CS412/413

Introduction to Compilers
Radu Rugina

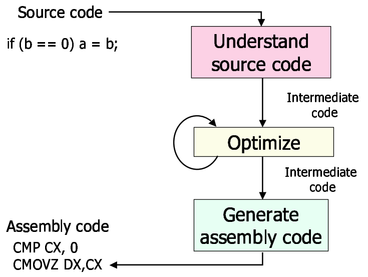
Lecture 2: Lexical Analysis
23 Jan 02

Outline

- Review compiler structure
- Compilation example

- What is lexical analysis?
- Writing a lexer
- Specifying tokens: regular expressions
- Writing a lexer generator

Simplified Compiler Structure



Source code
if (b == 0) a = b;

Understand source code

Intermediate code

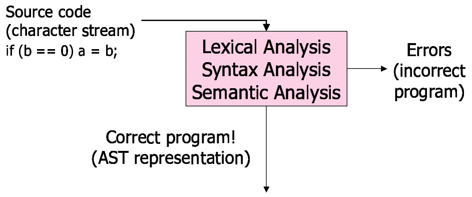
Optimize

Intermediate code

Generate assembly code

Assembly code
CMP CX, 0
CMOVZ DX,CX

Simplified Front End Structure



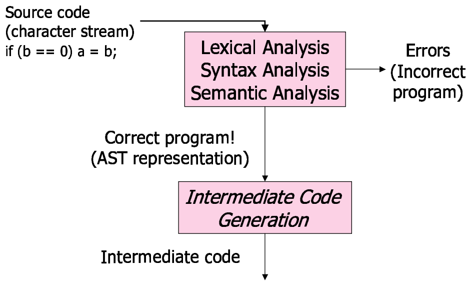
Source code
(character stream)
if (b == 0) a = b;

Lexical Analysis
Syntax Analysis
Semantic Analysis

Errors
(incorrect
program)

Correct program!
(AST representation)

More Precise Front End Structure



Source code
(character stream)
if (b == 0) a = b;

Lexical Analysis
Syntax Analysis
Semantic Analysis

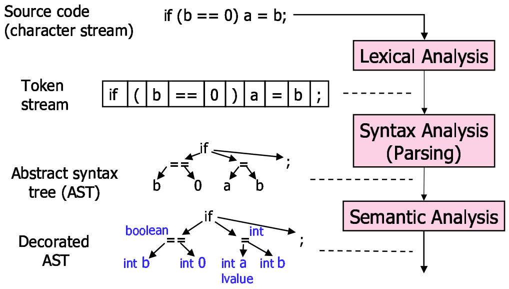
Errors
(Incorrect
program)

Correct program!
(AST representation)

Intermediate Code Generation

Intermediate code

How It Works



Source code
(character stream)

if (b == 0) a = b;

Lexical Analysis

Token
stream

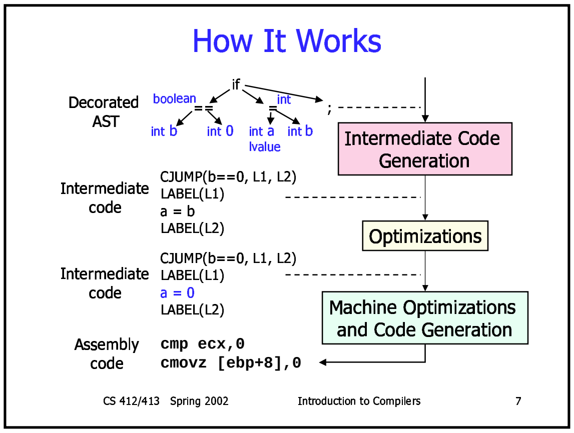
if	(	b	==	0	)	a	=	b	;

Syntax Analysis
(Parsing)

Abstract syntax
tree (AST)

Semantic Analysis

Decorated
AST



How It Works

Decorated AST

Intermediate Code Generation

Intermediate code

```
CJUMP(b==0, L1, L2)
LABEL(L1)
a = b
LABEL(L2)
```

Optimizations

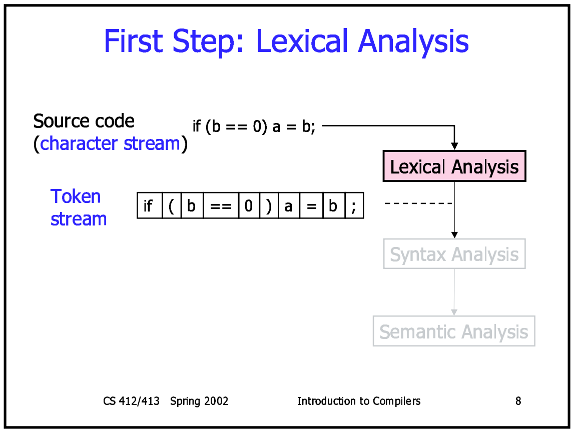
Intermediate code

```
CJUMP(b==0, L1, L2)
LABEL(L1)
a = 0
LABEL(L2)
```

