Nash Equilibria of a Two-Party Policy Competition Game

Speaker: Chuang-Chieh Lin (Joseph)
Tamkang University, TW

a joint work with

Chi-Jen Lu
Academia Sinica, TW

Po-An Chen
National Yang Ming Chiao Tung University, TW

17 May 2024

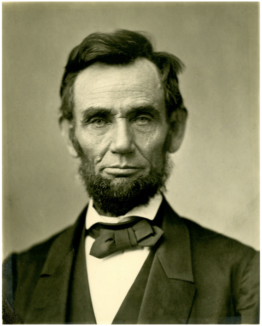
Authors

Chuang-Chieh Lin   Chi-Jen Lu   Po-An Chen

Outline

Outline

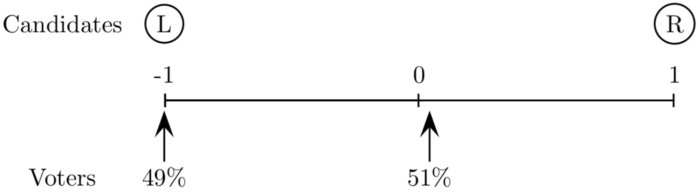
The Inspiration (an EC'17 paper)



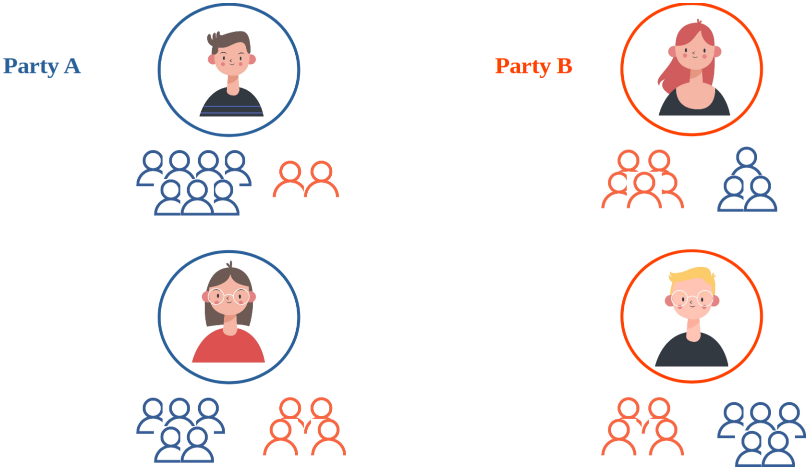
"[. . .] and that government of the people, by the people, for the people, shall not perish from the earth."

— Abraham Lincoln, 1863.

Previous Work (I): Distortion of Social Choice Rules



Previous Work (II): Two-Party Election Game



Previous Work (II): Two-Party Election Game

- Parties are players.
- Strategies: their candidates (or policies).
- A candidate beats the other candidates from other candidates of other parties with uncertainty.
- The payoff of each party: expected utility its supporters can get.

Previous Work (II): Two-Party Election Game (contd.)

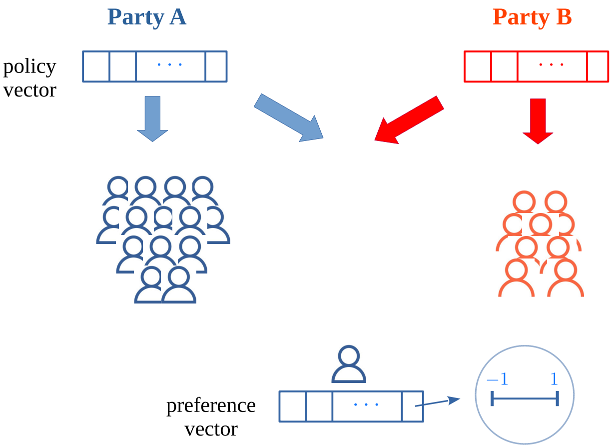
- Party A: m candidates, party B: n candidates.
- Candidate A_i can bring social utility $u(A_i) = u_A(A_i) + u_B(A_i) \in [0, \beta]$ for some real $\beta \geq 0$.
- $p_{i,j}$: $\Pr[A_i \text{ wins over } B_j]$.
  - E.g., Linear: $p_{i,j} := (1 + (u(A_i) - u(B_j))/\beta)/2$
- Payoff (reward) $r_A = p_{i,j}u_A(A_i) + (1 - p_{i,j})u_A(B_j)$.

