

# Optimization problems, Analytic solutions

## Computational Intelligence, Lecture 4

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- Optimization problem
- Feasibility problem
- Norms and quadratic forms
- Problems with analytical solutions
- Weighted pseudoinverse

# OPTIMIZATION PROBLEM

An optimization problem has the following form:

$$\begin{array}{ll} \underset{\text{decision variables}}{\text{minimize}} & \text{cost function,} \\ \text{subject to} & \text{constraints.} \end{array} \quad (1)$$

Where the solution to the optimization problem is the optimal value of the decision variables.

For example:

$$\begin{array}{ll} \underset{\mathbf{x}}{\text{minimize}} & f(\mathbf{x}), \\ \text{subject to} & \begin{cases} g(\mathbf{x}) = 0, \\ h(\mathbf{x}) \leq 0. \end{cases} \end{array} \quad (2)$$

In this example,  $\mathbf{x} \in \mathbb{R}^n$  is the decision variable,  $f(\mathbf{x}) : \mathbb{R}^n \rightarrow \mathbb{R}$  is a cost function,  $g(\mathbf{x}) = 0$  are equality constraints, and  $h(\mathbf{x}) \leq 0$  are inequality constraints.

A cost function is always scalar. A special case of a cost function is a constant:

$$\begin{array}{ll} \underset{\mathbf{x}}{\text{minimize}} & 0, \\ \text{subject to} & \begin{cases} g(\mathbf{x}) = 0, \\ h(\mathbf{x}) \leq 0. \end{cases} \end{array} \quad (3)$$

In this case any  $\mathbf{x}$  that satisfies constraints would be a solution to the problem. It is called a *feasibility problem*. We solved this type of problems to find out if there exist any  $\mathbf{x}$  that satisfies constraints.

Often an optimization problem would not feature constraints:

$$\underset{\mathbf{x}}{\text{minimize}} \quad f(\mathbf{x}) \quad (4)$$

We can call it *unconstrained optimization*.

Note that the decision variable  $\mathbf{x}$  can belong to a set  $\mathbf{x} \in \mathcal{X}$  or the cost function may have a domain  $f : \mathcal{D} \rightarrow \mathbb{R}$ ; in these cases, the set of allowed values of  $\mathbf{x}$ , as well as the domain of the function represent *implicit* constraints.

For example, the problem:

$$\underset{x}{\text{minimize}} \quad \ln x$$

has an implicit constraint  $x \geq 0$ .

# EQUALLY CONSTRAINED, LAGRANGIAN

Consider optimization problems with equality constraints:

$$\begin{array}{ll}\underset{\mathbf{x}}{\text{minimize}} & f(\mathbf{x}), \\ \text{subject to} & g(\mathbf{x}) = 0\end{array}\tag{5}$$

We solve it by constructing its *Lagrangian*:

$$L(\mathbf{x}, \lambda) = f(\mathbf{x}) + \lambda^\top g(\mathbf{x})\tag{6}$$

Extremum of the Lagrangian corresponds to the solution of the original problem:

$$\frac{\partial L(\mathbf{x}, \lambda)}{\partial \mathbf{x}} = 0\tag{7}$$

$$\frac{\partial L(\mathbf{x}, \lambda)}{\partial \lambda} = 0\tag{8}$$

Some types of optimization problems admit an analytic solution. For example:

Problem 1. minimize  $\|\mathbf{x}\|$ .

Problem 2. minimize  $\|\mathbf{Ax}\|$ .

Problem 3. minimize  $\|\mathbf{Ax} + \mathbf{b}\|$ .

We know solution of minimize  $\|\mathbf{Ax} - \mathbf{b}\|$ , which is  $\mathbf{x} = \mathbf{A}^+\mathbf{b}$ .  
Therefore the problem 3 has a solution  $\mathbf{x} = -\mathbf{A}^+\mathbf{b}$ .

Problem 4. (form 1)

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && ||\mathbf{x}||, \\ & \text{subject to} && \mathbf{Ax} = \mathbf{b}. \end{aligned} \tag{9}$$

All solutions to  $\mathbf{Ax} = \mathbf{b}$  are written as  $\mathbf{x} = \mathbf{A}^+\mathbf{b} + \mathbf{Nz}$ , where  $\mathbf{N} = \text{null}(\mathbf{A})$ , and  $\mathbf{A}^+\mathbf{b} \in \text{row}(\mathbf{A})$  as we proved previously.

