Compilers I - Chapter 3: Code generation

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- Materials:
  - Textbook
  - Course web pages
  - (http://www.doc.ic.ac.uk/~phjk/Compilers)
  - Piazza
    (http://piazza.com/imperial.ac.uk/fall2016/221)

Overview

- The next few lectures concern code generation. We will look at code generation for statements (up to now we have considered only arithmetic expressions). We will also consider target machine architectures with registers instead of (or as well as) a stack.

The plan

- A simple language with assignments, loops etc.
- A stack-based instruction set and its code generator
- Code generation for a machine with registers:
  - an unbounded number of registers
  - a fixed number of registers
  - avoiding running out of registers
  - register allocation across multiple statements
- Conditionals and Boolean expressions

A simple programming language with statements and loops

- Concrete syntax:

$$
\begin{aligned}
\text{stat} &\rightarrow \text{ident } \text{':='} \text{ exp} \mid \\
&\quad\ \text{stat } \text{';'} \text{ stat} \mid \\
&\quad\ \text{'for' ident 'from' exp 'to' exp 'do' stat 'od'} \\
\text{exp} &\rightarrow \text{exp binop exp} \mid \\
&\quad\ \text{unop exp} \mid \\
&\quad\ \text{ident} \mid \\
&\quad\ \text{num} \\
\text{binop} &\rightarrow \text{'+'} \mid \text{'-'} \mid \text{'*'} \mid \text{'/'} \\
\text{unop} &\rightarrow \text{'-'}
\end{aligned}
$$

(Language based on Maple)

Abstract syntax tree data type:

- data Stat = Assign name Exp |
  Seq Stat Stat |
  ForLoop Name Exp Exp Stat
- data Exp = Binop Op Exp Exp |
  Unop Op Exp |
  Ident Name |
  Const Int
- data Op = Plus | Minus |
  Times | Divide | Minus

- type Name = [Char]

Target machine: stack machine

- To begin with we consider a computer consisting of a main store, addressed from zero up to some limit, together with a program counter, a current instruction register, a pointer to the topmost item on the stack, and a temporary register.

- We can specify what the machine does by giving an interpreter for its instruction set.

```
PROCEDURE stackmachine()
VAR store : ARRAY [0..maxmem] OF WORD
PC, IR, SP, T : WORD;
BEGIN
   PC := 0;   SP := maxmem;        (* stack grows downwards *)
   REPEAT
    IR := store[PC];
    PC := PC + 1;
    CASE opcode(IR) OF
         ADD: ....action for ADD...
         SUB: ....action for SUB...
         PUSHIMM: ....action for PUSHIMM...
         PUSHABS: ....action for PUSHABS...
         COMPEQ: ....action for COMPEQ...
         JTRUE: ....action for JTRUE...
   FOREVER
END
```

This is a description of how the machine executes instructions

The function `opcode` selects the opcode part of the instruction word

Actions for each instruction defined shortly

Labels

- A typical assembly language sequence:

```
start:
  PushAbs i
  PushImm 1
  Sub
  Pop i
  PushAbs i
  PushImm 100
  CompEq
  JTrue start
```

- labels need to appear in the compiler's output stream—even though they don't really correspond to instructions.

Labels - representation

- So we include a pseudo-instruction "Define" in the instruction data type. Using it, the assembly code above is represented by the Haskell list:

```
[Define "start",
 PushAbs "i",
 PushImm 1,
 Sub,
 Pop "i",
 PushAbs "i",
 CompEQ,
 Jtrue "start"]
```

This is a Haskell representation of assembly language. In assembly language, cross-references are represented using labels which are resolved by the linker

Instruction set for stack machine

```
data Instruction
  = Add | Sub | Mul | Div                  (as before)
    | PushImm Int     (push constant onto stack)
    | PushAbs Name    (push variable at given location onto stack)
    | Pop Name        (remove top of stack & store it at given loc'n)
    | CompEq          (subtract top two elements of stack, and
                       replace with 1 if the result was zero, 0 otherwise)
    | JTrue Label     (remove top item from stack; if 1 jump to label)
    | JFalse Label    (jump if stack top is 0)
    | Define Label    (set up destination for jump)
```

