Static Games with Incomplete Information: Payoff Uncertainty

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Abstract
Some justifications of solution concepts make sense under the assumption that the rules of the game and players' personal preferences are common knowledge. A situation of strategic interaction features **incomplete information** when this is not the case. We represent this with **games with payoff uncertainty**, whereby the payoff functions depend on a vector of parameters about which players have partial and asymmetric knowledge. The game features **private values** if there is common knowledge of the outcome function, and **interdependent values** otherwise. It is relatively straightforward to extend rationalizability and pure self-confirming equilibrium to allow for payoff uncertainty.
[These slides summarize and complement parts of Sections 8.1-3 and 8.7 of Ch. 8 of GT-AST]

Introduction

- Whether a solution or equilibrium concept is consistent with incomplete information is a matter of *interpretation*. We must look at the conceptual *motivations*:
- Standard *rationalizability* (iterated deletion of strictly dominated actions) is explicitly motivated as representing the behavioral implications of rationality and common belief in rationality *under complete information* (common knowledge of the payoff functions).
- *Nash equilibrium* can be motivated as an "*obvious way to play* the game": See deductive interpretation, and self-enforcing agreement interpretation. Also this makes sense *under the complete information assumption*.
- *Deductive interpretation of NE*: it makes sense when there is a unique rationalizable outcome, see above.

Incomplete Information and Self-Enforcing Agreements

- *Self-enforcing agreement interpretation of NE*: Again we need complete information (or maybe something "close" to it) in order to make sense of this interpretation.
- Consider the following game and the Pareto dominant agreement (t, ℓ). The *agreement is self-enforcing if there is common belief* (or "almost common belief") *that there is no incentive to deviate from* (t, ℓ).

	ℓ	r
t	100,100	0,99
b	99,0	99,99

- Would Rowena (row player) play t if she is not sure of the payoff function of Colin (column player)? What if she is not sure that Colin is sure of her payoff function? What if...?
- [But **note**: as long as each player knows her/his payoff function, there is *no need to assume complete information to make sense of Nash* equilibrium *as* description of rest points *of adaptive processes*.]

Environments with Incomplete Information

- Rules of the game $\Rightarrow$ *outcome/consequence function* $g : A \to Y$.
- Each player $i \in I$ ranks (lotteries over) outcomes according to (the expectation of) a vNM utility function $v_i : Y \to \mathbb{R}$.
- In environments with **incomplete information** there is *lack of common knowledge of* g (outcome function) and/or $(v_i)_{i \in I}$ (personal preferences).
- Such situation can be described with *parameterized payoff functions*

$$u_i : \Theta \times A \to \mathbb{R},$$

with

  - $\theta \in \Theta$ parameter affecting payoffs,

$$\theta = (\theta_0, (\theta_i)_{i \in I}) \in \Theta = \Theta_0 \times (\times_{i \in I} \Theta_i)$$

  - $i \in I$ *knows* only θ_i =private information of i about payoffs.

Interpretation, Distributed Knowledge

- *Intuition*: it is common knowledge that $\theta \in \Theta$, Θ_i represents what is commonly believed possible about i's traits known to him (e.g., tastes, abilities), the "larger" Θ_i the more uncertain are the other players about such traits.
- If Θ_i is a *singleton* ($i \in I$), that is, $\Theta_i = \left\{\bar{\theta}_i\right\}$, it means that *what i knows is common knowledge* (it is common knowledge that $\theta_i = \bar{\theta}_i$) and Θ_i can be neglected: indeed, $\Theta_0 \times \left(\times_{j \in I \setminus \{i\}} \Theta_j\right)$ and Θ have the same cardinality; hence, they are (intuitively) isomorphic.
- Θ_0 represents the *residual uncertainty* that would remain if the players could pool their private information.
- We often *focus* on the case where Θ_0 is a singleton: there is *no residual uncertainty* after pooling private information (in this case it is said that there is "**distributed knowledge**" of θ). Thus, we will often neglect Θ_0.

Private Values

We distinguish between the case of **private values**, where u_i depends only on θ_i, and **interdependent values**, where u_i may depend on the whole θ.

- **Private values:** *Common knowledge of outcome function* g, but lack of common knowledge of preferences $(v_i)_{i\in I}$:
  - (it is common knowledge that) each i knows his vNM utility function $v_i \Rightarrow$ parameterized representation $v_i : \Theta_i \times Y \to \mathbb{R}$.
  - Note: $\{w_i \in \mathbb{R}^Y : \exists \theta_i \in \Theta_i, w_i = v_{i,\theta_i}\}$ is the set of utility functions that each $j \neq i$ thinks i might have $\Rightarrow$ get

$$u_i(\theta_i, a) = v_i(\theta_i, g(a))$$

  - Note: *under private values* we may assume w.l.o.g. that there is *distributed knowledge of* θ (Θ_0 singleton).

