Compiler construction 2012

Lecture 1

- Course info
- Introduction to compiling
- Some examples
- Project description

Compiler Construction 2012

What is it?

Hands-on, learning-by-doing course, where you implement your own compiler.

Related course

Companion course to (and optional continuation of) **Programming Language Technology** in period 3.

Focus

Compiler backend and runtime issues.

Why learn to write a compiler?

Few people ever write (or extend, or maintain) compilers for real programming languages.

But knowledge of compiler technology is useful anyhow:

- Tools and techniques are useful for other applications – including but not limited to small-scale languages for various purposes;
- Understanding compiling gives deeper understanding of programming language concepts – and thus makes you a more efficient programmer.

Course aims

After this course you will

- have experience of implementing a complete compiler for a simple programming language, including
  - lexical and syntactic analysis (using standard tools);
  - type checking and other forms of static analysis;
  - code generation and optimization for different target architectures (JVM, LLVM, x86, ...).
- understand basic principles of run-time organisation, parameter passing, memory management etc in programming languages;
- know the main issues in compiling imperative, object-oriented ~~and functional~~ languages.

Course organisation

Teachers

Nick Smallbone (supervision, grading)
Björn von Sydow (lectures, supervision, grading, course responsible)
Email addresses, offices at course web site.

Teaching

- 10 lectures. Tuesdays 10–12 and Thursdays 13–15.
  No lecture this Thursday; nor March 27; last lecture May 8.
- Project supervision. On demand vie email (anytime) or visit during our office hours:
  Nick: Thursdays 15–17.
  Björn: Thursdays 15–16 (after lecture).

Examination

Grading

- 3/4/5 scale is used.
- Your grade is entirely based on your project; there are several alternative options, detailed in the project description.
- Need not decide on ambition level in advance.
- Individual oral exam in exam week.

Details on the course web site.

Project groups

We recommend that you work in groups of two.
Individual work is permitted but discouraged.

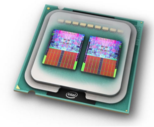
The course's Google group can be used to find project partner.

Compiler technology

- Very well-established field of computing science, with mature theory and tools for some subproblems and huge engineering challenges for others.
- Compilers provide a fundamental infrastructure for all of computing. Crucial to make efficient use of resources.
- Advances in computer architecture lead to new challenges both in programming language design and in compiling.

Current grand challenge

Multi-core processors.
How should programmers exploit parallellism?



What is a compiler?

A compiler is a translator

A compiler translates programs in one language (the **source** language) into another language (the **target** language).
Typically, the target laguage is more "low-level" than the source language.
Examples:

- C++ into assembly language.
- Java into JVM bytecode.
- JVM bytecode into x86 assembly.
- Haskell into C.

Why is compiling difficult?

The semantic gap

- The source program is structured into (depending on language) classes, functions, statements, expressions, ...
- The target program is structured into instruction sequences, manipulating memory locations, stack and/or registers and with (conditional) jumps.

Source code

```
8*(x+5)-y
```

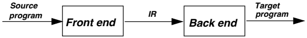
x86 assembly

```
movl    8(%ebp), %eax
sall    $3, %eax
subl    12(%ebp), %eax
addl    $40, %eax
```

JVM assembly

```
bipush 8
iload_0
iconst_5
iadd
imul
iload_1
isub
```


Basic structure of a compiler



Intermediate representation

A notation separate from source and target language, suitable for analysis and improvement of programs.

Examples:

- Abstract syntax trees.
- Three-address code.
- JVM assembly.

Front and back end

Front end: Source to IR.

- Lexing.
- Parsing.
- Type-checking.

Back end: IR to Target.

- Analysis.
- Code improvement.
- Code emission.

Some variations

One-pass or multi-pass

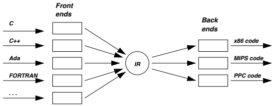
Already the basic structure implies at least two **passes**, where a representation of the program is input and another is output.

- For some source languages, one-pass compilers are possible.
- Most compilers are multi-pass, often using several IR:s.

Pros and cons of multi-pass compilers

– Longer compilation time.
– More memory consumption.
+ SE aspects: modularity, portability, simplicity,...
+ Better code improvement.
+ More options for source language.

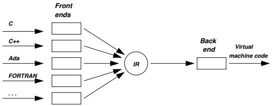
Compiler collections



More compilers with less work

- Compilers for *m* languages and *n* architectures with $m + n$ components.
- Requires an ***IR*** that is language and architecture neutral.
- Well-known example: GCC.

