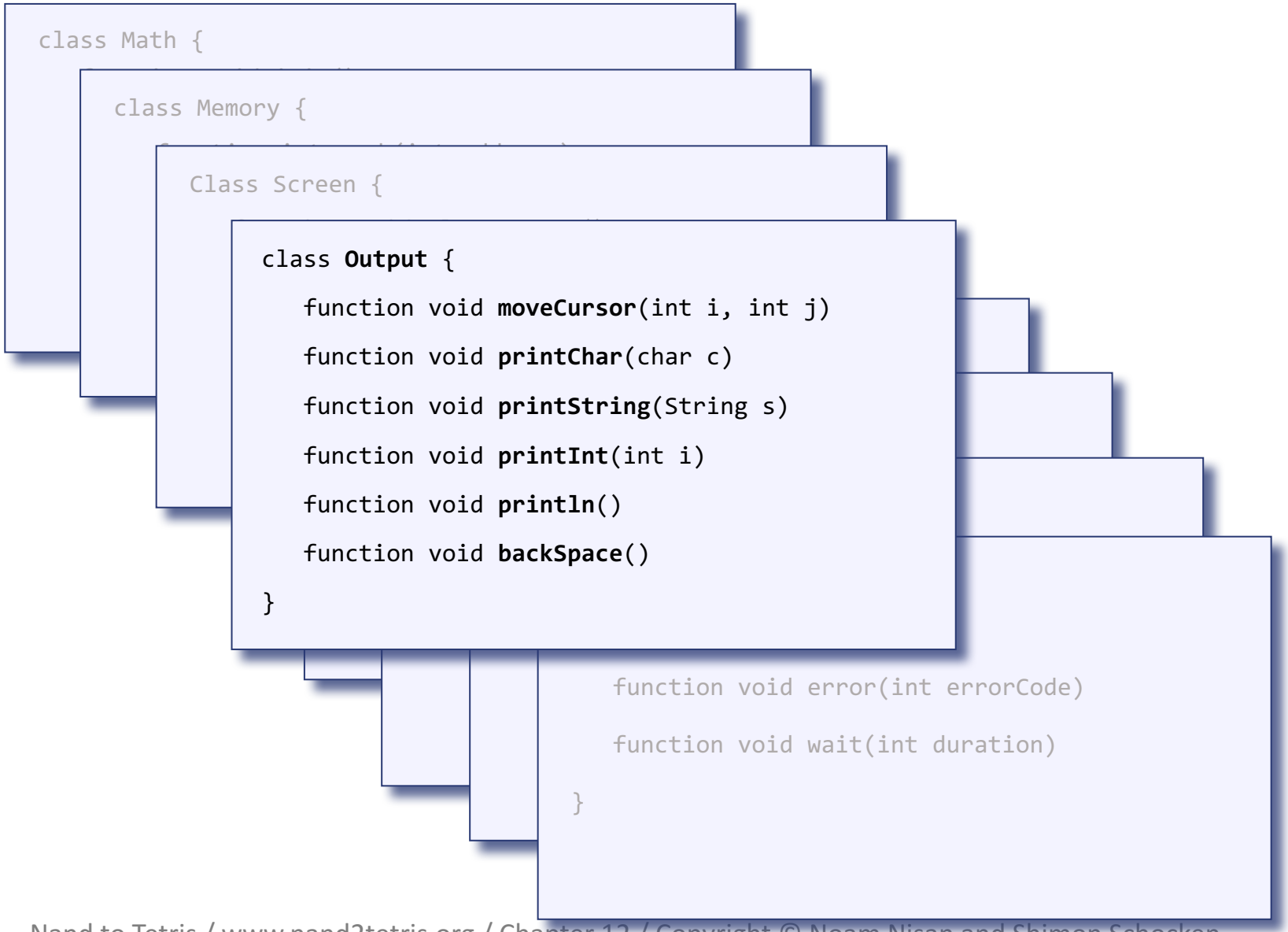
- can potentially lead to overflow
- to handle, limit *r* to no greater than 181.

Recap

```
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)

}
```

The implementation of the remaining `Screen` functions is simple.

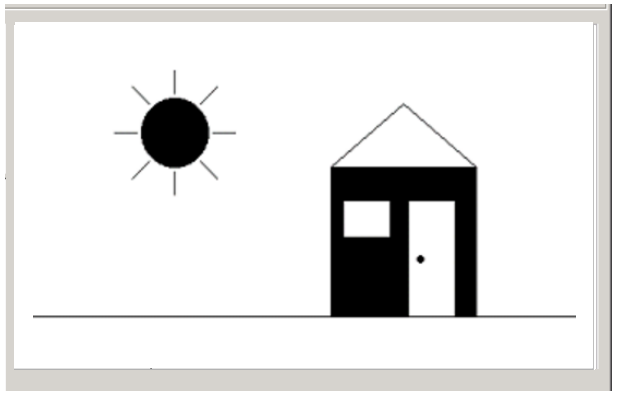
The Jack OS


class Math {
class Memory {
Class Screen {
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()
}
function void error(int errorCode)
function void wait(int duration)
}

Output modes

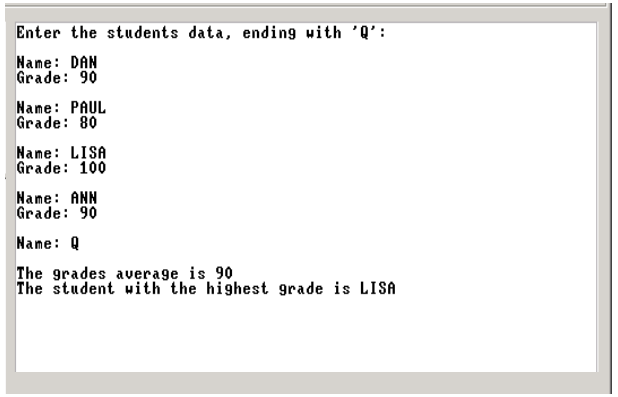
Graphical output

- Screen abstraction:
  256 rows of 512 pixels, b&w
- Managed by the Jack OS class `Screen`



Textual output:

- Screen abstraction:
  23 rows of 64 characters, b&w
- Managed by the Jack OS class `Output`



The Hack character set

printable characters

key	code
(space)	32
!	33
“	34
#	35
$	36
%	37
&	38
‘	39
(	40
)	41
*	42
+	43
,	44
-	45
.	46
/	47

