“On the Impact of PMU Placement On Observability and Cross-Validation”

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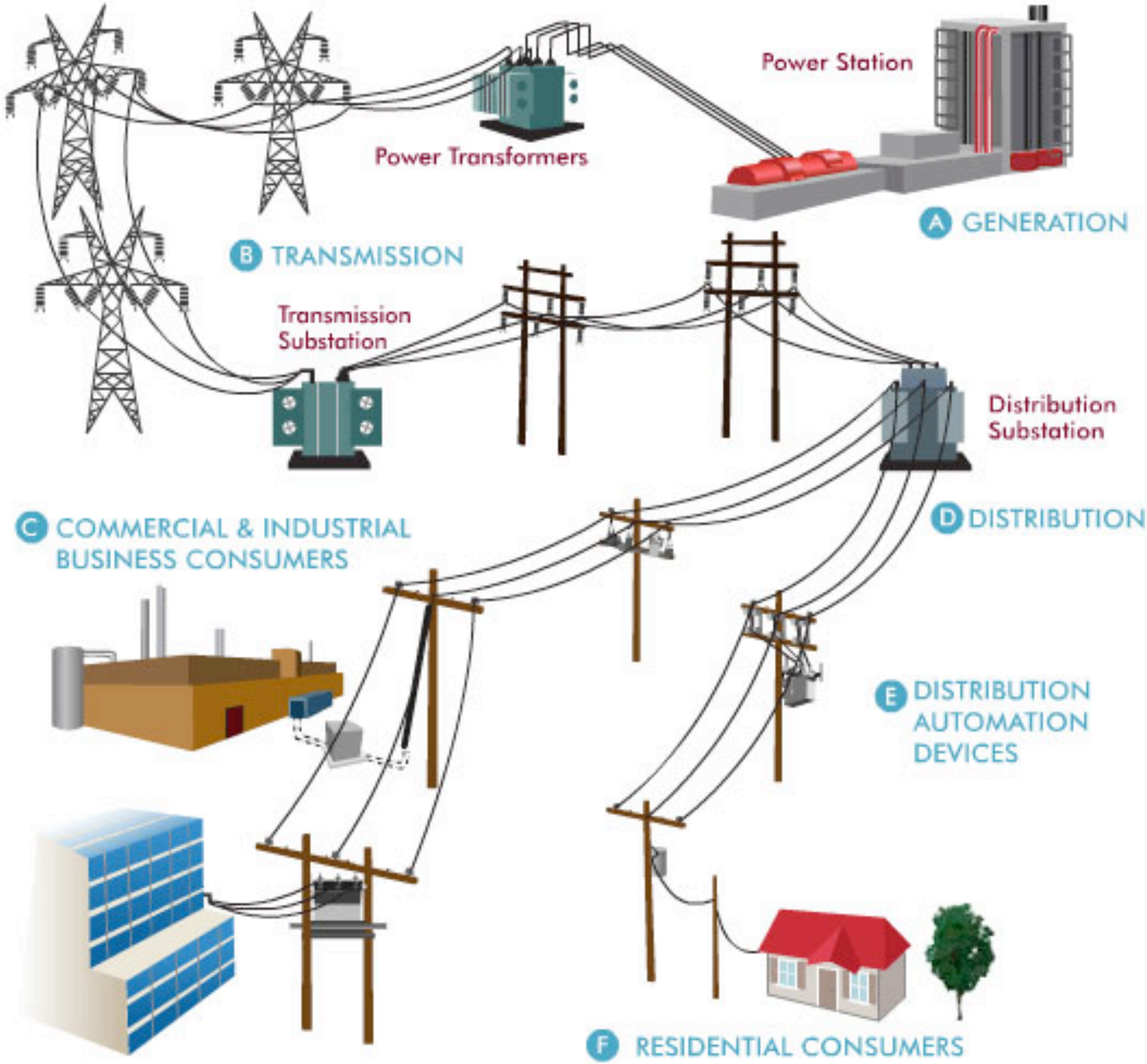
e-Energy 2012

Talk Outline

- Background
- PMU Placement for Max Observability
- PMU Placement with Error Detection
- Approximation Algorithms
- Evaluation via Simulation



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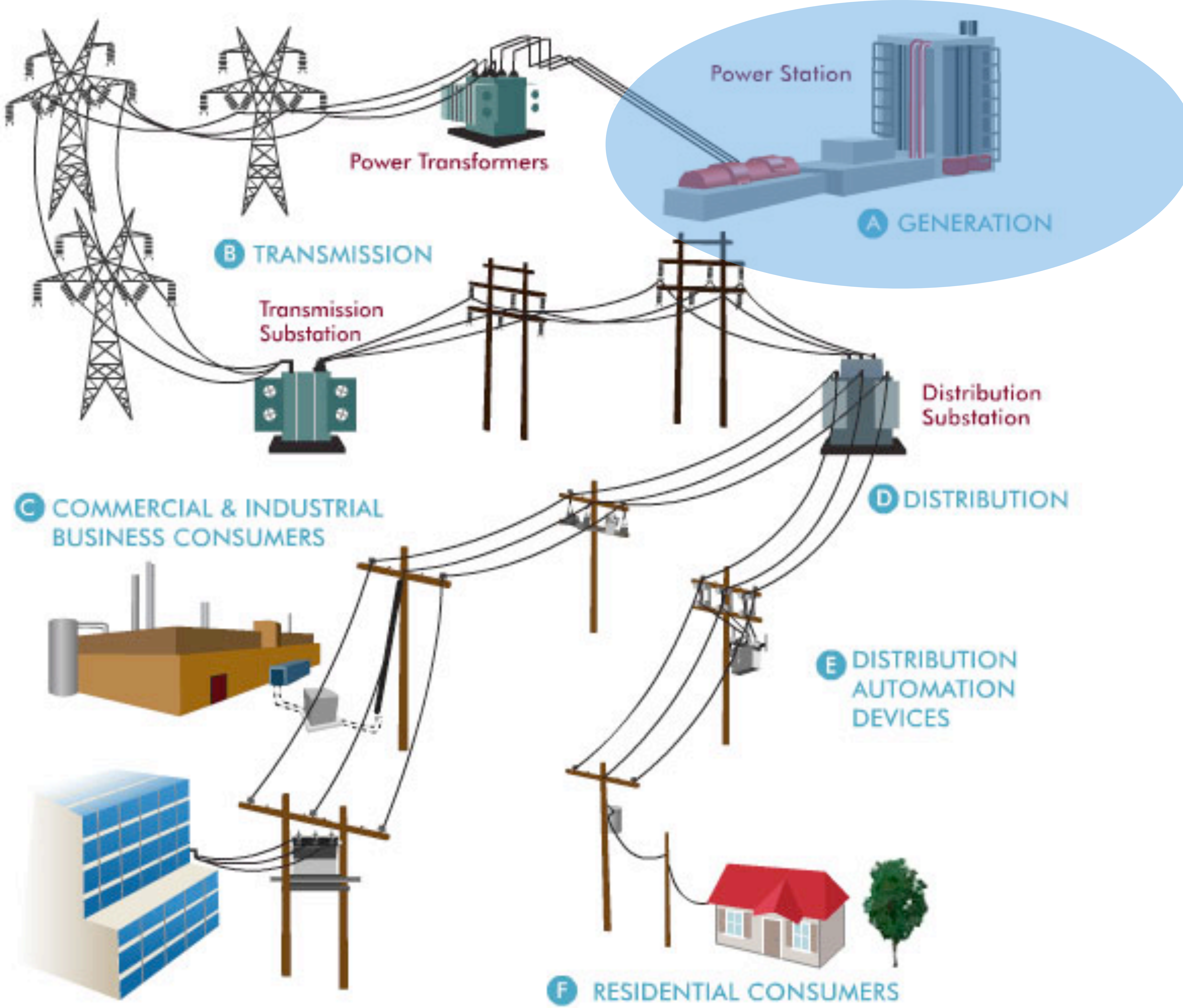

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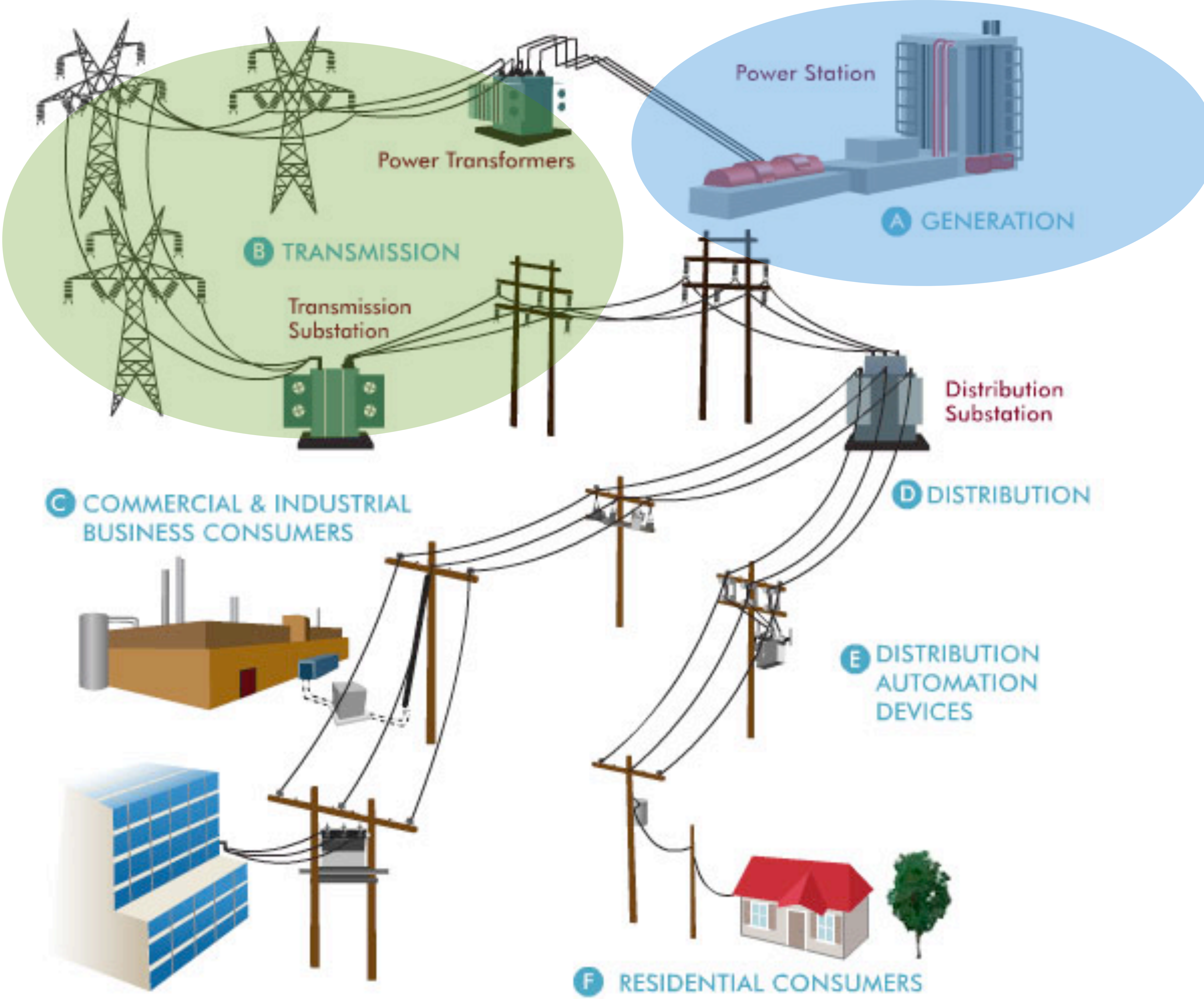

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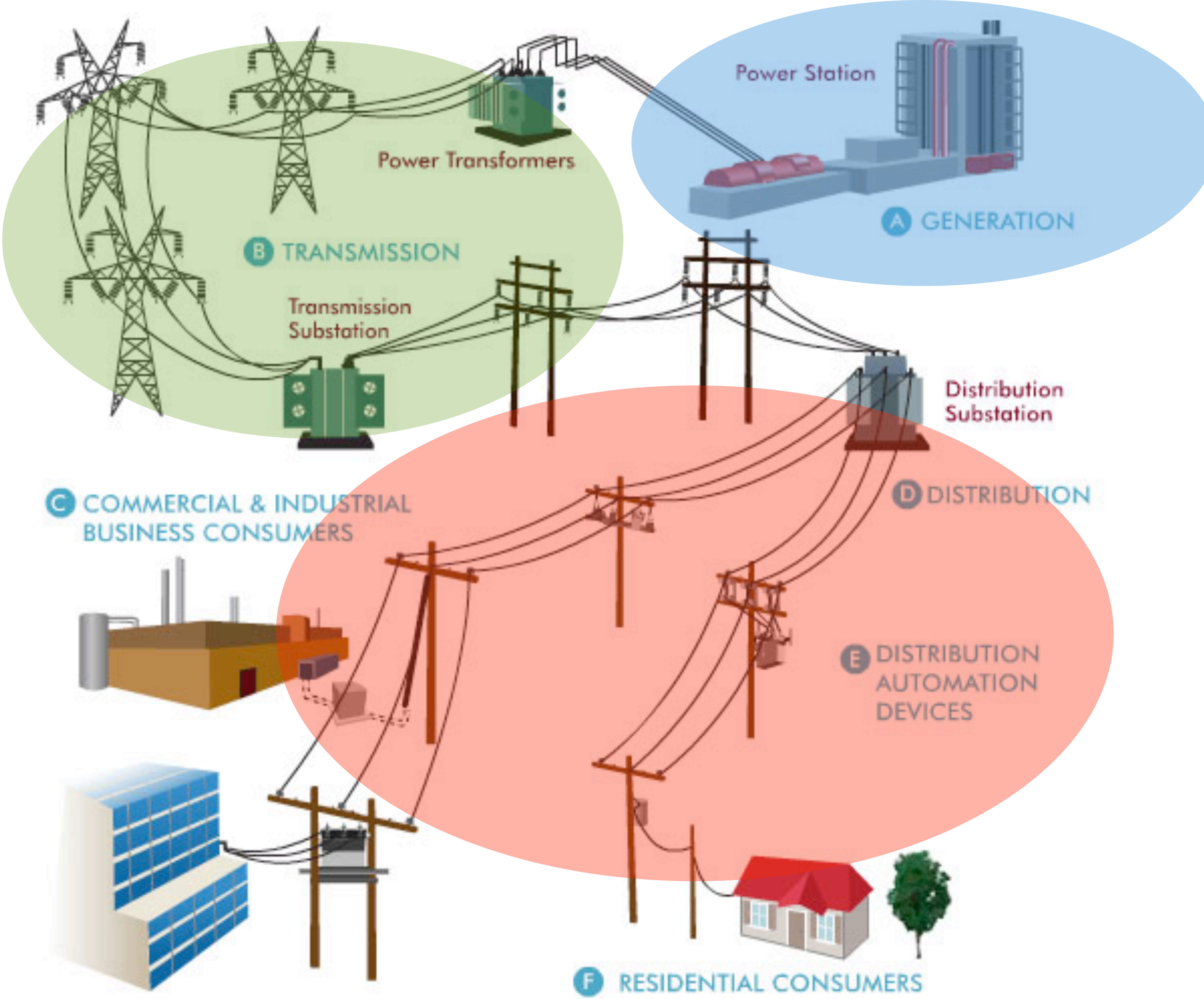

