Scheduling and Location Issues in Transforming Service Fleet Vehicles to Electric Vehicles

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Examples of Electric Vehicles (among many)

- **The Nissan Leaf and the Mitsubishi i MiEV**

By September 2011:

- Worldwide cumulative sales of **more than 15,000 units** each, the top selling highway-capable electric cars.
- **Can EVs (cars and buses) succeed significantly?**

Electric Vehicles – Pros, Cons, and Issues

- **Price**
  - EVs are generally more expensive than gasoline cars. The primary reason is the **high cost** of car **batteries**.
  - The **Nissan LEAF** is a five door family electric car in the U.S. at a price of $25K-$33K. There is a federal tax rebate of US$7,500, and some state tax rebates, bringing down the cost further.
- **Running costs and maintenance**
  - Most of the running cost can be attributed to the **maintenance and replacement** of the **battery pack**.
  - Concerns remain about **durability and longevity** of the battery.
- **Air quality and carbon emissions**
  - Contribute to cleaner air
- **Energy efficiency**
  - Typically, conventional gasoline engines effectively use only **15%** of the fuel energy content to move the vehicle or to power accessories, and diesel engines can reach on-board efficiencies of **20%**, while electric drive vehicles have on-board efficiency of around **80%**.

EV Batteries and range issue

- **EV batteries**
  - Electric cars often have less maximum range on one charge than cars powered by gasoline, and they can take **considerable time to recharge**. – **"OK for daily commuters"**
  - Range anxiety: people can be concerned that they would run out of energy from their battery before reaching their destination.

- **Solutions to range anxiety**
  - Plug-in Recharge: The Tesla Roadster (a EV sports car produced by the Tesla Motors in California) can travel 245 miles (394 km) per charge, can be fully recharged in **about 3.5 hours** from a 220-volt, 70-amp outlet which can be installed in a home.
  - Battery switch technology: Car goes to a battery exchange station and switchs a depleted battery with a fully charged one in minutes. There are two companies (**Better Place and Tesla Motors**) with plans to integrate battery switching technology to their electric vehicles.
  - Fast charging stations with high-speed charging capability: consumers could recharge the 100 mile battery of their EVs to 80 percent in **about 30 minutes**. A nationwide fast charging infrastructure is being deployed in the US. (supposedly, **by 2013** will cover the **entire nation**).

Battery Recharging and Battery Exchange

- **EVs and Battery Recharge/Exchange Stations**
  - EVs require an EV architecture (**Battery switch technology** & **Fast Charging stations**).
  - U.S. government research shows that **73%** of its domestic light vehicles could be replaced by EVs without requiring any additional capacity when the EV system is complemented with a "**smart grid**" that optimally manages the flow of available electricity.

Now to some new problems that arise – to help get increased market potential

Research Issues and Problems

1. Develop a performance and cost model for a single station.
2. Develop a performance and cost model for a given network of stations.
3. **Develop a location model on where to locate the recharge/exchange stations. ***
4. **Given a specified range for fully charged vehicle, and given station locations, what is the optimal route from origin to destination without running out of charge. ***
5. Study the inventory problems of how large a stock of charged batteries to maintain and how many charging pods to have.
6. Study the integrated supply chain problem of capacity planning and operations management of how much charging capacity to maintain and how to schedule recharging of exchanged batteries. systems and smart phones)
7. **Infrastructure design for Service vehicle fleet.***

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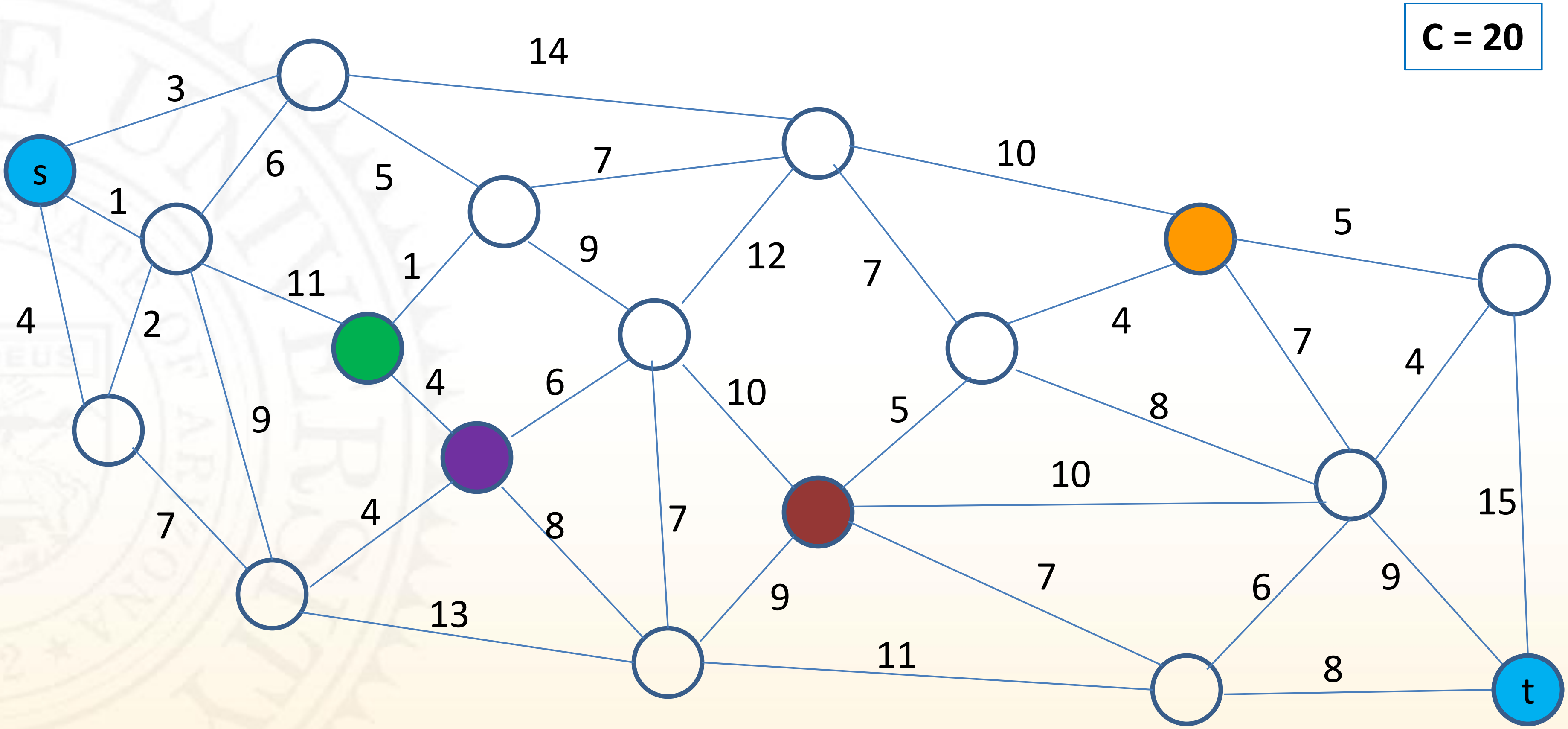
Constrained Shortest Route Problem: The EV Walk

- **Problem Description**
  Given a network, find a walk from an origin ***s*** and a destination ***t*** such that available recharge/exchange stations in this walk can support the EV to complete the journey.

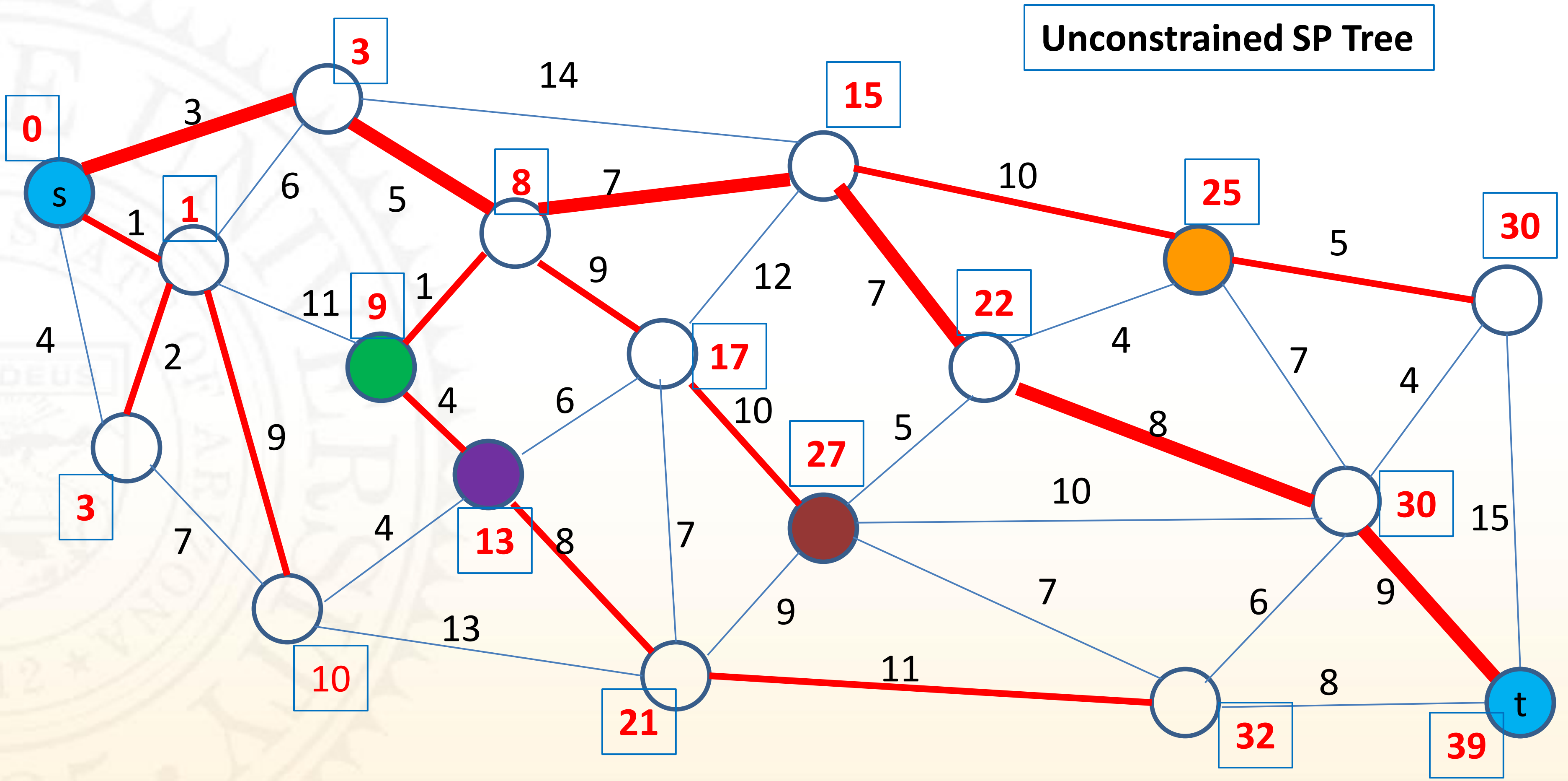
- **Notation**
  $G(V,A)$ a network with node set V and arc set A
  C maximum distance one fully charged battery can provide
  d_{ij} length of arc (i, j)
  R set of stations
  S set including origin and destination points, and all stations.