Note that `Define` is an assembler directive, not an executable instruction

What exactly do these instructions do?

```
CASE opcode(IR) OF
  ADD:
    T:=store[SP];
    SP := SP+1;
    T:=store[SP]+T;
    store[SP]:=T;
  PUSHIMM:
    SP:=SP-1;
    store[SP]:=operand(IR);
  PUSHABS:
    T:=store[operand(IR)];
    SP:=SP-1;
    store[SP]:=T;
  POP:
    T:=store[SP];
    SP:=SP+1;
    store[operand(IR)]:=T;
  COMPEQ:
    T:=store[SP];
    SP := SP+1;
    T:=store[SP]-T;
    store[SP]:=IF T=0 THEN 1 ELSE 0;
  JTRUE:
    T:=store[SP];
    SP:=SP+1;
    IF T=1 THEN PC:=operand(IR);
```

Syntax-directed translation

- The structure of our translator is derived *systematically* from the AST data type—which in turn is derived from the language's grammar. Thus translation is "syntax-directed".

- In fact some textbooks (eg EaC and The Dragon book) make this link explicit -
  - *attribute grammars* express syntax-directed translation directly in terms of the grammar
  - we use Haskell to traverse the AST. The principle is the same
  - In Java a common approach is to use a Visitor pattern, see example at the end of these notes
- (Using attribute grammars leads to interesting possibilities for automatically-generating the syntax-directed translator)

Ad-hoc syntax-directed translation

- Attribute grammars are a neat theory (see Appendix B of these notes)
  - For example, supports *incremental* calculation of attributes, so you can update them when small changes are made to the tree
  - Lots of academic researchers have developed compiler-construction tools based on attribute grammars

- In most cases it's just as easy to build your own syntax-directed translator directly (see EaC section 4.4)
- Especially if you use a nice functional language like Haskell… (if you want to see how it's done in Java see Appendix A).

A Naive code generator for a stack machine

- We now present a syntax-directed code generator for the language with assignment and 'for' loops
- The structure of the translator is derived directly from the AST data type: we deal with each of the alternatives using a separate rule
- Begin with assignment:

```
transStat :: stat -> [instruction]
transStat (Assign (Ident id) exp) = ...
transStat (Seq s1 s2) = ...
transStat (ForLoop id e1 e2 body) = ...
```

Assignment:

```
transStat (Assign (Ident id) exp)
  = transExp exp ++ [Pop id]
```

- The output code consists of instructions generated by `transExp` (see later), joined to the one element list '`[Pop id]`'.
- '`transExp exp`' yields a list of instructions, which, when executed, leave the value of the RHS of the assignment on the top of the stack.
- When the '`Pop id`' instruction is executed, it removes the value from the stack and stores it at the location specified by the name `id`.

Statement sequence:

```
transStat (Seq s1 s2)
  = transStat s1 ++ transStat s2
```

For loop:

The 'for' statement is a bit more complicated…

This is our "**code template**" for the 'for' loop

- Basic idea—given the source code:

```
for x := e1 to e2 do
  body
od
next statement
```

- we want the output code to look like:

```
  x := e1
label1:
  if x>e2 then goto label2
  body
  x := x + 1
  goto label1
label2:
  code for next statement
```

For loops…

- **Example**: Source code:

```
for x := 1 to 10 do
  a := a+x;
od
```

- … Resulting code:

```
[PushImm 1,        (initialisation)
Pop "x",
Define L1,
PushImm 10,        (test)
PushAbs "x",
CompGt.
JTrue L2,
PushAbs "a",       (body)
PushAbs "x",
Add,  Pop "a",     (store a+x in a)
PushAbs "x",       (increment)
PushImm 1,
Add,
Pop "x",           (store x+1 in x)
Jump L1,
Define L2]
```