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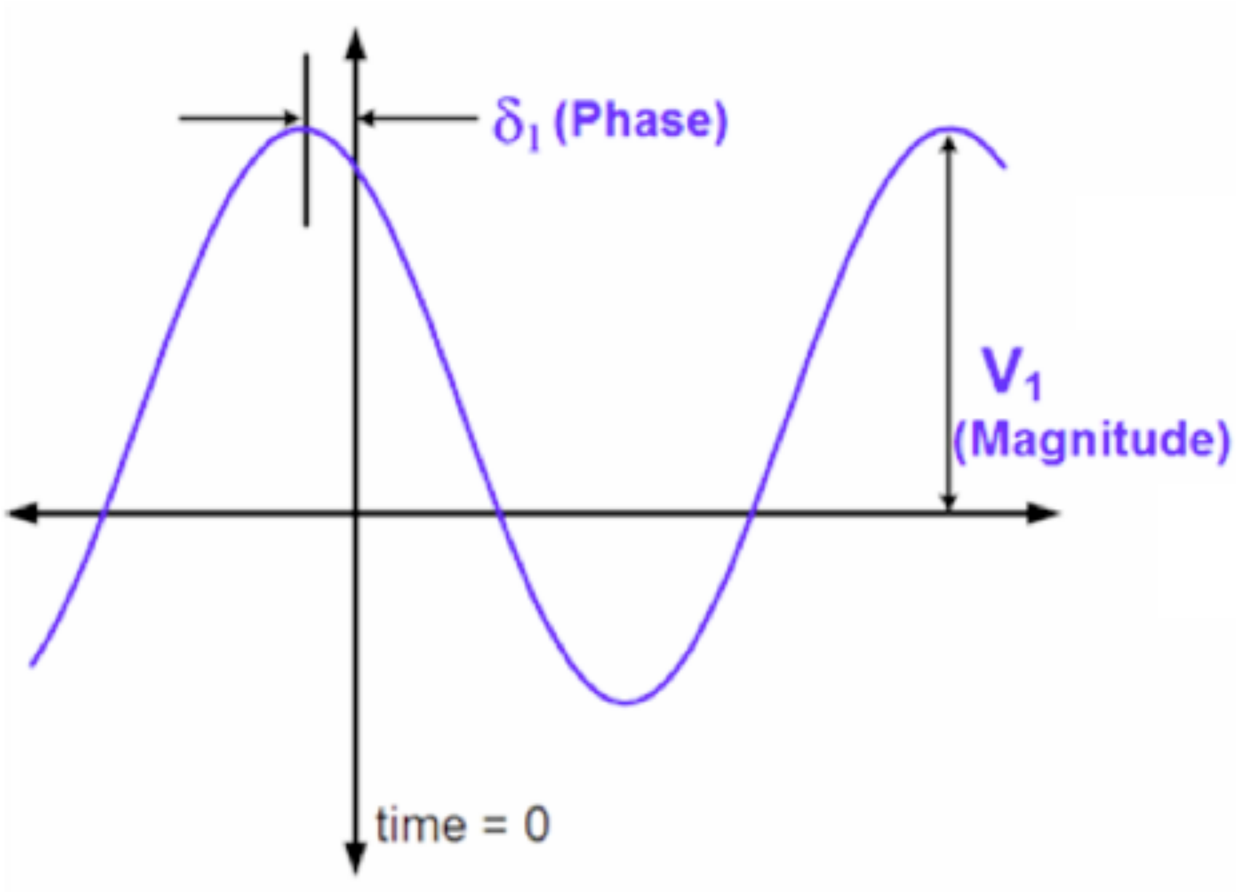
Phasor Measurement Unit (PMU) Sensor

PMU Sensors

=



phasor

PMU Sensors

high sampling rate:10-60 samples/sec

+

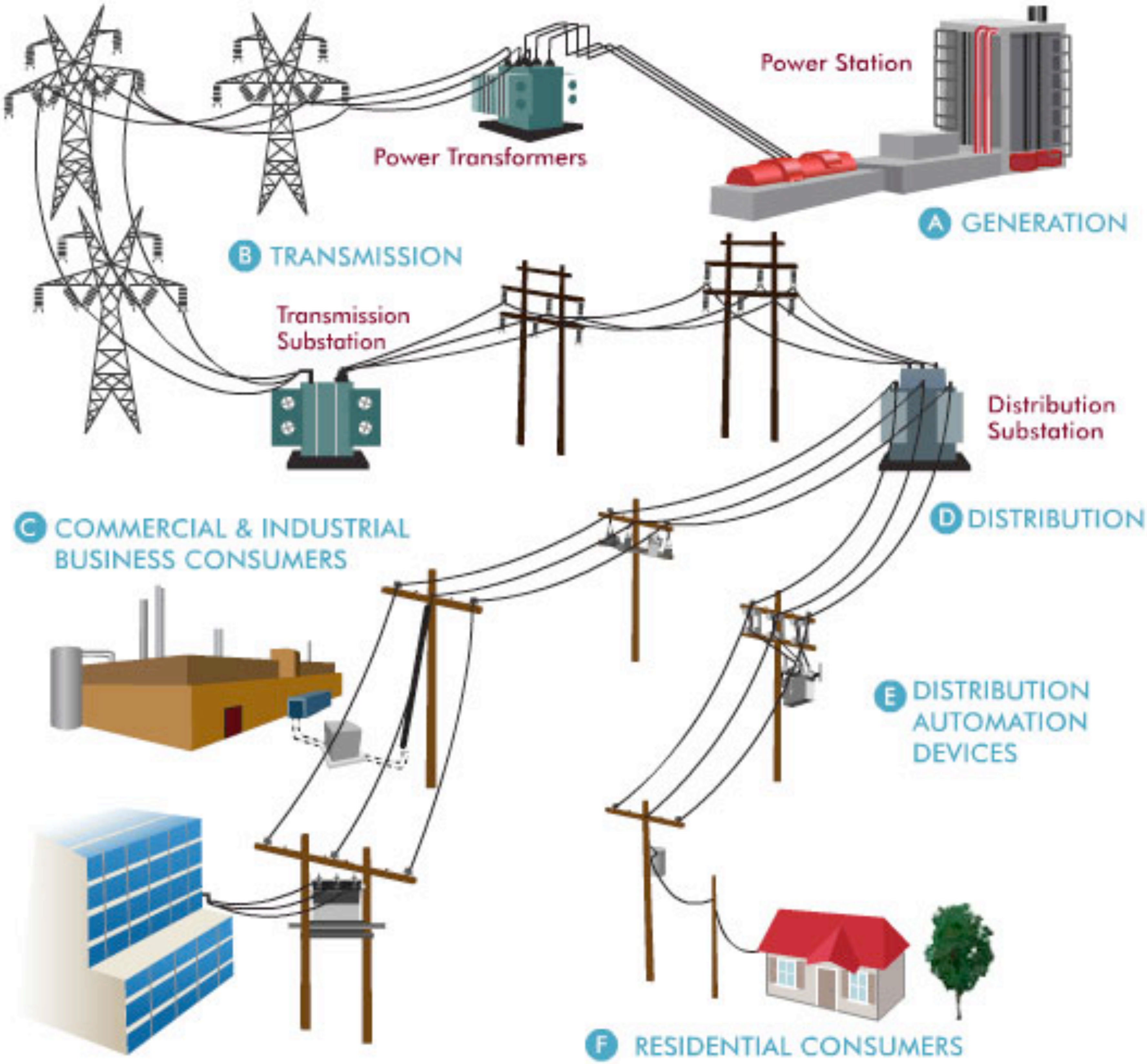
measurements are synchronized

PMU Applications

- Postmortem analysis
- Power grid visualization
- Real-time distributed control


Reliable
Integration
of
Renewables

Detailed Look at Power Grid



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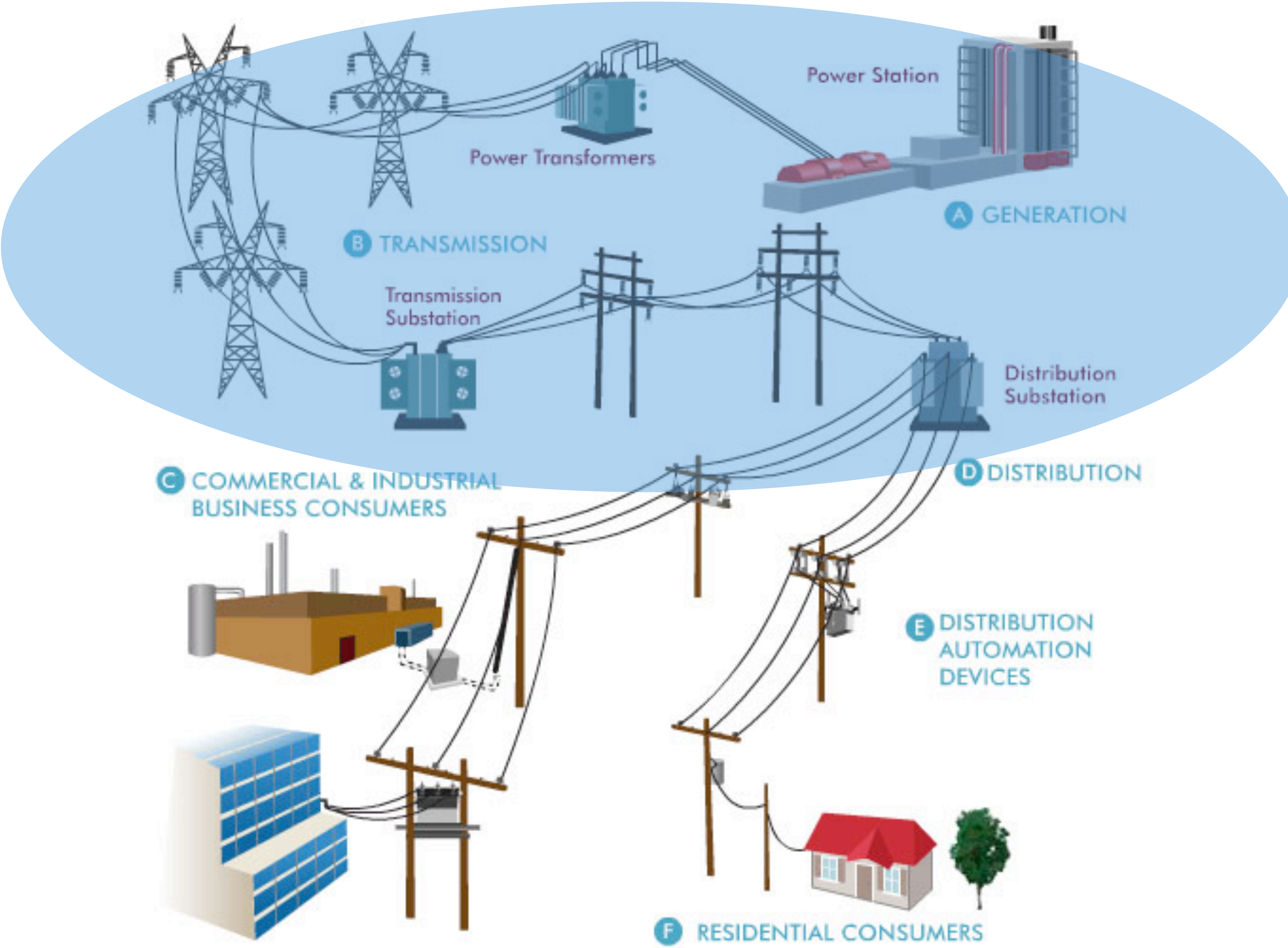
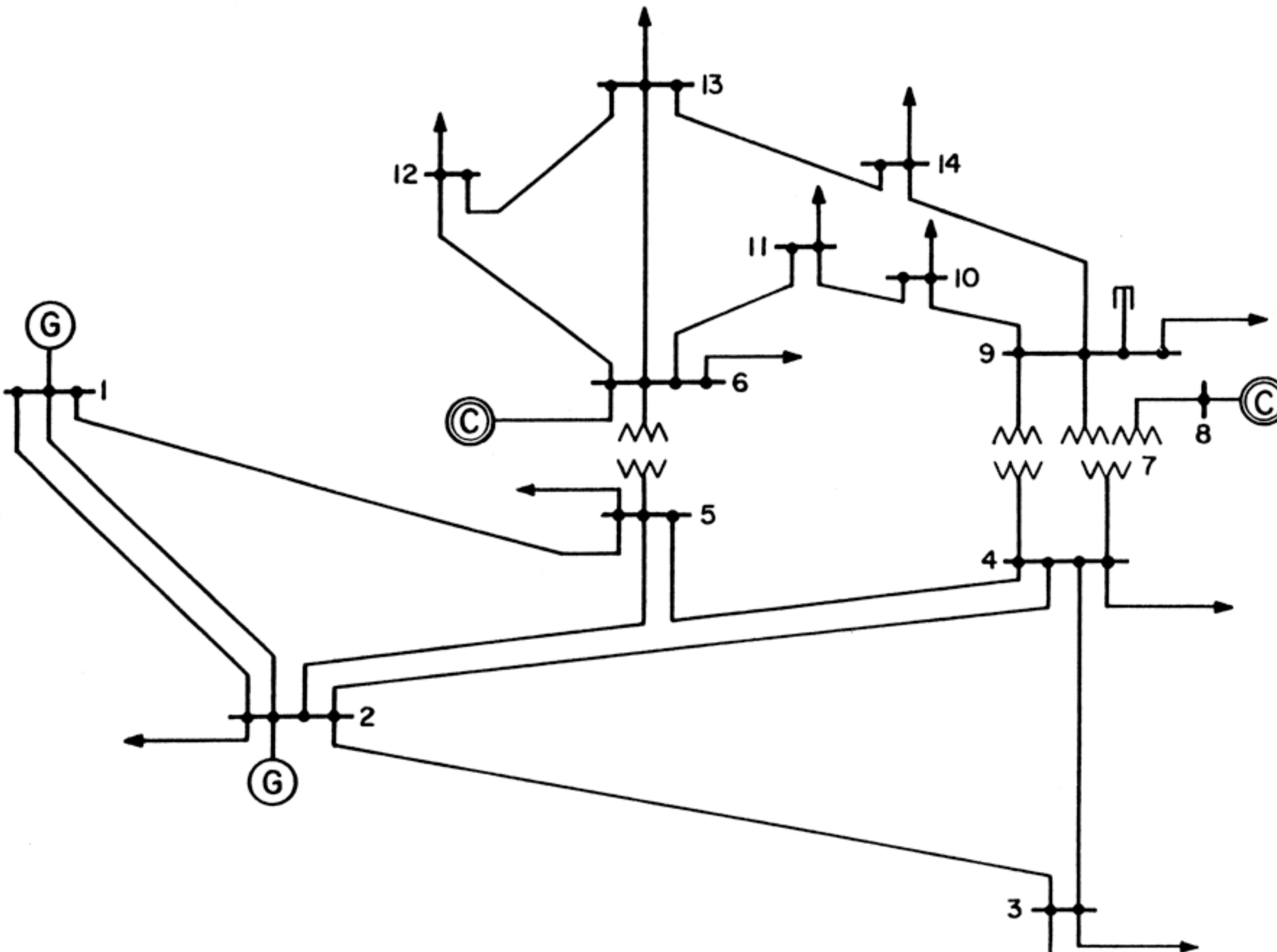


