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RELATING ELECTRIC VEHICLE CHARGING TO SPEED SCALING WITH JOB-SPECIFIC SPEED LIMITS

JOINT WORK WITH M.E.T. GERARDS, A. ANTONIADIS, G. HOOGSTEEN, J. HURINK

IN THIS PRESENTATION:

- USE CASE
- SPEED SCALING
- FOCS ALGORITHM
- FOCS PROOF SKETCH
- CONCLUSION

USE CASE - LIVING LAB

- Electric Vehicle (EV) charging infrastructure at parking lot
- ~250 charging stations
- ~450 charging stations 2030
- 900 kW peak PV
- Lease fleet

SmoothEMS
MET GRIDSHIELD

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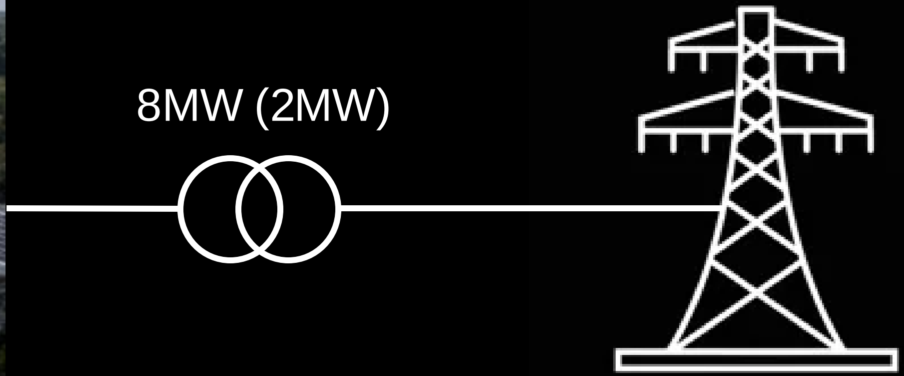
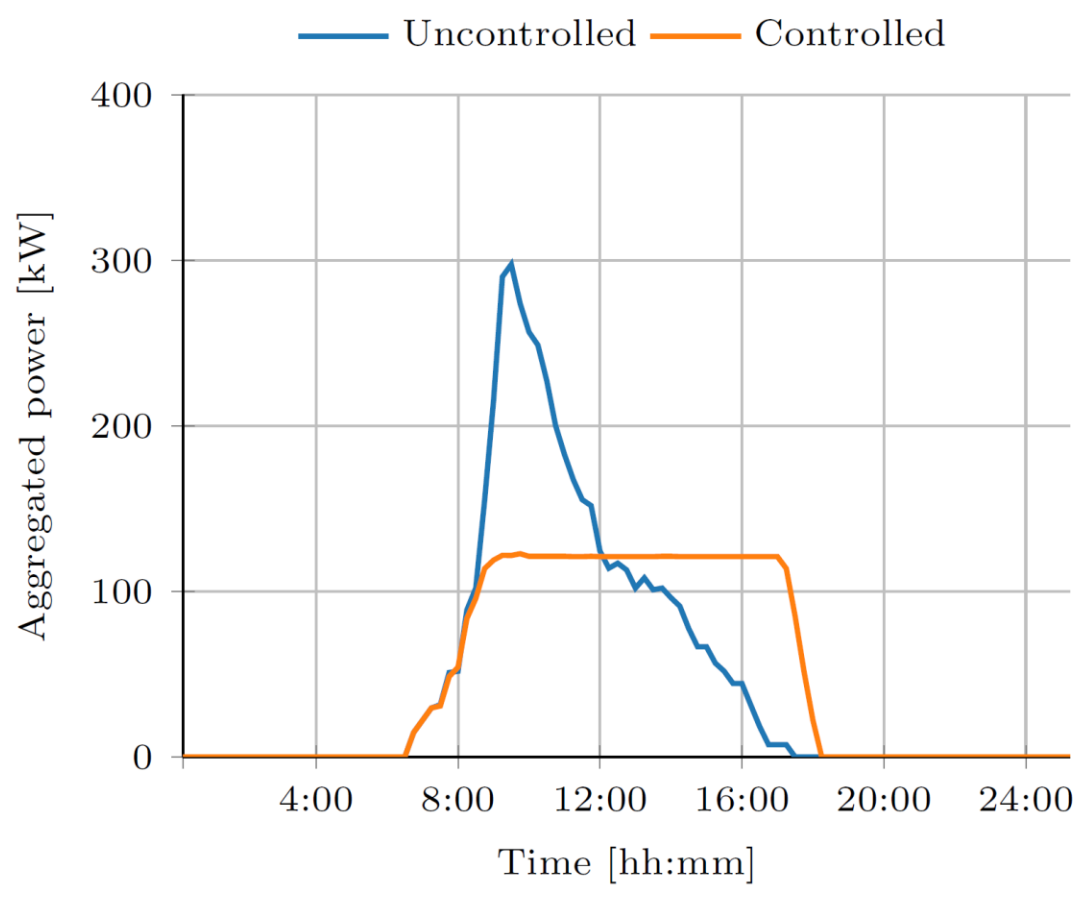
USE CASE - LIVING LAB



USE CASE - SCHEDULING



- Jobs j:
  - Arrival times
  - Departure times
  - Work (energy)
  - Speed limit (power)
- Decision variable:
  - Job schedules s_j(t)
- Objective function:
  - $\int_t (\sum_j s_j(t))^2 \, dt$

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INFORMATION GAP

- Given in practice:
  - Arrival time (upon arrival)
  - Energy ‘demand’ (upon completion)
  - Departure time (upon departure)
  - Maximum power (upon query)

MODEL PREDICTIVE CONTROL

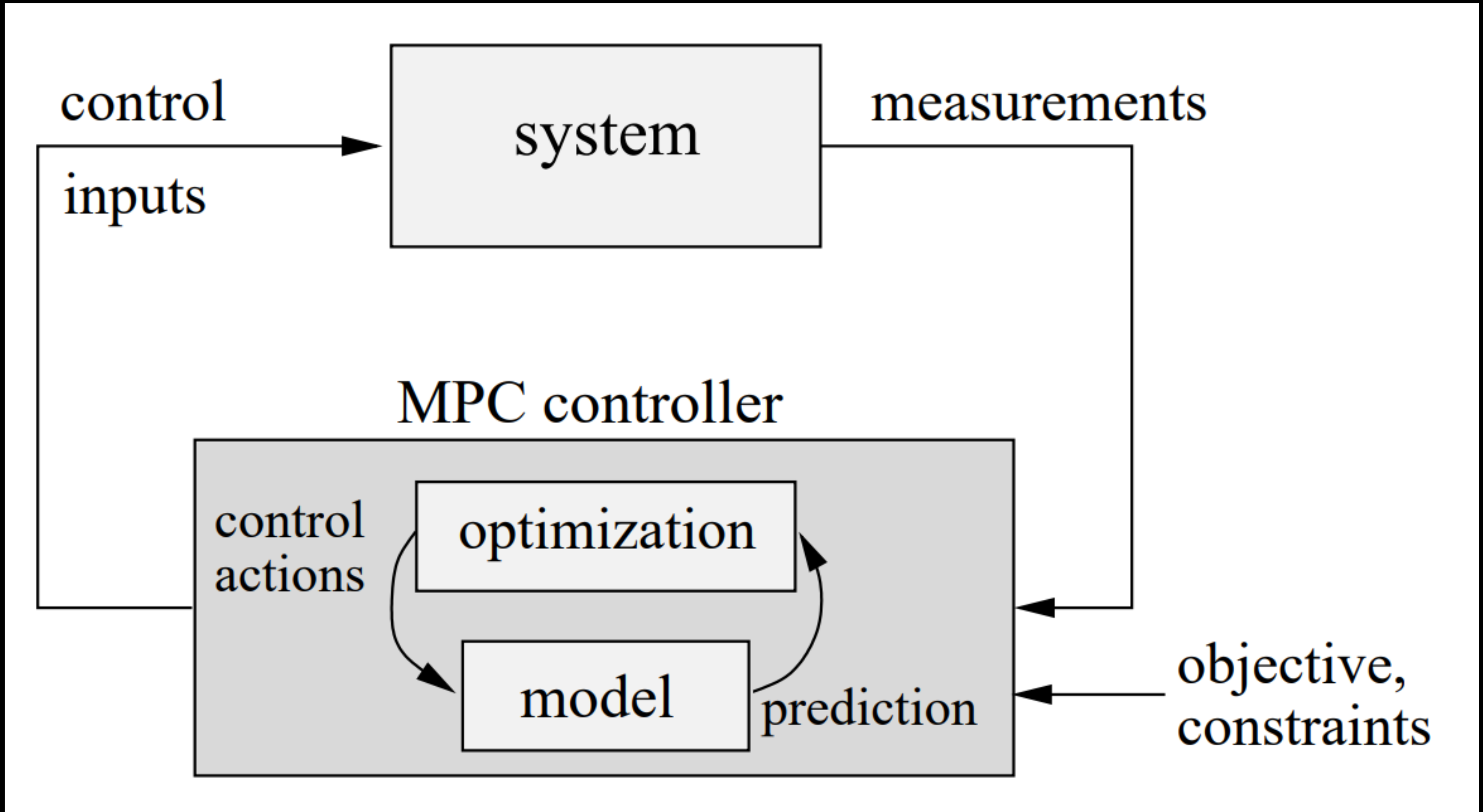
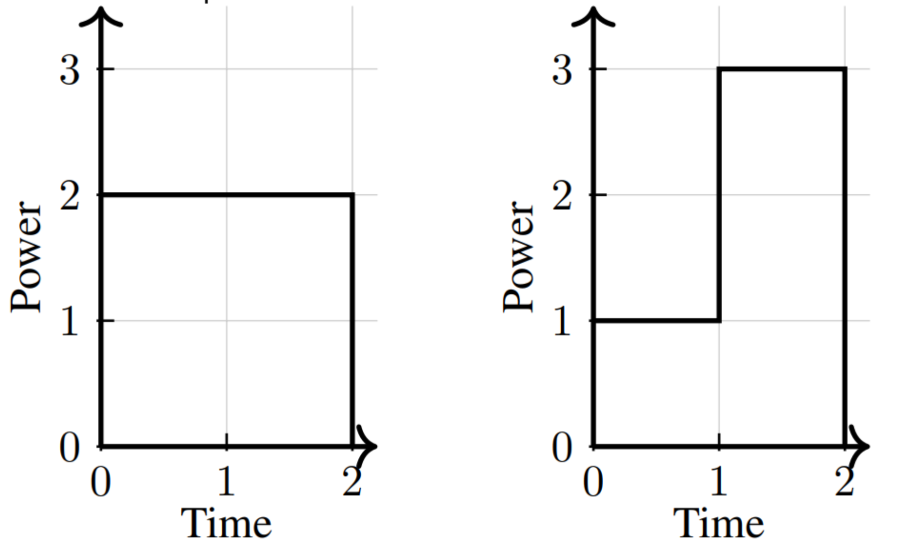


Figure: M. Arnold, R. R. Negenborn, G. Andersson and B. De Schutter, "Multi-area predictive control for combined electricity and natural gas systems," 2009 European Control Conference (ECC)

SPEED SCALING – PROCESSOR SCHEDULING

j	a_j	d_j	e_j	$p_j^{\max}$
1	0	2	2	1
2	1	2	2	2



Without speed-limits With speed-limits

- Jobs j:
  - Arrival times a_j
  - Departure times d_j
  - Work e_j
  - Maximum speed p_j^{max}
- Decision variable:
  - Job schedules s_j(t)
- Objective function (energy):
  - $\int_t (\sum_j s_j(t))^2 \, dt$

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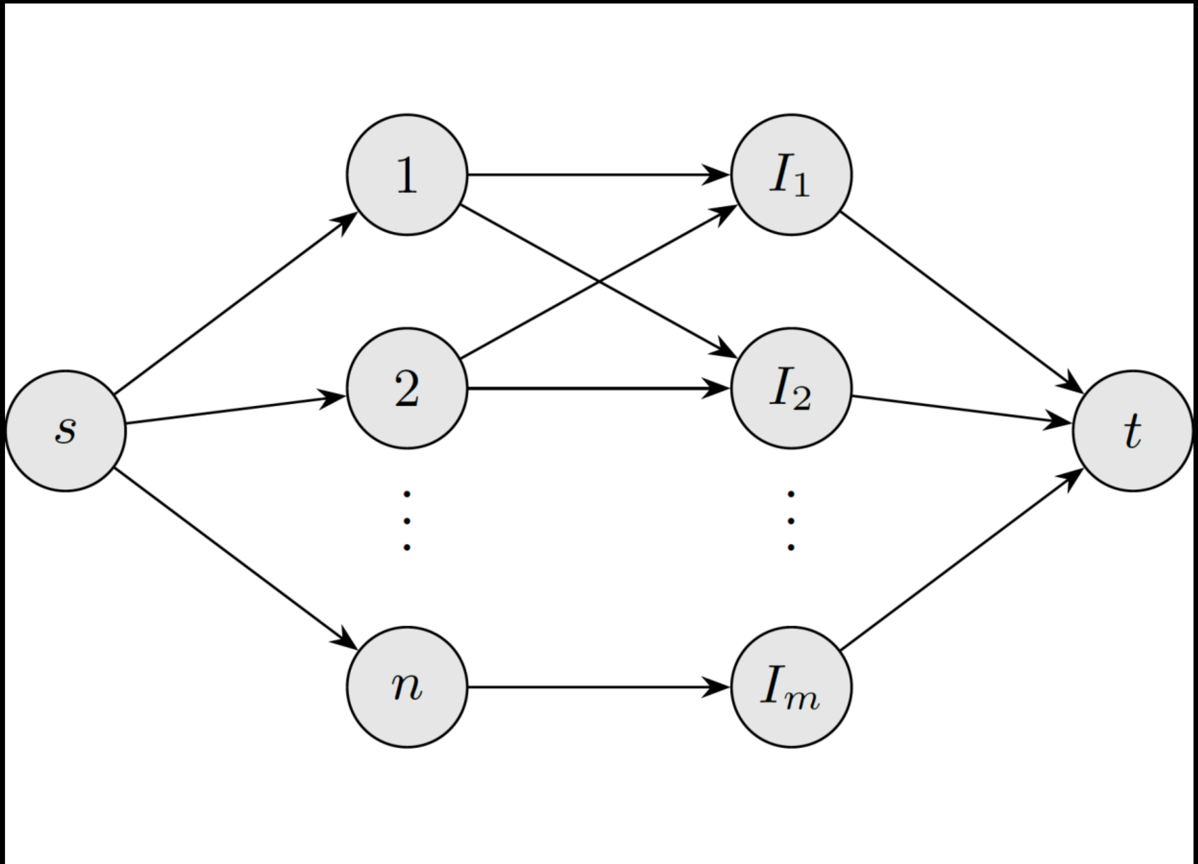
SPEED SCALING – FLOW MODEL



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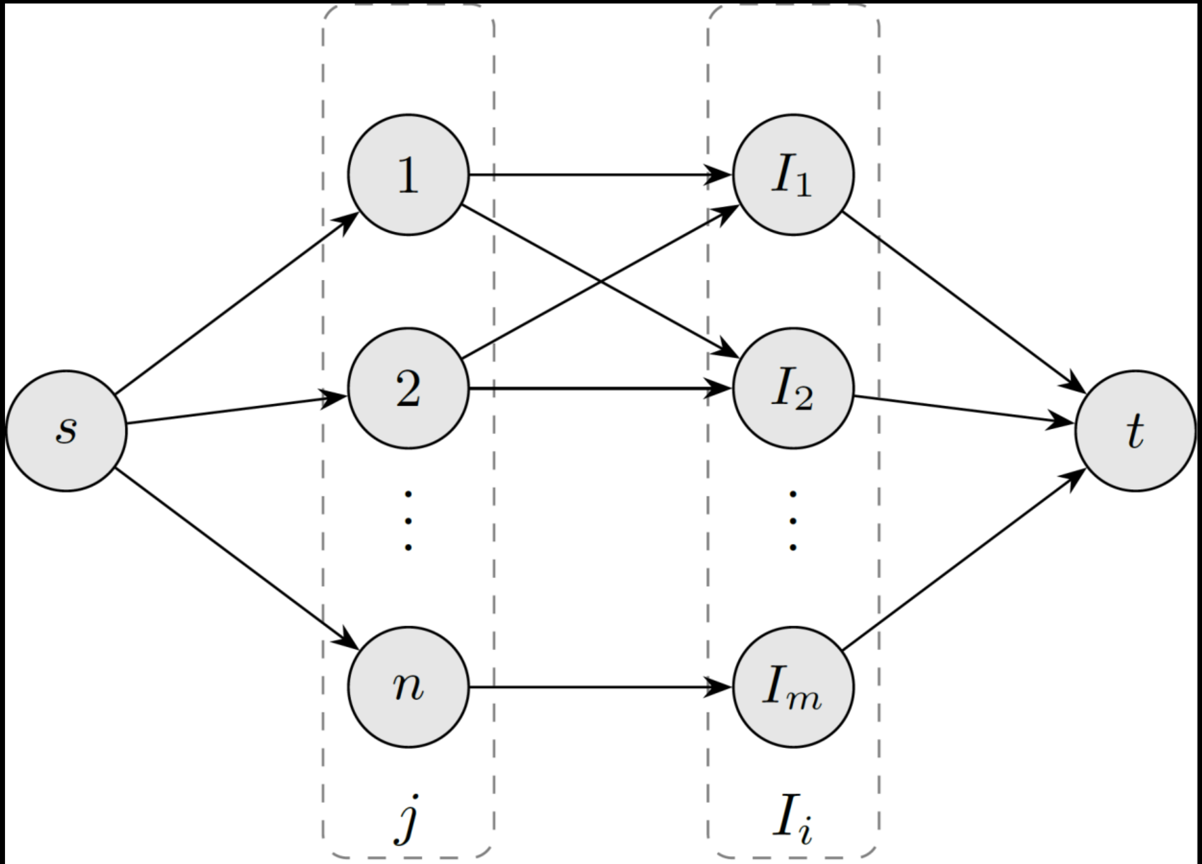

