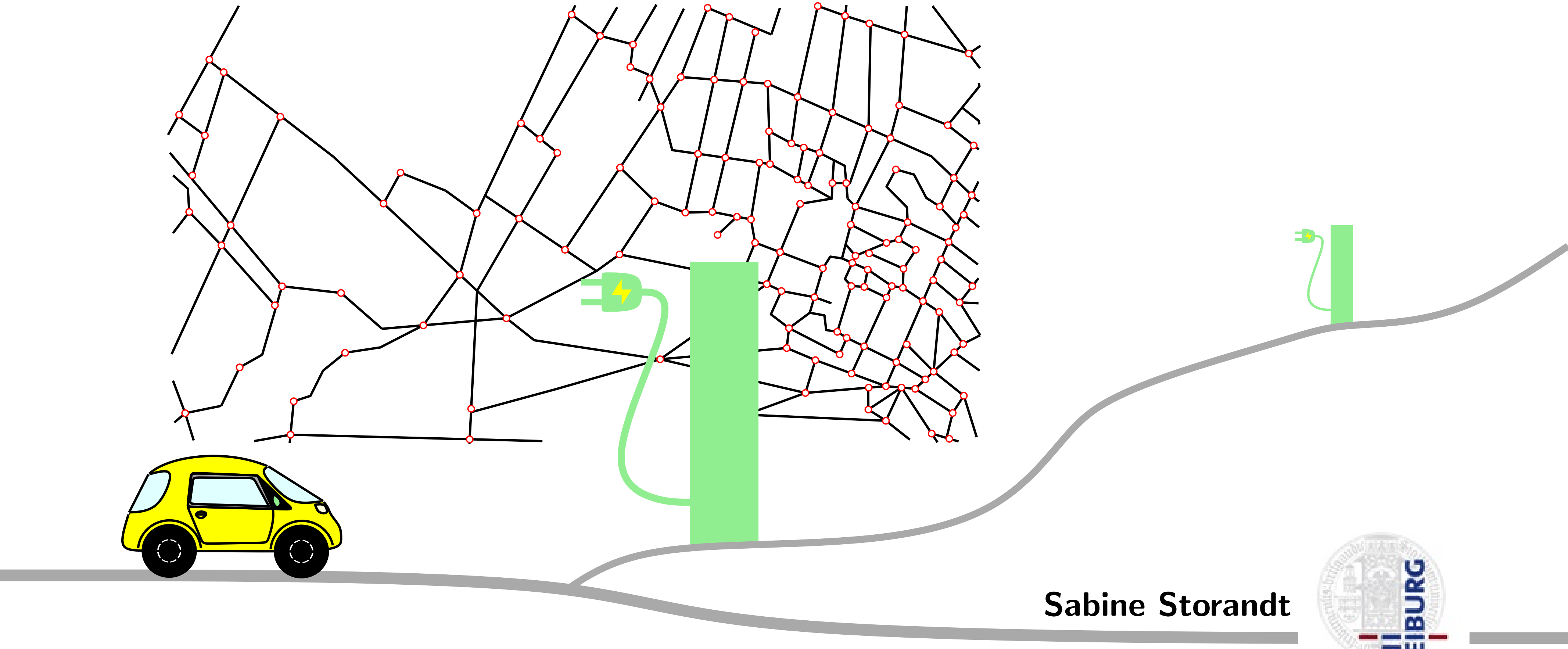
Route Planning for Electric Vehicles: Taking Energy Efficiency, Distance, and Reloading Opportunities into Account



Sabine Storandt

UNI FREIBURG

A BRIEF HISTORY

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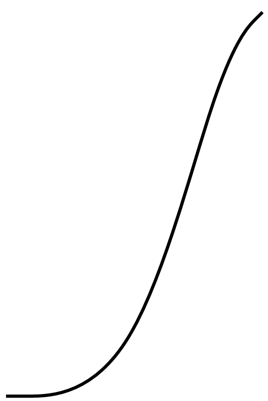
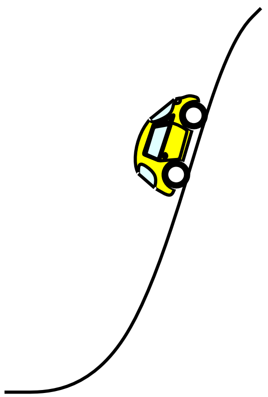


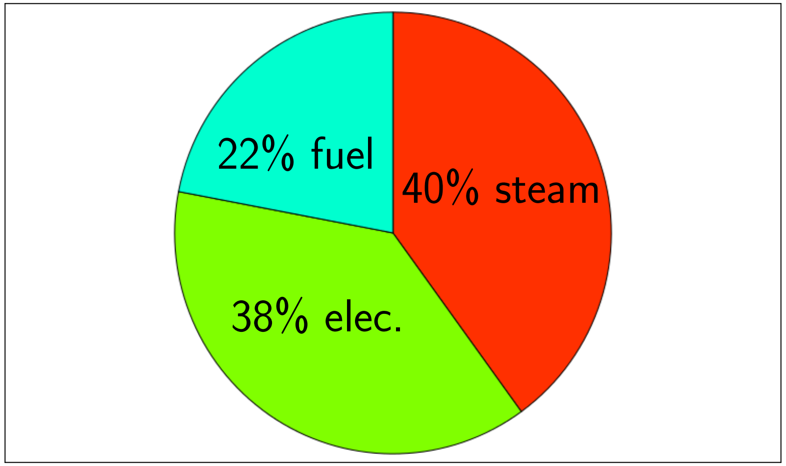
1896 **1910**

A BRIEF HISTORY



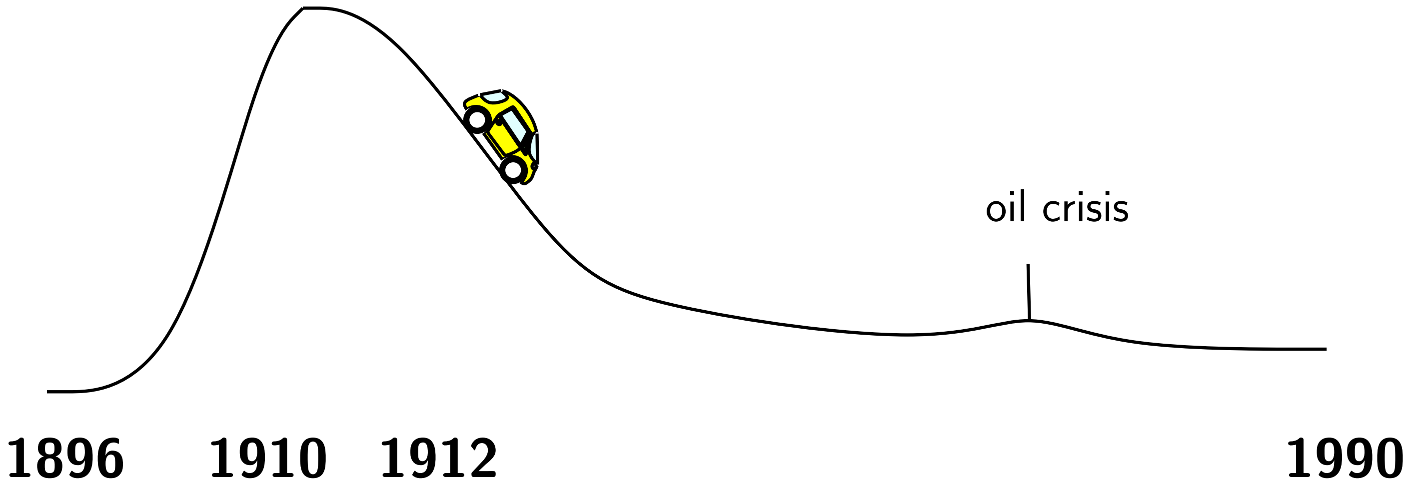
1896 1910

USA, 1900



A BRIEF HISTORY

- cheap oil
- larger cruising range with fuel-driven cars
- starter motors



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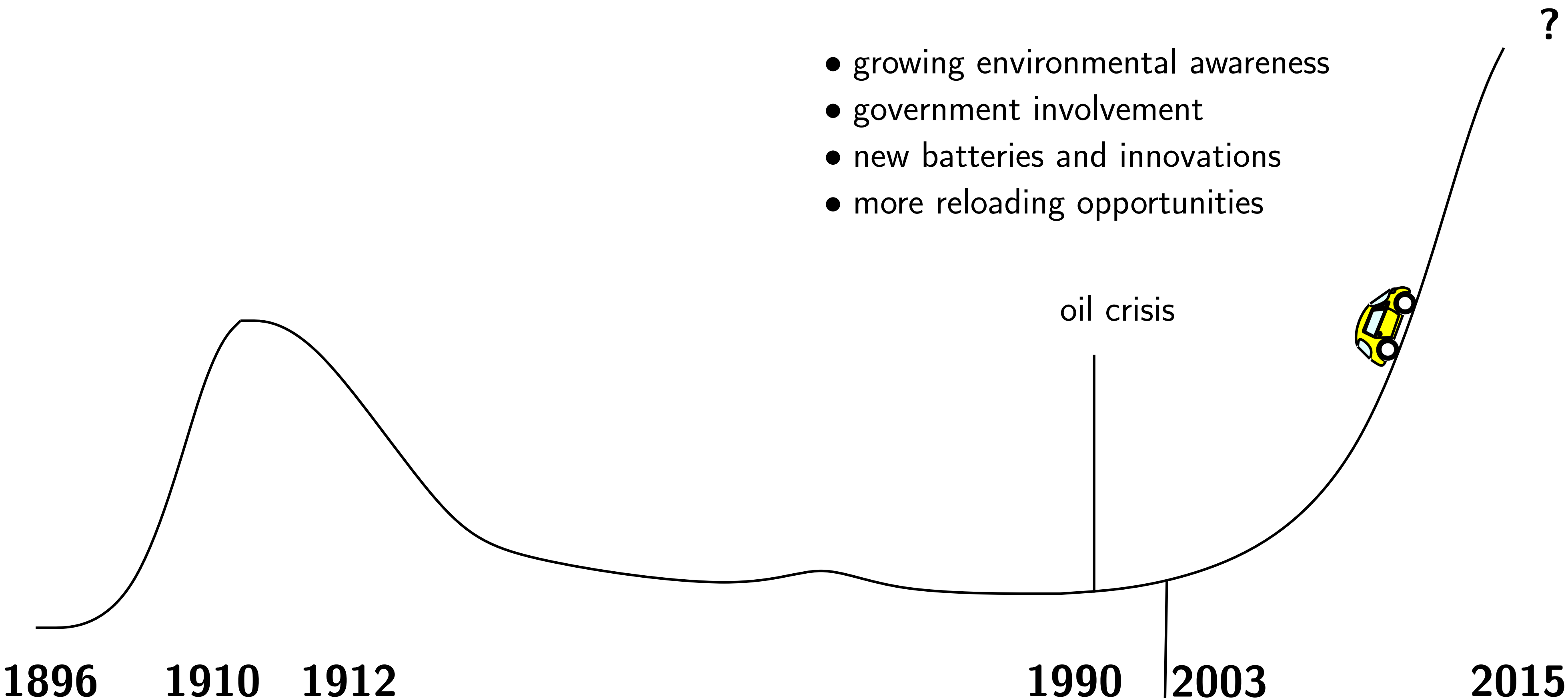
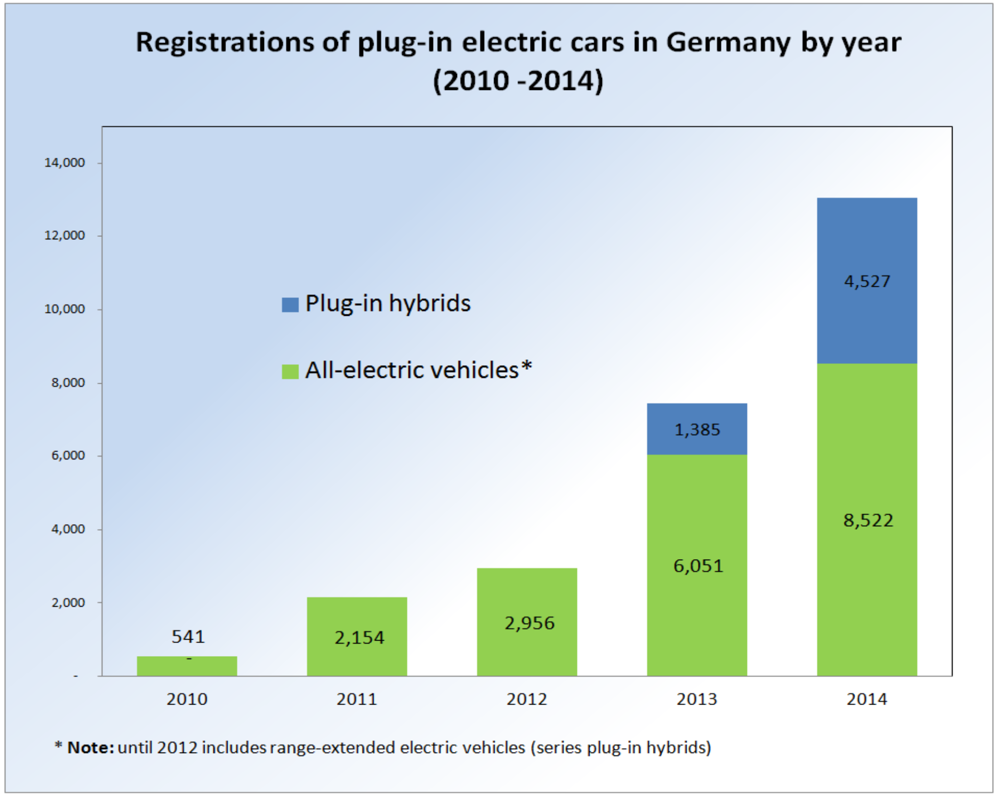


many new models
(Tesla, Mitsubishi, Nissan, Renault, VW, BMW, Apple?)

