Lecture 11

Compiler II: Code Generation

Slide deck for Chapter 11 of the book

The Elements of Computing Systems (2nd edition)

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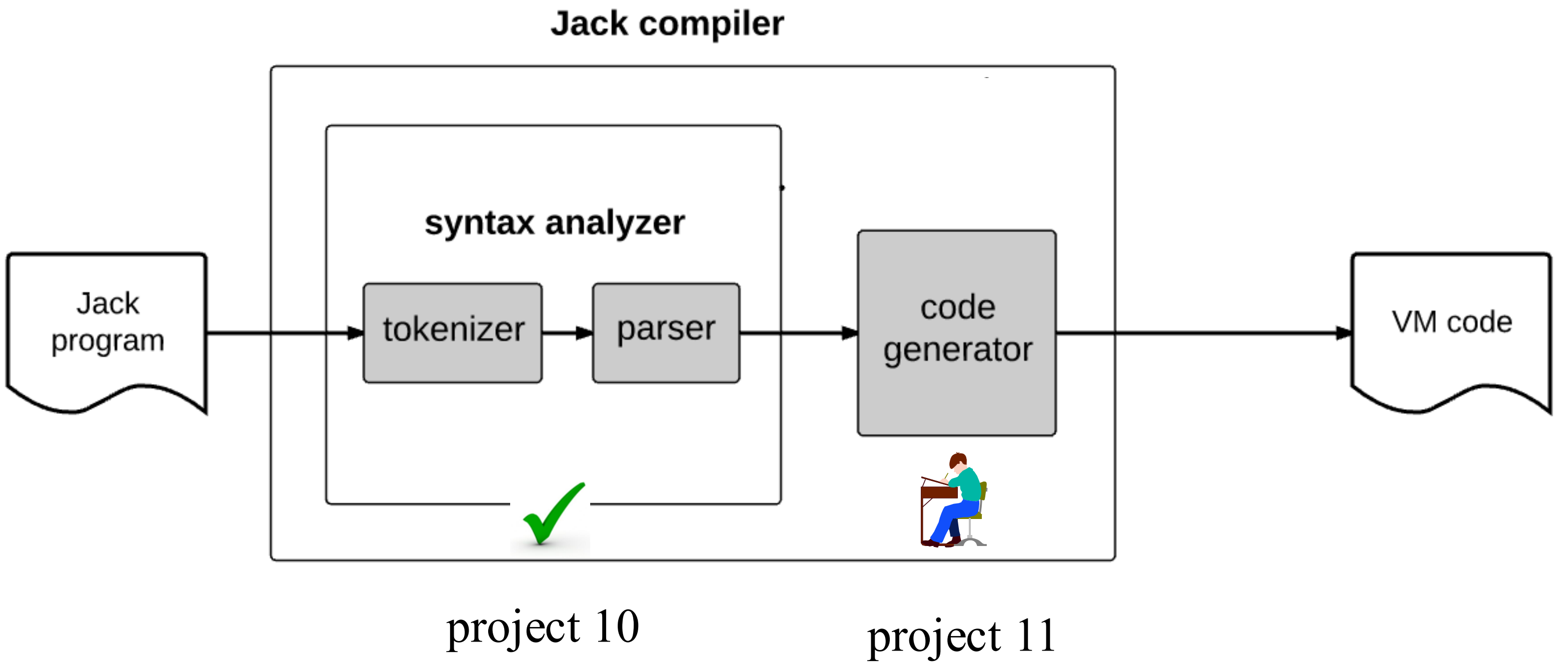
MIT Press

Compiler development roadmap



This lecture

Extending the syntax analyzer to a full-scale compiler.

Topics

Implementing a procedural programming language

- Variables
- Expressions
- Statements

Adding object-based programming features

- Objects
- Constructors
- Methods

Techniques

- Parsing (mostly done)
- Symbol tables
- Compilation engine
- Code generation.

Topics

Implementing a procedural programming language

- Variables
- Expressions
- Statements

Adding object-based programming features

- Objects
- Constructors
- Methods

Techniques

- Parsing (mostly done)
- Symbol tables
- Compilation engine
- Code generation.

Symbol table

Source code

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
    }
    ...
}
```

Symbol table

Source code

```
class Point {
   field int x, y;
   static int pointCount;

   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
    }
    ...
}
```

<u>Variable properties</u>

name (identifier)

type (`int`, `char`, `boolean`, class name)

kind (`field`, `static`, `local`, `argument`)

scope (class level, subroutine level)

Symbol table

Source code

```
class Point {
   field int x, y;
   static int pointCount;

   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
    }
    ...
}
```

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

method-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

`this` (`argument 0`) :
a system variable representing the object on which the method operates (discussed later in the lecture)

Variable properties

name (identifier)

type (`int`, `char`, `boolean`, class name)

kind (`field`, `static`, `local`, `argument`)

scope (class level, subroutine level)

During the compilation process:

The Jack compiler represents all the program's variables as entries in two symbol tables.

Symbol table: Construction

Source code

class declaration

method declaration

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
   }
   ...
}
```

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

method-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

`this` (`argument 0`) :
a system variable representing the object on which the method operates (discussed later in the lecture)

Compiling a class declaration

The compiler creates a class-level symbol table;

For each *field* and *static* variable found in the class declaration,
the compiler adds the variable to the symbol table as `this` *i* or as `static` *i*

Compiling a method declaration

The compiler creates a method-level symbol table, and adds to it the entry <`this` *className* `argument 0`>;

For each *parameter* and *local* variable found in the method declaration,
the compiler adds the variable to the symbol table as `argument` *i* or as `local` *i*

The compiler generates the *i* values from running counters, one for each of the four memory segments.

Symbol table: Usage

Source code

class declaration

method declaration

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
    }
    ...
}
```

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

method-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

`this` (`argument 0`) :
a system variable representing the object on which the method operates (discussed later in the lecture)

Compiling statements

For each variable found in a statement:

The compiler looks up the variable in the method-level symbol table;

If found, the variable is replaced with its *segment i* reference;

Else, the compiler looks up the variable in the class-level symbol table;

If found, the variable is replaced with its *segment i* reference;

Else, the compiler throws a compilation error.

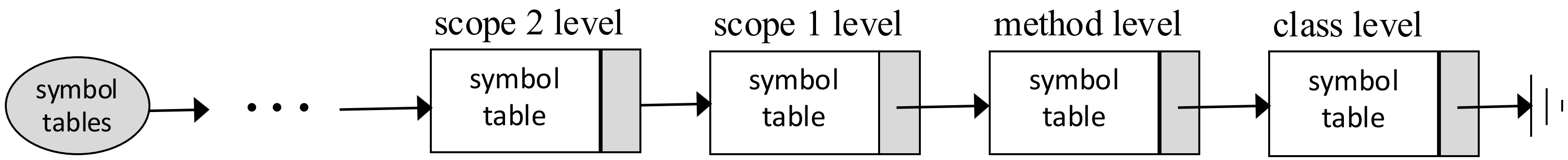
For example, `x + dx` is compiled into `push this 0`, `push local 0`, `add`.

Nested scoping

```
class foo {
    // class-level variable declarations
    method bar () {
        // method-level variable declarations
        ...
           {
              // scope-1-level variable declarations
              ...
                 {
                    // scope-2-level variable declarations
                    ...
```

Some high-level languages (but not Jack) feature nested variable scoping of unlimited depth

Nested scoping can be handled using a linked list of symbol tables:



Variable lookup: The variable is looked up in the first table in the list: if not found, the next table is looked up, and so on.

Variable life cycles

Source code

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
    }
    ...
}
```

Static variables: Persist throughout the program's execution

Field variables: Persist as long as the object is not disposed

Local variables: Each time a subroutine starts running during runtime, it gets a fresh set of local variables; Each time a subroutine returns, its local variables are recycled

Argument variables: Same as local variables

Managing these variable life cycles is a major headache;

But… this is taken care of by the VM implementation (projects 7 – 8);

The compiler need not worry about it!

Lecture plan

Compilation

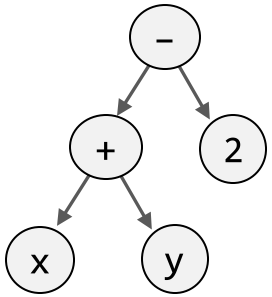
- ✓ Handling variables
- ➡ Handling expressions
- Handling statements
- Handling functions
- Handling objects
- Handling arrays

Compiling expressions

infix notation

```
x + y - 2
```

human
friendly



postfix notation

```
x y + 2 -
```

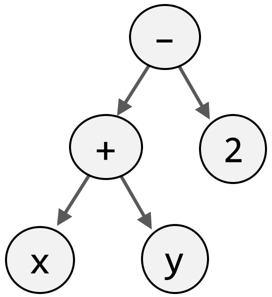
stack automata
friendly

Compiling expressions

source code

```
x + y - 2
```

parse



generate

VM code

```
// x + y - 2
push x
push y
add
push 2
sub
```

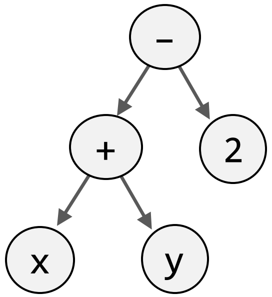
When executed during runtime, the generated code ends up leaving the value of the expression at the stack's top

Compiling expressions

source code

```
x + y - 2
```

parse



generate

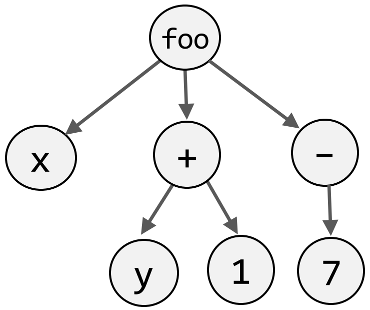
VM code

```
// x + y - 2
push x
push y
add
push 2
sub
```

another example

```
foo(x, y + 1, -7)
```

parse



generate

```
// foo(x, y + 1,-7)
push x
push y
push 1
add
push 7
neg
call foo 3
```

Needed:

An expression parsing algorithm (done in project 10)

A code generation algorithm (next)

Compiling expressions

Expression compilation algorithm:

```
compileExpression(exp):

  if exp is term:
     compileTerm(term)

  if exp is "term1 op1 term2  op2
             term3 op3 ...  termn ":
     compileTerm(term1)
     compileTerm(term2)
     output "op1"
     compileTerm(term3)
     output "op2"
     ...
     compileTerm(termn)
     output "opn–1"
```

```
compileTerm(term):

  if term is a constant c:
     output "push c"

  if term is a variable var:
     output "push var"

  if term is "unaryOp term":
     compileTerm(term)
     output "unaryOp"

  if term is "f (exp1, exp2, ...)":
     compileExpression(exp1)
     compileExpression(exp2)
     ...
     compileExpression(expn)
     output "call  f  n"

  if term is "(exp)":
     compileExpression(exp)
```

Generated code (examples)

```
// x + y – 2
push x
push y
add
push 2
sub
```

```
// foo(x, y + 1,-7)
push x
push y
push 1
add
push 7
neg
call foo 3
```

<u>From the Jack grammar</u>:

term: *constant* | *varName* | *unaryOp term* | *subroutineCall* | (*expression*)

subroutineCall: f ($expression_1$, $expression_2$, ... , $expression_n$)

expression: $term_1$ op_1 $term_2$ op_2 $term_3$ op_3 ... $term_n$

Compiling expressions

Expression compilation algorithm:

```
compileExpression(exp):

  if exp is term:
    compileTerm(term)

  if exp is "term1 op1 term2  op2
           term3 op3 ...  termn ":
    compileTerm(term1)
    compileTerm(term2)
    output "op1"
    compileTerm(term3)
    output "op2"
    ...
    compileTerm(termn)
    output "opn–1"
```

```
compileTerm(term):

  if term is a constant c:
    output "push c"

  if term is a variable var:
    output "push var"

  if term is "unaryOp term":
    compileTerm(term)
    output "unaryOp"

  if term is "f (exp1, exp2, ...)":
    compileExpression(exp1)
    compileExpression(exp2)
    ...
    compileExpression(expn)
    output "call  f  n"

  if term is "(exp)":
    compileExpression(exp)
```

Generated code (examples)

```
// x + y - 2
push x
push y
add
push 2
sub
```

```
// foo(x, y + 1,-7)
push x
push y
push 1
add
push 7
neg
call foo 3
```

Notes:

The algorithm must implement the complete grammar of Jack expressions;

The algorithm must generate VM code in which variables (like `x`, `y`, ...) are represented as their symbol table values (like `local` *i*, `argument` *i*, ...)

Lecture plan

<u>Compilation</u>

- ✓ Handling variables
- ✓ Handling expressions
- ➡ Handling statements
- Handling functions
- Handling objects
- Handling arrays

Lecture plan

<u>Compilation</u>

✓ Handling variables

✓ Handling expressions

➡ Handling statements

```
let
return
do
if
while
```

We'll describe how to compile each statement, and outline a compilation routine that handles it.

Lecture plan

Compilation

✓ Handling variables

✓ Handling expressions

- Handling statements

```
let
return
do
if
while
```

We'll describe how to compile each statement, and outline a compilation routine that handles it.

Compiling `let`

source code (Jack)

```
...
let varName = expression;
...
```

compiler

VM code (generated by `compileLet`)

```
...
VM code generated by compileExpression
pop varName
...
```

When the VM code generated by `compileExpression` will execute during runtime, it will end up leaving the expression's value at the stack's top.

The subsequent `pop` will then store this value in the segment entry.

