Introduction to Compilers

Compilers

What is a compiler?

- a program that translates an *executable* program in one language into an *executable* program in another language
- we expect the program produced by the compiler to be better, in some way, than the original

What is an interpreter?

- a program that reads an *executable* program and produces the results of running that program
- usually, this involves executing the source program in some fashion

This course deals mainly with *compilers*

Many of the same issues arise in *interpreters*

Motivation

Why study compiler construction?

Why build compilers?

Why attend class?

Interest

Compiler construction is a microcosm of computer science

artificial intelligence

greedy algorithms, learning algorithms

algorithms

graph algorithms, union-find, dynamic programming

theory

DFAs for scanning, parser generators, lattice theory

systems

allocation and naming, locality, synchronization

architecture

pipeline management, hierarchy management, instruction set use

Inside a compiler, all these things come together

Isn't it a solved problem?

Machines are constantly changing

Changes in architecture ⇒ changes in compilers

- new features pose new problems
- changing costs lead to different concerns
- old solutions need re-engineering

Changes in compilers should prompt changes in architecture

- New languages and features

Intrinsic Merit

Compiler construction is challenging and fun

- interesting problems
- primary responsibility for performance (*blame*)
- new architectures $\Rightarrow$ new challenges
- *real* results
- extremely complex interactions

Compilers have an impact on how computers are used

Some of the most interesting problems in computing

Experience

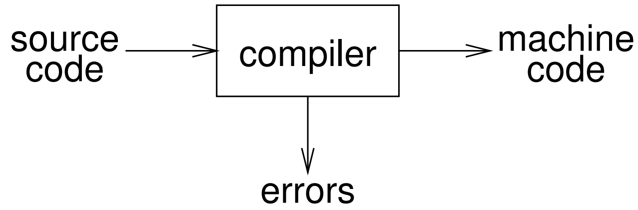
You have used several compilers

What qualities are important in a compiler?

1. Correct code
2. Output runs fast
3. Compiler runs fast
4. Compile time proportional to program size
5. Support for separate compilation
6. Good diagnostics for syntax errors
7. Works well with the debugger
8. Good diagnostics for flow anomalies
9. Cross language calls
10. Consistent, predictable optimization

Each of these shapes your expectations about this course

Abstract view

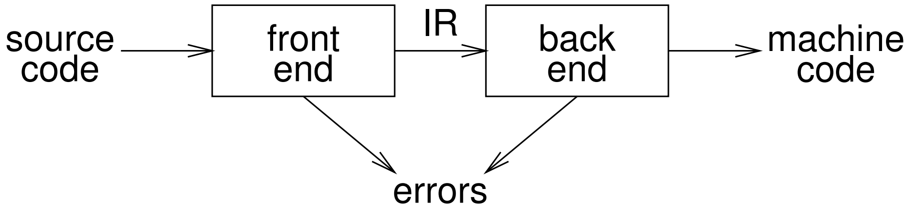


Implications:

- recognize legal (and illegal) programs
- generate correct code
- manage storage of all variables and code
- agreement on format for object (or assembly) code

Big step up from assembler — higher level notations

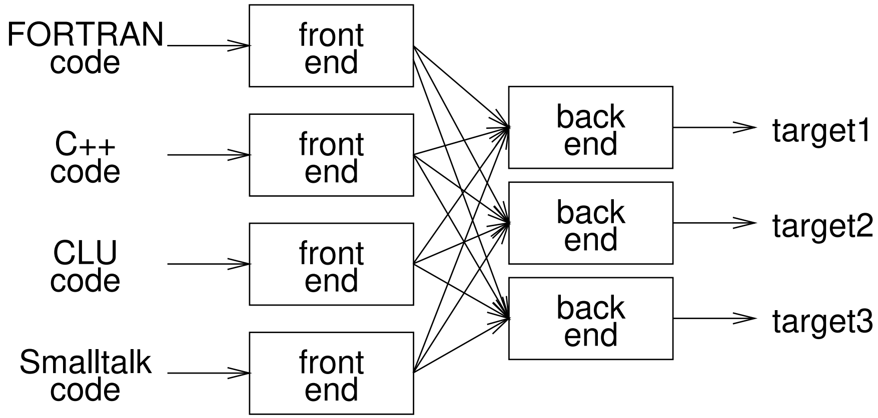
Traditional two pass compiler



Implications:

