12. Algorithms for constrained optimization

- penalty method
- augmented Lagrangian method
- ADMM
- distributed optimization via ADMM

Penalized formulation

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & h_i(x) = 0, \quad i = 1, \dots, p \end{array}$$

Penalized formulation

$$\text{minimize} \quad f(x) + \rho P(h(x))$$

- $h(x) = (h_1(x), \dots, h_p(x))$
- $P : \mathbb{R}^p \to \mathbb{R}$ is the *penalty function*
- $\rho \in \mathbb{R}$ is the *penalty parameter*
- $\rho P(x)$ penalize constraints violation, *i.e.*, has large values for infeasible points

Penalty function

Penalty function: the penalty function P satisfies the following conditions:

1. P is continuous
2. $P(h(x)) \geq 0$ for all $x \in \mathbb{R}^n$
3. $P(h(x)) = 0$ if and only if x is feasible ($h(x) = 0$)

Example: quadratic penalty function

$$P(h(x)) = \|h(x)\|^2 = \sum_{i=1}^{p} \left(h_i(x)\right)^2$$

Quadratic penalty formulation

$$\text{minimize} \quad f(x) + \rho \|h(x)\|^2$$

- a solution of the above problem might not feasible
- for large ρ we expect to have small values $(h_i(x))^2$
  i.e., an approximate solution to the original problem
- solving the above for an increasing sequence of ρ is called the *penalty method*

Quadratic penalty method

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given a starting point $x^{(0)}$, ρ_0, and a solution tolerance $\epsilon > 0$

repeat for $k = 0, 1, \ldots$

1. set $x^{(k+1)}$ to be the (approximate) solution to

$$x^{(k+1)} \approx \underset{x}{\operatorname{argmin}}\, f(x) + \rho_k \|h(x)\|^2$$

   using an unconstrained optimization method with initial point $x^{(k)}$

2. update $\rho_{k+1} = 2\rho_k$

- terminate if $\|h(x)\|^2$ is small enough
- simple and easy to implement
- but has a major issue:
  - ρ_k rapidly increases with iterations
  - solving penalty problem can be very slow or simply fail

Connection to optimality condition

recall the Lagrange optimality conditions:

$$\nabla f(x^\star) + Dh(x^\star)^T \lambda^\star = 0, \quad h(x^\star) = 0$$

- $x^{(k+1)}$ satisfies optimality condition for the unconstrained peanlized problem:

$$\nabla f(x^{(k+1)}) + 2\rho_k Dh(x^{(k+1)})^T h(x^{(k+1)}) = 0$$

- letting $\lambda^{(k+1)} = 2\rho_k h(x^{(k+1)})$, then

$$\nabla f(x^{(k+1)}) + Dh(x^{(k+1)})^T \lambda^{(k+1)} = 0$$

- so $x^{(k+1)}$ and $\lambda^{(k+1)}$ satisfy first equation in the Lagrange optimality condition
- feasibility $h(x^{(k+1)}) = 0$ is approximately satisfied for ρ_k large
  - feasibility holds in the limit only $\rho_k \to \infty$

Inequality constraints

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) \leq 0, \quad i = 1, \ldots, m \\ & h_j(x) = 0, \quad j = 1, \ldots, p \end{array}$$

can be handled using the penalized formulation

$$\text{minimize} \quad f(x) + \rho \|h(x)\|^2 + \rho \|g^+(x)\|^2$$

- $g^+(x) = (g_1^+(x), \ldots, g_m^+(x))$ and

$$g_i^+(x) = \max\{0, g_i(x)\} = \begin{cases} 0 & \text{if } g_i(x) \leq 0 \\ g_i(x) & \text{if } g_i(x) > 0 \end{cases}$$

- there are other choices of penalty functions
- we just consider the simple quadratic penalization function

Outline

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- **augmented Lagrangian method**
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Constrained problem

$$
\begin{array}{ll}
\text{minimize} & f(x) \\
\text{subject to} & h(x) = 0
\end{array}
$$

