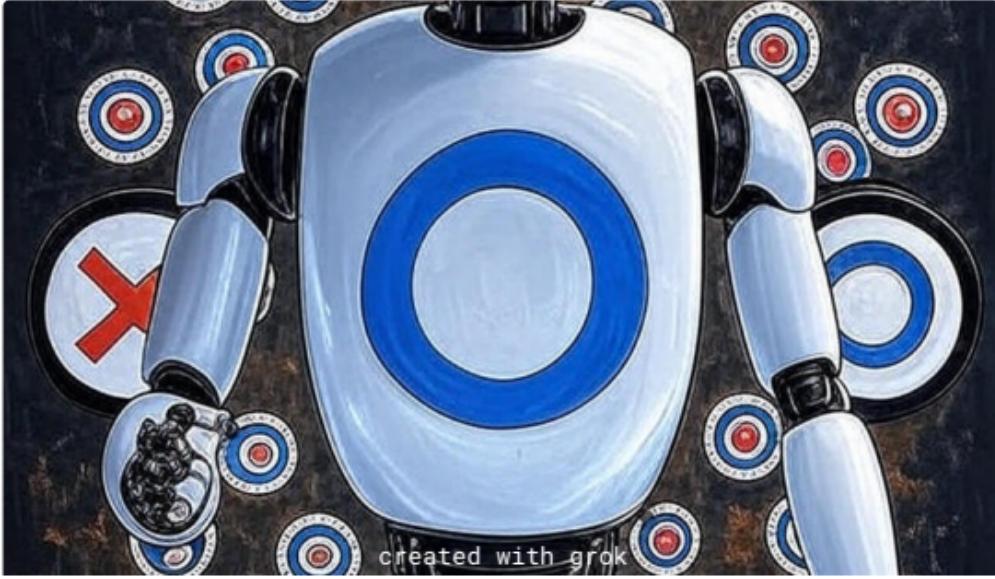


Game Theory and Control

Silvan Stadelmann - 12. November 2025 - v0.0.1

github.com/silvasta/summary-gtc



Contents

1 Static games	2
1.1 Basic Definitions	2
1.1.1 Matrix representation	3
1.1.2 Nash Equilibrium	3
1.1.3 Dominated actions	3
1.1.4 Reduced game	3
1.1.5 Security levels and policies	3
1.2 Multiple Nash Equilibria	3
1.2.1 Admissible Nash Equilibria	3
1.3 Mixed strategies	3
1.3.1 Security levels	3
1.3.2 Mixed Nash Equilibrium	3
1.4 Nash Theorem	3
2 Zero-sum games	3
2.1 Two-Person Zero-sum Games	3
2.1.1 Payoff Matrix	3
2.1.2 Rock, Paper, Scissors	3
2.2 Security levels and policies	3
2.2.1 Min-Max Property	3
2.3 Nash equilibrium in zero-sum games	3
2.4 Saddle-point and security levels	4
2.5 Mixed strategies	4
2.5.1 Computing the mixed security level via LP	4
2.5.2 Min-Max Property	4
2.5.3 Nash Equilibrium	4
3 Auctions	4
3.1 First-price auctions	4
3.2 The problem of private information	4
3.3 Second-price auctions	5
3.3.1 Dominant Strategy	5
3.3.2 Properties of second-price auction	5
3.4 Generalized auctions	5
3.4.1 Bids	5
3.4.2 Choice function	5
3.4.3 Payment function	5
3.5 VCG auctions	5
3.5.1 Social utility	5
3.5.2 Non-negative utility	6

