



Optimization

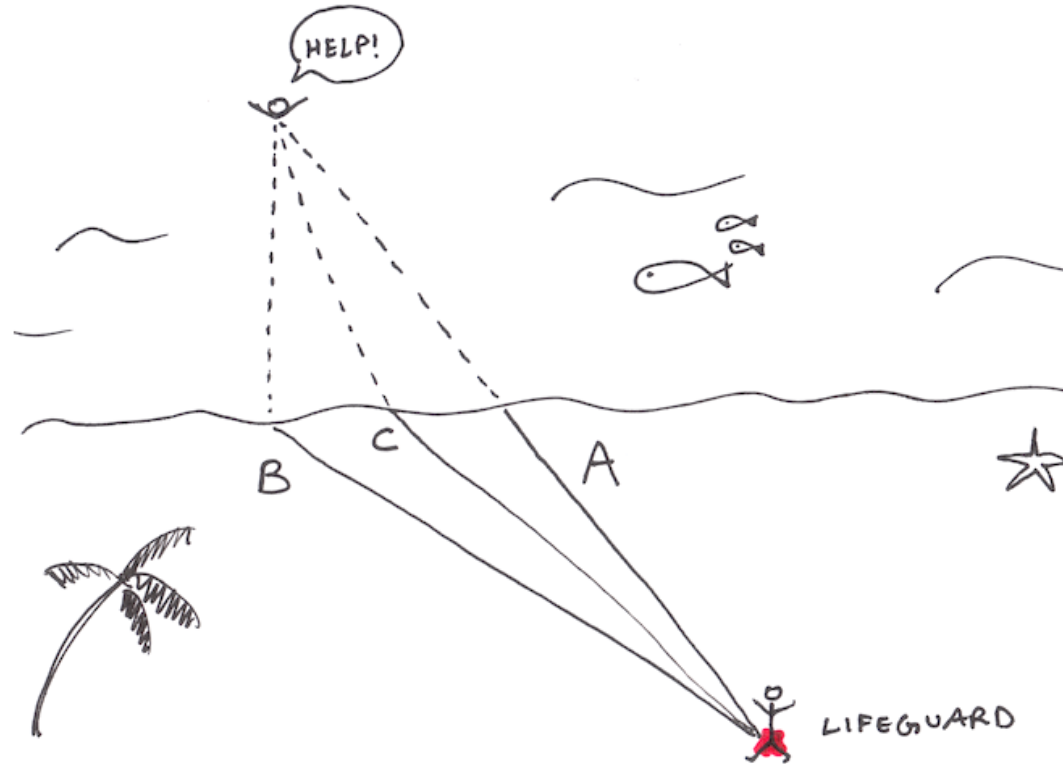
Industrial AI Lab.

Optimization

- An important tool in
 - 1) Engineering problem solving and
 - 2) Decision science
- People optimize
- Nature optimizes

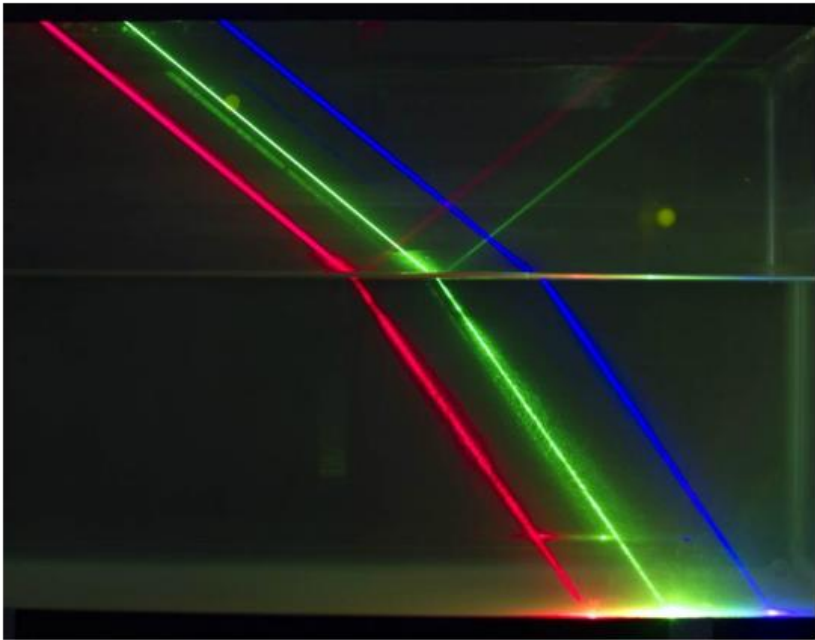
Optimization

- People optimize



Optimization

- Nature optimizes



Optimization

- 3 key components
 - 1) Objective function
 - 2) Decision variable or unknown
 - 3) Constraints
- Procedures
 - 1) The process of identifying objective, variables, and constraints for a given problem (known as "modeling")
 - 2) Once the model has been formulated, optimization algorithm can be used to find its solutions

Optimization: Mathematical Model

- In mathematical expression

$$\begin{array}{ll} \min_x & f(x) \\ \text{subject to} & g_i(x) \leq 0, \quad i = 1, \dots, m \end{array}$$

– $x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$ is the decision variable

– $f: \mathbb{R}^n \rightarrow \mathbb{R}$ is objective function

– Feasible region: $C = \{x: g_i(x) \leq 0, \quad i = 1, \dots, m\}$

– $x^* \in \mathbb{R}^n$ is an optimal solution if $x^* \in C$ and $f(x^*) \leq f(x), \forall x \in C$

Optimization: Mathematical Model

- In mathematical expression

$$\begin{array}{ll} \min_x & f(x) \\ \text{subject to} & g_i(x) \leq 0, \quad i = 1, \dots, m \end{array}$$

- Remarks: equivalent

$$\begin{array}{lll} \min_x f(x) & \leftrightarrow & \max_x -f(x) \\ g_i(x) \leq 0 & \leftrightarrow & -g_i(x) \geq 0 \\ h(x) = 0 & \leftrightarrow & \begin{cases} h(x) \leq 0 \\ h(x) \geq 0 \end{cases} \text{ and} \end{array}$$

