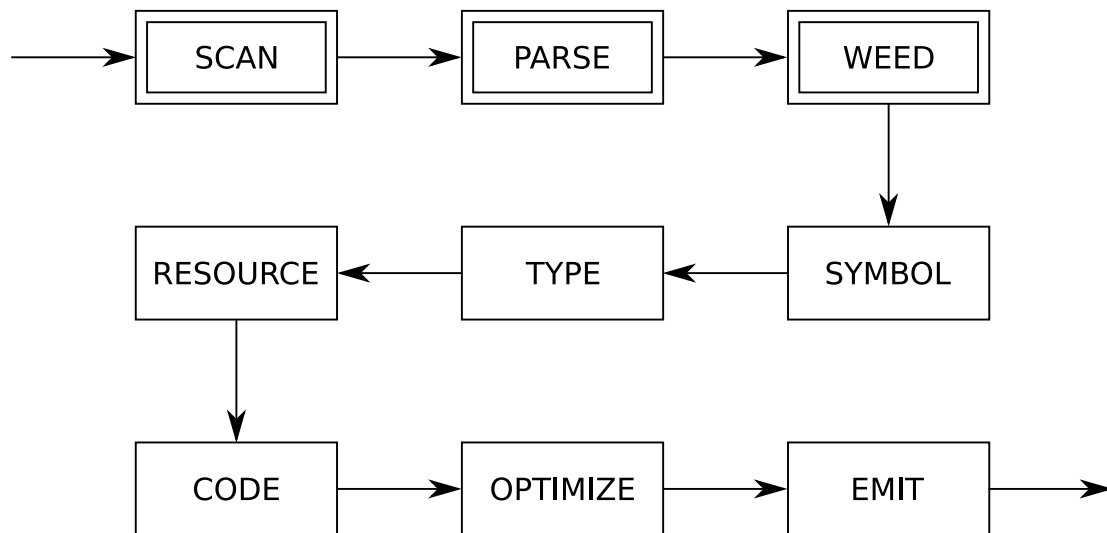


Abstract syntax trees



A compiler *pass* is a traversal of the program. A compiler *phase* is a group of related passes.

A *one-pass* compiler scans the program only once. It is naturally single-phase. The following all happen at the same time:

- scanning
- parsing
- weeding
- symbol table creation
- type checking
- resource allocation
- code generation
- optimization
- emitting

This is a terrible methodology:

- it ignores natural modularity;
- it gives unnatural scope rules; and
- it limits optimizations.

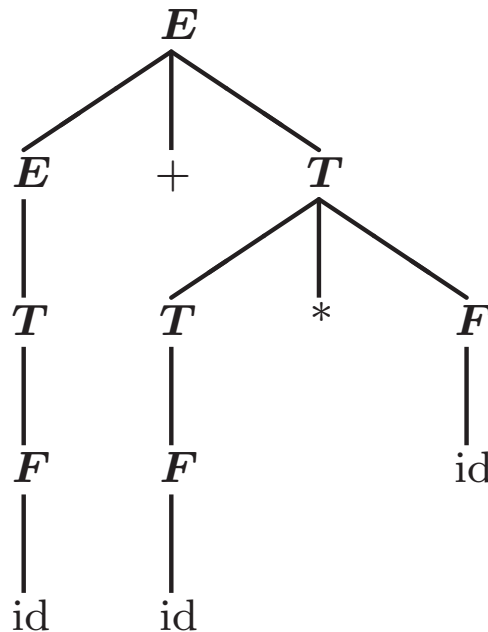
However, it used to be popular:

- it's fast (if your machine is slow); and
- it's space efficient (if you only have 4K).

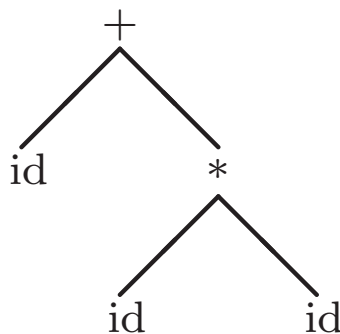
A modern *multi-pass* compiler uses 5–15 phases, some of which may have many individual passes: you should skim through the optimization section of ‘man gcc’ some time!

A multi-pass compiler needs an *intermediate representation* of the program between passes.

