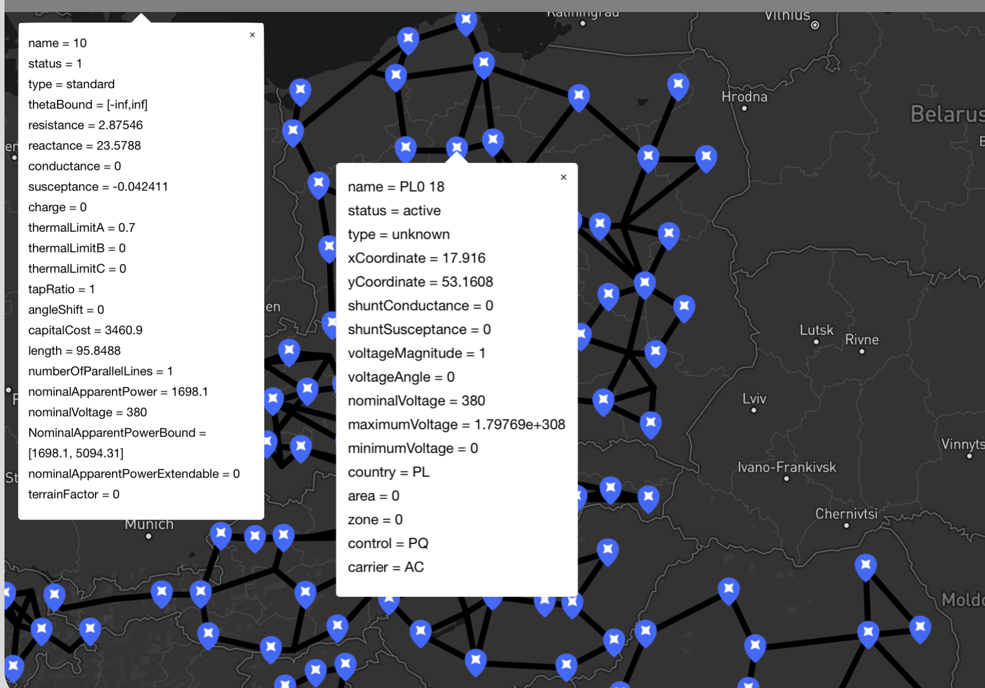
Karlsruhe Institute of Technology

Combinatorial Problems in Energy Networks

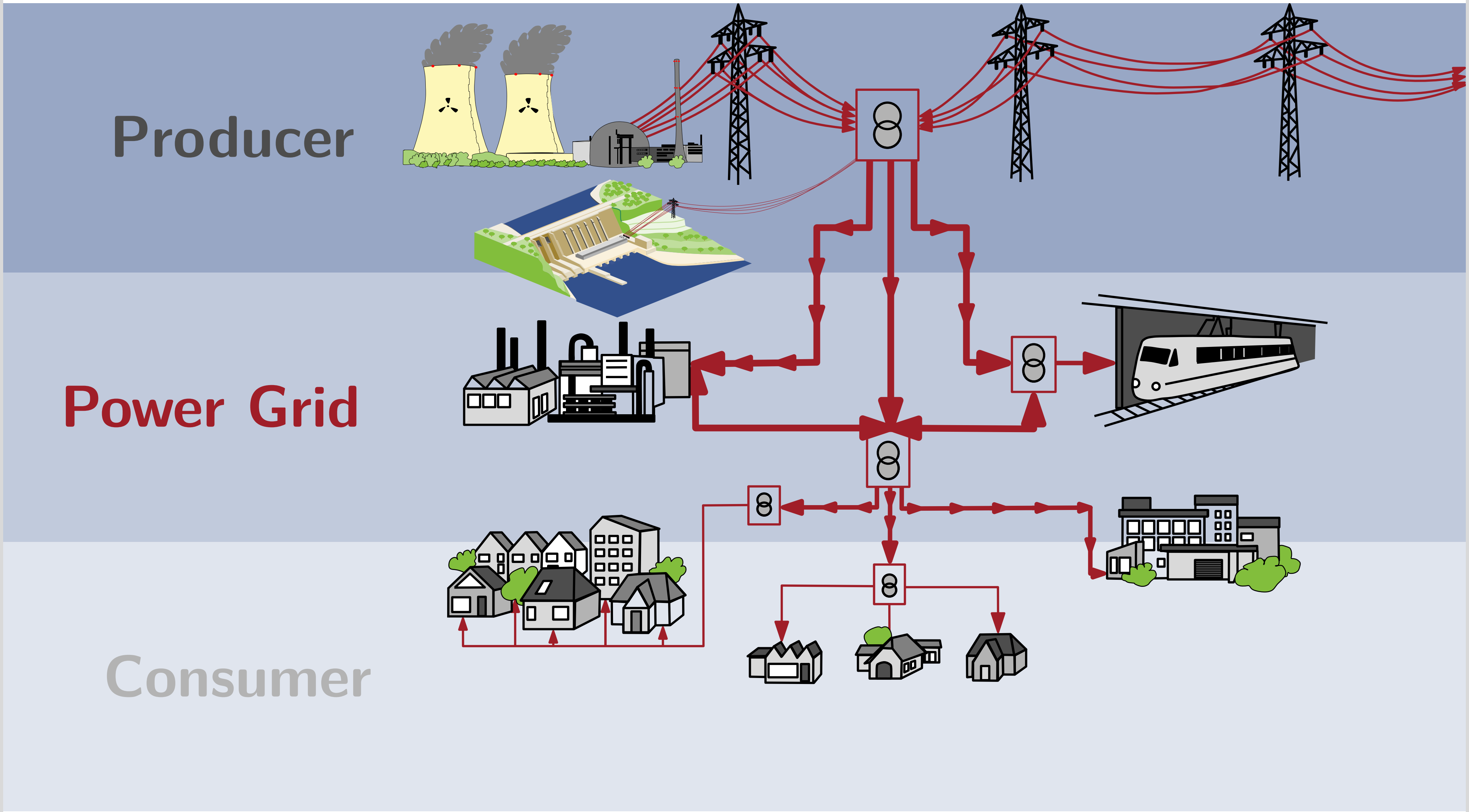
Graph-theoretic Models and Algorithms

Franziska Wegner

Doctoral Examination



Recent Development in Power Grids



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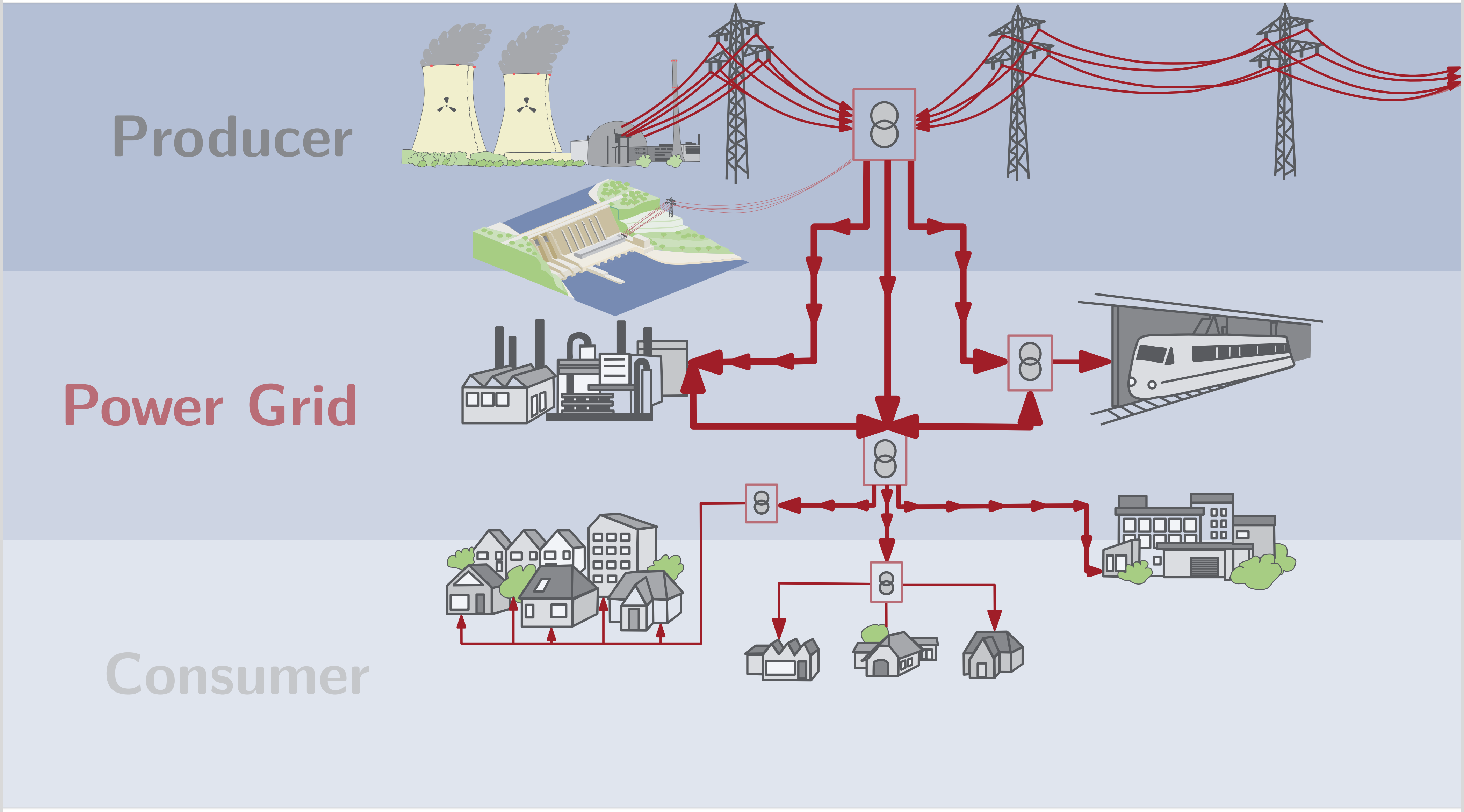
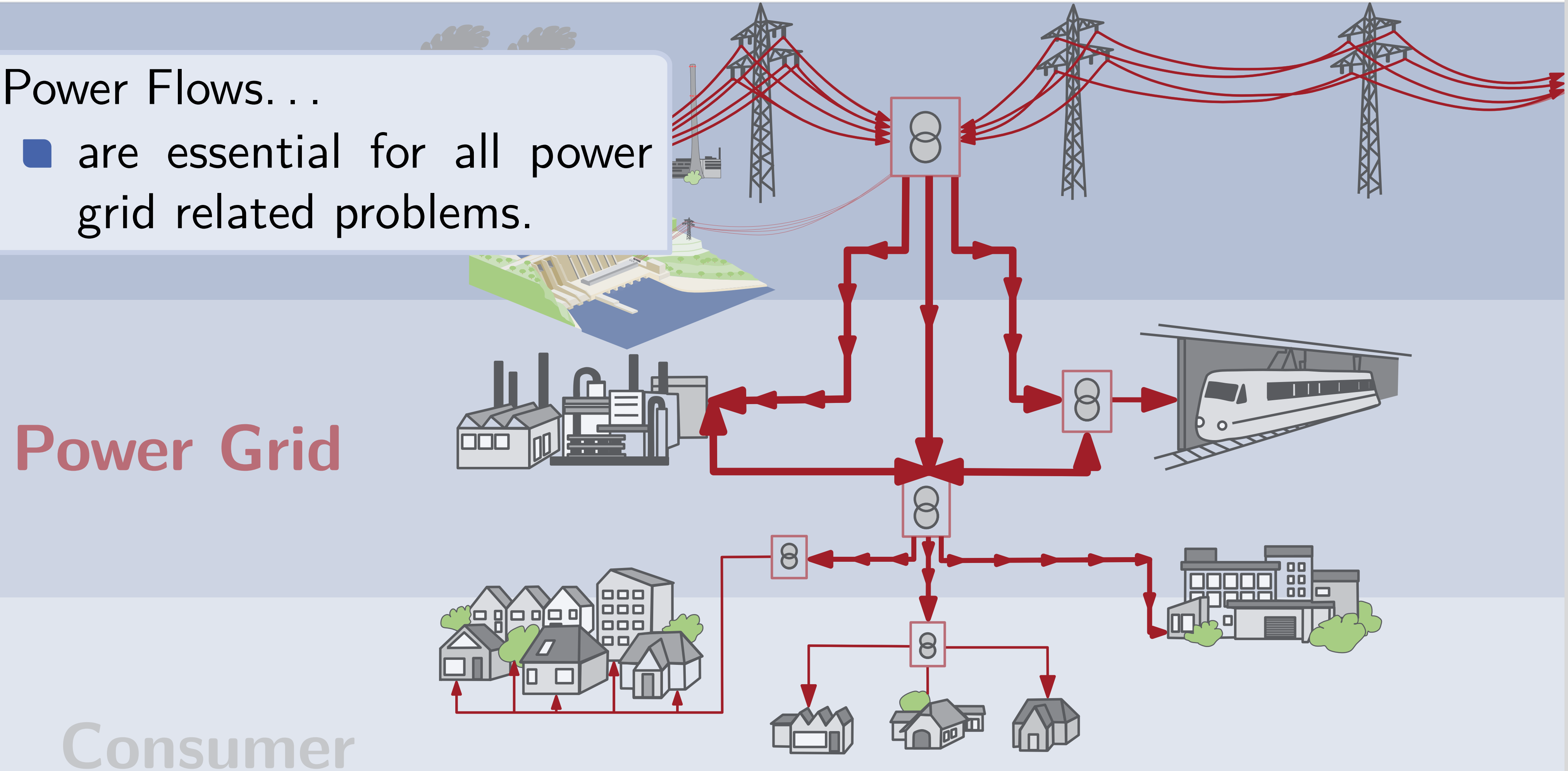


Recent Development in Power Grids

Power Flows. . .

- are essential for all power grid related problems.



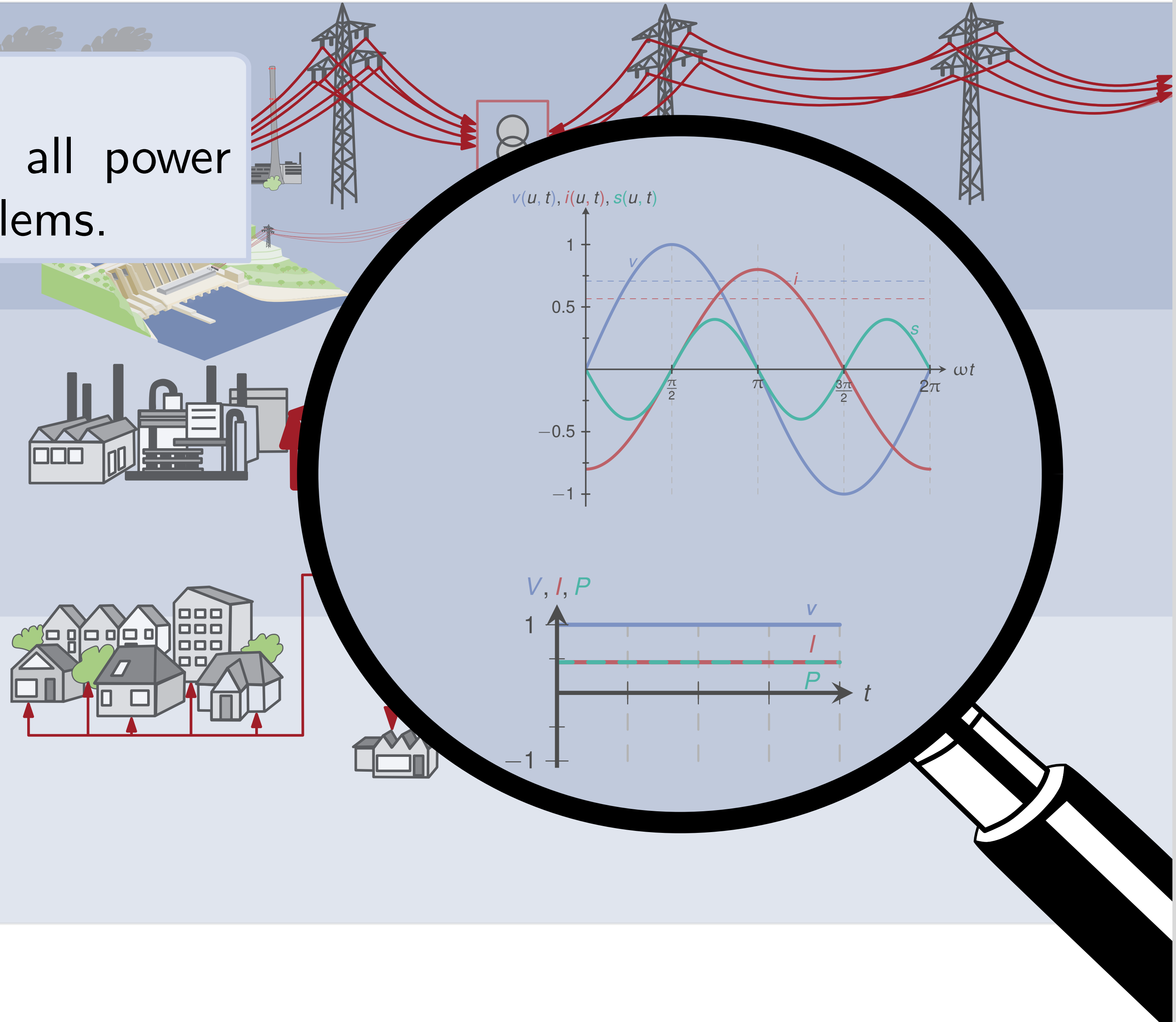
Recent Development in Power Grids

Power Flows…

- are essential for all power grid related problems.

Power Grid

Consumer



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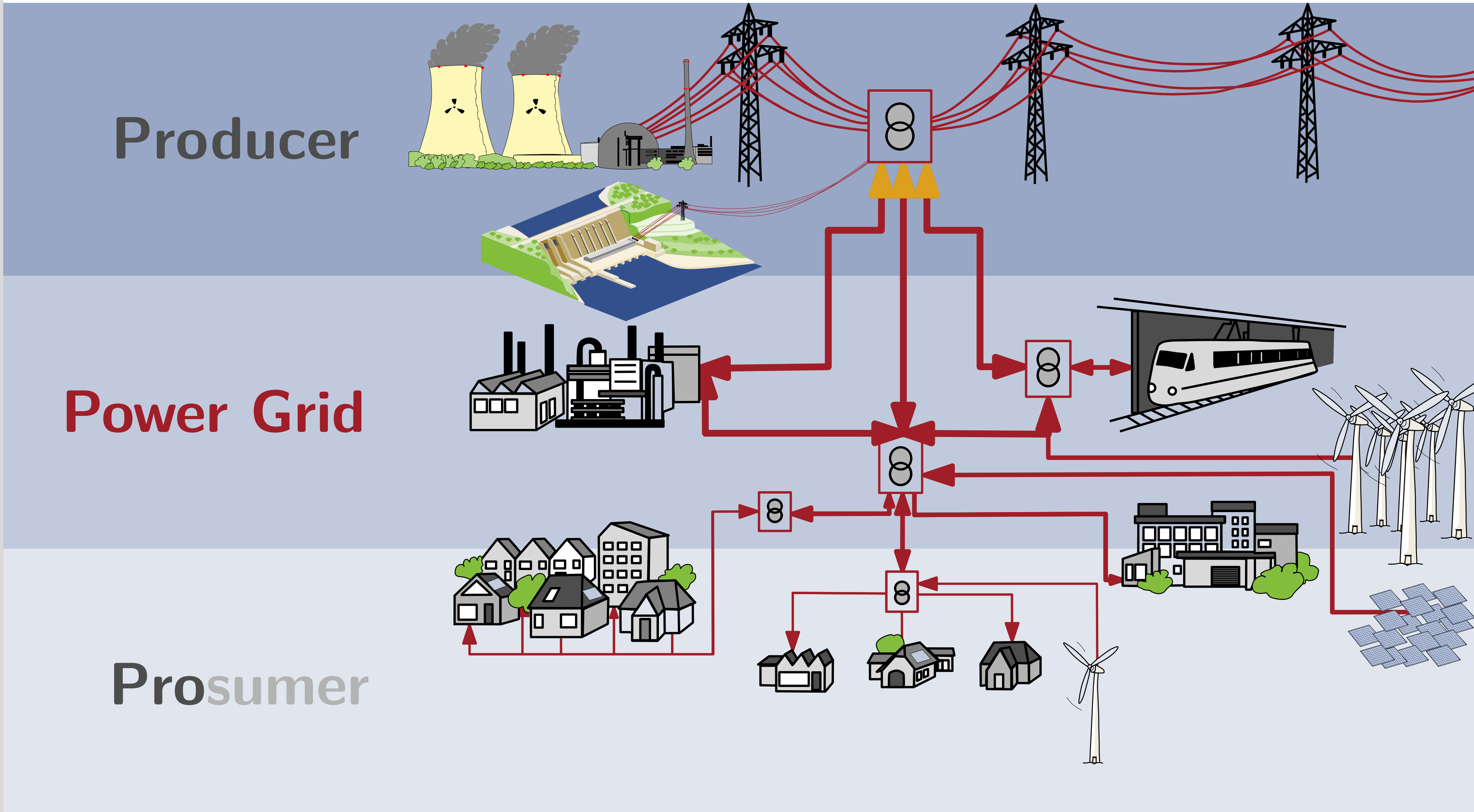

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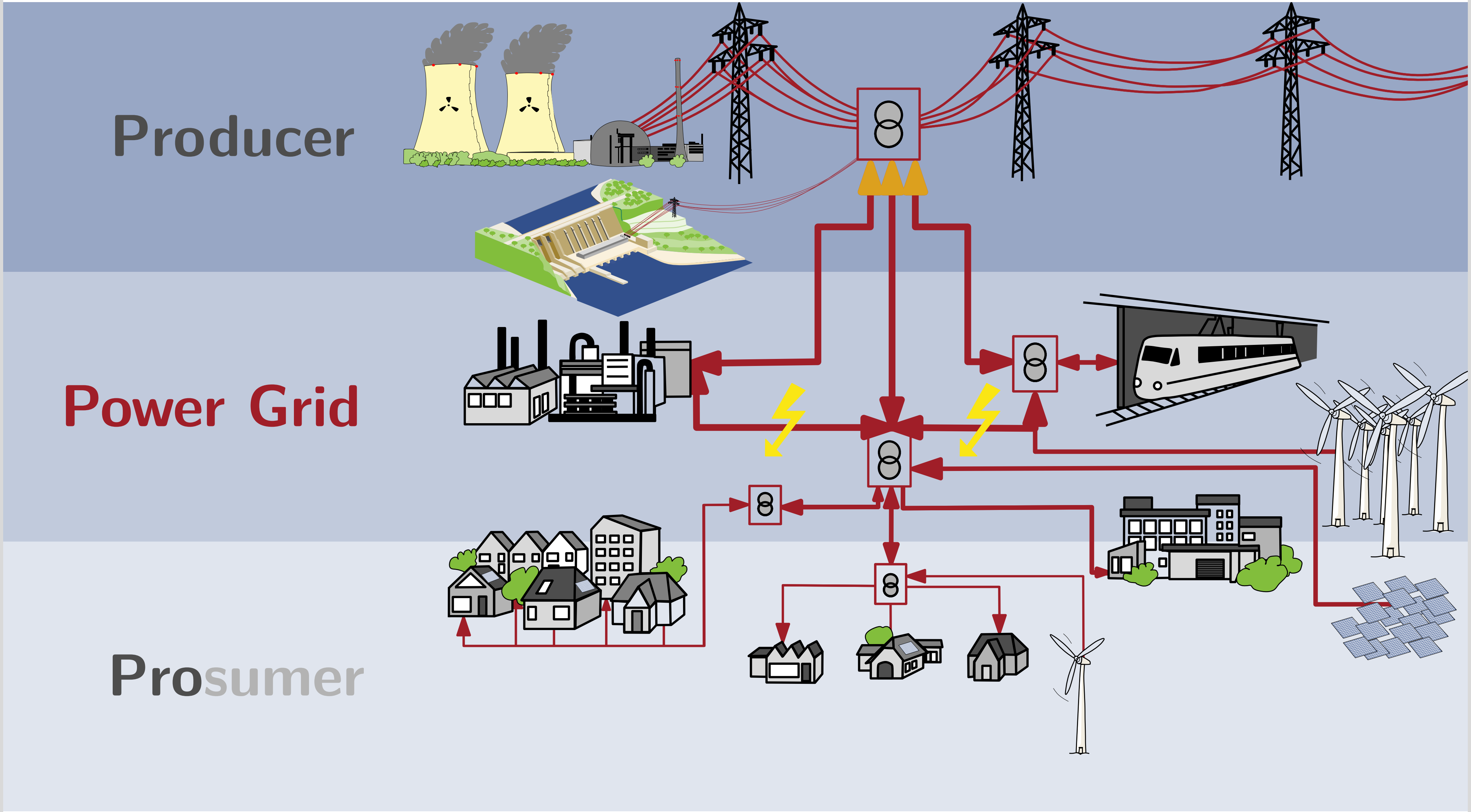

