

# Incentive Compatibility in Two-Stage Repeated Stochastic Games

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- Today's power system: Random demand + fossil-fuelled generators + no storage
- The core problem of power system operation: No storage, so generation must equal consumption at *every instant*.
- Attained via a combination of feedforward and feedback control
  - ▶ One day before power delivery, SO estimates demand.
  - ▶ Many generators available to meet the estimated demand.
  - ▶ To satisfy demand economically efficiently, SO runs a “day-ahead market” wherein generators compete by bidding supply curves (price vs. quantity graphs).
  - ▶ SO solves an economic dispatch (or OPF) problem to determine how much power to procure from each generator to satisfy estimated demand at minimum cost.
  - ▶ A few minutes before power delivery, SO runs a “real-time market” to compensate for residual demand by procuring power from fast-acting (typically diesel-powered) generators.



- Tomorrow's power system: High renewables in the generation portfolio.
- Renewable energy sources  $\implies$  uncertain power supply
  - ▶ How to integrate renewable generators in the market?
- Uncontrollable generators  $\implies$  Can no longer make supply follow demand
- Can we instead make demand follow the random supply?
  - ▶ Modulate demand via financial incentives.
- In the real-time market, SO typically has fairly accurate estimate of demand-supply mismatch.
- Inexpensive and environmentally friendly to curtail demand at short notice than increase production.
- Can think of demand-responsive loads as virtual power producers.
  - ▶ How to integrate VPPs in the market?
- VPPs have two features that make their integration into the markets a challenge: Private costs and Private baselines.



## The Problem of Private Costs

- Say demand reduction of  $d$  units is required.
- $n$  VPPs with costs  $c_1(x), \dots, c_n(x)$ .
- Social cost-minimizing allocation given by

$$\begin{aligned} \min_{(x_1, \dots, x_n)} \quad & \sum_{i=1}^n c_i(x_i) \\ \text{s.t.} \quad & \sum_{i=1}^n x_i = d. \end{aligned}$$

- But SO does not know costs.
- SO asks loads to bid costs.
- Truthful bidding not an equilibrium.
- Deteriorates social cost.
- Need mechanism to elicit costs truthfully.

# The Problem of Private (and Random) Baselines



- Payment is a function of demand reduction.
- Demand reduction measured against *counterfactual* baseline.
- Even if loads bid costs truthfully, can lie about baselines.
- Inflated baselines give perception of reduced consumption.
- Need mechanism to elicit baselines truthfully.

## FERC Settlements Illustrate Attempts to 'Game' Demand Response Programs

**JIM PIEROBON** 053769

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## FERC Sues in Federal Court to Affirm Demand Response Manipulation Orders

By Covington & Burling LLP on December 10, 2013  
POSTED IN ELECTRICITY GRID ENFORCEMENT

# The Main Result



## Theorem (Informal)

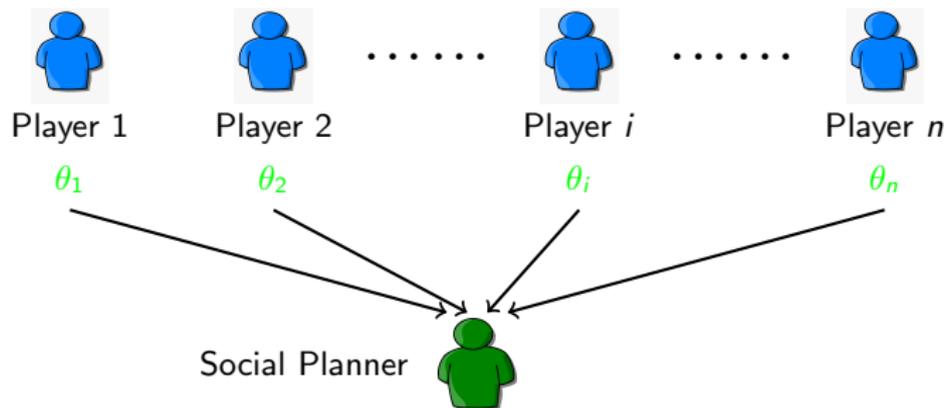
*The proposed mechanism guarantees that each load bidding its baseline and cost truthfully is in its own best interest.*



