SI 413, Unit 4: Scanning and Parsing

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1 Syntax & Semantics

Readings for this section: PLP, Section 2.1

In this unit, we are going to start looking at how compilers and interpreters work. Recall the main stages of compilation (this is a review from unit 1!):

1) Scanning: Turning source code into a token stream. This stage removes white space and comments, and identifies what kind of token each piece of the code is.
2) Parsing: Turning a token stream into a parse tree. This stage checks that the sequence of tokens is grammatically correct and can be grouped together according to the specifications of how the language works.
3) Semantic analysis: Turning a parse tree into an abstract syntax tree. This stage cuts out any unnecessary or redundant information from the parse tree to form a concise representation of what the program means (i.e., the AST).
4) Code generation: Turning that AST into executable machine code.

As you might of guessed, this unit is about steps (1) and (2), scanning and parsing. These are the compilation stages that focus on the *syntax* of the language, i.e., the way the program is allowed to look. Later we will focus more on *semantics*, i.e., what the program actually means and is supposed to be doing.

In class, we looked at some examples of English sentences that were syntactically or semantically valid/invalid. Hopefully you are starting to get a good feel for what syntax and semantics are. This might also be a good time to go back and review the problem from Homework 1 on syntax errors and semantics errors.

1.1 Programming Language Specification

A computer program is a way of communicating something to the computer. In particular, the program is telling the computer what to do; it's communicating an algorithm. The *programming language* is the medium or vehicle for that communication; it specifies a way to communicate algorithms.

Now we're thinking about compilers and interpreters, and we have this same problem at the next level. How do we communicate what a programming language is? If we can specify programming languages in some well-defined way, then we can more easily write compilers and interpreters for new programming languages.

As it turns out, the *syntax* of programming languages is relatively easy to specify. This is because scanners and parsers (the parts of a compiler that identify syntax) correspond exactly to the kinds of simple machines you learned about in Theory class:

- The tokens for a language are specified with *regular expressions*. These can be used to create a scanner, which is implemented as a finite automaton (FA).
- The rules for how tokens can come together are specified with *context-free grammars* (CFGs). These can be used to create a parser, which is implemented as a push-down automaton (PDA).

So now you see, all that stuff you learned about in SI 340 wasn't just for the incredible joy of proving interesting things about computation; those things actually exist inside every compiler and interpreter you've

ever used!

1.2 Some tactical syntactical considerations

In Theory class, you wrote regular expressions and grammars to carefully define a language. The concerns there were mostly about mathematical *correctness*, that is, does your regular expression or CFG actually define the correct strings that are in this language.

But now we're using these as tools to write compilers, so there are more concerns. For one, we want our compilers to be fast. This will affect some of our choices in how to write the regular expressions and grammars for our language, as we will see.

Another concern is how the information generated by one stage of compilation affects the next stage. For example, consider a simple calculator language with numbers and plus/minus/times/divides. We could specify the tokens as:

OP = "+"|"−"|"∗"|"/" NUM = ("−"|)[0−9]+ STOP = ";"

and the grammar as:

$S \rightarrow$ *exp* STOP *exp* $\rightarrow$ *exp* OP *exp* | NUM

This correctly defines the language we want. Any valid calculator program matches this specification. But this is a *really bad* way to specify this grammar, for at least two reasons. First, the grammar is *ambiguous*, meaning that we could get two different parse trees for the same program. For example, if we try to parse $5 + 3 * 2$; with this grammar, it could group the $5 + 3$ part together as a single *exp*, or the $3 * 2$ part. This will ultimately affect the semantics of the language - since one way of parsing will probably end up with 16 being computed, while the other way will end up with 11! This grammar is also bad for another reason, which has to do with the way parsers are implemented. More on that later...

2 Scanning

Readings for this section: PLP, Section 2.2.

