Dynamic Programming: Shortest Paths and DFA to Reg Expressions

Lecture 18
Thursday, November 2, 2017

I Part I

Shortest Paths with Negative Length Edges

Single-Source Shortest Paths with Negative Edge Lengths

Single-Source Shortest Path Problems

- **Input**: A directed graph \( G = (V, E) \) with arbitrary (including negative) edge lengths. For edge \( e = (u, v) \), \( \ell(e) = \ell(u,v) \) is its length.

- Given nodes \( s, t \) find shortest path from \( s \) to \( t \).
- Given node \( s \) find shortest path from \( s \) to all other nodes.

What are the distances computed by Dijkstra’s algorithm?

The distance as computed by Dijkstra algorithm starting from \( s \):

- \( (A) \) \( s = 0 \), \( x = 5 \), \( y = 1 \), \( z = 0 \).
- \( (B) \) \( s = 0 \), \( x = 1 \), \( y = 2 \), \( z = 5 \).
- \( (C) \) \( s = 0 \), \( x = 5 \), \( y = 1 \), \( z = 2 \).
- \( (D) \) IDK.
Dijkstra’s Algorithm and Negative Lengths

With negative length edges, Dijkstra’s algorithm can fail

![Graph example](image)

**False assumption:** Dijkstra’s algorithm is based on the assumption that if \( s = v_0 \rightarrow v_1 \rightarrow v_2 \ldots \rightarrow v_k \) is a shortest path from \( s \) to \( v_k \) then \( \text{dist}(s, v_i) \leq \text{dist}(s, v_{i+1}) \) for \( 0 \leq i < k \). Holds true only for non-negative edge lengths.

Shortest Paths and Negative Cycles

Given \( G = (V, E) \) with edge lengths and \( s, t \). Suppose

- \( G \) has a negative length cycle \( C \), and
- \( s \) can reach \( C \) and \( C \) can reach \( t \).

**Question:** What is the shortest distance from \( s \) to \( t \)?

Possible answers: Define shortest distance to be:

- undefined, that is \(-\infty\), OR
- the length of a shortest simple path from \( s \) to \( t \).

**Lemma**

If there is an efficient algorithm to find a shortest simple \( s \rightarrow t \) path in a graph with negative edge lengths, then there is an efficient algorithm to find the longest simple \( s \rightarrow t \) path in a graph with positive edge lengths.

Finding the \( s \rightarrow t \) longest path is difficult. **NP-Hard!**

Negative Length Cycles

**Definition**

A cycle \( C \) is a negative length cycle if the sum of the edge lengths of \( C \) is negative.

![Graph example](image)

Alternatively: Finding Shortest Walks

Given a graph \( G = (V, E) \):

- A path is a sequence of distinct vertices \( v_1, v_2, \ldots, v_k \) such that \((v_i, v_{i+1}) \in E\) for \( 1 \leq i \leq k - 1 \).
- A walk is a sequence of vertices \( v_1, v_2, \ldots, v_k \) such that \((v_i, v_{i+1}) \in E\) for \( 1 \leq i \leq k - 1 \). Vertices are allowed to repeat.

Define \( \text{dist}(u, v) \) to be the length of a shortest walk from \( u \) to \( v \).

- If there is a walk from \( u \) to \( v \) that contains negative length cycle then \( \text{dist}(u, v) = -\infty \)
- Else there is a path with at most \( n - 1 \) edges whose length is equal to the length of a shortest walk and \( \text{dist}(u, v) \) is finite

Helpful to think about walks...
Shortest Paths with Negative Edge Lengths

**Algorithmic Problems**

**Input:** A directed graph $G = (V, E)$ with edge lengths (could be negative). For edge $e = (u, v)$, $\ell(e) = \ell(u, v)$ is its length.

