

Game-theoretic Foundations of Multi-agent Systems

Lecture 6: Repeated Games

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Outline

1. Finitely Repeated Games
2. Infinitely Repeated Games
3. Folk Theorem
4. Repeated Games with Imperfect Monitoring



Repeated Games

- In a (typical) repeated game:
 - Agents play a given game (aka. **stage game**)
 - Then, they get their utilities
 - And, they play again ...



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 - Agents play a given game (aka. **stage game**)
 - Then, they get their utilities
 - And, they play again ...
- Can be repeated **finitely** or **infinitely** many times
- Really, an extensive form game
 - Would like to find subgame-perfect equilibria

Repeated Games (cont.)

- One subgame-perfect equilibrium:
 - Keep repeating some Nash equilibrium of the stage game
 - **Memoryless** strategy, called a **stationary strategy**



Repeated Games (cont.)

- One subgame-perfect equilibrium:
 - Keep repeating some Nash equilibrium of the stage game
 - **Memoryless** strategy, called a **stationary strategy**
- But are there other equilibria?
 - Strategy space of repeated game is much richer than that of stage game

Key Questions

- Do agents see what the other agents played earlier?
- Do they remember what they knew?
- Given utility of each stage game, what is the utility of the entire repeated game?



Finitely Repeated Games (with Perfect Monitoring)

- Agents play stage game G for R rounds



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- Agents' overall utility is sum of **discounted utilities** at each round
 - Discount factor is $0 \leq \delta \leq 1$
 - Game is denoted by $G^R(\delta)$



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- Agents' overall utility is sum of **discounted utilities** at each round
 - Discount factor is $0 \leq \delta \leq 1$
 - Game is denoted by $G^R(\delta)$
- Given sequence of utilities $u_i^{(1)}, \dots, u_i^{(R)}$, $u_i = \sum_{r=1}^R \delta^{r-1} u_i^{(r)}$

Example: Finitely Repeated Prisoner's Dilemma

- Two agents play Prisoner's Dilemma for R rounds ($\delta = 1$)

	D	C
D	-2, -2	-4, -1
C	-1, -4	-3, -3

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- Starting from last round, (C, C) is dominant strategy
- Hence, in second-to-last round, there is no way to influence what will happen
- So, (C, C) is dominant strategy at this round as well
- The unique SPE is (C, C) at each round

SPE in Finitely Repeated Games

[Theorem]

- If stage game G has unique strategy equilibrium s^* , then $G^R(\delta)$ has unique SPE in which $s^{(r)} = s^*$ for all $r = 1, \dots, R$, regardless of history

[Proof]

- By backward induction, at round R , we have $s^{(R)} = s^*$
- Given this, then we have $s^{(R-1)} = s^*$, and continuing inductively, $s^{(r)} = s^*$ for all $r = 1, \dots, R$, regardless of history



SPE: Example I

- Two agents play the following game for 2 rounds ($\delta = 1$)

	D1	D2	C
D1	4, 4	1, 1	6, 0
D2	1, 1	2, 2	6, 0
C	0, 6	0, 6	5, 5



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- Consider the following strategy:
 - In round 1, cooperate;
 - In round 2, if someone defected in round 1, play D2; otherwise, play D1



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- Consider the following strategy:
 - In round 1, cooperate;
 - In round 2, if someone defected in round 1, play D2; otherwise, play D1
- If both agents play this, is that SPE?

SPE: Example II

- Two agents play the following game for 2 rounds ($\delta = 1$)

	D	Crazy	C
D	4, 4	1, 0	6, 0
Crazy	0, 1	0, 0	0, 1
C	0, 6	1, 0	5, 5



SPE: Example II

- Two agents play the following game for 2 rounds ($\delta = 1$)

	D	Crazy	C
D	4, 4	1, 0	6, 0
Crazy	0, 1	0, 0	0, 1
C	0, 6	1, 0	5, 5

- What are the subgame perfect equilibria?