3.5.3	Dominant bidding strategy	6
3.6	Open problem of auction design	6
4	Potential games	6
4.1	N-player games	6
4.1.1	Best-response dynamics	6
4.2	Potential games	7
4.2.1	Paths	7
4.3	Congestion games	7
4.4	Social welfare	7
4.4.1	Price of Anarchy	7
5	Convex games	7
5.1	Games with infinite actions	7
5.1.1	Problems with infinite actions	8
5.1.2	Example: Cournot competition	8
5.1.3	Example: Bertrand competition	8
5.1.4	Definitions and background	8
5.2	Convex games	8
5.3	Variational inequalities	9
5.3.1	VI and Nash Equilibria	9
5.3.2	Uniqueness of Nash Equilibria	9
5.4	Computing the Nash Equilibrium of a convex game	9
5.4.1	Projected game map	9
5.4.2	Analysis of convergence	9
6	Stackelberg games	10
6.1	Definition of Stackelberg games	10
6.2	Stackelberg zero-sum games	10
6.2.1	Security strategies	10
6.2.2	Stackelberg vs Nash	10
6.3	Stackelberg non-zero-sum games	10
6.3.1	Computation of the Stackelberg equilibrium	10
6.4	Security games	10
6.4.1	Stackelberg solution of a security game	10
6.4.2	Nash equilibria of security games	10
7	Repeated games	11
8	Multistage games	11
9	Linear-quadratic games	11
10	Stochastic games	11

1 Static games

1.1 Basic Definitions

Game theory is the study of mathematical models of conflict and cooperation between rational decision-makers.

Several things are needed to characterize a game:

- The **players** are the agents that make decisions
- The **actions** available to each player at each decision point
- The **information structure** specifies what each player knows before making each decision, in particular with respect to other players' decisions
- The **outcome** for each player, which depends on all players' decisions

- 1.1.1 Matrix representation
- 1.1.2 Nash Equilibrium
- 1.1.3 Dominated actions
- 1.1.4 Reduced game
- 1.1.5 Security levels and policies
- 1.2 Multiple Nash Equilibria
- 1.2.1 Admissible Nash Equilibria

Poset

Hasse diagram

Minimal element

1.3 Mixed strategies

Careful! Refer to deterministic strategies as pure strategies!

1.3.1 Security levels

Mixed security level

Mixed security strategy

Computational complexity

1.3.2 Mixed Nash Equilibrium

1.4 Nash Theorem

2 Zero-sum games

- Zero-sum games model a large number of practical applications
- Nash equilibria in zero-sum games have many useful properties
- Nash equilibria in zero-sum games are much easier to compute

2.1 Two-Person Zero-sum Games

Games in which the two players have opposite payoffs:

$$J_1(\gamma, \sigma) = -J_2(\gamma, \sigma)$$

Static game with $B = -A$ (we only indicate one matrix, A)

2.1.1 Payoff Matrix

- Row player loses a_{ij}
- Column player gains a_{ij}
- Row player minimizes outcome V
- Column player maximizes outcome V

2.1.2 Rock, Paper, Scissors

Consider only one round of the game.

	Rock	Paper	Scissors	
A =	0	1	-1	Rock
	-1	0	1	Paper
	1	-1	0	Scissors

2.2 Security levels and policies

- Security level Player 1,2

- Security policy Player 1,2

2.2.1 Min-Max Property

Security levels in **zero-sum games** have a fundamental property that general static games don't have.

For every finite matrix A, the following properties hold:

- (i) Security levels are well defined and unique
- (ii) Both players have security policies (not necessarily unique)
- (iii) The security levels always satisfy:

2.3 Nash equilibrium in zero-sum games

Interpretation: As in static games: no regret, stable strategy when iterated, etc.

Also known as **saddle-point equilibrium**

$$a_{i^*j} \leq a_{i^*j^*} \leq a_{ij^*} \quad \forall i \in 1, \dots, n, \forall j \in 1, \dots, m$$

Saddle-point value $V^* := a_{i^* j^*}$

2.4 Saddle-point and security levels

Not all zero-sum games have a saddle point (f.e. Rock-Paper-Scissors). We can exactly characterize the zero-sum games that have a saddle point.

Theorem 1 (Saddle-point and security levels). A zero-sum game defined by A has a saddle-point equilibrium if and only if

$$\underline{V} = \bar{V} \quad (= V^* \text{ saddle-point value})$$

Important consequences follow (only for zero-sum games!)