- From the template, write down the translator:

```
transStat (ForLoop id e1 e2 body)
= transExp e1 ++ [Pop id] ++
  [Define label1] ++
  transExp e2 ++ [PushAbs id] ++ [CompGt] ++
  [JTrue label2] ++
  transStat body ++
  [PushAbs id] ++ [PushImm 1] ++ [Add] ++ [Pop id]++
  [Jump label1] ++
  [Define label2]
```

(initialisation)

(test)

(increment)

where label1 and label2 are fresh labels which have not been used so far

Expressions:

- This completes the statement part of the code generator; all that remains is to deal with expressions—which are handled just as they were in the introductory example:

```
transExp :: Exp -> [Instruction]
transExp (Binop op e1 e2)
= transExp e1 ++
  transExp e2 ++
  transOp op

transExp (Unop op e)
= transExp e ++
  transUnop op
  transExp (Ident id) = [PushAbs id]

transExp (Const v) = [PushImm v]
  transOp Plus = [Add]
  transOp Minus = [Sub]
  transOp Times = [Mul]
  transOp Divide = [Div]
  transUnop Minus = [Negate]
```

Conclusion

- This chapter has shown how a code generator can be written, which takes an AST as input and produces a working assembler program as output.
- We divided the problem into two parts: code generation for statements (e.g. assignment, if-then-else, while, for etc), and code generation for expressions.
- For each statement type, the code generator uses a standard "template"; the details of the statement determine how the gaps are filled in.
- For expressions we used a very simple, stack-based scheme; we will study better ways very shortly
- We haven't looked at procedures, declarations, records, etc.

Textbooks

- EaC
  - Section 4.4: ad-hoc syntax-directed translation
  - especially Figure 4.14 (pg 198)
  - Section 4.3: Attribute grammars
  - See also section 11.1
- Appel
  - Section 11.4: Expression trees, register allocation
  - Section 9: Instruction selection (Appel skips simple code generation and concentrates on finding the best instruction to match the context).
- Dragon Book
  - Chapter 2: introduction to code generation
  - Chapter 8, esp 8.1 and 8.6

This course vs the textbooks

- In this course, we translate the text into the AST, then translate the AST to assembler. Modern compilers tend to use an more than one *Intermediate Representation* (IR)
- **See EaC Chapter 5**
- The first IR is often a tree, the Abstract Syntax Tree
  – But may include statement operations and expressions uniformly
  – This is useful for more sophisticated instruction selection and register allocation techniques
- This tree is typically "flattened" into a control-flow graph or linear IR, that makes branches/jumps explicit
  – A data structure representing the assembler-level code
  – Useful for control-flow – sensitive optimisations like loop-invariant code motion
- Modern compilers often also use dependence-based graph representations, and "static single assignment" form

Appendix A

- To help clarify what is going on for students less familiar with Haskell, the next few slides offer a sketch of how to do this is Java.
- You can find the code at

  http://www.doc.ic.ac.uk/~phjk/CompilersCourse/SampleCode/Ex2-CodeGenInJava/

Step 1: define abstract syntax tree

```
public abstract class StatementTree {
    public abstract void Accept(StatementTreeVisitor v);
}

public class AssignNode extends StatementTree {
    String lhs; ExpressionTree rhs;
    AssignNode(String _lhs, ExpressionTree _rhs) {
        lhs = _lhs; rhs = _rhs;
    }
    public void Accept(StatementTreeVisitor v) {
        v.visitAssignNode(lhs, rhs);
    }
}
```

Each AST node type extends StatementTree abstract class
Each node has members, constructor, and accepts a visitor