GROWING INTEREST…



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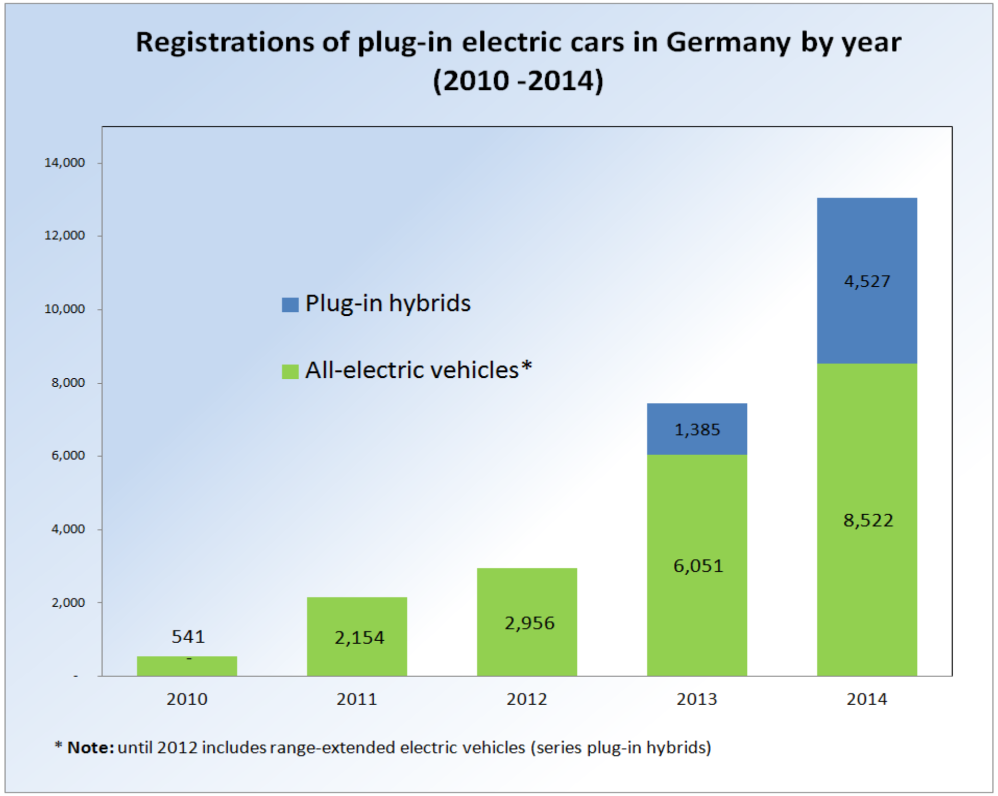

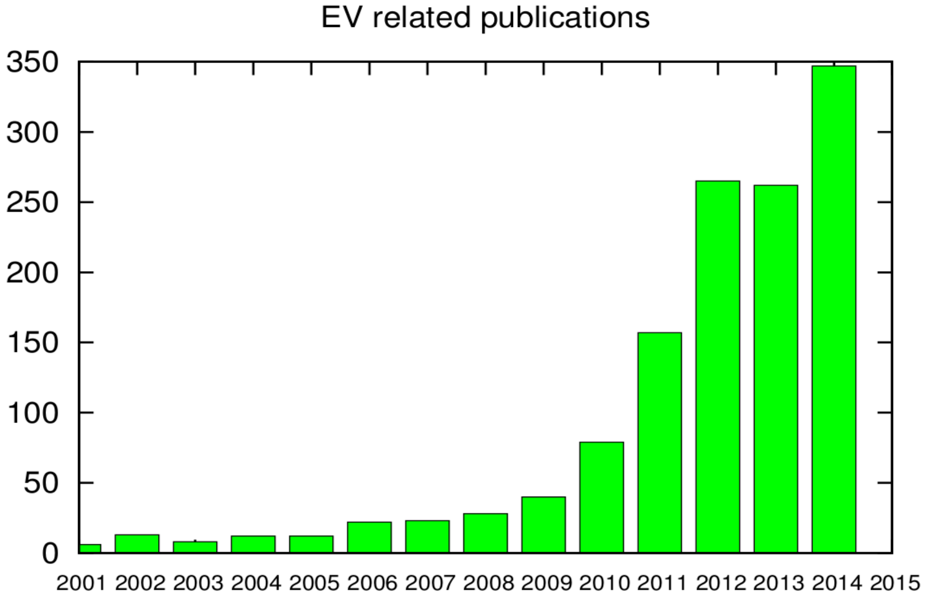

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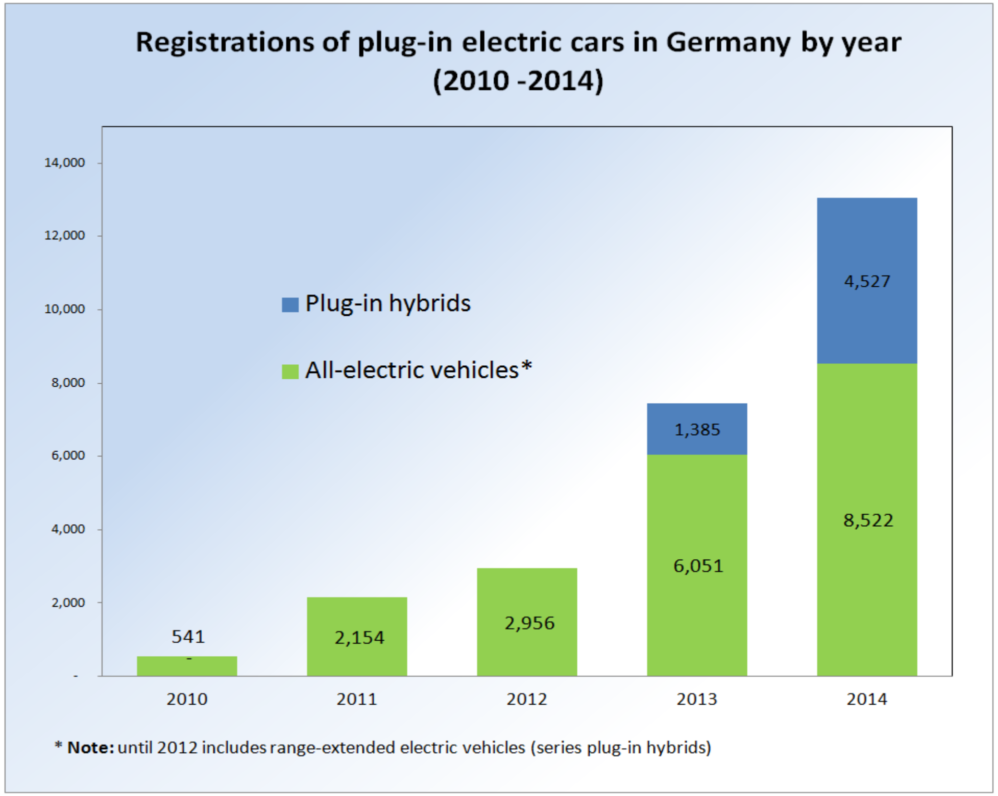
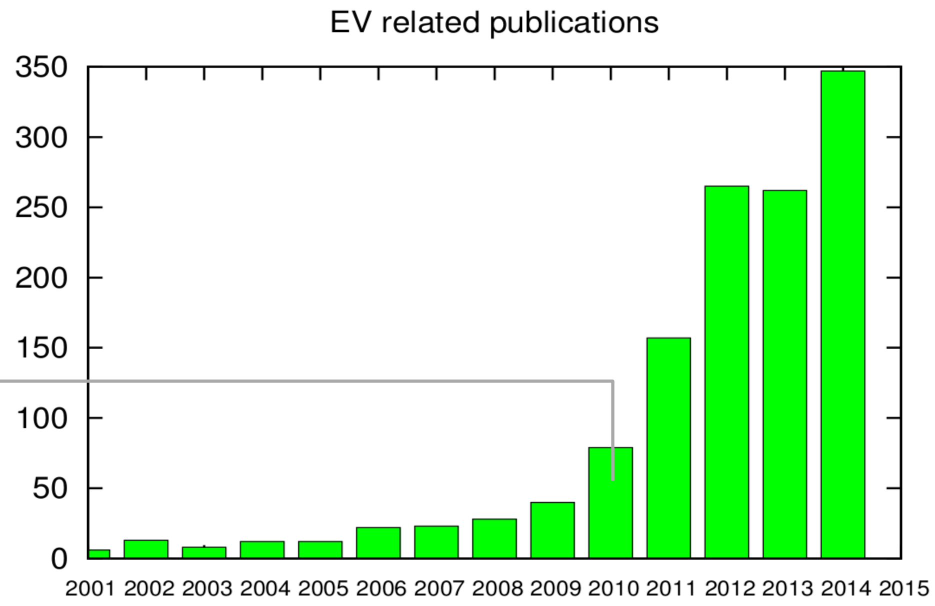




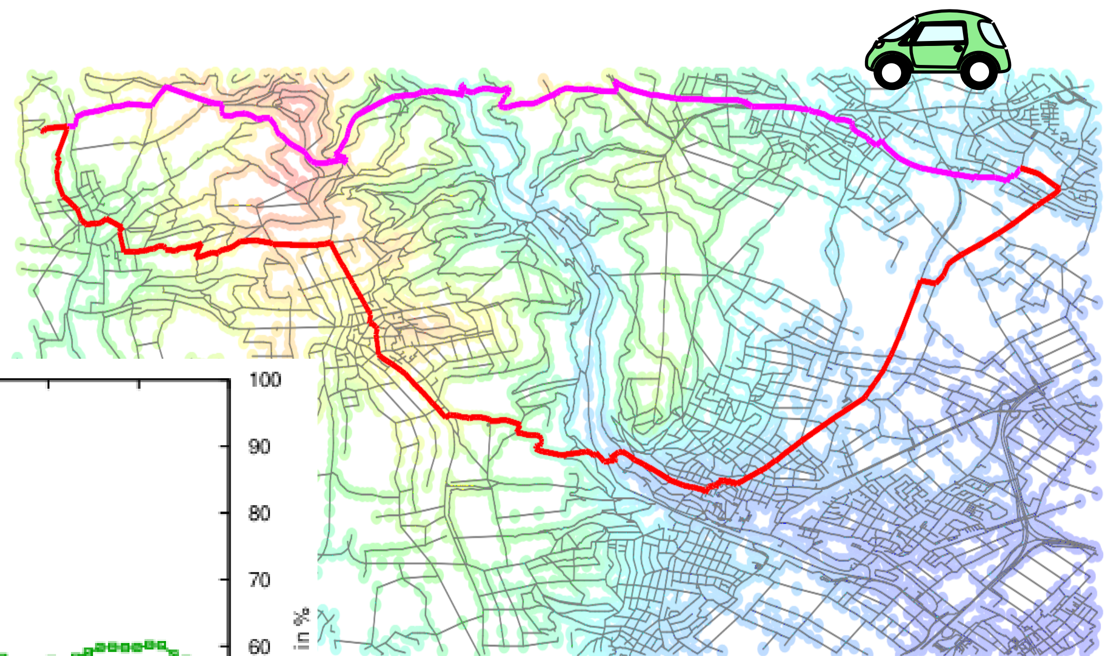
The Shortest Path Problem Revisited:
Optimal Routing for Electric Vehicles