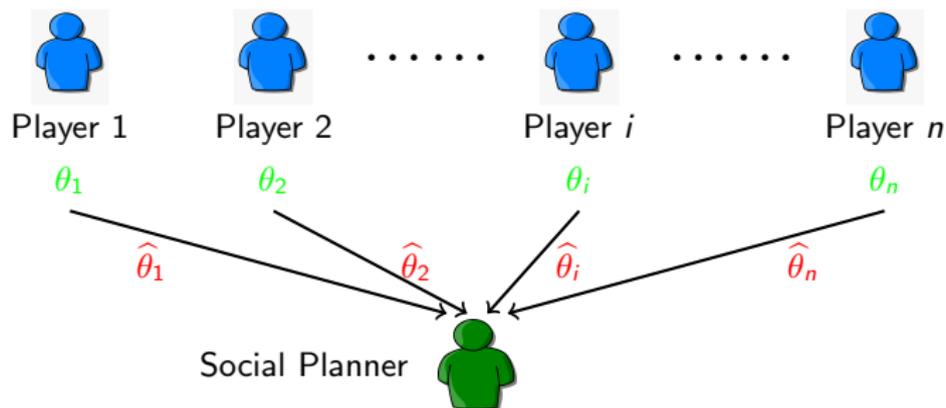
## Modeling Costs and Baselines as Types

- Denote by  $\delta_i(t)$  the type of DR provider  $i$  on day  $t$
- The type  $\delta_i(t)$  specifies the baseline and cost parameters of DR provider  $i$  on day  $t$
- Load  $i$  may not exactly know its type until few minutes before DR event
  - ▶ Models random baselines and random appetites for reducing consumption
- We model  $\delta_i(t)$  as a RV that realizes only few minutes before DR event
- Mechanism must allow for loads to bid only a *probabilistic description* of their types for DA planning
- It is only in real time, if and when called upon for DR, that the mechanism must require loads to report their actual types
- Denote by  $\theta_i$  the type distribution
- $\{\delta_i(1), \delta_i(2), \dots\} \sim \theta_i$  and IID

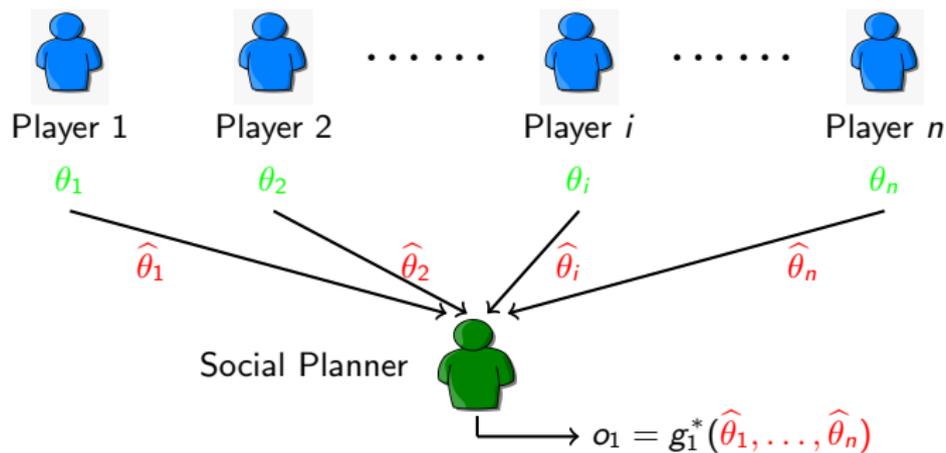
# Demand Response as a Two-Stage Stochastic Game