All saddle-point equilibria (Nash equilibria) of a zero-sum game have the same value V^* , which we denote as the value of the game.

2.5 Mixed strategies

2.5.1 Computing the mixed security level via LP pseudo, matlab code:

```
m = 5; n = 10; A = rand(m, n); y = sdpvar(m, 1); t = sdpvar(1, 1); obj = t; constraints = [A' * y <= ones(n, 1) * t, sum(y) == 1, y >= 0]; optimize(constraints, obj); SecurityLevel = double(t); SecurityPolicy = double(y);
```

2.5.2 Min-Max Property

2.5.3 Nash Equilibrium

Theorem 2 (Mixed Nash equilibrium for zero-sum games). Policy (y^*, z^*) is called mixed-strategy saddle-point equilibrium (or Nash equilibrium) if

$$y^{*T} Az^* \leq y^T Az^* \quad \forall y \quad (\text{minimizer})$$

$$y^{*T} Az^* \geq y^{*T} Az \quad \forall z \quad (\text{maximizer})$$

$y^{*T} Az^*$ is called **saddle point value**

3 Auctions

- N Players: bidders

- Action: bid $x_i \geq 0$

Outcome

- $w(x)$ the winner of the auction

- $p(x)$ the price that the winner has to pay

- t_i the true value of the item for agent i

The outcome (cost) for agent i is:

$$J_i = \begin{cases} p(x) - t_i & \text{if } i = w(x) \\ 0 & \text{otherwise} \end{cases}$$

3.1 First-price auctions

In first-price auctions, the best-response bid depends on the bids of the other agents and your own true value.

- Underbidding $x_i < t_i$

- Truthful bidding $x_i = t_i$

- Overbidding $x_i > t_i$

Proposition 1 (first-price auctions).

- any **overbidding** strategy is dominated by **truthful bidding**
- truthful bidding** is not a dominant strategy

3.2 The problem of private information

Until now, we always assumed that the cost functions of the agents are known to the other agents. Auctions are an application of game theory in which this is not true, and we encode all the **private information** in the true value t_i .

Lack of information leads to inefficiency!

3.3 Second-price auctions

Winner selection $w(x) = \operatorname{argmax}_i x_i$

(the bidder with the highest bid wins)

Payment rule $p(x) = \max_{i \neq w(x)} x_i$

(the winner pays the second-largest bid)

3.3.1 Dominant Strategy

In second-price auctions, a Nash equilibrium exists and **can be computed by each agent based on their own private information.**

Truthful bidding is a weakly dominant strategy in a second-price auction

Intuition: your bid determines whether you win, not how much you pay.

- Incentive compatibility

3.3.2 Properties of second-price auction

Social efficiency

Does the auctioneer achieve the highest return?

No (cost of eliciting truthful bidding...)

Incentive compatibility and **social efficiency** often go together

(the true value needs to be disclosed in order to be used for efficient allocation).

3.4 Generalized auctions

3.4.1 Bids

Each **bid** is represented by a pair $x_j = (b_j, m_j)$

- b_j is the bidden amount

- m_j describes the object of the bid

(Can be extended to allow multiple bids)

Fungible goods $m_j \in \mathbb{R}_{>0}$ parts of a total quantity M

Non-fungible goods $m_j \in 2^{\mathcal{M}}$ with finite set of items \mathcal{M}

3.4.2 Choice function

Choice function w maps bids x into N -dimensional binary vector

$$w_j(x) = \begin{cases} 1 & \text{if bid } j \text{ is accepted} \\ 0 & \text{otherwise} \end{cases}$$

- Choice constraints

3.4.3 Payment function

Payment function p maps bids x into N -dimensional vector where $p_j(x)$ is the payment requested from the player that placed the bid j

3.5 VCG auctions

- VCG choice function

- VCG payment function

In order to compute each payment p_j , we need to evaluate the choice function twice: with and without the bid j

3.5.1 Social utility

The social utility is the aggregate utility of all players and the auctioneer

$$U(t, w) = \sum_i t_i w_i$$

The social utility - depends on the true value of the goods according to the player that receives it

- does not depend on the entity of the payments

If **players bid truthfully** $b_j = t_j$ then VCG choice function

achieves maximal social utility U^*

Interpretation of the VCG payment if agents bid truthfully:

3.5.2 Non-negative utility

When an agent bids truthfully, his utility is non-negative.

