

## Programming Assignment V

**Due Date:** December 5, 2006.

**Purpose:** This project is intended to give you experience in writing a code generator as well as bring together the various issues of code generation discussed in the text and in class.

**Project Summary:** Your task is to implement a code generator for Cool. This assignment is the end of the line: when completed, you will have a fully functional Cool compiler, and you will have achieved full Compiler Wizardry status! This is a group project, and peer reviews will be used as in other projects during evaluation.

The code generator makes use of the AST constructed in PA3 and static analysis performed in PA4. Your code generator should produce MIPS assembly code that faithfully implements *any* correct Cool program. There is no error recovery in code generation—all erroneous Cool programs have been detected by the front-end phases of the compiler.

As with the static analysis assignment, this assignment has considerable room for design decisions. Your program is correct if it generates correct code; how you achieve that goal is up to you. We will suggest certain conventions that we believe will make your life easier, but you don't have to take our advice. As always, explain and justify your design decisions in the README file. This assignment is comparable in size and difficulty to the previous programming assignment. Start early!

### Files and Directories:

To get started, create a directory where you want to do the assignment and execute one of the following commands *in that directory*. For the C++ version of the assignment, you should type

```
gmake -f ~pollock/public/cool02/assignments/PA5/Makefile
```

For Java, type:

```
gmake -f ~pollock/public/cool02/assignments/PA5J/Makefile
```

(notice the “J” in the path name). This command will copy a number of files to your directory. Some of the files will be copied read-only (using symbolic links). You should not edit these files. In fact, if you make and modify private copies of these files, you may find it impossible to complete the assignment. See the instructions in the README file. The files that you will need to modify:

- **cgen.cc** (C++ version)

This file will contain your code generator. We have provided an implementation of some aspects of code generation; studying this code will help you write the rest of the code generator. It includes a call to code that will build an inheritance graph from the provided AST. You can use the provided code or replace it with your own.

- **cgen.h** (C++ version)

This file is the header for the code generator. You may add anything you like to this file. It provides classes for implementing the inheritance graph. You may replace or modify them as you wish.

- **emit.h** (C++ version)

This file contains code generation macros. You may modify this file.

- `cool-tree.h` and `cool-tree.handcode.h` (C++ version)  
As usual, these files contain the declarations of classes for AST nodes. You can add field declarations to the classes in `cool-tree.h` or `cool-tree.handcode.h`. The definitions of the methods should be added to `cgen.cc`.
- `cgen_supp.cc` (C++ version) / `CgenSupport.java` (Java version)  
This file contains general support code for the code generator. You will find a number of handy functions here. Modify the file as you see fit, but don't change anything that's already there.
- `CgenClassTable.java` and `CgenNode.java` (Java version)  
These files provide an implementation of the inheritance graph for the code generator. You will need to complete `CgenClassTable` in order to build your code generator.
- `StringSymbol.java`, `IntSymbol.java`, and `BoolConst.java` (Java version)  
These files provide support for Cool constants. You will need to complete the method for generating constant definitions.
- `cool-tree.java` (Java version)  
This file contains the definitions for the AST nodes. You will need to add code generation routines for Cool expressions in this file. The code generator is invoked by calling method `cgen()` of class `program`. Do not modify the existing declarations.
- `TreeConstants.java` (Java version)  
As before, this file defines some useful symbol constants. Feel free to add your own as you see fit.
- `example.c`  
This file should contain a test program of your own design. Test as many features of the code generator as you can manage to fit into one file.
- `README` This file will contain the write-up for your assignment. It is critical that you explain design decisions, how your code is structured, and why you believe your design is a good one (i.e., why it leads to a correct and robust program). It is part of the assignment to explain things in text as well as to comment your code.

As usual, there are other files used in the assignment that are symbolically linked to your directory or are included from `~pollock/public/cool02/include/PA5`. You should not modify these files. Almost all of these files have been described in previous assignments.

**Important:** All software supplied with this assignment is supported on Solaris SPARC, Solaris x86, and Linux x86 machines. Remember to run `gmake clean` if you switch architectures.

**Testing your Code Generator:** You will need a working scanner, parser, and semantic analyzer to test your code generator analyzer. You may use either your own components or the components from `coolc`. By default, the `coolc` components are used. To change that, replace the `lexer` and/or `parser` and/or `semant` executable (which are symbolic links in your project directory) with your own scanner/parser. Even if you use your own components, it is wise to test your semantic analyzer with the `coolc` scanner, parser, and semantic analyzer at least once, because we will grade your semantic analyzer using `coolc`'s version.

You will run your code generator using `mycoolc`, a shell script that "glues" together the generator with the rest of compiler phases. Note that `mycoolc` takes a `-c` flag for debugging the code generator;

using this flag merely causes `cgen_debug` (a global variable in the C++ version and a static field of class `Flags` in the Java version) to be set. Adding the actual code to produce useful debugging information is up to you. See the project README for details.

**Designing your Code Generator:** There are many possible ways to write the code generator. One reasonable strategy is to perform code generation in two passes. The first pass decides the object layout for each class, particularly the offset at which each attribute is stored in an object. Using this information, the second pass recursively walks each feature and generates stack machine code for each expression.

