BOSTON UNIVERSITY

Deep Learning for Data Science
DS 542

https://dl4ds.github.io/fa2025/

Gradient Descent

Original slides by Tom Gardos,
other content from Understanding Deep Learning unless otherwise cited

Announcements

- Re: discussion deadlines are moving to 11:59pm on the day of discussion.
  - Why? The practice is more important than the timing.
  - Still targeting ≤ 30 minutes to do, but more time if you need/want it.

- Shared Compute Cluster (SCC) Tutorial next Monday.
  - Please bring your laptop to class.
  - No graded exercise, but will be walking through account setup.

Plan for Today

- Loss functions for multiclass classification (spillover)
- Example of gradient descent
- Basics of gradient descent
- Gradient descent as a statistical process
- Challenges with gradient descent

Loss Function for Regression

If you recast regression as

1. Predicting the mean of a normal distribution with a fixed variance and
2. Optimize output for maximum likelihood,

Then the optimization is equivalent to optimizing with least squared errors (L_2) as your loss function.

Loss Function for Binary Classification

If you are modeling a binary classification problem,

1. The sigmoid function is handy to map arbitrary "scores" into probabilities, so
2. Your loss function is equivalent to

$$L[\phi] = \sum_i -(1 - y_i) \log[1 \ - \mathrm{sig}[f[x_i|\phi]] - y_i \log[\mathrm{sig}[f[x_i|\phi]]$$

Conceptualizing the Binary Loss Function

$$L[\phi] = \sum_i -(1 - y_i) \log[1 \ - \mathrm{sig}[f[x_i|\phi]] - y_i \log[\mathrm{sig}[f[x_i|\phi]]$$

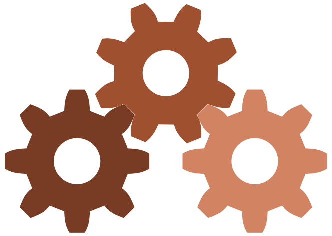
$$L[\phi] = \sum_i -(1 - y_i) \log \Pr[y_i \ = 0|x_i] - y_i \log \Pr[y_i \ = 1|x_i]$$

$$L[\phi] = \sum_i - \log \Pr[y_i| \ x_i]$$

Example 3: multiclass classification

Real world input | Model input | Model | Model output | Real world output

$$\begin{bmatrix} 124 \\ 140 \\ 156 \\ 128 \\ 142 \\ 157 \\ \vdots \end{bmatrix}$$



Supervised learning model

$$\begin{bmatrix} 0.00 \\ 0.00 \\ 0.01 \\ 0.89 \\ 0.05 \\ 0.00 \\ \vdots \\ 0.01 \end{bmatrix}$$

Aardvark
Apple
Bee
Bicycle
Bridge
Clown
⋮

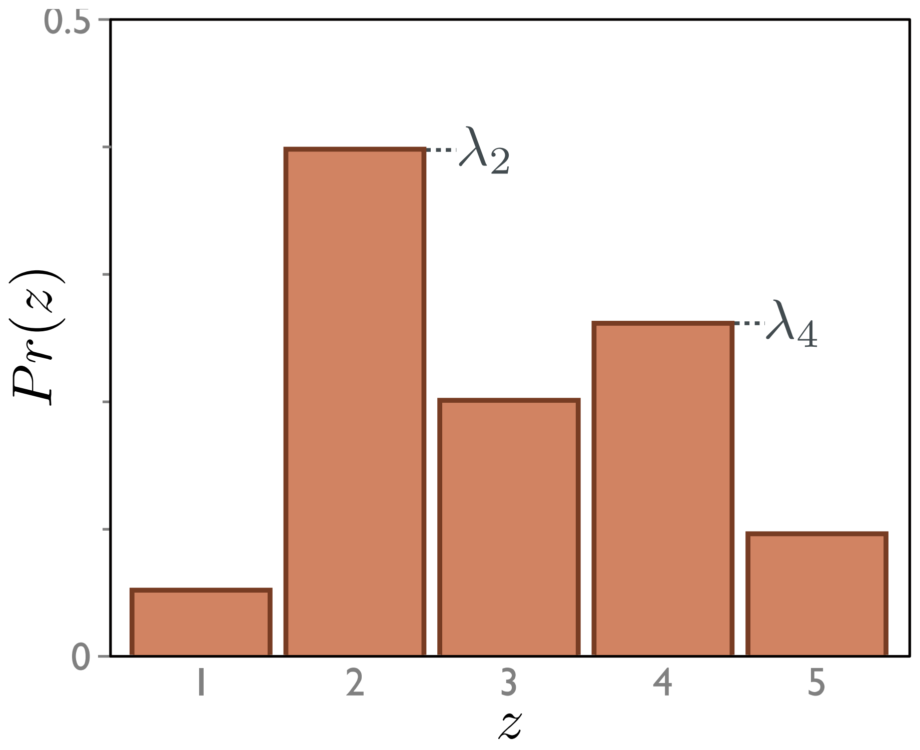
Goal: predict which of K classes $y \in \{1, 2, \ldots, K\}$ the input x belongs to.