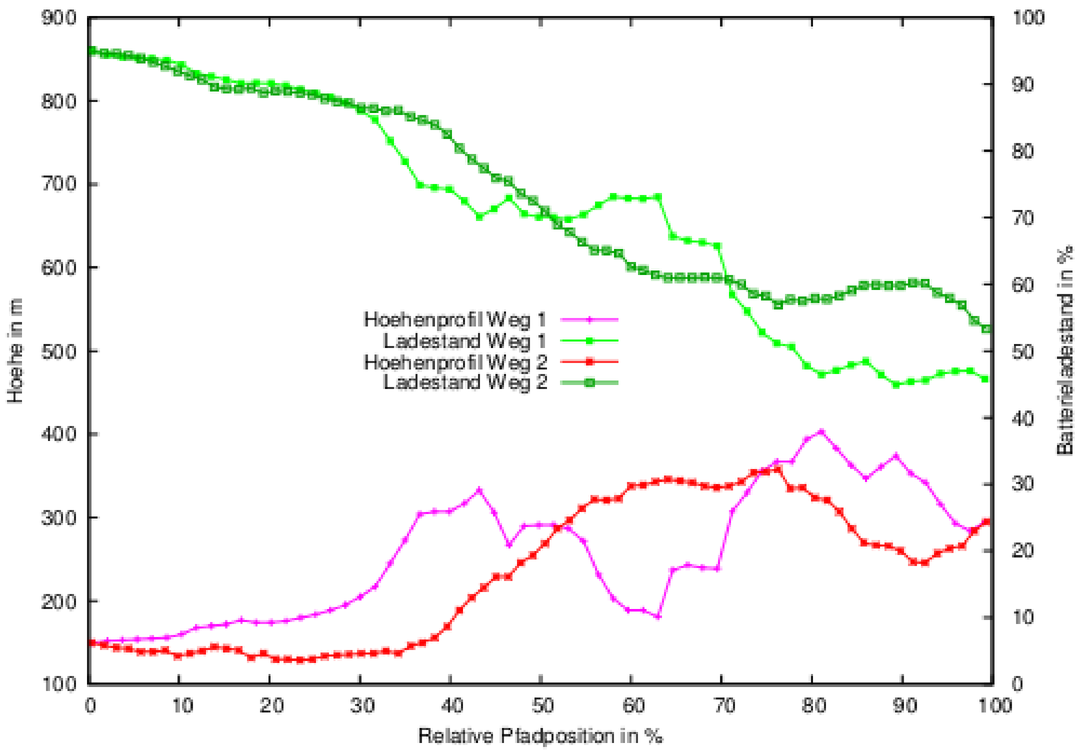
[Andreas Artmeier, Julian Haselmayr, Martin Leucker, Martin Sachenbacher] @KI

ROUTE PLANNING FOR EVs

ROUTE PLANNING FOR EVs

- battery-powered
  →limited cruising range
- time-intensive reloading
- sparse loading stations





Goal

computing energy-optimal routes

ROUTE PLANNING FOR EVs

Conventional Route Planning

given a road network $G(V, E)$ and edge costs (e.g. distance or travel time) $c : E \to \mathbb{R}^+$, compute the minimum cost path from $s \in V$ to $t \in V$.

Basic Algorithm

Dijkstra, runtime $\mathcal{O}(n \log n + m)$ with $n = |V|, m = |E|$

query time: seconds on Germany

Speed-Up Techniques

Contraction Hierarchies, Reach, Transit Nodes, . . .

query time: milli/microseconds

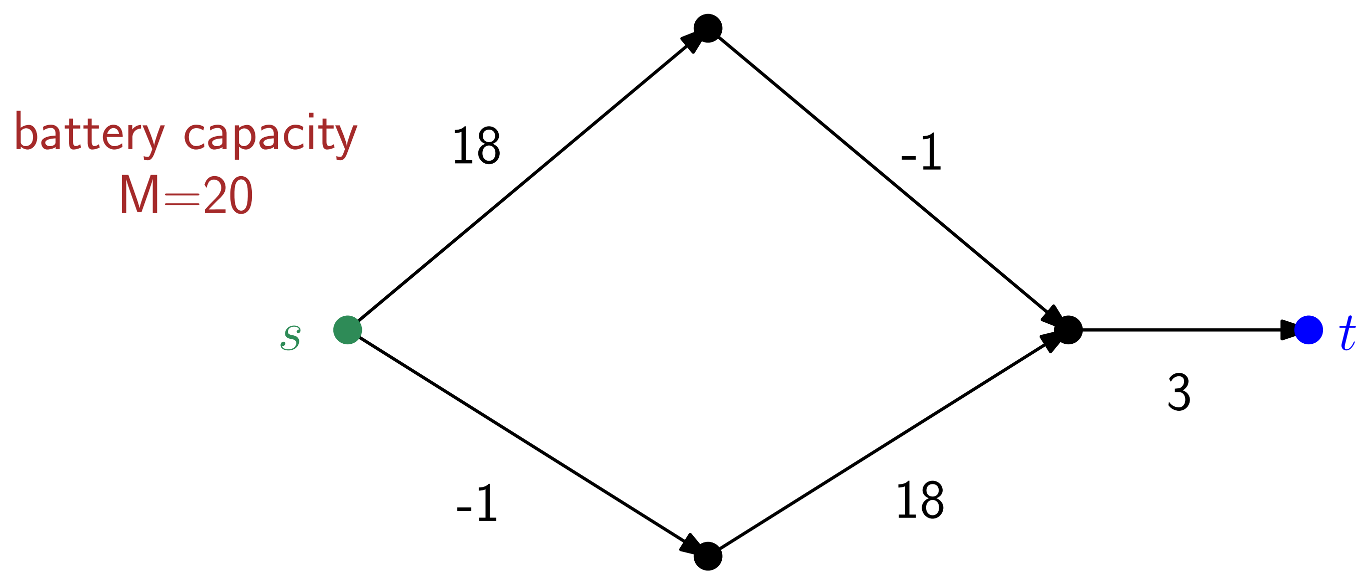
Conditions

edge costs constant and non-negative!

ROUTE PLANNING FOR EVs

Problem

- partly negative edge costs due to regenerative breaking
- battery should not overload
- battery should not run empty



ROUTE PLANNING FOR EVs

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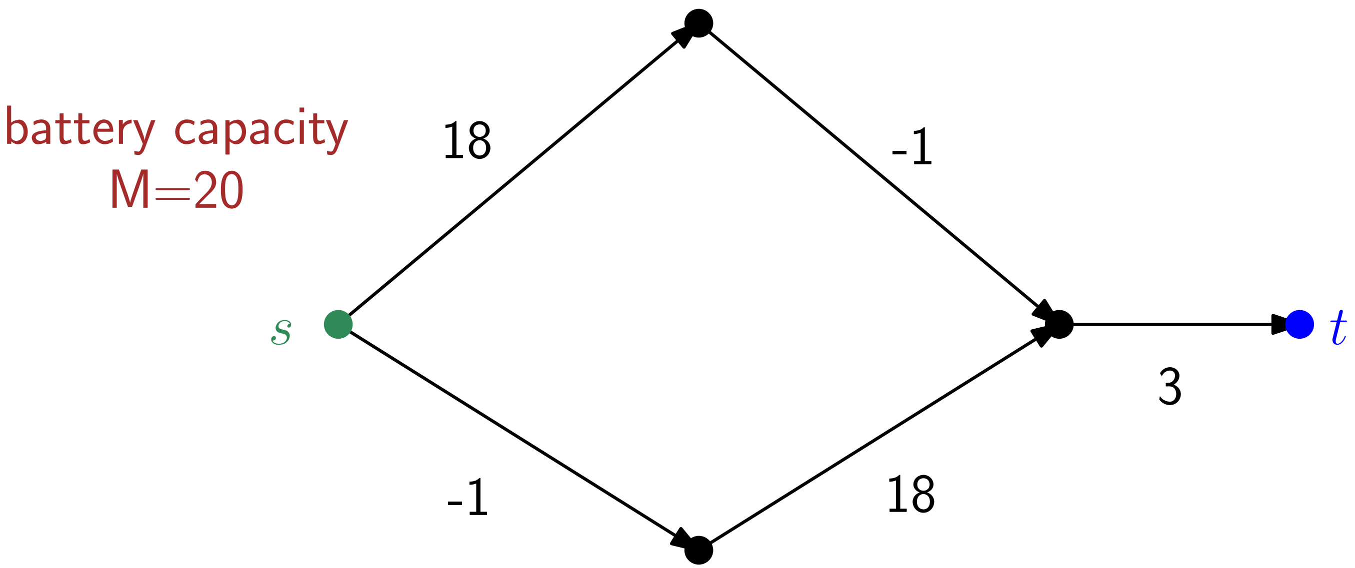
~~Dijkstra~~
Bellman-Ford $\mathcal{O}(nm)$



ROUTE PLANNING FOR EVs

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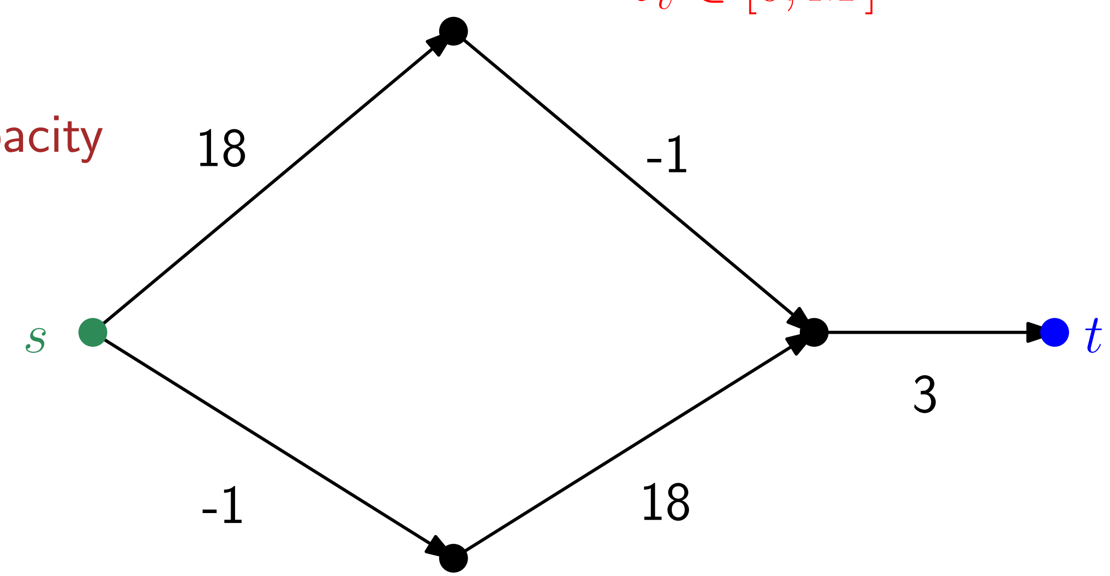
~~Dijkstra~~

Bellman-Ford $\mathcal{O}(nm)$

battery constraints

$b_v \in [0, M]$

battery capacity
M=20



ROUTE PLANNING FOR EVs

Problem

~~Dijkstra~~
Bellman-Ford $\mathcal{O}(nm)$

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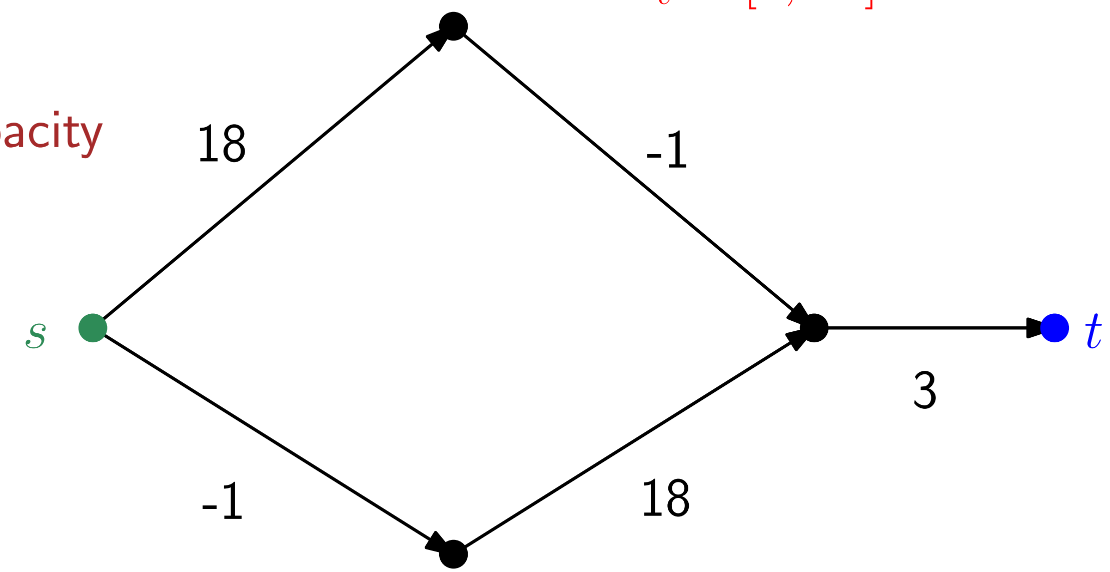


[Artmeier et al. 2010]

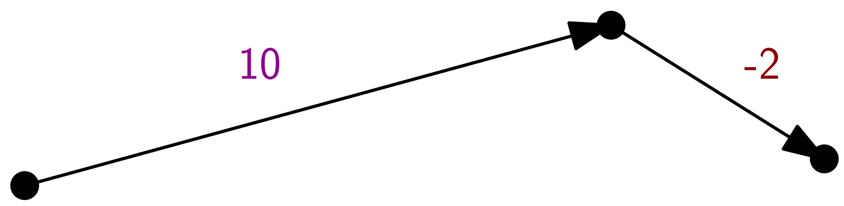
extended version of Bellman-Ford solves the problem

- check for every path prefix whether constraints are satisfied
- runtime $\mathcal{O}(nm)$ impractical for large networks! minutes to hours on Germany...

