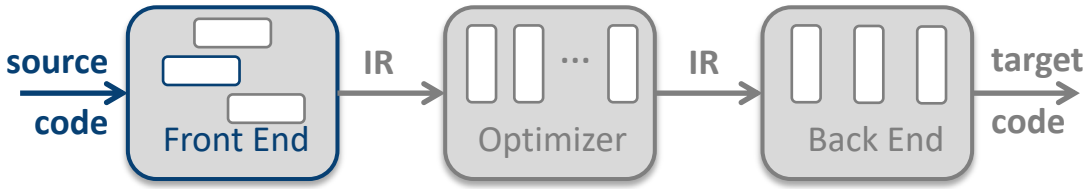
COMP 412
FALL 2018

Building a Scanner

(*from a lab 1 perspective*)

Comp 412



Chapter 1 & 2 in EaC2e

Lab 1

In Lab 1, you will build a front end for ILOC

- Handout and software will be online this afternoon
  - Handout at the course web site under "programming exercises"
  - Software is on **CLEAR** under `~comp412/students/lab1`
  - See also the **ILOC VM** tutorial under "additional materials on Lectures page
- For each lab, we provide an *execute-only* reference implementation
  - Shows you how we expect the lab to behave
  - Lets you discover the answers to some of your questions

Notable Points:

- See discussion in lab 1 handout on Honor Code Policy
  - Your labs must consist of code that you wrote
  - You may discuss anything with other COMP 412 students
  - You may collaborate on shell scripts and makefiles, but not on the code
- See remarks in lecture 1 on programming language choice

Example: Lab 1

ILOC was discussed in Chapter 1 of EaC2e, as well in Appendix A. You should have read Chapter 1 already.

In Lab 1, the input is written in a subset of ILOC

Syntax			Meaning	Latency
load	r_1	=> r_2	$r_2 \leftarrow MEM(r_1)$	3
store	r_1	=> r_2	$MEM(r_2) \leftarrow r1$	3
loadI	x	=> r_2	$r_2 \leftarrow x$	1
add	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 + r_2$	1
sub	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 - r_2$	1
mult	r_1, r_2	=> r_3	$r_3 \leftarrow r1 * r_2$	1
lshift	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 << r_2$	1
rshift	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 >> r_2$	1
output	x		prints MEM(x) to stdout	1
nop			idles for one cycle	1

ILOC is an abstract assembly language for a simple RISC processor. We will use it at times as an **IR** and at other times as a target language.

For more details **ILOC**, see the lab handout, the **ILOC** tutorial document on the web site, and Appendix A in EaC2e. (**ILOC** appears throughout the book.)

Note that **ILOC** is case sensitive. The 'I' in "loadI" must be an uppercase letter and the others must be lowercase letters.

'x' represents a non-negative integer constant.

The same **ILOC** subset (syntax & meaning) will be used in Labs 2 & 3, with different. You should plan to reuse your **ILOC** front end in Labs 2 & 3.

Lab 1

In Lab 1, you will build a FRONT END that reads ILOC.

It will need to

(1) read in a file of **ILOC** operations,

(2) check them for validity, and

(3) convert them into some internal representation.

In Lab 1, you will construct a hand-coded scanner and a simple hand-coded parser.