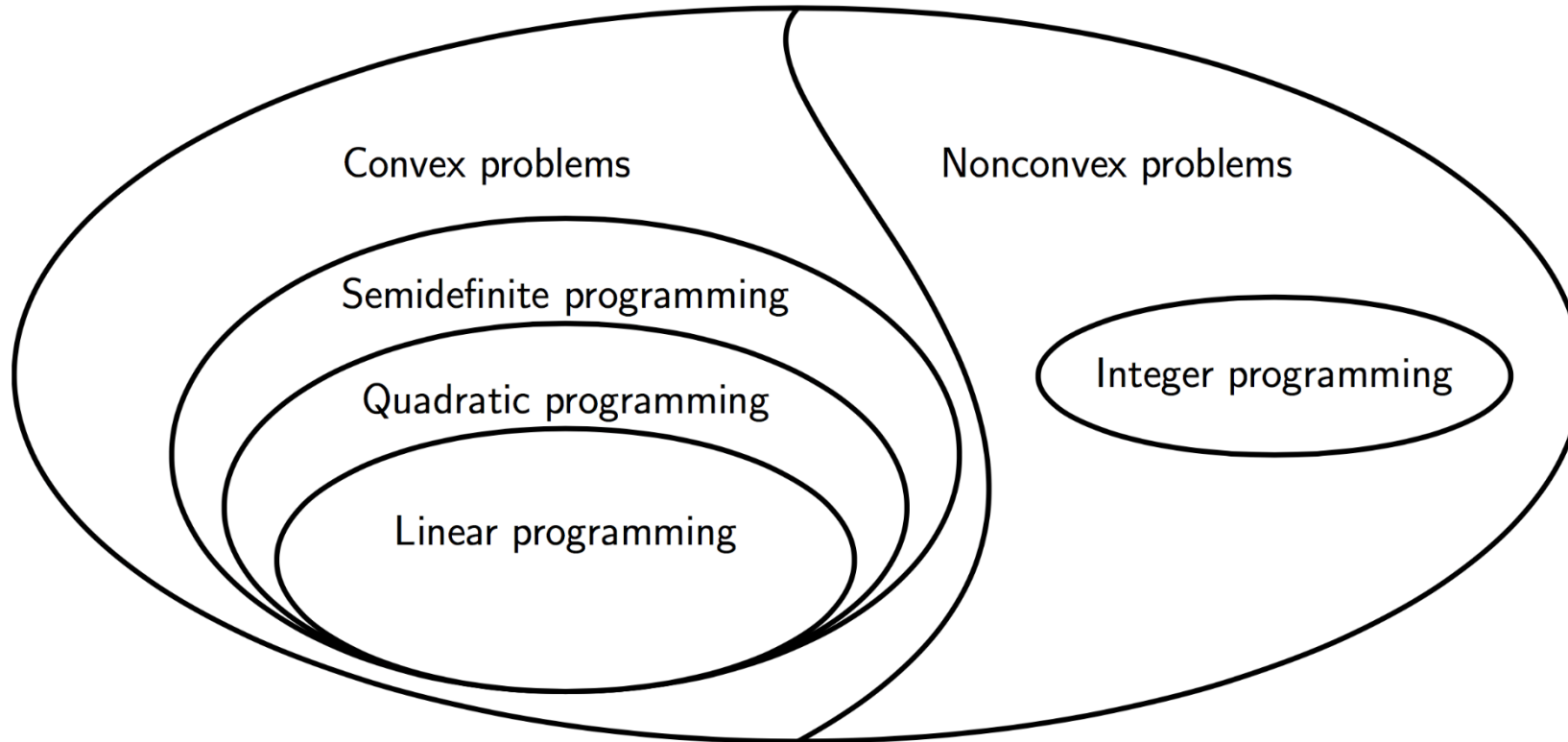
Unconstrained vs. Constrained

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

vs.

$$\begin{aligned} &\underset{x}{\text{minimize}} \quad f(x) \\ &\text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \dots, m \\ &\quad \quad \quad h_i(x) = 0, \quad i = 1, \dots, p \end{aligned}$$

Convex vs. Nonconvex



Convex Optimization

Convex Optimization

- An extremely powerful subset of all optimization problems

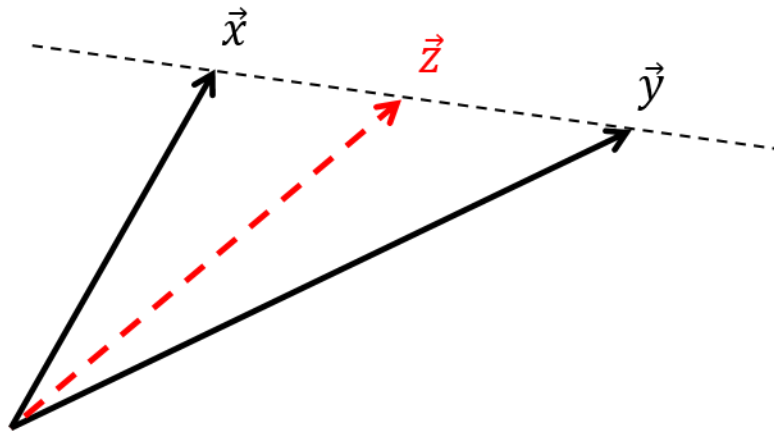
$$\begin{array}{ll}\underset{x}{\text{minimize}} & f(x) \\ \text{subject to} & x \in \mathcal{C}\end{array}$$

- $f: \mathbb{R}^n \rightarrow \mathbb{R}$ is a convex function and
- Feasible region \mathcal{C} is a convex set

- Key property of convex optimization:
 - all local solutions are global solutions
- We will use CVX (or CVXPY) as a convex optimization solver
 - <https://www.cvxpy.org/>
 - Many examples later

Linear Interpolation between Two Points

- $\vec{z} = \theta \vec{x} + (1 - \theta) \vec{y}$ and $\theta \in [0, 1]$

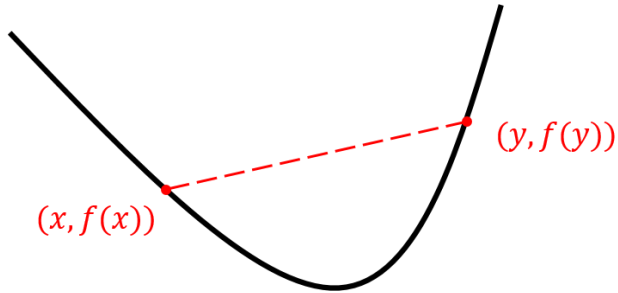


$$\begin{aligned}\vec{z} &= \vec{y} + \theta (\vec{x} - \vec{y}), & 0 \leq \theta \leq 1 \\ &= \theta \vec{x} + (1 - \theta) \vec{y}\end{aligned}$$

$$\vec{z} = \alpha \vec{x} + \beta \vec{y}, \quad \alpha + \beta = 1 \quad \text{and} \quad 0 \leq \alpha, \beta$$