Since the null space solution  $\mathbf{Nz}$  and the row space particular solution  $\mathbf{A}^+\mathbf{b}$  are orthogonal, the minimum norm solution corresponds to  $\mathbf{z} = \mathbf{0}$ , hence:

$$\mathbf{x} = \mathbf{A}^+\mathbf{b} \tag{10}$$



Thus, the solution is  $\mathbf{x} = \mathbf{A}^+\mathbf{b}$ . Notice that the solutions for the problems 3 and 4 are written identically (sans the sign), even though the problem 3 asks to minimize the residual of the linear system, while problem 4 - to find the minimum-norm solution.

This illustrates an important fact: the solution to the least squares problem, formulated either as “minimization of a residual” or as a “minimum norm solution” are given by the same formula, which we call Moore-Penrose pseudoinverse.

Problem 4. (form 2)

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && \frac{1}{2} \mathbf{x}^\top \mathbf{x}, \\ & \text{subject to} && \mathbf{Ax} = \mathbf{b}. \end{aligned} \tag{11}$$

Let us find Lagrangian  $L = \frac{1}{2} \mathbf{x}^\top \mathbf{x} + \lambda^\top (\mathbf{Ax} - \mathbf{b})$ . It achieves extremum at solution of the original problem:

$$\frac{\partial L}{\partial \mathbf{x}} = \mathbf{x} + \mathbf{A}^\top \lambda = 0 \tag{12}$$

$$\frac{\partial L}{\partial \lambda} = \mathbf{Ax} - \mathbf{b} = 0 \tag{13}$$

We can express  $\mathbf{x} = -\mathbf{A}^\top \lambda$  and substitute it  $\mathbf{AA}^\top \lambda = -\mathbf{b}$ . If  $\det(\mathbf{AA}^\top) \neq 0$ , then:

$$\lambda = -(\mathbf{AA}^\top)^{-1} \mathbf{b} \tag{14}$$

$$\mathbf{x} = \mathbf{A}^\top (\mathbf{AA}^\top)^{-1} \mathbf{b} \tag{15}$$

# LEAST SQUARES WITH CONSTRAINTS

We can prove that  $\mathbf{A}^\top (\mathbf{A}\mathbf{A}^\top)^{-1} = \mathbf{A}^+$ .

We can re-write the expression  $\mathbf{A}\mathbf{A}^\top \lambda = -\mathbf{b}$  using SVD decomposition  $\mathbf{A} = \mathbf{C}\Sigma\mathbf{R}^\top$ :

$$\mathbf{C}\Sigma\mathbf{R}^\top\mathbf{R}\Sigma\mathbf{C}^\top\lambda = -\mathbf{b} \quad (16)$$

$$\mathbf{C}\Sigma\Sigma\mathbf{C}^\top\lambda = -\mathbf{b} \quad (17)$$

$$\mathbf{C}^\top\lambda = -\Sigma^{-2}\mathbf{C}^\top\mathbf{b} \quad (18)$$

Next, we do the same with  $\mathbf{x} = -\mathbf{A}^\top\lambda$ :

$$\mathbf{x} = -\mathbf{R}\Sigma\mathbf{C}^\top\lambda \quad (19)$$

$$\mathbf{x} = \mathbf{R}\Sigma\Sigma^{-2}\mathbf{C}^\top\mathbf{b} \quad (20)$$

$$\mathbf{x} = \mathbf{R}\Sigma^{-1}\mathbf{C}^\top\mathbf{b} \quad (21)$$

But  $\mathbf{R}\Sigma^{-1}\mathbf{C}^\top = \mathbf{A}^+$ , so  $\mathbf{x} = \mathbf{A}^+\mathbf{b}$ . More in Appendix.

Problem 5.

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} \quad \|\mathbf{D}\mathbf{x}\|, \\ & \text{subject to} \quad \mathbf{A}\mathbf{x} = \mathbf{b}. \end{aligned} \tag{22}$$

One way to think about it is to first find all solution to the constraint equation  $\mathbf{A}\mathbf{x} = \mathbf{b}$  and then find optimal one among them. As we know, all solutions are given as:  $\mathbf{x} = \mathbf{A}^+\mathbf{b} + \mathbf{N}\mathbf{z}$ , where  $\mathbf{N} = \text{null}(\mathbf{A})$ . Then our cost function becomes:  $\|\mathbf{D}\mathbf{A}^+\mathbf{b} + \mathbf{D}\mathbf{N}\mathbf{z}\|$ , which is equivalent to the problem 3. Thus, we can write solution as:  $\mathbf{z}^* = -(\mathbf{D}\mathbf{N})^+\mathbf{D}\mathbf{A}^+\mathbf{b}$ . In terms of  $\mathbf{x}$  solution is:

$$\mathbf{x}^* = \mathbf{A}^+\mathbf{b} - \mathbf{N}(\mathbf{D}\mathbf{N})^+\mathbf{D}\mathbf{A}^+\mathbf{b} \tag{23}$$

$$\mathbf{x}^* = (\mathbf{I} - \mathbf{N}(\mathbf{D}\mathbf{N})^+\mathbf{D})\mathbf{A}^+\mathbf{b} \tag{24}$$

Problem 6.