Interdependent Values

- **Interdependent values:** *lack of common knowledge of outcome function* g, which may depend on θ_0 or on personal traits such as some players' "ability").
  - *common knowledge of preferences* $(v_i)_{i \in I}$ (simplest case) $\Rightarrow$ parameterized representation $g : \Theta \times A \longrightarrow Y$; note: $\{\gamma \in Y^A : \exists \theta \in \Theta, \gamma = g_\theta\}$ is the set of possible outcome functions $\Rightarrow$ get
$$u_i(\theta, a) = v_i(g(\theta, a)).$$
  - More generally, *if neither the outcome function nor preferences are common knowledge*, each v_i is parameterized by θ_i and
$$u_i(\theta, a) = v_i(\theta_i, g(\theta, a)).$$
  - *Interdependence*: The value for i depends on what j knows, e.g., a personal trait of j.

Cournot Oligopoly

Example

Cournot oligopoly *model (quantity setting): firm* $i = 1, ..., n$ *produces* $q_i \geq 0$ *units of homogeneous good*

- Inverse demand $P(Q) = [\bar{p} + \theta_0 - Q]_+$ (with $[x]_+ := \max\{0, x\}$, $Q = \sum_{i=1}^{n} q_i$)
- Cost function *of firm i:* $C_i(q_i, \theta_i) = \theta_i q_i$, $0 \leq q_i \leq \bar{q}$ ($\bar{q}$=common capacity)
- Common knowledge of risk neutrality *and of sets* $\Theta_0, \Theta_1, \ldots, \Theta_n$
- Payoff *of i:* $u_i(\theta_0, \theta_i, q_1, ..., q_n) = \left(\left[\bar{p} + \theta_0 - \sum_{j=1}^{n} q_j \right]_+ - \theta_i \right) q_i$
- *There are private values and distributed knowledge of* θ **if** *there is common knowledge of market demand* (Θ_0 *singleton)*

Team Production

Example

Team production: Team agents $i = 1, ..., n$, i exerts effort $e_i \geq 0$

- Cost of effort *(in units of output)* $C_i(e_i, k_i) = k_i e_i^2$, $k_i \in K_i \subseteq \mathbb{R}_+$
- Production function: $y = \prod_{i=1}^{n} e_i^{p_i}$, $p_i \in P_i \subseteq \mathbb{R}_+$
- $\theta_i = (k_i, p_i) \in K_i \times P_i = \Theta_i$
- Common knowledge of (output-)risk neutrality *and of sets* $\Theta_i = K_i \times P_i$
- Payoff function *of i*: $u_i(k_1, p_1, ..., k_n, p_n, e_1, ..., e_n) = \frac{1}{n} \prod_{j=1}^{n} e_j^{p_j} - k_i e_i^2$
- Private values iff *sets* $P_1, ..., P_n$ *are singletons (productivities are common knowledge), otherwise* interdependent *values*

Games with Payoff Uncertainty

- We can represent (simultaneous) strategic interaction under *incomplete information* with the mathematical structure

$$\hat{G} = \left\langle I, \Theta_0, (\Theta_i, A_i, u_i : \Theta \times A \to \mathbb{R})_{i \in I} \right\rangle;$$

  it is assumed that the interactive situation represented by $\hat{G}$ is common knowledge. This is called **game with payoff uncertainty**; θ_i is called the **information-type** of i [special: payoff-type].
- *Interpretation*: θ_0 affects the payoffs of somebody (if $\theta_0' \neq \theta_0''$, then $\exists i \in I, u_i(\theta_0', \cdot) \neq u_i(\theta_0'', \cdot)$). But part, or all, of i's private information θ_i *may be payoff irrelevant*. Yet even payoff-irrelevant information may be strategically relevant (e.g., θ_i may be the report to i by an art expert about the autenticity of a painting for sale).
- Take the obvious extension to payoff uncertainty of the definition of "**compact-continuous game**." To extend "**nice game**," add to the obvious properties the *convexity* (or connectedness) of each Θ_i .

Rationality and Common Belief in Rationality

- Games with payoff uncertainty are sufficient to describe certain aspects of strategic thinking, specifically, *rationality and common belief in rationality*.
- Write $\mathrm{B}_i(E)$ for "*i believes E*" (with prob. 1), and $\mathrm{B}(E) = \bigcap_{i \in I} \mathrm{B}_i(E)$ for "*everybody believes E*," R_i for "*i is rational*," $R = \bigcap R_i$ for "*everybody is rational*."
- What actions of i are consistent with R (rationality), $\mathrm{B}(R)$ (mutual belief in rationality), $\mathrm{B}(\mathrm{B}(R))$, $\mathrm{B}(\mathrm{B}(\mathrm{B}(R)))$ ... $R \cap \mathrm{CB}(R)$?