- intermediate representation (IR)
- front end maps legal code into IR
- back end maps IR onto target machine
- simplify retargeting
- allows multiple front ends
- multiple passes $\Rightarrow$ better code

A fallacy

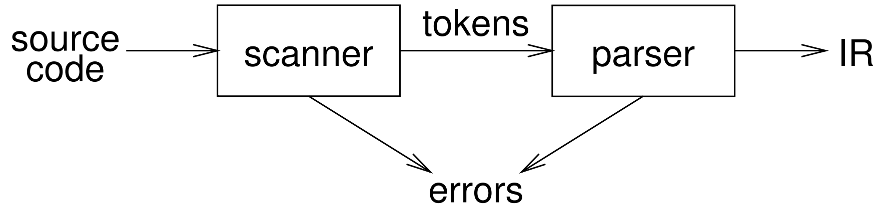


Can we build $n \times m$ compilers with $n + m$ components?

- must encode *all* the knowledge in each front end
- must represent *all* the features in one IR
- must handle *all* the features in each back end

Limited success with low-level IRs

Front end

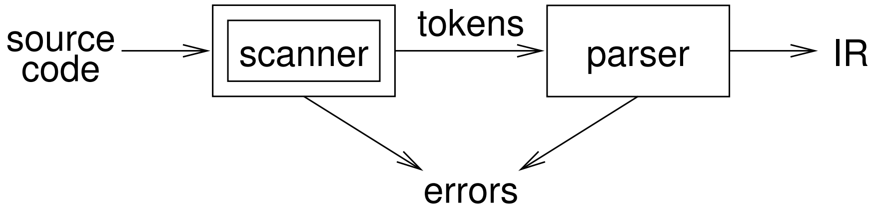


Responsibilities:

- recognize legal procedure
- report errors
- produce IR
- preliminary storage map
- shape the code for the back end

Much of front end construction can be automated

Front end



Scanner:

- maps characters into *tokens* – the basic unit of syntax

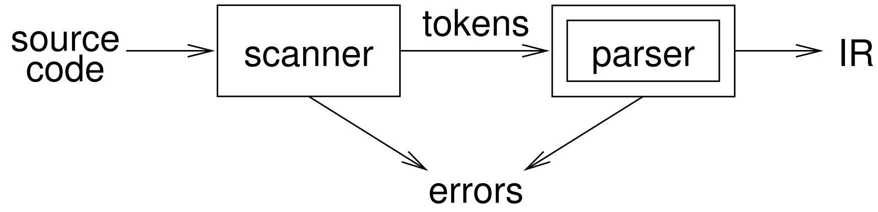
  `x = x + y;`

  becomes

  $<$id, `x`$>$ = $<$id, `x`$>$ + $<$id, `y`$>$ `;`
- character string value for a *token* is a *lexeme*
- typical tokens: *number*, *id*, `+`, `-`, `*`, `/`, `do`, `end`
- eliminates white space (*tabs, blanks, comments*)
- a key issue is speed

  $\Rightarrow$ use specialized recognizer (as opposed to `lex`)

Front end



Parser:

- recognize context-free syntax
- guide context-sensitive analysis
- construct IR(s)
- produce meaningful error messages
- attempt error correction

Parser generators mechanize much of the work

Front end

Context-free syntax is specified with a *grammar*

<sheep noise> ::= `baa`
  | `baa` <sheep noise>

The noises sheep make under normal circumstances

This format is called *Backus-Naur form* (BNF)

Formally, a grammar $G = (S, N, T, P)$ where

S is the *start symbol*
N is a set of *non-terminal symbols*
T is a set of *terminal symbols*
P is a set of *productions* or *rewrite rules*
  ($P : N \to N \cup T$)

