Engineering a Compiler

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Keith D. Cooper
Linda Torczon

Rice University
Houston, Texas

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2.4.4 DFA to Minimal DFA: Hopcroft’s Algorithm

As the final step in the RE → DFA construction, we can employ an algorithm to minimize the number of states in the DFA. The DFA that emerges from the subset construction can have a large set of states. While the size of the DFA does not affect its asymptotic complexity, it does determine the recognizer’s footprint in memory. On modern computers, the speed of memory accesses often governs the speed of computation. A smaller recognizer may fit better into the processor’s lowest level of cache memory.

To minimize the number of states in a DFA, \((D, \Sigma, \delta, d_0, D_A)\), we need a technique to detect when two states are equivalent—that is, they produce the same behavior on any input string. The particular algorithm covered in this section constructs a minimal DFA from an arbitrary DFA by grouping together sets of equivalent states. The algorithm finds the largest possible sets of behaviorally-equivalent states; each set becomes a state in the minimal DFA.

The algorithm constructs a set partition, \(P = \{p_1, p_2, p_3, \ldots, p_m\}\), of the DFA states. The partition constructed by the minimization algorithm groups together DFA states that have equivalent behavior. More formally, it constructs a partition with the smallest number of sets, subject to the following two rules:

1. \(\forall c \in \Sigma, \text{ if } d_i, d_j \in p_s; d_i \xrightarrow{c} d_x; d_j \xrightarrow{c} d_y; \text{ and } d_x \in p_t; \text{ then } d_y \in p_t.\)
2. If \(d_i, d_j \in p_i \text{ and } d_i \in D_A, \text{ then } d_j \in D_A\)

The first rule states that two states in the same set must, for every character \(c \in \Sigma\), transition to states that are, themselves, grouped together in a set in the partition. The second rule states that any single set contains either accepting states or nonaccepting states, but not both.

These two properties not only constrain the final partition, \(P\), but they also lead to a construction for \(P\). The algorithm, often called Hopcroft’s algorithm, starts with the coarsest partition on behavior, \(P_0 = \{D_A, \{D - D_A\}\}\). It then iteratively “refines” the partition until both properties hold true for each set in \(P\). To refine the partition, the algorithm splits sets based on the transitions out of DFA states in the set.

Figure 2.8 shows how the algorithm uses transitions to split sets in the partition. In Figure 2.8.a, all three DFA states in set \(p_1\) have transitions to DFA states in \(p_2\) on the input character a. Specifically, \(d_i \xrightarrow{c} d_x\), \(d_j \xrightarrow{c} d_y\), and \(d_k \xrightarrow{c} d_z\). Since \(d_i, d_j, d_k \in p_1\) and \(d_x, d_y, d_z \in p_2\), sets \(p_1\) and \(p_2\) conform to rule 1. Thus, \(p_1\) and \(p_2\) are behaviorally equivalent, and the algorithm would not split them.

In contrast, Figure 2.8.b shows a situation where the input a induces a split in \(p_1\). As before, \(d_i \xrightarrow{c} d_x\), \(d_j \xrightarrow{c} d_y\), and \(d_k \xrightarrow{c} d_z\), but \(d_x \in p_2\) while \(d_y, d_z \in p_3\). This situation violates rule 1, so the algorithm would
split \( p_1 \) into two sets, \( p_4 = \{ d_i \} \) and \( p_5 = \{ d_j, d_k \} \), as shown in Figure 2.8.c.

The algorithm in Figure 2.9 uses these two rules and the notion of splitting sets to construct a partition that maps into the minimal DFA. At each stage, the algorithm holds the current approximation in \( \text{Partition} \). It constructs the next approximation into \( \text{NextP} \), which allows it to update \( \text{NextP} \) without interfering in the current iteration.