Example Power Grid



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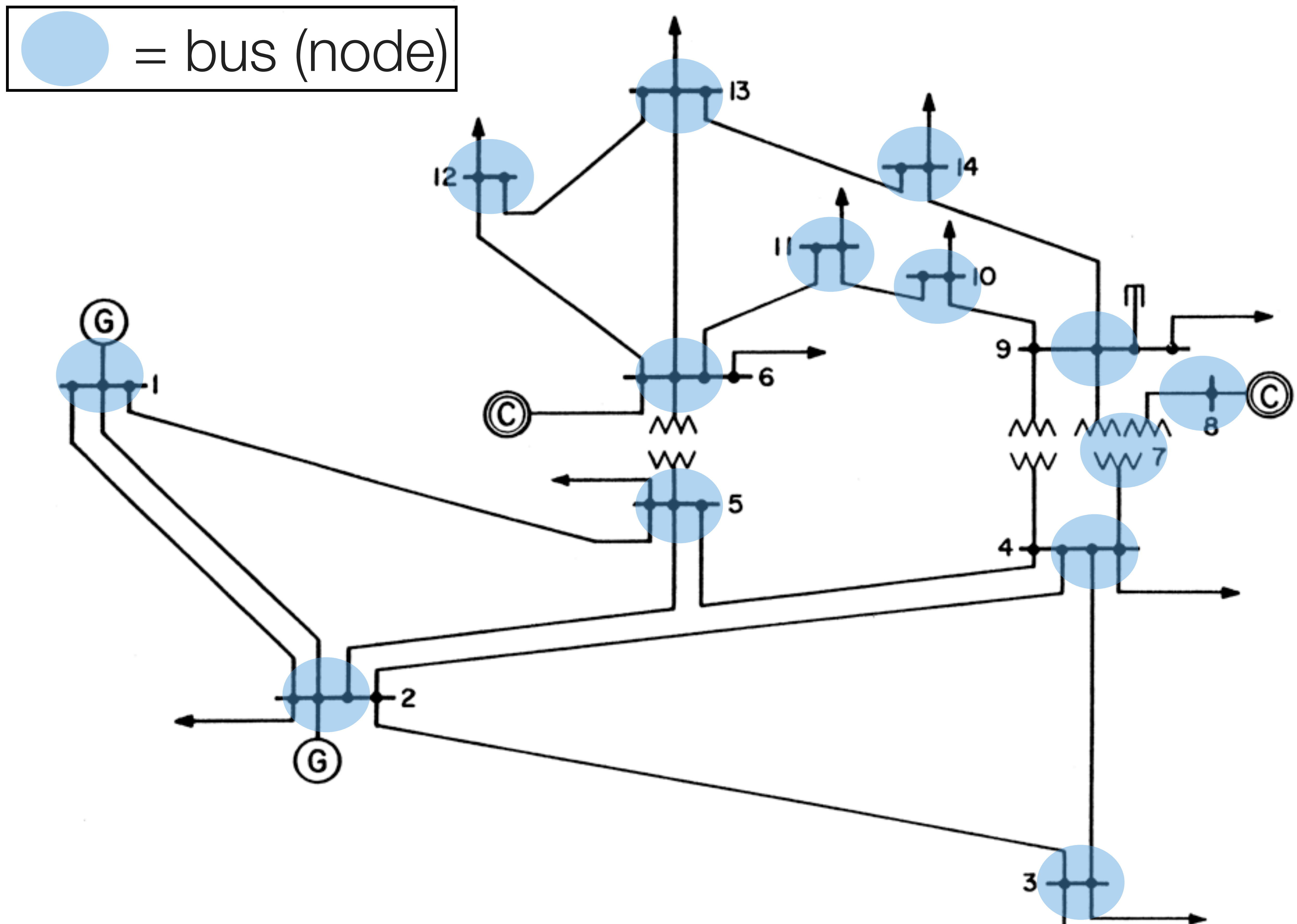
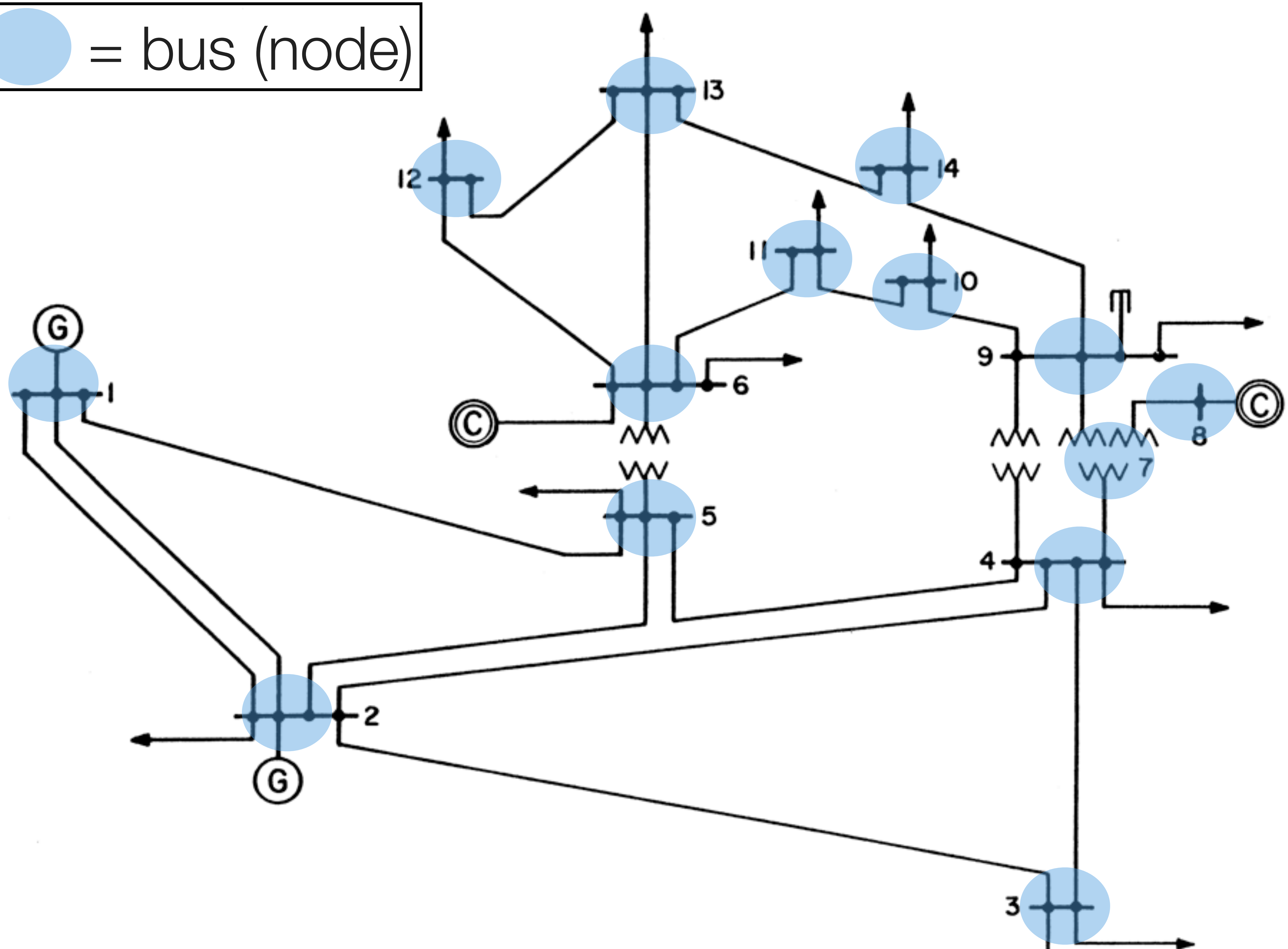


Terminology

- Node: system bus
  - injection node: power generation center or aggregation of loads + either pulls energy from grid or inserts energy into grid
  - zero-injection node: substation where electrical lines meet + does *not* insert or pull energy from grid
- Observed: if voltage phasor of node can be directly measured or calculated

Example Power Grid

= bus (node)



PMU Placement Problem

- PMUs expensive
  - high cost of placing PMU on each node
- Solution
  - place PMUs on subset of nodes
  - indirectly observe non-PMU nodes using basic laws of electricity

Our Paper

- Define 2 Placement Problems:
  - maximize observed nodes while minimizing number of PMUs used
    - similar to Vertex-Cover

Our Paper

- PMU errors occur in practice
- Error detection
  - place PMUs “near” each other
- Define 2 more PMU placement problems
  - place PMUs for maximum observability and to allow error detection

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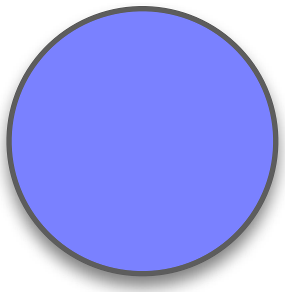
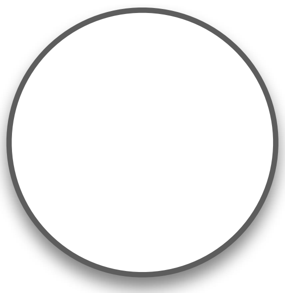
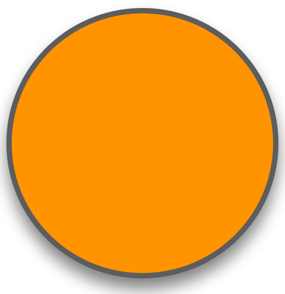
Key for Figures



A node with a PMU



An unobserved node



An observed node

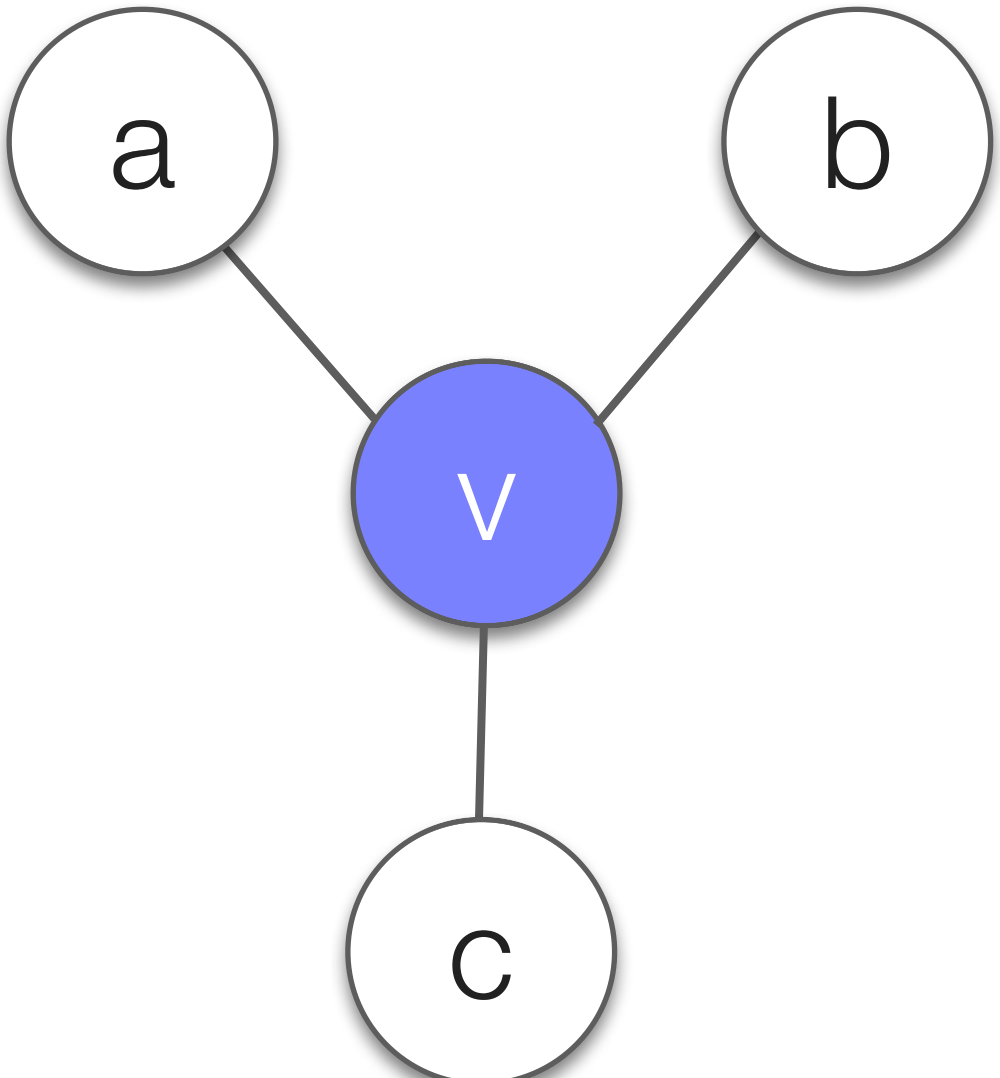
Edge

Observability Rule 1

If a node, v, has a PMU, then v and all of v's neighbors are observed

D. Brueni and L. Heath. The PMU Placement Problem. SIAM Journal on Discrete Math, 2005

Observability Rule 1



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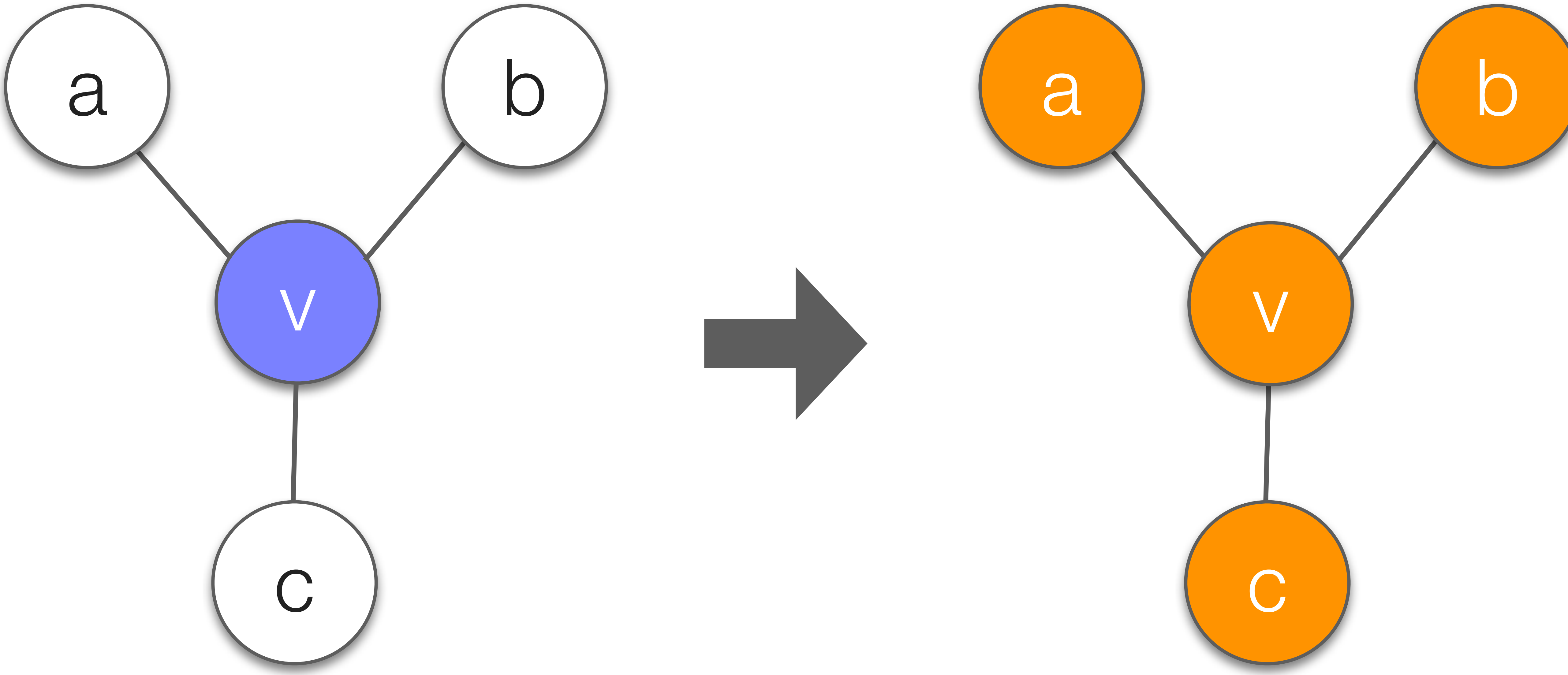

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Observability Rule 2

If a zero-injection node, v, is observed and all of v's neighbors are observed, except one, then all of v's neighbors are observed.

