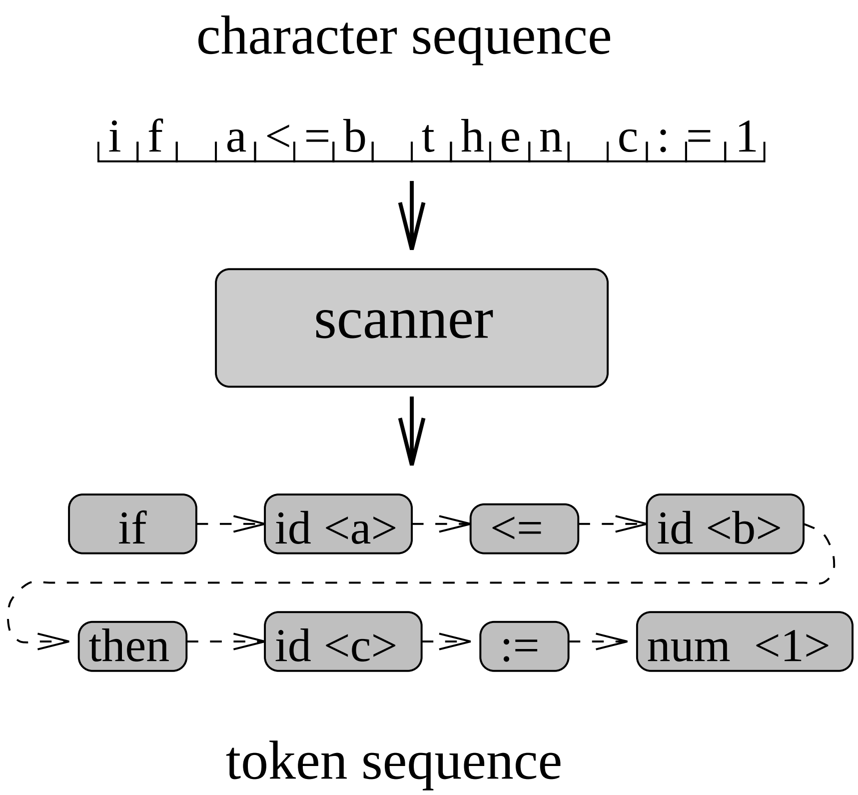
Class Announcements

- Remember our course web page:

  https://www.cs.rutgers.edu/courses/314/classes/spring_2023_kremer/

- Piazza and canvas sites are up. Please check every other day, at least.
- First homework is due next Tuesday at 11:59pm. Late homework submissions are not accepted.
- TA office hours have been posted. Please check whether major time conflict with popular classes. All TA office hours are held in CoRE 305.

Review - Lexical Analysis (Scott 2.1, 2.2)



Tokens (Terminal Symbols of CFG, Words of Lang.)

- Smallest "atomic" units of syntax
- Used to build all the other constructs
- Example, Pascal:

  keywords: `program begin if then` ...

  `= * / - < > = <= >= <>`

  `( ) [ ] ; := . ,` ...

  `number` (Example: `3.14 28` ...)

  `identifier` (Example: `b square addEntry` ...)

Review - Regular Expressions

A syntax (notation) to specify regular languages.

RE r	**Language L(r)**
a	{**a**}
ϵ	$\{\epsilon\}$
r | s	L(r) $\cup$ L(s)
rs	$\{rs \mid r \in$ L(r), $s \in$ L(s)$\}$
r$^+$	L(r) $\cup$ L(rr) $\cup$ L(rrr) $\cup \ldots$ (any number of r's concatenated)
r* (r* = r$^+ \vert \epsilon$)	$\{\epsilon\} \cup$ L(r) $\cup$ L(rr) $\cup$ L(rrr) $\cup \ldots$
(s)	L(s)

(all left-assoc. in order of increasing precedence.)

$\Rightarrow$ Note: Inductive definition!

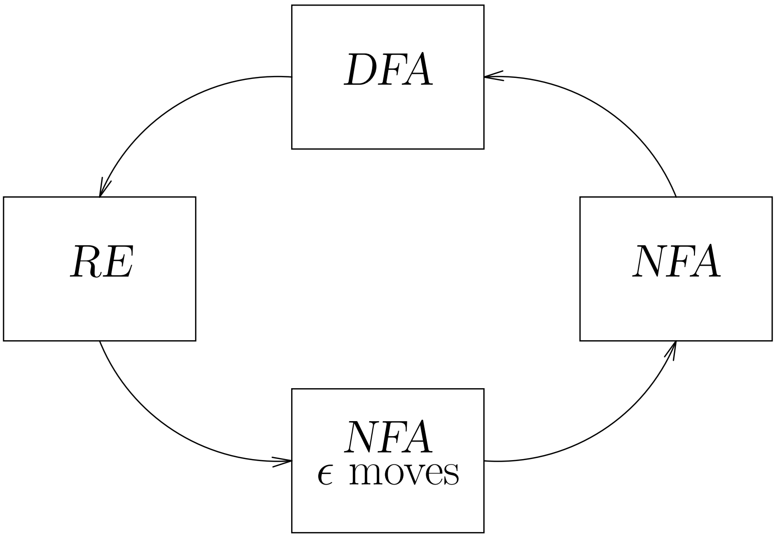
What do we want?

