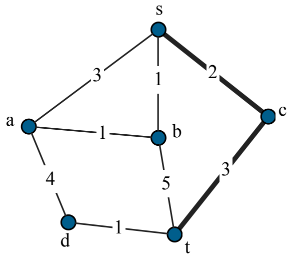
Module 3: Duality through examples (Shortest Path Algorithm)

Recap: Feasible Widths via Duality

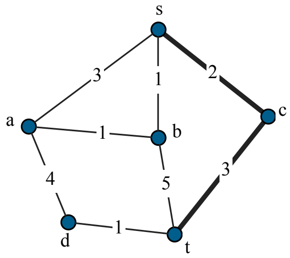
The figure on the right shows another simple instance of the shortest s, t-path problem.



Recap: Feasible Widths via Duality

The figure on the right shows another simple instance of the shortest s, t-path problem.

By inspection: shortest s, t-path (bold edges) has length 5

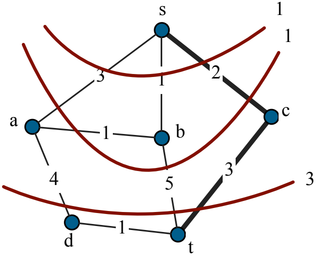


Recap: Feasible Widths via Duality

The figure on the right shows another simple instance of the shortest s, t-path problem.

By inspection: shortest s, t-path (bold edges) has length 5

There is a feasible width assignment of value 5, proving optimality!

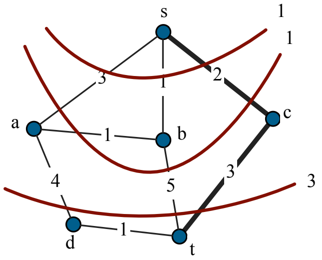


Recap: Feasible Widths via Duality

The figure on the right shows another simple instance of the shortest s, t-path problem.

By inspection: shortest s, t-path (bold edges) has length 5

There is a feasible width assignment of value 5, proving optimality!



Shortest path LP:

$$\min \quad \sum (x_e \,:\, e \in E)$$

$$\text{s.t.} \quad \sum (x_e \,:\, e \in \delta(S)) \geq 1 \quad (\delta(S)\ s,t\text{-cut})$$

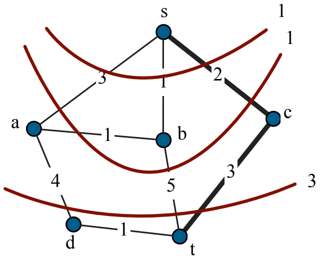
$$x \geq \mathbb{0}$$

Recap: Feasible Widths via Duality

The figure on the right shows another simple instance of the shortest s, t-path problem.

By inspection: shortest s, t-path (bold edges) has length 5

There is a feasible width assignment of value 5, proving optimality!



Shortest path LP:

$$\min \quad \sum (x_e \; : \; e \in E)$$

$$\text{s.t.} \quad \sum (x_e \; : \; e \in \delta(S)) \geq 1 \quad (\delta(S) \; s,t\text{-cut})$$

$$x \geq \mathbb{0}$$

Shortest path dual:

$$\max \quad \sum (y_S \; : \; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \; : \; e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Recap: Feasible Widths via Duality

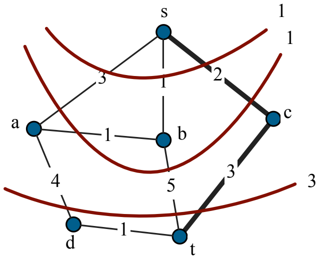
Shortest path LP:

$$\min \quad \sum(c_e x_e \,:\, e \in E)$$

$$\text{s.t.} \quad \sum(x_e \,:\, e \in \delta(S)) \geq 1$$

$$(\delta(S)\ s,t\text{-cut})$$

$$x \geq \mathbb{0}$$



Shortest path dual:

$$\max \quad \sum(y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum(y_S \,:\, e \in \delta(S)) \leq c_e$$

$$(e \in E)$$

$$y \geq \mathbb{0}$$

Letting

$$x_e = \begin{cases} 1 & e \textbf{ bold} \text{ in figure} \\ 0 & \text{otherwise} \end{cases}$$

for all $e \in E$ is feasible for shortest path LP.

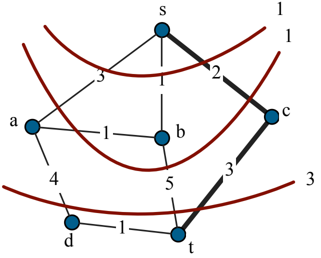
Recap: Feasible Widths via Duality

Shortest path LP:

$$\min \quad \sum (c_e x_e \;:\; e \in E)$$

$$\text{s.t.} \quad \sum (x_e \;:\; e \in \delta(S)) \geq 1 \qquad (\delta(S)\ s,t\text{-cut})$$

$$x \geq \mathbb{0}$$



Shortest path dual:

$$\max \quad \sum (y_S \;:\; \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \;:\; e \in \delta(S)) \leq c_e \qquad (e \in E)$$

$$y \geq \mathbb{0}$$

Letting

$$y_{\{s\}} = y_{\{s,b\}} = 1,\; y_{\{s,a,b,c\}} = 3,$$

and $y_S = 0$ for all other s, t-cuts $\delta(S)$ yields a feasible dual solution of value 5!

