Weighted graphs

Κ08 Δομές Δεδομένων και Τεχνικές Προγραμματισμού
Κώστας Χατζηκοκολάκης
Weighted graphs

• Graphs with numbers, called *weights*, attached to each edge
  - Often restricted to *non-negative*

• Directed or undirected

• Examples
  - *Distance* between cities
  - *Cost* of flight between airports
  - *Time* to send a message between routers
Weighted graphs

• Adjacency matrix representation

\[
T[i, j] = \begin{cases} 
  w_{i,j} & \text{if } i, j \text{ are connected} \\
  \infty & \text{if } i \neq j \text{ are not connected} \\
  0 & \text{if } i = j
\end{cases}
\]

• Similarly for adjacency lists
Example weighted graph
Example weighted graph

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
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<td>∞</td>
<td>8</td>
<td>2</td>
<td>∞</td>
<td>0</td>
</tr>
</tbody>
</table>

Adjacency matrix
Shortest paths

• The **length** of a path is the **sum of the weights** of its edges

• Very common problem
  - find the **shortest path** from $s$ to $d$

• Examples
  - Shortest route between cities
  - Cheapest connecting flight
  - Fastest network route
  - ...
Shortest path from vertex 1 to vertex 5
Shortest path problem

Two main variants:

- **Single source** \( s \)
  - Find the shortest path from \( s \) to each node
  - **Dijkstra's** algorithm
    - Only for **non-negative** weights (important!)

- **All-pairs**
  - Find the shortest path between all pairs \( s, d \)
  - **Floyd-Warshall** algorithm
    - Any weights
Dijkstra's algorithm

Main ideas:

• Keep a set $W$ of *visited* nodes
  - Start with $W = \{s\}$ (or $W = \{\}$)

• Keep a matrix $\Delta[u]$
  - Minimum distance from $s$ to $u$ **passing only through** $W$
  - Start with $\Delta[u] = T[s, u]$ (or $\Delta[s] = 0, \Delta[u] = \infty$)

• At each step we **enlarge** $W$ by adding a **new vertex** $w \notin W$
  - $w$ is the one with **minimum** $\Delta[w]$
Dijkstra's algorithm

Main ideas:

• Adding \( w \) to \( W \) might affect \( \Delta[u] \)
  - For some neighbour \( u \) of \( w \)

• We might now have a shorter path to \( u \) passing through \( w \)
  - Of the form \( s \rightarrow \ldots \rightarrow w \rightarrow u \)
  - If \( \Delta[u] > \Delta[w] + T[w, u] \)

• In this case we update \( \Delta \)
  - \( \Delta[u] = \Delta[w] + T[w, u] \)
Example graph
Expanding the vertex set \( w \) in stages

<table>
<thead>
<tr>
<th>Stage</th>
<th>( W )</th>
<th>( V-W )</th>
<th>( w )</th>
<th>( \Delta(w) )</th>
<th>( \Delta(1) )</th>
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</thead>
<tbody>
<tr>
<td>Start</td>
<td>{1}</td>
<td>{2,3,4,5,6}</td>
<td>-</td>
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</tbody>
</table>

![Graph](image-url)
Expanding the vertex set $w$ in stages

$W=2$ is chosen for the second stage.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$W$</th>
<th>$V-W$</th>
<th>$w$</th>
<th>$\Delta(w)$</th>
<th>$\Delta(1)$</th>
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![Graph Image](image_url)
Expanding the vertex set \( w \) in stages

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</table>

![Graph](image-url)
Expanding the vertex set $w$ in stages

$W=6$ is chosen for the third stage.

<table>
<thead>
<tr>
<th>Stage</th>
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![Graph with vertices and edges](image-url)
Expanding the vertex set \( w \) in stages

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![Graph](image-url)
Expanding the vertex set $w$ in stages

$W=4$ is chosen for the fourth stage.

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<td>7</td>
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</tbody>
</table>
Expanding the vertex set $w$ in stages

$W=3$ is chosen for the fifth stage.

<table>
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![Graph Diagram]
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<td>3</td>
<td>10</td>
<td>7</td>
<td>11</td>
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</tr>
</tbody>
</table>

![Graph](image-url)
Expanding the vertex set \( w \) in stages

\( W = 5 \) is chosen for the sixth stage.

<table>
<thead>
<tr>
<th>Stage</th>
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</tbody>
</table>

![Graph Diagram]

- The vertex set is expanded in stages, with each stage showing how the vertex set \( V-W \) changes.
- At each stage, the vertex set \( w \) is expanded by adding the smallest \( \Delta(w) \) value.
- The table shows the changes in the vertex set and the values of \( \Delta(1) \) through \( \Delta(6) \) for each stage.
Expanding the vertex set $w$ in stages

<table>
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<td>10</td>
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<td>11</td>
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</tr>
</tbody>
</table>
Dijkstra's algorithm in pseudocode

// Πληροφορίες που κρατάμε για κάθε κόμβο v
W[u] : 1 αν ο u είναι στο σύνολο W, θ διαφορετικά
dist[u] : o πίνακας Δ
prev[u] : o προηγούμενος του v στο βέλτιστο μονοπάτι

