Theory and Compiling

COMP360

"It has been said that man is a rational animal. All my life I have been searching for evidence which could support this."

Bertrand Russell

Reading

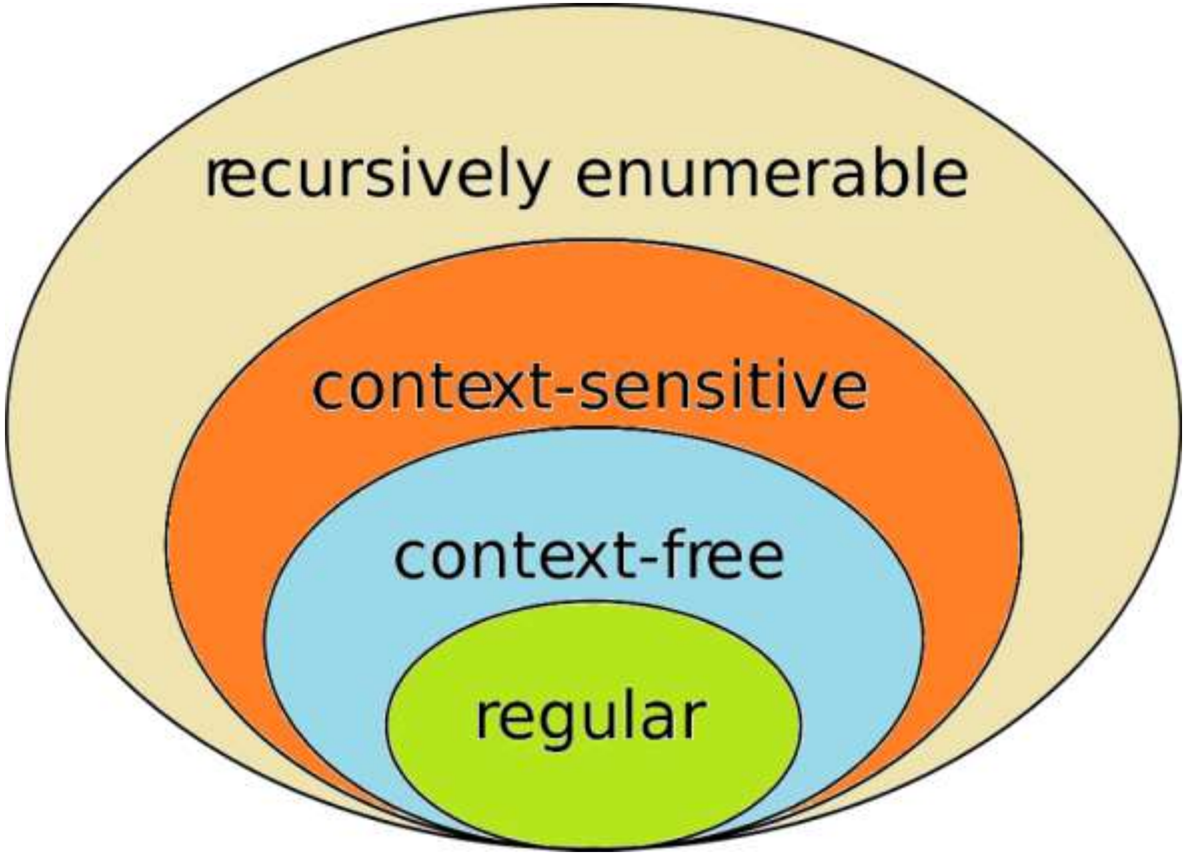
Read sections 2.1 – 3.2 in the textbook

Language Recognition

- We say a theoretical machine can recognize a language if it can correctly identify a string of characters as being a syntactically correct program
- If a theoretical machine can recognize a language, it can identify input that is not in the proper form, i.e. missing a semicolon or improper brackets

Chomsky Hierarchy

- There are four classes of languages
- Each class is a subset of another class
- Regular languages are the simplest while recursively enumerable (RE) languages are the most complex



Languages and Machines

Language	Machine	Examples
Regular Expressions	Deterministic Finite State Automata (DFA)	Regular Expressions
Context Free	Push Down Automata (PDA)	$a^n b^n$
Context Sensitive	Bounded Turing Machine	$a^n b^n c^n$
Recursively Enumerable	Turing Machine	Anything that can be recognized

