Compilation

Outline

1. Compilers
2. Why Study Compilers?
3. Phases of Compilation
4. The *j--* Compiler
5. Adding New Constructs to *j--*

Compilers

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A compiler translates a source language program into a target language program

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Examples of source language: C, Java

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source language program (high-level) $\longrightarrow$ $\boxed{\text{compiler}}$ $\longrightarrow$ target language program (low-level)

Examples of source language: C, Java

Examples of target language: MIPS instructions, JVM instructions (aka bytecode)

Compilers

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- Syntax of constructs such as classes, methods, statements, and expressions
- Semantics (ie, meaning) of the constructs

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- Intel i386: a complex instruction set computer (CISC)
- MIPS: a reduced instruction set computer (RISC)
- Java Virtual Machine (JVM): a virtual machine

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An interpreter executes a source language program directly

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Examples of interpreters: Bash, Python

Why Study Compilers?

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Compiler writing is a case study in software engineering

Compilers are programs and writing programs is fun

Phases of Compilation

Phases of Compilation

A compiler can be broken into a front end and a back end

source language program $\longrightarrow$ $\boxed{\text{front end}}$ $\longrightarrow$ IR† $\longrightarrow$ $\boxed{\text{back end}}$ $\longrightarrow$ target language program

mesh language

† Intermediate Representation

Phases of Compilation

Phases of Compilation

The front end can be decomposed into a sequence of analysis phases

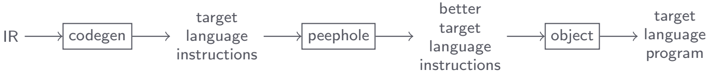
$$\text{source language program} \longrightarrow \boxed{\text{scanner}} \longrightarrow \text{tokens} \longrightarrow \boxed{\text{parser}} \longrightarrow \text{AST}^{\dagger} \longrightarrow \boxed{\text{semantics}} \longrightarrow \text{IR}$$

† Abstract Syntax Tree

Phases of Compilation

Phases of Compilation

The back end can be decomposed into a sequence of synthesis phases



Phases of Compilation

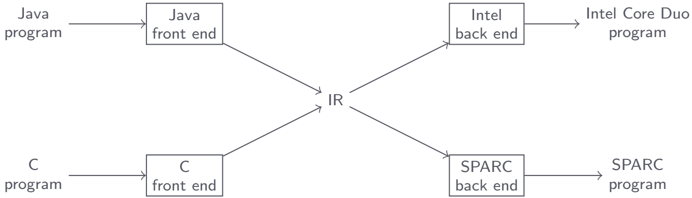
Phases of Compilation

A compiler sometimes has an optimizer between the front end and the back end

Phases of Compilation

Phases of Compilation

Separating the front end from the back end enables code re-use



The j-- Compiler

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Compiling a *j--* program `$j/j--/tests/jvm/HelloWorld.java` for the JVM

```
>_ ~/workspace/j--
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Running the JVM program `HelloWorld.class`

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>_ ~/workspace/j--
$ java HelloWorld
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Compiling a *j--* program `$j/j--/tests/spim/HelloWorld.java` for the MIPS machine

```
>_ ~/workspace/j--
$ bash ./bin/j-- -s naive tests/spim/HelloWorld.java
```

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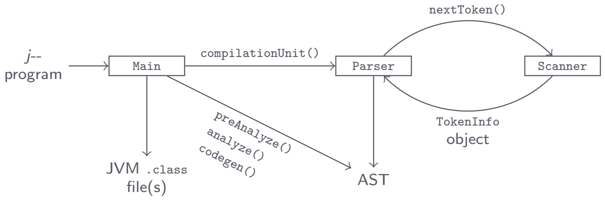
Compiling a *j--* program `$j/j--/tests/spim/HelloWorld.java` for the MIPS machine

```
>_ ~/workspace/j--
$ bash ./bin/j-- -s naive tests/spim/HelloWorld.java
```

Running the MIPS program `HelloWorld.s`

```
>_ ~/workspace/j--
$ spim -f HelloWorld.s
```

The *j--* compiler is organized in an object-oriented fashion



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For example, the following program

HelloWorld.java

```java
// Copyright 2012- Bill Campbell, Swami Iyer and Bahar Akbal-Delibas
//
// Writes to standard output the message "Hello, World".