Compiling `let`

source code (Jack)

```
...
let varName = expression;
...
```

compiler

VM code (generated by `compileLet`)

```
...
VM code generated by compileExpression
pop varName
...
```

example

```
let v = g + r2;
```

compiler

```
push g
push r2
add
pop v
```

1. first three commands are generated by `compileExpression`
2. Instead of symbolic variable names, the generated VM code uses segment entries.

<u>`compileLet`</u>:

`compileExpression`

output "`pop static` / `this` / `argument` / `local` *i* "

Lecture plan

<u>Compilation</u>

- Handling variables
- Handling expressions
- Handling statements

```
let
return
do
if
while
```

Compiling `return` *expression*

source code

```
...
return expression;
...
```

compiler

VM code (generated by `compileReturn`)

```
...
VM code generated by compileExpression
return
...
```

<u>`compileReturn`</u>:

`compileExpression`

output "`return`"

When the VM code generated by `compileExpression` will execute during runtime, it will end up leaving the expression's value at the stack's top;

The VM implementation of the subsequent `return` command will place the return value at the top of caller's working stack.

Compiling `return`

source code

```
...
return;
...
```

compiler

VM code (generated by `compileReturn`)

```
...
push constant 0
return
...
```

<u>`compileReturn`</u>:

output "`push constant 0`"

output "`return`"

When compiling a `return` Jack statement with no return value, the `compileReturn` routine generates code that pushes a dummy value onto the stack;

The dummy value will be tossed away by the compiled code of the caller (discussed next).

Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements

```
let
return
do
if
while
```

Compiling do

source code (Jack)

```
...
do subroutineName(exp1, exp2, ...)
...
```

Used to call a function or a method for its effect, ignoring the returned value

compiler

VM code (generated by `compileDo`)

```
...
VM code generated by compileExpression
pop temp 0
...
```

The `pop` gets rid of the return value.

Compiling do

source code (Jack)

```
...
do subroutineName(exp1, exp2, …)
...
```

Used to call a function or a method for its effect, ignoring the returned value

compiler

VM code (generated by `compileDo`)

```
...
VM code generated by compileExpression
pop temp 0
...
```

The pop gets rid of the return value.

example

```
do Output.printInt(7);
```

compiler

```
push constant 7
call Output.printInt 1
pop temp 0
```

first two commands are generated by `compileExpression`

Compiling do

source code (Jack)

```
...
do subroutineName(exp1, exp2, ...)
...
```

compiler

VM code (generated by `compileDo`)

```
...
VM code generated by compileExpression
pop temp 0
...
```

Used to call a function or a method for its effect, ignoring the returned value

The `pop` gets rid of the return value.

example

```
do Output.printInt(7);
```

compiler

```
push constant 7
call Output.printInt 1
pop temp 0
```

first two commands are generated by `compileExpression`

<u>`compileDo`</u>:

`compileExpression`

output "`pop temp 0`"

Explanation:

We compile `do` *subroutineName*(…) statements as if they where `do` *expression* statements;

The `compileExpression` routine knows how to handle method calls.

Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements

```
let
return
do
if
while
```

Compiling `if`

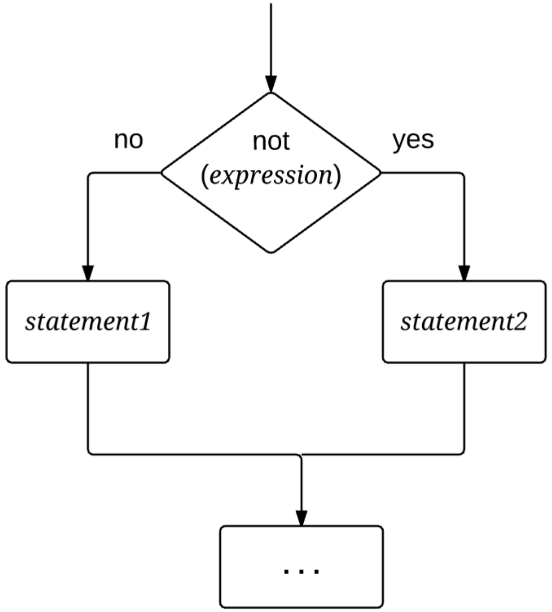
source code

```
if ( expression )
    { statements1 }
else
    { statements2 }
...
```

compiler

VM code (generated by `compileIf`)

```
  VM code generated by compileExpression
  not
  if-goto L1
  VM code generated by compileStatements
  goto L2
label L1
  VM code generated by compileStatements
label L2
  ...
```



`compileStatements`: a simple compilation routine that uses a loop to compile a sequence of zero or more `let`, `return`, `do`, `if`, `while` statements

Compiling `if`

source code

```
if ( expression )
    { statements1 }
else
    { statements2 }
...
```

compiler

VM code (generated by `compileIf`)

```
   VM code generated by compileExpression
   not
   if-goto L1
   VM code generated by compileStatements
   goto L2
label L1
   VM code generated by compileStatements
label L2
   ...
```

example

```
if (x < 0) {
   let y = 0;
} else {
   let y = 1;
}
...
```

compiler

```
   push x
   push 0
   lt
   not
if-goto L1
   push 0
   pop y
   goto L2
label l1
   push 1
   pop y
label L2
   ...
```

Compiling `if`

source code

```
if ( expression )
    { statements1 }
else
    { statements2 }
...
```

compiler

VM code (generated by `compileIf`)

```
   VM code generated by compileExpression
   not
   if-goto L1
   VM code generated by compileStatements
   goto L2
label L1
   VM code generated by compileStatements
label L2
   ...
```

<u>`compileIf`</u>:

- `compileExpression`
- output "`not`"
- generate a unique label `L1`, and output "`if-goto L1`"
- `compileStatements`
- generate a unique label `L2`, and output "`goto L2`"
- output "`label L1`"
- `compileStatements`
- output "`label L2`"

Compiling `while`

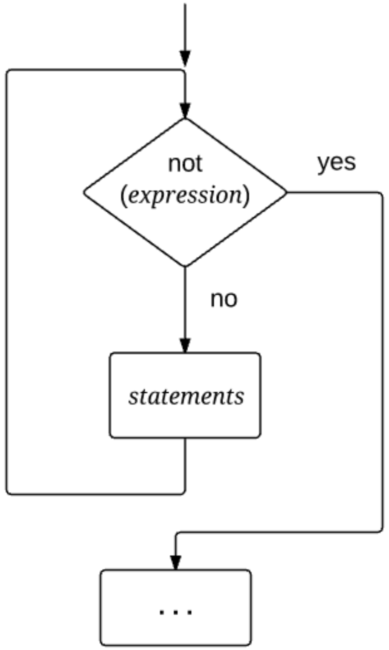
source code

```
while ( expression )
   { statements }
...
```

compiler

VM code (generated by `compileWhile`)

```
label L1
   VM code generated by compileExpression
   not
   if-goto L2
   VM code generated by compileStatements
   goto L1
label L2
   ...
```



Compiling `while`

source code

```
while ( expression )
    { statements }
...
```

compiler

VM code (generated by `compileWhile`)

```
label L1
   VM code generated by compileExpression
   not
   if-goto L2
   VM code generated by compileStatements
   goto L1
label L2
   ...
```

example

```
while (g = 0) {
    let x = x + 1;
}
...
```

compiler

```
label L1
   push g
   push 0
   eq
   not
   if-goto L2
   push x
   push 1
   add
   pop x
   goto L1
label L2
   ...
```

(pseudo code)

Compiling `while`

source code

```
while ( expression )
   { statements }
...
```

compiler

VM code (generated by `compileWhile`)

```
label L1
   VM code generated by compileExpression
   not
   if-goto L2
   VM code generated by compileStatements
   goto L1
label L2
   ...
```

<u>`compileWhile`</u>:

generate the unique label `L1`, and output "`label L1`"

`compileExpression`

output "`not`"

generate the unique label `L2`, and output "`if-goto L2`"

`compileStatements`

output "`goto L1`"

output "`label L2`"

Lecture plan

Compilation

- ✓ Handling variables
- ✓ Handling expressions
- ✓ Handling statements
- ➡ Handling functions
- Handling objects
- Handling arrays

Compiling function calls

source code

```
...
let y = Math.sqrt(x);
...
```

name	type	kind	#
x	int	local	0
y	int	local	1
...			

symbol table of the calling subroutine

Compiling function calls

source code

```
...
let y = Math.sqrt(x);
...
```

compiler

VM code

```
...
push local 0
call Math.sqrt 1
pop local 1
...
```

name	type	kind	#
x	int	local	0
y	int	local	1
...			

symbol table of the calling subroutine

Nothing special about it

Compiling *function calls* is part of *compiling expressions* (already discussed)

Observation

There's nothing special about compiling *function calls*;

They are handled as part of compiling *expressions*.

Compiling functions

source code

```
...
let y = Math.sqrt(x);
...
```

source code

```
class Math {
  ...
  /** Square root */
  function int sqrt(int x) {
     var int g, prevg, epsilon;
     let epsilon = 1;
     let g = x / 2;    // initial guess
     while (true) {
        let prevg = g;
        let g = (g + x / g) / 2;
        if (abs(prevg - g) < epsilon) {
           return g;
        }
     }
  }
  ...
}
```

Compiling functions

source code

```
...
let y = Math.sqrt(x);
...
```

source code

```
class Math {
  ...
  /** Square root */
  function int sqrt(int x) {
     var int g, prevg, epsilon;
     let epsilon = 1;
     let g = x / 2;    // initial guess
     while (true) {
        let prevg = g;
        let g = (g + x / g) / 2;
        if (abs(prevg - g) < epsilon) {
           return g;
        }
     }
  }
  ...
}
```

compiler

VM code

```
// class Math {
//// compileClass builds the class-level symbol table (omitted)
// function int sqrt(int x)
// var int g, prev, epsilon;
//// compileSubroutine calls compileParametersList and
//// compileVarDec, that build the subroutine's symbol table;
//// compileSoubroutine then generates VM code that declares
//// a VM function that has 3 local variables.
function Math.sqrt 3
    //// compileSoubroutine calls CompileStatements,
    //// that handles the method's body
    // let epsilon = 1;
   push constant 1
   pop local 2
   // let g = x / 2;
   push argument 0
   push constant 2
   call Math.divide 2
   ...
   push local 0
   return
```

name	type	kind	#
x	int	argument	0
g	int	local	0
prevg	int	local	1
epsilon	int	local	2

subroutine-level symbol table

Lecture plan

Compilation

- ✓ Handling variables
- ✓ Handling expressions
- ✓ Handling statements
- ✓ Handling functions
- Handling objects
- Handling arrays

We have what it takes to write a compiler for a procedural programming language!

Lecture plan Lecture plan

Compilation

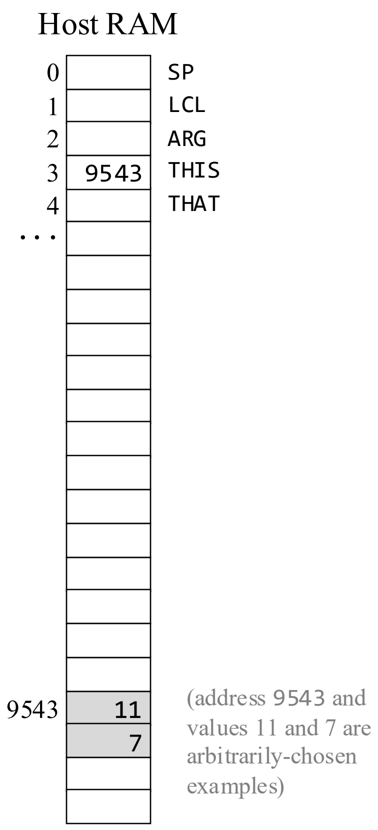
- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- Handling objects
  - Structures
  - Constructors
  - Methods
- Handling arrays

"Structures"

In the C language, a *structure* is a composite data type, consisting of several *fields*;

In the example shown here, `THIS` points at a two-field structure;

How can we create and manipulate structures using the VM language?



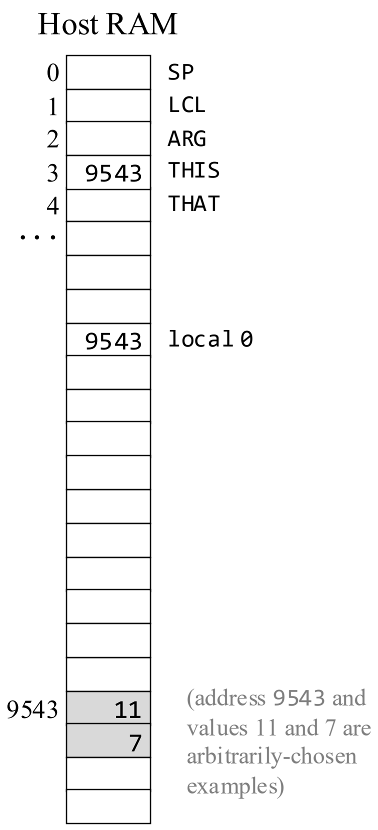
"Structures"

Creating a structure:

```
// Creates a 2-word structure, initializes it, and makes local 0 refer to it
push constant 2
call Memory.alloc 1
pop pointer 0     // pop THIS

push constant 11
pop this 0
push constant 7
pop this 1

push pointer 0    // push THIS
pop local 0
```



<u>Explanation</u>

`Memory.alloc`(*n*): This OS function finds a memory block of size *n* words, and returns (pushes onto the stack) its base address;

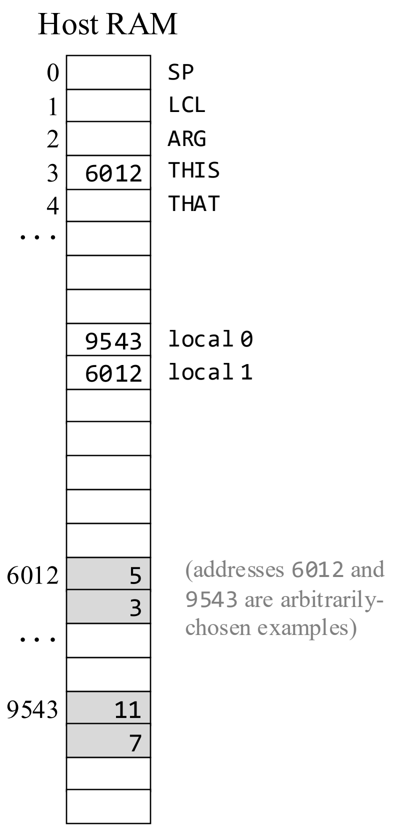
`pop pointer 0`: Pops the base address of the new structure into `THIS`;
Result: Subsequent `this` *i* references will effect RAM addresses `THIS` + *i*

Last two commands: Make `local 0` point to the new structure.