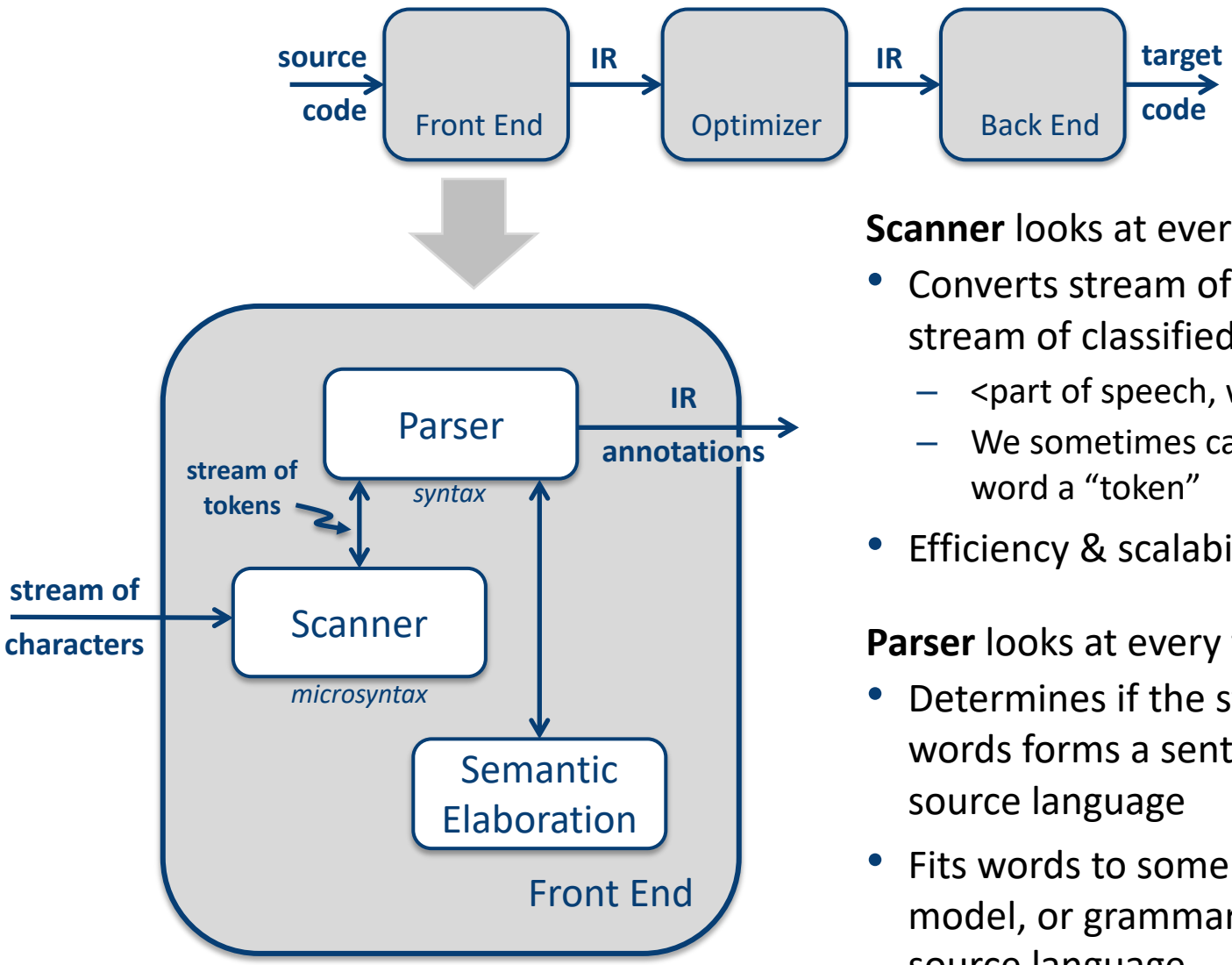
Today's lecture focuses on the scanner.

Lectures 2 & 3, together, provide a quick tour of a compiler's front end, without the theory.

Do not worry.

You will see the theory over the next three weeks. (EaC2e, Chapters 2 & 3).

