Espresso, A Java compiler written in Java

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A report that presents Espresso, a Java compiler developed at BU during a directed study in advanced compiler design. The main goal is to introduce the basic concepts and the architecture of Espresso, in order to provide a basis for future work.

Espresso, a Java compiler written in Java is presented. It was developed in the course of a directed study in advanced compiler design over a period of about 3 months under the supervision of Prof. A. Kfoury. The main contributors to design and implementation up to the current version 0.3 are Santiago M. Pericas (*email: santiago@cs.bu.edu*) and Karl Doerig (*email: kdoerig@cs.bu.edu*)

Espresso's main purpose is to serve as a workbench for students interested in applying their theoretical knowledge from programming languages and compiler design and construction in the context of a compiler for a modern object oriented programming language.

To enable and encourage to continue the work started, the overall architecture and important design aspects are documented.

A detailed list of language features that are currently missing or only partially available is compiled.

Suggestions for improvements for both functionality and performance are made.

A short guide on how to make Espresso available for use and development is given.

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1.0 Introduction

Java, an object oriented programming language developed at *Sun Micro Systems* was first released in 1996. It quickly became one of the most widely used programming language in industry, in particular for the client side programming of web based internet and intranet applications.

The strength of Java lies in a carefully designed language that includes most of the benefits provided by C++, while at the same time being more compact and consistent in its design. Among others, one major reason for its success was the standardization of the Java compiler and the portability of compiled class files across platforms and operating systems.

The Java language as specified in its current version 1.1 added only one major new feature to the grammar of the language presented in 1996, namely *inner classes*.

Espresso, a Java compiler developed at Boston University in a directed study project, provides a compiler for a state of the art object oriented programming language to students who are interested to turn their theoretical knowledge from graduate level programming language and compiler design and construction courses into practical application and improvement of a modern programming language compiler. Because Espresso is an open project and contributions are highly encouraged.

In its current version, Espresso grammatically conforms to the Java language specification version 1.0.

Section 2 first presents the overall architecture of Espresso. It then introduces to design and concepts of the abstract syntax tree AST, the *SymbolTable*, and the *JavaImportManager*, a component responsible for looking up and loading compiled Java classes into Espresso's environment.

Section 3 describes some general concepts applied during parsing and construction of the AST. It also documents the handling of special cases in this compilation step.

Section 4 introduces to type checking and highlights key concepts around which type checking is built up. It includes a detailed description of the type hierarchy and introduces to an interesting metric discovered by Santiago M. Pericas. This metric is central during type checking, because it allows to deal with the various situations involving primitive types, reference types and method types in a uniform way.

Section 5 presents the overall architecture of the code generation step and describes important concepts applied in this phase.

Section 6 contains a collection of proposals for future work. It first contains a list of Java language features that are currently only partly type checked, and/or for which code generation is missing or incomplete. It also points out possible improvements of the generated code by applying appropriate optimization techniques. Finally it makes some suggestions to improve error reporting.

Section 7 gives some basic information on Espresso's project structure. It also defines the procedure you have to follow if you want to contribute to Espresso's further improvement.

1.1 Goals

The main motivations and reasons for this project can be summarized as follows:

- Provide a modern and attractive platform for future work and experimentation to graduate students of both, programming languages and compiler design and construction.
- Open an opportunity to apply some of the technology from the *Church Projec*t, and the OO seminar at Boston University to a industry standard OO programming language.
- Demonstrate that a compiler for a major part of the Java language could be constructed in a one semester project involving 2 students.
- Show that the constructed compiler would compile in comparable time and would generate code of similar quality as Sun's javac compiler does.
- Explore the possibilities of modern compiler construction tools applied to the compilation of a modern object oriented programming language.

1.2 Results

Most of the implementation oriented objectives have been reached. A first version of Espresso was available for testing and performance evaluation after about 3 month of hard work in May 1998. During summer and fall 1998 further enhancements have been made to both performance and functionality. Espresso's most recent version in v0.3 For a list of missing or incomplete features in Espresso along with suggestions for optimizations and improvements see "Proposals for future work" on page 31.

1.3 Glossary

Abbreviation	Meaning	online reference
JLS	*Java language specification*	http://java.sun.com/docs/books/jls/index.html
JVM	*Java virtual machine*	http://java.sun.com/docs/books/vmspec/html/VMSpecTOC.doc.html
JIM	JavaImportManager	none
BNF	Backus Naur form	none
RHS	right-hand-side of a production	none
LHS	left-hand-side of production	none
UML	Unified Modelling Language	http://www.rational.com/uml/html/summary/index.html
AST	Abstract syntax tree	none

1.4 Conventions

Class names, Java language statement and expression names are written in *italic.*

2.0 Architecture

Espresso is built using a compiler construction tool called *JavaCC* from *SunSoft (trademark Sun Microsystems).* Given a *JavaCC* grammar file as input, *JavaCC* constructs a LL(k) parser along with a token manager implementing the lexer for the language to be compiled.

The *JavaCC* grammar file for Espresso *(Java1.0.2.jj)* contains the following building blocks :

- The lexical definitions using regular expressions
- The productions for the Java grammar using a BNF like notation. Embedded in these productions are semantic actions to direct the process of parsing and to construct the abstract syntax tree.
- A block of Java code which represents the skeleton for the parser class which is constructed.

Each RHS of a grammar productions is turned into a method of the constructed Java parser, and each LHS is turned into an appropriate method call.

The generated Java parser is used to parse the Java source code. During this compilation step, an abstract syntax tree is constructed which forms the basis for the type checking and code generation phase.

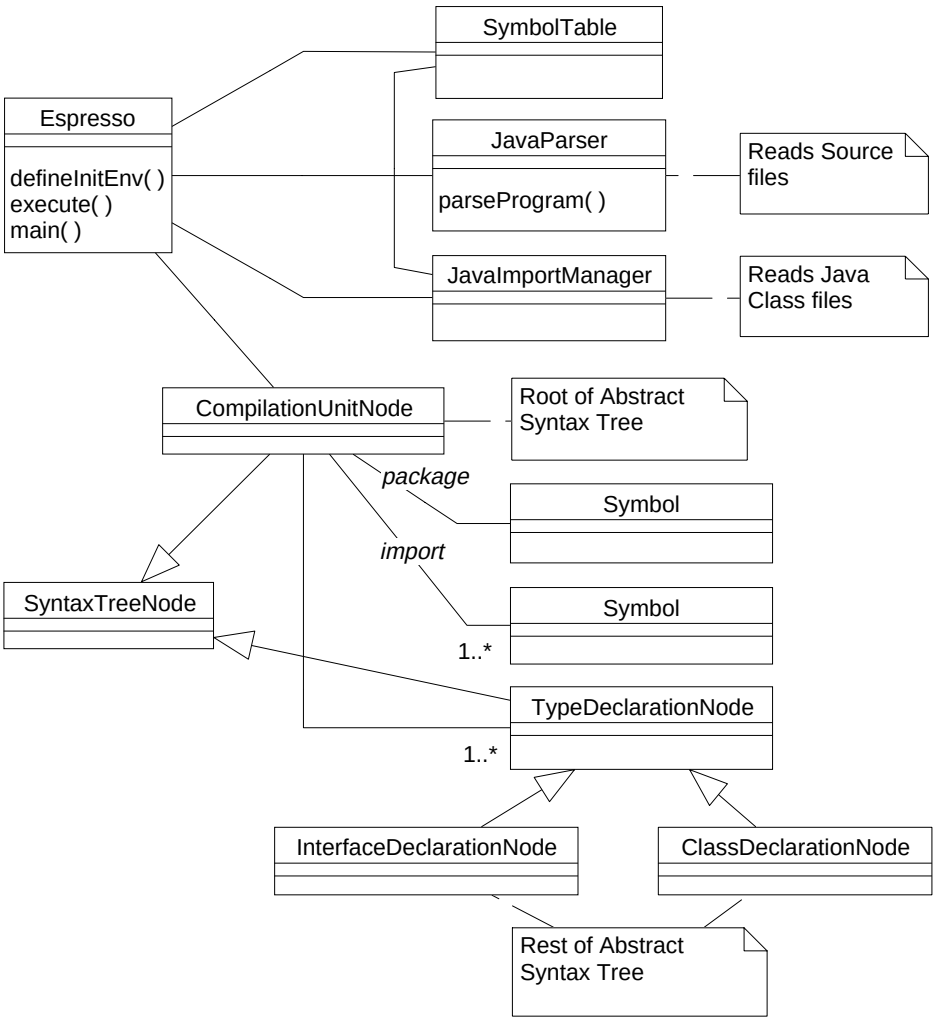
A complete set of documentation for *JavaCC* is available through the JavaCC homepage *http://www.metamata.com/javacc/DOC.* The Espresso home page also contains some introductory slides to basic concepts of *JavaCC.*

The package *JavaClass* used to read and write Java class files, and the package *Class-Gen* used during code generation were downloaded from Markus Dahm home page at *http://www.inf.fu-berlin.de/~dahm/JavaClass/* and adapted to our needs.

2.1 Overview

The UML class diagram in *Figure 1 on page 6* shows the top level structure of Espresso, including the root of the abstract syntax tree.

