Module 6 – Gradient Descent in Action

DSC 40A, Summer 2023

Agenda

- Brief recap of Module 5.
- Gradient descent demo.
- When is gradient descent guaranteed to work?

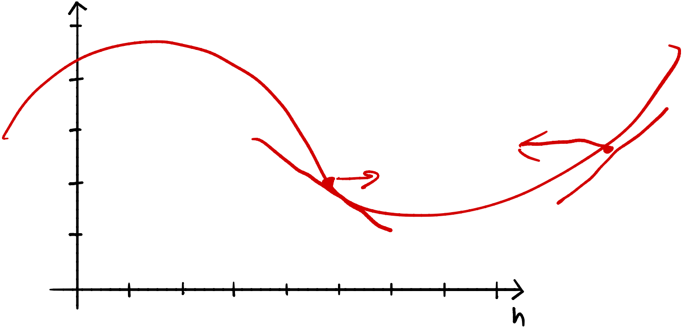
Gradient descent fundamentals

The general problem

- **Given:** a differentiable function $R(h)$.
- **Goal:** find the input h^* that minimizes $R(h)$.

Key idea behind gradient descent

- If the slope of R at h is **positive** then we'll **decrease** h.
- If the slope of R at h is **negative** then we'll **increase** h.



Gradient descent

- Pick a positive constant, α, for the **learning rate**.
- Pick a starting prediction, h_0.
- Repeatedly apply the gradient descent update rule.

$$h_i = h_{i-1} - \alpha \cdot \frac{dR}{dh}(h_{i-1})$$

- Repeat until convergence (when h doesn't change much).

↳ or validation loss not improving

↳ $\frac{dR}{dh}$ close to some small value

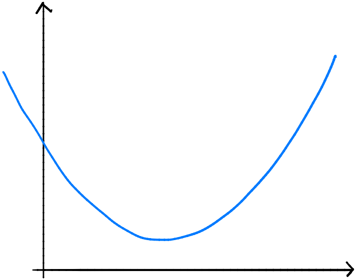
depends on α

Gradient descent demo

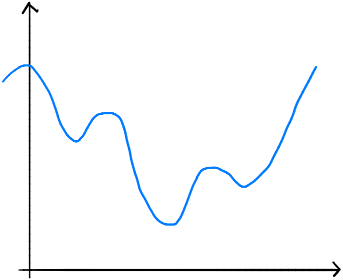
Let's see gradient descent in action. Follow along here.

When is gradient descent guaranteed to work?

Convex functions



Convex



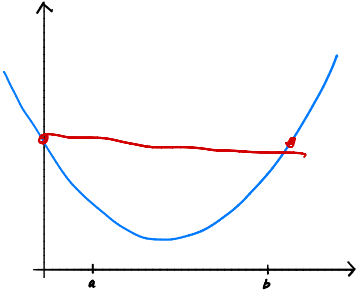
Non-convex

Convexity: Definition

- f is **convex** if for **every** a, b in the domain of f, the line segment between

$$(a, f(a)) \qquad \text{and} \qquad (b, f(b))$$

does not go below the plot of f.



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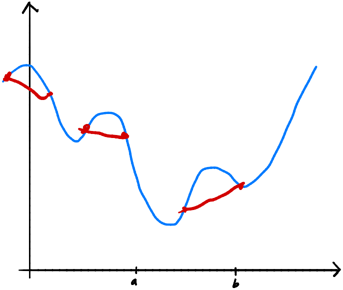


Discussion Question

Which of these functions is not convex?

a) $f(x) = |x|$

b) $f(x) = e^x$

c) $f(x) = \sqrt{x - 1}$

d) $f(x) = (x - 3)^{24}$

Why does convexity matter?

- Convex functions are (relatively) easy to minimize with gradient descent.
- **Theorem**: if $R(h)$ is convex and differentiable then gradient descent converges to a **global minimum** of R *provided* that the step size is small enough.
- **Why?**
  - If a function is convex and has a local minimum, that local minimum must be a global minimum.
  - In other words, gradient descent won't get stuck/terminate in local minimums that aren't global minimums.

