Converting a DFA into a regular expression

Here is a detailed, formal exposition of the conversion of a DFA into an equivalent regular expression, based on the dynamic programming idea we described in class. I am giving you these notes because this exposition differs quite a bit from that in your textbook. You are required to read and understand this material completely. For your exams, please be prepared to write proofs with this level of detail.

**Theorem:** If the language $L$ is recognized by a DFA, then it is generated by a regular expression.

**Proof:** Let $M = (\{q_1, \ldots, q_n\}, \Sigma, \delta, q_1, F)$ be a DFA that recognizes $L$. For $i, j \in \{1, \ldots, n\}$ and $k \in \{0, \ldots, n\}$, let $R_{ij}^k$ denote the set of all strings in $\Sigma^*$ that take the DFA $M$ from state $q_i$ to state $q_j$ without “going through” any state numbered higher than $q_k$. By “going through” we mean both entering and leaving, so the starting point $q_i$ and the end point $q_j$ are allowed to be numbered higher than $q_k$. To make this precise, we use a function $\hat{\delta} : Q \times \Sigma^* \rightarrow Q$ with the following “meaning:”

Imagine putting $M$ into state $q$ and then feeding it the string $w \in \Sigma^*$ as input. This leaves the DFA in a certain state after it processes the input; that state is denoted $\hat{\delta}(q, w)$.

A precise definition of $\hat{\delta}$ can be given using recursion, as follows:

$$
\hat{\delta}(q, \varepsilon) = q, \quad \forall q \in Q; \\
\hat{\delta}(q, xa) = \hat{\delta}(\hat{\delta}(q, x), a), \quad \forall q \in Q, x \in \Sigma^*, a \in \Sigma.
$$

Using $\hat{\delta}$, we can define $R_{ij}^k$ precisely:

$$
R_{ij}^k = \left\{ x \in \Sigma^* : \hat{\delta}(q_i, x) = q_j \text{ and } x \text{ does not have a prefix } y, \text{ with } y \neq \varepsilon \right\}
$$

and

$$
\hat{\delta}(q_i, y) = q_m \text{ where } m > k.
$$

Now we shall prove, by induction on $k$, that each of the sets $R_{ij}^k$ is generated by a regular expression. The base case is $k = 0$. According to the definition, a string in $R_{ij}^0$ must take $M$ from $q_i$ to $q_j$ without going through any intermediate states at all, because every state of $M$ is numbered higher than $q_0$. This makes it clear that

$$
R_{ij}^0 = \{ a \in \Sigma : \delta(q_i, a) = q_j \}, \quad \text{if } i \neq j, \text{ and}
$$

$$
R_{ii}^0 = \{ \varepsilon \} \cup \{ a \in \Sigma : \delta(q_i, a) = q_i \}.
$$

The important thing is that these are finite sets, so each of them is generated by a simple regular expression that simply lists out all the strings in the set and combines them using “∪”.

We now turn to the induction step. Suppose $1 \leq k \leq n$. The strings in $R_{ij}^k$ can be divided into two classes: those that do not take $M$ through state $q_k$ and those that do. The strings in the former class clearly do not take $M$ through any state numbered higher than $q_{k-1}$; therefore these strings are in fact in $R_{ij}^{k-1}$. It is also clear that a string which takes $M$ from $q_i$ to $q_j$ avoiding states numbered higher than $q_{k-1}$ also avoids states numbered higher than $q_k$; so, $R_{ij}^{k-1}$ is exactly the set of strings in the former class.

Now let us focus on the latter class; let $x$ be a string in this latter class. When $M$ is put in state $q_i$ and fed the input $x$, it must, at some point, reach state $q_k$ for the first time and, at some point, leave $q_k$ for the last time. In other words, it must be possible to write

$$
x = uvw
$$

where $u$ takes $M$ from $q_i$ to $q_k$ without going through any state numbered higher than $q_{k-1}$ and $w$ does the same from state $q_k$ to $q_j$. In other words, $u \in R_{ik}^{k-1}$ and $w \in R_{kj}^{k-1}$.

What about $v$? It takes $M$ from $q_k$ to $q_k$ without going through any state numbered higher than $q_k$, but it may go through $q_k$ itself several times (zero or more times), say $t$ times. Then we can clearly write

$$
v = v_1v_2 \ldots v_{t+1}$$
where each \( v_r \) (for \( r \in \{1, \ldots, t + 1\} \)) takes \( M \) from \( q_k \) to \( q_k \) without going through \( q_k \). In other words, each \( v_r \in R_{kk}^{k-1} \)
and so \( v \in (R_{kk}^{k-1})^* \). Combining this with our observations about \( u \) and \( w \), we have

\[
x = uvw \in R_{ik}^{k-1} (R_{kk}^{k-1})^* R_{kj}^{k-1}.
\]

Thus, the strings in \( R_{ij}^k \) in the latter class all belong to \( R_{ik}^{k-1} (R_{kk}^{k-1})^* R_{kj}^{k-1} \). It is also clear that, conversely, a string in \( R_{ik}^{k-1} (R_{kk}^{k-1})^* R_{kj}^{k-1} \) definitely takes \( M \) through state \( q_k \) and never through a state numbered higher than \( q_k \). Therefore, \( R_{ik}^{k-1} (R_{kk}^{k-1})^* R_{kj}^{k-1} \) is exactly the set of strings in the latter class.

Combining the two classes of strings in \( R_{ij}^k \), we get

\[
R_{ij}^k = R_{ij}^{k-1} \cup R_{ik}^{k-1} (R_{kk}^{k-1})^* R_{kj}^{k-1}.
\]

By our induction hypothesis, each of the sets on the right-hand side of this equation is generated by a regular expression. Combining these regular expressions using the union, concatenation and star operators gives us a regular expression for \( R_{ij}^k \). This completes the induction step.

Having completed our induction proof, we address the question of writing a regular expression for the language \( L \). Clearly, \( x \in L \) if and only if \( x \) takes \( M \) from its start state \( q_1 \) to some final state \( q_i \in F \) without going through a state numbered higher than \( q_n \) (there are no states numbered higher than \( q_n \)). Thus,

\[
L = \bigcup_{q_i \in F} R_{1i}^n,
\]

and since we have proved that each set \( R_{ij}^n \) is generated by a regular expression, and the above union is a finite union, we see that \( L \) is also generated by a regular expression. This completes the proof of the theorem. QED.

**Exercise:** Show that the above proof can in fact be modified to yield a dynamic programming algorithm that takes as input a description of a DFA and outputs a regular expression equivalent to it.