FIGURE 1. UML Class Diagram with class Espresso as top level class



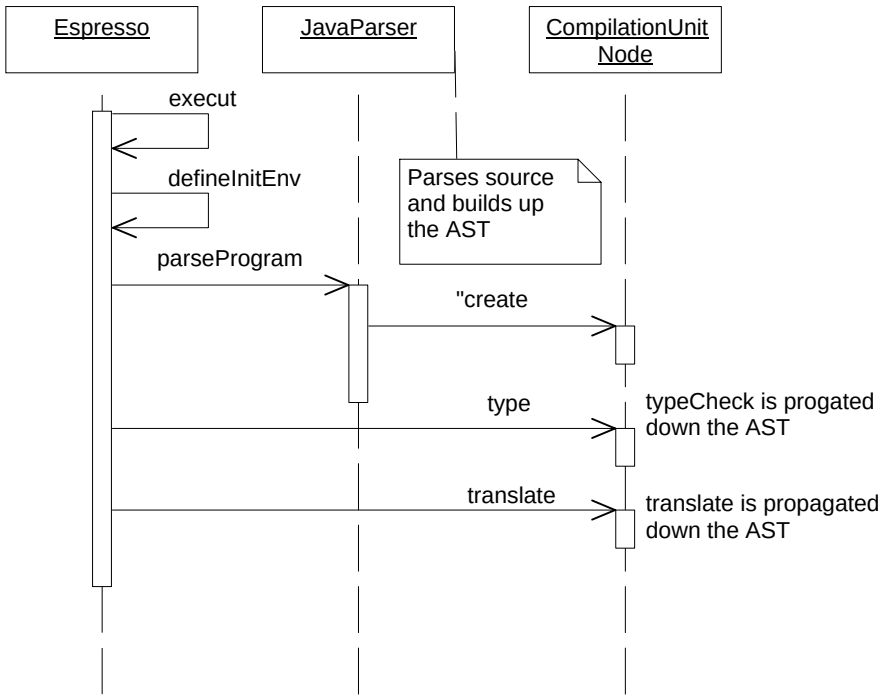
Note that an object of type *CompilationUnitNode* represents the root of the AST.

2.2 The main class Espresso

Espresso is the main class of the Espresso compiler. Its *execute* method creates an object for each, the *SymbolTable*, the *JavaParser* and the *JavaImportManager*.

The UML sequence diagram in *Figure 2 on page 7* shows an overall picture of the order, in which Espresso goes through the different phases of compiling.

FIGURE 2. UML Sequence Diagram for different compilation phases



First the initial environment is set up. Next the *parseProgram* method of *JavaParser* is called which returns the root of the AST that was constructed during this step.

On the root node of the AST (an object of type *CompilationUnitNode*), Espresso invokes the *typeCheck* method. Each node propagates the *typeCheck* call down the AST according to its own type checking logic.

If no error occurred during the type checking phase, Espresso calls the *translate* method on the root node of the AST which triggers the generation of code for the Java Virtual Machine JVM. Again, each node propagates the t*ranslate* call down the AST if required by its translation rules.

2.3 The abstract syntax tree (AST)

During the parsing step of Espresso, an AST is constructed. The nodes of the AST are instances of classes which are part of a large class hierarchy with the class *SyntaxTreeNode* as its common base class. All AST nodes dealing with the various types of expressions share the common base class *ExpressionNode*. Similarily, nodes representing the different types of statements share the common base class *StatementNode*.

A detailed documentation of the class hierarchy is available through the Espresso home page (*see javadoc*). A graphical representation of the class hierarchy is available through the *SGI Java Development Environment CosmoCode.*

With the nodes of the AST being related in a class hierarchy, methods for type checking, evaluating expressions and translating can be defined as abstract methods at the appropriate levels, and concrete implementations can be provided. Using this approach, common functionality of related classes can be factored out and appropriate code can be placed in common ancestors in the class hierarchy.

2.4 The symbol table

Espresso's symbol table is implemented as a flat data structure using a hashtable. In order to deal with the different scopes, a hierarchical key concept was developed. The key entries in the symbol table are represented by objects of type *Symbol*, a class that provides methods to construct symbols for the different entities, and to retrieve their parts.

Table 1 on page 8 shows the entities currently maintained in the symbol table, along with the symbol encoding scheme for each entity.

TABLE 1. Encoding scheme of symbol types

Symbol type	Encoding Scheme
Packages	*package name*
Types (Classes and Interfaces	*package name.class name*
Fields	*package name.class name* **.** *field name*
Methods	*package name.class name.method name.*()
Formal Parameters	*package name.class name.method name.0.formal parameter name*
Local Variables	*package name.class name.method name.scopeid.local variable name*
Labels	*label name.:*
Primitive Operators	symbol for operators. *Examples* : "+", "==" ...

For each of this entities, the symbol table provides an *add* and a l*ookup* method. The reason for having entities dealing with *primitive operators* will be discussed in *Section 4.3 on page 21*..

2.4.1 Relating symbol table and AST

During the parsing phase of Espresso, appropriate entities are added to the symbol table. This includes entities appearing in the compiled unit as well as relevant entities (type declarations, method declaration, field declarations) which needed to be imported from previously compiled Java class files.

Instead of providing new classes to contain relevant information associated with each type of entity in the symbol table, each entry points back to the node(s) in the in the AST where it was created, or where relevant data associated with it can be retrieved.

Table 2 on page 9 shows the different entities of the symbol table and the objects that are stored along with them.

TABLE 2. Symbol table entities and their related AST nodes

Symbol type	Related AST nodes
Packages	*CompilationUnitNode*
Types (Classes and Interfaces)	*TypeDeclarationNode*
Fields	*FieldDeclarationNode*
Methods	Vector[a] of *MethodDeclarationNode*
Formal Parameters	*FormalParameterNode*
Local Variables	*LocalvariableDeclarationNode*
Labels	*LabeledStatementNode*
Primitive Operators	Vector [b]of *MethodType*

a. Overloading of methods

b. Overloading of primitive operators

The approach of maintaining imported entities in the same manner as entities present in the compiled unit allows for a uniform handling during type checking and code generation.

Figure 3 on page 10 shows a small compilation unit along with the resulting AST and with the entries created in the symbol table.

FIGURE 3. Compilation unit with AST and symbol table

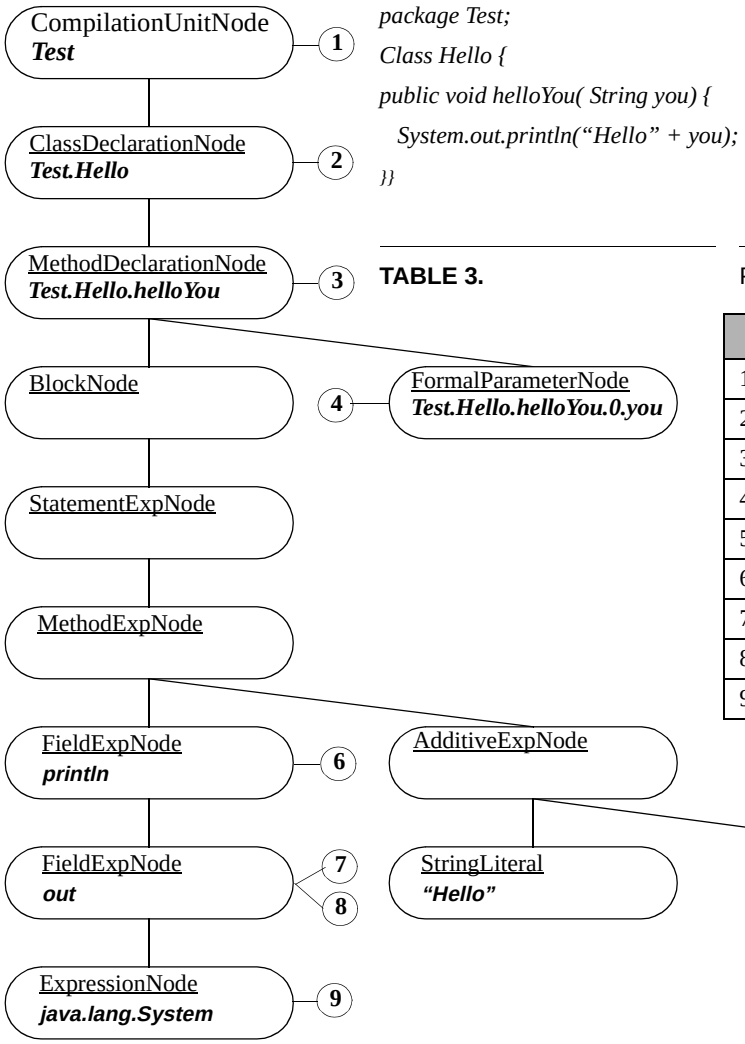


TABLE 3. Partial symbol table for code

	Symbol (key)	Rem.
1	Test	Package
2	Test.Hello	Class
3	Test.Hello.helloYou.()	Method
4	Test.Hello.helloYou.0.you	Formal
5	java.lang.String	Class (JIM)
6	java.io.PrintStream.println.()	Method (JIM)
7	java.lang.System.out	Field (JIM)
8	java.io.PrintStream	Class (JIM)
9	java.lang.System	Class (JIM)

Note, that for entries of the symbol table created by the *JavaImportManager* (marked JIM in rightmost column), appropriate nodes for the AST are also created but not shown. The AST nodes marked 6 to 9 have triggered loading of classes *java.lang.System* and *java.io.PrintStream* and as a result entries 6 to 9 were added to the symboltable.

