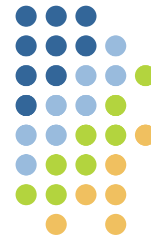
COMP 181

Lecture 2

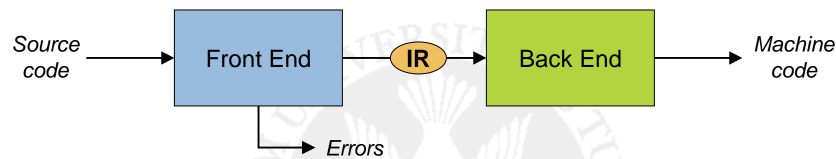
Lexical analysis



Wednesday, Sept. 14, 2005

Motivation…

Big picture

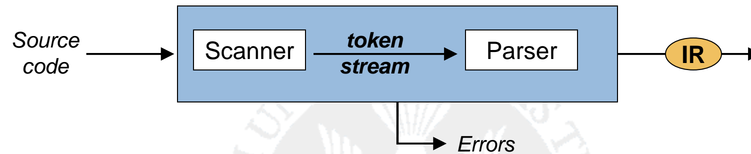


- Front end responsibilities
  - Check that the input program is legal
    - Check syntax and semantics
    - Emit meaningful error messages
  - Build IR of the code for the rest of the compiler

Front end

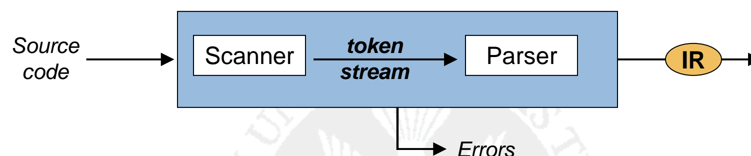
- Strategy:
  - Specify the input language formally
    Regular expressions, context-free grammars
  - Use automatons to recognize valid strings
    Hey, this stuff is actually useful?
  - Automate construction
    Or, in our case, learn how automation works
  - Add "actions" to state transitions
    - Build IR data structure
    - Perform additional semantic checks

Front end design



- Two part design
  - Scanner
    - Reads in characters
    - Classifies sequences into words or *tokens*
  - Parser
    - Checks sequence of tokens against grammar
    - Creates a representation of the program (AST)

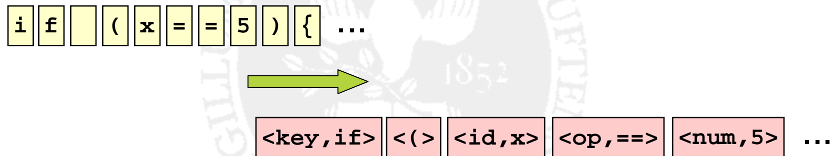
Scanner and parser



- Why separate scanner and parser?
  - Simplifies the implementation
  - Parsing is fundamentally harder
    - Word classification is easier – make it fast
    - Speed up parsing by working with tokens

Scanner

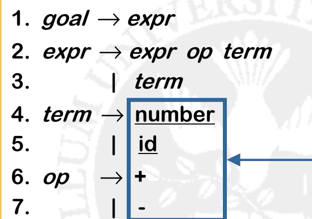
- Responsibilities
  - Read in characters
  - Produce a stream of tokens



  - Token has a type and a value

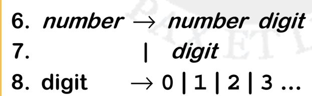
Scanner

- Relation to parser



Scanner provides the terminal symbols

- Could be encoded in grammar:



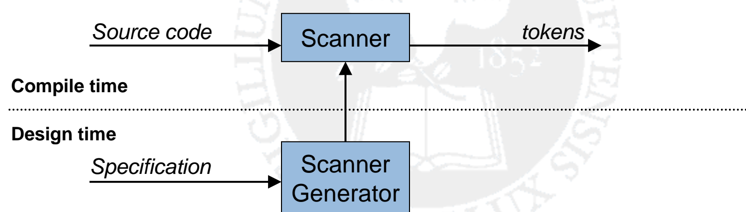
Hand-coded scanner

- Explicit test for each token
  - Read in a character at a time
  - Example: recognizing keyword “if”