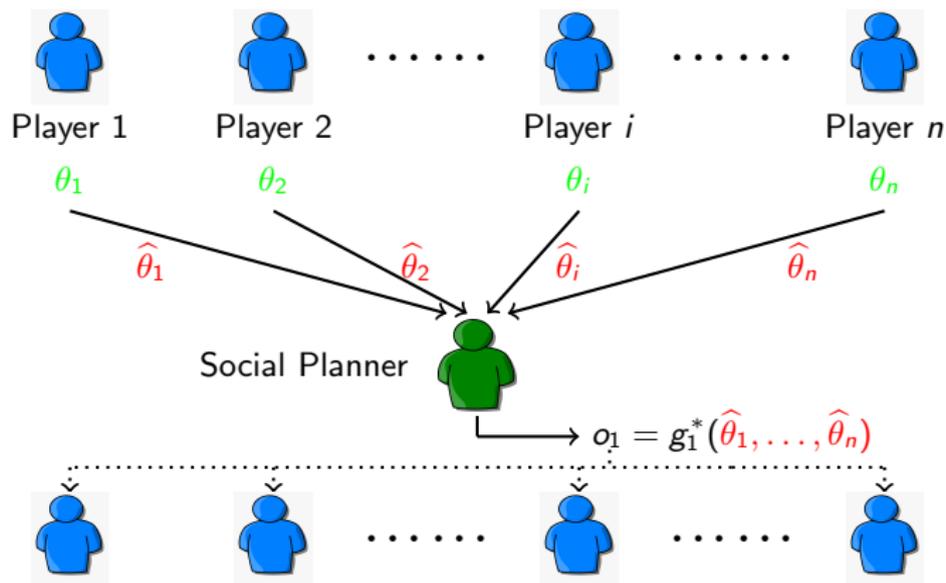
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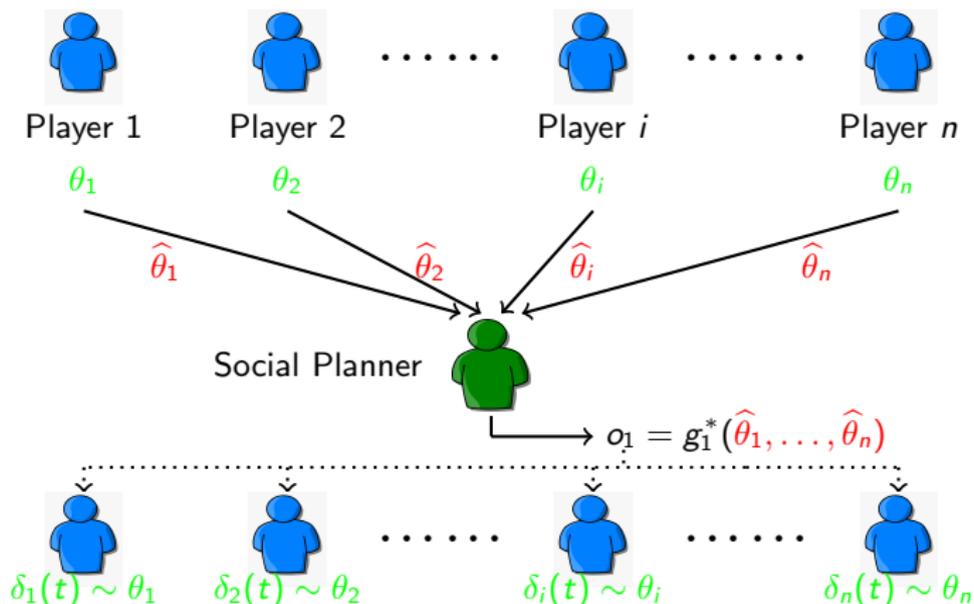
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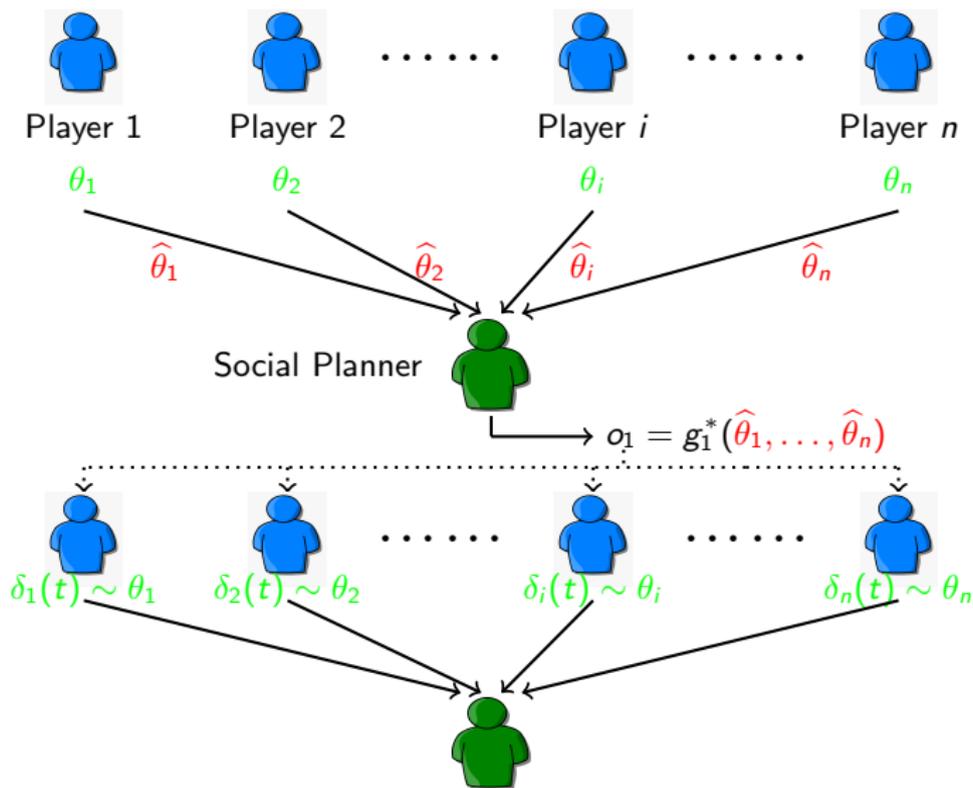