There are a number of things you must keep in mind while designing your code generator:

- Your code generator must work correctly with the Cool runtime system, which is explained in the *Cool Tour* manual.
- You should have a clear picture of the runtime semantics of Cool programs. The semantics are described informally in the first part of the *CoolAid*, and a precise description of how Cool programs should behave is given in Section 13 of the manual.
- You should understand the MIPS instruction set. An overview of MIPS operations is given in the `spim` documentation, which is in the course handout and on the class Web page.
- You should decide what invariants your generated code will observe and expect; i.e., what registers will be saved, which might be overwritten, etc. You may also find it useful to refer to information on code generation in the lecture notes and portions of the text, primarily ASU Chapter 9.

With this in mind, one possible organization for your code generator is:

1. compute the inheritance graph
2. assign tags to all classes in depth-first order
3. determine the layout of attributes, temporaries, and dispatch tables for each class
4. generate code for global data: constants, dispatch tables,...
5. generate code for each feature

Your code generator has to select MIPS instructions to emit, do some kind of register allocation (very simple is fine), and layout the memory for the runtime. You need to decide what strategy to use for each of these within the passes your code generator makes over the AST.

**Hints on Getting Started:** Before you dive into writing your code generator, we strongly recommend that you write some small Cool programs, compile them with `Coolc`, and carefully examine the relationship between the Cool program and the MIPS assembly program. That is particularly helpful when planning how to produce code for method calls, parameter passing, and other control constructs. Also, write your code generator in an incremental manner, generating code for very simple programs, getting them working, and then incrementally adding other more complex constructs to your code generator and corresponding test cases. Note that you do not have to generate the exact same code as that produced by `Coolc`. It just needs to maintain the semantics of the Cool program being compiled.

**Garbage Collection:** To receive full credit for this assignment, your code generator must work correctly with the generational garbage collector in the Cool runtime system. The skeletons contain functions `code_select_gc` (C++) and `CgenSupport.codeSelectGC` (Java) that generate code that sets GC

options from command line flags. The command line flags that affect garbage collection are `-g`, `-t`, and `-T`. Garbage collection is disabled by default; the flag `-g` enables it. When enabled, the garbage collector not only reclaims memory, but also verifies that “-1” separates all objects in the heap, thus checking that the program (or the collector!) has not accidentally overwritten the end of an object. The `-t` and `-T` flags are used for additional testing. With `-t` the collector performs collections very frequently (on every allocation). The garbage collector does not directly use `-T`; in `coolc` the `-T` option causes extra code to be generated that performs more runtime validity checks. You are free to use (or not use) `-T` for whatever you wish.

For your implementation, the simplest way to start is not to use the collector at all (this is the default). When you decide to use the collector, be sure to carefully review the garbage collection interface described in the *Cool Tour*. Ensuring that your code generator correctly works with the garbage collector in *all* circumstances is not trivial.

**Spim and XSpim:** You will find `spim` and `xspim` useful for debugging your generated code. `xspim` works like `spim` in that it lets you run MIPS assembly programs. However, it has many features that allow you to examine the virtual machine’s state, including the memory locations, registers, data segment, and code segment of the program. You can also set breakpoints and single step your program. Look at the documentation for `spim/xspim` in the course handout or in the course web page.

**Warning:** One thing that makes debugging with `spim` difficult is that `spim` is an interpreter for assembly code and not a true assembler. If your code or data definitions refer to undefined labels, the error shows up only if the executing code actually refers to such a label. Moreover, an error is reported only for undefined labels that appear in the code section of your program. If you have constant data definitions that refer to undefined labels, `spim` won’t tell you anything. It will just assume the value 0 for such undefined labels.

### Extra Credit:

You may earn extra credit by implementing some optimization in your compiler. Extra credit will be awarded for projects that, in addition to code generation, perform some significant optimization of the code. The amount of extra credit depends on how well the optimization is written, documented, and demonstrated. Two critical factors are: (1) correctness (the optimizations don’t result in incorrect programs) and (2) the percentage speedup your optimized code achieves over `coolc`, as measured in the number of instructions executed on `spim` over a suite of benchmarks of our choosing.

The total extra credit for optimization will not exceed 5% of the grade for PA5. In other words, if you elect not to do an optimization phase, you will not be at a disadvantage in the final grading with respect to those who do.

This extra-credit option is open-ended; you can do as much as you like. We will award credit for results. For example, a project that merely attempts, but does not complete, an optimization phase may receive as little as no extra credit.

There are many possible optimizations to implement; see the ASU chapters 9 and 10 for ideas. Assuming your initial code generator is straightforward (like `coolc`’s), then two directions that may yield significant improvement are (1) improving register usage and (2) specializing the implementation of the basic classes `Int` and `String`.

**WARNING.** We have not implemented an optimization phase in `coolc`, so we have no skeleton code to give you—you are on your own. If you want to do an optimization phase, you are encouraged to talk it over with one of the course staff first. *Under absolutely no circumstances should you try optimization before your code generator is finished!!*

There is a `-O` flag that controls the global variable `cgen_optimize` (C++) and `Flags.cgen_optimize`

(Java). If you do an optimization phase, it should have no effect unless **cgen\_optimize** is on. We will grade your code generator first with optimization off; this will prevent you from losing points due to bugs in your optimizer.

**What to Turn In:** Follow the TA's instructions, similar to PA4, unless otherwise notified by the TA.