“Structures”

Manipulating a structure:

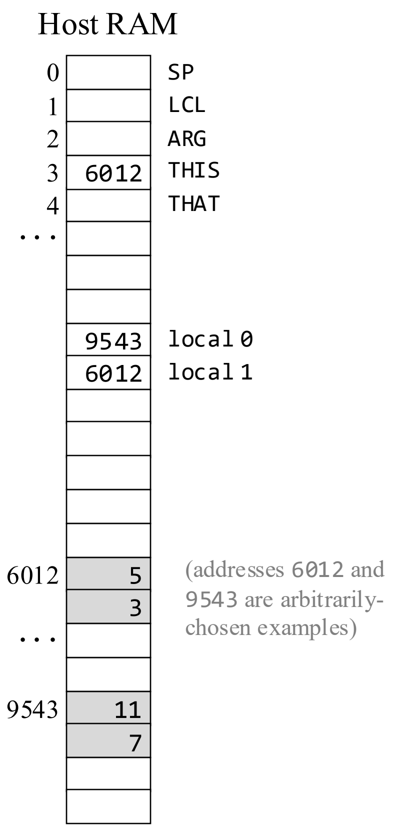
```
// Creates two structures and makes local 0 and local 1 point to them
// (code omitted)
...
```



"Structures"

Manipulating a structure:

```
// Creates two structures and makes local 0 and local 1 point to them
// (code omitted)
...
// Example of manipulating a structure:
// Sets the fields of the the structure that local 1 refers to
push local 1
pop pointer 0     // THIS = base address of the target structure
push constant 5
pop this 0
push constant 3
pop this 1
```



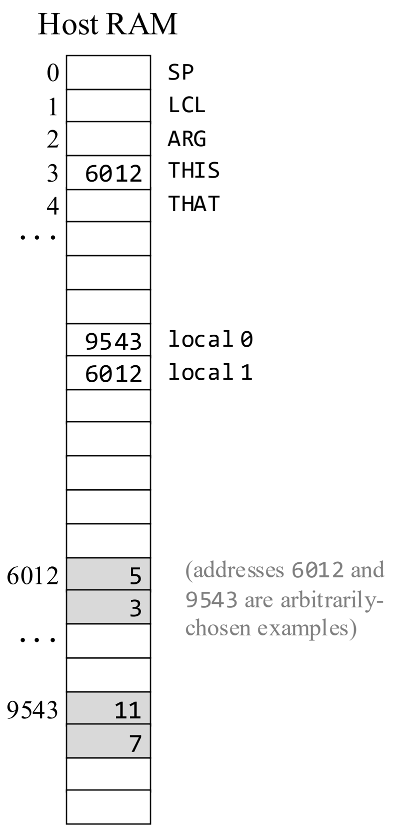
Note

Using this technique, we can get / set the fields of any given structure.

"Structures"

Manipulating a structure:

```
// Creates two structures and makes local 0 and local 1 point to them
// (code omitted)
...
// Example of manipulating a structure:
// Sets the fields of the the structure that local 1 refers to
push local 1
pop pointer 0     // THIS = base address of the target structure
push constant 5
pop this 0
push constant 3
pop this 1
```



From structures to objects

"Objects" are well-dressed structures;

The big step from C to C++ is that C++ compilers allow creating and manipulating objects using object-oriented syntax;

The Jack language and compiler feature such OOP capabilities (next).

Lecture plan Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- Handling objects
    - Structures
    - Constructors
    - Methods
- Handling arrays

Lecture plan Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- Handling objects
  - Structures
  - Constructors
  - Methods
- Handling arrays

Compiling constructor calls

Source code

```
class Foo {
   ...
   function void bar () {
      var Point p1;
      ...
      // Creates a new Point object
      let p1 = Point.new(2,3);
      ...
```

(such constructor calls can appear in any subroutine, in any class)

Caller: Creates an object by calling a constructor

Compiling constructor calls

Source code

```
class Foo {
   ...
   function void bar () {
      var Point p1;
      ...
      // Creates a new Point object
      let p1 = Point.new(2,3);
      ...
```

(such constructor calls can appear in any subroutine, in any class)

compiler

VM code

```
...
// let p1 = Point.new(2,3);
push constant 2
push constant 3
call Point.new 2
pop local 0
...
```

Observations

- There's nothing special about compiling *constructor calls*; We handle them as if they were regular subroutine calls.
- The heavy lifting is done by the compiled constructors.

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

Caller: Creates an object by calling a constructor

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
    ...
    /** Constructs a new point. */
    constructor Point new(int ax, int ay) {
       let x = ax;
       let y = ay;
       let pointCount = pointCount + 1;
       return this;   //// required in Jack constructors
    }
    ...
```

Callee: Does the object construction

What makes the magic work?

The compiled constructor's code.

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
    ...

    /** Constructs a new point. */
    constructor Point new(int ax, int ay) {
       let x = ax;
       let y = ay;
       let pointCount = pointCount + 1;
       return this;  //// required in Jack constructors
    }
    ...
```

compiler

VM code (created by compileClass)

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
   ...

   /** Constructs a new point. */
   constructor Point new(int ax, int ay) {
      let x = ax;
      let y = ay;
      let pointCount = pointCount + 1;
      return this;  //// required in Jack constructors
   }
   ...
```

compiler

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

VM code (created by compileClass)

```
// class Point {
//    field int x, y;
//    static int pointCount;
//// compileClass builds the class-level symbol table
```

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
    ...
    /** Constructs a new point. */
    constructor Point new(int ax, int ay) {
         let x = ax;
         let y = ay;
         let pointCount = pointCount + 1;
         return this;  //// required in Jack constructors
    }
    ...
```

compiler

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

constructor-level symbol table

name	type	kind	#
ax	int	argument	0
ay	int	argument	1

VM code (created by compileClass)

```
// class Point {
//    field int x, y;
//    static int pointCount;
//// compileClass builds the class-level symbol table
// constructor Point new(int ax, int ay);
//// compileSubroutine builds the subroutine's symbol table, and notes that
//// it is handling a constructor. It generates VM code that declares a VM function,
//// allocates memory for the new object, and sets THIS to its base address:
function Point.new 0
   push constant 2
   call Memory.alloc 1
   pop pointer 0
```

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
    ...

   /** Constructs a new point. */
   constructor Point new(int ax, int ay) {
      let x = ax;
      let y = ay;
      let pointCount = pointCount + 1;
      return this;  //// required in Jack constructors
   }
   ...
```

compiler

VM code (created by compileClass)

```
// class Point {
//    field int x, y;
//    static int pointCount;
//// compileClass builds the class-level symbol table
// constructor Point new(int ax, int ay);
//// compileSubroutine builds the subroutine's symbol table, and notes that
//// it is handling a constructor. It generates VM code that declares a VM function,
//// allocates memory for the new object, and sets THIS to its base address:
function Point.new 0
   push constant 2
   call Memory.alloc 1
   pop pointer 0
   //// CompileStatements handles the constructor's body
   // let x = ax;
   push argument 0
   pop this 0

   ...

   // return this;
   push pointer 0
   return
```

class-level symbol table

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

constructor-level symbol table

name	type	kind	#
ax	int	argument	0
ay	int	argument	1

Compiling constructors

Source code

```
...
// Creates a new Point object
let p1 = Point.new(2,3);
```

```
/** Represents a Point. */
class Point {
   field int x, y;
   static int pointCount;
   ...
   /** Constructs a new point. */
   constructor Point new(int ax, int ay) {
      let x = ax;
      let y = ay;
      let pointCount = pointCount + 1;
      return this;  //// required in Jack constructors
   }
   ...
```

compiler

VM code (created by compileClass)

```
// class Point {
//    field int x, y;
//    static int pointCount;
//// compileClass builds the class-level symbol table
// constructor Point new(int ax, int ay);
//// compileSubroutine builds the subroutine's symbol table, and notes that
//// it is handling a constructor. It generates VM code that declares a VM function,
//// allocates memory for the new object, and sets THIS to its base address:
function Point.new 0
   push constant 2
   call Memory.alloc 1
   pop pointer 0
   //// CompileStatements handles the constructor's body
  // let x = ax;
   push argument 0
   pop this 0

   ...

   // return this;
   push pointer 0
   return
```

C++, Java, Python, ...

In Jack, every constructor must end with the explicit statement `return this;`

All OOP compilers do the same thing, implicitly:

Before terminating the compiled constructor code, they inject low-level code that returns the address of the newly constructed object; That's how `p1` (in this example) ends up pointing at the new object.

Lecture plan Lecture plan

<u>Compilation</u>

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- Handling objects
  - Structures
  - Constructors
  - Methods
- Handling arrays

Lecture plan Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
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    - Structures
    - Constructors
    - Methods
- Handling arrays

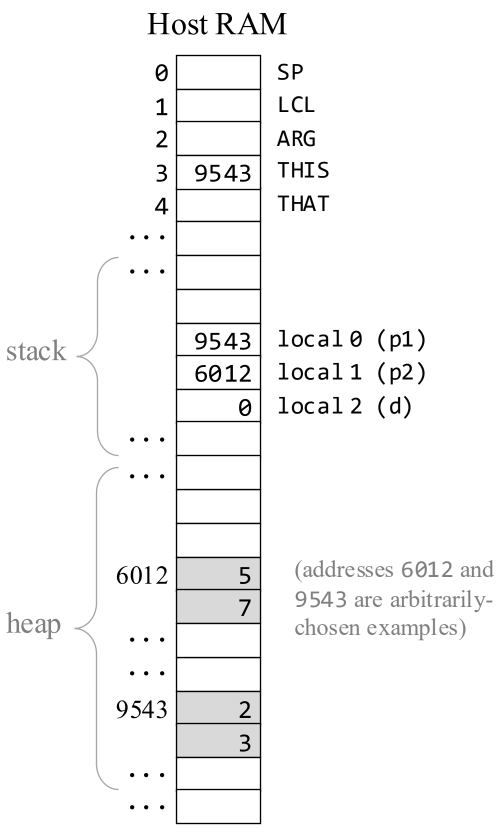
Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

We assume that the caller declared the local variables p1, p2, d, and constructed the objects p1 and p2 (code not shown)

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x – other.getx();
    let dy = y – other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```



Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

Caller: “Applies a method to an object”

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x - other.getx();
    let dy = y - other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

Callee: “Operates on the target object”

What makes the magic work?

The compiled method’s code.

Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

compiler

VM code

```
...
push local 0
push local 1
call Point.distance 2
pop local 2
...
```

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x - other.getx();
    let dy = y - other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

caller's symbol table

When compiling a *method call*:

The compiler generates code that passes the target object as the *first argument* for the called method

This is the key compilation trick that facilitates the OO "object first" method calling idiom:

objName.*methodName*(*args*)

Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

compiler

VM code

```
...
push local 0
push local 1
call Point.distance 2
pop local 2
...
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

caller's symbol table

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x - other.getx();
    let dy = y - other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

compiler

Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

compiler

VM code

```
...
push local 0
push local 1
call Point.distance 2
pop local 2
...
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

caller's symbol table

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x - other.getx();
    let dy = y - other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

compiler

```
// class Point {
//   field int x, y;
//   static int pointCount;
//// compileClass builds the class-level symbol table
```

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

class-level symbol table

Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

compiler

VM code

```
...
push local 0
push local 1
call Point.distance 2
pop local 2
...
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

caller's symbol table

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x – other.getx();
    let dy = y – other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

compiler

```
// class Point {
//   field int x, y;
//   static int pointCount;
//// compileClass builds the class-level symbol table
// method int distance(Point other)
// var int dx, dy;
//// compileSubroutine builds the subroutine's symbol table, and notes
//// that it is handling a method. It generates VM code that declares a VM
//// function and sets THIS to the object on which the method was called.
function Point.distance 2
   push argument 0
   pop pointer 0
```

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

class-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

method-level symbol table

When compiling a *method*: The compiler always adds the following entry to the method's symbol table:

`<this,` *className*`, argument, 0>`

Compiling methods

source code

```
...
let d = p1.distance(p2)
...
```

compiler

VM code

```
...
push local 0
push local 1
call Point.distance 2
pop local 2
...
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

caller's symbol table

```
/** Represents a Point. */
class Point {
  field int x, y;
  static int pointCount;
  ...
  /** Distance from this to the other point */
  method int distance(Point other) {
    var int dx, dy;
    let dx = x - other.getx();
    let dy = y - other.gety();
    return Math.sqrt((dx*dx) +
                     (dy*dy));
  }
  ...
}
```

compiler