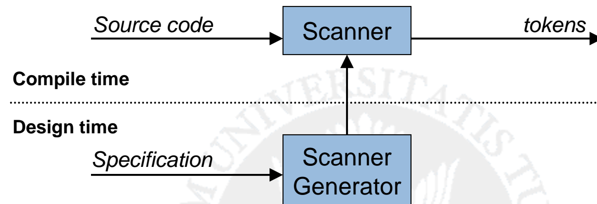
```
c = readchar();
if (c != 'i')
  error();
else {
  c = readchar();
  if (c != 'f')
    error();
  else
    return IF_TOKEN;
}
```

Scanner construction

- Goal: automate process
  - Avoid writing scanners by hand
  - Leverage the underlying theory of languages



Scanner construction



- Tokens specified as *regular expressions*
  Note: in PL, spelling identifies part of speech
- Scanner generator produces state machine
  - Recognizes the REs
  - Implemented as tables or directly in code

Regular expressions

- Rules or patterns to define *regular languages*
  - Alphabet Σ
  - Language is a set of strings
  - Let *L(r)* denote the language described by RE *r*
- Regular expressions over Σ
  - ε is an RE denoting empty set
  - if a is in Σ, then a is an RE for {a}
  - if *x* and *y* are REs then:
    - *xy* is an RE for *L(x)L(y)* — *Concatentation*
    - *x|y* is an RE for *L(x)* ∪ *L(y)* — *Alternation*
    - *x** is an RE for *L(x)** — *Kleene closure*

Set operations

Operation	Definition
Union of L and M Written L ∪ M	$L \cup M = \{s \mid s \in L \text{ or } s \in M\}$
Concatenation of L and M Written LM	$LM = \{st \mid s \in L \text{ and } t \in M\}$
Kleene closure of L Written L^*	$L^* = \cup_{0 \le i \le \infty} L^i$
Positive Closure of L Written L^+	$L^+ = \cup_{1 \le i \le \infty} L^i$

Using regular expressions

- Concatenation: build up words
- Kleene closure: repetition
- Alternation: collect sets of words

Examples

Identifiers:

Letter → (a|b|c| … |z|A|B|C| … |Z)
Digit → (0|1|2| … |9)
Identifier → *Letter* (*Letter* | *Digit*)*

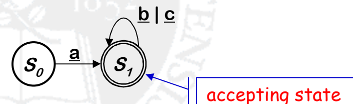
Numbers:

Integer → (+|-|ε) (0| (1|2|3| … |9)(*Digit* *))
Decimal → *Integer* . *Digit* *
Real → (*Integer* | *Decimal*) E (+|-|ε) *Digit* *
Complex → (*Real* , *Real*)

Numbers can get much more complicated!

Back to scanners

- How do we use regular expressions?
  - Every RE has an equivalent finite state automaton that recognizes its language
    (Actually, more than one)
  - Example: a(b|c)*

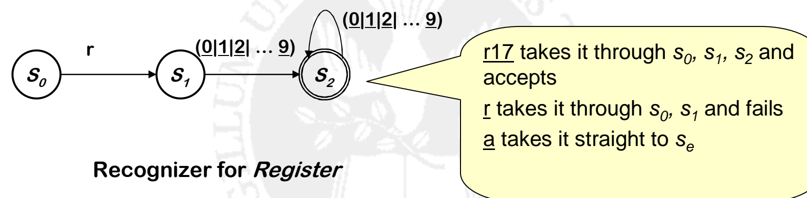


  - Idea: scanner simulates the automaton

Example

- Consider the problem of recognizing register names

Register → r (0|1|2| … | 9) (0|1|2| … | 9)*



Recognizer for *Register*

- Start in state S_0 & take transitions on each input character
- FA accepts a word *x iff x* leaves it in a final state (S_2)
- Other transition go to an error state, S_e