Previous Work (II): Two-Party Election Game (contd.)

- Party A: m candidates, party B: n candidates.
- Candidate A_i can bring social utility $u(A_i) = u_A(A_i) + u_B(A_i) \in [0, \beta]$ for some real $\beta \geq 0$.
- $p_{i,j}$: $\Pr[A_i \text{ wins over } B_j]$. more utility for all the people, more likely to win
  - E.g., Linear: $p_{i,j} := (1 + (u(A_i) - u(B_j))/\beta)/2$
- Payoff (reward) $r_A = p_{i,j} u_A(A_i) + (1 - p_{i,j}) u_A(B_j)$.

Outline

Policies and Preferences



The Setting

- Policy vectors: $\mathbf{z}_A, \mathbf{z}_B \in S \subset \mathbb{R}^k$.
  - $\|\mathbf{z}_A\| \leq 1$ and $\|\mathbf{z}_B\| \leq 1$.
  - State (or profile): $\mathbf{z} := (\mathbf{z}_A, \mathbf{z}_B)$.

The Setting

- Policy vectors: $\mathbf{z}_A, \mathbf{z}_B \in S \subset \mathbb{R}^k$.
  - $\|\mathbf{z}_A\| \leq 1$ and $\|\mathbf{z}_B\| \leq 1$.
  - State (or profile): $\mathbf{z} := (\mathbf{z}_A, \mathbf{z}_B)$.
- V_A and V_B: the supporters of A and B.
  - $V := V_A \dot{\cup} V_B$, $|V| = n$.
- Preference vector of a voter $v \in V$: $\mathbf{q}_v$.
- $Q_A := \sum_{v \in V_A} \mathbf{q}_v$, $Q_B := \sum_{v \in V_B} \mathbf{q}_v$ and $Q := Q_A + Q_B$.

The Setting

- Policy vectors: $\mathbf{z}_A, \mathbf{z}_B \in S \subset \mathbb{R}^k$.
  - $\|\mathbf{z}_A\| \leq 1$ and $\|\mathbf{z}_B\| \leq 1$.
  - State (or profile): $\mathbf{z} := (\mathbf{z}_A, \mathbf{z}_B)$.
- V_A and V_B: the supporters of A and B.
  - $V := V_A \dot{\cup} V_B$, $|V| = n$.
- Preference vector of a voter $v \in V$: $\mathbf{q}_v$.
- $Q_A := \sum_{v \in V_A} \mathbf{q}_v$, $Q_B := \sum_{v \in V_B} \mathbf{q}_v$ and $Q := Q_A + Q_B$.
- The utility

$$u_A(\mathbf{z}_A) = \sum_{v \in V_A} \mathbf{z}_A^\top \mathbf{q}_v = \mathbf{z}_A^\top Q_A, \; u_B(\mathbf{z}_A) = \sum_{v \in V_B} \mathbf{z}_A^\top \mathbf{q}_v = \mathbf{z}_A^\top Q_B.$$

$$u_A(\mathbf{z}_B) = \sum_{v \in V_A} \mathbf{z}_B^\top \mathbf{q}_v = \mathbf{z}_B^\top Q_A, \; u_B(\mathbf{z}_B) = \sum_{v \in V_B} \mathbf{z}_B^\top \mathbf{q}_v = \mathbf{z}_B^\top Q_B.$$

The Setting (Winning Prob. & Payoff)

- Winning probability:

$$p_{A\succ B} = \frac{1}{2} + \frac{1}{4kn}(\mathbf{z}_A - \mathbf{z}_B)^\top Q,$$
$$p_{B\succ A} = \frac{1}{2} + \frac{1}{4kn}(\mathbf{z}_B - \mathbf{z}_A)^\top Q.$$

  - $1/4kn$: a normalization factor.

