

Computer Science Track Core Course

Linear programming — recitation 2

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Homework 1

Deadline: Thursday 2023-05-25 at 14:45

Please do not send me scans.

- You can typeset it and send it to my e-mail¹.
- You can bring your hand-written solution to the lecture.

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Linear equalities versus inequalities

Remark about Rouché-Capelli theorem

We have $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$.

Rouché–Capelli theorem in [English speaking countries](#), [Italy](#) and [Brazil](#);
Kronecker–Capelli theorem in [Austria](#), [Poland](#), [Romania](#) and [Russia](#);
Rouché–Fontené theorem in [France](#);
Rouché–Frobenius theorem in [Spain](#) and many countries in [Latin America](#);
Frobenius theorem in the [Czech Republic](#) and in [Slovakia](#).

Rouché–Capelli theorem for the system of equalities $A\mathbf{x} = b \dots$

Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} = b$
- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} = \mathbf{0} \wedge b^\top \mathbf{y} \neq 0$

Rouché–Capelli theorem is typically stated as...

Let $A \in F^{m \times n}$ be a matrix and $b \in F^m$ be a vector over a field F .

The system of equalities $A\mathbf{x} = b$ is **inconsistent** (that is, no solution $\mathbf{x} \in F^n$ exists) **if and only if** $\text{rank}(A) < \text{rank}(A|b)$.

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Linear equalities versus inequalities

Rouché-Capelli theorem versus Farkas' lemma (I)

Now we fix $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$.

Rouché-Capelli theorem for the system of equalities $A\mathbf{x} = b \dots$
Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} = b$ (*)
- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} = \mathbf{0} \wedge b^\top \mathbf{y} < 0$ (**)

Farkas' lemma for the system of equalities $A\mathbf{x} = b$ over $\mathbf{x} \geq 0 \dots$
Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} = b \wedge \mathbf{x} \geq \mathbf{0}$ (*)
- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} \geq \mathbf{0} \wedge b^\top \mathbf{y} < 0$ (**)

Intuition behind the dichotomy: (*) The problem has a solution.
(**) There is a linear combination of rows that provides a contradiction.

Linear equalities versus inequalities

Rouché-Capelli theorem versus Farkas' lemma (II)

Now we fix $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$.

Rouché-Capelli theorem for the system of equalities $Ax = b \dots$
Exactly one of the following statements is true:

- $\exists x \in \mathbb{R}^n : Ax = b$ (*)

- $\exists y \in \mathbb{R}^m : A^T y = 0 \wedge b^T y < 0$ (**)

Farkas' lemma for the system of inequalities $Ax \leq b, x \geq 0 \dots$
Exactly one of the following statements is true:

- $\exists x \in \mathbb{R}^n : Ax \leq b$ (*)

- $\exists y \in \mathbb{R}^m : A^T y = 0 \wedge b^T y < 0 \wedge y \geq 0$ (**)

Intuition behind the dichotomy: (*) The problem has a solution.
(**) There is a linear/nnlin. combination of rows that provides a contradiction.

Linear equalities versus inequalities

Rouché-Capelli theorem versus Farkas' lemma (III)

Now we fix $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$.

Rouché-Capelli theorem for the system of equalities $A\mathbf{x} = b \dots$
Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} = b$ (*)

- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} = \mathbf{0} \wedge b^\top \mathbf{y} < 0$ (**)

Farkas' lemma for the system of inequalities $A\mathbf{x} \leq b, \mathbf{x} \geq 0 \dots$
Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} \leq b \wedge \mathbf{x} \geq \mathbf{0}$ (*)

- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} \geq \mathbf{0} \wedge b^\top \mathbf{y} < 0 \wedge \mathbf{y} \geq \mathbf{0}$ (**)

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Linear equalities versus inequalities

Summary of Farkas' lemmata

We have $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$.

Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} = b \wedge \mathbf{x} \geq \mathbf{0}$
- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} \geq \mathbf{0} \wedge b^\top \mathbf{y} < 0$

Exactly one of the following statements is true:

- $\exists \mathbf{x} \in \mathbb{R}^n : A\mathbf{x} \leq b$
- $\exists \mathbf{y} \in \mathbb{R}^m : A^\top \mathbf{y} = \mathbf{0} \wedge b^\top \mathbf{y} < 0 \wedge \mathbf{y} \geq \mathbf{0}$

Exactly one of the following statements is true:

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Farkas' lemmata have many applications.

Their staple use case is the proof of the Strong duality theorem(s).

Strong duality theorem

Let's outline the proof for the bounded case using Farkas' lemma (III)

We have $E \in \mathbb{R}^{m' \times n'}$ and $d \in \mathbb{R}^{m'}$.

Exactly one of the following statements is true:

- $\exists \mathbf{z} \in \mathbb{R}^{n'} : E\mathbf{z} \leq d \wedge \mathbf{z} \geq \mathbf{0}$
- $\exists \mathbf{w} \in \mathbb{R}^{m'} : E^T \mathbf{w} \geq \mathbf{0} \wedge d^T \mathbf{w} < 0 \wedge \mathbf{w} \geq \mathbf{0}$

LP duality (III): Let $A \in \mathbb{R}^{m \times n}$, $b \in \mathbb{R}^m$, $c \in \mathbb{R}^n \dots$

Primal problem:

$$\begin{array}{ll} \text{minimize} & c^T \mathbf{x} \\ \text{s.t.} & A\mathbf{x} \geq b \\ \text{where} & \mathbf{x} \geq \mathbf{0} \end{array}$$

Dual problem:

$$\begin{array}{ll} \text{maximize} & b^T \mathbf{y} \\ \text{s.t.} & A^T \mathbf{y} \leq c \\ \text{where} & \mathbf{y} \geq \mathbf{0} \end{array}$$

Systems of linear equalities versus inequalities

Complexity over rationals versus integers

Domain	Equalities	Inequalities
\mathbb{Q}^n		
\mathbb{Z}^n		

Systems of linear equalities versus inequalities

Complexity over rationals versus integers

Green color denotes that the problem is in **P** (i.e., can be solved in deterministic polynomial time).

Domain	Equalities	Inequalities
\mathbb{Q}^n	Gaussian elimination	
\mathbb{Z}^n		

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Exercise: Construct a polynomial reduction from 3-SAT to ILP.