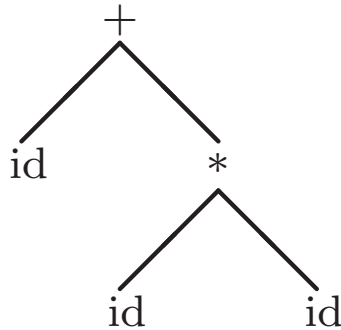
We could use a parse tree, or *concrete syntax tree* (CST):



or we could use a more convenient *abstract syntax tree* (AST), which is essentially a parse tree/CST but for a more abstract grammar:



Instead of constructing the tree:



a compiler can generate code for an internal compiler-specific grammar, also known as an *intermediate language*.

Early multi-pass compilers wrote their IL to disk between passes. For the above tree, the string `+(id,*(id,id))` would be written to a file and read back in for the next pass.

It may also be useful to write an IL out for debugging purposes.

Examples of modern intermediate languages:

- Java bytecode
- C, for certain high-level language compilers
- Jimple, a 3-address representation of Java bytecode specific to Soot that you learn about in COMP 621
- Simple, the precursor to Jimple that Laurie Hendren created for McCAT
- Gimple, the IL based on Simple that gcc uses

In this course, you will generally use an AST as your IR without the need for an explicit IL.

Note: somewhat confusingly, both industry and academia use the terms IR and IL interchangeably.

```
$ cat tree.h tree.c # AST construction for Tiny language
[...]
typedef struct EXP {
    enum {idK,intconstK,timesK,divK,plusK,minusK} kind;
    union {
        char *idE;
        int intconstE;
        struct {struct EXP *left; struct EXP *right;} timesE;
        struct {struct EXP *left; struct EXP *right;} divE;
        struct {struct EXP *left; struct EXP *right;} plusE;
        struct {struct EXP *left; struct EXP *right;} minusE;
    } val;
} EXP;

EXP *makeEXPid(char *id)
{ EXP *e;
  e = NEW(EXP);
  e->kind = idK;
  e->val.idE = id;
  return e;
}

[...]

EXP *makeEXPminus(EXP *left, EXP *right)
{ EXP *e;
  e = NEW(EXP);
  e->kind = minusK;
  e->val.minusE.left = left;
  e->val.minusE.right = right;
  return e;
}
```

```
$ cat tiny.y # Tiny parser that creates EXP *theexpression

%{
#include <stdio.h>
#include "tree.h"

extern char *yytext;
extern EXP *theexpression;

void yyerror() {
    printf ("syntax error before %s\n", yytext);
}
%}

%union {
    int intconst;
    char *stringconst;
    struct EXP *exp;
}

%token <intconst> tINTCONST
%token <stringconst> tIDENTIFIER

%type <exp> program exp

[...]
```



```
[...]
```

```
%start program
```

```
%left '+' '-'
```

```
%left '*' '/'
```

```
%%
```

```
program: exp  
        { theexpression = $1; }
```

```
;
```

```
exp : tIDENTIFIER  
    { $$ = makeEXPid ($1); }  
  | tINTCONST  
    { $$ = makeEXPintconst ($1); }  
  | exp '*' exp  
    { $$ = makeEXPMult ($1, $3); }  
  | exp '/' exp  
    { $$ = makeEXPdiv ($1, $3); }  
  | exp '+' exp  
    { $$ = makeEXPplus ($1, $3); }  
  | exp '-' exp  
    { $$ = makeEXPminus ($1, $3); }  
  | '(' exp ')'  
    { $$ = $2; }
```

```
;
```

```
%%
```

Constructing an AST with flex/bison:

- AST node kinds go in `tree.h`

```
enum {idK,intconstK,timesK,divK,plusK,minusK} kind;
```

- AST node semantic values go in `tree.h`

```
struct {struct EXP *left; struct EXP *right;} minusE;
```

- Constructors for node kinds go in `tree.c`

```
EXP *makeEXPminus(EXP *left, EXP *right)
{ EXP *e;
  e = NEW(EXP);
  e->kind = minusK;
  e->val.minusE.left = left;
  e->val.minusE.right = right;
  return e;
}
```

- Semantic value type declarations go in `tiny.y`

```
%union {
  int intconst;
  char *stringconst;
  struct EXP *exp;
}
```