Nonconvexity and gradient descent

- We say a function is **nonconvex** if it does not meet the criteria for convexity.

- Nonconvex functions are (relatively) hard to minimize.

- Gradient descent can still be useful, but it's not guaranteed to converge to a global minimum.
  - We saw this when trying to minimize $R_{ucsd}(h)$ with a smaller σ.

Second derivative test for convexity → note: not on exam

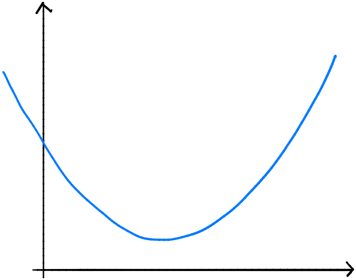
- If $f(x)$ is a function of a single variable and is twice differentiable, then:

- $f(x)$ is convex if and only if $\frac{d^2 f}{dx^2}(x) \geq 0$ for all x.

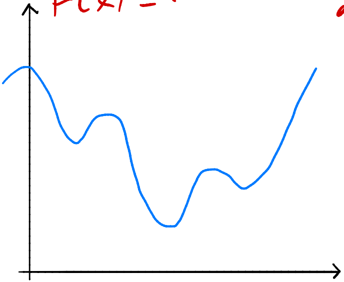
- Example: $f(x) = x^4$ is convex.

$f'(x) = 4x^3$

$f(x) = 12x^2 \geq 0$ for all x



Convex



Non-convex

Convexity of empirical risk

- If $L(h, y)$ is a convex function (when y is fixed) then

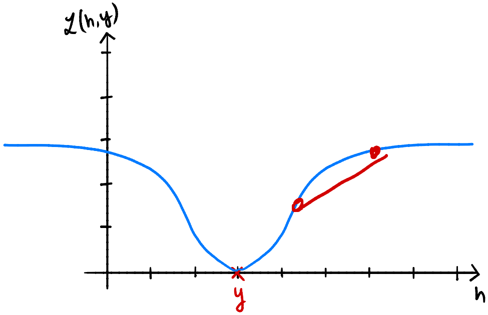
$$R(h) = \frac{1}{n} \sum_{i=1}^{n} L(h, y_i)$$

  is convex.
  - More generally, sums of convex functions are convex.

- What does this mean?
  - If a loss function is convex, then the corresponding empirical risk will also be convex.

Convexity of loss functions

- Is $L_{\text{sq}}(h, y) = (y - h)^2$ convex? **Yes** or **No**.
- Is $L_{\text{abs}}(h, y) = |y - h|$ convex? **Yes** or **No**.
- Is $L_{ucsd}(h, y)$ convex? **Yes** or **No**.



Convexity of R_{ucsd}

- A function can be convex in a region.

- If σ is large, $R_{ucsd}(h)$ is convex in a big region around data.
  - A large σ led to a very smooth, parabolic-looking empirical risk function with a single local minimum (which was a global minimum).

- If σ is small, $R_{ucsd}(h)$ is convex in only small regions.
  - A small σ led to a very bumpy empirical risk function with many local minimums.

Discussion Question

Recall the empirical risk for absolute loss,

$$R_{abs}(h) = \frac{1}{n}\sum_{i=1}^{n} |y_i - h|$$

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1 Is $R_{abs}(h)$ **convex**? Is gradient descent **guaranteed** to find a global minimum, given an appropriate step size?

a) **YES** convex, **YES** guaranteed
b) **YES** convex, **NOT** guaranteed
c) ~~**NOT** convex, **YES** guaranteed~~
d) ~~**NOT** convex, **NOT** guaranteed~~

Summary

Summary

- Gradient descent is a general tool used to minimize differentiable functions.

- Convex functions are (relatively) **easy** to optimize with gradient descent.

- We like **convex loss functions**, such as the squared loss and absolute loss, because the corresponding empirical risk functions are also convex.

What's next?

- So far, we've been predicting future values (salary, for instance) without using any information about the individual.
  - GPA.

    $(h_i - y_i)^2$

  - Years of experience.
  - Number of LinkedIn connections.
  - Major.
- How do we incorporate this information into our prediction-making process?