**Questions:**
- Given nodes $s, t$, either find a negative length cycle $C$ that $s$ can reach or find a shortest path from $s$ to $t$.
- Given node $s$, either find a negative length cycle $C$ that $s$ can reach or find shortest path distances from $s$ to all reachable nodes.
- Check if $G$ has a negative length cycle or not.

**Why Negative Lengths?**

Several Applications
- Shortest path problems useful in modeling many situations — in some negative lengths are natural
- Negative length cycle can be used to find arbitrage opportunities in currency trading
- Important sub-routine in algorithms for more general problem: minimum-cost flow

**Negative cycles**

Application to Currency Trading

**Currency Trading**

**Input:** $n$ currencies and for each ordered pair $(a, b)$ the exchange rate for converting one unit of $a$ into one unit of $b$.

**Questions:**
- Is there an arbitrage opportunity?
- Given currencies $s, t$ what is the best way to convert $s$ to $t$ (perhaps via other intermediate currencies)?

Concrete example:
- 1 Chinese Yuan = 0.1116 Euro
- 1 Euro = 1.3617 US dollar
- 1 US Dollar = 7.1 Chinese Yuan.

Thus, if exchanging 1 $\rightarrow$ Yuan $\rightarrow$ Euro $\rightarrow$ $, we get:
$$0.1116 \times 1.3617 \times 7.1 = 1.07896$$. 
Reducing Currency Trading to Shortest Paths

**Observation:** If we convert currency \( i \) to \( j \) via intermediate currencies \( k_1, k_2, \ldots, k_h \) then one unit of \( i \) yields \( \text{exch}(i, k_1) \times \text{exch}(k_1, k_2) \times \cdots \times \text{exch}(k_h, j) \) units of \( j \).

Create currency trading directed graph \( G = (V, E) \):
1. For each currency \( i \) there is a node \( v_i \in V \)
2. \( E = V \times V \): an edge for each pair of currencies
3. edge length \( \ell(v_i, v_j) = -\log(\text{exch}(i, j)) \) can be negative

**Exercise:** Verify that
1. There is an arbitrage opportunity if and only if \( G \) has a negative length cycle.
2. The best way to convert currency \( i \) to currency \( j \) is via a shortest path in \( G \) from \( i \) to \( j \). If \( d \) is the distance from \( i \) to \( j \) then one unit of \( i \) can be converted into \( 2^d \) units of \( j \).

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**Shortest Paths with Negative Lengths**

**Lemma**

Let \( G \) be a directed graph with arbitrary edge lengths. If \( s = v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_k \) is a shortest path from \( s \) to \( v_k \) then for \( 1 \leq i < k \):
1. \( s = v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_i \) is a shortest path from \( s \) to \( v_i \)
2. False: \( \text{dist}(s, v_i) \leq \text{dist}(s, v_k) \) for \( 1 \leq i < k \). Holds true only for non-negative edge lengths.

Cannot explore nodes in increasing order of distance! We need other strategies.

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**Shortest Paths and Recursion**

1. Compute the shortest path distance from \( s \) to \( t \) recursively?
2. What are the smaller sub-problems?

**Lemma**

Let \( G \) be a directed graph with arbitrary edge lengths. If \( s = v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_k \) is a shortest path from \( s \) to \( v_k \) then for \( 1 \leq i < k \):
1. \( s = v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_i \) is a shortest path from \( s \) to \( v_i \)

Sub-problem idea: paths of fewer hops/edges
Hop-based Recursion: Bellman-Ford Algorithm

Single-source problem: fix source $s$.
Assume that all nodes can be reached by $s$ in $G$.
Assume $G$ has no negative-length cycle (for now).

$d(v,k)$: shortest walk length from $s$ to $v$ using at most $k$ edges.

Note: $dist(s,v) = d(v,n-1)$. Recursion for $d(v,k)$:

$$d(v,k) = \min\left\{\begin{array}{ll}
\min_{u \in V} (d(u,k-1) + \ell(u,v)) \\
d(v,k-1)
\end{array}\right.$$

Base case: $d(s,0) = 0$ and $d(v,0) = \infty$ for all $v \neq s$.