A better syntax for the simple calculator language is as follows. The terminals will be:

OPA = [+−] OPM = [∗/] NUM = ("−"|)[0−9]+ LP = "(" RP = ")" STOP = ";"

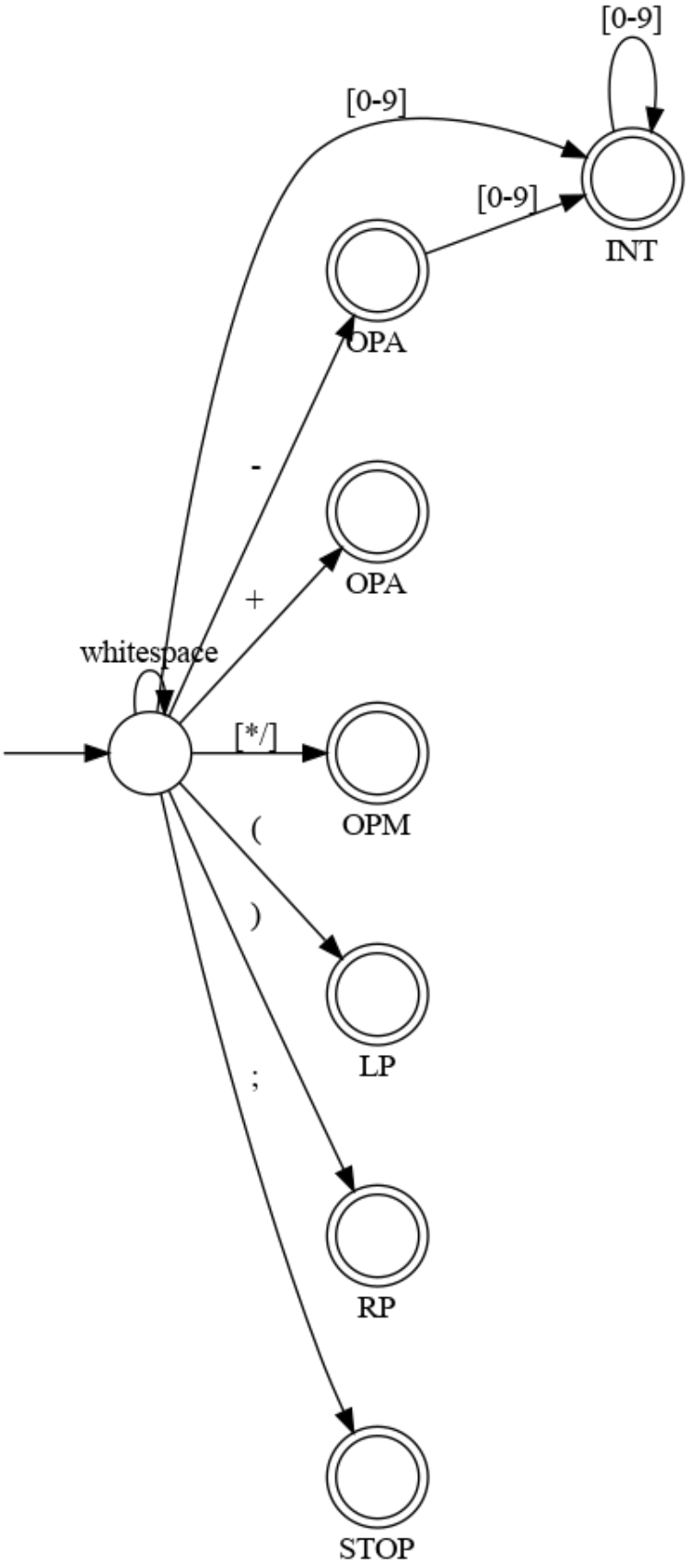
And the grammar is:

$S \rightarrow$ *exp* STOP *exp* $\rightarrow$ *exp* OPA *term* | *term* *term* $\rightarrow$ *term* OPM *factor* | *factor* *factor* $\rightarrow$ NUM | LP *exp* RP

See what we did? By splitting the operations according to their *precedence*, we will get an unambiguous grammar that corresponds to the ultimate meaning (semantics) of the language.

2.1 Scanner DFAs

Here is a DFA for the tokens in the language above:


[0-9]
[0-9]
[0-9]
INT
OPA
-
OPA
+
whitespace
[*/]
OPM
(
)
LP
;
RP
STOP

Well, it's *almost* a proper DFA. What's missing is a single "trap state" that is not accepting and which has a transition from every other state on every non-listed token. We won't draw the trap state with our scanner DFAs because it just makes the picture too messy.

Basically, we have a normal DFA, but each of the final (accepting) states is labeled with the type of that token. There will definitely be at least one final state for each token type in the list, but there can also be more than one final state for the same token type. In this example, notice that the OPA type has two accepting states. That's because the − character has to be treated specially: it can be the start of a number, or it can be a minus operator by itself.

