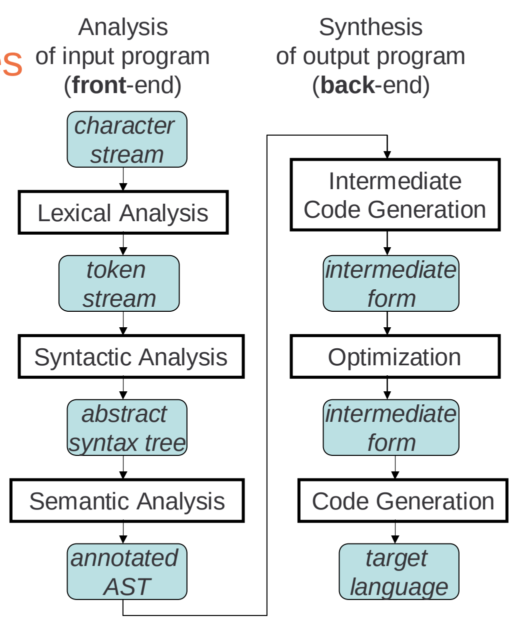
Lexical Analysis

Lexical analysis is the first phase of compilation: The file is converted from ASCII to tokens. It must be fast!

Compiler Passes



Lexical Pass/Scanning

Purpose: Turn the character stream (program input) into a **token** stream

- *Token*: a group of characters forming a basic, atomic unit of syntax, such as a identifier, number, etc.
- *White space*: characters between tokens that is ignored

Why separate lexical / syntactic analysis

Separation of concerns / good design

- scanner:
  - handle grouping chars into tokens
  - ignore white space
  - handle I/O, machine dependencies
- parser:
  - handle grouping tokens into syntax trees

Restricted nature of scanning allows faster implementation

- scanning is time-consuming in many compilers

Complications to Scanning

- Most languages today are free form
  - Layout doesn't matter
  - White space separates tokens
- Alternatives
  - Fortran -- line oriented
  - Haskell -- indentation and layout can imply grouping

```
   do 10 i = 1,100
    ...loop code...
10 continue
```

- Separating scanning from parsing is standard
- Alternative: C/C++/Java: ***type*** vs ***identifier***
  - Parser wants scanner to distinguish between names that are types and names that are variables
  - Scanner doesn't know how things are declared … done in semantic analysis, a\k\a type checking

Lexemes, tokens, patterns

Lexeme: group of characters that forms a pattern

Token: class of lexemes matching a pattern

- Token may have attributes if more than one lexeme is a token

Pattern: typically defined using regular expressions

- REs are the simplest class that's powerful enough for this purpose

Languages and Language Specification

Alphabet: finite set of characters and symbols

String: a finite (possibly empty) sequence of characters from an alphabet

Language: a (possibly empty or infinite) set of strings

Grammar: a finite specification for a set of strings

Language Automaton: an abstract machine accepting a set of strings and rejecting all others

A language can be specified by many different grammars and automata

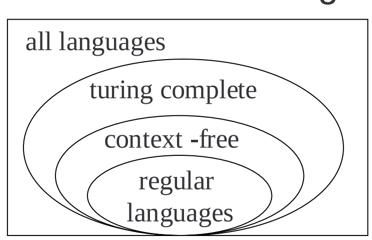
A grammar or automaton specifies a single language

Classes of Languages

Regular languages specified by regular expressions/grammars & finite automata (FSAs)

Context-free languages specified by context-free grammars and pushdown automata (PDAs)

Turing-computable languages are specified by general grammars and Turing machines



Syntax of Regular Expressions

- Defined inductively
  - Base cases
    - Empty string (ε, ∈)
    - Symbol from the alphabet (e.g. **x**)
  - Inductive cases
    - Concatenation (sequence of two REs) : E_1E_2
    - Alternation (choice of two REs): $E_1 \mid E_2$
    - Kleene closure (0 or more repetitions of RE): $E*$
- Notes
  - Use parentheses for grouping
  - Precedence: * is highest, then concatenate, | is lowest
  - White space not significant

Notational Conveniences

- E^+ means 1 or more occurrences of *E*
- E^k means exactly k occurrences of *E*
- [*E*] means 0 or 1 occurrences of *E*
- {*E*} means *E**
- ***not****(x)* means any character in alphabet by x
- ***not****(E)* means any strings from alphabet except those in *E*
- E_1-E_2 means any string matching E_1 that's not in E_2
- There is no additional expressive power here

Naming Regular Expressions

Can assign names to regular expressions

Can use the names in regular expressions

Example:

```
letter ::= a | b | ... | z
digit  ::= 0 | 1 | ... | 9
alphanum ::= letter | num
```

Grammar-like notation for regular expression is a regular grammar

Can reduce named REs to plain REs by “macro expansion”

