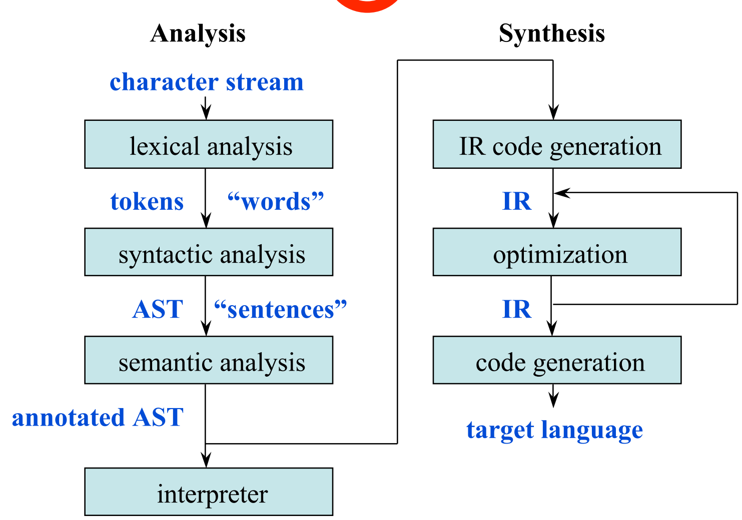
Undergraduate Compilers in a Day

Today

- Overall structure of a compiler
- Intermediate representations

Structure of a Typical ~~Interpreter~~ Compiler



Lexical Analysis (Scanning)

Break character stream into tokens ("words")

- Tokens, lexemes, and patterns
- Lexical analyzers are usually automatically generated from patterns (regular expressions) (*e.g.,* lex, flex)

Examples

token	lexeme(s)	pattern
const	`const`	`const`
if	`if`	`if`
relation	`<,<=,=,!=,...`	`< | <= | = | != | ...`
identifier	`foo,index`	`[a-zA-Z_]+[a-zA-Z0-9_]*`
number	`3.14159,570`	`[0-9]+ | [0-9]*.[0-9]+`
string	`"hi", "mom"`	`".*"`

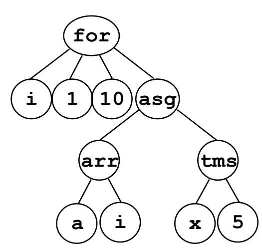
`const pi := 3.14159` ⇒ *const, identifier*(`pi`), *assign,number*(**3.14159**)

Syntactic Analysis (Parsing)

Impose structure on token stream

- Limited to syntactic structure
- Structure usually represented with an *abstract syntax tree* (AST)
- Theory meets practice:
  - Regular expressions, formal languages, grammars, parsing…
- Parsers are usually automatically generated from grammars (*e.g.,* yacc, bison, cup, javacc)

Example




```
for i = 1 to 10 do
   a[i] = x * 5;
```

*for id(*i*) equal number(*1*) to number(*10*) do*
*id(*a*) lbracket id(*i*) rbracket equal id(*x*) times number(*5*) semi*

Semantic Analysis

Determine whether source is meaningful

- Check for semantic errors
- Check for type errors
- Gather type information for subsequent stages
  - Relate variable uses to their declarations
- Some semantic analysis takes place during parsing

Example errors (from C)

```
function1 = 2.718282;
x = 570 + "hello, world!"
scalar[i]
```


Compiler Data Structures

Symbol Tables

- Compile-time data structure
- Holds names, type information, and *scope* information for variables

Scope

- A name space
  e.g., In Pascal, each procedure creates a new scope
  e.g., In C, each set of curly braces defines a new scope
- Can create a separate symbol table for each scope

Using Symbol Tables

- For each variable declaration:
  - Check for symbol table entry
  - Add new entry with type info
- For each variable use:
  - Check symbol table entry

Symbol Table Alternative

Idea

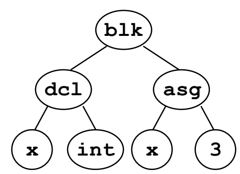
- Dispense with explicit symbol table structure
- Include declarations in AST

Why?