Example: Incomplete Information on One Side

Example

Possible payoff functions given by the following tables. Player 1 (Rowena) knows θ *while player 2* (Colin) does not *($\Theta \cong \Theta_1$)*

$\hat{G}^1$:

θ'	ℓ	r
t	4,0	2,1
b	3,1	1,0

θ''	ℓ	r
t	2,0	0,1
b	0,1	1,2

▶ $R_1 \Rightarrow [t \text{ if } \theta']$, *because* t dominates b given $\theta = \theta'$ *(recall, Row. knows* θ*)* $\Rightarrow (\theta', b)$ *is inconsistent with rationality (delete).*▶ $R_2 \cap B_2(R_1) \Rightarrow r$, *because* $u_2(\theta, x, \ell) < u_2(\theta, x, r)$ *for all* $(\theta, x) \neq (\theta', b)$ *(those consistent with* R_1*).*▶ $R_1 \cap B_1(R_2) \cap B_1(B_2(R_1)) \Rightarrow$ *Row. picks best reply to r given* θ
$\Rightarrow [b \text{ if } \theta = \theta'']$.

Envelope Game

Example

Players 1 and 2 receive an envelope. Envelope of i contains θ_i Euros, with $\theta_i = 1, ..., K$. Each player can offer to exchange (OE) by paying transaction cost $\varepsilon > 0$ (small). Exchange executed IFF both offer:

$\hat{G}^2$:

$a_i \backslash a_j$	OE	No
OE	$\theta_j - \varepsilon$	$\theta_i - \varepsilon$
No	θ_i	θ_i

Note: *A rational player i* offers to exchange only *if she assigns positive probability to event* $[\theta_j > \theta_i] \cap [a_j = OE]$.▶ $R_i \Rightarrow [a_i = No \text{ if } \theta_i = K]$ *because OE is dominated in this case.*▶ $R_i \cap \mathrm{B}_i(R_j) \Rightarrow [a_i = No \text{ if } \theta_i = K - 1]$ *because ...*▶ $R_i \cap \mathrm{B}_i(R_j) \cap \mathrm{B}_i(\mathrm{B}_j(R_i)) \Rightarrow [a_i = No \text{ if } \theta_i = K - 2]$ *because ...*▶ *It can be shown that:* $R \cap \mathrm{CB}(R) \Rightarrow (\forall \theta_i, a_i = No \text{ given } \theta_i)$ (*no-trade!*).

Rationalizability in Games with Payoff Uncertainty

- To ease notation, assume *distributed knowledge:* $\Theta \cong \times_{i\in I}\Theta_i$.
- Given conjecture $\mu^i \in \Delta(\Theta_{-i} \times A_{-i})$ and private information $\theta_i \in \Theta_i$, let

$$r_i(\mu^i, \theta_i) := \arg\max_{a_i \in A_i} \mathbb{E}_{\mu^i}\left(u_{i,\theta_i,a_i}\right)$$

where $u_{i,\theta_i,a_i} : \Theta_{-i} \times A_{-i} \to \mathbb{R}$ is the section of u_i at (θ_i, a_i); in the *finite support case*

$$\mathbb{E}_{\mu^i}\left(u_{i,\theta_i,a_i}\right) = \sum_{(\theta_{-i},a_{-i})\in \mathrm{supp}\mu^i} u\left(\theta_i, \theta_{-i}, a_i, a_{-i}\right) \mu^i\left(\theta_{-i}, a_{-i}\right)$$

- Let $C_i \subseteq \Theta_i \times A_i$ (with $\mathrm{proj}_{\Theta_i} C_i = \Theta_i$); interpretation: set of "surviving" pairs (see previous examples); $C_{-i} = \times_{j\neq i} C_j$, $\mathcal{C}$ collection of (closed) Cartesian products.
- Define the (monotone) **justification operator** $\rho : \mathcal{C} \to \mathcal{C}$.

$$\begin{aligned}
\rho_i(C_{-i}) &= \left\{(\theta_i, a_i) \in \Theta_i \times A_i : \exists \mu^i \in \Delta(C_{-i}), a_i \in r_i(\mu^i, \theta_i)\right\}. \\
\rho(C) &= \times_{i\in I}\rho_i(C_{-i}).
\end{aligned}$$

Behavioral Implications of RCBR

Assumptions about behavior and beliefs	Implications for $(\theta_i, a_i)_{i\in I}$
R	$\rho(\Theta \times A)$
$R \cap \mathrm{B}(R)$	$\rho^2(\Theta \times A)$
$R \cap \mathrm{B}(R) \cap \mathrm{B}^2(R)$	$\rho^3(\Theta \times A)$
...	...
$R \cap \left(\bigcap_{k=1}^{m} \mathrm{B}^k(R)\right)$	$\rho^{m+1}(\Theta \times A)$
...	...
$R \cap \left(\bigcap_{k=1}^{\infty} \mathrm{B}^k(R)\right) = R \cap \mathrm{CB}(R)$	$\rho^{\infty}(\Theta \times A)$

