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Title: Open-source Tools for Solving Grid Optimization Problems: ARPA-e Benchmark Algorithm Overview

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Los Alamos NATIONAL LABORATORY

Open-source Tools for Solving Grid Optimization Problems

ARPA-e Benchmark Algorithm Overview

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Advanced Network Science Initiative

https://lanl-ansi.github.io/

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

My Role in the Competition

- **Develop the ARPA-e Benchmark Algorithm**
  - Early test driving of the platform and datasets
  - Develop and test various solution approaches

- **Release the Benchmark Algorithm (PowerModelsSecurityConstrained)**
  - An open-source platform for R&D on SCOPF algorithms
  - https://github.com/lanl-ansi/PowerModelsSecurityConstrained.jl

What is the competition problem?

Why is it challenging?

Competition Problem Specification Document

- https://gocompetition.energy.gov/challenges/challenge-2/formulation
- **97 Pages (mathematical program 9-31)**
- **I will focus on key intuitions**
  - Skip the details

GRID OPTIMIZATION (GO) COMPETITION

Grid Optimization Competition
Challenge 2 Problem Formulation

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May 31, 2021

1 Introduction

1.1 Background

This document contains the official formulation that will be used for evaluation in Challenge 2 of the Grid Optimization (GO) Competition. Minor changes may occur within the formulation. Entrants will be notified when a new version is released. Changes are not expected to be of a significance that would cause a change in approach for the Entrants.

This formulation builds upon the Challenge 1 formulation published in ARPA-E DE-FOA-0001952. Entrants will be judged based on the current official Challenge 2 formulation posted on the GO Competition website (this document, which is subject to change), not the formulation posted in DE-FOA-0001952. Entrants are permitted and encouraged to use any alternative problem formulation and modeling convention within their own software (such as convex relaxation, decoupled power flow formulations, current-voltage formulations, etc.) in an attempt to produce an exact or approximate solution to this particular mathematical program. However, the judging of all submitted approaches must conform to the official formulation presented here.

The following mathematical programming problem is a type of a security-constrained (AC based) optimal power flow, or SCOPF. There are many ways to formulate the SCOPF problem; this document may present multiple equivalent options for specified constraints. Entrants are strongly encouraged to study this formulation precisely and to engage with the broader community if anything is not clear (please see the FAQs and forum on the GO Competition website, https://gocompetition.energy.gov/).

This SCOPF problem is defined to be an alternating current (AC) formulation, which is based on a bus-branch power system network model with security constraints. In general, Entrants are tasked with determining the optimal dispatch and control settings for power generation and grid control equipment in order to maximize the market surplus associated with the operation of the grid, subject to pre- and post-contingency constraints. Feasible solutions must conform to operating standards including, but not limited to: minimum and

. . .

Competition Problem Complexity and Instance Size

- **Problem Class Non-Convex MINLP**
  - Non-convex nonlinear equations
  - Discrete variables (component participation, control settings)

- **Competition network sizes**
  - Up to 31,000 nodes / 40,000 edges / 5,000 contingencies

- **Writing down the mathematical program as described**
  - 900,000,000 continuous decision variables
  - 250,000,000 discrete decision variables
  - comparable number of constraints

AND solve in
< 5 minutes
< 60 minutes

What is the completion problem?

Start with Optimal Power Flow as a building block

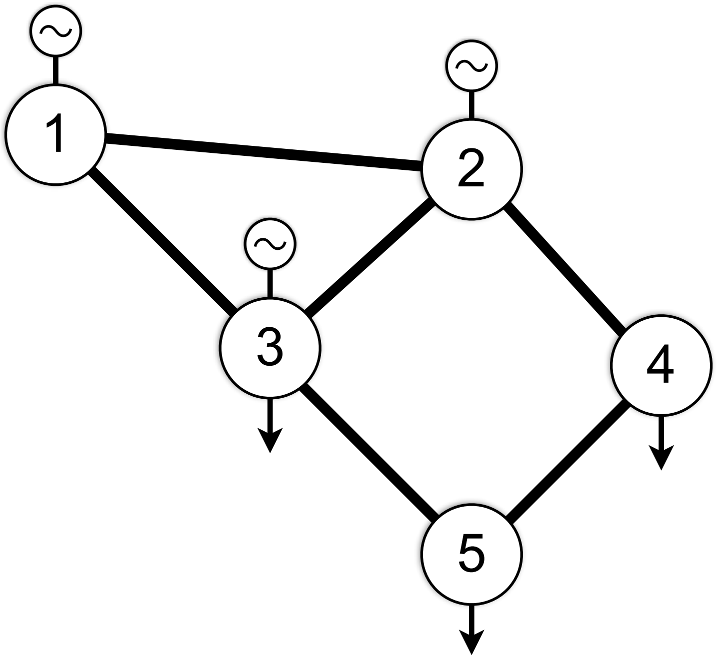
What is Optimal Power Flow?