Example 3: multiclass classification

1. Choose a suitable probability distribution $Pr(\mathbf{y}|\boldsymbol{\theta})$ that is defined over the domain of the predictions $\mathbf{y}$ and has distribution parameters $\boldsymbol{\theta}$.

- Domain: $y \in \{1, 2, \ldots, K\}$
- **Categorical distribution**
- K parameters $\lambda_k \in [0, 1]$
- $\sum_k \lambda_k = 1$

$$Pr(y = k) = \lambda_k$$



Example 3: multiclass classification

2. Set the machine learning model $\mathbf{f}[\mathbf{x}, \boldsymbol{\phi}]$ to predict one or more of these parameters so $\boldsymbol{\theta} = \mathbf{f}[\mathbf{x}, \boldsymbol{\phi}]$ and $Pr(\mathbf{y}|\boldsymbol{\theta}) = Pr(\mathbf{y}|\mathbf{f}[\mathbf{x}, \boldsymbol{\phi}])$.

Problem:

- Output of neural network can be anything
- Parameters λ_k ∈[0,1], sum to one

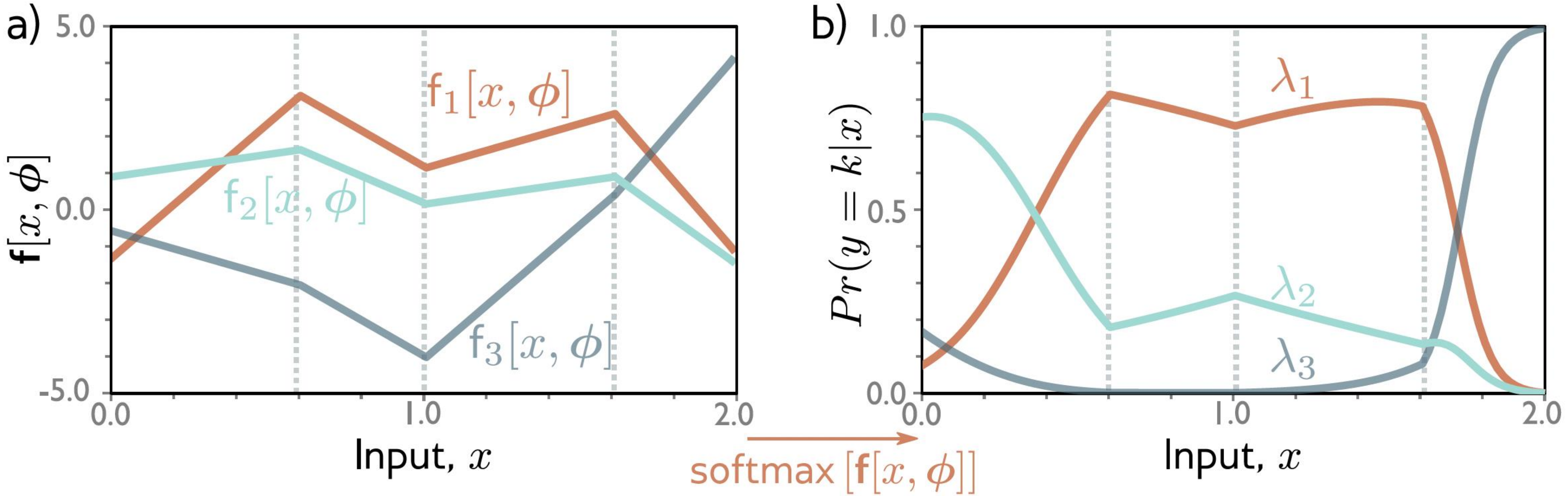
$$\text{softmax}_k[\mathbf{z}] = \frac{\exp[z_k]}{\sum_{k'=1}^{K} \exp[z_{k'}]}$$

Solution:

- Pass through function that maps "anything" to [0,1] and sums to one

$$Pr(y = k|\mathbf{x}) = \text{softmax}_k[\mathbf{f}[\mathbf{x}, \boldsymbol{\phi}]]$$

Example 3: multiclass classification



$$Pr(y = k|\mathbf{x}) = \mathrm{softmax}_k[\mathbf{f}[\mathbf{x}, \phi]]$$

Example 3: multiclass classification

3. To train the model, find the network parameters $\hat{\phi}$ that minimize the negative log-likelihood loss function over the training dataset pairs $\{\mathbf{x}_i, \mathbf{y}_i\}$:

$$\hat{\phi} = \underset{\phi}{\operatorname{argmin}} \left[L[\phi]\right] = \underset{\phi}{\operatorname{argmin}} \left[-\sum_{i=1}^{I} \log\left[Pr(\mathbf{y}_i | \mathbf{f}[\mathbf{x}_i, \phi])\right]\right]. \tag{5.7}$$

$$L[\phi] = -\sum_{i=1}^{I} \log\left[\text{softmax}_{y_i}\left[\mathbf{f}\left[\mathbf{x}_i, \phi\right]\right]\right]$$