key	code
0	48
1	49
…	…
9	57

:	58
;	59
<	60
=	61
>	62
?	63
@	64

key	code
A	65
B	66
C	…
…	…
Z	90

[	91
/	92
]	93
^	94
_	95
`	96

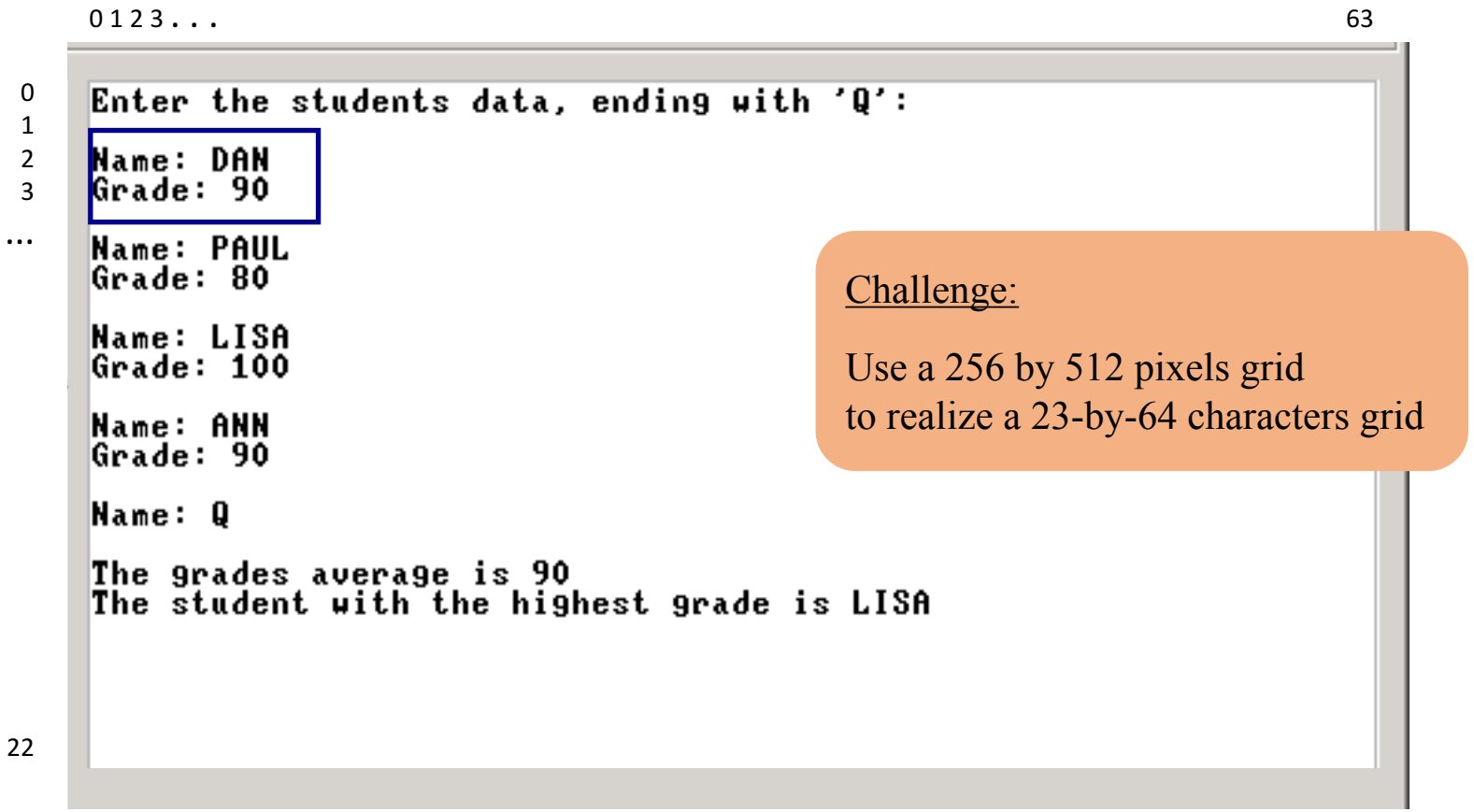
key	code
a	97
b	98
c	99
…	…
z	122

{	123
|	124
}	125
~	126

non-printables

key	code
newline	128
backspace	129
left arrow	130
up arrow	131
right arrow	132
down arrow	133
home	134
end	135
Page up	136
Page down	137
insert	138
delete	139
esc	140
f1	141
…	…
f12	152

Textual output



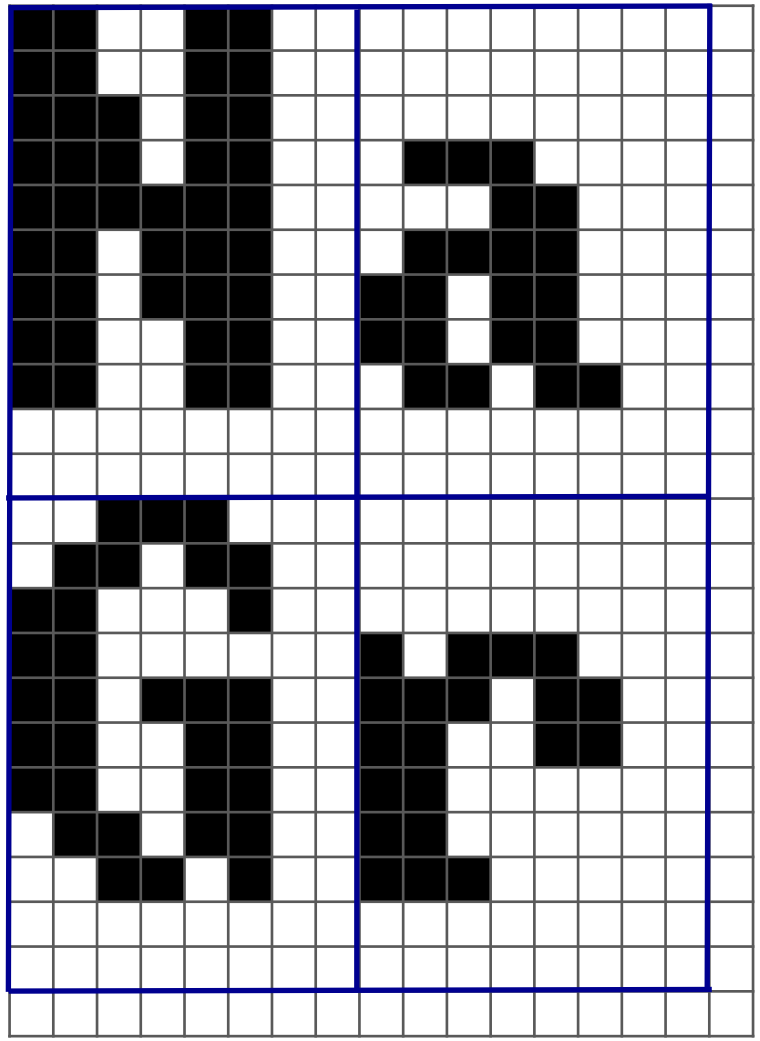
Challenge:

Use a 256 by 512 pixels grid
to realize a 23-by-64 characters grid

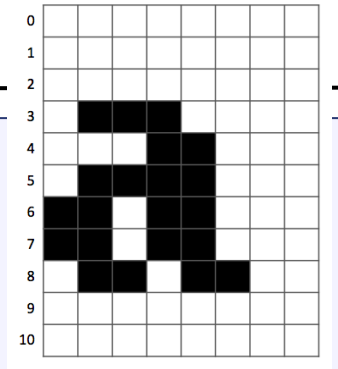
Font

Hack font

- Each character occupies a fixed 11-pixel high and 8-pixel wide frame
- The frame includes 2 empty right columns and 1 empty bottom row for character spacing

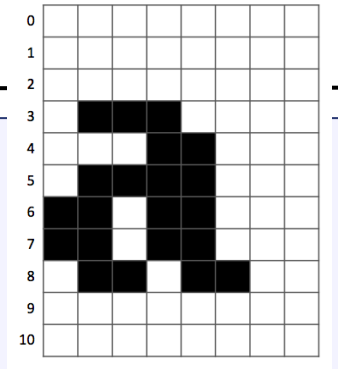


Font implementation



```
class Output {
    static Array charMaps;  // character map for displaying characters
    ...
    // Initializes the character map array
    function void initMap() {
        let charMaps = Array.new(127);

        // Assigns the bitmap for each character in the character set.
        do Output.create(97, 0,0,0,14,24,30,27,27,54,0,0);    // a
        do Output.create(98, 3,3,3,15,27,51,51,51,30,0,0);    // b
        do Output.create(99, 0,0,0,30,51,3,3,51,30,0,0);      // c
        ...
        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(51, 30,51,48,48,28,48,48,51,30,0,0); // 3
        ...
        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);  // #
        ...
        // black square (used for non printable characters)
        do Output.create(0,  63,63,63,63,63,63,63,63,63,0,0);
        return
}
```