- $f : \mathbb{R}^n \to \mathbb{R}$ and $h : \mathbb{R}^p \to \mathbb{R}$
- Lagrangian: $L(x, \lambda) = f(x) + \lambda^T h(x)$ where $\lambda \in \mathbb{R}^p$
- problem is equivalent to penalized formulation

$$
\begin{array}{ll}
\text{minimize} & f(x) + (\rho/2)\|h(x)\|^2 \\
\text{subject to} & h(x) = 0
\end{array}
$$

where ρ is a penalty parameter

Augmented Lagrangian

the **augmented Lagrangian** (AL) is

$$\begin{aligned} L_\rho(x,\lambda) &= L(x,\lambda) + (\rho/2)\|h(x)\|^2 \\ &= f(x) + \lambda^T h(x) + (\rho/2)\|h(x)\|^2 \end{aligned}$$

- augmented Lagrangian is the Lagrangian of the penalized problem
  - this is the Lagrangian $L(x,\lambda)$ augmented with a quadratic penalty
- if $x^\star$ is a solution of original (or penalized) problem and a regular point, then

$$\nabla_x L_\rho(x^\star,\lambda^\star) = 0 \quad \text{for some } \lambda^\star$$

- AL method minimizes $L_\rho(x,\lambda)$ for a sequence of values of λ and ρ

Lagrange multiplier update

- minimizer $\tilde{x}$ of augmented Lagrangian $L_\rho(x, \lambda)$ satisfies

$$\nabla f(\tilde{x}) + Dh(\tilde{x})^T(\rho h(\tilde{x}) + \lambda) = 0$$

- if we define $\tilde{\lambda} = \lambda + \rho h(\tilde{x})$ this can be written as

$$\nabla f(\tilde{x}) + Dh(\tilde{x})^T \tilde{\lambda} = 0$$

- this is the first equation in the optimality conditions

$$\nabla f(x) + Dh(x)^T \lambda = 0, \quad h(x) = 0$$

- shows that if $h(\tilde{x}) = 0$, then $\tilde{x}$ satisfies optimality conditions
- if $h(\tilde{x})$ is not small, suggests $\tilde{\lambda}$ is a good update for λ
- we hope for large enough ρ, minimizer of $L_\rho(x, \lambda)$ is feasible

Augmented Lagrangian algorithm

given $x^{(0)}$, $\lambda^{(0)}$, $\rho^{(0)}$, and a solution tolerance $\epsilon > 0$

repeat for $k = 0, 1, \ldots$

1. set $x^{(k+1)}$ to be an (approximate) solution to

$$x^{(k+1)} \approx \underset{x}{\operatorname{argmin}} f(x) + (\lambda^{(k)})^T h(x) + (\rho_k/2)\|h(x)\|^2$$

   using any unconstrained optimization method with initial point $x^{(k)}$

2. update $\lambda^{(k)}$:

$$\lambda^{(k+1)} = \lambda^{(k)} + \rho_k h(x^{(k+1)})$$

3. set ρ_k as constant or

$$\begin{cases} \rho_k & \text{if} \quad \|h(x^{(k+1)})\| < \|h(x^{(k)})\| \\ 2\rho_k & \text{otherwise} \end{cases}$$

- ρ is increased only when needed, more slowly than in penalty method
- continues until $h(x^{(k)})$ and $\nabla L(x^{(k)}, \lambda^{(k)})$ are sufficiently small

Example

consider applying the augmented Lagrangian method to the problem:

$$\begin{array}{ll} \text{minimize} & e^{3x_1} + e^{-4x_2} \\ \text{subject to} & x_1^2 + x_2^2 = 1 \end{array}$$

with $x^{(0)} = (1, 1)$ and $\lambda^{(0)} = 0$, we set a constant penalty parameter $\rho_k = 100$

the augmented Lagrangian function is

$$L_\rho(x, \lambda) = e^{3x_1} + e^{-4x_2} + \lambda\left(x_1^2 + x_2^2 - 1\right) + (\rho/2)\left(x_1^2 + x_2^2 - 1\right)^2$$

for the inner minimization problems, we employ Newton's method:

$$\hat{x} \leftarrow \hat{x} + \nabla^2 L_\rho(\hat{x}, \lambda^{(k)})^{-1} \nabla L_\rho(\hat{x}, \lambda^{(k)})$$

the gradient and Hessian are:

$$\nabla L_\rho(x,\lambda) = \begin{bmatrix} 3e^{3x_1} + 2\lambda x_1 + 2\rho x_1(x_1^2 + x_2^2 - 1) \\ -4e^{-4x_2} + 2\lambda x_2 + 2\rho x_2(x_1^2 + x_2^2 - 1) \end{bmatrix}$$

and

$$\nabla^2 L_\rho(x,\lambda) = \begin{bmatrix} 9e^{3x_1} + 2\lambda + 2\rho(x_1^2 + x_2^2 - 1) + 4\rho x_1^2 & 4\rho x_1 x_2 \\ 4\rho x_1 x_2 & 16e^{-4x_2} + 2\lambda + 2\rho(x_1^2 + x_2^2 - 1) + 4\rho x_2^2 \end{bmatrix}$$

iteration starts from $\hat{x} = x^{(k)}$ and continues until $\|\nabla L_\rho(\hat{x}, \lambda^{(k)})\| < 10^{-4}$

the value $x^{(k+1)}$ is then set to $\hat{x}$ and the Lagrange multiplier is subsequently updated:

$$\lambda^{(k+1)} = \lambda^{(k)} + \rho\big((x_1^{(k+1)})^2 + (x_2^{(k+1)})^2 - 1\big)$$

MATLAB code implementation

```
%% AL gradient and Hessian
g=@(x,lam,rho)[3*exp(3*x(1))+2*lam*x(1)+2*rho*x(1)*(x(1)^2+x(2)^2-1);
-4*exp(-4*x(2))+2*lam*x(2)+2*rho*x(2)*(x(1)^2+x(2)^2-1)];
hess=@(x,lam,rho)[9*exp(3*x(1))+2*lam+2*rho*(x(1)^2+x(2)^2-1)+4*rho*x(1)^2 4*rho*x(1)*x(2);
4*rho*x(1)*x(2)  16*exp(-4*x(2))+2*lam+2*rho*(x(1)^2+x(2)^2-1)+4*rho*x(2)^2];
h=@(x) x(1)^2+x(2)^2-1;
%% AL method
rho=100;
x=[1;1];
lam=0;
while (norm(g(x,lam,0)) >= 1e-10) || (norm(h(x))>= 1e-6)
xhat=x;
% Newton inner minimization
while (norm(g(xhat,lam,rho)) >= 1e-4)
v = -hess(xhat,lam,rho)\g(xhat,lam,rho);
xhat = xhat+v;
end
x=xhat;
% Lagrange update
lam=lam+rho*h(x);
end
```

running the algorithm, we get $x^\star = (-0.7483, 0.6633)$ and $\lambda^\star = 0.2123$

AL for nonlinear least squares objective

$$\begin{array}{ll} \text{minimize} & \|r(x)\|^2 \\ \text{subject to} & h(x) = 0 \end{array}$$

$r(x) = (r_1(x), \ldots, r_m(x))$, $h(x) = (h_1(x), \ldots, h_p(x))$

Augmented Lagrangian

$$\begin{aligned} L_\rho(x, \lambda) &= \|r(x)\|^2 + h(x)^T\lambda + (\rho/2)\|h(x)\|^2 \\ &= \|r(x)\|^2 + (\rho/2)\left\|h(x) + \tfrac{1}{\rho}\lambda\right\|^2 - \frac{1}{2\rho}\|\lambda\|^2 \\ &= \left\|\begin{bmatrix} r(x) \\ \sqrt{\rho/2}\,h(x) + \lambda/(\sqrt{2\rho}) \end{bmatrix}\right\|^2 - \frac{1}{2\rho}\|\lambda\|^2 \end{aligned}$$

can be minimized over x (for fixed ρ, λ) by Levenberg-Marquardt method:

$$\text{minimize} \quad \left\|\begin{bmatrix} r(x) \\ \sqrt{\rho/2}\,h(x) + \lambda/(\sqrt{2\rho}) \end{bmatrix}\right\|^2$$