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Observability Rule 2

zero-injection node: substation where electrical lines meet + does not insert or pull energy from grid

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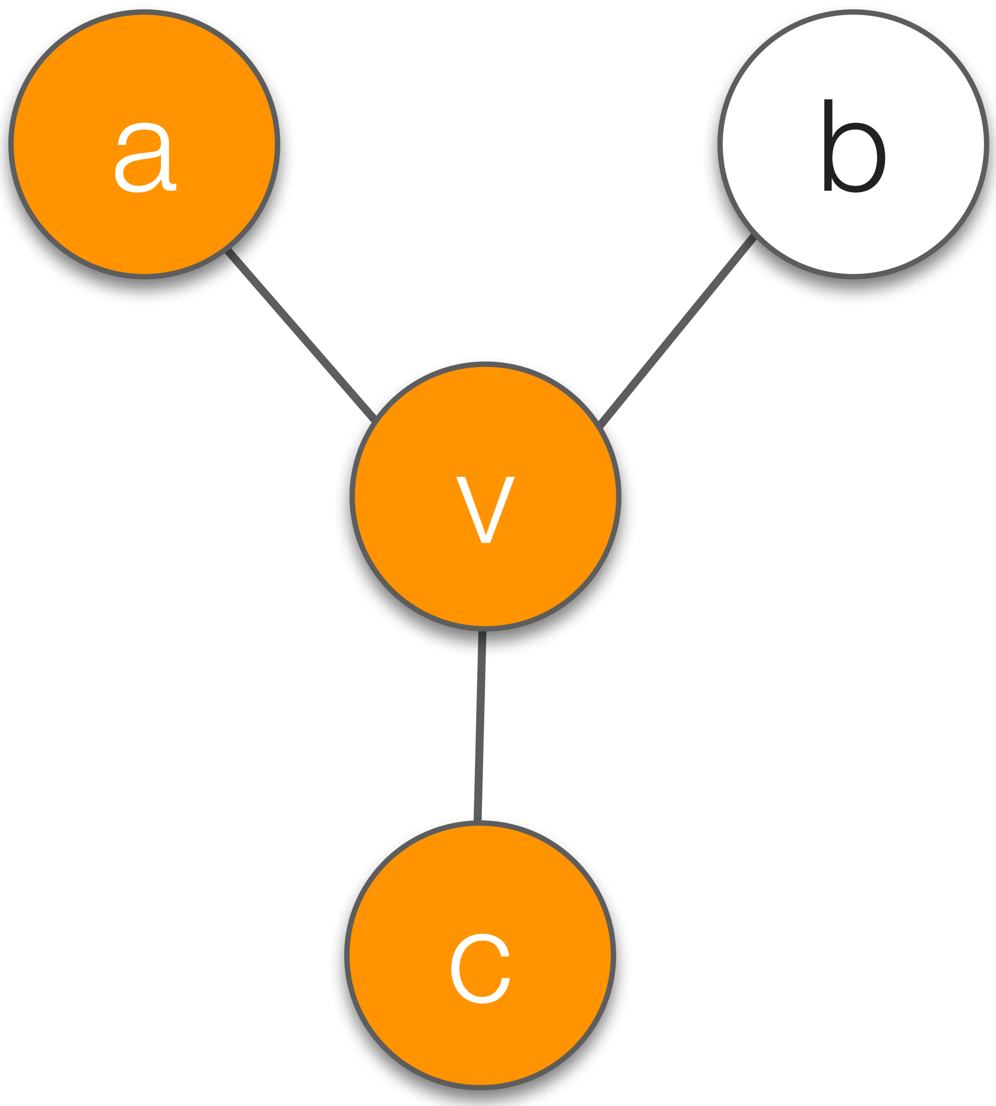

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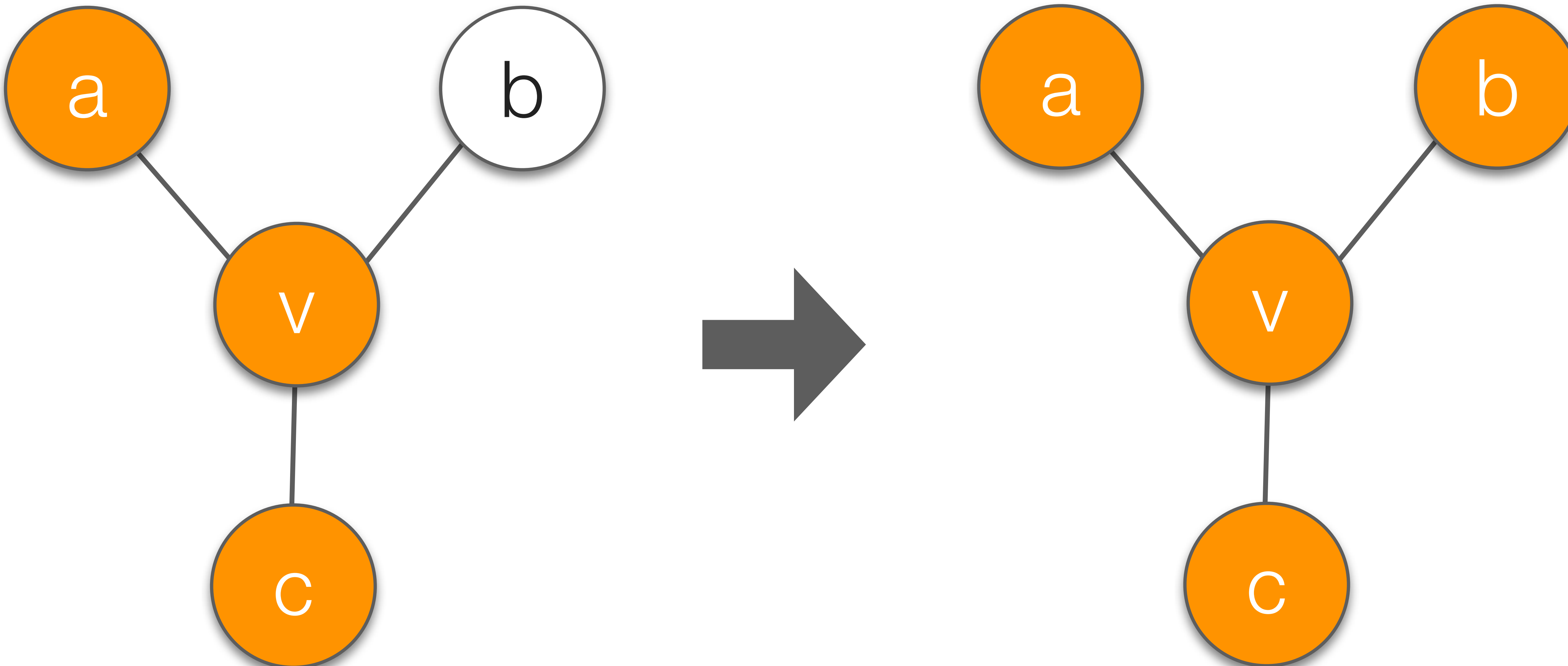

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MaxObserve Problem

- Input: `G=(V,E)` and `k` PMUs
- Output: placement of `k` PMUs to maximize number of observed nodes

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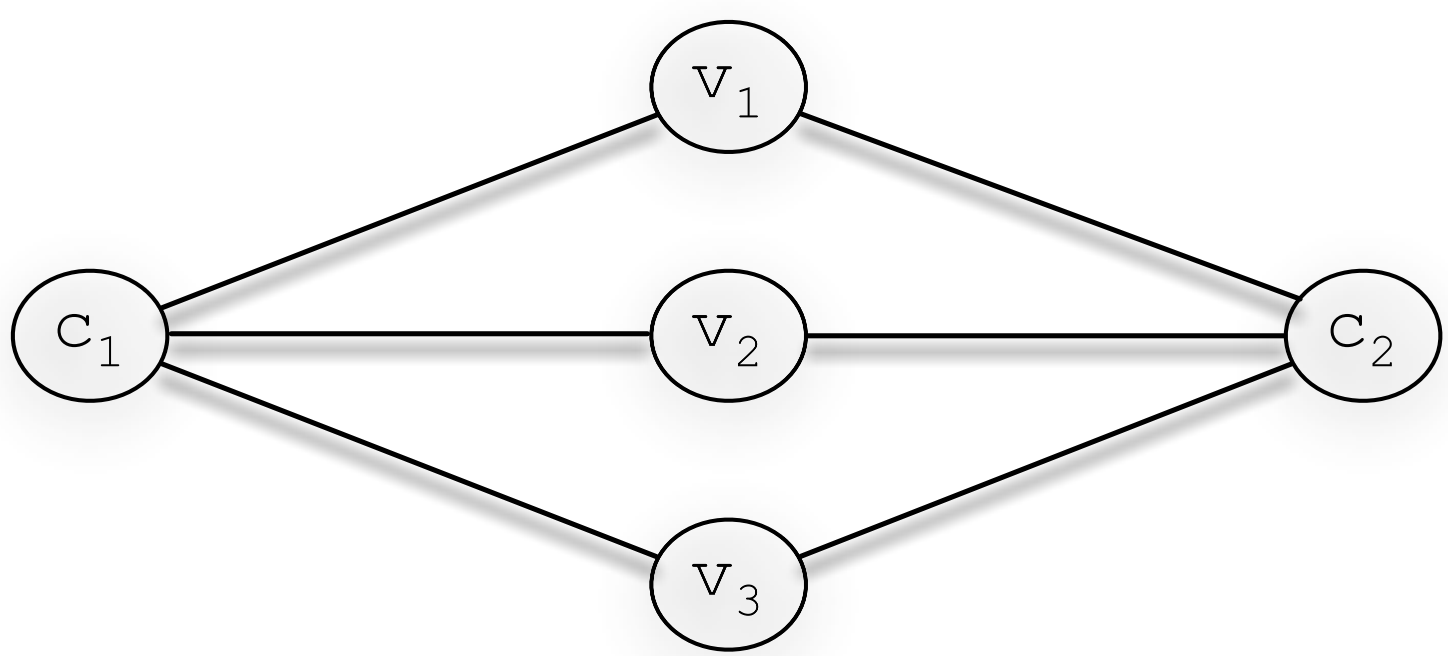
- Output: placement of `k` PMUs to maximize number of observed nodes

Key Result: MaxObserve is NP-Complete

Proof: MaxObserve is NPC

- Reduce from Planar 3SAT (P3SAT)

$$\phi = \underbrace{(\overline{v_1} \lor v_2 \lor v_3)}_{c_1} \land \underbrace{(v_1 \lor \overline{v_2} \lor \overline{v_3})}_{c_2}$$



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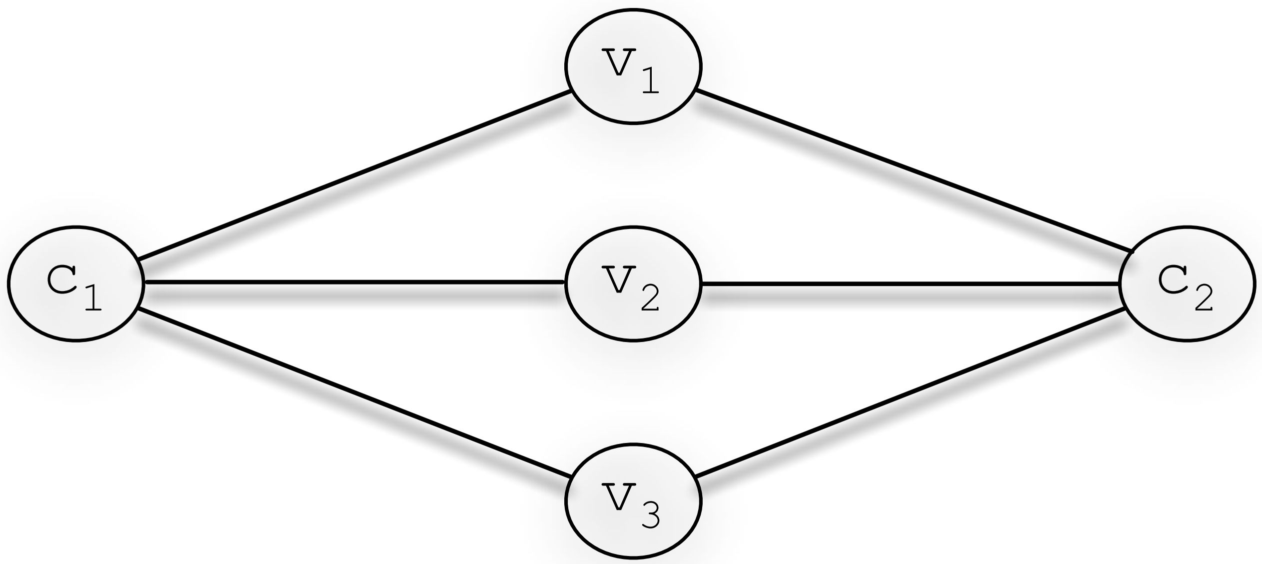

Proof: MaxObserve is NPC

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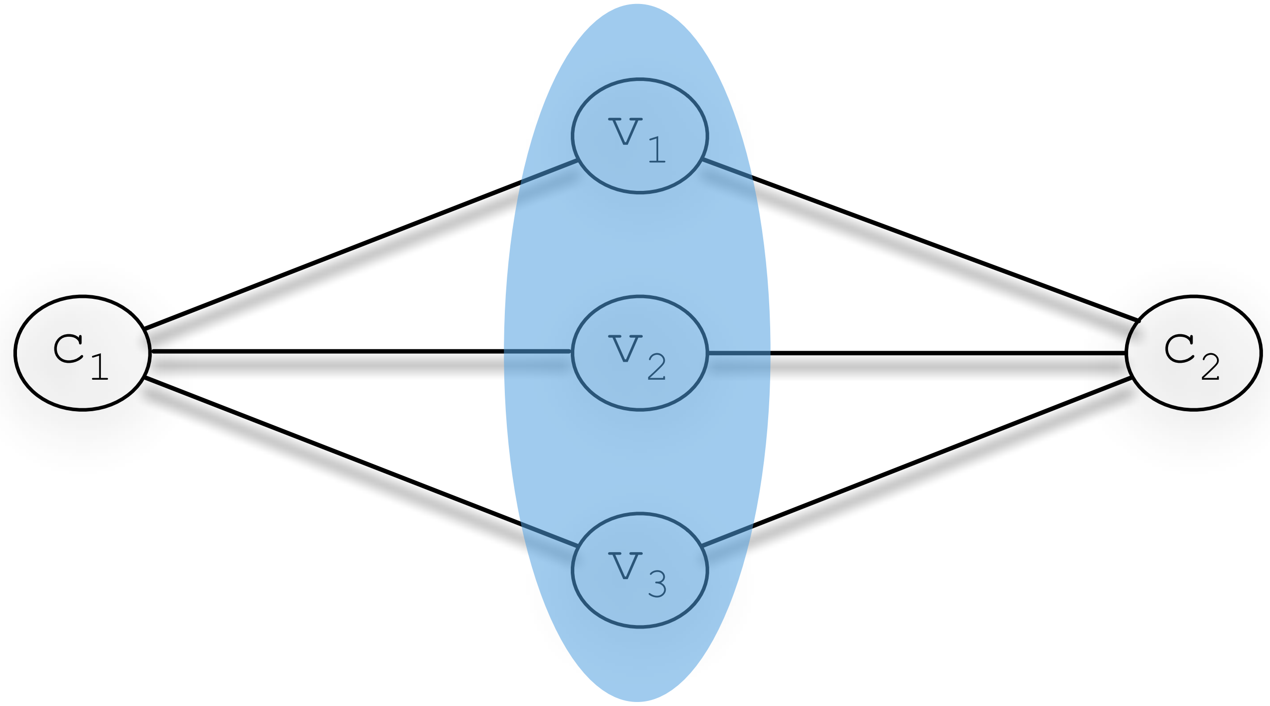

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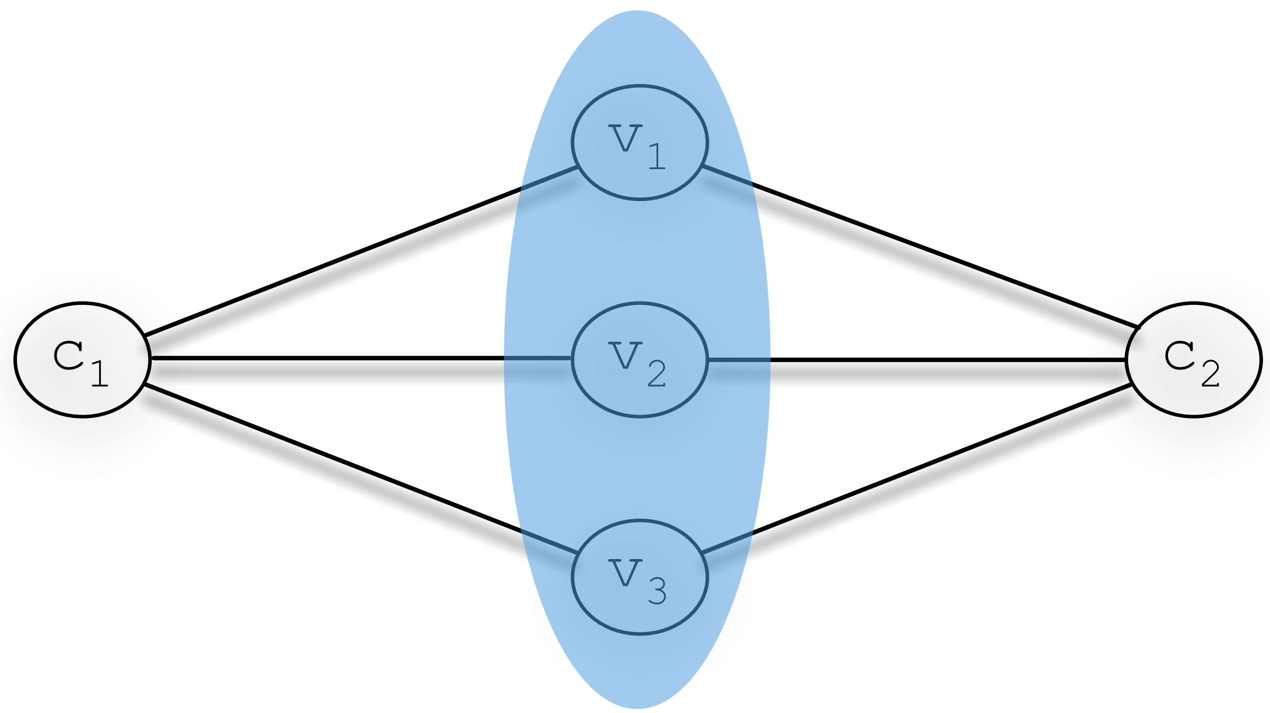
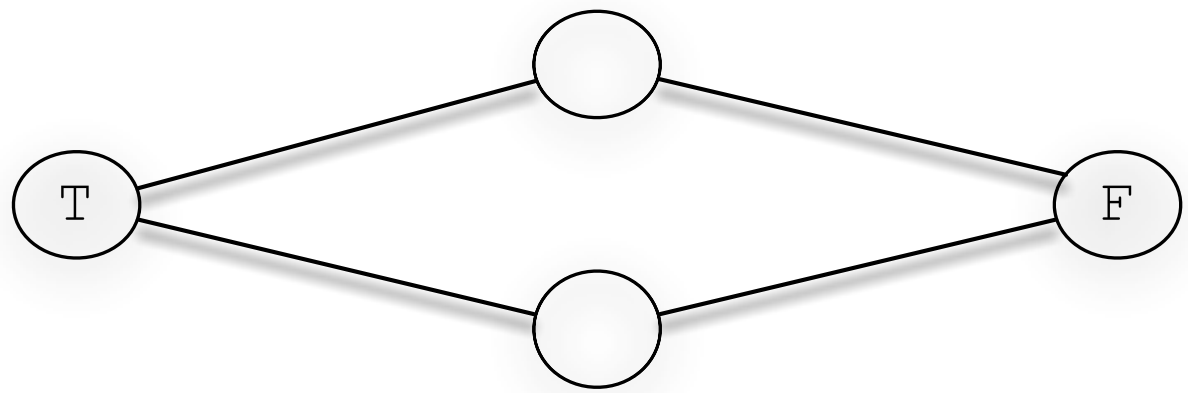


replace each variable with set of nodes below (gadget)