Recap: Feasible Widths via Duality

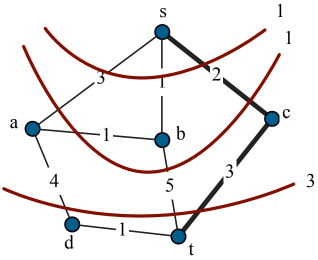
Shortest path LP:

$$\min \quad \sum (x_e \; : \; e \in E)$$

$$\text{s.t.} \quad \sum (x_e \; : \; e \in \delta(S)) \geq 1$$

$$(\delta(S) \; s,t\text{-cut})$$

$$x \geq \mathbb{0}$$



Shortest path dual:

$$\max \quad \sum (y_S \; : \; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \; : \; e \in \delta(S)) \leq c_e$$

$$(e \in E)$$

$$y \geq \mathbb{0}$$

Weak Duality Theorem

If $\bar{x}$ is feasible for shortest path LP, and $\bar{y}$ is feasible for its dual then $b^T\bar{y} \leq c^T\bar{x}$.

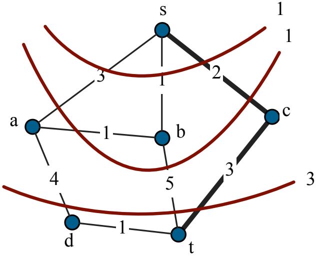
Recap: Feasible Widths via Duality

Shortest path LP:

$$\min \quad \sum (x_e \,:\, e \in E)$$

$$\text{s.t.} \quad \sum (x_e \,:\, e \in \delta(S)) \geq 1 \qquad (\delta(S)\ s,t\text{-cut})$$

$$x \geq \mathbb{0}$$



Shortest path dual:

$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \qquad (e \in E)$$

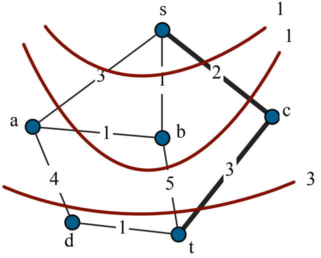
$$y \geq \mathbb{0}$$

Weak Duality Theorem

If $\bar{x}$ is feasible for shortest path LP, and $\bar{y}$ is feasible for its dual then $b^T\bar{y} \leq c^T\bar{x}$.

$\longrightarrow$ **Bold** path in figure is shortest s, t-path!

Recap: Feasible Widths via Duality



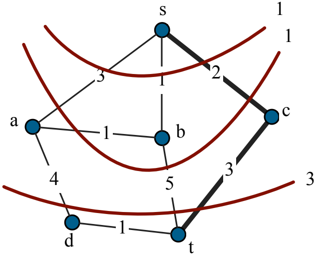
Today:

1. How did we find the bold path?

Weak Duality Theorem

If $\bar{x}$ is feasible for shortest path LP, and $\bar{y}$ is feasible for its dual then $b^T\bar{y} \leq c^T\bar{x}$.

Recap: Feasible Widths via Duality



Today:

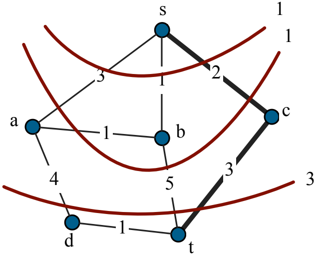
1. How did we find the bold path?
2. How did we find the dual solution?

Weak Duality Theorem

If $\bar{x}$ is feasible for shortest path LP, and $\bar{y}$ is feasible for its dual then $b^T\bar{y} \leq c^T\bar{x}$.

$\longrightarrow$ **Bold** path in figure is shortest s, t-path!

Recap: Feasible Widths via Duality



Weak Duality Theorem

If $\bar{x}$ is feasible for shortest path LP, and $\bar{y}$ is feasible for its dual then $b^T\bar{y} \leq c^T\bar{x}$.

$\longrightarrow$ **Bold** path in figure is shortest s,t-path!

Today:

1. How did we find the bold path?
2. How did we find the dual solution?
3. Is there always a shortest s,t-path and a dual solution whose value matches its length?

An Algorithm for the Shortest s, t-Path Problem

Arcs and Directed Paths

So far: edges of a graph $G = (V, E)$ are unordered pairs of vertices.

Arcs and Directed Paths

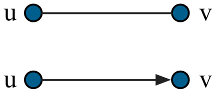
So far: edges of a graph $G = (V, E)$ are unordered pairs of vertices.

Now: introduce arcs – ordered pairs of vertices.

Arcs and Directed Paths

So far: edges of a graph $G = (V, E)$ are unordered pairs of vertices.

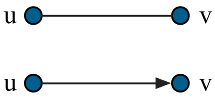
Now: introduce arcs – ordered pairs of vertices. Denote an arc from u to v as $\overrightarrow{uv}$, and draw it as arrow from u to v.



Arcs and Directed Paths

So far: edges of a graph $G = (V, E)$ are unordered pairs of vertices.

Now: introduce arcs – ordered pairs of vertices. Denote an arc from u to v as $\overrightarrow{uv}$, and draw it as arrow from u to v.

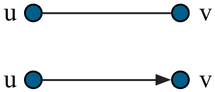


A directed path is then a sequence of arcs:

$$\overrightarrow{v_1 v_2}, \overrightarrow{v_2 v_3}, \ldots, \overrightarrow{v_{k-1} v_k},$$

where $\overrightarrow{v_i v_{i+1}}$ is an arc in the given graph, and $v_i \neq v_j$ for all $i \neq j$.