ROUTE PLANNING FOR EVs

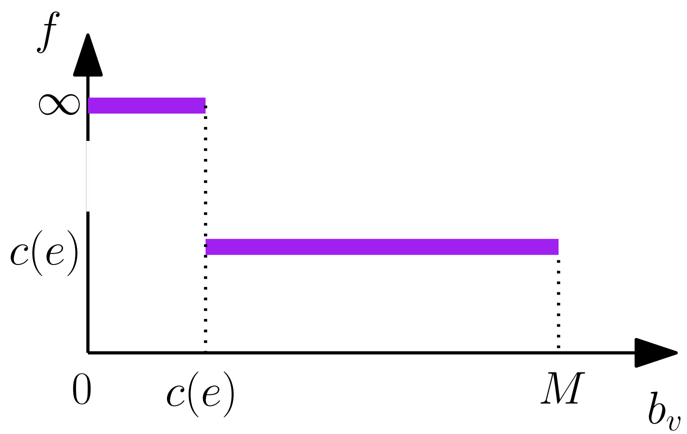
Energy costs depend on charge status

$\rightarrow$ can be modelled as edge cost functions



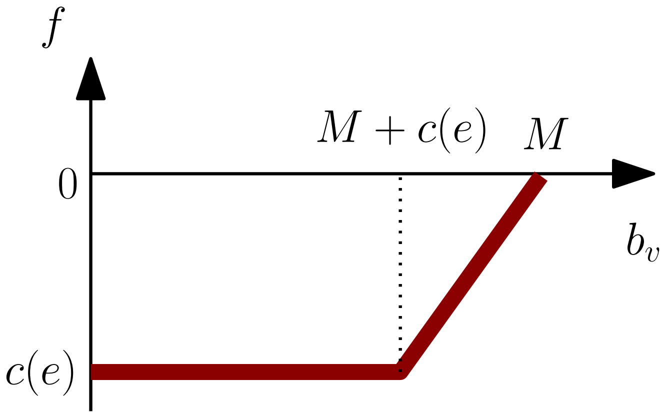
A) $c(e) \geq 0$

$$f(b_v) = \begin{cases} \infty & b_v < c(e) \\ c(e) & otherwise \end{cases}$$



B) $c(e) < 0$

$$f(b_v) = \begin{cases} c(e) & b_v < M + c(e) \\ b_v - M & otherwise \end{cases}$$



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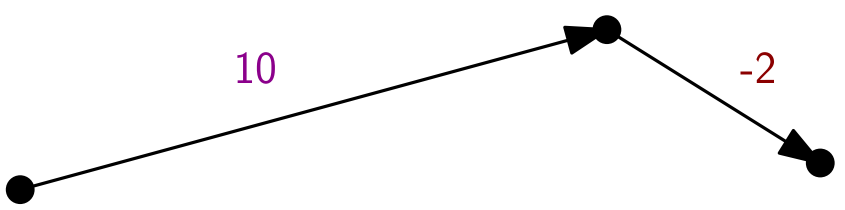

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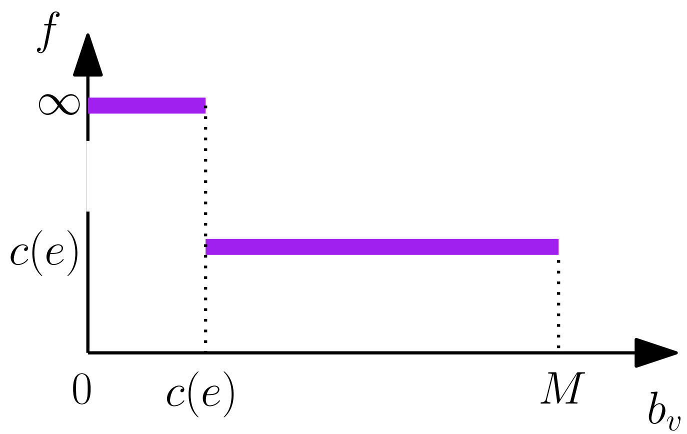

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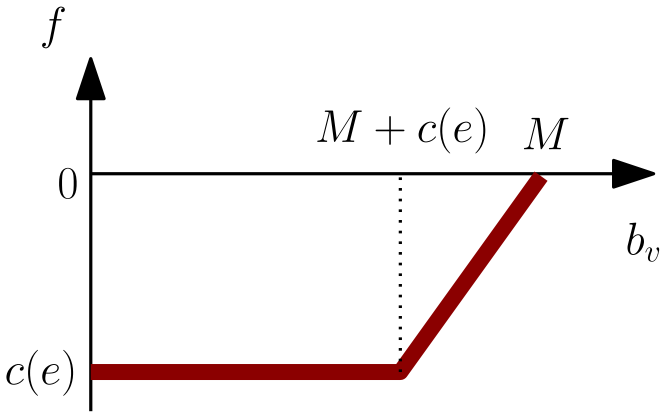


FIFO costs

$\Rightarrow$ Bellman-Ford can be applied directly

Dealing with negative edge costs

Assumption: G has no negative cost cycles

THEOREM [Johnson 1977]

There exists a potential function $\phi : V \to \mathbb{R}$, such that $\forall e = (v, w) \in E$ yields: $c'(e) = c(e) + \phi(v) - \phi(w) \geq 0$ and the structure of shortest paths remains the same under the new costs.

Generalisation to edge cost functions

$$f'(b_v) = f(b_v - \phi(v)) + \phi(v) - \phi(w)$$

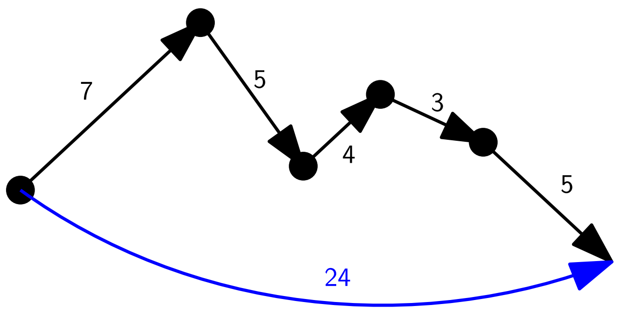
$\Rightarrow$ **Dijkstra applicable after preprocessing phase**

query times in the order of seconds on Germany!

ROUTE PLANNING FOR EVs

Acceleration with Contraction Hierarchies

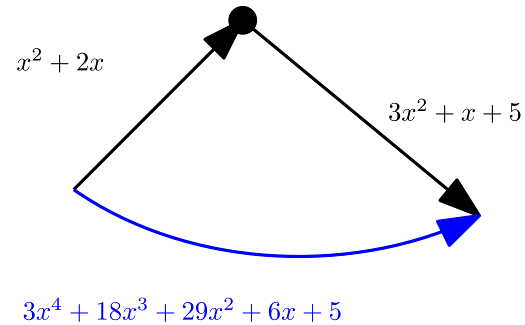
[Geisberger et al. 2008]



[Batz et al. 2009]

applicable for edge cost functions

BUT complexity increases with chaining



THEOREM

The descriptive complexity of energy cost functions is bounded.

$$f(b_v) = \begin{cases} \infty & b_v < l \\ c & b_v \in [l, u] \\ b_v - d & b_v > u \end{cases}$$

l...minimum charge to use the path

u...maximum charge to use the path without overcharging

c...summed path costs

d...final charge when initial charge $\geq u$

ROUTE PLANNING FOR EVs

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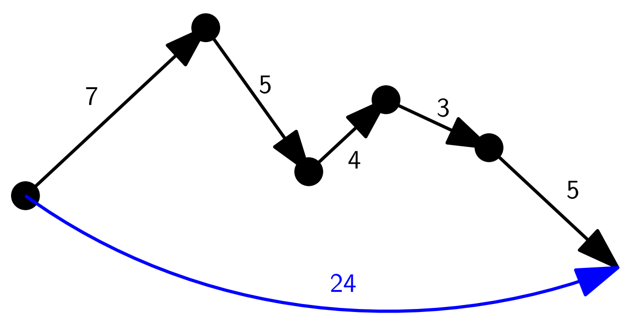

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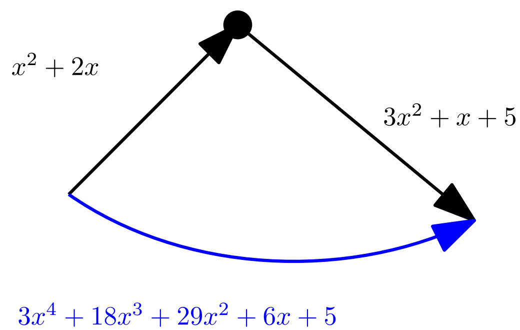

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d...final charge when initial charge $\geq u$

$\Rightarrow$ **CH applicable**

query times in the order of milliseconds on Germany!

ROUTE PLANNING FOR EVs

Optimal Route Planning for Electric Vehicles in Large Networks
Jochen Eisner, Stefan Funke, Sabine Storandt
AAAI, 2011

A* framework for dynamically changing energy costs

Efficient Energy-Optimal Routing for Electric Vehicles
Martin Sachenbacher, Martin Leucker, Andreas Artmeier, Julian Haselmayr
AAAI, 2011

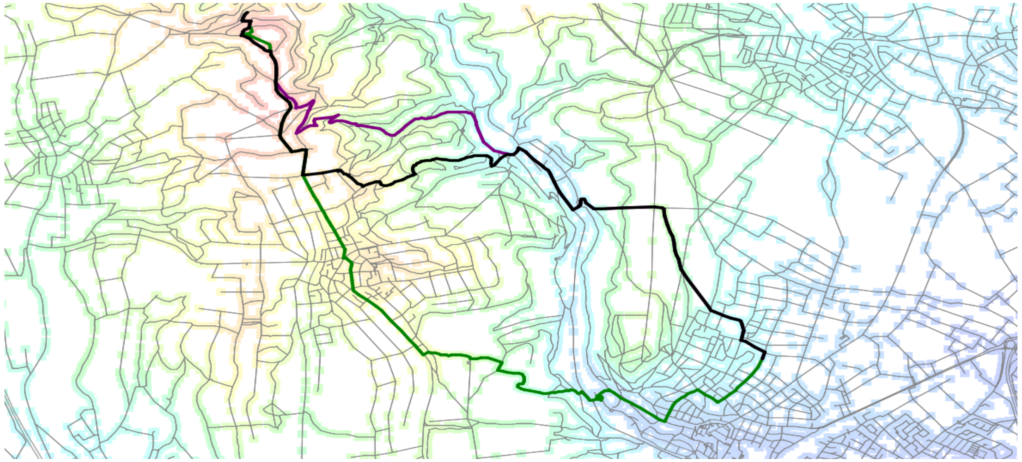
Customizable route planning for EVs

Energy-Optimal Routes for Electric Vehicles
Moritz Baum, Julian Dibbelt, Thomas Pajor, Dorotha Wagner
SIGSPATIAL, 2013

TAKING DISTANCE/TRAVEL TIME INTO ACCOUNT

quickest path

energy-optimal path



quickest path without running out of energy

energy-optimal path with bounded detour

TAKING DISTANCE/TRAVEL TIME INTO ACCOUNT

quickest path

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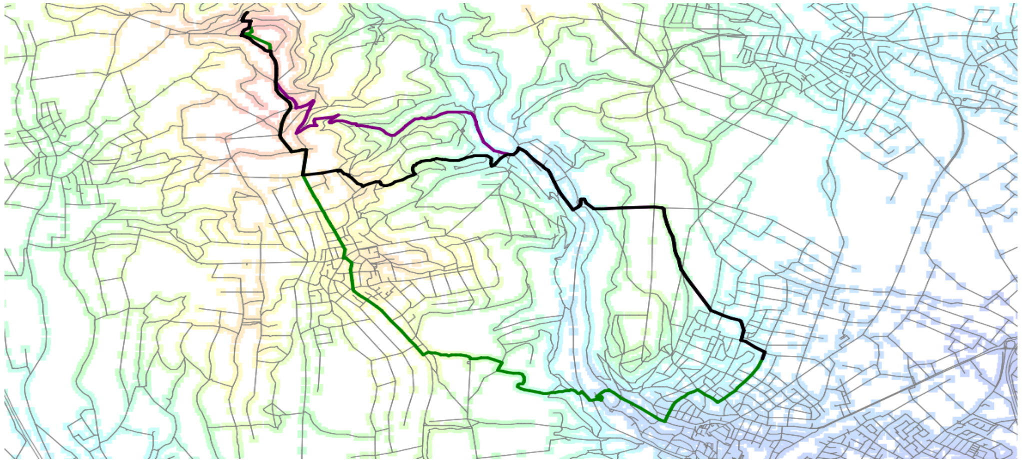