As its first approximation, the algorithm constructs the coarsest partition consistent with rule 2, \( \{ D_A, \{ D - D_A \} \} \). This choice has two consequences. First, since each set in the final partition is constructed by splitting a set in an earlier approximation, it ensures that no set in the final partition will contain both accepting and nonaccepting states. Second, by choosing the largest sets consistent with rule 2, it imposes the minimum constraints on the splitting process which, in turn, can lead to larger sets in the final partition. (Larger sets means fewer states in the corresponding DFA.)

The algorithm operates from a worklist of states, initially constructed as \( \{ D_A, \{ D - D_A \} \} \). It repeatedly picks a set \( s \) from the worklist and uses that set to refine the partition in \( \text{NextP} \) by splitting sets based on their transitions into \( s \).

To identify states that must split because of a transition into set \( s \) on some character \( c \), the algorithm inverts the transition function. It computes the set of DFA states that can reach a state in set \( s \) on a transition labelled \( c \) and assigns that set to \( \text{Image} \). It then systematically examines each set \( q \in \mathcal{P} \) to see if \( \text{Image} \) divides \( q \). If \( \text{Image} \) divides \( q \) into non-empty sets \( q_1 \) and \( q_2 \), it removes \( q \) from both \( \text{Partition} \) and \( \text{NextP} \) and then adds both \( q_1 \) and \( q_2 \) to \( \text{NextP} \).

All that remains, in processing \( q \) with respect to \( c \), is to update the worklist. If \( q \) is on the worklist, then the algorithm replaces \( q \) with
2.4 From Regular Expression to Scanner

\[\text{Partition} \leftarrow \{D\_A, \{D - D\_A\}\};\]
\[\text{NextP} \leftarrow \{D\_A, \{D - D\_A\}\};\]
\[\text{Worklist} \leftarrow \{D\_A, \{D - D\_A\}\};\]

\[\text{while}(\text{Worklist} \neq \emptyset)\]
\[\text{select a set } s \text{ from Worklist and remove it}\]
\[\text{for each character } c \in \Sigma\]
\[\text{Image} \leftarrow \{x \mid \delta(x, c) \in s\}\]
\[\text{for each set } q \in \text{Partition}\]
\[q_1 \leftarrow q \cap \text{Image}\]
\[q_2 \leftarrow q - q_1\]
\[\text{if } q_1 \neq \emptyset \text{ and } q_2 \neq \emptyset \text{ then } // \text{split } q \text{ around } s \text{ and } c\]
\[\text{remove } q \text{ from Partition}\]
\[\text{remove } q \text{ from NextP}\]
\[\text{NextP} \leftarrow \text{NextP} \cup q_1 \cup q_2\]
\[\text{if } q \in \text{Worklist} \text{ then } // \text{and update the Worklist}\]
\[\text{remove } q \text{ from Worklist}\]
\[\text{WorkList} \leftarrow \text{WorkList} \cup q_1 \cup q_2\]
\[\text{else if } |q_1| \leq |q_2|\]
\[\text{then WorkList} \leftarrow \text{WorkList} \cup q_1\]
\[\text{else WorkList} \leftarrow \text{WorkList} \cup q_2\]
\[\text{if } s = q \quad // \text{need another } s\]
\[\text{then break}\]
\[\text{Partition} \leftarrow \text{copy of NextP} \quad // \text{set up for the next iteration}\]

\[\text{FIGURE 2.9} \quad \text{DFA Minimization Algorithm}\]

both \(q_1\) and \(q_2\). The rationale is simple: \(q\) was on the worklist for some potential effect; that effect might be from some character other than \(c\), so all of the \(\text{DFA}\) states in \(q\) need to be represented on the worklist.

If, on the other hand, \(q\) is not on the worklist, then the only effect that splitting \(q\) can have on other sets is to split them. Assume that some set \(r\) has transitions on letter \(e\) into \(q\). Dividing \(q\) might create the need to split \(r\) into sets that transition to \(q_1\) and \(q_2\). In this case, either of \(q_1\) or \(q_2\) will induce the split, so the algorithm can choose between them. Using the smaller set will lead to faster execution; for example, computing \(\text{Image}\) takes time proportional to the size of the set.