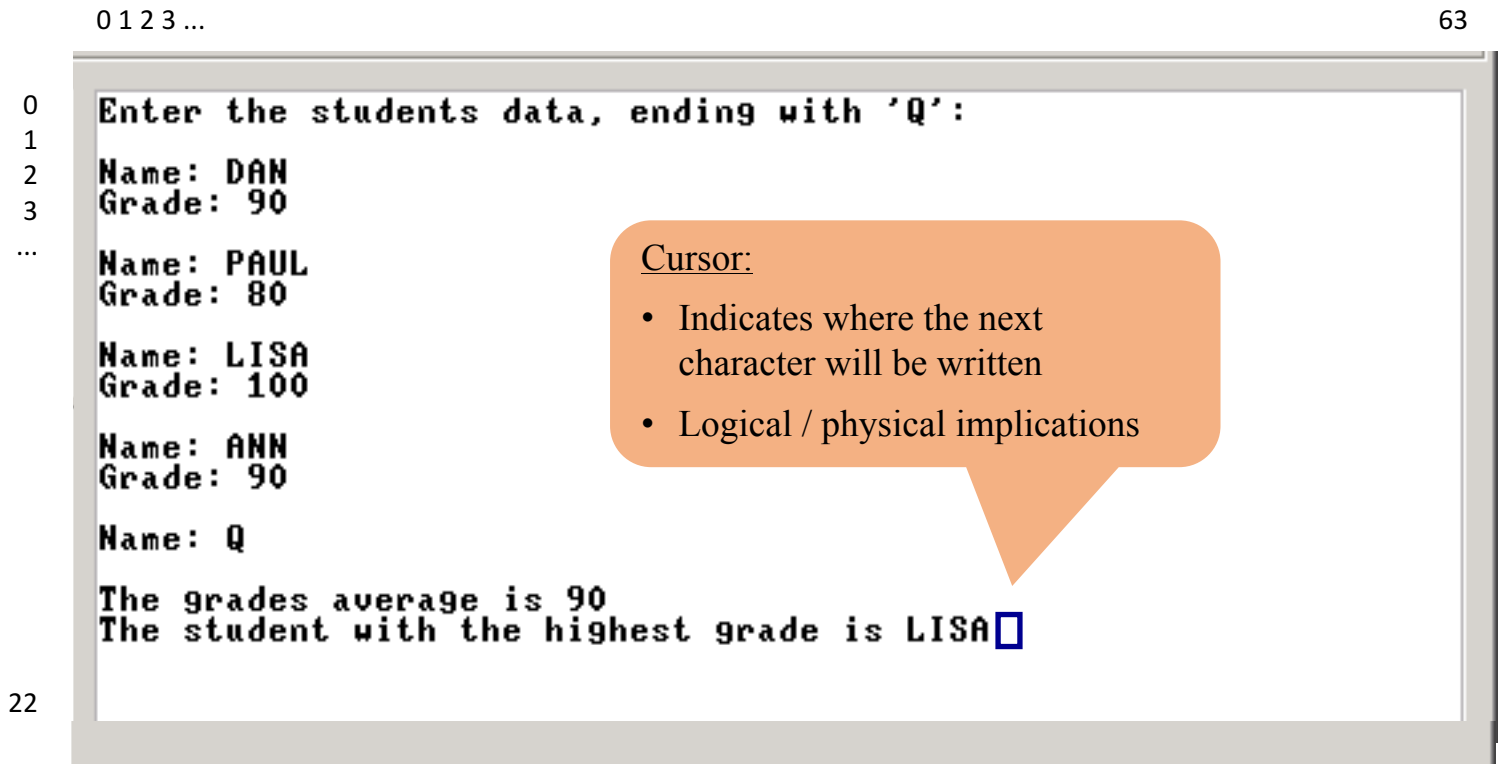
Font implementation



```
class Output {
    static Array charMaps;  // character map for displaying characters
    ...
    // Initializes the character map array
    function void initMap() {
        let charMaps = Array.new(127);

        // Assigns the bitmap for each character in the character set.
        do Output.create(97, 0,0,0,14,24,30,27,27,54,0,0);    // a
        do Output.create(98, 3,3,3,15,27,51,51,51,30,0,0);    // b
        do Output.create(99, 0,0,0,30,51,3,3,51,30,0,0);      // c
        ...
        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(51, 30,51,48,48,28,48,48,51,30,0,0); // 3
        ...
        do Out
        do Out
        do Out
        do Out
        ...
        // black
        do Out
        return
}
```

```
// Creates a character map array of the given char index with the given values.
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[3] = d;  let map[4] = e;  let map[5] = f;
   let map[6] = g;  let map[7] = h;  let map[8] = i;
   let map[9] = j;  let map[10] = k;
   return;
}
```

Cursor



Must be managed as follows:

- if asked to display `newLine`: move the cursor to the beginning of the next line
- if asked to display `backspace`: move the cursor one column left
- if asked to display any other character:
  display the character, and
  move the cursor one column to the right.

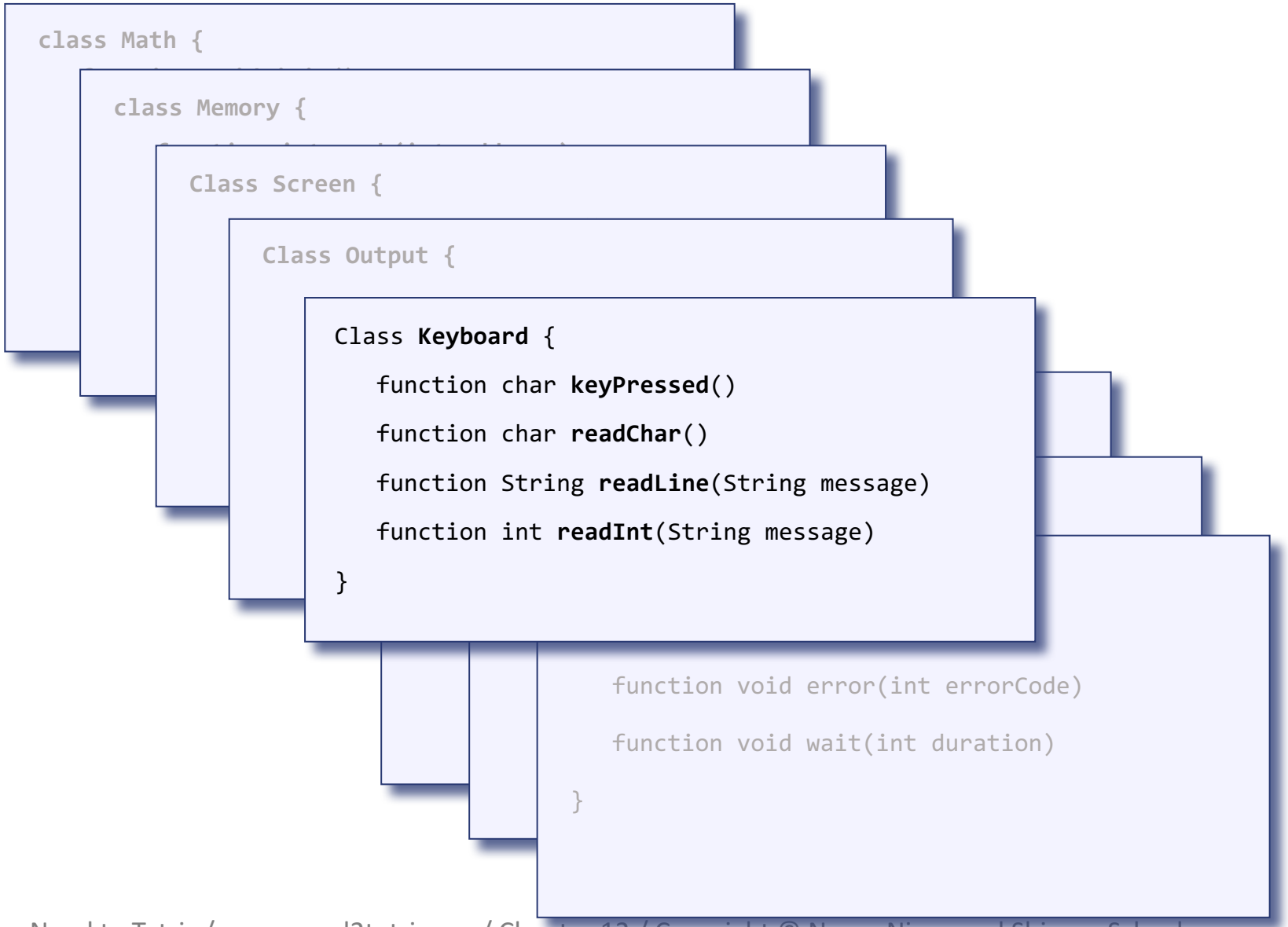
Implementation notes

```
class Output {
  function void init() {}

  /** Moves the cursor to the j'th column of the i'th row, erasing the character that was there. */
  function void moveCursor(int i, int j) {}

  /** Displays c at the cursor location, and advances the cursor one column right. */
  function void printChar(char c) {}

  /** Displays str starting at the cursor location, and advances the cursor appropriately. */
  function void printString(String str) {}

  /** Displays i starting at the cursor location, and advances the cursor appropriately. */
  function void printInt(int i) {}

  /** Advances the cursor to the beginning of the next line. */
  function void println() {}

  /** Erases the character that was last written and moves the cursor one column back. */
  function void backSpace() {}
}
```