3.5.3 Dominant bidding strategy

Truthful bidding is a weakly dominant strategy in a VCG auction.

3.6 Open problem of auction design

We saw how to design an auction which guarantees

- incentive compatibility / truthful bidding
- optimal social efficiency
- non-negative payments

Unfortunately, it comes with drawbacks. For example

- it yields low returns
- it can be manipulated by colluding agents
- it is computationally challenging to solve.

4 Potential games

4.1 N-player games

N -player non-zero-sum games

- Player i can choose one among m_i pure actions

$$\Gamma_i = \{\gamma_i^{(1)}, \gamma_i^{(2)}, \dots, \gamma_i^{(m_i)}\}$$

- The outcome of the game for Player i is given by

$$J_i = (\gamma_1, \gamma_2, \dots, \gamma_N) = J_i(\gamma_i, \gamma_{-i})$$

Definition 1 (Pure Nash equilibrium in N -player games). A pure strategy profile $\gamma^* = \{\gamma_1^*, \gamma_2^*, \dots, \gamma_N^*\}$ is a pure Nash equilibrium if for every player i

$$J_i(\gamma_i^*, \gamma_{-i}^*) \leq J_i(\gamma'_i, \gamma_{-i}^*) \quad \forall \gamma'_i \in \Gamma_i$$

- Randomized play \rightarrow mixed strategies, mixed Nash equilibria
- Multiple Nash equilibria are possible (non interchangeable, different payoffs)

Definition 2 (Pure Best Response in N -player games). The pure best response of player i is the set $R_i(\gamma_{-i}) \subseteq \Gamma_i$ such that $\gamma_i \in R_i(\gamma_{-i})$ if and only if

$$J_i(\gamma_i, \gamma_{-i}) \leq J_i(\gamma'_i, \gamma_{-i}) \quad \forall \gamma'_i \in \Gamma_i$$

Equivalent: $R_i(\gamma_{-i}) := \operatorname{argmin}_{\gamma_i \in \Gamma_i} J_i(\gamma_i, \gamma_{-i})$

- $R_i(\gamma_{-i})$ is a set, and it is not necessarily a singleton
- $R_i(\gamma_{-i})$ is never empty.
- $R_i(\gamma_{-i})$ is a function of the strategies of other players.

Proposition 2. A pure strategy profile $\gamma^* = \{\gamma_1^*, \gamma_2^*, \dots, \gamma_N^*\}$ is a pure Nash equilibrium if and only if $\gamma_i^* \in R_i(\gamma_{-i}^*)$ for every player i .

4.1.1 Best-response dynamics

Consider an initial pure strategy profile $\gamma^0 = \{\gamma_1^0, \gamma_2^0, \dots, \gamma_N^0\}$

Step $k = 0, \dots$:

1 - If γ^k is a pure Nash equilibrium \Rightarrow stop

2 - Else there exists a player i for which $\gamma_i^k \notin R(\gamma_{-i})$

3 - Update: $\gamma^{k+1} := (R(\gamma_{-i}), \gamma_{-i})$.

4 - $k = k + 1$, goto step 1.

Clearly, it does not converge if a pure Nash equilibrium does not exist.

Conjecture: It always converges to a pure Nash equilibrium, if that exists.

In this summary:

A class of N-player non-zero sum games for which

- a pure Nash equilibrium is guaranteed to exist
- best-response dynamics converge
- pure Nash equilibria are easy to find

4.2 Potential games

Definition 3 (Potential function). A function $P : \gamma_1 \times \gamma_2 \times \dots \times \gamma_N \rightarrow \mathbb{R}$ is a **potential function** if for every player i and every γ_{-i}

$$J_i(\gamma'_i, \gamma_{-i}) - J_i(\gamma''_i, \gamma_{-i}) = P(\gamma'_i, \gamma_{-i}) - P(\gamma''_i, \gamma_{-i})$$

for every $\gamma'_i, \gamma''_i \in \Gamma_i$

A game is a **potential game** if it admits a potential function.