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Constrained Shortest Path problems $\Rightarrow$ NP-hard

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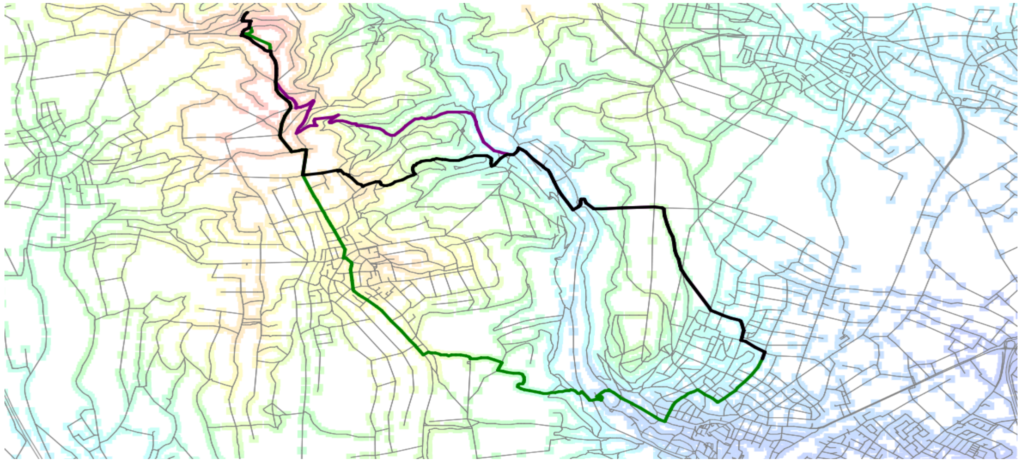

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Constrained Shortest Path problems $\Rightarrow$ NP-hard

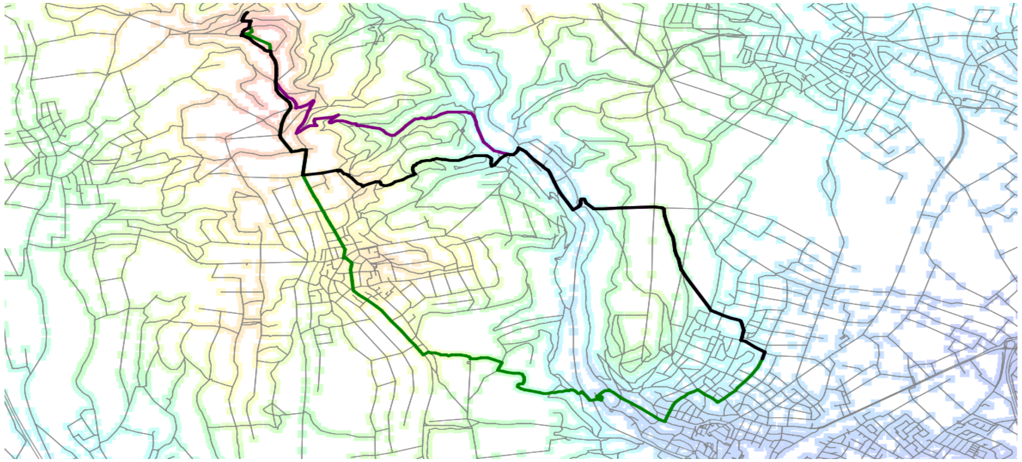
Acceleration schemes to still achieve query times in the order milliseconds

Quick and Energy-Efficient Routes - Computing Constrained Shortest Paths for Electric Vehicles
Sabine Storandt
IWCTS, 2012

TAKING DISTANCE/TRAVEL TIME INTO ACCOUNT

quickest path

energy-optimal path



quickest path without running out of energy

energy-optimal path with bounded detour

Constrained Shortest Path problems $\Rightarrow$ NP-hard

Taking into account that speed influences energy consumption

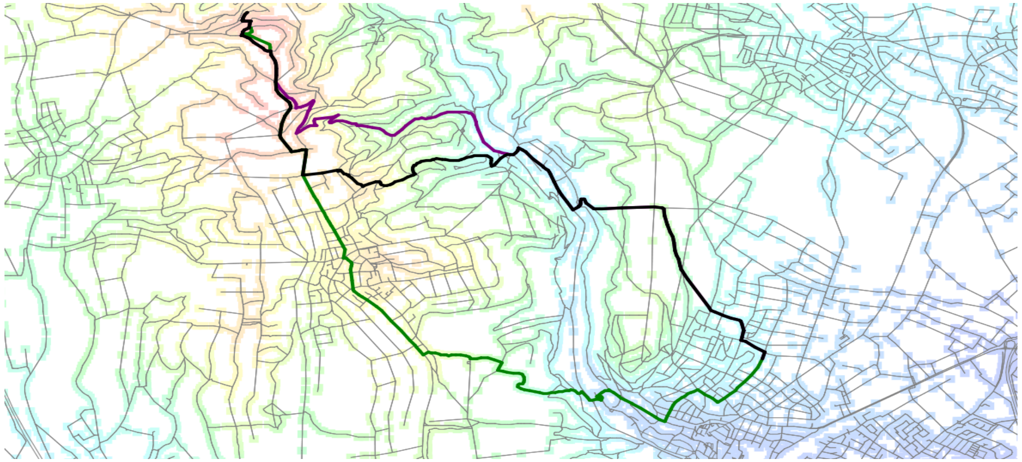
Speed-Consumption Tradeoff for Electric Vehicle Route Planning
Moritz Baum, Julian Dibbelt, Lorenz Hübschle-Schneider, Thomas Pajor, Dorothea Wagner
ATMOS, 2014

Energy-Efficient Routing: Taking Speed into Account
Frederik Hartmann, Stefan Funke
KI, 2014

TAKING DISTANCE/TRAVEL TIME INTO ACCOUNT

quickest path

energy-optimal path



quickest path without running out of energy

energy-optimal path with bounded detour

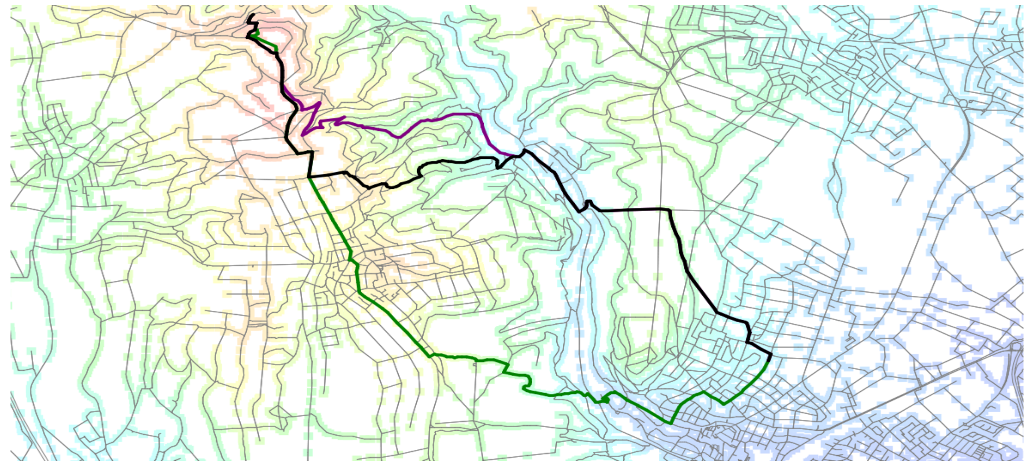
Constrained Shortest Path problems ⇒ NP-hard

Many, many, many more...

TAKING DISTANCE/TRAVEL TIME INTO ACCOUNT

quickest path

energy-optimal path

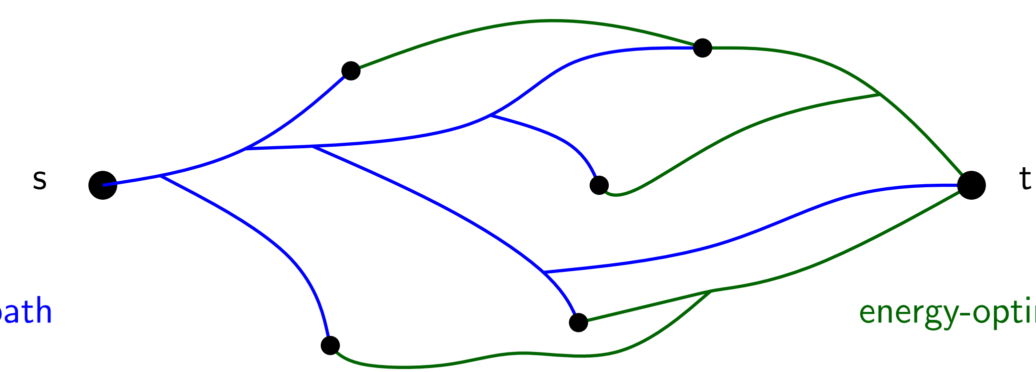


quickest path without running out of energy

energy-optimal path with bounded detour

~~Constrained Shortest Path problems ⇒ NP-hard~~

Two-phase bicriterion search for finding fast and efficient electric vehicle routes
Michael T. Goodrich, Pawe Pszona
SIGSPATIAL, 2014



quickest path

energy-optimal path

WHERE TO RELOAD

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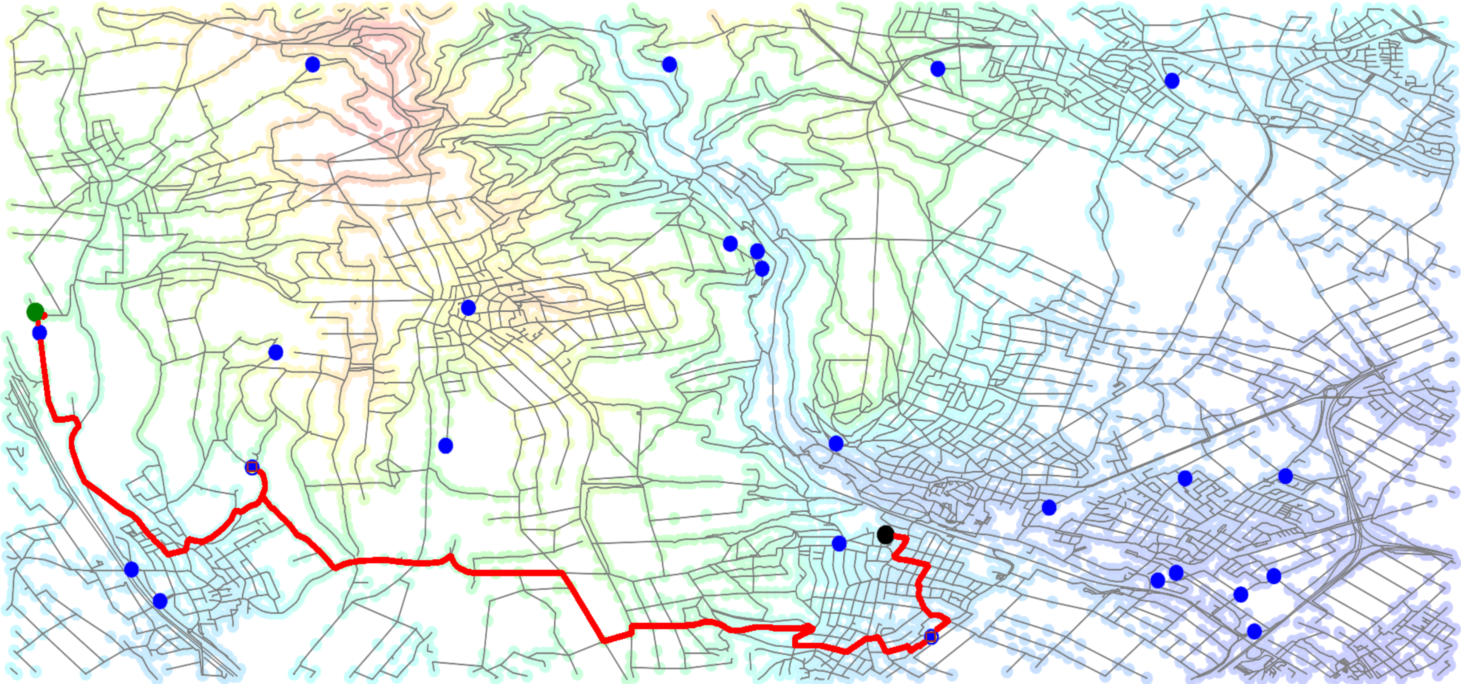


How often do I have to recharge?

