

CME 307 / MS&E 311 / OIT 676: Optimization

Gradient descent

Professor Udell

Management Science and Engineering
Stanford

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Outline

Unconstrained minimization

Quadratic approximations

Analysis via Polyak-Lojasiewicz condition

Unconstrained minimization

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

- ▶ $f : \mathbb{R}^n \rightarrow \mathbb{R}$ differentiable
- ▶ assume optimal value $f^* = \inf_x f(x)$ is attained (and finite)
- ▶ assume a starting point $x^{(0)}$ is known

unconstrained minimization methods

- ▶ produce sequence of points $x^{(k)}$, $k = 0, 1, \dots$ with

$$f(x^{(k)}) \rightarrow f^*$$

(we hope)

Gradient descent

minimize $f(x)$

idea: go downhill

Algorithm Gradient descent

Given: $f : \mathbb{R}^d \rightarrow \mathbb{R}$, stepsize t , maxiters

Initialize: $x = 0$ (or anything you'd like)

For: $k = 1, \dots, \text{maxiters}$

▶ update x :

$$x \leftarrow x - t \nabla f(x)$$

Gradient descent: choosing a step-size

- ▶ **constant step-size.** $t^{(k)} = t$ (constant)
- ▶ **decreasing step-size.** $t^{(k)} = 1/k$
- ▶ **line search.** try different possibilities for $t^{(k)}$ until objective at new iterate

$$f(x^{(k)}) = f(x^{(k-1)} - t^{(k)} \nabla f(x^{(k-1)}))$$

decreases enough.

tradeoff: line search requires evaluating $f(x)$ (can be expensive)

Line search

define $x^+ = x - t\nabla f(x)$

- ▶ exact line search: find t to minimize $f(x^+)$
- ▶ the **Armijo rule** requires t to satisfy

$$f(x^+) \leq f(x) - ct\|\nabla f(x)\|^2$$

for some $c \in (0, 1)$, e.g., $c = .01$.

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a simple **backtracking line search** algorithm:

- ▶ set $t = 1$
- ▶ if step decreases objective value sufficiently, accept x^+ :

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A: yes! see gradient descent demo

Demo: gradient descent

<https://github.com/stanford-cme-307/demos/blob/main/gradient-descent.ipynb>

How well does GD work?

for $x \in \mathbb{R}^n$,

- ▶ $f(x) = x^T x$
- ▶ $f(x) = x^T A x$ for $A \succeq 0$
- ▶ $f(x) = \|x\|_1$ (nonsmooth but differentiable **almost** everywhere)
- ▶ $f(x) = 1/x$ on $x > 0$ (strictly convex but not strongly convex)

[https:](https://github.com/stanford-cme-307/demos/blob/main/gradient-descent-contours.ipynb)

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Analysis via Polyak-Lojasiewicz condition

Quadratic approximation

Suppose $f : \mathbb{R} \rightarrow \mathbb{R}$ is twice differentiable. For any $x \in \mathbb{R}$, approximate f about x :

$$f(y) \approx f(x) + \nabla f(x)^T (y - x) + \frac{1}{2} (y - x)^T \nabla^2 f(x) (y - x).$$

If f is a quadratic function, $\nabla^2 f(x) = H$ is constant.

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Quadratic approximations are useful because quadratics are easy to minimize:

$$\begin{aligned} y^* &= \underset{y}{\operatorname{argmin}} f(x) + \nabla f(x)^T (y - x) + \frac{1}{2}(y - x)^T H(y - x) \\ &\implies \nabla f(x) + H(y^* - x) = 0 \\ y^* &= x - H^{-1}(\nabla f(x)). \end{aligned}$$

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If we approximate the Hessian of f by $H = \frac{1}{t}I$ for some $t > 0$ and choose x^+ to minimize the quadratic approximation, we obtain the **gradient descent** update with step size t :

$$x^+ = x + -t \nabla f(x)$$

Quadratic upper bound

Definition (Smooth)

A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is **L -smooth** if for all $x, y \in \mathbb{R}$,

$$f(y) \leq f(x) + \nabla f(x)^T (y - x) + \frac{L}{2} \|y - x\|^2.$$

Equivalently, assuming the derivatives exist,

- ▶ the operator $\frac{1}{L} \nabla f$ is **L -Lipschitz continuous**:

$$\|\nabla f(y) - \nabla f(x)\| \leq L \|y - x\|$$

- ▶ $\nabla^2 f(x) \preceq LI$ for all $x \in \text{dom } f$.