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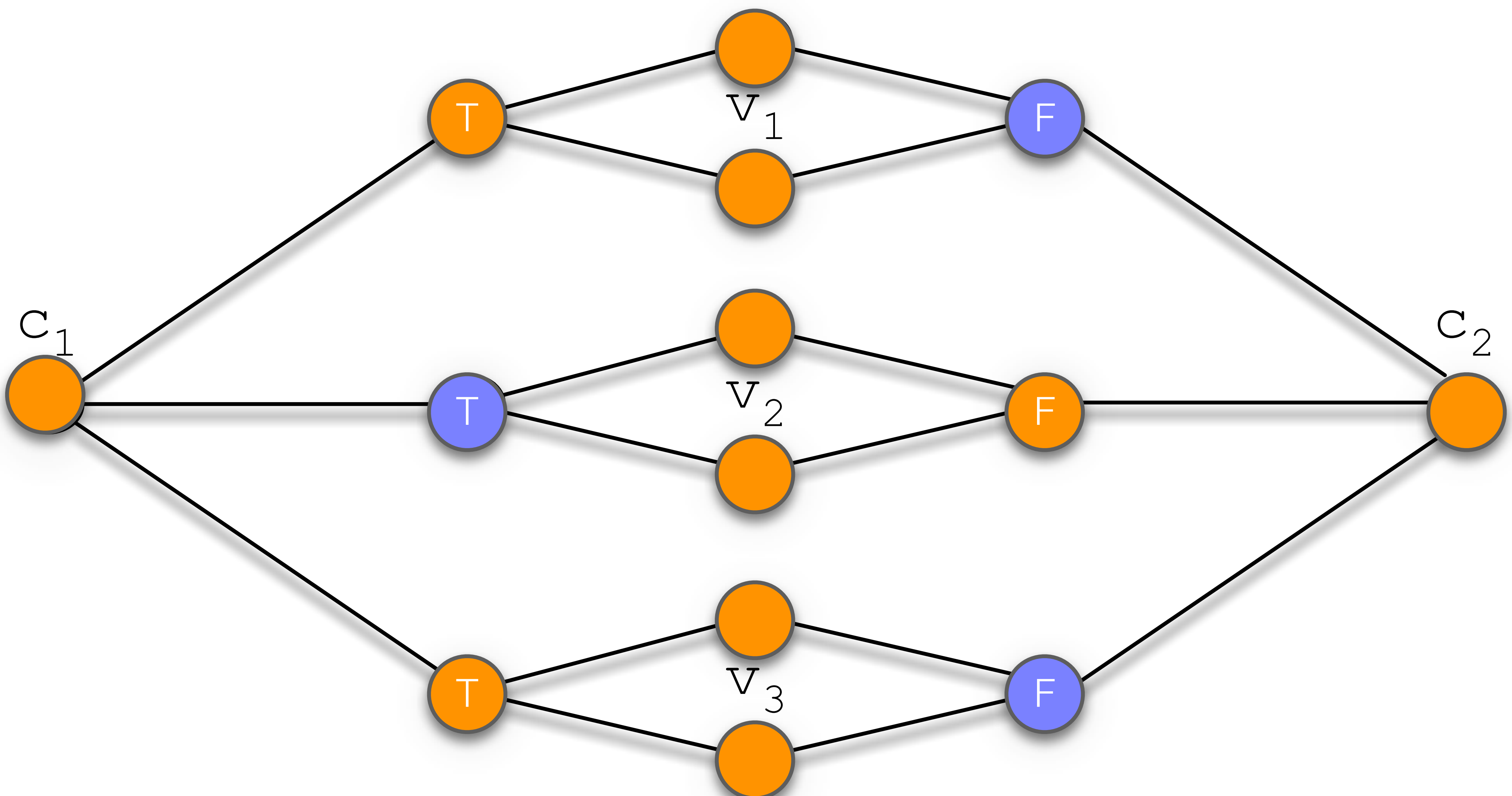

Show maximum nodes observed iff PMUs place on nodes corresponding to satisfying instance of P3SAT

Related Work for MaxObserve

- Adapt proof technique of Brueni and Heath [4]
- Unrealistic assumption (Brueni and Heath [4], Aazami and Stilp [2])
  - all nodes zero-injection
  - in practice, ~5% nodes are zero-injection

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Cross-Validation Rule 1

If PMUs placed on adjacent nodes, the PMUs cross-validate each other

Vanfretti et al. A Phasor-data-based State Estimator Incorporating Phase Bias Correction. IEEE Transactions on Power Systems, 2010

Cross-Validation Rule 2

If two PMUs share a common neighbor, the two PMUs cross-validate each other

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MaxObserve-XV

XV denotes cross-validation

- Input: `G=(V,E)` and `k` PMUs
- Output: placement of `k` PMUs so maximum number of nodes are observed, under the condition that each PMU is cross-validated

MaxObserve-XV

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- Input: `G=(V,E)` and `k` PMUs
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Key Result: MaxObserve-XV is NP-Complete

MaxObserve-XV is NP-Complete

- Reduce from Planar 3SAT (P3SAT)
  - new gadgets for variables nodes
  - require PMUs are cross-validated
- Proof details in paper

MaxObserve-XV Related Work

- Completely new problem
  - Chen and Abur [5] add PMUs so PMU loss can be tolerated
  - Vanfretti et al. [14] define cross-validation rules

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greedy algorithm

- Approximates MaxObserve

S: set of nodes with a PMU

1. $S = \emptyset$
2. iteratively add, v, to current solution S such that a PMU at v results in observation of max number of new nodes

xvgreedy algorithm

- Approximates MaxObserve-XV

S: set of nodes with a PMU

1. $S = \emptyset$
2. iteratively add, $\{\mathtt{u},\mathtt{v}\}$, to current solution S such that $\mathtt{u}$ and $\mathtt{v}$ are cross-validated and a PMU at results in observation of max number of new nodes

xvgreedy algorithm

- Approximates MaxObserve-XV

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Prove greedy and xvgreedy have polynomial running time

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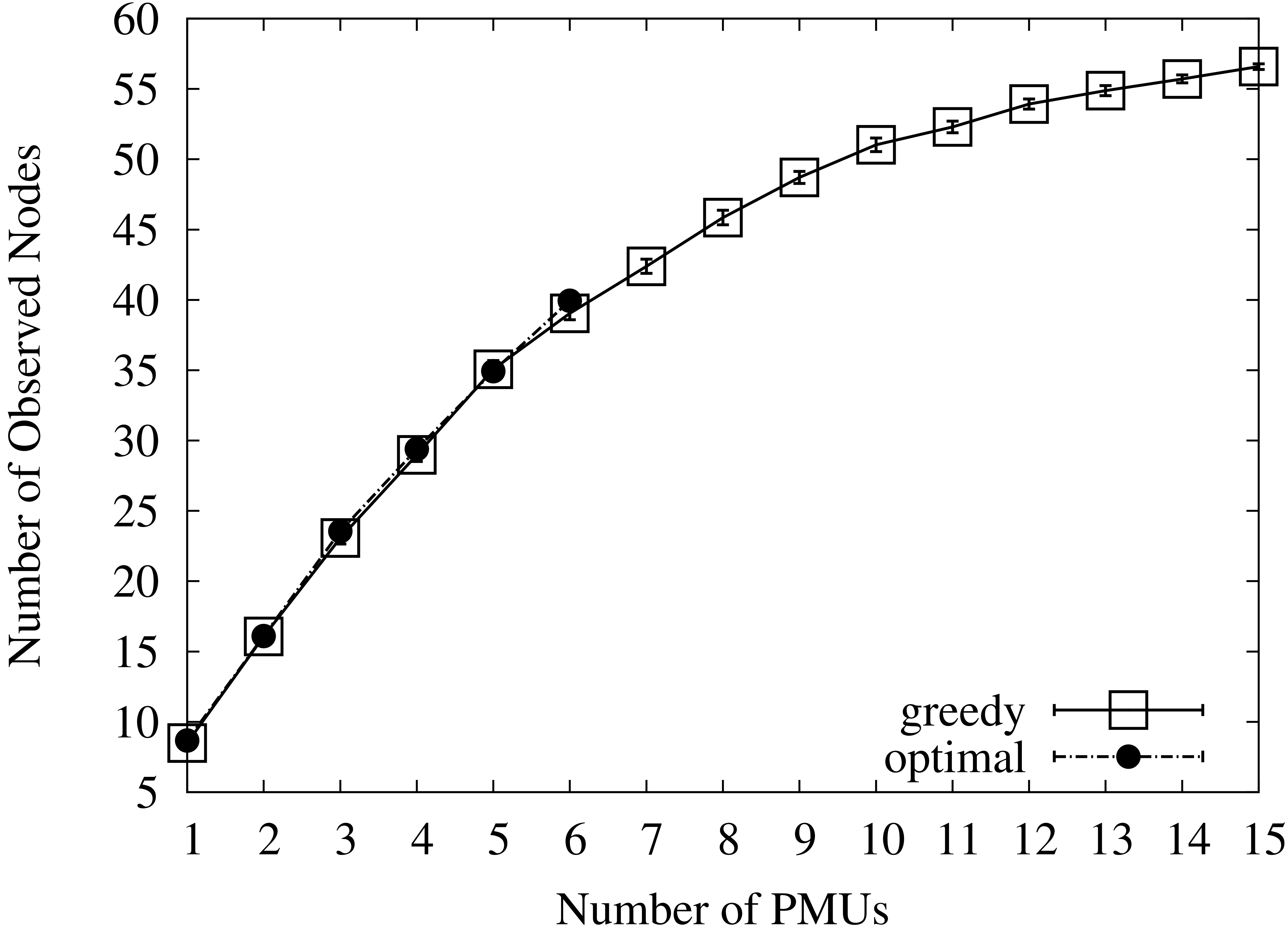
Simulation Setup

- Topologies
  - IEEE bus systems
  - synthetic graphs with same degree distribution
  - show results for synthetic topologies based on IEEE Bus 57
  - trends similar across other topologies

Simulation Setup

- Compare greedy solutions to brute-force optimal solution when possible
  - optimal: no cross-validation
  - xvoptimal: cross-validated PMUs

Impact of Number of PMUs



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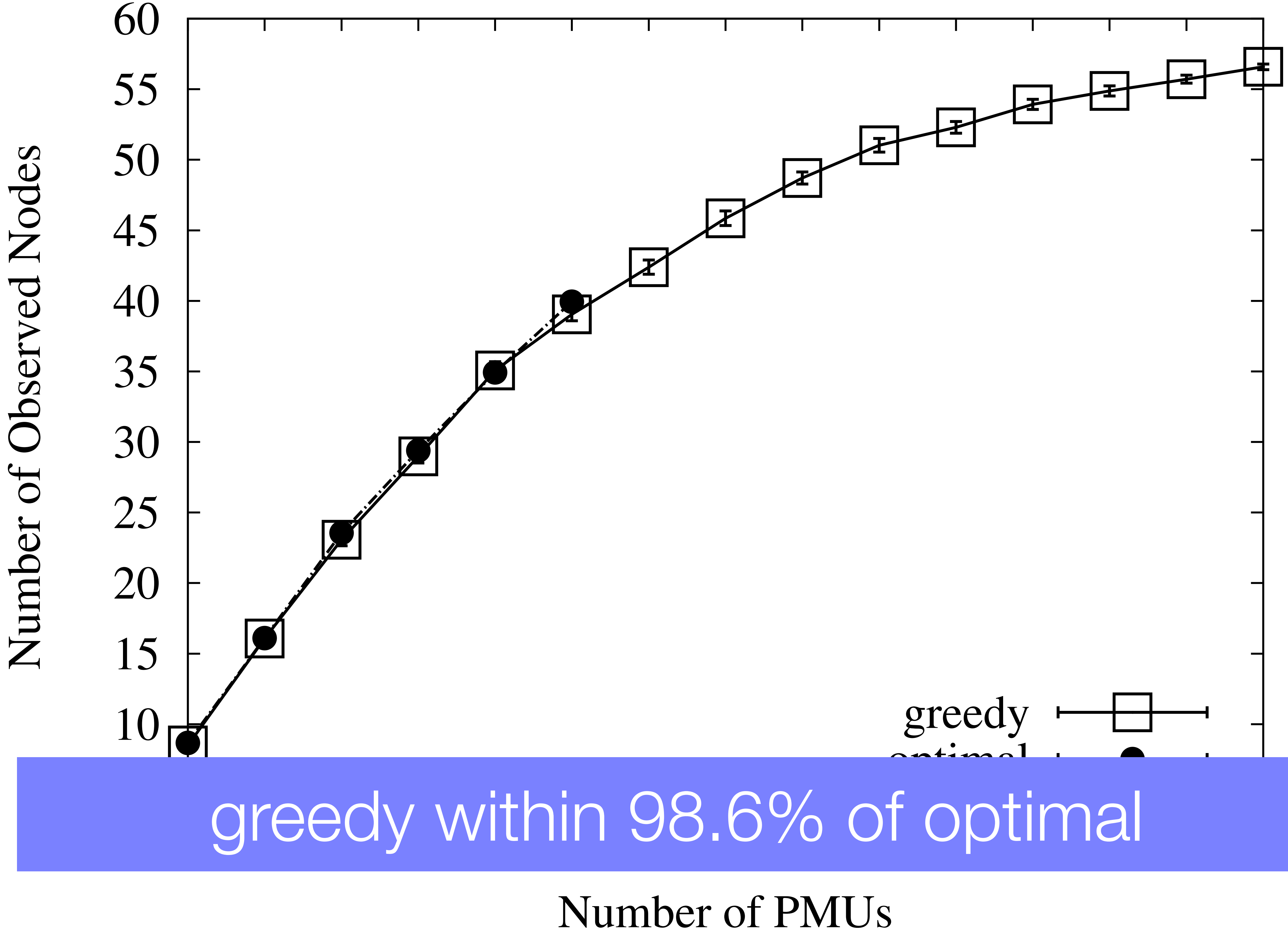
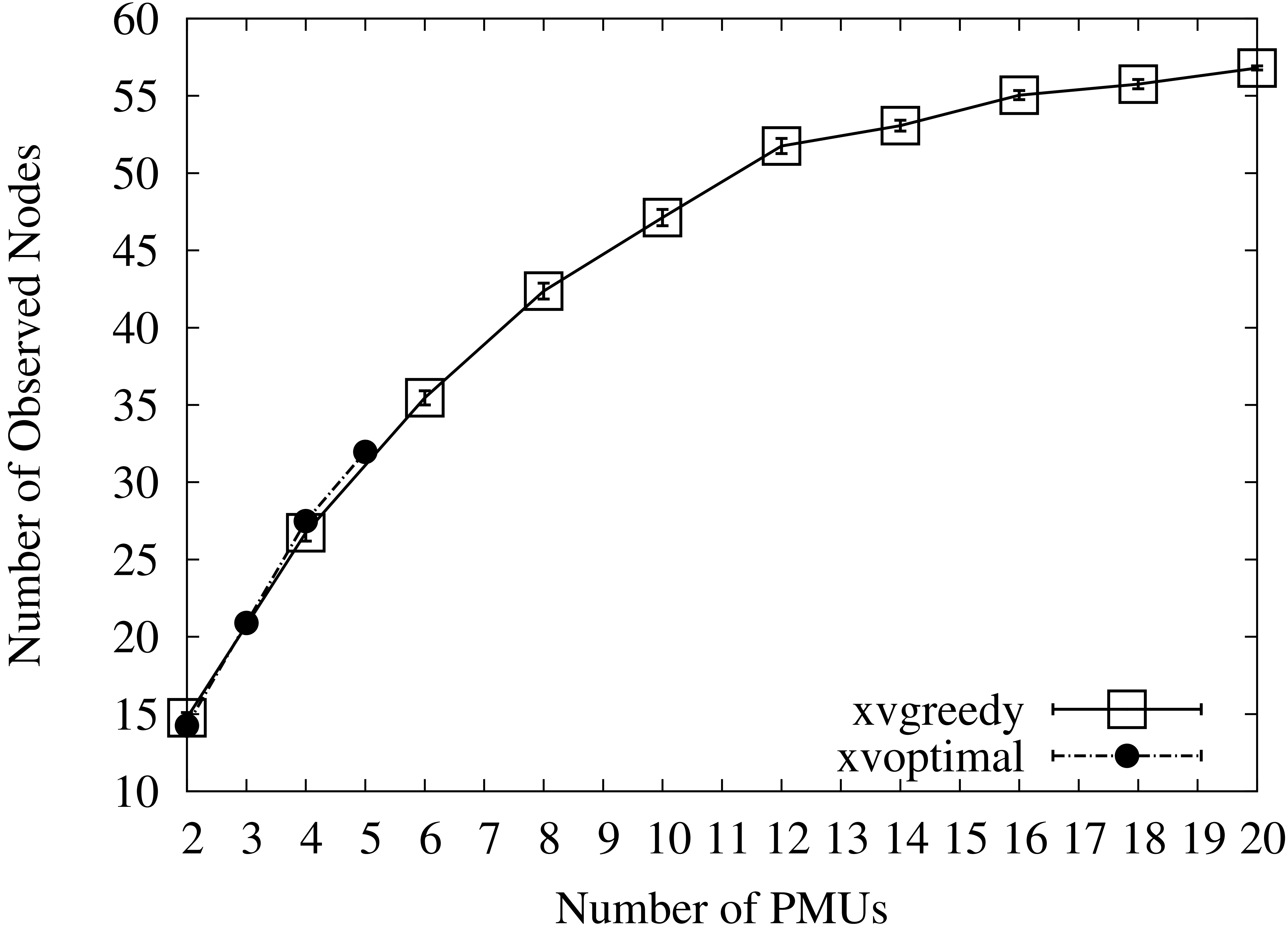


