

Optimization problems, Analytic solutions

Computational Intelligence, Lecture 4

by Sergei Savin

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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)

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

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.

LEAST SQUARES WITH CONSTRAINTS

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:

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

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

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:

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

Lagrangian of the problem is:

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

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

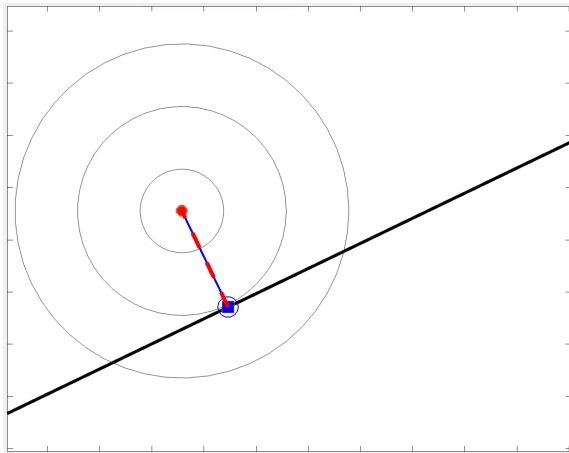
Partial derivatives of the Lagrangian:

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

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

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

EXAMPLE, 3



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

github.com/SergeiSa/Computational-Intelligence-2025



LEAST SQUARES WITH CONSTRAINTS

$$\begin{array}{ll}\underset{\mathbf{x}}{\text{minimize}} & \frac{1}{2}\mathbf{x}^\top\mathbf{x}, \\ \text{subject to} & \mathbf{Ax} = \mathbf{b}.\end{array}\tag{56}$$

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. The cost function is:

$$f_c = \frac{1}{2}(\mathbf{A}^+\mathbf{b} + \mathbf{Nz})^\top(\mathbf{A}^+\mathbf{b} + \mathbf{Nz})\tag{57}$$

We find extremum:

$$\frac{\partial f_c}{\partial \mathbf{z}} = \mathbf{N}^\top \mathbf{A}^+\mathbf{b} + \mathbf{N}^\top \mathbf{Nz} = 0\tag{58}$$

$$\mathbf{z} = -\mathbf{N}^\top \mathbf{A}^+\mathbf{b}\tag{59}$$

$$\mathbf{x} = \mathbf{A}^+\mathbf{b} - \mathbf{NN}^\top \mathbf{A}^+\mathbf{b}\tag{60}$$

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

$$\mathbf{x} = \mathbf{A}^+\mathbf{b}\tag{61}$$