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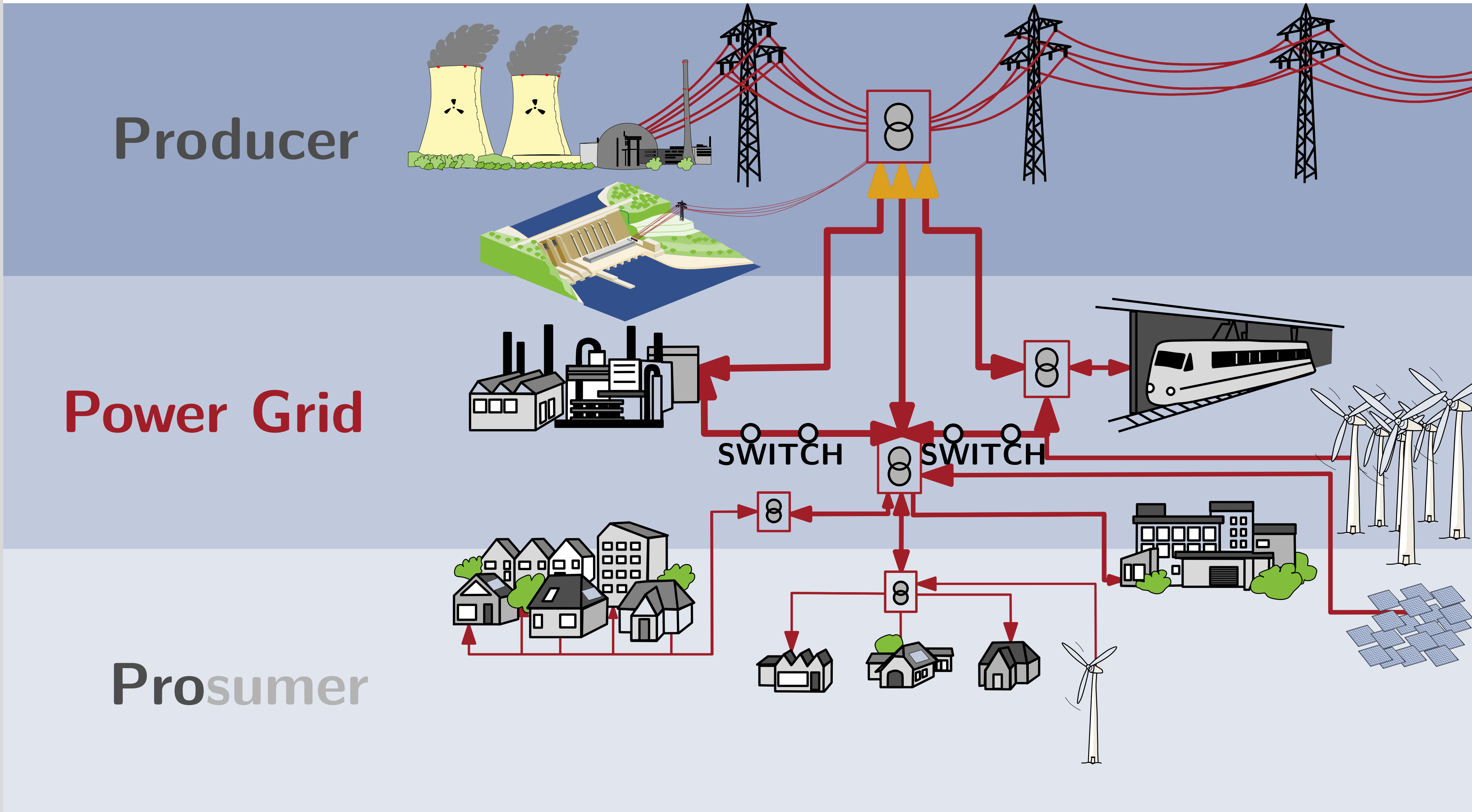

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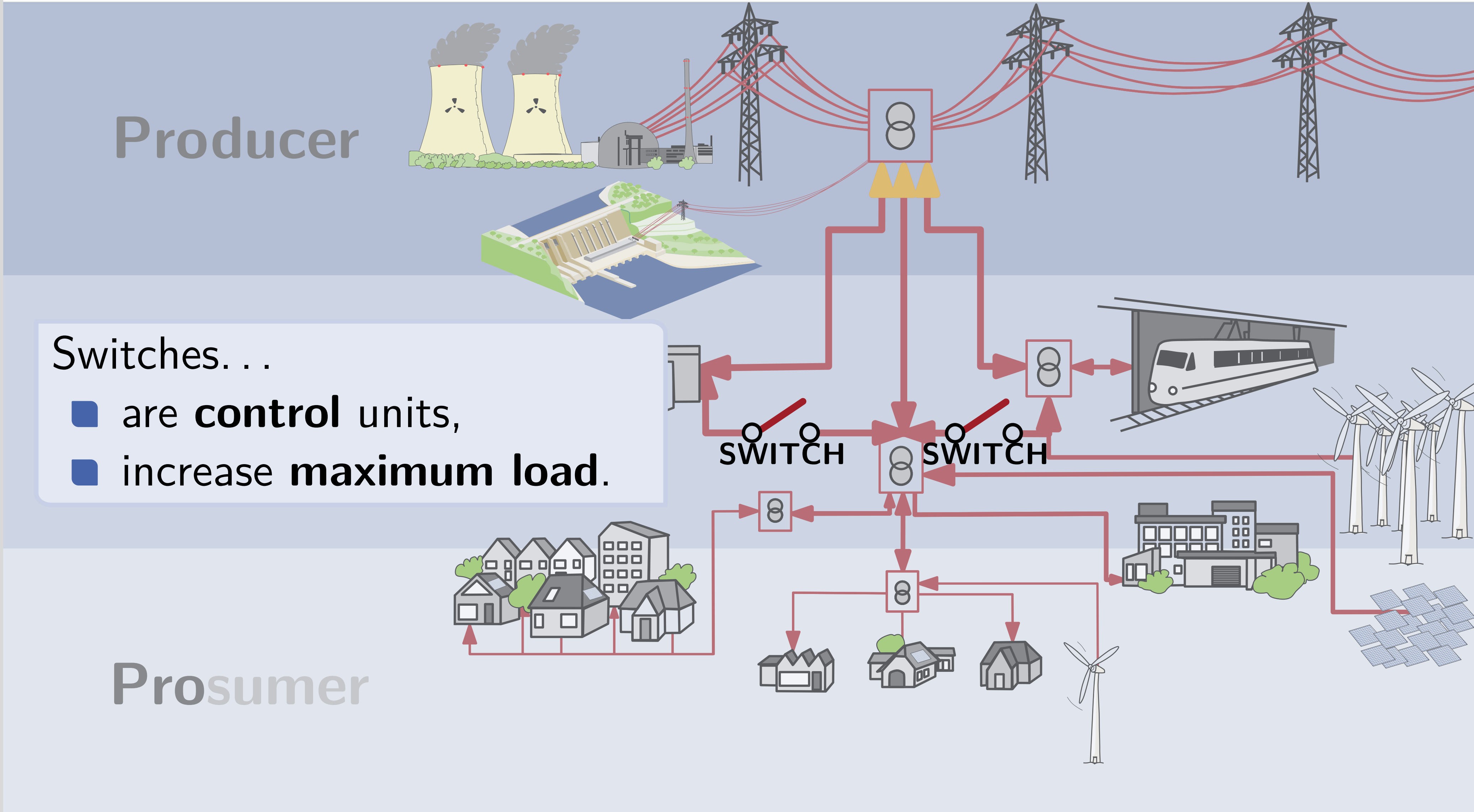
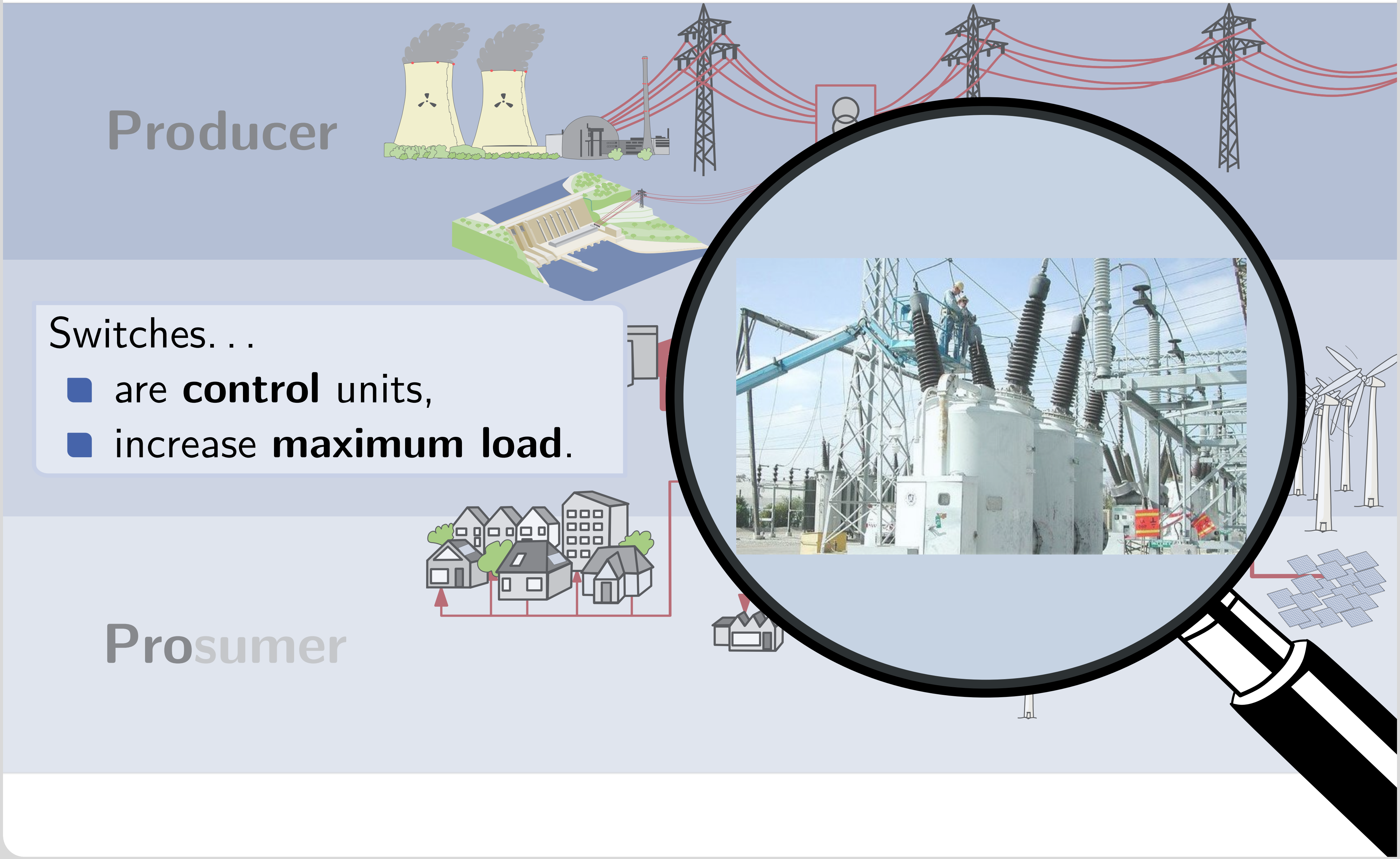


Switches. . .

- are **control** units,
- increase **maximum load**.

Recent Development in Power Grids



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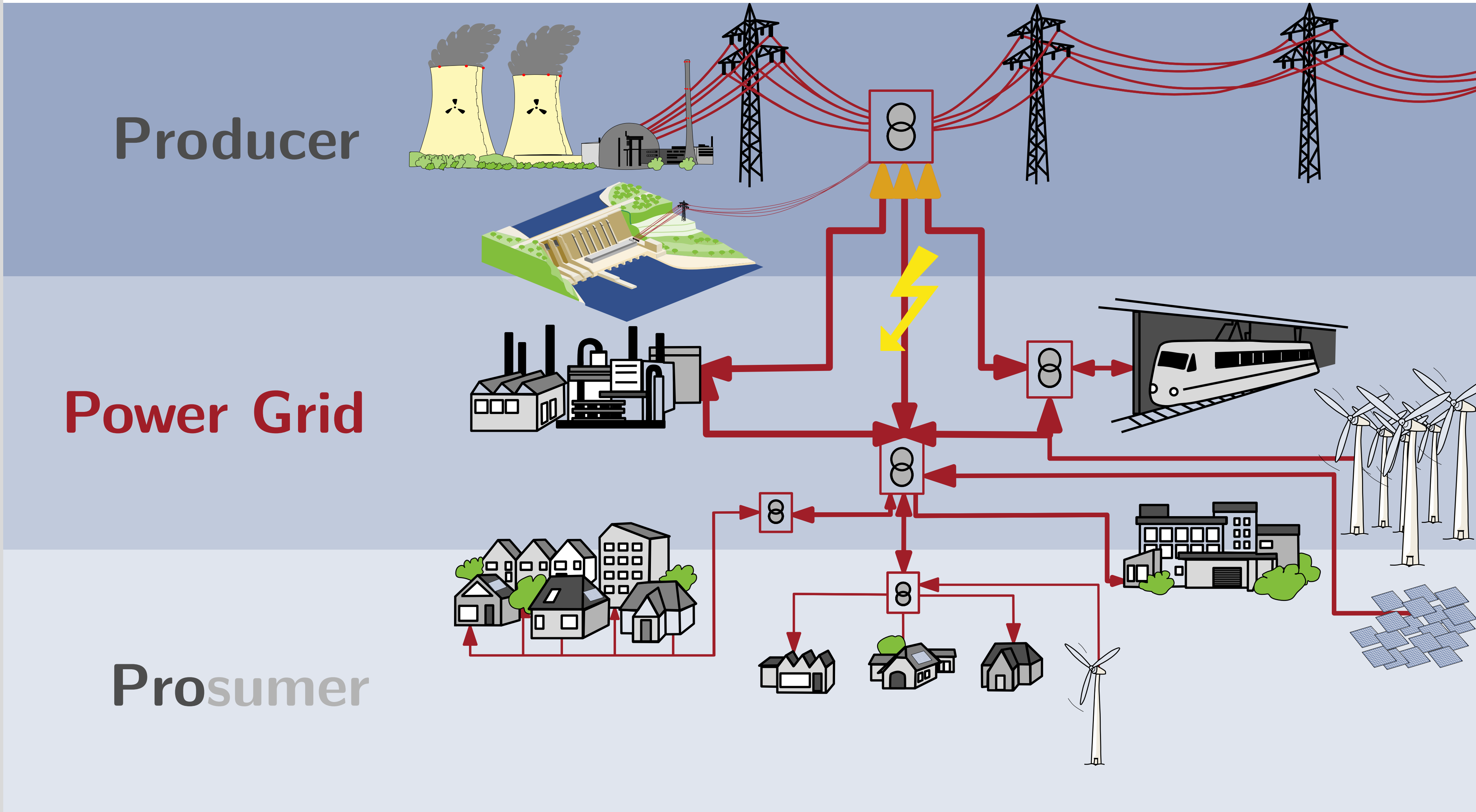

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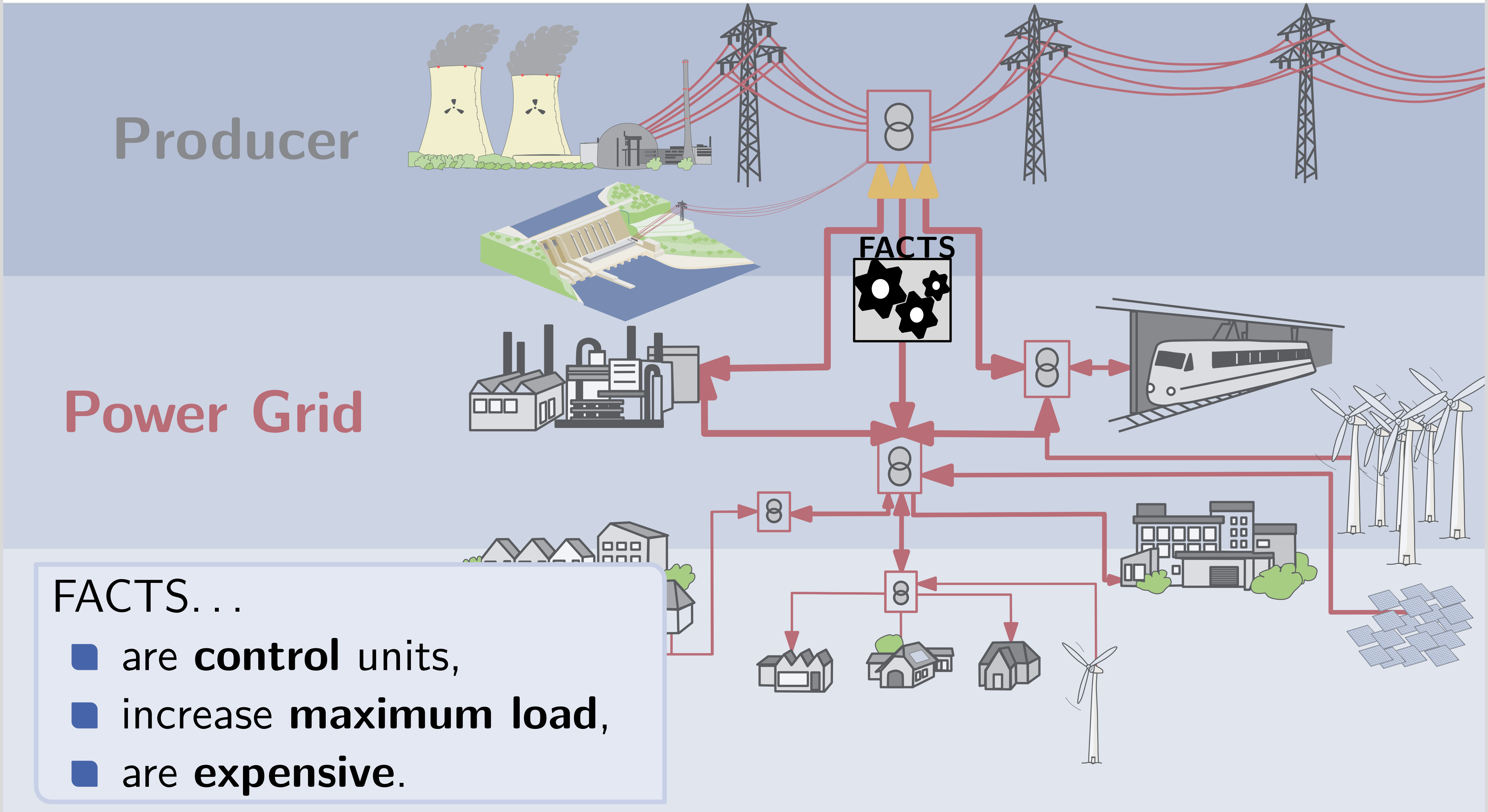
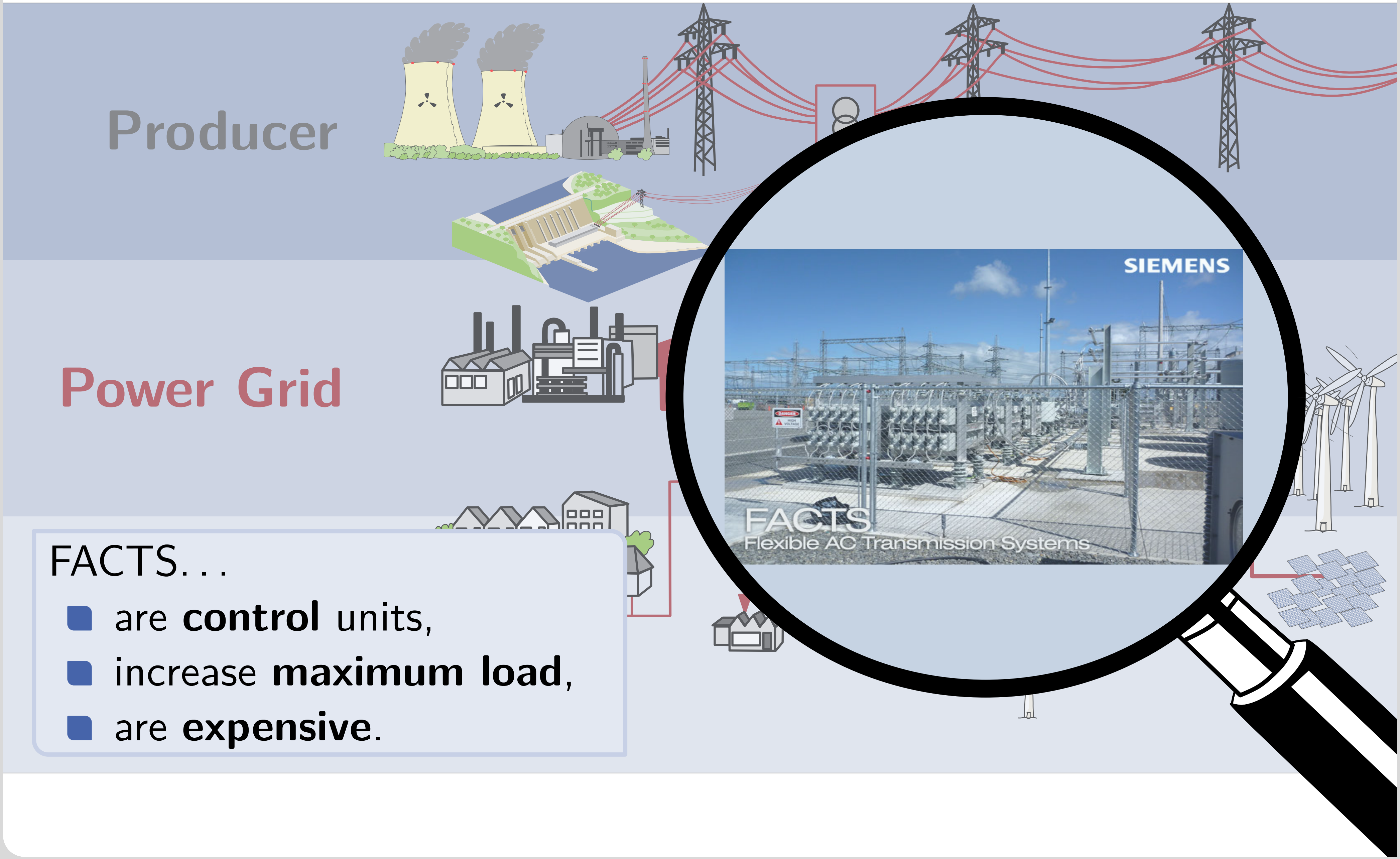


FACTS. . .

- are **control** units,
- increase **maximum load**,
- are **expensive**.

Recent Development in Power Grids



FACTS...

- are **control** units,
- increase **maximum load**,
- are **expensive**.