Step 1: define abstract syntax tree

```
public class CompoundNode extends StatementTree {
   Vector body; // Vector of StatementTree
   CompoundNode(Vector _body) {
      body = _body;
   }
   public void Accept(StatementTreeVisitor v) {
      v.visitCompoundNode(body);
   }}
public class IfThenNode extends StatementTree {
   ExpressionTree cond; StatementTree body;
   IfThenNode(ExpressionTree _cond, StatementTree _body) {
      cond = _cond; body = _body;
   }
   public void Accept(StatementTreeVisitor v) {
      v.visitIfThenNode(cond, body);
   }}
```

For this example we define an AST with three node types:

- Assignment statement
- Compound statement
- If-Then statement

Each AST node type extends StatementTree abstract class

Each node has members, constructor, and accepts a visitor

Step 2: define the Visitor class

```
public abstract class StatementTreeVisitor {
   abstract void visitCompoundNode(Vector body);
   abstract void visitAssignNode(String lhs, ExpressionTree rhs);
   abstract void visitIfThenNode(ExpressionTree cond, StatementTree body);
}
```

To define a function to walk the AST, create a Visitor like this:

```
public class ExampleVisitor extends StatementTreeVisitor {
   void visitCompoundNode(Vector body) {
      // case for Compound statement node
   }
   void visitAssignNode(String lhs, ExpressionTree rhs) {
      // case for Assign statement node
   }
   void visitIfThenNode(ExpressionTree cond, StatementTree body) {
      // case for If-Then statement node
}}
```

Step 3: define a Visitor that generates code

public class TranslateVisitor extends StatementTreeVisitor {

We implement the code generator as a visitor.
We define a “visit” method for each node type

Assign node case:

```
void visitAssignNode(String lhs, ExpressionTree rhs) {
    // print instructions which, when executed, will leave
    // expression value at top of stack
    rhs.Accept(new TranslateExpVisitor());
    System.out.println("pop "+lhs);
  }

  .....
```

Step 3: define a Visitor that generates code

Compound statement node case:

```
void visitCompoundNode(Vector body) {
  // Visit each statement in the list of statements
  // that make up the Compound statement body
  for (int i=0; i<body.size(); i++)
    ((StatementTree)body.elementAt(i)).Accept(this);
}
```

Step 3: define a Visitor that generates code

Assign node case:

```
…
void visitIfThenNode(ExpressionTree cond, StatementTree body) {
    // print instructions which, when executed, will leave
    // expression value at top of stack
    UniqueLabel skiplabel = new UniqueLabel();
    cond.Accept(new TranslateExpVisitor());
    System.out.println("JFalse "+skiplabel.toString());
    body.Accept(this);
    System.out.println("Define "+skiplabel.toString());
}
```

(to complete this code you need to add an AST for expressions)

If you don’t use a visitor…

```
public class TurnNode extends StatementTree {
    int degrees;

    TurnNode(int d) {
        degrees = d;
    }
    public void print() {
        System.out.println("turn "+degrees+" degrees");
    }
    public void interpret() {
        System.out.println("please turn "+degrees);
    }
    public void print() {
        System.out.println("turn "+degrees);
    }
}
```

- *You need to add a method for each operation that involves a traversal of the AST*
- *For every StatementTree subclass*

```
public class InterpretVisitor extends TreeVisitor {
  void visitStatementList(StatementTree first,
                          StatementTreeList rest) {
    first.Accept(this);
    if (rest != null) {
      rest.Accept(this);
    }
  }
  void visitTurnNode(int degrees) {
    System.out.println("Please turn "+degrees+" degrees");
  }
  void visitForwardNode(int distance) {
    System.out.println("Please move forward "+distance);
  }
  void visitTimesNode(int count, StatementTree body) {
    for (int i=0; i<count; ++i) {
      body.Accept(this);
    }
  }
  void visitBeginNode(StatementTreeList body) {
    body.Accept(this);
  }
}
```

- Now we can encapsulate all the interpreter code in a single file
- And we can write a “print” traversal in a similar, single file

Appendix B: Attribute grammars

Example grammar

Number	→	Sign List
Sign	→	<u>+</u>
	|	<u>-</u>
List	→	List Bit
	|	Bit
Bit	→	0
	|	1