Ideally: The language/compiler designer specifies the tokens using a regular expression, and some automatic tool (scanner generator) produces code that implements the scanner.

$\boxed{\text{How can this be done?}}$

Note: In practice, there are a few more issues that we are not discussion here. For example, how to make sure that a keyword is not recognized as an identifier.

Constructing a *DFA* from a regular expression



regular expression (RE) →*NFA* w/ϵ moves

build *NFA* for each term

connect them with ϵ moves

NFA w/ϵ moves to *NFA*

coalesce states

NFA→*DFA*

construct the simulation ("subset" construction)

minimize DFA (DFA with minimal number of states)

DFA→ regular expression

construct $R_{ij}^{k} = R_{ik}^{k-1}(R_{kk}^{k-1})^{*}R_{kj}^{k-1} \cup R_{ij}^{k-1}$

The entire process as used in compiler generation tools will be covered in `198:415 Compilers`.

Converting regular expressions to *NFA*s

Construction of *NFA* based on syntactic structure of regular expression. Each intermediate *nfa* has exactly one final state, no edge entering start state, and no edge leaving final state.

`"BASE"`: Build two-state automaton for atomic regular expression `a` (single symbol or ϵ) with `a` as the edge label. One automaton N(`a`) for each occurence of `a`.

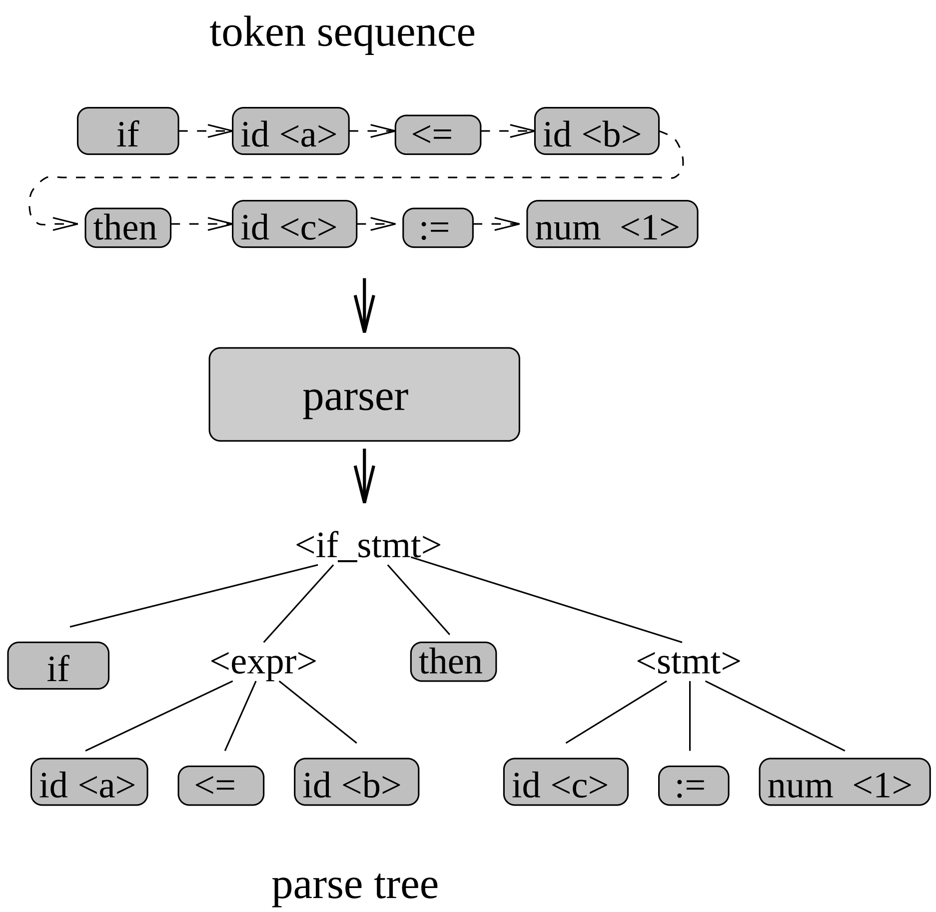
`"INDUCTIVE STEP"`: Compose automata as follows:

- concatenate: N(`st`) – given N(`s`) and N(`t`)

- union: N(`s|t`) – given N(`s`) and N(`t`)

- Kleene closure: N($\texttt{s}^*$) – given N(`s`)

Syntax Analysis (Scott 2.3 - 2.5 - skip 2.3.4)



BNF (Backus-Naur Form): A formal notation for describing syntax— how components can be combined to form a valid program.

- To specify which programs are legal
- To describe the structure of programs (*parse tree*)
- BNF is a way of writing context free grammars (CFGs)

Context Free Grammars (CFGs)

- A formalism for describing languages
- CFGs are a quadruple $< T, N, P, S >$:
  1. A set T of terminal symbols
  2. A set N of nonterminal symbols
  3. A set P production rules
  4. A special start symbol S
- BNF is a notation for describing CFGs.

