Chapter 3

Tree Structured Languages: Context Free Languages and Pushdown Automata

In the previous chapter we saw that many interesting languages are not regular, for example, \( L = \{a^i b^i \mid i \geq 0\} \). In this chapter we will be looking at a larger class of languages, called Context Free Languages, which includes the above language \( L \) as well as all regular languages.

To gain some intuition, let’s discuss how we might characterize the strings in \( L \). One approach is recursive: a string \( w \in L \) is either \( \lambda \), the empty string, or it can be written as \( avb \) where \( v \) is a shorter string, also in \( L \). This recursive structure can also be viewed as a tree, and this is why we say these languages are tree structured.

A second approach is to use a stack to recognize strings in \( L \). Given an input string \( w \), as we read the initial \( a \)'s in \( w \) we push them on the stack; then, for each \( b \) we read, we pop one \( a \) from the stack. Clearly, the stack becomes empty precisely when we finish reading \( w \) only if the number of \( a \)'s and \( b \)'s are equal (and also only if \( w \) is of the form \( a^* b^* \)).

As it turns out, these two approaches are equivalent. The first approach is formalized via Context Free Grammars (CFGs), and the second approach via Pushdown Automata (PDAs). The latter are Finite Automata with the addition of a stack.

Context Free Grammars are widely used in practice. Perhaps the most important usage is to specify and recognize legal programs (there is more to this than can be managed by Context Free Grammars alone, but the for each programming language, the basic form of a legal program is specified by a corresponding Context Free Grammar). One part of this, which we will look at more carefully, is the specification of legal arithmetic expressions.

Interestingly, Context Free Grammars were first introduced to provide a specification of the structure of natural language sentences. We will begin the next section with an informal description of this perspective focusing on the structure of English sentences, keeping in mind that while the details vary from language to language, every natural language is believed to have a specification of this sort.
3.1 Tree Structured Languages

We begin with an intuitive overview, by looking at two examples: natural languages and arithmetic expressions.

**Natural Languages** Let’s start by looking at some sentences in English. For example, consider the sentence “The hungry dog eagerly ate a crunchy biscuit”. This is an example of a simple sentence, which consists of a subject (“The hungry dog”), followed by a verb phrase (“eagerly ate”), followed by an object (“a crunchy biscuit”). Both the subject and the object are noun phrases. These noun phrases take the form: an article, followed by an adjective, followed by a noun. The verb phrase consists of an adverb followed by a verb. We can show this structure using a tree, as shown in Figure 3.1. The strings in the language (namely English sentences here) are just the leaf labels in left-to-right order (incidentally, the alphabet here is the set of English words). Such trees can be used to generate strings comprising English sentences, and to recognize these strings requires the construction, explicitly or implicitly, of the same trees. This does not mean that every string of words that can be generated in this way is a legitimate sentence (e.g. “the rainbow walked a cow”); there are further constraints that go beyond the constraints of this tree structure.

![Figure 3.1: The tree generating the sentence “The hungry dog eagerly ate a crunchy biscuit”](image)

We can create more complex sentences. For example: “The hungry dog eagerly ate a crunchy biscuit, which I had bought at the corner store.” Here the sentence consists of a main clause (“The hungry dog eagerly ate a crunchy biscuit”) and a dependent clause (“which I had bought at the corner store”). The tree structure for this sentence is a main clause followed by a connector (“which”) followed by the dependent clause “I had bought at the corner store”. The dependent clause has no explicit object — in fact its object is “the biscuit”, but this is meant to be understood by the reader and thus is not explicitly spelled out; this clause also has an indirect object (“at the store”).
We can add further dependent clauses, as in: “The hungry dog eagerly ate a crunchy biscuit, which I had bought at the corner store, which was owned by Jasmine Wolf, whom I had first met in kindergarten.” In principle, we can keep adding dependent clauses indefinitely, pointing to the recursive nature of spoken languages, but in practice, if there are more than a few dependent clauses, the listener quickly loses track of what is being said (or written).

The language structure of English, let alone of the thousands of other spoken languages, is a huge topic and one we are not going to explore further here.

**Arithmetic Expressions** The basic form for an arithmetic expression is to have an operand, followed by an operator, followed by another operand; the operands are themselves arithmetic expressions. This recursive formulation needs a base case: it is provided by arithmetic expressions that are plain numbers; for simplicity, we limit ourselves to non-negative integers. The operators we consider are $+, -, \times, \div$.

Arithmetic expressions are readily presented as trees, called *Expression Trees*; a few small examples are shown in Figure 3.2.

![Figure 3.2: Example expression trees.](image)

The expression trees in Figure 3.2 correspond respectively to the expressions $3 + 5$, $3 + 4 \times 5$, and $(3 + 4) \times 5$ (and not to $3 + 4 \times 5$ which equals $3 + (4 \times 5)$ because of operator precedence). We now see that an arithmetic expression could begin and end with matching left and right parentheses.

To match the way we presented the English sentence in tree form, we would like the text form of the arithmetic expression to be obtained from reading the leaves of the tree in left-to-right order. Accordingly, as shown in Figure 3.3, we create derivation trees for the arithmetic expressions in Figure 3.2.

Arithmetic expressions can be found in many, many programs. In order to execute these programs the arithmetic expressions have to be understood. This is done by implicitly building the corresponding derivation trees.

We are now ready to be more precise. In the next section we introduce *Context Free Grammars*, which provide the rules for creating the derivation trees of the sort we have been seeing.
3.2 Context Free Grammars

Context Free Grammars (CFGs) provide a way of specifying certain recursively defined languages.

Let’s begin by giving a recursive method for generating non-negative integers in decimal form. We will call this representation of integers decimal numbers. A decimal number is defined to be either a single digit (one of 0–9) or a single digit followed by another decimal number. For example, the derivation of the number 147 is shown in Figure 3.4. In fact, the strings of decimal numbers form a regular language, but we are using them to provide a simple example of the recursive structure that Context Free Grammars enable.

This tree is called a derivation tree or parse tree for 147. We write the rules specifying the
possible children of a node as follows.

\[
\langle \text{decimal number} \rangle \rightarrow \langle \text{digit} \rangle \mid \langle \text{decimal number} \rangle \langle \text{digit} \rangle \tag{3.1}
\]

\[
\langle \text{digit} \rangle \rightarrow 0 \mid 1 \mid 2 \mid \cdots \mid 9
\]

The vertical bar should be read as “or”. So the meaning of

\[
\langle \text{digit} \rangle \rightarrow 0 \mid 1 \mid 2 \mid \cdots \mid 9
\]

is that a node labeled by \( \langle \text{digit} \rangle \) will have a single child labeled by one of the digits 0–9. And the meaning of

\[
\langle \text{decimal number} \rangle \rightarrow \langle \text{digit} \rangle \mid \langle \text{decimal number} \rangle \langle \text{digit} \rangle
\]

is that a node labeled \( \langle \text{decimal number} \rangle \) will either have a single child labeled by \( \langle \text{digit} \rangle \), or two children, the left child being labeled by \( \langle \text{decimal number} \rangle \) and the right child by \( \langle \text{digit} \rangle \).

The angle brackets are not really necessary when the derivation of the string is presented in tree form. But often it is inconvenient to draw trees, and an inline presentation of the derivation is used instead. We show the inline derivation of the string 147 in Figure 3.5.

We write \( \sigma \Rightarrow \tau \) if the string \( \tau \) is the result of a single replacement in \( \sigma \). The possible replacements are those given in Equation (3.1). Each replacement takes one occurrence of an item on the left-hand side of an arrow and replaces it with one of the items on the right-hand side; these are the items separated by vertical bars. Specifically, the possible replacements are to take one occurrence of one of:

\[
\langle \text{decimal string} \rangle \quad \text{and replace it with one of } \langle \text{digit} \rangle \text{ or the sequence } \langle \text{decimal string} \rangle \langle \text{digit} \rangle.
\]

\[
\langle \text{digit} \rangle \quad \text{and replace it with one of } 0–9.
\]

Clearly, were we patient enough, in principle we could generate any number.

Next, let’s look at an example of a non-regular language that can be defined recursively.
Example 3.2.1. \( L = \{ a^i b^i \mid i \geq 0 \} \).

If \( w \in L \) then either \( i = 0 \) and \( w = \lambda \), or \( i \geq 1 \) and \( w = avb \) with \( v = a^{i-1} b^{i-1} \in L \). We can show these choices using a pair of trees as shown below.

\[
\begin{array}{c}
\text{Base case} \\
\lambda \\
B \\
\end{array} \quad \begin{array}{c}
\text{Recursive case} \\
\text{B} \\
a \quad \text{B} \quad b \\
\end{array}
\]

It is convenient to write the recursive rules without drawing trees, which we do as follows.

The term \( \langle \text{Balanced} \rangle \) is the label for every internal node in the generating trees for \( L \). Such a node either has a single child labeled \( \lambda \), or it has three children labeled \( a \), \( \langle \text{Balanced} \rangle \), \( b \), in left-to-right order. We write this as follows.

\[ \langle \text{Balanced} \rangle \rightarrow \lambda \mid a \langle \text{Balanced} \rangle b. \]

We can then think of the string generation as a process of repeatedly replacing the \( \langle \text{Balanced} \rangle \) term by either \( \lambda \) or \( a \langle \text{Balanced} \rangle b \). For example, to generate \( aabb \) we start (at the root) with the term \( \langle \text{Balanced} \rangle \). We replace it by \( a \langle \text{Balanced} \rangle b \); we replace the new instance of \( \langle \text{Balanced} \rangle \) by \( a \langle \text{Balanced} \rangle b \), yielding \( aa \langle \text{Balanced} \rangle bb \); finally we replace this instance of \( \langle \text{Balanced} \rangle \) by \( \lambda \). For brevity, we will use \( B \) to denote \( \langle \text{Balanced} \rangle \). We then write this string derivation as follows.

\[ B \Rightarrow aBb \Rightarrow aaBbb \Rightarrow aabb. \]

Now we are ready to define Context Free Grammars (CFGs), \( G \), (which have nothing to do with graphs).

Definition 3.2.2 (CFG). A Context Free Grammar has four parts:

1. A set \( V \) of variables (such as \( \langle \text{Balanced} \rangle \)); note that \( V \) is not a vertex set here.
   These are the labels for the internal nodes in a derivation tree.
   The individual variables are usually written using single capital letters, often from the end of the alphabet, e.g. \( X, Y, Z \); no angle brackets are used here. This has little mnemonic value, but it is easier to write. If you do want to use longer variable names, I advise using angle brackets to delimit them.

2. An alphabet \( T \) of terminals: these are the characters used to write the strings being generated.
   These, together with the empty string \( \lambda \), are the labels for the leaves of the derivation tree.
   Usually, the terminals are written with small letters.

3. \( S \in V \) is the start variable, the variable from which the string generation begins. This is the label for the root of every derivation tree.
   The start variable does not have to be the letter \( S \); this is simply the default choice.

4. A set of rules \( R \). Each rule has the form \( X \rightarrow \sigma \), where \( X \in V \) is a variable and \( \sigma \in (T \cup V)^{*} \) is a string of variables and terminals, which could be \( \lambda \), the empty string. In a derivation
3.2. CONTEXT FREE GRAMMARS

If \( X \) is the label of a parent node, then the left-to-right sequence of labels for its children must be a string \( s \), where \( s \) is the right-hand side of a rule with \( X \) on the left-hand side.

If we have several rules with the same left-hand side, for example \( X \to \sigma_1, X \to \sigma_2, \ldots, X \to \sigma_k \), they can be written as \( X \to \sigma_1 \mid \sigma_2 \mid \cdots \mid \sigma_k \) for short. The meaning is that an occurrence of \( X \) in a generated string can be replaced by any one of \( \sigma_1, \sigma_2, \ldots, \sigma_k \). Different occurrences of \( X \) can be replaced by distinct \( \sigma_i \), of course.

The generation of a string proceeds by a series of replacements starting from the string \( s_0 = S \), and which, for \( 1 \leq i \leq k \), obtains \( s_i \) from \( s_{i-1} \) by replacing some variable \( X \) in \( s_{i-1} \) by one of the replacements \( \sigma_1, \sigma_2, \ldots, \sigma_k \) for \( X \), as provided by the rule collection \( R \). We will write this as

\[
S = s_0 \Rightarrow s_1 \Rightarrow s_2 \Rightarrow \cdots \Rightarrow s_k \text{ or } S \Rightarrow^* s_k \text{ for short.}
\]

The language generated by grammar \( G \), \( L(G) \), is the set of strings of terminals that can be generated from \( G \)'s start variable \( S \):

\[
L(G) = \{ w \mid S \Rightarrow^* w \text{ and } w \in T^* \}.
\]

In the next example, we look at the language of properly nested parentheses, namely strings in which each right parenthesis is matched to a distinct left parenthesis to its left. We can think of this language as consisting of those strings that can be obtained from legal arithmetic expressions from which we remove every character apart from the parentheses.

**Example 3.2.3. Grammar \( G_2 \):**

The grammar generating the language of properly nested parentheses. It has:

- Variable set: \( \{ S \} \).
- Terminal set: \( \{(, )\} \).
- Rules: \( S \to (S) \mid SS \mid \lambda \).
- Start variable: \( S \).

Here are some example derivations:

\[
S \Rightarrow SS \Rightarrow (S)S \Rightarrow (S) \Rightarrow (())S \Rightarrow ((S)) \Rightarrow (()).
\]

\[
S \Rightarrow (S) \Rightarrow (SS) \Rightarrow ((S))S \Rightarrow ((S)) \Rightarrow (())S \Rightarrow (())(S) \Rightarrow (())S \Rightarrow (()) \Rightarrow (()).
\]

The above examples are all reasonably straightforward. For more of a challenge let’s look anew at the problem of generating all legal arithmetic expressions taking account of operator precedence.

Let’s use \( E \) to denote the start variable for this language, that is starting from \( E \) we want to be able to generate all legal arithmetic expressions. We classify the possible expressions in terms of their priority.

- The highest priority expressions are of the form:
  - Non-Negative Integer or \((E)\)
- The mid-priority expressions are of the form:
  - Operand \( \times \) Operand or Operand \( \div \) Operand
- And the low priority expressions are of the form:
  - Operand \( + \) Operand or Operand \( - \) Operand

We let \( H, M \) and \( L \) be the variables that generate the high, mid, and low priority expressions, respectively.
We will need to place some constraints on the operands in order to ensure that the resulting expressions are legal arithmetic expressions. To provide some intuition, consider the expression $5 - 3 - 2$, which evaluates to 0 as the operators are evaluated in left-to-right order. We show this expression in a derivation tree in Figure 3.6 along with the tree for a right-to-left order of evaluation. As the latter expression it not legitimate, it has to be ruled out. The way we rule it out is to require the right operand of a plus or minus operation to be of higher priority, i.e. generated by $H$ or $M$. Again, the right operand of a $\times$ or $\div$ has to have higher priority, i.e. be generated by an $H$. Similarly, its left operand cannot be of lower priority, i.e. it must be generated by an $H$ or $M$. We specify the resulting grammar in Example 3.2.4 (also see Equation (3.1) for the grammar generating non-negative decimal numbers).

![Derivation trees for arithmetic expressions.]

**Example 3.2.4.** Grammar $G_3$, which generates all legal arithmetic expressions involving non-negative integers and the operators $+,-,\times,\div$.

Variable set $\{E, N, D, H, M, L, A, P\}$, where $N$ generates the non-negative integers, $D$ generates the digits 0-9, $H, M, L$ generate the high, mid, and low priority arithmetic expressions respectively, $A$ generates $+$ and $-$, and $P$ generates $\times$ and $\div$.

The start variable is $E$.

Terminal set $T = \{+,-,\times,\div,(,),0-9\}$.

The rules are:

\[
\begin{align*}
E & \rightarrow \ H \mid M \mid L \\
H & \rightarrow \ N \mid (E) \\
M & \rightarrow \ MPH \mid HPH \\
L & \rightarrow \ EAM \mid EAH \\
A & \rightarrow \ + \mid - \\
P & \rightarrow \ \times \mid \div \\
N & \rightarrow \ D \mid ND \\
D & \rightarrow \ 0 \mid 1 \mid 2 \ \cdots \mid 9
\end{align*}
\]

The derivation of $(1 + 2) \times 4 - 2$ is shown in Figure 3.7.
Figure 3.7: Derivation tree for \((1 + 2) \times 4 - 2\).
3.2.1 Closure Properties

**Lemma 3.2.5.** Let $G_A$ and $G_B$ be CFGs generating languages $A$ and $B$, respectively. Then there are CFGs generating $A\cup B$, $A\cap B$, $A^*$.

**Proof.** Let $G_A = (V_A, \Sigma_A, R_A, S_A)$ and $G_B = (V_B, \Sigma_B, R_B, S_B)$. By renaming variables if needed, we can ensure that $V_A$ and $V_B$ are disjoint.

First, we show that $A\cup B$ is generated by the following grammar $G_{A\cup B}$.

$G_{A\cup B}$ has variable set $\{S_{A\cup B}\} \cup V_A \cup V_B$, terminal set $T_A \cup T_B$, start variable $S_{A\cup B}$; rules $R_A \cup R_B$ plus the rules $S_{A\cup B} \rightarrow S_A | S_B$.

To generate a string $w \in A$, $G_{A\cup B}$ performs a derivation with first step $S_{A\cup B} \Rightarrow S_A$, and then follows this with a derivation of $w$ in $G_A$: $S_A \Rightarrow^* w$. So if $w \in A$, $w \in L(G_{A\cup B})$. Likewise, if $w \in B$, then $w \in L(G_{A\cup B})$ also. Thus $A \cup B \subseteq L(G_{A\cup B})$.