Convex Function and Convex Set

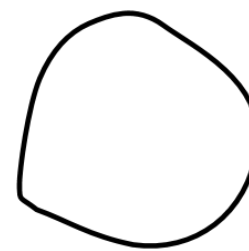
convex function



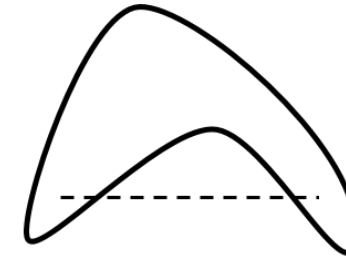
for any $x, y \in \mathbb{R}^n$ and $\theta \in [0, 1]$

$$f(\theta x + (1 - \theta)y) \leq \theta f(x) + (1 - \theta)f(y)$$

convex set



Convex set



Non-convex set

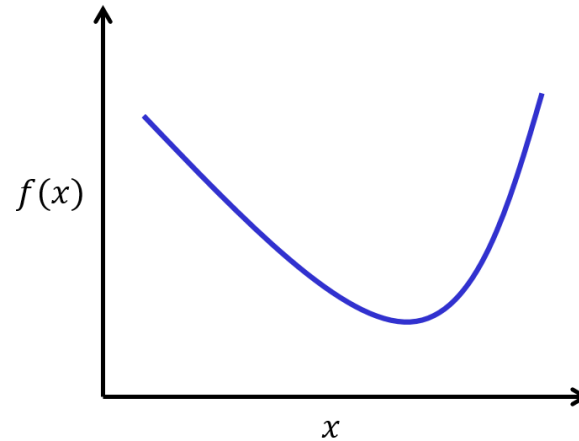
for a $x, y \in \mathcal{C}$ and $\theta \in [0, 1]$,

$$\theta x + (1 - \theta)y \in \mathcal{C}$$

Solving Optimization Problems

Solving Optimization Problems

- Starting with the unconstrained, one dimensional case



- To find minimum point x^* , we can look at the derivative of the function $f'(x)$
 - Any location where $f'(x) = 0$ will be a “flat” point in the function
- For convex problems, this is guaranteed to be a minimum

Solving Optimization Problems

- Generalization for multivariate function $f: \mathbb{R}^n \rightarrow \mathbb{R}$
 - the gradient of f must be zero

$$\nabla_x f(x) = 0$$

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

- For defined as above, *gradient* is a n -dimensional vector containing partial derivatives with respect to each dimension

$$\nabla_x f(x) = \begin{bmatrix} \frac{\partial f(x)}{\partial x_1} \\ \vdots \\ \frac{\partial f(x)}{\partial x_n} \end{bmatrix}$$

- For continuously differentiable f and unconstrained optimization, optimal point must have

$$\nabla_x f(x^*) = 0$$

How do we Find $\nabla_x f(x) = 0$

- Direct solution
 - In some cases, it is possible to analytically compute x^* such that $\nabla_x f(x^*) = 0$

$$f(x) = 2x_1^2 + x_2^2 + x_1 x_2 - 6x_1 - 5x_2$$

$$\implies \nabla_x f(x) = \begin{bmatrix} 4x_1 + x_2 - 6 \\ 2x_2 + x_1 - 5 \end{bmatrix}$$

$$\implies x^* = \begin{bmatrix} 4 & 1 \\ 1 & 2 \end{bmatrix}^{-1} \begin{bmatrix} 6 \\ 5 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$$

Gradients

- Matrix derivatives

y	$\frac{\partial y}{\partial x}$
Ax	A^T
$x^T A$	A
$x^T x$	$2x$
$x^T Ax$	$Ax + A^T x$

How to Find $\nabla_x f(x) = 0$

- Direct solution
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$$\Rightarrow x^* = \begin{bmatrix} 4 & 1 \\ 1 & 2 \end{bmatrix}^{-1} \begin{bmatrix} 6 \\ 5 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$$

Examples

- affine function $g(x) = a^T x + b$

$$\nabla g(x) = a, \quad \nabla^2 g(x) = 0$$

y	$\frac{\partial y}{\partial x}$
Ax	A^T
$x^T A$	A
$x^T x$	$2x$
$x^T Ax$	$Ax + A^T x$

- quadratic function $g(x) = x^T P x + q^T x + r$, $P = P^T$

$$\nabla g(x) = 2Px + q, \quad \nabla^2 g(x) = 2P$$

- $g(x) = \|Ax - b\|^2 = x^T A^T A x - 2b^T A x + b^T b$

$$\nabla g(x) = 2A^T A x - 2A^T b, \quad \nabla^2 g(x) = 2A^T A$$

Revisit: Least-Square Solution

- Scalar Objective: $J = \|Ax - y\|^2$

$$\begin{aligned} J(x) &= (Ax - y)^T (Ax - y) \\ &= (x^T A^T - y^T) (Ax - y) \\ &= x^T A^T Ax - x^T A^T y - y^T Ax + y^T y \end{aligned}$$

$$\begin{aligned} \frac{\partial J}{\partial x} &= A^T Ax + (A^T A)^T x - A^T y - (y^T A)^T \\ &= 2A^T Ax - 2A^T y = 0 \end{aligned}$$

$$\implies (A^T A) x = A^T y$$

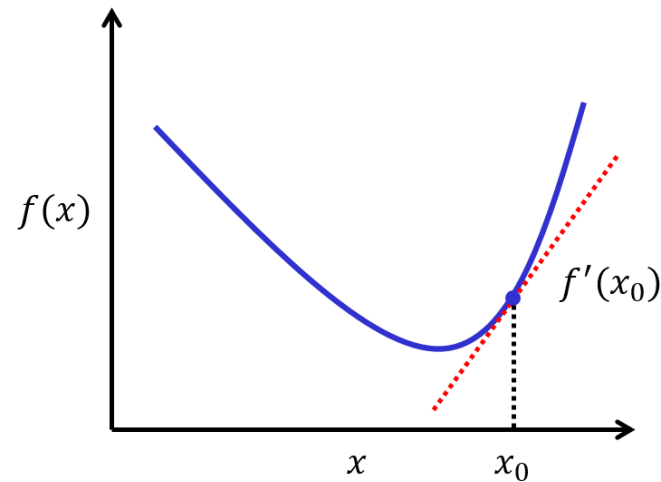
$$\therefore x^* = (A^T A)^{-1} A^T y$$

y	$\frac{\partial y}{\partial x}$
Ax	A^T
$x^T A$	A
$x^T x$	$2x$
$x^T Ax$	$Ax + A^T x$