SPE: Example II

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	D	Crazy	C
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Crazy	0, 1	0, 0	0, 1
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- What are the subgame perfect equilibria?
- Consider the following strategy:
 - In round 1, cooperate;
 - In round 2, if someone played D or Crazy in round 1, play Crazy; otherwise, play D



SPE: Example II

- Two agents play the following game for 2 rounds ($\delta = 1$)

	D	Crazy	C
D	4, 4	1, 0	6, 0
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- What are the subgame perfect equilibria?
- Consider the following strategy:
 - In round 1, cooperate;
 - In round 2, if someone played D or Crazy in round 1, play Crazy; otherwise, play D
- If both agents play this, is that NE (not SPE)?

TSPE: Example III

- If G has multiple equilibria, then $G^R(\delta)$ does not have unique SPE
- Consider following example

	x	y	z
x	3, 3	0, 4	-2, 0
y	4, 0	1, 1	-2, 0
z	0, -2	0, -2	-1, -1

- Stage game has two pure NE: (y, y) and (z, z)
- Consider the following policy:
 - Play x in first round
 - Play y in second round if opponent played x; otherwise, play z
- Is both agents playing this SPE?



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Utilities in Infinitely Repeated Games

- Limit-average utility:

$$u_i = \lim_{R \rightarrow \infty} \frac{\sum_{r=1}^R u_i^{(r)}}{R}$$

- Future-discounted utility:

$$u_i = (1 - \delta) \sum_{r=1}^{\infty} \delta^{r-1} u_i^{(r)},$$

for some $0 \leq \delta < 1$



Subgame Perfection in Infinitely Repeated Games

- **One-shot deviation** from strategy s means deviating from s in single stage and conforming to it thereafter
- Strategy profile s^* is SPE **if and only if** there are no **profitable** one-shot deviation for **each subgame** and **every agent**
- This follows from principle of optimality of **dynamic programming**
- This applies to finitely repeated games as well



Trigger Strategies (TS)

- Agents get **punished** if they deviate from agreed profile
- In **non-forgiving** TS (or grim TS), punishment continues forever

$$s_i^{(t)} = \begin{cases} s_i^* & \text{if } s^{(r)} = s^* \quad \forall r < t, \\ \underline{s}_i^j & \text{otherwise} \end{cases}$$

- Here, s^* is agreed profile, and \underline{s}_i^j is punishment strategy of i against agent j
- Single deviation by j triggers agent i to switch to \underline{s}_i^j **forever**



Example: Infinitely Repeated Prisoner's Dilemma

- Consider **trigger** strategy:
 - Cooperate as long as everyone cooperates
 - Once a player defects, defect **forever**

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 - Cooperate as long as everyone cooperates
 - Once a player defects, defect **forever**
- Is both agents playing this SPE?
- Does it depend on δ ?

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Trigger Strategy for Infinitely Repeated Prisoners' Dilemma

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 - Type 1: Both agents cooperated so far
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 - Utility from on-shot deviation: $(1 - \delta)(-1 + (-3\delta - 3\delta^2 + \dots)) = -(1 - \delta) - 3\delta$



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- Type-2 subgames: (C is best response to C)



Trigger Strategy for Infinitely Repeated Prisoners' Dilemma

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 - Type 1: Both agents cooperated so far
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 - Deviation is not beneficial if $\delta \geq 1/2$
- Type-2 subgames: (C is best response to C)
 - Other agents will always play C, thus C is best response

Tit-for-tat Strategy

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 - Cooperate in 1st round
 - Then, do whatever other agent did in previous round



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- Is both agents playing this SPE?



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- Is both agents playing this NE?
- Is both agents playing this SPE?
- What about one playing TFT and other trigger?