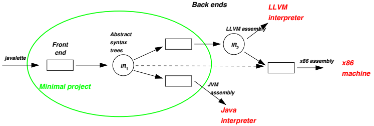
Compiling for virtual machines



Target code for virtual (abstract) machine

- Interpreter for virtual machine code written for each (real) architecture.
- Can be combined with JIT compilation to native code.
- Was popular 30 years ago but falling out of fashion in the 90's.
- Strongly revived by Java's JVM, Microsoft's .NET, LLVM.

Our course project



Many options

- Two or more backends; JVM/LLVM/x86 code.
- Various source language extensions.

More details later today. See also course web site.

Front end tasks

```
if (x > 100) y = 1;
```

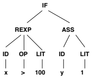
Lexing

Converts source code char stream to token stream.
Good theory and tools.

```
IF LPAR ID/x GT LIT/100
RPAR ID/y EQ LIT/1 SEMI
```

Parsing

Converts token stream to abstract syntax trees (AST:s).
Good theory and tools.



Type-checking

Checks and annotates AST.
Good theory and programming patterns.

Back end tasks

Some general comments

- Not as well-understood, hence more difficult.
- Several sub-problems are inherently difficult (e.g., NP-complete); hence heuristic approaches necessary.
- Large body of knowledge, using many clever algorithms and data structures.
- More diverse; many different IR:s and analyses can be considered.
- Common with many optimization passes; trade-off between compilation time and code quality.

Compiling and linking

Why is linking necessary?

- With separate compilation of modules, even native code compiler cannot produce executable machine code.
- Instead, **object** files with unresolved external references are produced by the compiler.
- A separate **linker** combines object files and libraries, resolves references and produces an executable file.

Separate compilation and code optimization

- Code improvement is easy within a **basic block** (code sequence with one entry, one exit and no internal jumps).
- More difficult across jumps.
- Still more difficult when interprocedural improvement is tried.
- And seldom tried across several compilation units . . .

The beginning: FORTRAN 1954 – 57

Target machine: IBM704

$\leq$ 36kb primary (magnetic core) memory.
One accumulator, three index registers.
$\approx 0.1 - 0.2$ ms/instruction.

Compiler phases

1. (Primitive) lexing, parsing, code generation for expressions.
2. Optimization of arrays/DO loop code.
3. Code merge from previous phases.
4. Data flow analysis, preparing for next phase.
5. Register assignment.
6. Assembly.

GCC: Gnu Compiler Collection 1985 –

Goals

- Free software; key part of GNU operating system.

Status

- 2.5 million lines of code, and growing.
- Many front- and backends.
- Very widespread use.
- Monolithic structure, difficult to learn internals.
- Up to 26 passes.

LLVM (Low Level Virtual Machine) 2002 –

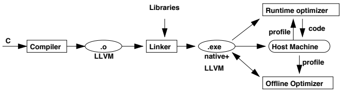
Goals

- Multi-stage code improvement, throughout life cycle.
- Modular design, easy to grasp internal structure.
- Practical, drop-in replacement for other compilers (e.g. GCC).
- LLVM IR: three-address code in SSA form, **with type information**.

Status

- New front end (CLANG) released (for C).
- GCC front end adapted to emit LLVM IR.
- LLVM back ends of good quality available.

LLVM optimization architecture



Code optimization opportunities

- During compilation to LLVM (as in all compilers).
- When linking modules and libraries.
- Recompilation of hot-spot code at run-time, based on run-time profiling (LLVM code part of executable).
- Off-line, when computer is idle, based on stored profile info.

CompCert 2005 –

Program verification

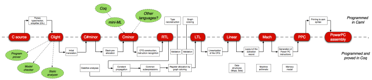
- For safety-critical software, formal verification of program correctness may be worth the cost.
- Such verification is typically done of the source program.
  So what if the compiler is buggy?

Note: This problem is less acute for software validated by testing.

Use a certified compiler!

- CompCert is a compiler for a large subset of C, with PowerPC assembler as target language.
- Written in Coq, a proof assistant for formal proofs.
- Comes with a machine-checked proof that for any program, which does not generate a compilation error, the source and target programs behave identically. (Precise statement needs more details.)

CompCert architecture



Intermediate constructions

- Eight intermediate languages.
- Six type systems.
- Thirteen passes.

Personal interest: The Timber compiler

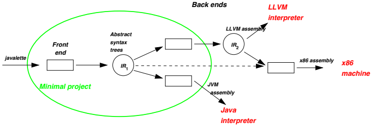
Timber programming language

Aimed at programming event-driven and embedded systems.
Includes timing constructs for describing real-time behaviour.
Features from functional, object-oriented and concurrent programming.
See `www.timber-lang.org`

Timber compiler

- Written in Haskell.
- 14 passes; three intermediate languages.
- Target language C (or LLVM).

Project languages



Recall

- Two or more backends; JVM/LLVM/x86 code.
- Various source language extensions.

Today we will discuss the languages involved.