What is the quickest feasible path with recharging?

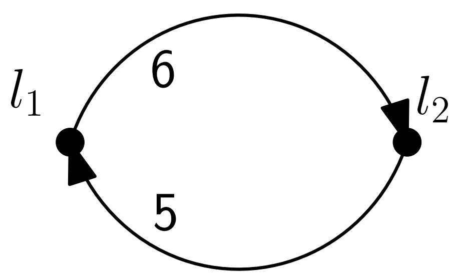
What is the quickest feasible path whith at most k recharging events?

WHERE TO RELOAD

Build reachability graph

$\mathbf{RG}(\mathbf{L}, \mathbf{E}) : e = (l, l') \in E$ iff it exists path from l to l' without recharging

$c(e)$ equals travel time on the quickest feasible path from l to l'



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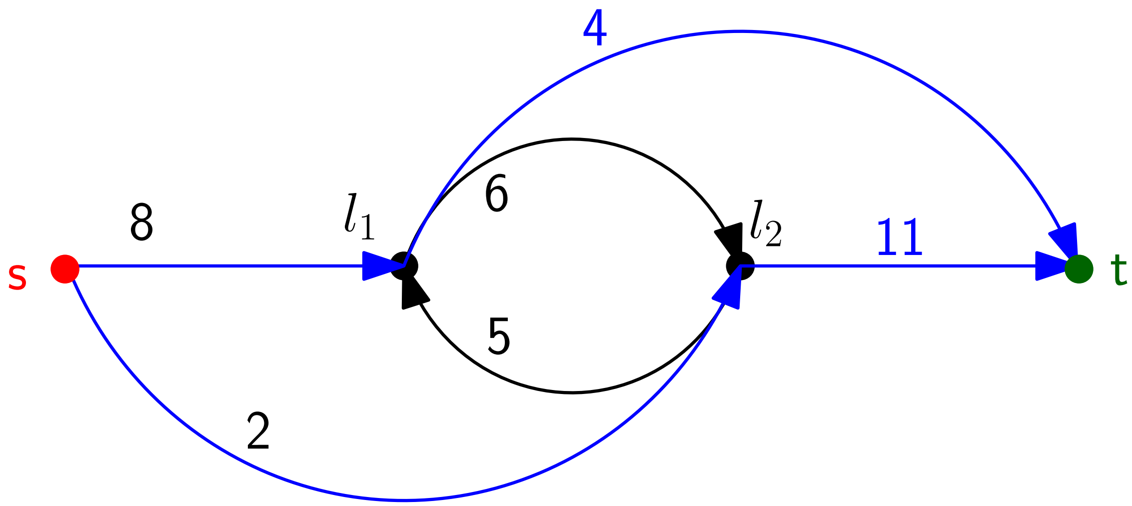

on query time augment RG with edges from s and to t

WHERE TO RELOAD

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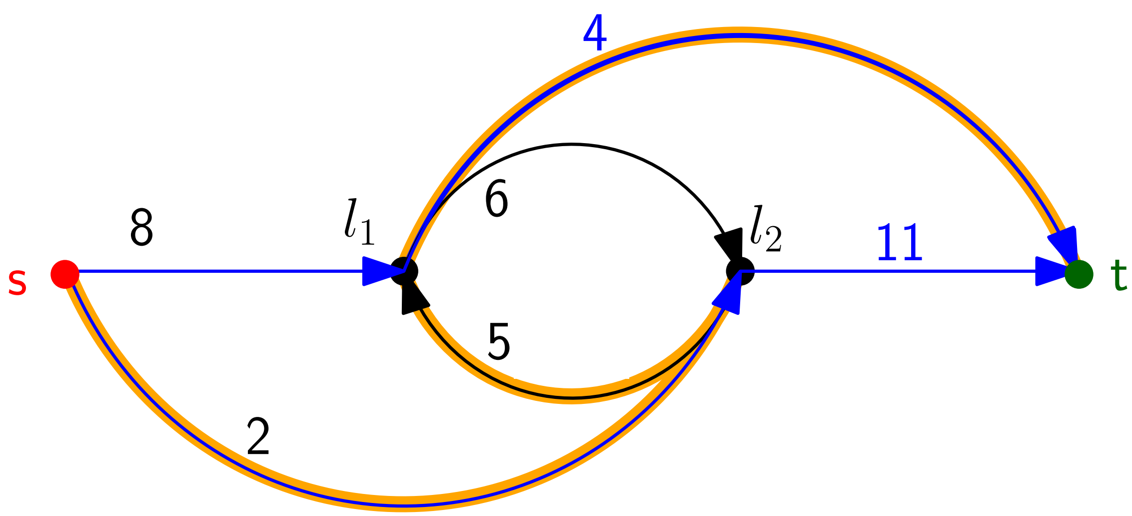

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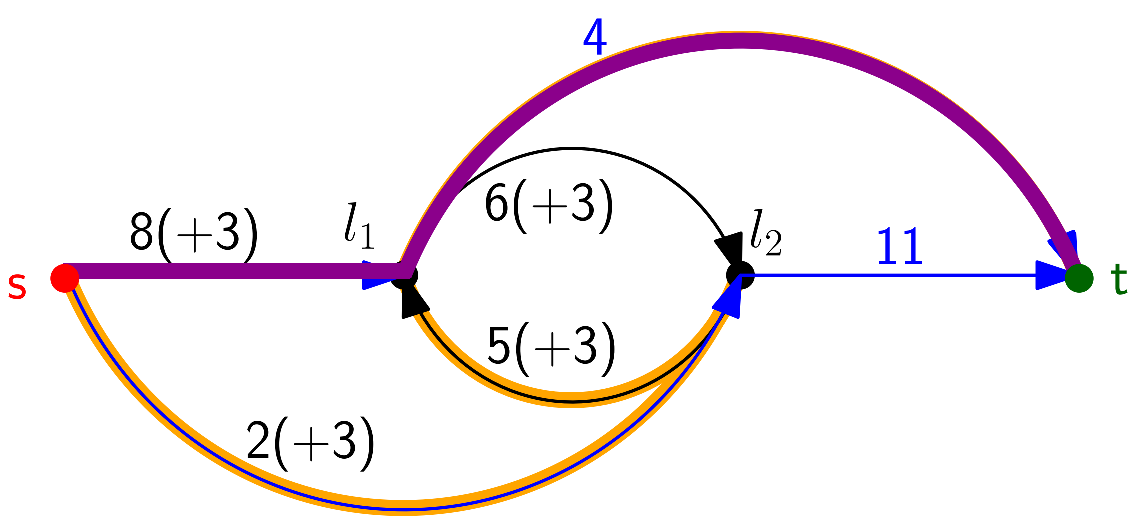

on query time augment RG with edges from s and to t

run Dijkstra

possibly with reloading penalties

WHERE TO RELOAD

Cruising with a Battery-Powered Vehicle and not getting Stranded
Sabine Storandt, Stefan Funke
AAAI, 2012

Quick and Energy-Efficient Routes - Computing Constrained Shortest Paths for Electric Vehicles
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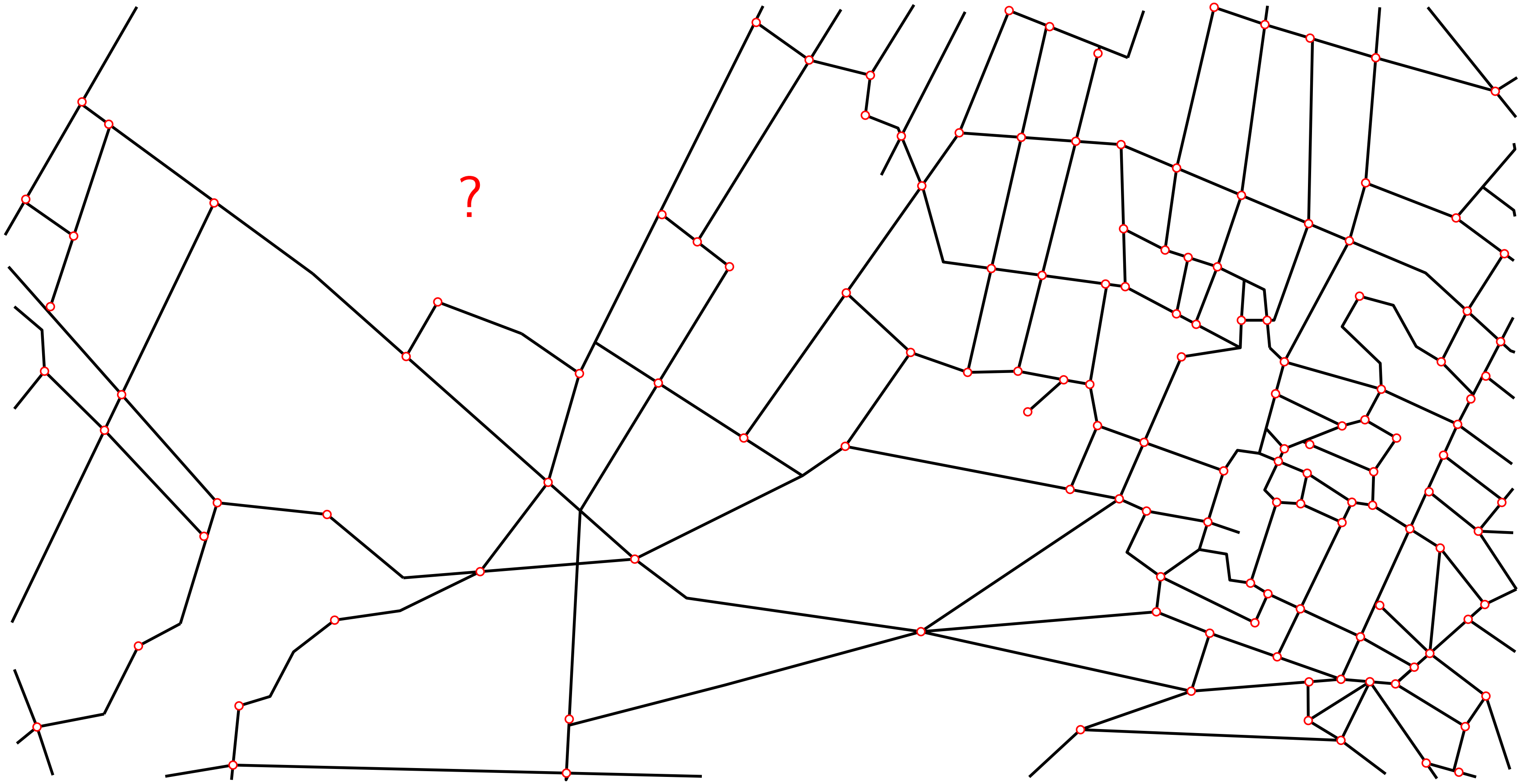
Many papers on more complicated settings...

... incomplete reloading allowed

... different kind of loading stations

LOADING STATION PLACEMENT

LOADING STATION PLACEMENT



Natural Goals place loading stations such that...

... one can drive from anywhere to anywhere (and back)

... one can always drive on shortest paths

... one can drive on shortest paths allowing small detours

LOADING STATION PLACEMENT

all of those problems are related to Hitting Set/ Set Cover problems

$\Rightarrow$ NP-hard and hard to approximate!