The Front End



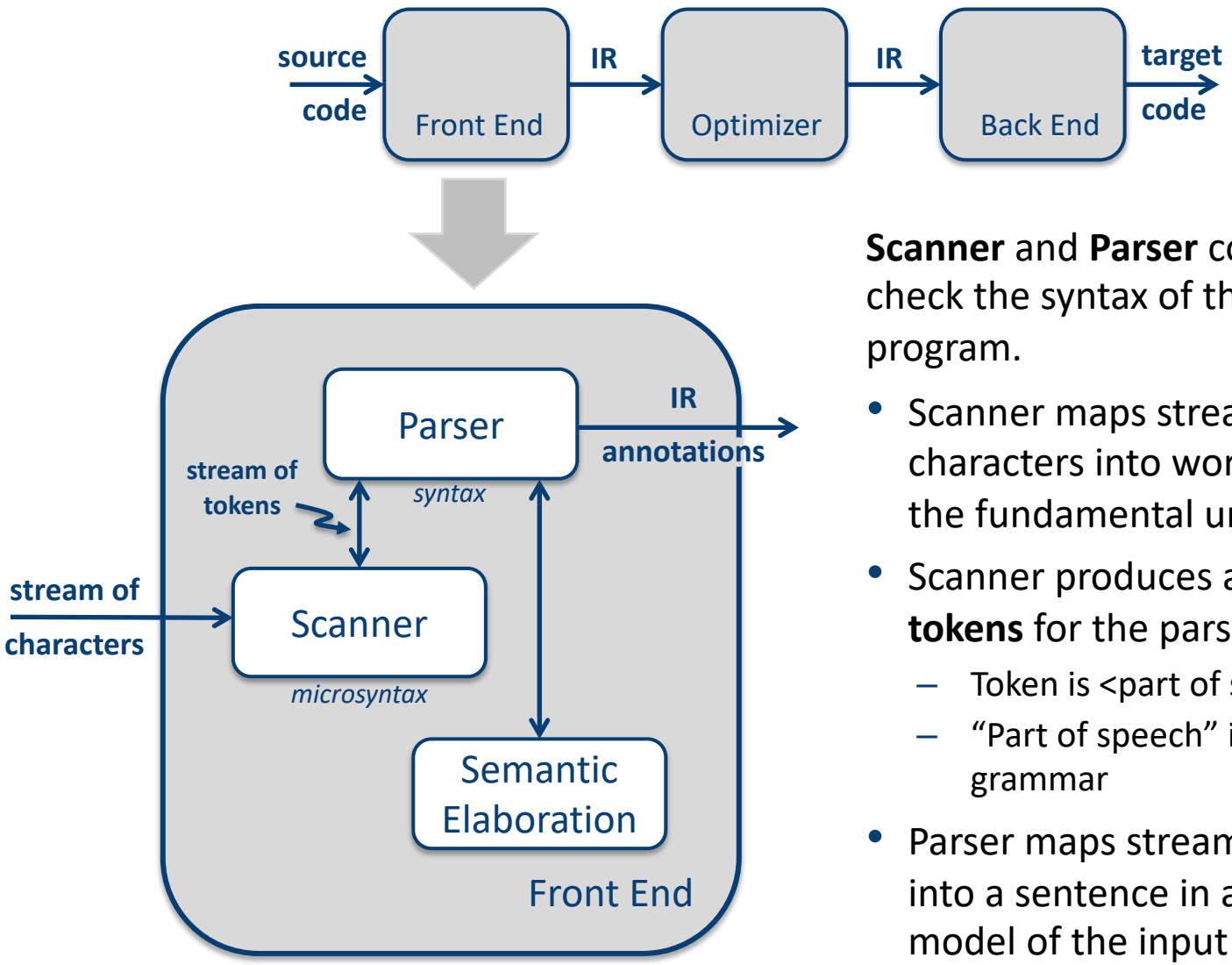
Scanner looks at every character

- Converts stream of chars to stream of classified words:
  - <part of speech, word>
  - We sometimes call a classified word a "token"
- Efficiency & scalability matter

Parser looks at every token

- Determines if the stream of words forms a sentence in the source language
- Fits words to some syntactic model, or grammar, for the source language

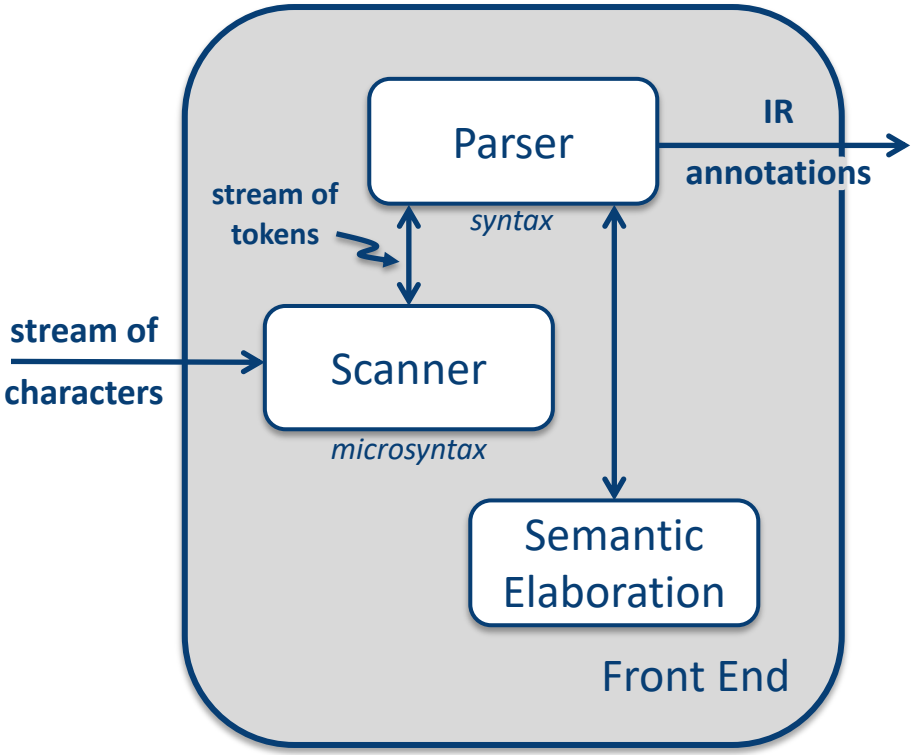
The Front End



Scanner and **Parser** collaborate to check the syntax of the input program.

- Scanner maps stream of characters into words (words are the fundamental unit of syntax)
- Scanner produces a stream of **tokens** for the parser
  - Token is <part of speech, word>
  - "Part of speech" is a unit in the grammar
- Parser maps stream of **tokens** into a sentence in a grammatical model of the input language

The Front End



Parser controls the process.

- Parser has a set of grammar rules that define the source language & guide its recognition
- Parser invokes scanner to get tokens as needed
- Parser invokes Semantic Elaboration to perform analysis that is deeper than syntax
  - *e.g.*, build an **IR**, lay out storage, check types, or compute

Scanner operates incrementally

- Batch scanner would require an unbounded buffer (*doesn't scale*[†])
- Scanner may need to look beyond end of current word

[†] One of the lab 1 test codes has 128,000 lines of input.

The Scanner / Parser Interface

The scanner has a simple interface

- Call to the scanner returns the next classified word
  - A <*part of speech*, *lexeme*> pair, where the *lexeme* can be explicit or implicit
- In these labs, the scanner can discard comments