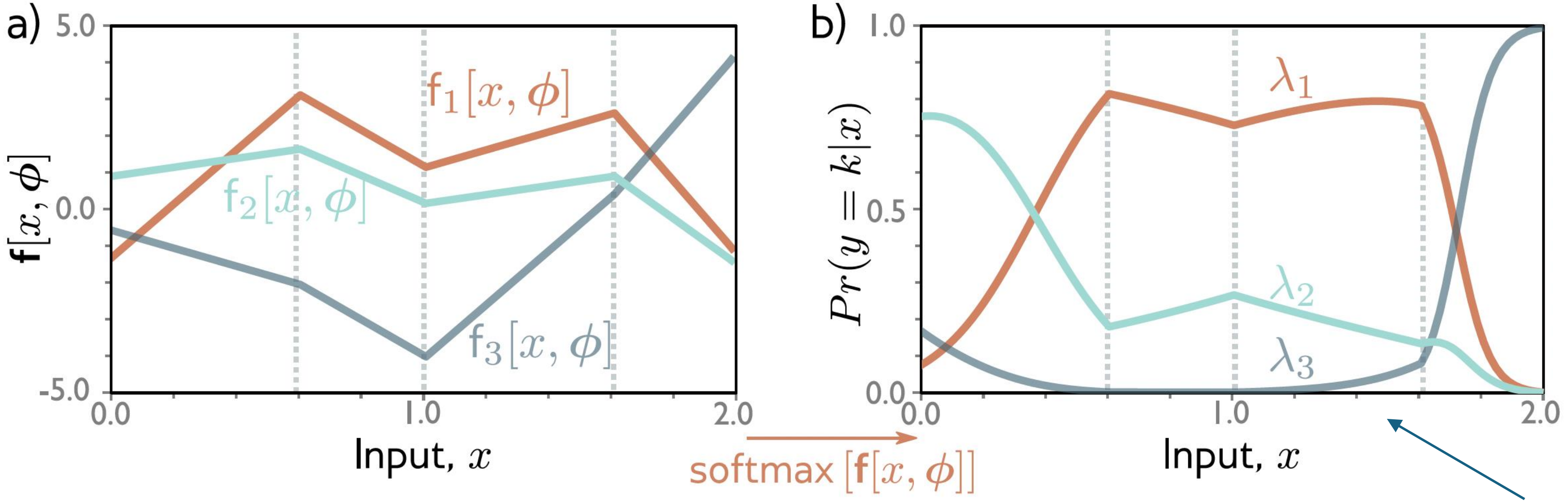
$$= -\sum_{i=1}^{I} \mathrm{f}_{y_i}\left[\mathbf{x}_i, \phi\right] - \log\left[\sum_{k=1}^{K} \exp\left[\,\mathrm{f}_k\left[\mathbf{x}_i, \phi\right]\right]\right]$$

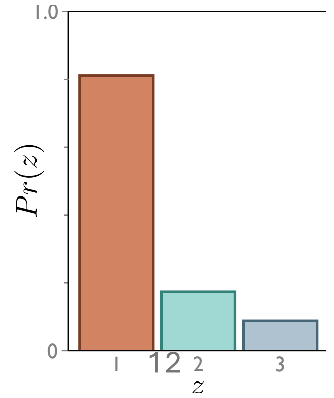
$$\text{softmax}_k[\mathbf{z}] = \frac{\exp[z_k]}{\sum_{k'=1}^{K} \exp[z_{k'}]}$$

Multiclass cross-entropy loss

Example 3: multiclass classification

4. To perform inference for a new test example $\mathbf{x}$, return either the full distribution $Pr(\mathbf{y}|\mathbf{f}[\mathbf{x}, \hat{\boldsymbol{\phi}}])$ or the maximum of this distribution.





Choose the class with the largest probability
We also get probability or “confidence”

Any questions?