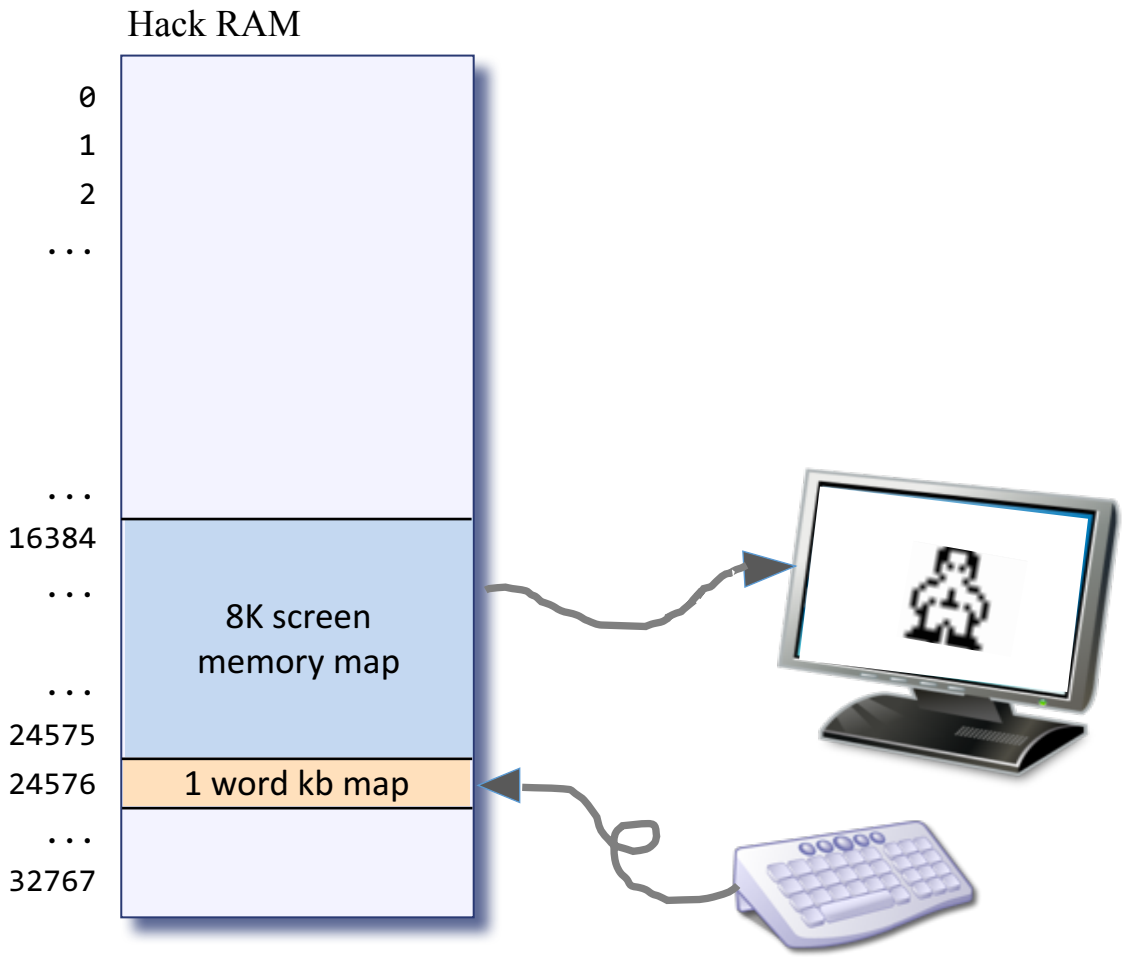
Implementation:

- The Hack font implementation: given
- Given that fonts are taken care of, the implementation of the `Output` functions is simple.

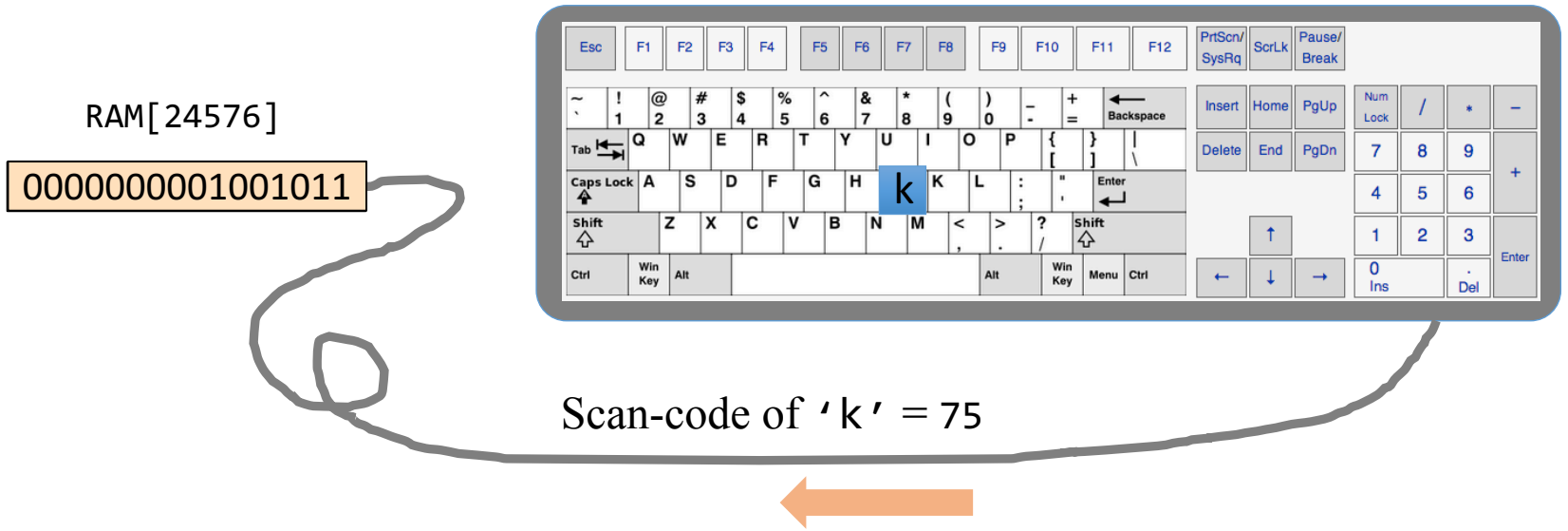
The Jack OS


class Math {
class Memory {
Class Screen {
Class Output {
Class Keyboard {
function char keyPressed()
function char readChar()
function String readLine(String message)
function int readInt(String message)
}
function void error(int errorCode)
function void wait(int duration)
}

Hack I/O


Hack RAM
0
1
2
...
...
16384
...
...
24575
24576
...
32767
8K screen
memory map
1 word kb map

Keyboard memory map

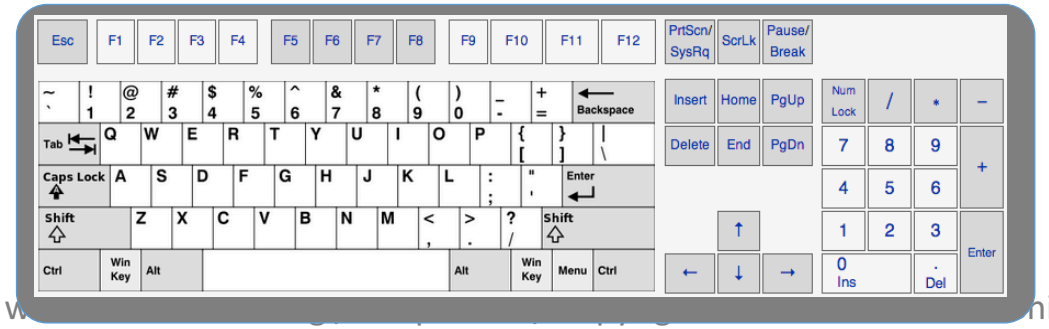


Keyboard memory map

- when a key is pressed on the keyboard,
  the keyboard register is set to the key's *scan code*
- when no key is pressed, the keyboard register is set to `0`

OS Keyboard class

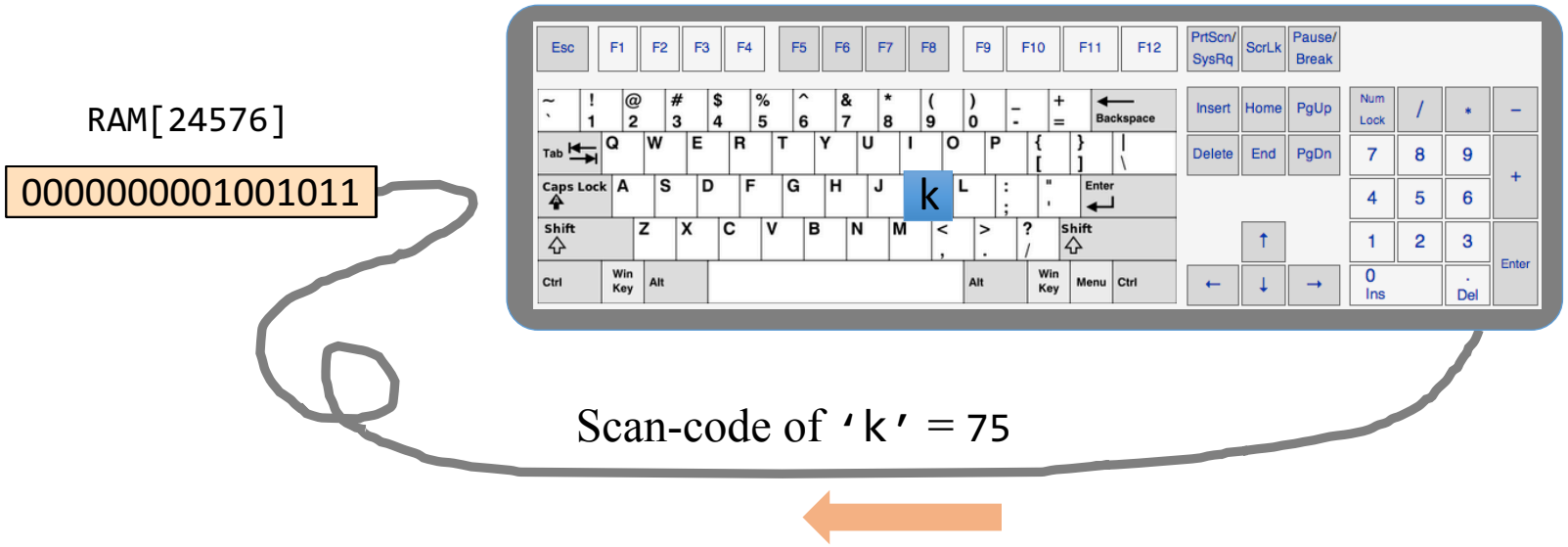
```
class Keyboard {

    /** Returns the ASCII code (as char) of the currently pressed key,
     *  or 0 if no key is currently pressed.*/
    function char keyPressed() {}

    /** Reads the next character from the keyboard:
     *  waits until a key is pressed and then released, then echoes
     *  the key to the screen, and returns the value of the pressed key.*/
    function char readChar() {}

    /** Prints the message on the screen, reads the next line (until a newLine
     *  character) from the keyboard, and returns its value. */
    function String readLine(String message) {}

    /** Prints the message on the screen, reads the next line
     * (until a newline character) from the keyboard, and returns its
     * integer value (until the first non numeric character). */
    function int readInt(String message) {}
}
```