- **A natural and fundamental transmission network optimization problem**
  - Instantaneous economic dispatch of the grid

- **Given**
  - A Power Transmission Network
  - Required Demands (i.e. customer loads)
  - Generator Cost Functions

- **Minimize**
  - The cost of generating power

- **Subject To**
  - Meeting the required demands
  - Network and generator operation constraints



Physics of power networks leads to non-convex nonlinear problem!

A Conical OPF Formulation [1]

variables:

$$S_i^g \;\; \forall i \in G$$
$$V_i \;\; \forall i \in N$$

minimize:

$$\sum_{i \in G} f(S_i^g)$$

subject to:

$$(\boldsymbol{v}_i^{\boldsymbol{l}})^2 \le V_i V_i^* \le (\boldsymbol{v}_i^{\boldsymbol{u}})^2 \;\; \forall i \in N$$
$$\boldsymbol{S}_i^{\boldsymbol{gl}} \le S_i^g \le \boldsymbol{S}_i^{\boldsymbol{gu}} \;\; \forall i \in G$$
$$\sum_{k \in G_i} S_k^g - \boldsymbol{S}_i^d = \sum_{(i,j) \in E_i \cup E_i^R} S_{ij} \;\; \forall i \in N$$
$$S_{ij} = \boldsymbol{Y}_{ij}^* V_i V_i^* - \boldsymbol{Y}_{ij}^* V_i V_j^* \;\; (i,j) \in E \cup E^R$$
$$|S_{ij}|^2 \le (\boldsymbol{s}_{ij}^{\boldsymbol{u}})^2 \;\; \forall (i,j) \in E \cup E^R$$

Large-Scale Non-Convex NLP!

[1] Coffrin, Carleton, Hassan L. Hijazi, and Pascal Van Hentenryck. "The QC relaxation: A theoretical and computational study on optimal power flow." IEEE Transactions on Power Systems 31.4 (2015): 3008-3018.

Solution Approaches and Scalability

- **Interior Point Algorithms (e.g. Ipopt, KNITRO)**
  - Second-order gradient descent like approaches
  - Only provide locally optimality, but seems to be very near globally optimal in practice

- **Sequential Linear/Quadratic Programming (e.g. gurobi, cplex)**
  - Linearized around an operating point; Optimize; Repeat
  - Only provide locally optimality, but seems to be sufficient in practice

- **Problem Scales**
  - 30,000 node network in 300 seconds
  - Cases curated here, https://github.com/power-grid-lib/pglib-opf

What is the completion problem?