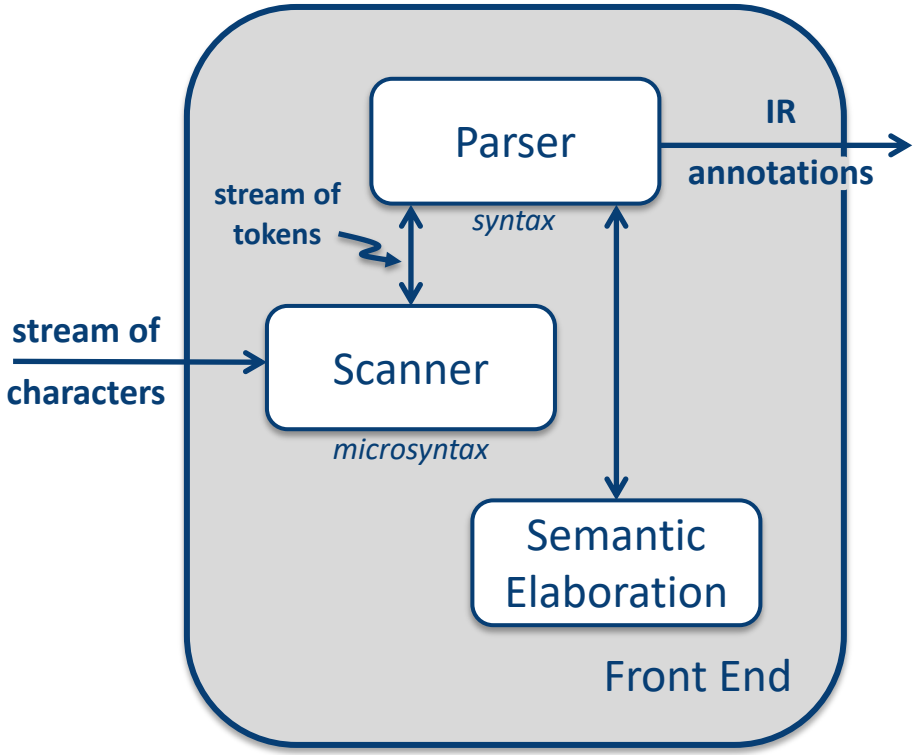
Efficiency in handling strings

- Strings are big, ugly, awkward, and slow (*See § 7, EaC2e*)
  - Require space proportional to their length
  - Comparisons require (worst case) **O**(string length) comparisons
- Integers are compact and fast
  - Space is constant, comparisons are simple & supported by the hardware

When possible, scanners should convert strings to integers

- Manipulate the integers, limit use of the string to printed output
- Implies an efficient map from integer to string

The Front End



Before we can build either a scanner or a parser, we need a definition of the input language.

- Definition must be formal — that is, mathematically well formed
- Definition must be operational — that is, it must lead to a piece of software that recognizes both valid & invalid inputs

Given the division of labor between scanner & parser, we want a similar split in the definition

- *Microsyntax* or *lexical structure* specifies valid spelling for each part of speech
- *Syntax* or *grammar* specifies how parts of speech fit together to form sentences

This structure explains one of the key differences between a ***programming*** language and a ***natural*** language. In a programming language, each word maps to exactly one part of speech. In a natural language, a word can have multiple parts of speech.

Example: Lab 1

ILOC was discussed in Chapter 1 of EaC2e, as well in Appendix A. You should have read Chapter 1 already.

In Lab 1, the input is written in a subset of ILOC

Syntax			Meaning	Latency
load	r_1	=> r_2	$r_2 \leftarrow MEM(r_1)$	3
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loadI	x	=> r_2	$r_2 \leftarrow c$	1
add	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 + r_2$	1
sub	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 - r_2$	1
mult	r_1, r_2	=> r_3	$r_3 \leftarrow r1 * r_2$	1
lshift	r_1, r_2	=> r_3	$r_3 \leftarrow r_1 << r_2$	1
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ILOC is an abstract assembly language for a simple RISC processor. We will use it at times as an **IR** and at other times as a target language.

For details on Lab 1 **ILOC**, see the lab handout, the **ILOC** simulator document and Appendix A in EaC2e. (**ILOC** appears throughout the book.)

Note that **ILOC** is case sensitive. The 'I' in "loadI" must be an uppercase letter and the others must be lowercase letters.

'x' represents a constant.

The same **ILOC** subset (syntax & meaning) will be used in Labs 2 & 3, with different latencies. You should plan to reuse your **ILOC** front end in Lab 3.

The Syntax of Lab 1 **ILOC**

The ILOC-subset operations fit one of five patterns or rules

An operation is	load / store	r_1	=> r_2	**MEMOP**
or	loadI	c	=> r_2	**LOADI**
or	add / sub / mult / lshift / rshift	r_1 , r_2	=> r_3	**ARITHOP**
or	output	c		**OUTPUT**
or	nop			**NOP**

- Scanner must recognize words & assign parts of speech or categories
- Parser must discover sentences in the stream of categorized words

The Syntax of Lab 1 **ILOC**

Rewriting the rules in a more standard notation

operation	→	**MEMOP**	**REG**	**INTO REG**
	|	**LOADI**	**CONSTANT**	**INTO REG**
	|	**ARITHOP**	**REG COMMA REG**	**INTO REG**
	|	**OUTPUT**	**CONSTANT**	
	|	**NOP**		
block	→	*block operation*		
	|	*operation*		

Where

- *Italics* indicates a syntactic variable
- '→' means "derives"
- '|' means "also derives"
- **All CAPITALS** indicate a category of word (*e.g.*, **INTO** contains one word, "=>")
- Categories may contain > 1 word

These rules form a ***grammar***. See the digression on page 87 in EaC2e titled "Backus-Naur Form".

