Today

Facility Location.

Lagrangian Dual. Already.

Convex Separator.

Farkas Lemma.

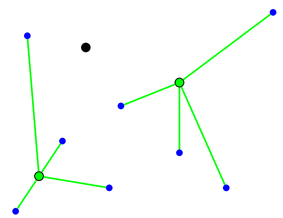
Facility location

Set of facilities: F, opening cost f_i for facility i

Set of clients: D.

d_{ij} - distance between i and j.
(notation abuse: clients/facility confusion.)

Triangle inequality: $d_{ij} \le d_{ik} + d_{kj}$.



Facility Location

Linear program relaxation:

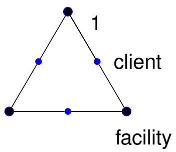
"Decision Variables".
y_i - facility i open?
x_{ij} - client j assigned to facility i.

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \ge 1$$
$$\forall i \in F, j \in D \quad x_{ij} \le y_i,$$
$$x_{ij}, y_i \ge 0$$

Facility opening cost.
Client Connnection cost.
Must connect each client.
Only connect to open facility.

Integer Solution?

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \ge 1$$
$$\forall i \in F, j \in D \quad x_{ij} \le y_i,$$
$$x_{ij}, y_i \ge 0$$



$x_{ij} = \frac{1}{2}$ edges.
$y_i = \frac{1}{2}$ edges.

Facility Cost: $\frac{3}{2}$ Connection Cost: 3
Any one Facility:
Facility Cost: 1 Client Cost: 3.7
Make it worse? Sure. Not as pretty!

Round solution?

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \ge 1$$
$$\forall i \in F, j \in D \quad x_{ij} \le y_i,$$
$$x_{ij}, y_i \ge 0$$

Round independently?

y_i and x_{ij} separately? Assign to closed facility!

Round x_{ij} and open facilities?
Different clients force different facilities open.

Any ideas?

Use Dual!

The dual.

$\min cx, Ax \ge b \leftrightarrow \max bx, y^T A \le c$.

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \ge 1$$
$$\forall i \in F, j \in D \quad x_{ij} \le y_i,$$

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \ge 1 \quad ; \alpha_j$$
$$\forall i \in F, j \in D \quad y_i - x_{ij} \ge 0 \quad ; \beta_{ij}$$
$$x_{ij}, y_i \ge 0$$

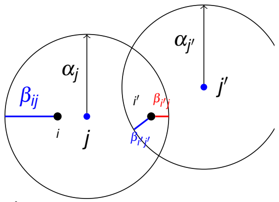
$$\max \sum_j \alpha_j$$
$$\forall i \quad \sum_{j \in D} \beta_{ij} \le f_i \quad ; y_i$$
$$\forall i \in F, j \in D \quad \alpha_i - \beta_{ij} \le d_{ij} \quad ; x_{ij}$$
$$\beta_{ij}, \alpha_j \ge 0$$

Interpretation of Dual?

$$\min \sum_{i \in F} y_i f_i + \sum_{i \in F, j \in D} x_{ij} d_{ij}$$
$$\forall j \in D \quad \sum_{i \in F} x_{ij} \geq 1$$
$$\forall i \in F, j \in D \quad x_{ij} \leq y_i,$$
$$x_{ij}, y_i \geq 0$$

$$\max \sum_j \alpha_j$$
$$\forall i \in F \quad \sum_{j \in D} \beta_{ij} \leq f_i$$
$$\forall i \in F, j \in D \quad \alpha_j - \beta_{ij} \leq d_{ij} \quad x_{ij}$$
$$\alpha_j, \beta_{ij} \leq 0$$

α_j charge to client.
maximize price paid by client to connect!
Objective: $\sum_j \alpha_j$ total payment.
Client j travels or pays to open facility i.
Costs client d_{ij} to get to there.
Savings is $\alpha_j - d_{ij}$.
Willing to pay $\beta_{ij} = \alpha_j - d_{ij}$.