Bellman-Ford Algorithm

for each $u \in V$ do
  $d(u,0) \leftarrow \infty$
  $d(s,0) \leftarrow 0$

for $k = 1$ to $n - 1$ do
  for each $v \in V$ do
    $d(v,k) \leftarrow d(v,k-1)$
    for each edge $(u,v) \in in(v)$ do
      \[ d(v,k) = \min\{d(v,k), d(u,k-1) + \ell(u,v)\} \]

for each $v \in V$ do
  $dist(s,v) \leftarrow d(v,n-1)$

Running time: $O(mn)$ Space: $O(m + n^2)$

Space can be reduced to $O(m + n)$.

Example

Bellman-Ford Algorithm

for each $u \in V$ do
  $d(u) \leftarrow \infty$
  $d(s) \leftarrow 0$

for $k = 1$ to $n - 1$ do
  for each $v \in V$ do
    for each edge $(u,v) \in in(v)$ do
      $d(v) = \min\{d(v), d(u) + \ell(u,v)\}$

for each $v \in V$ do
  $dist(s,v) \leftarrow d(v)$

Running time: $O(mn)$ Space: $O(m + n)$

Exercise: Argue that this achieves same results as algorithm on previous slide.
Bellman-Ford: Negative Cycle Detection

Check if distances change in iteration $n$.

```
for each $u \in V$ do
  $d(u) \leftarrow \infty$
  $d(s) \leftarrow 0$

for $k = 1$ to $n - 1$ do
  for each $v \in V$ do
    for each edge $(u, v) \in in(v)$ do
      $d(v) = \min \{d(v), d(u) + \ell(u, v)\}$

(* One more iteration to check if distances change *)

for each $v \in V$ do
  for each edge $(u, v) \in in(v)$ do
    if $(d(v) > d(u) + \ell(u, v))$
      Output "Negative Cycle"

for each $v \in V$ do
  $\text{dist}(s, v) \leftarrow d(v)$
```

Correctness of the Bellman-Ford Algorithm

**Via induction:** For each $v$, $d(v, k)$ is the length of a shortest walk from $s$ to $v$ with at most $k$ hops.

**Lemma**

Suppose $G$ does not have a negative length cycle reachable from $s$. Then for all $v$, $\text{dist}(s, v) = d(v, n - 1)$. Moreover, $d(v, n - 1) = d(v, n)$.

**Proof.**

Exercise.

**Corollary**

Bellman-Ford correctly outputs the shortest path distances if $G$ has no negative length cycle reachable from $s$.

Correctness: Detecting negative length cycle

**Lemma**

$G$ has a negative length cycle reachable from $s$ if and only if there is some node $v$ such that $d(v, n) < d(v, n - 1)$.

Lemma proves correctness of negative cycle detection by Bellman-Ford algorithm.

The only if direction follows from Lemma on previous slide. We prove the if direction in the next slide.

Correctness: detecting negative length cycle

**Lemma**

Suppose $G$ has a negative cycle $C$ reachable from $s$. Then there is some node $v \in C$ such that $d(v, n) < d(v, n - 1)$.

**Proof.**

Suppose not. Let $C = v_1 \rightarrow v_2 \rightarrow \ldots \rightarrow v_h \rightarrow v_1$ be negative length cycle reachable from $s$. $d(v_i, n - 1)$ is finite for $1 \leq i \leq h$ since $C$ is reachable from $s$. By assumption $d(v, n) \geq d(v, n - 1)$ for all $v \in C$; implies no change in $n$th iteration;

$d(v_i, n - 1) = d(v_i, n)$ for $1 \leq i \leq h$. This means

$d(v_i, n - 1) \leq d(v_{i-1}, n - 1) + \ell(v_{i-1}, v_i)$ for $2 \leq i \leq h$ and

$d(v_1, n - 1) \leq d(v_h, n - 1) + \ell(v_h, v_1)$. Adding up all these inequalities results in the inequality $0 \leq \ell(C)$ which contradicts the assumption that $\ell(C) < 0$. 