Multiple outputs

- Treat each output y_d as *independent*:

$$Pr(\mathbf{y}|\mathbf{f}[\mathbf{x}_i,\phi]) = \prod_d Pr(y_d|\mathbf{f}_d[\mathbf{x}_i,\phi])$$

where $\mathbf{f}_d[\mathbf{x},\phi]$ is the d^{th} set of network outputs

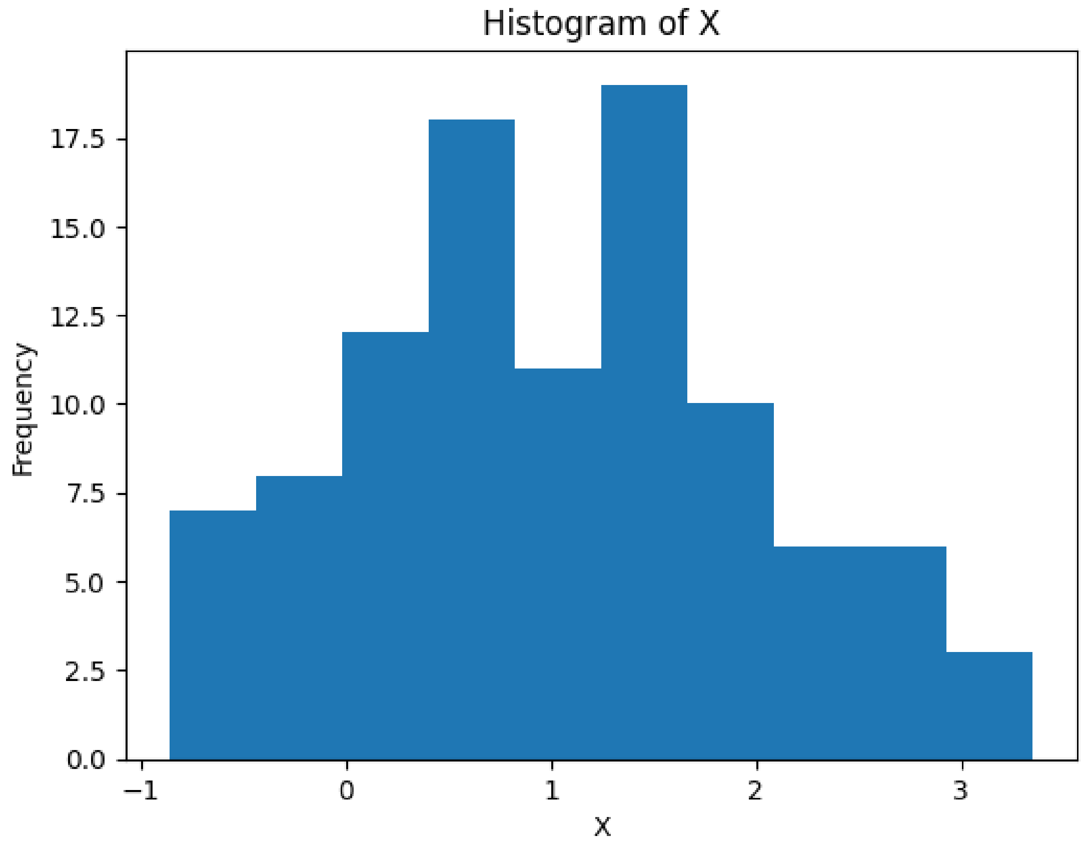
- Negative log likelihood becomes sum of terms:

$$L[\phi] = -\sum_{i=1}^{I} \log\Big[Pr(\mathbf{y}|\mathbf{f}[\mathbf{x}_i,\phi])\Big] = -\sum_{i=1}^{I}\sum_d \log\Big[Pr(\underbrace{y_{id}}_{d^{th}\text{output of the } i^{th} \text{ training example}}|\mathbf{f}_d[\mathbf{x}_i,\phi])\Big]$$

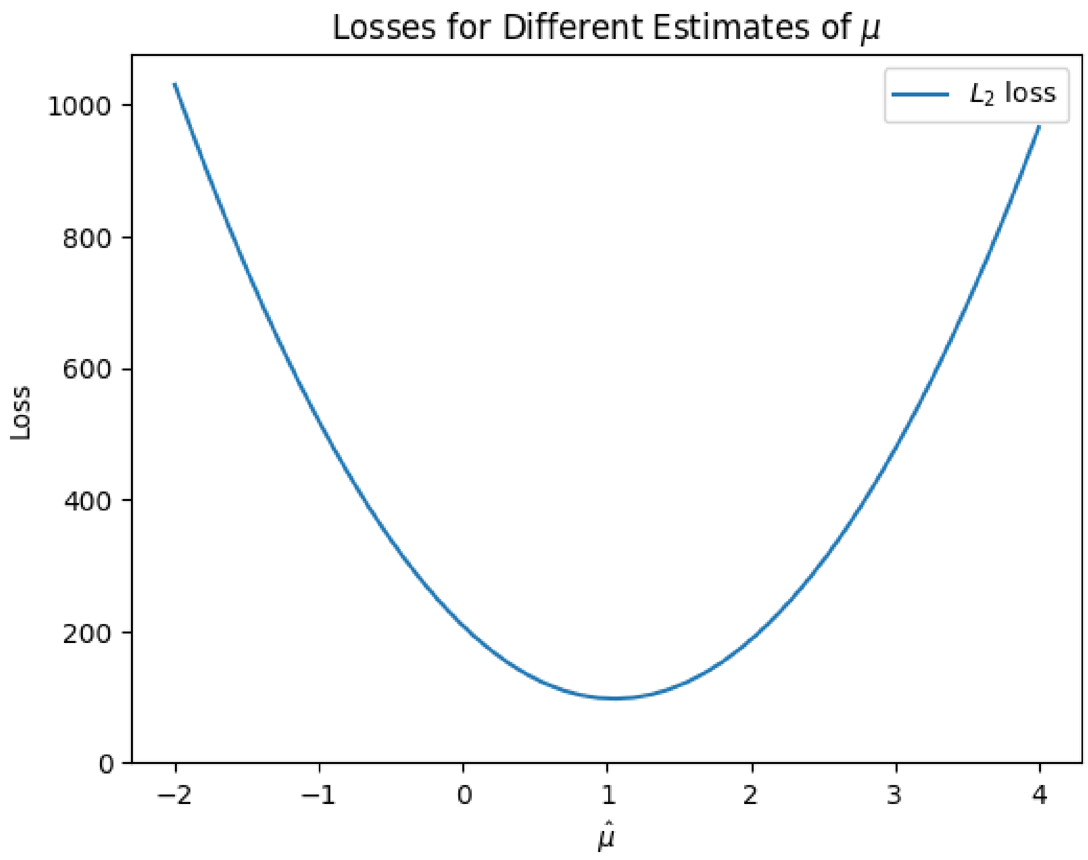
Any questions?