2.5 JavaImportManager JIM

JIM provides a set of methods to accomplish the following two tasks during compilation of a unit:

- Determine whether a simple name appearing in the source code can unambiguously be fully qualified as a type name.
- Make appropriate portions of compiled Java class files available to the environment of Espresso.

Each Java class file contains compiled code for exactly one class or interface. The exact format of a Java class file is part of a standard defined by *Sun Microsystems* and is available online at
http://java.sun.com/docs/books/vmspec/html/VMSpecTOC.doc.html.
This standard quarantees that compiled Java classes are portable across platforms and operating systems.

Alternatively, Java class files may be grouped together in *Zip* files, or starting with JDK 1.1.4 in *Jar* files, a new archive format promoted by Sun.

JIM fully supports all currently defined formats. To accomplish the rather tedious task of reading the content of class files and of constructing the corresponding *constant pool*, JIM uses a package called *classgen* which is available to the public under the *GNU* licence agreement.

2.5.1 The Java CLASSPATH

The Java Virtual Machine JVM runtime system provides access to the Java resource CLASSPATH.

This resource is a vector of locations in the host file system at which Java class files can be lookup up. This locations are either root directories of packages or path descriptions to class files which are grouped together in either *Zip* files or *Jar* files.

Part of the content of the CLASSPATH vector is predefined by resource definitions set up by the JDK installation procedure. Additional definitions can be added by the user through the CLASSPATH environment variable.

2.5.2 Fully qualifying names

The Java Language Specification JLS defines a mode of importing classes called *import on demand* (*Ex. java.lang.**).

Instead of explicitly listing each class in the import section of the java source file, import on demand can be used.

If during compilation, a simple name possibly representing a type name is encountered, JIM has to determine whether this simple name can be matched with a Java class file name. To accomplish this task it has to build the cross product between the entries in the CLASSPATH vector and the entries in the *import on demand* list, then patch the simple name to each of them and try to look it up. If a lookup was successful, the concatenation of the simple name and the appropriate portion of the *import on demand* entry repre-

sents the fully qualified name for the type. In addition, the JLS requires that a simple name never refers to a type name that is present in more than one package. JIM makes sure that a simple name can be qualified uniquely and issues an error otherwise.

To improve the lookup performance, JIM uses several caches to register misses as well as hits.

2.5.3 Loading class files

Portions of Java class files imported by the compiled unit need to be added to the environment of Espresso. For each imported class, JIM adds the appropriate type to the symbol table.

For each non private method found in the class file, JIM adds a method to the symbol table. Similarly, for each non private field, a field is added to the symbol table.

For each symbol added to the symbol table, an appropriate AST node is stored along with it.

The loading of a class file is triggered by the following situations (provided the class is not itself part of the compiled unit):

- a class is imported by default as defined by the JLS.
- a class is explicitly mentioned in the import section of the compiled unit.
- a class/interface is the superclass/superinterface of the class/interface that is compiled.
- a class is an interface, that is implemented by a class in the compiled unit.
- a class was imported on demand.
- if during type checking, a class is needed either to determine the most specific method to be invoked by a method expression or to verify access modifiers and types of fields appearing in field expressions.

3.0 Parsing and constructing the AST

Espresso's parser *JavaParser* is constructed by *JavaCC* from the JavaCC grammar file java1.0.2.jj, which contains the code specifying the lexical definitions and the grammar productions for the language. Grammar productions are augmented by semantic actions to manage and execute the construction of the AST and to control and update the environment as parsing goes along.

General concepts of LL(k) parsing are not discussed here and are available through textbooks on compiler construction. For details on the *JavaCC* grammar and the general environment of *JavaCC* read the mini tutorial on JavaCC available through the JavaCC home page..

This section mainly elaborates on special cases during parsing, which are related to the following fields of JavaParser:

- *className_d*

- *methodName_d*
- *scopes_d*
- *counter_d*
- *label_d*
- *fieldInit_d*
- *staticInit_d*
- *forwardTypes_d*

3.1 Keeping track of actual package, class, method

The class *JavaParser* provides a set of fields containing symbols which are used often during parsing. Those of particular importance for constructing symbols during parsing are presented here.

There is a field *className_d*. which at any point during parsing contains the fully qualified name of the currently parsed type (class/interface). Because a Java compilation unit may contain the definition of more than one type, this field needs to be updated each time a new type declaration is seen.

The field *methodName_d* always holds the fully qualified name of the currently parsed method. It is used in mostly in places where symbols for local variables need to be constructed.

3.2 Local scopes

During parsing, the scoping rules for classes, methods, fields, formal parameters and local variables have to be enforced. For classes, methods and fields, the scheme using *package name , class name* and *field-/method name* suffices to provide for the full flexibility defined by the language.

For names of formal parameter and local variables, an additional scope identifier is needed.

Espresso solution to this problem is to provide a scope stack, a data structure which is maintained in the *JavaParser* field *scopes_d*. The scope stack is implemented as a stack containing instances of *Integer* objects.

Each time a new local scope is entered, a fresh object of type integer is retrieved from *JavaParser* field *counter_d* and pushed onto the scope stack.

Names of formal parameters and local variables appearing within a particular scope receive the current top of the scope stack as their scope identifier. This identifier along with the fully qualified method name and the name of the variable itself suffices to uniquely identify a local variable or a formal parameter.

Whenever the parser sees the end of a scope, the current top of the scope stack is popped off.

It might be worth pointing out, that names of formal parameters and local variables defined at the outermost scope of a method share the same scope.

Similarly, variables declared in the initializer part of the *for* statement share the same scope with variables declared at the outermost level within the *for* statement.

3.3 Wrapping of control statements

In order to ease code generation and to avoid passing around *break lists* and *continue lists* (containing branch instructions to be backpatched) across statement and block boundaries, a number of control statements are wrapped with labeled statements during parsing. The list of control statements and expression lists currently wrapped by the parser includes those, which either potentially contain *break* and/or *continue* statements, or for which a special handling for the *continue* statement is needed.

The language constructs currently handled this way are:

- *switch* statement
- *while* statement
- *do* statement
- *for* statement
- The expression list representing the *for update* clause of the *for* statement.

If the statements listed above are not already labeled in the source program, the parser pushes a fresh label onto the label stack maintained in *JavaParser* field *label_d* and wraps the statement with a *labeled* statement using this newly created label. For the update clause of the *for* statement, a new label is always created. If during parsing of the above constructs, a *break* or *continue* statement is seen and the optional label associated with the statements is not present in the source program, than the parser assigns the current top of the label stack as the label to it.

Whenever the parser reaches the end of one of the statements above, the current top of the label stack is popped off.

Using this method, *break* and *continue* statements are always related to the proper surrounding statements, regardless of whether the source program contains a label or not.

The method used by the parser to construct unique labels is identical to the one used for generating unique scope identifiers.

3.4 Adding a default constructor

The Java language does not enforce the programmer to provide a constructor for a class, but instead requires the compiler to add a default constructor, if the source program does not contain one.

Therefore, whenever the end of a class declaration is reached, the parser has to verify whether at least one constructor was defined, and add a default constructor to the class

body otherwise. This default constructor needs to call of the default constructor of the superclass of the class.

3.5 Non static initializers for fields

Non static fields of a class (instance variables) are initialized by the JVM with a default value whenever a new object of this type is created. If the source program defines an initializer for the field, this initializers has to be used instead. The solution proposed by the JLS is to add all initializers in textual order to each constructor, by turning them into assignments to the appropriate fields.

To implement this solution in Espresso, *JavaParser* maintains a special field *fieldInit_d* representing a block, to which field initializers are added whenever they are encountered, and after constructing an assignment expression for it.

After verifying for the presence of at least one constructor in the class (at the end of *ClassDeclaration()*), the block containing these initializers is added to each constructor found in the body of the class.

3.6 Static initializers, and initializers for static fields

Static fields of a class are initialized exactly once, when a class is loaded by the JVM.

If the programmer provides initializers for static fields, or if special static initializer blocks are defined, then a special static constructor <*clinit*> needs to be added to the class body by the compiler.

The JLS requires, that these initializers are added to the static constructor, and that they are executed in the textual order of there appearance in the source program.

Whenever the parser encounters a declaration of a static field with an initializer, it turns the initializer into an assignment to that field, and adds it to the *JavaParser* field *staticInit_d*. In a similar way, statement expressions found in static initializer blocks are added to the same field, always taking the textual order into account.

At the end of parsing a *class declaration*, the parser adds a static constructor to the class body (provided *staticInit_d* is not empty).and adds statements and statement expressions contained in *static_init_d* to the block of the static constructor.

3.7 Verifying closure of the compiled unit

As a last step of the parsing phase, we need to verify whether all references to types (classes/interfaces), methods and fields appearing in the source code have been uniquely matched with either declarations found in the compiled unit itself or with classes loaded by JIM.

The step is needed, because the Java language allows forward references to types, methods and fields.

Resolving forward references to fields and methods is done during parsing.

If type names appearing in *type* expressions, *this* expressions and *super* expressions were not resolvable during parsing, the corresponding symbols are added to a special *JavaParser* field *forwardTypes_d*.

This last step has to verify, whether each type contained in this field is known in the environment by now, or reports an error otherwise.