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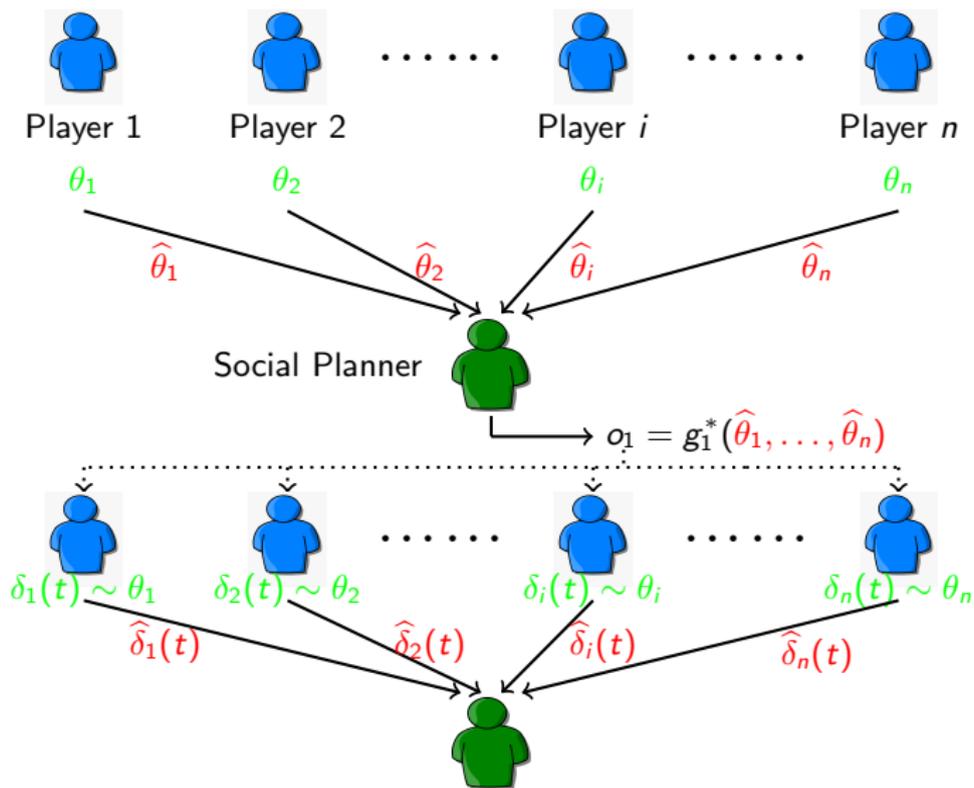
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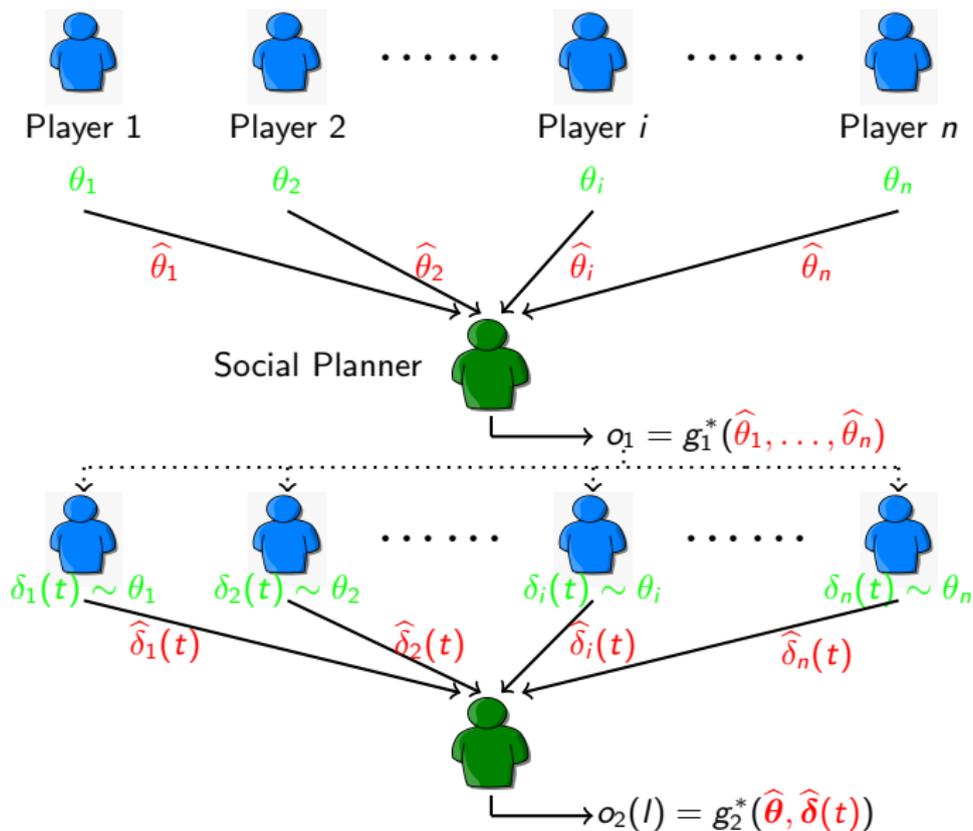
# Demand Response as a Two-Stage Stochastic Game