Problem Statements

Feasible electrical flows

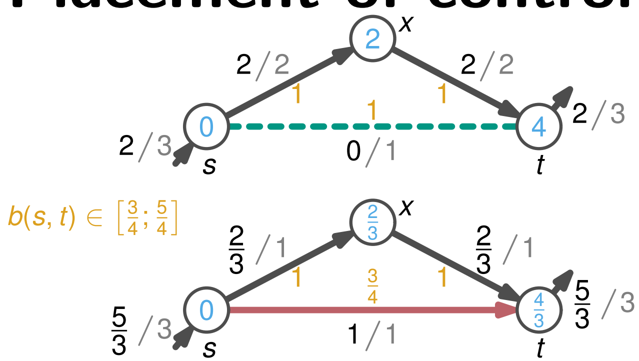
Dynamic models

Static models

Alternating Current (AC) model

Direct Current (DC) model

Placement of control units



Discrete control decision

[Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Continuous control decision

[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]

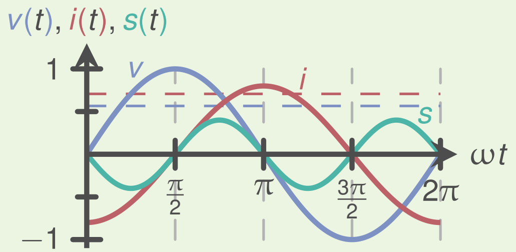
Cable layout

Wind farm cabling with multiple cable types

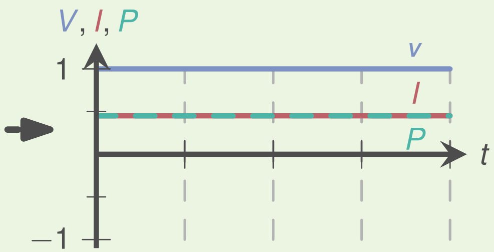
[Lehmann, Rutter, Wagner, and **W.**, 2017]

Methodology

Model



complex model



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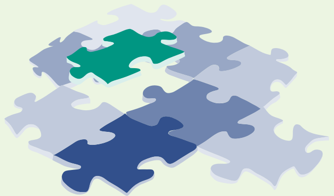

combinatorial optimization problem

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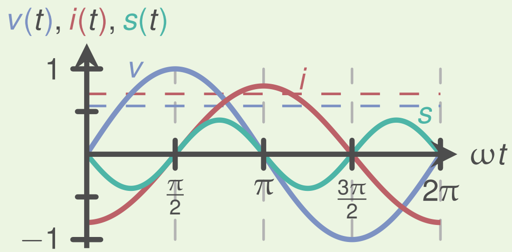

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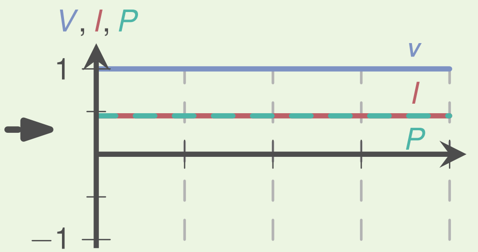

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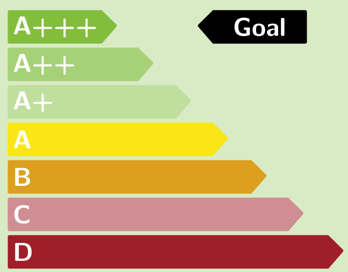
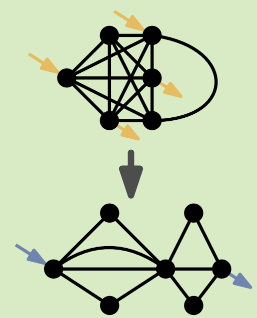
combinatorial optimization problem

Theory

problem and complexity analysis



efficient algorithms with guarantees



simplified graphs

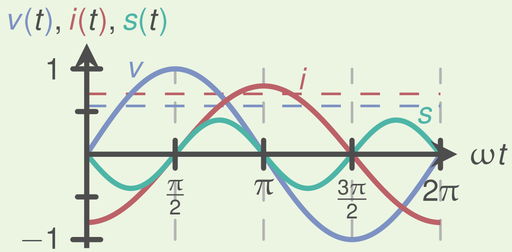
non-linear program

mixed-integer linear program

mathematical model

Methodology

Model



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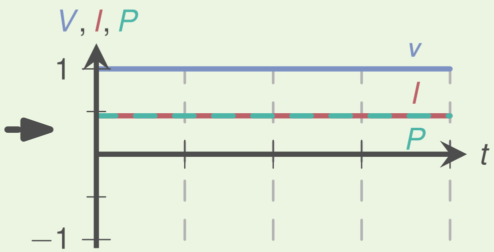

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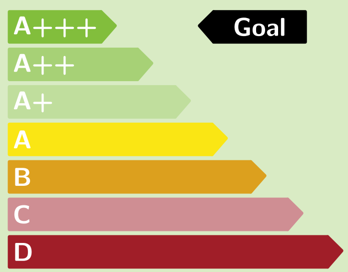

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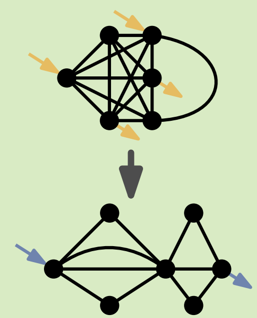

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approximation algorithms

optimal solution

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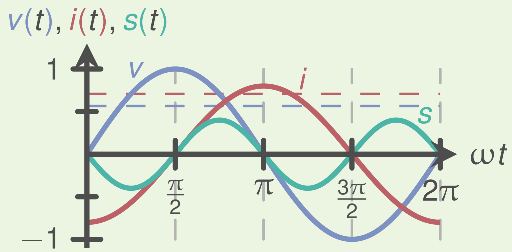

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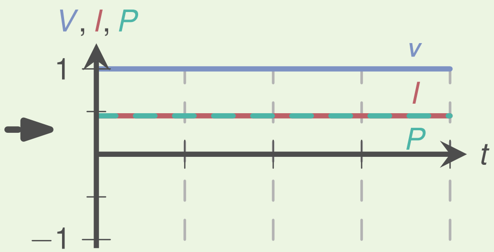

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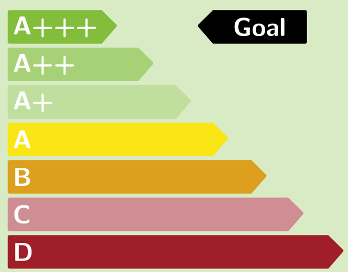

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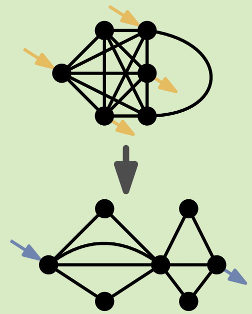

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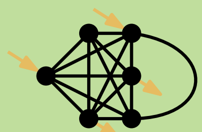

heuristics

optimal solution

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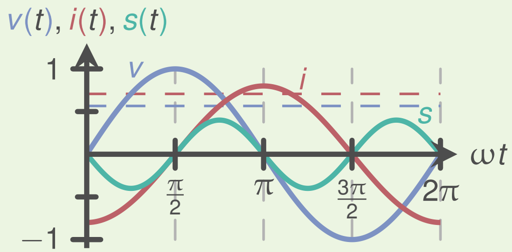

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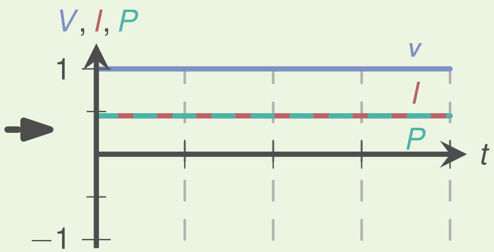

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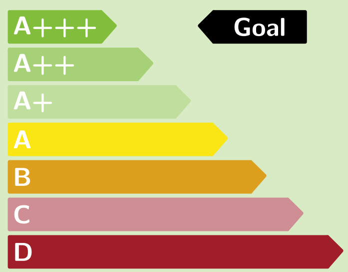

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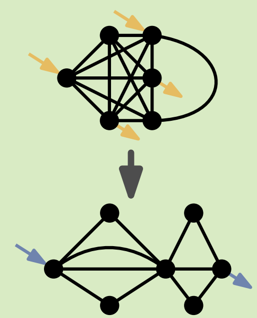

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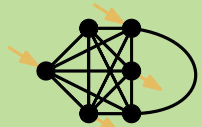

heuristics

real/realistic data

optimal solution

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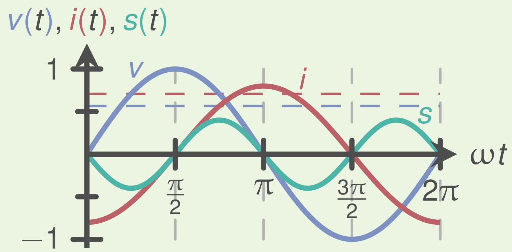

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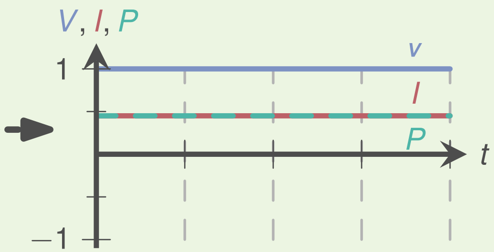

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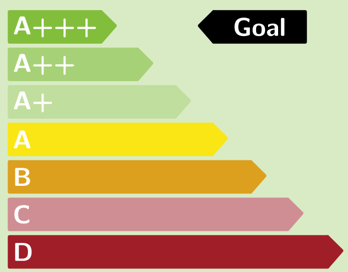

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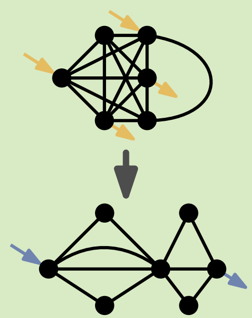

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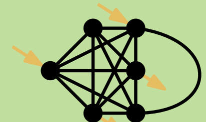


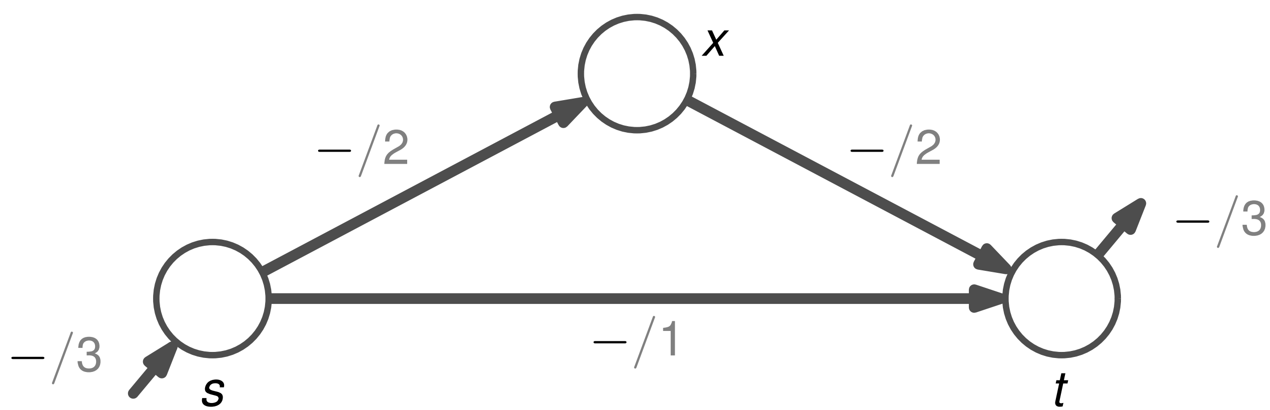
heuristics

real/realistic data

optimal solution

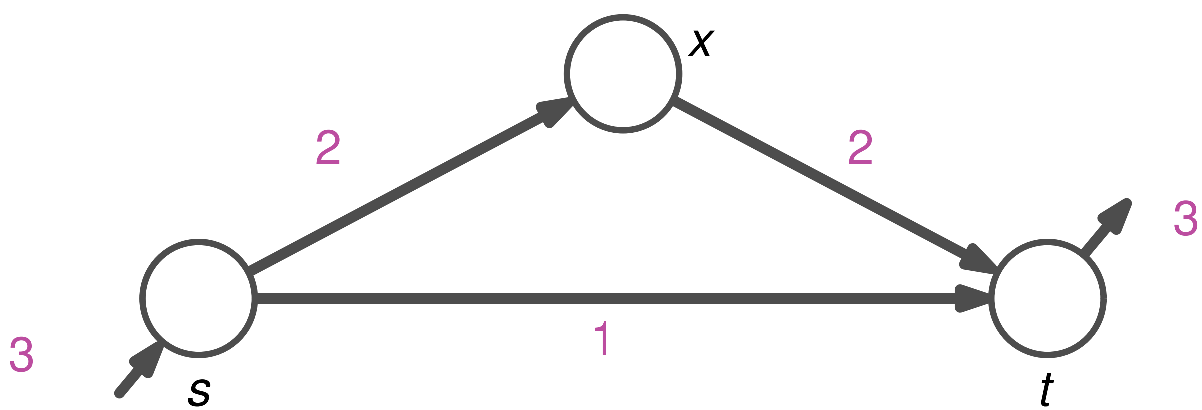
experimental evaluation

The Maximum Flow (MF) Problem



The Maximum Flow (MF) Problem

- Flow $f\colon E \to \mathbb{R}$ with $f_{\text{net}}\colon V \to \mathbb{R}$ defined as $f_{\text{net}}(u) \coloneqq \sum_{\{u,v\}\in E} f(u,v)$ and flow value $F(\mathcal{N}, f) \coloneqq \sum_{u \in V_G} f_{\text{net}}(u)$
- The value of the maximum flow is defined as
$$\mathrm{MF}(\mathcal{N}) = \max F(\mathcal{N}, f)$$
with f being a feasible flow meaning



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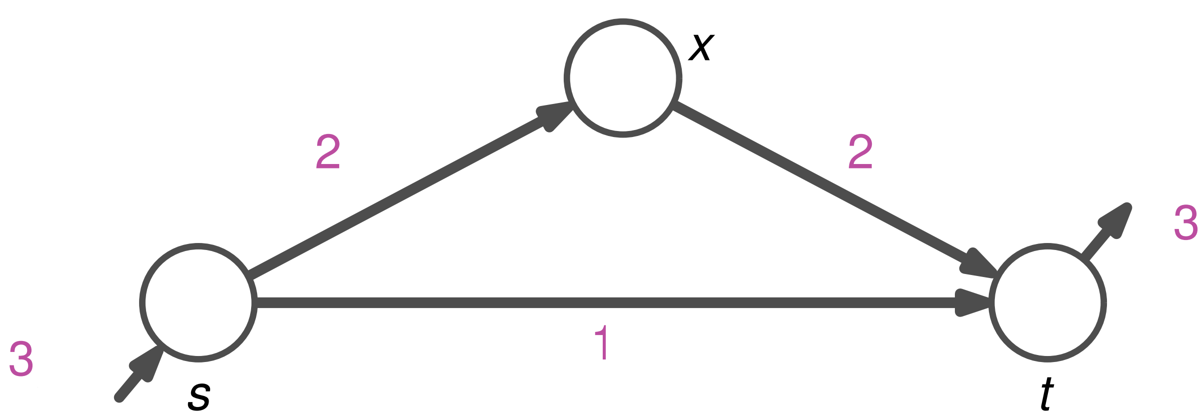
$$\begin{aligned} f_{\text{net}}(u) = \sum_{\{u,v\} \in E} f(u,v) &= 0 && \forall u \in V \setminus (V_G \cup V_D) \\ -\infty \leq f_{\text{net}}(u) &\leq -d && \forall u \in V_D \\ 0 \leq f_{\text{net}}(u) &\leq \infty && \forall u \in V_G \end{aligned}$$



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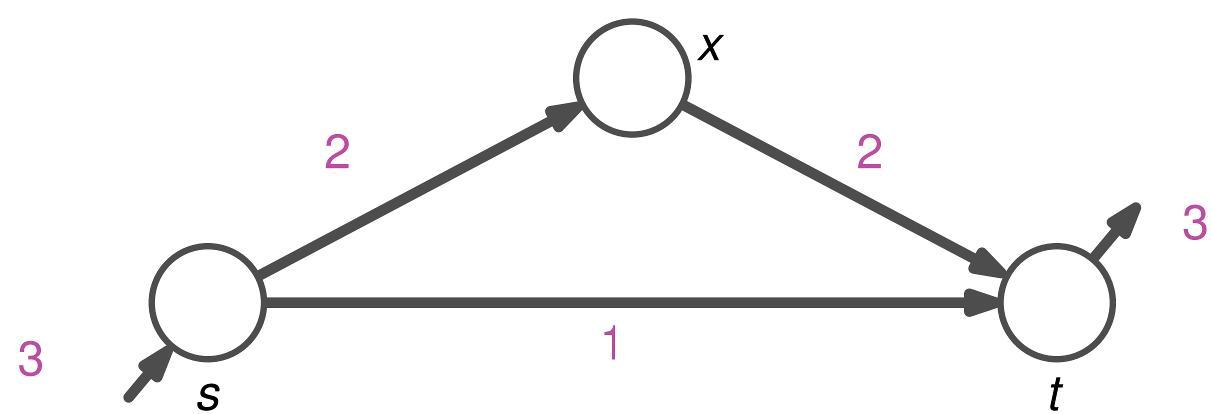

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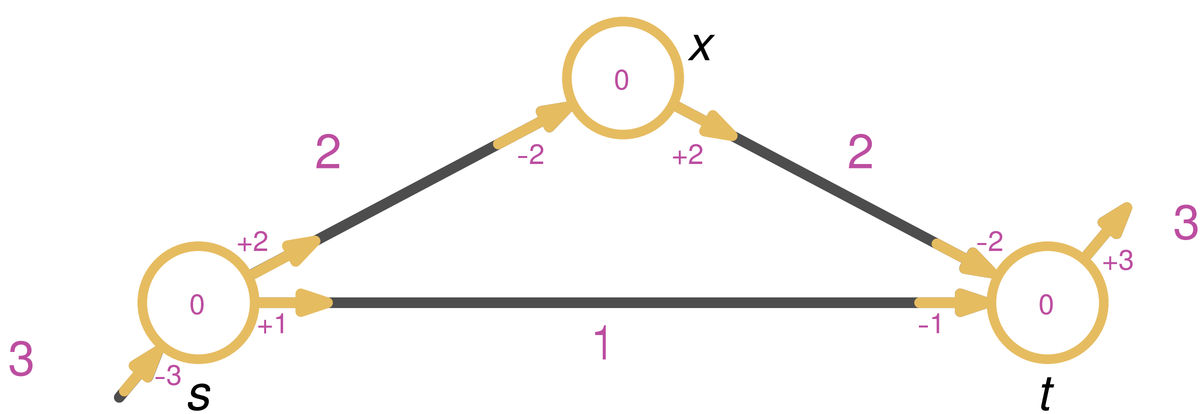

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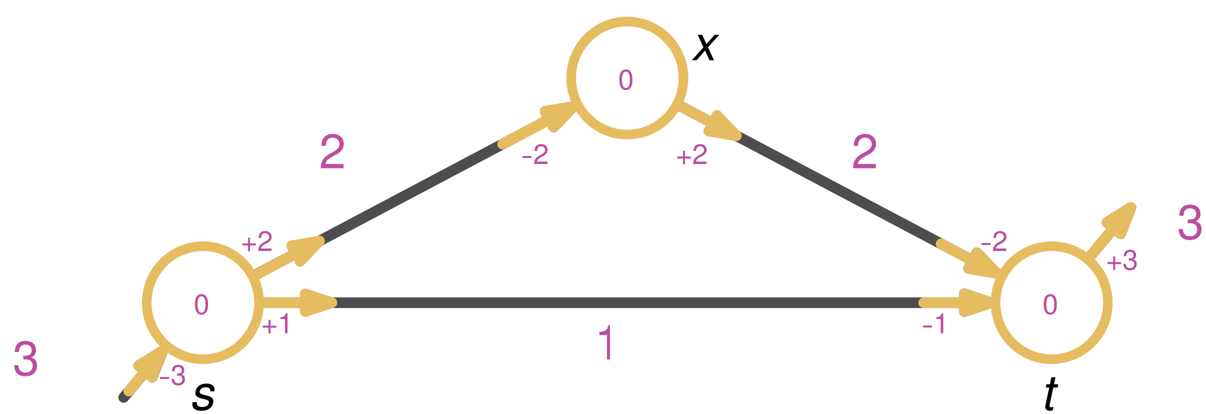

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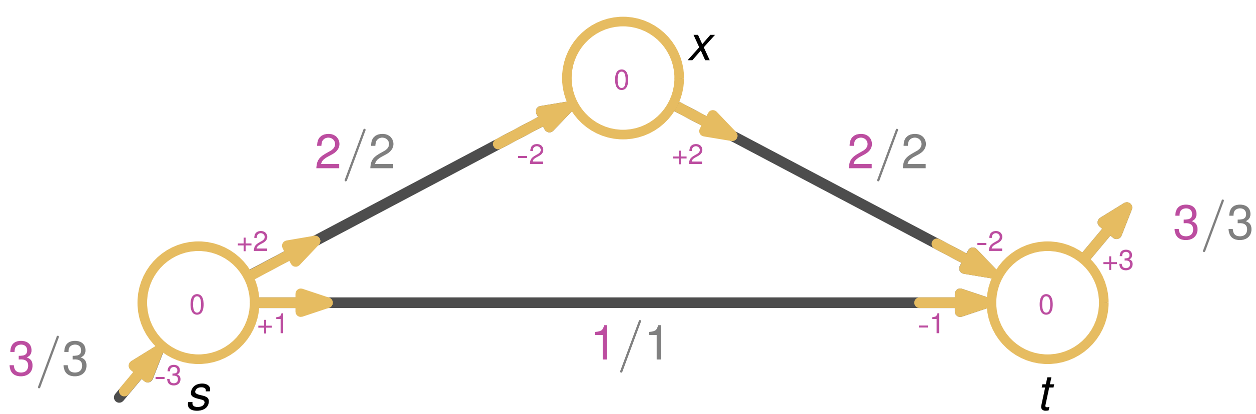
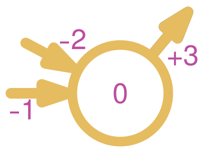


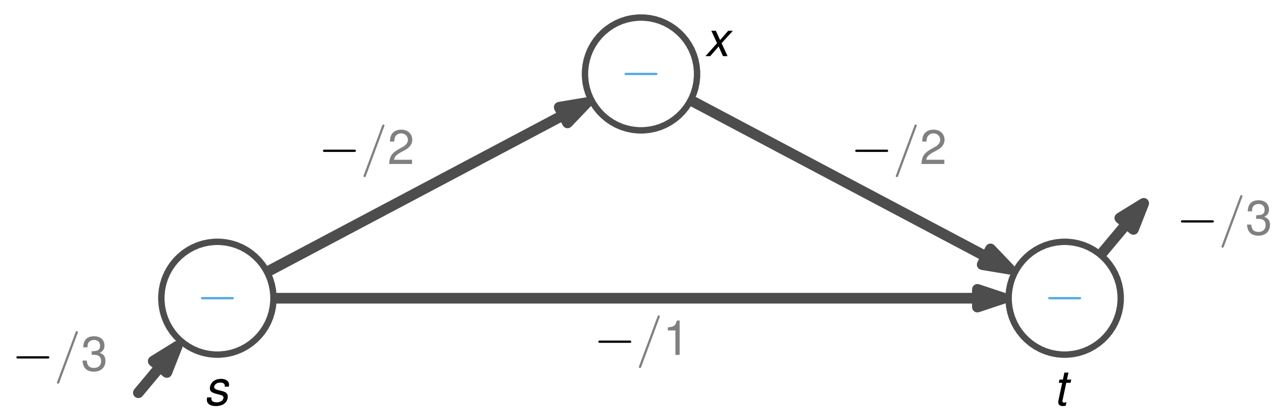
The Maximum Power Flow (MPF) Problem

[Zimmerman et al., 2011]

A feasible power flow has to satisfy (additional) physical constraints:

- The Kirchhoff's Current Law (KCL) which relates to flow conservation, i.e., $f_{\text{net}}(u) = 0$ for all $u \in V \setminus (V_G \cup V_D)$





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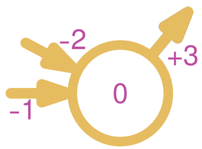
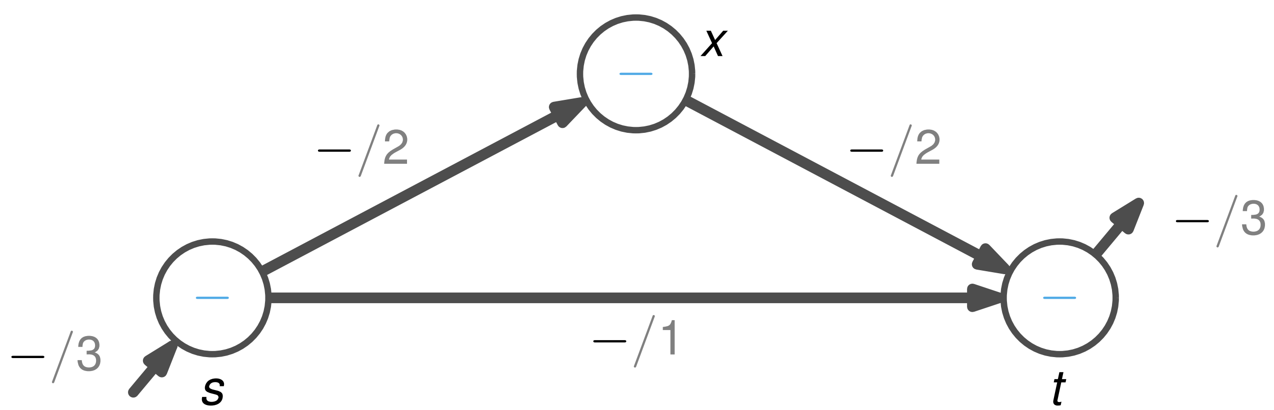


- In addition, the Kirchhoff's Voltage Law (KVL) with assignment of potentials (voltage angles) $\theta \colon V \to \mathbb{R}$



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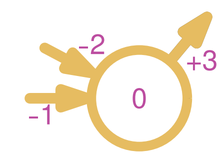

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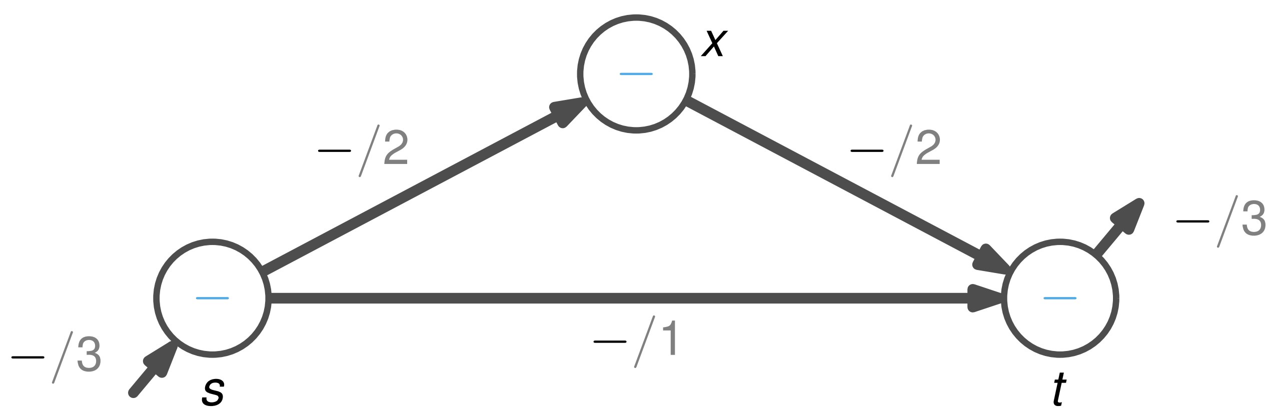