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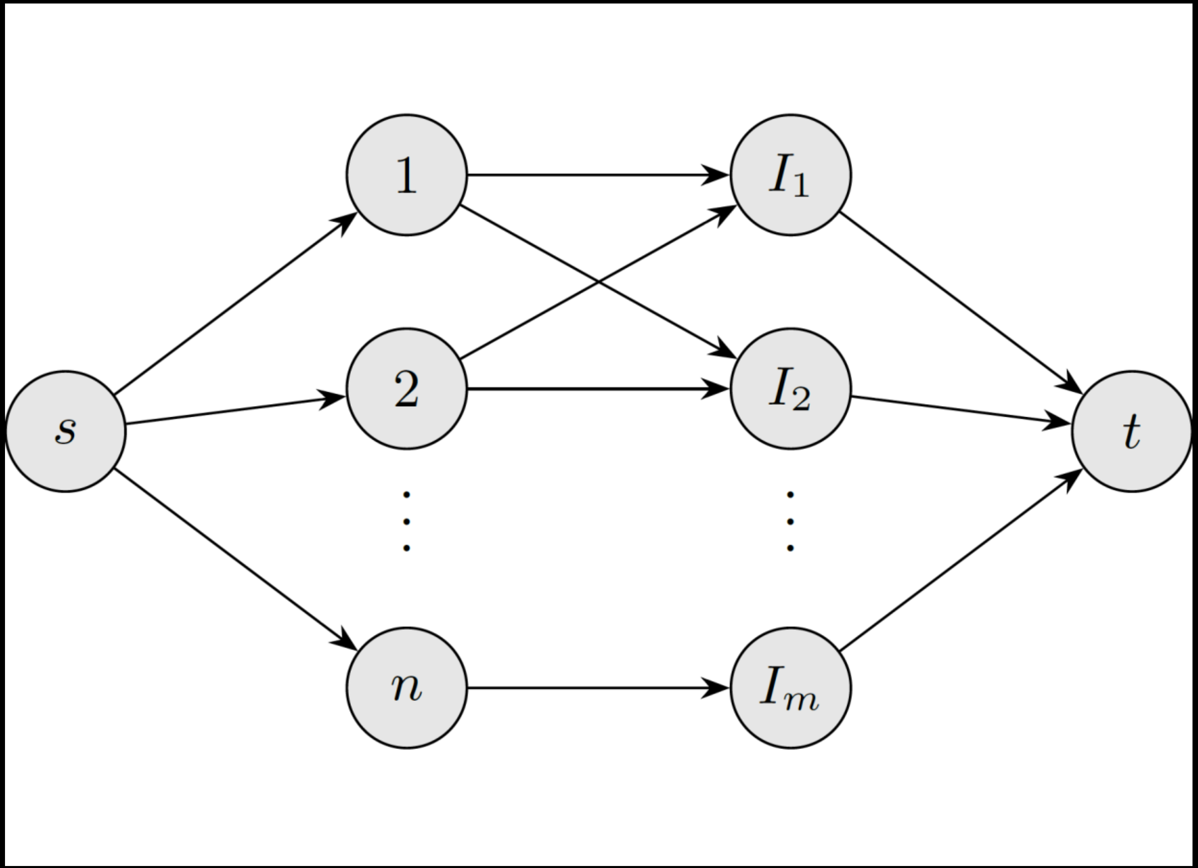
SPEED SCALING – FLOW MODEL



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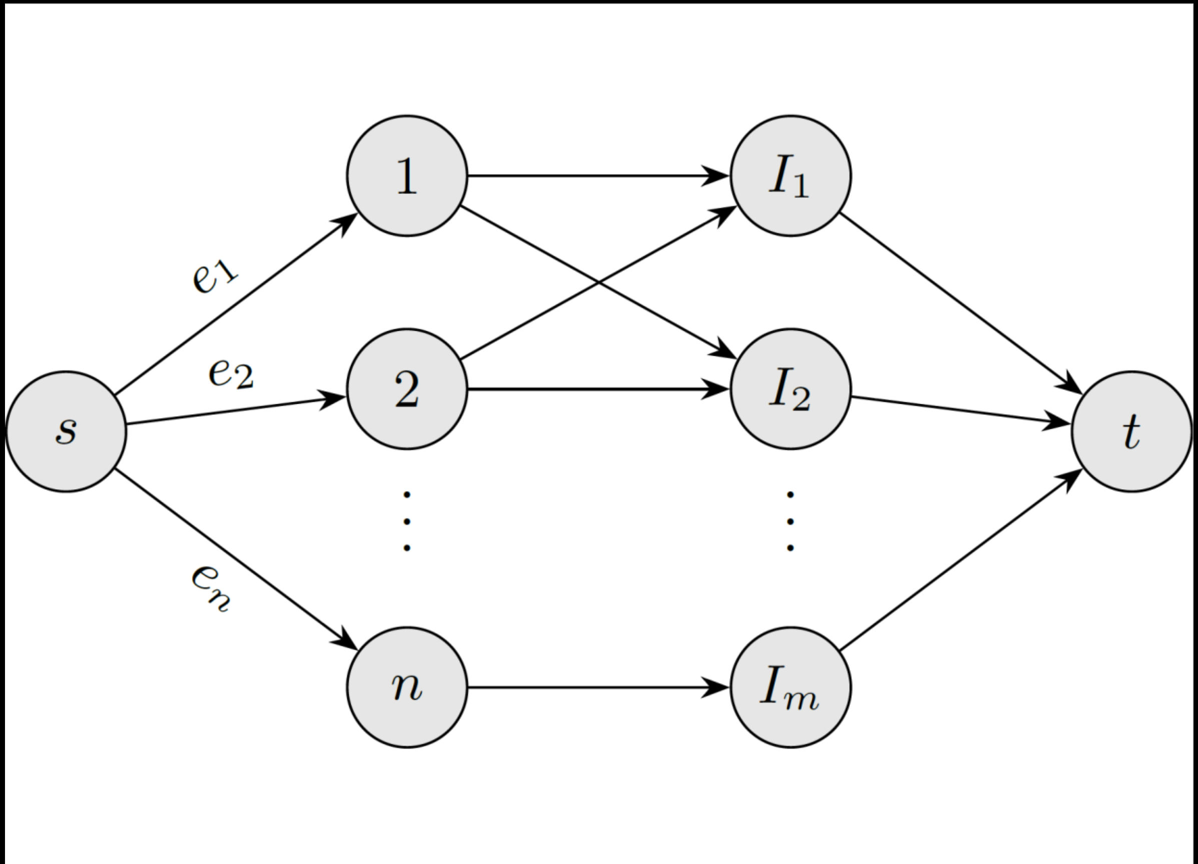
SPEED SCALING – FLOW MODEL



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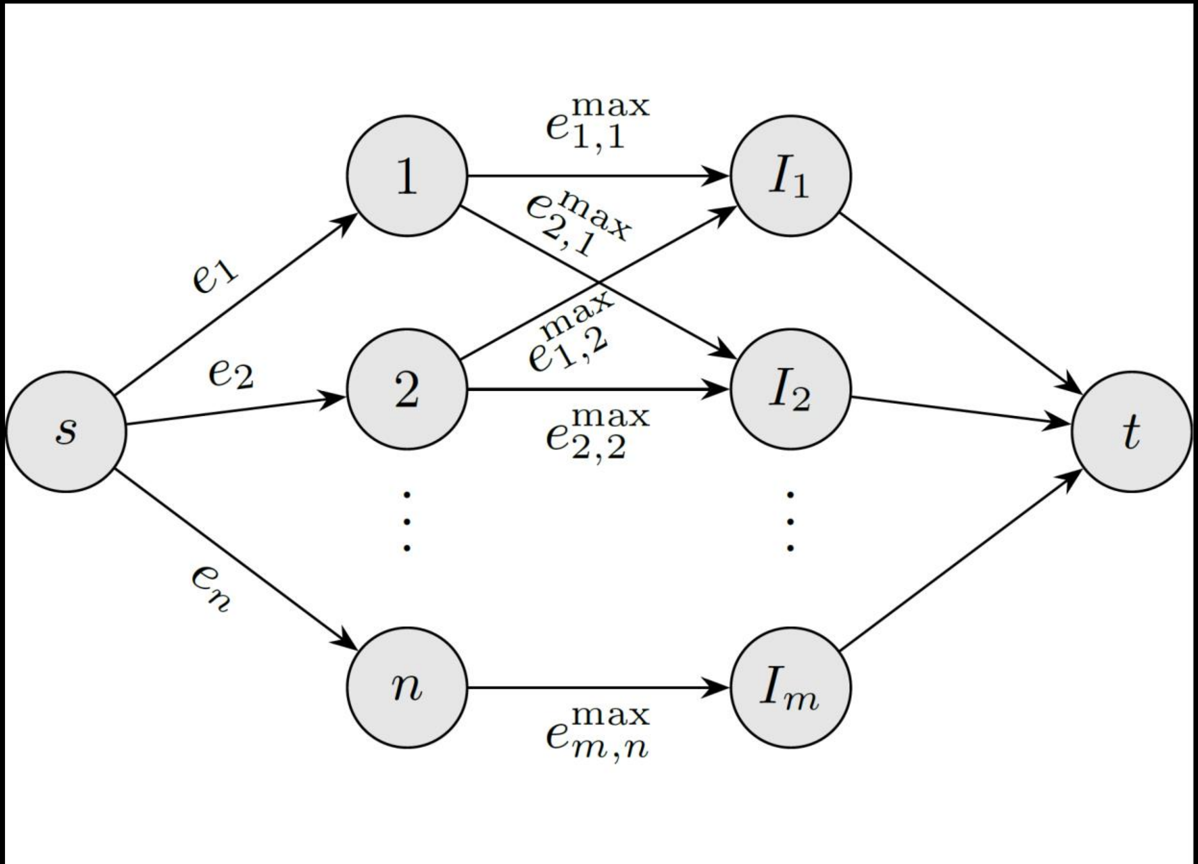

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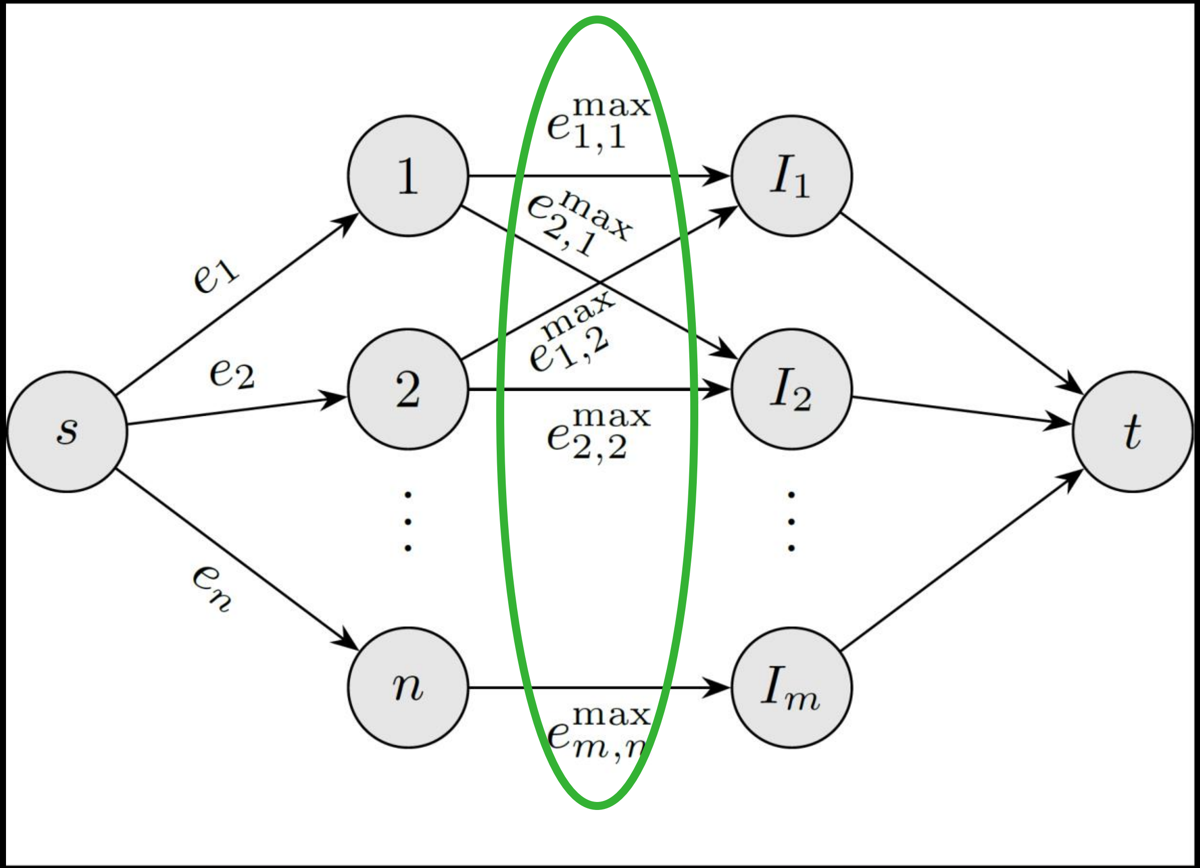
SPEED SCALING – FLOW MODEL



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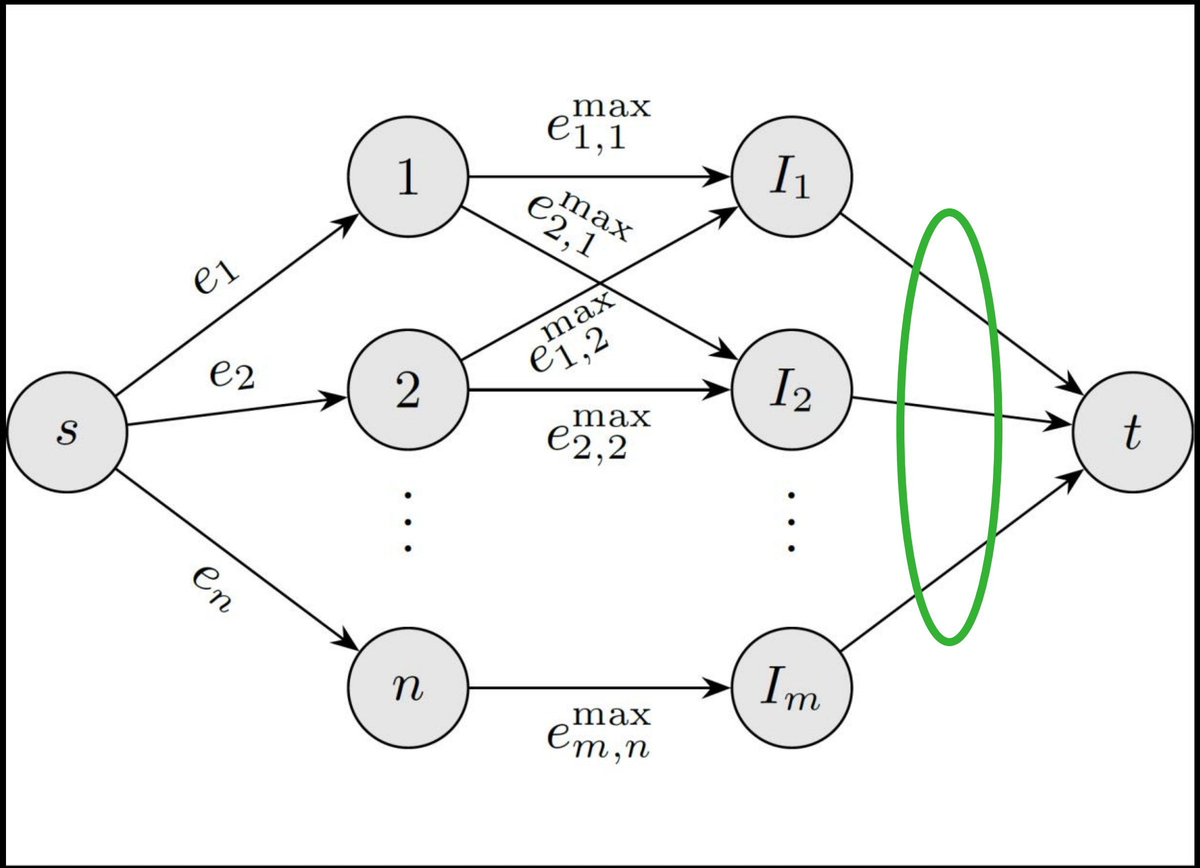
SPEED SCALING – FLOW MODEL