Remarks

- If s^* is NE of G , then “each agent plays s_i^* ” is SPE of $G^R(\delta)$
 - Future play of other agents is independent of how each agent plays
 - Optimal play is to maximize current utility, i.e., play static best response
- Sets of equilibria for finite and infinite horizon versions can be **different**
 - Multiplicity of equilibria in repeated prisoner's dilemma only occurs at $R = \infty$
 - For any finite R (thus for $R \rightarrow \infty$), repeated prisoners' dilemma has unique SPE



Repetition Could Lead to Bad Outcomes

- Consider the following game

	x	y	z
x	2, 2	2, 1	0, 0
y	1, 2	1, 1	-1, 0
z	0, 0	0, -1	-1, -1

- Strategy x strictly dominates y and z for both agents
- Unique NE of stage game is (x, x)
- If $\delta \geq 1/2$, this game has SPE in which (y, y) is played in every round
- It is supported by slightly more complicated strategy than grim trigger
 - I. Play y in every round unless someone deviates, then go to II
 - II. Play z. If no one deviates go to I. If someone deviates stay in II



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Characterizing NE of Infinitely Repeated Games

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- Such utilities must be **feasible**
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- They must also be **enforceable**
 - Deviation should lead to punishment that outweighs benefits of deviation



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 - There must be outcomes of game such that agents, on average, get these utilities
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- **Folk theorem** states that utility vector can be realized by some NE iff it is both feasible and enforceable

Feasibility

	Left	Right
Left	2, 2	0, 3
Right	3, 0	1, 1

- Utility vector $(2, 2)$ is feasible as it is one of outcomes of game



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- What about $(0.5, 2.75)$?



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- What about $(3, 0.1)$?



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- Utility vector (2, 2) is feasible as it is one of outcomes of game
- Utility vector (1, 2.5) is feasible as agents can alternate between (2, 2) and (0, 3)
- What about (0.5, 2.75)?
- What about (3, 0.1)?
- In general, convex hull of outcomes of game are feasible
 - $p_1x_1 + \dots + p_nx_n$ is convex hull of x_i if p_i sum to 1 and are non negative

Feasible and Individually Rational Utilities

- Feasible utilities:

$$V = \text{Conv}\{v \in \mathbb{R}^{|N|} \mid \text{there exists } a \in A \text{ such that } u(a) = v\}$$



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- Recall minmax value of agent i :

$$\underline{v}_i = \min_{s_{-i}} \max_{s_i} u_i(s_i, s_{-i})$$



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- Utility vector $v \in \mathbb{R}^{|N|}$ is strictly individually rational if $v_i > \underline{v}_i$ for all i

Nash Folk Theorem

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- If u is both feasible and enforceable, then u is utility profile for some NE of G



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- Consider infinitely repeated game G played by agents with **average utilities**
- If u is utility profile for any NE of repeated G , then u_i is enforceable for all i
- If u is both feasible and enforceable, then u is utility profile for some NE of G
- Folk theorem can be stated for agents with discounted utilities as well

Problems with Nash Folk Theorem

- Any feasible and enforceable utility can be achieved (for **patient enough** agents)



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- NE involves non-forgiving TS which may be costly for punishers



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 - If some agent j deviates, then play minmax strategy against that agent thereafter
- NE involves non-forgiving TS which may be costly for punishers
- NE may include **non-credible threats**
- NE may not be subgame perfect

Example

	L	R
U	6, 6	0, -100
D	7, 1	0, -100

- Unique NE in this game is (D, L)
- Minmax values are given by $\underline{v}_1 = 0$ and $\underline{v}_2 = 1$
- Minmax strategy against agent 1 requires agent 2 to play R
- R is strictly dominated by L for agent 2

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Motivation

- So far, we assumed that agents observe actions of others at each round of game
- Next, we consider games where agents' actions may not be directly observable
- We assume that agents observe only an **imperfect signal** of stage game actions



Example: Cournot Competition with Noisy Demand

[Green and Porter, Non-cooperative Collusion under Imperfect Price Information, 1984]

- Firms set production levels $q_1^{(r)}, \dots, q_n^{(r)}$ **privately** at round r
- Firms do not observe each others' output levels
- Market demand is **stochastic**
- Market price depends on total production and market demand
- Low price could be due to high production or low demand
- Firms utility depends on their own production and market price



Model

- We focus on game with **public information**
- At each round, **all agents** observe some **public outcome**
- Let $y^{(r)} \in Y$ denote publicly observed outcome at round r
- Each action profile a induces **probability distribution** over y
- Let $\pi(y, a)$ denote probability distribution of y under action profile a
- Public information at round r is $h^{(r)} = (y^{(1)}, \dots, y^{(r-1)})$
- Strategy of agent i is **sequence of maps** $s_i^{(r)} : h^{(r)} \rightarrow S_i$



Model (cont.)