- **Output**
  A walk w along G from s to t and set of refueling stations stops r contained in w and $|r| \leq p$; i.e. how to go from s to t with only refueling at most p times

Constrained Shortest Route Problem: The EV Walk - example



Constrained Shortest Route Problem: The EV Walk - example



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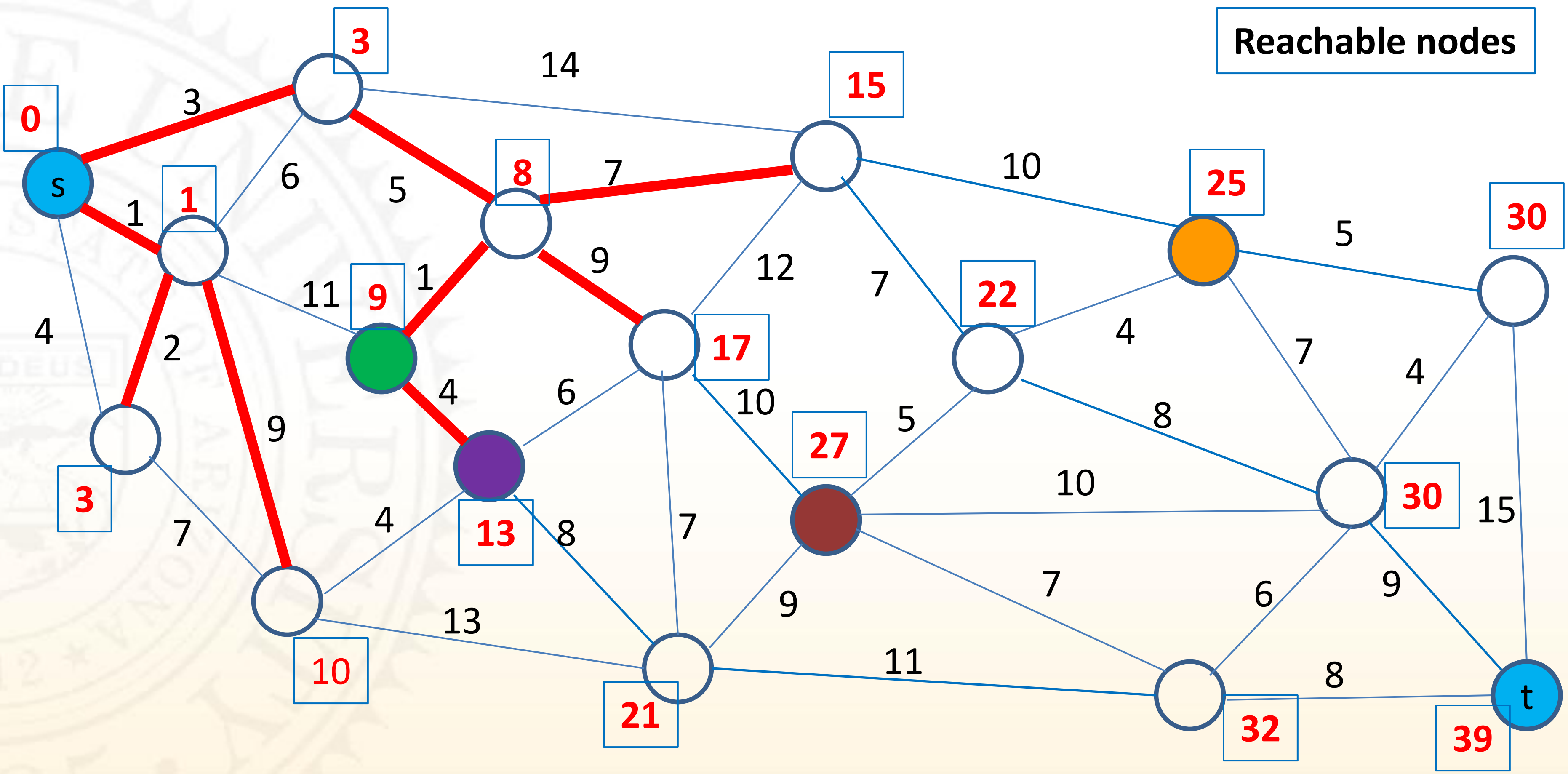
Constrained Shortest Route Problem: The EV Walk - example



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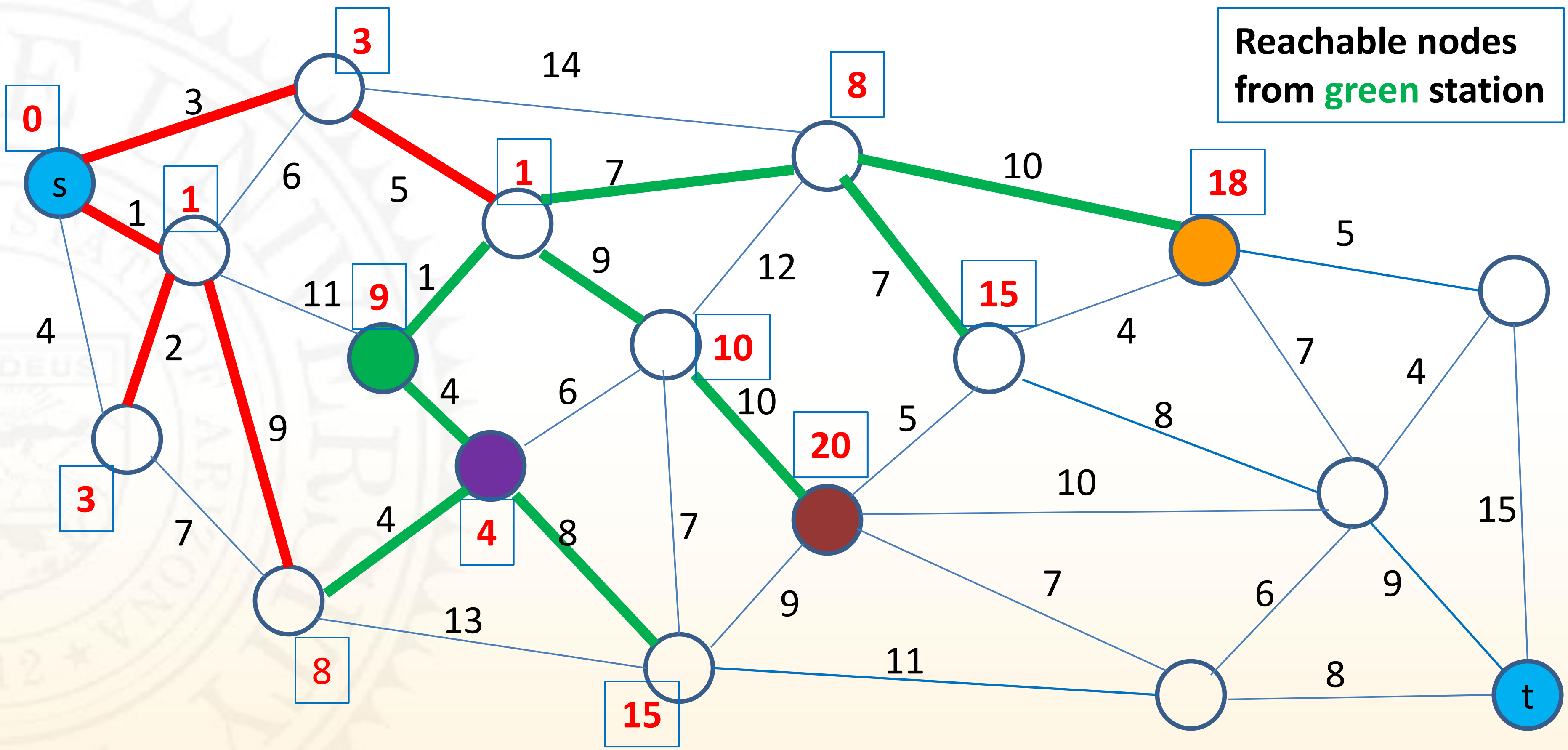
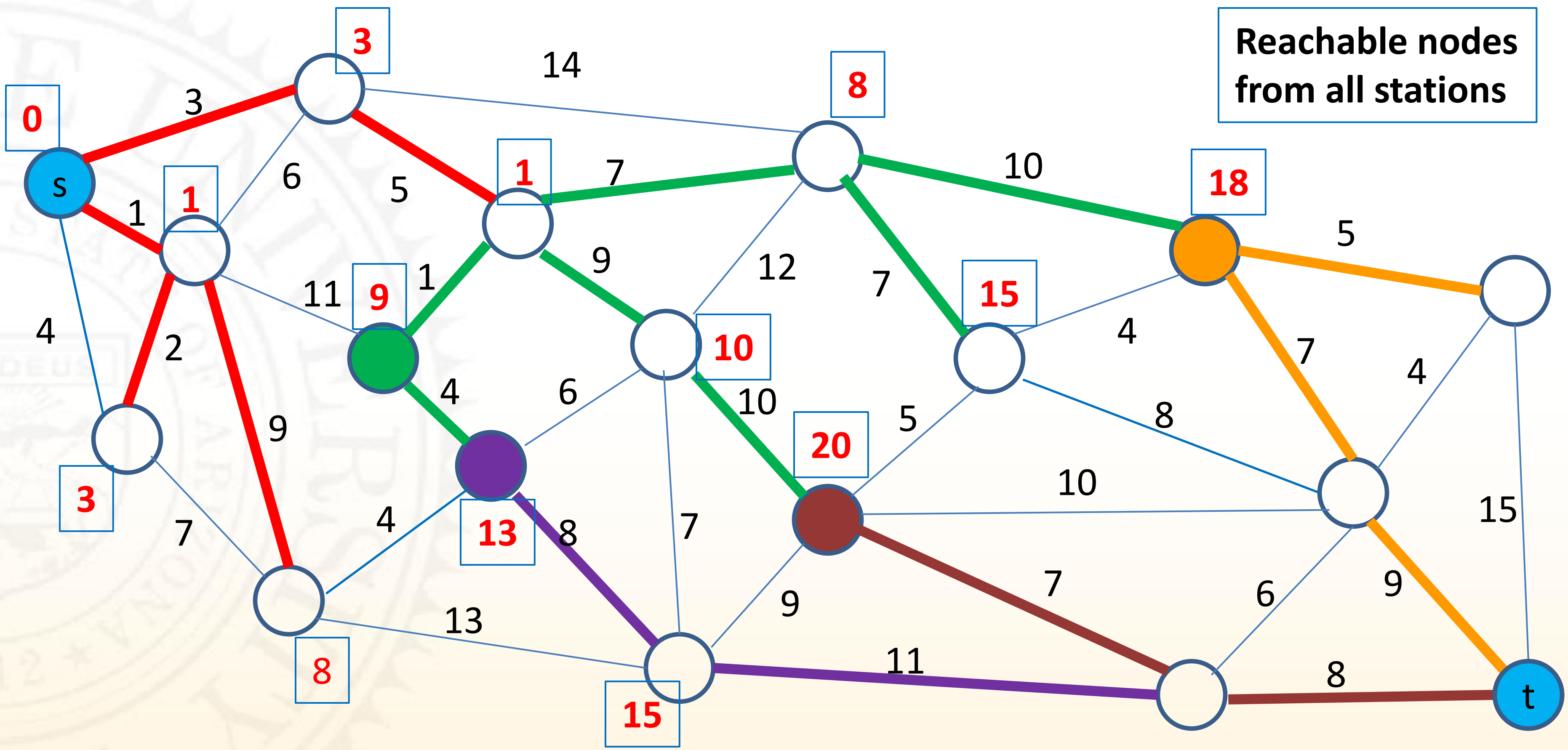
Constrained Shortest Route Problem: The EV Walk - example