Source language

Javalette

- A simple imperative language in C-like syntax.
- A Javalette program is a sequence of function definitions, that may be (mutually) recursive.
- One of the functions must be called `main`, have result type `int` and no parameters.
- What about order between function definitions?

Restrictions

Basic language is very restricted:
No arrays, no pointers, no modules . . .

Program environment

External functions

- Procedures:

```
void printInt (int i)
void printDouble (double d)
void printString (string s)
void error ()
```

- Functions:

```
int readInt ()
double readDouble ()
```

One file programs

Except for calling the above routines, the complete program is defined in one file.

Types and literals

Types

Javalette has the types

- `int`, with literals described by *digit*+;
- `double`, with literals *digit*+ `.` *digit*+ [(`e` | `E`) [+ | −] *digit*+];
- `bool`, with literals `true` and `false`.

In addition, the type `void` can be used as return type for “functions” to be used as statements.

Notes

- The type-checker may profit from having an internal type of functions.
- String literals can be used as argument to `printString`; otherwise, there is no type of strings.

Function definitions

Syntax

A function definition has a **result type**, a **name**, a **parameter list** in parentheses and a **body**, which is a block (see below).

A parameter list consists of **parameter declarations** separated by commas; it may be empty.

A parameter declaration is a **type** followed by a **name**.

`return` statements

All functions must `return` a result of their result type.

Procedures may `return` without a value and may also omit the `return` statement ("fall off the end").

Example of function definition

```
int fact (int n) {
  int i,r;
  i = 1;
  r = 1;
  while (i < n+1) {
    r = r * i;
    i++;
  }
  return r;
}
```


Statements

The following statements forms exist in Javalette (details in project description):

- Empty statement.
- Variable declaration.
- Assignment statement.
- Increment and decrement.
- Return-statement.
- Procedure call.
- If-statement (with and without else-part).
- While-statement.
- Block (a sequence of statements enclosed in braces).

Terminating semicolon

The first six statement forms end with semicolon; blocks do not.

Identifiers, declarations and scope

Identifiers

An identifier (a name) is a letter, optionally followed by letters, digits and underscores.
Reserved words (`else if return while`) are not identifiers.

Declarations

A variable (a name) must be declared before it is used.
Otherwise, declarations may be anywhere in a block.

Scope

A variable may only be declared once within a block.
A declaration shadows possible other declarations of the same variable in enclosing blocks.

Expressions

The following expression forms exist in Javalette:

- Variables and literals.
- Binary operator expressions with operators
  `+ - * / % < > >= <= == != && ||`
- Unary operator expressions with operators `-` and `!`.
- Function calls.

Notes

- `&&` and `||` have lazy semantics in the right operand.
- Arithmetic operators are overloaded in types `int` and `double`, but both operands must have the same type (no casts!).

Part A of the project

Contents

- Compiler front end, including
  - Lexing and parsing.
  - Building an IR of abstract syntax trees.
  - Type-checking and checking that functions always `return`.

  BNFC source file for Javalette offered for use.
  We expect that the front end can be mostly finished during week 1.
- JVM backend; only simple code generation.
  Code generation for JVM discussed in lectures week 2.

Deadline

You must submit part A **at the latest** Sunday, April 22 at midnight.

Late submissions will only be accepted if you have a really good reason.

Part B of the project

One more back end

Back end for LLVM. Typed version of three-address code (virtual register machine).
Submission deadline Thursday, May 17 at midnight.

Optional extensions

- Javalette language extensions. One or more of the following:
  - For loops and arrays; restricted forms. Two versions.
  - Dynamic data structures (lists, trees, etc).
  - Classes and objects. Two versions.
- Native code generator. (Support offered only for x86).
  Needs ~~register allocation and~~ complete treatment of function calls.

Jasmin

An assembly language for JVM

Jasmin was introduced as companion to a text book on JVM; not a standardised language.

Jasmin can be assembled to a (binary) Java class file by the `jasmin` assembler. The class file

- can be interpreted by the `java` interpreter.
- can be compiled to native code by a JIT compiler.

Your back end may stop at Jasmin and use the Jasmin assembler to produce a class file.

Java Virtual Machine

A stack machine

The JVM is a stack machine, i.e. most instructions manipulate a stack of values:

- Values are pushed to and popped from the stack; either immediate values (parts of the instruction) or values fetched from named memory locations.
- Arithmetic is performed on the values on top of the stack (which are popped), leaving the result on the stack.
- Conditional jumps are based on values on the top of stack (which are popped).
- In multi-threaded programs, there is one stack per thread (Javalette programs are single-threaded).

Using a virtual machine as target code gives portability
(but we need to write an interpreter for each real machine).