Front end

Context free syntax can be put to better use

1	<goal>	::=	<expr>
2	<expr>	::=	<expr> <op> <term>
3		|	<term>
4	<term>	::=	`number`
5		|	`id`
6	<op>	::=	`+`
7		|	`-`

Simple expressions with addition and subtraction over tokens `id` *and* `number`

S = *<goal>*

T = `number`, `id`, `+`, `-`

N = *<goal>*, *<expr>*, *<term>*, *<op>*

P = 1, 2, 3, 4, 5, 6, 7

Front end

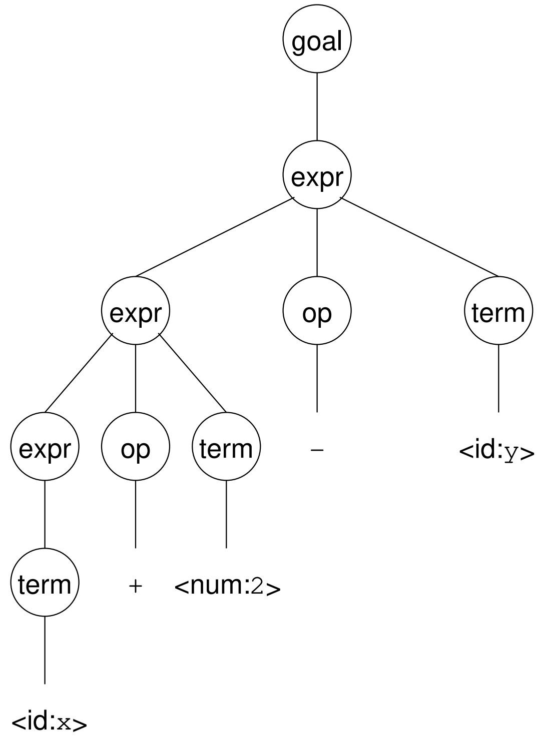
Given a grammar, valid sentences can be derived by repeated substitution.

Prod'n.	Result
	<goal>
1	<expr>
2	<expr> <op> <term>
5	<expr> <op> `y`
7	<expr> `- y`
2	<expr> <op> <term> `- y`
4	<expr> <op> `2 - y`
6	<expr> `+ 2 - y`
3	<term> `+ 2 - y`
5	`x + 2 - y`

To recognize a valid sentence in some CFG, we reverse this process and build up a *parse*

Front end

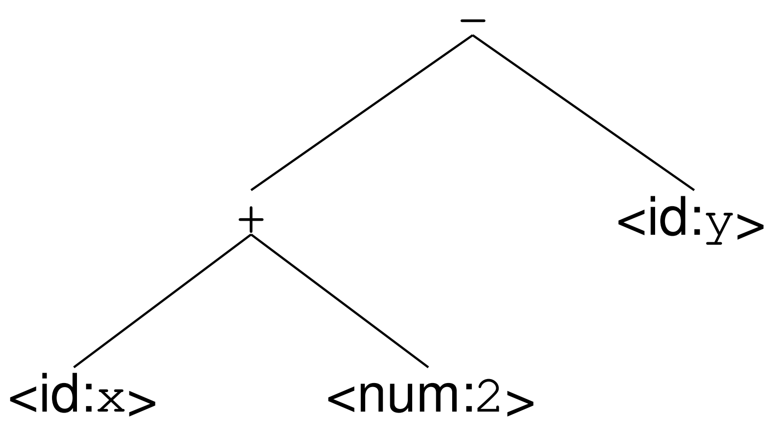
A parse can be represented by a *parse*, or *syntax*, tree