Reachable nodes from green station

Constrained Shortest Route Problem: The EV Walk - example



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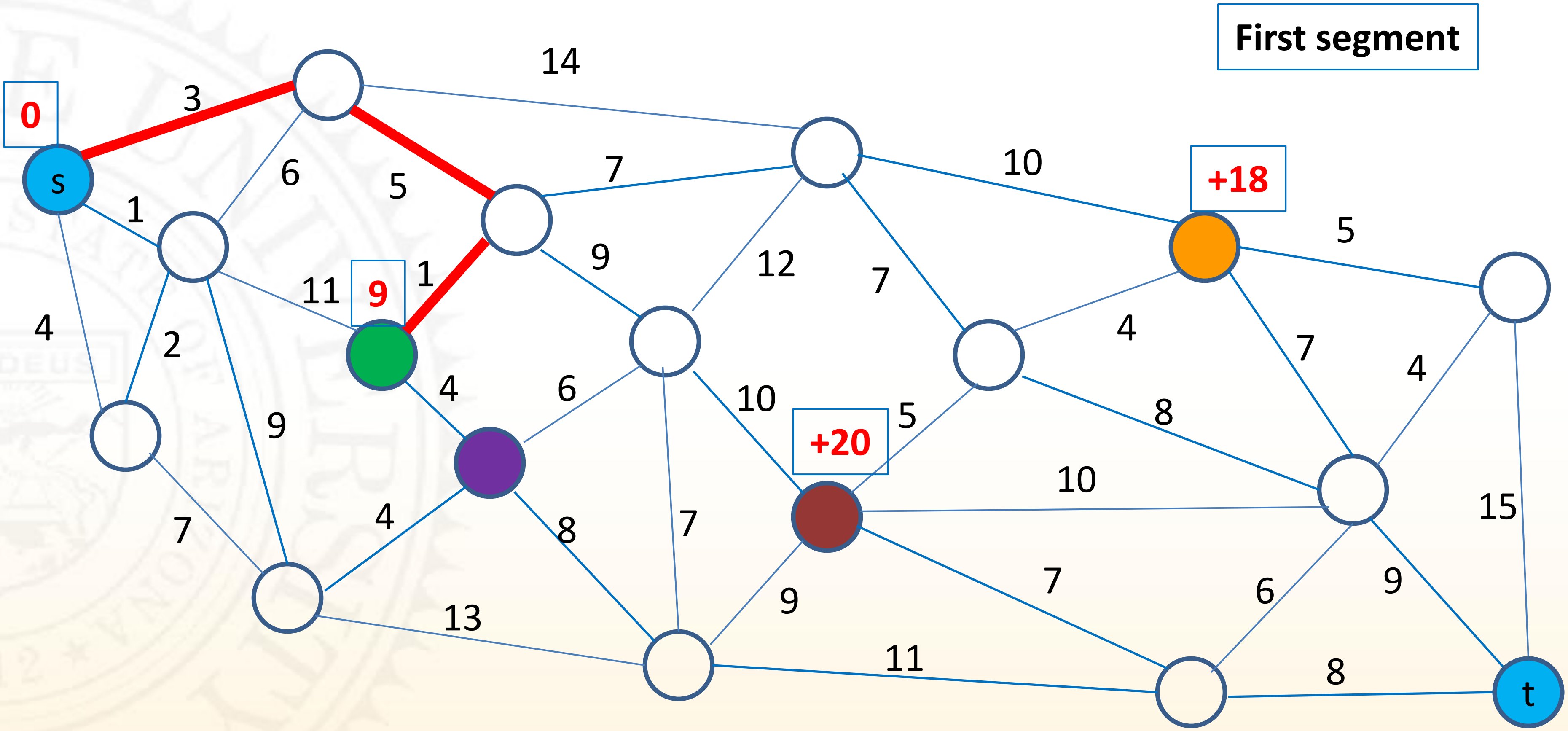

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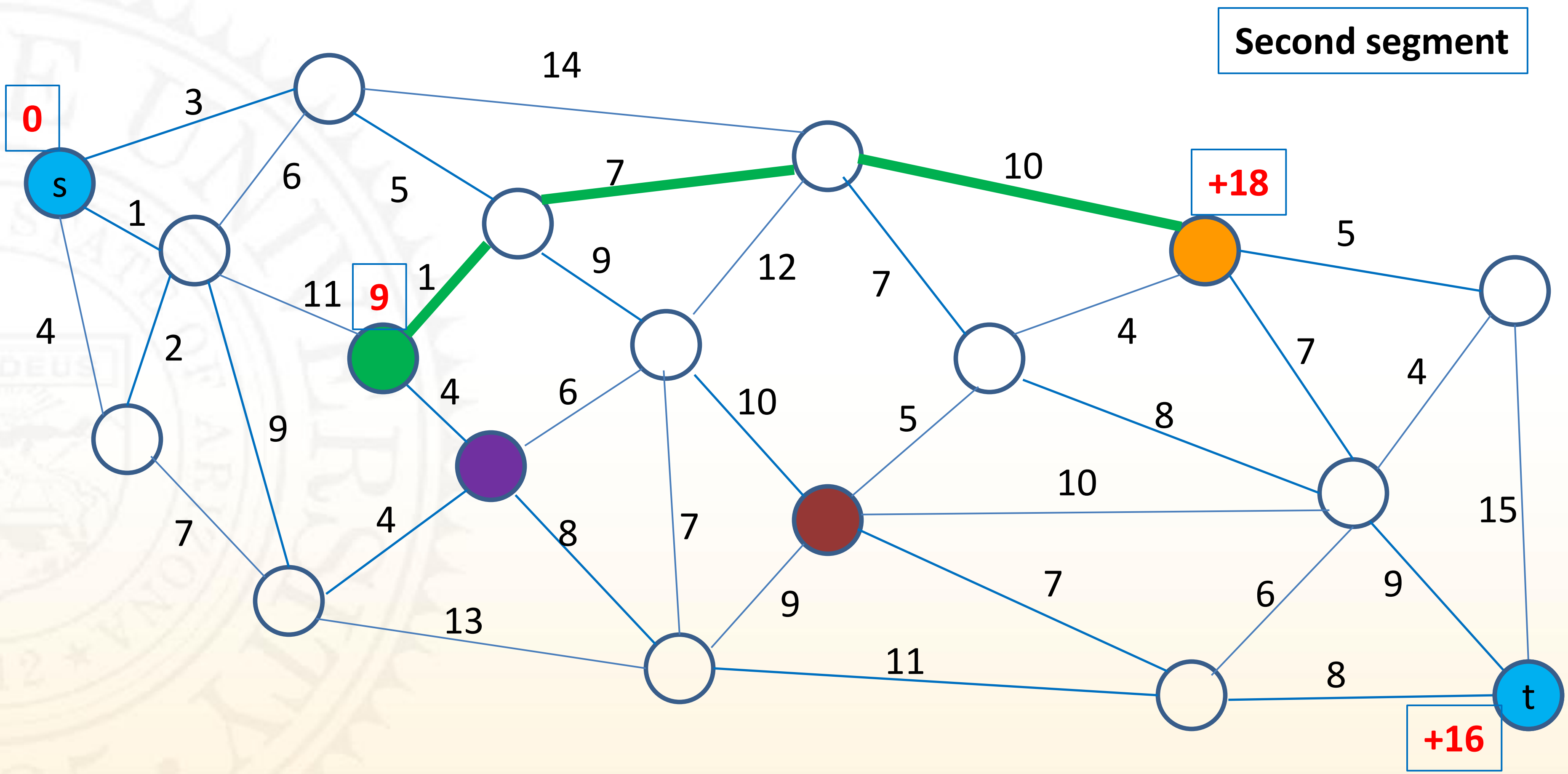
Constrained Shortest Route Problem: The EV Walk - example