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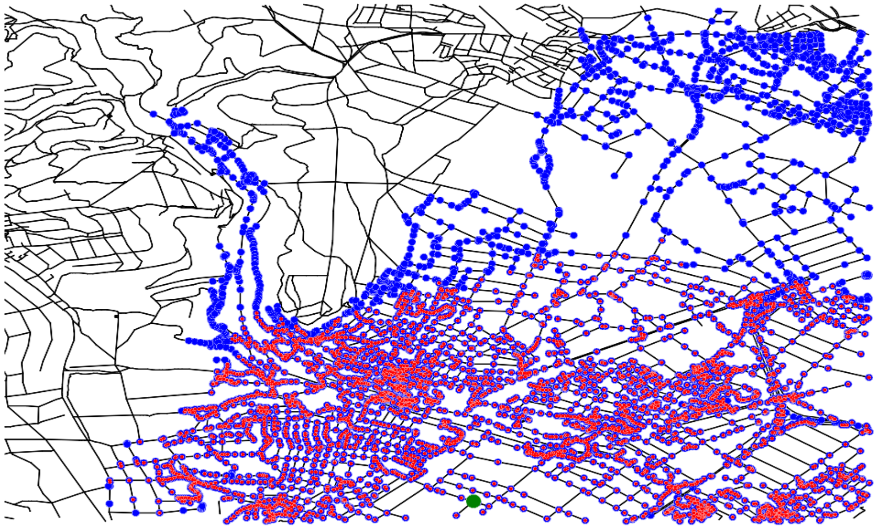
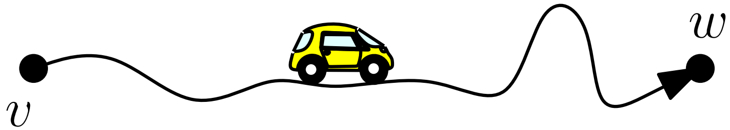
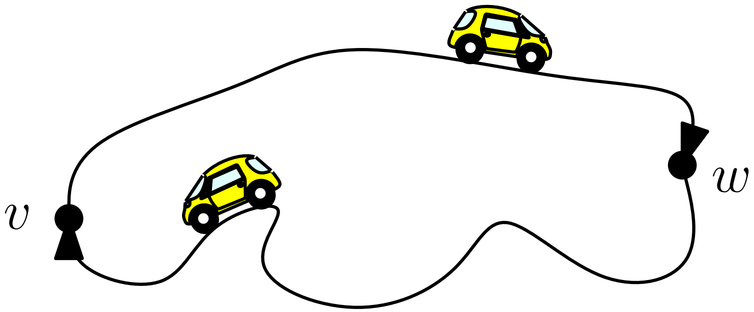


$\mathbf{R}(\mathbf{v} \in \mathbf{V})$... set of all ev-reachable nodes from v



$\mathbf{C}(\mathbf{v} \in \mathbf{V})$... set of all ev-connected nodes of v



LOADING STATION PLACEMENT

all of those problems are related to Hitting Set/ Set Cover problems

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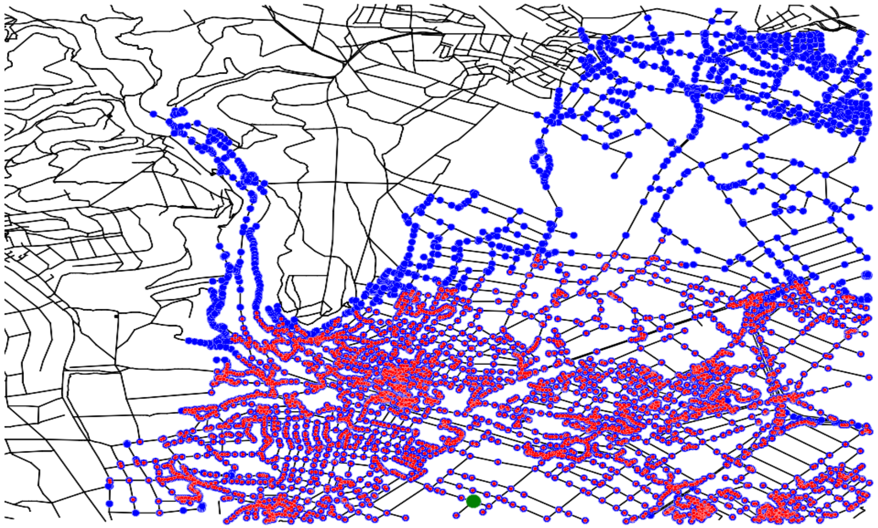
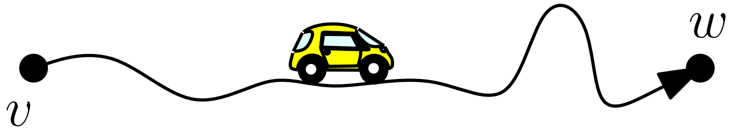


GOAL select $L \subseteq V$
1) $\forall v \in V : R_L(v) = V$
2) $\forall v \in V : C_L(v) = V$

$\mathbf{R}(\mathbf{v} \in \mathbf{V})$... set of all ev-reachable nodes from v



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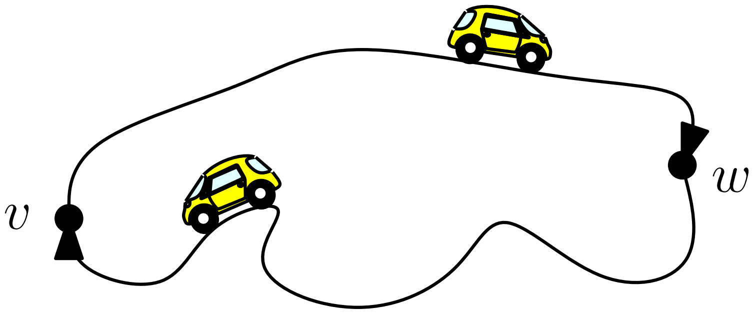
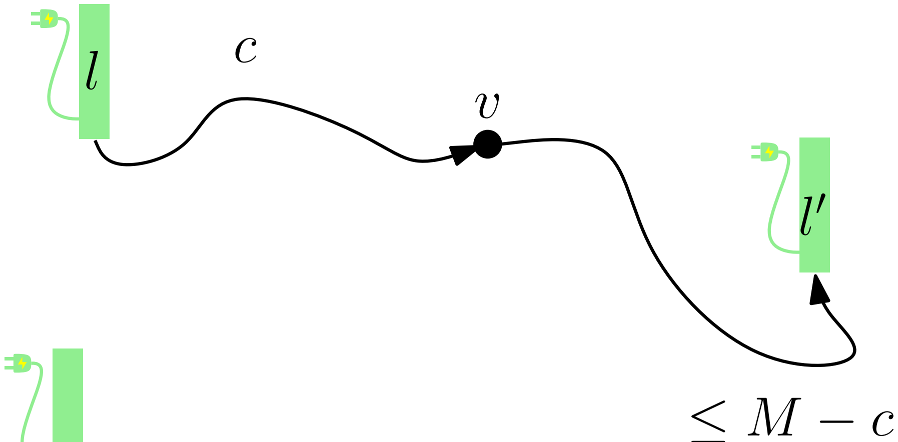


LOADING STATION PLACEMENT

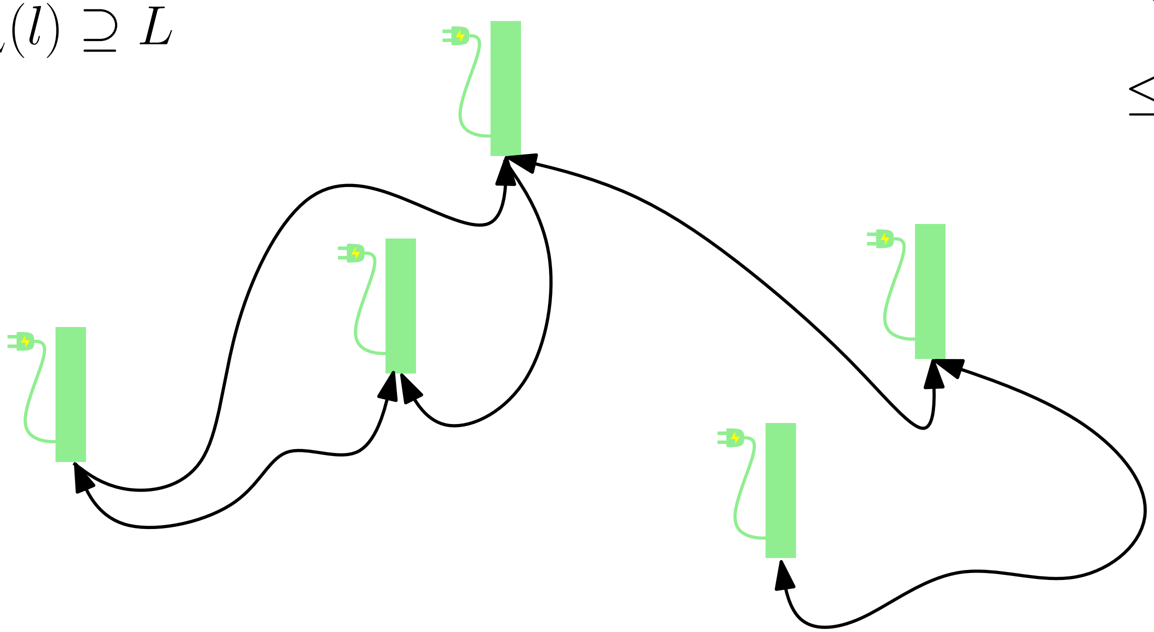
Choose $L \subseteq V$ such that $\forall v \in V : C_L(v) = V$.

Alternative Formulation

1. $\forall v \in V \exists l, l' \in L : l, \cdots, v, \cdots, l'$ feasible



2. $\forall l \in L : C_L(l) \supseteq L$



LOADING STATION PLACEMENT

Choose $L \subseteq V$ such that $\forall v \in V : C_L(v) = V$.

Alternative Formulation

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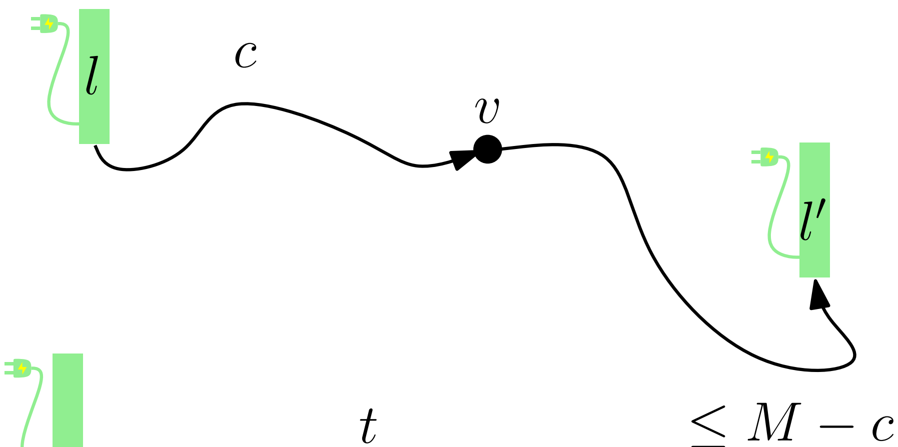

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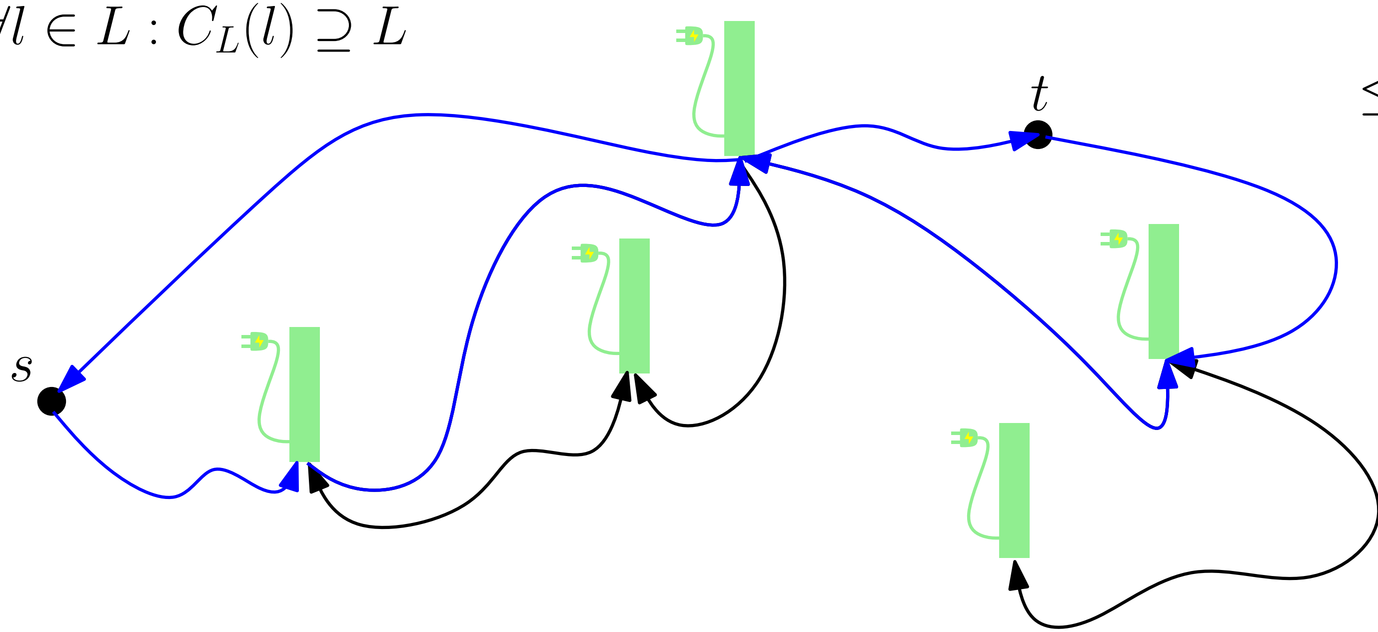