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A: $\lambda_{\max}(A)$ -smooth

Quadratic lower bound

Definition (Strongly convex)

A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is μ -**strongly convex** for $\mu > 0$ if for all $x, y \in \mathbb{R}$,

$$f(y) \geq f(x) + \nabla f(x)^T (y - x) + \frac{\mu}{2} \|y - x\|^2.$$

Equivalently, assuming the derivatives exist,

- ▶ the operator $\frac{1}{\mu} \nabla f$ is μ -**coercive**:

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A: $\lambda_{\min}(A)$ -strongly convex

Some important functions

for $A \in \mathbb{R}^{m \times n}$, $b \in \mathbb{R}^m$, $x \in \mathbb{R}^n$,

- ▶ **Quadratic loss.** $\|Ax - b\|^2$
- ▶ **Logistic loss.** $f(x) = \sum_{i=1}^m \log(1 + \exp(b_i a_i^T x))$
where a_i is i th row of A

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Q: Which of these are strongly convex? Under what conditions?

A: Quadratic loss is strongly convex if A is rank n . Logistic loss is strongly convex on a compact domain if A is rank n .

Optimizing the upper bound

start at $x^{(0)}$. suppose f is L -smooth, so for all $y \in \mathbb{R}$,

$$f(y) \leq f(x^{(0)}) + \nabla f(x)^T (y - x^{(0)}) + \frac{L}{2} \|y - x^{(0)}\|^2$$

let's choose next iterate $x^{(1)}$ to minimize this upper bound:

$$\begin{aligned} x^{(1)} &= \operatorname{argmin}_y f(x) + \nabla f(x)^T (y - x) + \frac{L}{2} \|y - x\|^2 \\ &\implies \nabla f(x^{(0)}) + L(x^{(1)} - x^{(0)}) = 0 \\ x^{(1)} &= x^{(0)} - \frac{1}{L} \nabla f(x^{(0)}) \end{aligned}$$

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- ▶ **gradient descent** update with step size $t = \frac{1}{L}$
- ▶ lower bound ensures true optimum can't be too far away, and can be used to prove convergence

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The Polyak-Lojasiewicz condition

Definition (Polyak-Lojasiewicz condition)

A function $f : \mathbb{R} \rightarrow \mathbb{R}$ satisfies the **Polyak-Lojasiewicz condition** if

$$\frac{1}{2} \|\nabla f(x)\|^2 \geq \mu(f(x) - f^*)$$

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Theorem ([Karimi, Nutini, and Schmidt (2016)])

Suppose $f(x) = g(Ax)$ where $g : \mathbb{R}^m \rightarrow \mathbb{R}$ is strongly convex and $A : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear. Then f is Polyak-Lojasiewicz.

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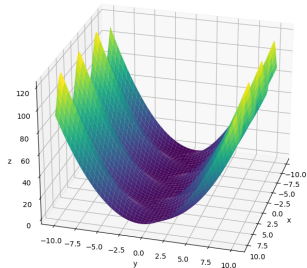
A: No. A river valley is Polyak-Lojasiewicz but not convex.

why use Polyak-Lojasiewicz? Polyak-Lojasiewicz is weaker than strong convexity and yields simpler proofs

River valley

$$f(x, y) = (y - \sin(x))^2$$

3D Plot of $(Y - \sin(X))^2 + .2 \cdot X$



Azimuth 0
Elevation 30

PL and invexity

Theorem

Every Polyak-Lojasiewicz function is invex. (That is, any stationary point of a Polyak-Lojasiewicz function is globally optimal.)