Implementation

- Finite automaton
  - States, characters
  - State transition δ(state,charclass) determines next state
  - ⇒ Automaton is *deterministic*
- Next character function
  - Reads next character into buffer
  - (May compute *character class* by fast table lookup)
- Transitions from state to state
  - Implement δ as a table
  - Access table using current state and character

Example

Turning the recognizer into code

δ	r	0,1,2,3,4, 5,6,7,8,9	All others
s_0	s_1	s_e	s_e
s_1	s_e	s_2	s_e
s_2	s_e	s_2	s_e
s_e	s_e	s_e	s_e

Table encoding RE

```
Char ← next character
State ← s0

while (Char ≠ EOF)
   State ← δ(State,Char)
   Char ← next character

if (State is a final state )
   then report success
   else report failure
```

Skeleton recognizer

Example

Adding actions

δ	r	0,1,2,3,4, 5,6,7,8,9	All others
s_0	s_1 start	s_e error	s_e error
s_1	s_e error	s_2 add	s_e error
s_2	s_e error	s_2 add	s_e error
s_e	s_e error	s_e error	s_e error

Table encoding RE

```
Char ← next character
State ← s0

while (Char ≠ EOF)
   State ← δ(State,Char)
   perform specified action
   Char ← next character

if (State is a final state )
   then report success
   else report failure
```

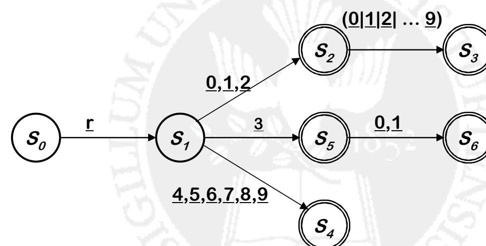
Skeleton recognizer

What if we need a tighter specification?

- r *Digit Digit** allows arbitrary numbers
  - Accepts r00000
  - Accepts r99999
  - What if we want to limit it to r0 through r31 ?
- Write a tighter regular expression
  - *Register* → r ((0|1|2) (*Digit* | ε) | (4|5|6|7|8|9) | (3|30|31))
  - *Register* → r0|r1|r2| … |r31|r00|r01|r02| … |r09
- Produces a more complex DFA
  - Has more states
  - Same cost per transition
  - Same basic implementation

Tighter register specification

- The DFA for
  Register → r ((0|1|2) (*Digit* | ε) | (4|5|6|7|8|9) | (3|30|31))



- Accepts a more constrained set of registers
- Same set of actions, more states

Tighter register specification

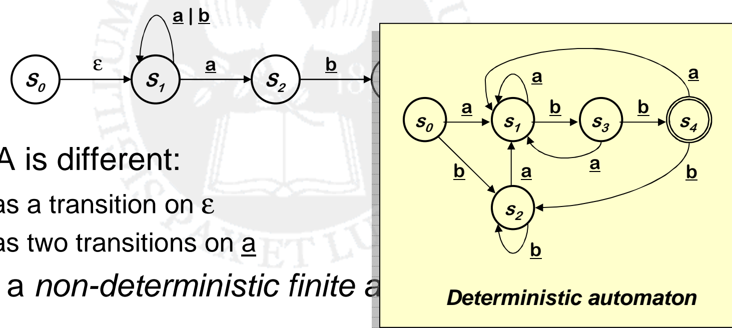
δ	r	0,1	2	3	4-9	All others
s_0	s_1	s_e	s_e	s_e	s_e	s_e
s_1	s_e	s_2	s_2	s_5	s_4	s_e
s_2	s_e	s_3	s_3	s_3	s_3	s_e
s_3	s_e	s_e	s_e	s_e	s_e	s_e
s_4	s_e	s_e	s_e	s_e	s_e	s_e
s_5	s_e	s_6	s_e	s_e	s_e	s_e
s_6	s_e	s_e	s_e	s_e	s_e	s_e
s_e	s_e	s_e	s_e	s_e	s_e	s_e

Runs in the same skeleton recognizer

Table encoding RE for the tighter register specification

Building DFAs

- Each RE has an equivalent DFA
  - May be hard to directly construct the right DFA
- What about an RE such as (a | b)* abb ?