To show $L(G_{A\cup B}) \subseteq A\cup B$ is also straightforward. For if $w \in L(G_{A\cup B})$, then there is a derivation $S_{A\cup B} \Rightarrow^* w$. Its first step is either $S_{A\cup B} \Rightarrow S_A$ or $S_{A\cup B} \Rightarrow S_B$. Suppose it is $S_{A\cup B} \Rightarrow S_A$. Then the remainder of the derivation is $S_A \Rightarrow^* w$; this says that $w \in A$. Similarly, if the first step is $S_{A\cup B} \Rightarrow S_B$, then $w \in B$. Thus $L(G_{A\cup B}) \subseteq A \cup B$.

Next, we show that $A\cap B$ is generated by the following grammar $G_{A\cap B}$.

$G_{A\cap B}$ has variable set $S_{A\cap B} \cup V_A \cup V_B$, terminal set $T_A \cup T_B$, start variable $S_{A\cap B}$, and rules $R_A \cup R_B$ plus the rule $S_{A\cap B} \rightarrow S_A S_B$.

If $w \in A\cap B$, then $w = uv$ for some $u \in A$ and $v \in B$. So to generate $w$, $G_{A\cap B}$ performs the following derivation. The first step is $S_{A\cap B} \Rightarrow S_A S_B$; this is followed by a derivation $S_A \Rightarrow^* u$, which yields the string $uS_B$; this is then followed by a derivation $S_B \Rightarrow^* v$, which yields the string $uv = w$. Thus $A \cap B \subseteq L(G_{A\cap B})$.

To show $L(G_{A\cap B}) \subseteq A \cap B$ is also straightforward. For if $w \in L(G_{A\cap B})$, then there is a derivation $S_{A\cap B} \Rightarrow^* w$. The first step can only be $S_{A\cap B} \Rightarrow S_A S_B$. Let $u$ be the string of terminals derived from $S_A$, and $v$ the string of terminals derived from $S_B$, in the full derivation. So $uv = w$, $u \in A$ and $v \in B$. Thus $L(G_{A\cap B}) \subseteq A \cap B$.

The fact that there is a grammar $G_{A^*}$ generating $A^*$ we leave as an exercise for the reader. □

**Lemma 3.2.6.** $\{\lambda\}$, $\phi$, $\{a\}$ are all context free languages.

**Proof.** The grammar with the single rule $S \rightarrow \lambda$ generates $\{\lambda\}$, the grammar with no rules generates $\phi$, and the grammar with the single rule $S \rightarrow a$ generates $\{a\}$, where, in each case, $S$ is the start variable. □

**Corollary 3.2.7.** All regular languages have CFGs.

**Proof.** It suffices to show that for any language represented by a regular expression $r$ there is a CFG $G_r$ generating the same language. This is done by means of a proof by induction on the number of operators in $r$. As this is identical in structure to the proof of Lemma 2.5.1, the details are left to the reader. □

### 3.3 Pushdown Automata

A Pushdown Automata, or PDA for short, is simply an NFA equipped with a single stack. As with an NFA, it moves from vertex to vertex as it reads its input, with the additional possibility of also
3.3. **PUSHDOWN AUTOMATA**

pushing to and popping from its stack as part of a move from one vertex to another. As with an NFA, there may be several viable computation paths. In addition, as with an NFA, to recognize an input string $w$, a PDA $M$ needs to have a recognizing path, from its start vertex to a recognizing vertex, which it can traverse on input $w$.

Recall that a stack is an unbounded store which one can think of as holding the items it stores in a tower (or stack) with new items being placed (written) at the top of the tower and items being read and removed (in one operation) from the top of the tower. The first operation is called a *Push* and the second a *Pop*. For example, if we perform the sequence of operations Push(A), Push(B), Pop, Push(C), Pop, Pop, the 3 successive pops will read the items B, C, A, respectively. The successive states of the stack are shown in Figure 3.8.

![Figure 3.8: Stack Behavior.](image)

Let’s see how a stack allows us to recognize the following language $L_1 = \{a^ib^i \mid i \geq 0\}$. We start by explaining how to process a string $w = a^ib^i \in L$. As the PDA reads the initial string of $a$'s in its input, it pushes a corresponding equal length string of $A$'s onto its stack (one $A$ for each $a$ read). Then, as $M$ reads the $b$'s, it seeks to match them one by one against the $A$'s on the stack (by popping one $A$ for each $b$ it reads). $M$ recognizes its input exactly if the stack becomes empty on reading the last $b$.

In fact, PDAs are not allowed to use a *Stack Empty* test. We use a standard technique, which we call `shielding`, to simulate this test. Given a PDA $M$ on which we want to perform Stack Empty tests, we create a new PDA $\overline{M}$ which is identical to $M$ apart from the following small changes. $\overline{M}$ uses a new, additional symbol on its stack, which we name $\dollar$. Then at the very start of the computation, $\overline{M}$ pushes a $\dollar$ onto its stack. This will be the only occurrence of $\dollar$ on its stack. Subsequently, $\overline{M}$ performs the same steps as $M$ except that when $M$ seeks to perform a Stack Empty test, $\overline{M}$ pops the stack and then immediately pushes the popped symbol back on its stack. The simulated stack is empty exactly if the popped symbol was a $\dollar$.

Next, we explain what happens with strings outside the language $L_1$. We do this by looking at several categories of strings in turn.

1. $a^ib^h$, $h < i$.
   After the last $b$ is read, there will still be one or more $A$’s on the stack, indicating the input is not in $L_1$.

2. $a^ib^j$, $j > i$.
   On reading the $(i+1)$st $b$, there is an attempt to pop the now empty stack to find a matching $A$; this attempt fails, and again this indicates the input is not in $L_1$.

3. The only other possibility for the input is that it contains the substring $ba$; as already described, the processing consists of an $a$-reading phase, followed by a $b$-reading phase. The $a$
in the substring $ba$ is being encountered during the $b$-reading phase and once more this input is easily recognized as being outside $L_1$.

As with an NFA, we can specify the computation using a directed graph, with the edge labels indicating the actions to be performed when traversing the given edge. To recognize an input $w$, the PDA needs to be able to follow a path from its start vertex to a recognizing vertex starting with an empty stack, where the path’s read labels spell out the input, and the stack operations on the path are consistent with the stack’s ongoing contents as the path is traversed. To emphasize the fact that a path traversal involves both input reading and stack operations, we will often call the traversed path a computation path. Also, as before, we say that a vertex $v$ is a destination vertex for string $s$ if the PDA can end up at vertex $v$ after reading all of string $s$.

A PDA $M_1$ recognizing $L_1$ is shown in Figure 3.9. So as to be able to refer to the vertices,

![Diagram](image)

Figure 3.9: PDA $M_1$ recognizing $L_1 = \{a^i b^j \mid i \leq 0\}$.

we have given them the names $p_1$–$p_4$. Their descriptors specify exactly those strings and the corresponding stack contents for which the vertex in question is a destination vertex. We call these (string, stack content) pairs data configurations.

**Definition 3.3.1.** $(s, \sigma)$ is called a data configuration of PDA $M$ at vertex $p$ if $M$ can end up at vertex $p$ having $\sigma$ on its stack and having read input string $s$ (when starting the computation at its start vertex with an empty stack).

An initial understanding of what $M_1$ recognizes can be obtained by ignoring what the stack does and viewing the machine as just an NFA (i.e. using the same graph but with just the reads labeling the edges). See Figure 3.10 for the graph of the NFA $N_1$ derived from $M_1$. The significant point is that if $M_1$ can reach vertex $p$ on input $w$ using computation path $P$ then so can $N_1$ (for the same reads label $P$ in both machines). It follows that any string recognized by $M_1$ is also recognized by $N_1$: $L(M_1) \subseteq L(N_1)$.

It is not hard to see that $N_1$ recognizes $a^* b^*$. If follows that $M_1$ recognizes a subset of $a^* b^*$. So to explain the behavior of $M_1$ in full it suffices to look at what happens on inputs the form $a^i b^j$, $i, j \geq 0$, which we do by examining five subcases that account for all such strings.
3.3. **PUSHDOWN AUTOMATA**

![Diagram of NFA N1 derived from M1.](image)

Figure 3.10: The NFA $N_1$ derived from $M_1$.

1. $\lambda$.
   
   $M_1$ starts at $p_1$. On pushing $\$\$, $p_2$ and $p_3$ can be reached. Then on popping the $\$, $p_4$ can be reached. Note that the specification of $p_2$ holds with $i = 0$, that of $p_3$ with $i = h = 0$, and that of $p_4$ with $i = 0$. Thus the specification at each vertex includes the case that the input is $\lambda$.

2. $a^i$, $i \geq 1$.
   
   To read $a^i$, $M_1$ needs to push $\$, then follow edge $(p_1, p_2)$, and then follow edge $(p_2, p_2)$ $i$ times. This puts $\$A^i$ on the stack. Thus on input $a^i$, $p_2$ can be reached and its specification is correct. In addition, the edge to $p_3$ can be traversed without any additional reads or stack operations, and so the specification for $p_3$ with $h = 0$ is correct for this input.

3. $a^ib^h$, $1 \leq h < i$.
   
   The only place to read $b$ is on edge $(p_3, p_3)$. Thus, for this input, $M_1$ reads $a^i$ to bring it to $p_3$ and then follows $(p_3, p_3)$ $h$ times. This leaves $\$A^{i-h}$ on the stack, and consequently the specification of $p_3$ is correct for this input. Note that as $h < i$, edge $(p_3, p_4)$ cannot be followed as $\$ is not on the stack top.

4. $a^ib^i$, $i \geq 1$.
   
   After reading the $i$ $b$'s, $M_1$ can be at vertex $p_3$ as explained in (3). Now, in addition, edge $(p_3, p_4)$ can be traversed and this pops the $\$ from the stack, leaving it empty. So the specification of $p_4$ is correct for this input.

5. $a^ib^j$, $j > i$.
   
   On reading $a^ib^j$, $M_1$ can reach $p_3$ with the stack holding $\$ or reach $p_4$ with an empty stack, as described in (4). From $p_3$ the only available move is to $p_4$, without reading anything further. At $p_4$ there is no move, so the rest of the input cannot be read, and thus no vertex can be reached on this input.

This is a very elaborate description which we certainly don't wish to repeat for each similar PDA. We can describe $M_1$'s functioning more briefly as follows.

$M_1$ checks that its input has the form $a^*b^*$ (i.e. all the a's precede all the b's) using its underlying NFA (i.e. without using the stack). The underlying NFA is often called its finite control. In tandem with this, $M_1$ uses its $\$-shielded stack to match the a's against the b's, first pushing the a's on the stack (it is understood that in fact A's are being pushed) and then popping them off, one for one, as the b's are read, confirming that the numbers of a's and b's are equal.
The detailed argument we gave above is understood, but not spelled out.

Now we are ready to define a PDA more precisely. As with an NFA, a PDA consists of a directed graph with one vertex, $\textit{start}$, designated as the start vertex, and a (possibly empty) subset of vertices designated as the recognizing set, $F$, of vertices. As before, in drawing the graph, we indicate recognizing vertices using double circles and indicate the start vertex with a double arrow. Each edge is labeled with the actions the PDA performs on following that edge.

For example, the label on edge $e$ might be: Pop $A$, read $b$, Push $C$, meaning that the PDA pops the stack, reads the next input character, and if the pop returns an $A$ and the character read is a $b$, then the PDA can traverse $e$, which entails it pushing $C$ onto the stack. Some or all of these values may be $\lambda$: Pop $\lambda$ means that no Pop is performed, read $\lambda$ that no read occurs, and Push $\lambda$ that no Push happens. To avoid clutter, we usually omit the $\lambda$-labeled terms; for example, instead of Pop $\lambda$, read $\lambda$, Push $C$, we write Push $C$. Also, to avoid confusion in the figures, if there are multiple triples of actions that take the PDA from a vertex $u$ to a vertex $v$, we use multiple edges from $u$ to $v$, one for each triple.

In sum, a label, which specifies the actions accompanying a move from vertex $u$ to vertex $v$, has up to three parts.

1. Pop the stack and check that the returned character has a specified value (in our example this is the value $A$).

2. Read the next character of input and check that it has a specified value (in our example, the value $b$).

3. Push a specified character onto the stack (in our example, the character $C$).

From an implementation perspective it may be helpful to think in terms of being able to peek ahead, so that one can see the top item on the stack without actually popping it, and one can see the next input character (or that one is at the end of the input) without actually reading forward.

One further rule is that an empty stack may not be popped.

A PDA also comes with an input alphabet $\Sigma$ and a stack alphabet $\Gamma$ (these are the symbols that can be written on the stack). It is customary for $\Sigma$ and $\Gamma$ to be disjoint, in part to avoid confusion. To emphasize this disjointness, we write the characters of $\Sigma$ using lowercase letters and those of $\Gamma$ using uppercase letters.

Because the stack contents make it difficult to describe the condition of the PDA after multiple moves, we use the transition function here to describe possible out edges from single vertices only. Accordingly, $\delta(p, A, b) = \{(q_1, C_1), (q_2, C_2), \ldots, (q_l, C_l)\}$ indicates that the edges exiting vertex $p$ and having both Pop $A$ and read $b$ in their label are the edges going to vertices $q_1, q_2, \ldots, q_l$ where the rest of the label for edge $(p, q_i)$ includes Push $C_i$, for $1 \leq i \leq l$. That is $\delta(p, A, b)$ specifies the possible moves out of vertex $p$ on popping character $A$ and reading $b$. (Recall that one or both of $A$ and $b$ might be $\lambda$, as might some or all of the $C_i$'s.)

We summarize this formally in the following definition.

**Definition 3.3.2 (PDA).** A PDA $M$ consists of a 6-tuple: $M = (\Sigma, \Gamma, V, \textit{start}, F, \delta)$, where

1. $\Sigma$ is the input alphabet,

2. $\Gamma$ is the stack alphabet,
3.3. **PUSHDOWN AUTOMATA**

3. $V$ is the vertex or state set,

4. $F \subseteq V$ is the recognizing vertex set,

5. $\text{start}$ is the start vertex, and

6. $\delta$ is the transition function, which specifies the edges and their labels.

Recognition is defined as for an NFA, that is, PDA $M$ recognizes input $w$ if there is a path that $M$ can follow on input $w$ that takes $M$ from its start vertex to a recognizing vertex. We call this path a $w$-recognizing computation path to emphasize that stack operations may occur in tandem with the reading of input $w$. More formally, $M$ recognizes $w$ if there is a path $\text{start} = p_0, p_1, \ldots, p_m$, where $p_m$ is a recognizing vertex, the label on edge $(p_{i-1}, p_i)$ is (Read $a_i$, Pop $B_i$, Push $C_i$), for $1 \leq i \leq m$, and the stack contents at vertex $p_i$ is $\sigma_i$, for $0 \leq i \leq m$, where

1. $a_1 a_2 \cdots a_m = w$,

2. $\sigma_0 = \lambda$,

3. and Pop $B_i$, Push $C_i$ applied to $\sigma_{i-1}$ produces $\sigma_i$ for $1 \leq i \leq m$.

We write $L(M)$ for the language, or set of strings, recognized by $M$.

Next, we show some more examples of languages that can be recognized by PDAs.

**Example 3.3.3.** $L_2 = \{a^i c b^i \mid i \geq 0\}$.

PDA $M_2$ recognizing $L_2$ is shown in Figure 3.11. The processing by $M_2$ is similar to that of $M_1$. $M_2$ checks that its input has the form $a^*_c b^*$ using its finite control. In tandem, $M_2$ uses its $\$$-shielded stack to match the $a$'s against the $b$'s, first pushing the $a$'s on the stack (actually $A$'s are being pushed), then reads the $c$ without touching the stack, and finally pops the $a$'s off, one for one, as the $b$'s are read, confirming that the numbers of $a$'s and $b$'s are equal.

![Figure 3.11: PDA $M_2$ recognizing $L_2 = \{a^i c b^i \mid i \geq 0\}$](image-url)
Example 3.3.4. \( L_3 = \{w c w^R \mid w \in \{a, b\}^*\} \).

PDA \( M_3 \) recognizing \( L_3 \) is shown in Figure 3.12. \( M_3 \) uses its \$-shielded stack to match the \( w \) against the \( w^R \), as follows. It pushes \( w \) on the stack (the end of the substring \( w \) being indicated by reaching the \( c \)). At this point, the stack content read from the top is \( w^R \$ \), so popping down to the \$ outputs the string \( w^R \). This stack contents is readily compared to the string following the \( c \). The input is recognized exactly if they match.

![Figure 3.12: PDA \( M_3 \) recognizing \( L_3 = \{w c w^R \mid w \in \{a, b\}^*\} \). Z denotes string z in capital letters.](image)

Example 3.3.5. \( L_4 = \{ww^R \mid w \in \{a, b\}^*\} \).

PDA \( M_4 \) recognizing \( L_4 \) is shown in Figure 3.13. This is similar to Example 3.3.4. The one difference is that the PDA \( M_4 \) can decide at any point to stop reading \( w \) and begin reading \( w^R \). Of course there is only one correct switching location, at most, but as \( M_4 \) does not know where it is, \( M_4 \) considers all possibilities by means of its nondeterminism.

Example 3.3.6. \( L_5 = \{a^i b^j c^k \mid i = j \text{ or } i = k\} \).

PDA \( M_5 \) recognizing \( L_5 \) is shown in Figure 3.14. This is the union of languages \( L_6 = \{a^i b^i c^k \mid i, k \geq 0\} \) and \( L_7 = \{a^i b^j c^j \mid i, j \geq 0\} \), each of which is similar to \( L_2 \). \( M_5 \), the PDA recognizing \( L_5 \) uses submachines to recognize each of \( L_6 \) and \( L_7 \). \( M_5 \)'s first move from its start vertex is to traverse (Push \$)-edges to the start vertices of the submachines. The net effect is that \( M_5 \) recognizes the union of the languages recognized by the submachines. As the submachines are similar to \( M_2 \) they are not explained further.