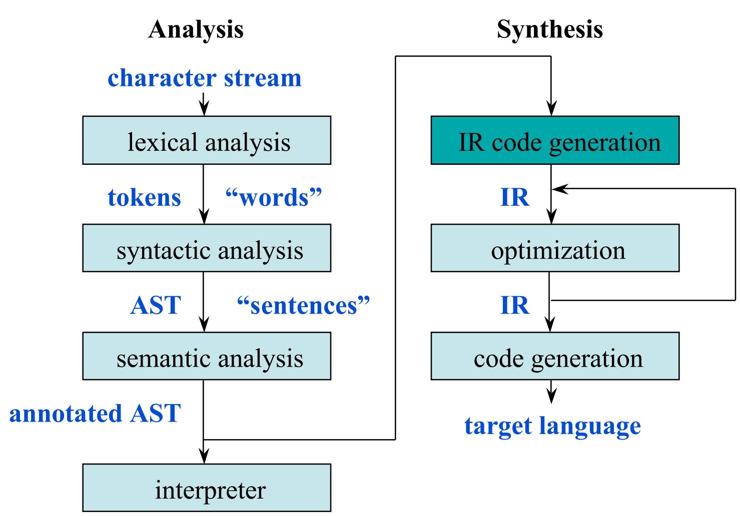
- Source language syntax matches access structure (in C, scoping is mostly flat and data types are primitive)
- Simple
- Easy to generate C code (with declarations)

Example

```
{
    int x;
    x = 3;
}
```



Structure of a Typical Compiler



IR Code Generation

Goal

– Transforms AST into low-level *intermediate representation* (IR)

Simplifies the IR

– Removes high-level control structures: **`for`**, **`while`**, **`do`**, **`switch`**

– Removes high-level data structures: arrays, structs, unions, enums

Results in assembly-like code

– Semantic lowering

– Control-flow expressed in terms of "gotos"

– Each expression is very simple (three-address code)

e.g., `x := a * b * c` ⇒

```
t := a * b
x := t * c
```


A Low-Level IR

Register Transfer Language (RTL)

– Linear representation

– Typically language-independent

– Nearly corresponds to machine instructions

Example operations

– Assignment	`x := y`
– Unary op	`x := op y`
– Binary op	`x := y op z`
– Address of	`p := & y`
– Load	`x := *(p+c)`
– Store	`*(p+c) := y`
– Call	`x := f()`
– Branch	`goto L1`
– Cbranch	`if (x==3) goto L1`

Example

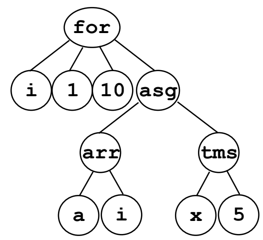
Source code

```
for i = 1 to 10 do
  a[i] = x * 5;
```

Low-level IR (RTL)

```
        i := 1
loop1:
        t1 := x * 5
        t2 := &a
        t3 := sizeof(int)
        t4 := t3 * i
        t5 := t2 + t4
        *t5 := t1
        i := i + 1
        if i <= 10 goto loop1
```

High-level IR (AST)



Compiling Control Flow

Switch statements

– Convert **`switch`** into low-level IR

e.g.,

```
switch (c) {
    case 0: f();
            break;
    case 1: g();
            break;
    case 2: h();
            break;
}
```

```
        if (c!=0) goto next1
        f ()
        goto done
next1:  if (c!=1) goto next2
        g()
        goto done
next2:  if (c!=3) goto done
        h()
done:
```

– Optimizations (depending on size and density of cases)
  – Create a jump table (store branch targets in table)
  – Use binary search

Compiling Control Flow (cont)

Switch statements (cont)

– Convert **`switch`** into optimized (jump table) low-level IR

e.g.,

```
switch (c) {
  case 0: f();
          break;
  case 1: g();
          break;
  case 2: h();
          break;
}
```

```
jtarr: .words targ0,targ1,targ2
       ...
       if (c < 0) goto done
       if (c > 2) goto done
       targ = jtarr[c]
       goto targ   /* this is not C */
targ0: f ()
       goto done
targ1: g()
       goto done
targ2: h()
done:  ...
```


Compiling Arrays

Array declaration

– Store name, size, and base type in symbol table

Array allocation

– Call **`malloc()`** or create space on the runtime stack

Array referencing

– *e.g.,* **`A[i]`**

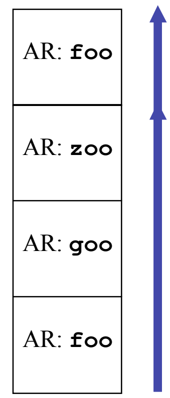
```
*(&A + i * sizeof(A_elem))
```

```
t1 := &A
t2 := sizeof(A_elem)
t3 := i * t2
t4 := t1 + t3
*t4
```

Compiling Procedures

Properties of procedures

- Procedures define scopes
- Procedure lifetimes are nested
- Can store information related to dynamic invocation of a procedure on a call stack (*activation record* (AR) or stack frame):
  - Space for saving registers
  - Space for passing parameters and returning values
  - Space for local variables
  - Return address of calling instruction



stack

Stack management

- Push an AR on procedure entry
- Pop an AR on procedure exit
- Why do we need a stack?