AL for constrained nonlinear least squares

given: $\lambda^{(0)} = 0$, $\rho_0 = 1$, and $x^{(0)}$

repeat for $k = 0, 1 \ldots$

1. set $x^{(k+1)}$ to be the (approximate) solution to:

$$x^{(k+1)} \approx \underset{x}{\operatorname{argmin}} \left\| \begin{bmatrix} r(x) \\ \sqrt{\rho_k/2}h(x) + \lambda^{(k)}/(\sqrt{2\rho_k}) \end{bmatrix} \right\|^2$$

   using Levenberg-Marquardt algorithm starting from initial point $x^{(k)}$

2. multiplier update:

$$\lambda^{(k+1)} = \lambda^{(k)} + \rho_k h(x^{(k+1)})$$

3. penalty parameter update:

$$\rho_{k+1} = \begin{cases} \rho_k & \text{if } \|h(x^{(k+1)})\| < \|h(x^{(k)})\| \\ \rho_{k+1} = 2\rho_k & \text{otherwise} \end{cases}$$

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ADMM problem form

the alternating direction method of multiplier (ADMM) solves problem of form:

$$\begin{array}{ll} \text{minimize} & f(x) + g(z) \\ \text{subject to} & Ax + Bz = c \end{array}$$

- variables are $x \in \mathbb{R}^n$ and $z \in \mathbb{R}^m$
- $A \in \mathbb{R}^{p \times n}$, $B \in \mathbb{R}^{p \times m}$, and $c \in \mathbb{R}^p$
- the augmented Lagrangian is

$$L_\rho(x, z, \lambda) = f(x) + g(z) + \lambda^T(Ax + Bz - c) + (\rho/2)\|Ax + Bz - c\|^2$$

ADMM update

$$
\begin{aligned}
x^{(k+1)} &= \underset{x}{\operatorname{argmin}}\ L_\rho(x, z^{(k)}, \lambda^{(k)}) \\
z^{(k+1)} &= \underset{z}{\operatorname{argmin}}\ L_\rho(x^{(k+1)}, z, \lambda^{(k)}) \\
\lambda^{(k+1)} &= \lambda^{(k)} + \rho(Ax^{(k+1)} + Bz^{(k+1)} - c)
\end{aligned}
$$

- $\rho > 0$ is the ADMM penalty parameter
- x and z are updated in an *alternating* or *sequential* fashion
- this is different from AL method where x and z are minimized jointly

$$
(x^{(k+1)}, z^{(k+1)}) = \underset{x,z}{\operatorname{argmin}}\, L_\rho(x, z, \lambda^{(k)})
$$

- separating the minimization over x and z allows to decompose large problems into smaller ones when f or g are separable

ADMM scaled form

define the residual $r = Ax + Bz - c$ and $u = (1/\rho)\lambda$, then

$$\begin{aligned}
\lambda^T r + (\rho/2)\|r\|^2 &= (\rho/2)\|r + (1/\rho)\lambda\|^2 - (1/2\rho)\|\lambda\|^2 \\
&= (\rho/2)\|r + u\|^2 - (\rho/2)\|u\|^2
\end{aligned}$$

ADMM scaled form

$$\begin{aligned}
x^{(k+1)} &= \operatorname*{argmin}_x \left(f(x) + (\rho/2)\|Ax + Bz^{(k)} - c + u^{(k)}\|^2 \right) \\
z^{(k+1)} &= \operatorname*{argmin}_z \left(g(z) + (\rho/2)\|Ax^{(k+1)} + Bz - c + u^{(k)}\|^2 \right) \\
u^{(k+1)} &= u^{(k)} + Ax^{(k+1)} + Bz^{(k+1)} - c
\end{aligned}$$

Example: quadratic programs

$$\begin{array}{ll}\text{minimize} & (1/2)x^TQx + r^Tx \\ \text{subject to} & Cx = d \\ & x \geq 0\end{array}$$

- Q is positive semidefinite (reduces to an LP when $Q = 0$)
- we can express this problem in the ADMM form:

$$\begin{array}{ll}\text{minimize} & f(x) + g(z) \\ \text{subject to} & x - z = 0\end{array}$$

where

$$f(x) = (1/2)x^TQx + r^Tx, \quad \mathrm{dom}\, f = \{x \mid Cx = d\}$$

and g is the indicator function of the nonnegative orthant $\mathbb{R}^n_+$

the scaled form of ADMM consists of the iterations

$$
\begin{aligned}
x^{(k+1)} &= \underset{x}{\operatorname{argmin}} \left(f(x) + (\rho/2)\|x - z^{(k)} + u^{(k)}\|^2 \right) \\
z^{(k+1)} &= (x^{(k+1)} + u^{(k)})_+ \\
u^{(k+1)} &= u^{(k)} + x^{(k+1)} - z^{(k+1)}
\end{aligned}
$$