An Example of Gradient Descent

- X is 100 samples from a normal distribution.
  - What were the parameters of that normal distribution?
  - What was the mean of that normal distribution?



Visualizing Gradient Descent



Basics of Gradient Descent

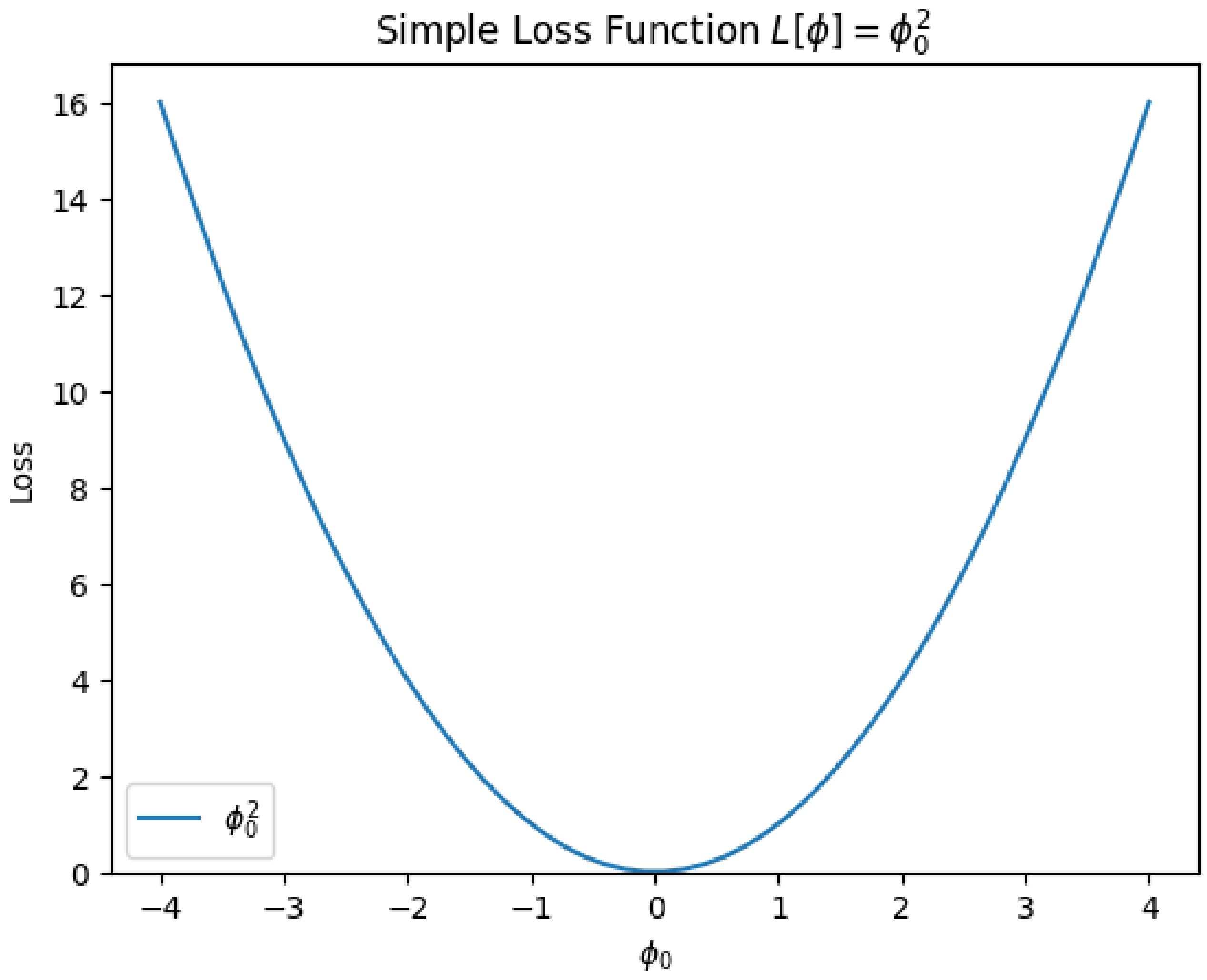
- Given current set of parameters ϕ_t,
    - Calculate all partial derivatives $\frac{\partial L[\phi]}{\partial \phi_i}$ based on current parameters ϕ_t.
    - The vector of these $\frac{\partial L[\phi]}{\partial \phi_i}$ is the gradient of the loss function $\nabla L[\phi]$.
    - Update $\phi_{t+1} = \phi_t - \alpha \, \nabla L[\phi]$