Total payment to facility i at most f_i before opening.
Complementary slackness: $x_{ij} \geq 0$ if and only if $\alpha_j \geq d_{ij}$.
only assign client to "paid to" facilities.

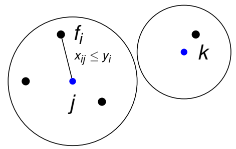
Use Dual.

1. Find solution to primal, (x, y). and dual, (α, β).
2. For smallest (remaining) α_j,
   (a) Let $N_j = \{i : x_{ij} > 0\}$.
   (b) Open cheapest facility i in N_j.
   Every client j' with $N_{j'} \cap N_j \neq \emptyset$ assigned to i.
3. Removed assigned clients, goto 2.

Integral facility cost at most LP facility cost.

Claim: Total facility cost is at most $\sum_i f_i y_i$.

2. For smallest (remaining) α_j,
   (a) Let $N_j = \{i : x_{ij} > 0\}$.
   (b) Open cheapest facility i in N_j.
   Every client j' with $N_{j'} \cap N_j \neq \emptyset$ assigned to i.

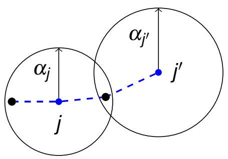


Proof: Step 2 picks client j.
$f_{\min}$ - min cost facility in N_j
$f_{\min} \leq f_{\min} \cdot \sum_{i \in N_j} x_{ij} \leq f_{\min} \sum_{i \in N_j} y_i \leq \sum_{i \in N_j} y_i f_i$.
For k used in Step 2.
$N_j \cap N_k = \emptyset$ for j and k in step 2.
$\rightarrow$ Any facility in ≤ 1 sum from step 2.
$\rightarrow$ total step 2 facility cost is $\sum_i y_i f_i$.

Connection Cost.

2. For smallest (remaining) α_j,
   (a) Let $N_j = \{i : x_{ij} > 0\}$.
   (b) Open cheapest facility i in N_j.
   Every client j' with $N_{j'} \cap N_j \neq \emptyset$ assigned to i.

Client j is directly connected. Clients j' are indirectly connected.



Connection Cost of j: $\leq \alpha_j$.
Connection Cost of j':
$\leq \alpha_{j'} + \alpha_j + \alpha_j \leq 3\alpha_{j'}$.
since $\alpha_j \leq \alpha_{j'}$

Total connection cost:
at most $3 \sum_{j'} \alpha_j \leq 3$ times Dual OPT.

Previous Slide: Facility cost:
$\leq$ primal "facility" cost $\leq$ Primal OPT.

Total Cost: 4 OPT.

Twist on randomized rounding.

Client j: $\sum_i x_{ij} = 1$, $x_{ij} \geq 0$.
Probability distribution! $\rightarrow$ Choose from distribution, x_{ij}, in step 2.

Expected opening cost:
$\sum_{i \in N_j} x_i j f_i \leq \sum_{i \in N_j} y_i f_i$.
and separate balls implies total $\leq \sum_i y_i f_i$.

$D_j = \sum_i x_{ij} d_{ij}$ Connection cost of primal for j.

Expected connection cost j' $\alpha_j + \alpha_{j'} + D_j$.

In step 2: pick in increasing order of $\alpha_j + D_j$.

$\rightarrow$ Expected cost is $(2\alpha_{j'} + D_{j'})$. Connection cost: $2\sum_j \alpha_j + \sum_j D_j$.
$2OPT(D)$ plus connection cost or primal.

Total expected cost:
Facility cost is at most facility cost of primal.
Connection cost at most $2OPT$ + connection cost of prmal.
$\rightarrow$ at most $3OPT$.

Primal dual algorithm.

1. Feasible integer solution.
2. Feasible dual solution.
3. Cost of integer solution $\leq \alpha$ times dual value.

Just did it. Used linear program. Faster?

Typically.
Begin with feasible dual.
Raise dual variables until tight constraint.
Set corresponding primal variable to an integer.