// Αρχικοποίηση: W={} (εναλλακτικά μπορούμε και W={src})
for each vertex u in Graph
    dist[u] = INT_MAX // infinity
    prev[u] = NULL
    W[u] = 0

dist[src] = 0
Dijkstra's algorithm in pseudocode

// Κύριως αλγόριθμος
while true
    w = vertex with minimum dist[w], among those with W[w] = 0

    W[w] = 1
    if w == dest
        stop  // optimal cost = dist[dest]
        // optimal path = dest <- prev[dest] <- ... <- src (inverse)

    for each neighbor u of w
        if W[u] == 1
            continue
        alt = dist[w] + weight(w, u)  // κόστος του src -> ... -> w
        if alt < dist[u]  // καλύτερο από πριν, update
            dist[u] = alt
            prev[u] = w
Using a priority queue

• Finding the $w \not\in W$ with minimum $\Delta[w]$ is slow
  - $O(n)$ time

• But we can use a priority queue for this!
  - We only keep vertices $w \not\in W$ in the queue
  - They are compared based on their $\Delta[w]$
    (each $w$ has “priority” $\Delta[w]$)

• Careful when $\Delta[w]$ is modified!
  - Either use a priority queue that allows updates
  - Or insert multiple copies of each $w$ with different priorities
    ◦ the queue might contain already visited vertices: ignore them
Dijkstra's algorithm with priority queue

// Δεδομένα
src : αρχικός κόμβος
dest : τελικός κόμβος

// Πληροφορίες που κρατάμε για κάθε κόμβο u
W[u] : 1 αν ο u είναι στο σύνολο W, θ διαφορετικά
dist[u] : ο πίνακας Δ
prev[u] : ο προηγούμενος του u στο βέλτιστο μονοπάτι
pq : Priority queue, εισάγουμε tuples {u,dist[u]}
    συγκρίνοντας με βάση το dist[u]

// Αρχικοποίηση: W={} (εναλλακτικά μπορούμε και W={src})
prev[src] = NULL
dist[src] = 0
pq.queue_insert(pq, {src,0})  // dist[src] = 0
Dijkstra's algorithm with priority queue

// Κυρίως αλγόριθμος
while pq is not empty
    w = pqueue_max(pq)  // w with minimal dist[u]
pqueue_remove_max(pq)

    if exists(W[w])  // το w μπορεί να υπάρχει πολλές φορές στην ο
        continue  // δεν κάνουμε replace), και να είναι ήδη vis
    W[w] = 1
    if w == dest
        stop  // optimal cost/path same as before

for each neighbor u of w
    if exists(W[u])
        continue
    alt = dist[w] + weight(w,u)  // cost of src->...->w->u
    if !exists(dist[u]) OR alt < dist[u]
        dist[u] = alt
        prev[u] = w
        pqueue_insert(pq, {u,alt})  // προαιρετικά: replace αν υπ
stop  // pq άδειασε πριν βρούμε το dest => δεν υπάρχει μονοπάτι
Notation

• $s \rightarrow d$
  - Direct step step from $s$ to $d$

• $s \xrightarrow{W} d$
  - Multiple steps $s \rightarrow \ldots \rightarrow d$
  - All intermediate steps belong to the set $W \subseteq V$

• $s \xrightarrow{W} d$
  - Shortest path among all $s \xrightarrow{W} d$
  - So $s \xrightarrow{V} d$ is the overall shortest one
Proof of correctness

• We need to prove that $\Delta[u]$ is the **minimum distance to** $u$
  - after the algorithm finishes

• But it's much easier to reason **step by step**
  - we need a property that holds **at every step**
  - this is called an **invariant** (property that never changes)
Proof of correctness

Invariant of Dijkstra's algorithm

- $\Delta[u]$ is the cost of the shortest path passing only through $W$
- And the shortest overall when $u \in W$

Formally:

1. For all $u \in V$ the path $s \xrightarrow{W} u$ has cost $\Delta[u]$
2. For all $u \in W$ the path $s \xrightarrow{V} u$ has cost $\Delta[u]$

Proof: induction on the size of $W$, for both (1), (2) together
Proof of correctness

Base case $W = \{s\}$

• Trivial, the only path $s \xrightarrow{W} u$ is the direct one $s \rightarrow u$

• For (1): its cost is exactly $T[s, u] = \Delta[u]$
  - initial value of $\Delta[u]$

• For (2): the only $u \in W$ is $s$ itself
Proof of correctness

Inductive case

• Assume \(|W| = k\) and (1),(2) hold

• The algorithm
  - Updates \(W\), adding a new vertex \(w \not\in W\)
  - Updates \(\Delta[u]\) for all neighbours \(u\) of \(w\)

• Let \(W', \Delta'\) be the values after the update

• Show that (1),(2) still hold for \(W', \Delta'\)
Proof of correctness

We start showing that (2) still holds for $W'$, $\Delta'$

- The interesting vertex is the $w$ we just added
  - Vertices $u \neq w$ are trivial from the induction hypothesis

- Show: $s \overset{V}{\rightarrow} w$ has cost $\Delta'[w]$
  - Note: $\Delta'[w] = \Delta[w]$ (we do not update $\Delta[w]$)
  - We already know that $s \overset{W}{\rightarrow} w$ has cost $\Delta[w]$ (ind. hyp)
  - So we just need to prove that there is no better path outside $W$
Proof of correctness

- Assuming such path exists, let \( r \) be its first vertex outside \( W \).
  - So the path \( s \xrightarrow{W} r \xrightarrow{V} w \) has cost \( c < \Delta[w] \).
  - So the path \( s \xrightarrow{W} r \) has cost at most \( c < \Delta[w] \) (no negative weights!)
  - So \( \Delta[r] < \Delta[w] \).