- (Non-)terminal types go in `tiny.y`

```
%token <intconst> tINTCONST
%token <stringconst> tIDENTIFIER
%type <exp> program exp
```

- Grammar rule actions go in `tiny.y`

```
exp : exp '-' exp { $$ = makeEXPminus ($1, $3); }
```

A “pretty”-printer:

```
$ cat pretty.h
#include <stdio.h>
#include "pretty.h"

void prettyEXP(EXP *e)
{ switch (e->kind) {
    case idK:
        printf("%s",e->val.idE);
        break;
    case intconstK:
        printf("%i",e->val.intconstE);
        break;
    case timesK:
        printf("(");
        prettyEXP(e->val.timesE.left);
        printf("*");
        prettyEXP(e->val.timesE.right);
        printf(")");
        break;

    [...]

    case minusK:
        printf("(");
        prettyEXP(e->val.minusE.left);
        printf("-");
        prettyEXP(e->val.minusE.right);
        printf(")");
        break;
}
}
```

The following pretty printer program:

```
$ cat main.c

#include "tree.h"
#include "pretty.h"

void yyparse();

EXP *theexpression;

void main()
{ yyparse();
  prettyEXP(theexpression);
}
```

will on input:

$a*(b-17) + 5/c$

produce the output:

$((a*(b-17))+(5/c))$

As mentioned before, a modern compiler uses 5–15 phases. Each phase contributes extra information to the IR (AST in our case):

- scanner: line numbers;
- symbol tables: meaning of identifiers;
- type checking: types of expressions; and
- code generation: assembler code.

Example: adding line number support.

First, introduce a global `lineno` variable:

```
$ cat main.c
```

```
[...]
```

```
int lineno;
```

```
void main()
```

```
{ lineno = 1;      /* input starts at line 1 */
```

```
  yyparse();
```

```
  prettyEXP(theexpression);
```

```
}
```

Second, increment `lineno` in the scanner:

```
$ cat tiny.l # modified version of previous exp.l
%{
#include "y.tab.h"
#include <string.h>
#include <stdlib.h>

extern int lineno;          /* declared in main.c */
%}

%%
[ \t]+    /* ignore */;    /* no longer ignore \n */
\n        lineno++;       /* increment for every \n */

[...]
```

Third, add a `lineno` field to the AST nodes:

```
typedef struct EXP {
    int lineno;
    enum {idK,intconstK,timesK,divK,plusK,minusK} kind;
    union {
        char *idE;
        int intconstE;
        struct {struct EXP *left; struct EXP *right;} timesE;
        struct {struct EXP *left; struct EXP *right;} divE;
        struct {struct EXP *left; struct EXP *right;} plusE;
        struct {struct EXP *left; struct EXP *right;} minusE;
    } val;
} EXP;
```

Fourth, set `lineno` in the node constructors:

```
extern int lineno;          /* declared in main.c */
```

```
EXP *makeEXPid(char *id)
```

```
{ EXP *e;
  e = NEW(EXP);
  e->lineno = lineno;
  e->kind = idK;
  e->val.idE = id;
  return e;
}
```

```
EXP *makeEXPintconst(int intconst)
```

```
{ EXP *e;
  e = NEW(EXP);
  e->lineno = lineno;
  e->kind = intconstK;
  e->val.intconstE = intconst;
  return e;
}
```

```
[...]
```

```
EXP *makeEXPminus(EXP *left, EXP *right)
```

```
{ EXP *e;
  e = NEW(EXP);
  e->lineno = lineno;
  e->kind = minusK;
  e->val.minusE.left = left;
  e->val.minusE.right = right;
  return e;
}
```

The SableCC 2 grammar for our Tiny language:

```
Package tiny;
```

Helpers

```
tab    = 9;
cr     = 13;
lf     = 10;
digit  = ['0'..'9'];
lowercase = ['a'..'z'];
uppercase = ['A'..'Z'];
letter = lowercase | uppercase;
idletter = letter | '_' ;
idchar  = letter | '_' | digit;
```

Tokens

```
eol    = cr | lf | cr lf;
blank  = ' ' | tab;
star   = '*';
slash  = '/';
plus   = '+';
minus  = '-';
l_par  = '(';
r_par  = ')';
number = '0' | [digit-'0'] digit*;
id     = idletter idchar*;
```