```
// class Point {
//   field int x, y;
//   static int pointCount;
//// compileClass builds the class-level symbol table
// method int distance(Point other)
// var int dx, dy;
//// compileSubroutine builds the subroutine's symbol table, and notes
//// that it is handling a method. It generates VM code that declares a VM
//// function and sets THIS to the object on which the method was called.
function Point.distance 2
   push argument 0
   pop pointer 0
   //// CompileStatements handles the method's body
   // let dx = x - other.getx();
   push this 0
   push argument 1
   call Point.getx 1
   sub
   pop local 0
   ...
   add
   call Math.sqrt 1
   return
```

name	type	kind	#
x	int	this	0
y	int	this	1
pointCount	int	static	0

class-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

method-level symbol table

Lecture plan Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- ✓ Handling objects
- Handling arrays
    - Creating arrays
    - Manipulating arrays

Lecture plan Lecture plan

<u>Compilation</u>

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- ✓ Handling objects
- Handling arrays
  - ➡ Creating arrays
  - Manipulating arrays

Compiling array construction

Source code

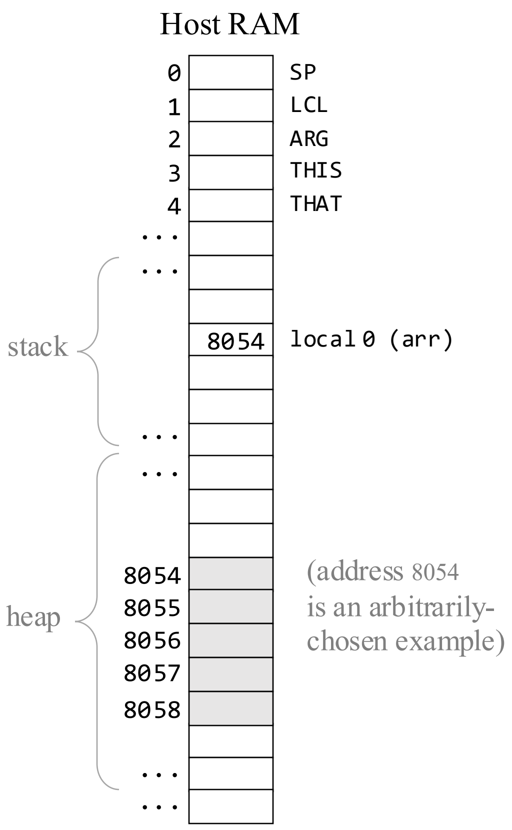
```
// Can appear in any class/subroutine:
method foo() {
   // Declares an array variable:
   var Array arr;
   ...
   // Constructs the array:
   let arr = Array.new(5);
   ...
```

Jack conventions:

Arrays are instances of the OS class `Array`

To construct an array, we call `Array.new`

(The `Array` class will be implemented later in the course, when we'll build the OS).



Compiling array construction

Source code

```
// Can appear in any class/subroutine:
method foo() {
  // Declares an array variable:
  var Array arr;
  ...
  // Constructs the array:
  let arr = Array.new(5);
  ...
```

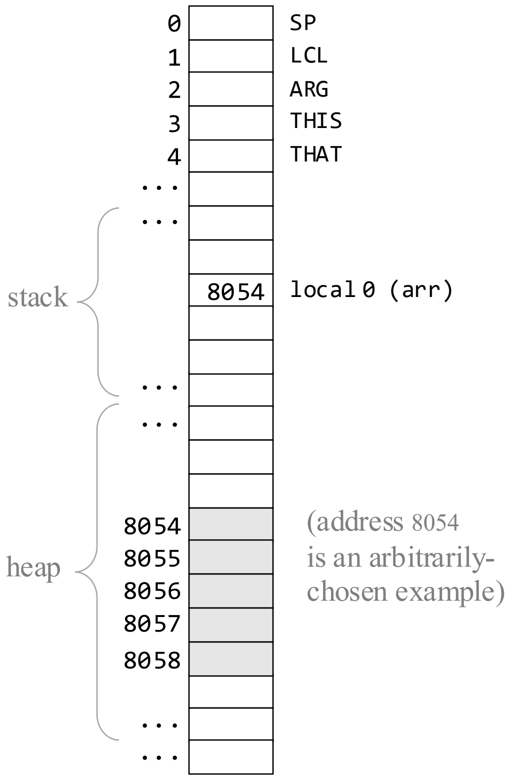
compile

VM code

```
// var Array arr;
//// compileSubroutine builds
//// the subrout.'s symbol table,
//// and adds to it variable arr.
```

name	type	kind	#
arr	Array	local	0

Host RAM



Compiling array construction

Source code

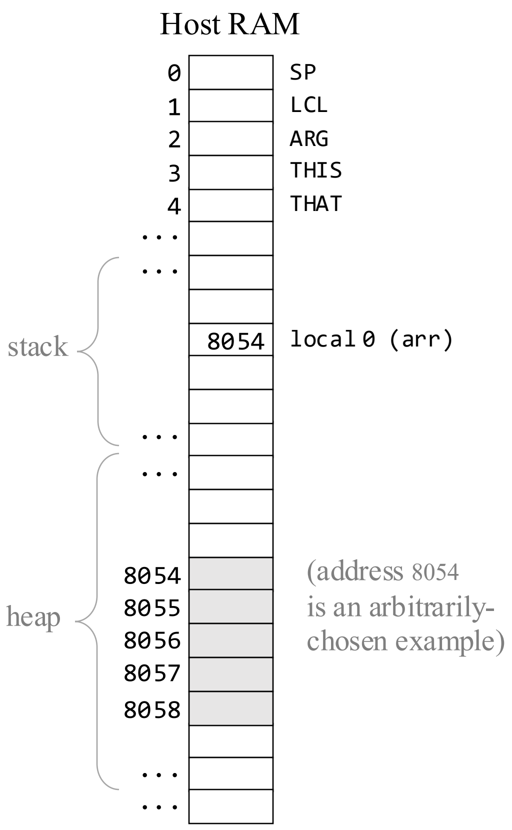
```
// Can appear in any class/subroutine:
method foo() {
   // Declares an array variable:
   var Array arr;
   ...
   // Constructs the array:
   let arr = Array.new(5);
   ...
```

compile

VM code

```
// var Array arr;
//// compileSubroutine builds
//// the subrout.'s symbol table,
//// and adds to it variable arr.
...
// let arr = Array.new(5);
push constant 5
call Array.new 1
pop local 0
...
```

name	type	kind	#
arr	Array	local	0



Compiling array construction:

We simply compile the `let` statement

(same as with calling an object constructor)

Lecture plan Lecture plan

Compilation

- Handling variables
- Handling expressions
- Handling statements
- Handling functions
- ✓ Handling objects
- Handling arrays
  - Creating arrays
  - Manipulating arrays

Accessing array elements

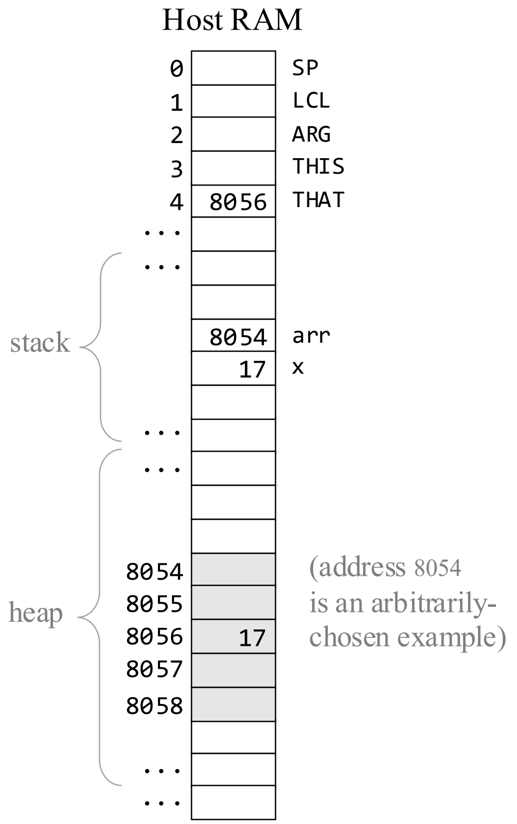
Examples

```
// let arr[2] = x
push arr
push 2
add
pop pointer 1
push x
pop that 0
```

Sets THAT to the address of the target array element

```
// let x = arr[2]
push arr
push 2
add
pop pointer 1
push that 0
pop x
```

same



Compiling array access

source code

```
let arr[i] = exp
```

compiler

VM code (generated by `compileLet`)

```
push arr
push i
add
pop pointer 1    // THAT = arr + 2
push exp
pop that 0
```

Generalizing:

<u>`compileLet`</u>: (`let` *varName*`[`*expression*`] =` *expression*`;`)

output "`push` *varName*"

call `compileExpression`

output "`add`"

output "`pop pointer 1`"

call `compileExpression`

output "`pop that 0`"

Compiling array access

source code (example)

```
let a[i] = b[j]
```

compiler

VM code (generated by `compileLet`)

```
push a
push i
add
pop pointer 1
// Now handle the right hand side
push b
push j
add
pop pointer 1
...
```

Generalizing:

`compileLet`: (`let` *varName*`[`*expression*`] =` *expression*`;`)

- output "`push` *varName*"
- call `compileExpression`
- output "`add`"
- output "`pop pointer 1`"
- call `compileExpression`
- output "`pop that 0`"

Compiling array access

source code (example)

```
let a[i] = b[j]
```

compiler

VM code (generated by `compileLet`)

```
push a
push i
add
pop pointer 1
// Now handle the right hand side
push b
push j
add
pop pointer 1
...
```

unfortunately, there's a problem

Generalizing:

`compileLet`: (`let` *varName*`[`*expression*`] =` *expression*`;`)

- output "`push` *varName*"
- `call compileExpression`
- output "`add`"
- output "`pop pointer 1`"
- `call compileExpression`
- output "`pop that 0`"

Compiling array access

source code (example)

```
let a[i] = b[j]
```

compiler

VM code (generated by `compileLet`)

```
push a
push i
add
push b
push j
add
pop pointer 1   // THAT = address of b[j]
push that 0     // stack top = b[j]
pop temp 0      // temp 0 = b[j]
pop pointer 1   // THAT = address of a[i]
push temp 0     // stack top = b[j]
pop that 0      // a[i] = b[j]
```

<u>`compileLet`</u>: (`let` *varName*`[`*expression*`] =` *expression*`;`)

// (both expressions can contain array elements, of any depth)

output "`push` *varName*"

call `compileExpression`

output "`add`"

call `compileExpression`

output "`pop pointer 1`"

...

output "`pop that 0`"

6 last pop/push commands at the VM code shown above

What about compiling, say,

`let a[a[i]] = a[b[a[b[j]]]]` ?

No problem...

Lecture plan

<u>Compilation</u>

- ✓ Handling variables
- ✓ Handling expressions
- ✓ Handling statements
- ✓ Handling functions
- ✓ Handling objects
- ✓ Handling arrays

<u>Implementation</u>

- ➡ Standard mapping
- Proposed design
- Project 11

Standard mapping

So far we described:

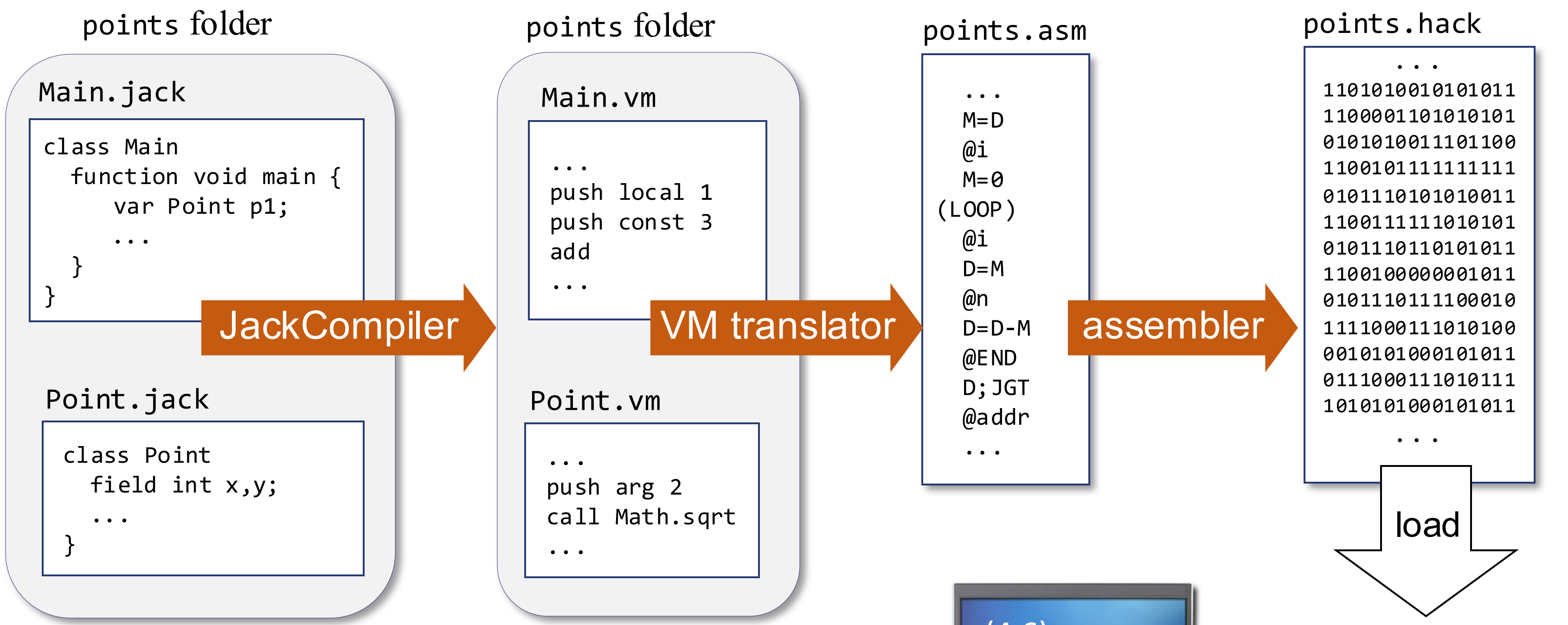
- General compilation techniques
- Compiling Jack code

We now turn to describe:

How to generate code for the the specific VM language and OS of the Hack computer

(There will be some repetition of things already described).

The big picture



<u>A Jack program</u> is a collection of one or more class files, in same folder (here, named `points`)

Each class file *ClassName*`.jack` is *compiled separately* into the file *ClassName*`.vm`

Subroutines (implementation notes)

Foo.jack