Machine Optimizations and Code Generation

Assembly code

```
cmp ecx,0
cmovz [ebp+8],0
```



First Step: Lexical Analysis

Source code (character stream) if (b == 0) a = b;

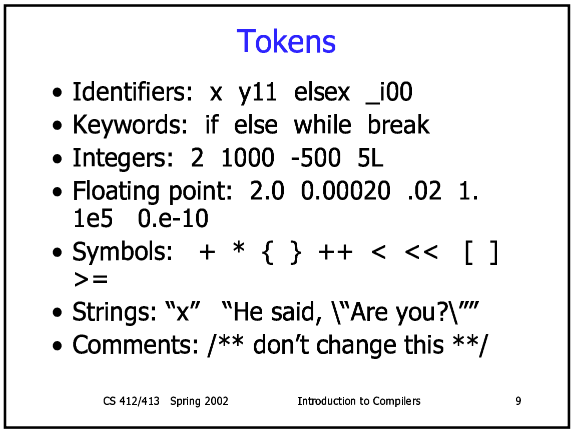
Lexical Analysis

Token stream

if	(	b	==	0	)	a	=	b	;

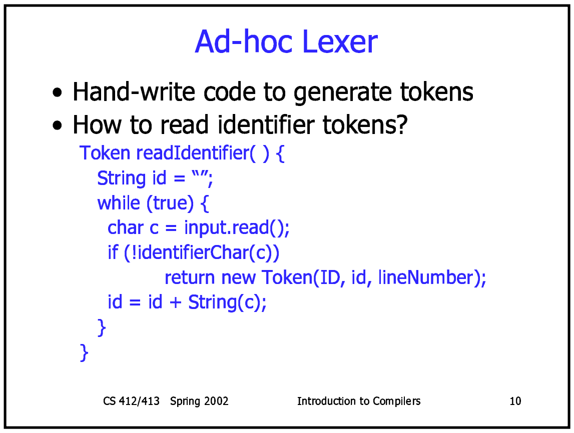
Syntax Analysis

Semantic Analysis



Tokens

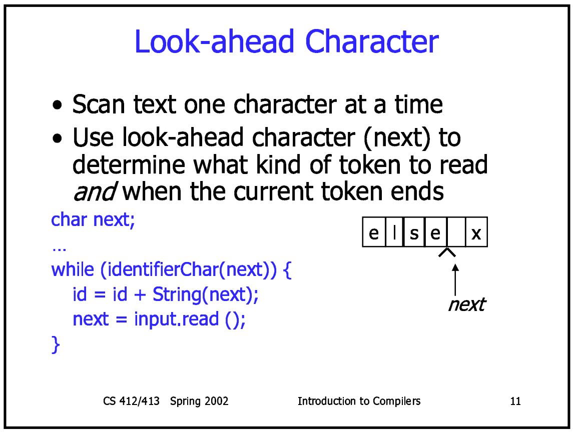
- Identifiers: x y11 elsex _i00
- Keywords: if else while break
- Integers: 2 1000 -500 5L
- Floating point: 2.0 0.00020 .02 1. 1e5 0.e-10
- Symbols: + * { } ++ < << [ ] >=
- Strings: “x” “He said, \“Are you?\””
- Comments: /** don’t change this **/



Ad-hoc Lexer

- Hand-write code to generate tokens
- How to read identifier tokens?

```
Token readIdentifier( ) {
   String id = “”;
   while (true) {
     char c = input.read();
     if (!identifierChar(c))
          return new Token(ID, id, lineNumber);
     id = id + String(c);
   }
 }
```



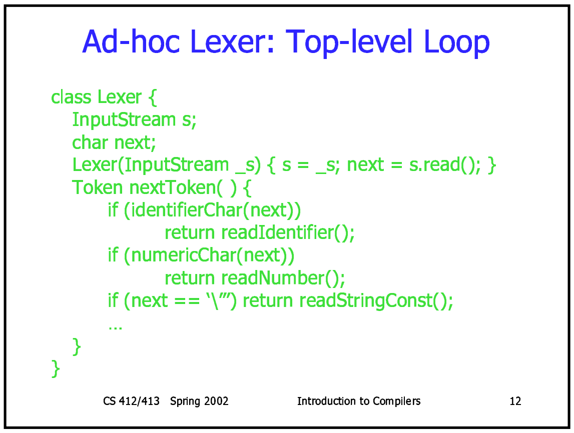
Look-ahead Character

- Scan text one character at a time
- Use look-ahead character (next) to determine what kind of token to read *and* when the current token ends

```
char next;
…
while (identifierChar(next)) {
   id = id + String(next);
   next = input.read ();
}
```