Ignored Tokens

```
blank, eol;
```


Productions

```
exp =  
  {plus}   exp plus factor |  
  {minus}  exp minus factor |  
  {factor} factor;  
  
factor =  
  {mult}   factor star term |  
  {divd}   factor slash term |  
  {term}   term;  
  
term =  
  {paren}  l_par exp r_par |  
  {id}     id |  
  {number} number;
```

SableCC generates subclasses of the 'Node' class for terminals, non-terminals and production alternatives:

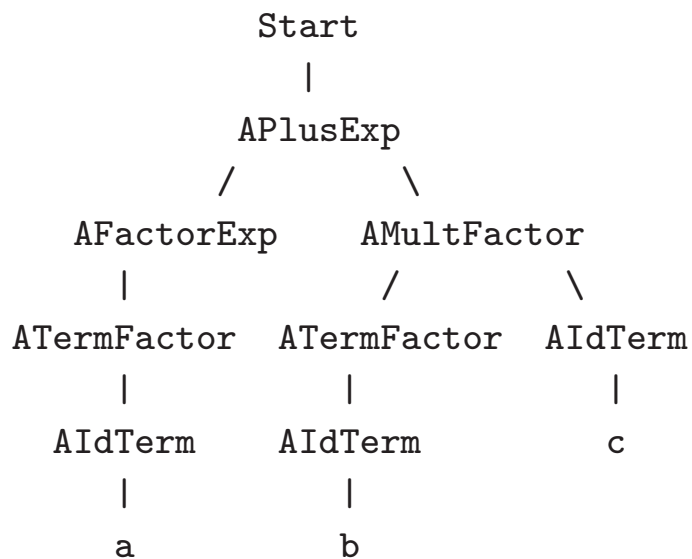
- Node classes for terminals: 'T' followed by (capitalized) terminal name:
TEol, TBlank, ..., TNumber, TId
- Node classes for non-terminals: 'P' followed by (capitalized) non-terminal name:
PExp, PFactor, PTerm
- Node classes for alternatives: 'A' followed by (capitalized) alternative name and (capitalized) non-terminal name:
APlusExp (extends PExp), ..., ANumberTerm (extends PTerm)

SableCC populates an entire directory structure:

```
tiny/  
  |--analysis/  Analysis.java  
  |              AnalysisAdapter.java  
  |              DepthFirstAdapter.java  
  |              ReversedDepthFirstAdapter.java  
  |  
  |--lexer/     Lexer.java lexer.dat  
  |              LexerException.java  
  |  
  |--node/      Node.java TEol.java ... TId.java  
  |              PExp.java PFactor.java PTerm.java  
  |              APlusExp.java ...  
  |              AMultFactor.java ...  
  |              AParenTerm.java ...  
  |  
  |--parser/    parser.dat Parser.java  
  |              ParserException.java ...  
  |  
  |-- custom code directories, e.g. symbol, type, ...
```

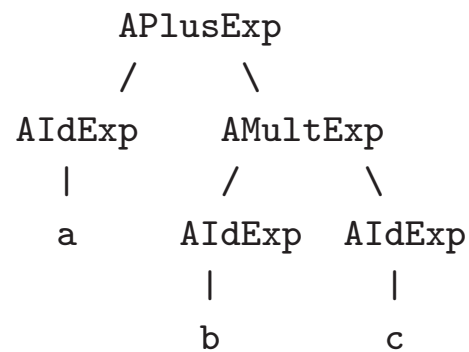
Given some grammar, SableCC generates a parser that in turn builds a concrete syntax tree (CST) for an input program.

A parser built from the Tiny grammar creates the following CST for the program ‘a+b*c’:



This CST has many unnecessary intermediate nodes. Can you identify them?

We only need an abstract syntax tree (AST) to operate on:



Recall that `bison` relies on user-written actions after grammar rules to construct an AST.

As an alternative, `SableCC 3` actually allows the user to define an AST and the $\text{CST} \rightarrow \text{AST}$ transformations formally, and can then translate CSTs to ASTs automatically.