□
Finding the Paths and a Shortest Path Tree

How do we find a shortest path tree in addition to distances?

- For each \( v \) the \( d(v) \) can only get smaller as algorithm proceeds.
- If \( d(v) \) becomes smaller it is because we found a vertex \( u \) such that \( d(v) > d(u) + \ell(u, v) \) and we update
  \[ d(v) = d(u) + \ell(u, v). \]
  That is, we found a shorter path to \( v \) through \( u \).
- For each \( v \) have a \( \text{prev}(v) \) pointer and update it to point to \( u \)
  if \( v \) finds a shorter path via \( u \).
- At end of algorithm \( \text{prev}(v) \) pointers give a shortest path tree
  oriented towards the source \( s \).

Negative Cycle Detection

Given directed graph \( G \) with arbitrary edge lengths, does it have a negative length cycle?

- Bellman-Ford checks whether there is a negative cycle \( C \) that is reachable from a specific vertex \( s \). There may negative cycles not reachable from \( s \).
- Run Bellman-Ford \( |V| \) times, once from each node \( u \)?
Part II

Shortest Paths in DAGs

Algorithm for $s$

- Want to find shortest paths from $s$. Ignore nodes not reachable from $s$.
- Let $s = v_1, v_2, v_{i+1}, \ldots, v_n$ be a topological sort of $G$

Observation:

- Shortest path from $s$ to $v_i$ cannot use any node from $v_{i+1}, \ldots, v_n$
- Can find shortest paths in topological sort order.

Algorithm for $s$

```plaintext
for $i = 1$ to $n$ do
    $d(s, v_i) = \infty$
    $d(s, s) = 0$

for $i = 1$ to $n - 1$ do
    for each edge $(v_i, v_j)$ in $\text{Adj}(v_i)$ do
        $d(s, v_j) = \min\{d(s, v_j), d(s, v_i) + \ell(v_i, v_j)\}$

return $d(s, \cdot)$ values computed
```

Correctness: induction on $i$ and observation in previous slide.

Running time: $O(m + n)$ time algorithm! Works for negative edge lengths and hence can find longest paths in a DAG.
Bellman-Ford and DAGs

Bellman-Ford is based on the following principles:

- The shortest walk length from \( s \) to \( v \) with at most \( k \) hops can be computed via dynamic programming.
- \( G \) has a negative length cycle reachable from \( s \) iff there is a node \( v \) such that shortest walk length reduces after \( n \) hops.

We can find hop-constrained shortest paths via graph reduction.

Given \( G = (V, E) \) with edge lengths \( \ell(e) \) and integer \( k \), construction new layered graph \( G' = (V', E') \) as follows.

- \( V' = V \times \{0, 1, 2, \ldots, k\} \).
- \( E' = \{((u, i), (v, i + 1)) \mid (u, v) \in E, 0 \leq i < k\} \).
- \( \ell((u, i), (v, i + 1)) = \ell(u, v) \)

Lemma

Shortest path distance from \((u, 0)\) to \((v, k)\) in \(G'\) is equal to the shortest walk from \(u\) to \(v\) in \(G\) with exactly \(k\) edges.

Part III

All Pairs Shortest Paths

Layered DAG: Figure

Shortest Path Problems

Input A (undirected or directed) graph \( G = (V, E) \) with edge lengths (or costs). For edge \( e = (u, v) \),

\[ \ell(e) = \ell(u, v) \] is its length.

- Given nodes \( s, t \) find shortest path from \( s \) to \( t \).
- Given node \( s \) find shortest path from \( s \) to all other nodes.
- Find shortest paths for all pairs of nodes.
Single-Source Shortest Paths

Single-Source Shortest Path Problems

Input A (undirected or directed) graph \( G = (V, E) \) with edge lengths. For edge \( e = (u, v) \), \( \ell(e) = \ell(u, v) \) is its length.