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && \|\mathbf{D}\mathbf{x} + \mathbf{f}\|, \\ & \text{subject to} && \mathbf{A}\mathbf{x} = \mathbf{b}. \end{aligned} \tag{25}$$

After the same initial step, we arrive at the cost function  $\|\mathbf{D}\mathbf{N}\mathbf{z} + \mathbf{D}\mathbf{A}^+\mathbf{b} + \mathbf{f}\|$ . It is only different in the constant term, and the solution is found as follows:

$$\mathbf{z}^* = -(\mathbf{D}\mathbf{N})^+(\mathbf{D}\mathbf{A}^+\mathbf{b} + \mathbf{f}) \tag{26}$$

$$\mathbf{x}^* = \mathbf{A}^+\mathbf{b} - \mathbf{N}(\mathbf{D}\mathbf{N})^+(\mathbf{D}\mathbf{A}^+\mathbf{b} + \mathbf{f}) \tag{27}$$

A symmetric positive-definite matrix  $\mathbf{M}$  has the following properties:

$$\mathbf{M} = \mathbf{M}^\top \quad (28)$$

$$\mathbf{x}^\top \mathbf{M} \mathbf{x} > 0, \quad \forall \mathbf{x} \neq 0 \quad (29)$$

$$\det(\mathbf{M}) \neq 0 \quad (30)$$

Positive-definite matrices (with non-repeating eigenvalues) have orthogonal eigenvectors, making their eigenbasis orthonormal:

$$\mathbf{M} \mathbf{V} = \mathbf{V} \Lambda \quad (31)$$

$$\mathbf{M} = \mathbf{V} \Lambda \mathbf{V}^\top \quad (32)$$

# MATRIX SQUARE ROOT

For a symmetric positive-definite matrix  $\mathbf{M}$  we can define a square root:

$$\mathbf{M} = \sqrt{\mathbf{M}}\sqrt{\mathbf{M}} \quad (33)$$

$$\mathbf{M} = \mathbf{M}^{\frac{1}{2}}\mathbf{M}^{\frac{1}{2}} \quad (34)$$

We can find a square root via eigendecomposition:

$$\mathbf{M} = \mathbf{V}\mathbf{\Lambda}\mathbf{V}^{\top} \quad (35)$$

$$\mathbf{\Lambda} = \mathbf{F}\mathbf{F} \quad (36)$$

$$\mathbf{M} = \mathbf{V}\mathbf{F}\mathbf{F}\mathbf{V}^{\top} \quad (37)$$

$$\mathbf{M} = \mathbf{V}\mathbf{F}\mathbf{V}^{\top}\mathbf{V}\mathbf{F}\mathbf{V}^{\top} \quad (38)$$

$$\sqrt{\mathbf{M}} = \mathbf{V}\mathbf{F}\mathbf{V}^{\top} \quad (39)$$

$$\mathbf{M} = \sqrt{\mathbf{M}}\sqrt{\mathbf{M}} \quad (40)$$

Problem 7.

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && \mathbf{x}^\top \mathbf{H} \mathbf{x} + \mathbf{c}^\top \mathbf{x}, \\ & \text{subject to} && \mathbf{A} \mathbf{x} = \mathbf{b}. \end{aligned} \tag{41}$$

where  $\mathbf{H}$  is positive-definite.

Assume that we found a decomposition  $\mathbf{H} = \mathbf{D}^\top \mathbf{D}$ . We can also find such  $\mathbf{f}$  that  $2\mathbf{f}^\top \mathbf{D} = \mathbf{c}^\top$ . Then our cost function becomes  $\mathbf{x}^\top \mathbf{D}^\top \mathbf{D} \mathbf{x} + 2\mathbf{f}^\top \mathbf{D} \mathbf{x}$ , which as we saw before has coinciding minimum with the cost function  $\|\mathbf{D} \mathbf{x} + \mathbf{f}\|$ .

Therefore the problem has the same solution as Problem 5, after the mentioned above change in constants.