This grammar describes signed binary numbers

We would like to augment it with rules that compute the decimal value of each valid input string

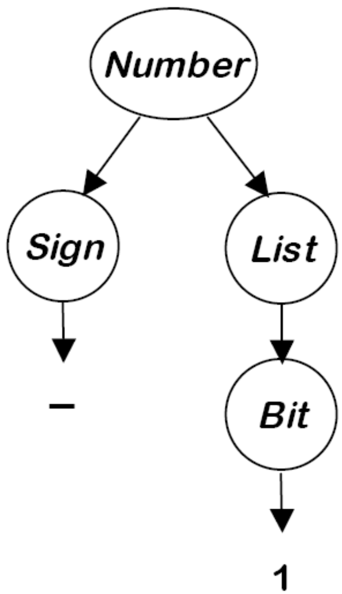
- Attribute grammars are a formal technique for specifying syntax-directed computation
- Invented by Knuth in 1968 – see EaC Section 4.3
- A kind of functional programming…

Example attributed to Scott K Warren

Numbers represented in our example grammar

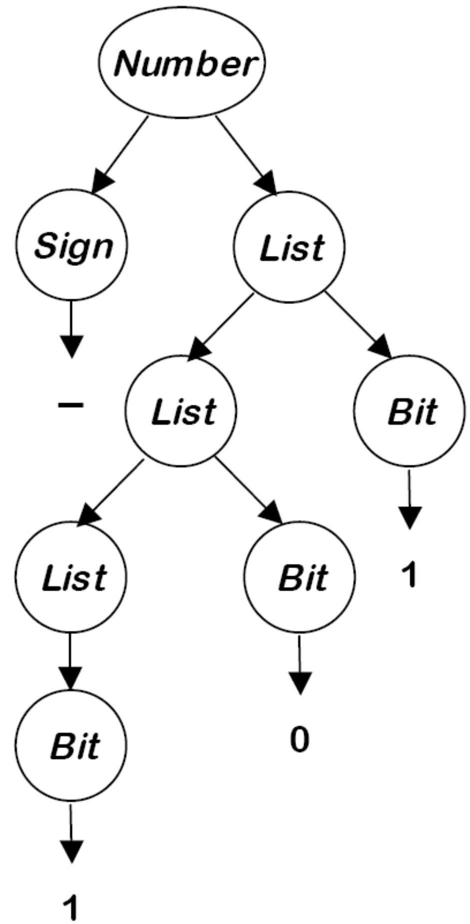
For "–1"

Number → *Sign List*
→ – *List*
→ – *Bit*
→ – *1*



For "–101"

Number → *Sign List*
→ *Sign List Bit*
→ *Sign List 1*
→ *Sign List Bit 1*
→ *Sign List 1 1*
→ *Sign Bit 0 1*
→ *Sign 1 0 1*
→ – *101*