- Given nodes \( s, t \) find shortest path from \( s \) to \( t \).
- Given node \( s \) find shortest path from \( s \) to all other nodes.

Dijkstra’s algorithm for non-negative edge lengths. Running time: \( O((m + n) \log n) \) with heaps and \( O(m + n \log n) \) with advanced priority queues.

Bellman-Ford algorithm for arbitrary edge lengths. Running time: \( O(nm) \).

All-Pairs Shortest Paths

All-Pairs Shortest Path Problem

Input A (undirected or directed) graph \( G = (V, E) \) with edge lengths. For edge \( e = (u, v) \), \( \ell(e) = \ell(u, v) \) is its length.

- Find shortest paths for all pairs of nodes.

Apply single-source algorithms \( n \) times, once for each vertex.

- Non-negative lengths. \( O(nm \log n) \) with heaps and \( O(nm + n^2 \log n) \) using advanced priority queues.
- Arbitrary edge lengths: \( O(n^2 m) \).
  \( \Theta(n^4) \) if \( m = \Omega(n^2) \).

Can we do better?

All-Pairs: Recursion on index of intermediate nodes

- Number vertices arbitrarily as \( v_1, v_2, \ldots, v_n \)
- \( \text{dist}(i, j, k) \): length of shortest walk from \( v_i \) to \( v_j \) among all walks in which the largest index of an intermediate node is at most \( k \) (could be \(-\infty\) if there is a negative length cycle).

For the following graph, \( \text{dist}(i, j, 2) \) is...

\[ \begin{align*}
\text{dist}(i, j, 2) &= 8 \\
\text{dist}(i, j) &= 10 \\
\text{dist}(i, j, 0) &= 100
\end{align*} \]

(A) 9
(B) 10
(C) 11
(D) 12
(E) 15
All-Pairs: Recursion on index of intermediate nodes

\[ \text{dist}(i, j, k) = \min \{ \text{dist}(i, j, k - 1), \text{dist}(i, k, k - 1) + \text{dist}(k, j, k - 1) \} \]

Base case: if \( (i, j) \notin E \), otherwise \( \infty \)

Correctness: If \( i \rightarrow j \) shortest walk goes through \( k \) then \( k \) occurs only once on the path — otherwise there is a negative length cycle.

Floyd-Warshall Algorithm

for All-Pairs Shortest Paths

\[
\text{for } i = 1 \text{ to } n \text{ do}
\]
\[
\text{for } j = 1 \text{ to } n \text{ do}
\]
\[
\text{dist}(i, j, 0) = \ell(i, j) \quad (* \ell(i, j) = \infty \text{ if } (i, j) \notin E, \ 0 \text{ if } i = j *)
\]

\[
\text{for } k = 1 \text{ to } n \text{ do}
\]
\[
\text{for } i = 1 \text{ to } n \text{ do}
\]
\[
\text{for } j = 1 \text{ to } n \text{ do}
\]
\[
\text{dist}(i, j, k) = \min \{ \text{dist}(i, j, k - 1), \text{dist}(i, k, k - 1) + \text{dist}(k, j, k - 1) \}
\]

\[
\text{for } i = 1 \text{ to } n \text{ do}
\]
\[
\text{if } \text{dist}(i, i, n) < 0 \text{ then}
\]
\[
\text{Output that there is a negative length cycle in } G
\]

Running Time: \( \Theta(n^3) \), Space: \( \Theta(n^3) \).

Correctness: via induction and recursive definition

Floyd-Warshall Algorithm: Finding the Paths

Question: Can we find the paths in addition to the distances?