greedy within 98.6% of optimal

Impact of Number of PMUs



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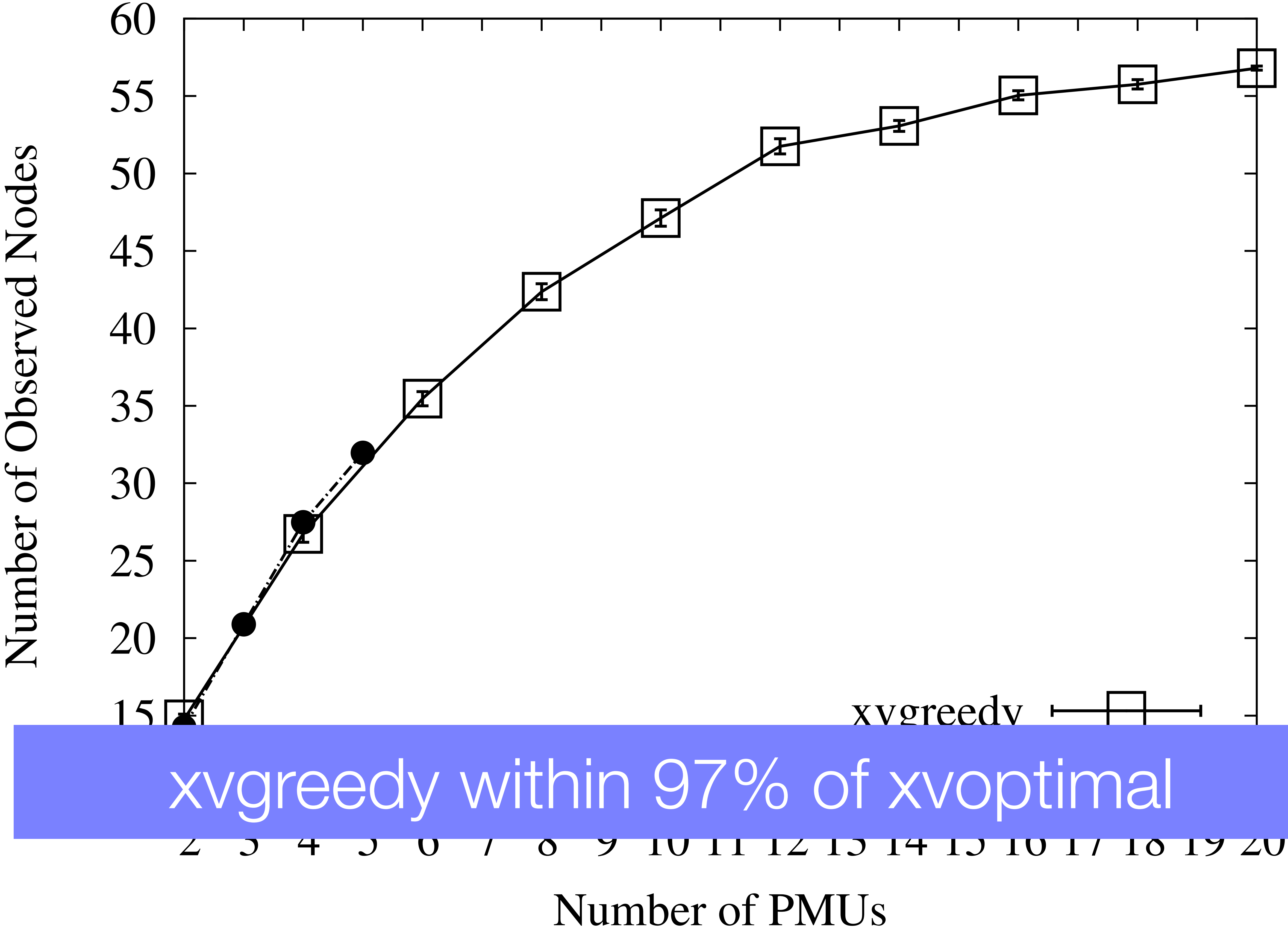
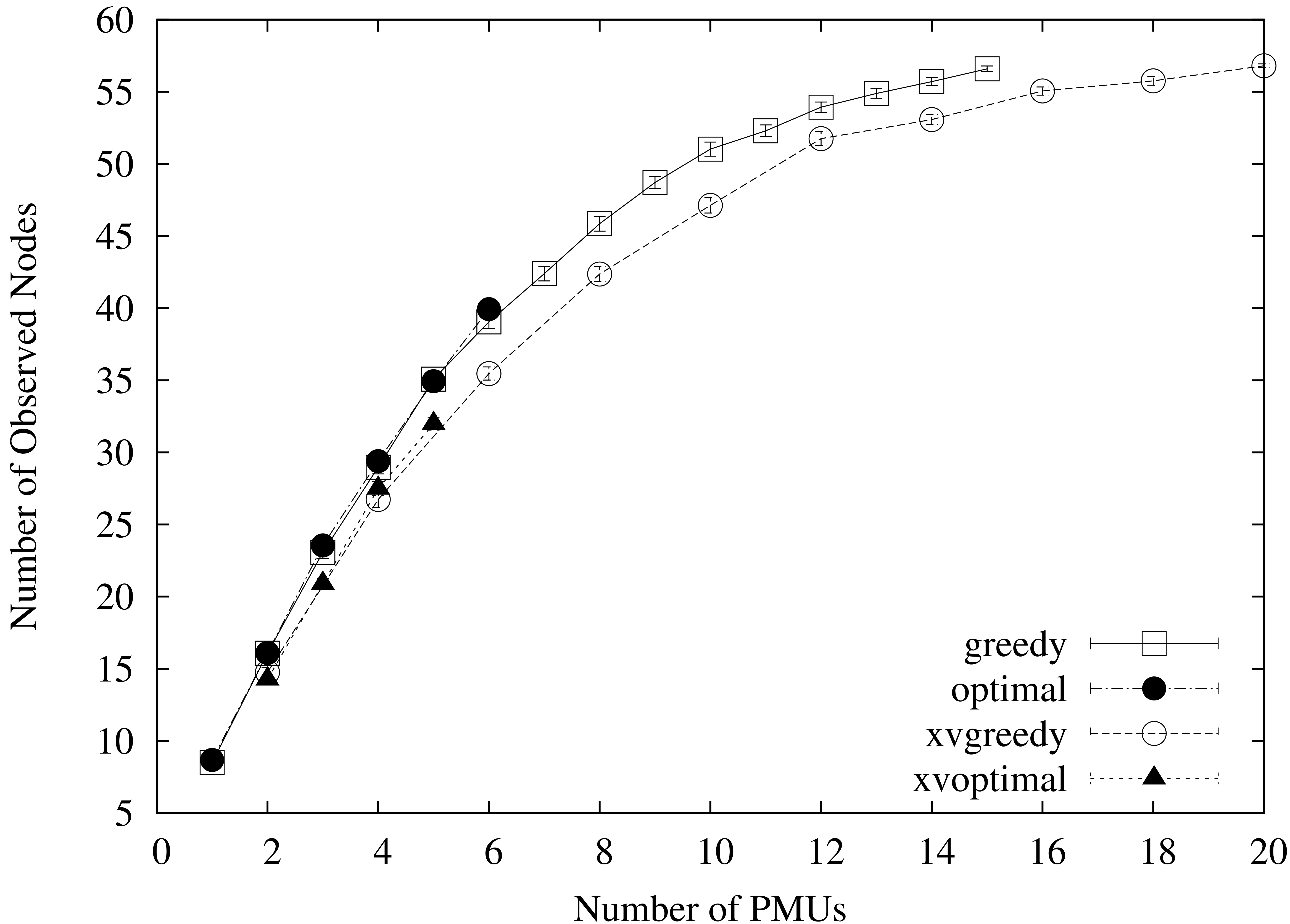


xvgreedy within 97% of xvoptimal

Impact of Number of PMUs



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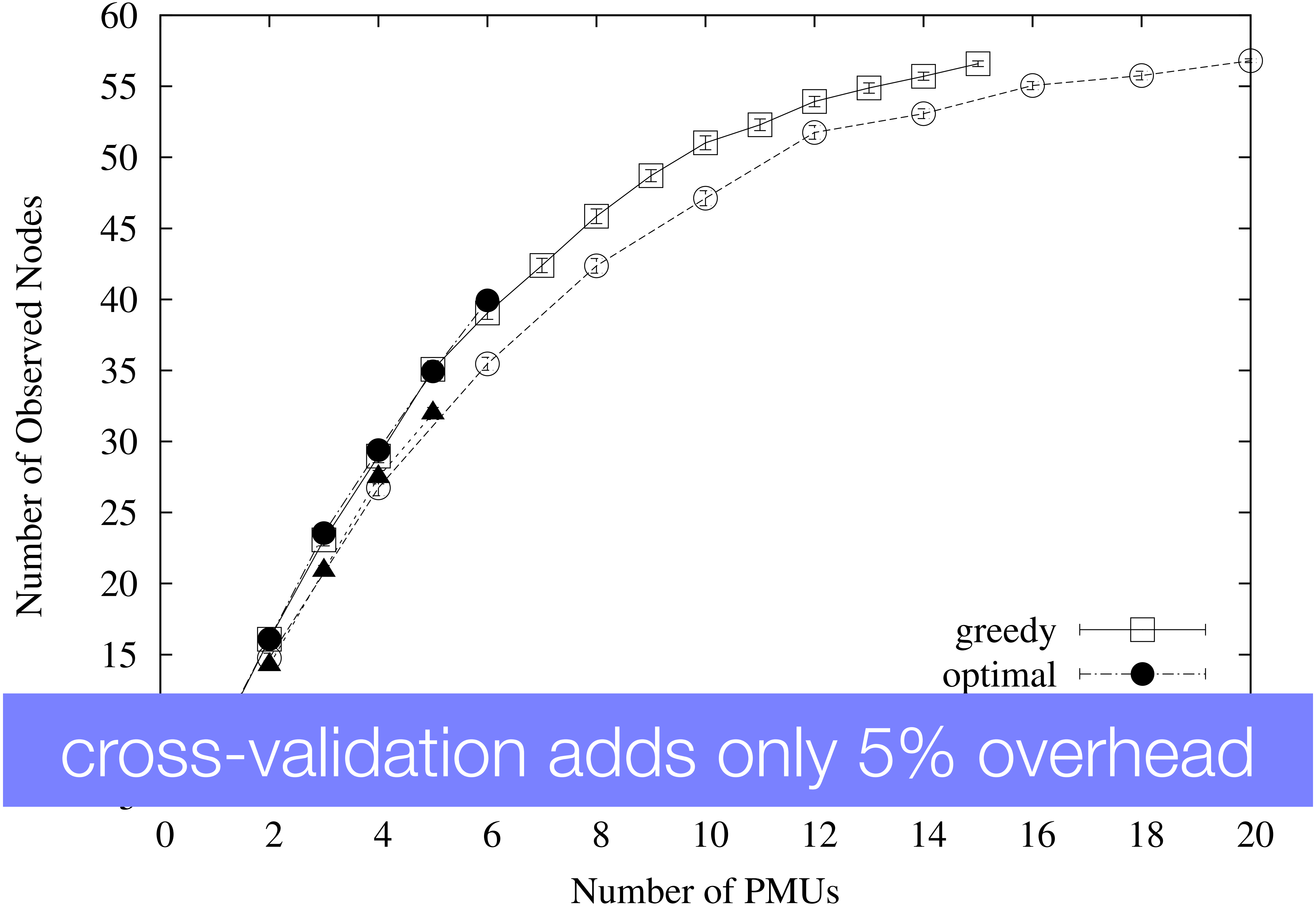


cross-validation adds only 5% overhead

Refresher Slide

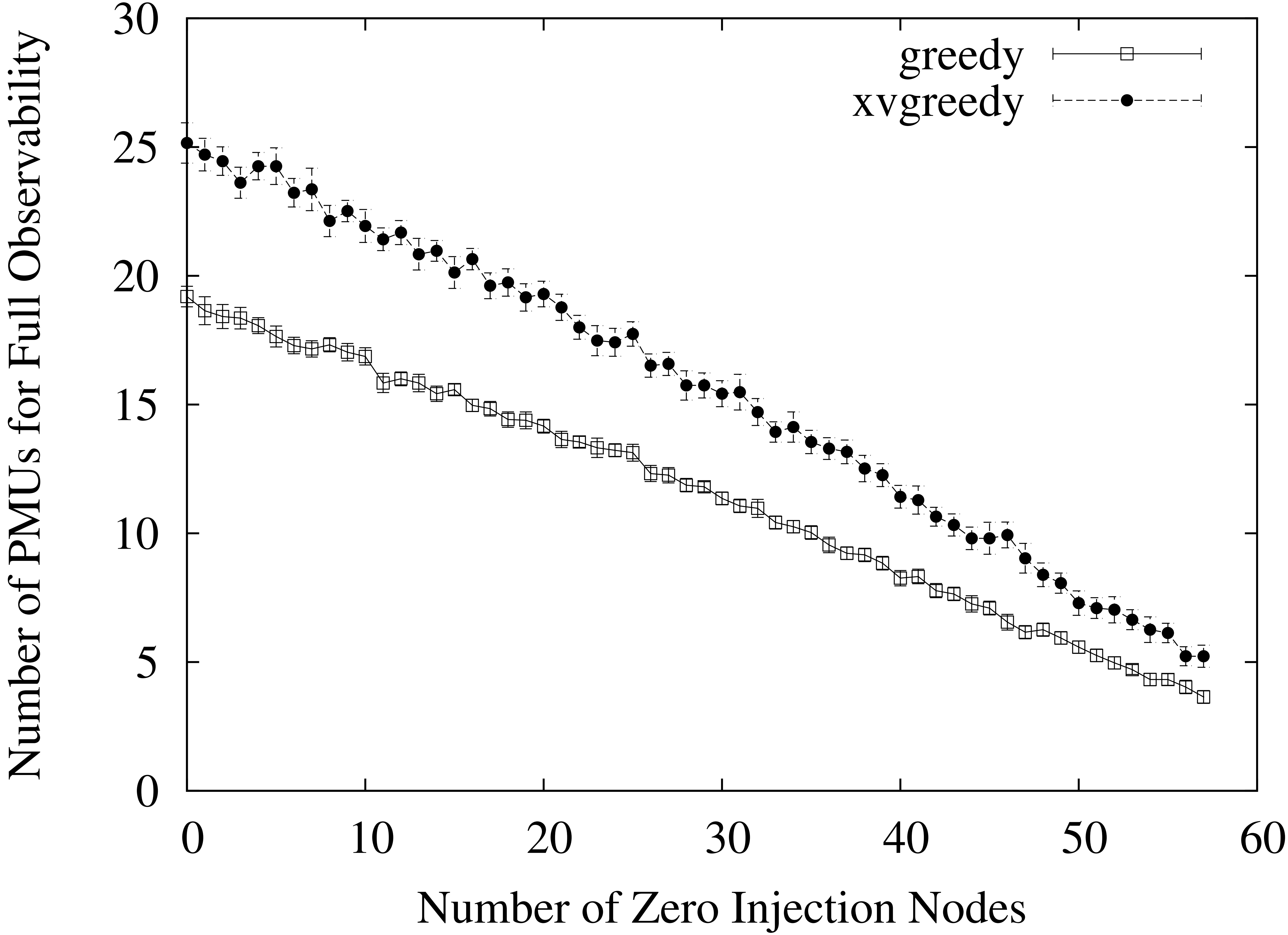
- Zero-injection node
  - substation where electrical lines meet
  - does not insert or pull energy from grid
  - node must be zero-injection to apply observability rule 2