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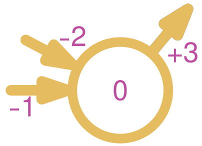

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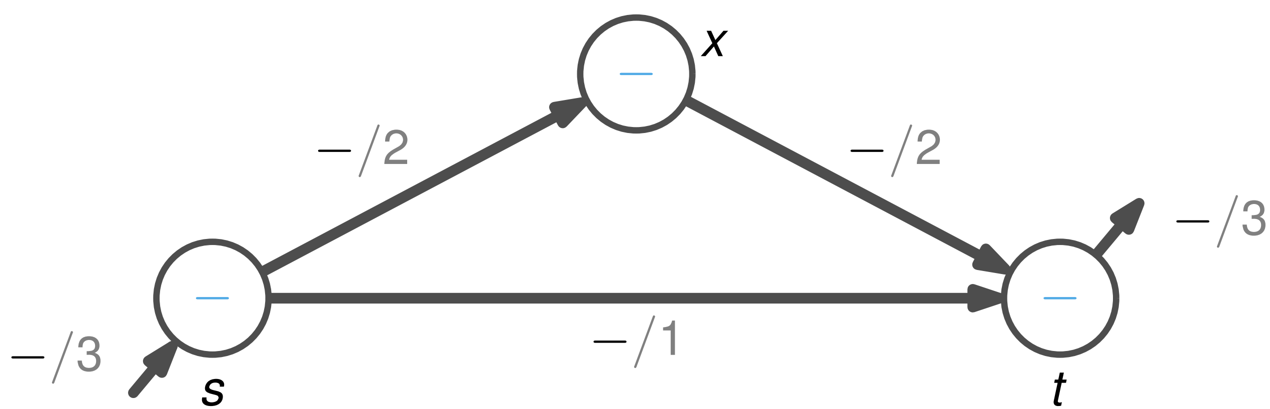

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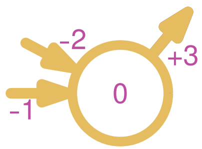

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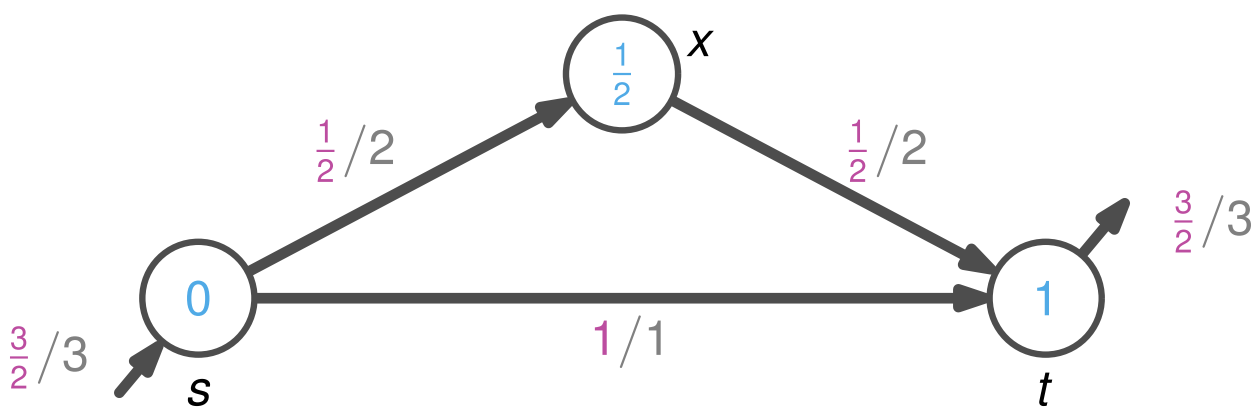

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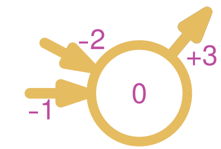

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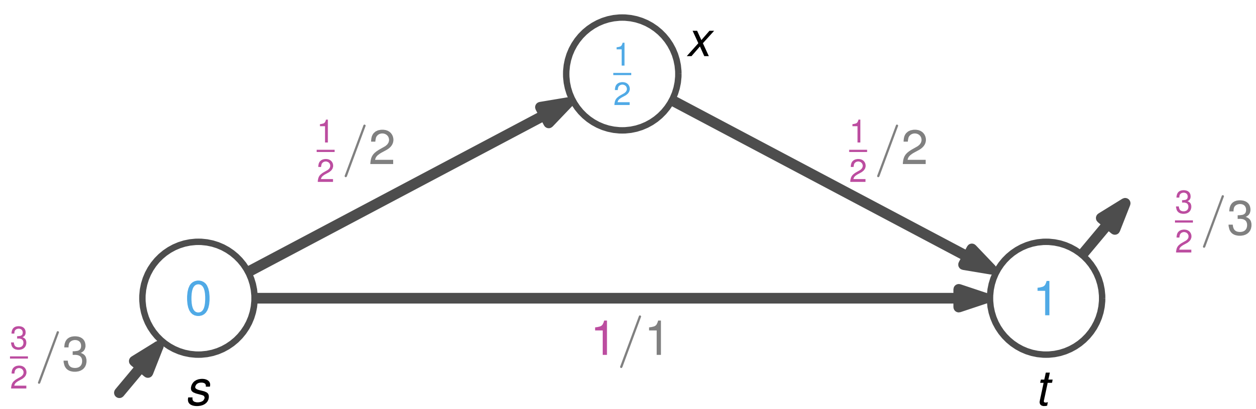

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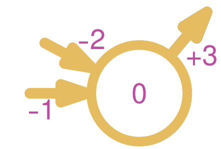

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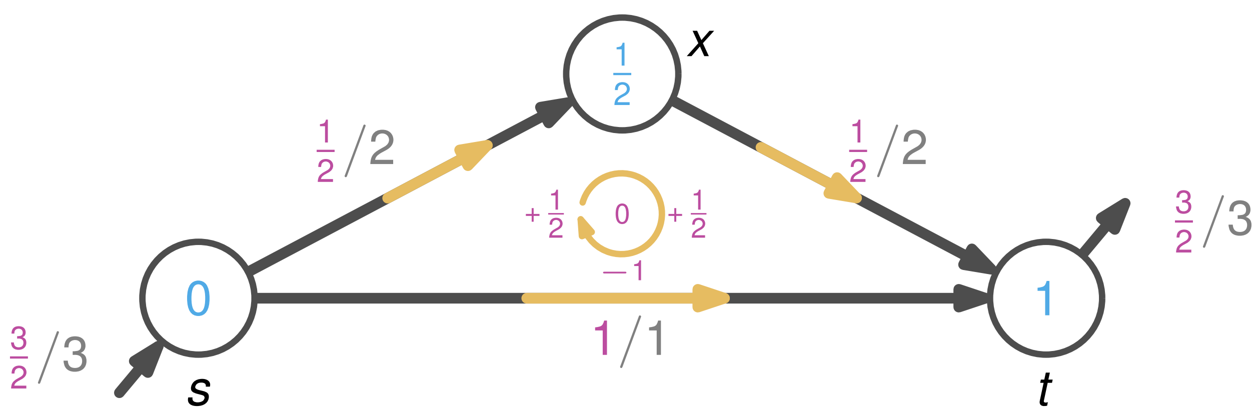


Classification

Feasible electrical flows

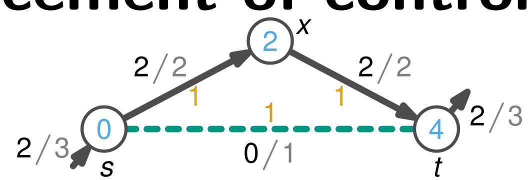
Dynamic models

Static models

Alternating Current (AC) model

Direct Current (DC) model

Placement of control units



Discrete control decision

[Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Continuous control decision

[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]

Cable layout

Wind farm cabling with multiple cable types

[Lehmann, Rutter, Wagner, and **W.**, 2017]

Placement of control units
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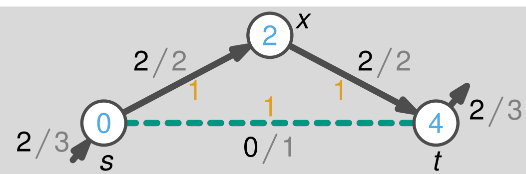

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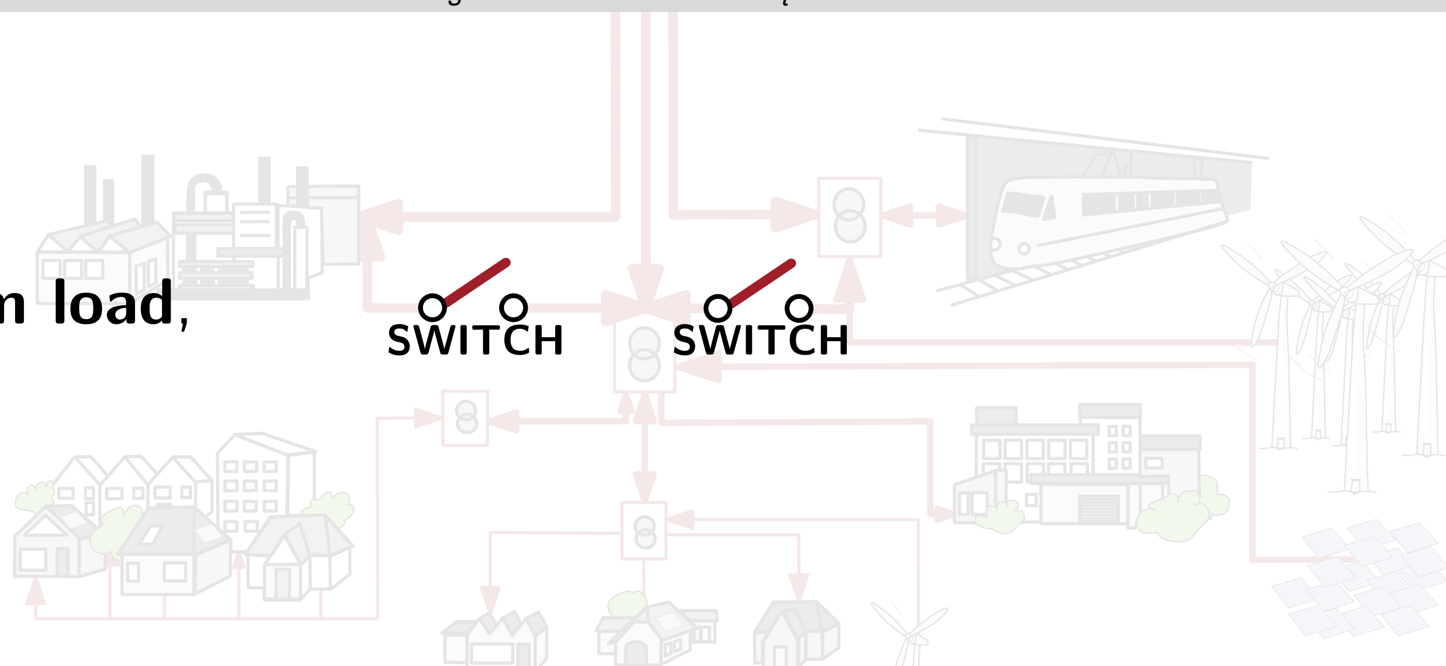
Switches. . .

- increase **maximum load**,
- are **control** units.



The Maximum Transmission Switching Flow (MTSF) Problem [Fisher et al., 2008]

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with f being a feasible power flow meaning

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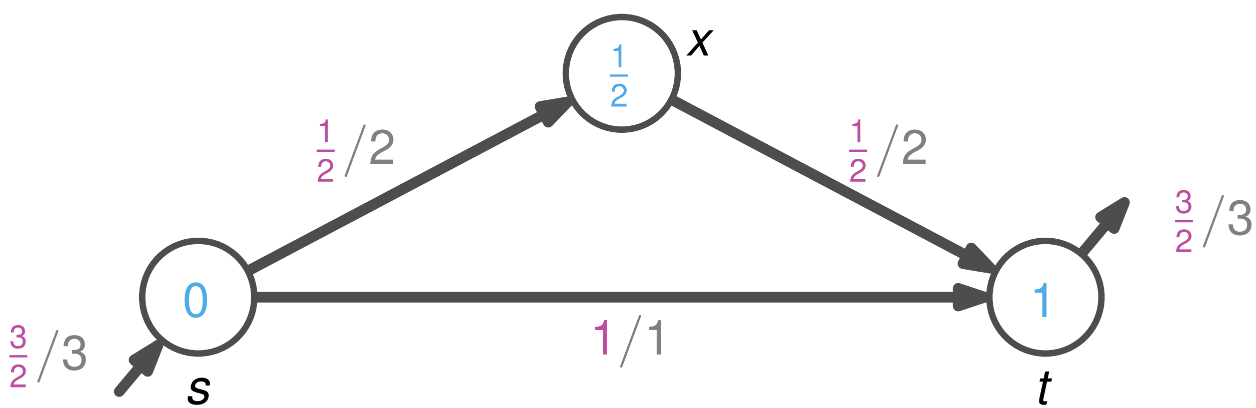

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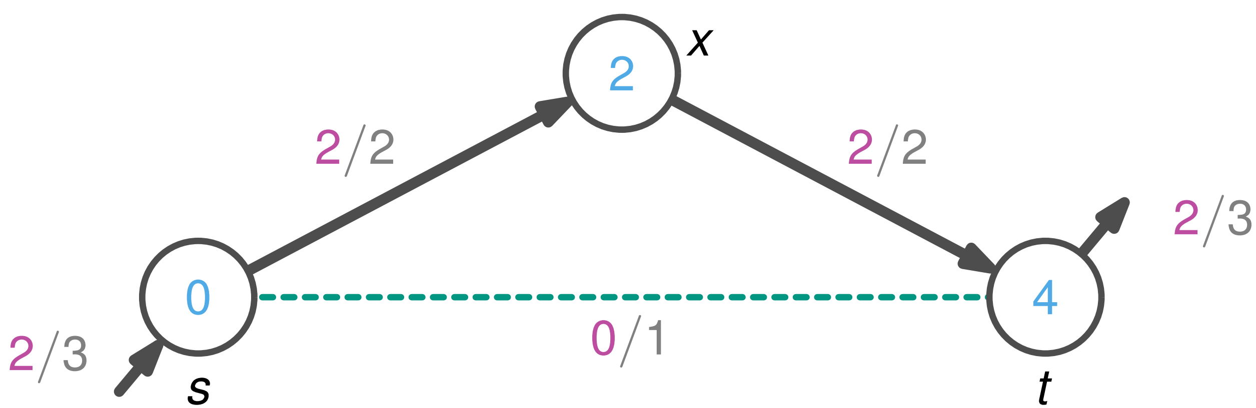

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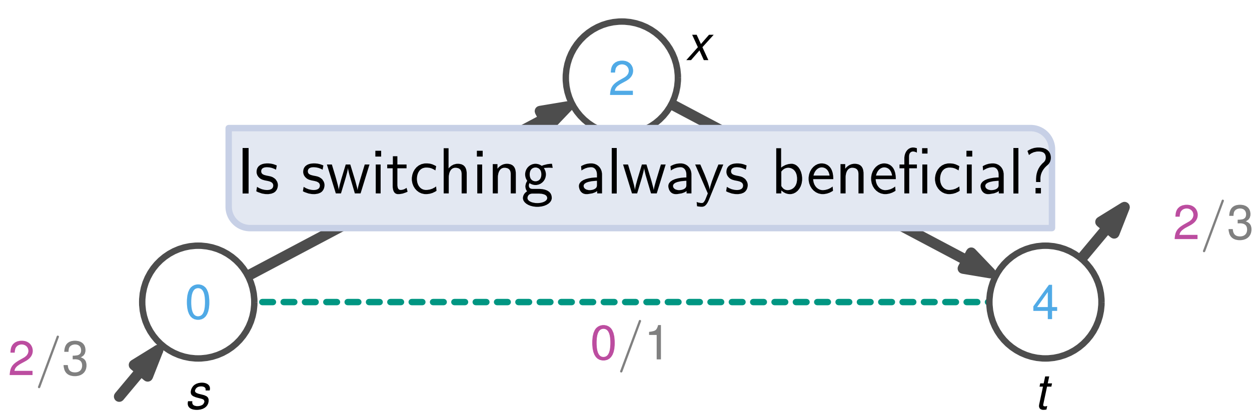

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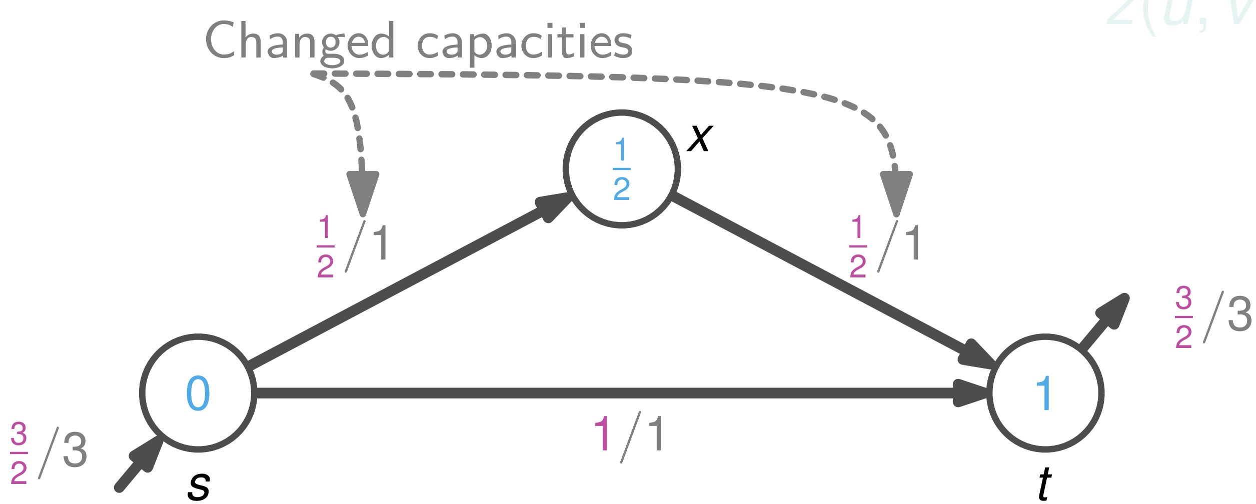

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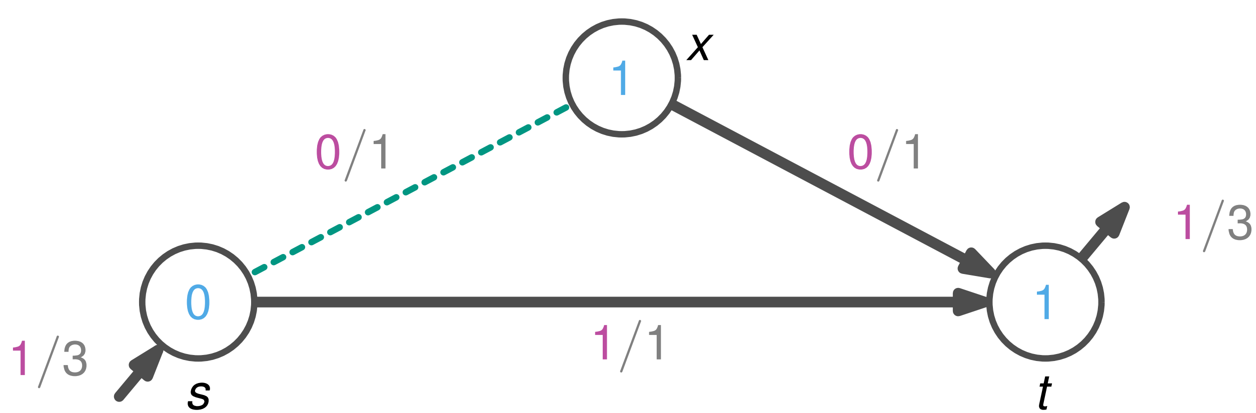

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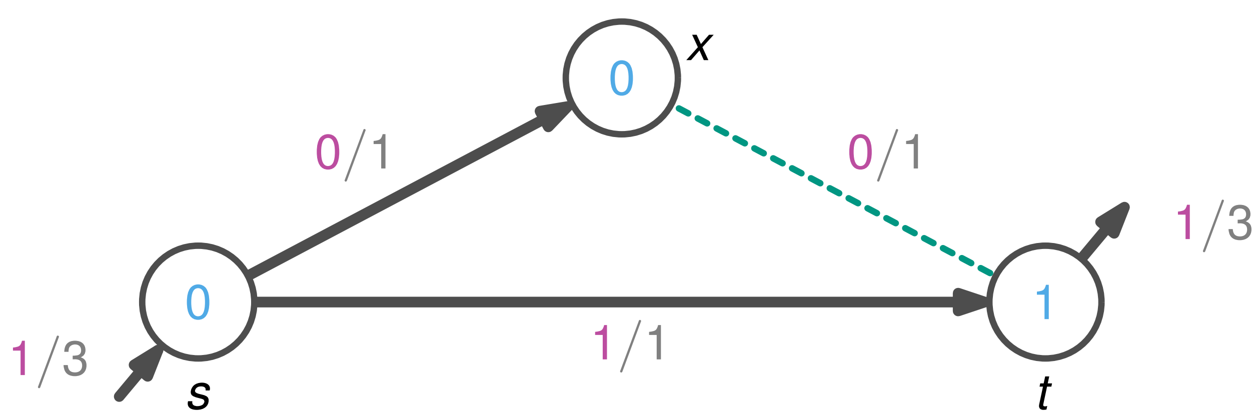

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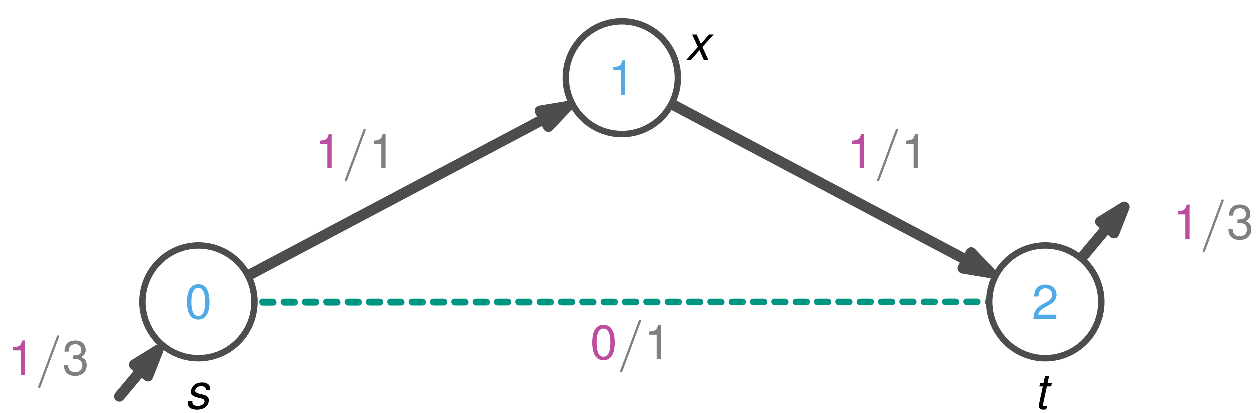

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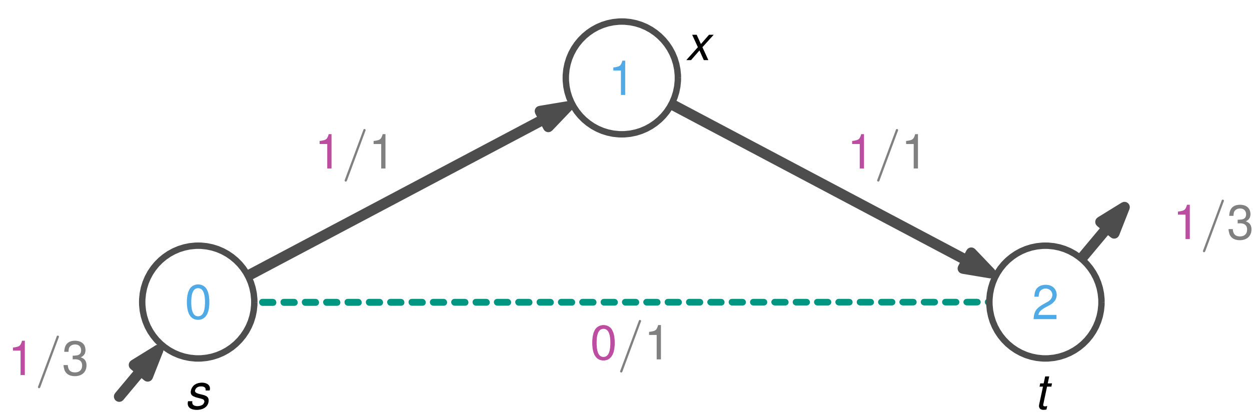
Optimization Problem MTSF

Instance: A power grid $\mathcal{N}$.

Objective: Find a set $S \subseteq E$ of switched edges such that $\mathrm{MPF}(\mathcal{N} - S)$ is maximum among all choices of switched edges S.