To construct the new \(\text{DFA}\) from the final partition \(P\), we can create a single state to represent each set \(p_i \in P\) and add the appropriate transitions between these new representative states. For the state representing \(p_m\), we add a transition to the state representing \(p_n\) on character \(c\) if some \(d_j \in p_m\) has a transition on \(c\) to some \(d_k \in p_n\). The construction
ensures that, if \( d_j \xrightarrow{c} d_k \), where \( d_j \in p_m \) and \( d_k \in p_n \), then every state in \( p_m \) has a similar transition to a state in \( p_n \). If this condition did not hold, the algorithm would have split \( p_m \) around the transitions on \( c \). The resulting \( \text{DFA} \) is minimal; the proof is beyond our scope.

### Examples

As a first example, consider the \( \text{DFA} \) in Figure 2.10a. It recognizes the language \( \text{fee} \mid \text{fie} \). Figure 2.10.b shows the progress of the minimization algorithm on this \( \text{DFA} \).

The first line shows the initial configuration of the algorithm, with \( \text{Partition} \), \( \text{NextP} \), and \( \text{Worklist} \) all set to contain \( \{ D_A, \{ D - D_A \} \} \), which is \( \{ \{ s_3, s_5 \}, \{ s_0, s_1, s_2, s_4 \} \} \). The algorithm enters the while loop and selects a first set for \( s \); it chooses \( p_0 \). Next, it iterates over the characters in the alphabet, in order, \( f, e, i \). With \( f \), \( p_0 \) does not split either \( p_0 \) or \( p_1 \). With \( e \), \( p_0 \) splits \( p_1 \) into two sets: \( p_2: \{ s_0, s_1 \} \) and \( p_3: \{ s_2, s_4 \} \). The algorithm removes \( p_1 \) from \( \text{Partition} \) and \( \text{NextP} \). It adds \( p_2 \) and \( p_3 \) to \( \text{NextP} \). Then, it updates the worklist, removing \( p_1 \) and adding \( p_2 \) and \( p_3 \), before advancing to the final character, \( i \).

The final iteration of the character loop generates no further splits. The only set it considers for splitting is \( q = p_0 \) because the algorithm removed \( p_1 \) from \( \text{Partition} \) when it was split. Note that the new sets were added to \( \text{NextP} \) rather than to \( \text{Partition} \). After processing \( s = p_0 \), \( c = i \), and \( q = p_0 \), the code updates \( \text{Partition} \) from \( \text{NextP} \) and proceeds into the second iteration of the while loop.

The second iteration proceeds in a similar fashion, until it considers \( q = p_2 \), \( c = f \), and \( q = p_2 \). This combination splits \( p_2 \). Since \( p_2 \) is both the set being split, \( q \), and the set that induces the split, \( s \), the algorithm breaks out of the rest of the second iteration.

The third, fourth, and fifth iteration of the while loop systematically go through the worklist and the alphabet. They discover no further splits, so the algorithm halts when the worklist is empty after the fifth iteration of the outer loop. The resulting \( \text{DFA} \) is shown in Figure 2.10.c. It has four states.

As a second example, consider the \( \text{DFA} \) for \( a(b \mid c)^* \) produced by Thompson’s construction and the subset construction, shown in Figure 2.11a. The first step of the minimization algorithm constructs an initial approximation to the partition as \( \{ \{ s_1, s_2, s_3 \}, \{ s_0 \} \} \). The algorithm selects \( p_0 \) as \( q \) and tries to split \( p_0 \) based on each of \( a \), \( b \), and \( c \). While \( p_1 \) has a transition into \( p_0 \) on \( a \), it causes no split. (First, every \( \text{DFA} \) state in \( p_1 \) has the same transition on \( a \). Second, the algorithm cannot split a singleton state.) For \( b \) and \( c \), all of the transitions into \( p_0 \) originate inside \( p_0 \) and neither \( b \) nor \( c \) split \( p_0 \).