4.0 Type checking

After an AST was successfully constructed by *JavaParser*, type checking is performed on the nodes of the AST. Each node of the AST provides a *typeCheck* method that is responsible to perform the type checking of the language construct is represents and to propagate type checking do its successors in the AST if required.

During parsing, types declared for methods, fields, formal parameters and local variables are collected by the parser, and turned into instance of classes of the type hierarchy. Constructing type instances also includes to encode these types according to the encoding scheme defined by the JVM to make them comparable to the ones loaded from class files.

The main tasks of type checking is to determine the resulting types of expressions, to verify, that access restriction for packages, classes, methods and fields are respected, and in general, to enforce the typing rules imposed by the JLS.

This section introduces to the Espresso's type checking concepts and highlights some of the more difficult or non standard cases.

4.1 Espresso's type hierarchy

The type hierarchy developed for Espresso is among the most important and central concepts of Espresso. Almost all non trivial functions for type checking are integrated in this hierarchy. It also plays a major role in supporting code generation.

Java's type system distinguishes between two kinds of types, *primitive* types and *reference* types.

Primitive types include the special type *boolean*, and all the *numeric* types.

Numeric types are further divided into *integral* types (which includes the types *byte, short, int, long* and *char*), and *floating point* types (*float, doubl*e).

There are three kinds of *reference* types in Java, *class* types, *interface* types and *array* types. In addition, a special *null* type is also defined.

For a comprehensive introduction to Java's type system see JLS Ch. 4.1

Espresso's type hierarchy reflects in large the hierarchy presented above. The differences are the following:

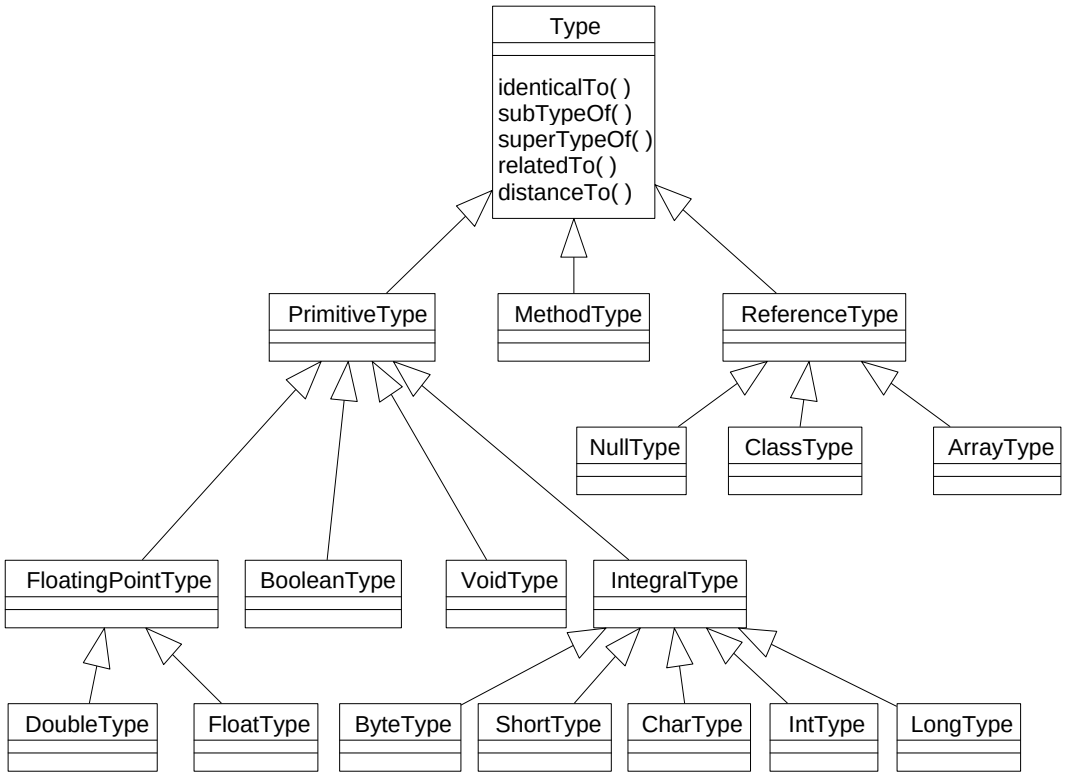
- The *null* type is part of the *reference* types
- The type *void* is included with the *primitive* types

Espresso's type hierarchy also contains a special type for *methods*. Although the Java language has no objects of type *method*, the availability of this special type proved to provide an elegant solution for many problems during type checking and code generation.

The common base class of Espresso's type hierarchy is the class *Type*. It defines a number of abstract binary predicates and a distance function.

The UML class diagram in *Figure 4 on page 17* shows Espresso's type hierarchy in detail.

FIGURE 4. UML class diagram of Espresso's type hierarchy



The remainder of the section provides an exact definition of the predicates shown in the above class diagram.

The definition of the distanceTo function will be given in the subsection covering the distance matrix.

4.1.1 indenticalTo

A primitive type is identical to another type, if the other type represents the same primitive type.

A class type is identical to another type, if the other type is a class type with the same name.

An array type is identical to another type, if the other type is an array type with the same dimensions, and if the two base types are identical to each other.

The null type is identical to another type, if the other type is also the null type.

A method type is identical to another type, if the other type is also a method type, and moreover, if the return types, and the types of the formal parameters are identical to each other. (There is also a version that ignores the return type: *equality modulo return type*).

4.1.2 subTypeOf

A primitive type is subtype of another type, if the two types are identical to each other.

A class type is a subtype of another type in the following cases:

- the two type are identical
- the supertype of the class type is a subtype of the other.
- if the class type extends or implements interfaces, and one of the interfaces is a subtype of the other type.

A class type is not a subtype of the other, if they are not identical and the class type itself is *Object*.

The null type is subtype of another type, if the other type is either identical to the null type, or the other type is a class type or an array type.

An array type is a subtype of another type in the following cases.

- the two types are identical
- the other type is also an array type with identical dimensions, and the base type of the array type is a subtype of the base type of the other array type.
- the other type is a class type of type *Object* or *Cloneable*.

A method type is a subtype of another type, if the two are identical.

4.1.3 superTypeOf

A primitive type is supertype of another type, if the two types are identical.

A class type is a supertype of the other type, if the other is a subtype of it.

The null type is a supertype of another type, if the other is also the null type.

An array type is a supertype of another type, if the other type is a subtype of it.

A method type is a supertype of another type, if the two are identical.

4.1.4 relatedTo

Two types are related to each other, if they are in subtype relation.

4.2 The distance metric

The typing rules imposed by JLS require a compiler to choose the most specific method among all the methods that are applicable for a particular method invocation. Moreover, the JLS also defines a host of conventions a compiler has to deal with, when type checking of expressions involving primitive operators is performed. This includes, which primitive types are assignable to each other, and what the result type of a unary or a binary primitive operator is, taking the types of the operands into consideration.

In the course of developing Espresso, Santiago M. Pericas discovered a central metric that allowed to cover the different requirements with a single concept, a distance function. The general idea is to define quantities bigger than or equal to zero for operations which are allowed between certain types, and to define negative quantities for operations which are not applicable between certain pairs of types.

During checking, the smallest quantity bigger than or equal to 0 is the one that needs to be chosen by the type checker. If no such smallest positive quantity was found for a particular case, then that case was not typeable.

The matrix in *Table 4 on page 19* documents the distanceTo function for all types of the type hierarchy.

TABLE 4. Distance matrix

	boolean	byte	short	char	int	long	float	double	void	Null	Class	Array	Method
boolean	0	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞
byte	-∞	0	1	-∞	2	3	4	5	-∞	-∞	-∞	-∞	-∞
short	-∞	-∞	0	-∞	1	2	3	4	-∞	-∞	-∞	-∞	-∞
char	-∞	-∞	-∞	0	1	2	3	4	-∞	-∞	-∞	-∞	-∞
int	-∞	-∞	-∞	-∞	0	1	2	3	-∞	-∞	-∞	-∞	-∞
long	-∞	-∞	-∞	-∞	-∞	0	1	2	-∞	-∞	-∞	-∞	-∞
float	-∞	-∞	-∞	-∞	-∞	-∞	0	1	-∞	-∞	-∞	-∞	-∞
double	-∞	-∞	-∞	-∞	-∞	-∞	-∞	0	-∞	-∞	-∞	-∞	-∞

TABLE 4. Distance matrix

	boolean	byte	short	char	int	long	float	double	void	Null	Class	Array	Method
void	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞
Null	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	0	0	0	-∞
Class	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	C	-∞	-∞
Array	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	A	-∞
Method	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	-∞	M

The distance between class types (*indicated by* **C** *in the matrix above*) is calculated as follows:

- The distance between two identical class types is 0
- The distance between *Object* and any other class type is $-\infty$.
- If the class type is a subtype of the other type, than the distance is equal to the number of levels of subtypes between them. The direct supertype is at distance 1.
- If none of the above is the case, but the type has superinterfaces, then the first superinterface that has a distance greater than or equal to 0 with the other type determines the distance between the two class types.

The distance between array types of identical dimensions (*indicated by* **A** *in the above matrix*) is defined as follows:

- If the base type of both types are class types, then the distance between an array type and another array type is equal to the distance of the base type of the array to the base type of the other type.
- If not both base types are class types, than the distance between the two array types is 0, if the base types are identical.
- In all other cases, the distance is $-\infty$.