$z(u, v) \in \{0, 1\}$



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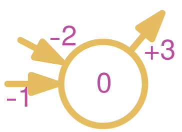

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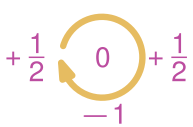

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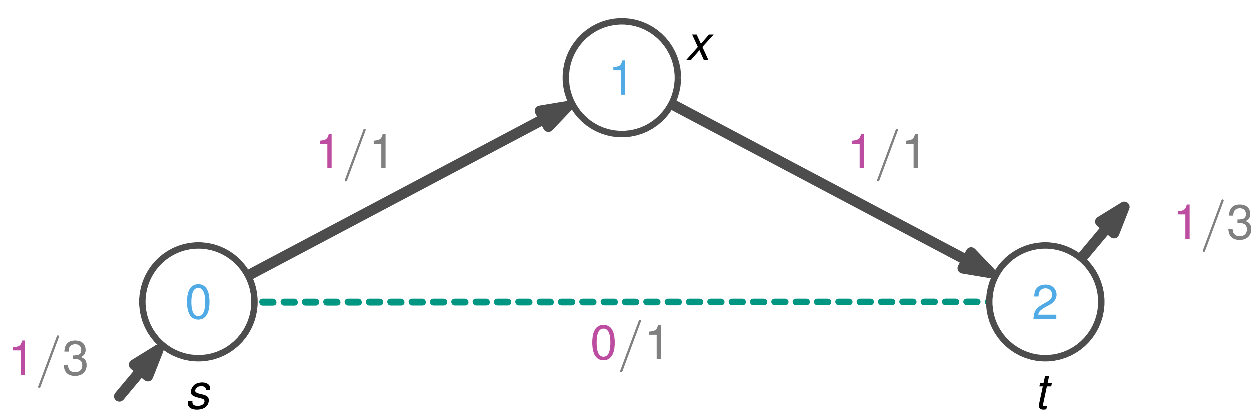
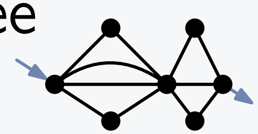
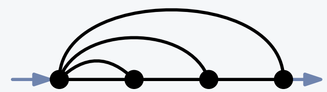
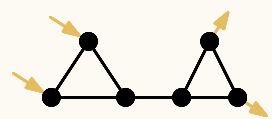
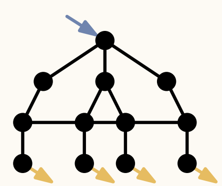
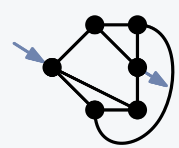
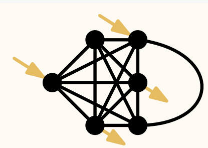


Overview of the MTSF Results

complexity

	Graph Structure		Complexity	Algorithm
one generator, one load	penrose-minor-free graphs		polynomial-time solvable	DTP ✓
	series-parallel graphs		NP-hard	✗
arbitrary generators, arbitrary loads	cacti with max degree of 3		NP-hard [Lehmann et al., 2014]	2-approx. ✓
	2-level trees		NP-hard [Lehmann et al., 2014]	✗
	planar graphs with max degree of 3		strongly NP-hard [Lehmann et al., 2014]	✗
$\lvert V_G \rvert = 2$, $\lvert V_D \rvert = 2$	arbitrary graphs		non-APX [Lehmann et al., 2014]	✗

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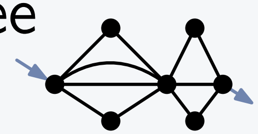
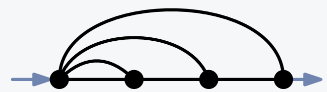
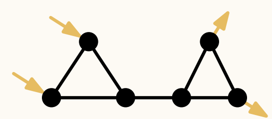
one generator, one load	penrose-minor-free graphs		polynomial-time solvable	DTP ✓
	series-parallel graphs		NP-hard	✗
arbitrary generators, arbitrary loads	cacti with max degree of 3		NP-hard [Lehmann et al., 2014]	2-approx. ✓
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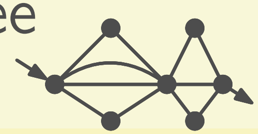
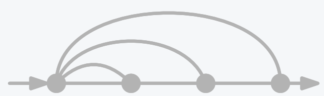
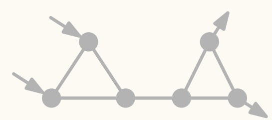
one generator, one load	penrose-minor-free graphs		polynomial-time solvable	DTP ✓
	series-parallel graphs		NP-hard	✗
arbitrary generators, arbitrary loads	cacti with max degree of 3		NP-hard [Lehmann et al., 2014]	2-approx. ✓
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Dominating Theta Path (DTP)

[Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Fix $u, v \in V$ and a u-v-path π.

Susceptance Norm:

$$\|\pi\|_b := \sum_{e \in E(\pi)} \frac{1}{b(e)}$$

Minimum Capacity:

$$\underline{\mathrm{cap}}(\pi) := \min\{\mathrm{cap}(e) \mid e \in \pi\}$$

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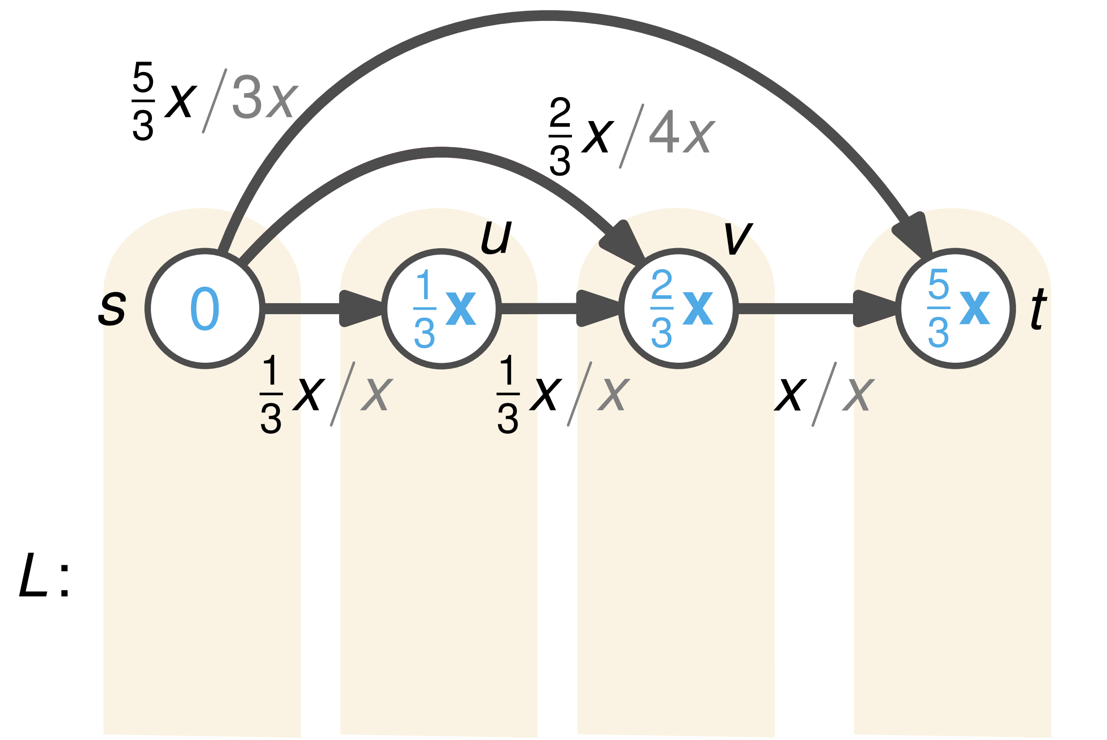
$$\Delta\theta^v_{\min}(u, v) := \min\{\Delta\theta^v(\pi) \mid \pi \text{ is a } u\text{-}v\text{-path}\}$$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

- Bicriterial Dijkstra with labels $(\|\pi\|_b, \underline{\mathrm{cap}}(\pi))$
- At most $|E|$ labels per vertex

$b(i,j) := 1 \quad \forall (i,j) \in E$



$\mathrm{OPT}_{\mathrm{MPF}} = \frac{8}{3}x$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

- Bicriterial Dijkstra with labels $(\|\pi\|_b, \underline{\mathrm{cap}}(\pi))$
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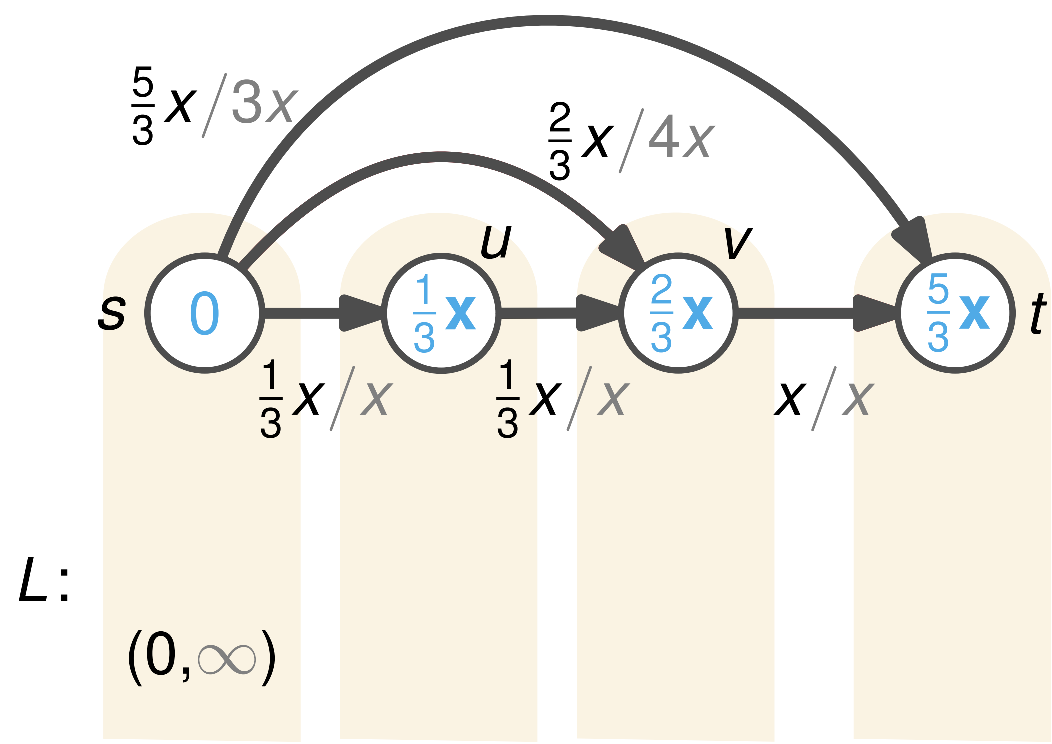

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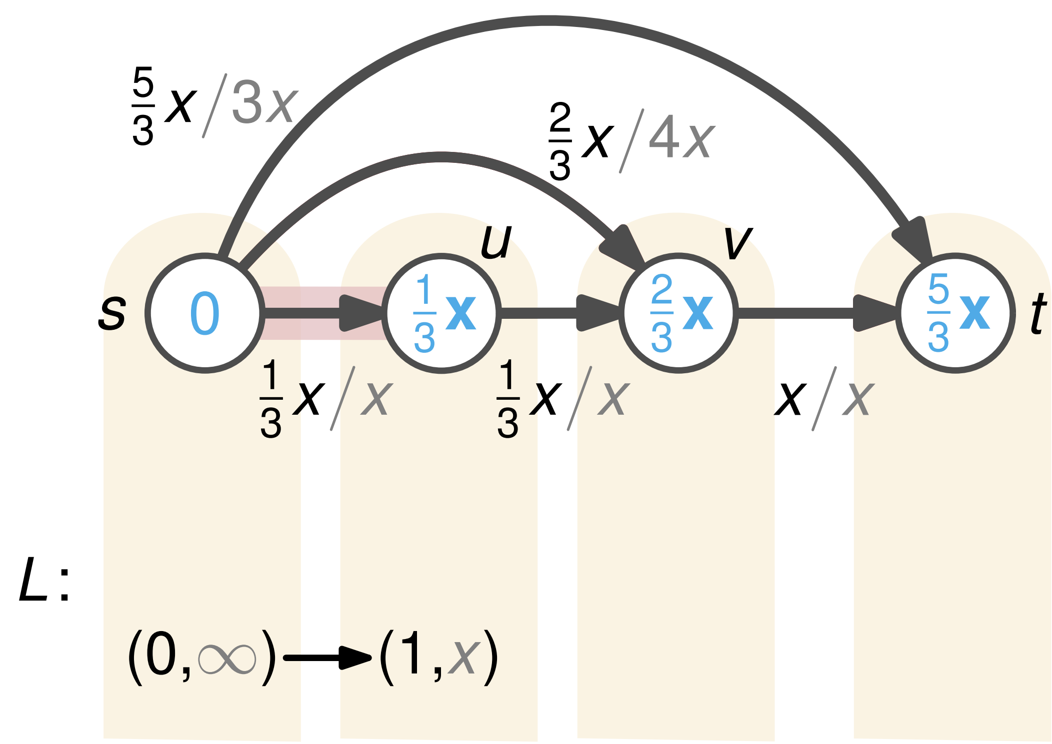

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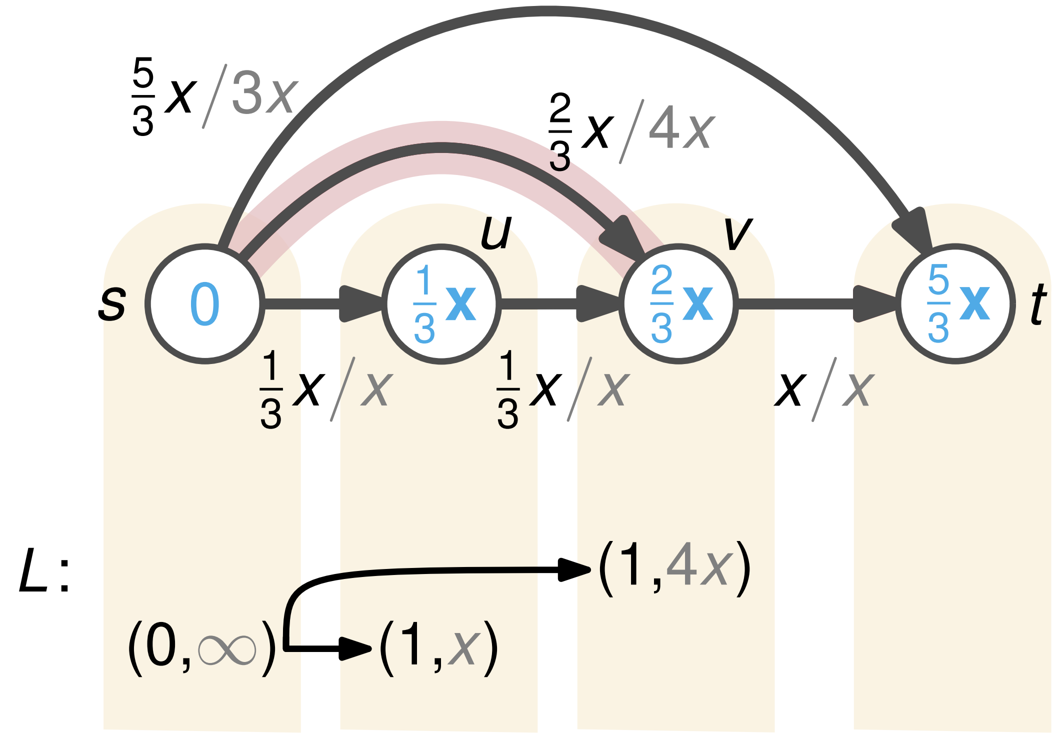

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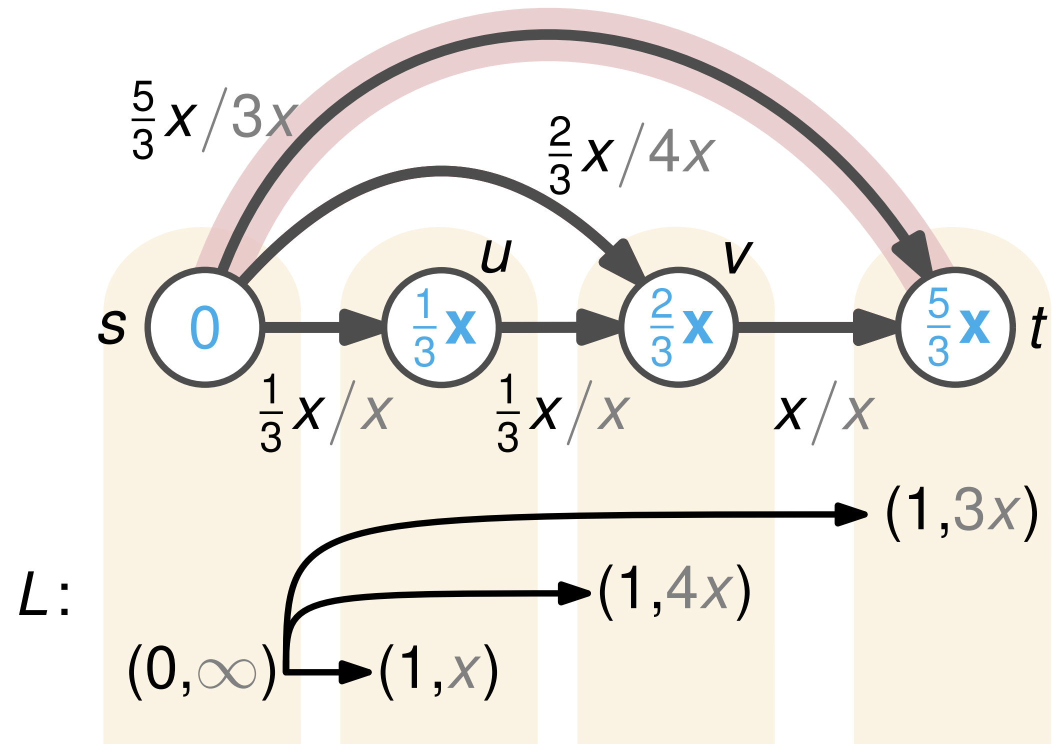

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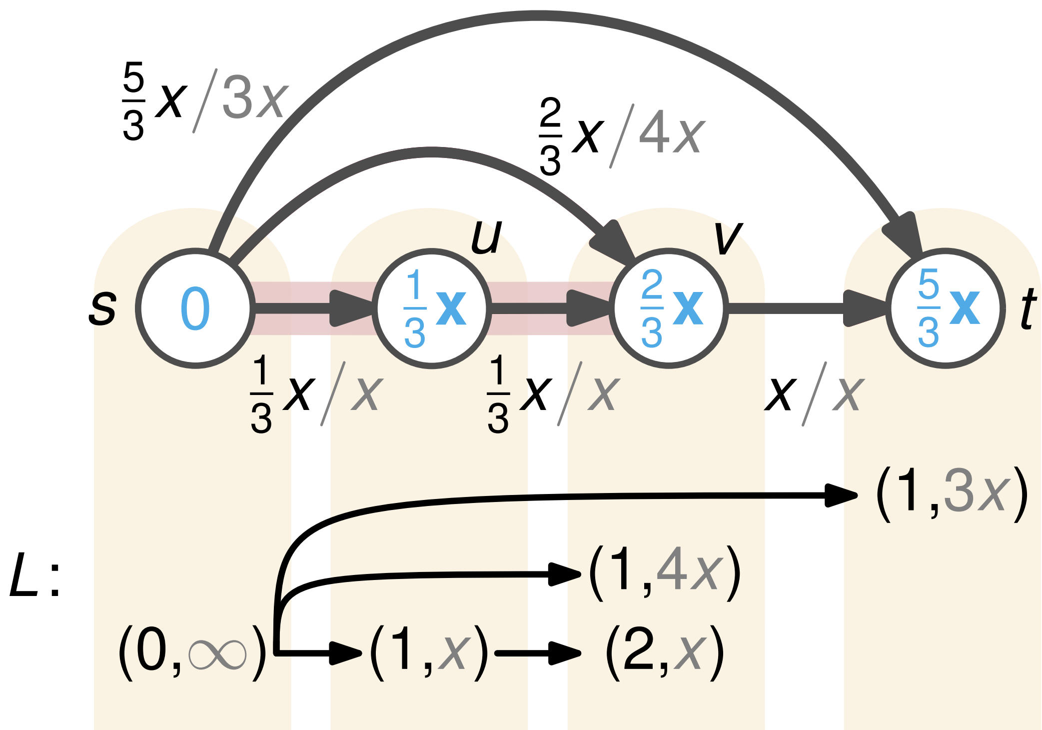

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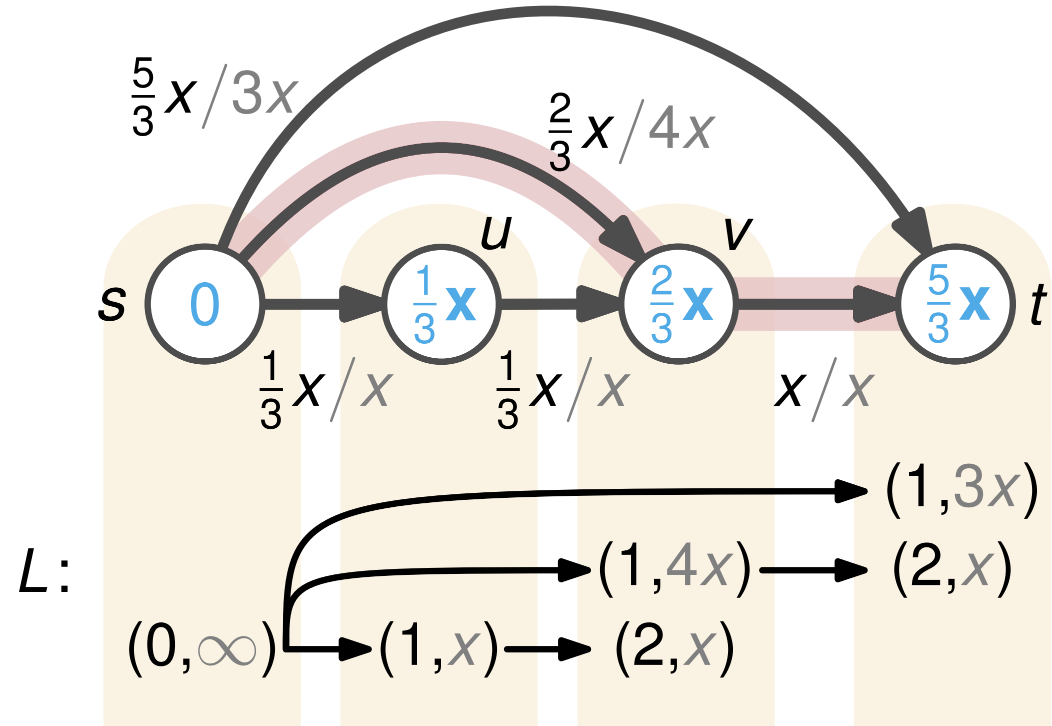

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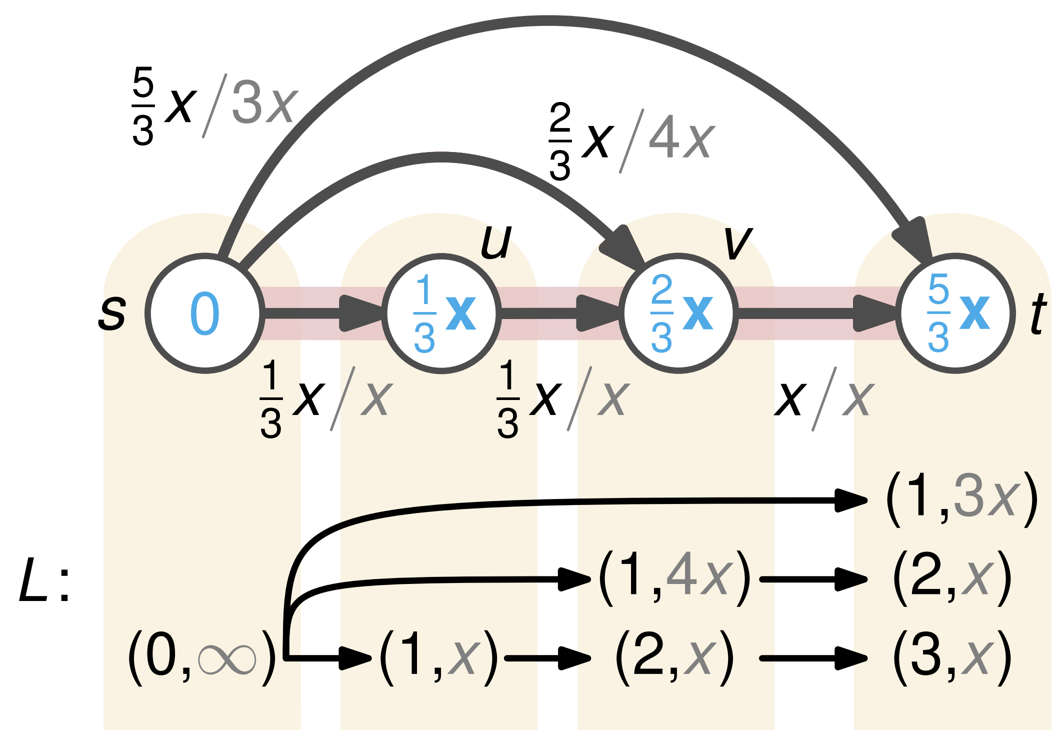