Obviously, this contains a lot of unnecessary information

Front end

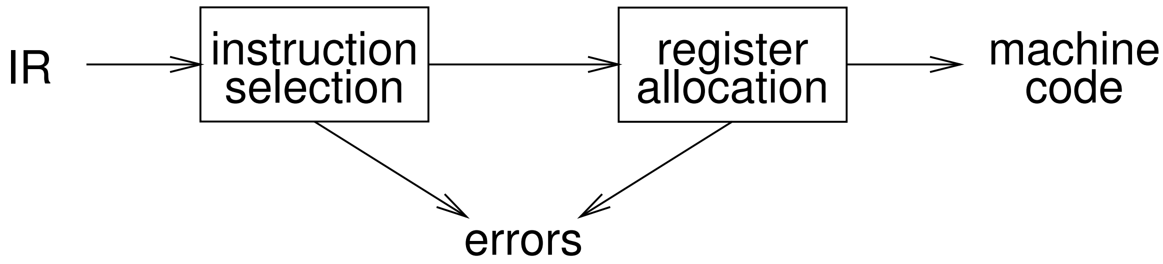
So, compilers often use an *abstract syntax tree*



This is much more concise

Abstract syntax trees (ASTs) are often used as an IR between front end and back end

Back end

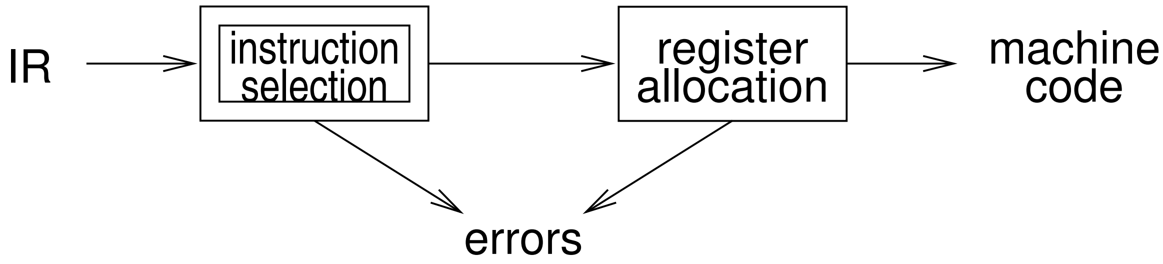


Responsibilities

- translate IR into target machine code
- choose instructions for each IR operation
- decide what to keep in registers at each point
- ensure conformance with system interfaces

Automation has been less successful here

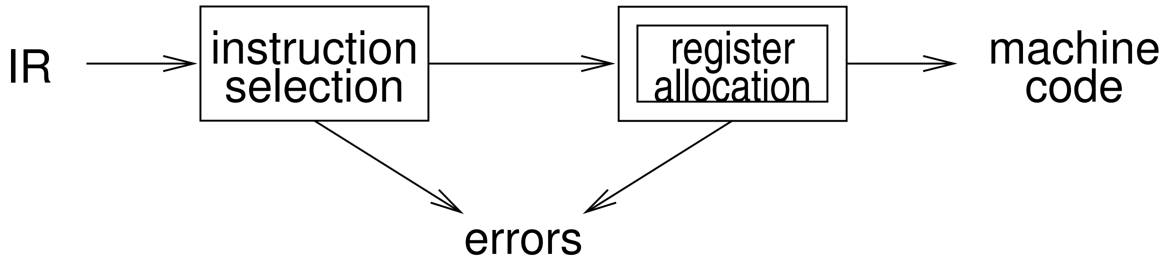
Back end



Instruction selection:

- produce compact, fast code
- use available addressing modes
- pattern matching problem
  - *ad hoc* techniques
  - tree pattern matching
  - string pattern matching
  - dynamic programming