import java.lang.System;

public class HelloWorld {
    // Entry point.
    public static void main(String[] args) {
        System.out.println("Hello, World");
    }
}
```

is broken down into `import`, `java`, `.`, `lang`, `.`, `System`,`;`, `public`, `class`, `HelloWorld`, `{`, `...`, `;`, `}`, `}`

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`import`, `public`, etc are reserved words with distinct names `IMPORT` and `PUBLIC`, etc

`java`, `lang`, etc are `IDENTIFIER` tokens with the images `"java"`, `"lang"`, etc

`.`, `;`, etc are separators with distinct names `DOT`, `SEMI`, etc

`"Hello, World"` is a `STRING_LITERAL` token with the image `"Hello, World"`

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The parser validates the syntax of a *j--* program against the *j--* grammar and represents the program as an AST

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Grammar rules describing a compilation unit and a qualified identifier

```
compilationUnit ::= [ PACKAGE qualifiedIdentifier SEMI ]
                    { IMPORT  qualifiedIdentifier SEMI }
                    { typeDeclaration }
                    EOF

qualifiedIdentifier ::= IDENTIFIER { DOT IDENTIFIER }
```

The j-- Compiler

Parser.java

```java
public JCompilationUnit compilationUnit() {
    int line = scanner.token().line();
    String fileName = scanner.fileName();
    TypeName packageName = null;
    if (have(PACKAGE)) {
        packageName = qualifiedIdentifier();
        mustBe(SEMI);
    }
    ArrayList<TypeName> imports = new ArrayList<TypeName>();
    while (have(IMPORT)) {
        imports.add(qualifiedIdentifier());
        mustBe(SEMI);
    }
    ArrayList<JAST> typeDeclarations = new ArrayList<JAST>();
    while (!see(EOF)) {
        JAST typeDeclaration = typeDeclaration();
        if (typeDeclaration != null) {
            typeDeclarations.add(typeDeclaration);
        }
    }
    mustBe(EOF);
    return new JCompilationUnit(fileName, line, packageName, imports, typeDeclarations);
}

private TypeName qualifiedIdentifier() {
    int line = scanner.token().line();
    mustBe(IDENTIFIER);
    String qualifiedIdentifier = scanner.previousToken().image();
    while (have(DOT)) {
        mustBe(IDENTIFIER);
        qualifiedIdentifier += "." + scanner.previousToken().image();
    }
    return new TypeName(line, qualifiedIdentifier);
}
```

Have(PACKAGE) are we look at Package

The j-- Compiler

```
{
    "JCompilationUnit:5":
    {
        "source": "tests/jvm/HelloWorld.java",
        "imports": ["java.lang.System"],
        "JClassDeclaration:7":
        {
            "modifiers": ["public"],
            "name": "HelloWorld",
            "super": "java.lang.Object",
            "JMethodDeclaration:9":
            {
                "name": "main",
                "returnType": "void",
                "modifiers": ["public", "static"],
                "parameters": [["args", "String[]"]],
                "JBlock:9":
                {
                    "JStatementExpression:10":
                    {
                        "JMessageExpression:10":
                        {
                            "ambiguousPart": "System.out", "name": "println",
                            "Argument":
                            {
                                "JLiteralString:10":
                                {
                                    "type": "", "value": "Hello, World"
                                }
                            }
                        }
                    }
                }
            }
        }
    }
}
```

pasar don’ t know type and “system.out”

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Types in *j--* are represented using:

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- `Method` (wraps `java.lang.reflect.Method`)
- `Constructor` (wraps `java.lang.reflect.Constructor`)

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- `Type` (wraps `java.lang.Class`)
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- `Constructor` (wraps `java.lang.reflect.Constructor`)
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An ambiguous expression such as `x.y.z` in `x.y.z.w()` is denoted as `AmbiguousName` by the parser and is reclassified during analysis

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A `LocalContext` object represents the scope of a block *j--* maintains a singly-linked list of `Context` objects in which it declares names

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A `ClassContext` object represents the scope of a class declaration

A `LocalContext` object represents the scope of a block

A `MethodContext` (subclass of `LocalContext`) object represents the scopes of methods/constructors

The j-- Compiler

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Example (analysis of a while-statement)

JWhileStatement.java