Theorem

If $\hat{G}$ is finite or compact-continuous, then

$$\rho^{\infty}(\Theta \times A) = \rho\left(\rho^{\infty}(\Theta \times A)\right) \quad \textit{and } \mathrm{proj}_{\Theta}\rho^{\infty}(\Theta \times A) = \Theta.$$

Furthermore, for each $C \in \mathcal{C}$, $C \subseteq \rho\left(C\right)$ implies $C \subseteq \rho^{\infty}(\Theta \times A)$.

Comments on RCBR and Rationalizability

- The previous theorem extends Theorems 2 and 3 of GT-AST from games with complete information to games with incomplete information (payoff uncertainty):
- $\rho^{\infty}(\Theta \times A) = \rho\left(\rho^{\infty}(\Theta \times A)\right)$ is the "fixed set property" of the rationalizable set: after countably many iterations there is no need to re-start the iterated deletion procedure.
- $\mathrm{proj}_{\Theta}\rho^{\infty}(\Theta \times A) = \Theta$ means that, for every $(\theta_i)_{i \in I} \in \Theta$, the *set of rationalizable actions for* information-type θ_i is *not empty*.
- $C \subseteq \rho(C) \Rightarrow C \subseteq \rho^{\infty}(\Theta \times A)$ means that every (Cartesian) subset of $\Theta \times A$ with the Best Reply Property is included in the rationalizable set.

Justifiability and Dominance

- Fix Cartesian subset $C = \times_{i \in I} C_i$ with $C_i \subseteq \Theta_i \times A_i$. Let $C_{i,\theta_i} := \{a_i \in A_i : (\theta_i, a_i) \in C_i\}$ (section of set C_i at θ_i).

Definition

Mixed action α_i **dominates** a_i **given** θ_i **within** C, written $\alpha_i \gg_{(\theta_i, C)} a_i$, if $\mathrm{supp}\alpha_i \subseteq C_{i,\theta_i}$ and

$$\forall (\theta_{-i}, a_{-i}) \in C_{-i}, \;\; u_i(\theta_i, \theta_{-i}, \alpha_i, a_{-i}) > u_i(\theta_i, \theta_{-i}, a_i, a_{-i}).$$

Lemma

Fix a finite or compact-continuous $\hat{G}$; let $C = \times_{i \in I} C_i$ be non-empty and compact. For all $i \in I$ and $(\theta_i, a_i^*) \in C_i$ the following are equivalent:
(1) $\nexists \alpha_i$ s.t. $\alpha_i \gg_{(\theta_i, C)} a_i^*$ (a_i^* undominated given θ_i within C)
(2) $\exists \mu^i \in \Delta(C_{-i})$ s.t. $a_i^* \in \arg\max_{a_i \in C_{i,\theta_i}} \mathbb{E}_{\mu^i}(u_{i,\theta_i,a_i})$.

Iterated Dominance

- The previous result (with $C = \Theta \times A$) extends the Wald-Pearce Lemma on justifiability and dominance to simultaneous-moves games with incomplete information (payoff uncertainty).
- For each $C \in \mathcal{C}$ ($\forall i \in I$, $C_i \subseteq \Theta_i \times A_i$), define $\mathrm{ND}(C)$ as follows:

$$\begin{aligned} \mathrm{ND}_i(C) &= C_i \backslash \left\{ (\theta_i, a_i) \in C_i : \exists \alpha_i \in \Delta(C_{i,\theta_i}), \alpha_i \gg_{(\theta_i, C)} a_i \right\}, \\ \mathrm{ND}(C) &= \times_{i \in I} \mathrm{ND}_i(C). \end{aligned}$$

- Similarly, dominance by pure actions (very relevant for nice games) gives

$$\begin{aligned} \mathrm{ND}_{p,i}(C) &= C_i \backslash \left\{ (\theta_i, a_i) \in C_i : \exists a_i' \in C_{i,\theta_i}, a_i' \gg_{(\theta_i, C)} a_i \right\}, \\ \mathrm{ND}_p(C) &= \times_{i \in I} \mathrm{ND}_{p,i}(C). \end{aligned}$$

Rationalizability and Iterated Dominance

Extension of the equivalence *"rationalizable IFF iteratively undominated"* to games with payoff uncertainty (r is the point-justification operator obtained with deterministic conjectures):

Theorem

If $\hat{G}$ is finite or compact-continuous, for all $m = 1, 2, ..., \infty$, $\rho^m(\Theta \times A) = \mathrm{ND}^m(\Theta \times A)$.