- The payoffs:

$$R_A(\mathbf{z}) = p_{A\succ B} \cdot \mathbf{z}_A^\top Q_A + p_{B\succ A} \cdot \mathbf{z}_B^\top Q_A,$$
$$R_B(\mathbf{z}) = p_{B\succ A} \cdot \mathbf{z}_B^\top Q_B + p_{A\succ B} \cdot \mathbf{z}_A^\top Q_B.$$

So, we can compute the gradients and Hessian...

$$\frac{\partial R_A(\mathbf{z})}{\partial \mathbf{z}_A} = \frac{1}{2} Q_A + \frac{(\mathbf{z}_A - \mathbf{z}_B)^\top Q}{4kn} Q_A + \frac{(\mathbf{z}_A - \mathbf{z}_B)^\top Q_A}{4kn} Q.$$

$$\frac{\partial R_B(\mathbf{z})}{\partial \mathbf{z}_B} = \frac{1}{2} Q_B + \frac{(\mathbf{z}_B - \mathbf{z}_A)^\top Q}{4kn} Q_B + \frac{(\mathbf{z}_B - \mathbf{z}_A)^\top Q_B}{4kn} Q.$$

$$\frac{\partial^2 R_A(\mathbf{z})}{\partial \mathbf{z}_A^2}[i,j] = \frac{1}{4kn} \left(Q[i] Q_A[j] + Q[j] Q_A[i] \right),$$

$$\frac{\partial^2 R_B(\mathbf{z})}{\partial \mathbf{z}_B^2}[i,j] = \frac{1}{4kn} \left(Q[i] Q_B[j] + Q[j] Q_B[i] \right).$$

Outline

Our Contribution

[Nash 1950]

Every FINITE game has a mixed-strategy Nash equilibrium.

Our Contribution

In this work, we show that there exists a pure-strategy Nash equilibrium (PSNE) in the two-party policy competition game for

- the degenerate case: $k = 1$
- the general case $k \geq 1$ under the consensus-reachable condition

- The two-party policy competition game is NOT a finite game.
- The above PSNE consists of dominant-strategies.

Claim of the Egoistic Property

Claim

The egoistic property must hold in the two-party policy competition game.

- $\mathbf{z}_A^\top Q_A \geq \mathbf{z}_B^\top Q_A$ and $\mathbf{z}_B^\top Q_B \geq \mathbf{z}_A^\top Q_B$.

The Degenerate Case: $k = 1$

$$R_A(\mathbf{z}) = \frac{1}{2}(z_A + z_B)Q_A + \frac{1}{4}QQ_A(z_A - z_B)^2,$$

$$\frac{\mathrm{d}R_A(\mathbf{z})}{\mathrm{d}z_A} = \frac{1}{2}Q_A + \frac{1}{2n}QQ_A(z_A - z_B),$$

$$\frac{\mathrm{d}^2R_A(\mathbf{z})}{\mathrm{d}z_A^2} = \frac{1}{2n}QQ_A.$$

- If $QQ_A \geq 0$ (resp., $QQ_A \leq 0$), then $R_A(\mathbf{z})$ is convex (resp., concave).
  $Q \geq 0$, $Q_A \geq 0$ plus the egoistic property $\Rightarrow$ $\frac{\mathrm{d}R_A(\mathbf{z})}{\mathrm{d}z_A} \geq 0$.

The Degenerate Case: $k = 1$

$$R_A(\mathbf{z}) = \frac{1}{2}(z_A + z_B)Q_A + \frac{1}{4}QQ_A(z_A - z_B)^2,$$

$$\frac{\mathrm{d}R_A(\mathbf{z})}{\mathrm{d}z_A} = \frac{1}{2}Q_A + \frac{1}{2n}QQ_A(z_A - z_B),$$

$$\frac{\mathrm{d}^2R_A(\mathbf{z})}{\mathrm{d}z_A^2} = \frac{1}{2n}QQ_A.$$

- If $QQ_A \geq 0$ (resp., $QQ_A \leq 0$), then $R_A(\mathbf{z})$ is convex (resp., concave).
  $Q \geq 0$, $Q_A \geq 0$ plus the egoistic property $\Rightarrow$ $\frac{\mathrm{d}R_A(\mathbf{z})}{\mathrm{d}z_A} \geq 0$.