How do we Find $\nabla_x f(x) = 0$

- Iterative methods

- More commonly the condition that the gradient equal zero will not have an analytical solution, require iterative methods

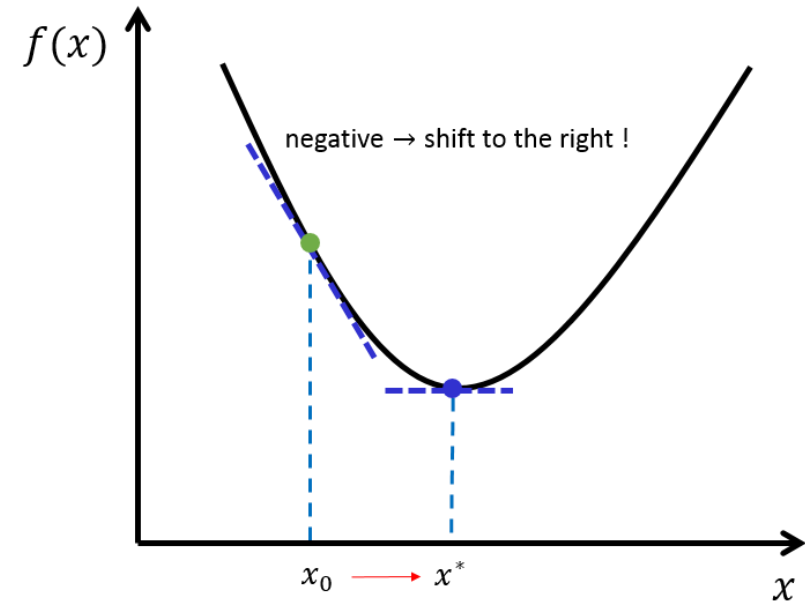
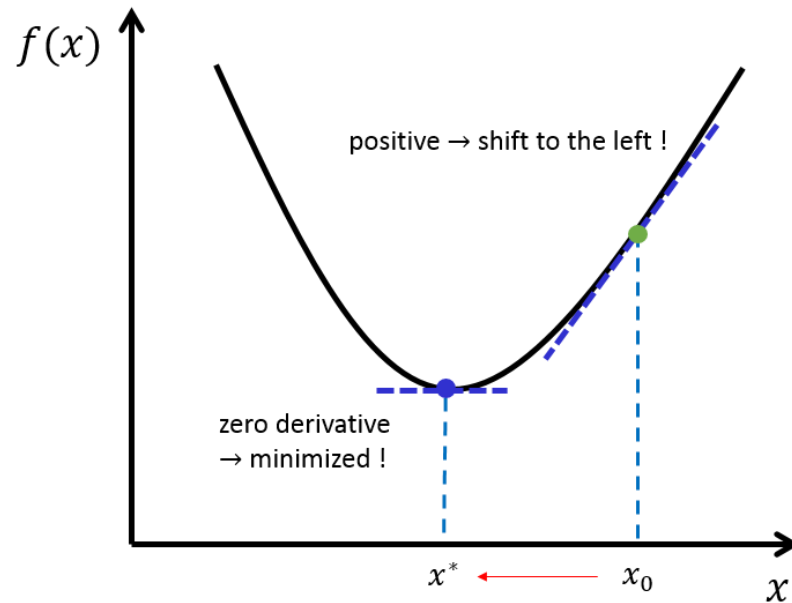


- The gradient points in the direction of “steepest ascent” for function f

Descent Direction (1D)

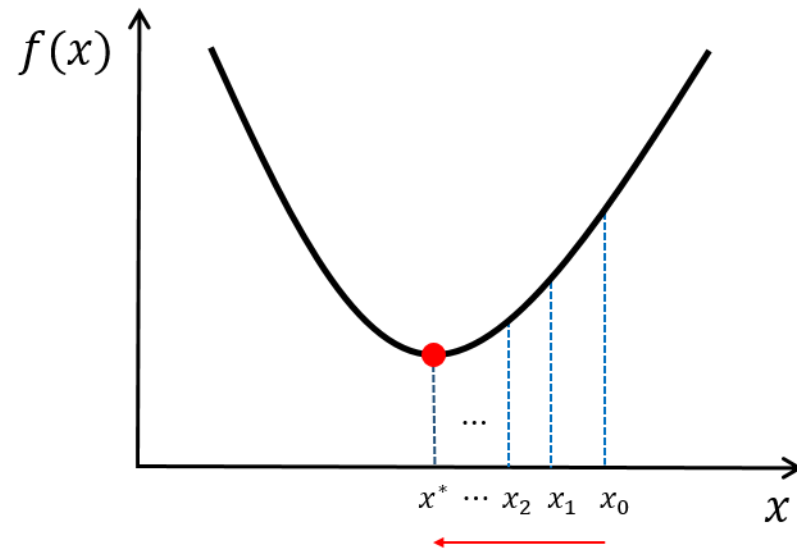
- It motivates the *gradient descent* algorithm, which repeatedly takes steps in the direction of the negative gradient

$$x \leftarrow x - \alpha \nabla_x f(x) \quad \text{for some step size } \alpha > 0$$