the x-update is a constrained least squares problem with optimality conditions

$$
\begin{bmatrix} Q + \rho I & C^T \\ C & 0 \end{bmatrix} \begin{bmatrix} x^{(k+1)} \\ \nu \end{bmatrix} + \begin{bmatrix} r - \rho(z^{(k)} - u^{(k)}) \\ -d \end{bmatrix} = 0
$$

Norm-one regularized least squares

the **lasso** problem is the ℓ_1 regularized least squares

$$\text{minimize} \quad (1/2)\|Ax - b\|^2 + \eta\|x\|_1$$

- $\eta > 0$ is a scalar regularization parameter
- in ADMM form, the lasso problem can be written as

$$\begin{array}{ll} \text{minimize} & f(x) + g(z) \\ \text{subject to} & x - z = 0 \end{array}$$

  where $f(x) = (1/2)\|Ax - b\|^2$ and $g(z) = \eta\|z\|_1$

the ADMM iteration is

$$
\begin{aligned}
x^{(k+1)} &= (A^TA + \rho I)^{-1}(A^Tb + \rho(z^{(k)} - u^{(k)})) \\
z^{(k+1)} &= S_{\eta/\rho}(x^{(k+1)} + u^{(k)}) \\
u^{(k+1)} &= u^{(k)} + x^{(k+1)} - z^{(k+1)}
\end{aligned}
$$

where S is the soft thresholding operator defined element-wise as

$$
\begin{aligned}
S_\kappa(a) &= \begin{cases} a - \kappa & a > \kappa \\ 0 & |a| \leq \kappa \\ a + \kappa & a < -\kappa \end{cases} \\
&= (a - \kappa)_+ - (-a - \kappa)_+
\end{aligned}
$$

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Consensus problem

$$\text{minimize} \quad f(x) = \sum_{i=1}^{N} f_i(x)$$

- variable $x \in \mathbb{R}^n$
- $f_i : \mathbb{R}^n \to \mathbb{R}$ represents the ith component of the objective function
- f_i is available only on machine processor i
- goal is to solve this problem with f_i handled by processor i only

Example

many classification or regression problems can be formulated as:

$$\text{minimize} \quad \sum_{j=1}^{m} \ell(x; \xi_j)$$

- $\ell(x; \xi_j)$ represent the loss function for data ξ_j
- for large m, storing the data on a single machine may not be feasible
- the problem can be solved by distributing the data across multiple machines,

$$f_i(x) = \sum_{j \in \mathcal{J}_i} \ell(x; \xi_j)$$

  where $\mathcal{J}_i$ is the set of training data indices at machine i

Equivalent formulation

$$
\begin{array}{ll}
\text{minimize} & \sum_{i=1}^{N} f_i\left(x_i\right) \\
\text{subject to} & x_i - z = 0, \quad i = 1, \ldots, N
\end{array}
$$

- $x_i \in \mathbb{R}^n$ handled by processing unit i
- z is a global variable handled by central processing unit called *central server*
- the constraints ensure that all local variables are equal
- objective is now separable in the variables x_i
- the augmented Lagrangian is

$$
L_\rho(x_1, \ldots, x_N, z, \lambda) = \sum_{i=1}^{N} \left(f_i(x_i) + (\lambda_i)^T (x_i - z) + \frac{\rho}{2} \|x_i - z\|^2 \right)
$$

ADMM updates

$$
\begin{aligned}
x_i^{(k+1)} &= \operatorname*{argmin}_{x_i} \left(f_i(x_i) + \lambda_i^{(k)T}(x_i - z^{(k)}) + \frac{\rho}{2}\|x_i - z^{(k)}\|^2 \right) \\
z^{(k+1)} &= \frac{1}{N}\sum_{i=1}^{N}(x_i^{(k+1)} + \frac{1}{\rho}\lambda_i^{(k)}) \\
\lambda_i^{(k+1)} &= \lambda_i^{(k)} + \rho(x_i^{(k+1)} - z^{(k+1)})
\end{aligned}
$$