The Microsyntax of **ILOC**

Microsyntax is just the spelling of the words in the language

Category	Specific Words
MEMOP	load, store
LOADI	loadI
ARITHOP	add, sub, mult, lshift, rshift
OUTPUT	output
NOP	nop
CONSTANT	A non-negative, base 10 number
REGISTER	'r' followed by a non-negative, base 10 number
COMMA	','
INTO	"=>"

- Categories are dictated by the needs of the grammar
- Scanner finds words and determines their categories (*or "token type"*)

For simplicity's sake, assign a small integer to each of these categories (e.g., 0 to 8). Then you can use an array of strings, statically initialized, to efficiently convert the integer to a string for debugging or final output.

Do **not** use a map or a dictionary. The array reference is a couple of instructions. The overhead on the function call is more like 30 or 40 instructions, before the real work of computing a hash and looking up the value in the table. (See § B.4 in EaC2e)

Scanning Lab 1 **ILOC**

How do we write a scanner for these syntactic categories?

- All of your training, to date, tells you to call some support routine
  - fscanf() in C, the Scanner class in Java, the extract operator (>>) in C++, a regex library in Python (or Java, or C++), …
- **COMP 412** is about *implementing* languages, so in **COMP 412**, you **WILL** (that means you **MUST**) use *character-by-character* input
  - Character-by-character algorithms have clarity & they expose complexity

You may not use a regular expression library or built-in facility.*

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  - Character-by-character algorithms have clarity & they expose complexity

You may not use a regular expression library or built-in facility.

If you want to use regex, implement the regex routines yourself.

→ **COMP 412 is about implementation of languages & their runtimes**

→ **In the next two weeks, you will learn enough to build a great regex library**

You can look at the simulator's front end, but you cannot reuse it

→ **In fact, it uses flex and bison, which are not allowed in this lab**

Scanning Lab 1 **ILOC**

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  - Character-by-character algorithms have clarity & they expose complexity

Let's look at an easy one.
How do we recognize a "**NOP**"?

- The spelling is 'n' followed by 'o' followed by 'p'
- The code is as simple as the description
  - Cost is **O**(1) per character
  - Asymptotically optimal

```
c ← next character
If c = 'n' then {
   c ← next character
   if c = 'o' then {
      c ← next character
      if c = 'p'
           then return <NOP,"nop">
           else report error
      }
      else report error
   }
   else report error
```