- No recursive definitions allowed as in normal context-free

Using REs to Specify Tokens

Identifiers

```
ident ::= letter ( digit | letter)*
```

Integer constants

```
integer ::= digit+
sign ::= + | -
signed_int ::= [sign] integer
```

Real numbers

```
real ::= signed_int [fraction] [exponent]
fraction ::= . digit+
exponent ::= (E | e) signed_int
```

More Tokens

String and character constants

```
string ::= " char* "
character ::= ' char '
char ::= not(" | ' | \) | escape
escape  ::= \(" | ' | \ | n | r | t | v | b | a )
```

White space

```
whitespace ::= <space> | <tab> | <newline> |
                   comment
comment ::= /*  not(*/)  */
```

Meta-Rules

Can define a rule that a legal program is a sequence of tokens and white space:

```
program ::= (token | whitespace)*
token ::= ident | integer | real | string | ...
```

But this doesn't say how to uniquely breakup a program into its tokens -- it's highly ambiguous

- E.G. what tokens to make out of `hi2bob`
  - One identifier, `hi2bob`?
  - Three tokes `hi 2 bob`?
  - Six tokens, each one character long?

The grammar states that it's legal, but not how to decide

Apply extra rules to say how to break up a string

- Longest sequence wins

RE Specification of initial MiniJava Lex

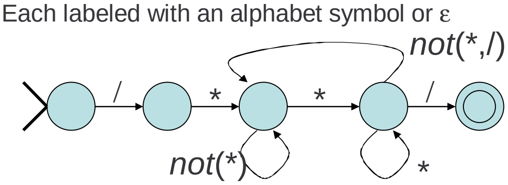
```
Program ::= (Token | Whitespace)*
Token ::= ID | Integer | ReservedWord | Operator |
           Delimiter
ID ::= Letter (Letter | Digit)*
Letter ::= a | ... | z | A | ... | Z
Digit ::= 0 | ... | 9
Integer ::= Digit+
ReservedWord::= class | public | static | extends |
       void | int | boolean | if | else |
       while|return|true|false| this | new | String
       | main | System.out.println
Operator ::= + | - | * | / | < | <= | >= | > | == |
       != | && | !
Delimiter ::= ; | . | , | = | ( | ) | { | } | [ | ]
```

Building Scanners with REs

- Convert RE specification into a **finite state automaton** (FSA)
- Convert FSA into a scanner implementation
  - By hand into a collection of procedures
  - Mechanically into a table-driven scanner

Finite State Automata

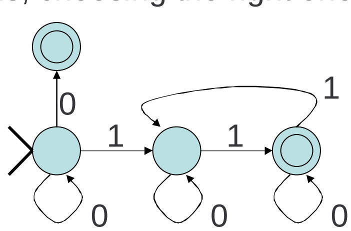
- A Finite State Automaton has
  - A set of states
    - One marked initial
    - Some marked final
  - A set of transitions from state to state
    - Each labeled with an alphabet symbol or ε



  - Operate by beginning at the start state, reading symbols and making indicated transitions
  - When input ends, state must be final or else reject

Determinism

- FSA can be deterministic or nondeterministic
- Deterministic: always know uniquely which edge to take
  - At most 1 arc leaving a state with a given symbol
  - No ε arcs
- Nondeterministic: may need to guess or explore multiple paths, choosing the right one later



NFAs vs DFAs

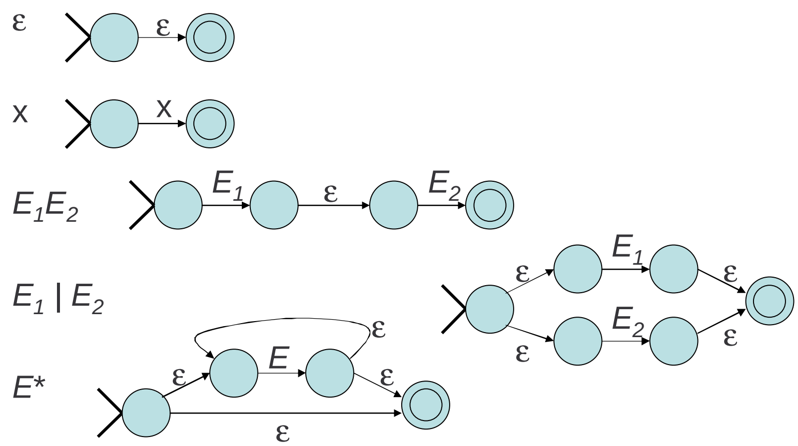
- A problem:
  - REs (e.g. specifications map easily to NFAs)
  - Can write code for DFAs easily
- How to bridge the gap?
- Can it be bridged?