- Create a \( n \times n \) array Next that stores the next vertex on shortest path for each pair of vertices
- With array Next, for any pair of given vertices \( i, j \) can compute a shortest path in \( O(n) \) time.
Floyd-Warshall Algorithm
Finding the Paths

\[
\text{for } i = 1 \text{ to } n \text{ do}
  \begin{align*}
  &\text{for } j = 1 \text{ to } n \text{ do} \\
  &\quad \text{dist}(i, j, 0) = \ell(i, j) \\
  &\text{Next}(i, j) = -1
  \end{align*}
\]

\[
\text{for } k = 1 \text{ to } n \text{ do}
  \begin{align*}
  &\text{for } i = 1 \text{ to } n \text{ do} \\
  &\quad \text{for } j = 1 \text{ to } n \text{ do} \\
  &\text{if } (\text{dist}(i, j, k - 1) > \text{dist}(i, k, k - 1) + \text{dist}(k, j, k - 1)) \\
  &\quad \text{dist}(i, j, k) = \text{dist}(i, k, k - 1) + \text{dist}(k, j, k - 1) \\
  &\quad \text{Next}(i, j) = k
  \end{align*}
\]

\[
\text{for } i = 1 \text{ to } n \text{ do}
  \begin{align*}
  &\text{if } (\text{dist}(i, i, n) < 0) \\
  &\quad \text{Output that there is a negative length cycle in } G
  \end{align*}
\]

Exercise: Given Next array and any two vertices \(i, j\) describe an \(O(n)\) algorithm to find a \(i-j\) shortest path.

Summary of results on shortest paths

<table>
<thead>
<tr>
<th></th>
<th>Single source</th>
<th>No negative edges</th>
<th>Edge lengths can be negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dijkstra</td>
<td>Bellman Ford</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(O(n \log n + m))</td>
<td>(O(nm))</td>
<td></td>
</tr>
</tbody>
</table>

All Pairs Shortest Paths

<table>
<thead>
<tr>
<th></th>
<th>No negative edges</th>
<th>No negative cycles</th>
<th>No negative cycles (*)</th>
<th>No negative cycles</th>
<th>Unweighted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n \times \text{Dijkstra})</td>
<td>(n \times \text{Bellman Ford})</td>
<td>(\text{BF} + n \times \text{Dijkstra})</td>
<td>(\text{Floyd-Warshall})</td>
<td>(\text{Matrix multiplication})</td>
</tr>
<tr>
<td></td>
<td>(O(n^2 \log n + nm))</td>
<td>(O(n^2 m) = O(n^4))</td>
<td>(O(nm + n^2 \log n))</td>
<td>(O(n^4))</td>
<td>(O(n^{2.38}), O(n^{2.58}))</td>
</tr>
</tbody>
</table>

(*): The algorithm for the case that there are no negative cycles, and doing all shortest paths, works by computing a potential function using Bellman-Ford and then doing Dijkstra. It is mentioned for the sake of completeness, but it outside the scope of the class.

Part IV

DFA to Regular Expression
Back to Regular Languages

We saw the following two theorems previously.

**Theorem**
For every NFA $N$ over a finite alphabet $\Sigma$ there is DFA $M$ such that $L(M) = L(N)$.

**Theorem**
For every regular expression $r$ over finite alphabet $\Sigma$ there is a NFA $N$ such that $L(N) = L(r)$.

We claimed the following theorem which would prove equivalence of NFAs, DFAs and regular expressions.

**Theorem**
For every DFA $M$ over a finite alphabet $\Sigma$ there is a regular expression $r$ such that $L(M) = L(r)$.

---

### DFA to Regular Expression

Given DFA $M = (Q, \Sigma, \delta, q_1, F)$ want to construct an equivalent regular expression $r$.