Note:

- The potential function P is the same for all players
- The potential function assigns a value to each joint strategy profile
- When player i chooses a best response, the potential decreases.

Proposition 3. Finite games with a potential function have a pure Nash equilibrium. Furthermore, best response dynamics converge.

- Provides a **computation method** and an intuition for **repeated games**
- These iterations converge to a Nash equilibrium that depends on the **initial conditions**
- It does not converge only to admissible Nash equilibria

Proposition 4. In potential games, Nash equilibria correspond to **directionally maxima** (or minima, if players are minimizers) of the potential.

4.2.1 Paths

- A path in Γ is a sequence ...
- closed path
- simple path

4.3 Congestion games

Theorem 3 (Potential function for Congestion games). The following is a potential function for congestion games.

$$P(\gamma) = \sum_{j=1}^M \sum_{k=1}^{\ell_j(\gamma)} f_j(k)$$

Consequently, congestion games admit a pure Nash equilibrium.

4.4 Social welfare

Definition 4 (Welfare function). In a N -person game, let $\gamma_i \in \Gamma_i$ be the strategy played by agent i .

Let $\gamma \in \Gamma := \Gamma_1 \times \Gamma_2 \times \dots \times \Gamma_N$ be the system-wide strategy.

A **welfare cost** $W : \Gamma \rightarrow \mathbb{R}$ is a measure of efficiency of each strategy for the social cost of the population of agents.

Let the **individual cost** be $J_i(\gamma)$ that player i wants to minimize.

4.4.1 Price of Anarchy

5 Convex games

5.1 Games with infinite actions

Examples:

- money (e.g., auctions)

- physical control inputs (force, velocity, ...)
- waiting time (e.g., Start-Stop)
- coverage path of a surveillance camera

5.1.1 Problems with infinite actions

Theory Most of the properties and results that we saw don't hold anymore!

- every time there is an argmin or argmax
- Nash Theorem

Algorithms The few algorithms that we have seen are also not suited for infinite actions

- algorithms *by inspection*
- linear programming

5.1.2 Example: Cournot competition

Problem Setup - Cournot competition

Consider two producers competing in a market.

Each player (producer) $i = 1, 2$ decides on the **quantity** to produce denoted by $x_i \geq 0$, and has a production marginal cost of $c > 0$.

The market price $p : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ is a linearly decreasing function of the total production $x_1 + x_2$

$$p(x_1, x_2) = a - b(x_1 + x_2)$$

1. Write each producer's losses as a function of the quantities produced.
2. Derive the Nash equilibrium.
3. What is the Nash equilibrium if producers' decisions are restricted to $[0, k]$?

5.1.3 Example: Bertrand competition

Problem Setup - Bertrand competition

Consider two producers competing in a market.

Each producer decides on the price $x_i \geq 0$ of their product, and has a production marginal cost of $c > 0$.

The total demand is 1 unit and the consumers choose to buy from the producer with the lowest price (if both firms declare the same price, then half of the demand chooses firm 1 and the other half chooses firm 2).

1. Write each producer's losses as a function of the price they charge.
2. Derive the Nash equilibrium.
3. What is the Nash equilibrium if each producer has the capacity to serve maximum $2/3$ of the unit demand?