When it considers splitting on \( p_1 \), the algorithm discovers that there are no transitions into \( p_1 \)—that is \( \text{Image} \) is empty. Thus, \( p_1 \)

It makes no sense to split the other sets based on a set that no longer exists.

When we draw the minimal \( \text{DFA} \), we combine the edges for \( e \) and \( i \) and label the edge with both letters. The algorithm might be viewed as creating separate edges for \( e \) and \( i \) that have the same behavior.
### From Regular Expression to Scanner

#### 2.4

**Example DFA**

(a) DFA for “fee | fie

![Diagram](a.png)

<table>
<thead>
<tr>
<th>Step</th>
<th>Partition</th>
<th>Worklist</th>
<th>s</th>
<th>c</th>
<th>q</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>{ p_0: {s_3, s_5}, p_1: {s_0, s_1, s_2, s_4} }</td>
<td>{ p_0, p_1 }</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>{ p_0: {s_3, s_5}, p_1: {s_0, s_1, s_2, s_4} }</td>
<td>{ p_1 }</td>
<td>p_0</td>
<td>f</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_0 }</td>
<td>e</td>
<td>p_1</td>
<td>split</td>
<td>p_1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_2, p_3 }</td>
<td>p_0</td>
<td>i</td>
<td>p_0</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>{ p_0: {s_3, s_5}, p_2: {s_0, s_1}, p_3: {s_2, s_4} }</td>
<td>{ p_3 }</td>
<td>p_2</td>
<td>f</td>
<td>p_0</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_3 }</td>
<td>p_2</td>
<td>e</td>
<td>p_2</td>
<td>split</td>
</tr>
<tr>
<td>3</td>
<td>{ p_0: {s_3, s_5}, p_3: {s_2, s_4} p_4: {s_0}, p_5: {s_1} }</td>
<td>{ p_4, p_5 }</td>
<td>p_3</td>
<td>f</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_4, p_5 }</td>
<td>p_3</td>
<td>e</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_4, p_5 }</td>
<td>p_3</td>
<td>i</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>{ p_0: {s_3, s_5}, p_3: {s_2, s_4} p_4: {s_0}, p_5: {s_1} }</td>
<td>{ p_5 }</td>
<td>p_4</td>
<td>f</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_5 }</td>
<td>p_4</td>
<td>e</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ p_5 }</td>
<td>p_4</td>
<td>i</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td>5</td>
<td>{ p_0: {s_3, s_5}, p_3: {s_2, s_4} p_4: {s_0}, p_5: {s_1} }</td>
<td>{ }</td>
<td>p_5</td>
<td>f</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ }</td>
<td>p_5</td>
<td>e</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{ }</td>
<td>p_5</td>
<td>i</td>
<td>all</td>
<td>none</td>
</tr>
<tr>
<td>final</td>
<td>{ p_0: {s_3, s_5}, p_3: {s_2, s_4} p_4: {s_0}, p_5: {s_1} }</td>
<td>{ }</td>
<td></td>
<td></td>
<td></td>
<td>algorithm halts</td>
</tr>
</tbody>
</table>

(b) Critical Steps in Minimizing the DFA

![Diagram](b.png)

(c) The Minimal DFA

**Figure 2.10** Applying the DFA Minimization Algorithm
induces no splits on any of $a$, $b$, or $c$, and the two set partition is the final partition. The final DFA has two states, as shown in the margin. Recall that this is the DFA that we suggested a human would derive. After minimization, the automatic techniques produce the same result.

Hopcroft’s DFA minimization algorithm is another example of a fixed-point computation. $\text{Partition}$ is finite; at most it can contain $|D|$ elements. The while loop splits sets in $\text{Partition}$, but never combines them. Thus, $\text{Partition}$ grows monotonically. The loop halts when some iteration performs no splits. The worst-case behavior occurs when each state in the DFA has distinct behavior; in that case, the while loop halts when $\text{Partition}$ consists of a singleton set for each $d_i$ in $D$. This worst case arises when the input DFA is already a minimal DFA.