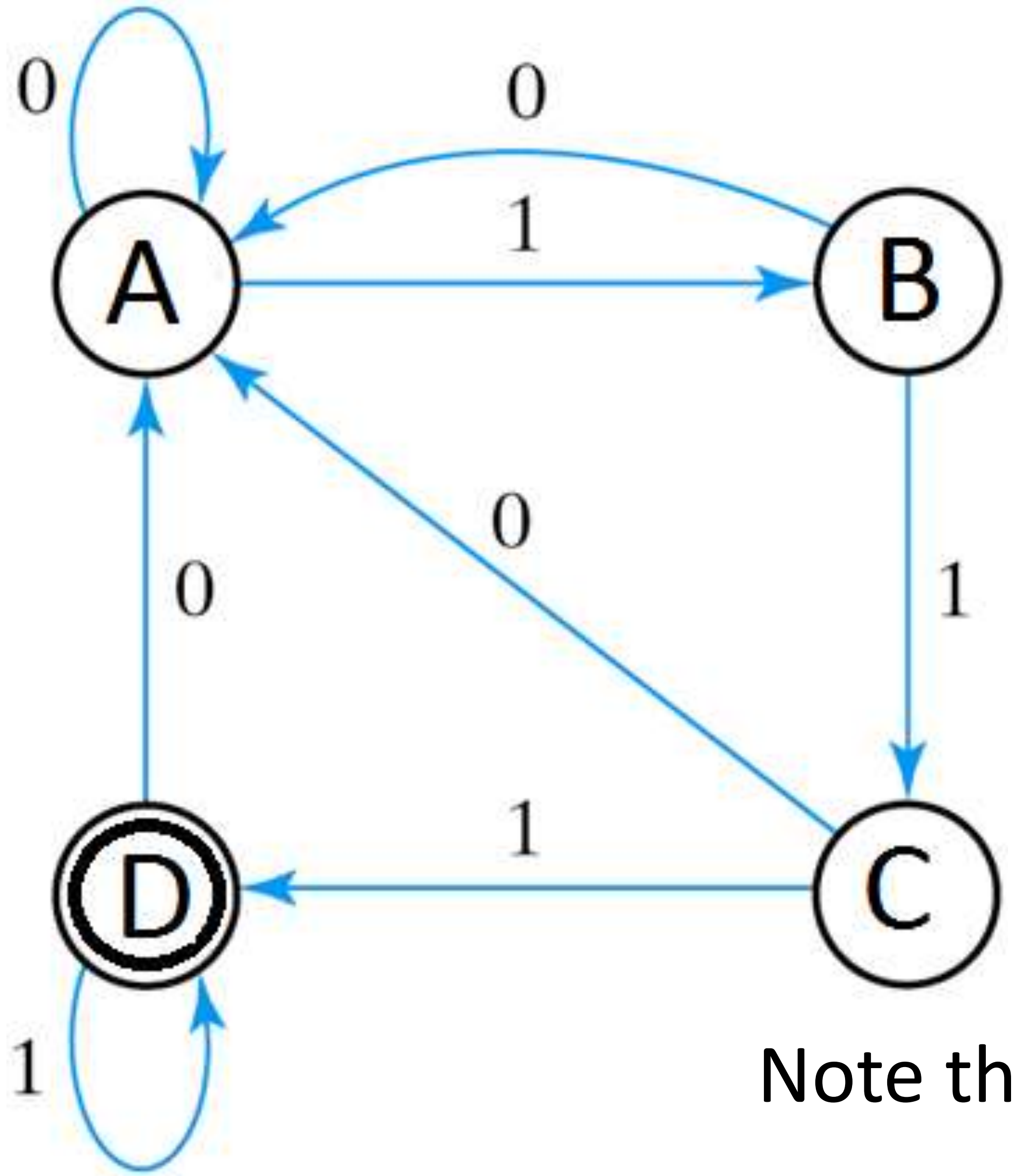
Finite State Automata

- An FSA has circles to represent states and arrows to represent transitions between states
- Arrows are labeled with a character. That transition is taken if the FSA is in that state and the next input character matches the arrow label
- There is one or more final states that indicate the input matches the language
- If there is no matching transition for an input, the FSA rejects the input as a member of the language

Nondeterministic FSA

- In Computer Science theory, a Nondeterministic FSA (NFSA) can have multiple out arrows with the same label
- An NFSA magically guesses which transition to take
- Since an NFSA is no more powerful than a deterministic FSA *(and we don't have magical programs)* we will only use deterministic FSA
- Our FSA cannot have duplicate out arrows with the same label

FSA for 3 Consecutive 1 inputs



- State A : no 1s detected
- State B : one 1 detected
- State C : two 1s detected
- State D : three 1s detected