The distance between two method types (*indicated by* **M** *in the matrix above*) is defined as the *sum of the distances* between the individual arguments of the two methods. More formally, let $S = (s_1 x .. x s_n)$ and $T = (t_1 x .. x t_n)$ be two method types and let δ be the distance function. Then the distance $\delta(S,T)$ is defined as:

$$\sum_{i=1}^{n} \delta(s_i, t_i)$$

If any single distance between an argument of the method type *S* and the corresponding argument of the method type *T* is less than 0, the resulting distance is $-\infty$.

4.3 Type checking for primitive operators on primitive types

The JLS defines pages and pages of rules that need to be enforced when applying primitive operators on primitive types, including conditions, under which widening or narrowing of primitive types has to take place.

Espresso's type checking implements all this rules in a uniform and very elegant way. For all the unary and binary operators on primitive types, an initial environment is added to the symbol table.This environment defines for each unary primitive operator, for which primitive type it is defined, and what the resulting primitive type for the operation is. This is done by adding the primitive operator to the symbol table, along with a method type for each possible type supported by the operator describing the type of the argument and the result type.

Binary operators on primitive types are defined in a similar way by providing a method type with two arguments and a result type.

Note that the order in which these method types are added to the symbol table for a particular operator directly affects the desired outcome of a lookup.

To type check an expression involving a primitive operator we only need to determine the types of its arguments, create an appropriate method type, and use the definitions given in the initial environment together with the *distanceTo* function presented above, to determine whether the expression type checks and what the result type is.

4.4 Finding the most specific method

Espresso's implementation of the type for class types (*ClassType*) provides a method *findMethod*, to determine the most specific method declaration for a particular method invocation expression (*MethodExpNode*) as defined in JLS *15.11.2.2*

Type checking of *MethodExpNode* first sets up an instance of class *MethodDesc,* which contains a method type describing the signature of the method invocation expression, the name of the method and some other fields that are used to keep track of additional information that is collected during the search.

The overall idea is to pass this information to the initial class type determined by the parser, and to get the most specific method back.

Within *findMethod*, the symbol table is looked up for matching methods using the name of the type and the method name that was initially provided. Methods obtained from the symbol table with a matching number of arguments are sorted out, and among those, the most specific is chosen by applying the *distanceTo* function of the initial method type to the type of each candidate method. Once the most specific candidate method declaration of a particular type (class/interface) is determined, the search continues recursively up to that types supertype.
The search either stops when an ambiguity among candidate method declarations was encountered (*throws a type check error*), or when Java's primordial type *Object* was reached. If searching was successful, the most specific method is returned to the initial caller.

During the search up the type inheritance hierarchy, *findMethod* also takes care of requesting JIM to load required class files in order to make the appropriate type information available in the symbol table.

The same search idea is also applied, when determining the most specific constructor declaration while type checking constructor invocation expressions and allocation expressions

4.5 Finding the right field

Espresso's *ClassType* also provides a method for finding fields in order to type check field expressions. Unlike for finding methods, finding the appropriate field declaration not only needs to check in superclasses of a particular type, but in its superinterfaces as well. The technique applied for this search is similar to the one used for finding methods.

4.6 Type checking of initializers for variables

The JLS defines special rules, that apply to initializers of variables.While in normal assignments an integer constant is always of type int, and the programmer needs to explicitly cast the type down when the RHS of the assignment is an integral type smaller than int, initializers of variables need to be treated differently.

In fact, the JLS requires, that initializers of variables are always evaluated. If the result of the evaluation is a constant expression, then the compiler needs to verify, whether the value of the constant expression fits into the primitive type that needs to be initialized.

The expression hierarchy of the AST provides a special evaluation function for each kind of expression which possibly evaluates to a constant expression. The expression base class *ExpressionNode* defines a method *evaluate*. Each subclass of *ExpressionNode* that potentially evaluates to a constant expression overwrites this method and invokes the *evaluate* method of its arguments. If no exception was thrown, the appropriate operation is performed (*Ex: addition or subtraction in AndExpNode)* on the constant expressions resulting from its arguments and handed up the expression tree in the AST. The *ExpressionNode* then provides a second method *evaluateExp* that can be called in the type checking phase, which either catches an exception and returns *null* indicating, that the initializer did not evaluate to a constant expression, or returns the evaluated value, which is used by the type checker to verify, whether it fits into the type of the initialized variable.

5.0 Code generation

After successful completion of type checking, the last phase of the compiler is responsible for generating code.

The main class Espresso initiates the translation phase by invoking the translate method of the root node of the AST. The different nodes in the AST propagate the translation calls down to their children as needed.

Espresso uses the package *classgen*, which is available under GNU's licence agreement. This package provides a complete infrastructure to build up a *constant pool*, from which at the end of the compilation, the content of a class file can be retrieved. It also includes a complete set of classes representing the instruction set of the JVM.

This section first introduces to the important classes and methods of the *classgen* package. Then it presents the translation step in the *TypeDeclarationNode*, which initiates the translation of methods and is responsible for adding them to them Constant Pool.

Further topics include Espresso's solution for lazy evaluation of boolean expressions, and the scheme that is used for back patching, as well the translation of break- and continue statement.

5.1 The overall translation picture

Generating code for a particular type declaration starts by creating an instance of *ClassGen*, the top level class of the package *classgen*, which is used to manage the construction of the Java class file. It provides methods to add the components of the class body and to access the class files constant pool directly if needed.
To construct an instance of *ClassGen*, the name of the Java source file, the type name, the name of the supertype, the types access flags and the list of interfaces that are extended or implemented by the type need to be supplied.
Translation proceeds by adding appropriate code for the entities of the class body.
Generating code for interface declarations mainly consists of adding entries for field declarations and method declarations to the constant pool.
Generating code for class declarations requires to translate the Java code contained in the method body, and is discussed in more detail in this section.

After completing translation of all entities of the class body, the content of the generated Java class is retrieved from *classgen*, obtaining an instance of class *JavaClass (contained in package javaclass)*, which provides a method to dump its content to a Java class file.

5.2 Translating a method body

For each method declaration with a non empty body, an instance of *classgen.MethodGen* needs to be created. We need to supply the methods access flags, the encoding of the return type and the types of the arguments together with the argument names (*become local variables*), the class and method name, and finally an instance of *classgen.InstructionList* to hold the byte code instruction stream.

Among the methods available in class *MethodGen*, Espresso mainly uses those for retrieving the methods instruction list and for dealing with *local variables*.

For nodes of the AST representing expressions or statements, the *translate* method has a uniform signature, taking the current java class and the currently translated method as parameters. This two objects suffice for most cases to provide access to the java class and to the code that was generated so far.

Espresso's solution for dealing with those cases, where access across statement or expression boundaries is needed is discussed in more detail in then following subsections.

After code generation for the method body is completed, *NOP's* are removed from the instruction list, and the translated method is added to the java class. Because of the way the package *classgen* is constructed, this needs to be done as the last step in translating a method body.

5.3 The role of Espresso's type hierarchy

Beyond type checking, Espresso's type hierarchy is also heavily used during translation. The JVM instruction set distinguishes operand types by providing distinct opcodes for operations on its various data types. The first distinction is made between reference types (*class type, array type, null type*) and primitive types. Looking in more detail at the instruction set of the JVM, the following instruction families can be made out:

- class type
- array type
- null type
- primitive type int
- primitive type long
- primitive type double

The primitive type *boolean* is always treated as type *int*. For most operations on the Java types *byte, char* and *short,* no special instructions are available. Instead a set of instructions is provided to convert forth and back between those types and the type *int.*

In order to minimize data type specific case analysis in the nodes of the AST during translation, Espresso's type hierarchy provides a set of methods to construct appropriate instructions depending on the type of the operand. Instructions constructed this way include:

- load and store instructions
- all primitive operations
- instructions for comparison and branching
- load and store array elements
- array creation
- cast instructions for narrowing and widening
- return instruction

To illustrate the principle, consider the case of translating the *return* statement. Espresso's top type *Type* declares an abstract method *RETURN*. *Table 5 on page 25* shows the different types of return instructions which need to be created, along with the subclass of *Type* which provides the appropriate implementation:

TABLE 5. Example using Espresso's type hierarchy to create appropriate *return* instructions

JVM instruction	Purpose	Espresso type that implements creation
ARETURN	Return a *reference* type	*ClassType*
DRETURN	Return a *double* type	*DoubleType*
FRETURN	Return a *float* type	*FloatType*
IRETURN	Return a *int* type	*IntType*
LRETURN	Return a *long* type	*LongType*
RETURN	Return *void*	*VoidType*

5.4 Controlling translation for lvalues and rvalues

One of the problems that needs to be solved when building a compiler for an imperative language is to make sure, that operations that change the state of variables are performed only on variables that represent updateable locations in memory. In the grammar used for Espresso, these updateable locations are represented by instances of the following classes of the AST.

- *FieldExpNode*
- *FormalExpNode*
- *LocalExpNode*
- *ArrayExpNode*

During the typechecking phase, the predicate *ExpressionNode.leftValue()* is used to verify, whether a updating operation is performed on an appropriate type of expression.

Generating code for these expressions requires to translate an expression according to its use as either a right value *rvalue* (read current content of location) or as a left value *lvalue* (write to location).