```java
    public JWhileStatement analyze(Context context) {
        condition = condition.analyze(context);
        condition.type().mustMatchExpected(line(), Type.BOOLEAN);
        body = (JStatement) body.analyze(context);
        return this;
    }
```

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Each time a method is called, the JVM:

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- Assigns positions on the frame for formal parameters and substitutes actual arguments for the parameters

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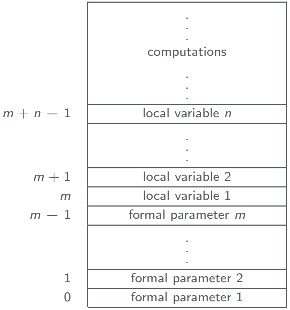
Each time a method is called, the JVM:

- Allocates a stack frame — contiguous block of memory locations on top of the stack
- Assigns positions on the frame for formal parameters and substitutes actual arguments for the parameters
- Assigns positions on the frame for values of local variables and temporary results

The j-- Compiler

Stack frame for a static method call with m formal parameters and n local variables



The j-- Compiler

Stack frame for an instance method call with m formal parameters and n local variables

	⋮ computations ⋮
$m + n$	local variable n
	⋮
$m + 2$	local variable 2
$m + 1$	local variable 1
m	formal parameter m
	⋮
2	formal parameter 2
1	formal parameter 1
0	`this`

A *j--* method

```
public static int multiply(int x, int y) {
    int z = x * y;
    return z;
}
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JVM code for the method

```
public static int multiply(int, int);
    stack=2, locals=3, args_size=2
       0: iload_0
       1: iload_1
       2: imul
       3: istore_2
       4: iload_2
       5: ireturn
```

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```

Stack frame for the call `multiply(6, 7)`

2	z :
1	y : 7
0	x : 6

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Stack frame for the call `multiply(6, 7)`

	6
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1	y : 7
0	x : 6

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Stack frame for the call `multiply(6, 7)`

	7
	6
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```

Stack frame for the call `multiply(6, 7)`

	42
2	z :
1	y : 7
0	x : 6

A *j*-- method

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}
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JVM code for the method

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       5: ireturn
```

Stack frame for the call `multiply(6, 7)`

2	$z : 42$
1	$y : 7$
0	$x : 6$

A *j*-- method

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```

Stack frame for the call `multiply(6, 7)`

	42
2	z : 42
1	y : 7
0	x : 6

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    stack=2, locals=3, args_size=2
       0: iload_0
       1: iload_1
       2: imul
       3: istore_2
       4: iload_2
       5: ireturn
```

Stack frame for the call `multiply(6, 7)`

poof!

A *j--* method

```
public static int multiply(int x, int y) {
    int z = x * y;
    return z;
}
```

JVM code for the method

```
public static int multiply(int, int);
    stack=2, locals=3, args_size=2
       0: iload_0
       1: iload_1
       2: imul
       3: istore_2
       4: iload_2
       5: ireturn
```

Stack frame for the call `multiply(6, 7)`

poof!

`CLEmitter` provides an abstraction for the JVM class file

GenFactorial.java

```
import java.util.ArrayList;

import jminusminus.CLEmitter;

import static jminusminus.CLConstants.*;

/**
 * This class programatically generates the class file for the following Java application:
 *
 * <pre>
 * public class Factorial {
 *     public static void main(String[] args) {
 *         int n = Integer.parseInt(args[0]);
 *         int result = factorial(n);
 *         System.out.println(n + "! = " + result);
 *     }
 *
 *     private static int factorial(int n) {
 *         if (n <= 1) {
 *             return 1;
 *         }
 *         return n * factorial(n - 1);
 *     }
 * }
 * </pre>
 */
public class GenFactorial {
    public static void main(String[] args) {
        // Create a CLEmitter instance
        CLEmitter e = new CLEmitter(true);

        // Create an ArrayList instance to store modifiers
        ArrayList<String> modifiers = new ArrayList<String>();

        // public class Factorial {
```