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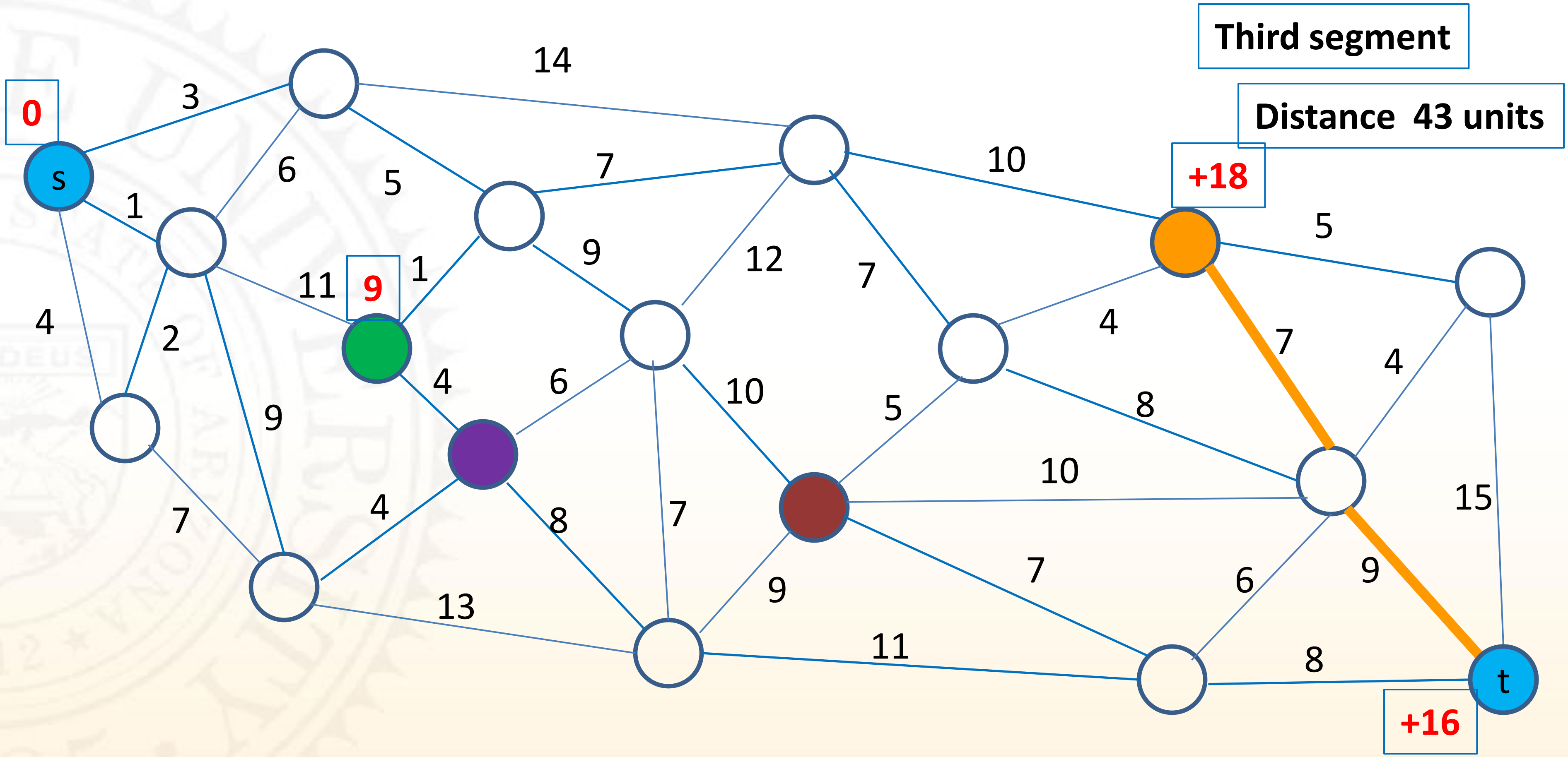


Analysis of EV Walk: IP Formulation

Minimize: $\sum_{(i,j)\in E} d_{ij}x_{ij}$ → To find a walk with shortest distance

Subject to:

$$\sum_{j\in V} x_{ij} - \sum_{j\in V} x_{ji} = \begin{cases} 1 & i = O \\ -1 & i = D \\ 0 & \text{otherwise} \end{cases}, \quad \text{for } \forall i \in V$$

→ Network conservation, generate a walk.

$$d_{ij}x_{ij} + \sum_{(j,k)} d_{jk}x_{jk} + d_{kl}x_{kl} \le C$$

$$\text{for } \forall i \in S, \forall j,k \in V - S, \forall l \in S$$

→ Guarantee any interval between two exchange stations along the walk is within the distance limit *C*.

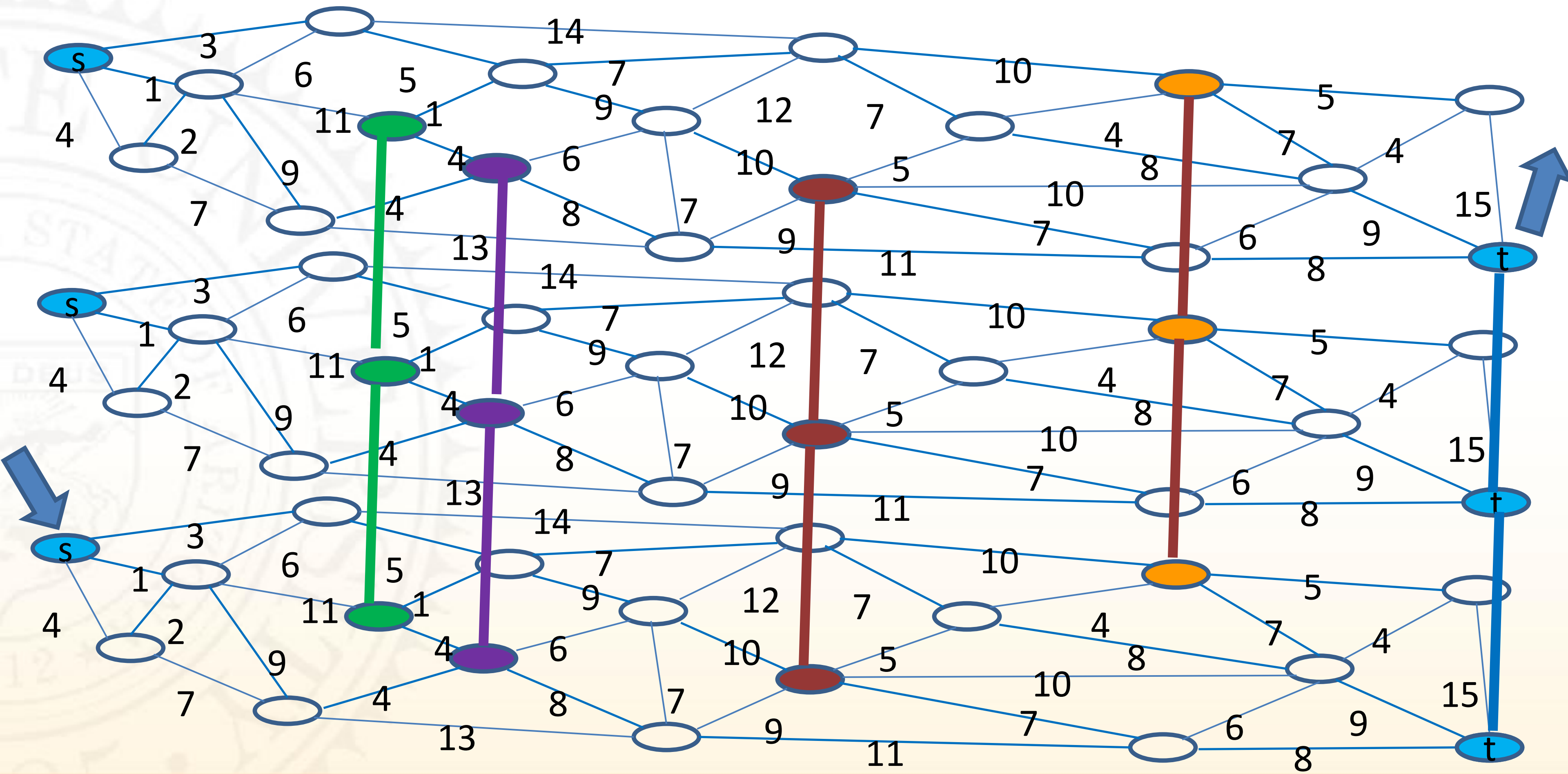
$$x_{ij} \in \{0,1\}$$

Analysis of EV Walk: Complexity

- Suppose complexity of SPT is C(SPT).
- |R| is number of "refueling" stations, then the complexity is |R|C(SPT).
- Best SPT algorithm gives complexity $O(|R|\,(n \log n + |A|))$ (i.e., polynomial)
- But this allowed as many stops as possible. What about the problem of at most *p* stops

(where $|V| = n$)

Constrained Shortest Route Problem: With max stops 2.