⋮

- The maximizers of R_A and R_B can be solved analytically case-by-case.

The General Case: $k \geq 1$

- It is sufficient for party A and B to consider the space $\text{span}(\{Q_A, Q_B\})$.

The General Case: $k \geq 1$ — Simplification by Polar Coordinates

- It is sufficient for party A and B to consider the space $\text{span}(\{Q_A, Q_B\})$.
- Represent $\mathbf{z}_A$ (resp., $\mathbf{z}_B$) in terms of polar coordinates (r_A, θ_A) (resp., (r_A, θ_B)).
  - $r_A = \|\mathbf{z}_A\|, r_B = \|\mathbf{z}_B\|$
  - θ_A (resp., θ_B) is the angle b/w Q_A and $\mathbf{z}_A$ (resp., Q_B and $\mathbf{z}_B$).

The General Case: $k \geq 1$ — Simplification by Polar Coordinates

- It is sufficient for party A and B to consider the space $\mathrm{span}(\{Q_A, Q_B\})$.
- Represent $\mathbf{z}_A$ (resp., $\mathbf{z}_B$) in terms of polar coordinates (r_A, θ_A) (resp., (r_A, θ_B)).
  - $r_A = \|\mathbf{z}_A\|, r_B = \|\mathbf{z}_B\|$
  - θ_A (resp., θ_B) is the angle b/w Q_A and $\mathbf{z}_A$ (resp., Q_B and $\mathbf{z}_B$).

For any two vectors $\mathbf{u}, \mathbf{v}$ in the Euclidean space $\mathbb{R}^k$ for $k \geq 1$,

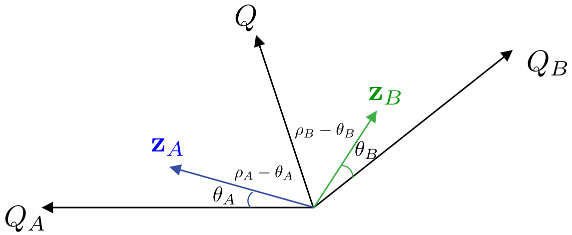
$$\langle \mathbf{u}, \mathbf{v} \rangle = \|\mathbf{u}\| \|\mathbf{v}\| \cos(\theta),$$

where θ is the angle b/w $\mathbf{u}$ and $\mathbf{v}$.

A Good Condition

Consensus-Reachable

A two-party policy competition game is *consensus-reachable* if $Q_A^\top Q \geq 0$ and $Q_B^\top Q \geq 0$.



Gradients w.r.t. r

$$\frac{\partial}{\partial r_A} R_A(\mathbf{r}, \boldsymbol{\theta}) = \frac{1}{2}\|Q_A\|\cos(\theta_A) + \frac{1}{4kn}\Big((\mathbf{z}_A^\top Q - \mathbf{z}_B^\top Q)(\|Q_A\|\cos(\theta_A)) + (\mathbf{z}_A^\top Q_A - \mathbf{z}_B^\top Q_A)(\|Q\|\cos(\rho_A - \theta_A))\Big).$$

and

$$\frac{\partial^2}{\partial r_A^2} R_A(\mathbf{r}, \boldsymbol{\theta}) = \frac{1}{4kn}\|Q_A\|\|Q\|\cos(\theta_A)\cos(\rho_A - \theta_A),$$

Gradients w.r.t. r

$$\frac{\partial}{\partial r_A} R_A(\mathbf{r}, \boldsymbol{\theta}) = \frac{1}{2}\|Q_A\|\cos(\theta_A) + \frac{1}{4kn}\Big((\mathbf{z}_A^\top Q - \mathbf{z}_B^\top Q)(\|Q_A\|\cos(\theta_A)) + (\mathbf{z}_A^\top Q_A - \mathbf{z}_B^\top Q_A)(\|Q\|\cos(\rho_A - \theta_A))\Big).$$

and

$$\frac{\partial^2}{\partial r_A^2} R_A(\mathbf{r}, \boldsymbol{\theta}) = \frac{1}{4kn}\|Q_A\|\|Q\|\cos(\theta_A)\cos(\rho_A - \theta_A),$$

- $\frac{\partial^2}{\partial r_A^2} R_A(\mathbf{r}, \boldsymbol{\theta}) \geq 0$ by the consensus-reachable condition ($\therefore$ convex).