Recall from your CS Theory class that every DFA defines a *language*, the set of strings accepted by the DFA. In this case, the language defined by our scanner DFA consists of all valid tokens of any type. The only extra part is the labelling of the accepting states, which tells you the type of each token.

This is all well and good for doing what a DFA does - determining whether a single string is in the language. But when we're writing a compiler, we have to scan the *entire source code* into tokens. The big question is, how do we know when to stop scanning this token and move on to the next token?

For example, consider the code fragment $123*-54$. Obviously we want this to be a NUM (123), then an OPM ($*$), then another NUM (-54). But what's to stop us from having two INTs before the OPM, say 12 and 3? Or treating the − as an OPA instead of part of the last NUM?

2.2 Maximal munch

Scanners resolve these questions systematically by using a rule with a memorable name:

> **Maximal munch rule**: Each token is made to contain as many characters as possible at the given starting position in the source code.

To implement this rule, you could imagine taking *all* possible prefixes of your source code, running them through the scanner DFA, and then returning the longest match as the first token. Then move past that token and repeat.

But that would be very slow! Even being clever about how all the prefixes are scanned, it would take $O(n)$ steps for each token, which in the worst case of all length-1 tokens would mean $O(n^2)$ total. Anything more than linear time is simply unacceptable if we hope to compile large programs quickly.

2.3 Scanner peeking

For many token sets — probably for every programming language you've ever used — it is possible to implement maximal munch scanning in $O(n)$ time, because of the following property:

- There never exist three strings a, b, c such that:
  1) a is a valid token
  2) ab is *not* a valid token
  3) abc is a valid token

So for example, in a language where = and === are both valid tokens, then the "intermediate" token == **must** also be valid. (In fact, these three tokens are all valid operators in some languages such as PHP. In other languages such as C++, all operators are only 1 or two characters, and every length-2 operator starts with a length-1 operator, which ensures this rule will be met.)

In terms of the DFA, given this condition we can implement maximal munch by scanning each token *until the next character would transition from an accepting to a non-accepting state.* Applying this rule makes scanners very efficient (since they just have to peek ahead to the next character), but also powerful enough to handle pretty much every programming language you could think of.

Does it mean there are some ways of defining a programming language that just won't work anymore? Unfortunately, yes. But programming language designers are more than happy to make this sacrifice to get

the speed and efficiency of DFAs.

2.4 Automatic Scanner Generation

Lots of people want to write Scanners (often called Lexers) for their language projects, and so there are a number of tools available that can take a list of regular expressions and token names, and automatically generate code for the lexer. flex is a standard UNIX/Linux utility to create lexers in C. In this class we will use ANTLR which automatically generates lexers in Java.

So far we have seen some examples creating DFAs by hand for simple scanners. But how does this process work in general? Here's an overview of the steps involved:

1. Turn each regular expression into an NDFA. You saw how this works in your CS Theory class.
2. Mark each accepting state of each NDFA with the name of that token.
3. Combine all those NDFAs into a single big NDFA using the "or" operation, like you learned in Theory class. What this means is that we will make a new start state, and empty-string ε-transitions from that new start state to each of the old start states.
4. Turn this big NDFA into a DFA, using the subset construction algorithm you learned in Theory class. Now there is a potential problem, if one of the accepting states in the DFA matches more than one token. In automatic tools like ANTLR, this issue is resolved by giving precedence to *whichever token is defined first.*
5. Finally, the DFA is minimized using various neat tricks, to make the scanner run as fast as possible.

We looked at some examples of this process in class. See the textbook for more details and examples.

2.5 Example code

The example code for this unit shows how to make scanners and parsers for the simple calculator language we are using. I strongly recommend downloading the tarball, extracting it, and actually running make to compile it and test it out.

Understanding the code in the example code will greatly help you on the next series of labs.

As far as scanners go, there are three implementations of a scanner for the Calc language in that code. Note that I used the term "Lexer" instead of "Scanner" in naming these classes; they mean the same thing.

- DFACalcLexer.java: An implementation of the DFA above for matching tokens.
- RegexCalcLexer.java: Another scanner that uses Java's built-in regular expressions to define each token and match them according to the maximal munch rule. This will be less efficient than the DFA version, but much easier to write.
- ACalcLexer.g4: A file in ANTLR syntax which can be used to automatically generate an efficient scanner for the Calc language. That will have all the speed of the DFA version and all the clarity of the Regex version, by using this powerful tool to do the code generation for us.