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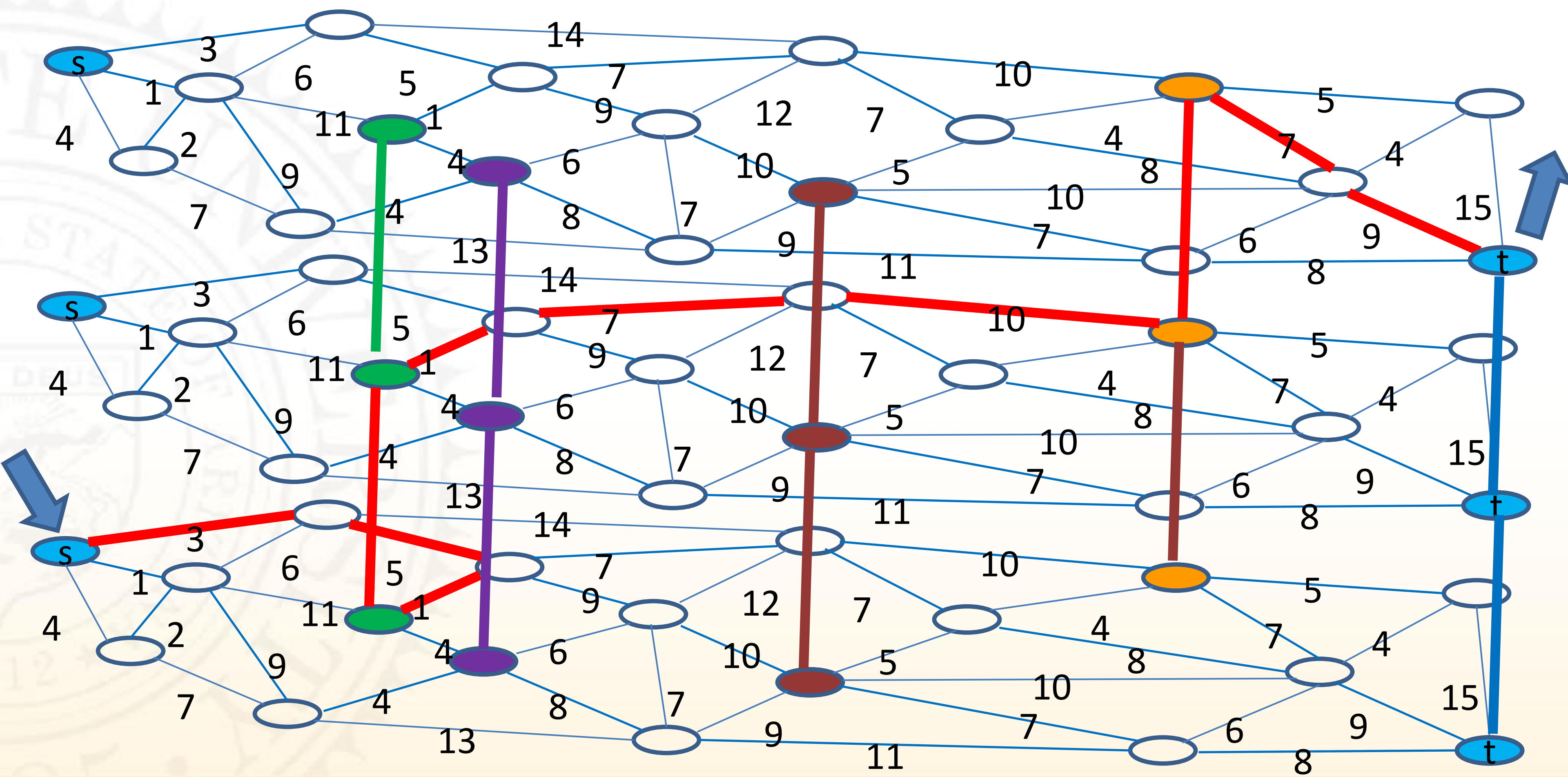
Constrained Shortest Route Problem: With max stops 2.



What if at most *p* stops is allowed?

- Transform network by adding *p* layers
- Each stop takes you to next layer
- The problem becomes constrained SPT where at most *p* vertical arcs are allowed.
- Can show complexity is $O(|R^2| (n \log n + |A|))$ (i.e., still polynomial)

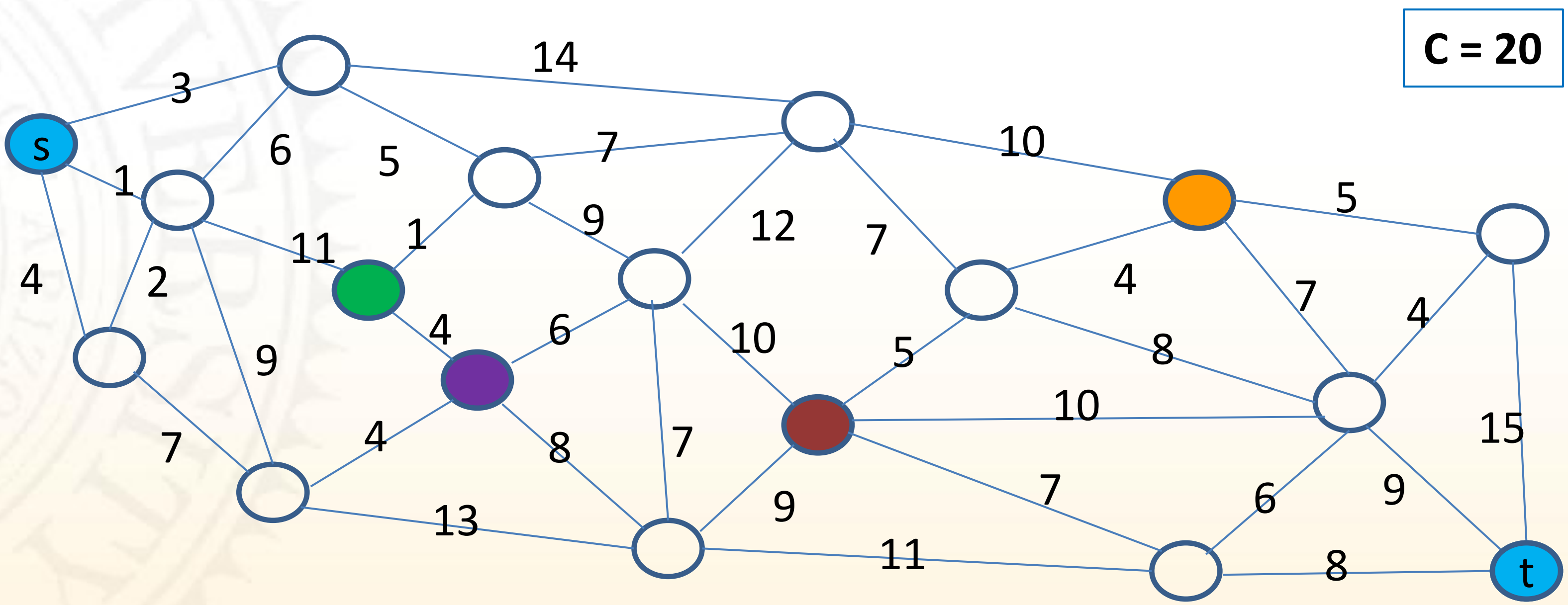
Trade-off between **total distance & number of stops** along the journey.

Now to Locating Exchange Stations on a Network

Are these the optimal locations for C=20?

Now the problem is much harder.

The **tree problem** is a little simpler -- we will address this first.



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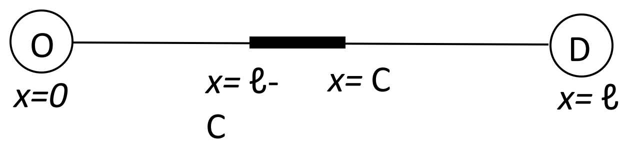
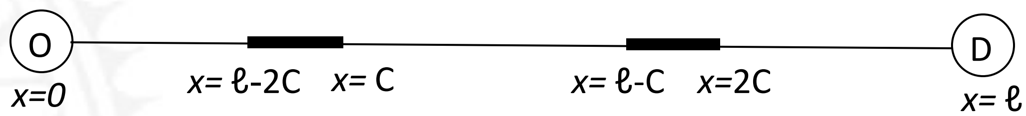
Now to Locating Exchange Stations on a Tree

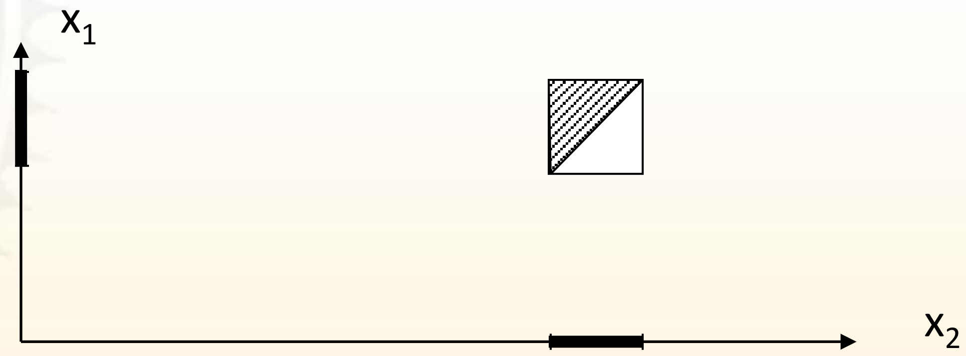
Consider single OD route

Bold line indicates possible location area



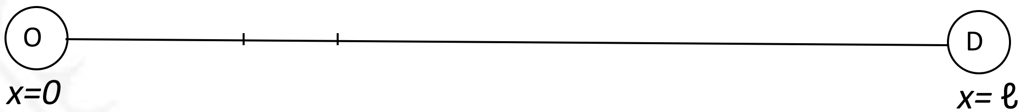


that $x_1 \varepsilon$ [ℓ-2C, C] and $x_2 \varepsilon$ [ℓ-C, 2C] and $x_2 - x_1 \leq C$



Locating Exchange Stations on a Tree

<u>Consider single OD route</u>



The feasible space Ω for $\mathbf{x} = (x_1, x_2, \ldots, x_p)$ is given by

$x_1 \varepsilon [\ell - pC, C]$

$x_2 \varepsilon [\ell-(p-1)C, 2C]$

.