Gradients w.r.t. $\mathbf{r}$ (contd.)

- Compute $R_A((0, r_B), \boldsymbol{\theta})$ and $R_A((1, r_B), \boldsymbol{\theta})$ we will find that

$$\begin{aligned}
R_A((1, r_B), \boldsymbol{\theta}) &= R_A((0, r_B), \boldsymbol{\theta}) + \frac{1}{2}\|Q_A\| \cos(\theta_A) \\
&\quad + \frac{1}{4kn} \big(\|Q\| \|Q_A\| \cos(\rho_A - \theta_A) \cos(\theta_A) \\
&\quad - \mathbf{z}_B^\top Q \|Q_A\| \cos(\theta_A) - \mathbf{z}_B^\top Q_A \|Q\| \cos(\rho_A - \theta_A)\big) \\
&\geq R_A((0, r_B), \boldsymbol{\theta}).
\end{aligned}$$

Gradients w.r.t. $\boldsymbol{\theta}$

- Assuming $\mathbf{r} = (1, 1)$, we derive that

$$R_A(\boldsymbol{\theta}) = p(\theta_A)(\|Q_A\| \cos(\theta_A)) + (1 - p(\theta_A))(\|Q_A\| \cos(\rho_A - \theta_A)),$$

where

$$\begin{aligned} p(\theta_A) &= p_{A \succ B} = \frac{1}{2} + \frac{1}{4kn}\left(\mathbf{z}_A^\top Q - \mathbf{z}_B^\top Q\right) \\ &= \frac{1}{2} + \frac{1}{4kn}\left(\|Q\| \cos(\rho_A - \theta_A) - \mathbf{z}_B^\top Q\right) \end{aligned}$$

and ρ_A is the angle between Q and Q_A.

Gradients w.r.t. $\boldsymbol{\theta}$ (contd.)

- It's straight-forward to derive

$$p'(\theta_A) = \frac{\|Q\|}{4kn}\sin(\rho_A - \theta_A) \geq 0$$

and

$$p''(\theta_A) = -\frac{\|Q\|}{4kn}\cos(\rho_A - \theta_A) \leq 0$$

- Hence,

$$\begin{aligned} R'_A(\boldsymbol{\theta}) &= p'(\theta_A)(\mathbf{z}_A^\top Q - \mathbf{z}_B^\top Q) - p(\theta_A)\sin(\theta_A)\|Q_A\| \\ &= \frac{\|Q\|}{4kn}\sin(\rho_A - \theta_A)(\mathbf{z}_A^\top Q_A - \mathbf{z}_B^\top Q_A) \\ &\quad -\frac{1}{2}\sin(\theta_A)\|Q_A\| - \frac{1}{4kn}\left(\|Q\|\cos(\rho_A - \theta_A) - \mathbf{z}_B^\top Q\right)\sin(\theta_A)\|Q_A\|, \end{aligned}$$

$$\begin{aligned} R''_A(\boldsymbol{\theta}_A) &= p''(\theta_A)(\mathbf{z}_A^\top Q_A - \mathbf{z}_B^\top Q_A) - 2p'(\theta_A)\|Q_A\|\sin(\theta_A) \\ &\quad -p(\theta_A)\cos(\theta_A)\|Q_A\| \leq 0. \end{aligned}$$

Gradients w.r.t. $\boldsymbol{\theta}$ (contd.)

- By the mean value theorem we know that there exists $\theta_A^* \in [0, \rho_A]$ such that $R_A'(\theta_A^*) = 0$.
  - $R_A(\theta_A)$ is continuous;
  - $R_A'(0) \geq 0$;
  - $R_A'(\rho_A) \leq 0$,

Then?

Gradients w.r.t. $\boldsymbol{\theta}$ (contd.)