Theorem

If $\hat{G}$ is nice, point-rationalizability, rationalizability, and pure iterated dominance coincide, that is, for all $m = 1, 2, ..., \infty$,
$\mathrm{r}^m(\Theta \times A) = \rho^m(\Theta \times A) = \mathrm{ND}_p^m(\Theta \times A)$;
furthermore, the projections of these sets onto A ($\mathrm{proj}_A \rho^m(\Theta \times A)$, $m \in \mathbb{N} \cup \{\infty\}$) are closed order-intervals (products of closed intervals).

Rationalizability in the Envelope Game

Example

Recall: *The game is symmetric, the envelope of* i *contains* €θ_i, *with* $\theta_i = 1, ..., K$. *Each player can offer to exchange (OE) by paying a* small *transaction cost* $\varepsilon > 0$. *Exchange executed IFF both offer:*

$\hat{G}^2$:

$a_i \backslash a_j$	OE	No
OE	$\theta_j - \varepsilon$	$\theta_i - \varepsilon$
No	θ_i	θ_i

Recall: *A rational player* i offers to exchange only *if she assigns positive probability to* $[\theta_j > \theta_i] \cap [a_j = OE]$. *With this, for each* i:▶ *OE is dominated for* $\theta_i = K$; *delete* $(\theta_i, a_i) = (K, OE)$.▶ *Given that* (K, OE) *is deleted for* j, *OE is dominated for* $\theta_i = K - 1$; *delete* $(K - 1, OE)$.▶ ...*Given that* (θ_j, OE) *is deleted for each* $\theta_j \in \{K - k + 1, ..., K\}$ $(1 \leq k < K)$, *OE is dominated for* $\theta_i = K - k$; *delete* $(K - k, OE)$...▶ $\rho^\infty (\Theta \times A) = \rho^K (\Theta \times A) = (\{1, ..., K\} \times \{No\})^2$ (*no type trades*).

Rationalizability in a Duopoly with Incomplete Inform., I

Example

The Cournot model presented above (with $n = 2$) is a *nice game with payoff uncertainty*. Thus, look at best replies (B.R.) to *deterministic* conjectures.

Assume: $\theta_0 = 0$ commonly known, marg. cost $\theta_i \in [0, 1]$, $\bar{p} > 2$ (highest average cost much lower than $\bar{p}$), $\bar{q}$ large ($\bar{q} > \bar{p} - 1$).

The model has *private values* and is *symmetric*: $A_i = [0, \bar{q}]$, $\Theta_i = [0, 1]$, and each firm i's payoff depends on θ_i and q_{-i} in the same way.

Hence, common B.R. function

$$r(\theta_i, q_{-i}) = \left[\frac{\bar{p} - \theta_i}{2} - \frac{1}{2} q_{-i}\right]_+$$

where $\frac{\bar{p} - \theta_i}{2} = r(\theta_i, 0)$=monopolistic output for cost-type θ_i.

Example

(Cont.) Let $\underline{r}(q_{-i}) = \left[\frac{\bar{p}-1-q_{-i}}{2}\right]_+$, $\bar{r}(q_{-i}) = \left[\frac{\bar{p}-q_{-i}}{2}\right]_+$ be the B.R. functions of, respectively, the *least efficient* ($\theta_i = 1$) and *most efficient* ($\theta_i = 0$) cost-type (see picture at the end).

Look at min and max output at each rationalizability step $k \in \mathbb{N}_0$:

$\underline{q}(k) = \underline{r}(\bar{q}(k-1))$ and $\bar{q}(k) = \bar{r}\left(\underline{q}(k-1)\right)$, with

$\underline{q}(0) = 0$, $\bar{q}(0) = \bar{q}$. Then, $\mathrm{proj}_A \rho^k (\Theta \times A) = \left[\underline{q}(k), \bar{q}(k)\right]^2$ with

$\underline{q}(1) = \underline{r}(\bar{q}) = \left[\frac{\bar{p}-1-\bar{q}}{2}\right]_+ = 0$, $\bar{q}(1) = \bar{r}(0) = \frac{\bar{p}}{2}$,

$\underline{q}(2) = \underline{r}\left(\frac{\bar{p}}{2}\right) = \frac{\bar{p}-2}{4}$, $\bar{q}(2) = \bar{r}(0) = \frac{\bar{p}}{2}$,

$\underline{q}(3) = \underline{r}\left(\frac{\bar{p}}{2}\right) = \frac{\bar{p}-2}{4}$, $\bar{q}(3) = \bar{r}\left(\frac{\bar{p}-2}{4}\right) = \frac{3\bar{p}+2}{8}$,

$\underline{q}(4) = \underline{r}\left(\frac{3\bar{p}+2}{8}\right) = \frac{5\bar{p}-10}{16}$, $\bar{q}(4) = \bar{r}\left(\frac{\bar{p}-2}{4}\right) = \frac{3\bar{p}+2}{8}$,

Show: $\mathrm{proj}_A \rho^\infty (\Theta \times A) = \left[\lim_{\ell\to\infty} (\underline{r} \circ \bar{r})^\ell (0), \bar{r}\left(\lim_{\ell\to\infty} (\underline{r} \circ \bar{r})^\ell (0)\right)\right]^2$

and compute $\underline{q}(\infty) = \underline{r}(\bar{q}(\infty))$, $\bar{q}(\infty) = \bar{r}\left(\underline{q}(\infty)\right)$.