.

.

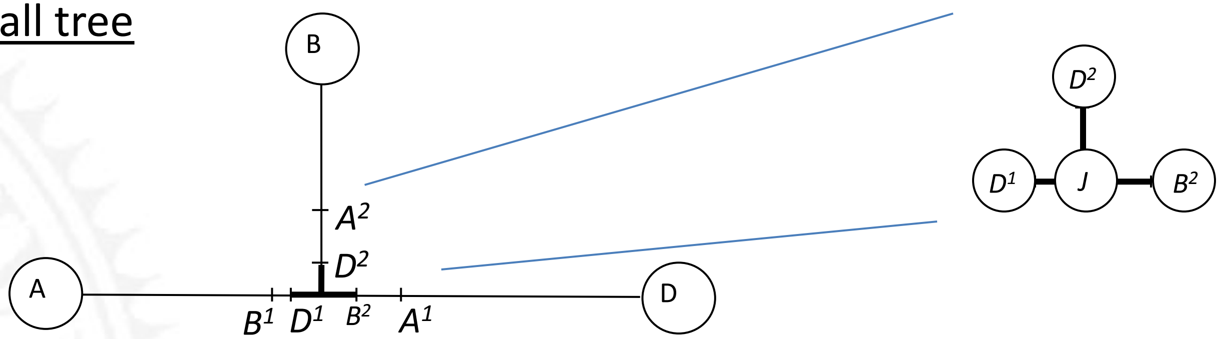
$x_p \varepsilon [\ell - C, pC]$

$x_{i+1} - x_1 \leq C$ I = 1,2,…, p-1

THM: When z(**x**) is linear or concave, then at least one extreme point **x** solves the problem

Locating Exchange Stations on a Tree

Consider a small tree

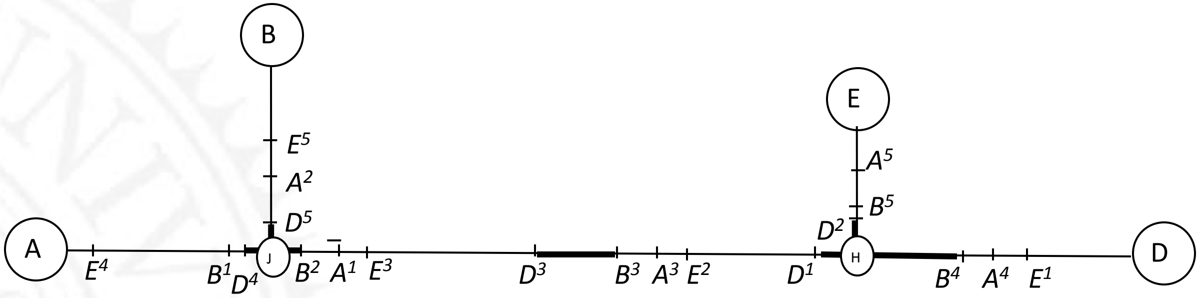


The breakpoints A^1, A^2, B^1, B^2, D^1, and D^2 are such the distances AA^1, AA^2, BB^1, BB^2, DD^1, and DD^2 are all equal to C.

Can show that when the objective is linear in terms of distances from the origins, then the optimal location is at an extreme point of the small intersection tree or at the nodes (junction point). (In the illustration these are D^1, D^2, B^2, J)

Locating Exchange Stations on a Tree

Consider a slightly bigger tree (with two ODs: {A,D} and {B,E})

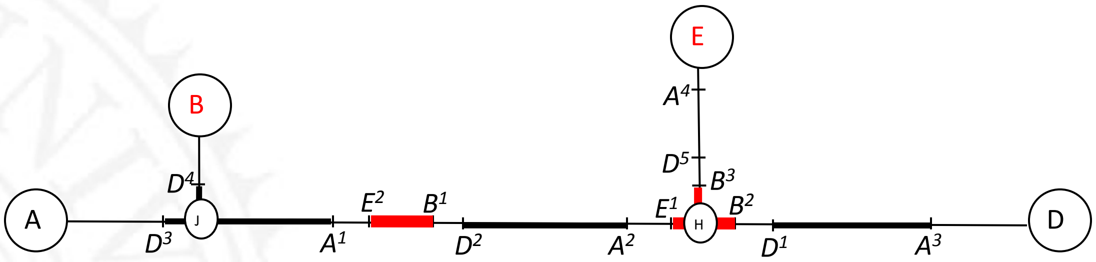


Bold lines give localization points for 3 facilities. 2 facilities cannot satisfy this case.

But two facilities can satisfy OD pair BE. Three would be needed for OD pair AD.

Locating Exchange Stations on a Tree

Consider another slightly different case (with two ODs: {A,D} and {B,E})

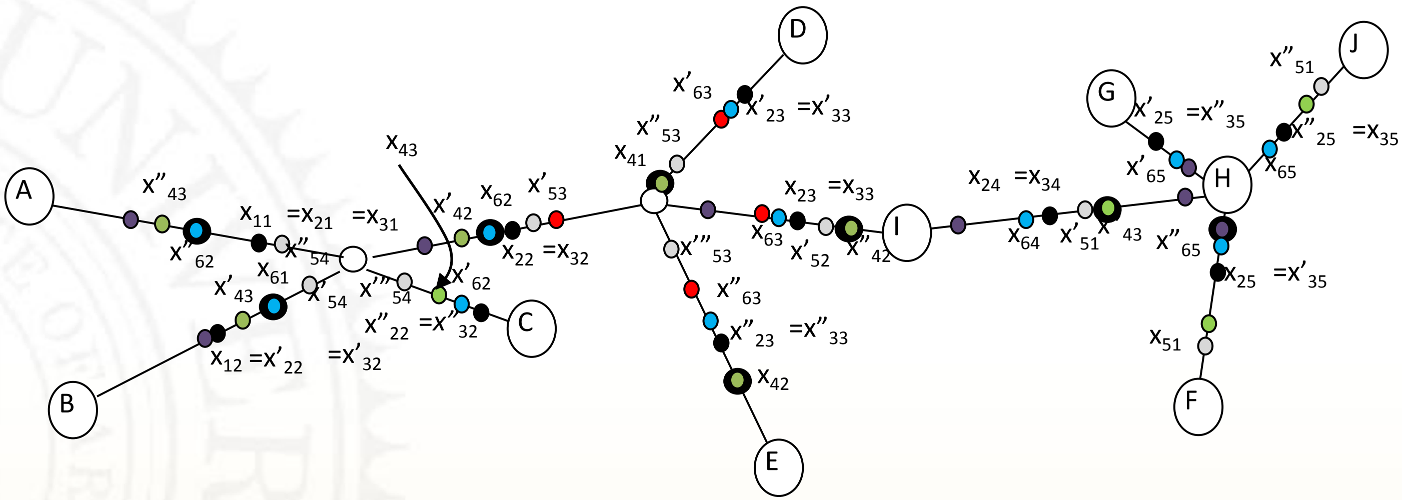


Black bold lines give localization points for 3 facilities to satisfy OD pair AD.

Red bold lines give localization points for 3 facilities to satisfy OD pair **BE**.

But minimum **four** facilities needed to satisfy OD pairs {BE, AD}. For example, J, B^1,H, A^3

Locating Exchange Stations on a Tree



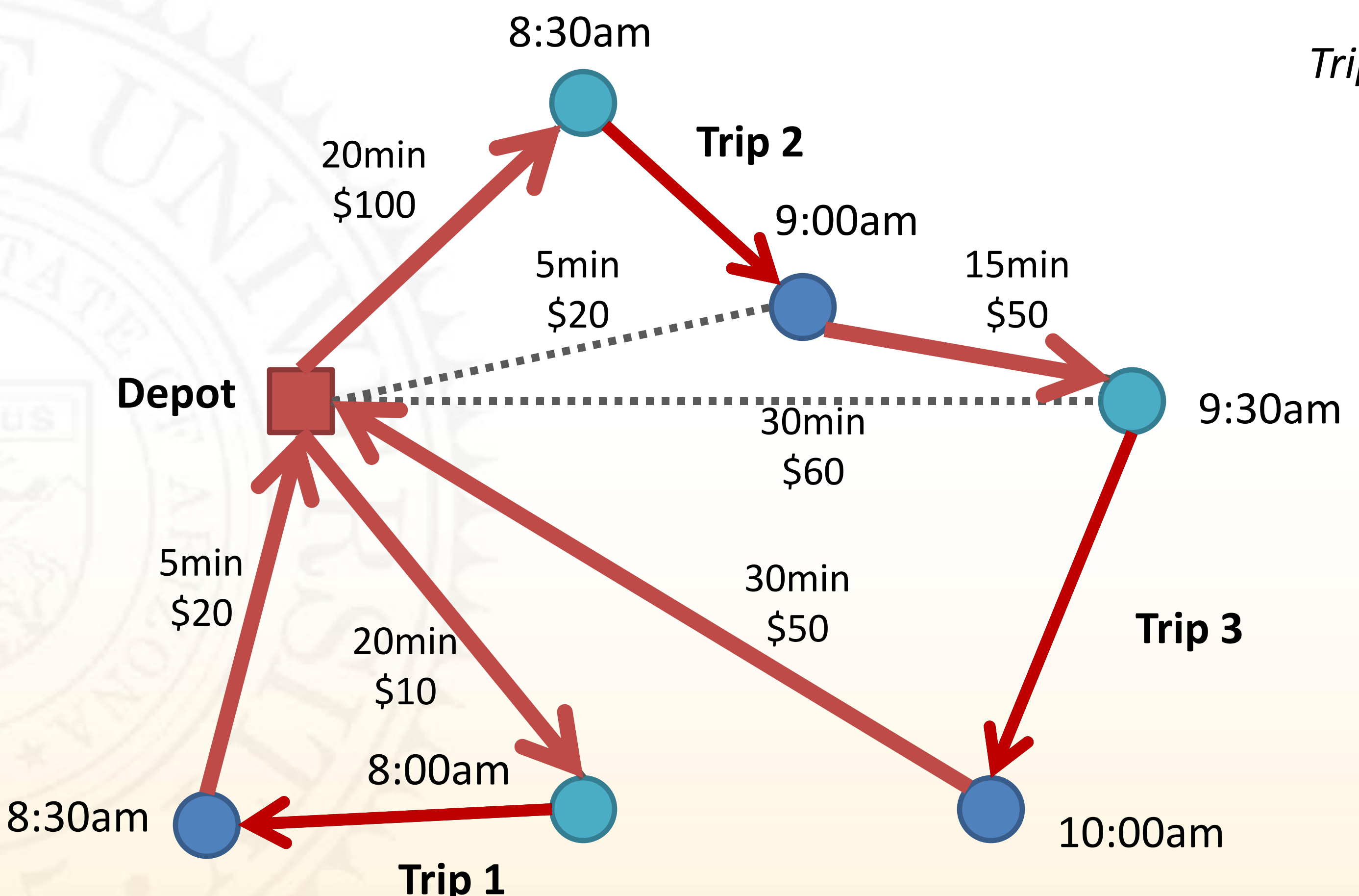
- Can come up with breakpoints for each origins in polynomial time
- Eliminating dominated breakpoints and dominated regions (investigating now)
- Can show this is still a NP Hard problem.
- Developing a heuristic with guaranteed bounds (investigating now)