      where α is the learning rate.

What should the learning rate be?

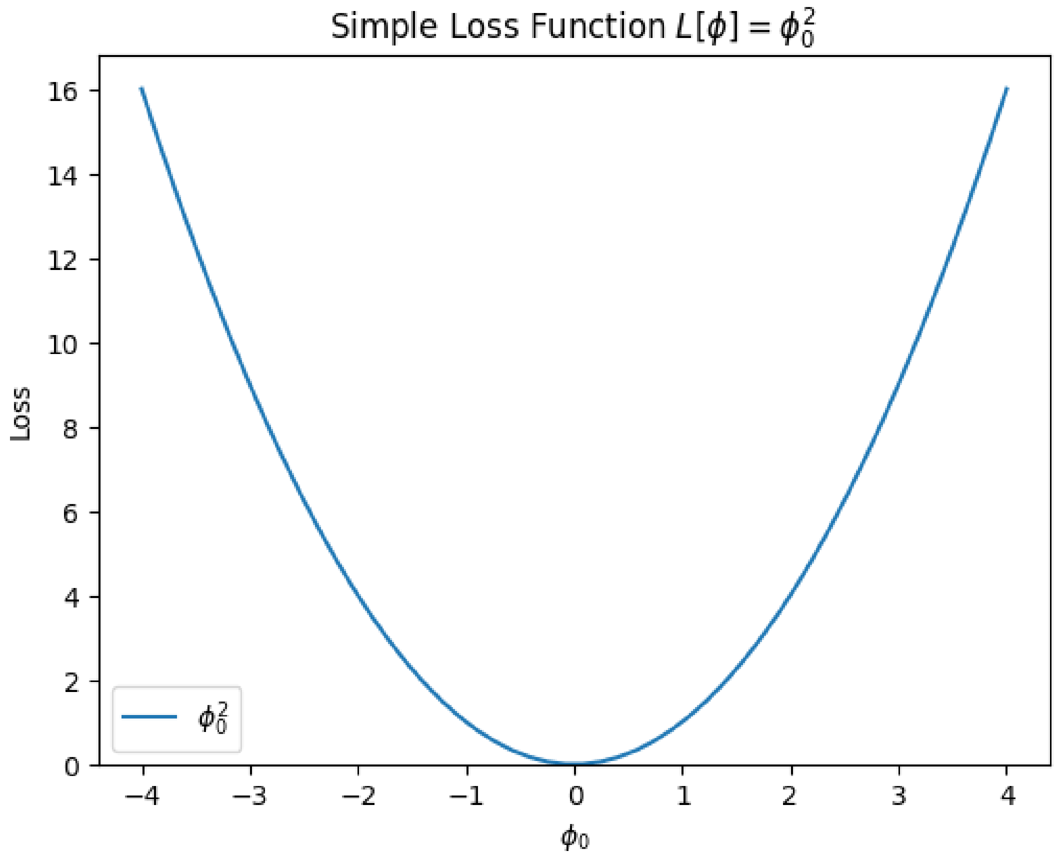
- Try $\alpha = 1$.

- Too small, and it takes many steps to get close.
- Too big, and it overshoots.



Convex Loss Functions

- Generally, a lot easier to optimize...
- With gradient descent, main issue is not overshooting minimum too much.