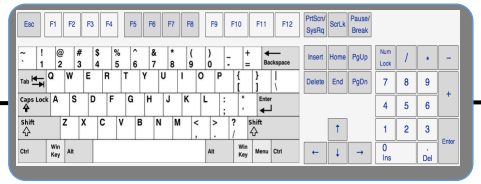
keypressed

listens to the keyboard

```
keyPressed():
  if a keyboard key is pressed:
      return the key's scan code
  else
      return 0
```



keypressed / readchar / readLine



listens to the keyboard

```
keyPressed():
  if a keyboard key is pressed:
      return the key's scan code
  else
      return 0
```

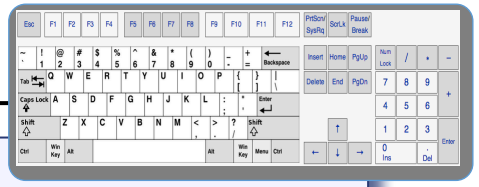
gets a character

```
/** Waits until a key is pressed and released;
echoes the key on the screen, advances the cursor,
and returns the key's character value. */
readChar():
  display the cursor
  // waits until a key is pressed
  while (keyPressed() == 0):
      do nothing
  c = code of the currently pressed key
  // waits until the key is released
  while (keyPressed() ≠ 0):
      do nothing
  display c at the current cursor location
  advance the cursor
  return c
```

gets a string

```
/** Displays the message on the screen, gets the next
line (until a newLine character) from the keyboard,
and returns its value, as a string. */
readLine():
  str = empty string
  repeat
    c = readChar()
    if (c == newLine):
      display newLine
      return str
    else if (c = backSpace):
        remove the last character from str
        do Output.backspace()
      else
        str = str.append(c)
  return str
```

Implementation notes



```
class Keyboard {

    /** Returns the ASCII code (as char) of the currently pressed key,
     *  or 0 if no key is currently pressed.*/
    function char keyPressed() {}

    /** Reads the next character from the keyboard:
     *  waits until a key is pressed and then released, then echoes
     *  the key to the screen, and returns the value of the pressed key.*/
    function char readChar() {}

    /** Prints the message on the screen, reads the next line (until a newLine
     *  character) from the keyboard, and returns its value. */
    function String readLine(String message) {}

    /** Prints the message on the screen, reads the next line
     * (until a newline character) from the keyboard, and returns its
     * integer value (until the first non numeric character). */
    function int readInt(String message) {}
}
```

- `keyPressed`: use `Memory.peek` to access the keyboard's memory map
- `readChar`: implement the algorithm
- `readLine`: implement the algorithm
- `readInt`: read characters (digits) and build the integer value.

The Jack OS


class Math {
class Memory {
Class Screen {
Class Out
cla
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()
}

String API

```
/** Represents a string object. Implements the String type. */
class String {

    /** Constructs a new empty string with a maximum length. */
    constructor String new(int maxLength) {}

    /** De-allocates the string and frees its memory space. */
    method void dispose() {}

    /** Returns the length of this string. */
    method int length() {}

    /** Returns the character value at the specified index */
    method char charAt(int j) {}

    /** Sets the j'th character of this string to the given character. */
    method void setCharAt(int j, char c) {}

    /** Appends the given character to the end of this string, and returns the string. */
    method String appendChar(char c) {}

    /** Erases the last character from this string. */
    method void eraseLastChar() {}

    /** Returns the integer value of this string until the first non-numeric character. */
    method int intValue() {}

    /** Sets this String to the representation of the given number. */
    method void setInt(int number) {}

    /** Returns the new line character. */
    function char newLine() {}

    /** Returns the backspace character. */
    function char backSpace() {}

    /** Returns the double quote (") character. */
    function char doubleQuote() {}
}
```

The client's view

Typical string usage (in some Jack class):

```
...
var String s;                // declares a String variable
var int x;
...
let s = String.new(6);       // constructs a string with a
                             // maximum capacity of 6 characters
...
let s = s.appendChar(97);    // s = "a"
let s = s.appendChar(98);    // s = "ab"
let s = s.appendChar(99);    // s = "abc"
let s = s.appendChar(100);   // s = "abcd"

...
let x = s.length();          // x = 4 (actual length)

...
do s.setInt(314);            // s = "314"

...
let x = 2 * s.intValue();    // x = 628
...
```

int to string

string to int

int ⟷ string algorithms

int to string:

```
// Returns the string representation of
// a non-negative integer
int2String (val) :
    lastDigit = val % 10
    c = character representing lastDigit
    if (val < 10)
        return  c  (as a string)
    else
        return  int2String (val / 10).append(c)
```

string to int:

```
// Returns the integer value of a string
// of digit characters, assuming that str[0]
// represents the most significant digit.
string2Int (str) :
    val = 0
    for ( i = 0 ... str.length ) do
        d = integer value of str[i]
        val = val * 10 + d
    return  val
```

These algorithms will help us implement the `String` class API.

`String` class implementation

```
/** Represents a string object. Implements the String type. */
class String {
    field Array str;
    field int length;

    /** Constructs a new empty String with a maximum length. */
    constructor String new(int maxLength) {
       let str = Array.new(maxLength);
       let length = 0;
       return this;
    }

    /** De-allocates the string and frees its memory space. */
    method void dispose() {}

    /** Returns the length of this string. */
    method int length() {}

    /** Returns the character value at the specified index */
    method char charAt(int j) {}

    /** Sets the j'th character of this string to the given character. */
    method void setCharAt(int j, char c) {}

    /** Appends the given character to the end of this string, and returns the string. */
    method String appendChar(char c) {}

    /** Erases the last character from this string. */
    method void eraseLastChar() {}

    /** Returns the integer value of this string until the first non-numeric character. */
    method int intValue() {}

    /** Sets this String to the representation of the given number. */
    method void setInt(int number) {}

    // Remaining functions: newLine(), backSpace(), doubleQuote()
}
```

Implementation notes:

- `length`, `charAt`, `setCharAt`, `appendChar`, `eraseLastChar`:

Implement using array manipulations

- `intValue`:

