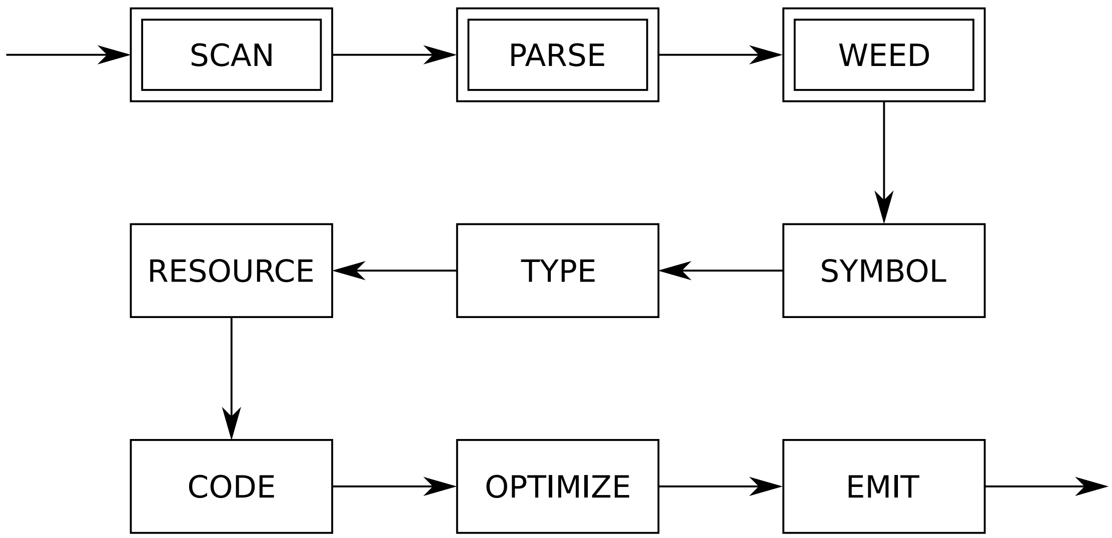
Abstract syntax trees



Language design is tied with compiler design.

A compiler is an actual software, and as engineers we have to make certain considerations in order to ship a viable product in a time-frame allotted.

"C is not a block-structured language; this may fairly be considered a defect."
(Dennis Ritchie, 1975)

"declarations of variables (including initializations) may follow the left brace that introduces any compound statement, not just the one that begins a function"
(K&R, 1978)

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.

What about propagating the result of the parser phase (the CST) through all the compiler phases ?

Cumbersome. We need something *better*.

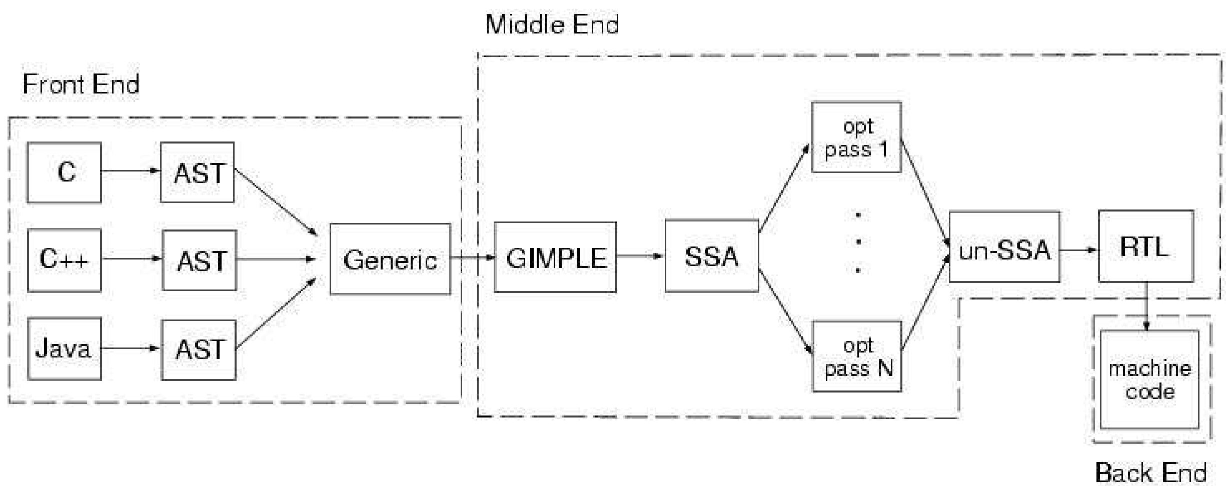
Abstract syntax tree:

A tree representation of the abstract syntactic structure of source code.

The syntax is ’abstract’ in not representing every detail appearing in the real syntax.

Examples of modern intermediate languages:

- Java bytecode
- C, for certain high-level language compilers
- LLVM IR
- GCC's



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

Why is GCC using so many different IRs internally ?

Because it needs different level of abstractions.

Famous LLVM ML thread:

LLVMdev

LLVM IR is a compiler IR Dan Gohman gohman at apple.com Tue Oct 4 13:53:18 CDT 2011

```
$ 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 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.