Consider a weighted pseudoinverse problem:

$$\text{minimize } \|\mathbf{Ax} - \mathbf{b}\|_{\mathbf{W}} \quad (42)$$

where  $\|\mathbf{x}\|_{\mathbf{W}} = \sqrt{\mathbf{x}^{\top} \mathbf{W} \mathbf{x}}$  and  $\mathbf{W} > 0$ . We can re-write the problem as:

$$\text{minimize } (\mathbf{Ax} - \mathbf{b})^{\top} \mathbf{W}^{\frac{1}{2}} \mathbf{W}^{\frac{1}{2}} (\mathbf{Ax} - \mathbf{b}) \quad (43)$$

But this is the same as solving least-squares problem for equality  $\mathbf{W}^{\frac{1}{2}} \mathbf{Ax} = \mathbf{W}^{\frac{1}{2}} \mathbf{b}$ , which is done via Moore-Penrose pseudoinverse:

$$\mathbf{x} = (\mathbf{W}^{\frac{1}{2}} \mathbf{A})^{+} \mathbf{W}^{\frac{1}{2}} \mathbf{b} \quad (44)$$

Consider a weighted pseudoinverse problem:

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && \mathbf{x}^\top \mathbf{W} \mathbf{x}, \\ & \text{subject to} && \mathbf{A} \mathbf{x} = \mathbf{b} \end{aligned} \tag{45}$$

We can use Lagrange multipliers to rewrite the problem as minimization of the function  $L(\mathbf{x}, \lambda) = \mathbf{x}^\top \mathbf{W} \mathbf{x} + \lambda^\top (\mathbf{A} \mathbf{x} - \mathbf{b})$ ; optimality conditions imply that  $\frac{\partial L}{\partial \mathbf{x}} = 0$  and  $\frac{\partial L}{\partial \lambda} = \mathbf{A} \mathbf{x} - \mathbf{b} = 0$ , so:

$$2\mathbf{x}^\top \mathbf{W} + \lambda^\top \mathbf{A} = 0 \tag{46}$$

This implies  $\mathbf{x} = \frac{1}{2} \mathbf{W}^{-1} \mathbf{A}^\top \lambda$ , and since  $\mathbf{A} \mathbf{x} - \mathbf{b} = 0$ , we get:

$$\frac{1}{2} \mathbf{A} \mathbf{W}^{-1} \mathbf{A}^\top \lambda = \mathbf{b} \tag{47}$$

$$\lambda = 2(\mathbf{A} \mathbf{W}^{-1} \mathbf{A}^\top)^+ \mathbf{b} \tag{48}$$

$$\mathbf{x} = \mathbf{W}^{-1} \mathbf{A}^\top (\mathbf{A} \mathbf{W}^{-1} \mathbf{A}^\top)^+ \mathbf{b} \tag{49}$$

## EXAMPLE, 1

A drone flies along a line defined by a point  $\mathbf{c}$  and a direction  $\mathbf{v}$ . Find a point at which it will pass closest to a ground station located at  $\mathbf{a}$ .

*Solution.* We can describe any point on the line as  $\mathbf{x} = \mathbf{v}\alpha + \mathbf{c}$ . So, the problem can be written as:

$$\begin{aligned} & \underset{\mathbf{x}, \alpha}{\text{minimize}} && \frac{1}{2}(\mathbf{x} - \mathbf{a})^\top (\mathbf{x} - \mathbf{a}), \\ & \text{subject to} && \mathbf{x} = \mathbf{v}\alpha + \mathbf{c} \end{aligned} \tag{50}$$

Lagrangian of the problem is:

$$L = \frac{1}{2}(\mathbf{x} - \mathbf{a})^\top (\mathbf{x} - \mathbf{a}) + \lambda^\top (\mathbf{v}\alpha + \mathbf{c} - \mathbf{x}) \tag{51}$$

## EXAMPLE, 2

$$L = \frac{1}{2}(\mathbf{x} - \mathbf{a})^\top (\mathbf{x} - \mathbf{a}) + \lambda^\top (\mathbf{v}\xi + \mathbf{c} - \mathbf{x}) \quad (52)$$

Partial dervatives of the Lagrangian:

$$\frac{\partial L}{\partial \mathbf{x}} = (\mathbf{x} - \mathbf{a}) - \lambda = 0 \quad (53)$$

$$\frac{\partial L}{\partial \alpha} = \lambda^\top \mathbf{v} = 0 \quad (54)$$

$$\frac{\partial L}{\partial \lambda} = \mathbf{v}\xi + \mathbf{c} - \mathbf{x} = 0 \quad (55)$$

This can be expressed as:

$$\begin{bmatrix} \mathbf{I} & 0 & -\mathbf{I} \\ 0 & 0 & \mathbf{v}^\top \\ -\mathbf{I} & \mathbf{v} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \xi \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{a} \\ 0 \\ -\mathbf{c} \end{bmatrix} \quad (56)$$

which can be solved via inverse.