3.3.1 Deterministic PDAs

Suppose that a DPA is constrained so that at each vertex, given the current character at the top of the stack and the next character of input, there is at most one possible move. It may be that this move does not read the next input character (i.e. it includes a Read \( \lambda \)) or it does not pop the stack (i.e. it includes a Pop \( \lambda \)). We call such a machine a Deterministic PDA, a DPDA for short.
3.3. PUSHDOWN AUTOMATA

Figure 3.13: PDA $M_4$ recognizing $L_4 = \{ww^R | w \in \{a, b\}^*\}$. $Z$ denotes string $z$ in capital letters.

This still leaves one possible ambiguity: whether to make additional moves once the input is fully read. To resolve this we treat the input as if there was an additional end-of-input character following the actual input. Thus instead of having an input $w$, the input will be of the form $wc$ where $c$ is a character that appears only once at the very end of the input. The DPDA will be allowed to have edges whose labels include the action $\text{Read } c$. In addition, all recognizing vertices will be reached by following an edge labelled $\text{Read } c$, and further these vertices will have no out-edges. In fact, it is easy to see that one such vertex suffices.

Notice that if there is an edge labeled $(\text{Read } \lambda, \text{Pop } B, \text{Push } C)$ exiting a vertex $v$, for some $B, C \in \Gamma \cup \{\lambda\}$, then there is no edge leaving $v$ with label $(\text{Read } a, \text{Pop } B, \text{Push } D)$ for any $a \in \Sigma$ and $D \in \Gamma \cup \{\lambda\}$. The following rules cover every possibility, and are exactly what is needed to ensure that there is always at most one move. Specifically, for each vertex $v$ its out-edges satisfy the following constraints:

- If there is an outedge labeled $(\text{Read } \lambda, \text{Pop } \lambda, \text{Push } C)$ for some $C \in \Gamma \cup \{\lambda\}$, then this is $v$'s only outedge.

- For all $a \in \Sigma \cup \{\lambda\}$, $B \in \Gamma \cup \{\lambda\}$, if there is an outedge labeled $(\text{Read } a, \text{Pop } B, \text{Push } C)$ for some $C \in \Gamma \cup \{\lambda\}$, then there is no outedge labeled $(\text{Read } a, \text{Pop } B, \text{Push } D)$, for any $D \neq C$, $D \in \Gamma \cup \{\lambda\}$.

- If there is an outedge labeled $(\text{Read } \lambda, \text{Pop } B, \text{Push } C)$ for some $B \in \Gamma$ and $C \in \Gamma \cup \{\lambda\}$, then there is no outedge labeled $(\text{Read } a, \text{Pop } B, \text{Push } D)$, for any $a \in \Sigma$ and $D \in \Gamma \cup \{\lambda\}$.

- If there is an outedge labeled $(\text{Read } a, \text{Pop } \lambda, \text{Push } C)$ for some $a \in \Sigma$ and $C \in \Gamma \cup \{\lambda\}$, then there is no outedge labeled $(\text{Read } a, \text{Pop } B, \text{Push } D)$, for any $B \in \Gamma$ and $D \in \Gamma \cup \{\lambda\}$.

DPDAs are readily implemented, for as the input is read it suffices to keep track of the current destination vertex and the current stack contents. As the next move is always uniquely specified, the change to these values is always unambiguous.
Figure 3.14: PDA $M_5$ recognizing $L_5 = \{a^i b^j c^k \mid i = j \text{ or } i = k\}$. 
Example 3.3.7. $L_1 = \{a^i b^i \mid i \geq 0 \}$. The PDA in Figure 3.9, recognizing $L_1$, is not a DPDA, but a small modification turns it into a DPDA $\tilde{M}_1$ recognizing $L_1$. The need for a modification is due to the $\lambda$-edge from $p_2$ to $p_3$, namely from the vertex where the $a$’s are read to the vertex where the $b$’s are read. We change the $\lambda$-edge to instead read the first $b$ in the input, as shown in Figure 3.15. Also, to be able to distinguish $\lambda$ from non-empty strings, we need to introduce a new vertex $p_5$ between $p_1$ and $p_2$. $p_5$ is reached by the initial Push $\$$. Then, if the input is $\lambda$, there is a direct transition to the recognizing vertex $p_4$. Otherwise an $a$ is read (and an $A$ pushed) to reach $p_2$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3_15.png}
\caption{DPDA recognizing $L_1 = \{a^i b^i \mid i \geq 0 \}$.}
\end{figure}

Next we show that as with DFAs, we can have a sink vertex so as to ensure that there is always exactly one move to make.

Lemma 3.3.8. Let $M$ be a DPDA. There is another DPDA $\tilde{M}$ with $L(M) = L(\tilde{M})$ such that on every input, at every step of its computation, $\tilde{M}$ has a unique move.

Proof. For each missing possible action, we add an edge to the sink vertex labeled by that move, as specified by the following rule.
For each $a \in \Sigma$ and $B \in \Gamma$, add an edge from non-recognizing vertex $v$ to the sink vertex labeled (Read $a$, Pop $B$, Push $B$) exactly if none of the following edges exiting $v$ are present:

- an outedge labeled (Read $a$, Pop $B$, Push $C$) for any $C \in \Gamma \cup \{\lambda\}$,
- an outedge labeled (Read $\lambda$, Pop $B$, Push $C$) for any $C \in \Gamma \cup \{\lambda\}$,
- an outedge labeled (Read $a$, Pop $\lambda$, Push $C$) for any $C \in \Gamma \cup \{\lambda\}$,
- an outedge labeled (Read $\lambda$, Pop $\lambda$, Push $C$) for any $C \in \Gamma \cup \{\lambda\}$

In addition, for each $a \in \Sigma$, a self-loop is added to the sink vertex with label Read $a$. \qed
Example 3.3.9. DPDA for \( L_1 = \{ a^i b^i \mid i \leq 0 \} \) with a unique move at every step.

In Figure 3.16 we show the result from applying Lemma 3.3.8 to the automata from Example 3.3.7.

![Diagram](image.png)

Figure 3.16: Unique move DPDA recognizing \( L_1 = \{ a^i b^i \mid i \leq 0 \} \).

3.4 Closure Properties

Lemma 3.4.1. Let \( A \) and \( B \) be languages recognized by PDAs \( M_A \) and \( M_B \), respectively, Then \( A \cup B \) is also recognized by a PDA called \( M_{A \cup B} \).

Proof. The graph of \( M_{A \cup B} \) consists of the graphs of \( M_A \) and \( M_B \) plus a new start vertex \( \text{start}_{A \cup B} \), which is joined by \( \lambda \)-edges to the start vertices \( \text{start}_A \) and \( \text{start}_B \) of \( M_A \) and \( M_B \), respectively. Its recognizing vertices are the recognizing vertices of \( M_A \) and \( M_B \). The graph is shown in figure 3.17.

While it is clear that \( L(M_{A \cup B}) = L(M_A) \cup L(M_B) \), we present the argument for completeness.

First, we show that \( L(M_{A \cup B}) \subseteq L(M_A) \cup L(M_B) \), i.e. if \( w \in L(M_{A \cup B}) \) then \( w \in L(M_A) \cup L(M_B) \).

So suppose that \( w \in L(M_{A \cup B}) \). Then there is a \( w \)-recognizing computation path from \( \text{start}_{A \cup B} \) to a recognizing vertex \( f \). If \( f \) lies in \( M_A \), then removing the first edge of \( P \) leaves a path \( P' \) from
start\textsubscript{A} to \( f \). Further, at the start of \( P' \), the stack is empty and nothing has been read, so \( P' \) is a \( w \)-recognizing path in \( M_A \). That is, \( w \in L(M_A) \). Similarly, if \( f \) lies in \( M_B \), then \( w \in L(M_B) \). In either case, \( w \in L(M_A) \cup L(M_B) \).

Second, we show that \( L(M_A) \cup L(M_B) \subseteq L(M_\text{A∪B}) \), i.e. if \( w \in L(M_A) \cup L(M_B) \) then \( w \in L(M_\text{A∪B}) \). Suppose that \( w \in L(M_A) \). Then there is a \( w \)-recognizing computation path \( P' \) from \( \text{start}_A \) to a recognizing vertex \( f \) in \( M_A \). Adding the \( \lambda \)-edge \((\text{start}_\text{A∪B}, \text{start}_A)\) to the beginning of \( P' \) creates a \( w \)-recognizing computation path in \( M_\text{A∪B} \), showing that \( L(M_A) \subseteq L(M_\text{A∪B}) \). Similarly, if \( w \in L(M_B) \), then \( w \in L(M_\text{A∪B}) \). Thus if \( w \in L(M_A) \cup L(M_B) \) then \( w \in L(M_\text{A∪B}) \).

Our next construction is simplified by the following technical lemma.

**Lemma 3.4.2.** Let PDA \( M \) recognize \( L \). There is an \( L \)-recognizing PDA \( M' \) with the following properties: \( M' \) has only one recognizing vertex, \( \text{recognize}_{M'} \), and \( M' \) will always have an empty stack when it reaches \( \text{recognize}_{M'} \). \( M' \) is called a single-destination, empty-stack PDA.

**Proof.** The idea is quite simple. \( M' \) simulates \( M \) using a \( \$ \)-shielded stack. When \( M' \)’s computation is complete, \( M' \) moves to a new stack-emptying vertex, \( \text{stack-emptier} \), at which \( M' \) empties its stack of everything apart from the \( \$ \)-shield. To then move to \( \text{recognize}_{M'} \), \( M' \) pops the \( \$ \), thus ensuring it has an empty stack when it reaches \( \text{recognize}_{M'} \). \( M' \) is illustrated in Figure 3.18. More precisely, \( M' \) consists of the graph of \( M \) plus three new vertices: \( \text{start}_{M'} \), \( \text{stack-emptier} \), and \( \text{recognize}_{M'} \). The following edges are also added: \((\text{start}_{M'}, \text{start}_M)\) labeled Push \( \$ \), \( \lambda \)-edges from each of \( M' \)’s recognizing vertices to \( \text{stack-emptier} \), self-loops \((\text{stack-emptier}, \text{stack-emptier})\) labeled Pop \( X \) for each \( X \in \Gamma \), where \( \Gamma \) is \( M' \)’s stack alphabet (so \( X \neq \$ \)), and edge \((\text{stack-emptier}, \text{recognize}_{M'})\) labeled Pop \( \$ \).

It is clear that \( L(M) = L(M') \). Nonetheless, we present the argument for completeness.

First, we show that \( L(M') \subseteq L(M) \), i.e. if \( w \in L(M') \) then \( w \in L(M) \) also. So let \( w \in L(M') \). Let \( P' \) be a \( w \)-recognizing path in \( M' \) and let \( f \) be the recognizing vertex of \( M \) preceding
stack-emptier on the path $P'$. Removing the first edge in $P'$ and every edge including and after $(f, \text{stack-emptier})$, leaves a path $P$ which is a $w$-recognizing path in $M$. Thus $w \in L(M)$ and consequently $L(M') \subseteq L(M)$.

Now we show $L(M) \subseteq L(M')$, i.e. if $w \in L(M)$ then $w \in L(M')$ also. Let $w \in L(M)$ and let $P$ be a $w$-recognizing path in $M$. Suppose that $P$ ends with string $s$ on the stack at recognizing vertex $f$. We add to $P$ the edges $(\text{start}_{M'}, \text{start}_M), (f, \text{stack-emptier}), |s|$ self-loops at \text{stack-emptier}, and $(\text{stack-emptier}, \text{recognize}_{M'})$, yielding path $P'$ in $M'$. By choosing the self-loops to be labeled with the characters of $s^R$ in this order, which corresponds to popping $s^R$ from the stack, we cause $P'$ to be a $w$-recognizing path in $M'$. Thus $w \in L(M')$ and consequently $L(M) \subseteq L(M')$. \hfill \Box

**Lemma 3.4.3.** Let $A$ and $B$ be languages recognized by PDAs. Then there is a PDA recognizing $A \circ B$.

**Proof.** Let $M_A$ and $M_B$ be single-destination, empty-stack PDAs recognizing $A$ and $B$, respectively.

We will construct PDA $M_{A\circ B}$ that recognizes $A \circ B$. It consists of $M_A$, $M_B$ plus one $\lambda$-edge $(\text{recognize}_A, \text{start}_B)$. Its start vertex is $\text{start}_A$ and its recognizing vertex is $\text{recognize}_B$.

To see that $L(M_{A\circ B}) = A \circ B$ is straightforward.

First, we show that $L(M_{A\circ B}) \subseteq A \circ B$, i.e. if $w \in L(M_{A\circ B})$ then $w \in A \circ B$ also. So suppose that $w \in L(M_{A\circ B})$, then there is a $w$-recognizing path $P$ in $M_{A\circ B}$; $P$ is formed from a path $P_A$ in $M_A$ going from $\text{start}_A$ to $\text{recognize}_A$ (and which therefore ends with an empty stack), $\lambda$-edge $(\text{recognize}_A, \text{start}_B)$, and a path $P_B$ in $M_B$ starting from $\text{start}_B$ with an empty stack and going to $\text{recognize}_B$. Let $u$ be the sequence of reads labeling $P_A$ and $v$ those labeling $P_B$. It follows that $P_A$ is $u$-recognizing, and $P_B$ is $v$-recognizing (see Figure 3.19) and thus $u \in A$ and $v \in B$. In addition, $w = u\lambda v = uv$, which implies that $w = uv \in A \circ B$.

Next, we show that $A \circ B \subseteq L(M_{A\circ B})$. So suppose that $w = uv \in A \circ B$, where $u \in A$ and $v \in B$. Then there is a $w$-recognizing path $P_A$ in $M_A$ and a $w$-recognizing path $P_B$ in $M_B$. We argue that the following path $P$ is $w$-recognizing: $P_A$ followed by the $\lambda$-edge $(\text{recognize}_A, \text{start}_B)$, followed by $P_B$. Note that by construction the stack is empty when at node $\text{recognize}_A$, and hence it is also empty at node $\text{start}_B$. Consequently, computation path $P$ in $M_{A\circ B}$ recognizes $u\lambda v = uv = w$, as claimed. It follows that $w = uv \in L(M_{A\circ B})$. \hfill \Box
Lemma 3.4.4. Suppose that \( L \) is recognized by a PDA and suppose that \( R \) is a regular language. Then there is a PDA recognizing \( L \cap R \).

Proof. We illustrate the construction below in Example 3.4.5.

Let \( M_L = (\Sigma, \Gamma_L, V_L, \text{start}_L, F_L, \delta_L) \) be a single-destination, empty-stack PDA recognizing \( M_L \), and let \( R \) be recognized by DFA \( M_R = (\Sigma, V_R, \text{start}_R, F_R, \delta_R) \). We will construct PDA \( M_{L \cap R} \) that recognizes \( L \cap R \). The vertices of \( M_{L \cap R} \) will be 2-tuples, the first component corresponding to a vertex of \( M_L \) and the second component to a vertex of \( M_R \). The computation of \( M_{L \cap R} \), when looking at the first components along with the stack will be exactly the computation of \( M_L \), and when looking at the second components, but without the stack, it will be exactly the computation of \( M_R \). This leads to the following vertices in \( M_{L \cap R} \).

1. If \( M_L \) has an edge \((u_L, v_L)\) with label \((\text{Pop} A, \text{Read} b, \text{Push} C)\) and \( M_R \) has an edge \((u_R, v_R)\) with label \( b \), then \( M_{L \cap R} \) has an edge \(((u_L, u_R), (v_L, v_R))\) with label \((\text{Pop} A, \text{Read} b, \text{Push} C)\).

2. If \( M_L \) has an edge \((u_L, v_L)\) with label \((\text{Pop} A, \text{Read} \lambda, \text{Push} C)\) then \( M_{L \cap R} \) has an edge \(((u_L, u_R), (v_L, u_R))\) with label \((\text{Pop} A, \text{Read} \lambda, \text{Push} C)\) for every \( u_R \in V_R \).

Example 3.4.5. PDA recognizing \( L_1 \cap (aa)^*b^* \), where \( L_1 = \{a^ib^i | i \geq 0 \} \).

We take the PDA \( M_1 \) recognizing \( L_1 \) from Figure 3.9 and the DFA recognizing \( (aa)^*b^* \) shown in Figure 3.20, and apply Lemma 3.4.4 to them. As it happens, only 5 vertices are reachable in the new automata; the others vertices are not shown.

The start vertex for \( M_{L \cap R} \) is \((\text{start}_L, \text{start}_R)\) and its set of recognizing vertices is \( F_L \times F_R \), the pairs of recognizing vertices, one from \( M_L \) and one from \( M_R \), respectively.

Assertion. On input \( w \), \((v_L, v_R)\) is a destination vertex of \( M_{L \cap R} \) if and only if \( v_L \) is a destination vertex of \( M_L \) and \( v_R \) a destination vertex of \( M_R \).

Next, we argue that the assertion is true. For suppose that on input \( w \), \( M_{L \cap R} \) ends up at vertex \((v_L, v_R)\) using computation path \( P_{L \cap R} \). If we consider the first components of the vertices in \( P_{L \cap R} \), we see that it is a computation path of \( M_L \) on input \( w \) with destination vertex \( v_L \). Likewise, if we consider the second components of the vertices of \( M_{L \cap R} \), we obtain a path \( P'_R \). The only difficulty is that this path may contain repetitions of a vertex \( u_R \) corresponding to reads of \( \lambda \) by \( M_{L \cap R} \). Eliminating such repetitions creates a path \( P_R \) in \( M_R \) with destination \( v_R \) and having the same label \( w \) as path \( P'_R \).