To control the translation of such an expression, the base class of all expressions *ExpressionNode* provides a flag *leftValue_d* which is turned on or off either already in the parsing phase, or when appropriate, later in the translation phase.

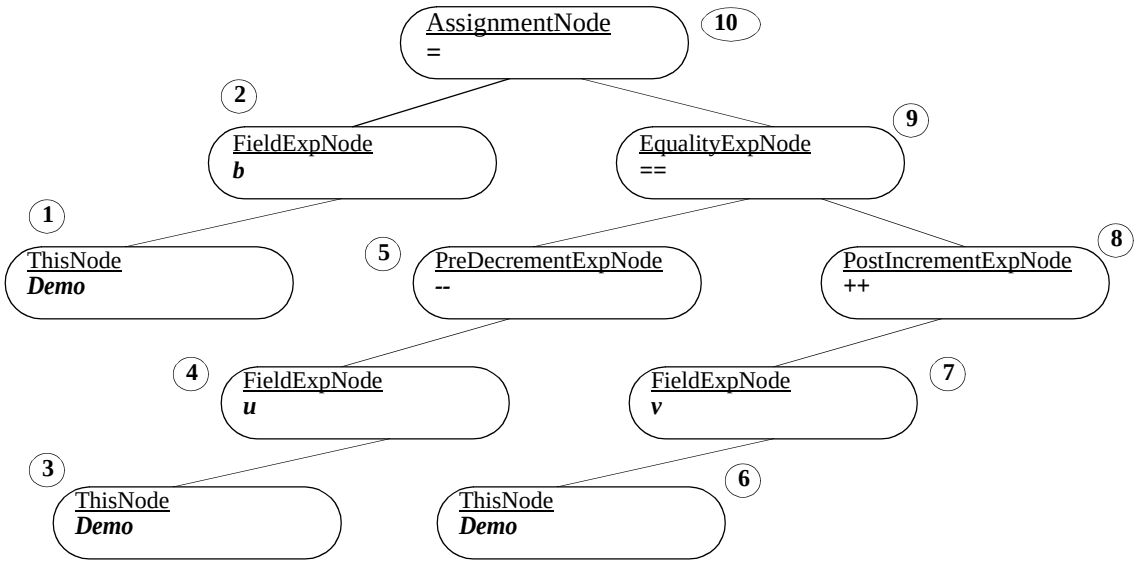
A number of expressions require, that code needs to be generated for a *lvalue* and for a *rvalue*. Among these expressions are field expressions in *pre-/postIncrement* expressions and *pre-/postDecrement* expressions, depending on the context of their use.

The following example illustrates Espresso's translation for a case, where *rvalue* and *lvalue* translation is needed (flag *leftValue_d* is turned *on* and *off*)

```
class Demo {
      boolean b;
       int u, v;
       public void preDecPostInc(  ) {
            b = --u==v++;
       }
}
```

Figure 5 on page 26 shows the relevant part of the AST, that results from parsing the code fragment containing the assignment *b = --u==v++*

FIGURE 5. AST *for assignment to field b*



Because the JVM is a stack based machine, translating code for it corresponds to a *post order* traversal of the AST. This is reflected by the numbering of the nodes above We will use the resulting code shown in Table 6 on page 27, to walk through the translation.

TABLE 6. JVM code resulting from translation of the AST for *Method void preDecPostInc()*

Code offset	JVM instruction	Step	Remark
0	*aload_0*	1	Since *FieldExpNode* for b is used as an *lvalue* here, no load is required, we prepare just for store
1	*aload_0*	3	*FieldExpNode* for *u* is translated as *lvalue* first, we prepare for store, and step 4 does not generate load instruction
2	*aload_0*	3	Now *FieldExpNode* for *u* is translated as *rvalue* *and a* load instruction is generated
3	*getfield #15 <Field int u>*	4	
6	*iconst_1*	5	This is the translation for the predecrement
7	*isub*	5	
8	*dup_x1*	5	We need to duplicate the current top of stack, because we need it for the comparison
9	*putfield #15 <Field int u>*	5	Store predecremented value to field u. *Here we use up the reference created at code offset 1 during lvalue translation*
12	*aload_0*	6	*FieldExpNode* for *v* is translated as *lvalue* first, we prepare for store, and step 7 does not generate load instruction
13	*aload_0*	6	Now *FieldExpNode* for *v* is translated as *rvalue* and a load instruction is generated
14	*getfield #17 <Field int v>*	7	
17	*dup_x1*	8	We need to duplicate the unmodified value of v, because comparison is performed on original value
18	*iconst_1*	8	This is the code for post increment
19	*iadd*	8	
20	*putfield #17 <Field int v>*	8	Store postincremented value to field v. *Here we use up the reference created at code offset 12 during lvalue translation*
23	*if_icmpne 30*	9	Translation of comparison == (check next section for reason of !=)

TABLE 6. JVM code resulting from translation of the AST for *Method void preDecPostInc()*

Code offset	JVM instruction	Step	Remark
26	*iconst_1*	9	Need to synthesize boolean value, because we need to make assignment
27	*goto 31*	9	
30	*iconst_0*	9	
31	*putfield #13 <Field boolean b>*	9	Store to field B. *Here we use up the reference created at code offset 0 during lvalue translation for b*

5.5 Lazy evaluation of boolean expressions, backpatching and synthesizing

Starting with Espresso v0.3 the translation of boolean expressions first tries to evaluate boolean expressions to obtain a *constant expression*. If not applicable, lazy evaluation of boolean expressions needs to be performed. To provide the necessary infrastructure for backpatching, the AST expression base class *ExpressionNode* defines a field *trueList_d* (for the true cases) to hold branch instructions created during translation, which need to be backpatched when the target of the branch instruction is known. Similarly, a field *falseList_d* is provided for the false case. As translation of boolean expressions proceeds, *trueList_d* and and *falseList_d* are passed up the expression tree and either merged or swapped according to the semantic of the particular expression. In most cases, backpatching is performed in the course of translating the enclosing control statement. Backpatching also needs to be performed, when boolean expressions need to be synthesized. This has to be done for instance in the following situations:

- A boolean expression is assigned to a boolean variable
- A boolean expression is passed as a parameter to a method call, a constructor invocation or a allocation expression
- A boolean expression is part of an additive expression which represents a string concatenation.

In order to synthesize boolean expressions, the class *ExpressionNode* provides a method *translateSynthesized* that performs the required task. Subclasses of *ExpressionNode* override this method if they require a more specific implementation.

In order to produce more compact code, Espresso translates boolean operators in a not obvious manner. All boolean operators found in the source code are translated to their negation. The true case always falls through, and the false case produced is added to the *falseList* to be packpatched later. The instruction at offset 23 in *Table 6 on page 27* is an example of this strategy, where an equality expression produces an *if_icmpne.*

Given this setup, *translateSynthesized* basically performs a regular *translate* on its parts, and then adds the appropriate code to leave the constant *one (iconst_1)* on the operand stack and appends an unconditional branch right after to the instruction stream. This

instruction handle is returned to the caller of the synthesized translation at the end. Then it appends the constant *zero (inconst_0)* to the instruction stream, and *backpatches* the branch instructions contained in the *falselist* to this location.

We will use the following code fragment and parts of the resulting AST shown in *Figure 6 on page 29* to illustrate this principle in more detail. The example shows lazy evaluation of boolean expression, Espresso's principle of translating boolean operators to their negation, and the process of synthesizing a boolean expression for the purpose of performing an assignment.

```
class Demo {
      boolean b;
      int u, v, w;
      public void demoLazy(  ) {
           b = u!=v and v==w ;
      }
}
```

FIGURE 6. *Partial* AST for example on lazy evaluation of boolean expressions

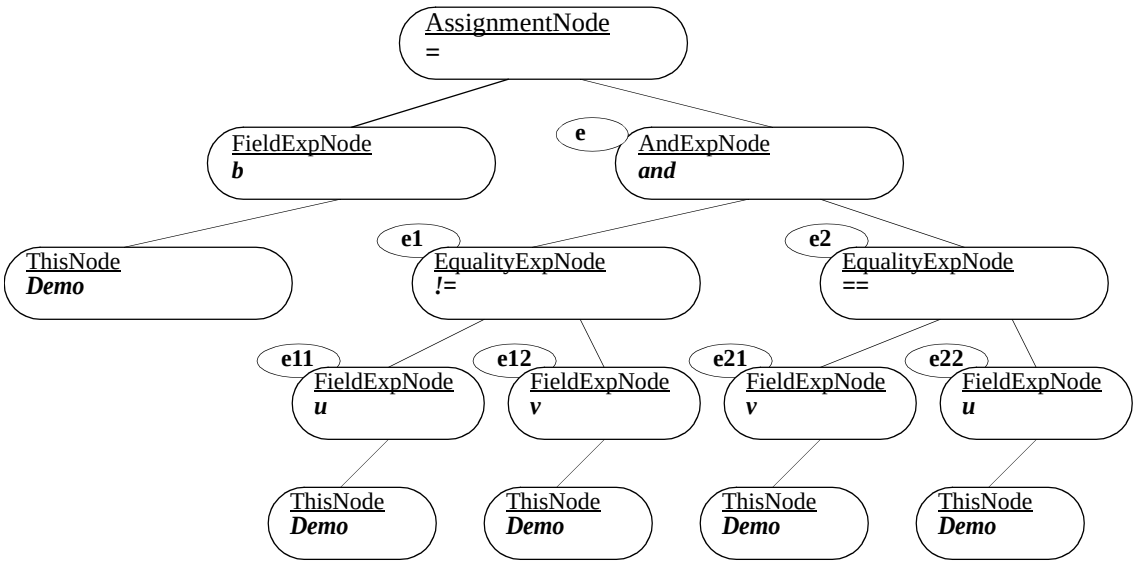


Table 7 on page 30 shows the code that was generated for the example above, along with remarks to particular translation steps.