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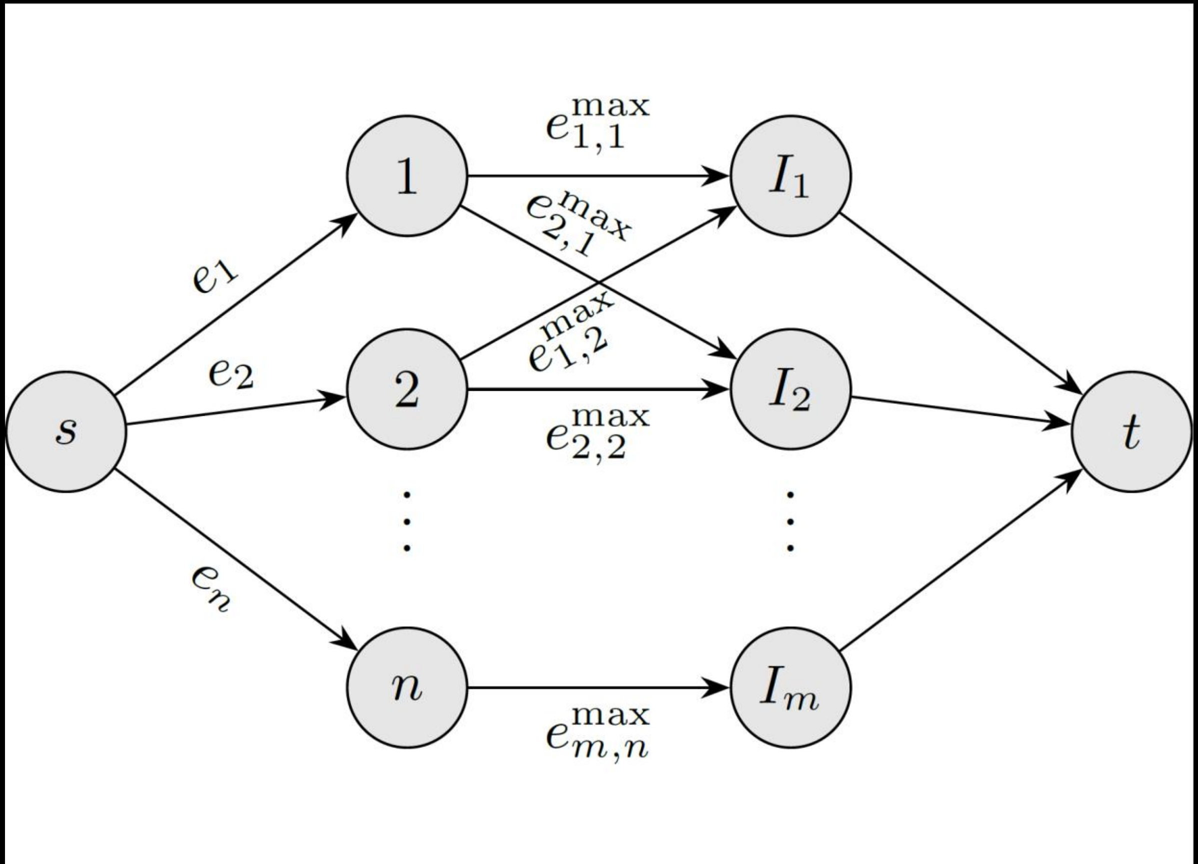

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FOCS:
FLOW-BASED OFFLINE CHARGING SCHEDULER

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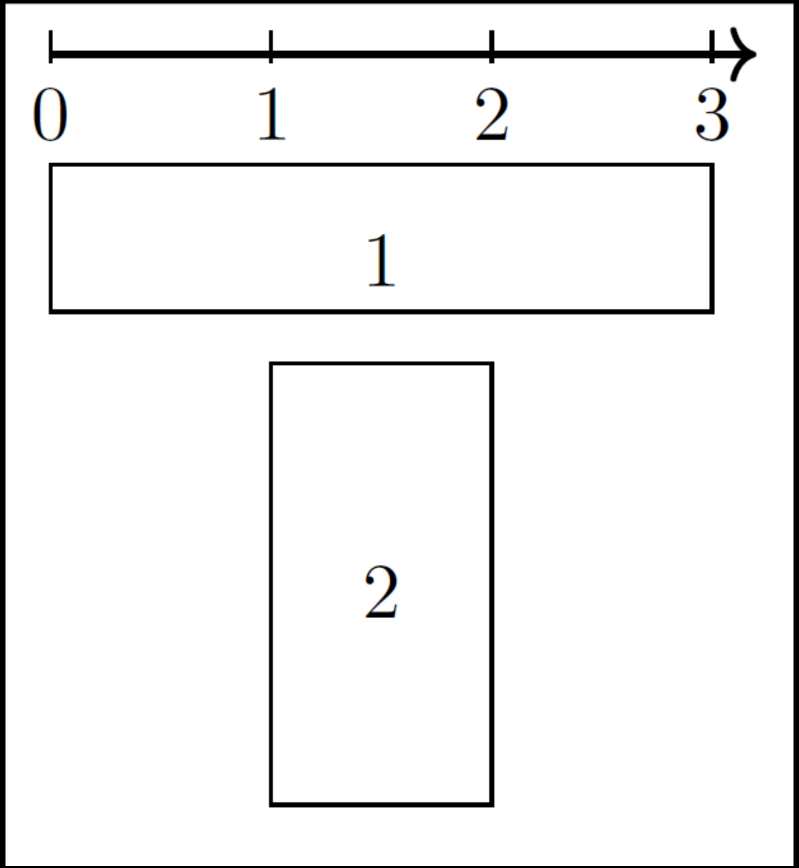
FOCS – ILLUSTRATIVE EXAMPLE

j	a_j	d_j	e_j	$p_j^{\max}$
1	0	3	2	2
2	1	2	2	2



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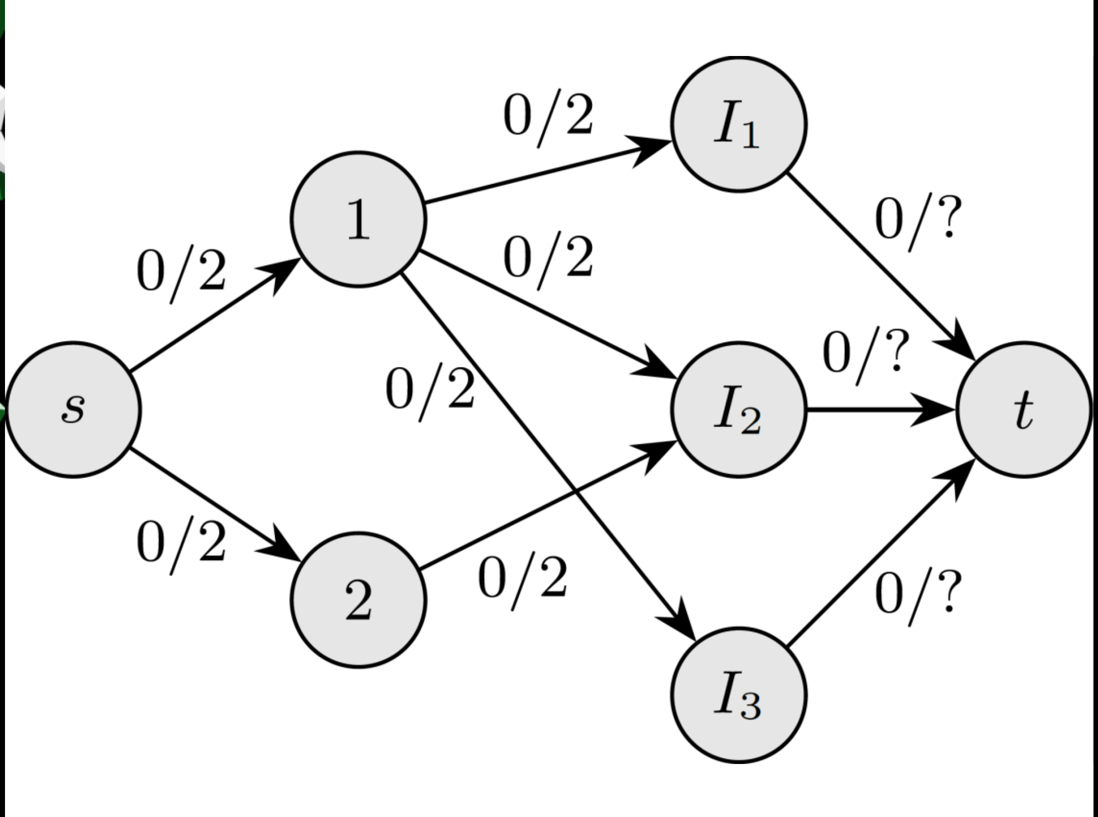

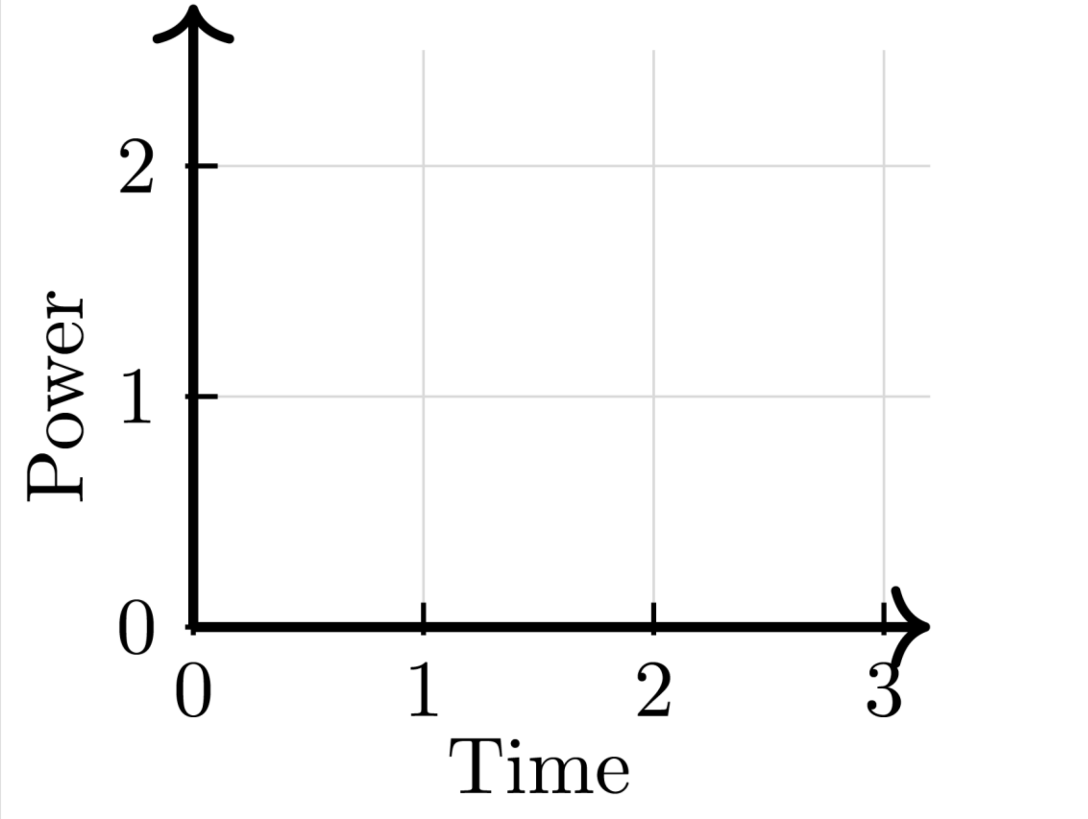

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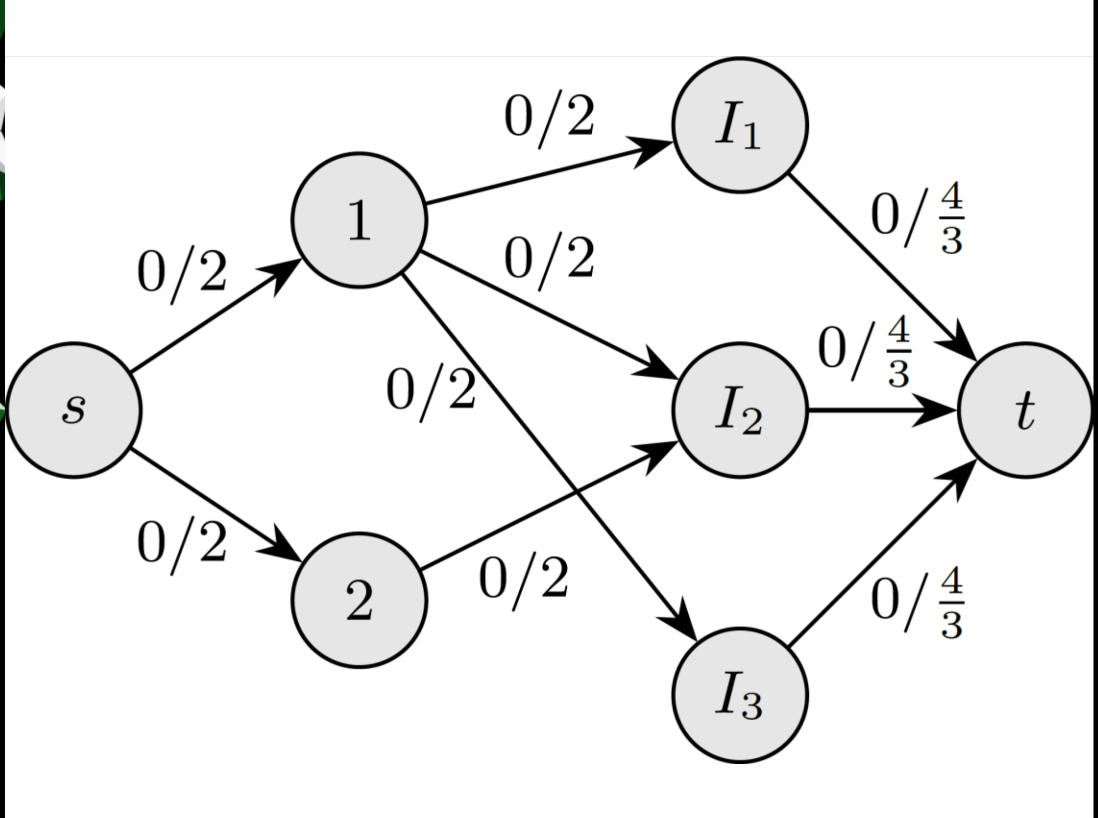