Arcs and Directed Paths



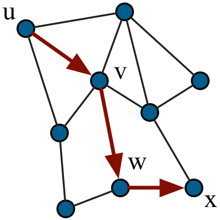
So far: edges of a graph $G = (V, E)$ are unordered pairs of vertices.

Now: introduce arcs – ordered pairs of vertices. Denote an arc from u to v as $\overrightarrow{uv}$, and draw it as arrow from u to v.

A directed path is then a sequence of arcs:

$$\overrightarrow{v_1 v_2}, \overrightarrow{v_2 v_3}, \ldots, \overrightarrow{v_{k-1} v_k},$$

where $\overrightarrow{v_i v_{i+1}}$ is an arc in the given graph, and $v_i \neq v_j$ for all $i \neq j$.



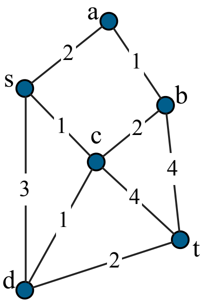
Example:

$$\overrightarrow{uv}, \overrightarrow{vw}, \overrightarrow{wx}$$

is a directed u, x-path.

Shortest Paths: Algorithmic Ideas

Idea: Find an s,t-path P and a feasible dual y s.t. $c(P) = \mathbb{1}^T y$. How?



Recall the shortest path dual:

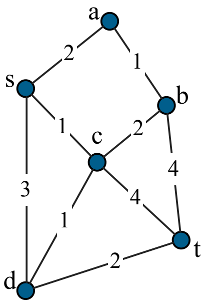
$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Algorithmic Ideas

Idea: Find an s, t-path P and a feasible dual y s.t. $c(P) = \mathbb{1}^T y$. How?



Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U \; : \; \delta(U) \; s,t\text{-cut}, \; e \in \delta(U))$$

Recall the shortest path dual:

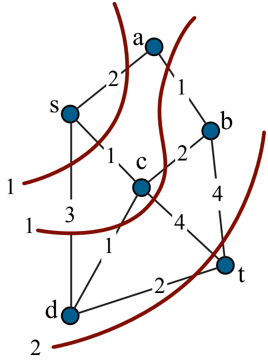
$$\begin{aligned} \max \quad & \sum(y_S \; : \; \delta(S) \; s,t\text{-cut}) \\ \text{s.t.} \quad & \sum(y_S \; : \; e \in \delta(S)) \leq c_e \quad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Algorithmic Ideas

Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U \; : \; \delta(U) \; s,t\text{-cut}, \; e \in \delta(U))$$



$$\max \quad \sum(y_S \; : \; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum(y_S \; : \; e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Examples: for the dual y given on the right,

- $\text{slack}_y(sa) =$

Shortest Paths: Algorithmic Ideas

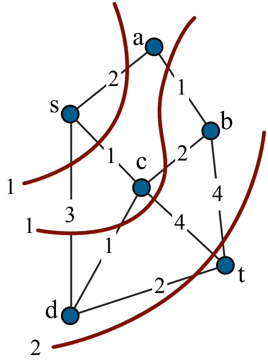
Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U \,:\, \delta(U)\ s,t\text{-cut},\ e \in \delta(U))$$

Examples: for the dual y given on the right,

- $\text{slack}_y(sa) = 2 - 1 = 1$



$$\max \quad \sum(y_S \,:\, \delta(S)\ s,t\text{-cut})$$

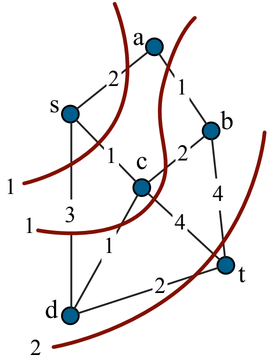
$$\text{s.t.} \quad \sum(y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum (y_U \ : \ \delta(U) \ s,t\text{-cut}, \ e \in \delta(U))$$



Examples: for the dual y given on the right,

- $\text{slack}_y(sa) = 2 - 1 = 1$
- $\text{slack}_y(sd) =$

$$\max \quad \sum (y_S \ : \ \delta(S) \ s,t\text{-cut})$$

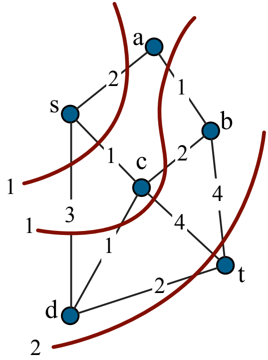
$$\text{s.t.} \quad \sum (y_S \ : \ e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U \; : \; \delta(U) \; s,t\text{-cut}, \; e \in \delta(U))$$



Examples: for the dual y given on the right,

- $\text{slack}_y(sa) = 2 - 1 = 1$
- $\text{slack}_y(sd) = 3 - 1 - 1 = 1$

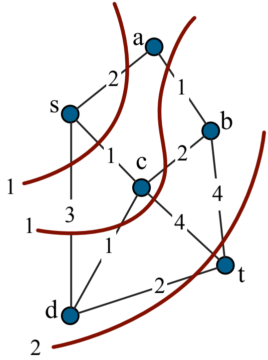
$$\begin{aligned} \max \quad & \sum(y_S \; : \; \delta(S) \; s,t\text{-cut}) \\ \text{s.t.} \quad & \sum(y_S \; : \; e \in \delta(S)) \leq c_e \\ & \qquad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Algorithmic Ideas

Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U \ : \ \delta(U) \ s,t\text{-cut}, \ e \in \delta(U))$$



Examples: for the dual y given on the right,

- $\text{slack}_y(sa) = 2 - 1 = 1$
- $\text{slack}_y(sd) = 3 - 1 - 1 = 1$
- $\text{slack}_y(ct) =$