Contextual Restrictions on Beliefs

- In many applications it is plausible to assume that the context makes some restrictions on players' beliefs about θ **transparent**, i.e., true and commonly believed (see examples in the book).
- It may also make sense to assume that restrictions on beliefs about both θ *and* behavior (i.e., on conjectures) are transparent.
- Such restrictions may depend on the information-type θ_i. We represent them with a restricted set of conjectures $\Delta_{i,\theta_i} \subseteq \Delta\left(\Theta_{-i} \times A_{-i}\right)$ (keep assuming distributed knowledge of θ) for each i and $\theta_i \Rightarrow$ profile of restricted sets $\Delta = \left(\Delta_{i,\theta_i}\right)_{i \in I, \theta_i \in \Theta_i}$.
- Modified justification operator (monotone!): for each $C \in \mathcal{C}$,

$$\rho_{i,\Delta}\left(C_{-i}\right) = \left\{(\theta_i, a_i) : \exists \mu^i \in \Delta_{i,\theta_i} \cap \Delta\left(C_{-i}\right), a_i \in r_i(\mu^i, \theta_i)\right\},$$

$$\rho_{\Delta}\left(C\right) = \times_{i \in I} \rho_{i,\Delta}\left(C_{-i}\right).$$

Directed Rationalizability

- The transparent restrictions (represented by) Δ "direct" the rationalizability procedure toward some results. Hence, the approach is called "**directed rationalizability**."
- Say that Δ represents **restrictions on exogenous beliefs** if, for every i and θ_i there is some $\bar{\Delta}_{i,\theta_i} \subseteq \Delta(\Theta_{-i})$ s.t. $\Delta_{i,\theta_i} = \left\{\mu^i \in \Delta(\Theta_{-i} \times A_{-i}) : \mathrm{marg}_{\Theta_{-i}} \mu^i \in \bar{\Delta}_{i,\theta_i}\right\}$: *only beliefs about exogenous θ_{-i} are restricted*. Then, for every information-type, the set of rationalizable actions is nonempty (*finiteness* for simplicity).

Theorem

Fix a finite game with payoff uncertainty $\hat{G}$ and and a profile Δ of restrictions about exogenous beliefs. Then

$$\rho_\Delta^\infty(\Theta \times A) = \rho_\Delta\left(\rho_\Delta^\infty(\Theta \times A)\right), \ \mathrm{proj}_\Theta \rho_\Delta^\infty(\Theta \times A) = \Theta.$$

Furthermore, for each $C \in \mathcal{C}$, $C \subseteq \rho_\Delta(C)$ implies $C \subseteq \rho_\Delta^\infty(\Theta \times A)$.

Self-Confirming Equilibrium with Incomplete Info., I

- Intuitively, the *SCE concept does not capture sophisticated strategic reasoning*. Players' *conjectures are only disciplined by long-run evidence*. Again, to ease notation, assume $\Theta \cong \times_{i \in I} \Theta_i$ (distributed knowledge).
- *As long as each player knows her payoff function (private values), we should get the same concept introduced in the previous lecture.* We will make this formal.
- Feedback is modeled by functions $f_i : \Theta \times A \longrightarrow M_i$ $(i \in I)$. Recall that $f_{i,\theta_i,a_i} : \Theta_{-i} \times A_{-i} \longrightarrow M_i$ is the **section** of f_i **at** (θ_i, a_i). If i observes m_i given (θ_i, a_i), she infers that the unknown profile (θ_{-i}, a_{-i}) must belong to the subset

$$f_{i,\theta_i,a_i}^{-1}(m_i) = \left\{ \left(\theta'_{-i}, a'_{-i}\right) : f_i\left(\theta_i, a_i, \theta'_{-i}, a'_{-i}\right) = m_i \right\}.$$

Self-Confirming Equilibrium with Incomplete Info., II

Definition

Fix a game with payoff uncertainty $\hat{G}$ and a profile of feedback functions $f = (f_i : \Theta \times A \to M_i)_{i \in I}$. A profile of actions and conjectures $\left(a_i^*, \mu^i\right)_{i \in I}$ is a (pure) **self-confirming equilibrium of** $\left(\hat{G}, f\right)$ **at** θ if, for each $i \in I$, (1, B.R.) $a_i^* \in r_i\left(\mu^i, \theta_i\right)$ and (2, CONF) $\mu^i\left(f_{i,\theta_i,a_i^*}^{-1}\left(f_i\left(a^*, \theta\right)\right)\right) = 1$.