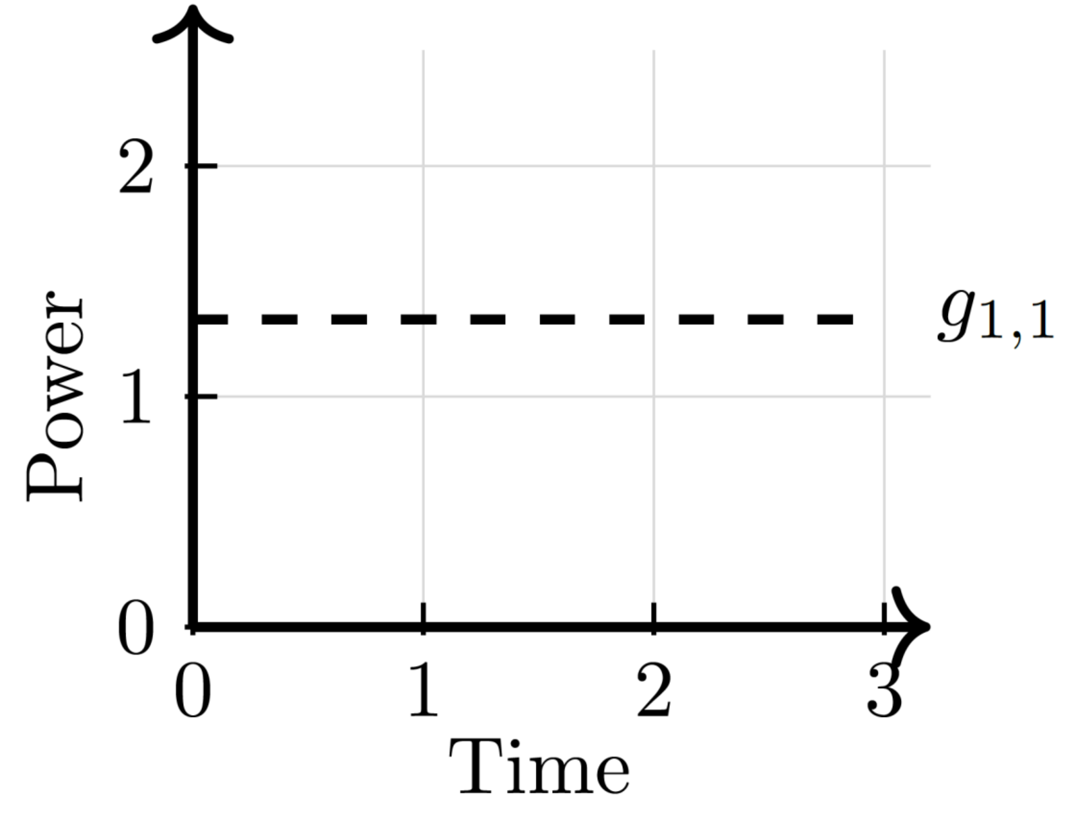

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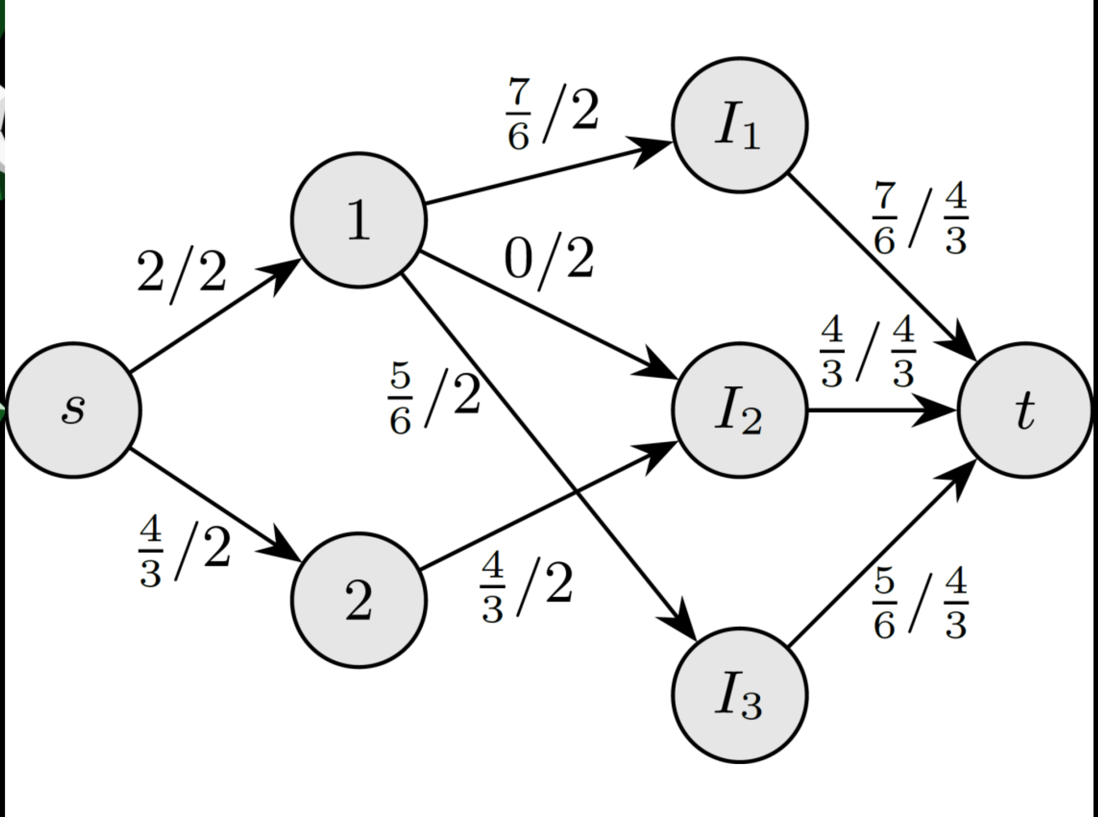

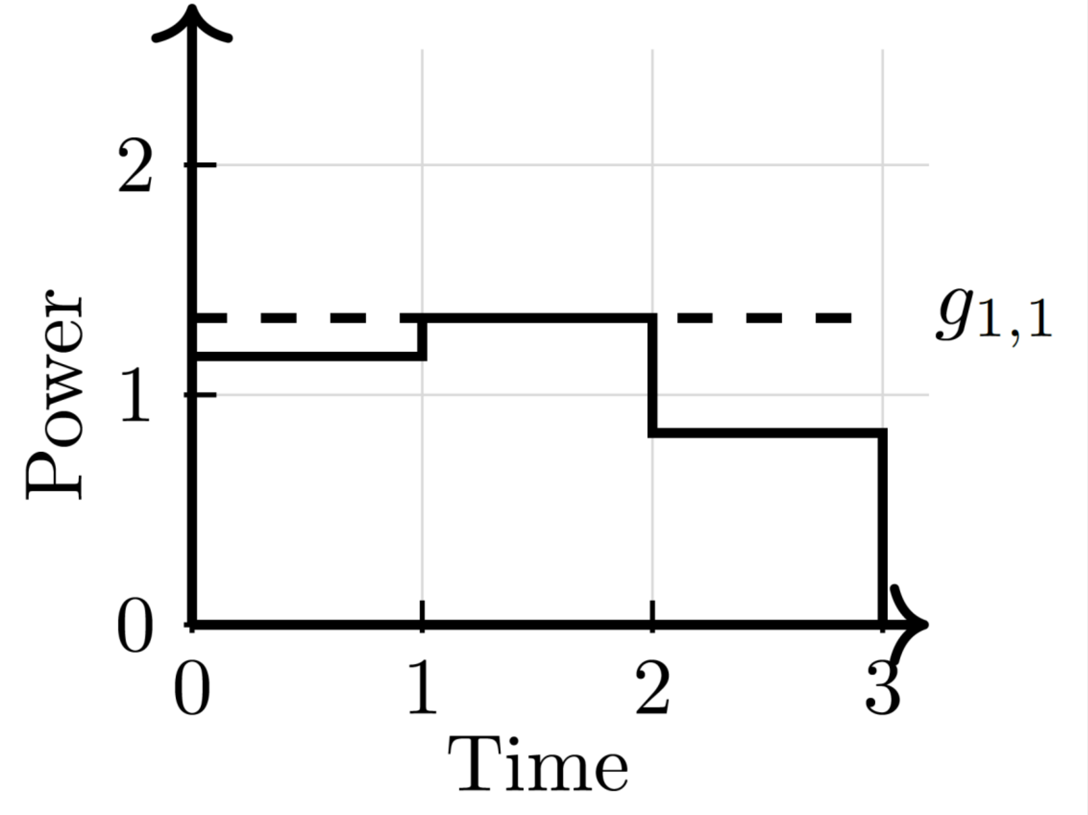

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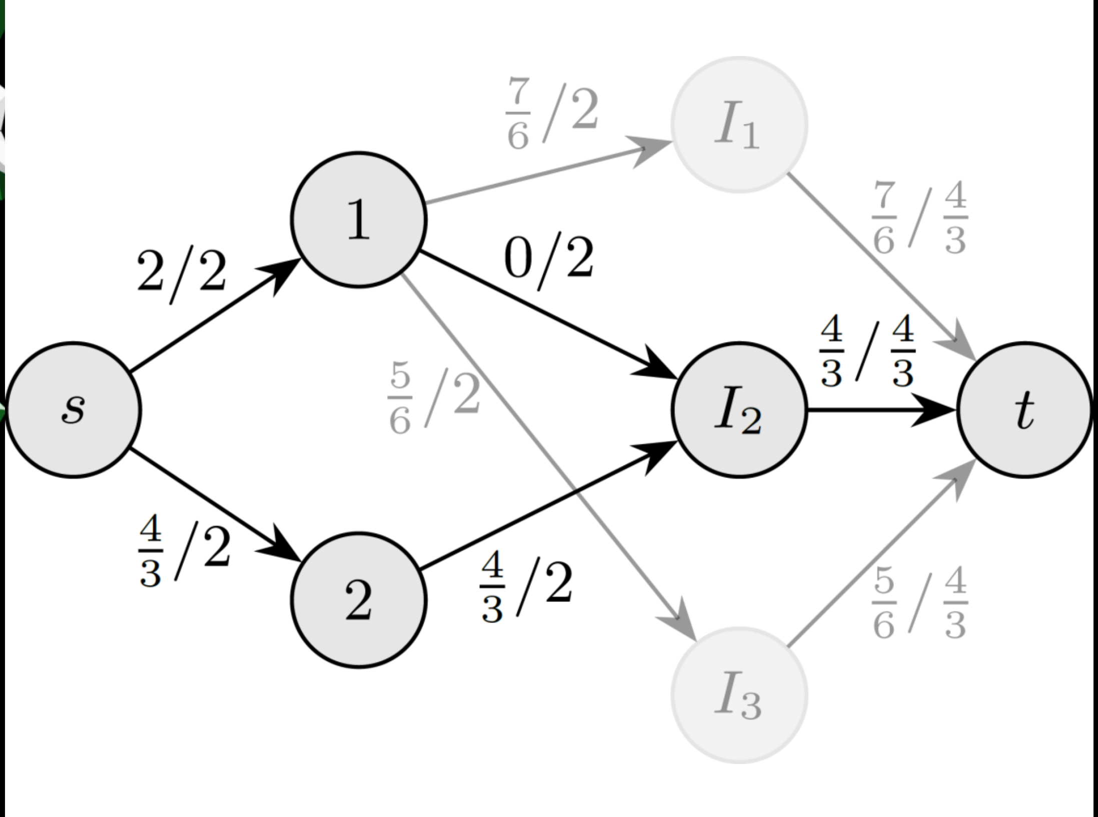

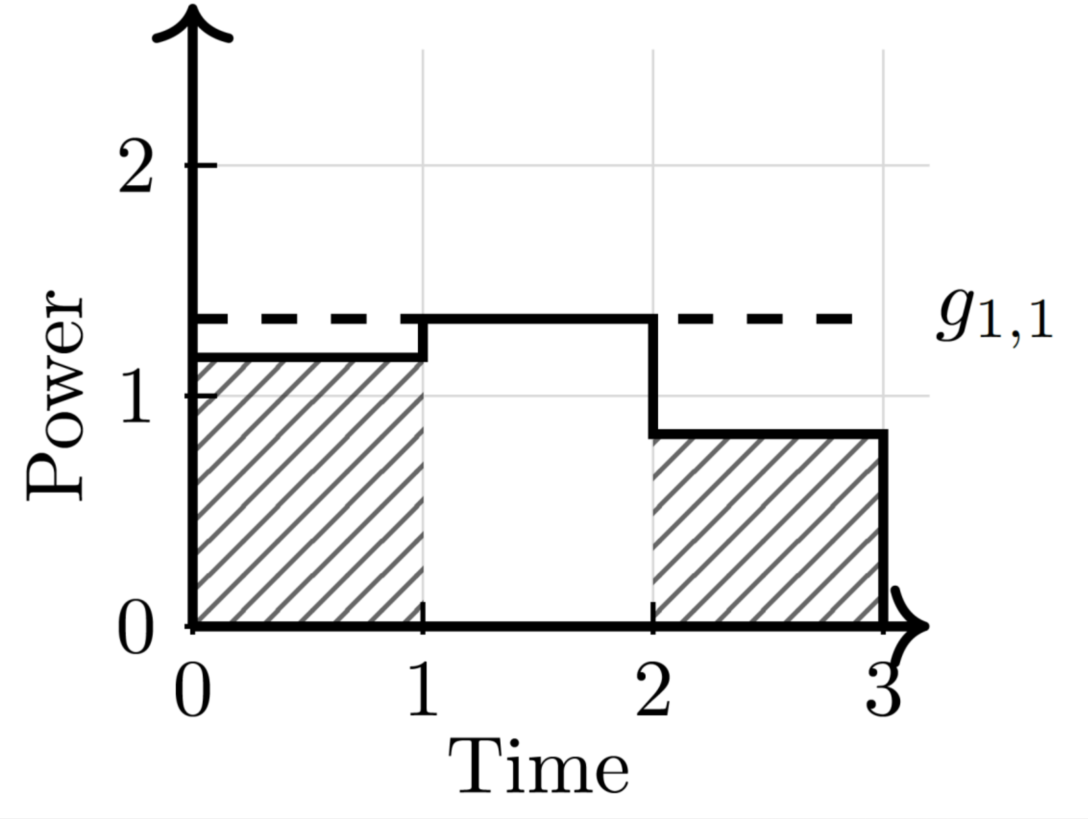

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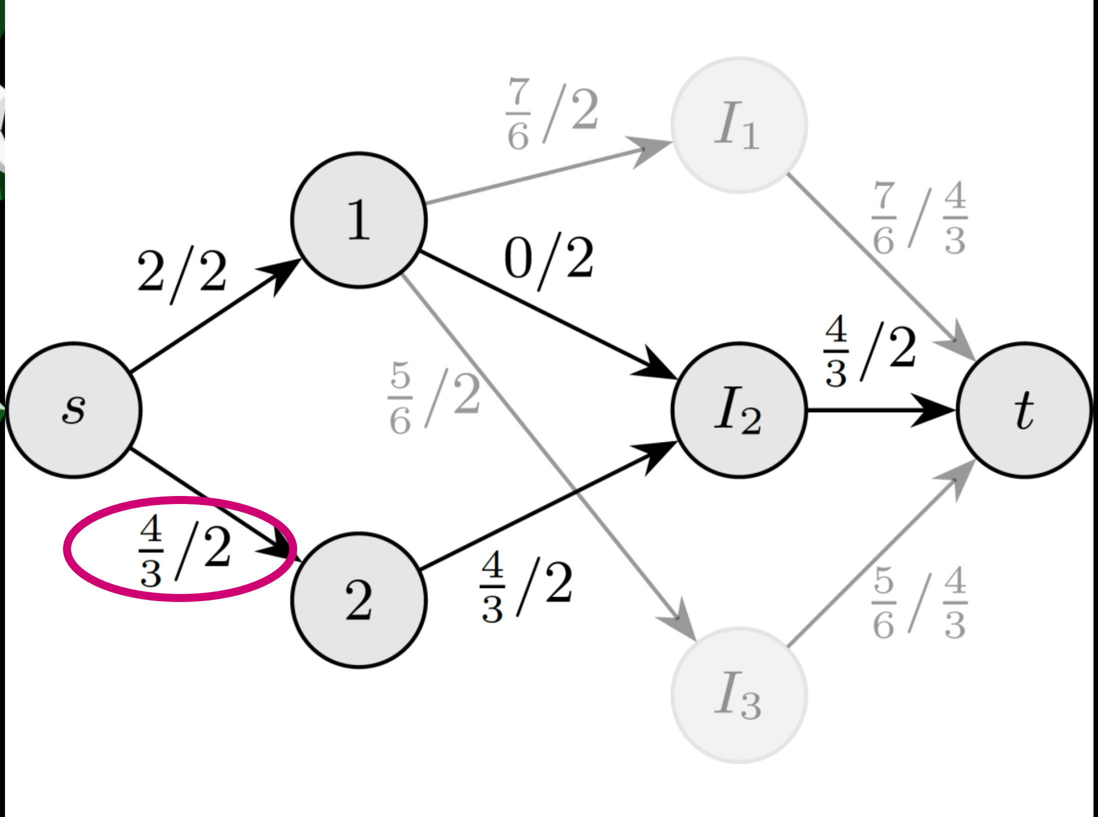