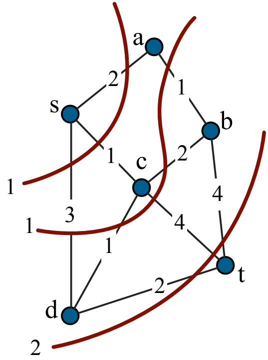
$$\begin{aligned} \max \quad & \sum(y_S \ : \ \delta(S) \ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum(y_S \ : \ e \in \delta(S)) \leq c_e \quad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Algorithmic Ideas

Definition

Let y be a feasible dual solution. The slack of an edge $e \in E$ is defined as

$$\text{slack}_y(e) = c_e - \sum(y_U : \delta(U)\ s,t\text{-cut},\ e \in \delta(U))$$



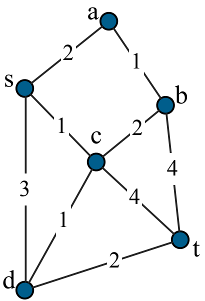
Examples: for the dual y given on the right,

- $\text{slack}_y(sa) = 2 - 1 = 1$
- $\text{slack}_y(sd) = 3 - 1 - 1 = 1$
- $\text{slack}_y(ct) = 4 - 1 - 2 = 1$

$$\begin{aligned} \max \quad & \sum(y_S : \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum(y_S : e \in \delta(S)) \leq c_e \quad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$



$$\max \quad \sum(y_S \,:\, \delta(S)\ s,t\text{-cut})$$

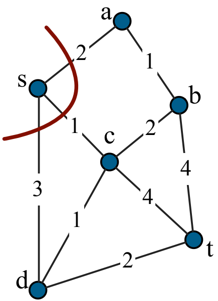
$$\text{s.t.} \quad \sum(y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s, t-cut: $\delta(\{s\})$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

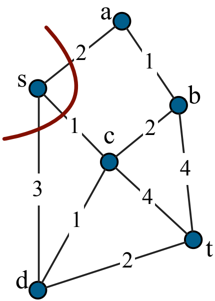
$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can
maintaining feasibility



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

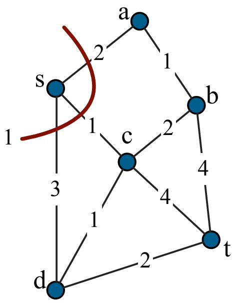
$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$



$$\max \quad \sum (y_S : \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E)$$

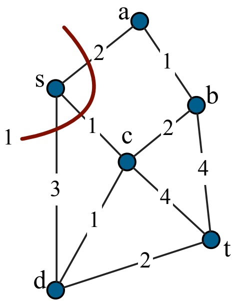
$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s, t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can
maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$

Note: This decreases the slack of sc to 0!



$$\max \quad \sum (y_S \,:\, \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

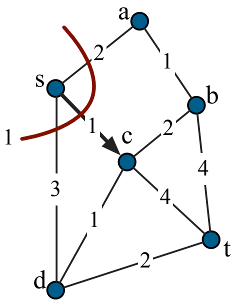
$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can
maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$

Note: This decreases the slack of sc to 0!
$\longrightarrow$ replace sc by $\overrightarrow{sc}$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

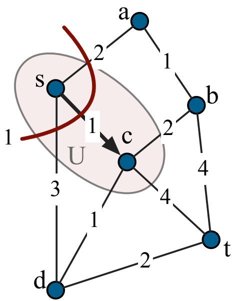
Start with the trivial dual $y = \mathbb{0}$

Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$

Note: This decreases the slack of sc to 0!
$\longrightarrow$ replace sc by $\overrightarrow{sc}$

Next: Look at all vertices that are reachable from s via directed paths:

$$U = \{s, c\}$$



$$\max \quad \sum (y_S \ : \ \delta(S) \ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \ : \ e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

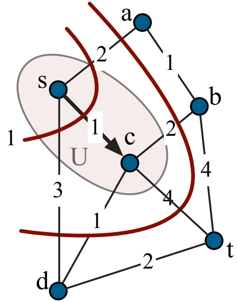
Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$

Note: This decreases the slack of sc to 0!
$\longrightarrow$ replace sc by $\overrightarrow{sc}$

Next: Look at all vertices that are reachable from s via directed paths:

$$U = \{s, c\}$$

and consider increasing y_U



$$\max \quad \sum(y_S \;:\; \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum(y_S \;:\; e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Start with the trivial dual $y = \mathbb{0}$

Simplest s,t-cut: $\delta(\{s\})$
$\longrightarrow$ increase $y_{\{s\}}$ as much as we can maintaining feasibility
$\longrightarrow$ $y_{\{s\}} = 1$

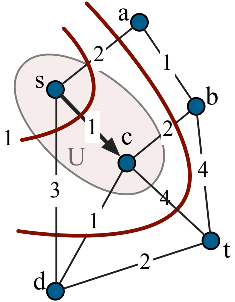
Note: This decreases the slack of sc to 0!
$\longrightarrow$ replace sc by $\overrightarrow{sc}$

Next: Look at all vertices that are reachable from s via directed paths:

$$U = \{s, c\}$$

and consider increasing y_U

Q: By how much can you increase y_U?