- the first and last steps are updated independently by each machine i
- central server updates z after it receives all x_i and then send it back to machines

Equivalent simpler update

- using overline to denote the average of a vector, we can express the z-update as:

$$z^{(k+1)} = \bar{x}^{(k+1)} + \frac{1}{\rho}\bar{\lambda}^{(k)}$$

- by taking the average of the λ-update, we get:

$$\bar{\lambda}^{(k+1)} = \bar{\lambda}^{(k)} + \rho(\bar{x}^{(k+1)} - z^{(k+1)})$$

- substituting 1st equation into the subsequent one, we obtain $\bar{\lambda}^{(k+1)} = 0$ for all k
- hence $z^{(k)} = \bar{x}^{(k)}$ and ADMM can be rewritten as:

$$\begin{aligned} x_i^{(k+1)} &= \underset{x_i}{\operatorname{argmin}} \left(f_i(x_i) + \lambda_i^{(k)T}(x_i - \bar{x}^{(k)}) + \frac{\rho}{2}\|x_i - \bar{x}^{(k)}\|^2 \right) \\ \lambda_i^{(k+1)} &= \lambda_i^{(k)} + \rho(x_i^{(k+1)} - \bar{x}^{(k+1)}) \end{aligned}$$

Regularized consensus problem

$$\begin{array}{ll} \text{minimize} & \sum_{i=1}^{N} f_i(x_i) + g(z) \\ \text{subject to} & x_i - z = 0, \quad i = 1, \dots, N \end{array}$$

- objective term g is a constraint or regularization (*e.g.*, $g(z) = \|z\|_1$)
- for this case, the ADMM method is:

$$\begin{aligned} x_i^{(k+1)} &= \operatorname*{argmin}_{x_i} \left(f_i(x_i) + \lambda_i^{(k)\,T}(x_i - z^{(k)}) + \frac{\rho}{2}\|x_i - z^{(k)}\|^2 \right) \\ z^{(k+1)} &= \operatorname*{argmin}_{z} \left(g(z) + \sum_{i=1}^{N}(-\lambda_i^{(k)\,T} z + \frac{\rho}{2}\|x_i^{(k+1)} - z\|^2) \right) \\ \lambda_i^{(k+1)} &= \lambda_i^{(k)} + \rho(x_i^{(k+1)} - z^{(k+1)}) \end{aligned}$$

- collecting linear and quadratic terms, the z-update can be expressed as:

$$z^{(k+1)} = \underset{z}{\operatorname{argmin}} \left(g(z) + \frac{N\rho}{2} \| z - \bar{x}^{(k+1)} - \frac{1}{\rho} \bar{\lambda}^{(k)} \|^2 \right)$$

- when g is nonzero, we don't typically get that $\bar{\lambda}^{(k)} = 0$

- hence λ_i terms cannot be eliminated as in the non-regularized case

- using the above update form for z, ADMM is:

$$\begin{aligned}
x_i^{(k+1)} &= \underset{x_i}{\operatorname{argmin}} \left(f_i(x_i) + \lambda_i^{(k)\,T}(x_i - z^{(k)}) + \frac{\rho}{2} \| x_i - z^{(k)} \|^2 \right) \\
z^{(k+1)} &= \underset{z}{\operatorname{argmin}} \left(g(z) + \frac{N\rho}{2} \| z - \bar{x}^{(k+1)} - \frac{1}{\rho} \bar{\lambda}^{(k)} \|^2 \right) \\
\lambda_i^{(k+1)} &= \lambda_i^{(k)} + \rho(x_i^{(k+1)} - z^{(k+1)})
\end{aligned}$$

Examples

- for $g(z) = \eta\|z\|_1$, the z-update translates into a soft threshold operation:

$$z^{(k+1)} = S_{\eta/N\rho}(\bar{x}^{(k+1)} - \frac{1}{\rho}\bar{\lambda}^{(k)})$$

- considering g as the indicator function of $\mathbb{R}^n_+$, then

$$z^{(k+1)} = (\bar{x}^{(k+1)} - \frac{1}{\rho}\bar{\lambda}^{(k)})_+$$

References and further readings

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