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proof: if $\nabla f(\bar{x}) = 0$, then

$$0 = \frac{1}{2} \|\nabla f(x)\|^2 \geq \mu(f(\bar{x}) - f^*) \geq 0$$

$\implies f(\bar{x}) = f^*$ is the global optimum.

strong convexity \implies Polyak-Lojasiewicz

Theorem

If f is μ -strongly convex, then f is μ -Polyak-Lojasiewicz.

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Theorem

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proof: minimize the strong convexity condition over y :

$$\begin{aligned}\min_y f(y) &\geq \min_y \left(f(x) + \nabla f(x)^T (y - x) + \frac{\mu}{2} \|y - x\|^2 \right) \\ f^* &\geq f(x) - \frac{1}{2\mu} \|\nabla f(x)\|^2\end{aligned}$$

since $y = x - \nabla f(x)/\mu$ minimizes the strong convexity upper bound

Types of convergence

- ▶ objective converges

$$f(x^{(k)}) \rightarrow f^*$$

- ▶ iterates converge

$$x^{(k)} \rightarrow x^*$$

under

- ▶ strong convexity: objective converges \implies iterates converge
proof: use strong convexity with $x = x^*$ and $y = x^{(k)}$:

$$f(x^{(k)}) - f^* \geq \frac{\mu}{2} \|x^{(k)} - x^*\|^2$$

- ▶ Polyak-Lojasiewicz: not necessarily true (x^* may not be unique)

Rates of convergence

- ▶ linear convergence with rate c

$$f(x^{(k)}) - f^* \leq c^k (f(x^{(0)}) - f^*)$$

- ▶ looks like a line on a semi-log plot
- ▶ example: gradient descent on smooth strongly convex function

- ▶ sublinear convergence

- ▶ looks slower than a line (curves up) on a semi-log plot
- ▶ example: $1/k$ convergence

$$f(x^{(k)}) - f^* \leq \mathcal{O}(1/k)$$

- ▶ example: gradient descent on smooth convex function
- ▶ example: stochastic gradient descent

Gradient descent converges linearly

Theorem

If $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is μ -Polyak-Lojasiewicz, L -smooth, and $x^ = \operatorname{argmin}_x f(x)$ exists, then gradient descent with stepsize L*

$$x^{(k+1)} = x^{(k)} - \frac{1}{L} \nabla f(x^{(k)})$$

converges linearly to f^ with rate $(1 - \frac{\mu}{L})$.*

Gradient descent converges linearly: proof

proof: plug in update rule to L -smoothness condition

$$\begin{aligned} f(x^{(k+1)}) - f(x^{(k)}) &\leq \nabla f(x^{(k)})^T (x^{(k+1)} - x^{(k)}) + \frac{L}{2} \|x^{(k+1)} - x^{(k)}\|^2 \\ &\leq \left(-\frac{1}{L} + \frac{1}{2L}\right) \|\nabla f(x^{(k)})\|^2 \\ &\leq -\frac{1}{2L} \|\nabla f(x^{(k)})\|^2 \\ &\leq -\frac{\mu}{L} (f(x^{(k)}) - f^*) \quad \triangleright \text{(using PL)} \end{aligned}$$

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decrement proportional to error \implies linear convergence:

$$\begin{aligned} f(x^{(k)}) - f^* &\leq \left(1 - \frac{\mu}{L}\right) (f(x^{(k-1)}) - f^*) \\ &\leq \left(1 - \frac{\mu}{L}\right)^k (f(x^{(0)}) - f^*) \end{aligned}$$

Practical convergence

- ▶ Gradient descent with optimal stepsize converges even faster.

$$f(x^{(k+1)}) = \inf_{\alpha} f(x^{(k)} - \alpha \nabla f(x^{(k)})) \leq f(x^{(k)} - \frac{1}{L} \nabla f(x^{(k)}))$$