```
class Foo {

  constructor Foo new(int x) {}

  method void bar(int x) {}

  function int baz(int x) {}

}
```

JackCompiler

Foo.vm

```
function Foo.new
  ...
function Foo.bar
  ...
function Foo.baz
  ...
```

Each subroutine (constructor, function, method) *subName* in a file *ClassName*`.jack` is compiled into a VM function named *ClassName*.*subName*

Constants (implementation notes)

The Jack language has four constants

`true` is implemented in VM code as `constant 1`, followed by `neg`

`false` is implemented in VM code as `constant 0`

`null` is implemented in VM code as `constant 0`

`this` is implemented in VM code as `pointer 0`

Variables (implementation notes)

Local variables

Are mapped on `local 0`, `local 1`, `local 2`, ...

Argument variables

Are mapped on `argument 0`, `argument 1`, `argument 2`, ...

Static variables

Are mapped on `static 0`, `static 1`, `static 2`, ...

Field variables

Are mapped on `this 0`, `this 1`, `this 2`, ...

Arrays (implementation notes)

<u>Access to array element</u> `arr[i]`

Is implemented by generating VM code that realizes:

set `pointer 1` to `arr + i`

`push` / `pop` `that 0`

Implementation tip: There is never a need use `that` *i* for *i* greater than 0.

Subroutine calls (implementation notes)

(Suppose that we are compiling the file *ClassName*`.jack`)

<u>Compiling a constructor call or a function call</u> *subName*(exp_1, exp_2, ..., exp_n)

The generated VM code pushes the expressions exp_1, exp_2, ..., exp_n onto the stack, followed by the command `call` *ClassName*`.`*subName* n

<u>Compiling a method call</u> *obj*`.`*subName*(exp_1, exp_2, ..., exp_n)

The generated VM code pushes *obj* and then exp_1, exp_2, ..., exp_n onto the stack, followed by the command `call` *ClassName*`.`*subName* $n+1$

If the called subroutine is *void*:

Just after the call, the generated VM code gets rid of the return value using the command `pop temp 0`

Subroutines (implementation notes)

<u>When compiling a Jack method:</u>

- The first entry in the method's symbol table must be a variable named `this` whose *type* is the name of the class to which the method belongs, *kind* is `argument`, and *index is* `0`
- The generated VM code starts by setting `pointer 0` to `argument 0`

<u>When compiling a Jack constructor:</u>

- The generated VM code starts by:

  Calling the OS function `Memory.alloc` *nFields* (the number of fields in the class declaration)

  Setting `pointer 0` to `alloc`'s return value
- The generated VM code ends with `return pointer 0`

<u>When compiling a *void* function or a *void* method:</u>

The generated VM code ends with `push constant 0` and then `return`

The OS (implementation notes)

The OS (here is the API) is organized as a set of 8 compiled Jack classes:

```
Math.vm
Memory.vm
Screen.vm
Output.vm
Keyboard.vm
String.vm
Array.vm
Sys.vm
```

Every OS subroutine (e.g. `Math.sqrt`) is treated as a regular VM function, and can be called by the generated VM code using the regular call command `call` *ClassName*`.`*subName nArgs* (e.g. `call Math.sqrt 1`)

OS implementations

Emulated: If you execute / test the generated VM code on the supplied VM emulator (recommended in this project), there is no need to worry about the 8 `.vm` OS files: The supplied VM emulator features a built-in implementation of all the OS subroutines.

Native: In project 12 we will implement the OS in Jack, and compile it, resulting in the 8 `.vm` OS files. If you wish to translate a Jack program to assembly, compile the program folder (`.jack` files) into `.vm` files, add the 8 `.vm` OS files to the same program folder, and apply the VM translator to the folder.

The OS (implementation notes)

Some OS routines come to play during compilation. In particular:

<u>The compiler handles…</u>

Multiplication (*) by calling the OS function `Math.multiply()`

Division (/) by calling the OS function `Math.divide()`

String constants by calling the OS constructor `String.new(`*length*`)`

String assignments like `x = "`*cc … c*`"` by making a sequence of calls to `String.appendChar(`*c*`)`

Object construction by calling the OS function `Memory.alloc(`*size*`)`

<u>Note:</u> The compiler generates VM code, and the OS routines are implemented as VM functions.
So, every call above is implemented using the regular VM command `call` *OSfunction nArgs*

Lecture plan

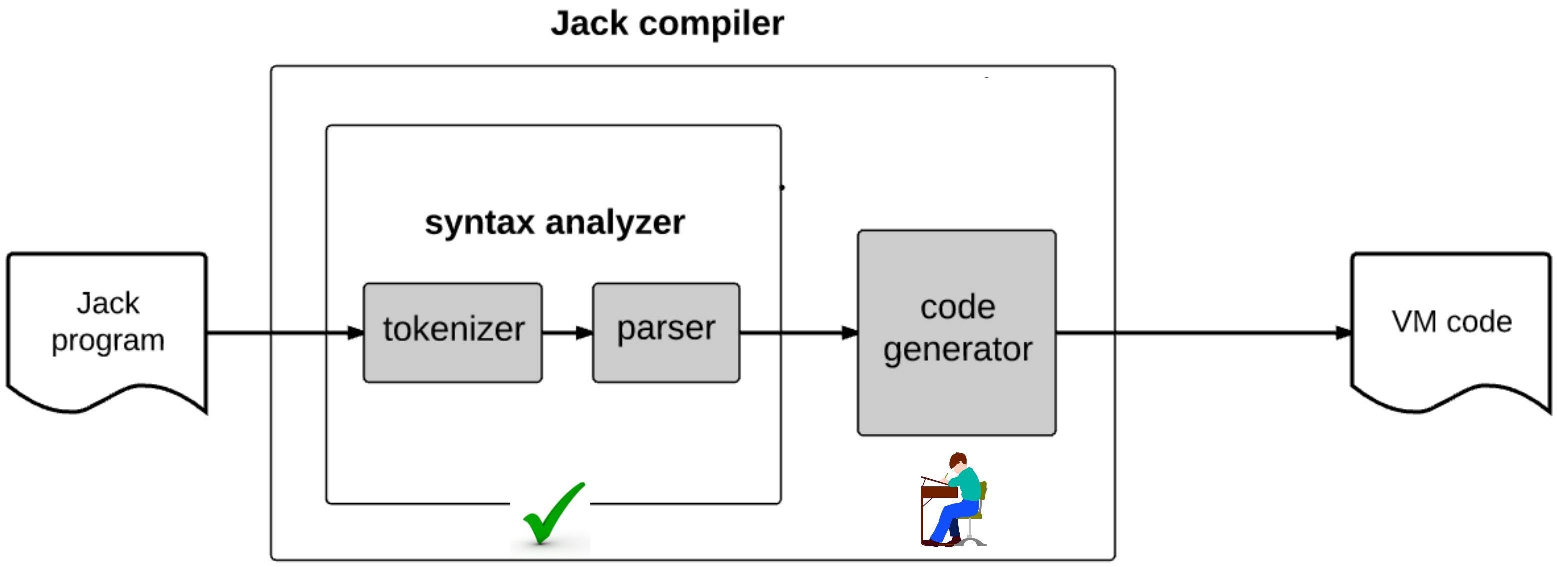
Compilation

- ✓ Handling variables
- ✓ Handling expressions
- ✓ Handling statements
- ✓ Handling functions
- ✓ Handling objects
- ✓ Handling arrays

Implementation

- ✓ Standard mapping
- ➡ Proposed design
- Project 11

The Jack compiler



project 10 project 11

<u>Project 11</u>

Morphing the syntax analyzer developed in project 10 into a full scale compiler.

The Jack compiler

<u>Usage</u> (if the compiler is implemented in Java; other languages will have a similar command line)

`$ JackCompiler` *input*

input: *fileName*`.jack`: name of a single file containing a Jack class, or

folderName: name of a folder containing one or more `.jack` files

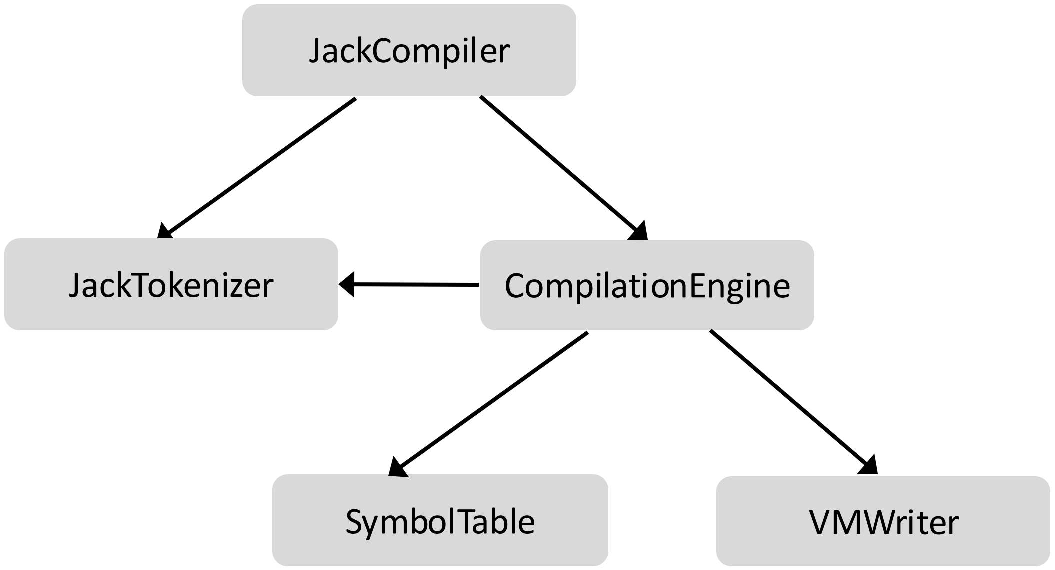
output: If the input is a single file, the compiler generates the file *fileName*`.vm`

If the input is a folder, the compiler generates one `.vm` file for every `.jack` file

(the generated `.vm` files are stored in the same folder containing the source `.jack` files)

The Jack compiler

Proposed software architecture:

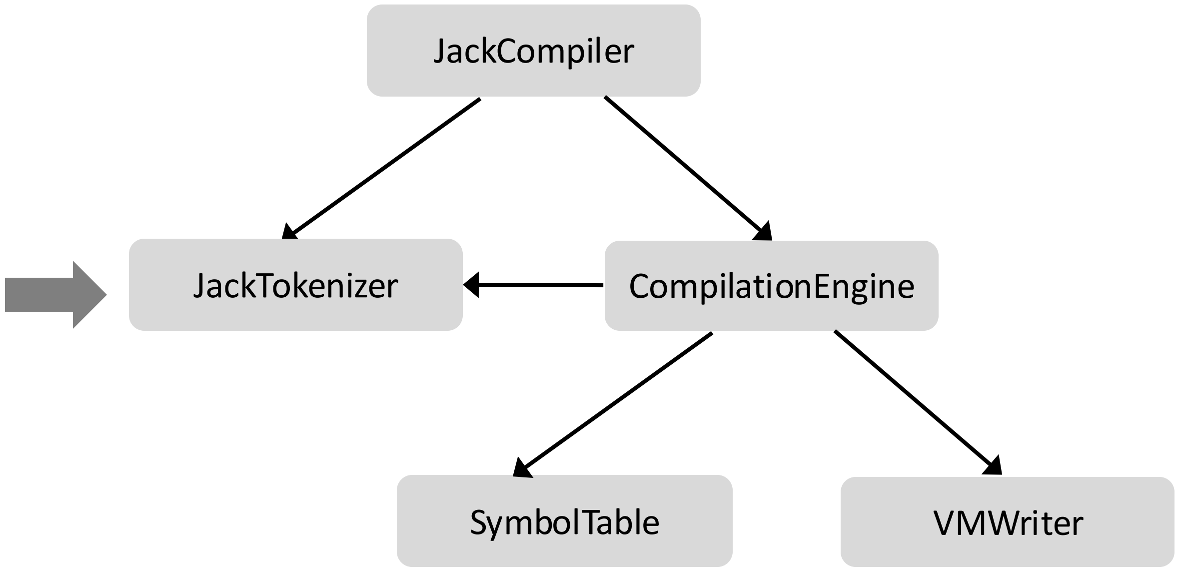


For each source `.jack` file, the compiler creates a `JackTokenizer` and an output `.vm` file;

Next, the compiler uses the `CompilationEngine` to write the VM code into the output `.vm` file.

The Jack compiler

Proposed software architecture:



For each source `.jack` file, the compiler creates a `JackTokenizer` and an output `.vm` file;

Next, the compiler uses the `CompilationEngine` to write the VM code into the output `.vm` file.

JackTokenizer

The `JackTokenizer` handles the compiler's input.

Provides services for:

- Skipping white space
- Getting the current token and advancing the input just beyond it
- Getting the type of the current token

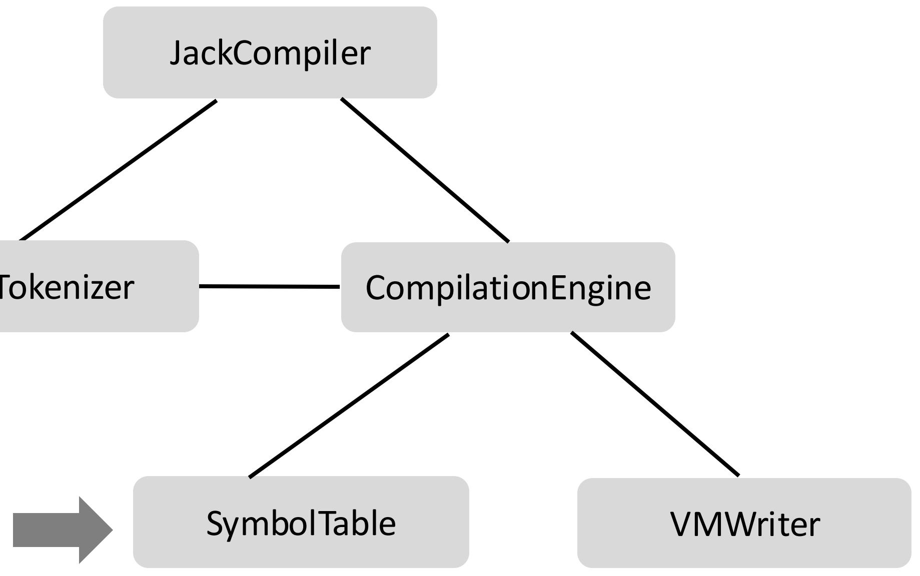
(Developed in project 10)

JackTokenizer (same as in project 10)

JackTokeinizer: Ignores all comments and white space, gets the next token,
and advances the input just beyond it

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	input file / stream	–	Opens the input `.jack` file / stream and gets ready to tokenize it.
`hasMoreTokens`	–	boolean	Are there more tokens in the input?
`advance`	–	–	Gets the next token from the input, and makes it the current token. This method should be called only if `hasMoreTokens` is true. Initially there is no current token.
`tokenType`	–	`KEYWORD`, `SYMBOL`, `IDENTIFIER`, `INT_CONST`, `STRING_CONST`	Returns the type of the current token, as a constant.
`keyWord`	–	`CLASS`, `METHOD`, `FUNCTION`, `CONSTRUCTOR`, `INT`, `BOOLEAN`, `CHAR`, `VOID`, `VAR`, `STATIC`, `FIELD`, `LET`, `DO`, `IF`, `ELSE`, `WHILE`, `RETURN`, `TRUE`, `FALSE`, `NULL`, `THIS`	Returns the keyword which is the current token, as a constant. This method should be called only if `tokenType` is `KEYWORD`.
`symbol`	–	char	Returns the character which is the current token. Should be called only if `tokenType` is `SYMBOL`.
`identifier`	–	string	Returns the string which is the current token. Should be called only if `tokenType` is `IDENTIFIER`.
`intVal`	–	int	Returns the integer value of the current token. Should be called only if `tokenType` is `INT_CONST`.
`stringVal`	–	string	Returns the string value of the current token, without the opening and closing double quotes. Should be called only if `tokenType` is `STRING_CONST`.

Architecture



SymbolTable

Jack source code

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx)+ (dy*dy));
    }
    ...
}
```