To try out these scanners yourself:

- Download the tarball u04−code.tar.gz to your favorite Linux environment
- Extract it by running , which will create a u04−code directory with all the source code
- Download ANTLR and compile the code by going into that directory and then running make
- Run any of these commands to get a program that reads input from standard in and uses the relevant scanner implementation to tokenize it. (If running directly on the command line, you just type your input and then hit Ctrl-D for EOF to end it.)

Here are some small example runs:

3 Parsing

Readings for this section: PLP, Sections 2.3 and 2.4.

Parsing is the process of turning a stream of tokens into a parse tree, according to the rules of some grammar. This is the second, and more significant, part of syntax analysis (after scanning).

We are going to see how to write grammars to describe programming languages. You already did this a bunch in Theory class. But in this class, the concern is deeper: we not only need the grammar to properly define the language in a strict mathematical sense; it also needs to *make the parser be fast.*

How fast? Well, scanning is going to be linear-time; just take one transition for every character in the input. We want our parsers to work in linear-time in the size of the input as well. This is important: if your code gets 10 times as long, you're OK if it takes 10 times as long to compile. But if it suddenly takes 1000 times longer to compile, that's going to be a problem! In fact, that's what the case would be if we allowed any old grammar for our languages; the fastest algorithms for parsing any language have complexity $O(n^3)$).

What this means is, we have to talk about parsers and grammars together. The grammar determines how fast the parser can go, and the choice of parser also affects what kind of grammar we will write!

Parsers are classified into two general categories, and we will look at both kinds in some detail. Here's a quick overview.

Top-down parsers construct the parse tree by starting at the root (the start symbol). The basic algorithm for top-down parsing is:

1) If the first unfinished part of the tree is a token (terminal symbol), *match* it against the next token of input, and discard that token (cross it off and move on).
2) Otherwise, the first unfinished part of the tree is a nonterminal symbol. By peeking ahead at the next unmatched token of input, figure out which right-hand-side production of that nonterminal to take, and expand the tree accordingly.
3) Repeat (1) and (2) until the tree is complete, or we run out of tokens, or another error occurs.

The big question that top-down parsers have to answer is on step (2): *which right-hand side do we take?* This is why top-down parsers are also called *predictive parsers*; they have to predict what is coming next, every time they see a non-terminal symbol.

Top-down parsers work well with a kind of grammar called LL. In fact, sometimes top-down parsers are called LL parsers. We'll mostly focus on a special case called LL(1) grammars, which will be defined in the next section.

Bottom-up parsers construct the parse tree by starting at the leaves of the tree (the tokens), and building up the higher constructs (the non-terminals), until the leaves all form together into a single parse tree. The basic bottom-up parsing algorithm is:

1) If *any suffix* of the current string of non-terminals and terminals matches a right-hand side of a grammar rule, apply that rule in reverse by "building up" the tree, combining the part of the right-hand side that matched. This is called a *reduce* step.
2) Otherwise, if we can't reduce, add a new leaf into the tree corresponding to the next token of the input. This is called a *shift* step.
3) Repeat (1) and (2) until the tree has been completely formed and is all connected with the start symbol at the top, or until an error occurs.

The big decision for bottom-up parsers is whether to do (1) or (2) every step along the way; that is, whether to shift or to reduce (and how to reduce, if there is more than one option). For this reason, bottom-up parsers are also called *shift-reduce parsers.*

Bottom-up parsers work well with LR grammars, so they're sometimes called LR parsers. We will focus specifically on SLR(0) and SLR(1) grammars, which will be described below.

Generally speaking, bottom-up parsers are a bit more *powerful* because their decisions are delayed until after reading in the relevant tokens; they essentially have more information available than top-down parsers. But the flip side is that bottom-up parsers tend to be more difficult to understand and give worse error messages, since we don't notice a parsing error has occurred until much later (when a reduce becomes impossible).

4 LL Parsers

Readings for this section: PLP, Sections 2.3.1 and 2.3.2.