Scanning Lab 1 **ILOC**

We can represent this recognizer as an automaton

```
c ← next character
If c = 'n' then {
   c ← next character
   if c = 'o' then {
      c ← next character
      if c = 'p'
          then return <NOP,"nop">
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```
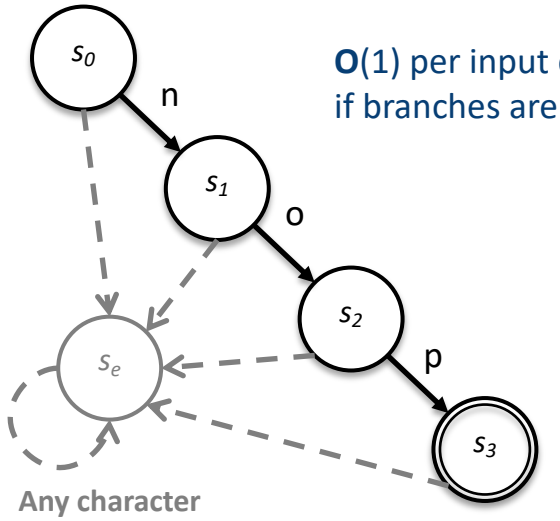



O(1) per input character, if branches are **O**(1)

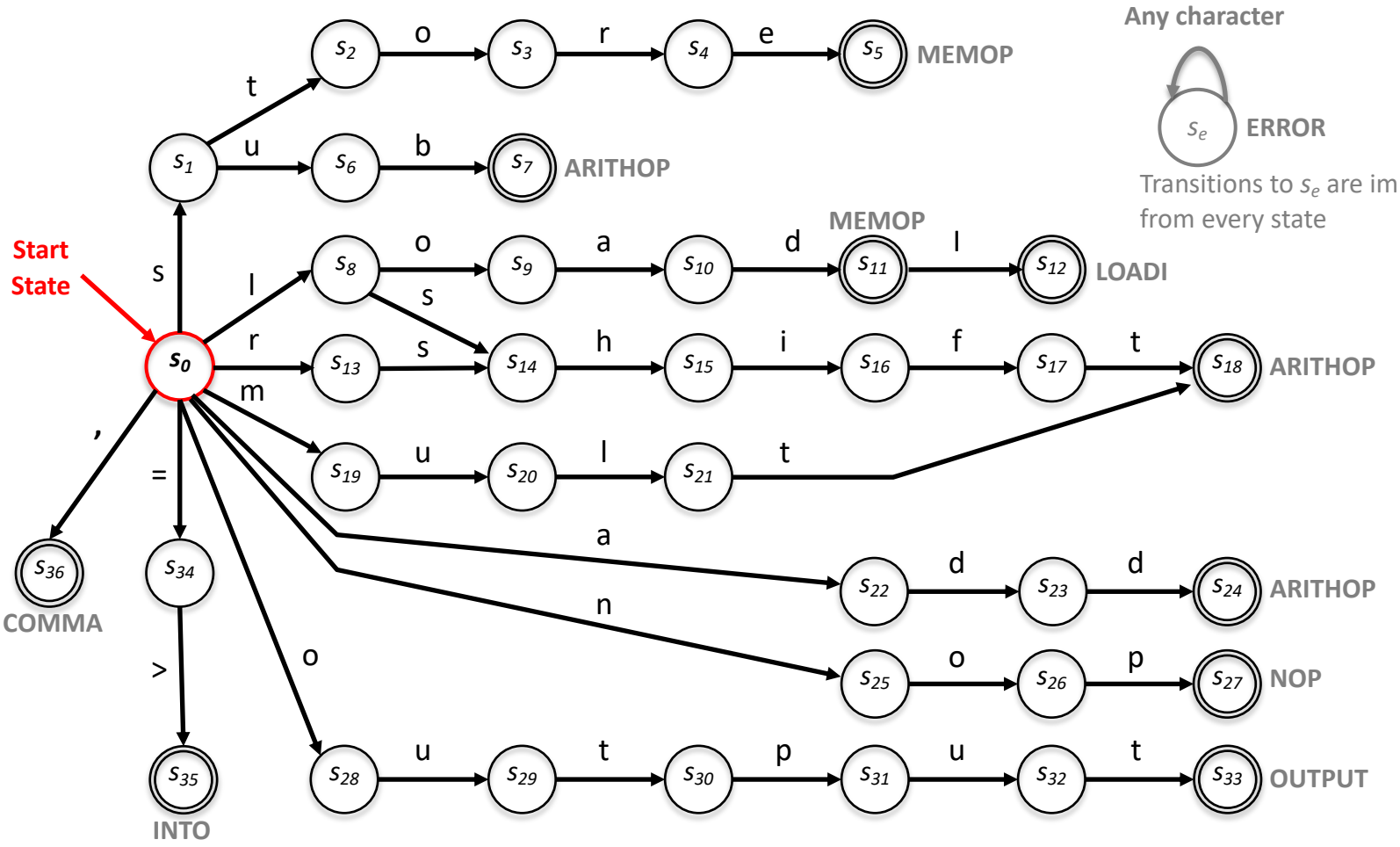
Transition Diagram for "nop"

- Execution begins in the start state, s_0
- On an input of 'n', it follows the edge labeled 'n', and so on, …
- Implicit transition to an error state, s_e, on any unexpected character
- Halts when it is out of input