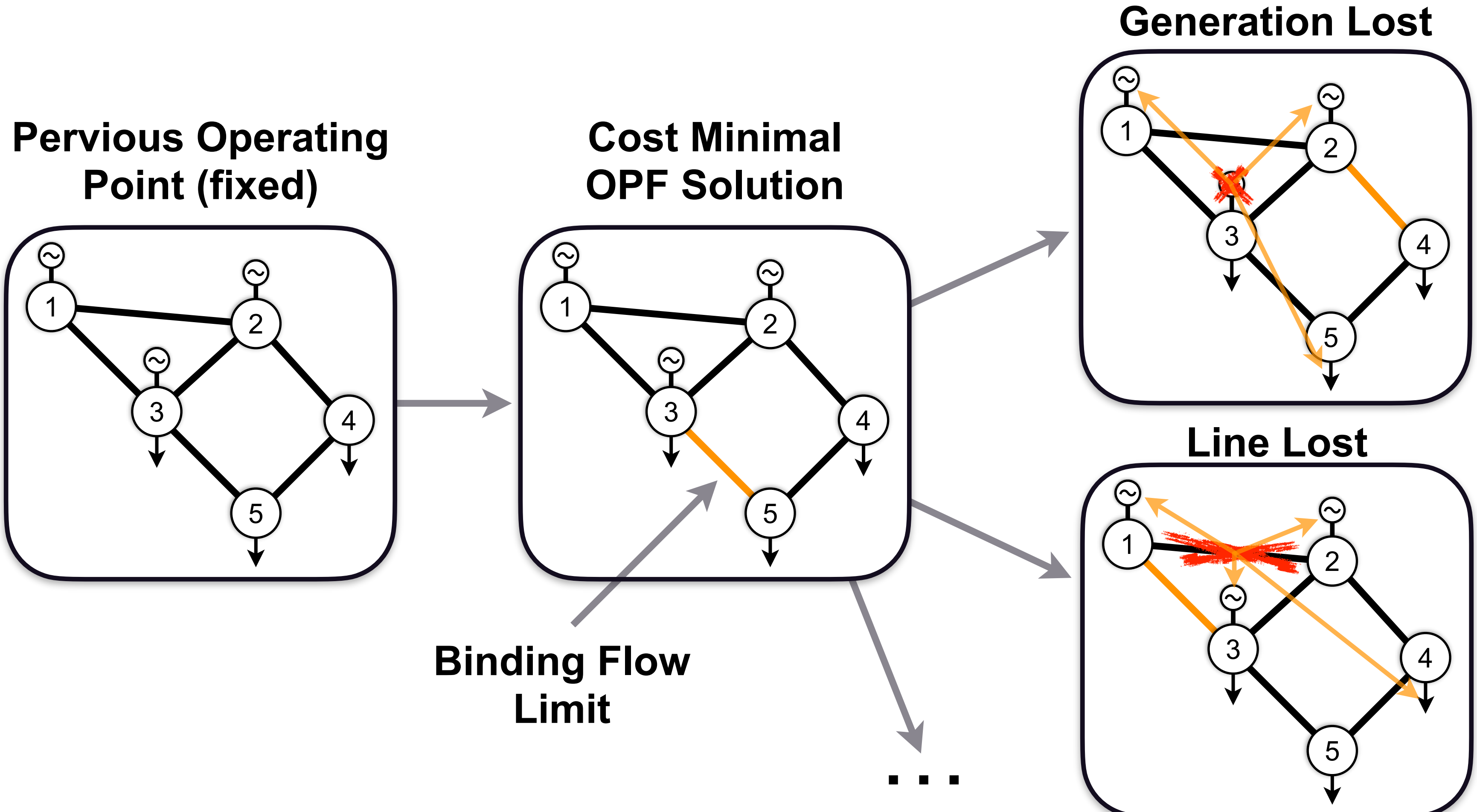
Beyond Optimal Power Flow

Balance Cost and Resilience

- **Power Networks are regulated to be "N-1 Secure"**
  - Intention, the network can withstand the spontaneous failure of any single component during daily operations

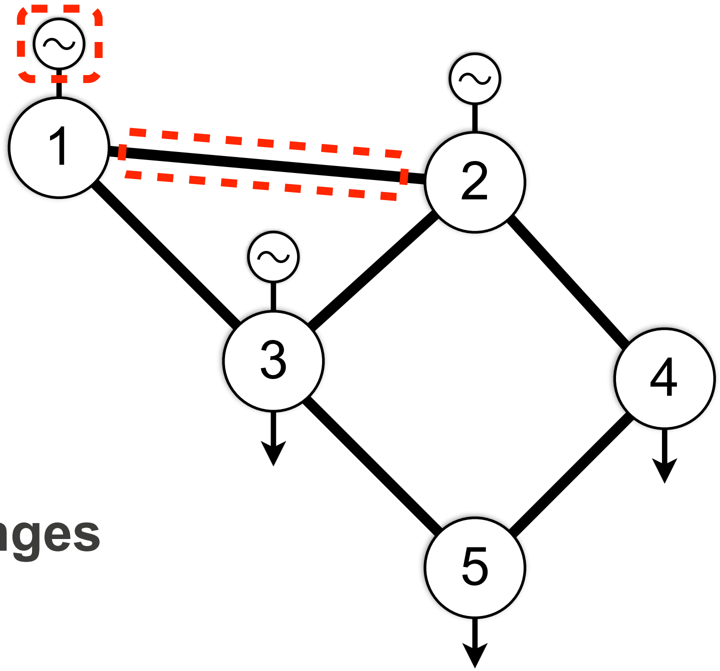
- **Lots of details in practice**
  - Focus on a specific subset of component failures
  - Many constraints can be exceeded for a short amount of time
  - What time scale? (e.g. seconds vs minutes)
  - Available recourse actions?