A grammar is called LL(1) if it can be parsed by a top-down parser that only requires a single token of "look-ahead". Remember that top-down parsers use look-ahead to *predict* which right-hand side of a non-terminal's production rules to take. So with an LL(1) grammar, we can always tell which right-hand side to take just by looking at whatever the next token is.

There are two common issues that make a grammar not be LL(1): common prefixes and left recursion. Fortunately, both these issues have somewhat standard fixes. Let's see what they are.

The following grammar is not LL(1):

$X \rightarrow$ a b $X \rightarrow$ a a

Do you see what the problem is? If we are trying to expand an instance of X in the top-down parse tree, we need to determine which of the two possible rules to apply, based on the next token of look-ahead. But that next token will always be an a, which doesn't give us enough information to distinguish the rules!

The standard fix is to "factor out" the common prefix. First, we make a "tail rule" that has every part of each right-hand side except the common prefix. This should be a new non-terminal in the language, like:

$Y \rightarrow$ b $Y \rightarrow$ a

Here, Y gets the part of each right-hand side from X, but without the common prefix of a. Once we have this tail rule, we can combine all the productions of the original nonterminal into a single rule with the common prefix, followed by the new non-terminal. So the whole grammar becomes:

$X \rightarrow$ a Y $Y \rightarrow$ b $Y \rightarrow$ a

See how that works? It is very important to realize that *the language did not change at all*! The strings that are defined by this grammar are the same as they were before; the only difference is that the grammar itself looks different. In fact, we can see that this new grammar doesn't have any common prefixes, and it is definitely LL(1). Hooray!

I should also point out that this process might have to be repeated more than once in more complicated situations. For example, try to make the following grammar LL(1):

$X \rightarrow$ a a a $X \rightarrow$ a a b $X \rightarrow$ a b b

Left recursion is the other common issue that makes a grammar not be LL(1). By "left recursion", we mean that the non-terminal on the left hand side of a grammar rule is the same as the first non-terminal on the right-hand side. For example, this grammar defines a language that's any string with at least one a:

$X \rightarrow$ a $X \rightarrow X$ a

Do you see what the problem is here? If we are trying to expand an X, the next token will always be an a! In fact, with more complicated kinds of left recursion, it won't be possible to distinguish between the two possible productions with *any* amount of look-ahead. Left recursion is pretty much the worst thing that can happen to a top-down parser!

To get rid of it, we have to reorder things somehow. Usually this means flipping around whichever rule is left-recursive to make it right-recursive instead. In this case it works like this:

$X \rightarrow$ a $X \rightarrow$ a X

Again, it's important to emphasize that *the language has not changed*, only the grammar. But what happened? We got rid of one problem (left recursion), only to get another one (common prefix). But now apply the fix we already know for common prefixes, and the solution emerges:

$X \rightarrow$ a Y $Y \rightarrow$ a Y $Y \rightarrow \varepsilon$

(Recall that in this class, we use ε to denote the empty string. You probably used λ for this in your CS theory class, but in the context of programming languages λ, or lambda, is an anonymous function.)

That's it! Now we have a properly LL(1) grammar for the same language, that will make top-down parsing nice and fast. Here, Y is called a "tail rule", and this kind of thing shows up in LL(1) grammars quite frequently.

4.1 LL(1) grammar for calculator language

Recall the grammar for the simple calculator language from before:

S → *exp* STOP
exp → *exp* OPA *term* | *term*
term → *term* OPM *factor* | *factor*
factor → NUM | LP *exp* RP

This grammar is not LL(1): it has left recursion in the *exp* and *term* nonterminals.

Here's how we can fix it, by reordering and making tail rules to factor out common prefixes:

S → *exp* STOP
exp → *term exptail*
exptail → OPA *term exptail* | ε
term → *factor termtail*
termtail → OPM *factor termtail* | ε
factor → NUM | LP *exp* RP

4.2 PREDICT and FOLLOW sets

As we can see, "looking ahead" at the next token of input is important for getting parsers to work quickly. There are two groups of sets of tokens which are used in these decisions, called PREDICT and FOLLOW. Both kinds of sets also sometimes contain the special token $, which indicates the end-of-file symbol.

Their definitions depend on each other.

> The PREDICT set of any production rule for a nonterminal contains any token which could come first in parsing that nonterminal, or in case of an epsilon production, anything which could come immediately afterwards.