- For any fixed $\theta \in \Theta$, let $\left(\hat{G}_\theta, f_\theta\right) := \left\langle I, \left(A_i, u_{i,\theta} : A \to \mathbb{R}, f_{i,\theta} : A \to M_i\right)_{i \in I}\right\rangle$ (a game with feedback as in the previous lecture).
- **Remark** *Fix* $a^* \in A$ *and* $\theta^* \in \Theta$ *arbitrarily; if* $\hat{G}$ *has* private values, *then* a^* *is part of an SCE of* $\left(\hat{G}, f\right)$ *at* θ^* *IF AND ONLY IF* a^* *is part of an SCE of* $\left(\hat{G}_{\theta^*}, f_{\theta^*}\right)$.
- **Proof** Let $\left(a_i^*, \mu^i\right)_{i \in I}$ be an SCE of $\left(\hat{G}, f\right)$ *at* θ^*. For each $i \in I$, let $\bar{\mu}^i = \mathrm{marg}_{A_{-i}}\mu^i \in \Delta\left(A_{-i}\right)$ (marginal of μ^i onto A_{-i}). Since each u_i is independent of θ_{-i}, $\left(a_i^*, \bar{\mu}^i\right)_{i \in I}$ must be an SCE of $\left(\hat{G}_{\theta^*}, f_{\theta^*}\right)$. ■

Incomplete Information and Properties of Feedback

- Recall, $f_{i,\theta_i,a_i}:\Theta_{-i}\times A_{-i}\longrightarrow M_i$ and $u_{i,\theta_i,a_i}:\Theta_{-i}\times A_{-i}\longrightarrow\mathbb{R}$ are the **sections** of f_i and u_i **at** (θ_i, a_i).
- Let $\mathcal{F}_{-i}(\theta_i, a_i)$ denote the "ex post information partition" of $\Theta_{-i}\times A_{-i}$ given (θ_i, a_i):

$$\mathcal{F}_{-i}(\theta_i, a_i)=\left\{C_{-i}\in 2^{\Theta_{-i}\times A_{-i}}:\exists m_i\in M_i, C_{-i}=f^{-1}_{i,\theta_i,a_i}(m_i)\right\}.$$

- $f_i:\Theta\times A\longrightarrow M_i$ satisfies
  - **own-action independence** of feedback about others (**OAI**) if $\mathcal{F}_{-i}(\theta_i, a'_i)=\mathcal{F}_{-i}(\theta_i, a''_i)$ for all θ_i and all a'_i, a''_i *justifiable* (undominated) *for* θ_i;
  - **observed payoffs (OP)** if $f_{i,\theta_i,a_i}(\theta'_{-i}, a'_{-i})=f_{i,\theta_i,a_i}(\theta''_{-i}, a''_{-i})\Rightarrow u_{i,\theta_i,a_i}(\theta'_{-i}, a'_{-i})=u_{i,\theta_i,a_i}(\theta''_{-i}, a''_{-i})$ for all $\theta_i, a_i, \theta'_{-i}, a'_{-i}$ and θ''_{-i}, a''_{-i} (u_{i,θ_i,a_i} is constant on each cell of $\mathcal{F}_{-i}(\theta_i, a_i)$, for all θ_i, a_i).

Properties of Feedback, SCE, and NE

- $\left(\hat{G}, f\right)$ satisfies OAI and OP if each f_i does $(i \in I)$.
- **Examples:**
  - The Envelope Game and Cournot Game with $f_i = u_i$ for each $i \in I$ satisfy OP (obviously), but do *not* satisfy OAI.
  - The Cournot Game with known inverse demand function $P(\cdot)$ and $f_i(\theta, \cdot) = P(\cdot)$ for all i and θ satisfies OP and OAI.

Theorem

Suppose that $\left(\hat{G}, f\right)$ satisfies OAI and OP and fix $a^* \in A$ and $\theta^* \in \Theta$ arbitrarily; then a^* is part of an SCE at θ^* of $\left(\hat{G}, f\right)$ IF AND ONLY IF a^* is a Nash equilibrium of $\hat{G}_{\theta^*} = \left\langle I, \left(A_i, u_{i,\theta^*} : A \to \mathbb{R}\right)_{i \in I} \right\rangle$.

References

Battigalli, P., E. Catonini, and N. De Vito (2025): *Game Theory: Analysis of Strategic Thinking*. Typescript, Bocconi University.