TABLE 7. Code generated for the AST shown in *Figure 6 on page 29*

Code offset	JVM instruction	Remark
0	aload_0	*lvalue* translation for **LHS** of assignment
1	aload_0	*rvalue* translation of ***e11***
2	getfield #16 <Field int u>	
5	aload_0	*rvalue* translation of ***e12***
6	getfield #18 <Field int v>	
9	if_icmpeq 27	Translation of **!=** in ***e1***. Note that original comparison was replaced by its negation. The branch instruction is added to *falseList* of ***e1.*** If condition is *false*, we don't need to evaluate ***e2*** (lazy evaluation) *True* case falls through
12	aload_0	*rvalue* translation of ***e21***
13	getfield #18 <Field int v>	
16	aload_0	*rvalue* translation of ***e22***
17	getfield #20 <Field int w>	
20	if_icmpne 27	Translation of **==** in ***e2*** Again original operation is negated, and branch is added to *falseList* of ***e2***
23	iconst_1	This is the synthesized translation in ***e.*** Since the *true* case falls through, we need to push ***one*** to the operand stack. Then we need to add an unconditional branch to jump over the instruction which synthesizes the *false* case (This branch is returned to *AssignmentNode* to be backpatched, when the *assignment instruction* is added. Next we synthesize for the *false* case by pushing *zero* to the operand stack) and backpatch the merged *falselists* of ***e11*** and ***e21*** to this location.
24	goto 28	
27	iconst_0	
28	putfield #14 <Field boolean b>	Translation of the assignment in *AssignmentNode*. Backpatch branch returned by *translateSynthesized* to this location.

5.6 Translating continue statement

A *continue* statement may occur only within one of the iteration statement *do, while* and *for.* Control is transferred to the *continue target*, which is either the innermost enclosing iteration statement in case no continue label was provided by the programmer, or to the *labeled* iteration statement that matches with the label of the *continue* statement. The current iteration is immediately terminated, and the next one is started.

As was pointed out in “Wrapping of control statements” on page 14, Espresso makes sure, that each *continue* and *break* statement is labeled, and therefore matching with the appropriate *continue target* is relatively easy.

The translation of a *continue* statement needs to add an unconditional branch to the instruction stream. In order to avoid passing around the instruction which represents the continue target, *continue* branch instructions belonging to a particular *continue target* are collected during code generation in the field *continuelist* of the appropriate enclosing labeled statement (*instance of LabeledStatementNode)*.

When translating a *labeled* statement, first a *NOP* instruction representing the most likely target of a potentially contained *continue* is added to the instruction stream. Then translation of the enclosed statement is performed. At the end, branch instructions added by enclosed *continue* statements to the *continuelist* need to be back patched with the *continue target.* In the general case, this target is the *NOP* instruction that was first created. If however the wrapped statement represents a *for* statement with an non empty *update* expression list, then the start of that expression list represents the correct *continue target* according to the semantic of the language. The *labeled* statement that encloses that expression list can be looked up in the symbol table using the label symbol that results from adding the string *“for”* to the label contained in labeled statement that wraps the *for* statement.

5.7 Translating break statement

Translation of the *break* statement works similar to translating the *continue* statement. The branch instruction created by the translation of the *break* statement are added to the *breaklist* of the appropriate *labeled* statement. After finishing translation of the enclosed statement in a *labeled* statement, a *NOP* instruction is added to the instruction stream, to serve as the target of the *branch* instructions contained in the *breaklist.*

6.0 Proposals for future work

This sections topic is to point out areas of future work.

It first presents a detailed list of language features of Java, that are currently not, or only partly implemented.

Next, some areas of possible optimizations are identified, with particular focus on generating more efficient code.

A last part suggests some fields of improvement concerning error handling and reporting.

6.1 Missing or incomplete features

This section identifies those parts of the Java language that are currently not implemented, or not fully available in Espresso.

In principle, Espresso in its current version conforms to the Java Language Specification JLS version 1.0

6.1.1 Parsing

With the exception of some wired cases of forward references, the entire grammar of JLS 1.0 is supported by Espresso.

In some cases, Espresso simply overwrites access modifiers that are potentially present in the source program by setting default access modifiers instead (*Example:* field- and method declarations in interfaces) JLS Ch. 9.3 and 9.4.
The reason for this is, that the same grammar productions are currently used for classes and interfaces.

Final fields need to be sorted out in step that collects initializers of static variables.

6.1.2 Type Checking, Semantic Checks

TABLE 8. Topics to be completed in type checking and in semantic checks

Main topic	Topic	Hints	Reference JLS	Status/ Contributor
Class/Interface Declaration	Consistency among Class modifiers	not more than one of public/private/protected	JLS Ch. 8.1.2	Needs to be done
Class/Interface Declaration	Consistency among Class modifiers. Final classes	modifier pair final/ abstract illegal	JLS Ch. 8.1.2.2	Needs to be done
Class/Interface Declaration	Consistency among Class modifiers. Final classes	Name of a class declared final may not appear in extents clause of the declaration of another class	JLS Ch. 8.1.2.2	Needs to be done
Method Declarations	Closure of non abstract classes	Closure of non abstract classes with respect to interface methods it promises to implement, and to abstract methods of superclasses.	JLS	Needs to be done
Interface Declarations	Circularity test for Interfaces		JLS 9.1.3	Needs to be done
Field Declaration	Initializers for fields of interfaces	Check for presence of initializers	JLS Ch. 9.3.1	Needs to be done
Field Declaration	Consistency among field modifiers	not more than one of public/private/protected	JLS Ch. 8.3.1	Needs to be done
Field Declaration	Consistency among field modifiers	modifier pair final/ volatile is illegal	JLS Ch. 8.3.1.4	Needs to be done
Field Declaration	Initializers of class (static) variables	Special rules apply	JLS 8.3.2.1	Needs to be done
Field Declaration	Initializers of instance variables	Special rules apply	JLS 8.3.2.2	Needs to be done
Field Declaration	Initializers of static variables	Check for abrupt completion by checked exception	JLS 8.3.2	Needs to be done

TABLE 8. Topics to be completed in type checking and in semantic checks

Main topic	Topic	Hints	Reference JLS	Status/ Contributor
Field Declaration	Initializers of static variables	Check for illegal reference of class variables declared in this class, whose declaration appear textually after the use.	JLS Ch. 8.5	Needs to be done
Interface Members	Initializers for fields	Initialization expression must not contain a reference by simple name to same field or to another field whose declaration occurs textually later in the same interface	JLS Ch. 9.3.1	Needs to be done
Array variables	Initializers of Arrays	90% missing	JLS Ch. 10.2	Needs to be done
Method Declaration	Consistency among method modifiers	not more than one of public/private/protected	JLS Ch. 8.4.3	Needs to be done
Method Declaration	Consistency among method modifiers	private/abstract, static/abstract, final/abstract, native/abstract pairs are illegal	JLS Ch. 8.4.3	Needs to be done
Class Declaration/ Method Declaration	Consistency between class modifiers and method modifiers	Abstract method in non abstract class	JLS 8.4.3.1	Needs to be done
Method Declaration	Final methods	Check for overriding of final methods	JLS 8.4.3.3	Needs to be done
Method Declaration	Native methods	None	JLS 8.4.3.4	Needs to be done
Method Declaration	Method Throws	None	JLS 8.4.4	Needs to be done
Method Declaration	Hiding methods of superclasses and interfaces	Special checks needed	JLS Ch. 8.4.6	Needs to be done
Constructor Declaration	Consistency among constructor modifiers	not more than one of public/private/protected	JLS 8.6.3	Needs to be done

TABLE 8. Topics to be completed in type checking and in semantic checks

Main topic	Topic	Hints	Reference JLS	Status/ Contributor
Constructor Declaration	Default Constructor	Access modifier is taken from class, if class is declared public	JLS Ch. 8.6.7	Needs to be done
Constructor body	Explicit constructor invocation	Check for illegal mention of instance variables or instance methods declared in this class or any superclass, as well as for the use of *this* or *super* in any expression contained within an explicit constructor invocation statement.	JLS 8.6.5	Needs to be done
Statements/ Expressions	Exception handling	*TryStatement* with associated Catch-Block or Finally-Block (100% missing)	JLS Ch. 11	Needs to be done
Statements/ Expressions	Altering of final fields	Values of finals fields can never be altered, once they have been initialized. (Idea: extend definition of left Value)	JLS Ch. 8.3.1.2 JLS 15.14.2	Needs to be done
Statements/ Expressions	Return statement	Using flow analysis, we need to check that in every possible path of execution, we have a return statement.	JLS Ch. 14.15	Needs to be done
Statements/ Expressions	Throw Statement	100% missing	JLS Ch. 14.16	Needs to be done
Statements/ Expressions	Try Statement	100% missing	JLS Ch. 14.18	Needs to be done
Statements/ Expressions		Check for unreachable statements	JLS Ch. 14.19	Needs to be done
Statements/ Expressions	Class Instance creation expression	Need to check, whether the class type mentioned in the expression is not an abstract class	JLS Ch. 15.8	Needs to be done