Implement the *string2int* algorithm

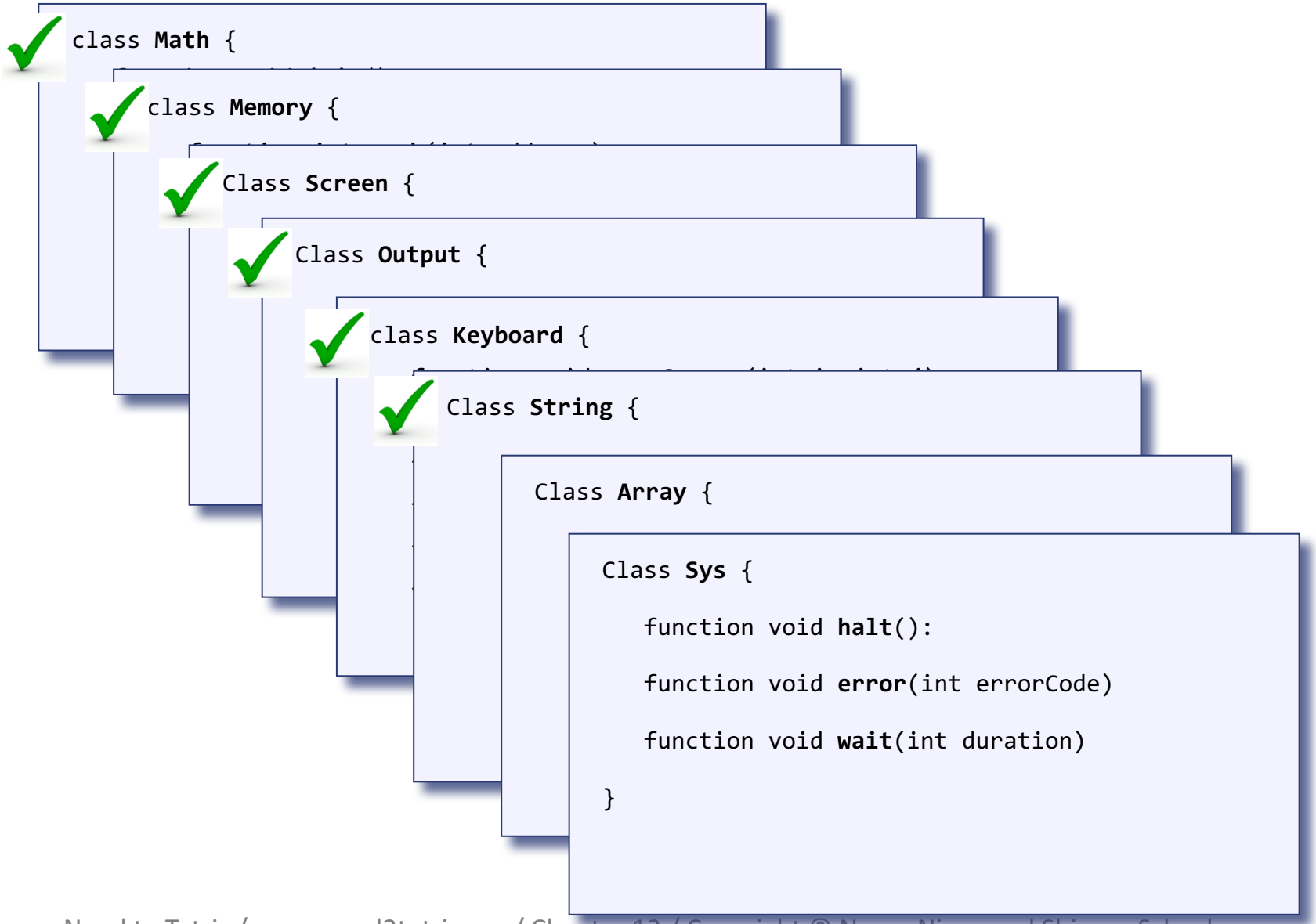
- `setInt`:

Implement the *int2String* algorithm

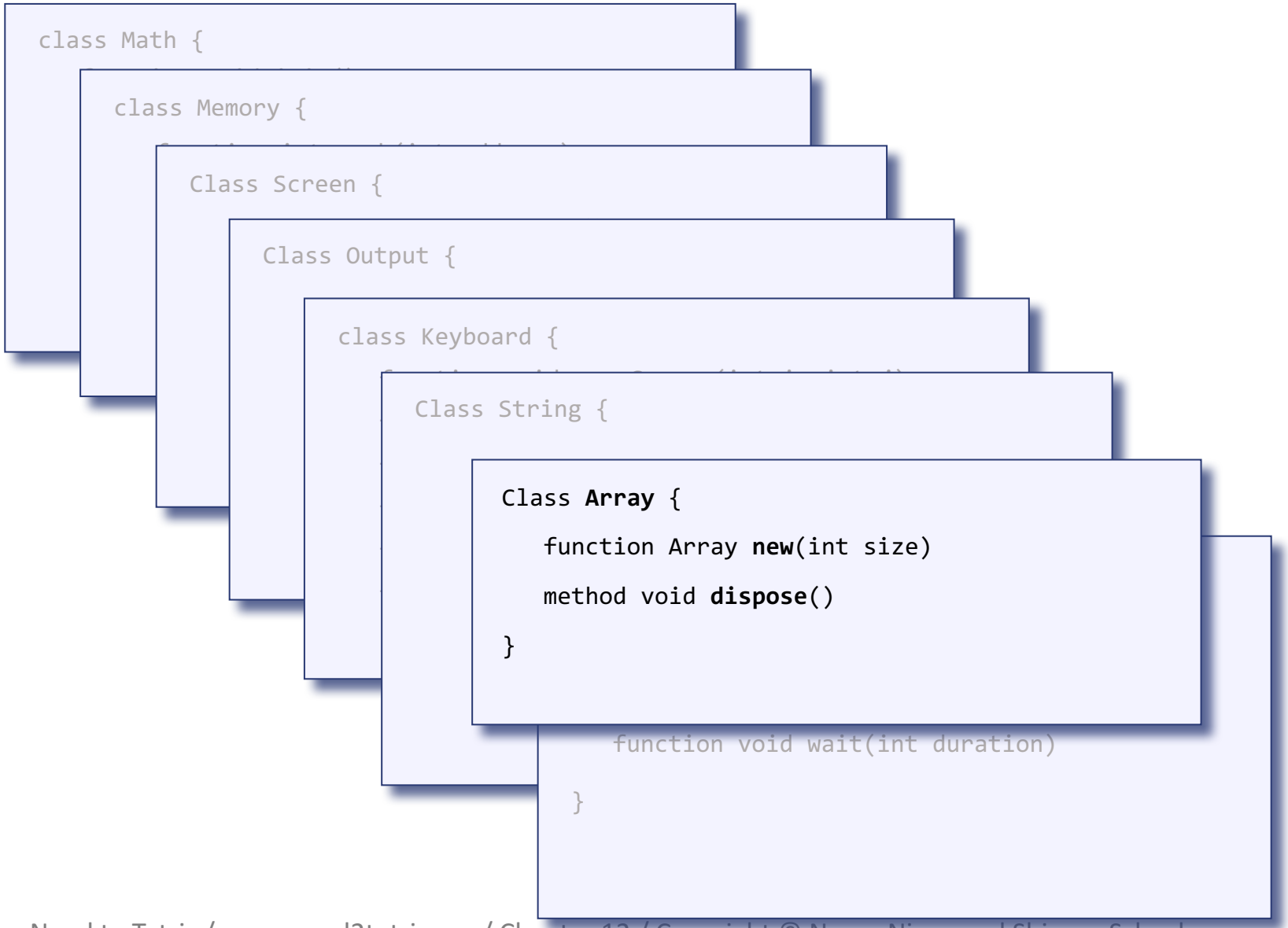
- `newLine`, `backSpace`, `doubleQuote`:

Implement by returning the `int` values `128`, `129`, `34`.

The Jack OS


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

The Jack OS: `Array`



The client's view

Typical array usage (in Jack):

```
...
var Array a, b;
...
let a = Array.new(3);
...
let a[2] = 222;
...
let b = Array.new(50);
...
let b[1] = a[2] - 100;
...
do a.dispose();
...
```

OS Array class

```
Class Array {

   function Array new(int size)

   method void dispose()

}
```