Conversely, suppose that \( M_L \) can end up at vertex \( v_L \) using computation path \( P_L \) and \( M_R \) can end up at vertex \( v_R \) using computation path \( P_R \). Combining these paths, with care, gives a computation path \( P \) in \( M_{L \cap R} \) on input \( w \) which ends at vertex \((v_L, v_R)\). We proceed as follows. The first vertex is \((\text{start}_L, \text{start}_R)\). Then we traverse \( P_L \) and \( P_R \) in tandem. Either the next edges
Figure 3.20: (a) DFA $M_R$ recognizing $(aa)^*b^*$, (b) PDA $M_{LR}$ recognizing $\{a^ib^i \mid i \geq 0\} \cap (aa)^*b^* = \{a^{2i}b^{2i} \mid i \geq 0\}$.
3.4. CLOSURE PROPERTIES

in $P_L$ and $P_R$ are both labeled by a Read $b$ (simply a $b$ on $P_R$) in which case we use Rule (1) above to give the edge to add to $P$, or the next edge on $P_L$ is labeled by Read $\lambda$ (together with a Pop and a Push possibly) and then we use Rule (2) to give the edge to add to $P$. In the first case we advance one edge on both $P_L$ and $P_R$, in the second case we only advance on $P_L$. Clearly, the path ends at vertex $(v_L, v_R)$ and reads input $w$.

It is now easy to see that $L(M_{L \cap R}) = L \cap R$. For on input $w$, $M_{L \cap R}$ ends up at a recognizing vertex $v \in F = F_L \times F_R$ if and only if on input $w$, $M_L$ ends up at a vertex $v_L \in F_L$ and $M_R$ ends up at a vertex $v_R \in F_R$. That is, $w \in L(M_{L \cap R})$ if and only if $w \in L(M_L) = L$ and $w \in L(M_R) = R$, or in other words $w \in L(M_{L \cap R})$ if and only if $w \in L \cap R$. 

**Exercise.** Show that if $A$ is recognized by PDA $M_A$ then there is a PDA $M_{A^*}$ recognizing $A^*$.

3.4.1 Closure Properties for DPDA

**Lemma 3.4.6.** Let $L$ be recognized by a DPDA $M$. Then $L$ is also recognized by a PDA.

*Proof.* This lemma is not quite immediate because of the addition of the $c$ to the DPDA input, but it is easy to simulate the missing $c$ in a PDA computation. We build PDA $M'$ to recognize $L$ as follows. Simply replace each Read $c$ in $M$ with a Read $\lambda$. Clearly if $w \in L$ then there is a recognizing path $P$ in $M$ which goes from $M$’s start vertex to a recognizing vertex. The Reads on this path, when concatenated, read the string $wc$. The same path in $M'$ will read the string $w$. Consequently $M'$ recognizes $w$.

Conversely if $M$ recognizes string $w$, the final edge on its recognizing path $P$ has read label Read $\lambda$. In $M$ this same final edge will have read label $c$, and as this is the only change, the path reads the string $wc$, and thus $M$ recognizes the string $w$. 

DPDAs have quite different closure properties from PDAs. As it happens, the complement of a language recognized by a DPDA is also recognized by a DPDA, but to prove this is quite difficult; the difficulties arise due to the possibility of a cycle on which nothing is read and which can be traversed infinitely often (see Problem 10). As we shall see later, this property does not hold for PDAs. Since every language recognized by a DPDA is recognized by a PDA, this implies PDAs recognize more languages that DPDAs, in contrast to the situation with DFAs and NFAs.

Another contrast is that the intersection of two languages recognized by a DPDA need not be recognized by a DPDA.

**Lemma 3.4.7.** There are languages $K_1$ and $K_2$ recognized by DPDAs, for which $K_3 = K_1 \cap K_2$ is not recognized by any DPDA.

*Proof.* Let $K_1 = \{a^ib^jc^k | i = j$ and $i,j,k \geq 0\}$ and $K_2 = \{a^ib^jc^k | i = k$ and $i,j,k \geq 0\}$. Then $K_3 = K_1 \cap K_2 = \{a^ib^jc^i | i \geq 0\}$. $K_1$ and $K_2$ are recognized by DPDAs similar to the DPDA in Figure 3.15, but as we shall see in Section 3.6, $K_3$ is not a Context Free Language (CFL), and hence as we shall see in Section 3.7, is not recognized by any PDA, and hence not by any DPDA either.

Likewise, it need not be the case that DPDAs are closed under union (this is left as an exercise for the reader). However, all regular languages are recognized by DPDAs.
Lemma 3.4.8. Every regular language is recognized by a DPDA.

Proof. Let \( L \) be a regular language and let \( M \) be a DFA recognizing \( L \). Add a new recognizing vertex to \( M \) with edges labeled \( \epsilon \) from each of the old recognizing vertices, which cease to be recognizing. Then the modified \( M \) is a DPDA recognizing \( L \). \( \square \)

3.5 Simpler Grammars

In this section, we show that we can impose some simple restrictions on the Context Free Grammars and still generate every CFL. The reason to do this is to simplify working with the grammars when we seek to prove certain properties of CFLs. The first will be a pumping Lemma for CFLs; the second is the demonstration that each CFL can be recognized by a PDA. We impose the following restrictions on the right-hand side of a rule.

i. Either a single terminal, e.g. \( A \to a \).

ii. Or the empty string, e.g. \( A \to \lambda \).

iii. Or two variables, e.g. \( A \to BC \).

Given a CFG \( G \), we show how to obtain a simplified grammar \( G' \) obeying the above rules, while generating the same language, i.e. with \( L(G) = L(G') \).

We proceed in a sequence of two steps which enforce the above criteria one by one; each step leaves the generated language unchanged.

**Step 1** For each terminal \( a \), we introduce a new variable, \( U_a \) say, add a rule \( U_a \to a \), and for each occurrence of \( a \) in a string of length 2 or more on the right-hand side of a rule, replace \( a \) by \( U_a \). Clearly, the generated language is unchanged.

Example: If we have the rule \( A \to Ba \), this is replaced by \( U_a \to a \), \( A \to BU_a \).

This ensures that terminals on the right-hand sides of rules obey criteria (i) above.

Nothing needs to be done to enforce criteria (ii).

**Step 2** For each rule with 3 or more variables on the right-hand side, we replace it with a new collection of rules obeying criteria (iii) above. Suppose there is a rule \( U \to W_1 W_2 \cdots W_k \), for some \( k \geq 3 \). Then we create new variables \( X_2, X_3, \cdots, X_{k-1} \), and replace the prior rule with the rules:

\[
U \to W_1 X_2; \quad X_2 \to W_2 X_3; \quad \cdots; \quad X_{k-2} \to W_{k-2} X_{k-1}; \quad X_{k-1} \to W_{k-1} W_k
\]

Clearly, the use of the new rules one after another, which is the only way they can be used, has the same effect as using the old rule \( U \to W_1 W_2 \cdots W_k \). Thus the generated language is unchanged.

This ensures criteria (iii), namely that no right-hand side has more than 2 variables.

One can in fact constrain the right-hand sides of the rules even further while still being able to generate all CFLs. This is a form known as Chomsky Normal Form (CNF for short). In this form, the following additional criteria are imposed.

iv. \( S \) can appear only on the LHS of a rule.
3.6. **SHOWING LANGUAGES ARE NOT CONTEXT FREE**

v. Every RHS of a rule has either no variables or 2 variables (i.e. a RHS consisting of one variable is not allowed).

vi. \(\lambda\) can appear on the RHS of a rule only for the start variable, i.e. the rule \(S \rightarrow \lambda\) is allowed, but for \(A \neq S\), \(A \rightarrow \lambda\) is not allowed.

Demonstrating that every CFL has a CNF grammar is more of a challenge than the simplification we showed, and will be left to the exercises.

### 3.6 Showing Languages are not Context Free

We will do this with the help of a Pumping Lemma for Context Free Languages. To prove this lemma we need two results relating the height of derivation trees and the length of the derived strings, when using CNF grammars.

**Lemma 3.6.1.** Let \(T\) be a derivation tree of height \(h\) for string \(w \neq \lambda\) using simplified grammar \(G\). Then \(w \leq 2^{h-1}\).

**Proof.** The result is easily confirmed by strong induction on \(h\). Recall that the height of the tree is the length, in edges, of the longest root to leaf path.

The base case, \(h = 1\), occurs with a tree of two nodes, the root and a leaf child. Here, \(w\) is the one terminal character labeling the leaf, so \(|w| = 1 = 2^{h-1}\); thus the claim is true in this case.

Suppose that the result is true for trees of height \(k\) or less. We show that it is also true for trees of height \(k + 1\). To see this, note that the root of \(T\) has at most two children, each one being the root of a subtree of height \(k\) or less. Thus, by the inductive hypothesis, each subtree derives a string of length at most \(2^{k-1}\), yielding that \(T\) derives a string of length at most \(2 \cdot 2^{k-1} = 2^{k}\). This shows the inductive claim for \(h = k + 1\).

It follows that the result holds for all \(\geq 1\). \(\square\)

**Corollary 3.6.2.** Let \(w\) be the string derived by derivation tree \(T\) using simplified grammar \(G\). If \(|w| > 2^{h-1}\), then \(T\) has height at least \(h + 1\) and hence has a root to leaf path with at least \(h + 1\) edges and at least \(h + 1\) internal nodes.

Now let’s consider the language \(L = \{a^ib^jc^i \mid i \geq 0\}\) which is not a CFL as we shall proceed to show. Let’s suppose for a contradiction that \(L\) were a CFL. Then it would have a simplified grammar \(G\), with \(m\) variables say. Let \(p = 2^m\).

To prove the pumping lemma for CFLs, we need the notion of a minimal derivation. A minimal derivation never derives the variable \(A\) from itself. For example, if the grammar included the rules \(A \leftarrow B\) and \(B \leftarrow A\) one could have the derivation \(A \Rightarrow B \Rightarrow A\); but one could have a shorter derivation by simply omitting these two steps. Again, if one had the rules \(A \leftarrow AC\) and \(C \leftarrow \lambda\), one could have the derivation \(A \Rightarrow AC \Rightarrow A\); again, one could have a shorter derivation by simply omitting these two steps.

Let’s consider string \(s = a^pb^rc^p \in L\), and look at a minimal derivation tree \(T\) for \(s\). As \(|s| > 2^{m-1}\), by Corollary 3.6.2, \(T\) has a root to leaf path with at least \(m + 1\) internal nodes. Let \(P\) be a longest such path. Each internal node on \(P\) is labeled by a variable, and as \(P\) has at least \(m + 1\) internal nodes, some variable must be used at least twice.
Working up from the bottom of $P$, let $c$ be the first node to repeat a variable label. So on the portion of $P$ below $c$ each variable is used at most once. The derivation tree is shown in Figure 3.21.

Let $d$ be the descendant of $c$ on $P$ having the same variable label as $c$, $A$ say. Let $w$ be the substring derived by the subtree rooted at $d$. Let $vwx$ be the substring derived by the subtree rooted at $c$ (so $v$, for example, is derived by the subtrees hanging from $P$ to its left side on the portion of $P$ starting at $c$ and ending at $d$’s parent). Let $uvwxy$ be the string derived by the whole tree.

**Observation 1.** The height of $c$ is at most $m + 1$. This follows because $P$ is a longest root to leaf path and because no variable label is repeated on the path below node $c$. Hence, by Lemma 3.6.1, $|vwx| \leq 2^m = p$.

**Observation 2.** Either $|v| \geq 1$ or $|x| \geq 1$ (or both). We abbreviate this as $|vx| \geq 1$. This follows because the derivation is minimal, and if both $v = \lambda$ and $x = \lambda$ the derivation would not be minimal.

Let’s consider replicating the middle portion of the derivation tree, namely the wedge $W$ formed by taking the subtree $C$ rooted at $c$ and removing the subtree $D$ rooted at $d$, to create a derivation
3.6. SHOWING LANGUAGES ARE NOT CONTEXT FREE

Note that \( W \)'s root has label \( A \), and the vertex reached by the one edge descending down from \( W \), \( W \)'s child for short, is also labeled by \( A \). Thus \( W \)'s child could be the root of subtree \( D \), but it could also be the root of another copy of \( W \). Consequently, \( W \) plus a nested subtree \( D \) is a legitimate replacement for subtree \( D \). The resulting tree, with two copies of \( W \), one nested inside the other, is a derivation tree for \( uvwxy \). Thus \( uvwxy \in L \).

Clearly, we could duplicate \( W \) more than once, or remove it entirely, showing that all the strings \( uv^iwx^iy \in L \), for any integer \( i \geq 0 \).

Now let's see why \( uvwxy \notin L \). Note that we know that \( |vx| \geq 1 \) and \( |vwx| \leq p \), by Observations 1 and 2. Further recall that \( a^p b^p c^p \) = \( uvwxy \). As \( |vwx| \leq p \), it is contained entirely in either one or two adjacent blocks of letters, as illustrated in Figure 3.23.

Therefore, when \( v \) and \( x \) are duplicated, as \( |vx| \geq 1 \), the number of occurrences of one or two of the characters increases, but not of all three. Consequently, in \( uvwxy \) there are not equal numbers of \( a \)'s, \( b \)'s, and \( c \)'s, and so \( uvwxy \notin L \).

We have shown both that \( uvwxy \in L \) and \( uvwxy \notin L \). This contradiction means that the original assumption (that \( L \) is a CFL) is mistaken. We conclude that \( L \) is not a CFL.

We are now ready to prove the Pumping Lemma for Context Free Languages, which will provide a tool to show many languages are not Context Free, in the style of the above argument.

**Lemma 3.6.3.** (Pumping Lemma for Context Free Languages.) Let \( L \) be a Context Free Language. Then there is a constant \( p = p_L \) such that if \( s \in L \) and \( |s| \geq p \) then \( s \) is pumpable, that is \( s \) can be written in the form \( s = uvwxy \) with

1. \( |vx| \geq 1 \).
2. \( |vwx| \leq p \).
3. For every integer \( i, i \geq 0 \), \( uv^iwx^iy \in L \).

**Proof.** Let \( G \) be a simplified grammar for \( L \), with \( m \) variables say. Let \( p = 2^m \). Let \( s \in L \), where \( |s| \geq p \), and let \( T \) be a derivation tree for \( s \). As \( |s| \geq 2^m - 1 \), by Corollary 3.6.2, \( T \) has a root to leaf path with at least \( m + 1 \) internal nodes. Let \( P \) be a longest such path. Each internal node on \( P \) is labeled by a variable, and as \( P \) has at least \( m + 1 \) internal nodes, some variable must be used at least twice.

Working up from the bottom of \( P \), let \( c \) be the first node to repeat a variable label. So on the portion of \( P \) below \( c \) each variable is used at most one. Thus \( c \) has height at most \( m + 1 \). The derivation tree is shown in Figure 3.21. Let \( d \) be the descendant of \( c \) on \( P \) having the same variable label as \( c \), \( A \) say. Let \( w \) be the substring derived by the subtree rooted at \( d \). Let \( vwx \) be the substring derived by the subtree rooted at \( c \). Let \( uvwxy \) be the string derived by the whole tree.
By Observation 1, c has height at most \( m+1 \); hence, by Lemma 3.6.1, \( vw x \), the string c derives, has length at most \( 2^m = p \). This shows Property (2). Property (1) is shown in Observation 2, above.

Finally, we show property (3). Let’s replicate the middle portion of the derivation tree, namely the wedge \( W \) formed by taking the subtree \( C \) rooted at \( c \) and removing the subtree \( D \) rooted at \( d \), to create a derivation tree for a longer string, as shown in Figure 3.22.

We can do this because the root of the wedge is labeled by \( A \) and hence \( W \) plus a nested subtree \( D \) is a legitimate replacement for subtree \( D \). The resulting tree, with two copies of \( W \), one nested inside the other, is a derivation tree for \( u w w x x y \). Thus \( u w w x x y \in L \).

Clearly, we could duplicate \( W \) more than once, or remove it entirely, showing that all the strings \( u w^i w x x y \in L \), for any integer \( i \geq 0 \).

Next, we demonstrate by example how to use the Pumping Lemma to show languages are not context free. The argument structure is identical to that used in applying the Pumping Lemma for regular languages.

**Example 3.6.4.** \( J = \{w w \mid w \in \{a, b\}^*\} \).

We will show that \( J \) is not context free.

**Step 1.** Suppose, for a contradiction, that \( J \) were context free. Then, by the Pumping Lemma, there is a constant \( p = p_J \) such that for any \( s \in J \) with \( |s| \geq p \), \( s \) is pumpable.

**Step 2.** choose \( s = a^{p+1} b^{p+1} a^{p+1} b^{p+1} \). Clearly \( s \in J \) and \( |s| \geq p \), so \( s \) is pumpable.

**Step 3.** As \( s \) is pumpable we can write \( s \) as \( s = uvwxy \) with \( |vwx| \leq p \), \( |vx| \geq 1 \) and \( uv^iwx'y \in J \) for all integers \( i \geq 0 \). Also, by condition (3) with \( i = 0 \), \( s' = uwy \in J \). We argue next that in fact \( s' \notin J \). As \( |vwx| \leq p \), \( vw x \) can overlap one or two adjacent blocks of characters in \( s \) but no more. Now, to obtain \( s' \) from \( s \), \( u \) and \( x \) are removed. This takes away characters from one or two adjacent blocks in \( s \), but at most \( p \) characters in all (as \( |vx| \leq p \)). Thus \( s' \) has four blocks of characters, with either one of the blocks of \( a \)'s shorter than the other, or one of the blocks of \( b \)'s shorter than the other, or possibly both of these. In every case \( s' \notin J \). We have shown that both \( s' \in J \) and \( s' \notin J \). This is a contradiction.

**Step 4.** The contradiction shows that the initial assumption was mistaken. Consequently, \( J \) is not context free.

**Comment.** Suppose, by way of example, that \( vw x \) overlaps the first two blocks of characters. It would be incorrect to assume that \( v \) is completely contained in the block of \( a \)'s and \( x \) in the block of \( b \)'s. Further, it may be that \( v = \lambda \) or \( x = \lambda \) (but not both). All you know is that \( |vw x| \leq p \) and that one of \( |v| \geq 1 \) or \( |x| \geq 1 \). Don’t assume more than this.
3.6. SHOWING LANGUAGES ARE NOT CONTEXT FREE

When applying the Pumping Lemma, it seems a nuisance to have to handle the cases where one of \( v \) or \( x \) may be the empty string, and fortunately, we can prove a variant of the Pumping Lemma in which both \(|v| \geq 1\) and \(|x| \geq 1\).