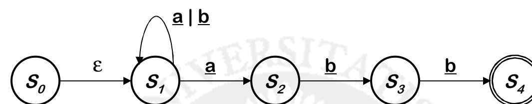


- This FA is different:
  - S_0 has a transition on ε
  - S_1 has two transitions on a
- This is a *non-deterministic finite a*

Non-deterministic finite automata

- An NFA accepts a string *x* iff ∃ a path though the transition graph from s_0 to a final state such that the edge labels spell *x*
  (Transitions on ε consume no input)
- To "run" the NFA, start in s_0 and *guess* the right transition at each step
  - Always guess correctly
  - If some sequence of correct guesses accepts x then accept
- Why study NFAs?
  - They are the key to automating the RE→DFA construction
  - (We can paste together NFAs with ε-transitions)

NFA Example



- Input: a a a b b

This 'a' transitions back to s_1

This 'a' transitions to s_2

- Must know the future

Relationship between NFAs and DFAs

- DFA is a special case of an NFA
  - DFA has no ε transitions
  - DFA's transition function is single-valued
  - Same rules will work
- DFA can be simulated with an NFA *(obvious)*
- NFA can be simulated with a DFA *(less obvious)*
  - Simulate sets of possible states
  - Possible exponential blowup in the state space
  - Still, one state per character in the input stream

Automatic scanner construction

- To convert a specification into code:
  1. Write down the RE for the input language
  2. Build a big NFA
  3. Build the DFA that simulates the NFA
  4. Systematically shrink the DFA
  5. Turn it into code
- Scanner generators
  - Lex and Flex work along these lines
  - Algorithms are well-known and well-understood
  - Key issue is interface to parser *(define all parts of speech)*
  - You could build one in a weekend!

Automatic scanner construction

RE→ NFA *(Thompson's construction)*

- Build an NFA for each term
- Combine them with ε-moves

NFA → DFA *(subset construction)*

- Build the simulation

DFA → Minimal DFA

- Hopcroft's algorithm

DFA →RE *(Not part of the scanner construction)*

- All pairs, all paths problem
- Take the union of all paths from s_0 to an accepting state

C scanner

Section
Declarations
Short-hand
REs and actions

```
%{
#include "c_breeze.h"
#include "parser.tab.h“
%}
identifier      ([a-zA-Z_][0-9a-zA-Z_]*)
octal_escape  ([0-7][^'"\n]*)
any_white       ([ \011\013\014\015])
%%
{any_white}+     {  }
for                   { lval.tok = get_pos(); return ctokFOR;}
if                     { lval.tok = get_pos(); return ctokIF;}
{identifier}       { lval.tok = get_pos();
                          lval.idN = new idNode(cbtext, cblval.tok);
                          if ( is_typename(cbtext))   return TYPEDEFname;
                          else                                 return IDENTIFIER; }
{decimal_constant}  { lval.exprN = atoi(cbtext);
                                 return INTEGERconstant; }
%%
...any special code...
```

Next time...

- Sign up on mailing list:

  `https://www.eecs.tufts.edu/mailman/listinfo/comp181`

- RE *-to-* NFA *-to-* DFA *-to-* scanner

- Algorithms (yikes!)

Automatic scanner construction

- Construct a DFA to recognize any RE
- Overview:
  - Direct construction of a nondeterministic finite automaton (NFA) to recognize a given RE
  - Construct a deterministic finite automaton (DFA) to simulate the NFA
  - Minimize the number of states
  - Generate the scanner code