name	type	kind	#
x	int	field	0
y	int	field	1
pointCount	int	static	0

class-level symbol table

name	type	kind	#
this	Point	argument	0
other	Point	argument	1
dx	int	local	0
dy	int	local	1

subroutine-level symbol table

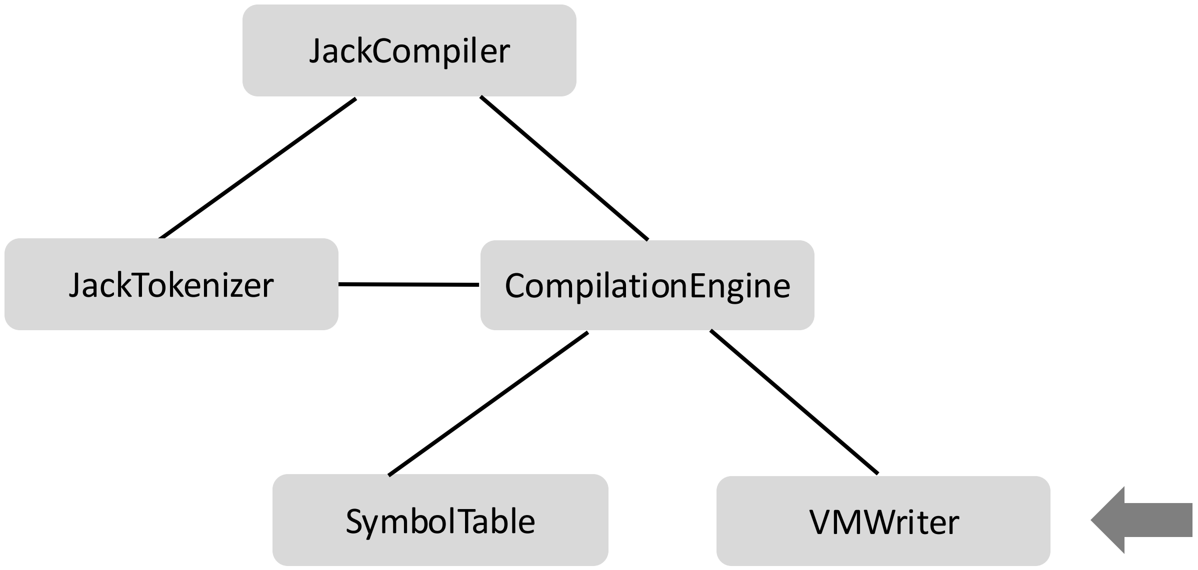
Implementation notes

- symbol table = instance of a `SymbolTable` class (next slide)
- When compiling a Jack class, we need one class-level symbol table and one subroutine-level symbol table
- When we start compiling a subroutine, we reset the latter table
- Each variable is assigned a running index within its *scope* (table) and *kind*. The index starts at 0, increments by 1 after each time a new symbol is added to the table, and is reset to 0 when starting a new scope (table)
- When compiling an error-free Jack code, each identifier not found in the symbol tables can be assumed to be either a *subroutine name* or a *class name*.

SymbolTable

Routine	***Arguments***	***Returns***	***Function***
Constructor / initializer	—	—	Creates a new symbol table.
`reset`	—	—	Empties the symbol table, and resets the four indexes to 0. Should be called when starting to compile a subroutine declaration.
`define`	`name` (string) `type` (string) `kind` (`STATIC`, `FIELD`, `ARG`, or `VAR`)	—	Defines (adds to the table) a new variable of the given `name`, `type`, and `kind`. Assigns to it the index value of that `kind`, and adds 1 to the index.
`varCount`	`kind` (`STATIC`, `FIELD`, `ARG`, or `VAR`)	int	Returns the number of variables of the given `kind` already defined in the table.
`kindOf`	`name` (string)	(`STATIC`, `FIELD`, `ARG`, `VAR`, `NONE`)	Returns the `kind` of the named identifier. If the identifier is not found, returns `NONE`.
`typeOf`	`name` (string)	string	Returns the `type` of the named variable.
`indexOf`	`name` (string)	int	Returns the `index` of the named variable.

Architecture

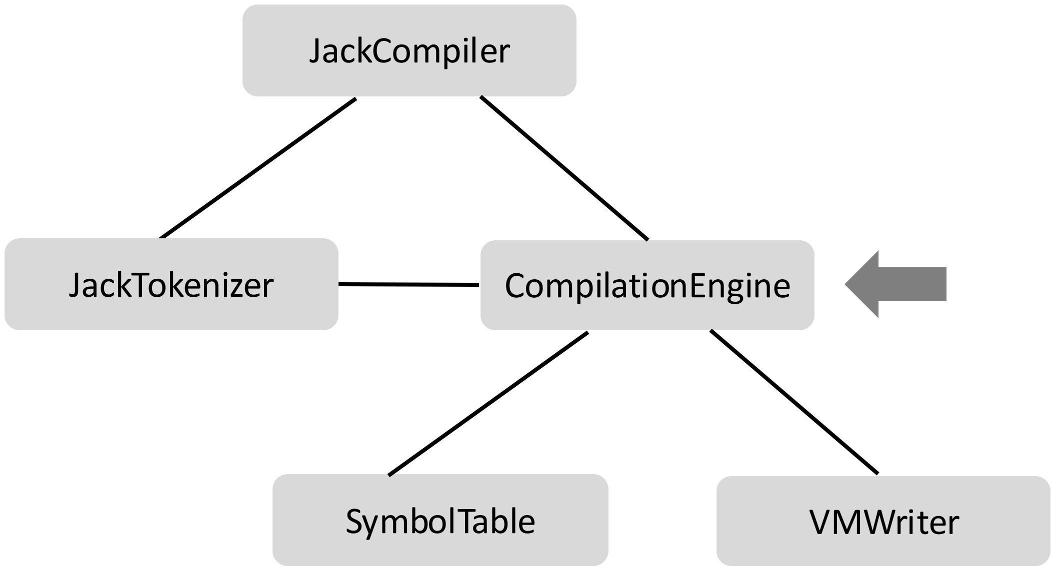


VMWriter

Routine	***Arguments***	***Returns***	***Function***
Constructor / initializer	output file / stream	—	Creates a new output `.vm` file / stream, and prepares it for writing.
`writePush`	`segment` (`CONSTANT`, `ARGUMENT`, `LOCAL`, `STATIC`, `THIS`, `THAT`, `POINTER`, `TEMP`) `index` (int)	—	Writes a VM `push` command.
`writePop`	`segment` (`ARGUMENT`, `LOCAL`, `STATIC`, `THIS`, `THAT`, `POINTER`, `TEMP`) `index` (int)	—	Writes a VM `pop` command.
`writeArithmetic`	`command` (`ADD`, `SUB`, `NEG`, `EQ`, `GT`, `LT`, `AND`, `OR`, `NOT`)	—	Writes a VM arithmetic-logical command.
`writeLabel`	`label` (string)	—	Writes a VM `label` command.
`writeGoto`	`label` (string)	—	Writes a VM `goto` command.
`writeIf`	`label` (string)		Writes a VM `if-goto` command.
`writeCall`	`name` (string) `nArgs` (int)	—	Writes a VM `call` command.
`writeFunction`	`name` (string) `nVars` (int)	—	Writes a VM `function` command.
`writeReturn`	—	—	Writes a VM `return` command.
`close`	—	—	Closes the output file / stream.

A simple module that writes individual VM commands to the output `.vm` file.

Architecture



CompilationEngine

The `CompilationEngine` of the *compiler* (project 11) and the *syntax analyzer* (project 10) have the same design and API: a set of `compile`*xxx* methods

However, the `compile`*xxx* methods generate different outputs. For example:

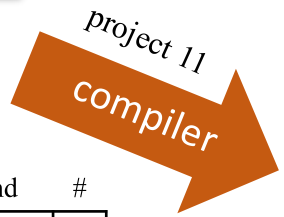
source code

```
(x + y) * 2
```

Output of `compileExpression`:

```
<expression>
  <term>
    <symbol> ( </symbol>
    <expression>
      <term> <varName> x </varName> </term>
      <op> + </op>
      <term> <varName> y </varName> </term>
    </expression>
    <symbol> ) </symbol>
  </term>
  <op> * </op>
  <term> <intConstant> 2 </intConstant> </term>
</expression>
```

Infix code with symbolic variables, written as XML marked-up data



name	type	kind	#
x	int	local	0
y	int	local	1

Output of `compileExpression`:

```
push local 0
push local 1
add
push constant 2
Call Math.multiply 2
```

Postfix code with *segment i* references, written in the VM language

CompilationEngine

- Gets its input from a `JackTokenizer` and writes its output using the `VMWriter`
- Organized as a set of `compile`*xxx* routines, *xxx* being a syntactic element in the Jack grammar:
  - Each `compile`*xxx* routine should read *xxx* from the input, `advance()` the input exactly beyond *xxx*, and emit to the output VM code effecting the semantics of *xxx*
  - `compile`*xxx* is called only if *xxx* is the current syntactic element
  - If *xxx* is part of an expression and thus has a value, the emitted VM code will end up computing the value and leaving it at the top of the VM's stack

CompilationEngine (same API as in project 10)

Routine	***Arguments***	***Returns***	***Function***
Constructor / initializer	Input file / stream Output file / stream		Creates a new compilation engine with the given input and output. The next routine called must be `compileClass`.
`compileClass`	–	–	Compiles a complete class.
`compileClassVarDec`	–	–	Compiles a static variable declaration, or a field declaration.
`compileSubroutine`	–	–	Compiles a complete method, function, or constructor.
`compileParameterList`	–	–	Compiles a (possibly empty) parameter list. Does not handle the enclosing parentheses tokens `(` and `)`.
`compileSubroutineBody`	–	–	Compiles a subroutine's body.
`compileVarDec`	–	–	Compiles a `var` declaration.
`compileStatements`	–	–	Compiles a sequence of statements. Does not handle the enclosing curly bracket tokens `{` and `}`.

CompilationEngine (same API as in project 10)

Routine	*Arguments*	*Returns*	*Function*
`compileLet`	–	–	Compiles a `let` statement.
`compileIf`	–	–	Compiles an `if` statement, possibly with a trailing `else` clause.
`compileWhile`	–	–	Compiles a `while` statement.
`compileDo`	–	–	Compiles a `do` statement.
`compileReturn`	–	–	Compiles a `return` statement.
`compileExpression`	–	–	Compiles an expression.
`compileTerm`	–	–	Compiles a *term*. If the current token is an *identifier*, the routine must resolve it into a *variable*, an *array entry*, or a *subroutine call*. A single lookahead token, which may be `[`, `(`, or `.`, suffices to distinguish between the possibilities. Any other token is not part of this term and should not be advanced over.
`compileExpressionList`	–	int	Compiles a (possibly empty) comma-separated list of expressions. Returns the number of expressions in the list.