A Jasmin example: `fact`

```
.method public static fact(I)I
.limit locals 3
.limit stack 3
     entry:
       iconst_1
       istore_1
       iconst_1
       istore_2
       goto lab0
     lab1:
       iload_2
       iload_1
       imul
```

```
       istore_2
       iinc 1 1
     lab0:
       iload_1
       iload_0
       iconst_1
       iadd
       if_icmpge lab2
       goto lab1
     lab2:
       iload_2
       ireturn
.end method
```


Generating Jasmin

Basically simple

- Generate code for arithmetic expressions by walking the AST, emitting postfix code.
- Generate code for control structures using compilation schemes with conditional jumps.
- Function calls easy, using invoke/return instructions of Jasmin. (local vars of calling function remain undisturbed on stack).

Book-keeping

Keep track of variable numbers, labels and stack size.

Some optimizations

- Use wider collection of jump instructions.
- Peephole optimization for code improvement.

LLVM: A virtual register machine

Not so different

- Instead of pushing values onto a stack, store them in registers (assume unbounded supply of registers).
- Control structures similar to Jasmin.
- High-level function calls with parameter lists.

LLVM can be interpreted/JIT-compiled directly or serve as input to a retargeting step to real assembly code.

LLVM example: `fact` Part 1

```
define i32 @main() {
entry: %t0 = call i32 @fact(i32 7)
       call void @printInt(i32 %t0)
       ret i32 0
}

define i32 @fact(i32 %__p__n) {
entry: %n = alloca i32
       store i32 %__p__n , i32* %n
       %i = alloca i32
       %r = alloca i32
       store i32 1 , i32* %i
       store i32 1 , i32* %r
       br label %lab0
```


LLVM example: `fact` Part 2

```
lab0:  %t0 = load i32* %i
       %t1 = load i32* %n
       %t2 = icmp sle i32 %t0 , %t1
       br i1 %t2 , label %lab1 , label %lab2
lab1:  %t3 = load i32* %r
       %t4 = load i32* %i
       %t5 = mul i32 %t3 , %t4
       store i32 %t5 , i32* %r
       %t6 = load i32* %i
       %t7 = add i32 %t6 , 1
       store i32 %t7 , i32* %i
       br label %lab0
lab2:  %t8 = load i32* %r
       ret i32 %t8
}
```


Optimization of LLVM code

Many possibilities

Important optimizations can be done using this IR, many based on **data flow analysis** (lecture 8). LLVM tools great for studying effects of various optimizations.
Examples:

- Constant propagation
- Common subexpression elimination
- Dead code elimination
- Moving code out of loops.

You should generate straightforward code and rely on LLVM tools for optimization.

LLVM optimization: example

```
proj> cat myfile.ll | llvm-as | opt -std-compile-opts > myfile
proj> llvm-dis myfileopt.bc
proj> more myfileopt.ll
declare void @printInt(i32)
define i32 @main() {
entry:
tail call void @printInt(i32 5040)
ret i32 0
}
```

continues on next slide

LLVM optimization: example

```
define i32 @fact(i32 %__p__n) nounwind readnone {
entry: %t23 = icmp slt i32 %__p__n, 1
       br i1 %t23, label %lab2, label %lab1
lab1:  %indvar = phi i32 [ 0, %entry ], [ %i.01, %lab1 ]
       %r.02 = phi i32 [ 1, %entry ], [ %t5, %lab1 ]
       %i.01 = add i32 %indvar, 1
       %t5 = mul i32 %r.02, %i.01
       %t7 = add i32 %indvar, 2
       %t2 = icmp sgt i32 %t7, %__p__n
       br i1 %t2, label %lab2, label %lab1
lab2:  %r.0.lcssa = phi i32 [ 1, %entry ], [ %t5, %lab1 ]
       ret i32 %r.0.lcssa
}
```


From LLVM to (x86) assembly

The main tasks

- Instruction selection
- (Register allocation)
- (Instruction scheduling)
- Function calls: explicit handling of activation records. Calling conventions, special registers . . .

Final words

How to choose implementation language?

- Haskell is the most powerful language. Data types and pattern-matching makes for efficient programming. State requires monadic programming; if you never did it, it may take a while to adjust.
- Java, C++ is more mainstream, but will require a lot of code. But you get a visitor framework for free when using BNFC. BNFC patterns for Java are more powerful than for C++.

Testing

On the web site you can find a moderately extensive testsuite of Javalette programs. Test at every stage!

You have a lot of code to design, write and test; it will take more time than you expect. Plan your work and allow time for problems!

What next?

- Find a project partner and choose implementation language.
- Read the project instruction.
- Get started!
- Really, get started!
- If you reuse front end parts, e.g. from Programming languages, make sure you conform to Javalette definition.
- Front end should ideally be completed during this week. Next week's lectures cover JVM and Jasmin code generation.

  No lecture on Thursday!