Now to Electric Bus Scheduling

- Given
  - a set of *n* bus trips(already scheduled), each with specific starting times,
  - a depot location, and
  - how long it takes to travel between trips (and how much is the travelling costs),

  how would you assign buses to serve all the routes (VSP)?
- Vehicle Scheduling Problem With Fuel – add the constraint that the buses must refuel (recharge) after travelling a given distance, at a set of possible refueling points
- VSP is polynomial time solvable, But VSP-EV is NP-hard

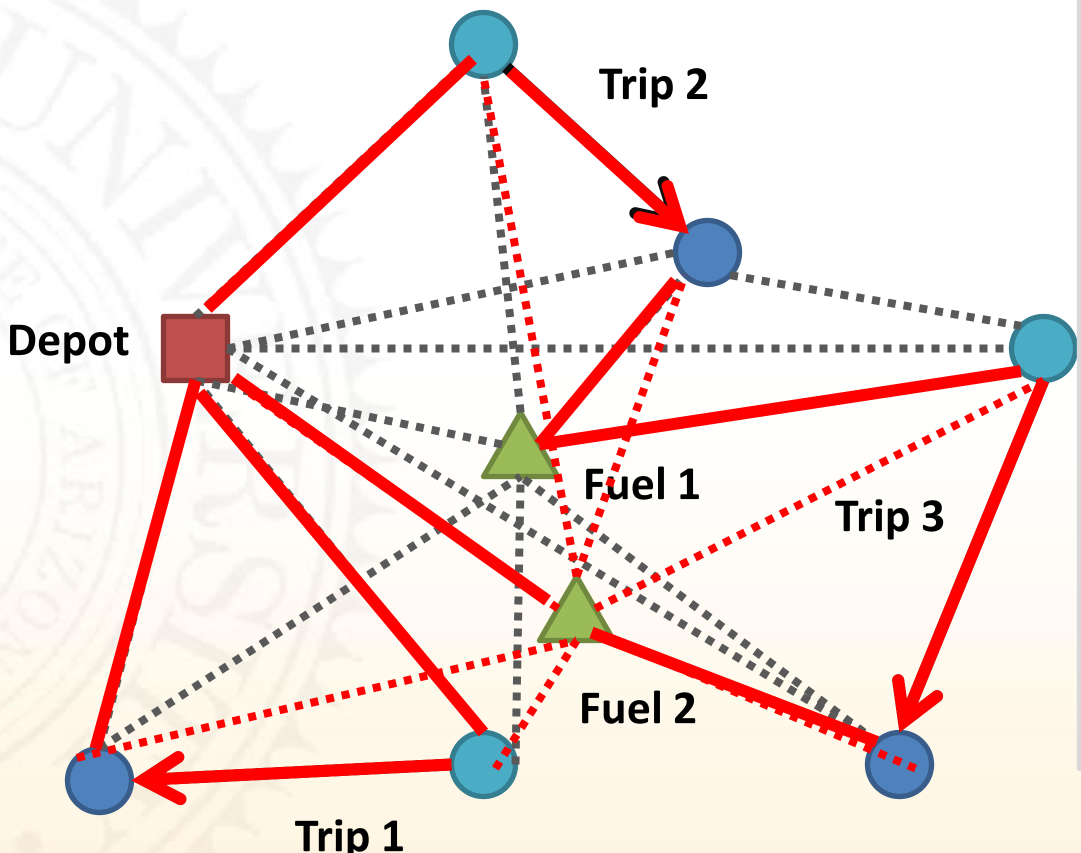
Electric Bus Scheduling



Trip 2 & 3 compatible

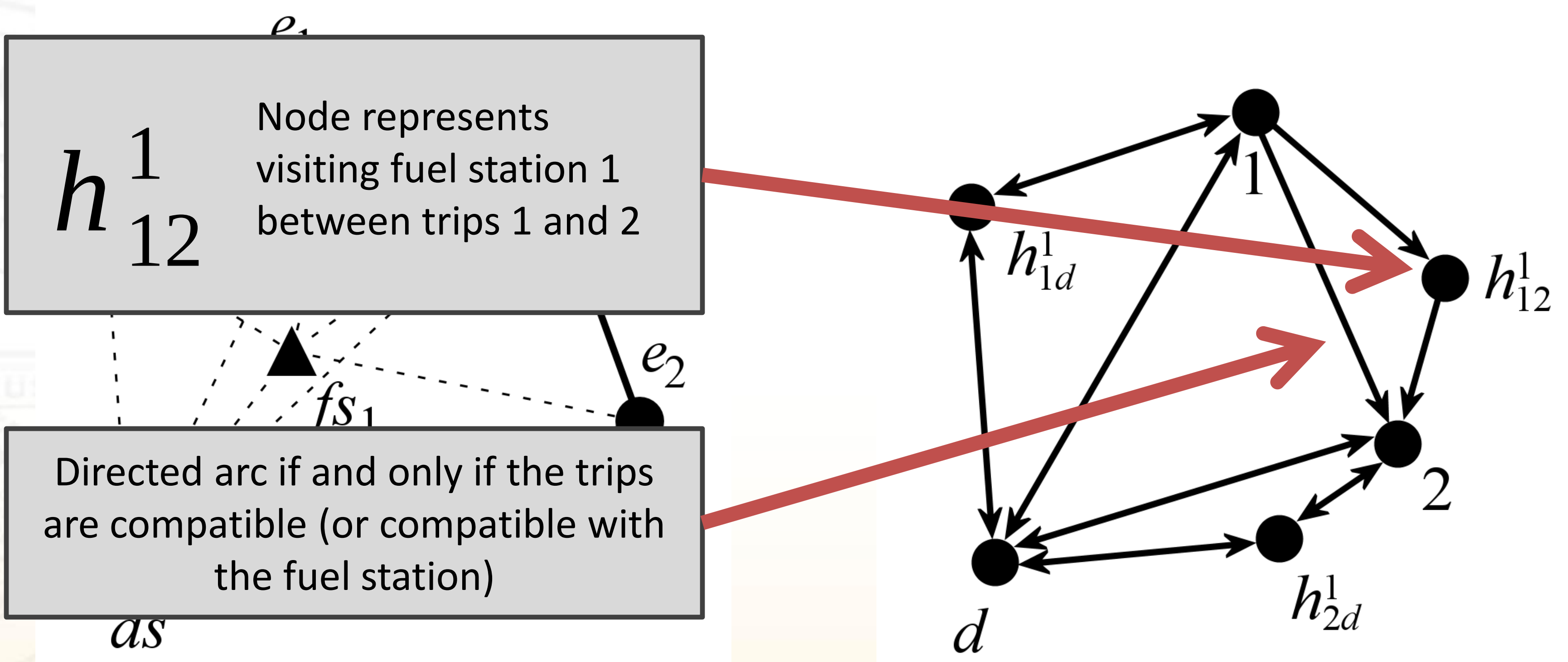
Solution:
Bus 1 – Trip 2 & 3
Bus 2 – Trip 1
Total of $230

Electric Bus Scheduling



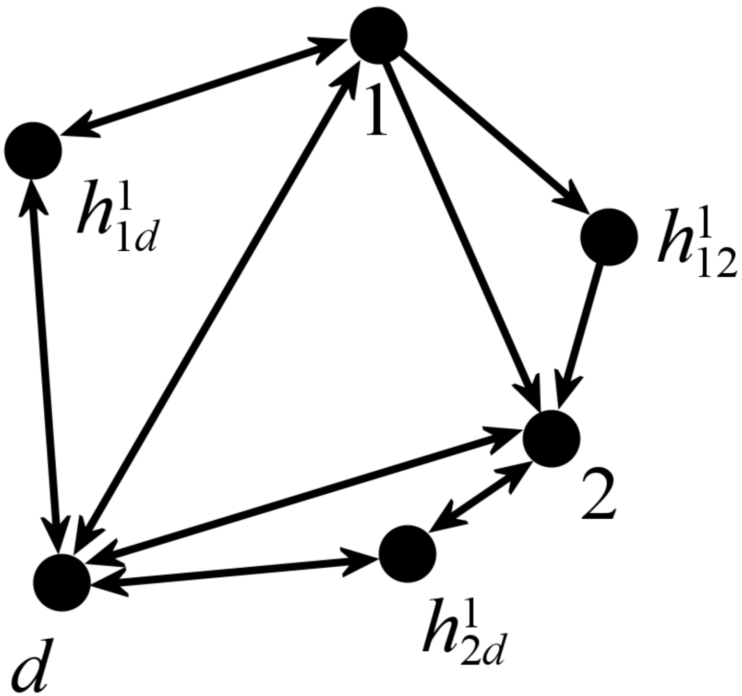
- Each dead-heading trip now has: time, cost, fuel requirement
- Trips also require fuel
- May have multiple fuel stations, but only one can be visited between trips (SPT-EV)
- Depot not assumed to be fuel station
- Trips now can be compatible and/or compatible with fuel station *k*

