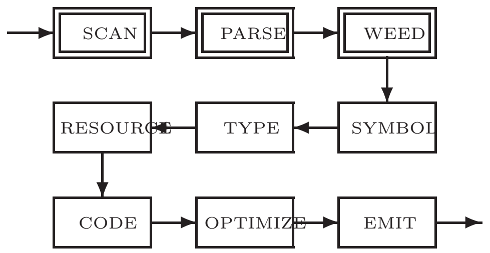
Abstract syntax trees



A one-pass compiler only looks through the program once.

Scanning, parsing, symbol tables, type checking, and code generation happens at the same time.

A terrible methodology:

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

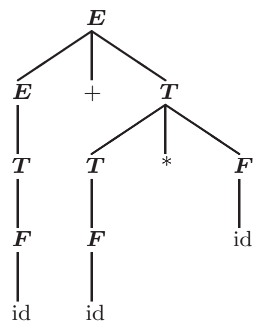
Used to be popular:

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

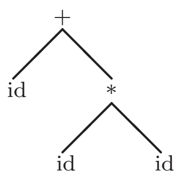
A modern compiler uses 5-15 passes.

Between passes, the program needs an intermediate representation.

An *abstract syntax tree (AST)* is essentially a parse tree:

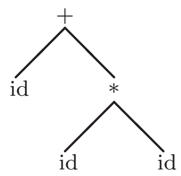


but for a more abstract grammar:



Early multi-pass compilers used *intermediate languages*.

Instead of constructing the tree:



the string:

```
+(id,*(id,id))
```

is written to a file.

If the compiler has k passes, then $k-1$ intermediate languages must be designed.

```
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;
}
```



```
%{
#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;}
;

%%
```


How to construct AST with flex/bison:

- design AST node stuctures (semantic values) (tree.h)
  `kinds of nodes`, `associated semantic values`
- write constructors for node kinds (tree.c)
- add "%union" declaration of semantic value types in the grammar file (bison)
- give types to terminals and nonterminals

```
%token <type> id num
%type  <type> exp
```

- associate actions to each grammar rule
  exp: exp '*' exp {$$ = makeEXPmult($1, $3); }

As mentioned before, a modern compiler uses 10-15 passes. Each pass contributes extra information to the AST nodes:

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

The AST types must include extra fields:

```
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;
```


Line numbers in the scanner:

```
%{
#include "y.tab.h"
#include <string.h>

extern int lineno;
%}

%%
[ \t]+  /* ignore */;
\n        lineno++;

"*"       return '*';
"/"       return '/';
"+"       return '+';
"-"       return '-';
"("       return '(';
")"       return ')';

0|([1-9][0-9]*)
        { yylval.intconst = atoi(yytext);
          return tINTCONST;
        }
[a-zA-Z_][a-zA-Z0-9_]*
        { yylval.stringconst =
              (char *)malloc(strlen(yytext)+1);
          sprintf(yylval.stringconst,"%s",yytext);
          return tIDENTIFIER;
        }
%%
```


Line numbers in the constructors:

```
extern int lineno;

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;
}
```


A “pretty” printer:

```
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 program:

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

int lineno;

void yyparse();

EXP *theexpression;

void main()
{ lineno = 1;
  yyparse();
  prettyEXP(theexpression);
}
```

will on input:

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

produce the output:

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


SableCC grammar for our TINY expression langauge:

```
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 terminal, non-terminals and alternatives:

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

SableCC generates file structures which look like following:

```
tiny/
    |--analysis/  Analysis.java
    |             AnalysisAdapter.java
    |             DepthFirstAdapter.java
    |             ReversedDepthFirstAdapter.java
    |
    |--lexer/     Lexer.java lexer.dat
    |             LexerException.java
    |
    |--node/      Node.java TEol.java TNumber.java ...
    |             PExp.java PFactor.java PTerm.java
    |             APlusExp.java, ..., AMultFactor, ...,
    |             AParenTerm, ...
    |
    |--parser/    parser.dat Parser.java
    |             ParserException.java, ...
    |
    |--your code directories ...
```


Given previous grammar, SableCC generates a parser which builds a concrete syntax tree (CST) for an input program.

For example, the CST of the program "a+b*c":

```
              APlusExp
             /        \
     AFactorExp      AFactorExp
         |            /       \
    ATermFactor  AMultFactor  AIdTerm
         |            |          |
      AIdTerm      AIdTerm       c
         |            |
         a            b
```

The CST has many redundant intermediate nodes, we only need an Abstract Syntax Tree (AST) to operate on:

```
             APlusExp
             /     \
      AIdExp    AMultExp
         |       /     \
         a    AIdExp  AIdExp
                |        |
                b        c
```


Bison uses actions after grammar rules. A compiler writer puts code in actions for constructing ASTs.

SableCC allows a user define AST in a grammar file, then it translates CST to AST automatically. Define AST for the EXP 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;
```


Here, a new section, "*Abstract Syntax Tree*", has been added after the production section. AST rules have the same syntax as rules in production section, except:

- no transformation (DO NOT write `exp {-> foo}` in the AST section);

AST example:

```
exp =
  {plus}        [l]:exp [r]:exp
  ......
| {number}      number;

stm =
  ......
| {block}       [stmts]:stm*;
```

The productions of the EXP language are expanded with 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)};
```


In the production section, a CST node, matched by

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

, is transformed to an AST node using the following rule:

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

The left-hand side, `cst_exp {-> exp}`, says that a CST node (*cst_exp*) should be transformed to an AST node (*exp*).

The transformation at the right-hand side, `{-> New exp.plus(cst_exp.exp, factor.exp)}`, gives the action for constructing the AST node.

The *cst_exp.exp* refers to the transformed AST node of the first term, *cst_exp*, in the right-hand side of the production rule.

There are FIVE types of transformations (actions) that can happen on the right-hand side of a production:

- getting an existing identifier (token) :: *ident*
  `{paren} l_par` **`cst_ exp`** `r_par {->` **`cst_ exp`**`.exp}`
- creating a new AST node :: *New ...*
  `{cst_id} id {->` **`New exp.id`**`(id)}`
- list creation :: *[elm1, elm2,...]*
  `{block} l_brace stm* r_brace {-> New stm.block(`**`[stm]`**`)}`
- elimination :: *Null*
- empty transformation :: `{-> }`

It might be tedious to write down AST transformations for all CST productions even if a CST production has the same structure as its AST counterpart.

SableCC3 allows implicit transformations in these cases. For example, a production without explicit transformation:

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

is equivalent to

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

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);}
;
```

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);
  }
}
```


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 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); or
- an LALR(1) grammar is too large and complex.

In these cases we use a liberal grammar, which accepts a slightly larger language.

A separate pass may then weed out the bad parse trees.

Division by constant 0 is not allowed:

```
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.

Not a very modular technique.

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 to JOOS programs:

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

  ```
  int i;
  int j;
  i=17;
  int b;
  b=i;
  ```

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

  ```
  if (x.equals(y)) return true;
  else x=null;
  ```

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

Weed 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;
     }
  }
}
```

Weed 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 abstract syntax trees usually involves a pretty printer.

If $\mathit{parse}(\boldsymbol{P})$ constructs a tree and $\mathit{pretty}(\boldsymbol{T})$ reconstructs the text, then:

$$\mathit{pretty}(\mathit{parse}(\boldsymbol{P})) \approx \boldsymbol{P}$$

Even better, we have that:

$$\mathit{pretty}(\mathit{parse}(\mathit{pretty}(\mathit{parse}(\boldsymbol{P})) \equiv \mathit{pretty}(\mathit{parse}(\boldsymbol{P}))$$

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