PREDICT sets are used to determine, based on the next token of look-ahead, which rule to apply in a top-down parse.

> The FOLLOW set of any nonterminal consists of all the tokens which might come immediately after that nonterminal in a parse.

FOLLOW sets are used in bottom-up parsing when deciding whether to reduce to that nonterminal at some point during the parse.

In most cases, figuring out the PREDICT and FOLLOW sets is not too difficult to do by hand by looking at the grammar. But because it can be a little tricky in some edge cases, and to make sure you don't miss anything, we can use a program to do this for us.

Luckily for you, your instructor wrote a Scheme program to compute these things! It's in file predfol.scm that you can download yourself and run using racket from the command line.

For example, let's say we wanted to define a grammar for Western names such as "Mr. T", "Margaret Hamilton", or "Rev. Dr. Martin Luther King". Assuming two tokens TITLE (e.g. "Mr.", "Dr.", ...) and NAME ("T", "Margaret", "King", ...), here is a simple grammar for full names:

$S \rightarrow$ *titles names* *titles* $\rightarrow$ TITLE *titles* *titles* $\rightarrow \varepsilon$ *names* $\rightarrow$ NAME *names* *names* $\rightarrow$ NAME

The PREDICT sets for each production rule are:

rule	PREDICT
$S \rightarrow$ *titles names*	TITLE, NAME
titles $\rightarrow$ TITLE *titles*	TITLE
titles $\rightarrow \varepsilon$	NAME
names $\rightarrow$ NAME *names*	NAME
names $\rightarrow$ NAME	NAME

symbol	FOLLOW
S	$
titles	NAME
names	$

Here's how you can run predfol.scm to get this information (blue is output from the program, green is what you type in):

Notice, the PREDICT sets tell us that this grammar is *not* LL(1). To see why, look at the PREDICT sets for each nonterminal. *S* is fine; there is only one production rule. *titles* is also fine, because the two production rules have non-overlapping PREDICT sets. But an LL(1) parser would not be able to expand *names* with one token of look-ahead, since the PREDICT sets for both production rules for *names* are the same. (This could be fixed by factoring out the common prefix with a new non-terminal though!)

4.3 Types of top-down parsers

The full details of how a top-down parser works are detailed in the book, and you'll also see it in lab. Here are the main points:

- *Recursive descent* parsers do top-down parsing by making recursive calls for every non-terminal in the language. Each function has to use the look-ahead token to figure out which right-hand side to apply. This is what hand-written parsers usually look like. They are the simplest kind of parsers and usually give the most helpful error messages.
- *Table-driven* top-down parsers do the same thing as recursive descent parsers, but instead of using recursive calls to keep track of what is going on, they store the currently-expanded nonterminals explicitly in a stack. This is what an auto-generated top-down parser will usually look like.
- Both of these kinds of parsers rely on PREDICT and FOLLOW sets to determine which look-ahead tokens mean to apply which right-hand side. Specifically, the PREDICT set for each grammar production says which tokens could come first when that production appears in the grammar. The look-ahead tokens in a top-down parser are compared against those in the PREDICT sets to see which rule to apply.

5 LR Parsers

Readings for this section: PLP, Section 2.3.3.

Bottom-up parsers are the counterpoint to top-down parsers. They create the parse tree by alternatively adding the next token as a leaf (shifting) or combining some partial parse trees according to a grammar rule

(reducing). The grammars for bottom-up parsers are called LR grammars; the second "R" has to do with the fact that things tend to be grouped from the right instead of from the left.

Just like with top-down parsers, the way a bottom-up parser is actually implemented is with a stack. Now with a top-down parser, each "prediction" step involves popping a *single* nonterminal from the top of the stack, and replacing it with one of its right-hand sides. A bottom-up parser works in the opposite way: a *reduce* in LR parsing involves popping an entire right-hand side off the top of the stack and replacing it with the corresponding nonterminal. The bottom-up parse is complete when the stack consists just of the start symbol and nothing else, and there are no more tokens left on the input stream.

Again, the way we write grammars for LR parsers is influenced by the goal of making parsing faster. For example, consider this grammar for a bunch of NUMs added/subtracted together:

exp → NUM OPA *exp* *exp* → NUM

Now consider the bottom-up parse for a token stream like NUM OPA NUM OPA NUM using this grammar. If you try to parse this bottom-up, it works, but it's not very efficient. That's because *all* of the tokens have to be shifted onto the stack before any reducing can occur. Besides that, the parser also has to constantly look ahead to see if the next token is an OPA or not, to know whether to shift or reduce.