TABLE 8. Topics to be completed in type checking and in semantic checks

Main topic	Topic	Hints	Reference JLS	Status/ Contributor
Statements/ Expressions	Method invocation expressions	Method invocations using **super**.*methodname* may appear only in a class different than Object, and only in the body of an instance method, the body of a constructor or an initializer for a instance variable	JLS Ch. 15.11.1	Needs to be done
Statements/ Expressions	Method invocation expressions	Verify accessibility of methods in type check of method invocation	JLS Ch. 15.11.2	Needs to be done
Statements/ Expressions	Additive operator (+)	Need to extend type check for additive operator (+) to support String concatenation operator	JLS 15.17.1	Available in Espresso v0.3 *Karl Doerig*
Statements/ Expressions	Conditional operator (?)	The current type check in Espresso works perfect, but is not as restrictive as required by JLS.	JLS 15.24	Needs to be done
Statements/ Expressions	Definite Assignment for variables in Blocks	Enjoy	JLS Ch. 16	Needs to be done

6.1.3 Code generation

TABLE 9. Topics to be worked on in code generation

Topic	Hints	Reference JLS	Status/ Contributor
Initializers for fields of interfaces	Need to be added to constant pool	JLS Ch.	Needs to be done
Array Initializers	100% missing	JLS Ch.	Needs to be done
TryStatement/*ThrowStatement*	Exception Handling 100% missing	JLS Ch. 14.16 JLS Ch. 14.18	Needs to be done

TABLE 9. Topics to be worked on in code generation

Topic	Hints	Reference JLS	Status/ Contributor
Synchronized Statement	simple, need to add only *monitorenter* and *monitorexit*	JLS Ch. 14.17	Needs to be done
bitwise logical operators (&, ^, !)	Maybe done	JLS Ch. 15.21	Needs to be done
Postfix Increment, Postfix Decrement	Does currently not generate proper code for integral types smaller than int	JLS Ch 15.13.2 JLS Ch 15.13.2	Needs to be done
Prefix Increment, Prefix Decrement	Does currently not generate proper code for Integral types smaller than int	JLS Ch 15.14.1 JLS Ch 15.14.2	Needs to be done
Bitwise complement operator	100% missing	JLS Ch. 15.14.5	Needs to be done
String concatenation operator	100% missing	JLS 15.17.1	Available in Espresso v0.3 *Karl Doerig*
Shift operators	100% missing	JLS Ch. 15.18	Needs to be done
Type comparison operator *instanceof*	100% missing	JLS Ch. 15.19.2	Needs to be done
Compound assignment operators	100% missing	JLS Ch. 15.25.2	Needs to be done
Calculation of maximum stack size	Code attribute in the Java Class File. Is currently set to a fixed value	JVM	Needs to be done
Generation of LineNumber attribute	This is used only, to support debugging, and is thus not very critical	JVM	Needs to be done

6.2 Optimization

TABLE 10. Topics for optimizations

Main benefit	Hints	Status/ Contributor
Reduce size of the generated JVM code	Removal of NOP instructions	Available in Espresso v0.3 *Santiago M. Pericas*
Reduce size of generated code and improve execution time	Removal of goto's to the next instruction	Available in Espresso v0.3 *Santiago M. Pericas*
Reduce size of generated code and improve execution time	Replacing patterns of conditional branches, immediately followed by *goto* by the negation of the conditional branch, with the target of the *goto* as the branch target	Available in Espresso v0.3 *Santiago M. Pericas*
Reduce size of generated code and improve execution time Improve time required for compiling	Consequent evaluation of expressions throughout the translation process, so that constant expressions get transformed into single load instructions. This can be done during the code generation phase, by providing and applying the evaluation function in all expressions.	Available in Espresso v0.3 *Santiago M. Pericas*
Reduce size of generated code and improve execution time	Traditional optimizations based on flow analysis, like common sub expression elimination, code motion (place loop invariant outside loops) a.s.f	Needs to be done

6.3 Improvements to error reporting

The following improvements should be considered or need to be done, concerning error reporting.

- We need to report location of syntax errors. Right now, no source code information is printed, when a syntax error occurs.
- Espresso exits after the first syntax error. It might be worthwhile, to study and investigate, whether this can be improved. It mainly depends on the possibilities available in *javacc*
- The current error reporting concerning errors discovered during type checking needs to be improved. Right now, only the line number in the source code is printed. In order to provide the proper fragment of the source code that caused the error, we need the *end token* in addition to the *start token* that is already recorded using the *JavaParser* method *recordSourceCoordinates*. Some suggestions are available through the *JavaCC* home page in the FAQ section.

6.4 What to pick first

Among the language constructs which are currently not available, type checking and code generation for declaring, throwing and catching exceptions are the most important to be added first. This will allow us to compile a much larger number of Java programs with Espresso.

The second most important deals with type checking and code generation for array initializers.

Both topics are suitable as part of a practical project in compiler design.

7.0 How to get involved in the project

The following section describes the procedure you have to follow, in order to get access to the Espresso source code, and what changes you have to make to your environment before fetching the sources from CVS. It also establishes a few basic rules you have to stick to, when updating CVS with modified versions of Espresso source files.

7.1 How to get access to Espresso's most recent source code

Currently the Espresso source code is maintained on a local machine named *quasar* using CVS. This machine is Santiago M. Pericas (*email: santiago@cs.bu.edu)* private machine. He has volunteered to play the role of a "supervisor" for Espresso.
Follow these steps to get involved:

- Send an email to Santiago M. Pericas asking for an account on node *quasar*
- Once you got the account, you need to set up the following environment variables to get ready for a CVS checkout

Variable	set to
CVSROOT	:ext:quasar.bu.edu:/usr/people/santiago/Repository
CVS_RSH	ssh
CVS_UMASK	07

- Go to your home directory and type
  cvs checkout espresso
  This will checkout all sources, binaries and shell scripts into a directory tree whose root is home/espresso.
- Add *$$home/espresso/bin* to your path variable. This will make javacc and some useful shell scripts available to you, that you will need to either build (make) Espresso, and run it as your Java compiler
- Next you need to construct Espresso's lexer and parser using *javacc.* Use the command *javacc -STATIC =false java1.0.2.jj* in directory *espresso/parser*
- If you want to use *CosmoCode* as your Java Development Environment, use the Cosmocode project file *Espresso.proj* in directory *espresso* and edit manually the directory path for the Java source files to match to your local structure.

- If you don't want to use CosmoCode, you will need to compile Espresso by using a make file contained in directory *espresso.* Use command:
  make -f Makefile
- In either case, if the compilation was successful, Espresso is now available through the shell script *espresso.*

7.2 How to obtain a particular version of Espresso from CVS

If you want a particular version of Espresso for testing, proceed as above, but to check-out from CVS, use command: *cvs checkout -r **versionid** espresso*, where *versionid* is the name of the version you want to test. (Ask Santiago M. Pericas for available versions).

7.3 What are the rules for committing changes back to CVS

In order to commit changes back to CVS, you need to do the following:

- Make sure you tested your changes before
- If you made substantial changes, you might show your results first to Santiago M. Pericas
- Issue the command *cvs commit* from Espresso's root directory *espresso.* Under all circumstances **`add a comment stating the changes you made. when cvs is prompting for it.`** This will allow us to identify, who changed what and for what reason, in case something gets messed up.

7.4 Espresso's directory structure

This section introduces to the project structure of Espresso, as it is defined in CVS. The structure is described in terms of the directory structure, which results, when the entire project is checked out from CVS.

The main purpose of this section is, to help a user navigate through the different parts of the compilers source code.

Espresso was developed using *Silicon Graphics* Java Development Environment *CosmoCode.* The use of *CosmoCode* is optional, but highly recommended. In order to use *CosmoCode*, an appropriate *project file* defining the project structure needs to be defined. A template project file named *Espresso.pro*j is managed within CVS and checked out to directory espresso. You will need to edit the file paths, in order to use it.*Table 11 on page 41* shows Espresso's directory structure together with the groups of files, which are located there.

TABLE 11. Espresso's Directory structure

Directory	Content/Remarks
espresso	*Espresso.java*
espresso/classfile	*Constants.java*
espresso/classfile/javaclass	Files provided by package available under GNU's public license agreement, to load existing Java Class Files
espresso/classfile/classgen	Files provided by package available under GNU's public license agreement, to generate Byte Code and to store to Java Class Files
espresso/classfile/util	Some utilities provided with *classgen* package
espresso/espresso	Root Directory of Espresso's Class Files
espresso/parser	*java1.0.2.jj* *(File containing definitions for Espresso's lexer and parser).* *To generate JavaParser.java, JavaParserTokenManager.java, ... from it type* *javacc - STATIC=false java1.0.2.jj)* *JavaImportManager.java (JIM)*
espresso/syntaxtree	Java sources for classes used to represent the AST
espresso/util	Java sources representing Espresso's type hierarchy Java sources used for Espresso's symbol table Java sources used for error handling Helper classes for scope stack and label stack
espresso/bin	Contains the shell scripts you need for *javacc* and *espresso*
espresso/JavaCC	Directory containing code for Java Compiler Compiler.