Back end

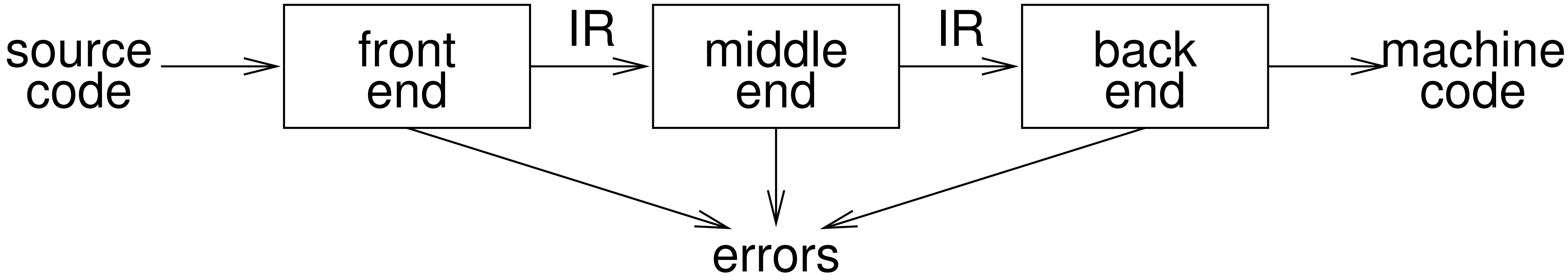


Register Allocation:

- have value in a register when used
- limited resources
- changes instruction choices
- can move loads and stores
- optimal allocation is difficult

Modern allocators often use an analogy to graph coloring

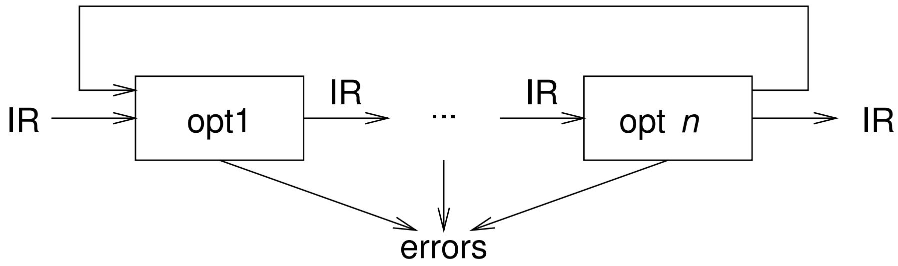
Traditional three pass compiler



Code Improvement

- analyzes and changes IR
- goal is to reduce runtime
- must preserve values

Optimizer (middle end)