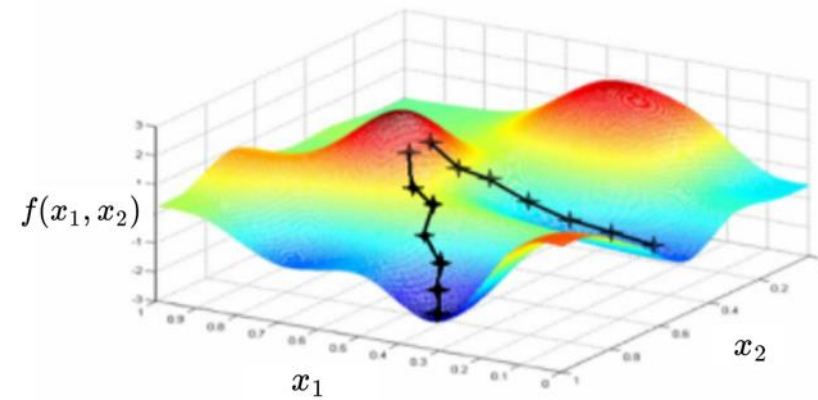
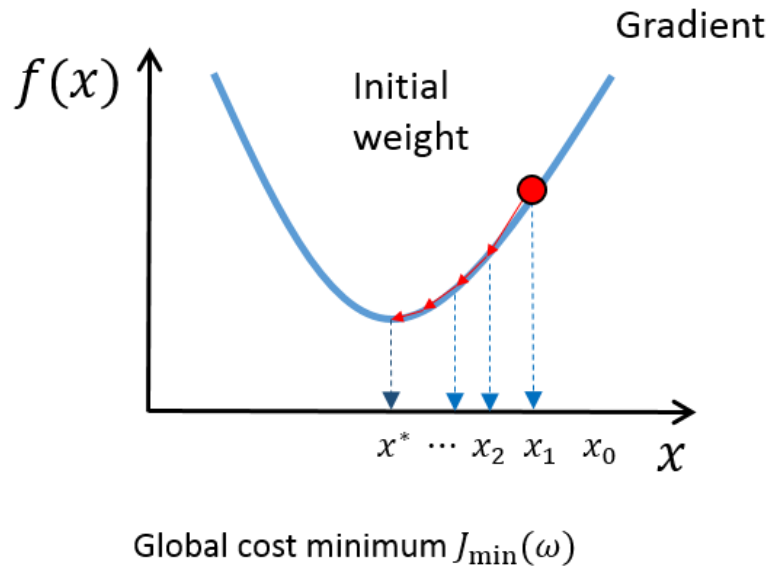
Gradient Descent

Repeat: $x \leftarrow x - \alpha \nabla_x f(x)$ for some *step size* $\alpha > 0$



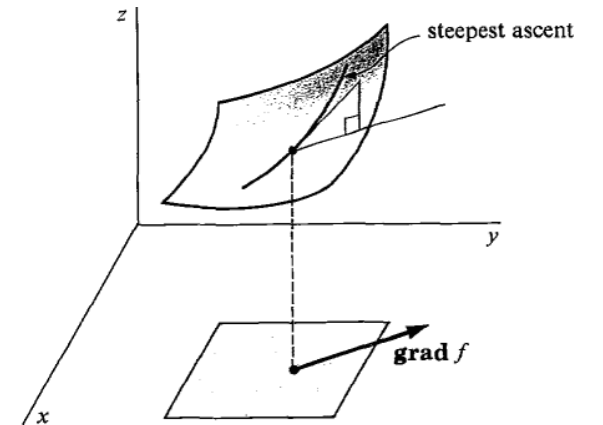
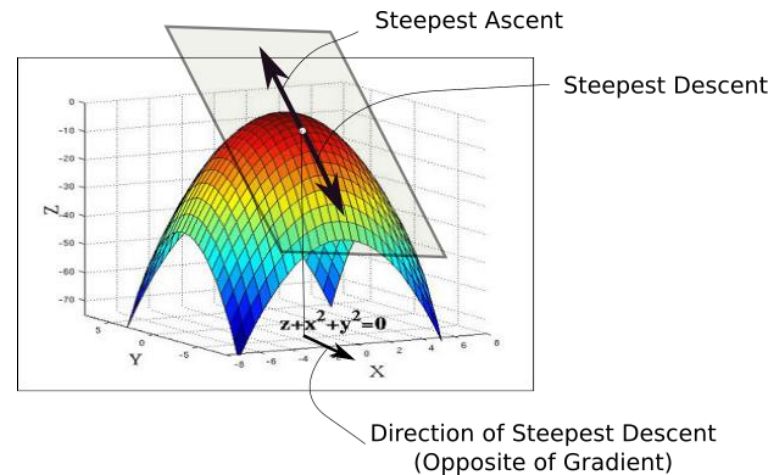
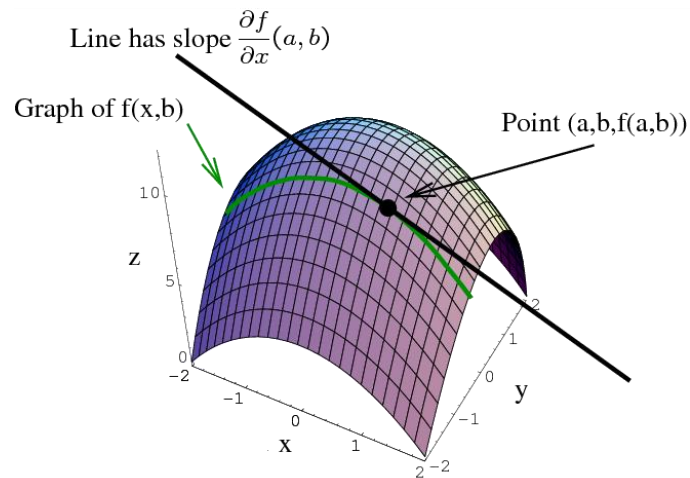
Gradient Descent in High Dimension

Repeat: $x \leftarrow x - \alpha \nabla_x f(x)$ for some *step size* $\alpha > 0$



Gradient Descent in High Dimension

Repeat: $x \leftarrow x - \alpha \nabla_x f(x)$ for some *step size* $\alpha > 0$



Gradient Descent

$$\begin{aligned} \min \quad & (x_1 - 3)^2 + (x_2 - 3)^2 \\ = \min \quad & \frac{1}{2} \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} - \begin{bmatrix} 6 & 6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + 18 \end{aligned}$$

$$\begin{aligned} f &= \frac{1}{2} X^T H X + g^T X \\ \nabla f &= H X + g \end{aligned}$$