Lecture plan

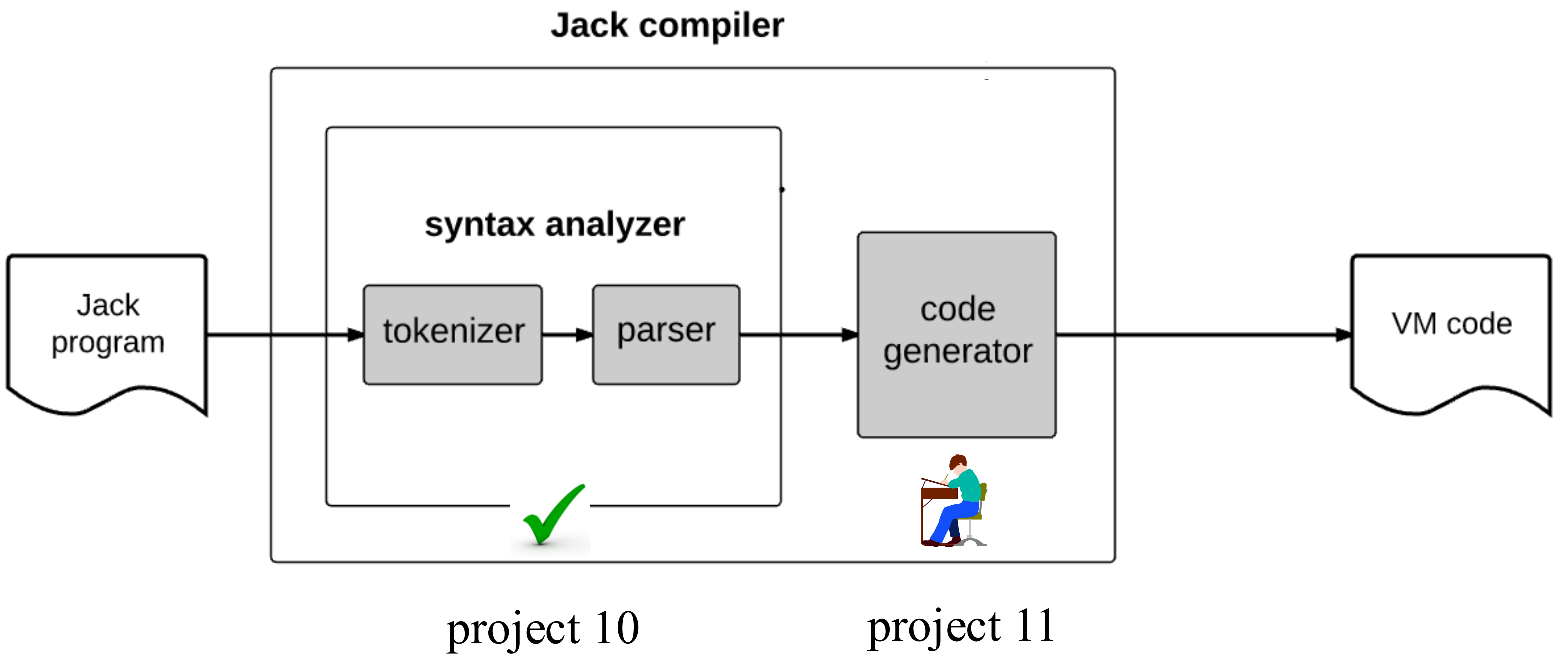
<u>Compilation</u>

- ✓ Handling variables
- ✓ Handling expressions
- ✓ Handling statements
- ✓ Handling functions
- ✓ Handling objects
- ✓ Handling arrays

<u>Implementation</u>

- ✓ Standard mapping
- ✓ Proposed design
- ➡ Project 11

Compiler development stages



Project 11: Extend the syntax analyzer into a full-scale compiler

Stage 0: Syntax analyzer (done)

Stage 1: Symbol table handling

Stage 2: Code generation.

Symbol table

Output of the syntax analyzer (project 10)

```
...
<expression>
    <term>
        <identifier> count </identifier>
    </term>
    <symbol> < </symbol>
    <term>
        <intConstant> 100 </intConstant>
    </term>
</expression>
...
```

In the syntax analyzer built in project 10, identifiers were handled by outputting `<identifier>` *identifier* `</identifier>`

Extending the handling of identifiers:

In addition to outputting the identifier, we'll also output:

- the identifier's *category*: `var`, `argument`, `static`, `field`, `class`, `subroutine`
- if the category is `var`, `argument`, `static`, `field`: the *running index* assigned to this variable
- whether the identifier is being *defined*, or being *used*

Implementation / testing

1. Implement the `SymbolTable` API
2. Extend the syntax analyzer developed in project 10 with the outputs described above (plan and use your own output format)
3. Test your symbol table implementation by running the extended syntax analyzer on the test programs given in project 10.

Compiler development stages

Project 11: Extend the syntax analyzer into a full-scale compiler

- ✓ Stage 0: Syntax analyzer (done)
- ✓ Stage 1: Symbol table handling
- ➡ Stage 2: Code generation.

Code generation

Test programs

```
Seven
ConvertToBin
Square
Average
Pong
ComplexArrays
```

Test your evolving compiler on the supplied test programs, in the shown order

Each test program is designed to test some of the compiler's capabilities.

For each test program:

1. Use your compiler to compile the program folder
2. Inspect the generated code;
   If there's a problem, fix your compiler and go to stage 1
3. Load the folder into the VM emulator
4. Run the compiled program, inspect the results
5. If there's a problem, fix your compiler and go to stage 1.

Test program: Seven

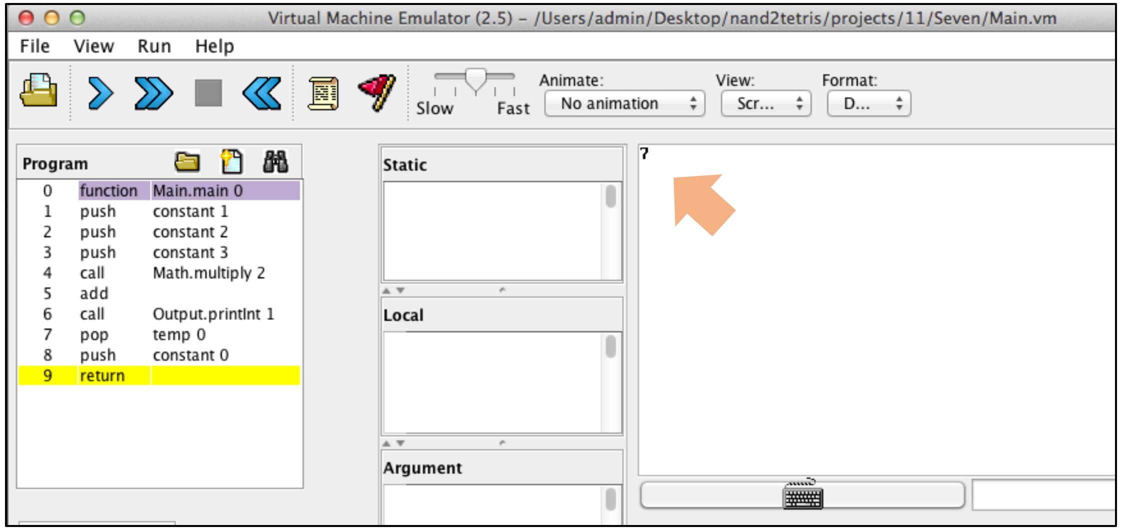
projects/11/Seven/Main.jack

```
/** Computes the value of 1 + (2 * 3)
 * and prints the result at the top-left
 * corner of the screen. */
class Main {
   function void main() {
       do Output.printInt(1 + (2 * 3));
       return;
   }
}
```

JackCompiler

projects/11/Seven/Main.vm

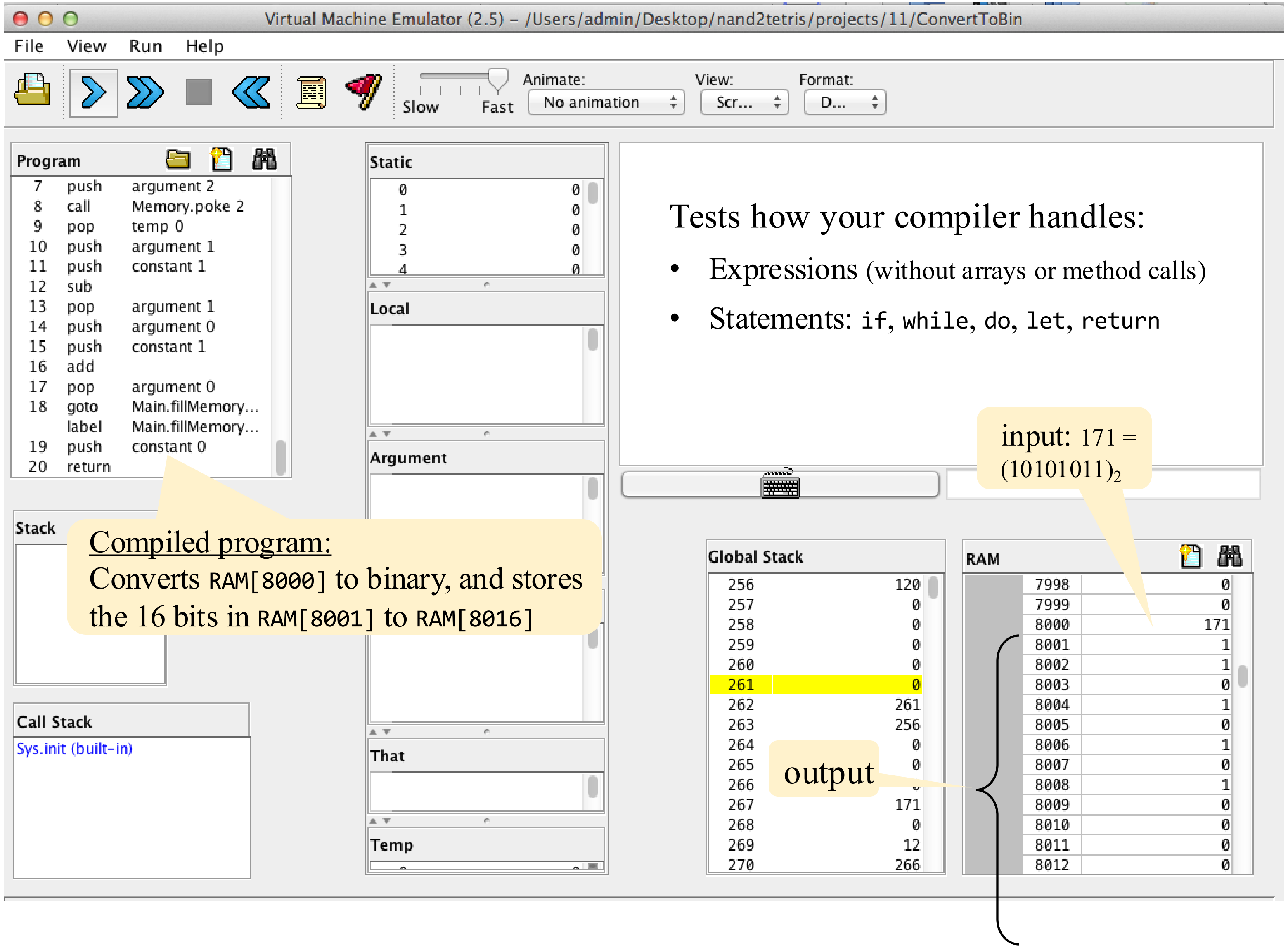
```
function Main.main 0
  push constant 1
  push constant 2
  push constant 3
  call Math.multiply 2
  add
  call Output.printInt 1
  pop temp 0
  push constant 0
  return
```



Tests how your compiler handles:

- A simple program
- An arithmetic expression involving constants only
- A `do` statement
- A `return` statement

Test program: Decimal-to-binary conversion



Tests how your compiler handles:

- Expressions (without arrays or method calls)
- Statements: `if`, `while`, `do`, `let`, `return`

input: 171 = $(10101011)_2$

<u>Compiled program:</u>
Converts `RAM[8000]` to binary, and stores the 16 bits in `RAM[8001]` to `RAM[8016]`

output

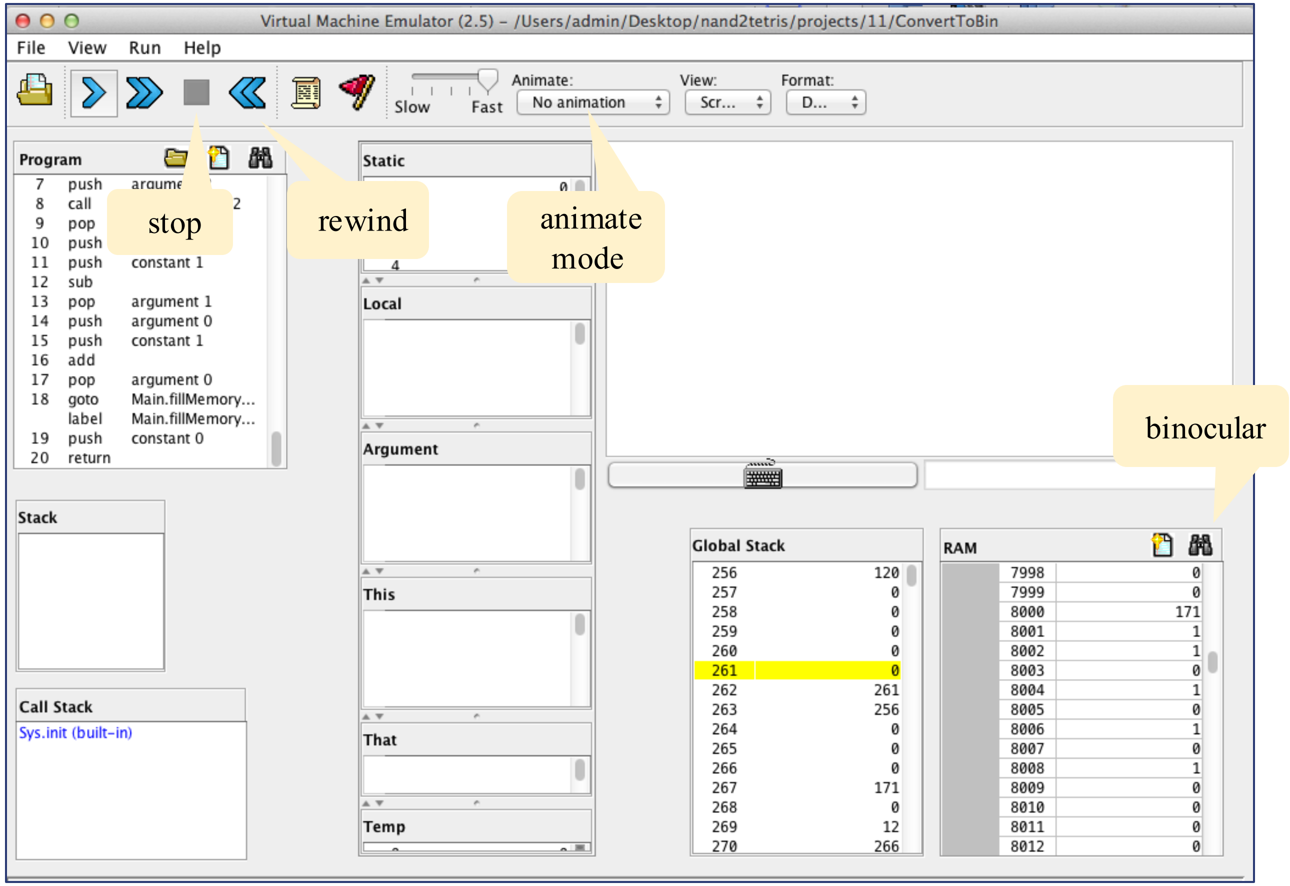
Test program: Decimal-to-binary conversion

```
class Main {
   // Converts RAM[8000] to binary, putting the resulting bits in RAM[8001]..RAM[8016]
   function void main() {
      var int value;
      do Main.fillMemory(8001, 16, -1);  // sets RAM[8001]..RAM[8016] to -1
      let value = Memory.peek(8000);     // gets the input from RAM[8000]
       do Main.convert(value);           // performs the conversion
      return;
   }

   // Fills 'length' consecutive memory locations with 'value',
   // starting at 'startAddress'.
   function void fillMemory(int startAddress, int length, int value) { // code omitted }

   // Converts the value to binary, and puts the result in RAM[8001]..RAM[8016] */
   function void convert(int value) { // code omitted }

   // Some more functions (code omitted)
}
```

Tests how your compiler handles:

- Expressions (without arrays, without method calls)
- Statements: `if`, `while`, `do`, `let`, `return`

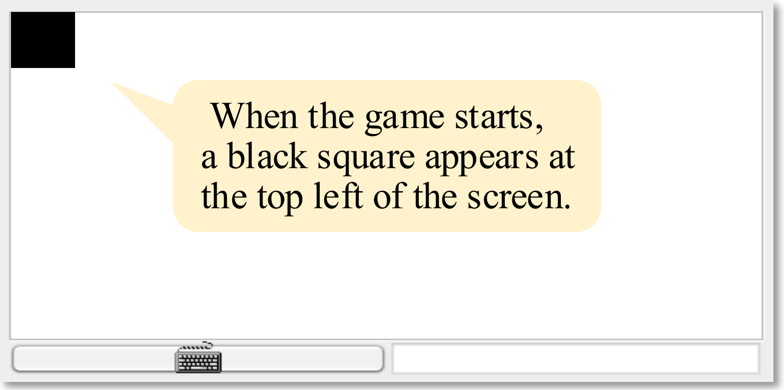
Test program: Decimal-to-binary conversion

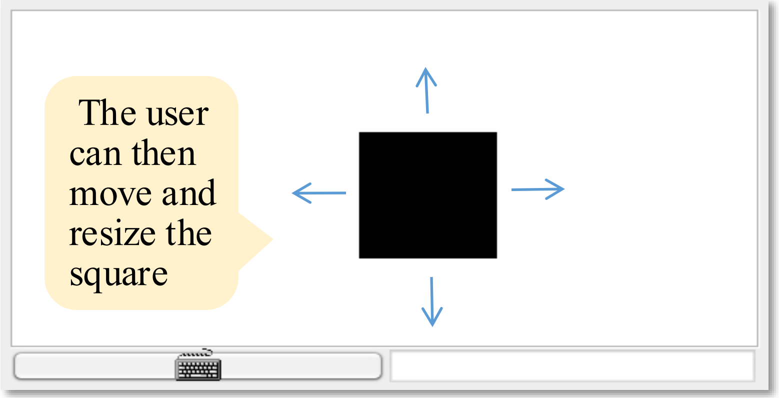


Testing tips:

- Use the "binocular" control for inspecting specific RAM addresses
- Note that the "rewind" control erases the RAM
- Note that you cannot enter input into the RAM in "no animation" mode
- To see the program's results (RAM state), click the "stop" control

Test program: Square

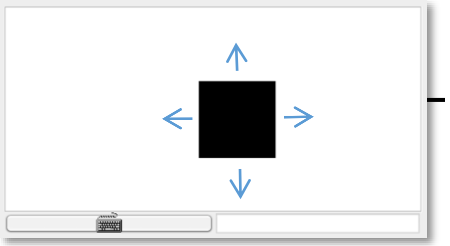




Tests how your compiler handles object-oriented features of the Jack language:

- Constructors
- Methods
- Expressions that include method calls.

Test program: Square



`projects/11/Square/Square.jack` (showing only method signatures)

```
/** Represents a graphical square object */
class Square {

   /** Constructs a new square with a given location and size */
   constructor Square new(int Ax, int Ay, int Asize)

   /** Disposes this square */
   method void dispose()

   /** Draws the square on the screen *
   method void draw()

   /** Erases the square from the scree
   method void erase()

   /** Increments the square’s size by
   method void incSize()

   /** Decrements the square’s size by
   method void decSize()

   /** Moves up by 2 pixels */
   method void moveUp()

   /** Moves down by 2 pixels */
   method void moveDown()

   /** Moves left by 2 pixels */
   method void moveLeft()

   /** Moves right by 2 pixels */
   method void moveRight()
}
```

`SquareGame.jack`

```
/** Represents a square game */
class SquareGame {

   field Square square; // the square
   field int direction; // the square’s direction:
                        // 0=none, 1=up, 2=down,
                        // 3=left, 4=right

   /** Constructs a new Square Game */
   constructor SquareGame new() {
      let square = Square.new(0, 0, 30);
      let direction = 0;
      return this;
   }

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

   ...
```

`Main.jack`

```
/** Main class of the square game. */
class Main {

   /** Initializes and starts a new game */
   function void main() {
      var SquareGame game;

      let game = SquareGame.new();
      do game.run();
       do game.dispose();
      return;
    }
}
```

Test program: Average

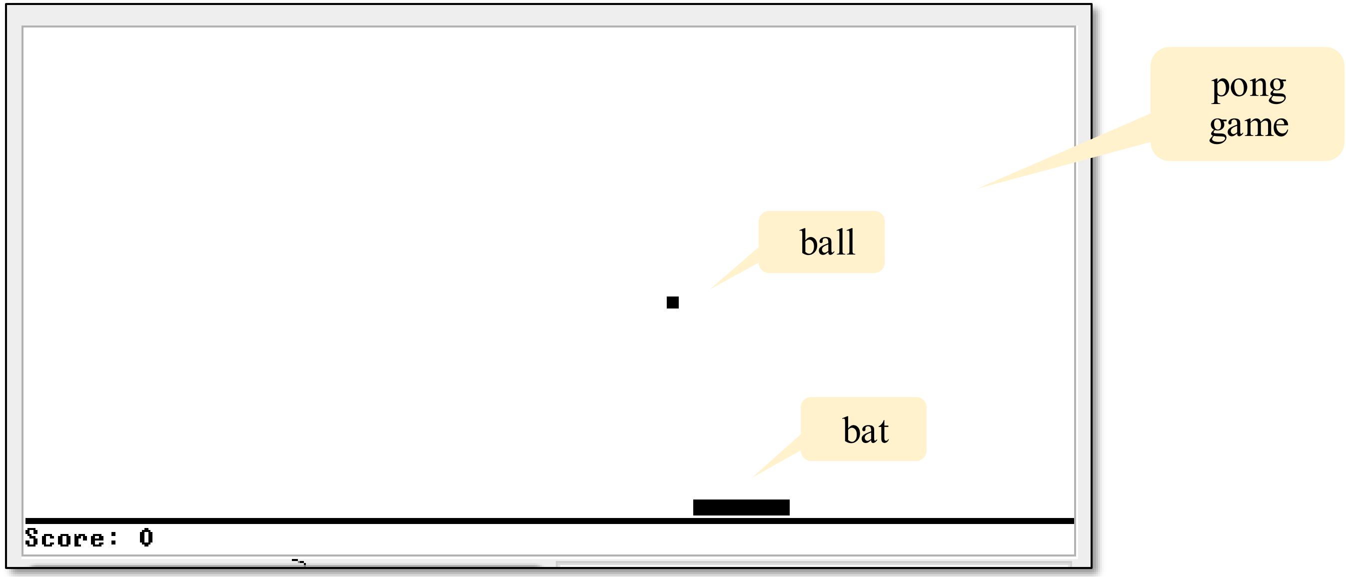
```
/** Computes the average of a sequence of integers */
class Main {
   function void main() {
      var Array a;
      var int length;
      var int i, sum;

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

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

      let i = 0; let sum = 0;

       while (i < length) {
        let sum = sum + a[i];
         let i = i + 1;
       }

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

```
How many numbers? 3
Enter the next number: 10
Enter the next number: 20
Enter the next number: 30
The average is: 20
```

Tests how your compiler handles:

- Arrays
- Strings

Test program: Pong



Tests how your compiler handles a complete object-oriented application, including the handling of objects and static variables.

Test program: Pong

projects/11/Pong/Ball.jack

```
/** A graphic ball, with methods for drawing, erasing
 * and moving on the screen. */
class Ball {

    // Ball'
    field in

    // Dista
    field in

    // Used
    field in
    field bo

    // Locat
    field in

    // last
    field in

    /** Cons
     * loca
    construc

    ...

    // More

}
```

Bat.jack

```
/** A graphic paddle with methods for drawing,
 *  erasing, moving left and right changing width. */
class Bat {

    // Screen location
    field int x, y;

    // Bat's width and height
    field int width, height;

    // Bat's direction of mov
    field int direction; // 1

    /** Constructs a new bat
    constructor Bat new(int A
                        int A
       let x = Ax;
       let y = Ay;
       let width = Awidth;
       let height = Aheight;
       let direction = 2;
       do show();
       return this;
    }

    ...

    // More Bat methods

}
```

PongGame.jack

```
/** Pong game */
class PongGame {

   static PongGame instance;  // the game
   field Bat bat;             // the bat
   field Ball ball;           // the ball
   ...
   /** Creates an instance of a PongGame */
   function void newInstance() {
      let instance = PongGame.new();
      return;
    }
    ...
    /** Runs the g
    method void ru
       var char ke
       while (~exi
          // waits
          while ((
             let k
             do ba
             do mo
          }

          if (key
              do
          }
          ...
       }
    }
    ...
}
```

Main.jack

```
/** Main class of the Pong game */
class Main {
   /** Initializes a Pong game and
   starts running it. */
   function void main() {
      var PongGame game;
      do PongGame.newInstance();
      let game = PongGame.getInstance();
      do game.run();
      do game.dispose();
      return;
   }
}
```

Test program: ComplexArrays

projects/11/ComlpexArrays/Main.jack

```
class Main {
   function void main() {
      var Array a, b, c;
      let a = Array.new(10);
      let b = Array.new(5);
      ...
      // Fills the arrays with some data (omitted)
      ...
      // Manipulates the arrays using some complex index expressions
      let a[b[a[3]]] = a[a[5]] * b[7 - a[3] - Main.double(2) + 1];
      ...
      // Prints the expected and the actual values of a[b[a[3]]]
      ...
   }

   // A trivial function that tests how the compiler handles a subroutine
   // call within an expression that evaluates to an array index
   function int double(int a) {
      return a * 2;
   }

   // Creates a two dimensional array
   function void fill(Array a, int size) {
      while (size > 0) {
         let size = size - 1;
         let a[size] = Array.new(3);
      }
      return;
   }
}
```

```
Test 1 - Required result: 5, Actual result: 5
Test 2 - Required result: 40, Actual result: 40
Test 3 - Required result: 0, Actual result: 0
Test 4 - Required result: 77, Actual result: 77
Test 5 - Required result: 110, Actual result: 110
```

Tests how your compiler handles array manipulations using index expressions that include complex array references