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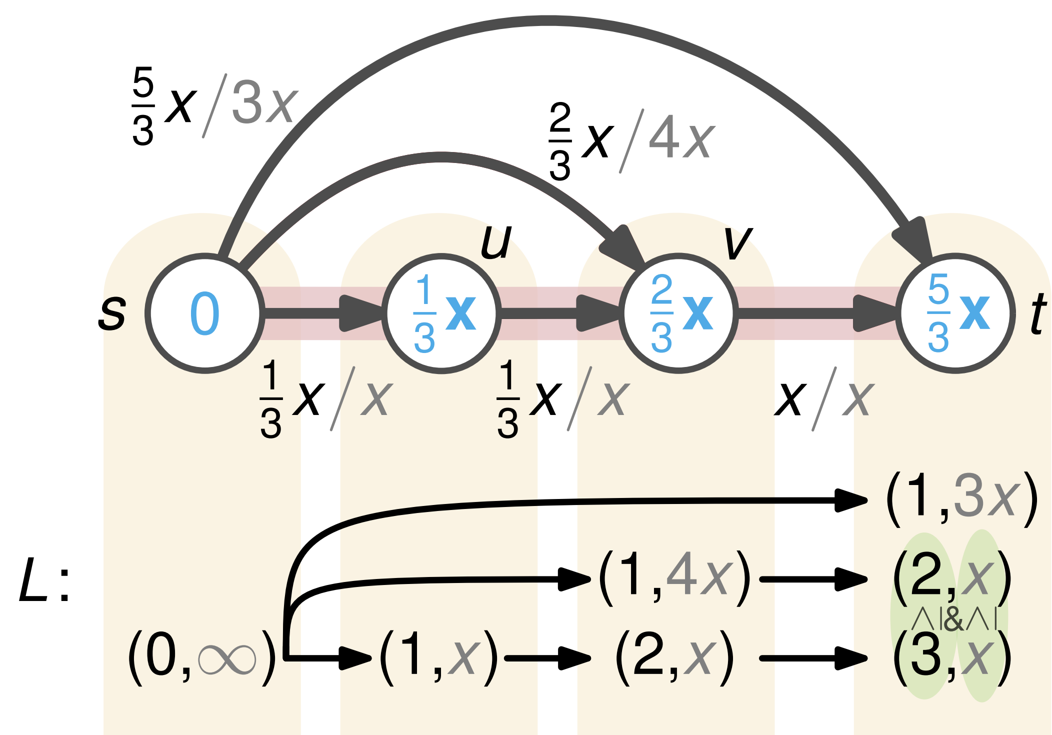

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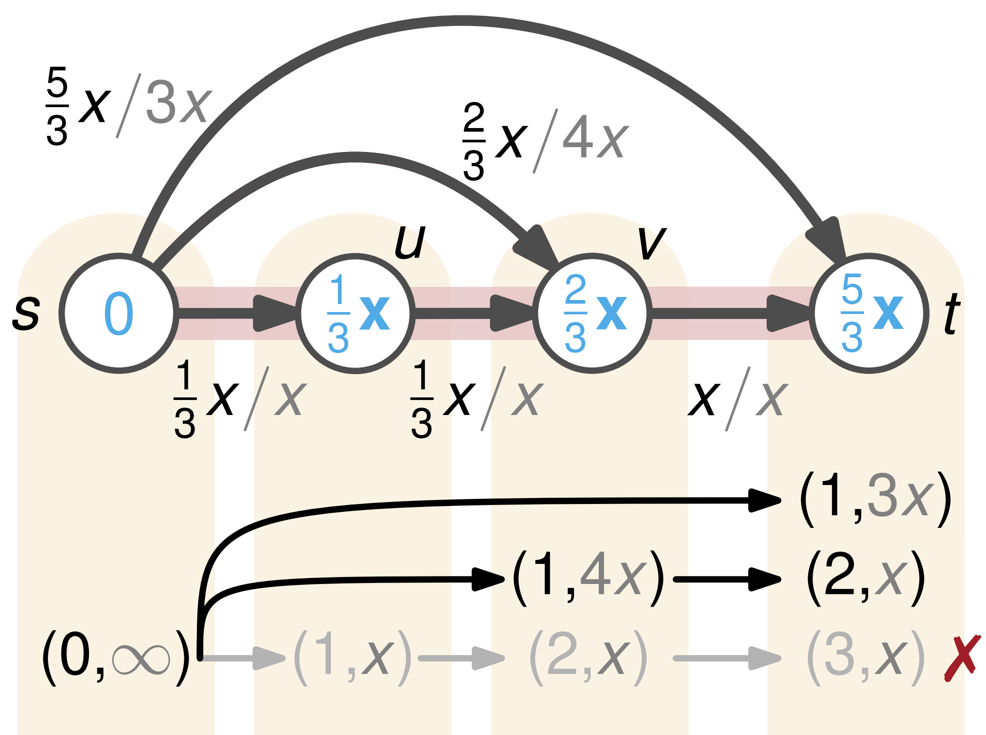

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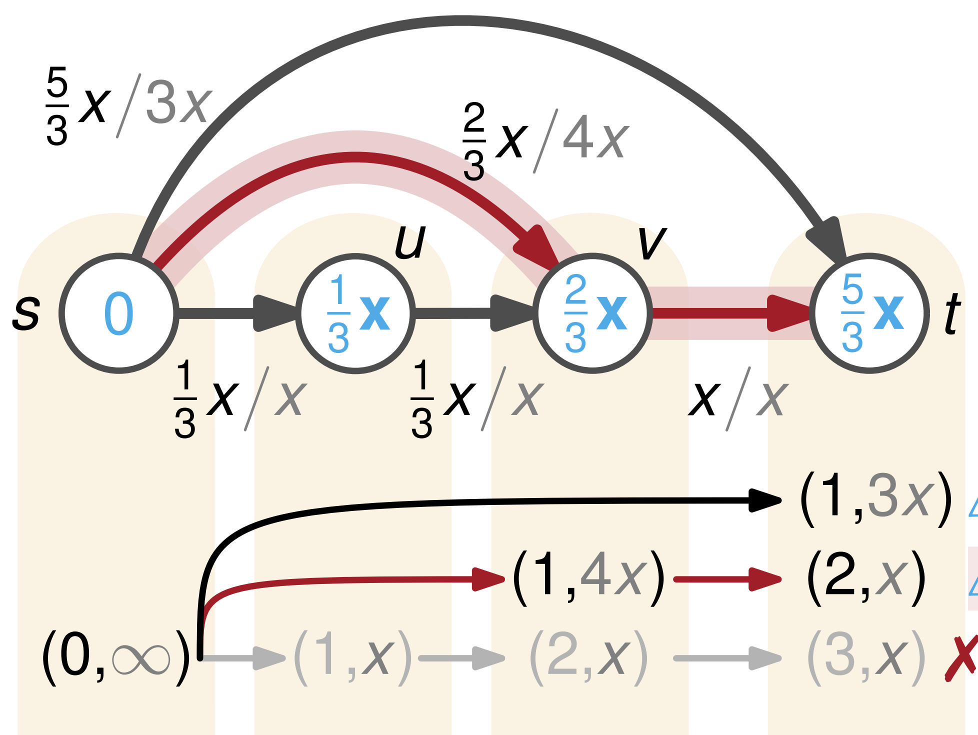

$\Delta\theta^{v}(s,t) = 1 \cdot 3x = 3x$

$\vee|$

$\Delta\theta^{v}(s,v,t) = 2 \cdot x = 2x$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

- Bicriterial Dijkstra with labels $(\|\pi\|_b, \underline{\text{cap}}(\pi))$
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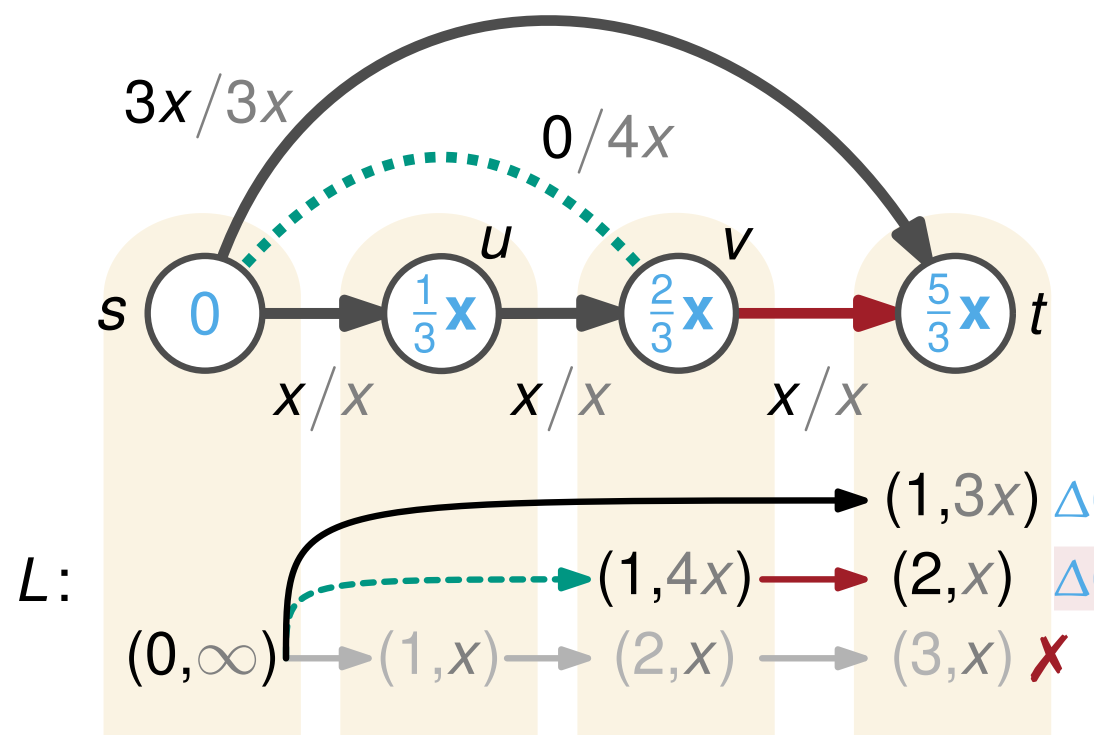
$b(i,j) := 1 \quad \forall (i,j) \in E$



$\text{OPT}_{\text{MPF}} = 4x$
$= \text{OPT}_{\text{MTSF}}$

$\Delta\theta^v(s,t) = 1 \cdot 3x = 3x$

$\vee|$

$\Delta\theta^v(s,v,t) = 2 \cdot x = 2x$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

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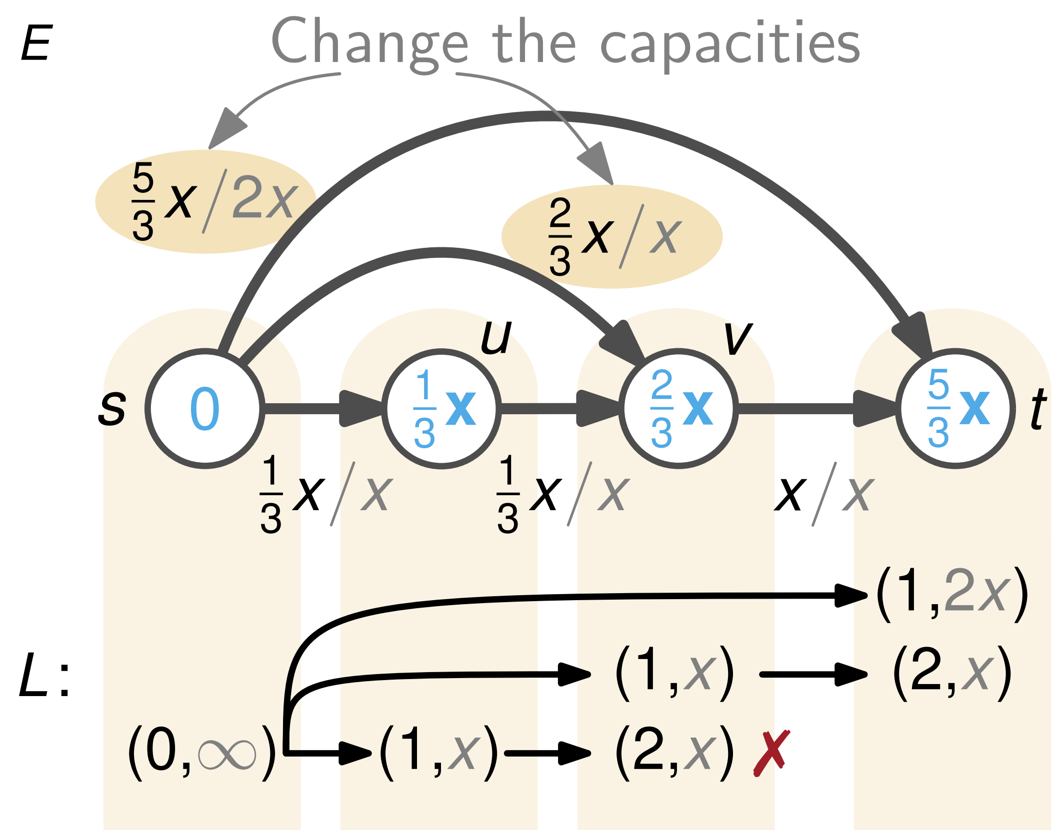

$\text{OPT}_{\text{MPF}} = \frac{8}{3}x$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

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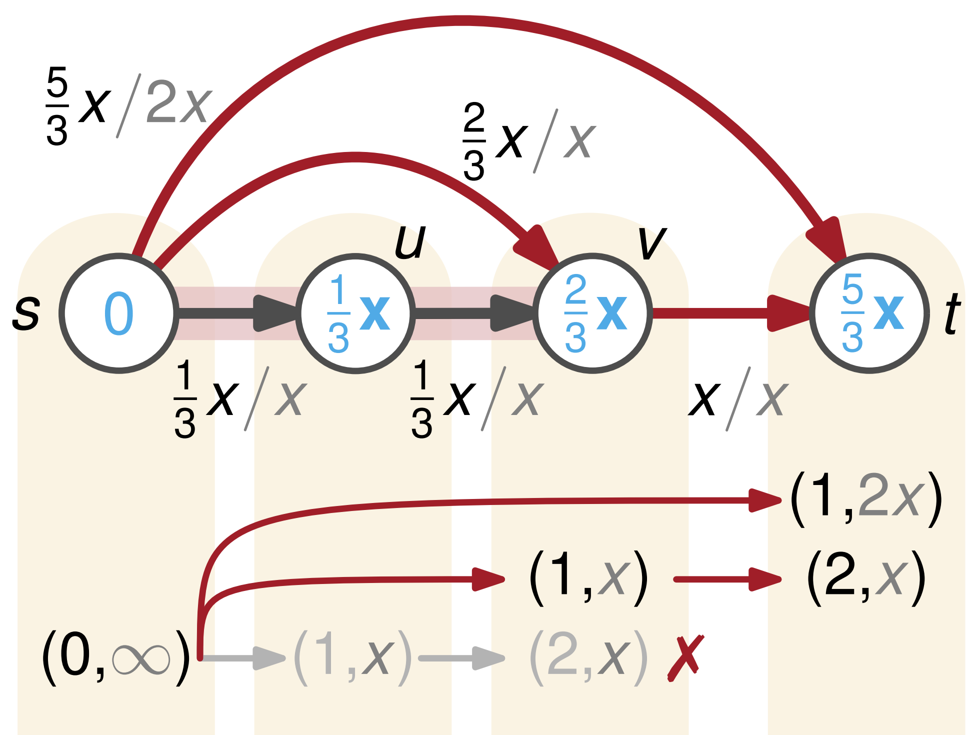
- Bicriterial Dijkstra with labels $(\|\pi\|_b, \underline{\text{cap}}(\pi))$
- At most $|E|$ labels per vertex

$b(i,j) := 1 \quad \forall (i,j) \in E$

- DTPs from s do not have to form a tree



$\text{OPT}_{\text{MPF}} = \frac{8}{3}x$

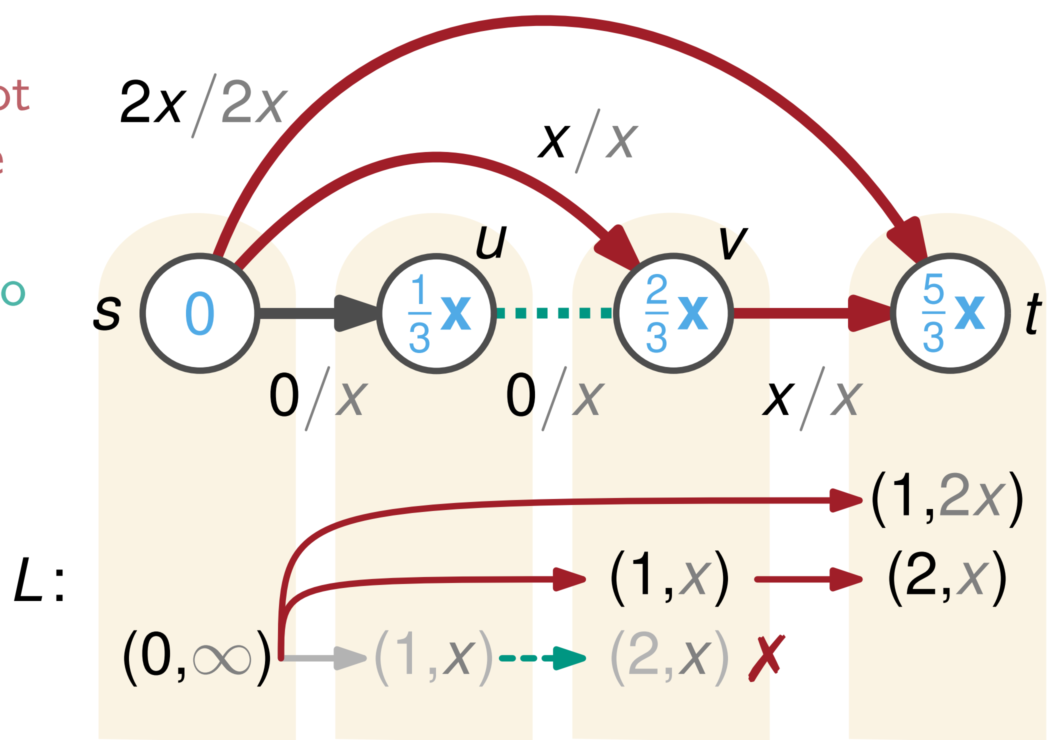
Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

- Bicriterial Dijkstra with labels $(\|\pi\|_b, \underline{\text{cap}}(\pi))$
- At most $|E|$ labels per vertex

$b(i,j) := 1 \quad \forall (i,j) \in E$

- DTPs from s do not have to form a tree
- Optimal switches do not have to lie on the DTP if the structure is not penrose-minor free



$\text{OPT}_{\text{MPF}} = 3x$
$= \text{OPT}_{\text{MTSF}}$

Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

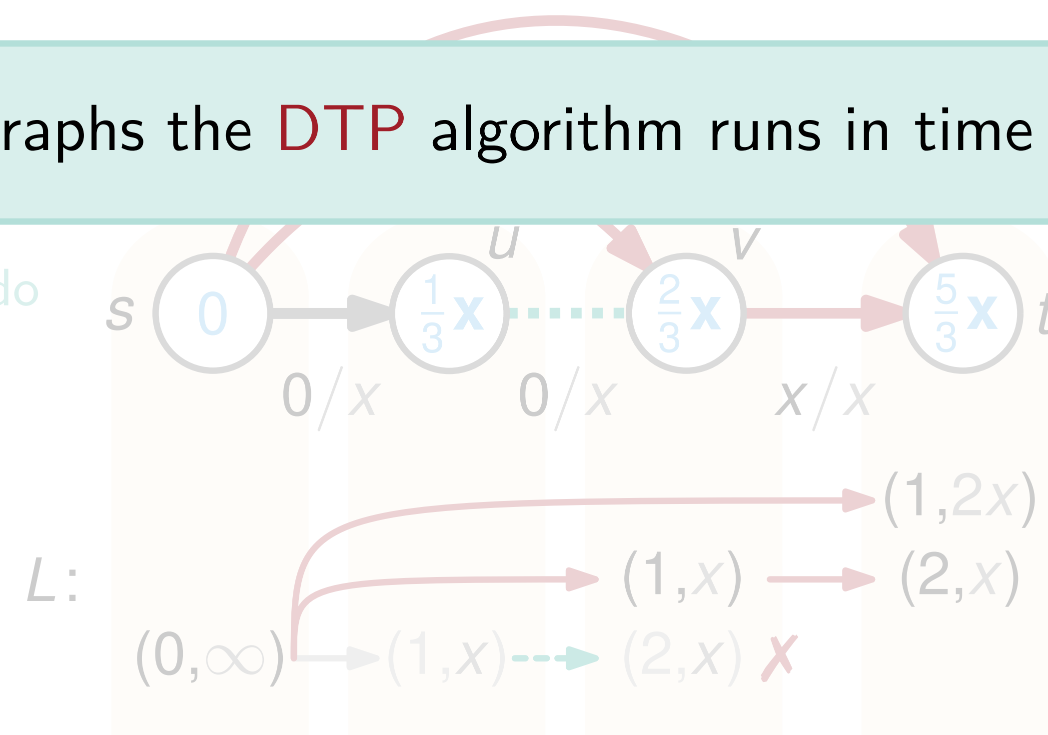
Description:

- Bicriterial Dijkstra with labels $(\|\pi\|_b, \text{cap}(\pi))$
- At most $|E|$ labels per vertex

$b(i,j) := 1 \quad \forall (i,j) \in E$

On general graphs the DTP algorithm runs in time $\mathcal{O}\left(2^{|V|}|V| \cdot |E|^3\right)$.

- Optimal switches do not have to lie on the DTP if the structure is not penrose-minor free



Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description:

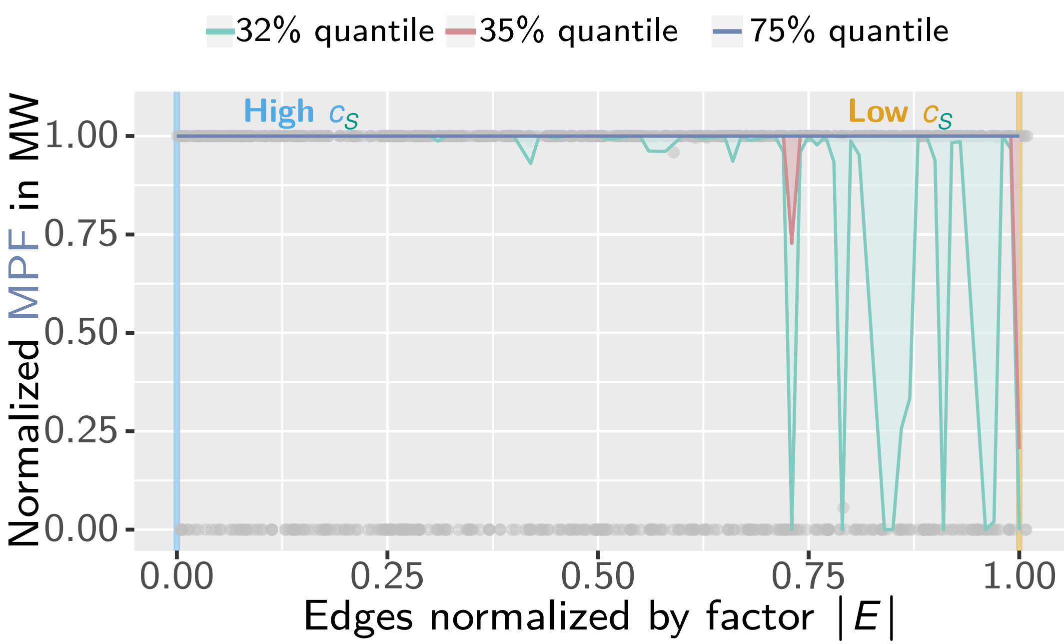
- Bicriterial Dijkstra with labels $(\|\pi\|_b, \text{cap}(\pi))$
- At most $|E|$ labels per vertex

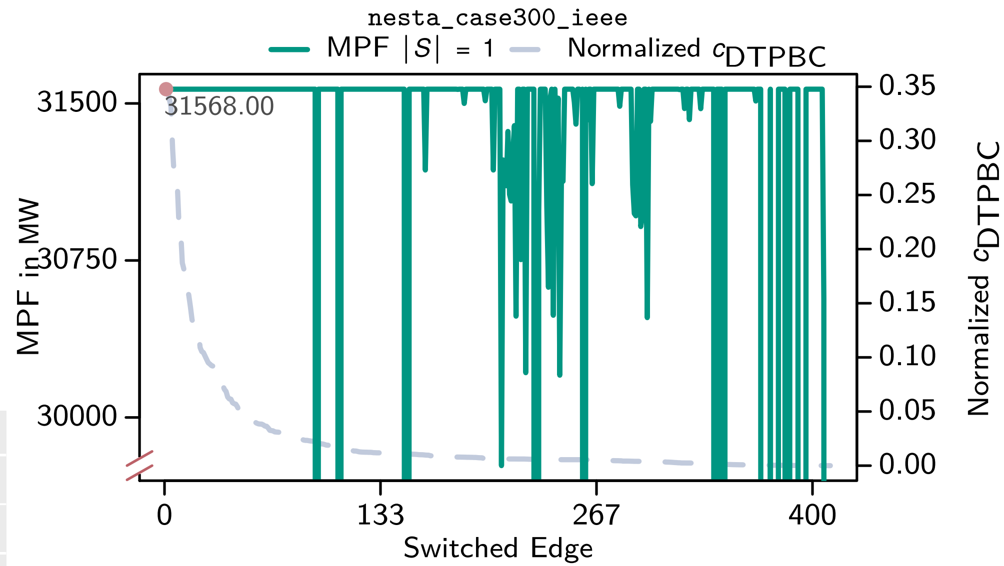
$b(i,j) := 1 \quad \forall (i,j) \in E$

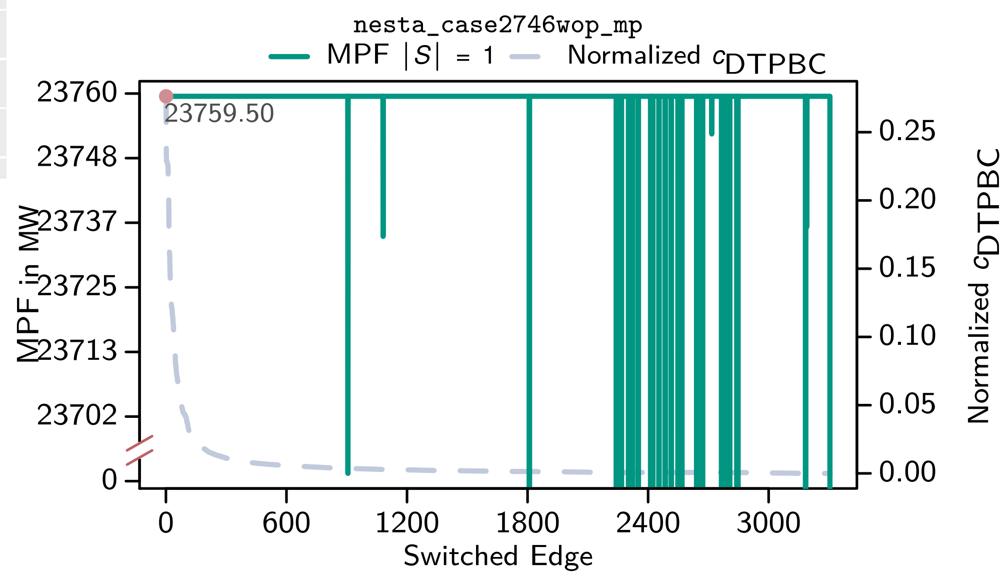
On general graphs a DTP algorithm exists that runs in polynomial time and calculates one DTP between each pair of u and v.