Non-Convex Loss Functions

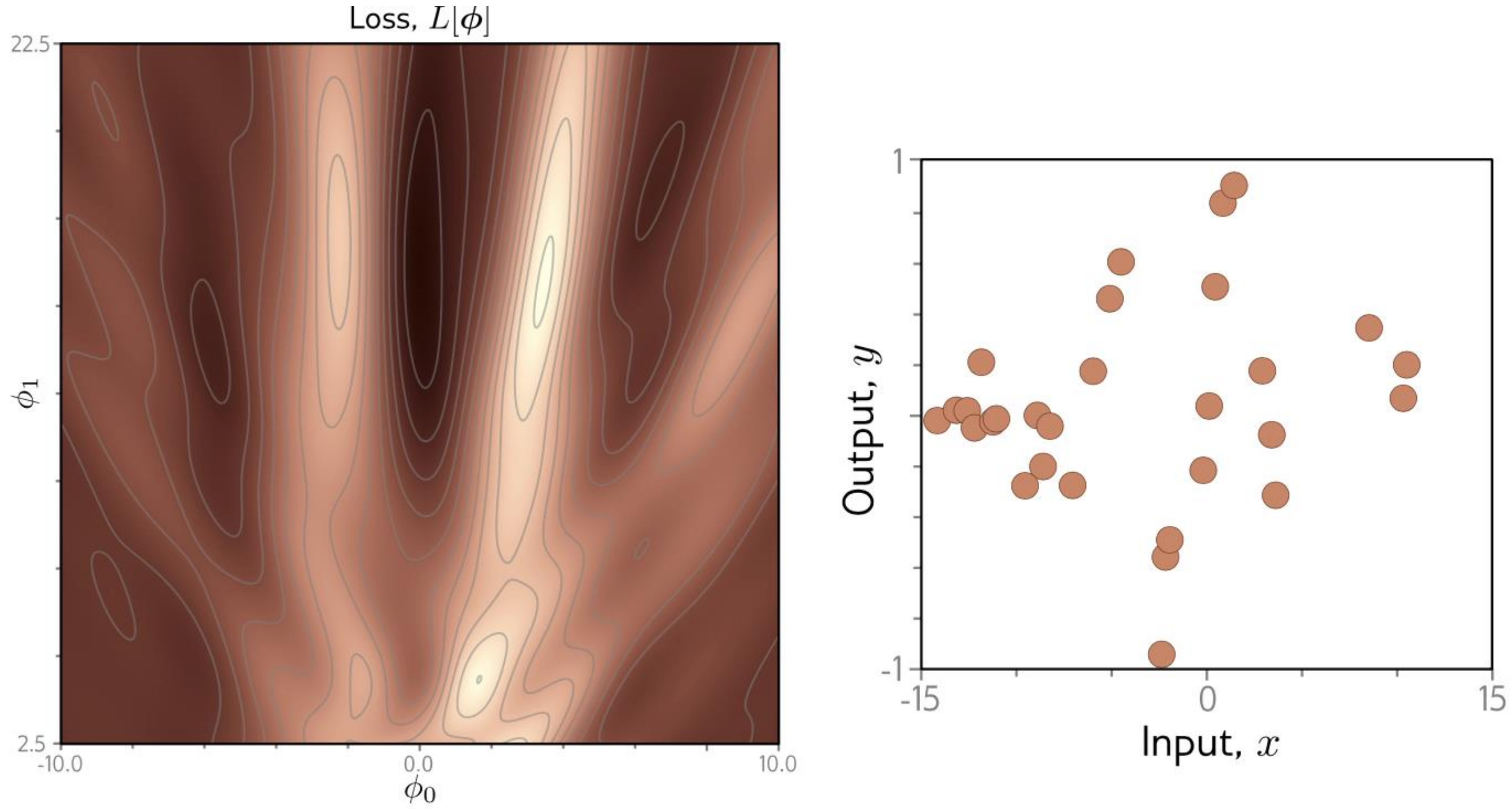
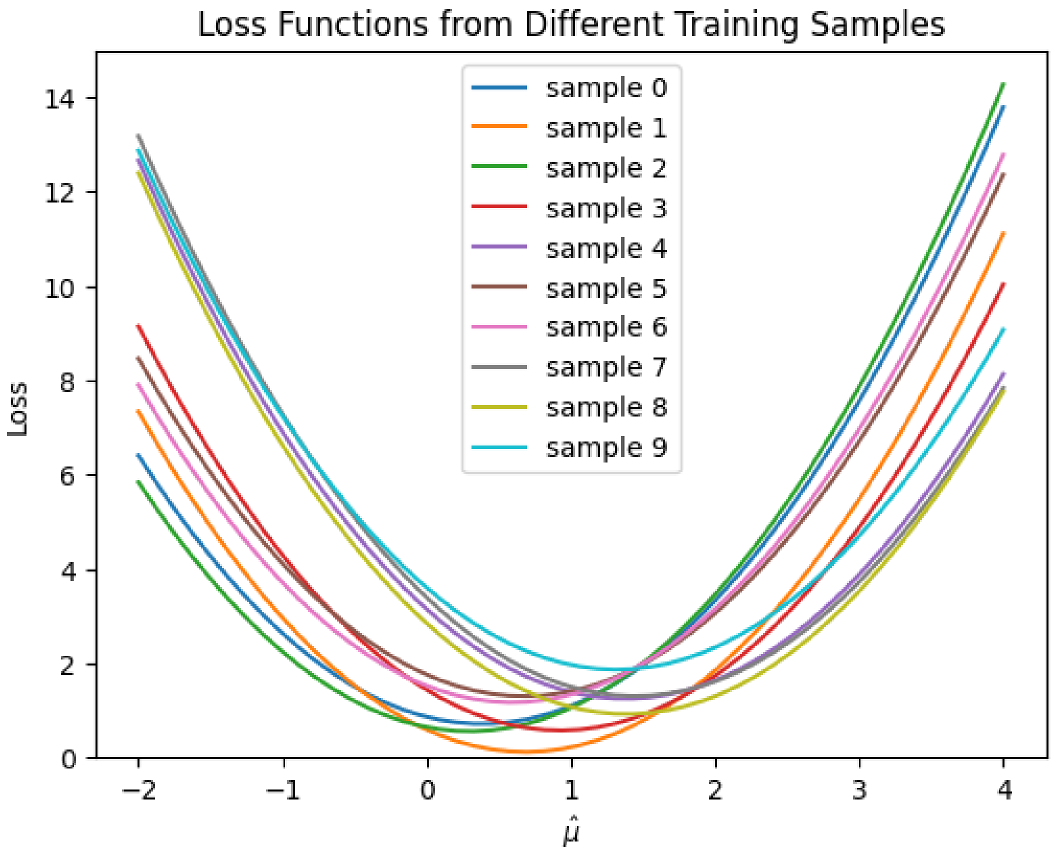