GenFactorial.java

```
        modifiers.add("public");
        e.addClass(modifiers, "Factorial", "java/lang/Object", null, true);

        // public static void main(String[] args) {
        modifiers.clear();
        modifiers.add("public");
        modifiers.add("static");
        e.addMethod(modifiers, "main", "([Ljava/lang/String;)V", null, true);

        // int n = Integer.parseInt(args[0]);
        e.addNoArgInstruction(ALOAD_0);
        e.addNoArgInstruction(ICONST_0);
        e.addNoArgInstruction(AALOAD);
        e.addMemberAccessInstruction(INVOKESTATIC, "java/lang/Integer", "parseInt",
                "(Ljava/lang/String;)I");
        e.addNoArgInstruction(ISTORE_1);

        // int result = factorial(n);
        e.addNoArgInstruction(ILOAD_1);
        e.addMemberAccessInstruction(INVOKESTATIC, "Factorial", "factorial", "(I)I");
        e.addNoArgInstruction(ISTORE_2);

        // System.out.println(n + "! = " + result);

        // Get System.out on stack
        e.addMemberAccessInstruction(GETSTATIC, "java/lang/System", "out", "Ljava/io/PrintStream;");

        // Create an intance (say sb) of StringBuffer on stack for string concatenations
        //    sb = new StringBuffer();
        e.addReferenceInstruction(NEW, "java/lang/StringBuffer");
        e.addNoArgInstruction(DUP);
        e.addMemberAccessInstruction(INVOKESPECIAL, "java/lang/StringBuffer", "<init>", "()V");

        // sb.append(n);
        e.addNoArgInstruction(ILOAD_1);
```

GenFactorial.java

```
        e.addMemberAccessInstruction(INVOKEVIRTUAL, "java/lang/StringBuffer", "append",
                "(I)Ljava/lang/StringBuffer;");

        // sb.append("!=");
        e.addLDCInstruction("! = ");
        e.addMemberAccessInstruction(INVOKEVIRTUAL, "java/lang/StringBuffer", "append",
                "(Ljava/lang/String;)Ljava/lang/StringBuffer;");

        // sb.append(result);
        e.addNoArgInstruction(ILOAD_2);
        e.addMemberAccessInstruction(INVOKEVIRTUAL, "java/lang/StringBuffer", "append",
                "(I)Ljava/lang/StringBuffer;");

        // System.out.println(sb.toString());
        e.addMemberAccessInstruction(INVOKEVIRTUAL, "java/lang/StringBuffer",
                "toString", "()Ljava/lang/String;");
        e.addMemberAccessInstruction(INVOKEVIRTUAL, "java/io/PrintStream", "println",
                "(Ljava/lang/String;)V");

        // return;
        e.addNoArgInstruction(RETURN);

        // private static int factorial(int n) {
        modifiers.clear();
        modifiers.add("private");
        modifiers.add("static");
        e.addMethod(modifiers, "factorial", "(I)I", null, true);

        // if (n > 1) branch to "Recurse"
        e.addNoArgInstruction(ILOAD_0);
        e.addNoArgInstruction(ICONST_1);
        e.addBranchInstruction(IF_ICMPGT, "Recurse");

        // Base case: return 1;
        e.addNoArgInstruction(ICONST_1);
```

GenFactorial.java

```
        e.addNoArgInstruction(IRETURN);

        // Recursive case: return n * factorial(n - 1);
        e.addLabel("Recurse");
        e.addNoArgInstruction(ILOAD_0);
        e.addNoArgInstruction(ILOAD_0);
        e.addNoArgInstruction(ICONST_1);
        e.addNoArgInstruction(ISUB);
        e.addMemberAccessInstruction(INVOKESTATIC, "Factorial", "factorial", "(I)I");
        e.addNoArgInstruction(IMUL);
        e.addNoArgInstruction(IRETURN);

        // Write Factorial.class to file system
        e.write();
    }
}
```

The j-- Compiler

Compile `GenFactorial.java`

```
>_ ~/workspace/j--

$ bash ./bin/clemitter tests/clemitter/GenFactorial.java
```

The j-- Compiler

Compile `GenFactorial.java`

```
>_ ~/workspace/j--

$ bash ./bin/clemitter tests/clemitter/GenFactorial.java
```

Run `Factorial.class`

```
>_ ~/workspace/j--

$ java Factorial 5
5! = 120
```

The j-- Compiler

The `codegen()` method, starting at the root, recursively descends the AST, generating JVM bytecode

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Example (code generation for a method declaration)

JMethodDeclaration.java

```java
public void codegen(CLEmitter output) {
    output.addMethod(mods, name, descriptor, null, false);
    if (body != null) {
        body.codegen(output);
    }
    if (returnType == Type.VOID) {
        output.addNoArgInstruction(RETURN);
    }
}
```

The j-- Compiler

The j-- Compiler

The zip file `j--.zip` for the base *j--* compiler may be unzipped into any directory (referred to as `$j`) of your choosing

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The directory `$j/j--/src/jminusminus` contains:

The j-- Compiler

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The directory `$j/j--/src/jminusminus` contains:

- `Main.java`, the driver program

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The directory `$j/j--/src/jminusminus` contains:

- `Main.java`, the driver program
- A hand-crafted scanner (`Scanner.java`) and parser (`Parser.java`)

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The directory `$j/j--/src/jminusminus` contains:

- `Main.java`, the driver program
- A hand-crafted scanner (`Scanner.java`) and parser (`Parser.java`)
- `J*.java` files defining classes representing the AST nodes

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- `N*.java` files for translating JVM bytecode into MIPS code
- `j--.jj`, the JavaCC specification file for generating a scanner and parser

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- `j--.jj`, the JavaCC specification file for generating a scanner and parser
- `JavaCCMain.java`, the driver program that uses the generated scanner and parser

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- Other supporting Java files

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- `JavaCCMain.java`, the driver program that uses the generated scanner and parser
- Other supporting Java files

The directory `$j/j--/bin` contains wrapper scripts

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- `J*.java` files defining classes representing the AST nodes
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- `N*.java` files for translating JVM bytecode into MIPS code
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- `JavaCCMain.java`, the driver program that uses the generated scanner and parser
- Other supporting Java files

The directory `$j/j--/bin` contains wrapper scripts

The directory `$j/j--/tests` contains test programs

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- A hand-crafted scanner (`Scanner.java`) and parser (`Parser.java`)
- `J*.java` files defining classes representing the AST nodes
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- `N*.java` files for translating JVM bytecode into MIPS code
- `j--.jj`, the JavaCC specification file for generating a scanner and parser
- `JavaCCMain.java`, the driver program that uses the generated scanner and parser
- Other supporting Java files

The directory `$j/j--/bin` contains wrapper scripts

The directory `$j/j--/tests` contains test programs

The file `$j/j--/build.xml` is the Ant build configuration file

The j-- Compiler

Usage syntax for the *j--* compiler (`$j/j--/bin/j--`)

```
>_ ~/workspace/j--

$ bash ./bin/j--
Usage: j-- <options> <source file>
Where possible options include:
  -t  Only tokenize input and print tokens to STDOUT
  -p  Only parse input and print AST to STDOUT
  -pa Only parse and pre-analyze input and print AST to STDOUT
  -a  Only parse, pre-analyze, and analyze input and print AST to STDOUT
  -s  <naive|linear|graph> Generate SPIM code
  -r  <num> Physical registers (1-18) available for allocation; default = 8
  -d  <dir> Specify where to place output files; default = .
```

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  -d  <dir> Specify where to place output files; default = .
```

For example, to just tokenize the *j--* program `$j/j--/tests/jvm/HelloWorld.java`, run

```
>_ ~/workspace/j--

$ bash ./bin/j-- -t tests/jvm/HelloWorld.java
```

The j-- Compiler

Usage syntax for the *j--* compiler (`$j/j--/bin/j--`)

```
>_ ~/workspace/j--
```

```
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Where possible options include:
  -t  Only tokenize input and print tokens to STDOUT
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  -s  <naive|linear|graph> Generate SPIM code
  -r  <num> Physical registers (1-18) available for allocation; default = 8
  -d  <dir> Specify where to place output files; default = .
```

For example, to just tokenize the *j--* program `$j/j--/tests/jvm/HelloWorld.java`, run

```
>_ ~/workspace/j--
```

```
$ bash ./bin/j-- -t tests/jvm/HelloWorld.java
```

And to compile the program for the JVM, run

```
>_ ~/workspace/j--
```

```
$ bash ./bin/j-- tests/jvm/HelloWorld.java
```

Adding New Constructs to j--

Adding New Constructs to j--

j-- provides an elaborate framework for adding new Java constructs to the *j*-- language

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For example, to add the division operator (`/`) to *j*--, we must:

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- Modify the (lexical and syntactic) grammar and semantics files

Adding New Constructs to j--

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For example, to add the division operator (/) to *j--*, we must:

- Modify the (lexical and syntactic) grammar and semantics files
- Modify the scanner

Adding New Constructs to j--

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For example, to add the division operator (`/`) to *j*--, we must:

- Modify the (lexical and syntactic) grammar and semantics files
- Modify the scanner
- Modify the parser

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For example, to add the division operator (`/`) to *j*--, we must:

- Modify the (lexical and syntactic) grammar and semantics files
- Modify the scanner
- Modify the parser
- Implement type checking (aka semantic analysis)

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- Modify the parser
- Implement type checking (aka semantic analysis)
- Implement code generation

Adding New Constructs to j--

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For example, to add the division operator (`/`) to *j*--, we must:

- Modify the (lexical and syntactic) grammar and semantics files
- Modify the scanner
- Modify the parser
- Implement type checking (aka semantic analysis)
- Implement code generation
- Test the changes

Adding New Constructs to j--

Adding New Constructs to j--

lexicalgrammar