Recall Dual:

$$\max \sum_j \alpha_j$$
$$\forall i \in F \quad \sum_{j \in D} \beta_{ij} \leq f_i$$
$$\forall i \in F, j \in D \quad \alpha_j - \beta_{ij} \leq d_{ij}$$
$$\alpha_j, \beta_{ij} \leq 0$$

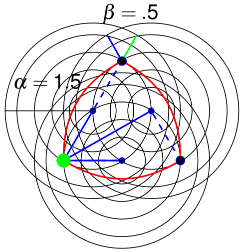
Facility location primal dual.

Phase 1: 1. Initially $\alpha_j, \beta_{ij} = 0$.
2. Raise α_j for every (unconnected) client.
When $\alpha_j = d_{ij}$ for some i
raise β_{ij} at same rate   Why? Dual: $\alpha_j - \beta_{ij} \le d_{ij}$.
Intution:Paying β_{ij} to open i.
Stop when $\sum_i \beta_{ij} = f_i$.
Why? Dual: $\sum_i \beta_{ij} \le f_i$
Intution: facility paid for.
Temporarily open i.
Connect all tight ji clients j to i.

3. Continue until all clients connected.

Phase 2:
Connect facilities that were paid by same client.
Permanently open an independent set of facilities.

For client j, connected facility i is opened. Good.
Connected facility not open
$\rightarrow$ exists client j' paid i and connected to open facility.
Connect j to j''s open facility.



Constraints for dual.
$\sum_j \beta_{ij} \le f_i$
$\alpha_i - \beta_{ij} \le d_{ij}$.
Grow α_j.
$\alpha_j = d_{ij}$!
Tight constraint: $\alpha_j - \beta_{ij} \le d_{ij}$.
Grow β_{ij} (and α_j).
$\sum_j \beta_{ij} = f_i$ for all facilities.
Tight: $\sum_j \beta_{ij} \le f_i$
LP Cost: $\sum_j \alpha_j = 4.5$

Temporarily open all facilities.
Assign Clients to "paid to" open facility.
Connect facilities with client that pays both.
Open independent set.
Connect to "killer" client's facility.
Cost: 1 + 3.7 = 4.7.
A bit more than the LP cost.

Analysis

Claim: Client only pays one facility.

Independent set of facilities.

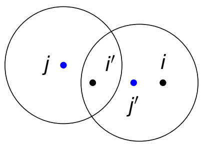
Claim: S_i - directly connected clients to open facility i.
$f_i + \sum_{j \in S_i} d_{ij} \le \sum_j \alpha_j$.

Proof:
$f_i = \sum_{j \in S_i} \beta_{ij} = \sum_{j \in S_i} \alpha_j - d_{ij}$.
Since directly connected: $\beta_{ij} = \alpha_j - d_{ij}$. □

Analysis.

Claim: Client j is indirectly connected to i
$\rightarrow d_{ij} \le 3\alpha_j$.

Directly connected to (temp open) i'
conflicts with i.
exists j' with $\alpha_{j'} \ge d_{ij'}$ and $\alpha_j \ge d_{i'j'}$.
When i' opens, stops both α_j and α_j'.
α_j' stopped no later (..maybe earlier..)
$\alpha_j \le \alpha_j'$.
Total distance from j to i'.
$d_{ij} + d_{ij'} + d_{i'j'} \le 3\alpha_j$ □



Putting it together!

Claim: Client only pays one facility.
Claim: S_i - directly connected clients to open facility i.
$f_i + \sum_{j \in S_i} d_{ij} \le \sum_j \alpha_j$.
Claim: Client j is indirectly connected to i
$\rightarrow d_{ij} \le 3\alpha_j$.

Total Cost:
direct clients dual (α_j) pays for facility and own connections.
plus no more than 3 times indirect client dual.
Total Cost: 3 times dual.
feasible dual upper bounds fractional (and integer) primal.

3 OPT.

Fast! Cheap! Safe!

See you on Thursday.