**Lemma 3.6.5.** (Variant of the Pumping Lemma for Context Free Languages.) Let \( L \) be a Context Free Language. Then there is a constant \( p = p_L \) such that if \( s \in L \) and \(|s| \geq p\) then \( s \) is pumpable, that is \( s \) can be written in the form \( s = uvwx \) with

1. \(|v|, |x| \geq 1\).
2. \(|vwx| \leq p\).
3. For every integer \( i \), \( i \geq 0 \), \( uv^iwx^iy \in L \).

**Proof.** Let \( \hat{p}_L \) be the pumping constant for the standard pumping lemma applied to \( L \). We will chose \( p_L = 2\hat{p}_L \).

Now let \( s \in L \) be any string of length at least \( p = p_L \).

We apply the standard pumping lemma to \( s \) and conclude that we can write \( s \) as \( s = \hat{u} \hat{v} \hat{w} \hat{x} \hat{y} \) with

1. \(|\hat{v} \hat{x}| \geq 1\).
2. \(|\hat{v} \hat{w} \hat{x}| \leq \hat{p}_L\).
3. For every integer \( i \), \( i \geq 0 \), \( \hat{u} \hat{v}^i \hat{w} \hat{x}^i \hat{y} \in L \).

If both \(|\hat{v}| \geq 1\) and \(|\hat{x}| \geq 1\) then the new result follows on setting \( u = \hat{u} \), \( v = \hat{v} \), \( w = \hat{w} \), \( x = \hat{x} \), \( y = \hat{y} \).

Otherwise, if \(|\hat{v}| \geq 1\) and \(|\hat{x}| = 0\), then we set \( u = \hat{u} \), \( v = \hat{v} \), \( w = \lambda \), \( x = \hat{x} \), \( y = \hat{w} \hat{y} \). We observe that for all \( i \), \( uv^iwx^iy = \hat{u} \hat{v}^i \lambda \hat{v}^i \hat{w} \hat{x} \hat{y} = \hat{u} \hat{v}^{2i} \hat{w} \hat{x}^2 \hat{y} \in L \); we also observe that \(|vw| = 2|\hat{v}| \leq 2|\hat{v} \hat{w} \hat{x}| \leq 2\hat{p}_L = p_L \). Likewise, if \(|\hat{v}| = 0\) and \(|\hat{x}| \geq 1\), then we set \( u = \hat{u} \hat{w} \), \( v = \hat{x} \), \( w = \lambda \), \( x = \hat{x} \), \( y = \hat{y} \). Again, \( uv^iwx^iy \in L \) for all integer \( i \geq 0 \) and \(|vw| \leq p_L \).

The following example uses the yet to be proven result that if \( L \) is context free and \( R \) is regular then \( L \cap R \) is also context free.

**Example 3.6.6.** \( H = \{ z | z \in \{a, b, c\}^* \text{ and } z \text{ has equal numbers of } a\text{'s, } b\text{'s and } c\text{'s} \} \). . . .

Consider \( H \cap a^+b^+c^+ = L = \{a^ib^jc^j \} \). If \( H \) were context free, then \( L \) would be context free too.

But we have already seen that \( L \) is not context free. Consequently, \( H \) is not context free either.

This could also be shown directly by pumping on string \( s = a^{p+q}b^pc^p \).
Example 3.6.7. \( K = \{ a^ib^jc^k \mid i < j < k \} \).
We show that \( K \) is not context free.

**Step 1.** Suppose, for a contradiction, that \( K \) were context free. Then, by the Pumping Lemma, there is a constant \( p = p_K \) such that for any \( s \in K \) with \(|s| \geq p\), \( s \) is pumpable.

**Step 2.** Choose \( s = a^pb^{p+1}c^{p+2} \). Clearly, \( s \in K \) and \(|s| \geq p\), so \( s \) is pumpable.

**Step 3.** As \( s \) is pumpable we can write \( s = uvwx \) with \(|vwx| \leq p\), \(|vx| \geq 1\) and \( uv^iw^jx^k \in K \) for all integers \( i \geq 0 \).

As \(|vwx| \leq p\), \( vw \) can overlap one or two blocks of the characters in \( s \), but not all three. Our argument for obtaining a contradiction depends on the position of \( vx \).

**Case 1.** \( vx \) does not overlap the block of \( c \)’s.
Then consider \( s' = uvwxxy \). As \( s \) is pumpable, by Condition (3) with \( i = 2 \), \( s' \in K \). We argue next that in fact \( s' \not\in K \). As \( v \) and \( x \) have been duplicated in \( s' \), the number of \( a \)'s or the number of \( b \)'s is larger than in \( s \) (or possibly both numbers are larger); but the number of \( c \)'s does not change. If the number of \( b \)'s has increased, then \( s' \) has at least as many \( b \)'s as \( c \)'s, and then \( s' \not\in K \). Otherwise, the number of \( a \)'s increases, and the number of \( b \)'s is unchanged, so \( s' \) has at least as many \( a \)'s as \( b \)'s, and again \( s' \not\in K \).

**Case 2.** \( vx \) does not overlap the block of \( a \)'s.
Then consider \( s' = uvxy \). Again, as \( s \) is pumpable, by Condition (3) with \( i = 0 \), \( s' \in K \). Again, we show that in fact \( s' \not\in K \). To obtain \( s' \) from \( s \), the \( v \) and the \( x \) are removed. So in \( s' \) either the number of \( c \)'s is smaller than in \( s \), or the number of \( b \)'s is smaller (or both). But the number of \( a \)'s is unchanged. If the number of \( b \)'s is reduced, then \( s' \) has at least as many \( a \)'s as \( b \)'s, and so \( s' \not\in K \). Otherwise, the number of \( c \)'s decreases and the number of \( b \)'s is unchanged; but then \( s' \) has at least as many \( b \)'s as \( c \)'s, and again \( s' \not\in K \).

In either case, a pumped string \( s' \) has been shown to be both in \( K \) and not in \( K \). This is a contradiction.

**Step 4.** The contradiction shows that the initial assumption was mistaken. Consequently, \( K \) is not context free.

### 3.7 PDAs Recognize exactly the Context Free Languages

The notion of a leftmost derivation is useful for the next construction.

**Definition 3.7.1.** A leftmost derivation of a string \( s \) by a CFG \( G \) is a derivation in which the leftmost variable in the currently derived string is always the one to be replaced.

The derivations in Example 3.2.3 are both leftmost derivations. Also, a leftmost derivation corresponds to a Depth First traversal of the derivation tree.

**Lemma 3.7.2.** Let \( L \) be a CFL. Then there is a PDA \( M_L \) that recognizes \( L \).

*Proof.* Let \( L \) be generated by simplified grammar \( G_L = (V_L, T, R_L, S_L) \). The corresponding \( M_L \) is illustrated in Figure 3.24. The computation centers on vertex Main. Each return visit to Main corresponds to the simulation of one step of a leftmost derivation in \( G_L \). Specifically

**Claim 3.7.3.** Let \( s \in T^* \) and \( \sigma \in V^* \). Then
3.7. PDAS Recognize Exactly the Context Free Languages

Figure 3.24: PDA $M_L$ simulating CFL $G_L$.

$G_L$ generates string $s\sigma$

exactly if

$M_L$ can reach vertex Main with data configuration $(s, \$\sigma^R)$.

Note that the derivation is always replacing the leftmost symbol in $\sigma$. In order to simulate the derivation’s use of rule $A \rightarrow a$, $M_L$ has a self-loop labeled (Pop $A$, Read $a$). To simulate the use of rule $A \rightarrow \lambda$, $M_L$ has a self-loop labeled (Pop $A$, Read $\lambda$). To simulate the use of rule $A \rightarrow B$, $M_L$ has a self-loop labeled (Pop $A$, Push $B$). To simulate the use of rule $A \rightarrow BC$, $M_L$ will execute the sequence Pop $A$, Push $C$, Push $B$ (remember, $\$\sigma^R$ is on the stack, so the $B$ needs to be at the top of the stack). To achieve this, $M_L$ has an additional vertex called “Sim $A \rightarrow BC$” and edges (Main, “Sim $A \rightarrow BC$”) and (“Sim $A \rightarrow BC$”, Main), labeled (Pop $A$, Push $C$) and Push $B$, respectively. It will be helpful to refer to these actions, that take $M_L$ from vertex Main back to itself, as *supermoves*. So each supermove of $M_L$ corresponds to one derivation step in $G_L$.

A derivation of a terminal string $s$ occurs if $\sigma = \lambda$. To allow this to be recognized, $M_L$ uses a $\$-$shielded stack. Then if $M_L$ is at vertex Main with data-configuration $(s, \$)$, it can pop its stack and move to its recognizing vertex. Thus if we can show the claim it is immediate that $G_L \Rightarrow^* w$ exactly if $M_L$ can reach vertex Main with data configuration $(w, \$)$, which is the case exactly if $M_L$ can reach its recognizing vertex on input $w$, i.e. exactly if $w \in L(M_L)$.

Proof. (Of Claim 3.7.3.) We show the claim in two steps. First, suppose that $G_L \Rightarrow^* s\sigma$. Then there is a leftmost derivation $S = s_1\sigma_1 \Rightarrow s_2\sigma_2 \Rightarrow \cdots \Rightarrow s_{k+1}\sigma_{k+1} = s\sigma$. (In a leftmost derivation, at step $i$, the leftmost variable in $\sigma_i$, for $1 \leq i < k$, is always the one to be replaced using a rule of the grammar. It corresponds to a Depth First Traversal of the derivation tree.) The corresponding
$k$ supermove computation by $M_L$ starts by moving to vertex Main with $\lambda$ read and $SS$ on its stack, i.e. it has data configuration $C_1 = (\lambda, SS) = (s_1, S\sigma_1^R)$. It then proceeds through the following $k$ data configurations at vertex Main: $C_2 = (s_2, S\sigma_2^R), \ldots, C_{k+1} = (s_{k+1}, S\sigma_{k+1}^R) = (s, S\sigma^R)$, and it goes from $C_i$ to $C_{i+1}$, for $1 \leq i \leq k$, by means of the supermove corresponding to the application of the rule taking $s_i\sigma_i$ to $s_{i+1}\sigma_{i+1}$.

Next suppose that $M_L$ reaches vertex Main with configuration $(s, S\sigma^R)$. It does so by means of a computation using $k$ supermoves, for some $k \geq 0$. The computation begins by moving to vertex Main, while reading $\lambda$ and pushing $SS$ on the stack, i.e. it is at configuration $C_1 = (\lambda, SS) = (s_1, S\sigma_1^R)$. It then moves through the following series of data configurations at vertex Main: $C_2 = (s_2, S\sigma_2^R), \ldots, C_{k+1} = (s_{k+1}, S\sigma_{k+1}^R)$, where, for $1 \leq i \leq k$, $C_{i+1}$ is reached from $C_i$ by means of a supermove. By construction, the $i$th supermove corresponds to the application of the rule that takes string $s_i\sigma_i$ to $s_{i+1}\sigma_{i+1}$. Thus, the following is a derivation in grammar $G_L$: $S = s_1\sigma_1 \Rightarrow s_2\sigma_2 \Rightarrow \cdots \Rightarrow s_{k+1}\sigma_{k+1}$. \hfill \square

Now we conclude the proof of the lemma by showing that $L = L(M_L)$.

First, suppose that $w \in L$ i.e. that $G_L$ can generate the string $w = w\sigma$ with $\sigma = \lambda$. Then, by the just proved claim, $M_L$ can reach vertex Main with configuration $(w, S)$. And from this configuration, $M_L$ can follow the edge to its recognizing vertex, by popping the $S$ now at the top of its stack. Thus $w \in L(M_L)$.

Next, suppose that $w \in L(M_L)$. This means that $M_L$ reaches its recognizing vertex having read $w$. But then its last move must be a Pop $S$ from vertex Main. This means that it had reached configuration $(w, S)$ at vertex main. Then, by the claim, $G_L$ can generate string $w$; i.e. $w \in L$. \hfill \square

Lemma 3.7.4. Let $L \subseteq \Sigma^*$ be context-free and let $R \subseteq \Sigma^*$ be regular. Then $L \cap R$ is context free.

Proof. We illustrate the construction we give in this proof in Example 3.7.5 below.

Let $G_L = (V_L, \Sigma, R_L, S_L)$ be a simplified grammar generating $L$ and let $M_R = (V_R, \text{start}, F_R, \delta_R)$ be a DFA recognizing $R$. We will build a grammar $G_{L \cap R} = (V_{L \cap R}, \Sigma, R_{L \cap R}, S_{L \cap R})$ to generate $L \cap R$. Let $V_R = \{q_1, q_2, \ldots, q_m\}$. For each variable $U \in V_L$, we create $m^2$ variables $U_{ij}$ in $V_{L \cap R}$. The rules we create will ensure that:

$U_{ij} \Rightarrow^* w \in \Sigma^*$

exactly if

$U \Rightarrow^* w$ and there is a path labeled $w$ in $M_R$ going from $v_i$ to $v_j$.

Thus a variable in $G_{L \cap R}$ records the name of the corresponding variable in $G_L$ and also records a "start" and a "finish" vertex in $M_R$. The constraint we are imposing is that $U_{ij}$ can generate $w$ exactly if both $U$ can generate $w$ and $M_R$ when started at $q_i$ will end up at $q_j$ on input $w$. It follows that if $q_f$ is a recognizing vertex of $M_R$ and if $q_1 = \text{start}$, then

$(S_L)_{1f} \Rightarrow^* w$ for some $q_f \in F_R$

exactly if

$w \in L \cap R$.

If there is more than one $q_f \in F_R$ we cannot use $(S_L)_{1f}$ as the start variable in $G_{L \cap R}$, as this is not a single variable. Instead, we introduce an additional start variable $S_{R \cap L}$ and add the rules

$\bullet \quad S_{R \cap L} \rightarrow (S_L)_{1f}$ for all $q_f \in F_R$. 


3.7. PDAs RECOGNIZE EXACTLY THE CONTEXT FREE LANGUAGES

To simulate the use of a single rule in $G_L$, together with the corresponding move in $M_R$ in the case that the rule generates a terminal, we create the following rules.

- $A_{ij} \rightarrow a$ if $A \rightarrow a$ is a rule in $G_L$ and $\delta_R(q_i, a) = q_j$.

- $A_{ii} \rightarrow \lambda$ if $A \rightarrow \lambda$ is a rule in $G_L$, for all $i$, $1 \leq i \leq m$.

- $A_{ij} \rightarrow B_{ij}$ if $A \rightarrow B$ is a rule in $G_L$, for all $i, j$, $1 \leq i, j \leq m$.

- $A_{ik} \rightarrow B_{ij}C_{jk}$ if $A \rightarrow BC$ is a rule in $G_L$, for all $i, j, k$, $1 \leq i, j, k \leq m$.

To see why this works, we first consider any non-empty string $w \in L \cap R$ and look at a derivation tree $T$ for $w$ with respect to $G_L$. At the same time we look at a $w$-recognizing path $P$ in $M_R$.

We label each leaf of $T$ with the names of two vertices in $M_R$: the vertices that $M_R$ is at right before and right after reading the input character corresponding to the character labeling the leaf. If we read across the leaves from left to right, recording vertex and character or $\lambda$ labels, we obtain a sequence $p_1w_1p_2, p_2w_2p_3, \ldots, p_nw_np_{n+1}$, where each $w_i$ is either a single character or the empty string, $p_1 = \text{start}$, $p_{n+1} \in F_R$, if $w_i$ is a character then $\delta_R(p_i, w_i) = p_{i+1}$, and if $w_i = \lambda$ then $p_{i+1} = p_i$, for $1 \leq i \leq n$.

Next, we provide vertex labels to the internal nodes in $T$. A node receives as its first label the first label of its leftmost leaf and as its second label the second label of its rightmost leaf. Suppose that $A$ is the variable label at an internal node with children having variable labels $B$ and $C$ (see Figure 3.25).

![Figure 3.25: Vertex Labels in Derivation Tree T: first label on left, second label on right.](image)

Suppose further that $B$ receives vertex labels $p$ and $q$ (in that order), and $C$ receives vertex labels $r$ and $s$. Then $q = r$ and $A$ receives vertex labels $p$ and $s$. To obtain the derivation in $G_{L \cap R}$, we simply replace $A \Rightarrow BC$ by $A_{ps} \Rightarrow B_{pq}C_{qs}$. Similarly, we replace $A \Rightarrow B$ by $A_{pq} \Rightarrow B_{pq}$. In addition, at the leaf level, we replace $A \Rightarrow a$ by $A_{pq} \Rightarrow a$ where $p$ and $q$ are the vertex labels on the leaf (and on its parent), and $A \Rightarrow \lambda$ by $A_{pq} \Rightarrow \lambda$, where $p$ is the start and finish vertex label for the leaf. Clearly, this is a derivation in $G_{L \cap R}$ and further it derives $w$. Thus if $w \in L \cap R$, then $S_{L \cap R} \Rightarrow^* w$, i.e. $w \in (G_{L \cap R})$. 
Example 3.7.5. CFG for $L \cap R$
where $R = a^*bb^*$ and $L$ has grammar $G$ given below.

$G$ is given by the rules:

$$S \rightarrow WX$$
$$W \rightarrow \lambda | aWb$$
$$X \rightarrow \lambda | Xa$$

First, we convert $G$ to a simplified grammar, given the rules:

$$S \rightarrow WX$$
$$W \rightarrow \lambda | U^aY$$
$$Y \rightarrow WU^b$$
$$X \rightarrow \lambda | XU^a$$
$$U^a \rightarrow a$$
$$U^b \rightarrow b$$

We use a 2-vertex automata $M_R$ to recognize $R = a^*bb^*$, as shown in Figure 3.26.

This means that we need up to three versions of each variable, e.g. for $W$ we may need $W_{11}, W_{12}, W_{22}$. $W_{21}$ is not needed as one cannot go from vertex $p_2$ to vertex $p_1$ in $M_R$.