Competition OPF with Security Constraints



Discrete Decision Variables

- **Occur in first-stage and all contingency stages**
- **Unit Commitment: {0,1}**
- **Tranmission Switching: {0,1}**
  - a network design problem!
- **Transformer Taps: {-20, -19, …, 19, 20}**
  - with impedance correction tables
- **Bus Shunts: a variety of small integer ranges**



How to approach competition problem?

Competition Problem, Core Insights

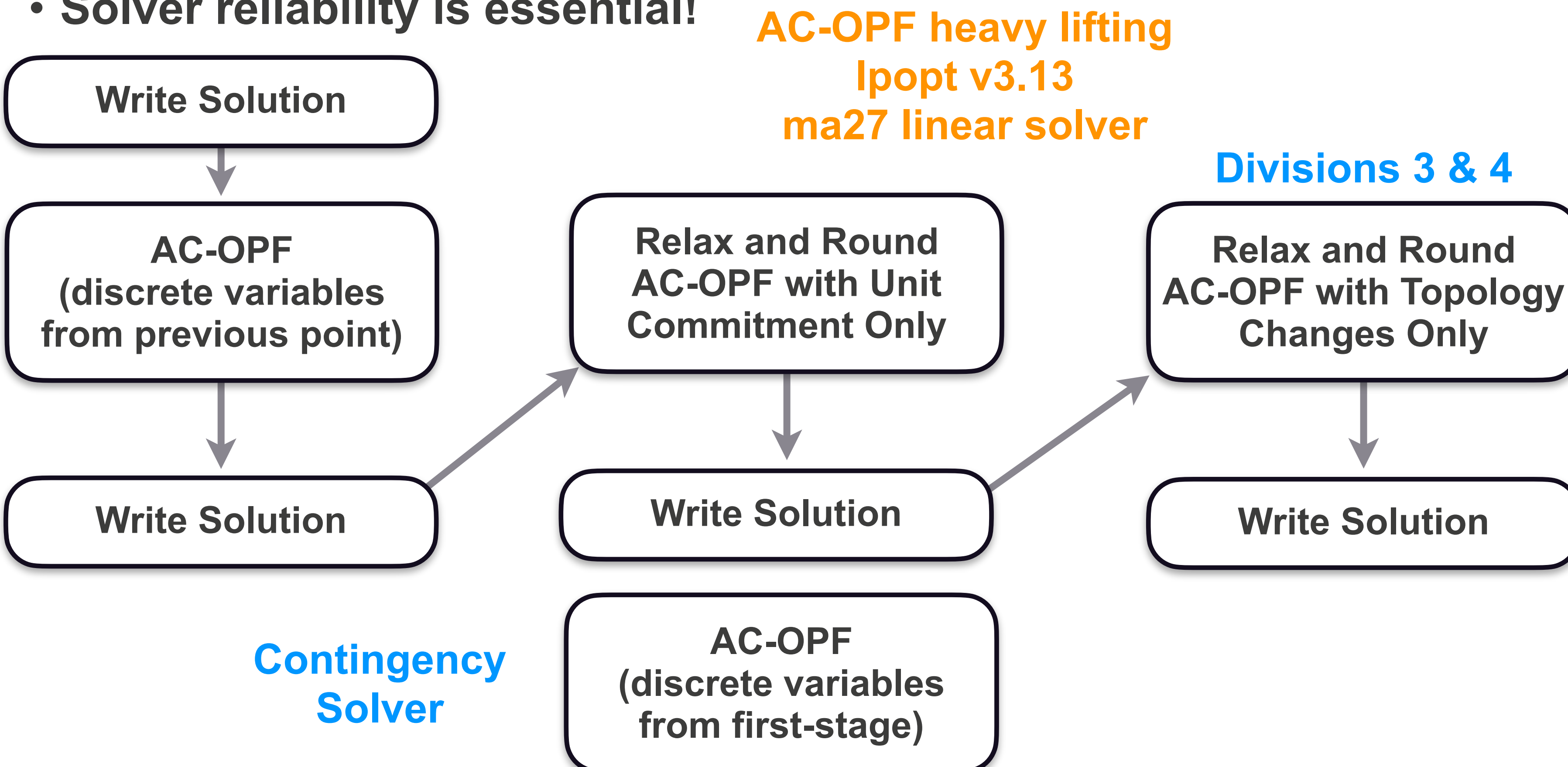
- **How to treat the discrete parameters?**
  - Carefully tuned rounding heuristics

- **Pose the full non-convex MINLP problem (with discrete variables)**
  - Relax the discrete variables to a continuous range
  - Solve relaxed non-convex NLP problem
  - Round discrete variables that are “close” to an integer value (0,1)
  - Resolve rounded non-convex NLP problem

- **Most important discrete variables**
  - Unit Commitment is the most valuable (solve first)
  - Topology control is less valuable and also impacted by UC (solve second)

ARPA-e Benchmark Algorithm

- Solver reliability is essential!