- Update rule: $X_{i+1} = X_i - \alpha_i \nabla f(X_i)$

```
H = np.matrix([[2, 0],[0, 2]])
g = -np.matrix([[6],[6]])

x = np.zeros((2,1))
alpha = 0.2

for i in range(25):
    df = H*x + g
    x = x - alpha*df

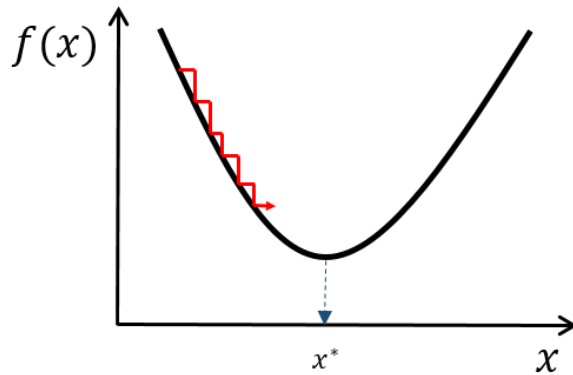
print(x)
```

```
[[ 2.99999147]
 [ 2.99999147]]
```

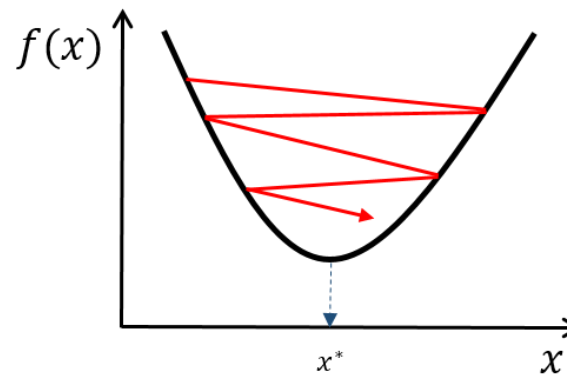
y	$\frac{\partial y}{\partial x}$
Ax	A^T
$x^T A$	A
$x^T x$	$2x$
$x^T Ax$	$Ax + A^T x$

Choosing Step Size α

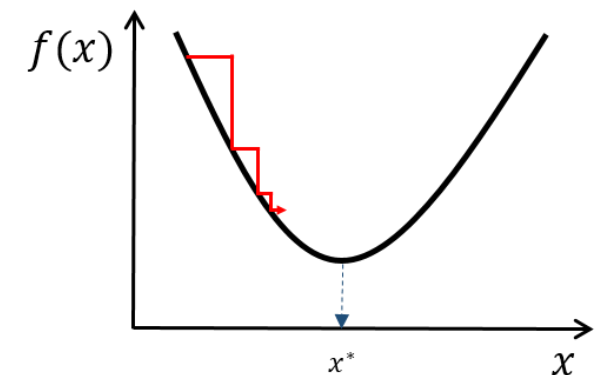
- Learning rate



Too small: converge
very slowly

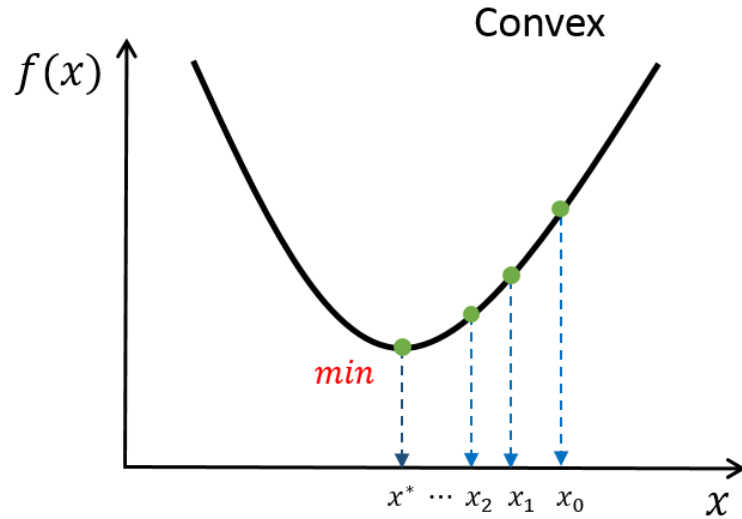


Too big: overshoot and
even diverge

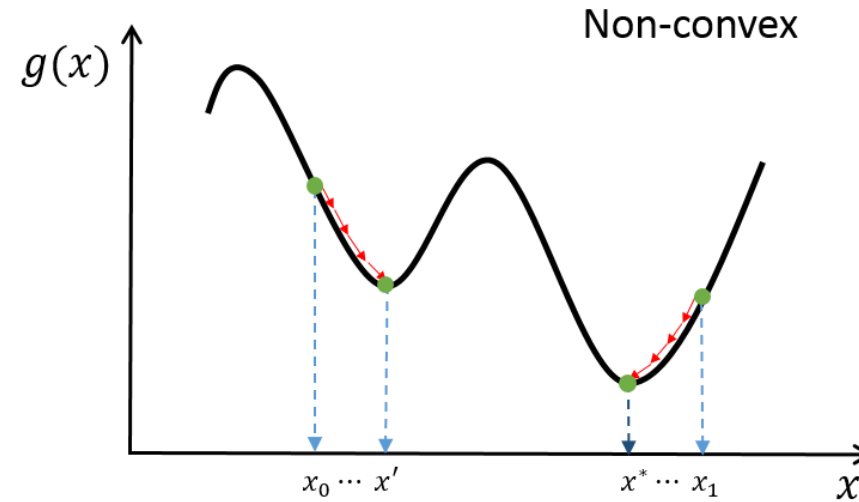


Reduce size over time

Where will We Converge?