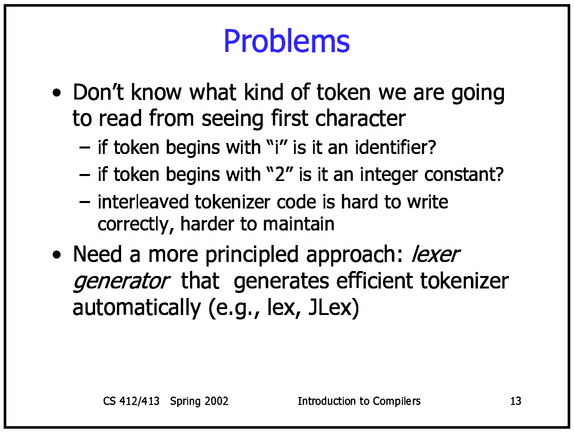
e	l	s	e		x

next



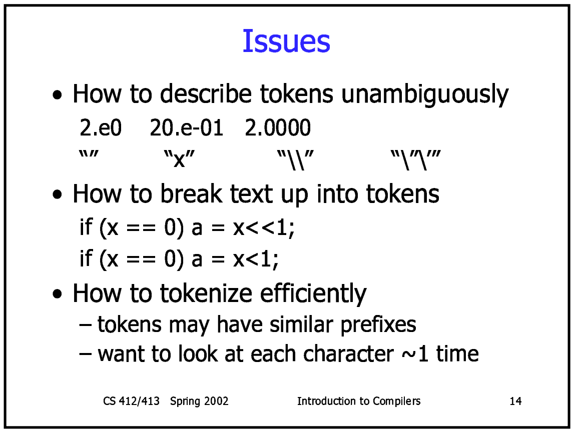
Ad-hoc Lexer: Top-level Loop

```
class Lexer {
   InputStream s;
   char next;
   Lexer(InputStream _s) { s = _s; next = s.read(); }
   Token nextToken( ) {
        if (identifierChar(next))
              return readIdentifier();
        if (numericChar(next))
              return readNumber();
        if (next == ‘\”’) return readStringConst();
        …
   }
}
```



Problems

- Don’t know what kind of token we are going to read from seeing first character
  - if token begins with “i” is it an identifier?
  - if token begins with “2” is it an integer constant?
  - interleaved tokenizer code is hard to write correctly, harder to maintain
- Need a more principled approach: *lexer generator* that generates efficient tokenizer automatically (e.g., lex, JLex)



Issues

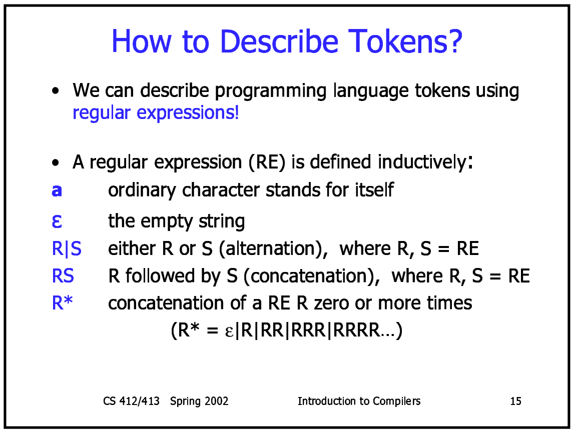
- How to describe tokens unambiguously

  2.e0 20.e-01 2.0000

  “” “x” “\\” “\”\””
- How to break text up into tokens

  if (x == 0) a = x<<1;

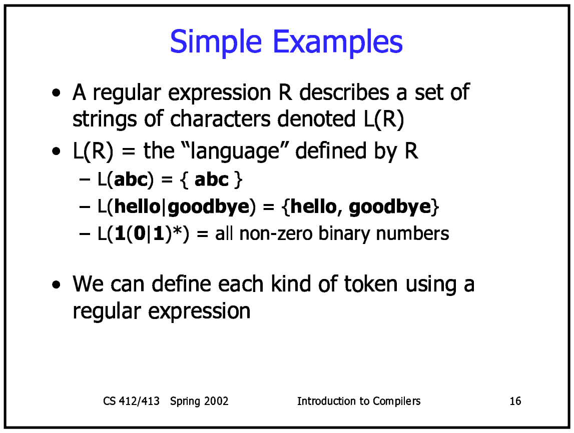
  if (x == 0) a = x<1;
- How to tokenize efficiently
  - tokens may have similar prefixes
  - want to look at each character ~1 time



How to Describe Tokens?