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

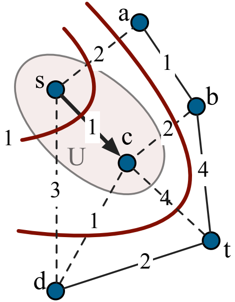
$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!



$$\max \quad \sum(y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum(y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

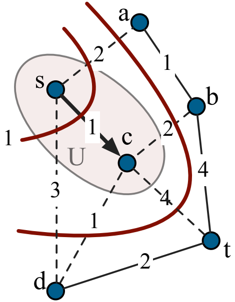
$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$\begin{aligned} \text{slack}_y(sa) &= \\ \text{slack}_y(cb) &= \\ \text{slack}_y(ct) &= \\ \text{slack}_y(cd) &= \\ \text{slack}_y(sd) &= \end{aligned}$$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

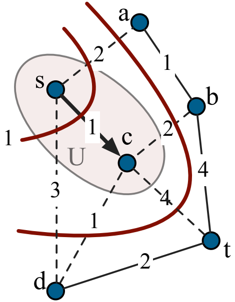
$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$\begin{aligned}
\text{slack}_y(sa) &= 2 - 1 = 1 \\
\text{slack}_y(cb) &= \\
\text{slack}_y(ct) &= \\
\text{slack}_y(cd) &= \\
\text{slack}_y(sd) &=
\end{aligned}$$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

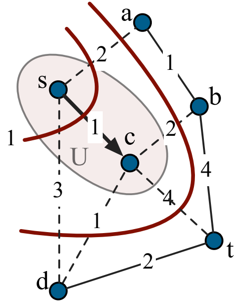
$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$\begin{aligned}\text{slack}_y(sa) &= 2-1=1\\ \text{slack}_y(cb) &= 2\\ \text{slack}_y(ct) &= \\ \text{slack}_y(cd) &= \\ \text{slack}_y(sd) &= \end{aligned}$$



$$\max \quad \sum(y_S \ : \ \delta(S) \ s,t\text{-cut})$$

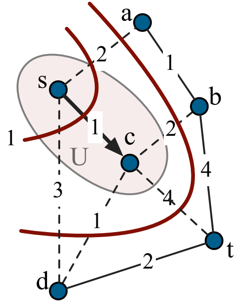
$$\text{s.t.} \quad \sum(y_S \ : \ e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!



$$\begin{aligned}
\mathsf{slack}_y(sa) &= 2 - 1 = 1 \\
\mathsf{slack}_y(cb) &= 2 \\
\mathsf{slack}_y(ct) &= 4 \\
\mathsf{slack}_y(cd) &= \\
\mathsf{slack}_y(sd) &=
\end{aligned}$$

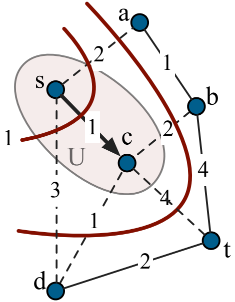
$$\begin{aligned}
\max \quad & \sum (y_S \,:\, \delta(S)\ s,t\text{-cut}) \\
\text{s.t.} \quad & \sum (y_S \,:\, e \in \delta(S)) \leq c_e \\
& \qquad (e \in E) \\
& y \geq \mathbb{0}
\end{aligned}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$\begin{aligned} \text{slack}_y(sa) &= 2-1=1 \\ \text{slack}_y(cb) &= 2 \\ \text{slack}_y(ct) &= 4 \\ \text{slack}_y(cd) &= 1 \\ \text{slack}_y(sd) &= \end{aligned}$$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

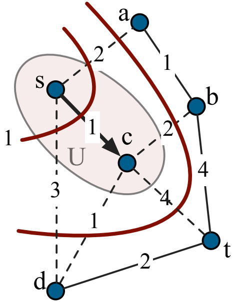
$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$
\begin{aligned}
\text{slack}_y(sa) &= 2-1=1\\
\text{slack}_y(cb) &= 2\\
\text{slack}_y(ct) &= 4\\
\text{slack}_y(cd) &= 1\\
\text{slack}_y(sd) &= 3-1=2
\end{aligned}
$$

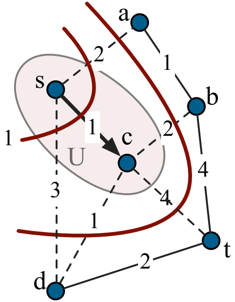


$$
\begin{aligned}
\max \quad & \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})\\
\text{s.t.} \quad & \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)\\
& y \ge \mathbb{0}
\end{aligned}
$$

Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!



$$\begin{aligned} \text{slack}_y(sa) &= 2-1=1 \\ \text{slack}_y(cb) &= 2 \\ \text{slack}_y(ct) &= 4 \\ \text{slack}_y(cd) &= 1 \\ \text{slack}_y(sd) &= 3-1=2 \end{aligned}$$

$$\max \quad \sum (y_S : \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Edges cd and sa minimize slack. Pick one arbitrarily: sa.