Refresher Slide

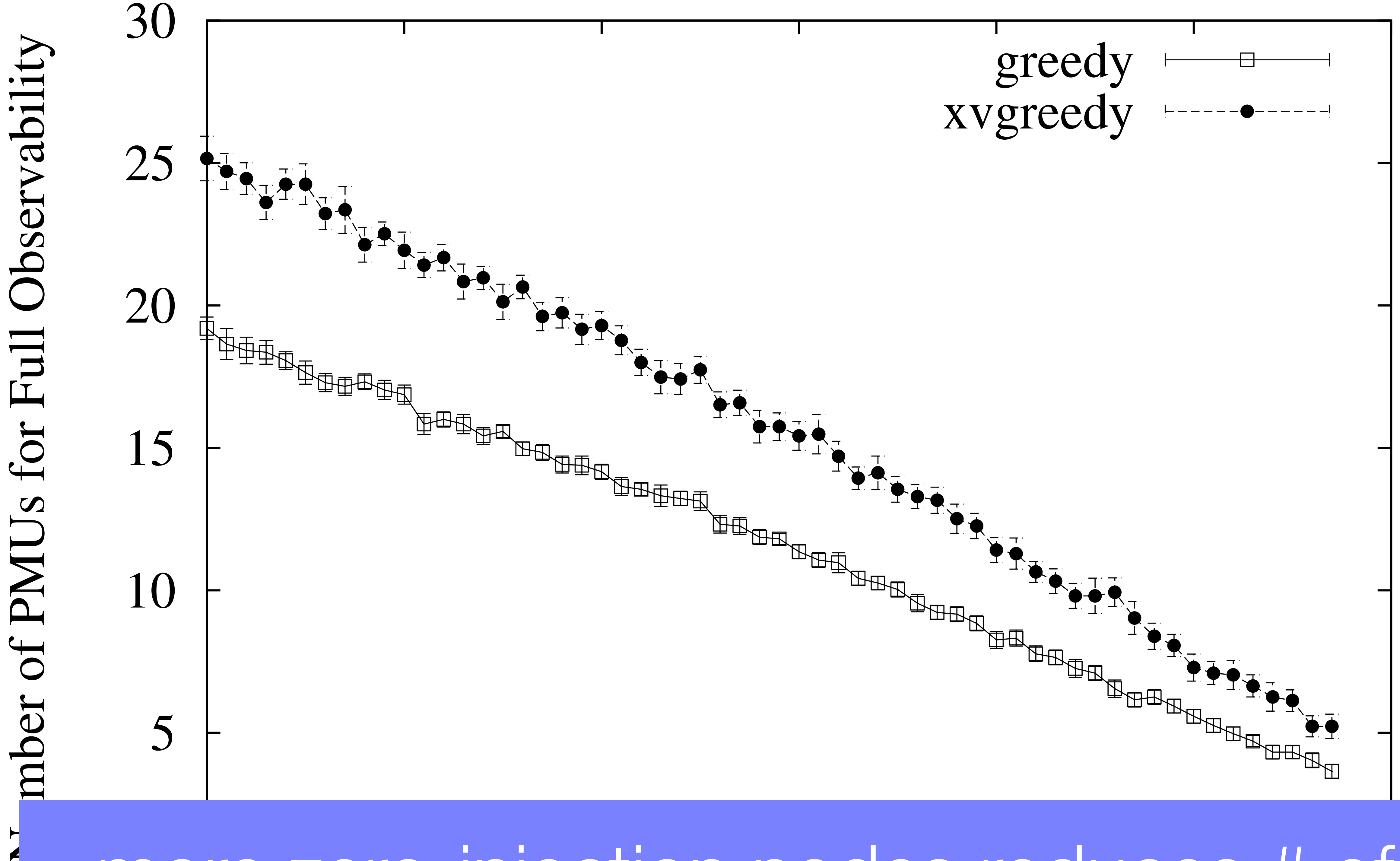
- Zero-injection node
  - substation where electrical lines meet
  - does not insert or pull energy from grid
  - node must be zero-injection to apply observability rule 2

How does number of zero-injection nodes effect observability?

Vary # Zero-Injection Nodes



Vary # Zero-Injection Nodes



more zero-injection nodes reduces # of PMUs needed to observe all graph nodes

Conclusions

- Defined 4 new PMU placement problems
  - proved NP-Complete
- Presented 2 simple greedy approximations
- Simulations
  - greedy gives close to optimal solutions
  - cross-validation imposes small cost

The End

Thank You

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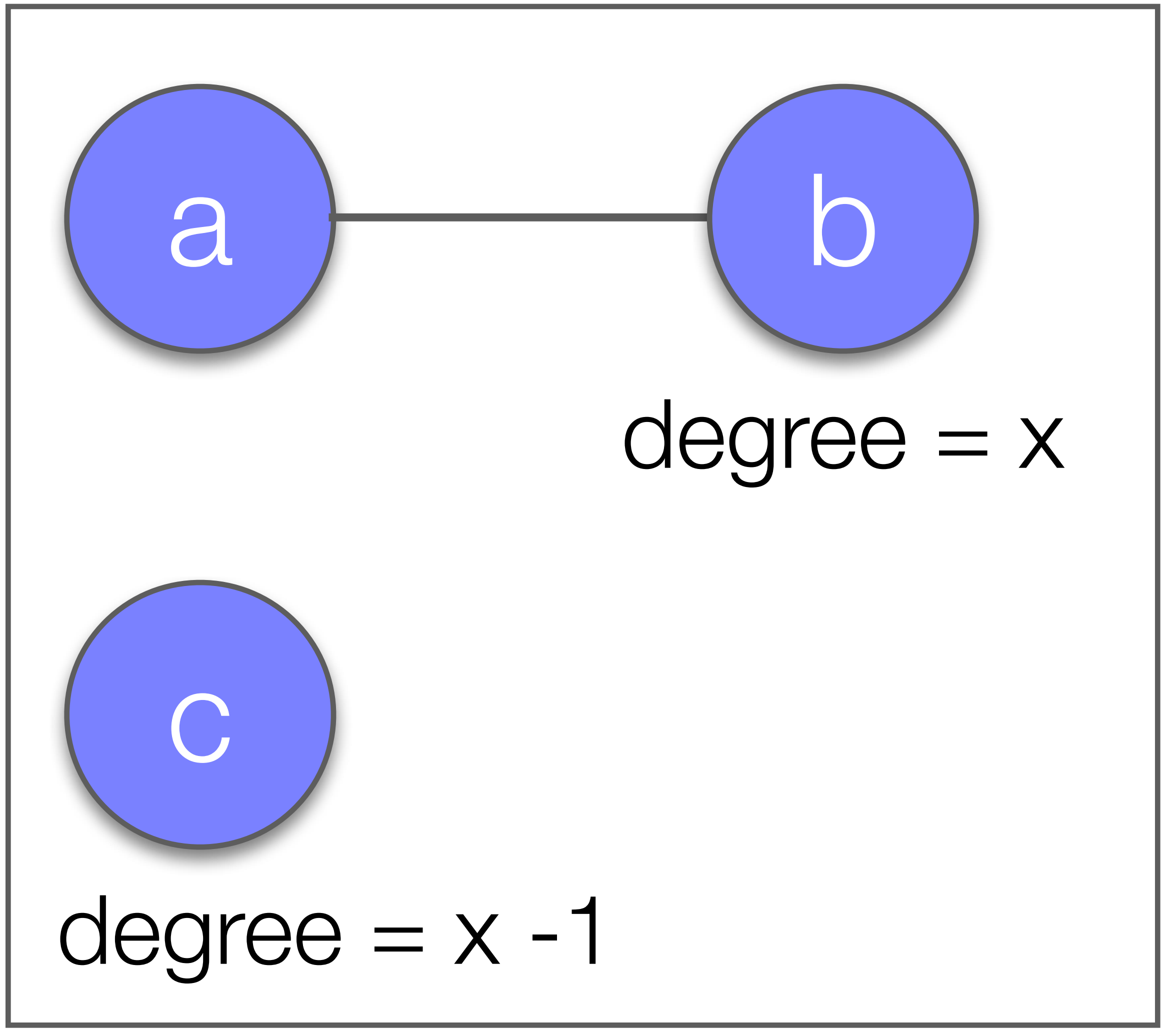
Questions?

Backup Slides

Synthetic Graph Generation

1. start with IEEE graph
2. swap edges until new graph shares no edges with original

Output = same # number of nodes but new connectivity



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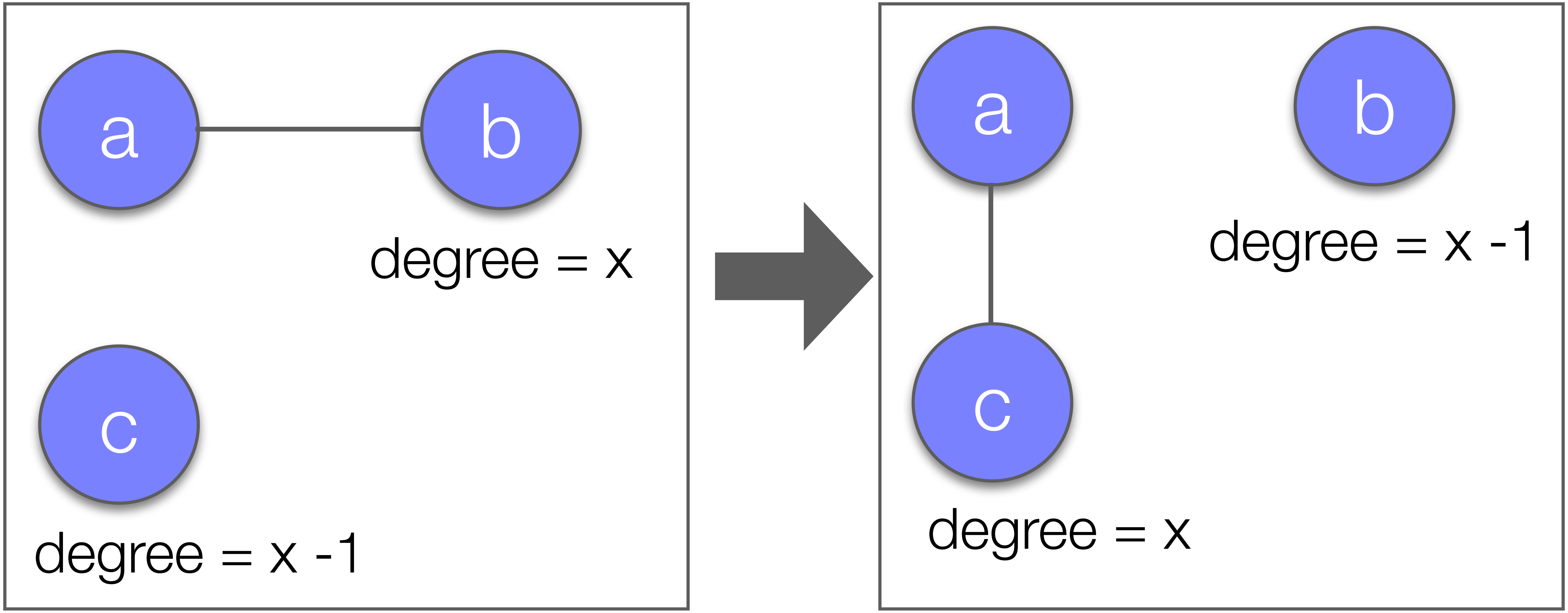
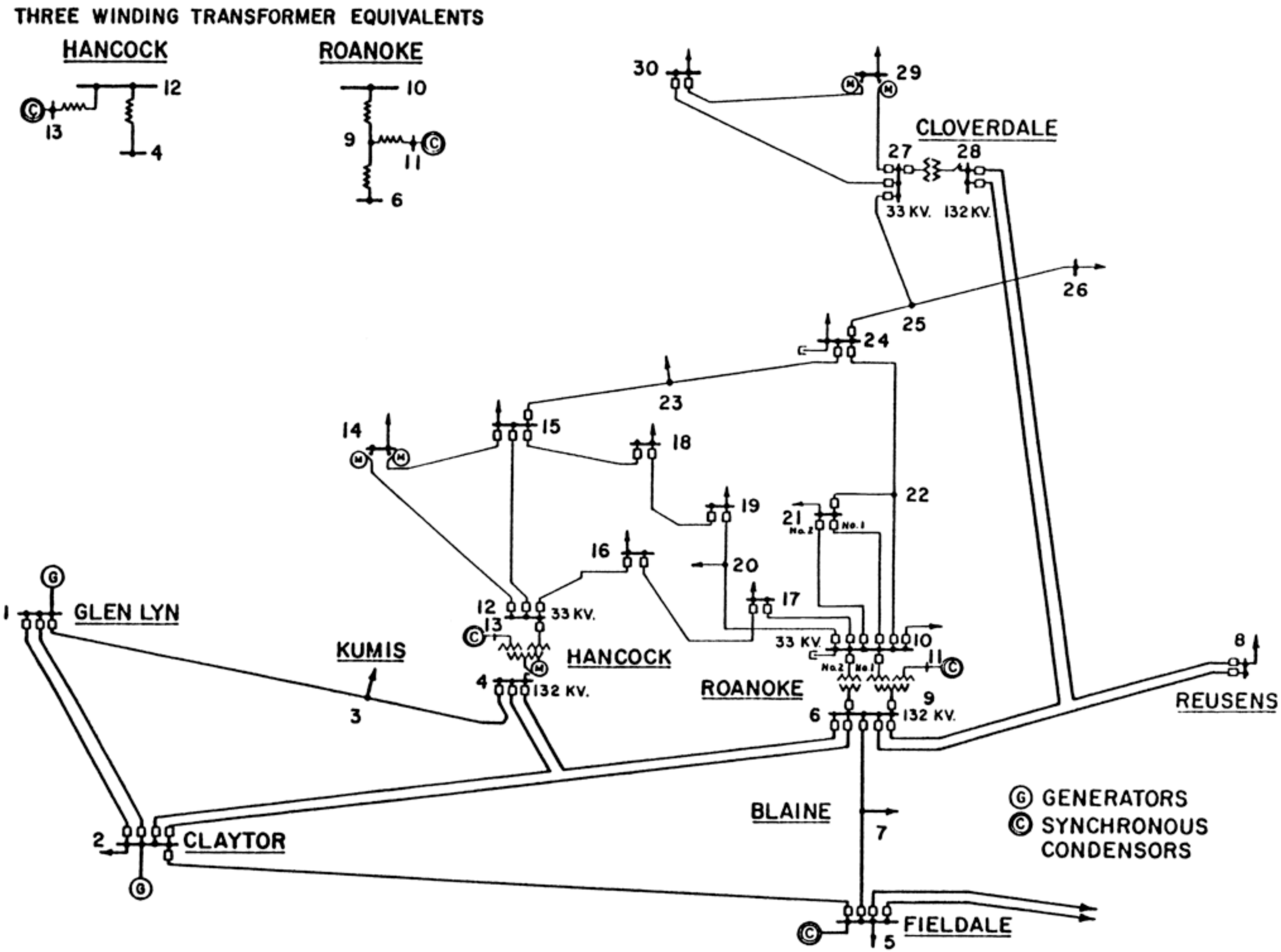


Simulation Topologies

- IEEE Bus System 14, 30, 57, 118, and 300
- No results for brute-force optimal for larger topologies

IEEE Bus System 30



Why is XV Limited to 2-hops?