The new grammar has start vertex $S_{12}$ and rules:

$$S_{12} \rightarrow W_{12}X_{22}$$
$$W_{11} \rightarrow \lambda$$
$$W_{12} \rightarrow U^a_{11}Y_{12}$$
$$X_{22} \rightarrow \lambda$$
$$Y_{12} \rightarrow W_{11}U^b_{12} | W_{12}U^b_{22}$$
$$U^a_{11} \rightarrow a$$
$$U^b_{12} \rightarrow b$$
$$U^b_{22} \rightarrow b$$

None of the other variables can generate a string of terminals. For an $a$ can be read by $M_R$ only along the self-loop from $p_1$ to itself, so the only useful copy of variable $U^a$ is $U^a_{11}$. Similarly only $U^b_{12}$ and $U^b_{22}$ are useful. Since $X$ appears only on the RHS of the rule for $S_{12}$ it must be in the form $X_{12}$ or $X_{22}$. The variable $X_{12}$ can only generate $X_{12}U^a_{22}$ or $X_{11}U^a_{12}$, but neither of these forms of $U_a$ can generate terminals. Thus $X$ appears only in the form $X_{22}$, meaning that the only RHS for the rule with $S$ on the LHS is the rule shown. Similarly $W_{12}$ can only be replaced by $U^a_{12}Y_{12}$. The two possible replacements for $Y_{12}$ are as shown. Finally $W_{11}$ can be replaced by $\lambda$ or by $U^a_{11}Y_{11}$; but the only possible replacement for $Y_{11}$ is $W_{11}U^b_{11}$, and we have already ruled out $U^b_{11}$ as a useful variable, which rules out $Y_{11}$ as a useful variable, leaving just the rules shown.

On the other hand, suppose that $S_{L \cap R} \Rightarrow^* w$. Then consider the derivation tree for $w$ in
3.7. PDAS RECOGNIZE EXACTLY THE CONTEXT FREE LANGUAGES

\( G_{L \cap R} \). On removing the root and replacing each variable \( U_i \) by \( U \) we obtain a derivation tree for \( w \) in \( G_L \) (for recall that the root has one child labeled by \((S_L)_{i_f} \) for some \( q_f \in F_R \); the variable replacement process turns this child’s label to \( S_L \)). Thus \( S_L \Rightarrow^+ w \) also. On looking at the leaf level, and labeling each leaf with the vertex indices on the variable at its parent, we obtain a sequence \( p_1 w_1 p_2 p_3 w_2 \cdots p_n w_n p_{n+1} \), where \( w = w_1 w_2 \cdots w_n \), each \( w_i \) is either a single character or the empty string, \( p_1 = \text{start and } p_{n+1} \in F_R \). For each \( w_i \) that is a single character, \( \delta_R(p_i, w_i) = p_{i+1} \), and for each \( w_i = \lambda, \ p_{i+1} = p_i \), for \( 1 \leq i \leq n \), by the first and second rules in the definition of \( G_{L \cap R} \). Now we see that \( p_1 p_2 p_i \cdots p_{n+1} \), minus the duplicated vertices for “reading” \( w_i = \lambda \), is a \( w \)-recognizing path in \( M_R \), and so \( w \in R \). This shows that if \( S_{L \cap R} \Rightarrow^+ w \) then \( w \in L \cap R \).

\[ \text{Figure 3.26: DFA recognizing } a^*bb^*. \]

3.7.1 Construcing a CFG Generating a PDA-Recognized Language

Our final construction will show that if \( L \) is recognized by a PDA, then there is a CFG generating \( L \). The first step in the construction it to represent the computation of the PDA in terms of matching pushes and pops to the stack.

A little more terminology will be helpful.

**Definition 3.7.6.** A computation of \( M \) that goes from vertex \( p \) to vertex \( q \) and begins and ends with \( \sigma \) on the stack is called \( \sigma \)-preserving if throughout the computation \( \sigma \) remains on the stack (possibly with other characters pushed on top some of the time); i.e. none of \( \sigma \) is popped during this part of the computation.

Matching Pushes and Pops: The Trapezoidal Decomposition

Let \( M_L = (Q, T, \Gamma, F, s, \delta) \) be a \( S \)-shielded PDA recognizing \( L \) that has a single recognizing vertex \( f \) which is reachable only with an empty stack (see Lemma 3.4.2). Let us further suppose that on each move \( M_L \) does either a Pop or a Push but not both (if there is a move in which neither a Pop nor a Push occurs, it can be replaced by two moves, the first being an unnecessary Push and the second being a Pop; likewise, a move which has both a Pop and a Push can be replaced by two moves: a Pop followed by a Push). Finally, we suppose that the first step of the computation goes from vertex \( s \) to vertex \( s' \), and this move pushes the \( S \)-shield onto the stack, but does no read (i.e. it reads \( \lambda \)); in addition, \( s \) cannot be visited again, which is ensured by having no in-edges to \( s \). Also note that \( s \) has just the one out-edge. Likewise, we suppose that the last step of a recognizing computation will go from vertex \( f' \) to vertex \( f \), while popping the \( S \)-shield and again reading \( \lambda \); further, this is the only visit to \( f \), which is ensured by having no other in-edges to \( f \) and no out-edges at all. Finally, note that \( s \) and \( f \) are distinct vertices (since one has a single in-edge and the other a single out-edge).
We begin with an example that illustrates the general construction. Consider the following PDA $M_L$ which recognizes the set $L$ of strings with equal numbers of $a$’s and $b$’s. The diagram for $M_L$ is shown in Figure 3.27. Now consider a possible computation of $M_L$ on input $a(ab)(bbaa)(ba)b$

![Diagram](image)

Figure 3.27: PDA recognizing strings with equal numbers of $a$’s and $b$’s.

(the brackets indicate one way of matching the $a$’s and $b$’s). It is helpful to view $M_L$’s computation in terms of a Stack Contents Diagram, as shown in Figure 3.28. It shows the height of the stack evolving as the computation proceeds. The successive nodes in the diagram represent the successive vertices reached by $M_L$ over the course of its computation. For clarity in our example, so as to distinguish the multiple instances of vertex $p$, we name them $p_1, p_2,$ etc. In general, though, we will label a node in the diagram with the name of the corresponding vertex in $M_L$; thus multiple nodes could have the same label. When no confusion will result, we will often name a node by using its label (even when this is not a unique identifier). Also, each read is shown as a label on an edge; so for example in going from $p_1$ to $p_2$ an $a$ is read (i.e. in going from the first visit to vertex $p$ to the second visit to $p$). In addition, the stack contents at any point in the computation can be obtained by reading vertically up the series of trapezoids; e.g. at $p_6$, the stack contents are $\$ABB$.

Notice that the string recognized by this computation can be obtained by concatenating the series of edge labels in left to right order. Our goal is to create a derivation tree that has one leaf for each edge, in the same left to right order, and with each leaf having the same label as the corresponding edge. One way to do this is to introduce one internal node for each trapezoid and one leaf for each edge in the Stack Contents Diagram. Clearly, this derivation tree derives the string recognized by the computation of $M_L$ represented in the Stack Contents Diagram. Of course, we have yet to specify the variables and rules of the grammar that would actually let us generate this derivation tree. But the goal is clear: we want to generate the derivation tree shown in Figure 3.29.

Now we are ready to describe how to create the grammar $G_L$ generating $L$.

**Forming the trapezoids** We associate each node in the Stack Contents Diagram with a matching successor or predecessor node (or possibly both), as follows.
Definition 3.7.7. Nodes \( p \) and \( q \) are matched if \( q \) is the first vertex following \( p \) for which the computation path in \( M_L \), from \( p \) to \( q \) is \( \sigma \)-preserving.

If we draw the edges connecting matched vertices in the Stack Contents Diagram, this naturally partitions the diagram into trapezoids. We call this the Trapezoidal Decomposition. In our example, the first and last vertices are \( s \) and \( f \), and they are matched. All the other vertices are instances of vertex \( p \). Note that \( p^2 \) is matched with \( p^4 \), and \( p^4 \) is also matched with \( p^8 \). (The vertices at a point in the computation where \( M_L \) switches from doing Pops to Pushes will be the ones that are double matched.)

We give each trapezoid \( T \) a name that exactly specifies the two computation steps it represents. Each such name has the form \( T_{pqr}^{ab} \), where the first computation step comprises “Read(\( a \)), Push(\( A \))” operations and goes from vertex \( p \) to vertex \( q \), and the second computation step comprises “Read(\( b \)), Pop” operations and goes from vertex \( r \) to vertex \( s \). Notice that either or both of \( a \) and \( b \) could equal \( \lambda \); indeed, in our example the bottommost trapezoid is \( T_{sppf}^{AAA} \). We will only allow values for the parameters \( A, a, b, p, q, r, s \) that correspond to possible computation steps of \( M_L \) and to emphasize this point we refer to such trapezoids \( T_{pqr}^{ab} \) as realizable trapezoids. In our example, \( T_{pppp}^{Aab} \) is realizable but \( T_{pppp}^{Aaa} \) is not, for opposite characters must be read by the two computation steps represented by a trapezoid.

We also note that the intermediate computation that takes \( M_L \) from \( q \) to \( r \) must be stack-preserving. The consequence is that the Pop performed in \( T \)’s second step pops the very \( A \) pushed in its first step. And so the full computation going from \( p \) to \( s \) is also stack-preserving. We call this computation a phase. Note that the phase starting at node \( p \) is simply the shortest stack-preserving computation beginning at node \( p \).

Let \( \mathcal{P} \) be the phase associated with trapezoid \( T \). We call \( T \) the base trapezoid for \( \mathcal{P} \). If \( T = T_{pqr}^{Aab} \), then \( \mathcal{P} \) consists of \( T \) plus a stack-preserving computation that goes from \( q \) to \( r \). As this computation is stack-preserving, it consists of zero or more (sub)-phases, \( \mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_k \), say,
where $k \geq 0$ (the case $k = 0$ can occur only when $q = r$, though even when $q = r$ it could be that $k \geq 1$). In our example, the phase $P$ that begins at $p^1$ ends at $p^{11}$. $p^1 p^2 p^{10} p^{11}$ is its base trapezoid. $P$ contains three subphases that begin and end at, respectively, $p^2$ and $p^4$, $p^4$ and $p^8$, and $p^8$ and $p^{10}$.

Figure 3.29: Derivation Tree for string $a(ab)(bbaa)(ab)b$ recognized by $M_L$.

If a phase consists of just two steps, we call its base trapezoid a \textit{triangle}. In our example, the subphase which goes from $p^2$ to $p^4$ is a triangle.

A key property of the trapezoids (and phases) is their nesting. Suppose that realizable trapezoid $T$ has $k$ realizable trapezoids $T_1, T_2, \ldots, T_k$ immediately above it in the trapezoidal decomposition. We will say that $T_{i+1}$ follows $T_i$, for $1 \leq i < k$, meaning that the bottom right-hand corner of $T_i$ has the same label as the bottom left-hand corner of $T_{i+1}$. We will also say that $T_1, T_2, \ldots, T_k$ are nested in $T$, meaning that $T$’s top left-hand corner has the same label as the bottom left-hand corner of $T_1$, and $T$’s top right-hand corner has the same label as the bottom right-hand corner of $T_k$, and that $T_{i+1}$ follows $T_i$, for $1 \leq i < k$. In terms of the trapezoid names, we have that $T_i = T_{q_{i-1}q_i q_{i+1}}^{a_{i-1}a_i a_{i+1}}$ for $1 \leq i \leq k$, and $T = T_{q_1q_2q_{k+1}}^{a_{1a_2a_{k+1}}}$, for some $q_1, q_2, \ldots, q_{k+1}$, where each $o$ indicates an unspecified parameter value.

\textbf{The Context Free Grammar} For each realizable trapezoid $T = T_{pqr}^{Aab}$ in the trapezoidal decomposition we will create a node in the derivation tree labeled by a variable $U = U_{pqr}^{Aab}$.

\textbf{Example, continued.} In our example, this yields the following three variables:

\[ U_{spq}^{a}, U_{ppp}^{a}, \text{ and } U_{ppp}^{b}. \]

The start variable in our example is $U_{spq}^{a}$; it corresponds to the initial and final moves of a recognizing computation, which are respectively, a move from vertex $s$ to $p$ pushing $\$\$, and a move from vertex $p$ to $f$ popping this same $\$\$.

Let $T$ be a realizable trapezoid and suppose that realizable trapezoids $T_1, T_2, \ldots, T_k$ are nested inside $T$. Let the corresponding nodes in the derivation tree be named $v$ and $v_1, v_2, \ldots, v_k$, respectively, and let them be labeled by $U$ and $U_1, U_2, \ldots, U_k$, respectively. We will say that $U_1, U_2, \ldots, U_k$ are nested inside $U$ and that $U_{i+1}$ follows $U_i$, for $1 \leq i < k$. 


A Difficulty: High Degree Nodes  However, there is one difficulty: we would like \( v_1, v_2, \ldots, v_k \) to be the children of \( v \) in left to right order. But nodes in a derivation tree can have only bounded degree, so for large \( k \), \( v \) cannot have \( k \) children. Instead, we replace each high degree node with an equivalent subtree of low degree nodes, which we do using the standard construction for representing a tree with high degree nodes using a binary tree. We illustrate the solution for our example in Figure 3.30. In detail, if \( k > 1 \), we introduce \( k - 1 \) vertices \( x_1, \ldots, x_{k-1} \). \( x_1 \) is made the middle child of \( v \) (\( v \)'s other two children being the leaves labeled by \( a \) and \( b \), where \( T = T_a^o b^o \) is the trapezoid corresponding to node \( v \)). For \( 1 \leq i \leq k-2 \), \( x_i \) is given left child \( v_i \) and right child \( x_{i+1} \), while \( x_{k-1} \) is given left child \( v_{k-1} \) and right child \( v_k \).

![Figure 3.30: Derivation Tree including Intermediate Nodes](image)

The Grammar  All that remains is to specify the rules of our grammar.

Suppose that realizable trapezoids \( T_1, T_2, \ldots, T_k \) are nested inside realizable trapezoid \( T \), where \( T \) begins with a “Read \( a \)” operation and ends with a “Read \( b \)”. Then we need to be able to perform the corresponding derivation, namely:

\[
U \Rightarrow^* a U_1 U_2 \cdots U_k b.
\]

If \( k = 0 \) we add the rule

\[
U \rightarrow ab.
\]

If \( k = 1 \) we add the rule

\[
U \rightarrow a U_1 b.
\]

For larger values of \( k \), first recall that \( U_i = U_{q_i q_i q_{i+1}} \) for \( 1 \leq i \leq k \) and \( U = U_{q_k q_k} \). We will introduce \( k - 1 \) intermediate variables \( X_i = X_{q_i q_{i+1}} \) for \( 1 \leq i < k \), where \( X_i \) will be able to derive \( U_i \cdots U_k \). This derivation will use the following rules:

\[
U \rightarrow a X_1 b
\]

\[
X_i \rightarrow U_i X_{i+1}, \text{ for } 1 \leq i \leq k - 2
\]

\[
X_{k-1} \rightarrow U_{k-1} U_k.
\]
To ensure these rules are available we create the following (possibly larger) collection of rules.

\[
\begin{align*}
U_{pqrs}^{A_{ab}} &\to ab, \text{ for all variables } U_{pqrs}^{A_{ab}}, \text{i.e. for all realizable triangles } T_{pqrs}^{A_{ab}}; \\
U_{pqts}^{A_{ab}} &\to aU^{C_{cd}}_{qrst}, \text{ for all variables } U_{pqts}^{A_{ab}} \text{ and } U^{C_{cd}}_{qrst}, \text{i.e. for all realizable } T_{pqts}^{A_{ab}} \text{ and } T_{qrst}^{C_{cd}}; \\
U_{pqrs}^{A_{ab}} &\to aX_{qr}, \text{ for all variables } U_{pqrs}^{A_{ab}}; \\
X_{pt} &\to U_{pqrs}^{A_{ab}}X_{st}, \text{ for all variables } U_{pqrs}^{A_{ab}} \text{ and all } t \in Q; \\
X_{pq} &\to U_{pqrs}^{A_{ab}}U_{styz}^{C_{cd}}, \text{ for all variables } U_{pqrs}^{A_{ab}} \text{ and } U_{styz}^{C_{cd}}.
\end{align*}
\]

**Example, continued.** For our example, this creates the following rules.

\[
\begin{align*}
U_{pppp}^{A_{ab}} &\to U_{pppp}^{A_{ab}} | U_{pppp}^{B_{ba}} | X_{pp} | \lambda \\
U_{pppp}^{A_{ab}} &\to aU_{pppp}^{A_{ab}} | aU_{pppp}^{B_{ba}} | aX_{pp} | ab \\
U_{pppp}^{B_{ba}} &\to bU_{pppp}^{A_{ab}} | bU_{pppp}^{B_{ba}} | bX_{pp} | ba \\
X_{pp} &\to U_{pppp}^{A_{ab}}U_{pppp}^{A_{ab}} | U_{pppp}^{B_{ba}}U_{pppp}^{B_{ba}} | U_{pppp}^{A_{ab}}U_{pppp}^{B_{ba}} | U_{pppp}^{B_{ba}}U_{pppp}^{A_{ab}} \\
X_{pp} &\to U_{pppp}^{A_{ab}}X_{pp} | U_{pppp}^{B_{ba}}X_{pp}
\end{align*}
\]

We let \( G_L \) denote the grammar created by the above construction.

It should be clear that if \( M_L \) recognizes \( w \) then we can build a derivation tree for \( w \) in \( G_L \) as described above, though we will prove this formally in Lemma 3.7.9. We also need to confirm that the only strings having derivation trees are those recognized by \( M_L \), which we do in Lemma 3.7.10. First, we give a preliminary lemma regarding the grammar.