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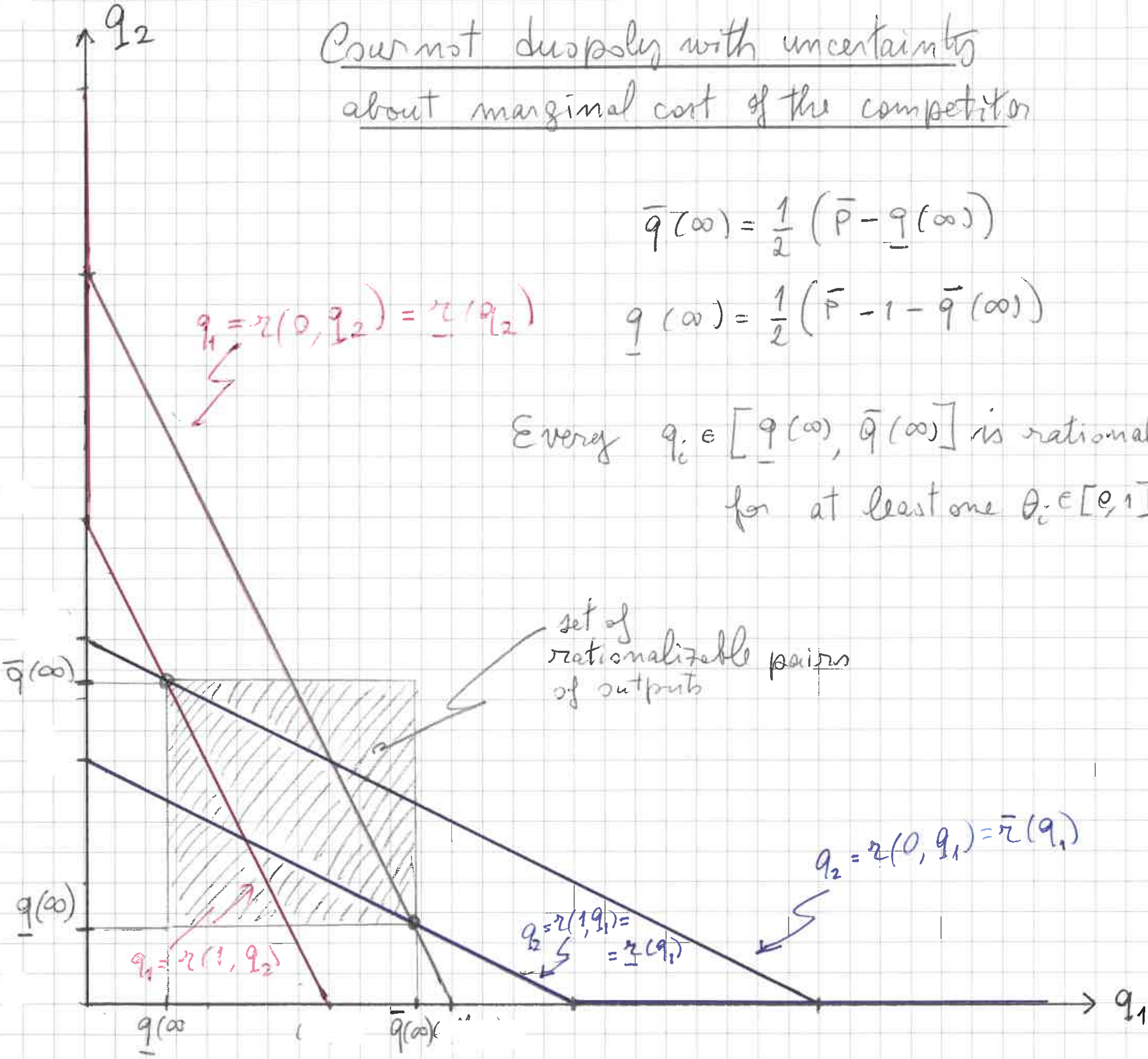
Cournot duopoly with uncertainty about marginal cost of the competitor

$$\bar{q}(\infty) = \frac{1}{2}\left(\bar{P} - \underline{q}(\infty)\right)$$

$$\underline{q}(\infty) = \frac{1}{2}\left(\bar{P} - 1 - \bar{q}(\infty)\right)$$

Every $q_i \in [\underline{q}(\infty), \bar{q}(\infty)]$ is rationalizable for at least one $\theta_i \in [0,1]$



θ_i = marg. cost of firm i (private information)

$\theta_i \in [0, 1]$ $\quad \theta_i = 0$ most efficient type $\quad \theta_i = 1$ least efficient type

Inverse demand $P(q_1 + q_2) = \max\{0, \bar{P} - (q_1 + q_2)\}$

Ex ante symmetric nice game with payoff uncertainty