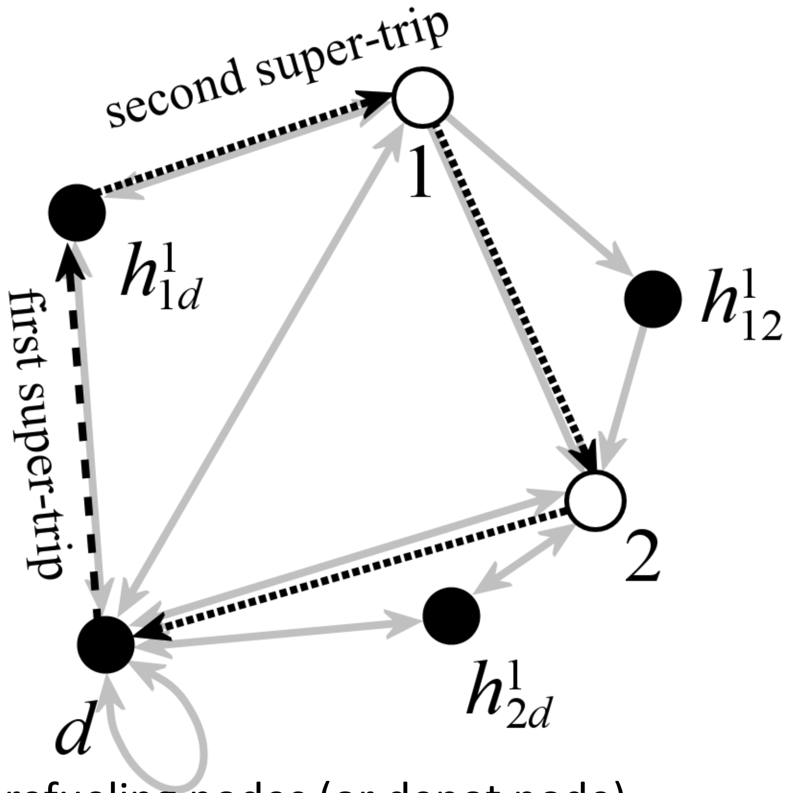
Electric Bus Scheduling



Reformulate the problem so that each trip is a node, the depot is a node, and there is are multiple fuel station nodes for each original fuel station. Now time is encoded in the graph arcs.

Formulating the VSP-EV Problem





A *super-trip* is any trip between any two refueling nodes (or depot node)

Any solution can be broken up into super-trips, each bus has at most *n* super trips

Formulating the VSP-EV Problem

Decision variable: $x_{ij}^{by} = 1,$ should a dead heading trip be taken between nodes *i* and *j* by bus *b* on its y^{th} super trip?

Formulating the VSP-EV Problem

$$\text{Minimize} \quad \sum_{b\in B}\sum_{y\in Y}\sum_{\substack{i,j\in V\\(i,j)\in A'}} c_{ij}x_{ij}^{by} \qquad (1)$$

$$\text{subject to} \quad \sum_{b\in B}\sum_{y\in Y}\sum_{\substack{i\in V\\(i,j)\in A'}} x_{ij}^{by} = 1 \qquad \forall j \in N \qquad (2)$$

$$\sum_{\substack{i\in V\\(i,j)\in A'}} x_{ij}^{by} = \sum_{\substack{k\in V\\(j,k)\in A'}} x_{jk}^{by} \qquad \forall j\in N \quad \forall b\in B \quad \forall y\in Y \qquad (3)$$

Each trip is served by exactly one vehicle

$$\sum_{i\in H\cup\{d\}}\sum_{\substack{j\in V\\(i,j)\in A'}} x_{ij}^{by} = 1 \qquad \forall b\in B \quad \forall y\in Y \qquad (4)$$

$$\sum_{j\in H\cup\{d\}}\sum_{\substack{i\in V\\(i,j)\in A'}} x_{ij}^{by} = 1 \qquad \forall b\in B \quad \forall y\in Y \qquad (5)$$

Super-trip start and end at exactly one depot or fuel station

$$\sum_{i\in V}\sum_{\substack{j\in V\\(i,j)\in A'}} f_{ij}x_{ij}^{by} \le w \qquad \forall b\in B \quad \forall y\in Y \qquad (6)$$

Fuel for each super trip must be less that *w*.

$$\sum_{\substack{i\in V\\(i,j)\in A'}} x_{ij}^{by} = \sum_{\substack{k\in V\\(j,k)\in A'}} x_{jk}^{b(y+1)} \qquad \forall b\in B \quad \forall y\in Y: y<n \quad \forall j\in H\cup\{d\} \qquad (7)$$

Start of super trip must be end of one.

$$\sum_{j\in V} x_{dj}^{b1} = 1 \qquad \forall b\in B \qquad (8)$$

$$\sum_{i\in V} x_{id}^{bn} = 1 \qquad \forall b\in B \qquad (9)$$

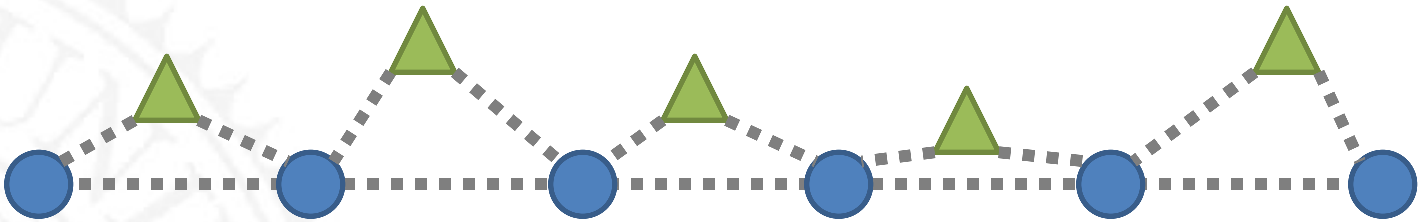
First super-trip must start and last super-trip must end depot

$$\sum_{y\in Y}\sum_{j\in V\setminus\{d\}} x_{dj}^{by} \le 1 \qquad \forall b\in B \qquad (10)$$

Each vehicle must leave depot only once

$$x_{ij}^{by} \in \{0,1\} \qquad \forall i,j\in V:(i,j)\in A' \quad \forall b\in B \quad \forall y\in Y \qquad (11)$$

Fuel Sequencing Problem



- Given a sequence of trips and fuel stations between them and only one bus, when should the bus fill up?
- Can the trips even be served by a single bus?
- Linear time solvable, given that the routes have length at least α

VSP-EV Heuristic

- While there remain unassigned trips:
  - Solve the VSP for the unassigned trips
  - For each bus in the solution to the VSP:
    - For each trip the bus takes in the solution to the VSP:
      - If the bus can serve this route plus all the routes it has already been assigned, give the bus this route, otherwise leave it unassigned [use fuel sequencing algorithm to check this]
  - Repeat

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VSP-EV: Some computations

n	Cost		Buses		Trips/Bus		Runtime	
	VSP	VSPWF	VSP	VSPWF	VSP	VSPWF	VSP	VSPWF
25	18,335.5	20,467.0	6.4	6.6	3.94	3.82	0.29	0.36
50	32,335.5	40,170.0	11.1	12.2	4.52	4.10	0.76	0.91
75	48,047.0	62,475.5	16.6	18.6	4.53	4.03	1.45	1.67
100	58,168.0	78,244.5	19.7	22.6	5.08	4.43	1.88	2.22
150	82,128.5	116,161.0	28.3	33.4	5.31	4.49	3.77	4.29
200	102,322.0	147,659.5	35.1	41.9	5.71	4.78	5.79	6.56
250	127,134.0	184,309.5	43.9	51.9	5.69	4.82	7.74	8.69
300	148,564.0	222,432.5	51.9	62.3	5.78	4.82	10.81	12.02
400	189,819.5	293,426.0	65.2	80.4	6.13	4.98	16.20	17.91
500	234,225.0	359,707.0	81.9	99.4	6.11	5.03	30.18	31.99
750	342,460.5	541,078.0	117.6	143.8	6.38	5.22	60.39	64.18
1,000	437,101.0	685,438.0	155.7	188.0	6.42	5.32	99.22	104.15

Conclusions

- Introduced rich families of interesting EV infrastructure related problems.
- Some problems solved, others need to be.
- Introduced SPP-EV, locating EV stations on a Tree, and VRP-EV
- Unfortunately, DOE, car companies have neglected this problem. Maybe NSF will be interested.

Thank you!

Questions?

Research motivation & background

Electric Vehicles (EVs)

- **Energy**
  - Over the last 100 years, oil has fueled industrial development, mobility and prosperity.
  - Remaining supply is limited.
  - Only **2%** of global electricity (and an even lower percentage of transportation energy) is currently generated by non-hydro **renewable sources**.
  - EVs promote the substitution of nonrenewable energy with renewable sources
  - EVs offer energy efficiency up to three times greater than that of gasoline-powered vehicles

- **Environment**
  - **Negative effects of carbon emissions**: Gasoline-powered vehicles are a major contributor to carbon emissions in the developed world, accounting for **33%** of carbon emissions in **the United States**, and as much as **50%** of carbon emissions in some of the countries in **Europe**.
  - **Air quality**: according to the World Health Organization, **900,000** people die each year from causes directly attributable to air pollution.

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