Note that each state has 2 output arrows

Regular Expressions

- Regular expressions are often used to specify a regular language
- A regular expression defines a series of symbols in the order they can appear in the language
- Consider a very simple language with only the letters "**`a`**" and "**`b`**"
- **`aabb`** is a regular expression for a string with two letters **`a`** followed by two **`b`**'s

Regular Expression Alternatives

- A regular expression can specify alternatives using the vertical bar character, |
- **`aabb | ba`** defines a regular language that accepts two **`a`**'s then two **`b`**'s or a string with just a **`b`** and an **`a`**
- You can use parenthesis to group strings
- **`(aabb | ba)a`** defines a regular language that accepts **`aabba`** or **`baa`**

Regular Expression Repetitions

- A symbol or (group) might repeat multiple times in a valid string of the language
- A "*" indicates that a symbol or (group) repeats zero, one or many times
- A "+" indicates that a symbol or (group) repeats once or many times, but at least once
- **`a`**$^{0..1}$ mean the symbol may appear zero or 1 time
- **`(aabb | ba)`**$^{+}$ **`a`** defines the strings

  `aabbaabba, aabbbaa, baa` and more

Which strings are **NOT** `(aa | bb)*a`$^+$

A. a
B. bbaabba
C. aaa
D. aabb
E. bbbbbbaaaaa

Write a Regular Expression

- Write a regular expression to define a string that begins and ends with an **a** and can have an even number of **b**’s between them

Possible Solution

- Write a regular expression to define a string that begins and ends with an **a** and can have an even number of **b**'s between them

a (bb)* a

Equivalent

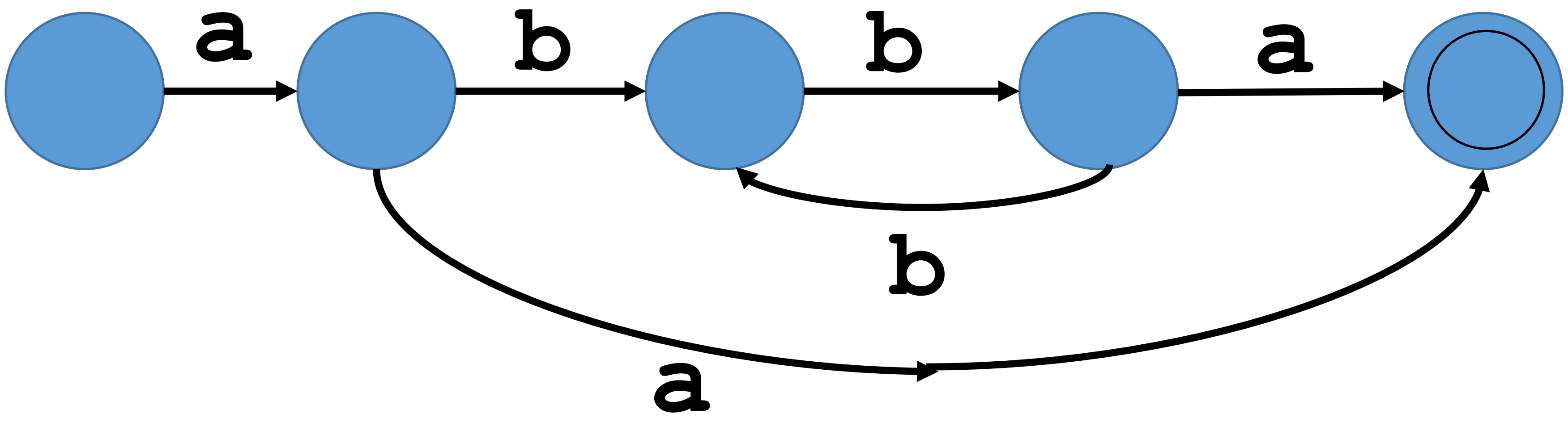
- A FSA and a regular expression can define a regular language
- Regular expressions can be recognized by a regular language

Converting a Regular Expression to a FSA

- Consider the regular expression

`a (bb)* a`

- It can be recognized by the FSA



Try it

- Write a regular expression that defines a double number, such as 12.3 or -12.3
- Use **`n`** to represent a numerical digit, 0..9

Possible Solution

- Write a regular expression that defines a double number, such as 12.3 or -12.3
- Use **n** to represent a numerical digit, 0..9

$$-^{0..1}\ \mathbf{n}^{+}\ .\ \mathbf{n}^{*}$$

Degenerate Case

- 123. and .123 are both valid numbers
- A single period is not a valid number
- There must be a digit before or after the decimal point
- A possible solution might be

$$-^{0..1}\ ((\mathbf{n}^{+}\ .\ \mathbf{n}^{*})\ |\ (\mathbf{n}^{*}\ .\ \mathbf{n}^{+}))$$