Implementation notes

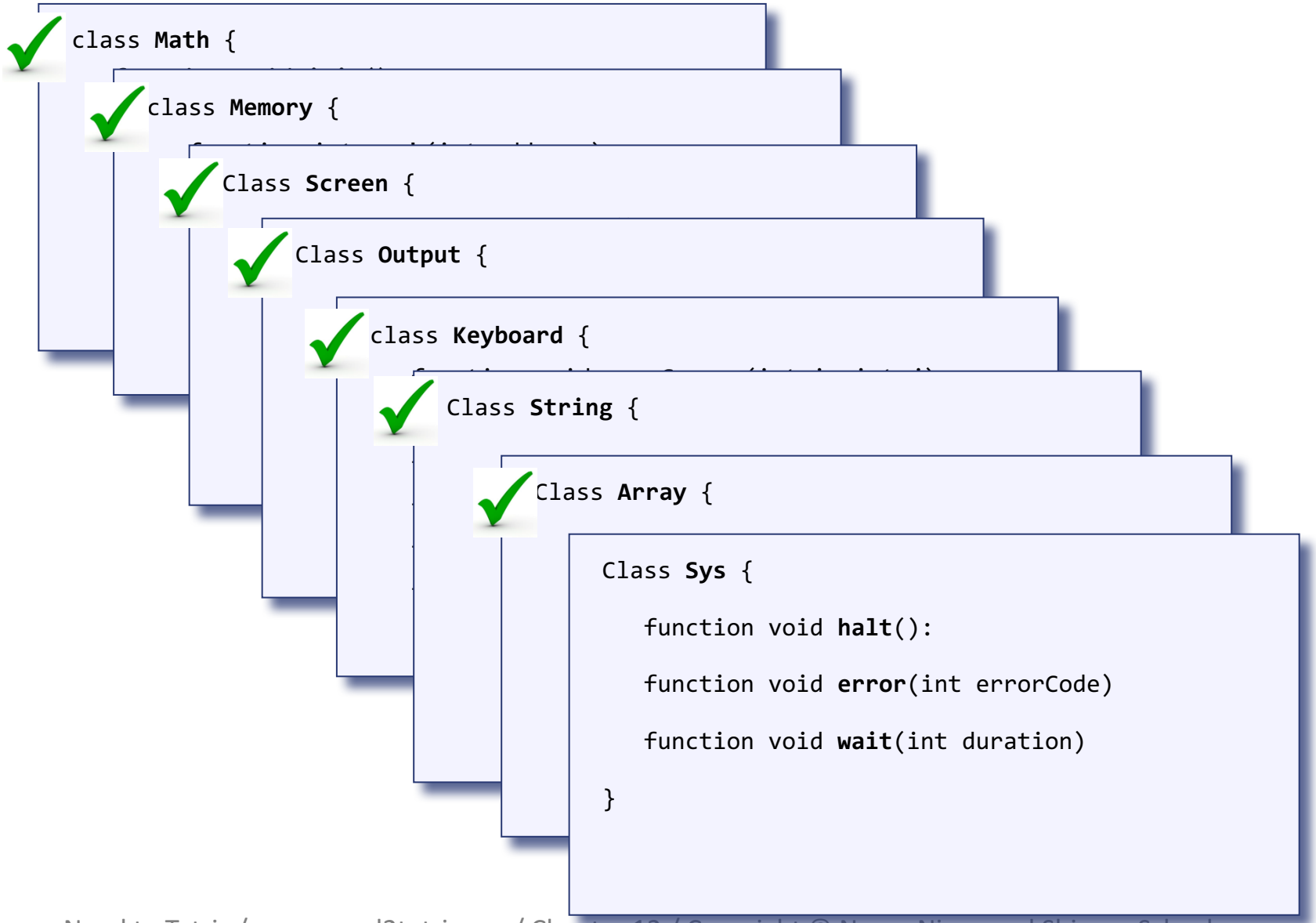
- `Arrray.new`: implemented as a *function*, not as a *constructor*
  (the implementatin of `Array.new` must call `Memory.alloc`)

- `Array.dispose`: uses `Memory.deAlloc`

OS `Array` class

```
Class Array {

   function Array new(int size)

   method void dispose()

}
```

The Jack OS


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

Bootstrapping

Bootstrapping (booting): the process of loading the basic software into the memory of a computer after power-on or general reset, especially the operating systems which will then take care of loading other software as needed (Wikipedia)

Hardware contract

When the computer is reset, execution starts with the instruction in `ROM[0]`

VM contract

The following code should be placed at the top of the `ROM`, beginning in `ROM[0]`:

```
sp = 256
call Sys.init
```

Jack contract

Program execution starts with the function `Main.main()`

OS contract

`Sys.init` should initialize the OS, and then call `Main.main()`

Implementation notes

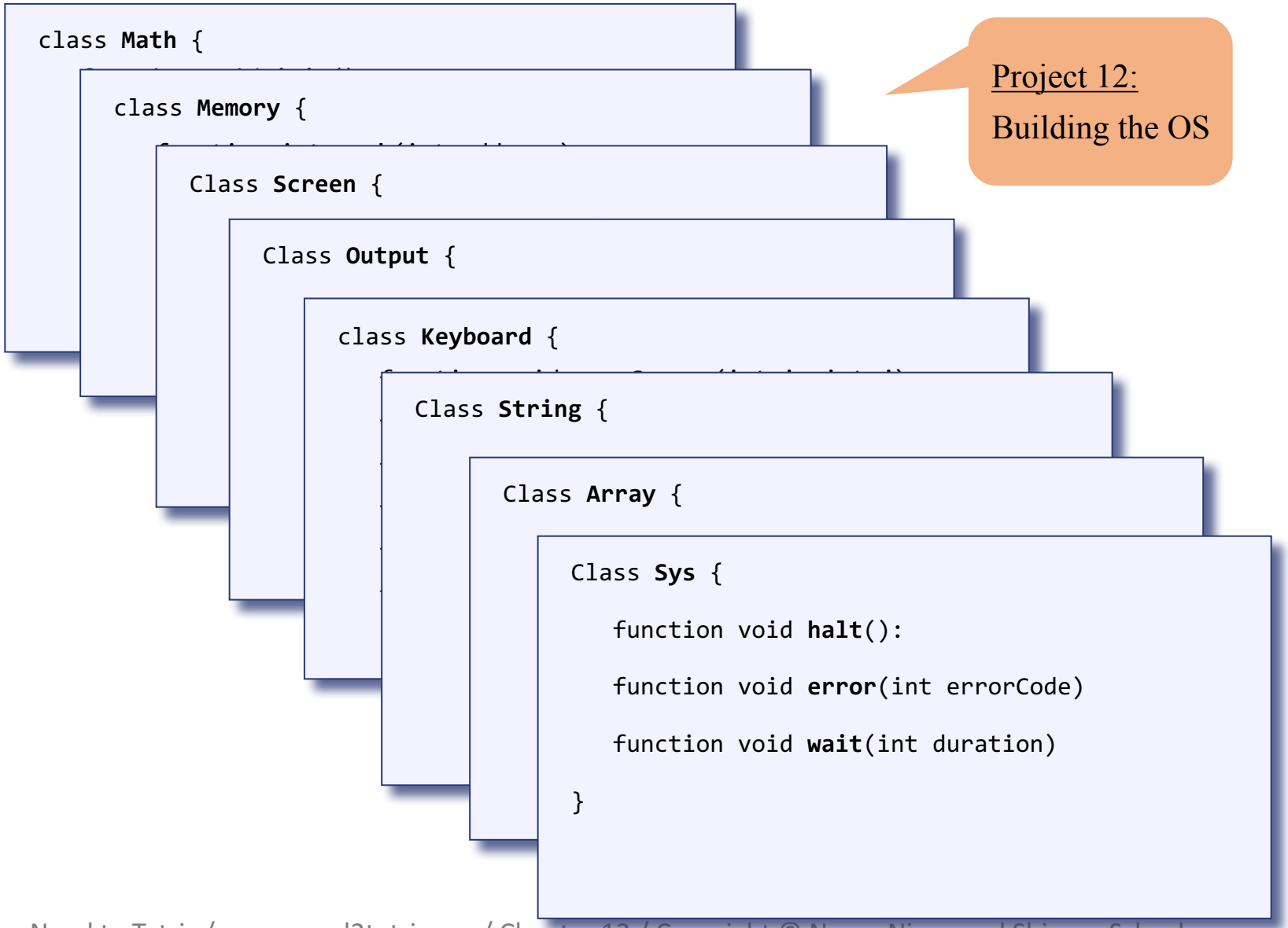
```
/**A library of basic system services. */
class Sys {

    /** Performs all the initializations required by the OS. */
    function void init() {
       do Math.init();
       do Memory.init();
       do Screen.init();
       ...
       do Main.main();
   }
```

Implementation notes

```
/**A library of basic system services. */
class Sys {

    /** Performs all the initializations required by the OS. */
    function void init() {}

    /** Halts execution. */
    function void halt() {}

    /** Waits approximately duration milliseconds, and returns. */
    function void wait(int duration) {}

    /** Prints the given error code in the form "ERR<errorCode>", and halts. */
    function void error(int errorCode) {}

}
```

- `Sys.halt`: can be implemented using an infinite loop
- `Sys.wait`: can be implemented using a loop, machine-specific
- `Sys.error`: simple.