Any local minimum is a global minimum



Multiple local minima may exist

- Random initialization
- Multiple trials

Gradient Descent vs. Analytical Solution

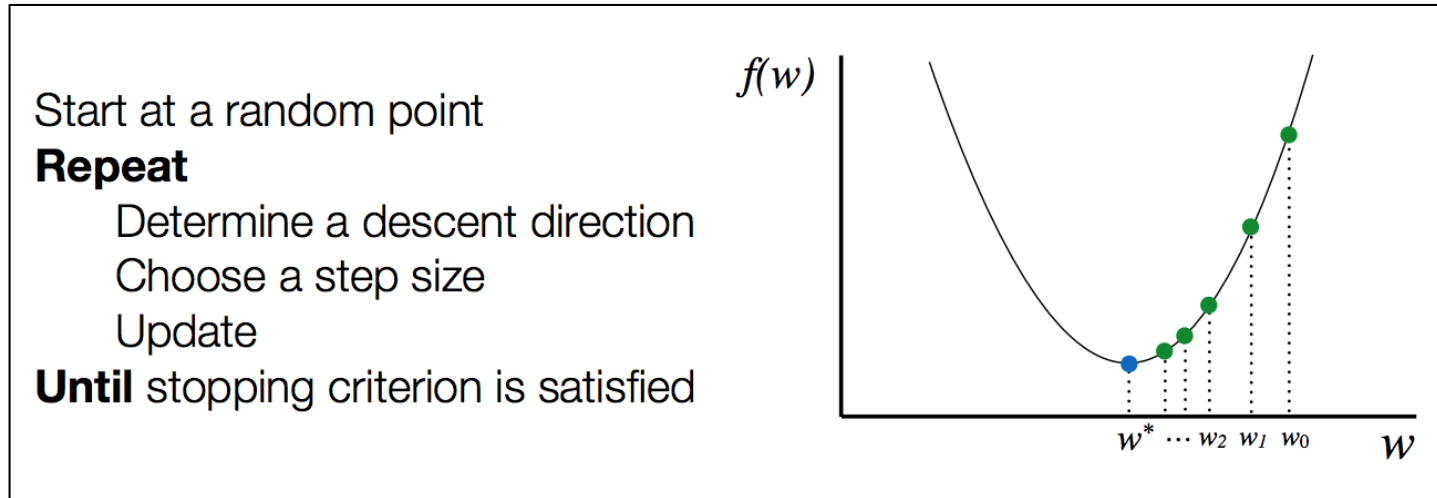
- Analytical solution for MSE
- Gradient descent
 - Easy to implement
 - Very general, can be applied to any differentiable loss functions
 - Requires less memory and computations (for stochastic methods)
- Gradient descent provides a general learning framework
- Can be used both for classification and regression
- Training Neural Networks: Gradient Descent

Practically Solving Optimization Problems

- The good news: for many classes of optimization problems, people have already done all the “hard work” of developing numerical algorithms
 - A wide range of tools that can take optimization problems in “natural” forms and compute a solution
- We will use CVX (or CVXPY) as an optimization solver
 - Only for convex problems
 - Download: <https://www.cvxpy.org/>
- Gradient descent
 - Neural networks/deep learning
 - TensorFlow

Summary: Training Neural Networks

- Optimization procedure



- It is not easy to numerically compute gradients in network in general.
 - The good news: people have already done all the "hard work" of developing numerical solvers (or libraries)
 - There are a wide range of tools
 - We will use **TensorFlow**

Examples

Linear Programming

- Objective function and constraints are both linear
- Convex

$$\max \quad 3x_1 + \frac{3}{2}x_2 \quad \leftarrow \text{objective function}$$

$$\begin{aligned} \text{subject to} \quad & -1 \leq x_1 \leq 2 \\ & 0 \leq x_2 \leq 3 \end{aligned} \quad \leftarrow \text{constraints}$$

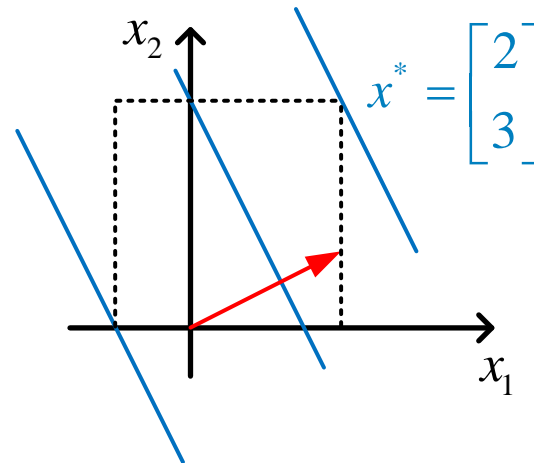
Method 1: Geometric Approach

$$\max \quad 3x_1 + \frac{3}{2}x_2 \quad \leftarrow \text{objective function}$$

$$3x_1 + 1.5x_2 = C \quad \Rightarrow$$

$$\begin{aligned} \text{subject to} \quad & -1 \leq x_1 \leq 2 \quad \leftarrow \text{constraints} \\ & 0 \leq x_2 \leq 3 \end{aligned}$$

$$x_2 = -2x_1 + \frac{2}{3}C$$



Method 2: CVXPY

- Many examples will be provided throughout the lecture

$$\begin{array}{ll} \max_x & 3x_1 + \frac{3}{2}x_2 \\ \text{subject to} & -1 \leq x_1 \leq 2 \\ & 0 \leq x_2 \leq 3 \end{array} \quad \Longrightarrow \quad \begin{array}{ll} \min_x & -\begin{bmatrix} 3 \\ 3/2 \end{bmatrix}^T \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \\ \text{subject to} & \begin{bmatrix} -1 \\ 0 \end{bmatrix} \leq \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq \begin{bmatrix} 2 \\ 3 \end{bmatrix} \end{array}$$

Method 2: CVXPY

```
import numpy as np
import cvxpy as cvx

f = np.array([[3], [3/2]])
lb = np.array([[ -1], [ 0]])
ub = np.array([[ 2], [ 3]])

x = cvx.Variable(2,1)

obj = cvx.Minimize(-f.T*x)
constraints = [lb <= x, x <= ub]

prob = cvx.Problem(obj, constraints)
result = prob.solve()

print(x.value)
print(result)
```

```
[[ 1.99999999]
 [ 2.99999999]]
-10.499999966365493
```

$$\begin{array}{ll} \min_x & -\begin{bmatrix} 3 \\ 3/2 \end{bmatrix}^T \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \\ \text{subject to} & \begin{bmatrix} -1 \\ 0 \end{bmatrix} \leq \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq \begin{bmatrix} 2 \\ 3 \end{bmatrix} \end{array}$$

Quadratic Form

$$q(x_1, \dots, x_n) = \sum_{i=1}^n \sum_{j=1}^n h_{ij} x_i x_j = x^T H x$$

Quadratic Programming

$$\begin{array}{ll} \min & \frac{1}{2}x^2 + 3x + 4y \\ \text{subject to} & x + 3y \geq 15 \\ & 2x + 5y \leq 100 \\ & 3x + 4y \leq 80 \\ & x, y \geq 0 \end{array} \quad \Rightarrow \quad \begin{array}{ll} \min_X & X^T H X + f^T X \\ \text{subject to} & A X \leq b \\ & A_{eq} X = b_{eq} \\ & lb \leq X \leq ub \end{array}$$