ARPA-e Benchmark Algorithm

- **Trial 3 Datasets**
  - 81 networks ranging from 600 to 31000 buses
- **AC-OPF in Base Case Only**
  - Typical objective improvement 70%
- **Additional UC Improvement**
  - Improves 75% of cases
  - Typical objective improvement 43%
- **Additional OTS Improvement**
  - Improves 20% of cases
  - Typical objective improvement 1%

ARPA-e Benchmark Algorithm

- **Focus on finding the best-possible solutions (not performance)**

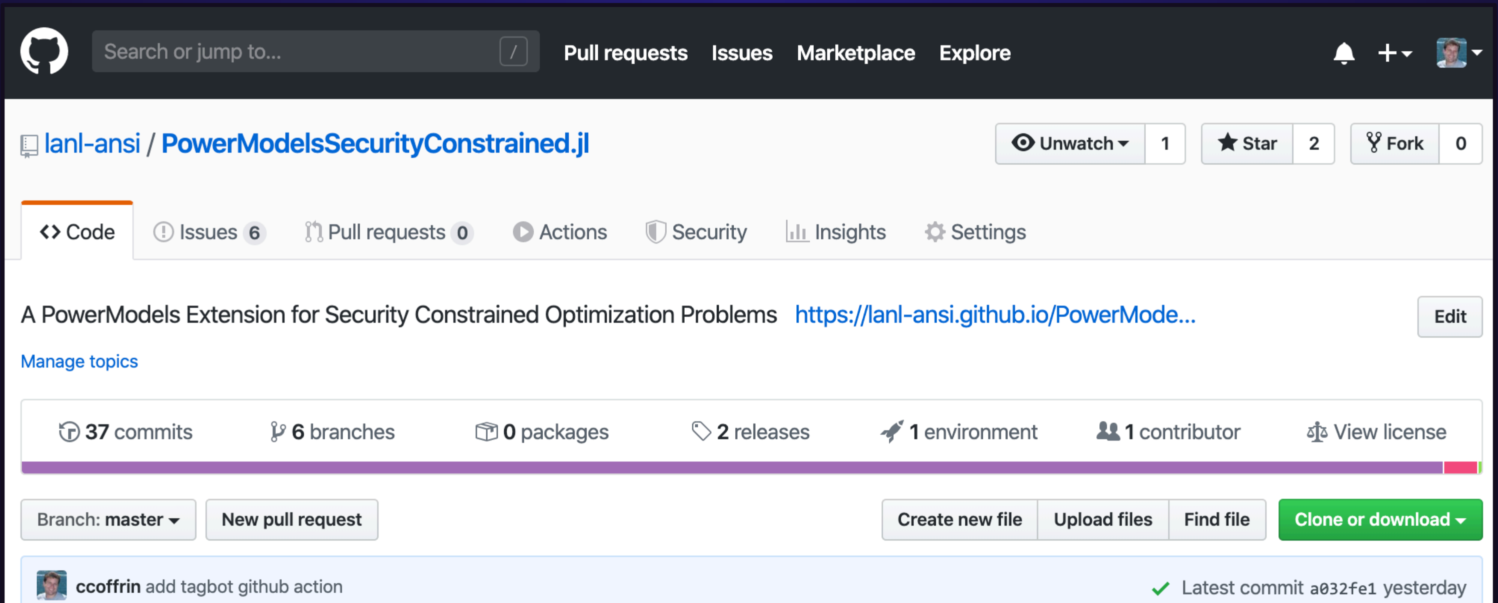
- **Solves 3-5 OPF-like problems to find the base-case operating point**
  - Significant engineering is required to speed up this core AC-OPF
  - Parallel derivative computations, improve cacheing of pre-compiled Julia code

- **Notable performance degradation under aggressive time limits**
  - Divisions 1 & 3 - 5 minute time limit
    - First AC-OPF fails to converge on largest network cases
  - Divisions 2 & 4 - 60 minute time limit
    - Usually all stages complete

