Proof (completed)
Q. How many h a's cause x and y to collide?
A. There are m choices for each of a_1, a_2, ..., a_r, but once these are chosen, exactly one choice for a_0 causes x and y to collide, namely
\[
\begin{bmatrix}
\vdots \\
\end{bmatrix}
\begin{bmatrix}
\vdots \\
\end{bmatrix} = \begin{bmatrix}
\vdots \\
\end{bmatrix} \cdot 1 \\
\mod m.
\]
Thus, the number of h a's that cause x and y to collide is m r = |H|/m.

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Shortest Paths III
• All-pairs shortest paths
• Matrix-multiplication algorithm
• Floyd-Warshall algorithm
• Johnson’s algorithm

Prof. Charles E. Leiserson
Shortest paths

Single-source shortest paths

• Nonnegative edge weights
  • Dijkstra’s algorithm: $O(E + V \lg V)$

• General
  • Bellman-Ford algorithm: $O(VE)$

• DAG
  • One pass of Bellman-Ford: $O(V + E)$
Shortest paths

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All-pairs shortest paths

• Nonnegative edge weights
  • Dijkstra’s algorithm $|V|$ times: $O(VE + V^2 \lg V)$
• General
  • Three algorithms today.
All-pairs shortest paths

Input: Digraph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$, with edge-weight function $w : E \rightarrow \mathbb{R}$.

Output: $n \times n$ matrix of shortest-path lengths $\delta(i, j)$ for all $i, j \in V$. 
All-pairs shortest paths

**Input:** Digraph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$, with edge-weight function $w : E \rightarrow \mathbb{R}$.

**Output:** $n \times n$ matrix of shortest-path lengths $\delta(i, j)$ for all $i, j \in V$.

**Idea:**
- Run Bellman-Ford once from each vertex.
- Time $= O(V^2E)$.
- Dense graph ($n^2$ edges) $\Rightarrow \Theta(n^4)$ time in the worst case.

*Good first try!*
Dynamic programming

Consider the $n \times n$ adjacency matrix $A = (a_{ij})$ of the digraph, and define

$$d_{ij}^{(m)} = \text{weight of a shortest path from } i \text{ to } j \text{ that uses at most } m \text{ edges.}$$

**Claim:** We have

$$d_{ij}^{(0)} = \begin{cases} 0 & \text{if } i = j, \\ \infty & \text{if } i \neq j; \end{cases}$$

and for $m = 1, 2, \ldots, n - 1$,

$$d_{ij}^{(m)} = \min_k \left\{ d_{ik}^{(m-1)} + a_{kj} \right\}.$$
Proof of claim

\[ d_{ij}^{(m)} = \min_k \left\{ d_{ik}^{(m-1)} + a_{kj} \right\} \]

\[ \leq m - 1 \text{ edges} \]

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\[ \kappa \text{'s} \]
Proof of claim

\[ d_{ij}^{(m)} = \min_k \{ d_{ik}^{(m-1)} + a_{kj} \} \]

Relaxation!

for \( k \leftarrow 1 \) to \( n \)

do if \( d_{ij} > d_{ik} + a_{kj} \)

then \( d_{ij} \leftarrow d_{ik} + a_{kj} \)

\( \leq m-1 \) edges
Proof of claim

\[ d_{ij}^{(m)} = \min_k \{ d_{ik}^{(m-1)} + a_{kj} \} \]

Relaxation!

for \( k \leftarrow 1 \) to \( n \)

do if \( d_{ij} > d_{ik} + a_{kj} \)

then \( d_{ij} \leftarrow d_{ik} + a_{kj} \)

≤ \( m-1 \) edges

Note: No negative-weight cycles implies

\[ \delta(i, j) = d_{ij}^{(n-1)} = d_{ij}^{(n)} = d_{ij}^{(n+1)} = \ldots \]
Matrix multiplication

Compute $C = A \cdot B$, where $C$, $A$, and $B$ are $n \times n$ matrices:

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj}.$$ 

Time $= \Theta(n^3)$ using the standard algorithm.
Matrix multiplication

Compute $C = A \cdot B$, where $C$, $A$, and $B$ are $n \times n$ matrices:

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Time = $\Theta(n^3)$ using the standard algorithm. What if we map “+” $\rightarrow$ “min” and “$\cdot$” $\rightarrow$ “+”?
Matrix multiplication

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Time $= \Theta(n^3)$ using the standard algorithm.

What if we map “$+$” $\to$ “min” and “$\cdot$” $\to$ “$+$”?

$$c_{ij} = \min_k \{a_{ik} + b_{kj}\}.$$ 

Thus, $D^{(m)} = D^{(m-1)} \times A$.

Identity matrix $= I = \begin{pmatrix} 0 & \infty & \infty & \infty \\ \infty & 0 & \infty & \infty \\ \infty & \infty & 0 & \infty \\ \infty & \infty & \infty & 0 \end{pmatrix} = D^0 = (d_{ij}^{(0)}).$
Matrix multiplication (continued)

The \((\min, +)\) multiplication is **associative**, and with the real numbers, it forms an algebraic structure called a **closed semiring**.

Consequently, we can compute

\[
D^{(1)} = D^{(0)} \cdot A = A^1 \\
D^{(2)} = D^{(1)} \cdot A = A^2 \\
\vdots \\
D^{(n-1)} = D^{(n-2)} \cdot A = A^{n-1},
\]

yielding \(D^{(n-1)} = (\delta(i, j))\).