5.1.4 Definitions and background

Convexity

- Convex set - Convex function

Differentiable functions

- Convex function - Characterization: Hessian

5.2 Convex games

N-player game with continuous action spaces

- N player game

- Player i 's action $x_i \in K_i \subset \mathbb{R}^n$

- K_i is non-empty, closed and convex

- def: $K = K_1 \times K_2 \times \cdots \times K_N \mathbb{R}^{nN}$

- Player i 's outcome $J_i : K \rightarrow \mathbb{R}$

- Compact notation: $J_i(x_i, x_{-i})$

Definition 5 (Nash Equilibrium - Convex Games). mostly the same as usual

Theorem 4 (Existence of Pure NE - Convex Games). Consider an N -player game with continuous action spaces K_i . Suppose

- action spaces $K_i \subset \mathbb{R}^n$ are **compact and convex**

- J_i are **continuous** in $x \in K$

- J_i are **convex** in x_i for fixed x_{-i} .

Then a pure Nash equilibrium x^* exists.

Games that satisfy those conditions are called **convex games**.

Theorem 5 (Maximum theorem).

Upper hemi-continuity

Cournot and Bertrand models

5.3 Variational inequalities

Definition 6 (Variational inequality).

VI and convex optimization

Definition 7 (First-order optimality conditions).

5.3.1 VI and Nash Equilibria

Characterization of Nash Equilibria of convex games

Definition 8 (Nash Equilibria and Variational Inequality).

Two important advantages coming from the connection between **variational inequalities** and **Nash equilibria**.

- Borrow **theoretical results** from VI (e.g. uniqueness)

- Borrow **numerical methods** to solve VI / find NE.

Monotone maps

Definition 9 (Monotonicity).

How to check monotonicity of a map F ?

5.3.2 Uniqueness of Nash Equilibria

Definition 10 ($\text{SOL}(K, F)$ is a singleton).

Corollary 1.

5.4 Computing the Nash Equilibrium of a convex game

Learning/computing the Nash Equilibrium

Definition 11 (Best-response iteration).

Iterative NE-seeking algorithm

Definition 12 (Iterative update).

5.4.1 Projected game map

Definition 13 (Conjecture).

Interpretation

Analysis

Definition 14 (Assumptions).

5.4.2 Analysis of convergence

Equilibrium

Proposition 5.

Contractive maps

Theorem 6 (Banach Fixed Point).

Contractiveness of the projected-game-map iteration

Projection is non-expansive

Theorem 7 (Projection non-expansive).

Convergence result

Theorem 8 (Convergence of projection).

Example TCP congestion

6 Stackelberg games

6.1 Definition of Stackelberg games

- Γ : pure-strategy space of the **leader** (Player 1)
- Σ : pure-strategy space of the **follower** (Player 2)

Rational reaction set

Stackelberg equilibrium

A pair of strategies $\tilde{y} \in \mathcal{Y}$ and $\tilde{\sigma}(y) : \mathcal{Y} \rightarrow \Sigma$ is a Stackelberg Equilibrium if

- Player 1 plays the best response to $\tilde{\sigma}(y)$:
- Player 2 plays the best response to y :

Applications

6.2 Stackelberg zero-sum games

Stackelberg Equilibrium in zero-sum games

6.2.1 Security strategies

Mixed security strategy

Pure security strategy

6.2.2 Stackelberg vs Nash

In zero-sum games, mixed Stackelberg equilibria and Nash equilibria coincide.

6.3 Stackelberg non-zero-sum games

Highest leader cost

Theorem 9 (Upper bound on Stackelberg cost).

Theorem 10 (Nash vs Highest Leader Cost).

Lowest leader cost

Theorem 11 (Nash vs Lowest Leader Cost).

Generic Stackelberg games

6.3.1 Computation of the Stackelberg equilibrium

Divide-and-conquer algorithm

Linear programming

In non-zero-sum games with mixed strategies, computing Stackelberg Equilibria is much easier than computing Nash Equilibria!

6.4 Security games

Randomized defender strategy in security games

Definition 15 (Coverage vector).

Randomized attacker strategy in security games

6.4.1 Stackelberg solution of a security game

6.4.2 Nash equilibria of security games

Auxiliary zero-sum security game

Interpretation

Stackelberg equilibria are Nash equilibria

- 7 Repeated games**
- 8 Multistage games**
- 9 Linear-quadratic games**
- 10 Stochastic games**