- Impossible! We chose \( w \) to be the one with \( \min \Delta[w] \).
Proof of correctness

It remains to show (1) for $W'$, $\Delta'$

- Take some arbitrary $u$
  - Let $c$ be the cost of $s \xrightarrow{W'} u$
  - Show: $c = \Delta'[u]$

- Three cases for the optimal path $s \xrightarrow{W'} u$

- Case 1: the path does not pass through $w$
  - So it is of the form $s \xrightarrow{W} u$
  - This path has cost $\Delta[u]$ (induction hypothesis)
  - No update: $\Delta'[u] = \Delta[u] = c$
Proof of correctness

• Case 2: \( w \) is right before \( u \)
  
  - So the path is of the form \( s \xrightarrow{W} w \rightarrow u \)
  
  - The cost of \( s \xrightarrow{W} w \) is \( \Delta[w] \) (induction hypothesis)
  
  - So \( c = \Delta[w] + T[w, u] \)
  
  - So the algorithm will set \( \Delta'[u] = \Delta[w] + T[w, u] \) when updating the neighbours of \( w \)
  
  - So \( c = \Delta'[u] \)
Proof of correctness

- Case 3: some other $x$ appears after $w$ in the path
  - So the path is of the form $s \xrightarrow{W} w \rightarrow x \xrightarrow{W} u$
  - But the path $s \xrightarrow{W} w \rightarrow x$ is no shorter than $s \xrightarrow{W} x$
    - From the induction hypothesis for $x \in W$
  - So $s \xrightarrow{W} x \rightarrow u$ is also optimal, reducing to case 1!
Complexity

Without a priority queue:

• Initialization stage: loop over vertices: $O(n)$

• The while-loop adds one vertex every time: $n$ iterations

• Finding the new vertex loops over vertices: $O(n)$
  - same for updating the neighbours

• So total $O(n^2)$ time
Complexity

With a priority queue:

- Initialization stage: loop over vertices, so $O(n)$

- Count the number of updates (steps in the inner loop)
  - Once for every neighbour of every node: $e$ total
  - Each update is $O(\log n)$ (at most $n$ elements in the queue)

- Total $O(e \log n)$
  - Assuming a connected graph ($e \geq n$)
  - And an implementation using adjacency lists

- Only good for sparse graphs!
  - But $O(n \log n)$ can be hugely better than $O(n^2)$
The all-pairs shortest path problem

• Find the shortest path between all pairs $s, d$

• **Floyd-Warshall** algorithm

• Any weights
  - Even negative
  - But no **negative loops** (why?)
The all-pairs shortest path problem

Main idea

• At each step we compute the shortest path through a subset of vertices
  - Similarly to $W$ in Dijkstra
  - But now the set at step $k$ is $W_k = \{1, \ldots, k\}$
    ◦ Vertices are numbered in any order
• Step $k$: the cost of $i \xrightarrow{W_k} j$ is $A_k[i, j]
  - Similar to $\Delta$ in Dijkstra (but for all pairs $i, j$ of nodes)
Floyd-Warshall algorithm

• The algorithm at each step computes $A_k$ from $A_{k-1}$

• Initial step $k = 0$
  - Start with $A_0[i, j] = T[i, j]$
  - Only direct paths are allowed
Floyd-Warshall algorithm

$k$-th iteration: the optimal $i \xrightarrow{W_k} j$ either passes thorough $k$ or not.

$$A_k[i, j] = \min \left\{ A_{k-1}[i, j], A_{k-1}[i, k] + A_{k-1}[k, j] \right\}$$
Floyd-Warshall algorithm in pseudocode

```java
void floyd_warshall() {
    for (int i = 0; i <= size-1; i++)
        for (int j = 0; j <= size-1; j++)
            A[i][j] = weight(i, j)

    for (int i = 0; i <= size-1; i++)
        A[i][i] = 0;

    for (int k = 0; k <= size-1; k++)
        // Compute A_k from A_{k-1}
        for (int i = 0; i <= size-1; i++)
            for (int j = 0; j <= size-1; j++)
}
```

A is the current $A_k$ at every step $k$. 
Complexity

• Three simple loops of $n$ steps
• So $O(n^3)$
• Not better than $n$ executions of Dijkstra in complexity
  - But much simpler
  - Often faster in practice
  - And works for negative weights
Readings

• T. A. Standish. *Data Structures, Algorithms and Software Principles in C*. Chapter 10