A partial example:

...

<if-stmt> ::= **if** <expr> **then** <stmt>
<expr> ::= **id** <= **id**
<stmt> ::= **id** := **num**

Elements of BNF Syntax

Terminal Symbol: **Symbol-In-Boldface**

Non-Terminal Symbol: *Symbol-In-Angle-Brackets*

Production Rule:

Non-Terminal ::= Sequence of Symbols

or

Non-Terminal ::= Sequence | Sequence | ...

Alternative Symbol: |

Empty String: ϵ

How a BNF Grammar Describes a Language

- A *sentence* is a sequence of terminal symbols (tokens)
- A *language* is a set of (acceptable) sentences
- The language $L(G)$ of a BNF grammar G is the set of sentences generated using the grammar:
  - Begin with start symbol.
  - Iteratively replace non-terminals with terminals according to rules.

This is a rewrite system!

Simple Grammar ($\mathcal{G}$)

Terminals letters, digits, **:=**

Nonterminals <letter> <digit> <identifier> <stmt>

Productions

1. <letter> ::= A | B | C | . . . | Z
2. <digit> ::= 0 | 1 | 2 | . . . | 9
3. <identifier> ::= <letter> |
   <identifier> <letter> |
   <identifier> <digit>
4. <stmt> ::= <identifier> := 0

Start Symbol <stmt>

Derivation in a Grammar ($\mathcal{G}$)

Is `X2 := 0` $\in L(\mathcal{G})$, i.e., can `X2 := 0` be derived in G?

In which order to apply the rules?

Typically, there are three options:

- leftmost ($\Rightarrow_L$)
- rightmost($\Rightarrow_R$)
- any ($\Rightarrow$)

Does it matter?

Derivation in a Grammar ($\mathcal{G}$)

Is `X2 := 0` $\in L(\mathcal{G})$, i.e., can `X2 := 0` be derived in $\mathcal{G}$?

leftmost derivation		rule applied
<stmt>	$\Rightarrow_L$	4
<identifier> := 0	$\Rightarrow_L$	3c
<identifier><digit> := 0	$\Rightarrow_L$	3a
<letter><digit> := 0	$\Rightarrow_L$	1
X <digit> := 0	$\Rightarrow_L$	2
X2 := 0		

rightmost derivation		rule applied
<stmt>	$\Rightarrow_R$	4
<identifier> := 0	$\Rightarrow_R$	3c
<identifier><digit> := 0	$\Rightarrow_R$	2
<identifier> 0 := 0	$\Rightarrow_R$	3a
<letter> 0 := 0	$\Rightarrow_R$	1
X2 := 0		

Parsing in a Grammar ($\mathcal{L}$)

Can we **recognize** `X2 := 0` as being in $\mathcal{L}$?

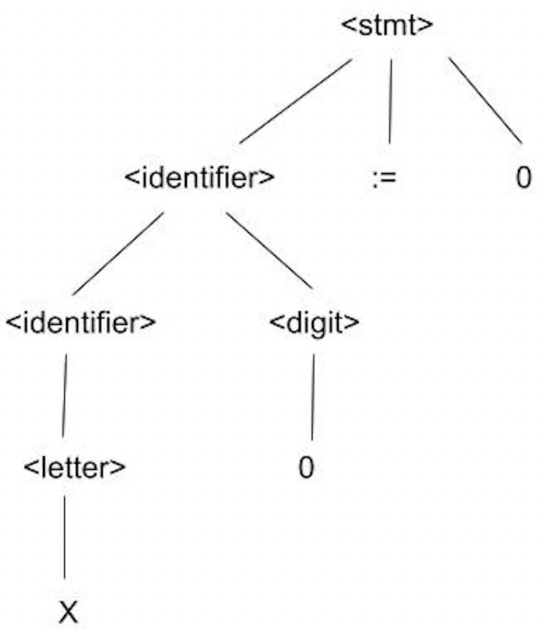
In other words, can write a program, called **a parser for L(G)**, that given an input string of terminal symbols (tokens) can construct a derivation (leftmost or rightmost) for the input using rules in G? If a deriviation does not exist, the program should report an error.

Note: Different parsing techniques, i.e., the automatic recognition sentences $w \in L(G)$ will be discussed in more detail in `198:415 Compilers`.

We will talk about LL(1) grammars and an example parser for a small language (tinyL) that is implemented using mutually recursive procedures (recursive descent parser).

Parse Trees (in $\mathcal{G}$)

A *parse tree* of `X2 := 0` in $\mathcal{G}$:



Each internal node is a nonterminal; its children are the RHS of a production for that NT.

The parse tree demonstrates that the grammar generates the terminal string on the frontier.

Note: Different parsing techniques, i.e., the automatic recognition sentences $w \in L(G)$ will be discussed in `198:415 Compilers`.

Next Lecture

Ambiguity, top-down parsing

Things to do:

- Please check our web site every other day for announcements etc.;
- read Scott, Ch. 2.3 - 2.5 (skip 2.3.3 Bottom-up Parsing)