- States drawn with double lines indicate success (a "final" state)

See § 2.2 in EaC2e

Scanning Lab 1 **ILOC**

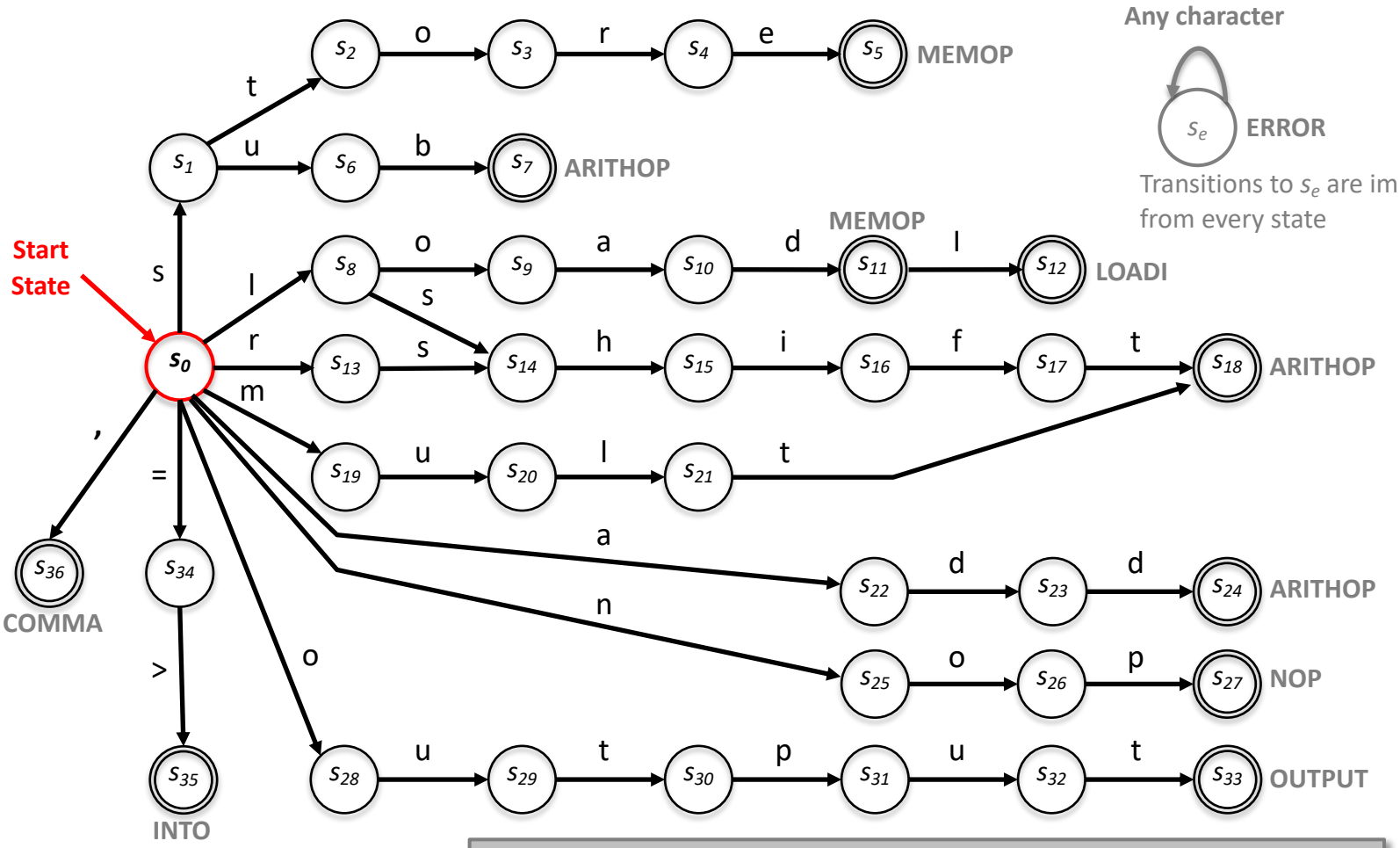
Recognizing the rest of the finite categories is (relatively) easy



Still O(1) per input character

Scanning Lab 1 **ILOC**

Recognizing the rest of the finite categories is (relatively) easy



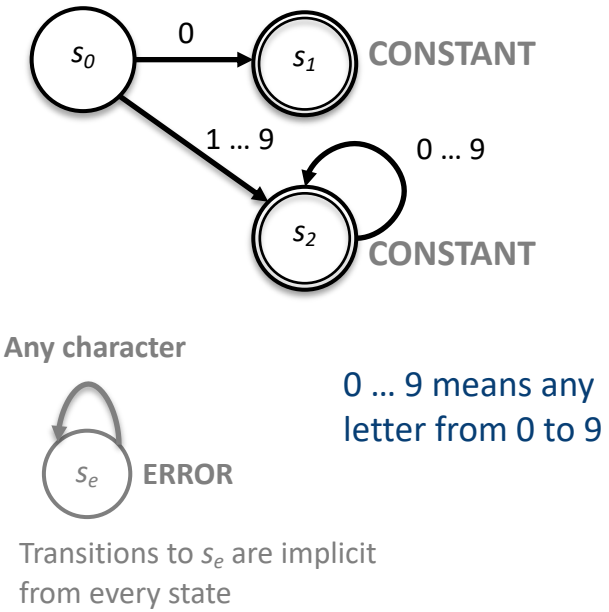
§ 2.5 in EaC2e discusses how to convert a transition diagram into code. The reference implementation uses a table-driven scanner.

Scanning Lab 1 **ILOC**

Recognizing the unbounded categories is conceptually harder

Consider unsigned integers — a **CONSTANT** in Lab 1 **ILOC**