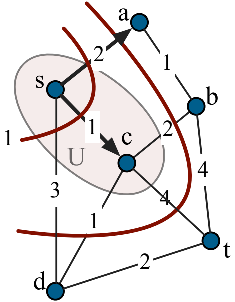
Shortest Paths: Building Duals Incrementally

Q: By how much can you increase y_U? The

maximum increase possible for $y_{\{s,c\}}$ is determined by the slack of edges in $\delta(\{s,c\})$!

$$
\begin{aligned}
\text{slack}_y(sa) &= 2-1=1 \\
\text{slack}_y(cb) &= 2 \\
\text{slack}_y(ct) &= 4 \\
\text{slack}_y(cd) &= 1 \\
\text{slack}_y(sd) &= 3-1=2
\end{aligned}
$$

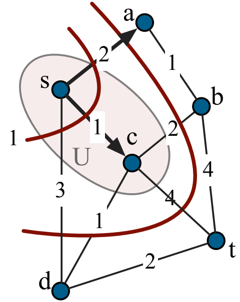
Edges cd and sa minimize slack. Pick one arbitrarily: sa.
Set $y_U = \text{slack}_y(sa) = 1$ and convert sa into arc $\overrightarrow{sa}$



$$
\begin{aligned}
\max \quad & \sum (y_S \ : \ \delta(S) \ s,t\text{-cut}) \\
\text{s.t.} \quad & \sum (y_S \ : \ e \in \delta(S)) \le c_e \\
& \qquad (e \in E) \\
& y \ge \mathbb{0}
\end{aligned}
$$

Shortest Paths: Building Duals Incrementally

Q: Which vertices are reachable from s via directed paths?



$$\max \quad \sum (y_S \ : \ \delta(S) \ s,t\text{-cut})$$

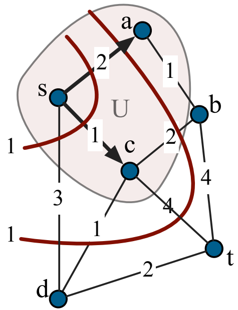
$$\text{s.t.} \quad \sum (y_S \ : \ e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: Which vertices are reachable from s via directed paths?

$$U = \{s, a, c\}$$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

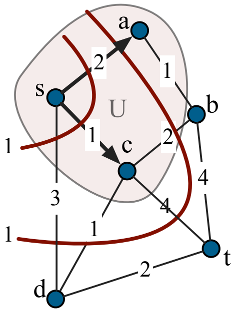
$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: Which vertices are reachable from s via directed paths?

$$U = \{s, a, c\}$$

Natural idea: Increase $y_{\{s,a,c\}}$ by as much as we can. How much?



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

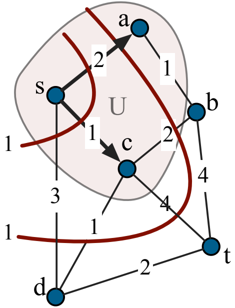
Shortest Paths: Building Duals Incrementally

Q: Which vertices are reachable from s via directed paths?

$$U = \{s, a, c\}$$

Natural idea: Increase $y_{\{s,a,c\}}$ by as much as we can. How much?
$\longrightarrow$ the slack of cd is 0, and hence

$$y_{\{s,a,c\}} = 0$$



$$\max \quad \sum (y_S \, : \, \delta(S) \ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \, : \, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Q: Which vertices are reachable from s via directed paths?

$$U = \{s, a, c\}$$

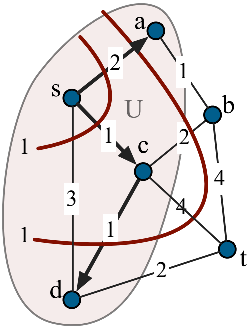
Natural idea: Increase $y_{\{s,a,c\}}$ by as much as we can. How much?
$\longrightarrow$ the slack of cd is 0, and hence

$$y_{\{s,a,c\}} = 0$$

Also: change cd into $\overrightarrow{cd}$, and let

$$U = \{s, a, c, d\}$$

be the reachable vertices from s



$$\max \quad \sum (y_S : \delta(S)\ s,t\text{-cut})$$

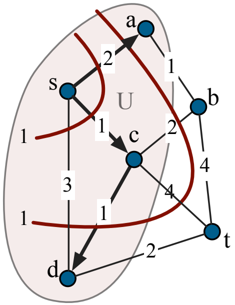
$$\text{s.t.} \quad \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$



$$\max \quad \sum (y_S \,:\, \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

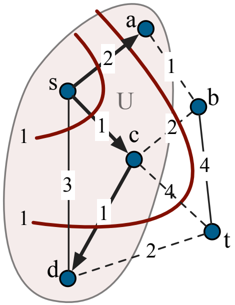
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \mathsf{slack}_y(ab) &= \\ \mathsf{slack}_y(cb) &= \\ \mathsf{slack}_y(ct) &= \\ \mathsf{slack}_y(dt) &= \end{aligned}$$



$$\begin{aligned} \max \quad & \sum (y_S \,:\, \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum (y_S \,:\, e \in \delta(S)) \le c_e \\ & \qquad (e \in E) \\ & y \ge \mathbb{0} \end{aligned}$$

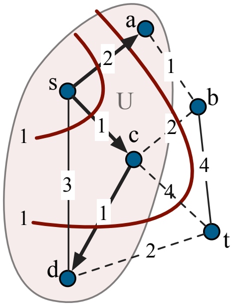
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \text{slack}_y(ab) &= 1 \\ \text{slack}_y(cb) &= \\ \text{slack}_y(ct) &= \\ \text{slack}_y(dt) &= \end{aligned}$$



$$\max \quad \sum (y_S \,:\, \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

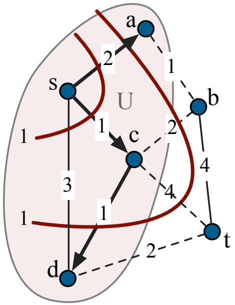
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned}
\text{slack}_y(ab) &= 1 \\
\text{slack}_y(cb) &= 2 - 1 = 1 \\
\text{slack}_y(ct) &= \\
\text{slack}_y(dt) &=
\end{aligned}$$



$$\max \quad \sum (y_S : \delta(S) \ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