FSA Limits

- The only “memory” that a FSA has is the current state
- As a FSA inputs symbols, it moves to different states
- A FSA cannot count or compare an arbitrary number of symbols

Push Down Automata

- A PDA has a FSA and a stack memory
- The top of the stack, input symbol and FSA state determine what a PDA will do
- A PDA can:
  - Push a new symbol on the stack
  - Pop the top symbol from the stack
  - Change the FSA state

Push Down Automata Languages

- A Push Down Automata (PDA) can recognize context free grammars
- Almost all modern programming languages are context free grammars
- A PDA can “count” things
- Nobody has developed a programming language more complicated than a context free grammar

Defining a Language

- For a program to be able to recognize a member of a language, you have to be able to accurately and unambiguously define the language
- A regular language can be defined by a regular expression
- A context free language can be defined by a BNF

Backus-Naur Form

- Backus-Naur Form or **BNF** can be used to define Context Free Grammars
- Created by John Backus and Peter Naur. Independently created by Noam Chomsky
- BNF is a **metalanguage**, a language used to describe a language

BNF Fundamentals

- Terminal symbols are tokens or symbols in the language. They come from the lexical scanner
- Nonterminal symbols are “variables” that represent patterns of terminals and nonterminal symbols
- A BNF consists of a set of **productions** or **rules**
- A language description is called a **grammar**

BNF Structure

- Nonterminal symbols are sometimes enclosed in brackets to differentiate them from terminal symbols
- I will use **bold font** for terminal symbols and no brackets
- Productions are of the form:

nonterminal → nonterminals or terminals

- Multiple definitions are separated by | meaning OR

whatever → this | that

BNF to Define a Language

- There must be one nonterminal start symbol which must appear at least once on the left hand side of a rule
- The start symbol defines the language and all other rules follow from it

BNF Example

wloop → **while (** logical **)** stmt

logical → exp relation exp

relation → > | **<** | **==** | **!=**

stmt → *something not defined here*

exp → *something not defined here*

Compiler's Purpose

- A compiler converts program source code into a form that can be executed by the hardware
- A compiler works with the language libraries and the system linker

Stages of a Compiler

- Source preprocessing
- Lexical Analysis (scanning)
- Syntactic Analysis (parsing)
- Semantic Analysis
- Optimization
- Code Generation
- Link to libraries

Source Preprocessing

- In C and C++, preprocessor statements begin with a #
- The preprocessor edits the source code based on the preprocessor statements
- **`#include`** is the same as copying the included file at that point with the editor
- The output of the preprocessor is expanded source code with no # statements
- Old C compilers had a separate preprocessor program

Lexical Analysis

- Lexical Analysis or scanning reads the source code (or expanded source code)
- It removes all comments and white space
- The output of the scanner is a stream of tokens
- Tokens can be words, symbols or character strings
- A scanner can be a finite state automata

Syntactic Analysis

- Syntactic Analysis or parsing reads the stream of tokens created by the scanner
- It checks that the language syntax is correct
- The output of the Syntactic Analyzer is a parse tree
- The parser can be implemented by a context free grammar stack machine

Semantic Analysis

- The Semantic Analysis inputs the parse tree from the parser
- Semantic Analysis checks that the operations are valid for the given operands *(i.e. cannot divide a String)*
- This stage determines what the program is to do
- The output of the Semantic Analysis is an intermediate code. This is similar to assembler language, but may include higher level operations

Optimization

- Most compilers will attempt to optimize the intermediate code
- Some compilers will also optimize after code generation
- There are many optimizations possible such as moving computations out of loops, avoiding redundant loads and stores, efficient use of registers, etc.

Code Generation

- The Code Generator inputs the intermediate language and outputs machine language for the target machine
- The code generator is specific to the machine architecture

Linking and Loading

- While not truly part of the compiler, the libraries provide the functionality that is more than just a few machine language statements
- The linker reads the object files and outputs and executable file