```
DIV          ::= "/"
```

Adding New Constructs to j--

lexicalgrammar

```
DIV          ::= "/"
```

grammar

```
multiplicativeExpression ::= unaryExpression
                               { ( STAR | DIV ) unaryExpression }
```

Adding New Constructs to j--

lexicalgrammar

```
DIV          ::= "/"
```

grammar

```
multiplicativeExpression ::= unaryExpression
                                { ( STAR | DIV ) unaryExpression }
```

semantics

```
JBinaryExpression:
- JDivideOp
  - lhs and rhs must be integers.
```

Adding New Constructs to j--

Adding New Constructs to j--

TokenInfo.java

```
enum TokenKind {
    DIV ("/"),
}
```

Adding New Constructs to j--

TokenInfo.java

```
enum TokenKind {
    DIV ("/"),
}
```

Scanner.java

```
            if (ch == '/') {
                nextCh();
                if (ch == '/') {
                    // CharReader maps all new lines to '\n'.
                    while (ch != '\n' && ch != EOFCH) {
                        nextCh();
                    }
                } else {
                    return new TokenInfo(DIV, line);
                }
            }
```

Adding New Constructs to j--

Adding New Constructs to j--

JBinaryExpression.java

```
class JDivideOp extends JBinaryExpression {
    public JDivideOp(int line, JExpression lhs, JExpression rhs) {
        super(line, "/", lhs, rhs);
    }

    public JExpression analyze (Context context) {
        // TODO
        return this;
    }

    public void codegen(CLEmitter output) {
        // TODO
    }
}
```

Adding New Constructs to j--

Adding New Constructs to j--

Parser.java

```java
    private JExpression multiplicativeExpression() {
        int line = scanner.token().line();
        boolean more = true;
        JExpression lhs = unaryExpression();
        while (more) {
            if (have(STAR)) {
                lhs = new JMultiplyOp(line, lhs, unaryExpression());
            }
            else if (have(DIV)) {
                lhs = new JDivideOp(line, lhs, unaryExpression());
            }
            else {
                more = false;
            }
        }
        return lhs;
    }
```

Adding New Constructs to j--

Adding New Constructs to j--

JBinaryExpression.java

```java
class JDivideOp extends JBinaryExpression {
    public JExpression analyze(Context context) {
        lhs = (JExpression) lhs.analyze(context);
        rhs = (JExpression) rhs.analyze(context);
        lhs.type().mustMatchExpected(line(), Type.INT);
        rhs.type().mustMatchExpected(line(), Type.INT);
        type = Type.INT;
        return this;
    }

    public void codegen(CLEmitter output) {
        lhs.codegen(output);
        rhs.codegen(output);
        output.addNoArgInstruction(IDIV);
    }
}
```

Adding New Constructs to j--

Adding New Constructs to j--

Division.java

```java
import java.lang.Integer;
import java.lang.System;

public class Division {
    public static void main(String[] args) {
        int a = Integer.parseInt(args[0]);
        int b = Integer.parseInt(args[1]);
        System.out.println(a / b);
    }
}
```

Adding New Constructs to j--

Adding New Constructs to j--

To compile the changes to the *j*-- compiler, go to `$j/j--`, and run

```
>_ ~/workspace/j--
$ ant
```

Adding New Constructs to j--

To compile the changes to the *j--* compiler, go to `$j/j--`, and run

```
>_ ~/workspace/j--
$ ant
```

To compile the test program using *j--*, run

```
>_ ~/workspace/j--
$ bash ./bin/j-- tests/jvm/Division.java
```

Adding New Constructs to j--

To compile the changes to the *j--* compiler, go to `$j/j--`, and run

```
>_ ~/workspace/j--
$ ant
```

To compile the test program using *j--*, run

```
>_ ~/workspace/j--
$ bash ./bin/j-- tests/jvm/Division.java
```

To run the test program (`Division.class`), run

```
>_ ~/workspace/j--
$ java Division 42 6
7
```