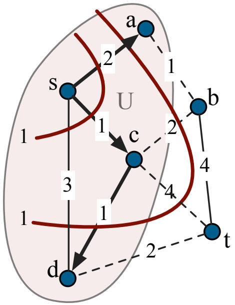
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \text{slack}_y(ab) &= 1 \\ \text{slack}_y(cb) &= 2 - 1 = 1 \\ \text{slack}_y(ct) &= 4 - 1 = 3 \\ \text{slack}_y(dt) &= \end{aligned}$$



$$\max \quad \sum (y_S \;:\; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \;:\; e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, c, d\}$$

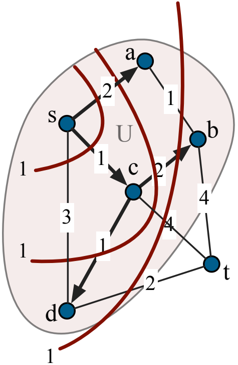
Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \text{slack}_y(ab) &= 1 \\ \text{slack}_y(cb) &= 2 - 1 = 1 \\ \text{slack}_y(ct) &= 4 - 1 = 3 \\ \text{slack}_y(dt) &= 2 \end{aligned}$$

Let $y_{\{s,a,c,d\}} = 1$, add equality arc $\overrightarrow{cb}$, and update the set

$$U = \{s, a, b, c, d\}$$

of vertices reachable from s

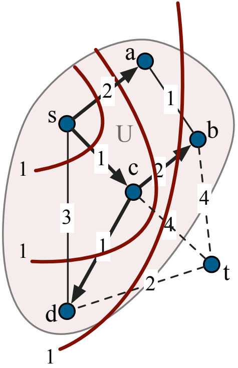


$$\begin{aligned} \max \quad & \sum (y_S : \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$



$$\max \quad \sum (y_S \;:\; \delta(S)\ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \;:\; e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \ge \mathbb{0}$$

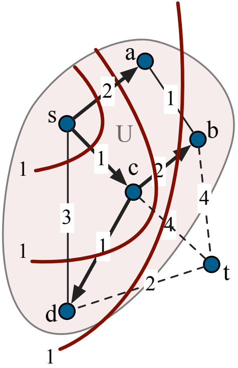
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \mathsf{slack}_y(bt) &= \\ \mathsf{slack}_y(ct) &= \\ \mathsf{slack}_y(dt) &= \end{aligned}$$



$$\begin{aligned} \max \quad & \sum (y_S \;:\; \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum (y_S \;:\; e \in \delta(S)) \le c_e \\ & \qquad (e \in E) \\ & y \ge \mathbb{0} \end{aligned}$$

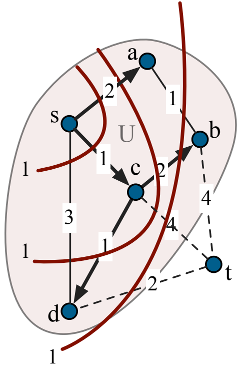
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \text{slack}_y(bt) &= 4 \\ \text{slack}_y(ct) &= \\ \text{slack}_y(dt) &= \end{aligned}$$



$$\max \quad \sum (y_S : \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S : e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

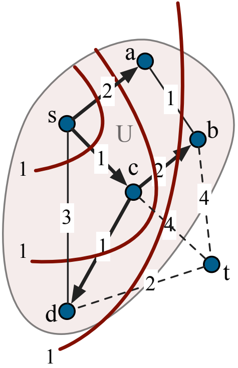
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \text{slack}_y(bt) &= 4 \\ \text{slack}_y(ct) &= 4 - 2 = 2 \\ \text{slack}_y(dt) &= \end{aligned}$$



$$\begin{aligned} \max \quad & \sum (y_S \,:\, \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum (y_S \,:\, e \in \delta(S)) \leq c_e \\ & \qquad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

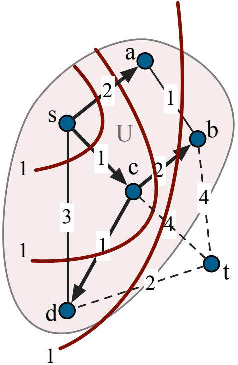
Shortest Paths: Building Duals Incrementally

Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned} \mathsf{slack}_y(bt) &= 4 \\ \mathsf{slack}_y(ct) &= 4 - 2 = 2 \\ \mathsf{slack}_y(dt) &= 2 - 1 = 1 \end{aligned}$$



$$\max \quad \sum (y_S \,:\, \delta(S) \ s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \leq c_e \qquad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

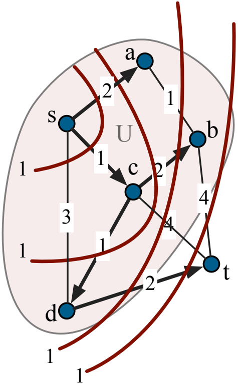
Vertices reachable from s by directed paths:

$$U = \{s, a, b, c, d\}$$

Let us compute the slack of edges in $\delta(U)$:

$$\begin{aligned}\mathsf{slack}_y(bt) &= 4\\ \mathsf{slack}_y(ct) &= 4-2=2\\ \mathsf{slack}_y(dt) &= 2-1=1\end{aligned}$$

Let $y_{\{s,a,b,c,d\}} = 1$, add equality arc $\overrightarrow{dt}$.