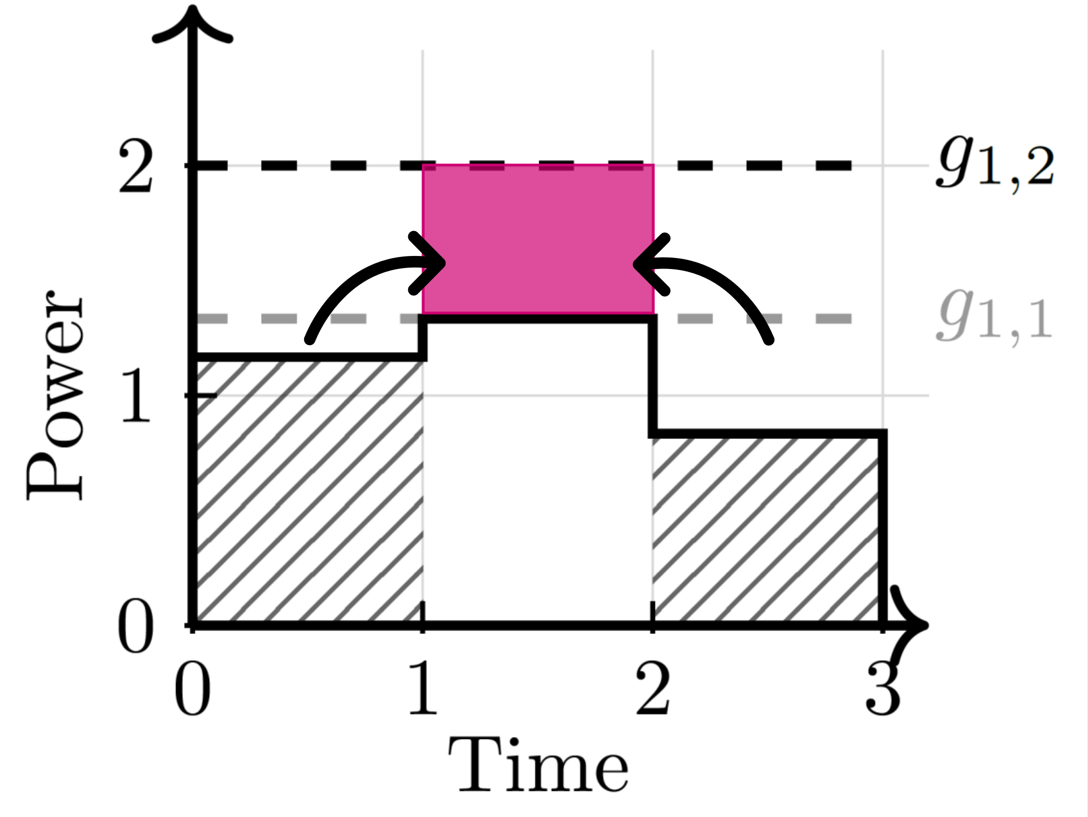

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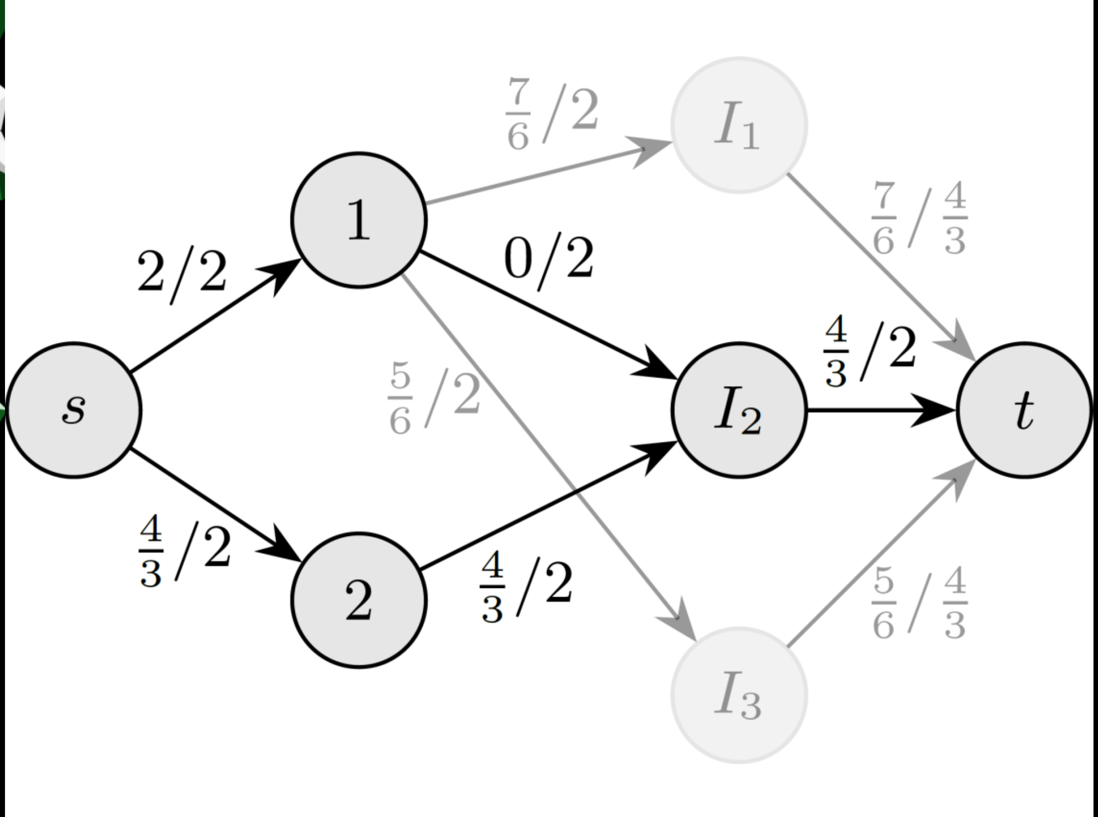

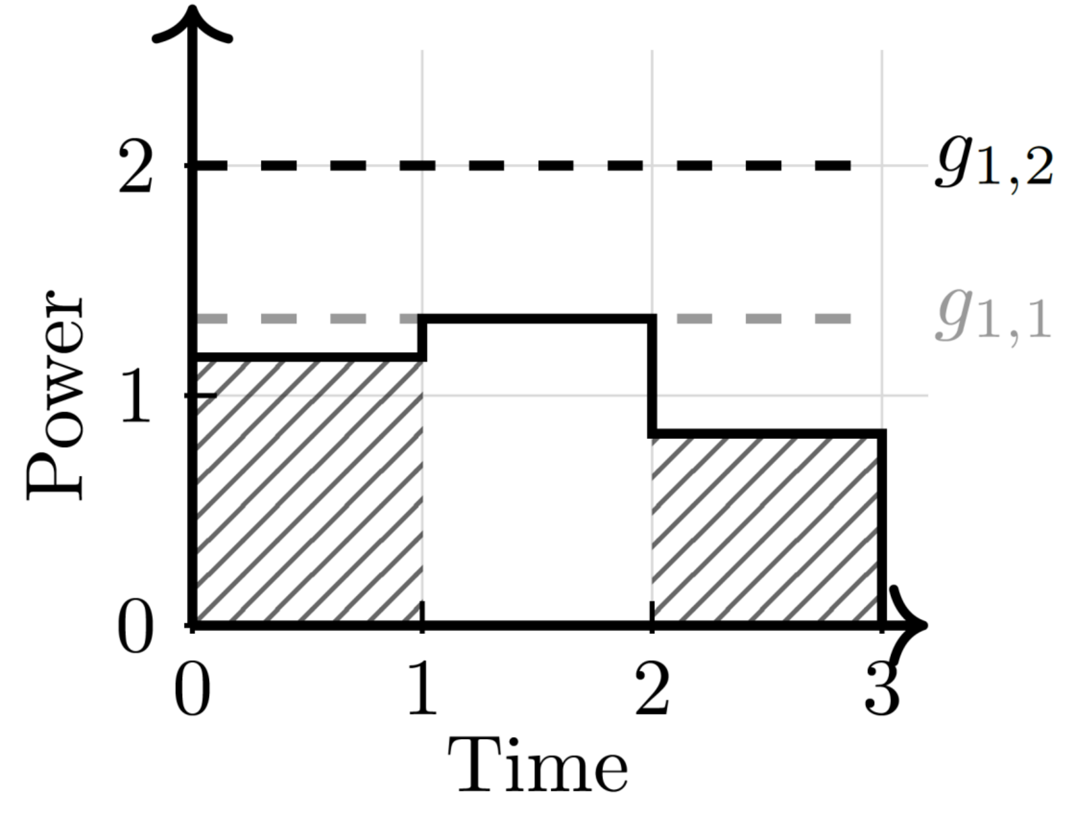

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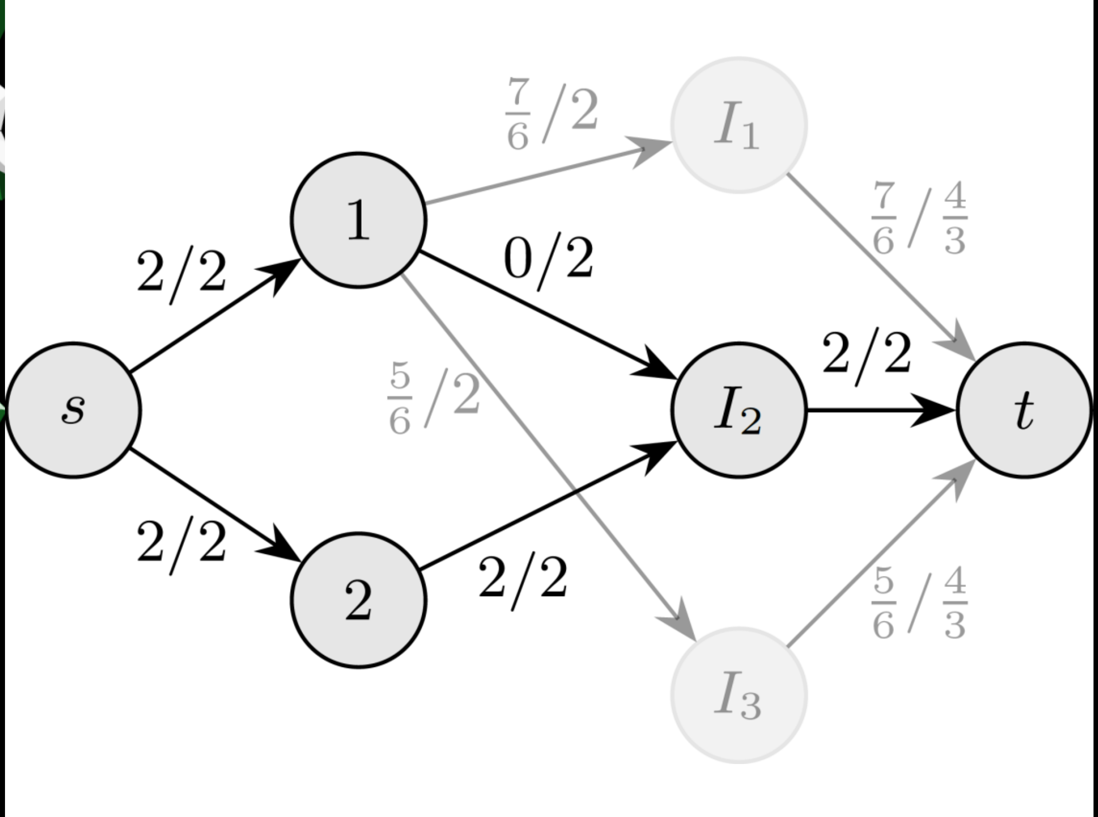

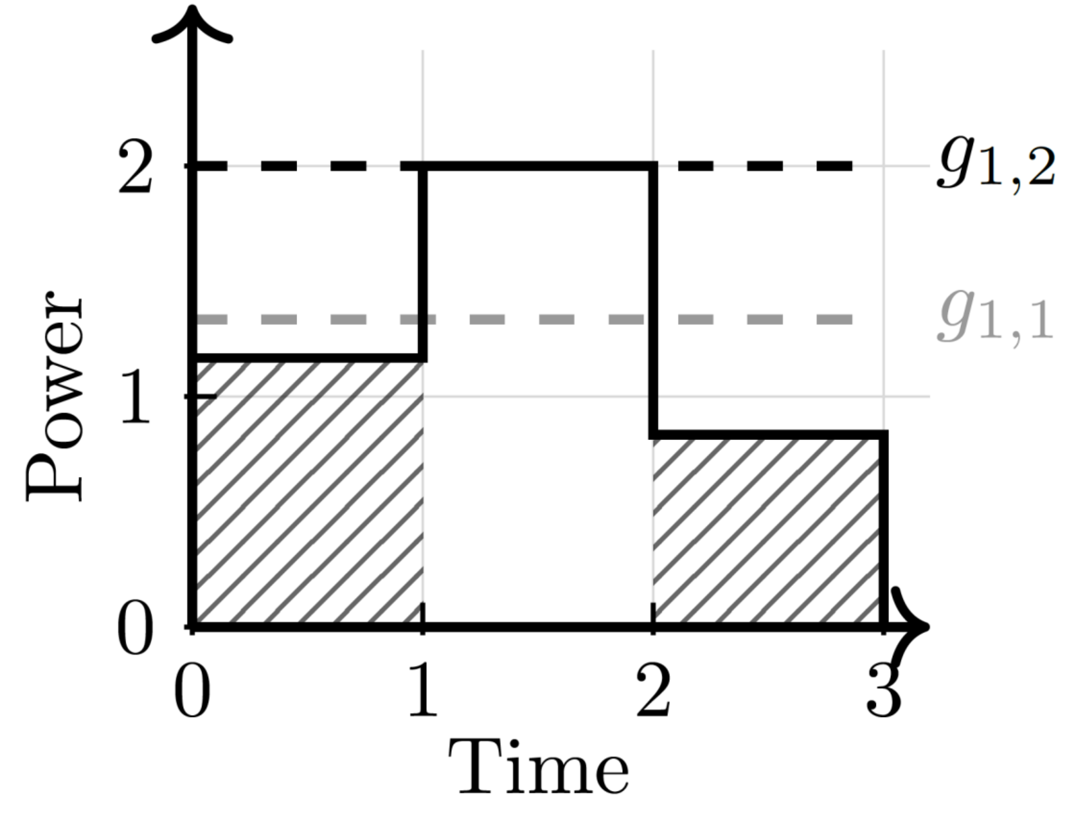

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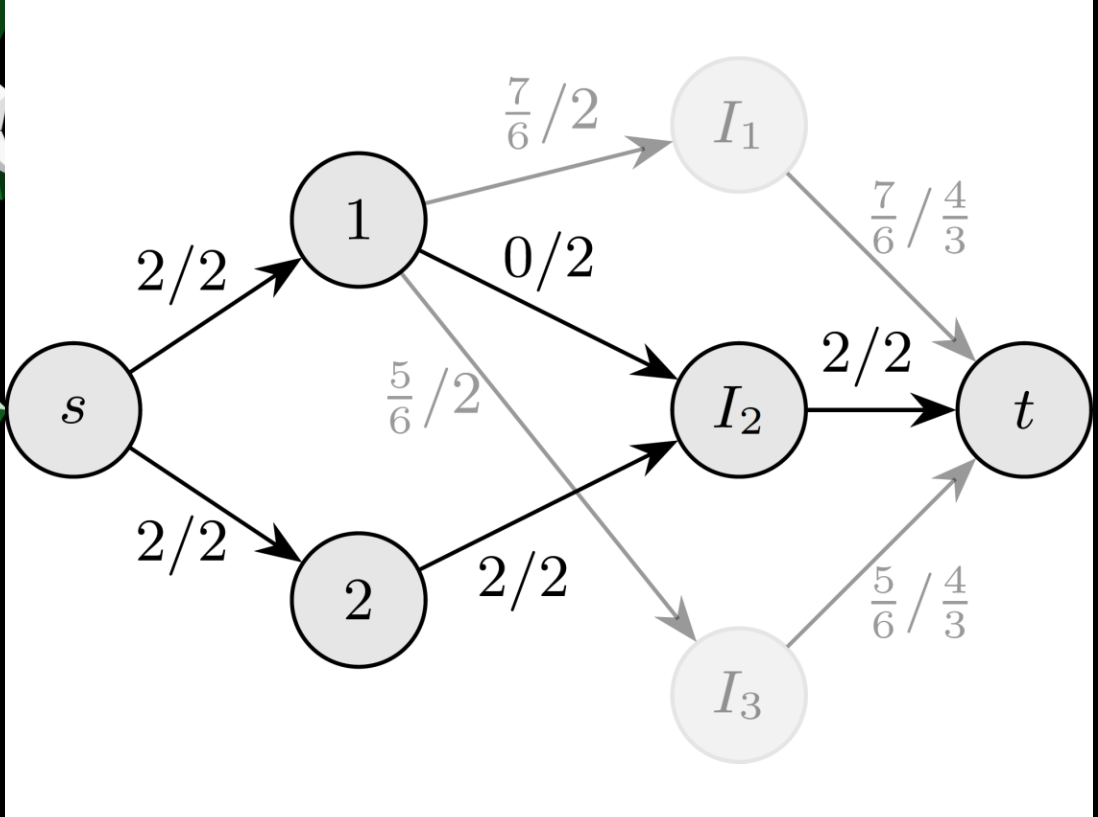