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# Demand Response as a Two-Stage Stochastic Game



# The Mechanism Design Problem



- ISO wants players to bid type distributions and realizations truthfully so that it can compute the social cost-minimizing day-ahead and real-time decisions.
- On the other hand, Player  $i$  wants to maximize its own utility

$$u_i(S_i, \mathbf{S}_{-i}, \delta^\infty, \theta) = \liminf_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T p_{i,t}(\hat{\theta}, \hat{\delta}^t) - c_i\left(\delta_i(t), g_1^*(\hat{\theta}), g_2^*(\hat{\theta}, \hat{\delta}(t))\right)$$

- The strategy  $S_i$  includes both day-ahead bidding policy and real-time (possibly history-dependent) bidding policy.
- How to design the payment rule  $\{p_{i,t} : (i, t) \in \{1, \dots, n\} \times \mathbb{Z}_{>0}\}$  so that setting  $S_i = T_i$  by every player  $i$  is an equilibrium?
  - ▶ VCG yields DSE only in one-shot deterministic environments.
  - ▶ Here, VCG only implements truth-telling as a Nash equilibrium. I.e., for a player to employ a truthful strategy, they must assume that all others are bidding truthfully — an assumption that the players may not be comfortable making.
  - ▶ Can we remove the burden of speculation to implement truth-telling in stronger equilibria?

# Dominant Strategy Non-Bankrupting Equilibrium



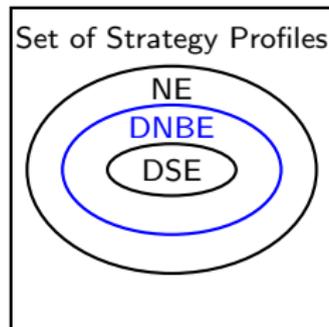
## Definition

A strategy profile  $\mathbf{S} = (S_1, \dots, S_n) \in \mathcal{NB}$  is a *Dominant Strategy Non-Bankrupting Equilibrium (DNBE)* if for all  $i \in \{1, \dots, n\}$ , all  $S'_{-i} \in \mathcal{NB}_{-i}$ , and all  $\theta$ ,

$$u_i(S_i, S'_{-i}, \delta^\infty, \theta) \geq u_i(S'_i, S'_{-i}, \delta^\infty, \theta)$$

for all  $\delta^\infty$ , except perhaps on a set of measure zero.