You see, right recursion is great for top-down parsers, but it's not so great for bottom-up parsers. Here's the same language, rewritten to use left recursion instead.

exp → *exp* OPA NUM *exp* → NUM

Now when we parse a string of tokens like NUM OPA NUM OPA NUM with a bottom-up parser using this grammar, it works out great! The stack never has more than three symbols on it, and no look-ahead at all is required.

Here you see two strong indications of why LR parsers are a bit more powerful than LL parsers: First, they can handle both left recursion and right recursion (although left recursion will make them run much more efficiently). Second, they can parse some pretty interesting grammars, like the one above, *without requiring any look-ahead tokens*. Now that's going to be fast!

The greater power of LR parsers is why some automatic parser generation tools - including the standard Linux utility bison - generate bottom-up parsers. It's easier to take a grammar specification and make a reasonably fast LR parser from it. There are disadvantages, however, and they mostly have to do with nice error messages. The problem with LR parsers for compilers is that they try so hard to parse the language, that sometimes they shift everything onto the stack before realizing the parse is never going to work. In such cases, a recursive-descent parser probably would give a much nicer error message, right at the source of the mistake in the code. But as we discussed, the LL(1) grammars required to make recursive-descent parsers work quickly are more restrictive. This is the trade-off that must be made!

5.1 CFSMs

OK, back to LR parsers. How do they work exactly? How are those difficult shift/reduce decisions made, when look-ahead is necessary? Believe it or not, they use a DFA to make these decisions - specifically, the DFA that accepts strings consisting of *valid stack contents* for the parser itself! This is called the Characteristic Finite State Machine (CFSM) for the parser. We'll outline the main steps of creating a CFSM, using the calculator grammar from above as an example:

S → *exp* STOP *exp* → *exp* OPA *term* *exp* → *term* *term* → *term* OPM *factor* *term* → *factor* *factor* → NUM *factor* → LP *exp* RP

1. **Make the LR item parser states**.

   An "LR item" sort of represents the hopes and dreams of our bottom-up parser at any given moment in time. It says "I might be expanding THIS right-hand-side at THIS point".

Specifically, each LR item consists of some right-hand-side from the grammar, with a "bullet" in some position indicating the current position within that right-hand side that we could be in. For example, the LR item

exp → *exp* • OPA *term*

indicates that there is an *exp on the top of the stack, and if we see an OPA followed by a* term* coming up, these can be reduced to a single *exp* using this grammar rule.

So we start by making an NDFA with each LR item as a state. There will be a lot of states here, one for every possible bullet position in every production rule of the grammar.

2. **Make the transitions**

   The start state will be the production for the start symbol with the bullet all the way at the beginning, as you might expect. Now how can we transition between states? There are two ways:

   - A *shift* transition means reading the next symbol on the stack and moving the "bullet" past that symbol. **Important**: this only really corresponds to the parser performing a shift from the input stream if we're at the end of the stack. Otherwise, it just means reading past the tokens and non-terminals that are already on the stack.

     For example, from the state with this LR item:

     exp → *exp* • OPA *term*

     we will have a transition on the symbol OPA to the state containing

     exp → *exp* OPA • *term*

     The shift transitions can be nonterminals as well, so there's a subsequent shift transition from that state to the one containing

     exp → *exp* OPA *term* •

   - A *closure* transition is an empty-string transition that happens when the "bullet" is right before some non-terminal in the grammar. In other words, we are expecting to see that non-terminal come up next. What the closure transition means is that, instead of directly shifting that non-terminal symbol, we start to parse that non-terminal symbol instead, by transitioning to an LR item where the bullet is at the beginning of an expansion of that non-terminal.

     For example, from the state with the LR item

     term → *term* OPM • *factor*

     there will be two ε-transitions to states containing the items

     factor → • NUM

     and

     factor → • LP *exp* RP

   I think this will be most clear if you review the examples from class, specifically the slide on "Pieces of the CFSM". More examples can be found in your textbook too!