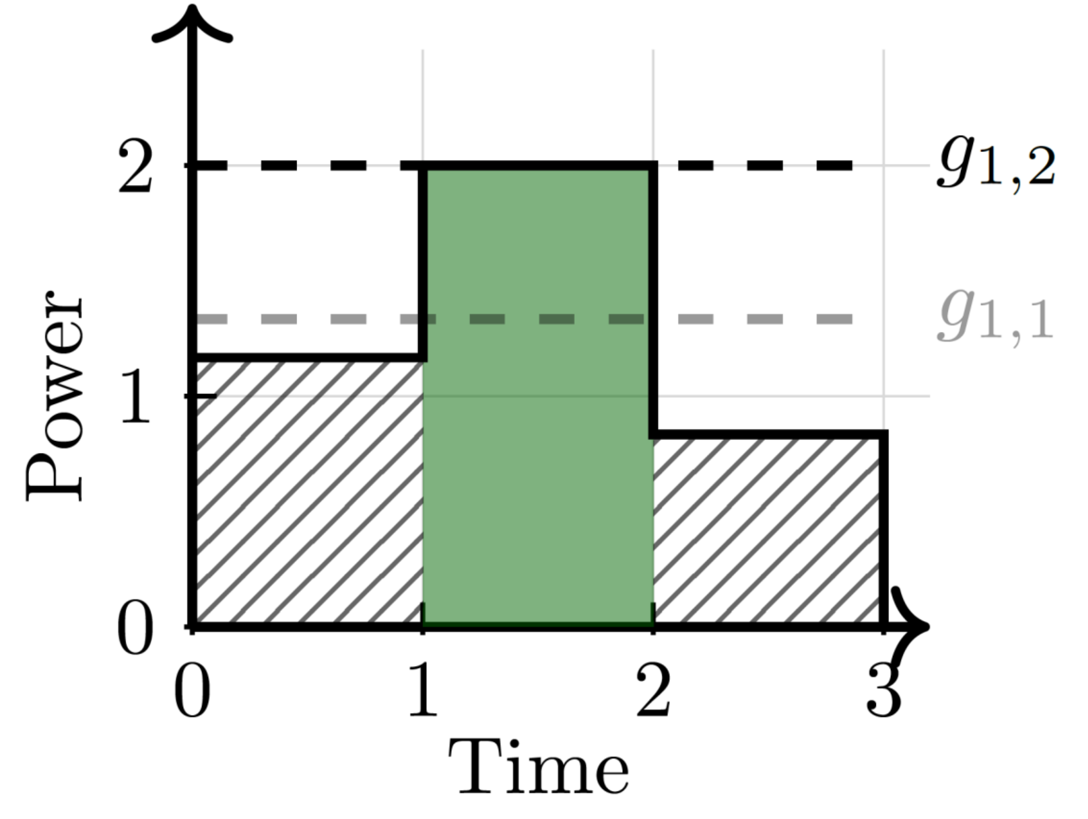

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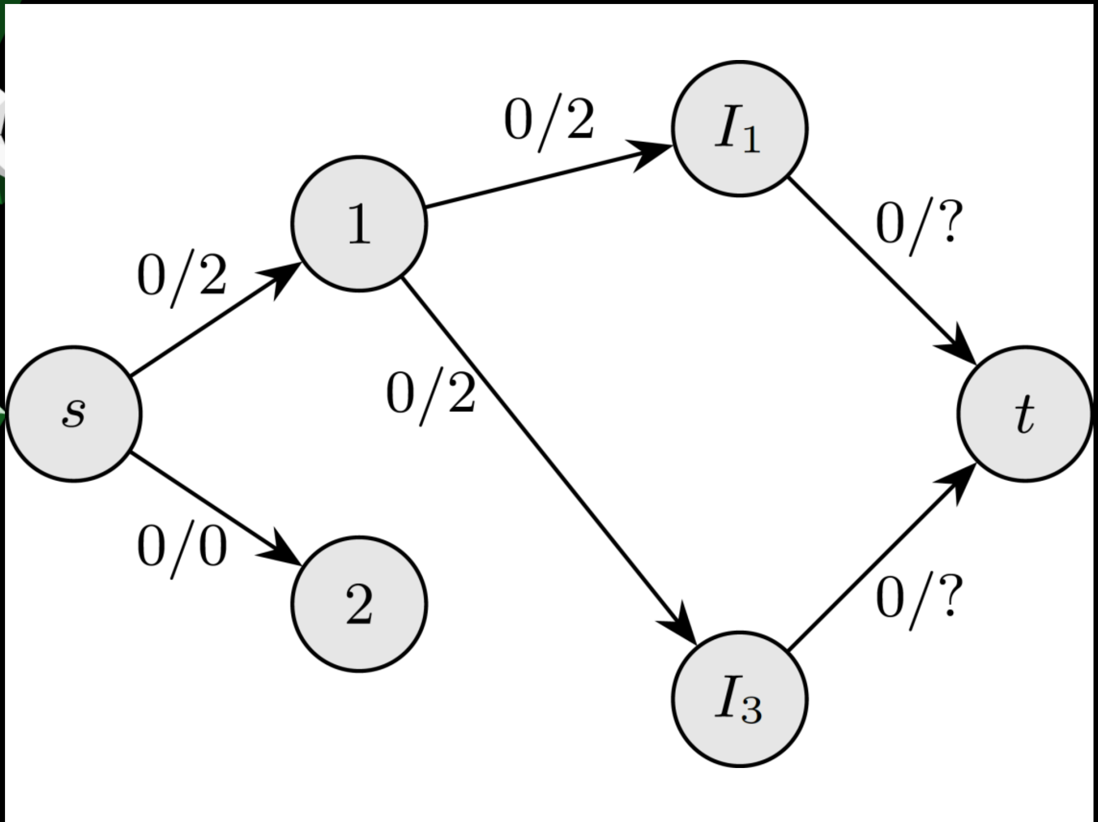

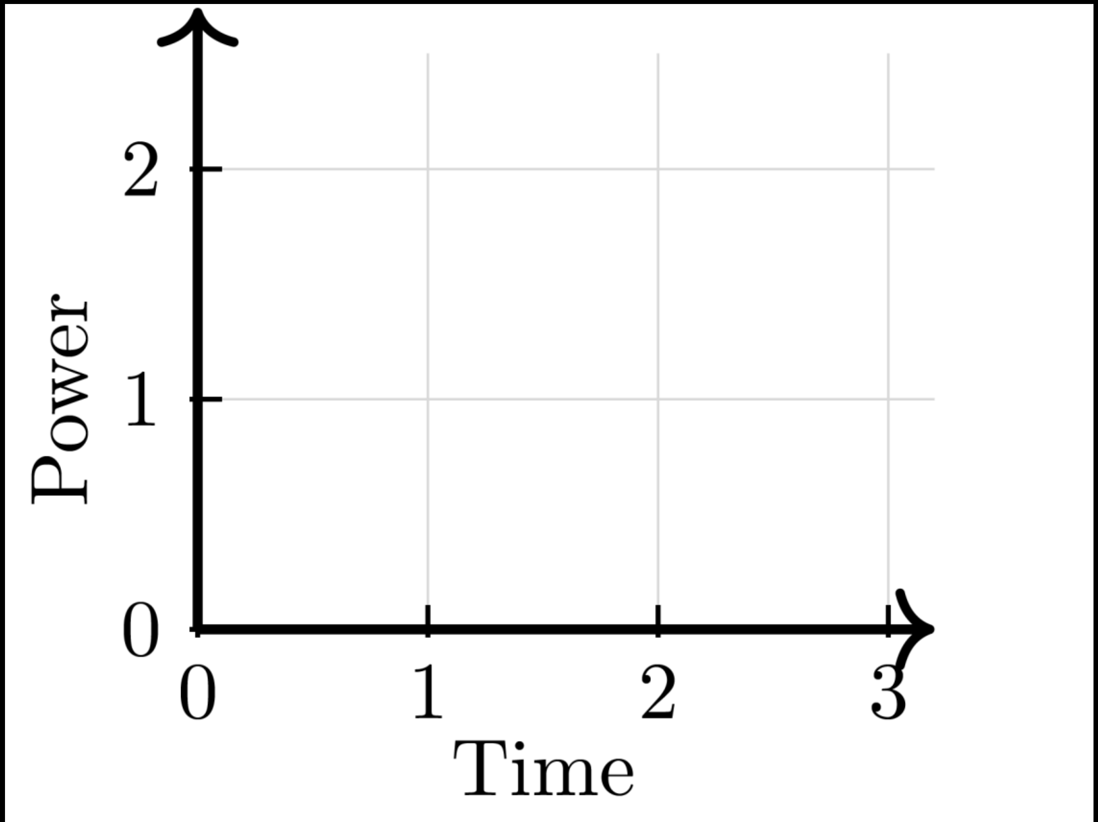

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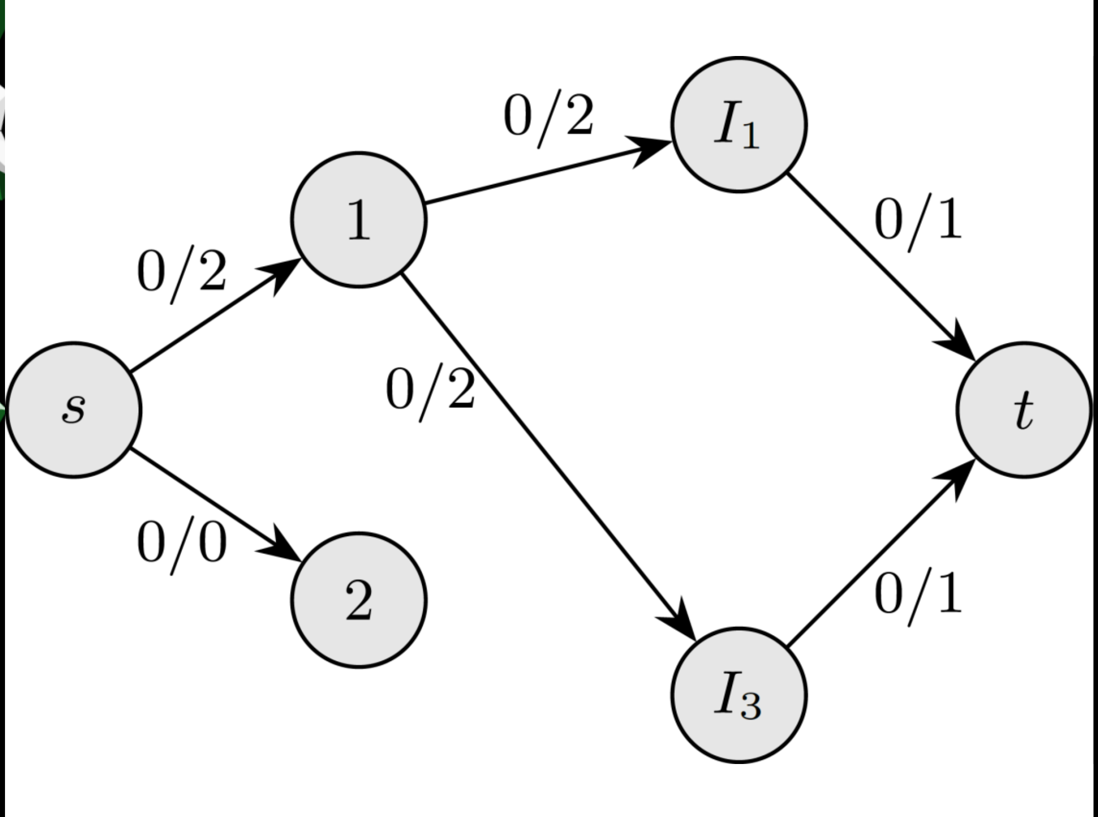

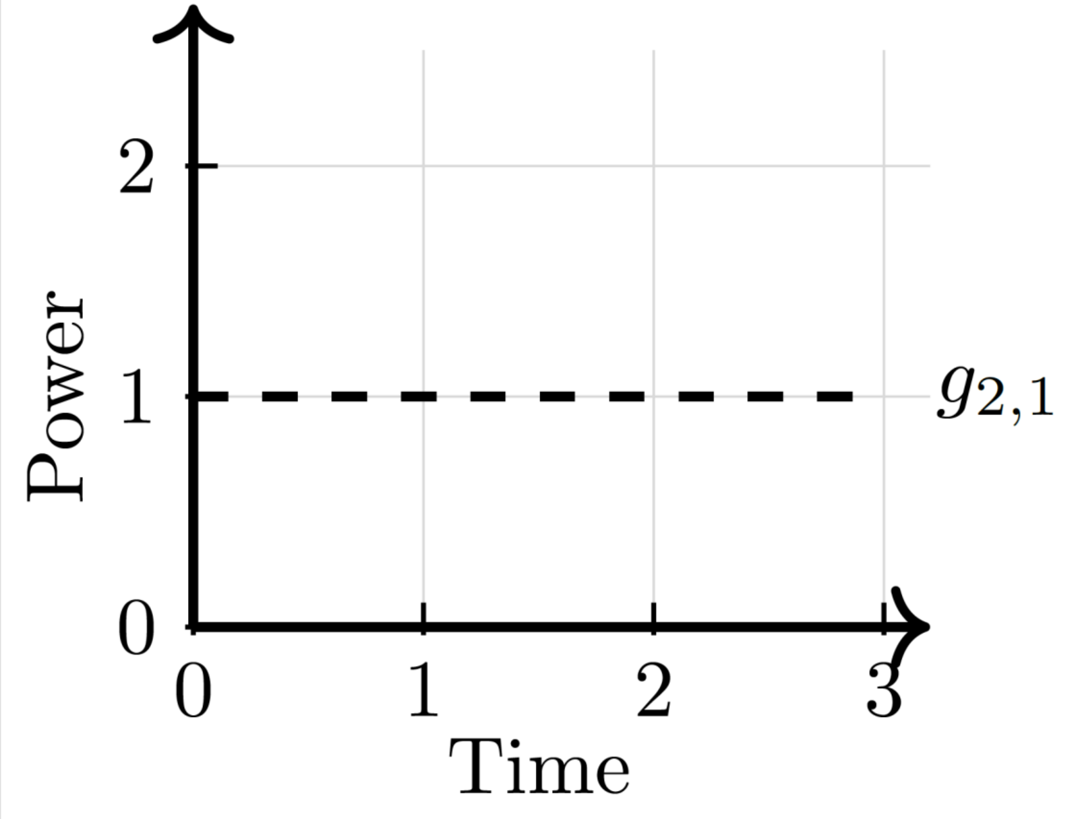

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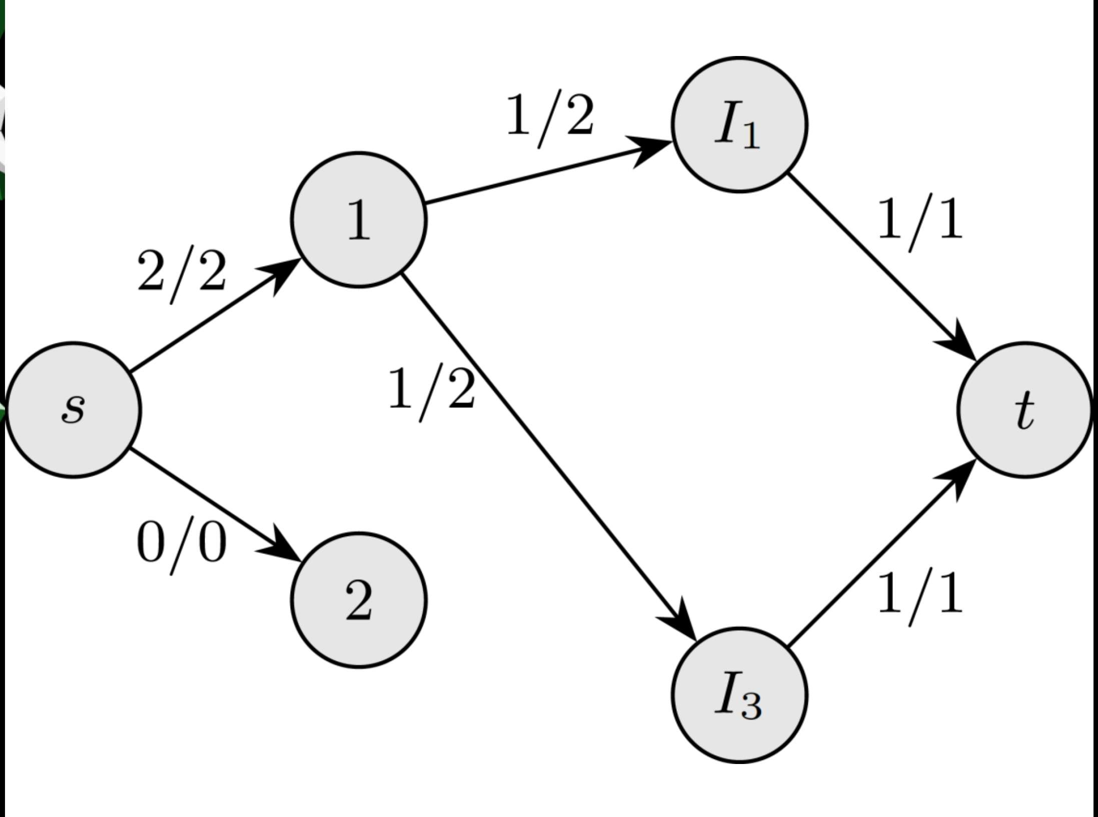