**Lemma 3.7.8.** Suppose that \( U_1, U_2, \ldots, U_k \) are nested inside \( U = U_{pqrs}^{A_{ab}} \). Then there is a derivation \( U \Rightarrow^* aU_1U_2 \cdots U_k b \).

**Proof.** Note that for \( 1 \leq i \leq k \), \( U_i = U_{q_i q_{i+1}}^{q_{i+1}} \), for some \( q_1, q_2, \ldots, q_{k+1} \), with \( q_1 = q \) and \( q_{k+1} = r \), where \( \circ \) denotes an unspecified value.

If \( k = 0 \), then \( q = r \), and the derivation uses the rule \( U_{pqrs}^{A_{ab}} \to ab \) which is a rule because \( U_{pqrs}^{A_{ab}} \) is a variable.

If \( k = 1 \), the derivation uses the rule \( U_{pqrs}^{A_{ab}} = U_{pq_{q_2}}^{A_{ab}} \to aU_{q_1 q_{1+1}}^{q_{1+1}} b = aU_1 b \) which is a rule because \( U_{pq_{q_2}}^{A_{ab}} \) and \( U_1 \) are variables.

For \( k > 1 \), we use the following series of rules to derive \( aU_1U_2 \cdots U_k b \).

i. \( U = U_{pqrs}^{A_{ab}} \to aX_{qr} b = aX_{q_1 q_{k+1}} b \).

ii. In turn, for \( 1 \leq i \leq k - 2 \), \( X_{q_i q_{i+1}} \to U_{q_i q_{i+1}}^{q_{i+1}} X_{q_{i+1} q_{k+1}} = U_i X_{q_{i+1} q_{k+1}} \).

iii. Finally, \( X_{q_k q_{k+1}} \to U_{q_k q_{k+1}}^{q_{k+1}} X_{q_{k+1} q_{k+1}} = U_{k-1} U_k \).

It is readily confirmed that these are all rules of the grammar, and the net effect of applying this series of rules is to make the derivation \( U \Rightarrow^* aU_1U_2 \cdots U_k b \). \( \square \)

**Lemma 3.7.9.** Let \( \sigma \) be read by a phase of \( M_L \)'s computation that goes from vertex \( p \) to vertex \( s \) and has base trapezoid \( T_{pqrs}^{A_{ab}} \). Then, in grammar \( G_L \), \( U_{pqrs}^{A_{ab}} \) can derive \( \sigma \).
Proof. We create the derivation tree, as described above.

We now prove by induction that if a computation corresponding to a Phase $\mathcal{P}$ with base trapezoid $T_{pqrs}^{Aab}$ reads string $\sigma$, then the corresponding derivation tree derives string $\sigma$. If $\mathcal{P}$ corresponds to a triangle, $T_{pqrs}^{Aab}$, then $\mathcal{P}$ reads string $\sigma = ab$ ($r = q$ in this case); also $U_{pqrs}^{Aab} \Rightarrow ab$ is a rule, so $U_{pqrs}^{Aab}$ can derive $ab$.

Otherwise, suppose that $\mathcal{P}$ has base trapezoid $T_{pqrs}^{Aab}$ and subphases $\mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_k$, with base trapezoids $T_1, T_2, \ldots, T_k$. Let $U_i$ be the variable corresponding to $T_i$, for $1 \leq i \leq k$. $T_1, T_2, \ldots, T_k$ are nested inside $T_{pqrs}^{Aab}$. Correspondingly, $U_1, U_2, \ldots, U_k$ are nested inside $U_{pqrs}^{Aab}$. By Lemma 3.7.8, $U \Rightarrow^* aU_1U_2\cdots U_kb$. If the computation corresponding to phase $\mathcal{P}_i$ reads $\sigma_i$ then phase $\mathcal{P}$ reads $a\sigma_1\sigma_2\cdots\sigma_kb = \sigma$. By induction, $U_i$ can derive $\sigma_i$. It follows that $U_{pqrs}^{Aab}$ can derive $a\sigma_1\sigma_2\cdots\sigma_kb = \sigma$.

Lemma 3.7.10. Suppose that, in the grammar $G_L$, $U_{pqrs}^{Aab}$ can derive $\sigma$; then there is a phase of $M_L$'s computation that reads $\sigma$ while going from vertex $p$ to vertex $s$, and which has base trapezoid $T_{pqrs}^{Aab}$.

Proof. Consider a derivation tree for $w$ starting at a root node labeled by variable $U_{pqrs}^{Aab}$. For each node labeled by variable $U_{wxyz}^{Cd}$ create a Phase $\mathcal{P}$ with base trapezoid $T_{wxyz}^{Cd}$. Suppose that variables $U_1, U_2, \ldots, U_k$ are nested inside variable $U$. Let $\mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_k$ and $\mathcal{P}$ be the corresponding phases and let $\mathcal{P}_i$ have base trapezoid $T_i$, for $1 \leq i \leq k$; then $T_1, T_2, \ldots, T_k$ are nested inside $T$.

We argue by induction that the resulting computation is a phase which reads string $\sigma$, and has base trapezoid $T_{pqrs}^{Aab}$. If the derivation tree has two leaf nodes, then the derivation has the form $U_{pqrs}^{Aab} \Rightarrow ab$ ($r = q$ in this case). The corresponding computation comprises a single trapezoid $T_{pqrs}^{Aab}$ which forms a phase, and this computation reads $ab$. Otherwise, suppose that $U_1, U_2, \ldots, U_k$ are nested inside $U_{pqrs}^{Aab}$. Then, by Lemma 3.7.8, $U_{pqrs}^{Aab}$ can derive the sequence $aU_1U_2\cdots U_kb$. For $1 \leq i \leq k$, let $\mathcal{P}_i$ be the subphase created corresponding to the node labeled by variable $U_i$; $\mathcal{P}_i$ has base trapezoid $T_i = T_{q_1s_{q_1+1}}^{a\sigma_i}$, for some $q_1, q_2, \ldots, q_{k+1}$, with $q = q_1$ and $r = q_{k+1}$. Suppose that $U_i$ derives $\sigma_i$ in the derivation tree; then by induction $\mathcal{P}_i$ reads string $\sigma_i$ goes from vertex $q_i$ to $q_{i+1}$ and is a phase. It follows that $\mathcal{P}$ is a phase (for it comprises a base trapezoid along with a sequence of subphases), and it reads string $a\sigma_1\sigma_2\cdots\sigma_kb = \sigma$, and finally it goes from vertex $p$ to vertex $s$.

The main result now follows readily.

Theorem 3.7.11. Let PDA $M_L$ recognize language $L$. Then there is a CFL generating $L$.

Proof. WLOG, assume that $M_L$ has the form assumed in the current section (a single start vertex, a single recognizing vertex, each move performs either a Pop or a Push but not both etc.). Let $G_L$ be the grammar built by the construction of this section. Then, if $M_L$ recognizes string $\sigma$, in must be via a computation with base trapezoid $T_{ss'f'f'}^{\lambda\lambda}$, and by Lemma 3.7.9, $U_{ss'f'f'}^{\lambda\lambda}$ generates $\sigma$, i.e. $\sigma$ is generated by $G_L$. While if $\sigma \in L(G_L)$, $U_{ss'f'f'}^{\lambda\lambda}$ generates $\sigma$, and by Lemma 3.7.10 there is a computation of $M_L$ that reads $\sigma$ while going from $s$ to $f$, i.e. $M_L$ recognizes $\sigma$.

Exercises

1. For the PDA in Figure 3.31 answer the following questions.
CHAPTER 3. TREE STRUCTURED LANGUAGES

![PDA Diagram]

Figure 3.31: Figure for Problem 1.

i. What is its start vertex?

ii. What are its recognizing vertices?

iii. Give the sequence of vertices and associated data configurations the PDA goes through in a recognizing computation on input \textit{abba}. Are there any other computation paths that can be followed on this input, and if yes, give the sequence of vertices such a computation goes through.

iv. What is the language accepted by this PDA?

2. For the PDA in Figure 3.27 answer the following questions.

i. What is its start vertex?

ii. What are its recognizing vertices?

iii. What are the possible stack contents after reading input \textit{ab}?

3. Give PDAs to recognize the following languages. You are to give both an explanation in English of what each PDA does plus a graph of the PDA; seek to label the graph vertices accurately (i.e. for each vertex, specify the possible data configurations reached at that vertex).

i. \( A = \{w \mid w \text{ has odd length, } w \in \{a,b\}^* \text{ and the middle symbol of } w \text{ is an } a\} \)

ii. \( B = \{w \mid w \text{ has even length, } w \in \{a,b\}^* \text{ and the two middle characters of } w \text{ are equal}\} \)

iii. \( C = \{w \mid w \in \{a,b\}^* \text{ and } w \neq a^ib^i \text{ for any integer } i\} \)

iv. \( D = \{wcw^Rx \mid w, x \in \{a,b\}^*\} \)

v. \( E = \{w \mid w \in \{a,b\}^* \text{ and } w \text{ contains equal numbers of } a's \text{ and } b's\} \)

vi. \( F = \{w \mid w \in \{a,b\}^* \text{ and every initial string in } w \text{ contains at least as many } a's \text{ as } b's\} \)

vii. \( H = E \cap F \)

viii. \( I = \{w \mid w \in \{(),[]\}^* \text{, } w \text{ is a string of nested parentheses with each } "(" \text{ matching a } "\)" \text{ to its right, and each } "[" \text{ matching a } "\]" \text{ also to its right}\} \)
ix. \( J = \{ w\#x \mid w, x \in \{a, b\}^* \text{ and } w^R \text{ is an initial substring of } x \} \).

Hint: \( x \) can be written as \( x = w^R y \) for some \( x \in \{a, b\}^* \). Also note that \( \# \) is just another character.

x. \( K = \{ x \mid x \in \{a, b\}^* \text{ and } x \neq w w^R \text{ for any } w \in \{a, b\}^* \} \).

4. Suppose that \( A \) is recognized by PDA \( M \). Give a PDA to recognize \( A^* \).

5. Let \( C \) be a language over the alphabet \( \{a, b\} \).
   i. Let \( \text{Suffix}(C) = \{ w \mid \text{there is a } u \in \{a, b\}^* \text{ with } uw \in C \} \). Show that if \( C \) is recognized by a PDA then so is \( \text{Suffix}(C) \).
   ii. Similarly, let \( \text{Prefix}(C) = \{ w \mid \text{there is an } x \in \{a, b\}^* \text{ with } wx \in C \} \). Show that if \( C \) is recognized by a PDA then so is \( \text{Prefix}(C) \).

6. This problem aims to show that there is a PDA recognizing the following language: \( \{ s\#t \mid s, t \in \{a, b\}^* \text{ and } s \neq t \} \).
   i. Let \( A = \{ uv\#x y \mid u, v, x, y \in \{a, b\}^* \text{ and } (|u| - |v|) = (|x| - |y|) \} \). Give a PDA to recognize \( A \).
   ii. Let \( B = \{ w\#z \mid w, z \in \{a, b\}^* \text{ and } |w| \neq |z| \} \). Give a PDA to recognize \( B \).
   iii. Show that \( A \cup B = \{ s\#t \mid s, t \in \{a, b\}^* \text{ and } s \neq t \} \).

7. Consider the PDA in Figure 3.31. Add descriptors to the vertices. What language does this PDA recognize?

8. Give DPDA\( s \) to recognize the following languages. You are to give both an explanation in English of what each DPDA does plus a graph of the DPDA; seek to label the graph vertices accurately (i.e. for each vertex, specify the possible data configurations reached at that vertex).
   i. \( A = \{ wcx \mid w, x \in \{a, b\}^* \text{ and } |w| = |x| \} \)
   ii. \( B = \{ w \mid w \in \{a, b\}^* \text{ and } w \neq a^i b^i \text{ for any integer } i \} \)
   iii. \( C = \{ wcw^R \mid w \in \{a, b\}^* \} \)
   iv. \( D = \{ wcx \mid w, x \in \{a, b\}^* \text{ and } w \neq x^R \} \)
   v. \( E = \{ w \mid w \in \{a, b\}^* \text{ and } w \text{ contains equal numbers of } a's \text{ and } b's \} \)
   vi. \( F = \{ w \mid w \in \{a, b\}^* \text{ and } \text{ every initial string in } w \text{ contains at least as many } a's \text{ as } b's \} \)
   vii. \( F = E \cap F \)
   viii. \( H = \{ w \mid w \in \{(, [\}, [\}, \}^* \), \( w \) is a string of nested parentheses with each "(" matching a ")" to its right, and each "[" matching a "]" also to its right.
   ix. \( I = \{ w\#x \mid w, x \in \{a, b\}^* \text{ and } w^R \text{ is an initial substring of } x \} \).

Hint: \( x \) can be written as \( x = w^R y \) for some \( x \in \{a, b\}^* \). Also note that \( \# \) is just another character.

9. Assuming that the complement of a language recognized by a DPDA is also recognized by a DPDA, show that DPDA\( s \) are not closed under union; i.e. give two languages \( L_1 \) and \( L_2 \) which are recognized by DPDA\( s \), and show that \( L_1 \cup L_2 \) is not recognized by any DPDA.
10. This exercise will show that DPDA s are closed under complementation. Let $M$ be a DPDA recognizing language $L$. $M$ will be modified as follows while leaving the language it recognizes unchanged.

i. Duplicate each vertex, partitioning the incoming edges so that each new vertex has the same label on all its incoming edges.

ii. Perform the following changes. Suppose the two successive edges $(u, v)$ and $(v, w)$ have the following edge labels.

- $(\text{Read } \lambda, \text{Pop } A, \text{Push } B)$, $(\text{Read } \lambda, \text{Pop } B)$, where $A, B \neq \lambda$, but perhaps $A = B$. Then replace these two edges with edge $(u, w)$ labeled by $(\text{Read } \lambda, \text{Pop } A)$.
- $(\text{Read } \lambda, \text{Push } B)$, $(\text{Read } \lambda, \text{Pop } B)$, where $B \neq \lambda$. Then change all the inedges to $u$ to be inedges to $w$ instead, and remove edge $(u, v)$.
- $(\text{Read } \lambda, \text{Push } B)$, $(\text{Read } \lambda, \text{Pop } C)$ where $B, C \neq \lambda$, and $B \neq C$. Then remove edge $(v, w)$.
- $(\text{Read } \lambda, \text{Pop } A, \text{Push } B)$, $(\text{Read } \lambda, \text{Pop } C)$ where $A, B, C \neq \lambda$, and $B \neq C$. Then remove edge $(v, w)$.

Now conclude that each cycle of edges with labels that all include Read $\lambda$ must all have labels with a Push but no Pop, or a Pop but no Push (where we mean these operations to be on actual characters, and not $\lambda$).

iii. Replace each such cycle with Push labels by a single vertex.

Conclude that there are no infinite computational loops in the resulting machine.

Show what further modifications are needed to make it recognize $\overline{L}$.

11. Consider the following context free grammar: $S \rightarrow (S) | [S] | SS | ( ) | [ ]$

i. What are its terminals?

ii. What are its variables?

iii. What are its rules?

iv. Show the derivation tree for string $([ ] ( ))$.

v. Describe in English the set of strings generated by this grammar.

12. Consider the following context free grammar:

$$S \rightarrow XY$$

$$X \rightarrow aXb | \lambda$$

$$Y \rightarrow cYd | \lambda$$

i. What are its terminals?

ii. What are its variables?

iii. What are its rules?

iv. Show the derivation tree for string $abcd$. 

v. Describe in English the set of strings generated by this grammar.

13. Consider the following context free grammar:

\[ S \rightarrow XY \]
\[ X \rightarrow aXb \mid aYb \mid \lambda \]
\[ Y \rightarrow cYd \mid \lambda \]

i. What are its terminals?
ii. What are its variables?
iii. What are its rules?
iv. Show the derivation tree for string acdb.
v. Describe in English the set of strings generated by this grammar.

14. Consider the following context free grammar:

\[ S \rightarrow XY \mid YX \]
\[ X \rightarrow aXb \mid \lambda \]
\[ Y \rightarrow cXd \mid cYd \mid \lambda \]

i. What are its terminals?
ii. What are its variables?
iii. What are its rules?
iv. Describe in English the set of strings generated by this grammar.
v. Give a simpler grammar for this language.

15. Give CFG's to generate the following languages. Remember to specify for each variable the set of strings it generates. Of course, \( S \), the start variable, should generate the language in question.

i. \( A = \{ w \mid w \text{ has odd length}, w \in \{a, b\}^* \text{ and the middle character of } w \text{ is an } a \} \).
ii. \( B = \{ w \mid w \text{ has even length}, w \in \{a, b\}^* \text{ and the two middle characters of } w \text{ are equal} \} \).
iii. \( C = \{ w \mid w \in \{a, b\}^* \text{ and } w \neq a^i b^i \text{ for any integer } i \} \).
iv. \( D = \{ w \mid w \in \{a, b\}^* \text{ and } w = w^R \} \). \( D \) is the language of palindromes, strings that read the same forward and backward.
   Hint: Be sure to handle strings of all possible lengths.
v. \( E = \{ wcw^Rx \mid w, x \in \{a, b\}^* \} \).
vi. \( F = \{ w \mid w \in \{a, b\}^* \text{ and } w \text{ contains an equal number of } a's \text{ and } b's \} \).
   Hint: suppose that the first character in \( w \) is an \( a \). Let \( x \) be the shortest initial substring of \( w \) having an equal number of \( a's \) and \( b's \). If \( |x| < |w| \), then \( w \) can be written as \( w = xy \); what can you say about \( y \)? Otherwise, \( x = w \) and \( w \) can be written as \( w = axb \); what can you say about \( z \)?
vii. $H = \{ w \mid w \in \{a, b\}^* \text{ and every initial string in } w \text{ contains at least as many } a \text{'s as } b \text{'s} \}$.

viii. $I = E \cap F$.

ix. $J = \{ w \mid |w| \in \{(,)[,] \}^* \text{, } w \text{ is a string of nested parentheses with each } ( \text{ matching } a \text{ ) to its right, and each } [ \text{ matching } a \text{ ] also to its right} \}$.

x. $K = \{ w#x \mid w, x \in \{a, b\}^* \text{ and } w^R \text{ is an initial substring of } x \}$.