A Solution

- Cool algorithm to translate any NFA to a DFA
  - Proves that NFAs aren't any more expressive
- Plan:
  1) Convert RE to NFA
  2) Convert NFA to DFA
  3) Convert DFA to code
- Can be done by hand or fully automatically

RE => NFA

Construct Cases Inductively



NFA => DFA

- Problem: NFA can “choose” among alternative paths, while DFA must pick only one path
- Solution: subset construction
  - Each state in the DFA represents the set of states the NFA could possibly be in

Subset Construction

Given NFA with states and transitions

- label all NFA states uniquely

Create start state of DFA

- label it with the set of NFA states that can be reached by ε transitions, i.e. w/o consuming input
- Process the start state

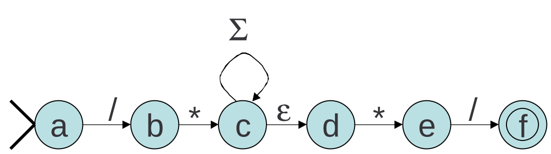
To process a DFA state S with label [$S_1,\ldots,S_n$]

For each symbol x in the alphabet:

- Compute the set T of NFA states from $S_1,\ldots,S_n$ by an x transition followed by any number of ε transitions
- If T not empty
  - If a DFA state labeled [T] add an x transition from S to [T]
  - Else create new DFA state [T] and add an x transition S to [T]

A DFA state is final iff at least one of the NFA states is

Subset Construction



To Tokens

- Every “final” symbol of a DFA emits a token
- Tokens are the internal compiler names for the lexemes

  == becomes equal

  (becomes leftParen

  private becomes private
- You choose the names
- Also, there may be additional data … **`\r\n`** might include line count

DFA => Code

- Option 1: Implement by hand using procedures
  - one procedure for each token
  - each procedure reads one character
  - choices implemented using if and switch statements
- Pros
  - straightforward to write
  - fast
- Cons
  - a fair amount of tedious work
  - may have subtle differences from the language specification

DFA => code [continued]

- Option 2: use tool to generate table driven parser
  - Rows: states of DFA
  - Columns: input characters
  - Entries: action
    - Go to next state
    - Accept token, go to start state
    - Error
- Pros
  - Convenient
  - Exactly matches specification, if tool generated
- Cons
  - "Magic"
  - Table lookups may be slower than direct code, but switch implementation is a possible revision

Automatic Scanner Generation in MiniJava

We use the `jflex` tool to automatically create a scanner from a specification file, `Scanner/minijava.jflex`

(We use the CUP tool to automatically create a parser from a specification file, `Parser/minijava.cup`, which also generates all of the code for the token classes used in the scanner, via the `Symbol` class

The MiniJava `Makefile` automatically rebuilds the scanner (or parser) whenever its specification file changes

Symbol Class

Lexemes are represented as instances of class Symbol

```
class Symbol {
Int sym;      // which token class?
Object value; // any extra data for this lexeme
...
}
```

A different integer constant is defined for each token class in the `sym` helper class

```
class sym {
    static int CLASS = 1;
    static int IDENTIFIER = 2;
    static int COMMA = 3;
 ...
}
```

Can use this in printing code for `Symbols`; see `symbolToString in minijava.jflex`

Token Declarations

Declare new token classes in `Parser/minijava.cup`, using `terminal` declarations

- include Java type if `Symbol` stores extra data

- Examples

```
/* reserved words: */
terminal CLASS, PUBLIC, STATIC, EXTENDS;
 ...
/* operators: */
terminal PLUS, MINUS, STAR, SLASH, EXCLAIM;
...
/* delimiters: */
terminal OPEN_PAREN, CLOSE_PAREN;
terminal EQUALS, SEMICOLON, COMMA, PERIOD;
...
/* tokens with values: */
terminal String IDENTIFIER;
terminal Integer INT_LITERAL;
```

`jflex` Token Specifications

Helper definitions for character classes and regular expressions

```
letter = [a-z A-Z]
eol = [\r\n]
```

Simple) token definitions are of the form:

`regexp { Java stmt }`

`regexp` can be (at least):

- a string literal in double-quotes, e.g. `"class", "<="`
- a reference to a named helper, in braces, e.g. `{letter}`
- a character list or range,in square brackets ,e.g. `[a-z A-Z]`
- a negated character list or range, e.g. `[^\r\n]`
- . (which matches any single character)
- *`regexp regexp`*`,`*`regexp`*`|`*`regexp`*`,`*`regexp`*`*,`*`regexp`*`+,` *`regexp`*`?, (`*`regexp`*`)`

`jflex` Tokens [Continued]

Java stmt (the accept action) is typically:

- `return symbol(sym.CLASS);` for a simple token
- `return symbol(sym.CLASS,yytext());` for a token with extra data based on the lexeme `stringyytext()`
- empty for whitespace