- Optimal switches do not have to lie on the DTP if the structure is not penrose-minor free

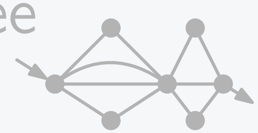
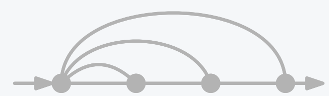
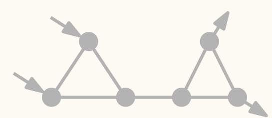
Computing DTP [Section 5; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]







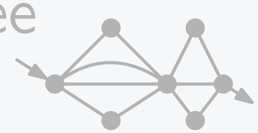
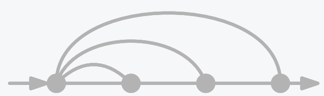
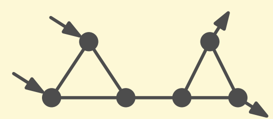
Overview of the MTSF Results

	Graph Structure		Complexity	Algorithm
one generator, one load	penrose-minor-free graphs		polynomial-time solvable	DTP ✓
	series-parallel graphs		NP-hard	✗
arbitrary generators, arbitrary loads	cacti with max degree of 3		NP-hard [Lehmann et al., 2014]	2-approx. ✓
	2-level trees		NP-hard [Lehmann et al., 2014]	✗
	planar graphs with max degree of 3		strongly NP-hard [Lehmann et al., 2014]	✗
$\|V_G\|=2$, $\|V_D\|=2$	arbitrary graphs		non-APX [Lehmann et al., 2014]	✗

complexity

Overview of the MTSF Results

complexity

	Graph Structure		Complexity	Algorithm
one generator, one load	penrose-minor-free graphs		polynomial-time solvable	DTP ✓
	series-parallel graphs		NP-hard	✗
arbitrary generators, arbitrary loads	cacti with max degree of 3		NP-hard [Lehmann et al., 2014]	2-approx. ✓
	2-level trees		NP-hard [Lehmann et al., 2014]	✗
	planar graphs with max degree of 3		strongly NP-hard [Lehmann et al., 2014]	✗
$\lvert V_G \rvert = 2$, $\lvert V_D \rvert = 2$	arbitrary graphs		non-APX [Lehmann et al., 2014]	✗

2-approximation on Cacti [page 349; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

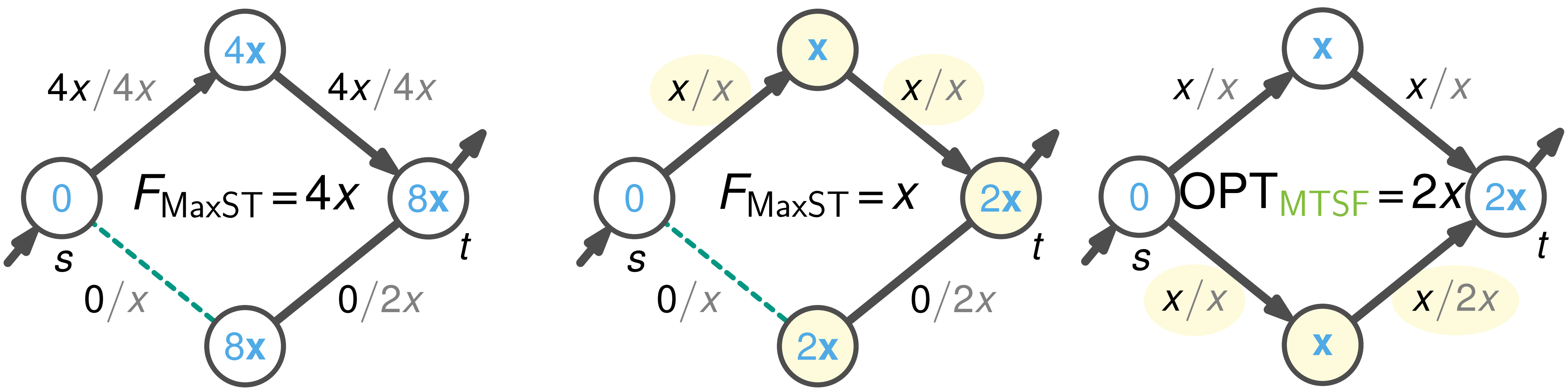
Description

- Remove from each cycle the edge with the smallest capacity

⇔ the Maximum Spanning Tree (MaxST)

MaxST on Cacti

- MTSF is NP-hard on cacti [Lehmann et al., 2014]



Theorem 1 [page 348; Grastien et al., 2018]

MaxST is a factor 2-approximation algorithm for the MF and MTSF problem on cacti.

2-approximation on Cacti [page 349; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Description

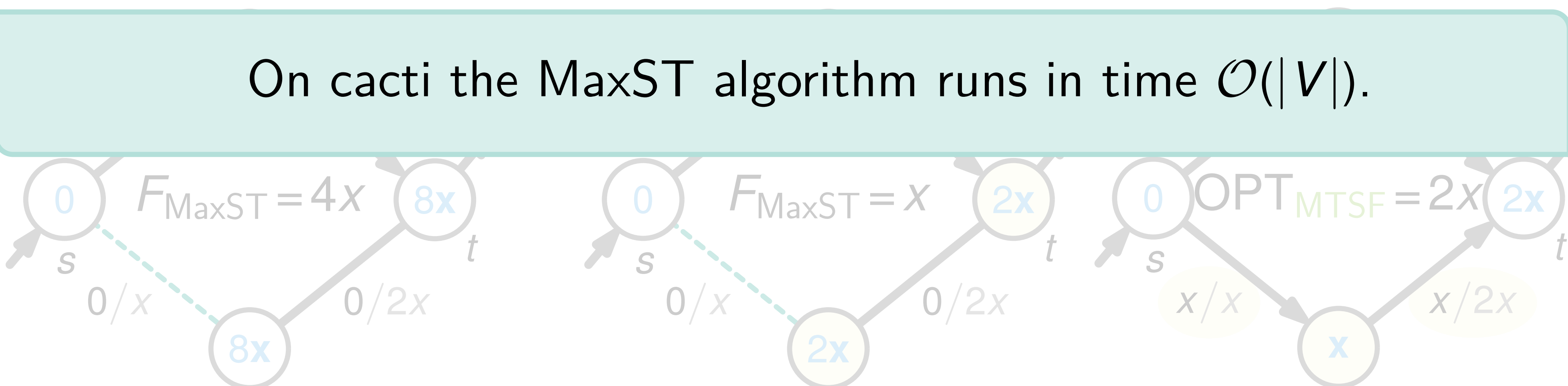
- Remove from each cycle the edge with the smallest capacity

⇔ the Maximum Spanning Tree (MaxST)

MaxST on Cacti

- MTSF is NP-hard on cacti [Lehmann et al., 2014]

On cacti the MaxST algorithm runs in time $\mathcal{O}(|V|)$.



Theorem 1 [page 348; Grastien et al., 2018]

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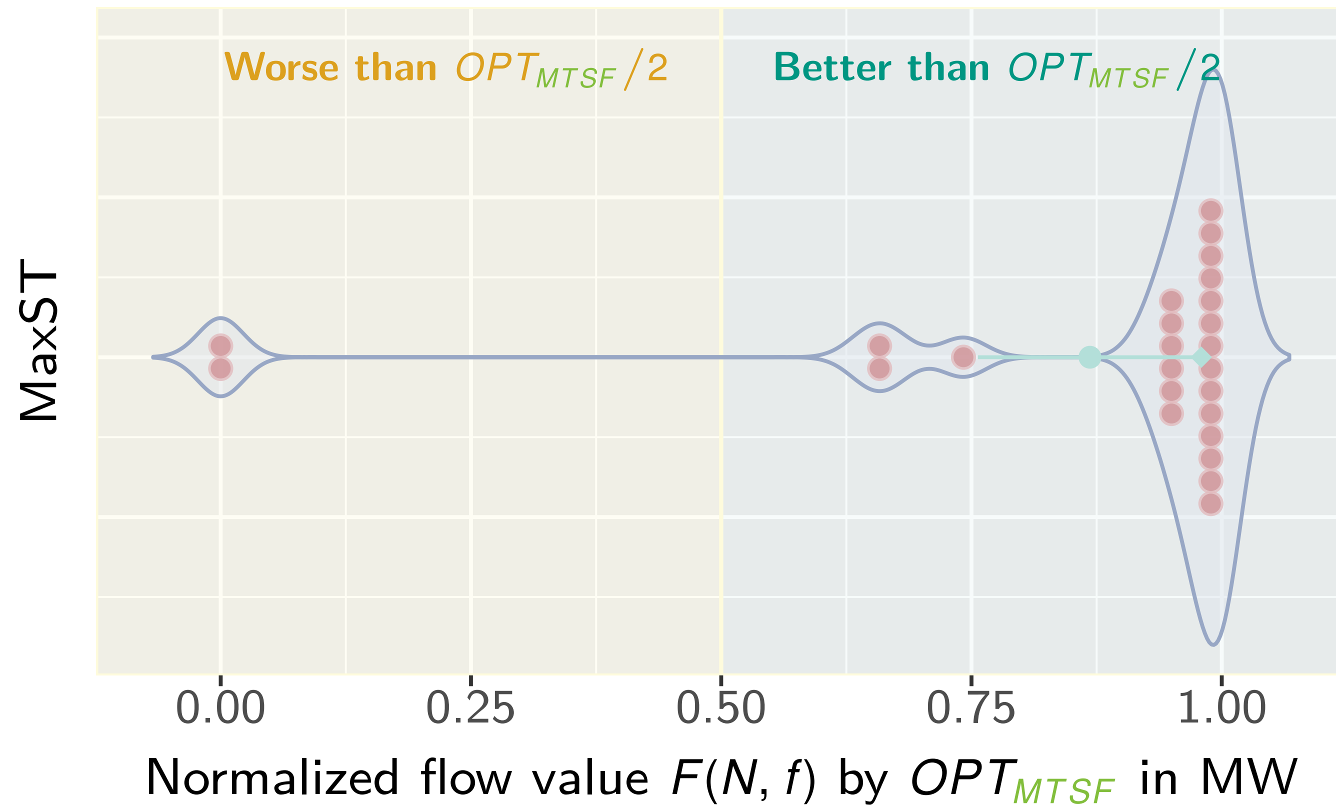
2-approximation on Cacti [page 349; Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]



Classification

Feasible electrical flows

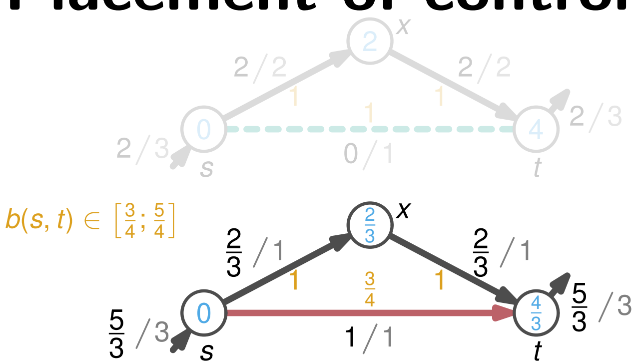
Dynamic models

Static models

Alternating Current (AC) model

Direct Current (DC) model

Placement of control units



Discrete control decision

[Grastien, Rutter, Wagner, W., and Wolf, 2018]

Continuous control decision

[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

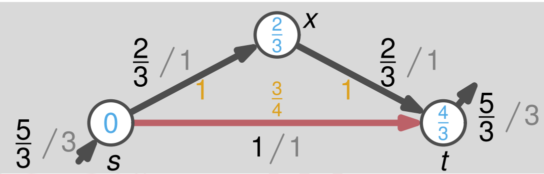
[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]

Cable layout

Wind farm cabling with multiple cable types

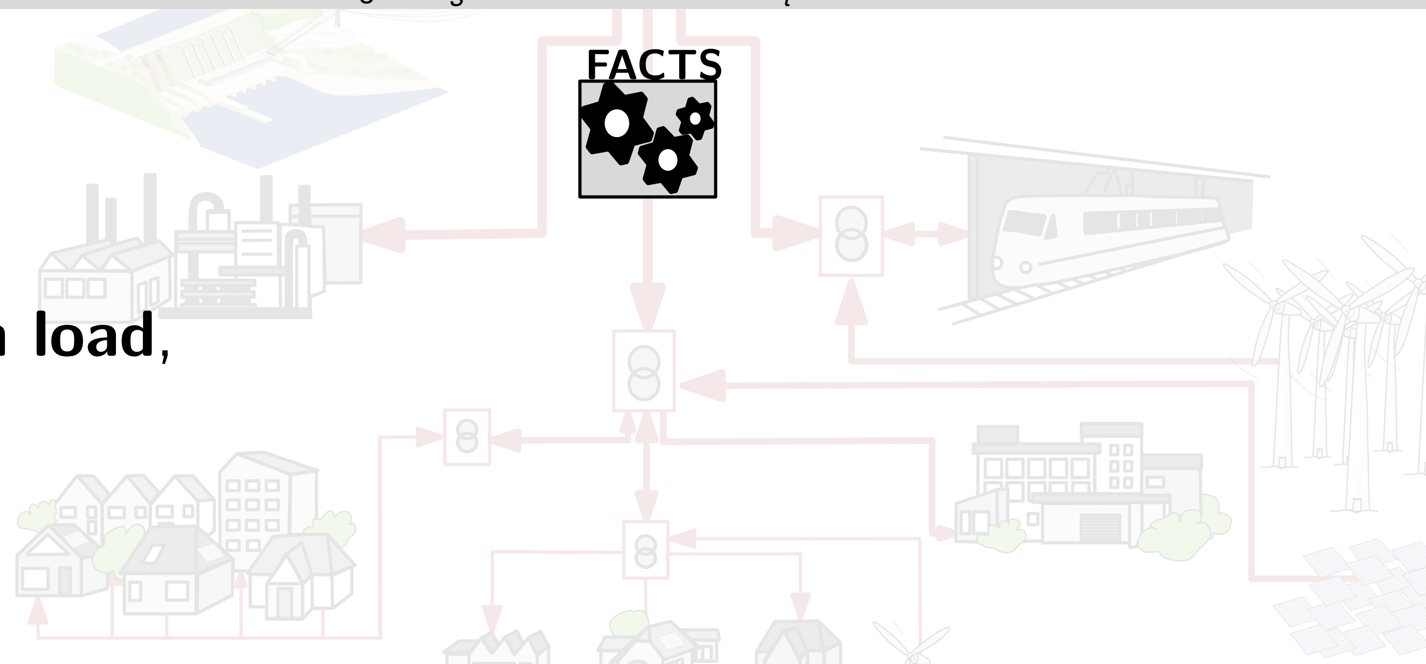
[Lehmann, Rutter, Wagner, and W., 2017]

Placement of control units
Continuous control decision



[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]



FACTS...

- are **control** units,
- increase **maximum load**,
- are **expensive**.

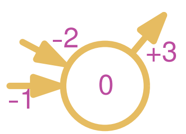
The Maximum FACTS Flow (MFF) Problem

[Lehmann et al., 2015]

- The value of the Maximum Flexible AC Transmission Switching Flow (MFF) is defined as

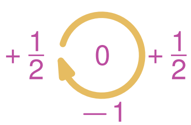
$$\mathrm{MFF}(\mathcal{N}, k) := \max_{E' \subseteq E, b} \mathrm{MPF}(\mathcal{N}) \qquad |E'| \leq k$$

with f being a feasible power flow meaning



$$f_{\text{net}}(u) = 0 \qquad \forall u \in V \setminus (V_G \cup V_D)$$

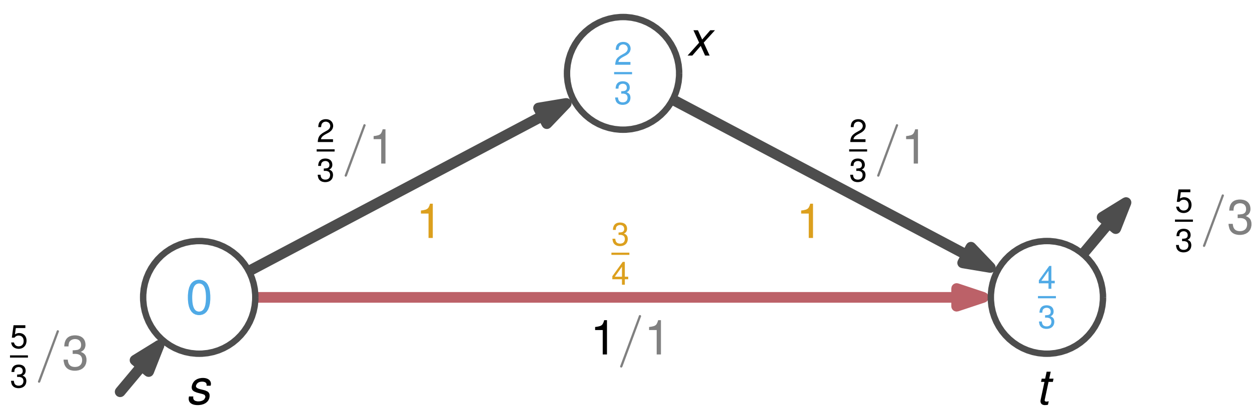
$$|f(u, v)| \leq \mathrm{cap}(u, v) \cdot z(u, v) \qquad \forall (u, v) \in E$$



$$z(u, v) \cdot \big(\theta(v) - \theta(u)\big) = f(u, v) \qquad \forall (u, v) \in E$$

$$z(u, v) \in \{0, 1\} \qquad \forall (u, v) \in E'$$

$k = 1$



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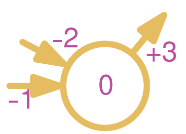

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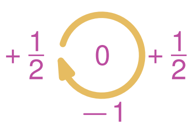
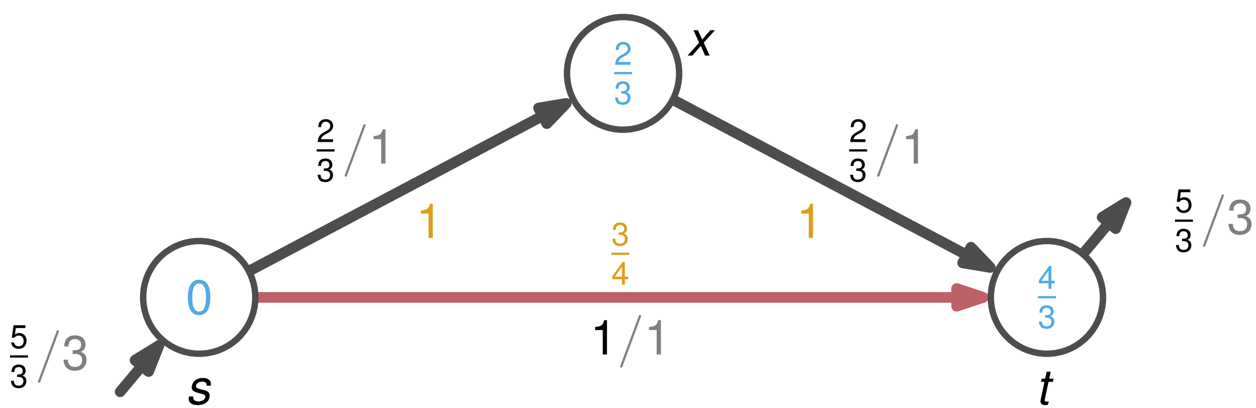
$$|f(u,v)| \leq \mathrm{cap}(u,v) \qquad \forall (u,v) \in E$$



$$b(u,v) \cdot \big(\theta(v) - \theta(u)\big) = f(u,v) \qquad \forall (u,v) \in E$$

$$b(u,v) \in \left[\tfrac{3}{4}, \tfrac{5}{4}\right] \qquad \forall (u,v) \in E'$$

$k = 1$



The Maximum FACTS Flow (MFF) Problem

[Lehmann et al., 2015]

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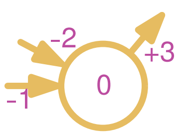
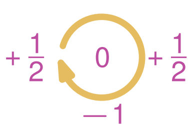
with f being a feasible power flow meaning



$$f_{\text{net}}(u) = 0 \qquad \forall u \in V \setminus (V_G \cup V_D)$$

$$|f(u,v)| \leq \mathrm{cap}(u,v) \qquad \forall (u,v) \in E$$



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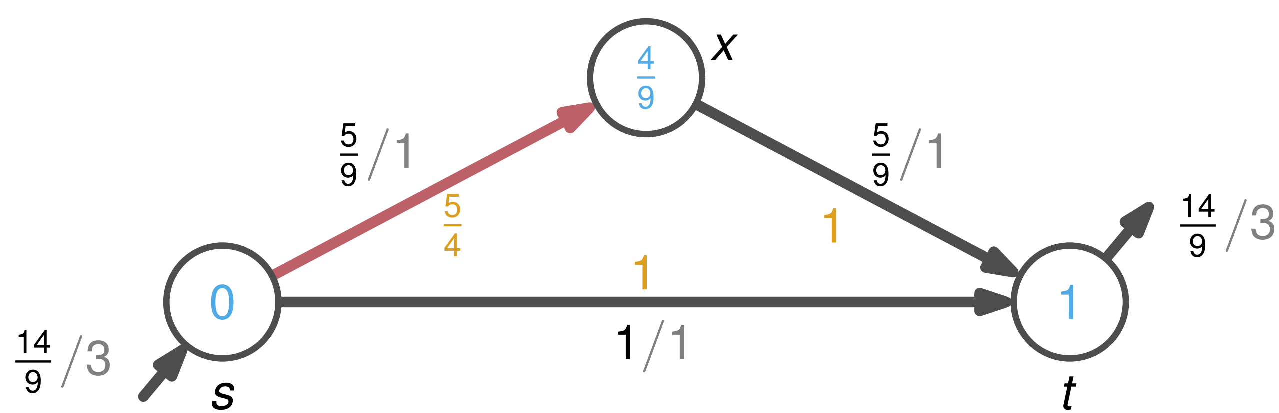

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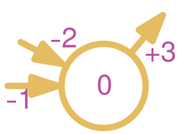
[Lehmann et al., 2015]

- The value of the Maximum Flexible AC Transmission Switching Flow (MFF) is defined as