AST for the Tiny expression language:

Abstract Syntax Tree

exp =

{plus} [l]:exp [r]:exp |

{minus} [l]:exp [r]:exp |

{mult} [l]:exp [r]:exp |

{divd} [l]:exp [r]:exp |

{id} id |

{number} number;

AST rules have the same syntax as rules in the Production section except for $CST \rightarrow AST$ transformations (obviously).

Extending Tiny productions with CST \rightarrow AST transformations:

Productions

```

cst_exp {-> exp} =
  {cst_plus}    cst_exp plus factor
                {-> New exp.plus(cst_exp.exp,factor.exp)} |
  {cst_minus}  cst_exp minus factor
                {-> New exp.minus(cst_exp.exp,factor.exp)} |
  {factor}     factor {-> factor.exp};

factor {-> exp} =
  {cst_mult}   factor star term
                {-> New exp.mult(factor.exp,term.exp)} |
  {cst_divd}   factor slash term
                {-> New exp.divd(factor.exp,term.exp)} |
  {term}       term {-> term.exp};

term {-> exp} =
  {paren}     l_par cst_exp r_par {-> cst_exp.exp} |
  {cst_id}    id {-> New exp.id(id)} |
  {cst_number} number {-> New exp.number(number)};

```

A CST production alternative for a plus node:

```
cst_exp = {cst_plus} cst_exp plus factor
```

needs extending to include a $CST \rightarrow AST$ transformation:

```
cst_exp {-> exp} =
  {cst_plus} cst_exp plus factor
      {-> New exp.plus(cst_exp.exp, factor.exp)}
```

`cst_exp {-> exp}` on the LHS specifies that the CST node `cst_exp` should be transformed to the AST node `exp`.

`{-> New exp.plus(cst_exp.exp, factor.exp)}` on the RHS specifies the action for constructing the AST node.

`exp.plus` is the kind of `exp` AST node to create. `cst_exp.exp` refers to the transformed AST node `exp` of `cst_exp`, the first term on the RHS.

5 types of explicit RHS transformation (action):

1. Getting an existing node:

```
{paren} l_par cst_exp r_par {-> cst_exp.exp}
```

2. Creating a new AST node:

```
{cst_id} id {-> New exp.id(id)}
```

3. List creation:

```
{block} l_brace stm* r_brace {-> New stm.block([stm])}
```

4. Elimination (but more like nullification):

```
{-> Null}
```

```
{-> New exp.id(Null)}
```

5. Empty (but more like deletion):

```
{-> }
```

Writing down straightforward, non-abstracting
CST \rightarrow AST transformations can be tedious.

```
prod = elm1 elm2* elm3+ elm4?;
```

This is equivalent to:

```
prod{-> prod} = elm1 elm2* elm3+ elm4?  
{-> New prod.prod(elm1.elm1, [elm2.elm2],  
                  [elm3.elm3], elm4.elm4)};
```

More SableCC 3 documentation:

- <http://sablecc.sourceforge.net/documentation.html>
- <http://sablecc.org/wiki/DocumentationPage>

The JOOS compiler has the AST node types:

| | | |
|-------------|-----------|----------|
| PROGRAM | CLASSFILE | CLASS |
| FIELD | TYPE | LOCAL |
| CONSTRUCTOR | METHOD | FORMAL |
| STATEMENT | EXP | RECEIVER |
| ARGUMENT | LABEL | CODE |

with many extra fields:

```
typedef struct METHOD {
    int lineno;
    char *name;
    ModifierKind modifier;
    int localslimit; /* resource */
    int labelcount; /* resource */
    struct TYPE *returntype;
    struct FORMAL *formals;
    struct STATEMENT *statements;
    char *signature; /* code */
    struct LABEL *labels; /* code */
    struct CODE *opcodes; /* code */
    struct METHOD *next;
} METHOD;
```

The JOOS constructors are as we expect:

```
METHOD *makeMETHOD(char *name, ModifierKind modifier,  
                    TYPE *returntype, FORMAL *formals,  
                    STATEMENT *statements, METHOD *next)
```

```
{ METHOD *m;  
  m = NEW(METHOD);  
  m->lineno = lineno;  
  m->name = name;  
  m->modifier = modifier;  
  m->returntype = returntype;  
  m->formals = formals;  
  m->statements = statements;  
  m->next = next;  
  return m;  
}
```

```
STATEMENT *makeSTATEMENTwhile(EXP *condition,  
                               STATEMENT *body)
```

```
{ STATEMENT *s;  
  s = NEW(STATEMENT);  
  s->lineno = lineno;  
  s->kind = whileK;  
  s->val.whileS.condition = condition;  
  s->val.whileS.body = body;  
  return s;  
}
```