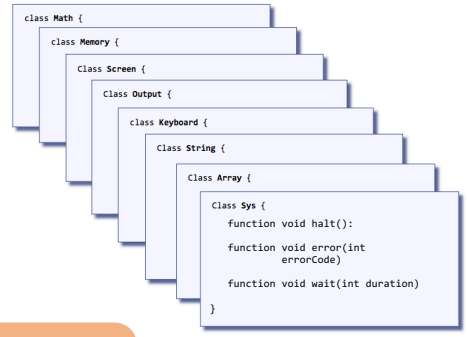
The Jack OS



Project 12:
Building the OS

OS abstraction

OS abstraction: specified by the Jack OS API



example:

```
/** A library of OS functions for displaying graphics on the screen. */
class Screen {

    /** Erases the entire screen. */
    function void clearScreen()

    /** Sets the current color,
     *  to be used for all subsequent drawXXX commands. */
    function void setColor(boolean b)

    /** Draws the (x,y) pixel, using the cur
    function void drawPixel(int x, int

    /** Draws a line from pixel (x1,y1) to p
     *  using the current color. */
    function void drawLine(int x1, int
    ...
}
```

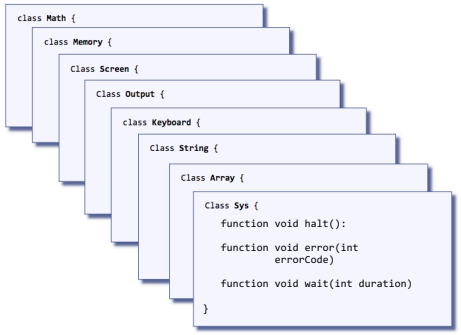
describes the class functionality

testing / using the Screen class:

```
/** Test program for the OS Screen class. */
class Main {

   /** Uses the Screen class primitives: */
   function void main() {
     do Screen.drawLine(0,220,511,220);
     do Screen.drawRectangle(280,90,410,220);
     do Screen.setColor(false);
     do
    Screen.drawRectangle(350,120,390,219);
     ...
}
```

OS implementation

OS abstraction: specified by the Jack OS API



OS implementations

- **VM emulator:** features a Java-based (built-in) OS implementation

- **nand2tetris/tools/os:** features an executable Jack-based OS implementation:

  `Math.vm`, `Memory.vm`, `Screen.vm`, `Output.vm`, `Keyboard.vm`,

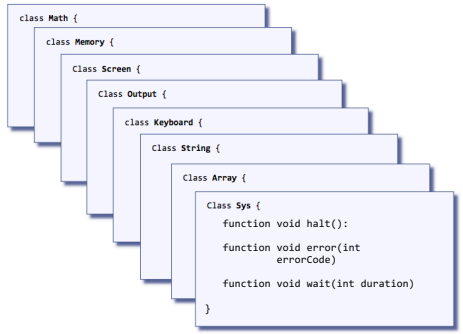
  `String.vm`, `Array.vm`, `Sys.vm`

- **Project 12:** write your own Jack-based OS implementation.

Reverse engineering

Suppose you wish to implement an existing OS.

The OS consists of *n* supplied executable modules, with high inter-dependency



Strategy: For each module in the OS, implement the module separately, using the remaining *n*-1 supplied executable modules to service it

Example:

Suppose you wish to develop the OS class `Screen`, and test it using some class `Main.jack`

<u>If using the supplied VM emulator:</u>

- put your `Screen.jack` implementation and `Main.jack` in some directory
- compile the directory
- load and execute the directory
- (every call to a `Screen.`*function* will be serviced by the respective `Screen.vm` function; every call to any other OS function will be serviced by the built-in implementations of the remaining 7 OS classes)

<u>If using the supplied CPU emulator:</u>

- put the files `Screen.jack` and `Main.jack` in some directory;
  add all the `OS.vm` files except for `Screen.vm`
- compile the directory
- use a VM translator to translate the directory into the file `dirName.asm`
- load and execute `dirName.asm`, using the supplied CPU emulator.

Example: the OS `Screen` class

"stub file", supplied by us

```
/** A library of OS functions for displaying graphics on the screen. */
class Screen {

    /** Initializes the Screen. */
    function void init() {}

    /** Erases the entire screen. */
    function void clearScreen() {}

    /** Sets the current color, to be used for all subsequent drawXXX commands.
     *  Black is represented by true, white by false. */
    function void setColor(boolean b) {}

    /** Draws the (x,y) pixel, using the curr
    function void drawPixel(int x, int y) {}

    /** Draws a line from pixel (x1,y1) to pixel (x2,y2), using the current color. */
    function void drawLine(int x1, int y1, int x2, int y2) {}

    /** Draws a filled rectangle whose top left corner is (x1, y1)
     * and bottom right corner is (x2,y2), using the current color. */
    function void drawRectangle(int x1, int y1, int x2, int y2) {}

    /** Draws a filled circle of radius r<=181 around (x,y), using the current color. */
    function void drawCircle(int x, int y, int r) {}
}
```

class sekeleton

- subroutine declarations (including non-API subroutines)

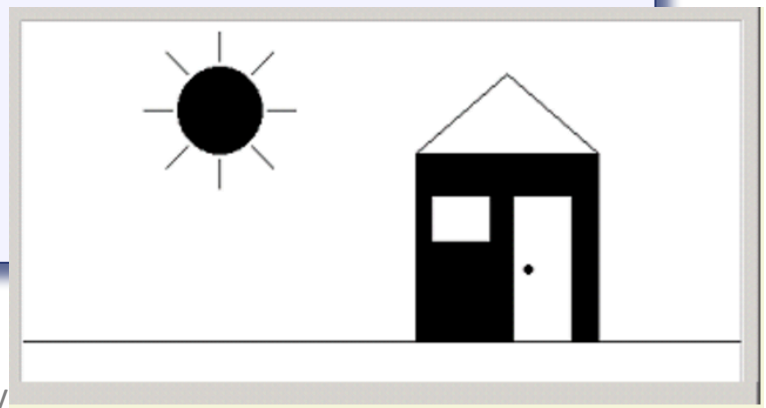
Implementation tips

- see relevant slides in this lecture
- read chapter 12

Example: the OS `Screen` class / testing

test code, supplied by us

```
/** Test program for the OS Screen class. */
class Main {

    /** Draws a sample pictue on the screen using lines and circles. */
    function void main() {
        do Screen.drawLine(0,220,511,220);        // base line
        do Screen.drawRectangle(280,90,410,220);  // house

        do Screen.setColor(false);
        do Screen.drawRectangle(350,120,390,219); // door
        do Screen.drawRectangle(292,120,332,150); // window

        do Screen.setColor(true);
        do Screen.drawCircle(360,170,3);          // door handle
        do Screen.drawLine(280,90,345,35);        // roof
        do Screen.drawLine(345,35,410,90);        // roof

        do Screen.drawCircle(140,60,30);          // sun
        do Screen.drawLine(140,26, 140, 6);
        ...

        return;
    }
}
```



Project 12

Step-wise development:

- `Screen`, `Output`, `String`, `Keyboard`, `Sys`: develop/test separately, using the supplied `Main.jack` programs
- `Memory`, `Array`, `Math`: develop/test separately, using the supplied `.jack`, `.tst` and `.cmp` files
- can be developed in any order

Final test:

1. make a copy of the directory `nand2tetris/projects/11/Pong`
2. copy the 8 compiled `.vm` files of your OS into this directory
3. execute this directory in the VM emulator.

Project 12

Perspective

Missing elements in our OS

- Multi-threading
- Multi-processing
- File system
- Shell / windowing
- Security
- Communications
- Many more missing services.

Perspective

Our OS...

- Closes significant gaps between the underlying hardware and application programs
- Hides many gory low-level details from the application programmer
- Performs its job in an elegant and efficient manner
- provides a feeling of what it takes to design and implement an OS, or an OS module.

Perspective

OS code is typically considered *privileged*:

- Accessing OS services requires a permission mechanism that is more elaborate than a simple function call
- OS functions execute in a special protected mode
- OS functions receive more hardware resources
- (in the Hack system, user-level code and OS code are treated the same way).

Perspective

Efficiency

- Mathematical operations
- Graphical operations.

Perspective

Efficiency / mathematical operations

- In most computers, core mathematical operations are implemented in hardware
- The hardware and software implementations of these operations are often based on the same algorithmic ideas
- The running time of the multiplication and division algorithms that we presented is $O(N)$ addition operations, N being the number of bits
- Since our addition implementation also requires $O(N)$ operations, the overall running time of our multiplication and division algorithms is $O(N^2)$
- There exist multiplication and division algorithms whose running time is asymptotically much faster than $O(N^2)$
- However, these algorithms are useful only when the number of bits that we have to process is very large.

Perspective

Efficiency / graphical operations

- The line drawing algorithms that we presented are quite efficient
- In most systems these graphics primitives are implemented by a combination of software and special graphics-acceleration hardware
- Today, most computers are equipped with a *Graphical Processing Unit*
- The GPU off-loads the CPU from handling high-performance graphics tasks, like drawing 3D images and rendering smooth surfaces
- In the Hack-Jack platform, there is no such separation of responsibilities between the CPU and other dedicated processors.