Compiling Procedures (cont)

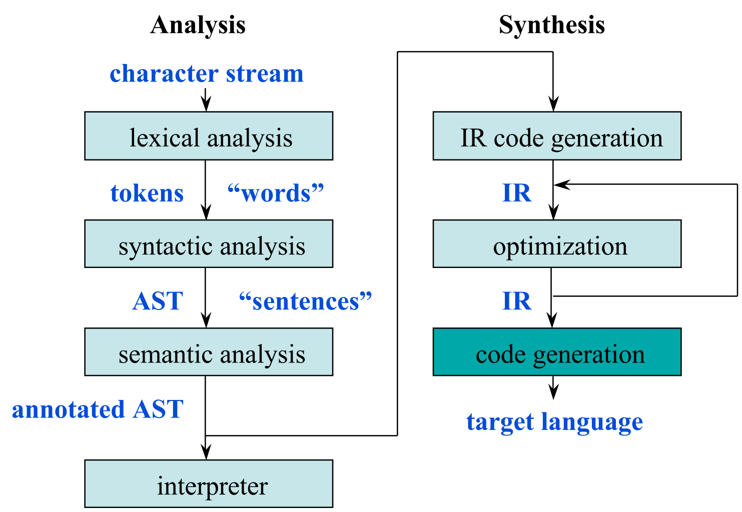
Code generation for procedures

- Emit code to manage the stack
- Are we done?

Translate procedure body

- References to local variables must be translated to refer to the current activation record
- References to non-local variables must be translated to refer to the appropriate activation record or global data space

Structure of a Typical Compiler



Code Generation

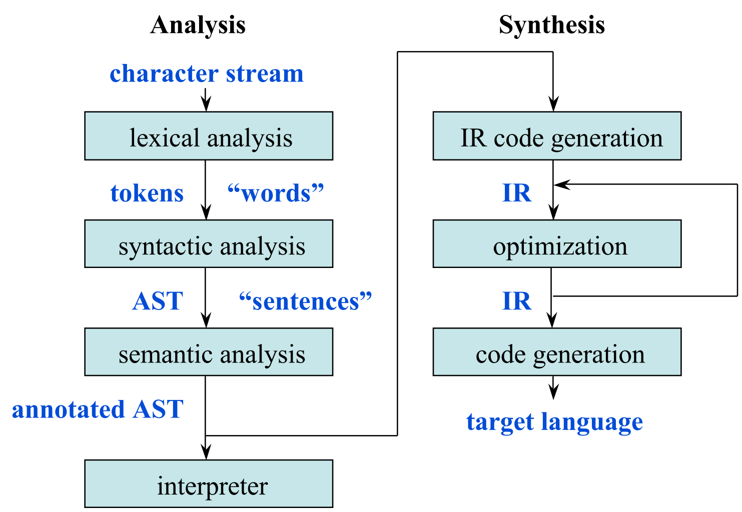
Conceptually easy

– Three address code is a generic machine language
– Instruction selection converts the low-level IR to real machine instructions

The source of heroic effort on modern architectures

– Alias analysis
– Instruction scheduling for ILP
– Register allocation
– More later. . .

Structure of a Typical Compiler



Question

Q: How can I have fun without the use of alcohol?

A: gcc -S

Example

```
% gcc -O0 -S file.c

int main() {
  int var1, var2, var3;

  var1 = 123;
  var2 = 3;
  var3 = var1/var2 + 1;

  return var3;
}
```

Tada! (file.s)

```
_main:
        stmw r30,-8(r1)
        stwu r1,-64(r1)
        mr r30,r1
        li r0,123
        stw r0,32(r30)
        li r0,3
        stw r0,28(r30)
        lwz r2,32(r30)
        lwz r0,28(r30)
        divw r2,r2,r0
        addi r0,r2,1
        stw r0,24(r30)
        lwz r0,24(r30)
        mr r3,r0
        lwz r1,0(r1)
        lmw r30,-8(r1)
        blr
```


Concepts

Compilation stages

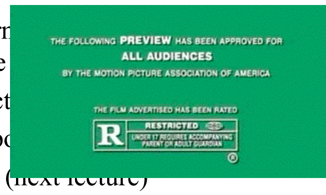
– Scanning, parsing, semantic analysis, intermediate code generation, optimization, code generation

Representations

– AST, low-level IR (RTL)

Coming Attractions

Optimizing compilers reason about program behavior

Q: With a low level intern 

o's), how does a compiler reason about the
– *e.g.* What is the struct
– *e.g.* What paths are po rogram to another?

A: Control-flow analysis (next lecture)

Q: How do humans understand a program's behavior?

A: We typically simulate its behavior.

Q: How do compilers "understand" a program's behavior?

A: Data-flow analysis (lecture 4)

Next Time

Lecture
– Control flow analysis

Next Tuesday
– Discussion of Sites paper
– Discussion questions online
– Email me answers