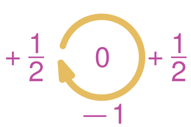
$$\mathrm{MFF}(\mathcal{N}, k) := \max_{E' \subseteq E, b} \mathrm{MPF}(\mathcal{N}) \qquad |E'| \leq k$$

with f being a feasible power flow meaning



$$f_{\text{net}}(u) = 0 \qquad \forall u \in V \setminus (V_G \cup V_D)$$

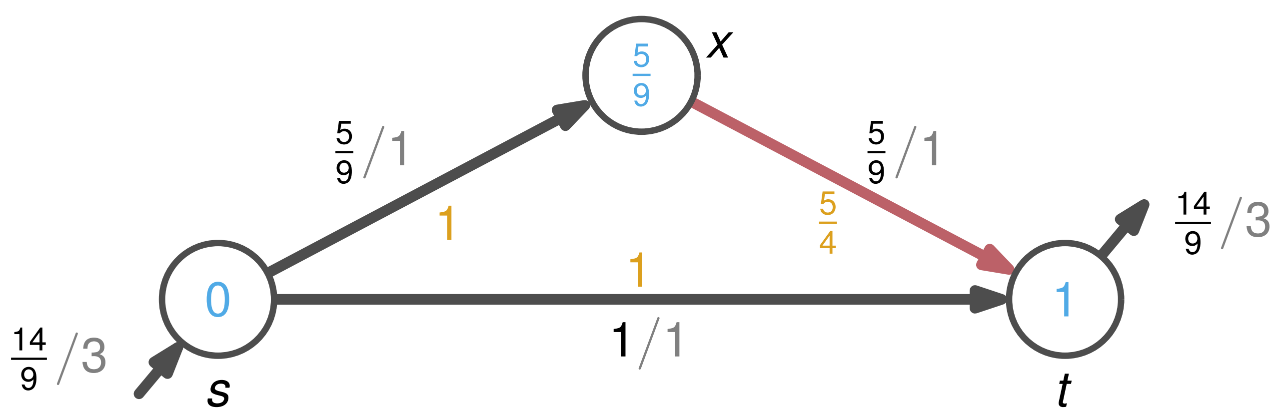
$$|f(u,v)| \leq \mathrm{cap}(u,v) \qquad \forall (u,v) \in E$$



$$b(u,v) \cdot \big(\theta(v) - \theta(u)\big) = f(u,v) \qquad \forall (u,v) \in E$$

$$b(u,v) \in \left[\tfrac{3}{4}, \tfrac{5}{4}\right] \qquad \forall (u,v) \in E'$$

$k = 1$



The Maximum FACTS Flow (MFF) Problem

[Lehmann et al., 2015]

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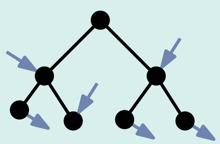
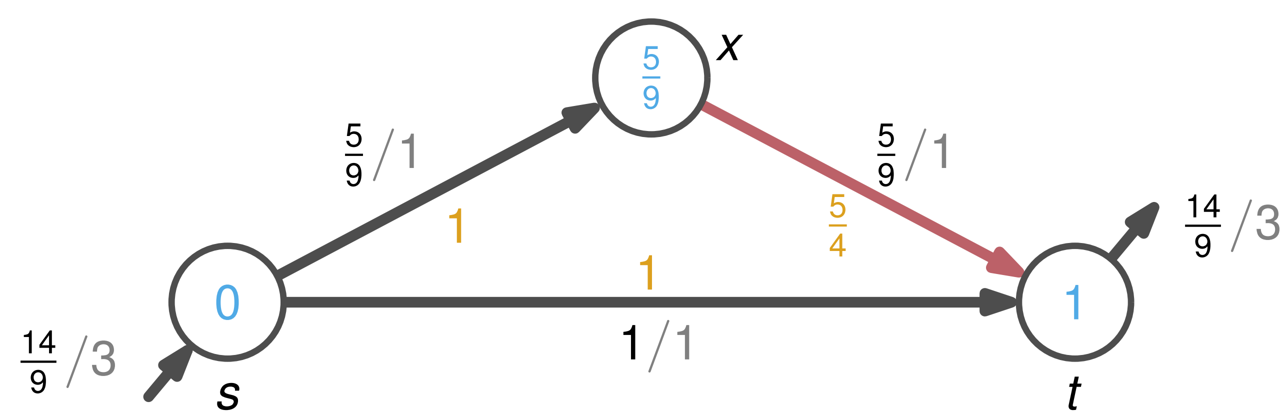


Physical Model (MPF) = Maximum FACTS Flow (MFF) = Flow Model (MF)

$k = 1$



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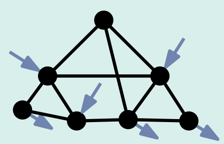
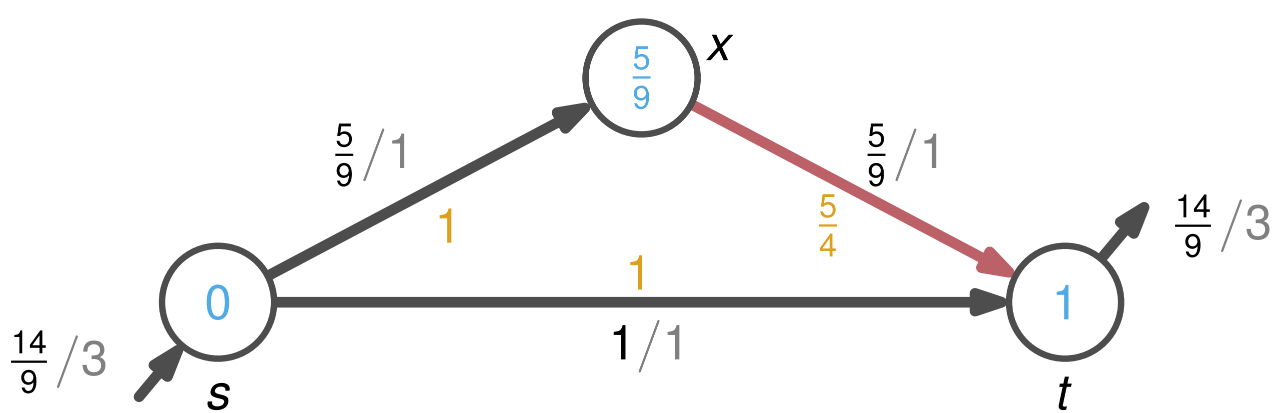


Physical Model (MPF) $\leq$ Maximum FACTS Flow (MFF) $\leq$ Flow Model (MF)

$k = 1$



The Optimal FACTS Flow (OFF) Problem

- The value of the Optimal Power Flow (OPF) is defined as

$$\mathrm{OPF}(\mathcal{N}) = \min \gamma(\mathcal{N}, f)$$

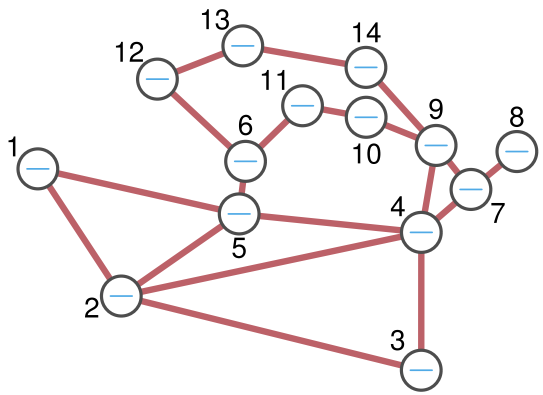
with f being a feasible power flow and the generator cost function γ.

Optimization Problem OFF

Instance: A power grid $\mathcal{N}$.

Objective: Find a set $E' \subseteq E$ of edges with FACTS and a susceptance configuration $b(e)$ with $e \in E'$ such that $\mathrm{OPF}(\mathcal{N})$ is minimum among all choices of FACTS placements and susceptance configurations while complying with $|E'| \leq k$.

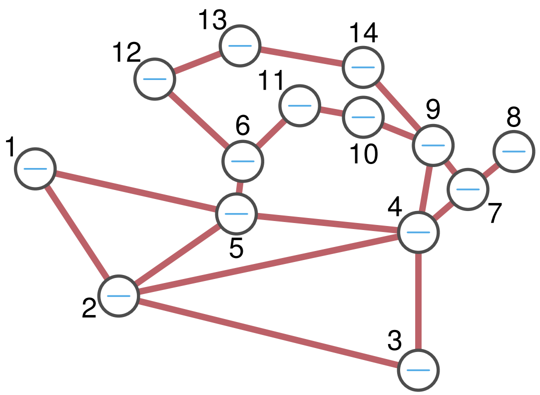
Optimal FACTS Flow (OFF)



Full Control

Can we become as good as the Flow Model with fewer FACTS?

Optimal FACTS Flow (OFF)



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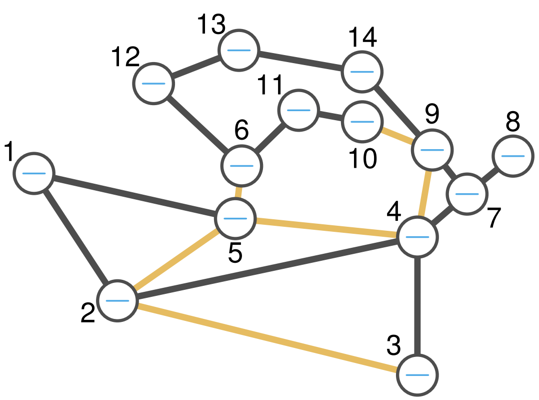
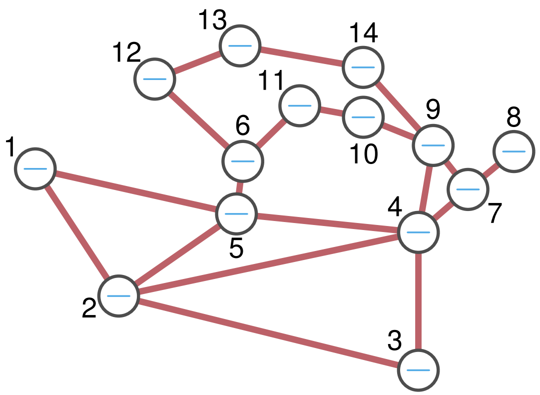


Feedback Edge Set

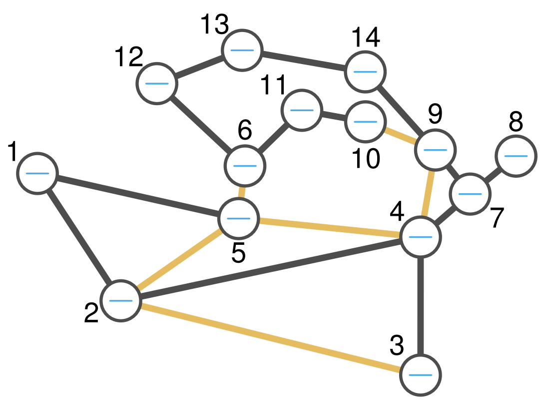
If the graph without FACTS represents a forest all flows represent feasible power flows.

Optimal FACTS Flow (OFF)



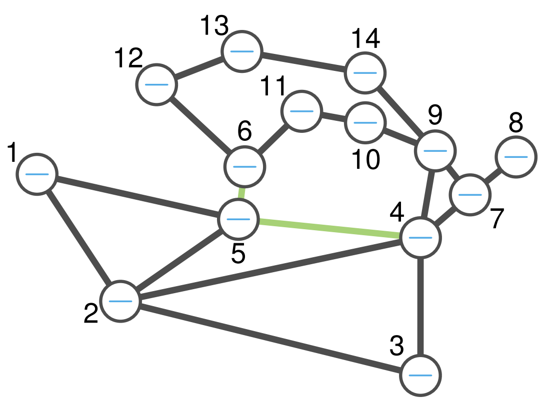
— Full Control

Can we become as good as the Flow Model with fewer FACTS?



— *Feedback Edge Set*

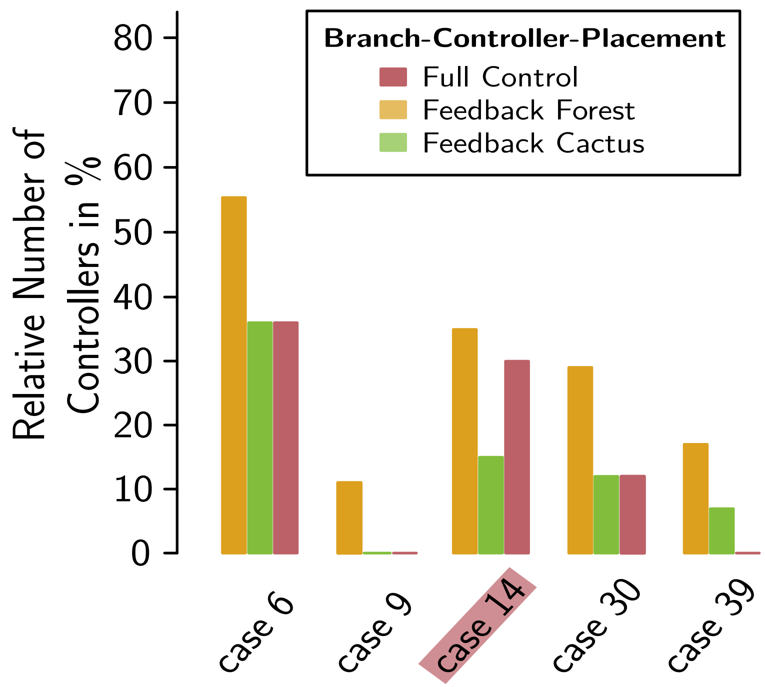
If the graph without FACTS represents a forest all flows represent feasible power flows.

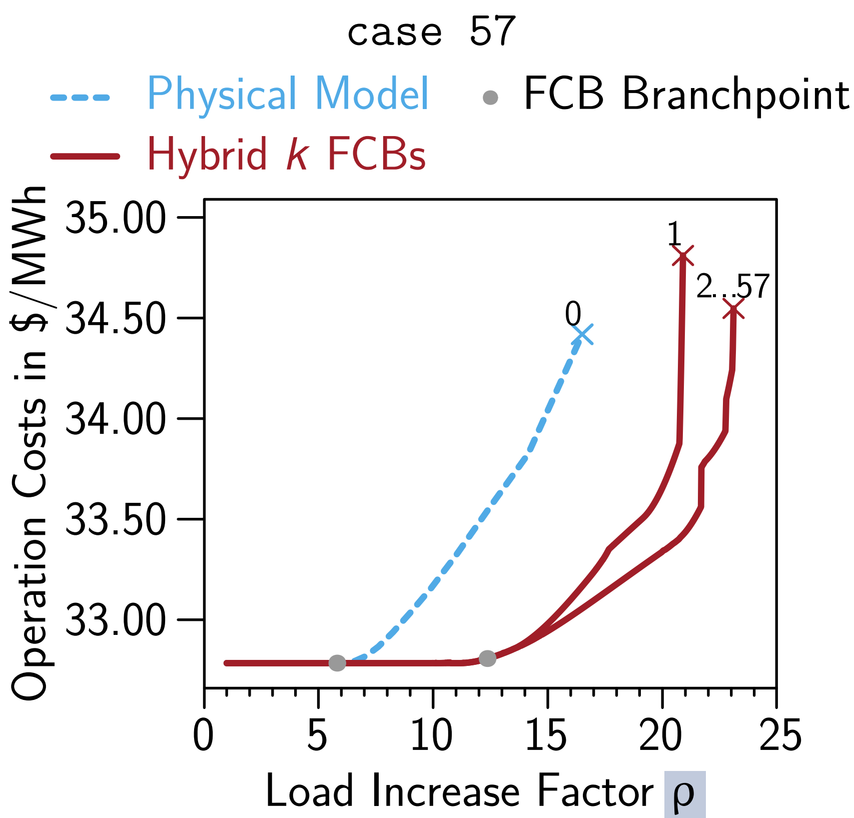


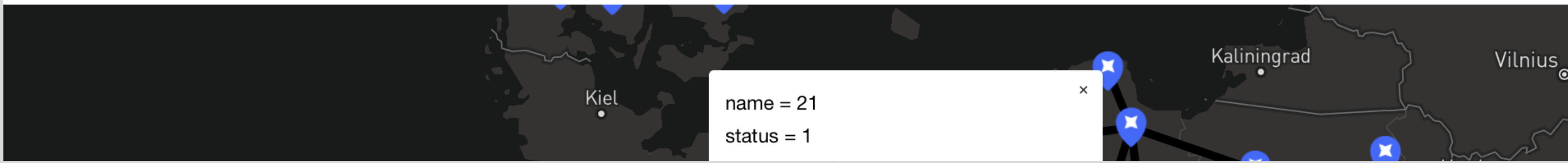
— *Diamond Hitting Set*

If the remaining graph is a cactus and the capacities on the cycles are suitably bounded then there is for every flow a cost-equivalent feasible power flow.

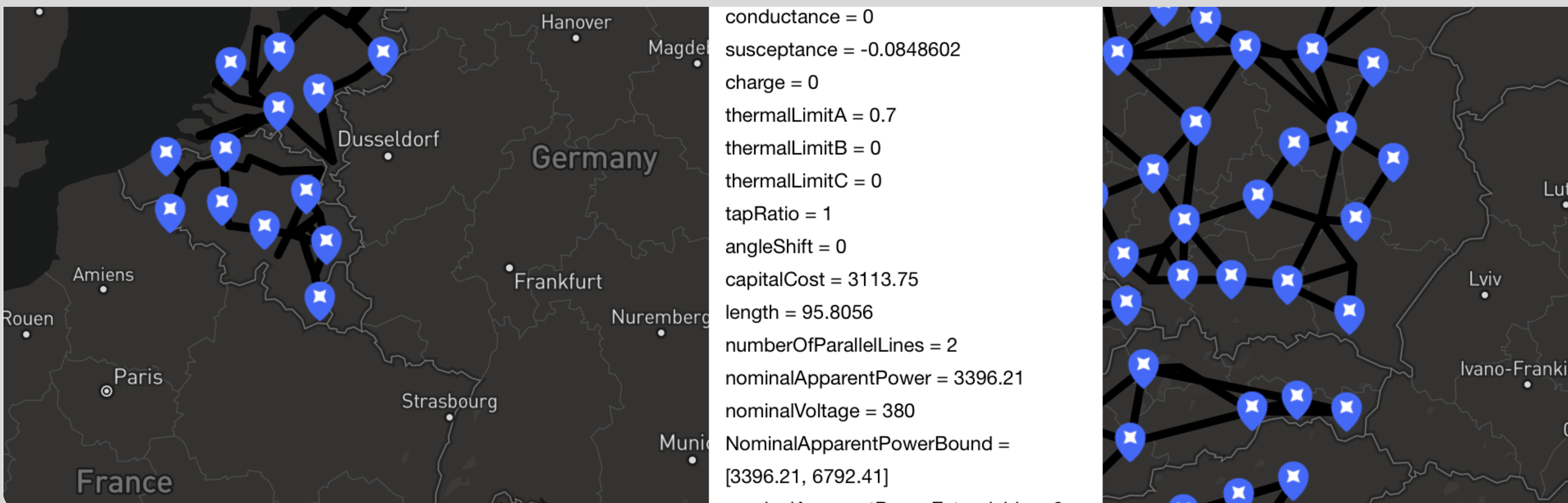
Optimal FACTS Flow (OFF)





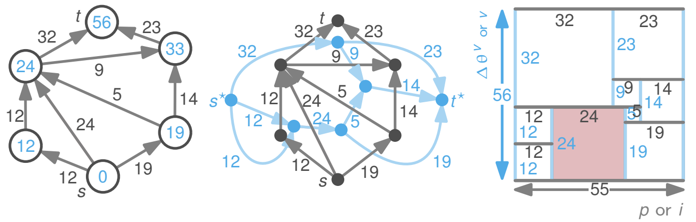

Kiel
Kaliningrad
Vilnius
name = 21
status = 1

Summary


Hanover
Magdel
Dusseldorf
Germany
Amiens
Frankfurt
Rouen
Nuremberg
Paris
Strasbourg
Muni
France
Lutsk
Lviv
Ivano-Frankivs
conductance = 0
susceptance = -0.0848602
charge = 0
thermalLimitA = 0.7
thermalLimitB = 0
thermalLimitC = 0
tapRatio = 1
angleShift = 0
capitalCost = 3113.75
length = 95.8056
numberOfParallelLines = 2
nominalApparentPower = 3396.21
nominalVoltage = 380
NominalApparentPowerBound =
[3396.21, 6792.41]

Summary

Feasible electrical flows



Dynamic models

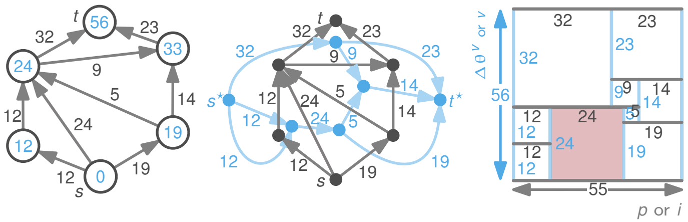
Static models

Alternating Current (AC) model

Direct Current (DC) model

Summary

Feasible electrical flows



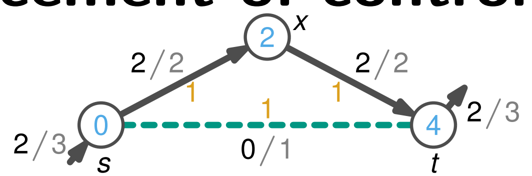
Dynamic models

Static models

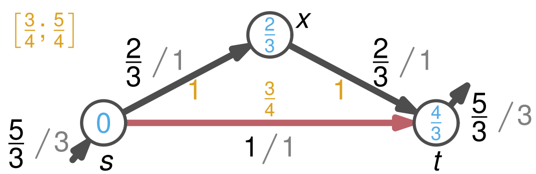
Alternating Current (AC) model

Direct Current (DC) model

Placement of control units



$b(s, t) \in \left[\frac{3}{4}; \frac{5}{4}\right]$



Discrete control decision

[Grastien, Rutter, Wagner, **W.**, and Wolf, 2018]

Continuous control decision

[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]

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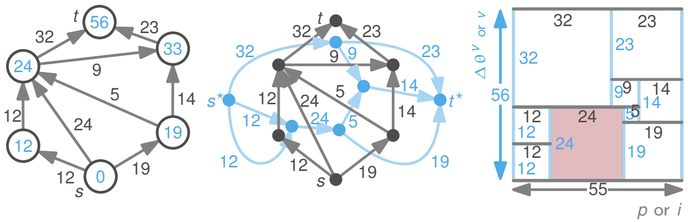

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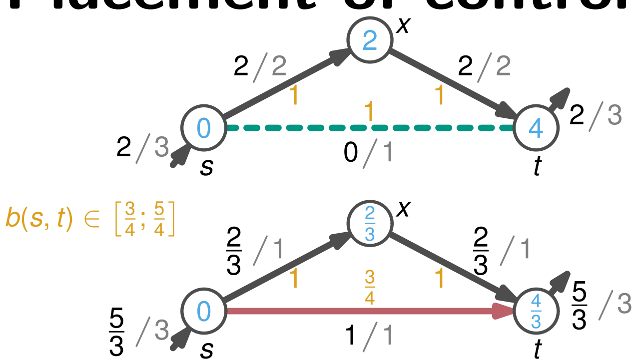

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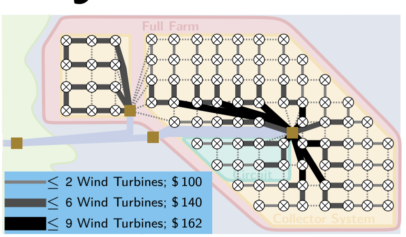
Cable layout

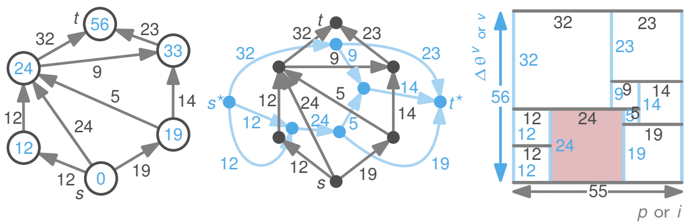


Wind farm cabling with multiple cable types

[Lehmann, Rutter, Wagner, and **W.**, 2017]

Summary

Feasible electrical flows



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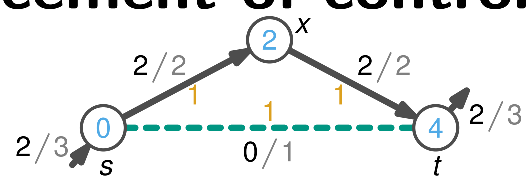

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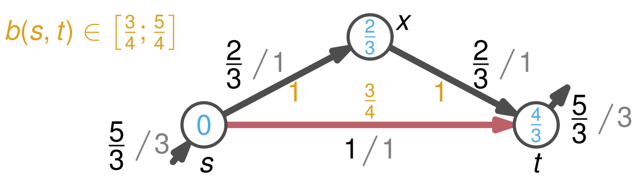

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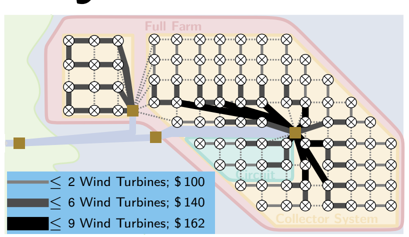
Cable layout



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Algorithm Engineering

- Quality and efficiency **guarantee**,
- **Practical** methods.

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