3. Convert from NFA to DFA

   Since there will never be any ε-transitions in this construction (unless there is something seriously wrong with your grammar), turning this *nonterterministic* machine into a DFA is pretty easy: it will just involve consolidating multiple states into single states. This leaves us with the actual CFSM, which is a deterministic finite state machene that accepts valid stack contents.

   For example, the start state of the grammar above contains all of these items:

$S \rightarrow \bullet$ *exp* STOP *exp* $\rightarrow \bullet$ *exp* OPA *term exp* $\rightarrow \bullet$ *term term* $\rightarrow \bullet$ *term* OPM *factor term* $\rightarrow \bullet$ *factor factor* $\rightarrow \bullet$ NUM *factor* $\rightarrow \bullet$ LP *exp* RP

and it has a transition on the symbol *term* to a state with just two items:

exp $\rightarrow$ *term* $\bullet$ *term* $\rightarrow$ *term* $\bullet$ OPM *factor*

Now here's why this matters: bottom-up parsers use CFSMs to figure out what actions to take (shift or reduce). Specifically, any time the CFSM comes to a state with an LR item with a bullet all the way at the end, like

$E \rightarrow E$ OPA $T \bullet$

this means we can reduce! The reason is, it means that we've just read in the right-hand side from the stack, so we can safely pop those symbols off and replace them with the left-hand side. So what a bottom-up parser is really doing is just following the transitions in a CFSM, shifting onto the stack every time it goes over a transition, and reducing whenever it hits a state with a reduce item like the one above. What about when it could do either, you ask? Well, that means we have a ...

5.2 Conflicts

A *conflict* arises when there's a state in the CFSM that contains some kind of ambiguity about what to do. Now the only thing a bottom-up parser really "does" that involves a hard decision is reducing. If we do a reduction at any time, the stack contents at that moment are destroyed and replaced by something else. And if we choose *not* to do a reduction, we'll never be able to go back to it later. What this means is that the two kinds of LR parser conflicts both involve reducing:

- A *shift-reduce* conflict is the most common type and occurs when a single CFSM state has at least one reduce item (where the bullet is at the end of the right-hand side), and at least one shift item (where the bullet is somewhere in the middle). As the name implies, we don't know whether to shift the next token, or to reduce the stuff we already have.

  For example, the CFSM state mentioned above:

  exp $\rightarrow$ *term* $\bullet$ *term* $\rightarrow$ *term* $\bullet$ OPM *factor*

  has a shift-reduce conflict. What this says is, when the stack contains *term*, we don't know whether to immediately reduce it to *exp*, or to keep trying to read OPM and *factor*.

  In this example, the FOLLOW set of *exp* allows us to resolve the conflict. The only shift transition out of that state will be on the OPM token, and the *exp* symbol can only be followed by STOP, OPA, or RP. So by looking ahead at the next token, we can decide whether to shift (if we see OPM) or reduce to *exp* (if we see STOP, OPA, or RP).

- A *reduce-reduce* conflict occurs when a single CFSM state has more than one reduce item (where the bullet is at the end of the right-hand side). Here we know that we need to reduce, but we don't know *which way* to do the reduction; i.e., which symbols should we pop off the stack and replace?

  The grammar above actually has no reduce/reduce conflicts! But you can check out an example of this in the slides that we covered in class.

SLR parsers (stands for "Simple LR") resolve these kinds of conflicts by using look-ahead tokens and the FOLLOW sets that we saw earlier. The general rule is, if the next token (the lookahead) is in the follow set of some nonterminal, then we can reduce to that nonterminal. If the lookahead token is an outgoing edge from the current state, then we can shift that token. **As long as there is no overlap** between these outgoing transitions and the FOLLOW sets in any given state, then the parser can always resolve the conflicts above by using one token of lookahead. In this case, the grammar is SLR(1), and an SLR(1) parser can parse any string in the language in linear time. Hooray!

I will expect you to be able to make CFSMs and determine whether grammars are SLR(1), and this will be our main goal in creating bottom-up parsers. However, you should also be aware that there is another kind of

parser called LALR ("look-ahead LR") that uses a more specific kind of follow set to resolve conflicts. LALR parsers can handle everything that SLR parsers can, and just a little bit more because their FOLLOW sets end up being smaller. For this reason, automatic bottom-up parser generators such as bison usually create LALR(1) parsers. You can read more about this in your textbook.

As always, be sure to review the slides and your notes from class for more details and examples on these parsing things.