## EXAMPLE, 3

Using equations  $\mathbf{x} - \mathbf{a} = \lambda$  and  $\lambda^\top \mathbf{v} = 0$  and  $\mathbf{v}\xi + \mathbf{c} = \mathbf{x}$  we can write:

$$\mathbf{v}^\top (\mathbf{x} - \mathbf{a}) = 0 \quad (57)$$

$$\mathbf{v}^\top \mathbf{v}\xi + \mathbf{v}^\top \mathbf{c} - \mathbf{v}^\top \mathbf{a} = 0 \quad (58)$$

Since  $\mathbf{v}^\top \mathbf{v} = 1$ , so  $\xi = \mathbf{v}^\top (\mathbf{a} - \mathbf{c})$ . With that:

$$\mathbf{x} = \mathbf{v}\mathbf{v}^\top \mathbf{a} + (\mathbf{I} - \mathbf{v}\mathbf{v}^\top) \mathbf{c} \quad (59)$$

$$\lambda = (\mathbf{I} - \mathbf{v}\mathbf{v}^\top) (\mathbf{c} - \mathbf{a}) \quad (60)$$

## EXAMPLE, 4

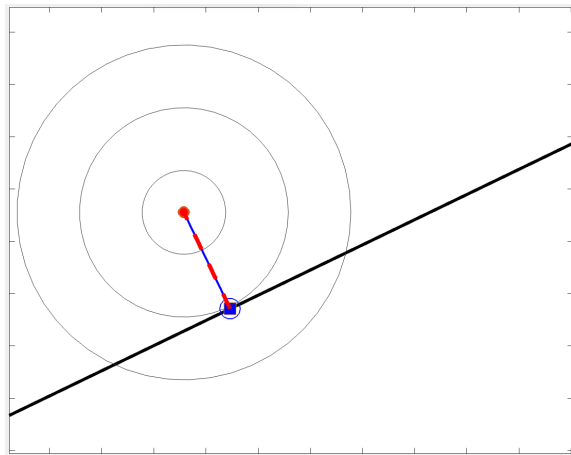


Figure 1: An illustration of the problem

Lecture slides are available via Github, links are on Moodle:

[github.com/SergeiSa/Computational-Intelligence-2025](https://github.com/SergeiSa/Computational-Intelligence-2025)



# LEAST SQUARES WITH CONSTRAINTS

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && \frac{1}{2} \mathbf{x}^\top \mathbf{x}, \\ & \text{subject to} && \mathbf{A} \mathbf{x} = \mathbf{b}. \end{aligned} \tag{61}$$

All solutions to  $\mathbf{A} \mathbf{x} = \mathbf{b}$  are written as  $\mathbf{x} = \mathbf{A}^+ \mathbf{b} + \mathbf{N} \mathbf{z}$ , where  $\mathbf{N} = \text{null}(\mathbf{A})$ , and  $\mathbf{A}^+ \mathbf{b} \in \text{row}(\mathbf{A})$  as we proved previously. The cost function is:

$$f_c = \frac{1}{2} (\mathbf{A}^+ \mathbf{b} + \mathbf{N} \mathbf{z})^\top (\mathbf{A}^+ \mathbf{b} + \mathbf{N} \mathbf{z}) \tag{62}$$

We find extremum:

$$\frac{\partial f_c}{\partial \mathbf{z}} = \mathbf{N}^\top \mathbf{A}^+ \mathbf{b} + \mathbf{N}^\top \mathbf{N} \mathbf{z} = 0 \tag{63}$$

$$\mathbf{z} = -\mathbf{N}^\top \mathbf{A}^+ \mathbf{b} \tag{64}$$

$$\mathbf{x} = \mathbf{A}^+ \mathbf{b} - \mathbf{N} \mathbf{N}^\top \mathbf{A}^+ \mathbf{b} \tag{65}$$

Columns of  $\mathbf{A}^+$  lie in the row space of  $\mathbf{A}$ , so  $\mathbf{N}^\top \mathbf{A}^+ = 0$ :

$$\mathbf{x} = \mathbf{A}^+ \mathbf{b} \tag{66}$$