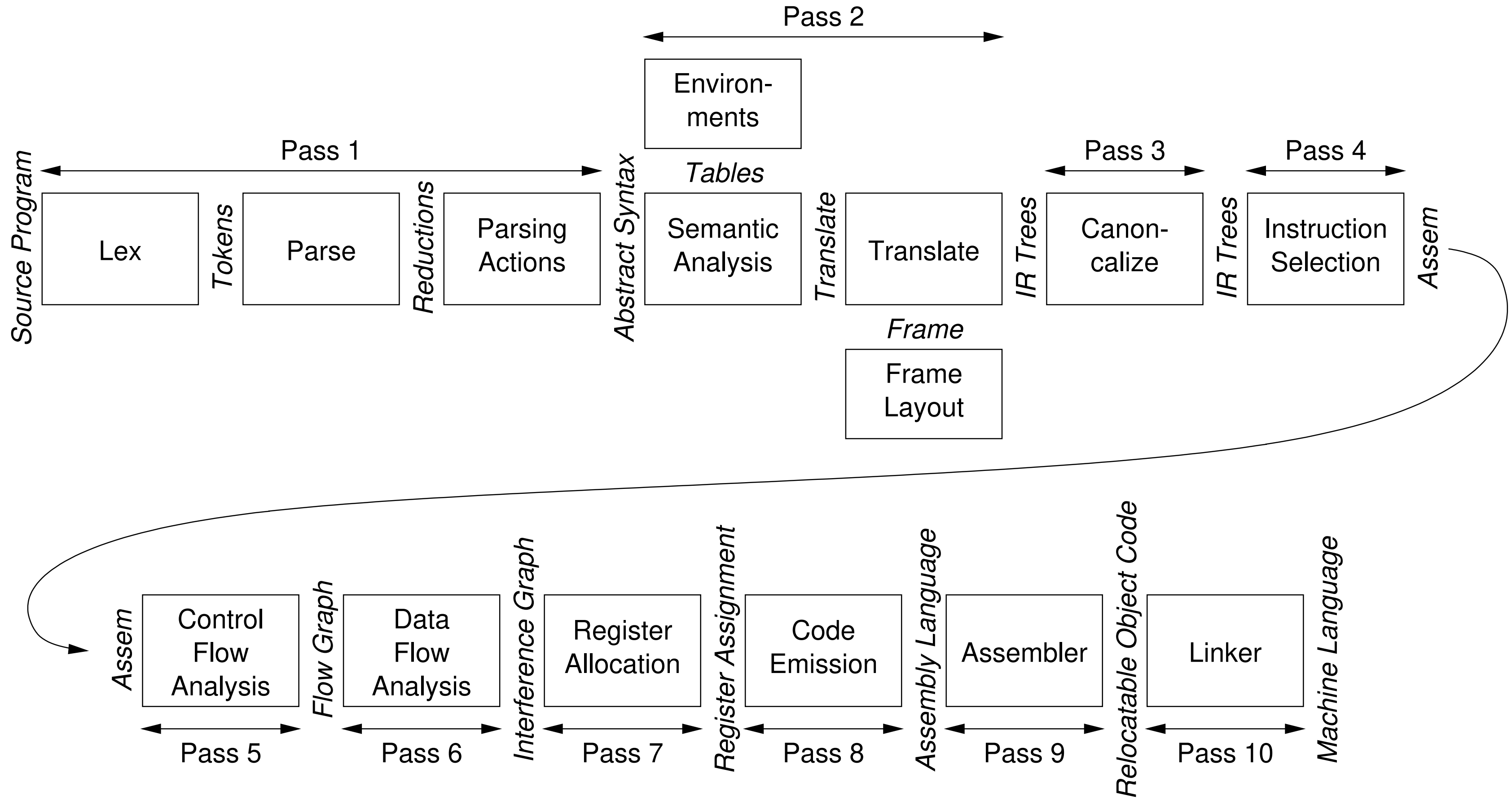


Modern optimizers are usually built as a set of passes

Typical passes

- constant propagation and folding
- code motion
- reduction of operator strength
- common subexpression elimination
- redundant store elimination
- dead code elimination

The project compiler



The project compiler phases

Lex	Break source file into individual words, or *tokens*
Parse	Analyse the phrase structure of program
Parsing Actions	Build a piece of *abstract syntax tree* for each phrase
Semantic Analysis	Determine what each phrase means, relate uses of variables to their definitions, check types of expressions, request translation of each phrase
Frame Layout	Place variables, function parameters, etc., into activation records (stack frames) in a machine-dependent way
Translate	Produce *intermediate representation trees* (IR trees), a notation that is not tied to any particular source language or target machine
Canonicalize	Hoist side effects out of expressions, and clean up conditional branches, for convenience of later phases
Instruction Selection	Group IR-tree nodes into clumps that correspond to actions of target-machine instructions
Control Flow Analysis	Analyse sequence of instructions into *control flow graph* showing all possible flows of control program might follow when it runs
Data Flow Analysis	Gather information about flow of data through variables of program; e.g., *liveness analysis* calculates places where each variable holds a still-needed (*live*) value
Register Allocation	Choose registers for variables and temporary values; variables not simultaneously live can share same register
Code Emission	Replace temporary names in each machine instruction with registers

A straight-line programming language

Stm	$\rightarrow$	*Stm* ; *Stm*	CompoundStm
Stm	$\rightarrow$	`id` := *Exp*	AssignStm
Stm	$\rightarrow$	`print` (*ExpList*)	PrintStm
Exp	$\rightarrow$	`id`	IdExp
Exp	$\rightarrow$	`num`	NumExp
Exp	$\rightarrow$	*Exp Binop Exp*	OpExp
Exp	$\rightarrow$	(*Stm* , *Exp*)	EseqExp
ExpList	$\rightarrow$	*Exp* , *ExpList*	PairExpList
ExpList	$\rightarrow$	*Exp*	LastExpList
Binop	$\rightarrow$	$+$	Plus
Binop	$\rightarrow$	$-$	Minus
Binop	$\rightarrow$	$\times$	Times
Binop	$\rightarrow$	$/$	Div