Quadratic Programming

```
f = np.array([[3], [4]])
H = np.array([[1/2, 0], [0, 0]])

A = np.array([[-1, -3], [2, 5], [3, 4]])
b = np.array([[-15], [100], [80]])
lb = np.array([[0], [0]])

x = cvx.Variable(2,1)

obj = cvx.Minimize(cvx.quad_form(x, H) + f.T*x)
constraints = [A*x <= b, lb <= x]

prob = cvx.Problem(obj, constraints)
result = prob.solve()

print(x.value)
print(result)
```

\Rightarrow

$$\begin{array}{ll} \min_X & X^T H X + f^T X \\ \text{subject to} & A X \leq b \\ & A_{eq} X = b_{eq} \\ & lb \leq X \leq ub \end{array}$$

```
[[ 6.90879937e-10]
 [ 5.00000000e+00]]
20.000000000914817
```

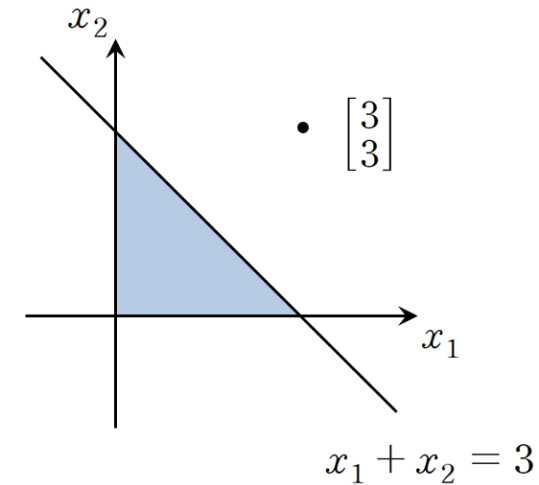

Example: Shortest Distance

- Find the best location to listen to singer's voice

$$\begin{aligned} \min \quad & \sqrt{(x_1 - 3)^2 + (x_2 - 3)^2} \quad \Rightarrow \quad \min \quad (x_1 - 3)^2 + (x_2 - 3)^2 \\ \text{subject to} \quad & x_1 + x_2 \leq 3 \\ & x_1 \geq 0 \\ & x_2 \geq 0 \end{aligned}$$

$$\begin{aligned} \Rightarrow \quad & x_1^2 - 6x_1 + 9 + x_2^2 - 6x_2 + 9 \\ & = x_1^2 + x_2^2 - 6x_1 - 6x_2 + 18 \\ & = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} - \begin{bmatrix} 6 & 6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + 18 \\ & \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq 3 \\ & \begin{bmatrix} 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq \begin{bmatrix} \\ \end{bmatrix} \end{aligned}$$

$$\begin{bmatrix} 1.5 \\ 1.5 \end{bmatrix}$$



```
f = np.array([[ -6], [ -6]])
H = np.array([[ 1, 0], [ 0, 1]])

A = np.array([ 1, 1])
b = 3
lb = np.array([[ 0], [ 0]])

x = cvx.Variable(2, 1)

obj = cvx.Minimize(cvx.quad_form(x, H) + f.T*x)
constraints = [A*x <= b, lb <= x]

prob = cvx.Problem(obj, constraints)
result = prob.solve()

print(x.value)
```

Example: Shortest Distance

$$\min d_1 + d_2 = \min \left\| \vec{a} - \begin{bmatrix} x \\ 0 \end{bmatrix} \right\|_2 + \left\| \vec{b} - \begin{bmatrix} x \\ 0 \end{bmatrix} \right\|_2$$

```
a = np.array([[0], [1]])
b = np.array([[4], [2]])

Aeq = np.array([0, 1])
beq = 0

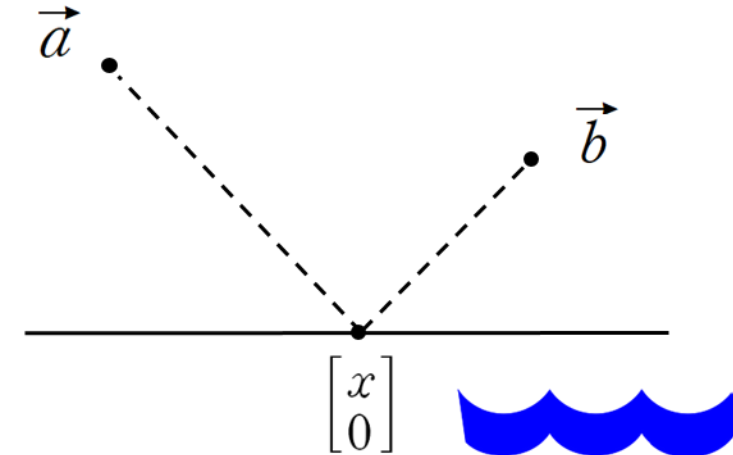
x = cvx.Variable(2, 1)

mu = 1
obj = cvx.Minimize(cvx.norm(a-x, 2) + mu*cvx.norm(b-x, 2))
constraints = [Aeq*x == beq]

prob = cvx.Problem(obj, constraints)
result = prob.solve()

print(x.value)
print(result)
```

```
[[ 1.33325114e+00]
 [ 5.33304239e-12]]
4.9999999941398166
```



Example: Supply Chain Management

- Find a point that minimizes the sum of the transportation costs (or distance) from this point to 3 destination points

```
a = np.array([[np.sqrt(3)], [0]])
b = np.array([[-np.sqrt(3)], [0]])
c = np.array([[0],[3]])

x = cvx.Variable(2,1)

obj = cvx.Minimize(cvx.norm(a-x, 2) + cvx.norm(b-x, 2) + cvx.norm(c-x, 2))
#obj = cvx.Minimize(cvx.norm(a-x, 1) + cvx.norm(b-x, 1) + cvx.norm(c-x, 1))

prob = cvx.Problem(obj)
result = prob.solve()

print(x.value)
```

```
[[ -1.58674964e-16]
 [  1.00000001e+00]]
```