**Idea:**
- Number states of DFA: $Q = \{q_1, \ldots, q_n\}$ where $|Q| = n$.
- Define $L_{i,j} = \{w \mid \delta(q_i, w) = q_j\}$. Note $L_{i,j}$ is regular. Why?
- $L(M) = \bigcup_{q_i \in F} L_{1,i}$.
- Obtain regular expression $r_{i,j}$ for $L_{i,j}$.
- Then $r = \sum_{q_i \in F} r_{1,i}$ is regular expression for $L(M)$ – here the summation is the $\lor$ operator.

**Note:** Using $q_1$ for start state is intentional to help in the notation for the recursion.

---

### A recursive expression for $L_{i,j}$

Define $L_{i,j}^k$ be set of strings $w$ in $L_{i,j}$ such that the highest index state visited by $M$ on walk from $q_i$ to $q_j$ (not counting end points $i$ and $j$) on input $w$ is at most $k$.

From definition

$L_{i,j} = L_{i,j}^n$

**Claim:**

$L_{i,j}^0 = \begin{cases} 
\{a \in \Sigma \mid \delta(q_i, a) = q_j\} & \text{if } i \neq j \\
\{a \in \Sigma \mid \delta(q_i, a) = q_j\} \cup \{\epsilon\} & \text{if } i = j
\end{cases}

L_{i,j}^k = L_{i,j}^{k-1} \cup (L_{i,k}^{k-1} \cdot (L_{k,k}^{k-1})^* \cdot L_{k,j}^{k-1})$

**Proof:** by picture
A recursive expression for $L_{i,j}$

$$L_{i,j} = L_{i,j}^n$$

Claim:

$$L_{i,j}^0 = \{ a \in \Sigma \mid \delta(q_i, a) = q_j \}$$

$$L_{i,j}^k = L_{i,j}^{k-1} \cup \left( L_{i,k}^{k-1} \cdot (L_{k,k}^{k-1})^* \cdot L_{k,j}^{k-1} \right)$$

From claim, can easily construct regular expression $r_{i,j}^k$ for $L_{i,j}^k$. This leads to a regular expression for

$$L(M) = \bigcup_{q_i \in F} L_{1,i} = \bigcup_{q_i \in F} L_{1,i}^n$$

Correctness

Similar to that of Floyd-Warshall algorithms for shortest paths via induction.

The length of the regular expression can be exponential in the size of the original DFA.

Example

$$L(M) = L_{1,2}^2$$

$$r_{1,2}^2 = r_{1,2}^1 + r_{1,2}^1 (r_{2,2}^1)^* r_{2,2}^1$$

$$r_{1,2}^1 = r_{1,2}^0 + r_{1,1}^0 (r_{1,1}^0)^* r_{1,2}^0$$

$$r_{1,1}^0 = r_{2,2}^0 = (b + \epsilon)$$

$$r_{1,2}^0 = r_{2,1}^0 = a$$

Dynamic Programming: Postscript

Dynamic Programming = Smart Recursion + Memoization

- How to come up with the recursion?
- How to recognize that dynamic programming may apply?
Some Tips

- Problems where there is a natural linear ordering: sequences, paths, intervals, DAGs etc. Recursion based on ordering (left to right or right to left or topological sort) usually works.
- Problems involving trees: recursion based on subtrees.
- More generally:
  - Problem admits a natural recursive divide and conquer
  - If optimal solution for whole problem can be simply composed from optimal solution for each separate pieces then plain divide and conquer works directly
  - If optimal solution depends on all pieces then can apply dynamic programming if interface/interaction between pieces is limited. Augment recursion to not simply find an optimum solution but also an optimum solution for each possible way to interact with the other pieces.

Examples

- Longest Increasing Subsequence: break sequence in the middle say. What is the interaction between the two pieces in a solution?
- Sequence Alignment: break both sequences in two pieces each. What is the interaction between the two sets of pieces?
- Independent Set in a Tree: break tree at root into subtrees. What is the interaction between the subtrees?
- Independent Set in an graph: break graph into two graphs. What is the interaction? Very high!
- Knapsack: Split items into two sets of half each. What is the interaction?