Time \(= \Theta(n \cdot n^3) = \Theta(n^4)\). No better than \(n \times A - F\).
**Improved matrix multiplication algorithm**

**Repeated squaring:** $A^{2k} = A^k \times A^k$.

Compute $A^2, A^4, \ldots, A^{2\left\lfloor \lg(n-1) \right\rfloor}$.

$O(\lg n)$ squarings

**Note:** $A^{n-1} = A^n = A^{n+1} = \ldots$.

Time $= \Theta(n^3 \lg n)$.

To detect negative-weight cycles, check the diagonal for negative values in $O(n)$ additional time.
Floyd-Warshall algorithm

Also dynamic programming, but faster!

Define $c_{ij}^{(k)} =$ weight of a shortest path from $i$ to $j$ with intermediate vertices belonging to the set $\{1, 2, \ldots, k\}$.

Thus, $\delta(i, j) = c_{ij}^{(n)}$. Also, $c_{ij}^{(0)} = a_{ij}$. 
Floyd-Warshall recurrence

\[ c_{ij}^{(k)} = \min_k \{ c_{ij}^{(k-1)}, c_{ik}^{(k-1)} + c_{kj}^{(k-1)} \} \]

intermediate vertices in \( \{1, 2, \ldots, k\} \)
Pseudocode for Floyd-Warshall

for \( k \leftarrow 1 \) to \( n \)
    do for \( i \leftarrow 1 \) to \( n \)
        do for \( j \leftarrow 1 \) to \( n \)
            do if \( c_{ij} > c_{ik} + c_{kj} \)
                then \( c_{ij} \leftarrow c_{ik} + c_{kj} \) \}

relaxation

Notes:

- Okay to omit superscripts, since extra relaxations can’t hurt.
- Runs in \( \Theta(n^3) \) time.
- Simple to code.
- Efficient in practice.
Transitive closure of a directed graph

Compute \( t_{ij} = \begin{cases} 1 & \text{if there exists a path from } i \text{ to } j, \\ 0 & \text{otherwise.} \end{cases} \)

**Idea:** Use Floyd-Warshall, but with \((\vee, \wedge)\) instead of \((\min, +)\):

\[
t_{ij}^{(k)} = t_{ij}^{(k-1)} \vee (t_{ik}^{(k-1)} \wedge t_{kj}^{(k-1)}).
\]

Time = \(\Theta(n^3)\).
Graph reweighting

**Theorem.** Given a function $h : V \rightarrow \mathbb{R}$, reweight each edge $(u, v) \in E$ by $w_h(u, v) = w(u, v) + h(u) - h(v)$. Then, for any two vertices, all paths between them are reweighted by the same amount.
Graph reweighting

**Theorem.** Given a function $h : V \rightarrow \mathbb{R}$, reweight each edge $(u, v) \in E$ by $w_h(u, v) = w(u, v) + h(u) - h(v)$. Then, for any two vertices, all paths between them are reweighted by the same amount.

**Proof.** Let $p = v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_k$ be a path in $G$. We have

\[
\begin{align*}
  w_h(p) &= \sum_{i=1}^{k-1} w_h(v_i, v_{i+1}) \\
         &= \sum_{i=1}^{k-1} (w(v_i, v_{i+1}) + h(v_i) - h(v_{i+1})) \\
         &= \sum_{i=1}^{k-1} w(v_i, v_{i+1}) + h(v_1) - h(v_k) \\
         &= w(p) + h(v_1) - h(v_k).
\end{align*}
\]

*Same amount!*
Shortest paths in reweighted graphs

Corollary.  \( \delta_h(u, v) = \delta(u, v) + h(u) - h(v). \)
Shortest paths in reweighted graphs

**Corollary.** \( \delta_h(u, v) = \delta(u, v) + h(u) - h(v) \).

**Idea:** Find a function \( h : V \rightarrow \mathbb{R} \) such that \( w_h(u, v) \geq 0 \) for all \( (u, v) \in E \). Then, run Dijkstra’s algorithm from each vertex on the reweighted graph.

**Note:** \( w_h(u, v) \geq 0 \) iff \( h(v) - h(u) \leq w(u, v) \).
Johnson’s algorithm

0. Add new vertex $s$, with 0 weight edges to all vertices in $V$, making shortest path from $s$ to each vertex at most 0.

1. Run Bellman-Ford, finding shortest path distance $h(v)$ from $s$ to each vertex. If a negative weight cycle exists, exit. Otherwise $w_h(u,v)=w(u,v)+h(u)-h(v)$ is non-negative since $h(v)-h(u) \leq w(u,v)$.
   - Time $= O(VE)$.

2. Run Dijkstra’s algorithm using $w_h$ from each vertex $u \in V$ to compute $\delta_h(u,v)$ for all $v \in V$.
   - Time $= O(VE + V^2 \log V)$.

3. For each $(u,v) \in V \times V$, compute $\delta(u,v) = \delta_h(u,v) - h(u) + h(v)$.
   - Time $= O(V^2)$.

Total time $= O(VE + V^2 \log V)$. 
Johnson’s algorithm

Example

The first three stages of Johnson's algorithm are depicted in the illustration below.

original graph with negative edges
shortest path tree found by Bellman-Ford
rewighted graph with no negative edges