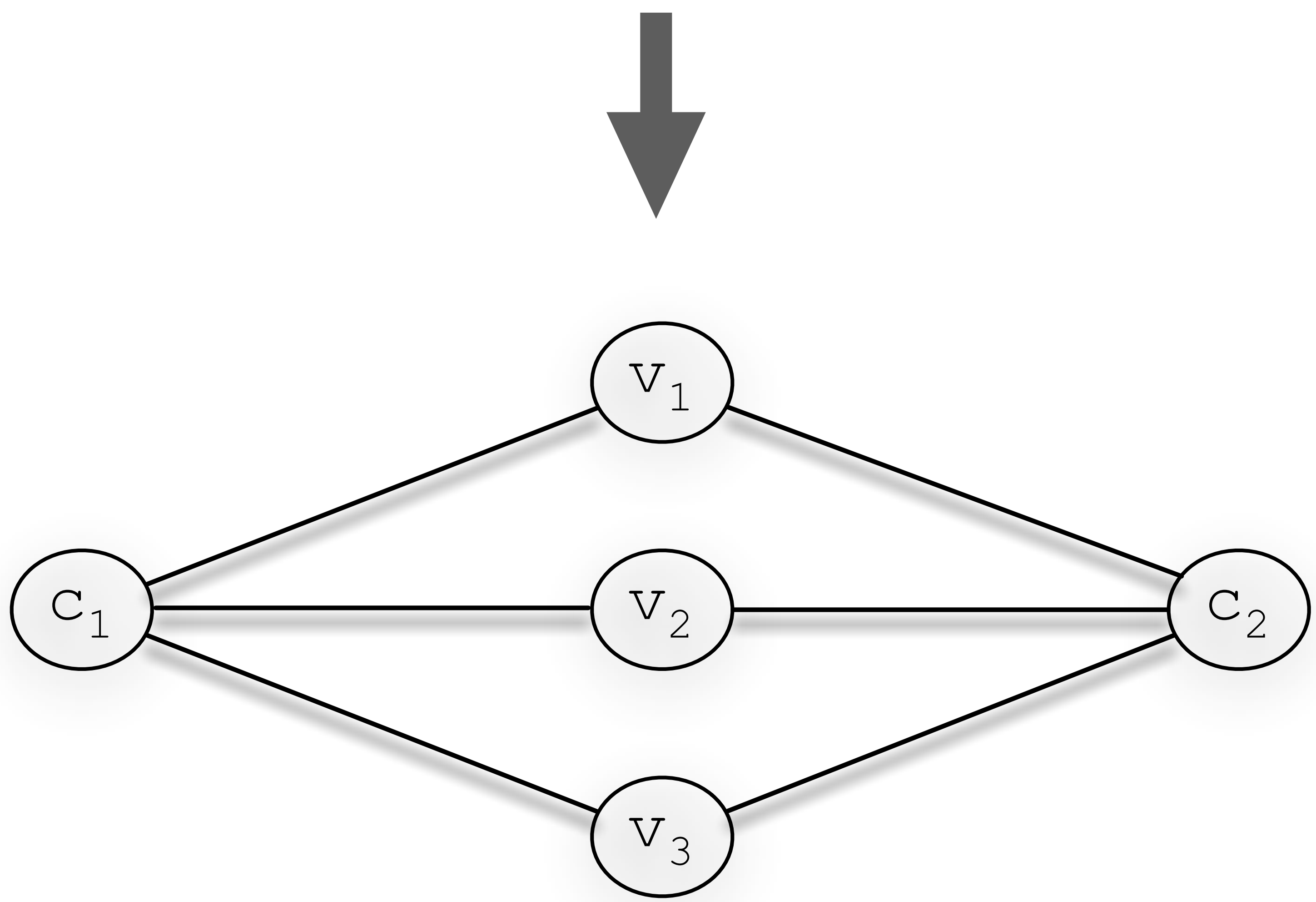
- Computing voltage phasor of non-PMU nodes
  - equations have variables to account for measurement error
- More than 2 Hops
  - have more unknowns that equations

    => no error detection

Proof: MaxObserve-XV is NPC

- Reduce from Planar 3SAT (P3SAT)

$$\boxed{\phi = (\overline{v_1} \vee v_2 \vee v_3) \wedge (v_1 \vee \overline{v_2} \vee \overline{v_3})}$$



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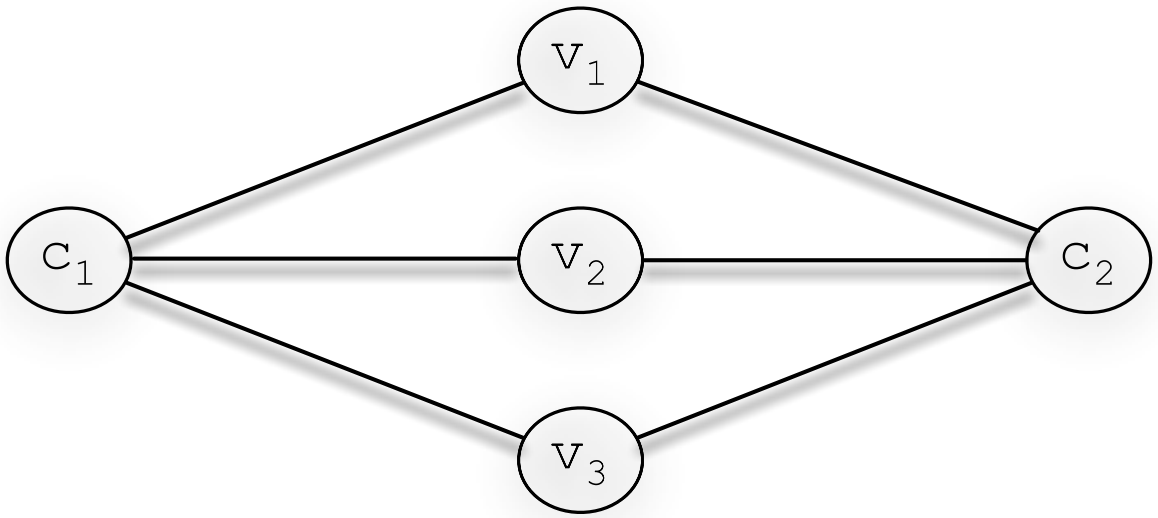

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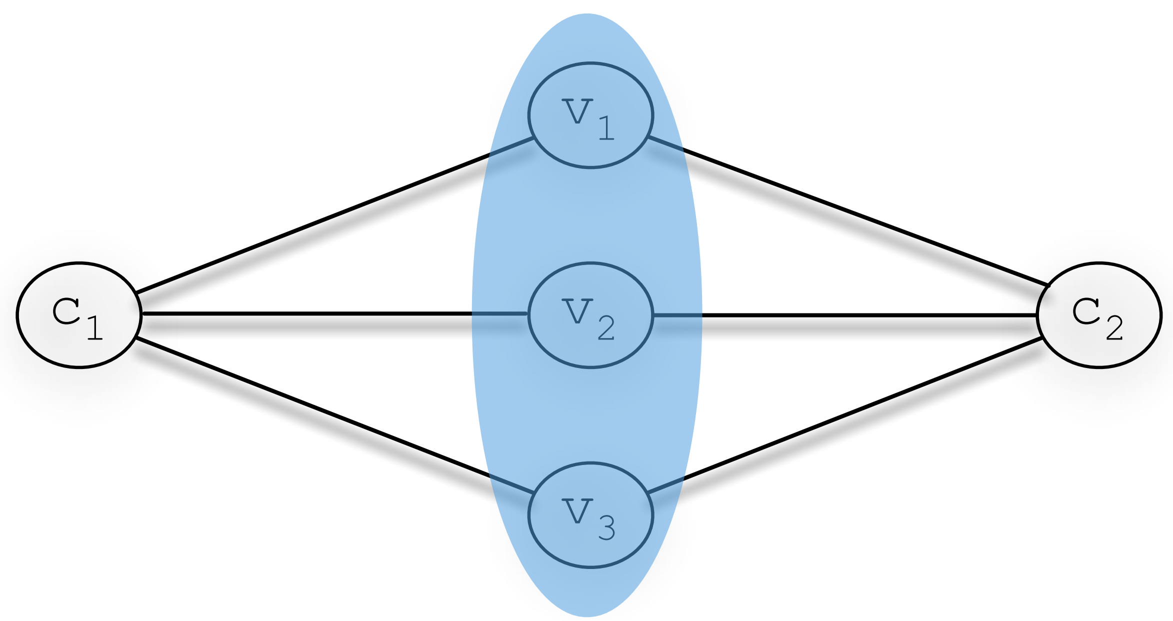

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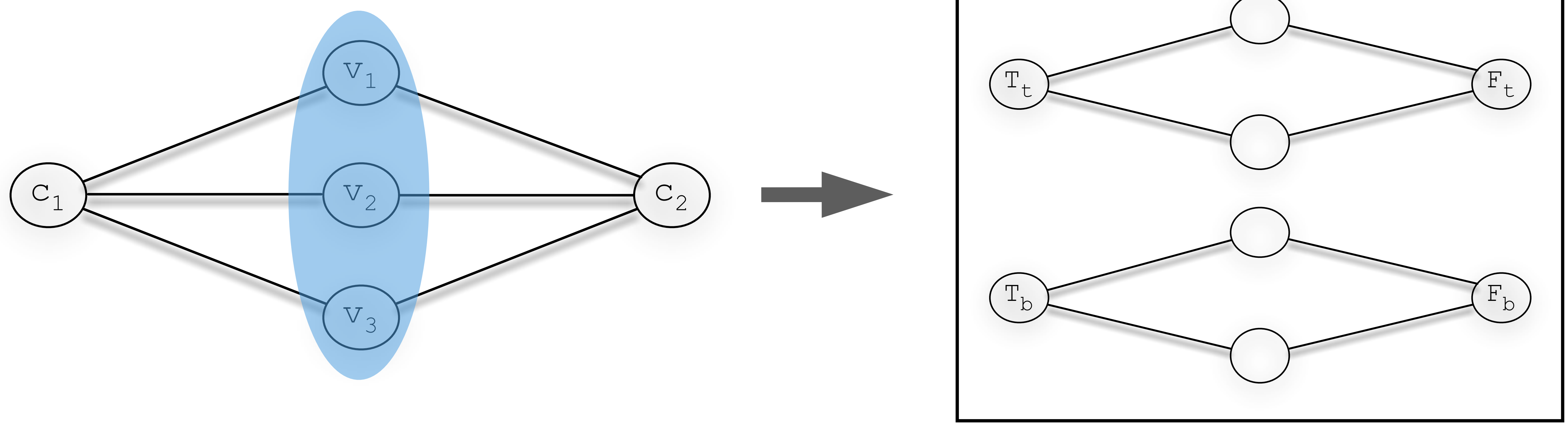

replace each variable with set of nodes (gadget)

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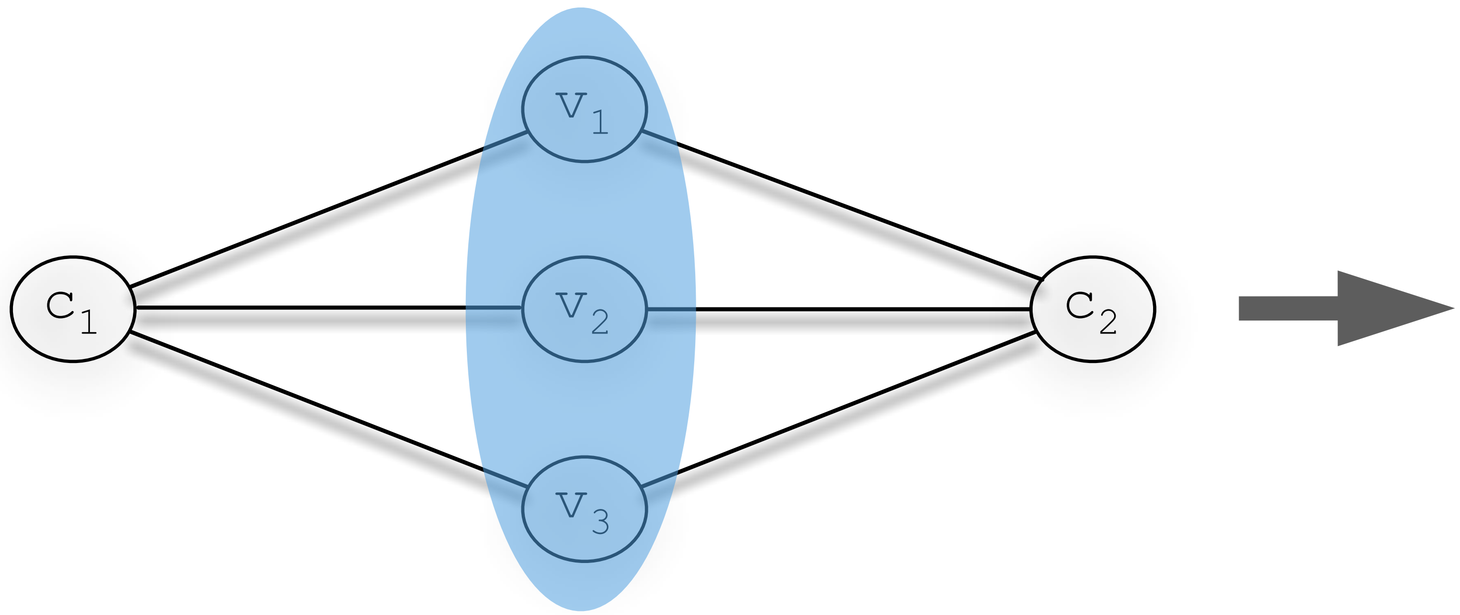

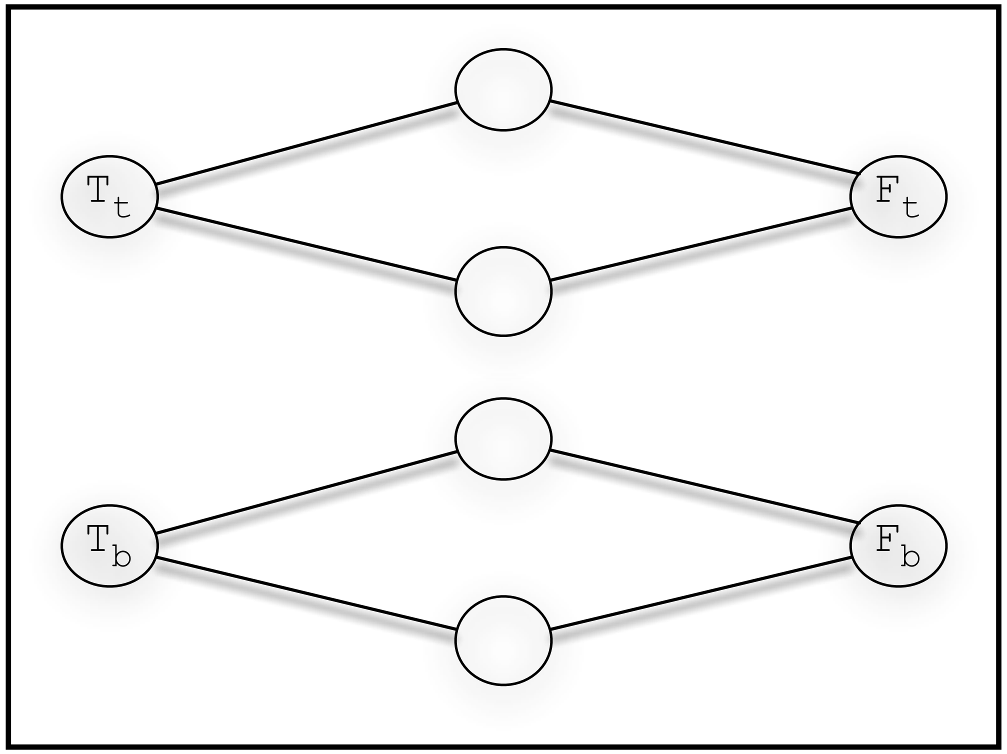

replace each variable with set of nodes (gadget)

Show maximum nodes observed iff PMU pairs placed on nodes corresponding to satisfying instance of P3SAT. PMUs are cross-validated