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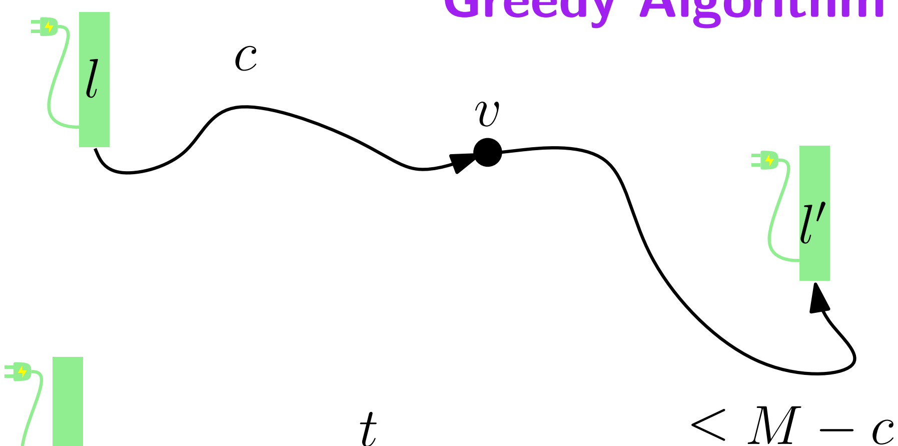
Greedy Algorithm



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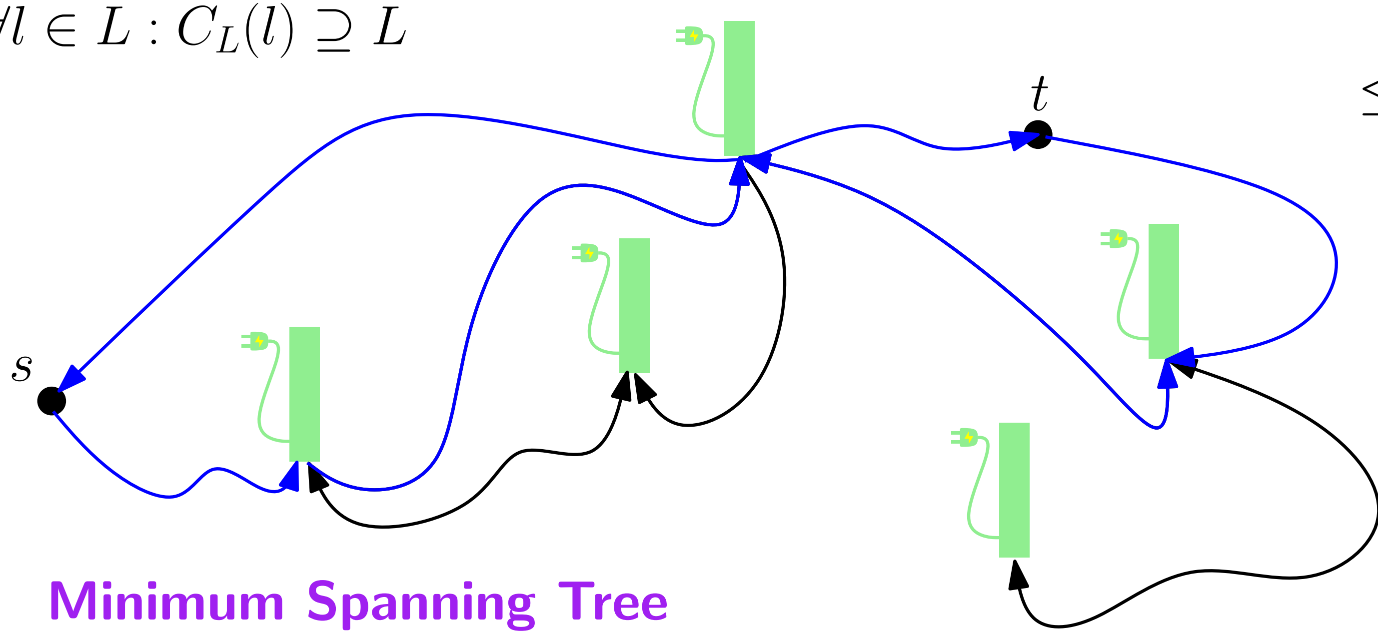

Minimum Spanning Tree

LOADING STATION PLACEMENT

number of loading stations

avg. cruising range	lower bound	reachability	connectivity
75 km	105	339	812
100 km	49	147	379
125 km	37	103	268
150 km	22	61	187
175 km	14	46	138

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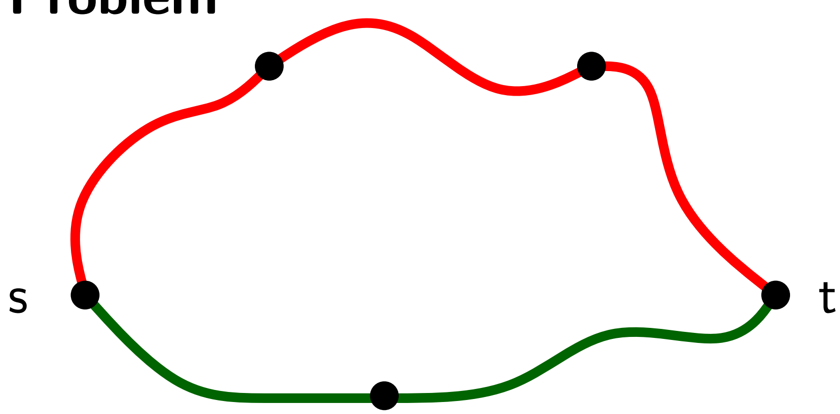
Problem

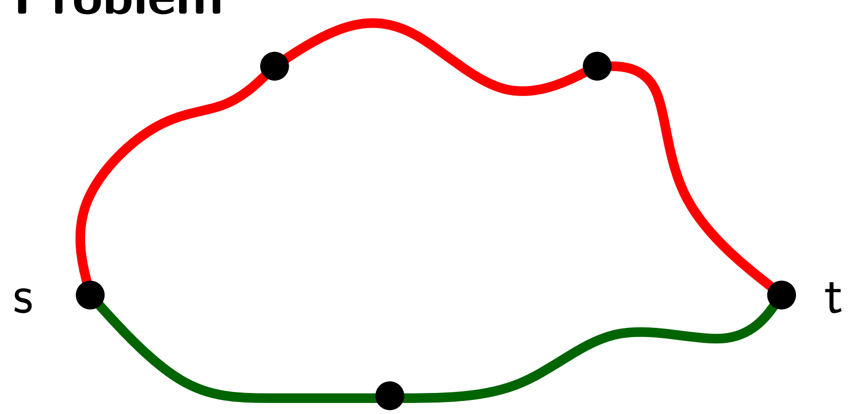


LOADING STATION PLACEMENT

number of loading stations

avg. cruising range	lower bound	reachability	connectivity	shortest paths
75 km	105	339	812	
100 km	49	147	379	
125 km	37	103	268	728
150 km	22	61	187	
175 km	14	46	138	

Problem



$\Rightarrow$ hit all (almost) shortest paths

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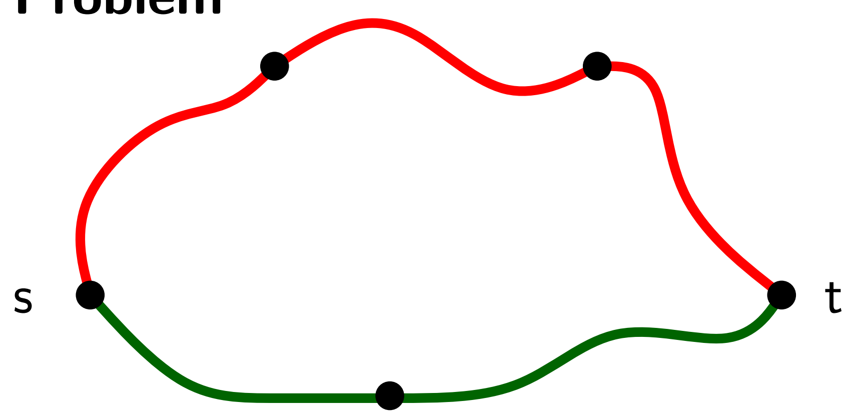

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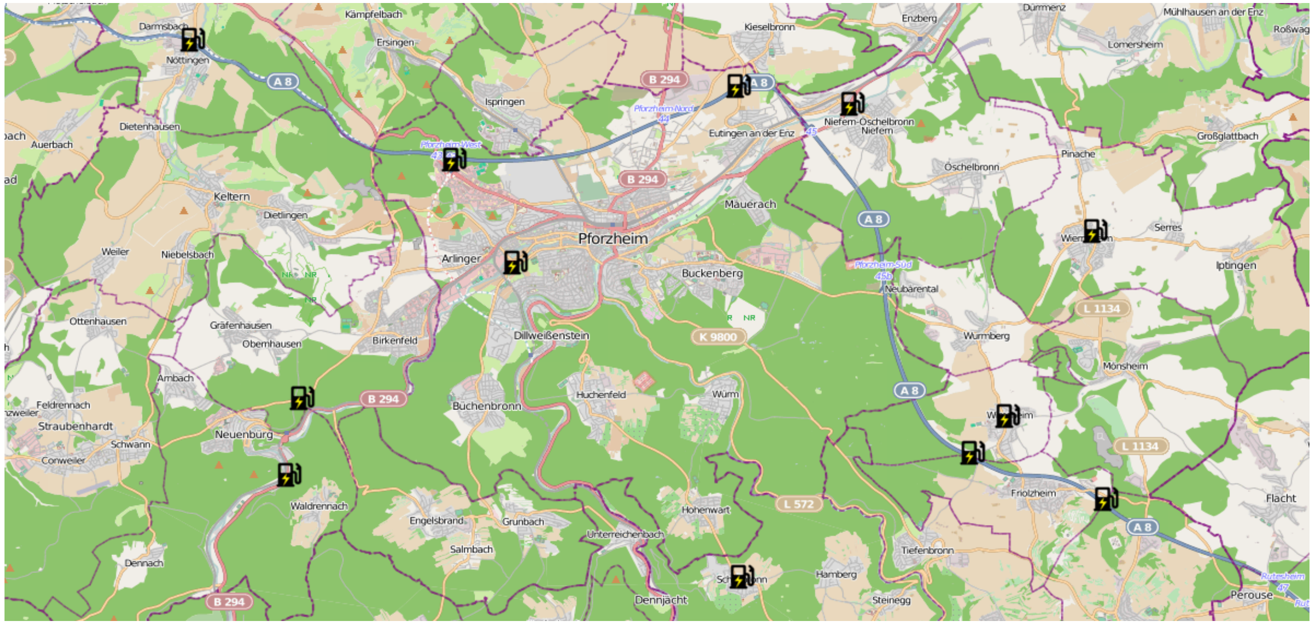
LOADING STATION PLACEMENT

Enabling E-Mobility: Facility Location for Battery Loading Stations
Sabine Storandt, Stefan Funke
National Conference of the American Association for Artificial Intelligence (AAAI, 2013)

Placement of Loading Stations for Electric Vehicles: No Detours Necessary!
Stefan Funke, Andre Nusser, Sabine Storandt
National Conference of the American Association for Artificial Intelligence (AAAI, 2014)



traffic planning

higher demand in cities

considering different kinds of charching stations

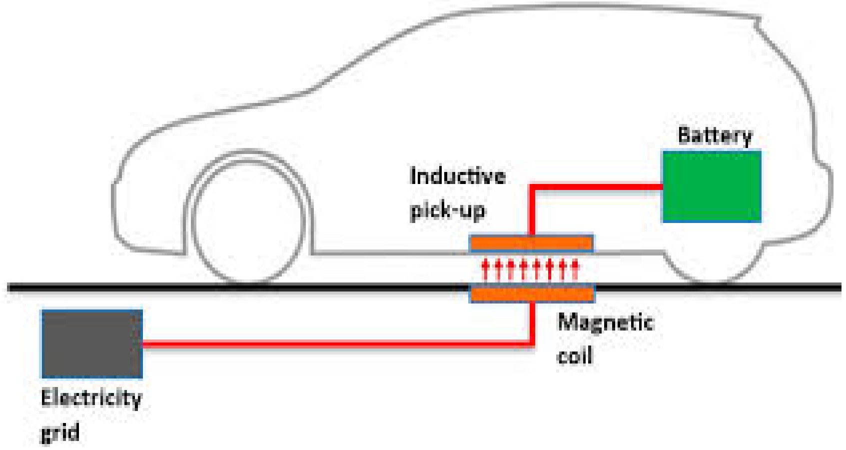
WHAT NEXT

new battery and recharging technologies might make most of the developed algorithms superfluous

WHAT NEXT

new battery and recharging technologies might make most of the developed algorithms superfluous

or require novel ones



WHAT NEXT

new battery and recharging technologies might make most of the developed algorithms superfluous

new challenges to the power grid

THANK YOU

for your attention!

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Questions?