Highlights from the JOOS scanner:

```
[ \t]+      /* ignore */;
\n         lineno++;
\\\/[^\n]*  /* ignore */;
abstract   return tABSTRACT;
boolean    return tBOOLEAN;
break      return tBREAK;
byte       return tBYTE;
.
.
.
"!="       return tNEQ;
"&&"      return tAND;
"||"      return tOR;
"+"        return '+';
"-"        return '-';
.
.
.
0|([1-9][0-9]*) {yylval.intconst = atoi(yytext);
                  return tINTCONST;}
true       {yylval.boolconst = 1;
            return tBOOLCONST;}
false      {yylval.boolconst = 0;
            return tBOOLCONST;}
\"([^\"])*\" {yylval.stringconst =
              (char*)malloc(strlen(yytext)-1);
              yytext[strlen(yytext)-1] = '\\0';
              sprintf(yylval.stringconst,"%s",yytext+1);
              return tSTRINGCONST;}
```

Highlights from the JOOS parser:

```

method : tPUBLIC methodmods returntype
        tIDENTIFIER '(' formals ')' '{' statements '}'
        { $$ = makeMETHOD($4,$2,$3,$6,$9,NULL); }
| tPUBLIC returntype
        tIDENTIFIER '(' formals ')' '{' statements '}'
        { $$ = makeMETHOD($3,modNONE,$3,$5,$8,NULL); }
| tPUBLIC tABSTRACT returntype
        tIDENTIFIER '(' formals ')' ';'
        { $$ = makeMETHOD($4,modABSTRACT,$3,$6,NULL,NULL); }
| tPUBLIC tSTATIC tVOID
        tMAIN '(' mainargv ')' '{' statements '}'
        { $$ = makeMETHOD("main",modSTATIC,
                          makeTYPEvoid(),NULL,$9,NULL); }
;

whilestatement : tWHILE '(' expression ')' statement
                { $$ = makeSTATEMENTwhile($3,$5); }
;

```

Notice the conversion from concrete syntax to abstract syntax that involves dropping unnecessary tokens.

Building LALR(1) lists:

```
formals : /* empty */
         { $$ = NULL; }
         | neformals
         { $$ = $1; }
;

neformals : formal
           { $$ = $1; }
           | neformals ',' formal
           { $$ = $3; $$->next = $1; }
;

formal : type tIDENTIFIER
        { $$ = makeFORMAL($2,$1,NULL); }
;
```

The lists are naturally backwards.

Using backwards lists:

```
typedef struct FORMAL {
    int lineno;
    char *name;
    int offset; /* resource */
    struct TYPE *type;
    struct FORMAL *next;
} FORMAL;

void prettyFORMAL(FORMAL *f)
{ if (f!=NULL) {
    prettyFORMAL(f->next);
    if (f->next!=NULL) printf(", ");
    prettyTYPE(f->type);
    printf(" %s",f->name);
}
}
```

What effect would a call stack size limit have?

The JOOS grammar calls for:

```
castexpression :  
    '(' identifier ')' unaryexpressionnotminus
```

but that is not LALR(1).

However, the more general rule:

```
castexpression :  
    '(' expression ')' unaryexpressionnotminus
```

is LALR(1), so we can use a clever action:

```
castexpression :  
    '(' expression ')' unaryexpressionnotminus  
    {if ($2->kind!=idK) yyerror("identifier expected");  
     $$ = makeEXPcast($2->val.idE.name,$4);}  
;
```

Hacks like this only work sometimes.

LALR(1) and Bison are not enough when:

- our language is not context-free;
- our language is not LALR(1) (for now let's ignore the fact that Bison now also supports GLR); or
- an LALR(1) grammar is too big and complicated.

In these cases we can try using a more liberal grammar which accepts a slightly larger language.

A separate phase can then weed out the bad parse trees.