```
c ← next character
n ← 0
if c = '0'
   then return <n,CONSTANT>
   else if ('1' ≤ c ≤ '9') then {
      n ← atoi(c)
      c ← next character
      while ('0' ≤ c ≤ '9') {
        t ← atoi(c)
        n ← n * 10 + t
      }
      return <n,CONSTANT>
   }
   else report error
```

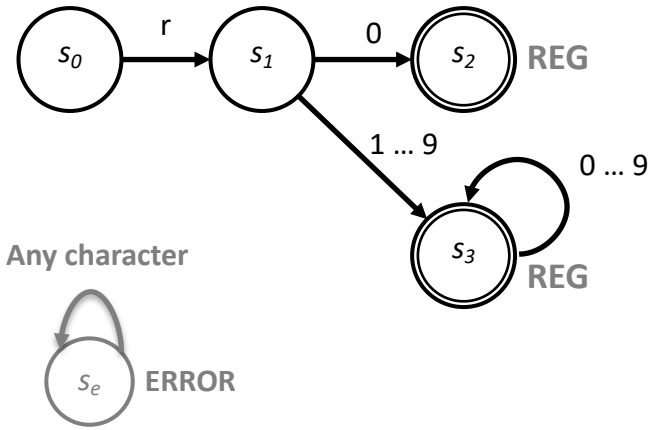


- Recognizes a valid unsigned integer of arbitrary magnitude
- Cycle in transition diagram admits an unbounded set of numbers

Unsigned integers are an infinite, but *recursively enumerable* set.

Scanning Lab 1 **ILOC**

REG follows from CONSTANT



Transitions to s_e are implicit from every state

This particular recognizer allows r01, r02, and so on. The recognizer for integer constants on the previous slide did not allow leading zeroes.

Registers are simple

- 'r' followed by an unsigned integer
- We concatenate a recognizer for 'r' onto the front of the one for unsigned integer
- Resulting recognizer is **still O**(1) cost per character, with very low constant overhead (if done well)

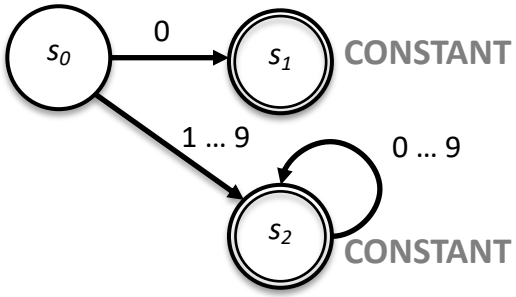
We can add the recognizers for **REG** and **CONSTANT** to the recognizer on slide 12 by combining the start states & merging the edges for 'r'.

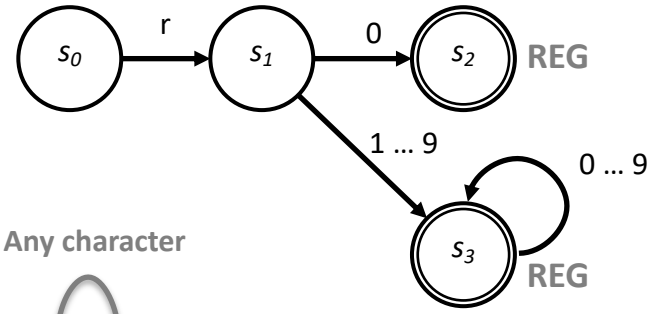
One recognizer gets all the words in Lab 1, at **O**(1) cost per letter.

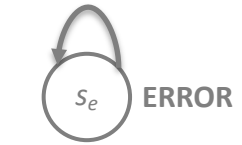
Scanning Lab 1 **ILOC**

In lab 1, you should allow leading zeroes in register names. You may allow them in constants.

These DFAs do not allow leading zeroes

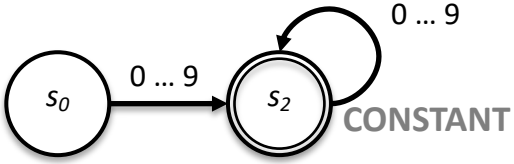


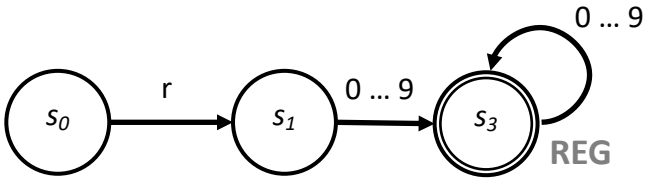


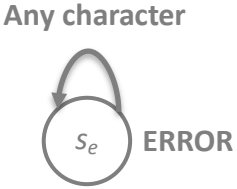


Transitions to s_e are implicit from every state

DFAs that allow leading zeroes are simpler and smaller





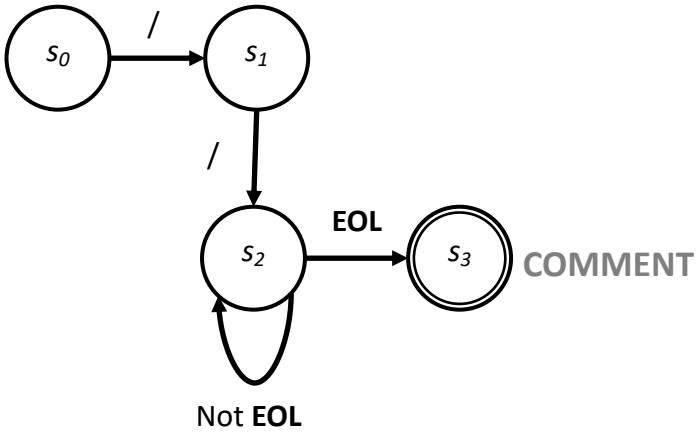


Transitions to s_e are implicit from every state

Either way, the cost is **O**(1) per character

Scanning Lab 1 **ILOC**

Comments are easy to handle



- A comment begins with "//" and includes any character up to the "end of line" sequence
  - Windows uses "\r\n"
  - Linux & MacOS use '\n'
- Your code will be **graded** on a Linux system, so you need to get the **EOL** thing right
- Comment handler should invoke the scanner, recursively, from s_3

Differences in **EOL** trip up even the most experienced developers. For example, do not try to write a shell script on a Windows machine & copy it to clear.

The error messages from the shell will be less than helpful.

Scanning Lab 1 **ILOC**

This seems pretty simple. How do real compilers scan their input?

- The approach used in the previous slides is built on the theory of regular languages and their relationship to deterministic finite automata (**DFA**).
  - Deep theoretical foundations (**COMP 481**)
  - General techniques
- Automata based scanners have been used in industry and research since the 1960s
  - Same techniques form the basis for "*regular expression*" search in editors, wildcard matching in shells, and regex libraries in programming languages
  - Pervasive technology

Next week, we will see how to construct **DFA**s automatically from specifications written as regular expressions.

Tools such as **lex**, **flex**, and the regular expression libraries common in programming languages are based on these techniques.

For Lab 1, merge the transition diagrams on 17,18, 19, & 21, then implement with one of the schemes in § 2.5.