Simple Program

```
/*  This is an example program */
A = Boy + Cat + Dog;
```

After Lexical Scan

A

=

Boy

+

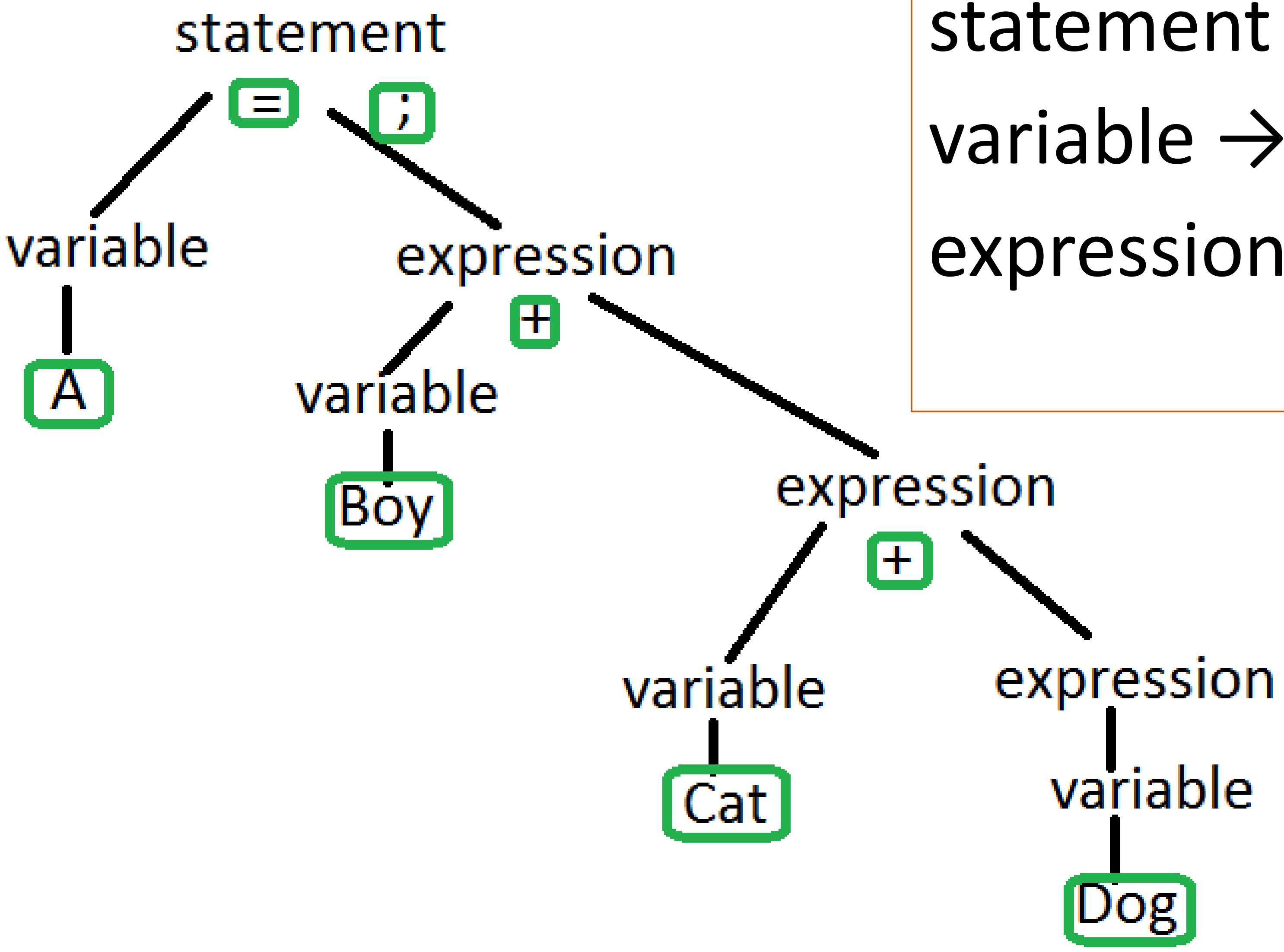
Cat

+

Dog

;

Parsing



statement → variable = expression ;

variable → *string of characters*

expression → variable + expression

| variable

Semantic Analysis

- Semantic analysis will check
- Intermediate code defines a series of simple steps that will execute the program
- Example shown as text instead of an internal format

Temp1 = B + C

Temp2 = Temp1 + D

A = Temp2

Simple Machine Language

- Load register with B
- Add C to register
- Store register in Temp1
- Load register with Temp1
- Add D to register
- Store register in Temp2
- Load register with Temp2
- Store register in A

Optimized Machine Language

- Load register with B
- Add C to register
- Store register in Temp1
- Load register with Temp1
- Add D to register
- Store register in Temp2
- Load register with Temp2
- Store register in A

Symbol Table

- Many stages of a compiler create and reference a symbol table
- The symbol table keeps a list of all of the names used in the program along with information about the name
- To assist debugging, the symbol table can be written into the output object file. This tells debuggers where variables are located

Reading

Read sections 2.1 – 3.2 in the textbook