PowerModelsSecurityConstrained

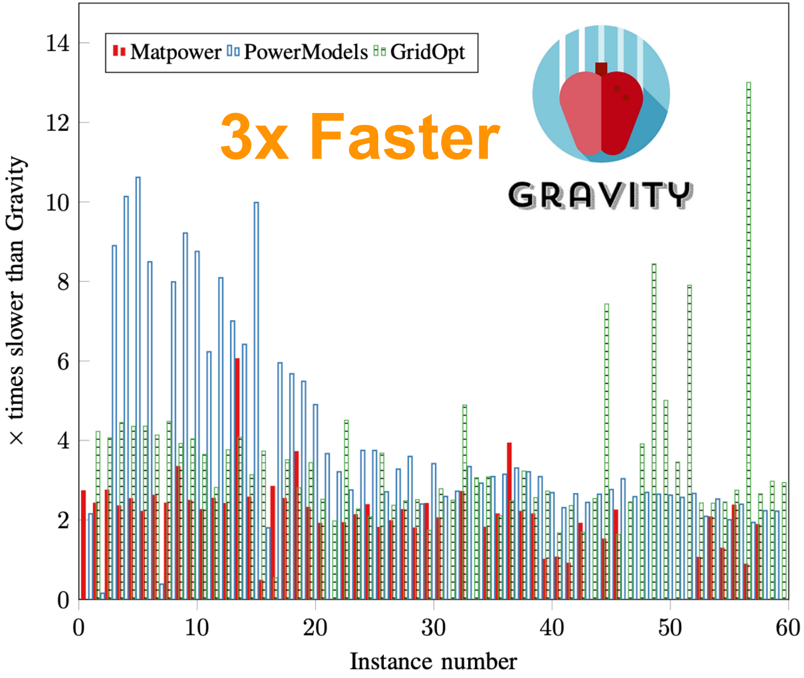
The ARPA-e Benchmark Algorithm Source Code

https://github.com/lanl-ansi/PowerModelsSecurityConstrained.jl

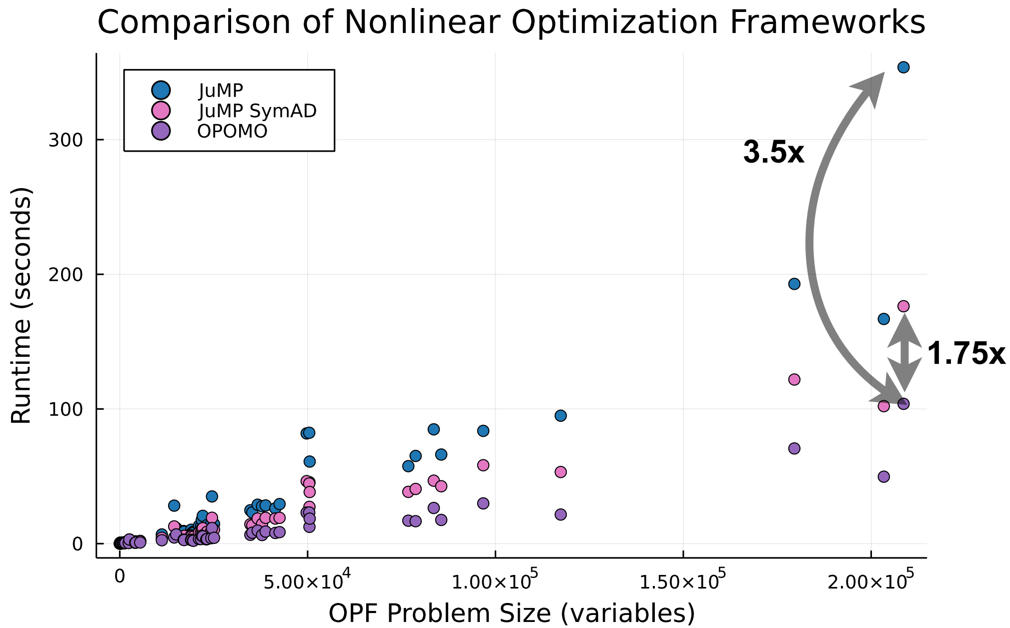


NLP Solver Performance

Benchmarking Large-Scale ACOPF Solutions and Optimality Bounds
arXiv:2203.11328



JuMP julia



Conclusions

- **Challenge 2, keys to success**
  - Recognize AC-OPF is “good enough”
  - Focus computing efforts on the most valuable decision variables
- **Notable Success of Julia and JuMP**
  - As easy as Matlab, high performance, free and open-source
- **PowerModelsSecurityConstrained**
  - Ripe testbed for R&D

Thanks!

Registration for Challenge 3 is open!