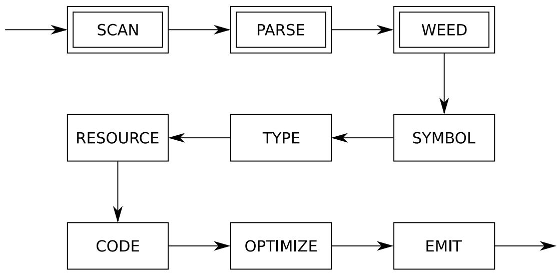
Abstract syntax trees



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.

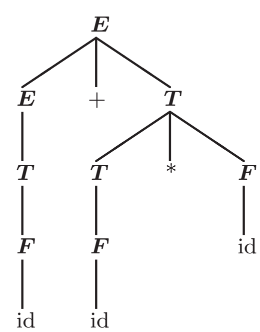
However, it used to be popular:

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

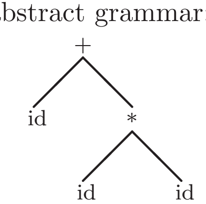
A modern *multi-pass* compiler uses 5–15 phases, some of which may have many individual passes: you should skim through the optimization section of 'man gcc' some time!

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

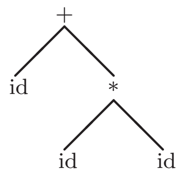
We could use a parse tree, or *concrete syntax tree* (CST):



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':

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

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

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

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

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 CST→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→AST transformations (obviously).

Extending Tiny productions with CST→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→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→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 $\boldsymbol{T}$ from a program $\boldsymbol{P}$ usually involves a pretty printer.

If $\mathit{parse}(\boldsymbol{P})$ constructs $\boldsymbol{T}$ and $\mathit{pretty}(\boldsymbol{T})$ reconstructs the text of $\boldsymbol{P}$, 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 for parser correctness.