- $NE \ll DNBE \approx DSE$ 
  - ▶  $\mathbf{S}$  is DNBE  $\implies \mathbf{S}$  is NE.
  - ▶  $\mathbf{S}$  is DSE  $\implies \mathbf{S}$  is DNBE.
  - ▶  $DSE \subseteq DNBE \subseteq NE$ .



# The Main Result: Truth-Telling is a Dominant Strategy Non-Bankrupting Equilibrium



## Theorem

Consider the mechanism defined by the decision rule  $(g_1^*, g_2^*)$  and the payment rule (1).

- 1 A Truthful strategy profile is a dominant strategy non-bankrupting equilibrium.
- 2 Every player obtains a nonnegative utility by employing a truthful strategy regardless of the strategies that the other players employ.
- 3 If every player employs a truthful strategy, then the long-term average social cost is almost surely equal to its optimal value.

# Penalizing Distribution Mismatch



- If Player  $i$  truthful, then

$$\frac{1}{T} \sum_{t=1}^T \mathbb{1}_{\{\hat{\delta}_i(t)=\tau\}} \approx \hat{\theta}_i(\tau).$$

- So, construct window of size  $r(T)$  around  $\hat{\theta}_i(\tau)$  and impose penalty  $J_p(T)$  if

$$\frac{1}{T} \sum_{t=1}^T \mathbb{1}_{\{\hat{\delta}_i(t)=\tau\}} \notin \left[ \hat{\theta}_i(\tau) - r(T), \hat{\theta}_i(\tau) + r(T) \right].$$

- Need

$$\lim_{T \rightarrow \infty} r(T) = 0,$$

and for some  $\gamma > \frac{1}{2}$ ,

$$r(T) \geq \sqrt{\frac{\ln T^\gamma}{T}}.$$

- Need  $J_p(T) = \Omega(T)$ .
- **Consequence:** If  $\{\hat{\delta}_i(1), \hat{\delta}_i(2), \dots\} \approx \hat{\theta}_i$ , Player  $i$  goes bankrupt.

# Penalizing Correlated Bids



- Second-stage outcomes can be observed by all players which serve as common randomness.
  - ▶ Players can use CR to correlate bids.

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- So, construct window of size  $r(T)$  around 0 and impose penalty  $J_p(T)$  if

$$\widehat{h}_{i,\mathbf{d}}(T) \notin [-r(T), r(T)].$$

- **Consequence:** If  $\{\widehat{\delta}_i(1), \widehat{\delta}_i(2), \dots\}$  is not independent of other players' bids, then player  $i$  goes bankrupt.

# Payment = VCG + Retoractive Compensation + Penalty



- First-Stage Payment Rule: VCG

$$p_i^F(\hat{\theta}) := q^*(\hat{\theta}_{-i}) - \mathbb{E}_{\delta \sim \mathbb{P}_{\hat{\theta}}} \left[ \sum_{j \neq i} v_j(\delta_j, g_1^*(\hat{\theta}), g_2^*(\hat{\theta}, \delta)) - c(g_1^*(\hat{\theta}), g_2^*(\hat{\theta}, \delta)) \right].$$

- Second-Stage Payment Rule: Retroactive payment + Penalty

$$p_{i,l}^S(\hat{\delta}_i^l, \hat{\delta}_{-i}(l), \hat{\theta}) := \left[ v_i(\hat{\delta}_i(l), g_1^*(\hat{\theta}), g_2^*(\hat{\theta}, \hat{\delta}(l))) - \mathbb{E}_{\delta \sim \mathbb{P}_{\hat{\theta}}} [v_i(\delta_i, g_1^*(\hat{\theta}), g_2^*(\hat{\theta}, \delta))] \right] + J_p(l) \mathbb{1}_{\{E_i(l; \hat{\delta}_i^l, \hat{\theta}_i)\}}.$$

- Total payment  $p_{i,l}$  that player  $i$  transfers to the social planner on day  $l$  is the sum

$$p_{i,l}(\hat{\delta}_i^l, \hat{\delta}_{-i}(l), \hat{\theta}) := p_i^F(\hat{\theta}) + p_{i,l}^S(\hat{\delta}_i^l, \hat{\delta}_{-i}(l), \hat{\theta}). \quad (1)$$

# Questions?



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