- Agents utility depends **only** on their own action and public outcome



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- Dependence on actions of others is through their effect on distribution of y



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- Agent i 's **realized** utility at round r is $u_i(a_i^{(r)}, y^{(r)})$



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- Agents utility depends **only** on their own action and public outcome
- Dependence on actions of others is through their effect on distribution of y
- Agent i 's **realized** utility at round r is $u_i(a_i^{(r)}, y^{(r)})$
- Agent i 's expected stage utility is

$$u_i(a) = \sum_{y \in Y} \pi(y, a) u_i(a_i, y)$$



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- Agent i 's expected stage utility is

$$u_i(a) = \sum_{y \in Y} \pi(y, a) u_i(a_i, y)$$

- Agent i 's average discounted utility when sequence $\{a^{(t)}\}$ is played is

$$(1 - \delta) \sum_{r=1}^{\infty} \delta^{r-1} u_i(a^{(r)})$$

Simpler Example: Noisy Prisoner's Dilemma

- Prisoners do not observe each others actions, instead, they observe signal y



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 - $u_1(D, y) = 1 + y$ $u_1(C, y) = 4 + y$



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- Signal y is defined by cont. random variable X with CDF $F(x)$ and $\mathbb{E}[X] = 0$



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- Signal y is defined by cont. random variable X with CDF $F(x)$ and $\mathbb{E}[X] = 0$
 - If $a = (D, D)$, then $y = X$



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- Prisoners do not observe each others actions, instead, they observe signal y
 - $u_1(D, y) = 1 + y$ $u_1(C, y) = 4 + y$
 - $u_2(D, y) = 1 + y$ $u_2(C, y) = 4 + y$
- Signal y is defined by cont. random variable X with CDF $F(x)$ and $\mathbb{E}[X] = 0$
 - If $a = (D, D)$, then $y = X$
 - If $a = (D, C)$ or (C, D) , then $y = X - 2$



Simpler Example: Noisy Prisoner's Dilemma

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- Normal-form stage game is

	D	C
D	$1 + X, 1 + X$	$-1 + X, 2 + X$
C	$2 + X, -1 + X$	X, X

Trigger-price Strategy

- Consider following trigger strategy
 - (I) - Play (D, D) until $y \leq y^*$, then go to (II)
 - (II) - Play (C, C) for R rounds, then go back to (I)
- Notice that strategy is stationary and symmetric
- Also notice that punishment uses **NE of stage game**
- We can choose y^* and R such that this strategy profile is SPE



Trigger-price Strategy (cont.)

- We use one-shot deviation principle
- Deviation in (II) is obviously not beneficial
- In (I), if agents do not deviate, their **expected utility** is

$$v = (1 - \delta) \left((1 + 0) + \delta \left(F(y^*) \delta^R v + (1 - F(y^*)) v \right) \right)$$

- From this, we obtain

$$v = \frac{1 - \delta}{1 - \delta(1 - \delta)(1 - F(y^*)(1 - \delta^R))}$$



Trigger-price Strategy (cont.)

- If some agent deviates in (1), then her expected utility is

$$v_d = (1 - \delta) \left((2 + 0) + \delta \left(F(y^* + 2) \delta^R v + (1 - F(y^* + 2)) v \right) \right)$$

- Deviation provides immediate utility, but increases probability of entering (II)
- To have SPE, we must have $v \geq v_d$ which means

$$v \geq \frac{2(1 - \delta)}{1 - \delta(1 - \delta)(1 - F(y^* + 2)(1 - \delta^R))}$$
$$\Rightarrow F(y^* + 2) - 2F(y^*) \geq \frac{1 - \delta(1 - \delta)}{\delta(1 - \delta)(1 - \delta^R)}$$

- Any R and y^* that satisfy this constraint construct SPE
- **Best trigger-price strategy** can be found by maximizing v s.t. this constraint



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