- By the mean value theorem we know that there exists $\theta_A^* \in [0, \rho_A]$ such that $R_A'(\theta_A^*) = 0$.
  - $R_A(\theta_A)$ is continuous;
  - $R_A'(0) \geq 0$;
  - $R_A'(\rho_A) \leq 0$,

Then?

Better Responses

Define the relation $\succsim_A$ over θ_A as $(\theta', \theta_B) \succsim_A (\theta'', \theta_B)$ if $R_A(\theta', \theta_B) \geq R_A(\theta'', \theta_B)$.

Gradients w.r.t. $\boldsymbol{\theta}$ (quasi-concaveness)

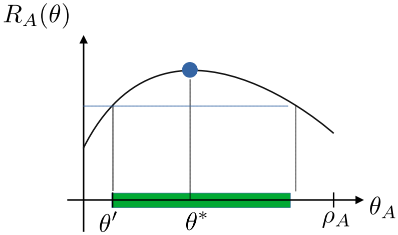
Quasi-Concave

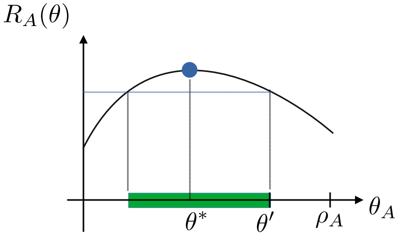
$\succsim_A$ is *quasi-concave* on $[0, \rho_A]$ if for all $\boldsymbol{\theta} = (\theta_A, \theta_B)$, the set $\{\theta' \in [0, \rho_A] \mid (\theta', \theta_B) \succsim_A (\theta_A, \theta_B)\}$ is convex.

Gradients w.r.t. $\boldsymbol{\theta}$ (quasi-concaveness)

Quasi-Concave

$\succsim_A$ is *quasi-concave* on $[0, \rho_A]$ if for all $\boldsymbol{\theta} = (\theta_A, \theta_B)$, the set $\{\theta' \in [0, \rho_A] \mid (\theta', \theta_B) \succsim_A (\theta_A, \theta_B)\}$ is convex.





Gradients w.r.t. $\boldsymbol{\theta}$ (Kakutani's Fixed-Point Theorem)

Theorem [Concluding]

Since

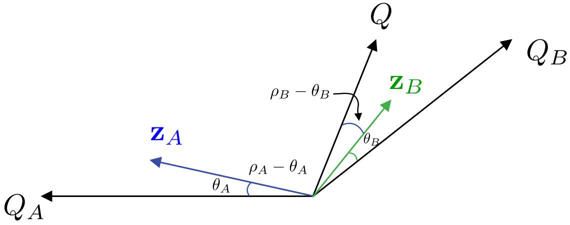
- $[0, \rho_A]$ is nonempty, compact and convex in $\mathbb{R}$;
- $R_A(\boldsymbol{\theta})$ is continuous w.r.t. θ_A;
- $\succsim_A$ is quasi-concave on $[0, \rho_A]$

The two-party policy competition game has a pure-strategy Nash equilibrium (PSNE) under the consensus-reachable condition.

Outline

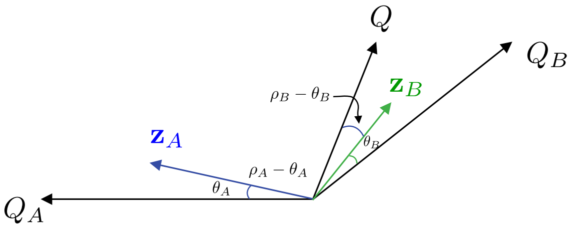
Concluding Remarks

- The unsolved case:



Concluding Remarks

- The unsolved case:



- Update the policy using gradient ascent:

$$\mathbf{z}_A \leftarrow \mathbf{z}_A + \eta \frac{\partial R_A(\mathbf{z})}{\partial \mathbf{z}_A}, \quad \mathbf{z}_B \leftarrow \mathbf{z}_B + \eta \frac{\partial R_B(\mathbf{z})}{\partial \mathbf{z}_B},$$

where η is called *learning rate*

Thanks for your attention!

Q & A