Hint: $x$ can be written as $x = w^Ry$ for some $x \in \{a, b\}^*$.

16. i. Let $E = \{a^ib^j \mid i < j \}$. Give a CFG to generate $E$.

ii. Let $F = \{a^ib^j \mid 2i > j \}$. Give a CFG to generate $F$.

iii. Let $J = \{a^ib^j \mid i < j < 2i \}$. Give a CFG to generate $J$.

Hint: Let $i = h + l$ and $j = h + 2l$. What can you say about $h$ and $l$?

17. Give a context free grammars to generate the following languages. Remember to specify for each variable the set of strings it generates.

i. $L_1 = \{a^ib^j+c^a \mid i, j \geq 0 \}$. (Recall that $#$ is just another character.)

ii. $L_2 = \{ w#x\$y \mid w, x, y \in \{a, b\}^* \text{ and } |x| = |w| + |y| \}$.

iii. $L_3 = \{ uv \mid |u| = |v| \text{ but } u \neq v \}$.

Hint: think of the $#$ and the $\$ from part (2) as a pair of aligned yet unequal characters in $u$ and $v$; what is the relation among the lengths of the remaining pieces of $u$ and $v$?

Further hint: Use the ideas from the first two parts.

18. Let $A$ be a CFL generated by a CFG $G_A$. Give a CFG grammar $G_{A^*}$, based on $G_A$, to generate $A^*$. Show that $L(G_{A^*}) = A^*$.

19. Convert the following grammars to simplified form—see Section 3.5.

i. $G_1$ has start variable $S$, terminal set $\{a, b\}$ and rule $S \rightarrow ab$.

ii. $G_2$ has start variable $S$, terminal set $\{a, b, c, d\}$ and rules $S \rightarrow ABCD$, $A \rightarrow a$, $B \rightarrow b$, $C \rightarrow c$, $D \rightarrow d$.

20. This exercise derives an algorithm to convert a grammar to Chomsky Normal Form (CNF)—see Section 3.5. Let $G$ be a grammar in simplified form.

i. We start by removing $S$ from the RHS of any rule in which it appears. Simply add a new variable $S'$ and use it to replace $S$ in every rule in which $S$ appeared, and then add the rule $S \rightarrow S'$.

Argue that the resulting grammar $G'$ generates the same language as $G$: $L(G') = L(G)$.

ii. Next, we will remove $\lambda$ from the RHS of all rules except possibly a rule with $S$ on the LHS. Begin by using the following method to determine the set of variables that can generate $\lambda$:

For each rule of the form $A \rightarrow \lambda$ add $A$ to the set.

For each rule of the form $A \rightarrow B$ with $B$ in the set, add $A$ to the set.

For each rule of the form $A \rightarrow BC$ with both $B$ and $C$ in the set, add $A$ to the set.
Iterate this process until the set of these variables grows no further.

Then we modify the grammar as follows.

- Remove all rules of the form \( A \rightarrow \lambda \).

- If \( S \) is in the set include the rule \( S \rightarrow \lambda \) in the grammar.

- Finally, for each rule \( A \rightarrow BC \), if \( B \) is in the set, include \( A \rightarrow C \) in the grammar,
  and if \( C \) is in the set, include \( A \rightarrow B \) in the grammar.

Argue that the resulting grammar \( G'' \) generates the same language as \( G' \): \( L(G'') = L(G') \).

iii. Now we give an algorithm to remove all rules of the form \( A \rightarrow B \). We say the variables \( A_1, A_2, \ldots, A_k \) are equivalent if there is sequence of rules \( A_1 \rightarrow A_2, A_2 \rightarrow A_3, \ldots, A_{k-1} \rightarrow A_k \). We will identify all equivalent variables, and replace each collection of equivalent variables by a new single variable. So in the above instance we would replace each occurrence of \( A_1, A_2, \ldots, A_k \) in any rule by the new variable \( A \) say. We then remove all the copies of the resulting rule \( A \rightarrow A \).

Give an algorithm to identify all equivalent variables.

Argue that the resulting grammar generates the same language as the original grammar.

Next, for each sequence of rules \( A_1 \rightarrow A_2, A_2 \rightarrow A_3, \ldots, A_{k-1} \rightarrow A_k \), we add the rules \( A_1 \rightarrow A_2, A_1 \rightarrow A_3, A_1 \rightarrow A_k \) (and \( A_2 \rightarrow A_4, \ldots, A_2 \rightarrow A_k \), etc.).

Give an algorithm to perform these changes, and argue that the resulting grammar generates the same language as the original grammar.

Finally, for each pair of rules \( A \rightarrow B, B \rightarrow b \) we add the rule \( A \rightarrow b \), and for each pair of rules \( A \rightarrow B, B \rightarrow CD \) we add the rule \( A \rightarrow CD \). We finish by removing all rules of the form \( A \rightarrow B \).

Give an algorithm to identify all changes, and argue that the resulting grammar generates the same language as the original grammar.

At this point the grammar is in CNF form.

21. Convert the following CFGs to CNF form—see Section 3.5.

i. \( G_1 \) has start variable \( S \), terminal set \( \{a, b\} \) and rules \( S \rightarrow A, A \rightarrow B | SA | a, B \rightarrow C | b, C \rightarrow a \).

ii. \( G_2 \) has start variable \( S \), terminal set \( \{a, b\} \) and rules \( S \rightarrow AB, A \rightarrow a | \lambda, B \rightarrow b | \lambda \).

iii. \( G_3 \) has start variable \( S \), terminal set \( \{a, b\} \) and rules \( S \rightarrow AB, A \rightarrow X | BB | a, X \rightarrow Y | AA, Y \rightarrow A | AB, B \rightarrow b \).

22. Show that the following languages are not context free.

i. \( A = \{a^i b^j c^k | i, j, k \geq 0\} \).

ii. \( B = \{a^m b^n c^m d^n | m, n \geq 0\} \).

iii. \( C = \{z | z \in \{a, b, c\}^* \text{ and the number of } a's, b's \text{ and } c's \text{ in } z \text{ are all equal}\} \).

iv. \( D = \{z_1 \# z_2 \# z_3 | z_1, z_2, z_3 \in \{a, b\}^*, \text{ the number of } a's \text{ in } z_1 \text{ equals } |z_2|, \text{ and the number of } b's \text{ in } z_2 \text{ equals } |z_3| \} \).
v. \( E = \{ z \mid z \in \{a, b, c, d\}^* \text{ and } z \text{ contains equal numbers of } a \text{'s and } b \text{'s, and equal numbers of } c \text{'s and } d \text{'s} \} \).

vi. \( F = \{ a^i b^i \mid i \geq 1 \} \).

Comment. Any CFL over a 1-character alphabet is a regular language. Give a proof without using this fact.

vii. \( H = \{ a^i b^i \mid i \geq 0 \} \).

Comment. Any CFL over a 1-character alphabet is a regular language. Give a proof without using this fact.

viii. \( J = \{ z_1 \# z_2 \# \cdots \# z_l \mid z_h \in \{a, b\}^*, 1 \leq h \leq l, \text{ and for some } i, j, k, 1 \leq i < j < k \leq l, \quad |z_i| = |z_j| = |z_k| \} \).

ix. \( K = \{ z_1 \# z_2 \# \cdots \# z_k \mid z_h \in \{a, b\}^*, 1 \leq h \leq k, \text{ and for some } i, j, 1 \leq i < j \leq k, \quad z_i = z_j \} \).

x. \( L = \{a^i b^j \mid i \text{ is an integer multiple of } j \} \).

xi. \( N \) is the language consisting of all palindromes over the alphabet \( \Sigma = \{a, b, c\} \) having equal numbers of \( a \)'s and \( b \)'s.

xii. \( P = \{ a^i b^j c^j \mid j > i \} \).

xiii. \( Q = \{ a^i b^j c^k \mid k = \max\{i, j\} \} \).

xiv. \( R = \{ a^i b^j c^j \mid j > i \} \).

23. This exercise concerns a variant of the Pumping Lemma, called Ogden’s Lemma. Ogden’s Lemma is useful for it can be used to show certain languages are not CFLs, languages for which the standard pumping lemma does not suffice.

i. Let \( L \) be a CFL and let \( s \in L \) be a string in which some characters have been marked. Ogden’s Lemma states that there is a constant \( p = p_L \) such that if \( s \in L \) is a string with at least \( p \) marked characters then \( s \) can be written as \( s = uvwx \), where

a. \( vx \) contains at least one marked character.

b. \( vwx \) contains at most \( p \) marked characters.

c. For all \( i \geq 0 \), \( uv^iwx^i \in L \).

Prove Ogden’s Lemma.

Hint. Proceed in the same way as for the proof of the standard pumping lemma. In order to obtain analogs of Observations 1 and 2 you will need to count just the marked characters; you will also need to redefine the notion of “height” to count just those internal nodes with two subtrees both of which have marked characters.

ii. Prove a variant of Ogden’s Lemma in which both \( v \) and \( x \) contain at least one marked character.

iii. Using Ogden’s Lemma prove that the following languages are not context free.

a. \( L = \{a^i b^j c^k d^l \mid i = 0 \text{ or } j = k = l \} \).

Why will the ordinary Pumping Lemma fail to prove that \( L \) is not a CFL, i.e. show that any string \( s \in L \) can be pumped so that all the resulting strings are in \( L \).
Exercises

b. \( K = \{a^i b^j c^j \mid j \neq i\} \).

Hint. Consider the string \( s = a^p b^p s^p \).

Again, why will the ordinary Pumping Lemma fail to prove that \( L \) is not a CFL, i.e. show that any string \( s \in L \) can be pumped so that all the resulting strings are in \( L \).

24. Show the PDAs generated by applying the construction of Lemma 3.7.2 to the following context free grammars.

i. \( S \rightarrow AB, A \rightarrow AA, A \rightarrow a, B \rightarrow b. \)

ii. \( S \rightarrow XX | \lambda; X \rightarrow a. \)

25. Consider the PDA shown in Figure 3.9.

i. Modify this PDA so that it meets the requirements given in Section 3.7.1. (Do this carefully.)

ii. Draw the trapezoidal diagram for the computation of the modified PDA recognizing input \( aabb. \)

iii. Give the CFL generated by applying the construction of Section 3.7.1 to the modified PDA.

26. Repeat Question 25 for PDA \( M_2 \) shown in Figure 3.11 but use input \( aacbba \) for part (iii).

27. Repeat Question 25 for PDA \( M_3 \) shown in Figure 3.12 but use input \( abcbab \) for part (iii).

28. For each of the language transformations \( T \) defined in the parts below, answer the following two questions.

a. Suppose that \( L \) is a CFL. Show that \( T(L) \) is also a CFL by giving a CFG to generate \( T(L) \). Remember to explain why your solution is correct.

b. Now suppose that \( L \) is recognized by a PDA. Show that \( T(L) \) is also recognized by a PDA. Again, remember to explain why your solution is correct.

Comment: The two parts are equivalent; nonetheless, you are being asked for a separate construction for each part.

i. Let \( w \in \{a, b, c\}^* \). Define \( Sbst(w, a, b) \) to be the string obtained by replacing all instances of the character \( a \) in \( w \) with \( b \). e.g. \( Sbst(ac, a, b) = bc, Sbst(cc, a, b) = cc, Sbst(abc, a, b) = bbb, Sbst(acacac, a, b) = bcbcbc. \)

Let \( L \) be a language over the alphabet \( \{a, b, c\} \). Define \( T(L) = Sbst(L, a, b) = \{x \mid x = Sbst(w, a, b) \text{ for some } w \in L\}. \)

ii. Let \( w \in \{a, b, c\}^* \). Define \( OneSubst(w, a, b) \), or \( OS(w, a, b) \) for short, to be the set of strings obtained by replacing one instance of the character \( a \) from \( w \) with a \( b \). e.g. \( OS(acacac, a, b) = \{bcacac, abacac, acaacbc}. \)

Let \( L \) be a language over the alphabet \( \{a, b, c\} \). Define \( T(L) = OS(L, a, b) = \{x \mid x = OS(w, a, b) \text{ for some } w \in L\}. \)
iii. Let \( w \in \{a, b, c\}^* \). Define \( \text{Remove-c}(w) \) to be the string obtained by deleting all instances of the character \( c \) from \( w \). e.g. \( \text{Remove-c}(ab) = ab \), \( \text{Remove-c}(cc) = \lambda \), \( \text{Remove-c}(abc) = ab \), \( \text{Remove-c}(acacac) = aaa \).

Let \( L \) be a language over the alphabet \( \{a, b, c\} \). Define \( T(L) = \text{Remove-c}(L) = \{ x \mid x = \text{Remove-c}(w) \text{ for some } w \in L \} \).

iv. Let \( w \in \{a, b, c\}^* \). Define \( \text{Remove-One-c}(w) \) to be the set of strings obtained by deleting one instance of the character \( c \) from \( w \). e.g. \( \text{Remove-One-c}(acacac) = \{aacac, acaac, acaca\} \).

Let \( L \) be a language over the alphabet \( \{a, b, c\} \). Define \( T(L) = \text{Remove-One-c}(L) = \{ x \mid x \in \text{Remove-One-c}(w) \text{ for some } w \in L \} \).

v. Let \( h \) be a mapping from \( \Sigma \) to \( \Sigma^* \), that is \( h \) maps each character in \( \Sigma \) to a string of zero or more characters. Define \( h(s) \) for a string \( s = s_1s_2\cdots s_k \) to be the string \( h(s_1)h(s_2)\cdots h(s_k) \).

Define \( T(L) = \{ h(w) \mid w \in L \} \).

vi. Let \( h \) be a mapping from \( \Sigma \) to \( R \) where \( R \) is the set of regular expressions over alphabet \( \Sigma \); i.e. \( h(a) \) is a regular expression for each \( a \in \Sigma \). Define \( h(s) \) for a string \( s = s_1s_2\cdots s_k \) to be the set of strings specified by the regular expression \( h(s_1)h(s_2)\cdots h(s_k) \).

Define \( T(L) = \bigcup_{w \in L} h(w) \).

vii. Let \( \Sigma \) be an alphabet, and for each \( a \in \Sigma \) let \( L_a \) be a CFL. Let \( w = w_1w_2\cdots w_k \) be a string in \( \Sigma^* \). Define \( h(w) = L_{w_1} \circ L_{w_2} \circ \cdots \circ L_{w_k} \).

Define \( T(L) = \bigcup_{w \in L} h(w) \).

29. i. Show that \( \{b^ic^jd^i \mid j \geq 0\} \) is not a CFL.

ii. Conclude that \( \{a^ib^jc^kd^i \mid i \geq 0 \text{ and } j = k = l\} \) is not a CFL.

iii. Let \( L = \{a^ib^jc^kd^i \mid i = 0 \text{ or } j = k = l\} \). See Problem 28v. By using a suitable mapping \( h \) from \( \Sigma \) to \( \Sigma^* \), show that \( L \) is not a CFL.

Comment. See Problem 23.iii.a. Note that Ogden’s Lemma is not needed to show \( L \) is not a CFL.

30. A 2wayPDA is a variant of a PDA in which it is possible to go back and forth over the input, with no limit on how often the reading direction is reversed.

This can be formalized as follows. The input \( x \in \Sigma^* \) to the PDA is sandwiched between symbols $ and $, so the PDA can be viewed as reading string \( x_0x_1x_2\cdots x_nx_{n+1} \), where \( x = x_1x_2\cdots x_n \), \( x_0 = $ \), and \( x_{n+1} = $ \). The PDA is equipped with a read head which will always be over the next symbol to be read. At the start of the computation, the read head is over the symbol \( x_1 \), and the PDA is at its start vertex.

In general, the PDA will be at some vertex \( v \), with its read head over character \( x_i \) for some \( i, 0 \leq i \leq n + 1 \). On its next move the PDA will follow an edge leaving \( v \) whose label includes Read \( x_i \). This edge will also carry a label L or R indicating whether the read head moves left (so that it will be over symbol \( x_{i-1} \)), or right (so that it will be over \( x_{i+1} \)). Note that as we can do two moves in succession say to the left and then to the right, there is no need for a Read \( \lambda \) operation, which would leave the read head in the same place. There are two constraints: when reading $ only moves to the right are allowed and when reading $ only moves to the left are allowed. If there is no move, the computation ends.
A 2wayPDA \( M \) recognizes an input \( x \) if it is at a recognizing vertex when the computation ends.

Give descriptions in English of 2way-PDAs for the following languages.

i. \( L = \{a^ib^ic^i \mid i \geq 0\}. \)
   Note that by contrast with 2wayDFAs, this shows 2wayPDAs can recognize languages not recognized by PDAs.

ii. Show that if \( L_1 \) and \( L_2 \) are recognized by a 2wayPDA then so are \( L_1 \cup L_2 \) and \( L_1 \cap L_2 \).

31. Define 2wayDPDAs analogous to the 2wayPDAs in Question 30. Again, there is a read head, but the 2wayDPDA always has at most one move.
   Show that 2wayDPDAs are closed under intersection, union and complement.

32. Show that the following languages can be recognized by 2wayDPDAs.

   *i. \( H = \{a^ib^{2i} \mid i \geq 1\}. \)
      Hint. An intermediate data configuration will have \( a^{i-h}b^{2h} \) for \( h \leq i \) on the stack.

   *ii. \( J = \{a^ib^i \mid i \geq 0\}. \)
      Hint. Find another helpful intermediate data configuration.

   *iii. \( J_c = \{a^ib^c \mid i \geq 0\}, \) where \( c \geq 2 \) is a fixed integer.

   *iv. \( K = \{a^ib^jc^{i+j} \mid i, j \geq 0\}. \)
      Hint. You will need to count in two ways. At times the stack contents will be used as a counter. At other times the position of the read head in the string of \( c \)'s will serve as a counter.