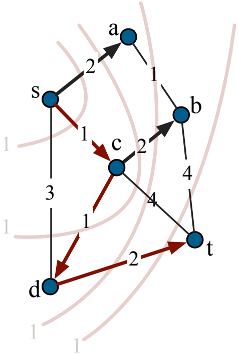
$$\begin{aligned}\max \quad & \sum (y_S : \delta(S)\ s,t\text{-cut})\\ \text{s.t.} \quad & \sum (y_S : e \in \delta(S)) \le c_e \quad (e \in E)\\ & y \ge \mathbb{0}\end{aligned}$$

Shortest Paths: Building Duals Incrementally

Note: we now have a directed s, t-path in our graph:

$$P = \overrightarrow{sc}, \overrightarrow{cd}, \overrightarrow{dt},$$

and its length is 4!



$$\begin{aligned} \max \quad & \sum (y_S : \delta(S)\ s,t\text{-cut}) \\ \text{s.t.} \quad & \sum (y_S : e \in \delta(S)) \leq c_e \\ & \qquad\qquad (e \in E) \\ & y \geq \mathbb{0} \end{aligned}$$

Shortest Paths: Building Duals Incrementally

Note: we now have a directed s,t-path in our graph:

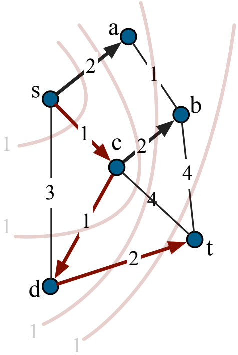
$$P = \overrightarrow{sc}, \overrightarrow{cd}, \overrightarrow{dt},$$

and its length is 4!

We also have a feasible dual solution:

$$y_{\{s\}} = y_{\{s,c\}} = y_{\{s,a,c,d\}} = y_{\{s,a,b,c,d\}} = 1,$$

and $y_U = 0$ otherwise.



$$\max \quad \sum (y_S \;:\; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \;:\; e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Note: we now have a directed s,t-path in our graph:

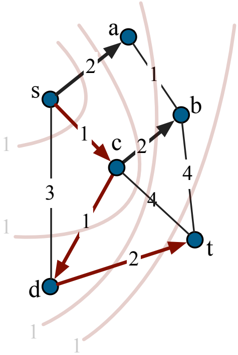
$$P = \overrightarrow{sc}, \overrightarrow{cd}, \overrightarrow{dt},$$

and its length is 4!

We also have a feasible dual solution:

$$y_{\{s\}} = y_{\{s,c\}} = y_{\{s,a,c,d\}} = y_{\{s,a,b,c,d\}} = 1,$$

and $y_U = 0$ otherwise. Its value is 4!



$$\max \quad \sum (y_S \,:\, \delta(S) \text{ } s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \,:\, e \in \delta(S)) \le c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Paths: Building Duals Incrementally

Note: we now have a directed s,t-path in our graph:

$$P = \overrightarrow{sc}, \overrightarrow{cd}, \overrightarrow{dt},$$

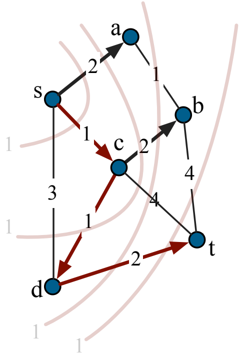
and its length is 4!

We also have a feasible dual solution:

$$y_{\{s\}} = y_{\{s,c\}} = y_{\{s,a,c,d\}} = y_{\{s,a,b,c,d\}} = 1,$$

and $y_U = 0$ otherwise. Its value is 4!

$\longrightarrow$ Path P is a shortest path!



$$\max \quad \sum (y_S \; : \; \delta(S) \; s,t\text{-cut})$$

$$\text{s.t.} \quad \sum (y_S \; : \; e \in \delta(S)) \leq c_e \quad (e \in E)$$

$$y \geq \mathbb{0}$$

Shortest Path Algorithm

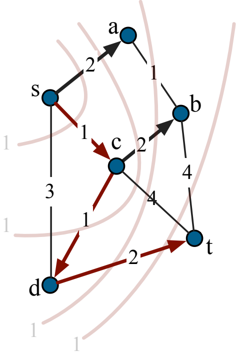
To compute the shortest Path for the instance on the right, we used the following algorithm:

Algorithm 3.2 Shortest path.

Input: Graph $G = (V, E)$, costs $c_e \geq 0$ for all $e \in E$, $s, t \in V$ where $s \neq t$.

Output: A shortest st-path P

$y_W := 0$ for all st-cuts $\delta(W)$. Set $U := \{s\}$
while $t \notin U$ **do**
    Let ab be an edge in $\delta(U)$ of smallest slack for y where $a \in U$, $b \notin U$
    $y_U := \text{slack}_y(ab)$
    $U := U \cup \{b\}$
    change edge ab into an arc $\overrightarrow{ab}$
end while
return A directed st-path P.



Recap

- We saw a shortest path algorithm that computes
  (a) an s, t-path P, and
  (b) a feasible solution y for the dual of the shortest path LP

  simultaneously

Recap

- We saw a shortest path algorithm that computes
  (a) an s, t-path P, and
  (b) a feasible solution y for the dual of the shortest path LP

  simultaneously
- We will soon show, that the length of the output path P, and the value of the dual solution y are the same, showing that both P and y are optimal

Recap

- We saw a shortest path algorithm that computes
  (a) an s, t-path P, and
  (b) a feasible solution y for the dual of the shortest path LP

  simultaneously

- We will soon show, that the length of the output path P, and the value of the dual solution y are the same, showing that both P and y are optimal

- Have a look at the book. It has another full example run of the shortest path algorithm