Example: disallowing division by constant 0:

```
exp : tIDENTIFIER
    | tINTCONST
    | exp '*' exp
    | exp '/' pos
    | exp '+' exp
    | exp '-' exp
    | '(' exp ')'
;

pos : tIDENTIFIER
    | tINTCONSTPOSITIVE
    | exp '*' exp
    | exp '/' pos
    | exp '+' exp
    | exp '-' exp
    | '(' pos ')'
;
```

We have doubled the size of our grammar.

This is not a very modular technique.

Instead, weed out division by constant 0:

```
int zerodivEXP(EXP *e)
{ switch (e->kind) {
  case idK:
  case intconstK:
    return 0;
  case timesK:
    return zerodivEXP(e->val.timesE.left) ||
           zerodivEXP(e->val.timesE.right);
  case divK:
    if (e->val.divE.right->kind==intconstK &&
        e->val.divE.right->val.intconstE==0) return 1;
    return zerodivEXP(e->val.divE.left) ||
           zerodivEXP(e->val.divE.right);
  case plusK:
    return zerodivEXP(e->val.plusE.left) ||
           zerodivEXP(e->val.plusE.right);
  case minusK:
    return zerodivEXP(e->val.minusE.left) ||
           zerodivEXP(e->val.minusE.right);
}
}
```

A simple, modular traversal.

Requirements of JOOS programs:

- all local variable declarations must appear at the beginning of a statement sequence:

```
int i;  
int j;  
i=17;  
int b;    /* illegal */  
b=i;
```

- every branch through the body of a non-void method must terminate with a return statement:

```
boolean foo (Object x, Object y) {  
    if (x.equals(y))  
        return true;  
}                                     /* illegal */
```

Also may not return from within a while-loop etc.

These are hard or impossible to express through an LALR(1) grammar.

Weeding bad local declarations:

```
int weedSTATEMENTlocals(STATEMENT *s,int localsallowed)
{ int onlylocalsfirst, onlylocalssecond;
  if (s!=NULL) {
    switch (s->kind) {
      case skipK:
        return 0;
      case localK:
        if (!localsallowed) {
          reportError("illegally placed local declaration",s->lineno);
        }
        return 1;
      case expK:
        return 0;
      case returnK:
        return 0;
      case sequenceK:
        onlylocalsfirst =
          weedSTATEMENTlocals(s->val.sequenceS.first,localsallowed);
        onlylocalssecond =
          weedSTATEMENTlocals(s->val.sequenceS.second,onlylocalsfirst);
        return onlylocalsfirst && onlylocalssecond;
      case ifK:
        (void)weedSTATEMENTlocals(s->val.ifS.body,0);
        return 0;
      case ifelseK:
        (void)weedSTATEMENTlocals(s->val.ifelseS.thenpart,0);
        (void)weedSTATEMENTlocals(s->val.ifelseS.elsepart,0);
        return 0;
      case whileK:
        (void)weedSTATEMENTlocals(s->val.whileS.body,0);
        return 0;
      case blockK:
        (void)weedSTATEMENTlocals(s->val.blockS.body,1);
        return 0;
      case superconsK:
        return 1;
    }
  }
}
```

Weeding missing returns:

```
int weedSTATEMENTreturns(STATEMENT *s)
{ if (s!=NULL) {
    switch (s->kind) {
        case skipK:
            return 0;
        case localK:
            return 0;
        case expK:
            return 0;
        case returnK:
            return 1;
        case sequenceK:
            return weedSTATEMENTreturns(s->val.sequenceS.second);
        case ifK:
            return 0;
        case ifelseK:
            return weedSTATEMENTreturns(s->val.ifelseS.thenpart) &&
                weedSTATEMENTreturns(s->val.ifelseS.elsepart);
        case whileK:
            return 0;
        case blockK:
            return weedSTATEMENTreturns(s->val.blockS.body);
        case superconsK:
            return 0;
    }
}
}
```

The testing strategy for a parser that constructs an abstract syntax tree T from a program P usually involves a pretty printer.

If $parse(P)$ constructs T and $pretty(T)$ reconstructs the text of P , then:

$$pretty(parse(P)) \approx P$$

Even better, we have that:

$$pretty(parse(pretty(parse(P)))) \equiv pretty(parse(P))$$

Of course, this is a necessary but not sufficient condition for parser correctness.