An example straight-line program:

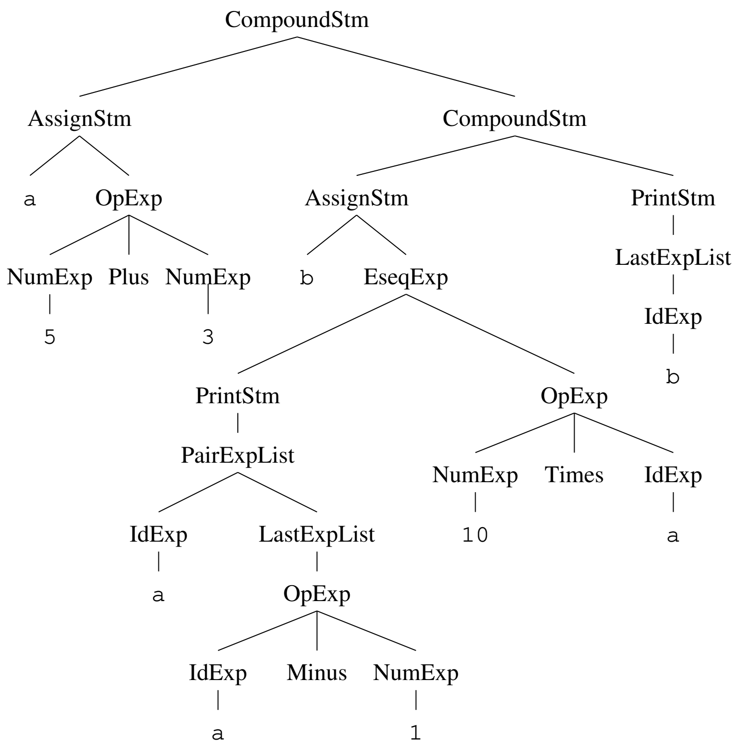
$$\mathtt{a} := 5+3;\ \mathtt{b} := (\mathtt{print}(\mathtt{a}, \mathtt{a}-1), 10 \times \mathtt{a});\ \mathtt{print}(\mathtt{b})$$

prints:

```
8  7
80
```

Tree representation

$\mathtt{a} := 5+3;\ \mathtt{b} := (\mathtt{print}(\mathtt{a}, \mathtt{a}-1), 10 \times \mathtt{a});\ \mathtt{print}(\mathtt{b})$



This is a convenient internal representation for a compiler to use.

Java classes for trees

```
abstract class Stm {}
class CompoundStm extends Stm
   Stm stm1, stm2;
   CompoundStm(Stm s1, Stm s2)
   { stm1=s1; stm2=s2; }
}
class AssignStm extends Stm
{
   String id; Exp exp;
   AssignStm(String i, Exp e)
   { id=i; exp=e; }
}
class PrintStm extends Stm {
   ExpList exps;
   PrintStm(ExpList e)
   { exps=e; }
}
```

Java classes for trees (continued)

```
abstract class Exp {}
class IdExp extends Exp {
   String id;
   IdExp(String i) {id=i;}
}
class NumExp extends Exp {
   int num;
   NumExp(int n) {num=n;}
}
class OpExp extends Exp {
   Exp left, right; int oper;
   final static int
     Plus=1,Minus=2,Times=3,Div=4;
   OpExp(Exp l, int o, Exp r)
   { left=l; oper=o; right=r; }
}
```

```
class EseqExp extends Exp {
   Stm stm; Exp exp;
   EseqExp(Stm s, Exp e)
   { stm=s; exp=e; }
}
abstract class ExpList {}
class PairExpList extends ExpList {
   Exp head; ExpList tail;
   public PairExpList(Exp h, ExpList t)
   { head=h; tail=t; }
}
class LastExpList extends ExpList {
   Exp head;
   public LastExpList(Exp h)
   { head=h; }
}
```