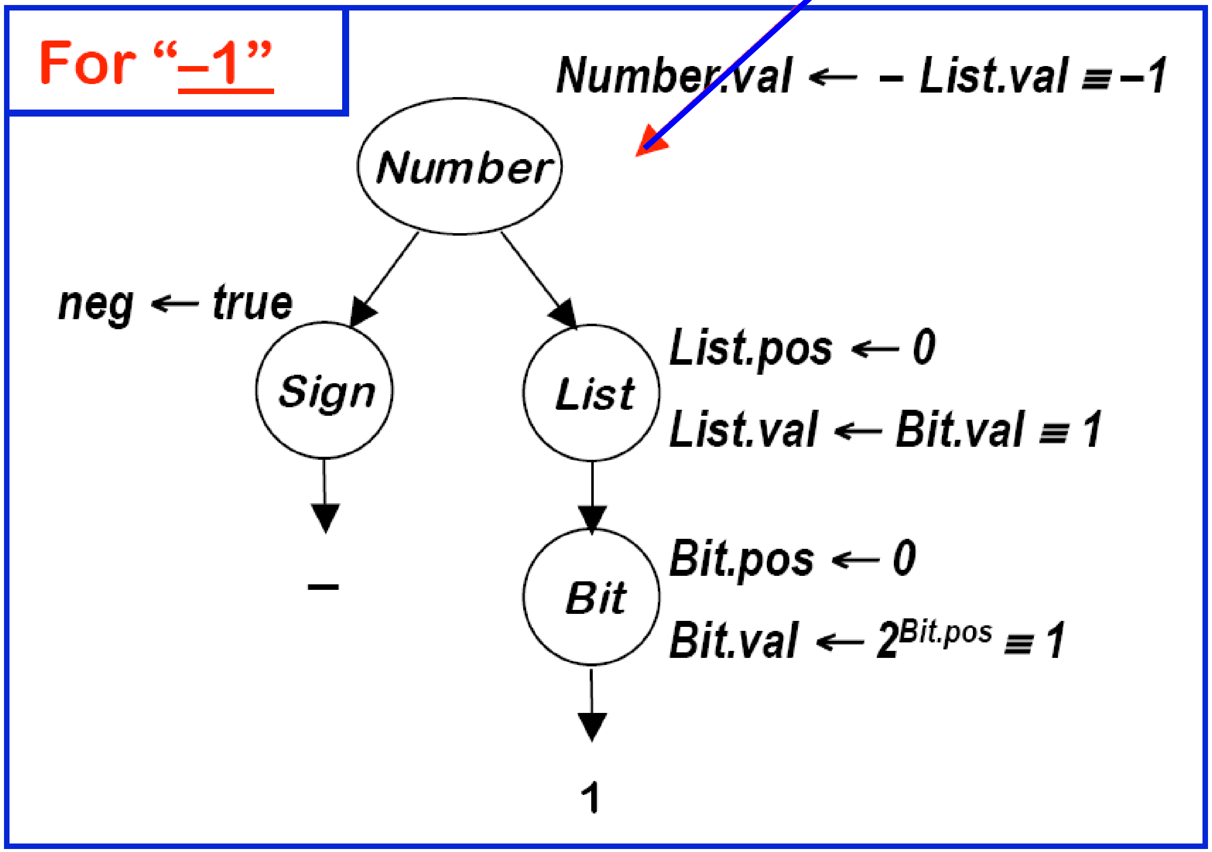
Extending the grammar with attributes

Productions			Attribution Rules
Number	$\rightarrow$	*Sign List*	$List.pos \leftarrow 0$ If $Sign.neg$ then $Number.val \leftarrow -List.val$ else $Number.val \leftarrow List.val$
Sign	$\rightarrow$	$\underline{+}$	$Sign.neg \leftarrow false$
	|	$\underline{-}$	$Sign.neg \leftarrow true$
$List_0$	$\rightarrow$	$List_1$ *Bit*	$List_1.pos \leftarrow List_0.pos + 1$ $Bit.pos \leftarrow List_0.pos$ $List_0.val \leftarrow List_1.val + Bit.val$
	|	*Bit*	$Bit.pos \leftarrow List.pos$ $List.val \leftarrow Bit.val$
Bit	$\rightarrow$	0	$Bit.val \leftarrow 0$
	|	1	$Bit.val \leftarrow 2^{Bit.pos}$

Symbol	Attributes
Number	val
Sign	neg
List	pos, val
Bit	pos, val

- Each non-terminal carries attributes
- Each production of the grammar is extended with rules
- The rules specify how the attributes are calculated

- Parse tree, combined with attribute rules, define functional program to calculate all the attribute values



One possible evaluation order:

1. List.pos
2. Sign.neg
3. Bit.pos
4. Bit.val
5. List.val
6. Number.val

Other orders are possible

- Evaluation order must be consistent with attribute dependence graph

(Example from Ken Kennedy's EaC-based course notes)