Advanced Microeconomics: Game Theory

Lesson 6:
Congestion Games

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What You will learn

After studying Lesson 6, You

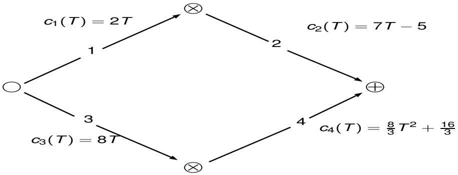
- Know what congestion games are about.
- should be able to perform a game theoretic analysis of simple congestion games.

Introduction

In this lesson we are going to consider the real world problem of congestion and present a simple game theoretic model for it. In fact, below You can find a quick and efficient route for understanding the very basics of congestion games.

Let us start with a very simple example by considering the following traffic network:

Simple traffic network



The intended interpretation is as follows.

- Each morning n commuters want to go from node (i.e. place) $\bigcirc$ to node $\bigoplus$.
- There are 4 roads: 1, 2, 3, 4. The configuration of these roads makes that there are two routes for commuting: roads 1–2 (route 1) and roads 3–4 (route 2).
- $c_j(T)$ denotes the costs for a commuter of using road j if T commuters use this road. (So this costs are the same for all commuters who take the road.)

Questions

Questions we want to answer:

- How the commuters will behave?
- Is this behaviour social optimal?
- Is it Pareto efficient?

We shall answer these questions by looking to them from a game theoretical perspective. In order to do so we make out of situations as the above one (with only two routes) as follows a game in strategic form.

Of course we assume that the commuters are rational and intelligent. But also that they simultaneously and independently choose a route.

Game structure

The commuters are the players and the strategy set of a commuter is the set of routes he can use. Note that in the above simple model each commuter has the same strategy set. We label (in some way) the commuters by $1, 2, \ldots, n$ and the strategies by $1, 2, 3, \ldots$.

Denote by $(x_1, \ldots, x_n)$ a strategy profile, i.e. player 1 plays x_1, player 2 plays x_2, ...

Analysis

Further we suppose $n = 2$, i.e. there are 2 commuters. Denote by $C_1(x_1, x_2)$ the total costs of commuter 1 if this commuter chooses strategy x_1 and commuter 2 strategy x_2. Define $C_2(x_1, x_2)$ is the same way.

For example: at the strategy profile $(2, 1)$ (i.e. player 1 takes route 2 and player 2 takes route 2).
Player 1 has costs $8 \cdot 1$ for road 3 and $\frac{8}{3}1^2 + \frac{16}{3} = 8$ for road 4.

Thus $C_1(2, 1) = 8 + 8 = 16$. And for player 2 this leads to $C_2(2, 1) = 2 + 2 = 4$.

Analysis (ctd)

We find
$C_1(1,1) = 13,\ C_2(1,1) = 13$
$C_1(1,2) = 4,\ C_2(1,2) = 16$
$C_1(2,1) = 16,\ C_2(2,1) = 4$
$C_1(2,2) = 32,\ C_2(2,2) = 32$

This can be represented as follows by means of a so-called bimatrix:

$$\begin{pmatrix} 13; 13 & 4; 16 \\ 16; 4 & 32; 32 \end{pmatrix}.$$

Analysis (ctd)

$$\begin{pmatrix} 13;13 & 4;16 \\ 16;4 & 32;32 \end{pmatrix}.$$

A simple game theoretic analysis shows the following.

Prediction of behaviour : both choose route 1.

Social optimal : each commuter chooses a different route.

We see:

Equilibrium is not social optimal. However, equilibrium (for our case) is Pareto efficient.
The case of more than two commuters is more difficult to handle.

Fundamental result

There are various results about congestion games, like the existence of Nash equilibria. The first one was:

Theorem

Rosenthal; A Class of Games Possessing Pure-Strategy Equilibria; International Journal of Game Theory; 1973.

Pioneers concerning congestion games: Rosenthal, Milchtaich, Monderer, and Shapley (Nobel Prize Economics).

Braess' Paradox

The Braess' Paradox is named after the mathematician Dietrich Braess. It states that adding a link to a transportation network can increase the travel cost for all commuters in the network. It is a counterintuitive phenomenon.

The paradox occurs only in networks in which the commuters operate independently and non cooperatively, in a decentralized manner.

In fact the Braess' Paradox is not limited to traffic flow. It also occurs in other types of 'networks'. In fact it is widespread occurring for example with biological or electricity systems. This makes this paradox extra interesting!

Example from sport: removing a key player from a basketball team can result in the improvement of the team's offensive efficiency. ('When less is actually more.')

Braess' Paradox (ctd.)

The Braess paradox has been observed in various cities, for example in Seoul, New York and Stuttgart.
In New York the often congested 42nd was closed for a parade. People suspected that the closing of this road would lead to the worst traffic jams in history. Instead, the traffic flow actually improved that day.
The Braess' paradox may arise as Nash equilibria have not to be 'optimal'.

Braess' Paradox (ctd.)

Let us now look to the following Youtube video:
`https://www.youtube.com/watch?v=cALezV_Fwi0`

Outlook

This finishes the theory for the second part of the course. Various extensions of this theory exist; they especially relate to the type of information. In the third part of the course You will study this a little bit.

Concerning extensions, i provide now a little outlook (which You may skip if You like).

Three extensions:

- Imperfect information.
- Incomplete information: the solution concept here is that of Bayesian equilibrium (Subsection 7.2.3. in the text book).
- Randomization.

Imperfect information

- Imperfect information can be dealt with by using information sets. The information sets form a partition of the decision nodes. (Example: Figure 7.10 in text book.)
- Perfect information: all information sets are singletons.
- Solution concept: Nash equilibrium.
- Remember: also games in strategic form are games with imperfect information.

Imperfect information (ctd.)

- Strategy: specification at each information set how to move.
- The procedure of backward induction cannot be applied anymore, but the notion of subgame perfect Nash equilibria still makes sense (when 'subgame' is properly defined).
- Subgame: not all decision nodes define anymore a subgame. (Example: Figure 7.20 in text book.)
- Nash equilibria need not always exist. (Example: Figure 7.23 in text book.)

Three types of strategies

Three types of strategies: pure, mixed and behavioural strategies.

- A pure strategy of player *i* is a book with instructions where there is for each decision node for *i* a page with the content which move to make at that node. So the set of all pure strategies of player *i* is a library of such books.
- A mixed strategy of player *i* is a probability density on his library. Playing a mixed strategy now comes down to choosing a book from this library by using a chance device with the prescribed probability density.

Three types of strategies (ctd.)

- A behavioural strategy, is like a pure strategy also a book, but of a different kind. Each page in the book still refers to a decision node, but now the content is not which move to make but a probability density between the possible moves.
- For many games (for instance those with perfect recall) it makes no difference whatever if players employ mixed or behavioural strategies.

John Nash

Our hero:

- John Nash (1928 – 2015).
- Mathematician.
- Nobel price for economics in 1994, together with Harsanyi and Selten.
- Abel Price for mathematics in 2015. Just after having received it he was killed in a car crash.
- Got this price for his PhD dissertation (27 pages) in 1950.
- Enjoy looking to the following video about our main hero:

  `http://topdocumentaryfilms.com/a-brilliant-madness-john-nash`.