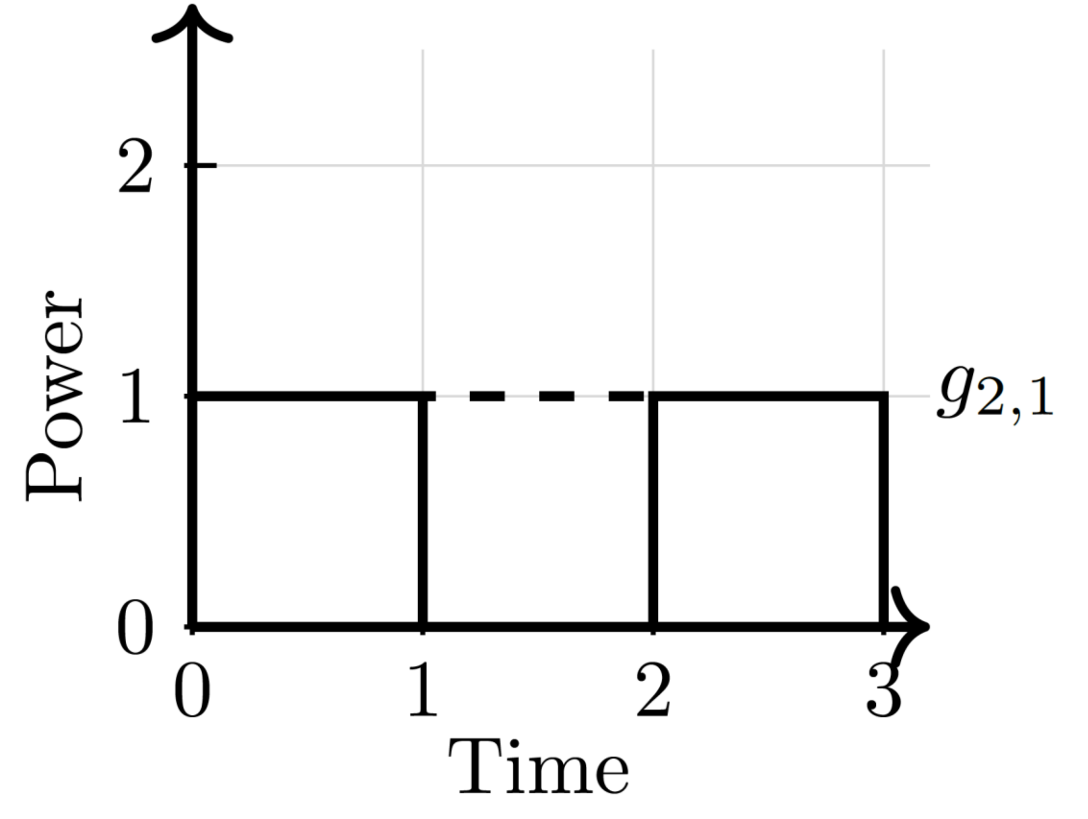

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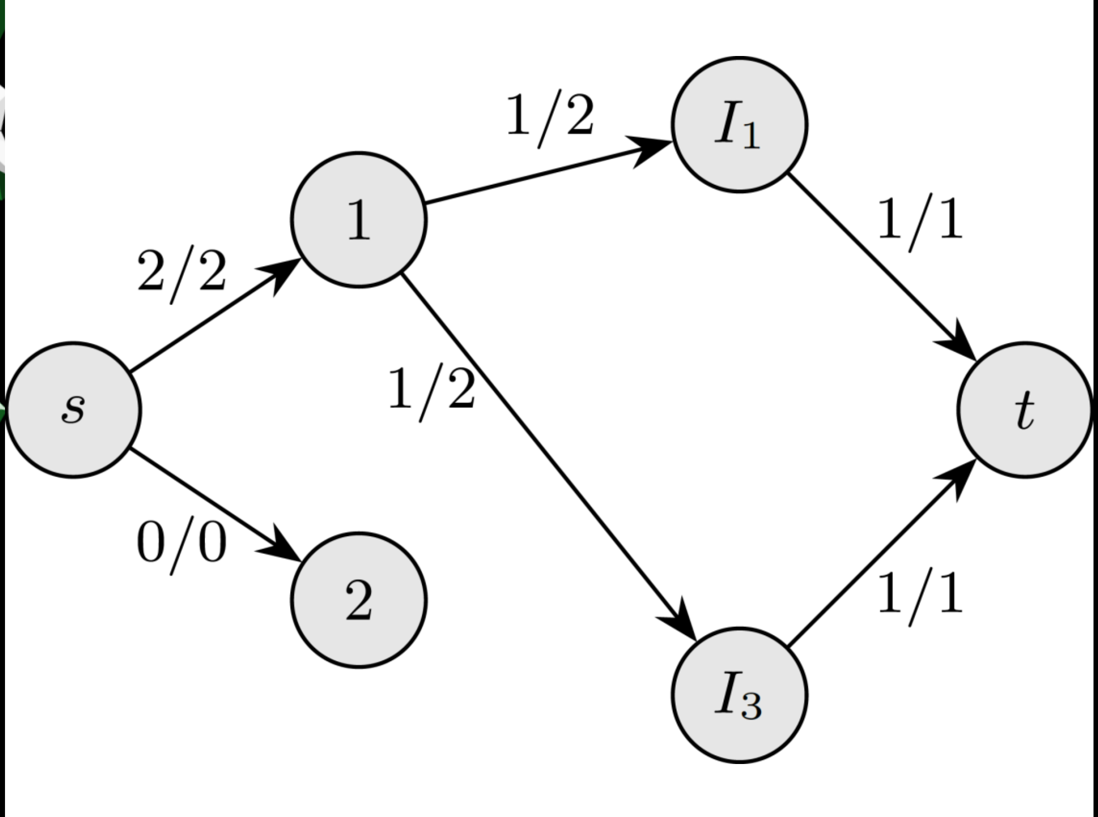

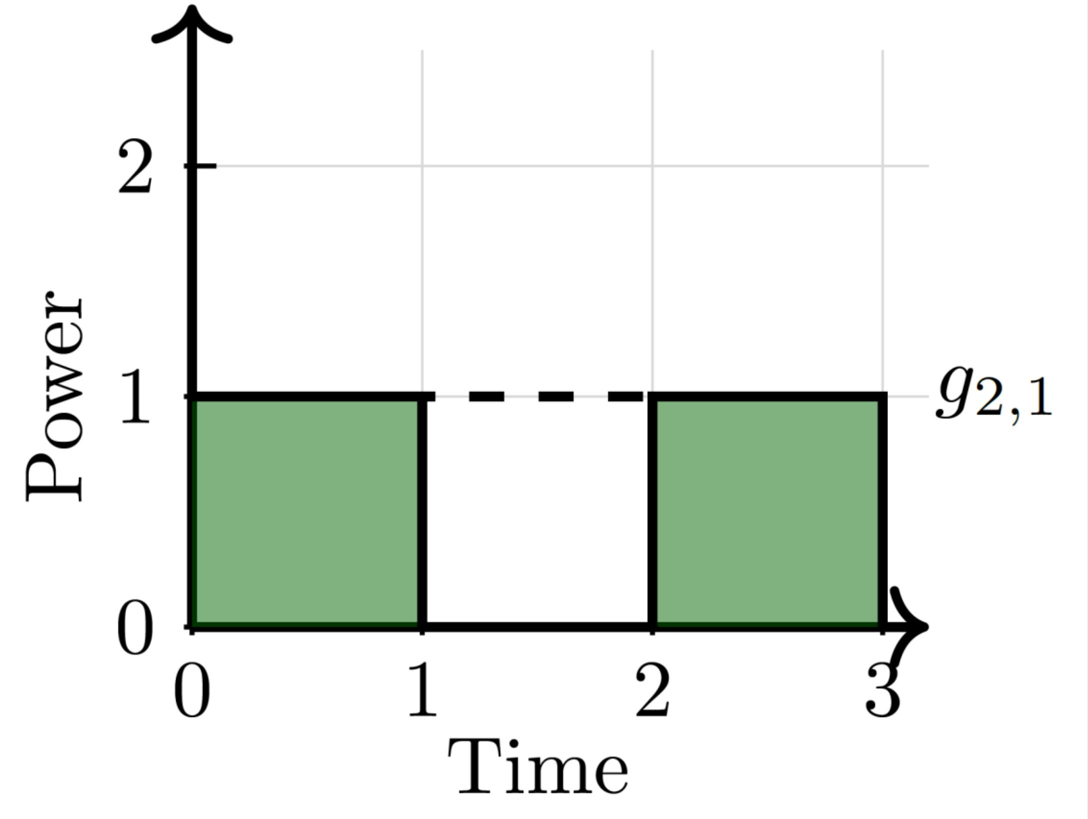

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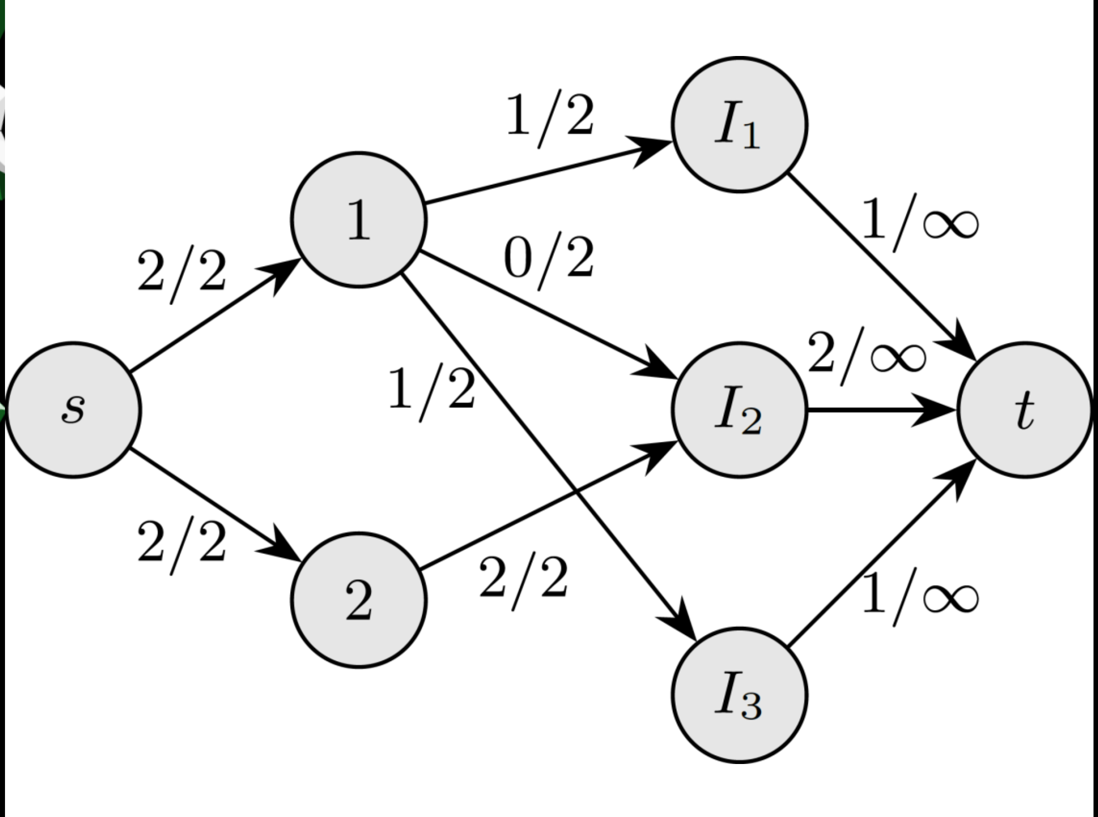

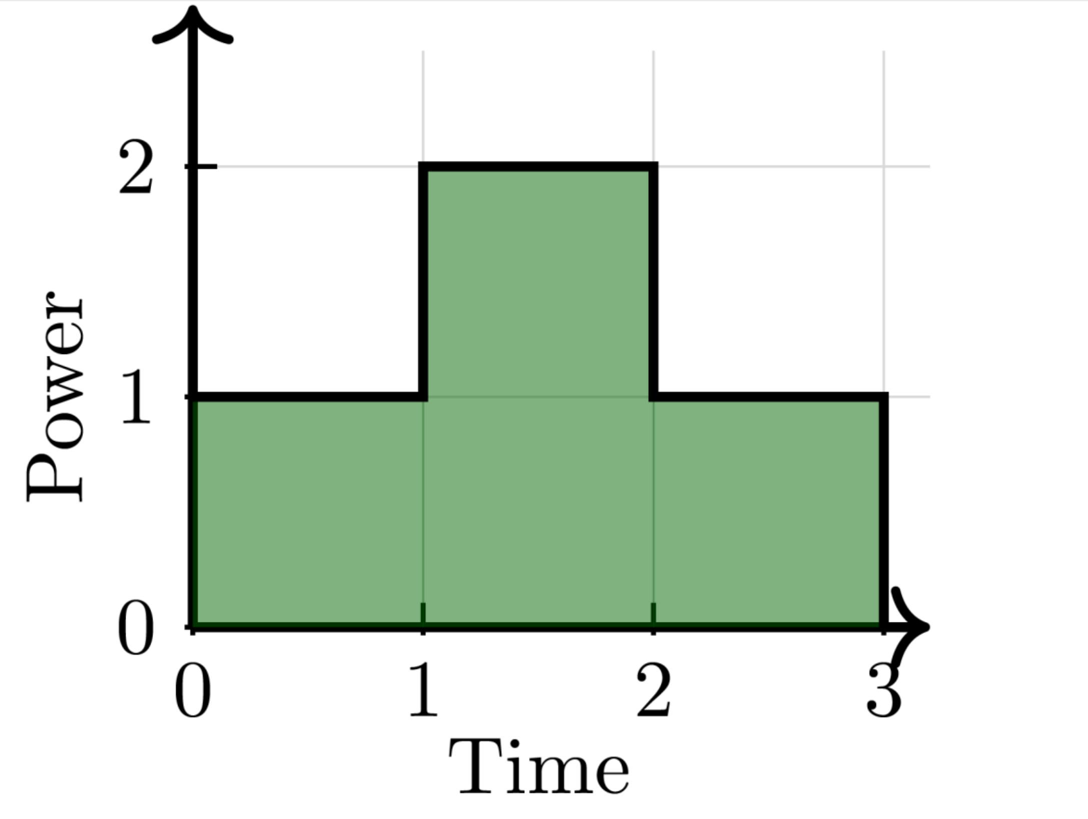

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FOCS ALGORITHM

- Flow-based Offline Charging Scheduler (FOCS)
- O(n^2μ)
- Optimal for objective functions that are:
  - Functions of the aggregated power (seperable)
  - Increasing
  - Differentiable
  - Convex

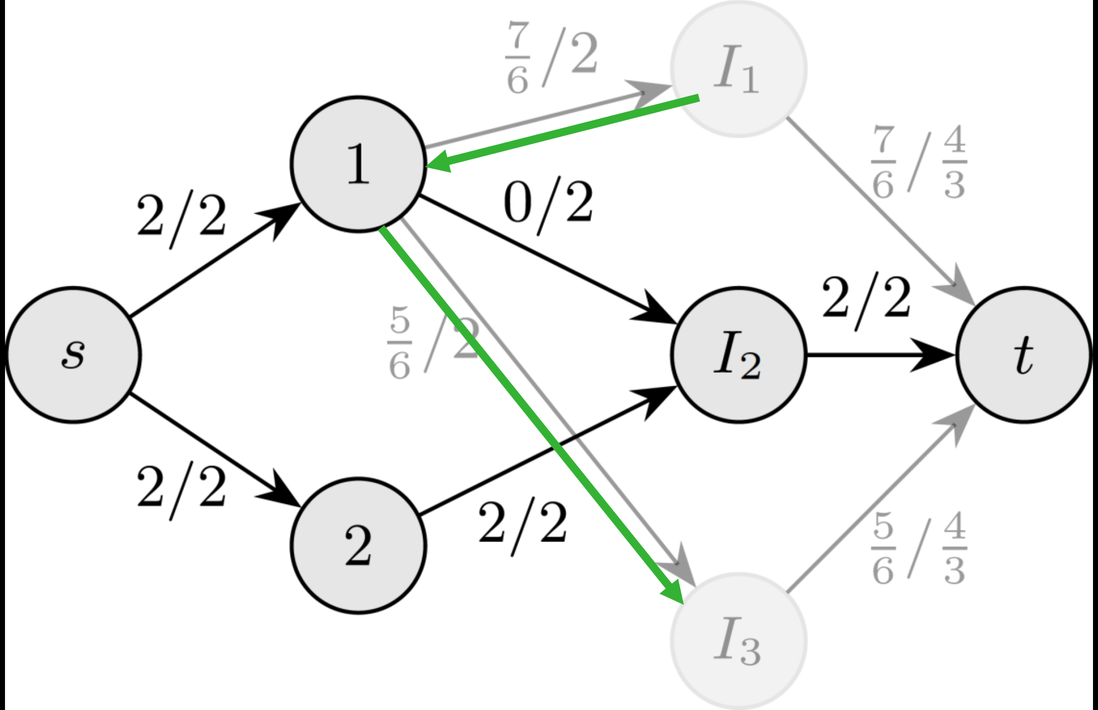
SKETCH OF OPTIMALITY PROOF

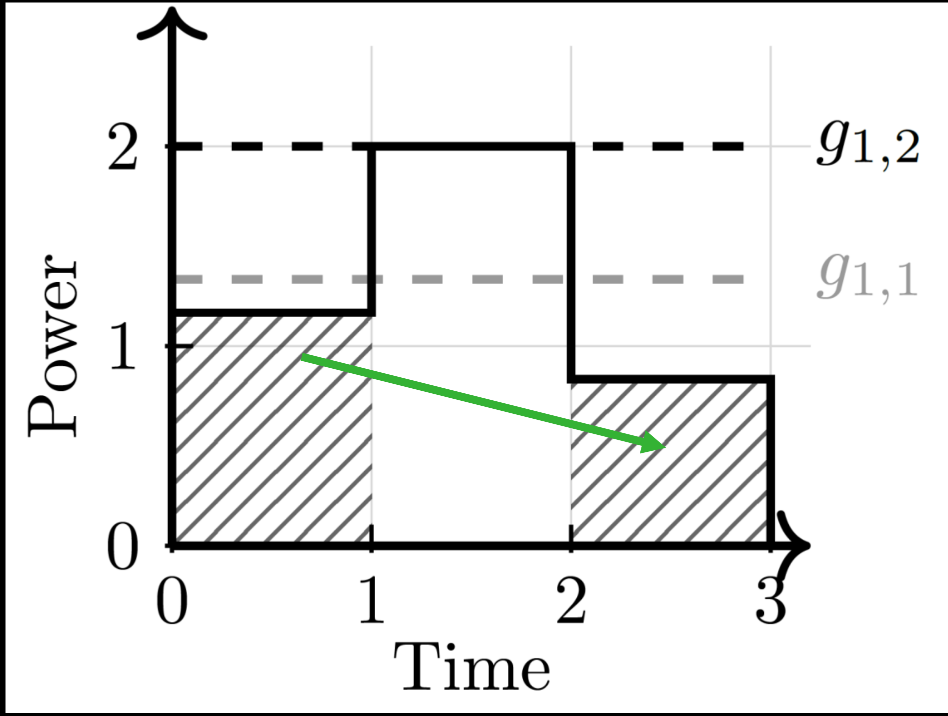
Lemma 1: The following are necessary and sufficient optimality conditions for a schedule solving speed scaling with job-specific speed limits:

- The aggregated power in all intervals where j charges but does not reach its power-limit is the same.
- The aggregated power in intervals where j could but does not charge is at least as high as where j is actually charging.
- The aggregated power in intervals where j charges at maximum power is smaller or equal than in intervals where j is charging and does not reach its limit.