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- ▶ Local vs global convergence

Quiz

- ▶ A strongly convex function always satisfies the Polyak-Lojasiewicz condition
 - A. true
 - B. false
- ▶ Suppose $f : \mathbb{R} \rightarrow \mathbb{R}$ is L -smooth and satisfies the Polyak-Lojasiewicz condition. Then any stationary point $\nabla f(x) = 0$ of f is a global optimum:
 $f(x) = \operatorname{argmin}_y f(y) =: f^*$.
 - A. true
 - B. false
- ▶ Suppose $f : \mathbb{R} \rightarrow \mathbb{R}$ is L -smooth and satisfies the Polyak-Lojasiewicz condition. Then gradient descent on f converges linearly from any starting point.
 - A. true
 - B. false

Outline

Applications of quadratic programs

Classification

Quadratic program: application

Markowitz portfolio optimization problem:

$$\begin{array}{ll}\text{minimize} & \gamma x^T \Sigma x - \mu^T x \\ \text{subject to} & \sum_i x_i = 1 \\ & Ax = 0 \\ \text{variable} & x \in \mathbb{R}^n\end{array}$$

where

- ▶ $\Sigma \in \mathbb{R}^{n \times n}$: asset covariance matrix
- ▶ $\mu \in \mathbb{R}^n$: asset return vector
- ▶ $\gamma \in \mathbb{R}$: risk aversion parameter
- ▶ rows of $A \in \mathbb{R}^{m \times n}$ correspond to other portfolios
 - ▶ ensures new portfolio is independent, e.g., of market returns

Quadratic program: application

control system design problem:

$$x^+ = Ax + Bu$$

- ▶ $x \in \mathbb{R}^n$: state (e.g., position, velocity)
- ▶ $u \in \mathbb{R}^m$: control (e.g., force, torque)

$$\begin{array}{ll} \text{minimize} & \sum_{t=1}^T x_t^T Q x_t + u_t^T R u_t \\ \text{subject to} & x_{t+1} = Ax_t + Bu_t, \quad t = 0, \dots, T-1 \\ & x_0 = x^{\text{init}} \end{array}$$

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Applications of quadratic programs

Classification

Application: classification

classification problem: m data points

- ▶ feature vector $a_i \in \mathbb{R}^n$, $i = 1, \dots, m$
- ▶ label $b_i \in \{-1, 1\}$, $i = 1, \dots, m$

choose decision boundary $a^T x = 0$ to separate data points into two classes

- ▶ $a^T x > 0 \implies$ predict class 1
- ▶ $a^T x < 0 \implies$ predict class -1

classification is correct if $b_i a^T x > 0$

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- ▶ projective transformation transforms affine boundary to linear boundary
- ▶ classification is invariant to scalar multiplication of x

Logistic regression

(regularized) **logistic regression** minimizes the **finite sum**

$$\begin{array}{ll} \text{minimize} & \sum_{i=1}^m \log(1 + \exp(-b_i a_i^T x)) + r(x) \\ \text{variable} & x \in \mathbb{R}^n \end{array}$$

where

- ▶ $b_i \in \{-1, 1\}$, $a_i \in \mathbb{R}^n$
- ▶ $r : \mathbb{R}^n \rightarrow \mathbb{R}$ is a **regularizer**, e.g., $\|x\|^2$ or $\|x\|_1$

Support vector machine

support vector machine (SVM) minimizes the **finite sum**

$$\begin{array}{ll} \text{minimize} & \sum_{i=1}^m \max(0, 1 - b_i a_i^T x) + \gamma \|x\|^2 \\ \text{variable} & x \in \mathbb{R}^n \end{array}$$

where $b_i \in \{-1, 1\}$ and $a_i \in \mathbb{R}^n$.

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how to solve?

- ▶ use **subgradient** method
- ▶ transform to **conic form**
- ▶ solve **dual** problem instead
- ▶ **smooth** the objective