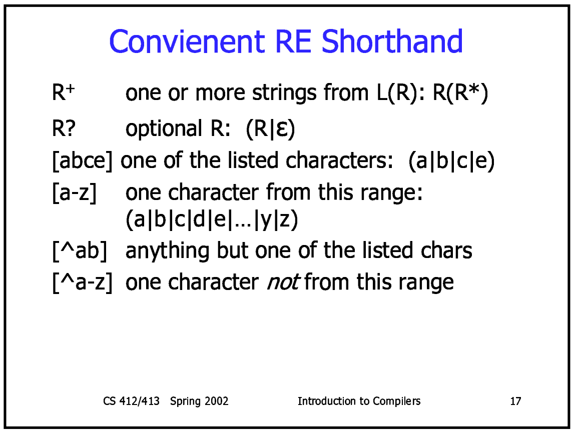
- We can describe programming language tokens using regular expressions!
- A regular expression (RE) is defined inductively:

a	ordinary character stands for itself
ε	the empty string
R|S	either R or S (alternation), where R, S = RE
RS	R followed by S (concatenation), where R, S = RE
R*	concatenation of a RE R zero or more times (R* = ε|R|RR|RRR|RRRR…)



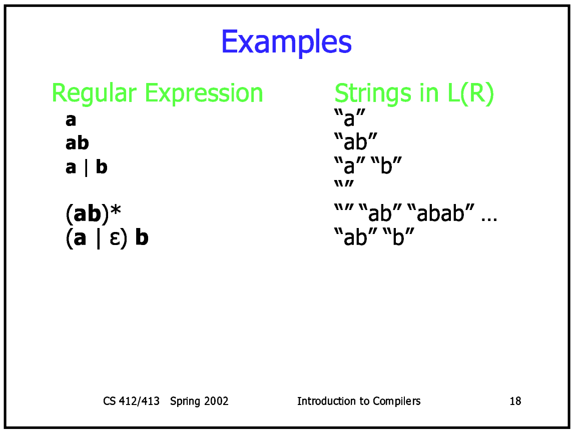
Simple Examples

- A regular expression R describes a set of strings of characters denoted L(R)
- L(R) = the “language” defined by R
  - L(**abc**) = { **abc** }
  - L(**hello**|**goodbye**) = {**hello**, **goodbye**}
  - L(**1**(**0**|**1**)*) = all non-zero binary numbers
- We can define each kind of token using a regular expression



Convienent RE Shorthand

R^+	one or more strings from L(R): R(R*)
R?	optional R: (R|ε)
[abce]	one of the listed characters: (a|b|c|e)
[a-z]	one character from this range: (a|b|c|d|e|…|y|z)
[^ab]	anything but one of the listed chars
[^a-z]	one character *not* from this range



Examples

Regular Expression	Strings in L(R)
a	“a”
ab	“ab”
a | **b**	“a” “b”
	“”
(**ab**)*	“” “ab” “abab” …
(**a** | ε) **b**	“ab” “b”

More Examples

Regular Expression	Strings in L(R)
digit = [**0**-**9**]	"0" "1" "2" "3" …
posint = *digit*+	"8" "412" …
int = -? *posint*	"-42" "1024" …
real = *int* (ε | (. *posint*))	"-1.56" "12" "1.0"
= -?[0-9]+(ε | (. [0-9]+))	
[**a**-**zA**-**Z**_][**a**-**zA**-**Z0**-**9**_]*	C identifiers

- Lexer generators support abbreviations
  - cannot be recursive

How To Break Up Text

elsex = 0;

1	else	x	=	0
2	elsex	=	0	

- REs alone not enough: need rule for choosing
- Most languages: longest matching token wins
  - even if a shorter token is only way
- Ties in length resolved by prioritizing tokens
- RE's + priorities + longest-matching token rule = lexer definition

Lexer Generator Spec

- Input to lexer generator:
  - list of regular expressions in priority order
  - associated *action* for each RE (generates appropriate kind of token, other bookkeeping)
- Output:
  - program that reads an input stream and breaks it up into tokens according to the REs. (Or reports lexical error -- *"Unexpected character"*)

Example: JLex

```
%%
digits = 0|[1-9][0-9]*
letter = [A-Za-z]
identifier = {letter}({letter}|[0-9_])*
whitespace = [\ \t\n\r]+
%%
{whitespace} {/* discard */}
{digits}      { return new IntegerConstant(Integer.parseInt(yytext()); }
"if"          { return new IfToken(); }
"while"       { return new WhileToken(); }
…
{identifier}  { return new IdentifierToken(yytext()); }
```

Summary

- Lexical analyzer converts a text stream to tokens
- Ad-hoc lexers hard to get right, maintain
- For most languages, legal tokens conveniently, precisely defined using regular expressions
- Lexer generators generate lexer code automatically from token RE's, precedence
- Next lecture: how lexer generators work

Groups

- If you haven't got a full group lined up, hang around and talk to prospective group members
- Send mail to cs412 if you still cannot make a full group

- Submit questionnaire!