SKETCH OF OPTIMALITY PROOF

- Definition 1: Work-transferability





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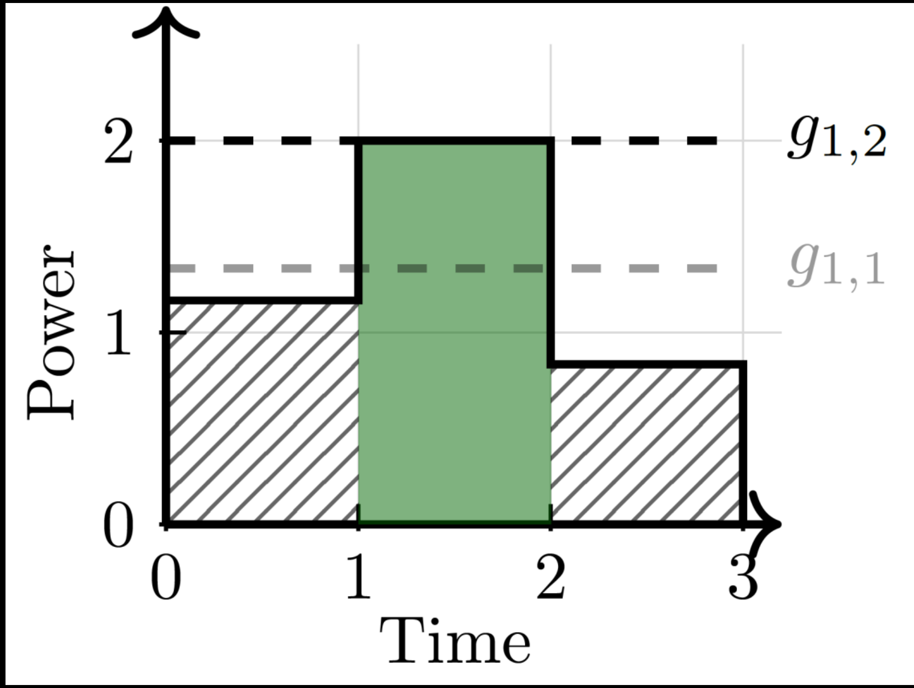
SKETCH OF OPTIMALITY PROOF

Lemma 2: Isolation of critical intervals



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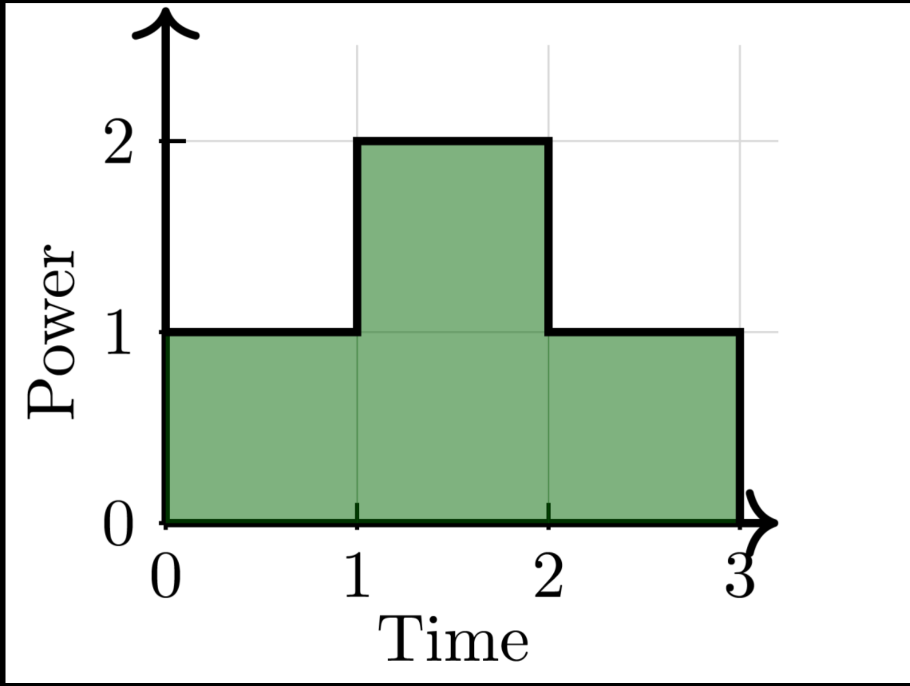
SKETCH OF OPTIMALITY PROOF

Lemma 3: Monotonicity



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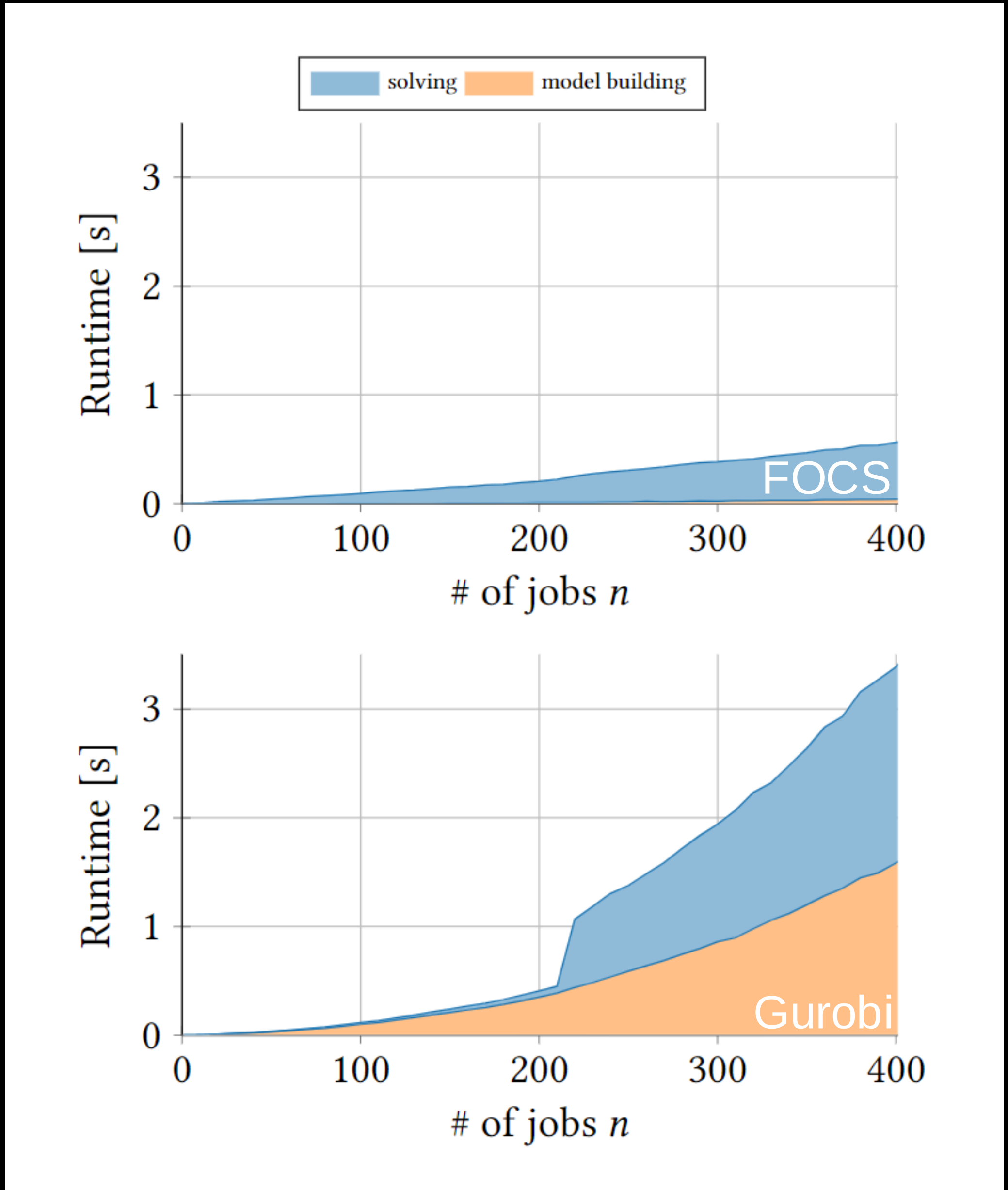
OUTLOOK

- Numerical experiments
- Performance guarantees of online algorithms
- Learning augmentation



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CONCLUSION

- EV scheduling as speed scaling with job-specific speed limits
- FOCS as optimal algorithm

Project website:

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MET GRIDSHIELD

FOCS paper: https://arxiv.org/abs/2309.06174

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SKETCH OF OPTIMALITY PROOF

<u>Definition 1:</u> (Work-transferability)
For a given schedule and atomic intervals I_i and $I_{i'}$, the work-transferable relation $i \rightarrow i'$ holds if there exists a job $j \in J(i) \cap J(i')$ such that $e_{i,j} > 0$ and $e_{i',j} < e_{\mathrm{i',j}}^{\mathrm{max}}$. Furthermore, let $\twoheadrightarrow$ be the transitive closure of $\rightarrow$.

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SKETCH OF OPTIMALITY PROOF

Lemma 2: (Isolation of critical intervals)
If I_i is a critical interval in round r and if the round consists of multiple iterations whereby I_i, was subcritical in one of those iterations, then there is no work-transferable relation between i and i' in the schedule corresponding to the flow at the end of round r, i.e., $i \nrightarrow i'$ with respect to flow f_r.

SKETCH OF OPTIMALITY PROOF

Lemma 3: (Monotonicity)
Given the schedule corresponding to output flow f of algorithm FOCS and atomic intervals I_i and $I_{i'}$, where $r(i) < r(i')$, the aggregated power in I_i is strictly larger than in $I_{i'}$:

$$p_i > p_{i'}$$

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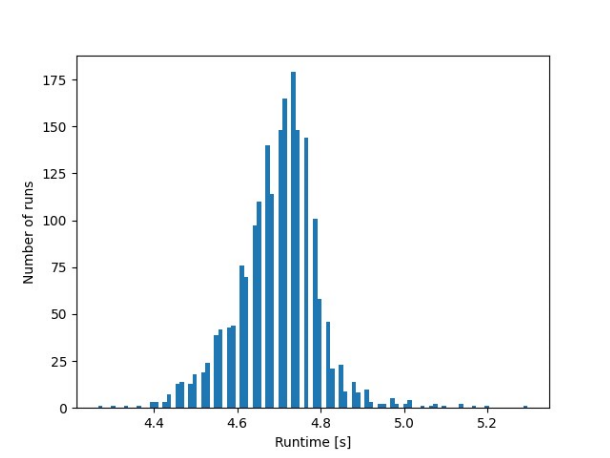
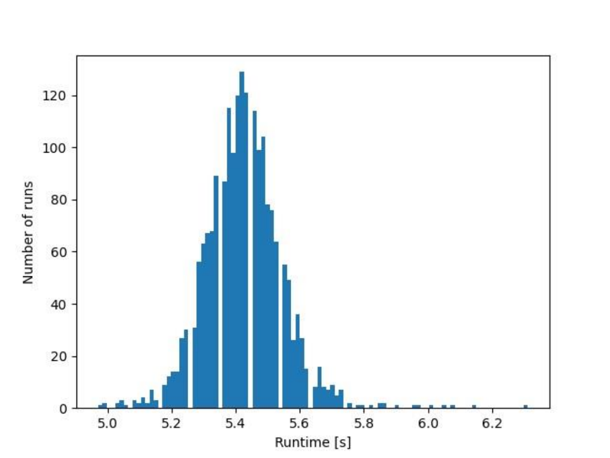
NUMERICAL RESULTS





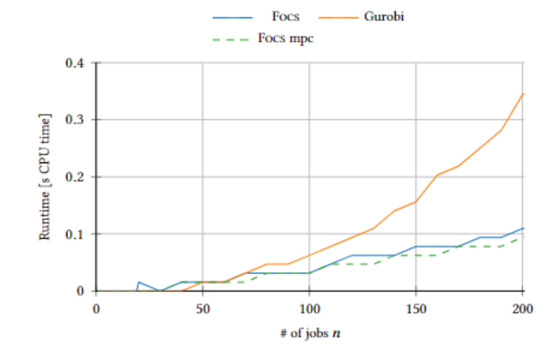


Figure 4: Runtimes for instances with realistic instance sizes, timestep = 3600s, and using shortest path embedded in Focs.

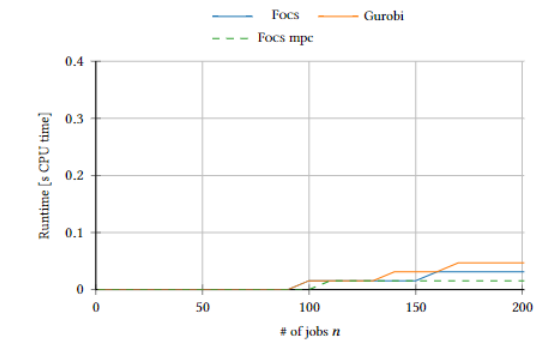


Figure 5: Runtimes for instances with realistic instance sizes, timestep = 3600s, and using shortest path embedded in Focs.

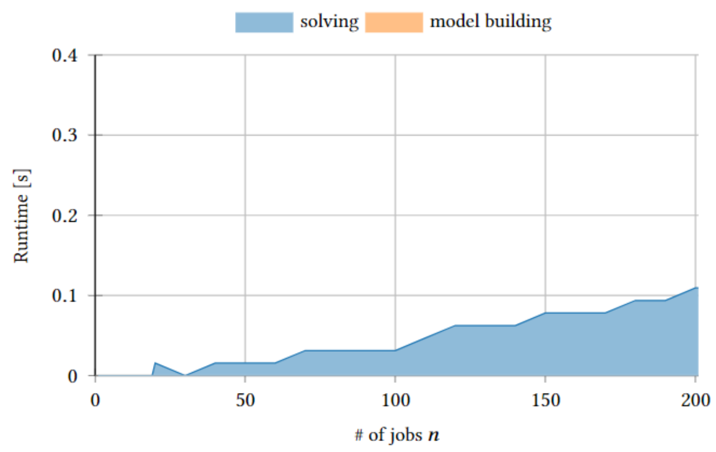


Figure 11: Runtimes of Focs. Optimized in hour-granularity.

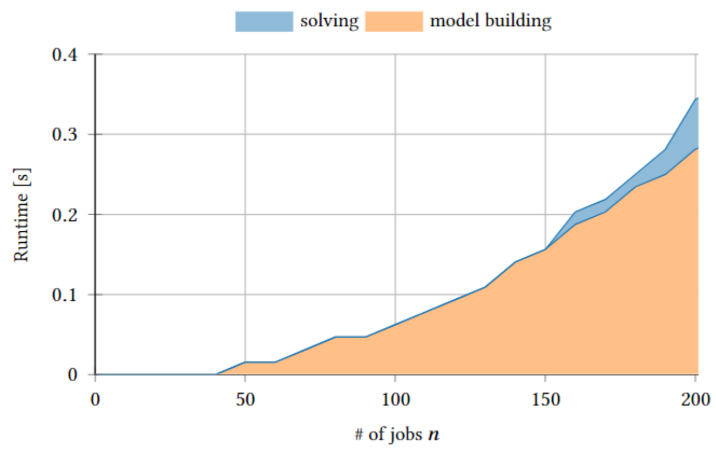


Figure 12: Runtimes of Gurobi. Optimized in hour-granularity.