Image Source: Understanding Deep Learning, via https://udlbook.github.io/udlfigures/

Any questions?

Gradient Descent as a Statistical Process

- Our training data is a sample of the whole population.
  - Different training samples yield different training loss functions.



Loss Functions for Different Training Samples

- If we collect different training data sets, will we get different models?

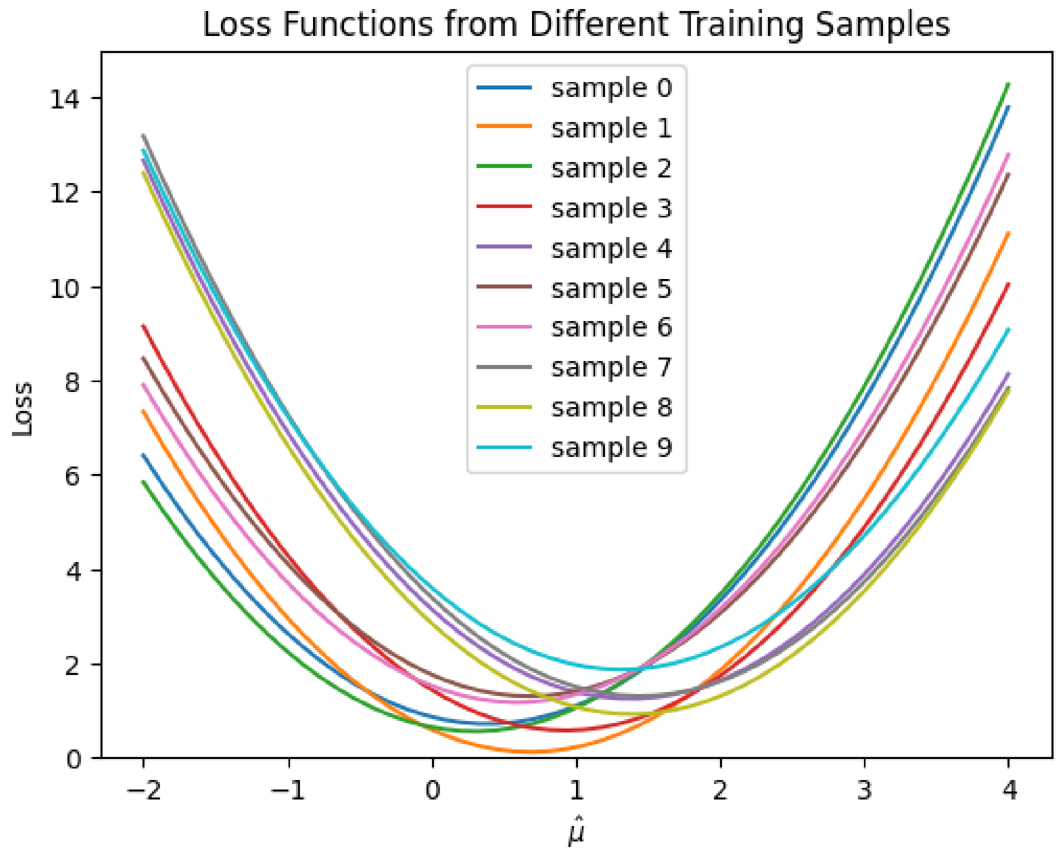
Loss Functions for Samples of the Training Set

- If we sample the training data, will we get different models?

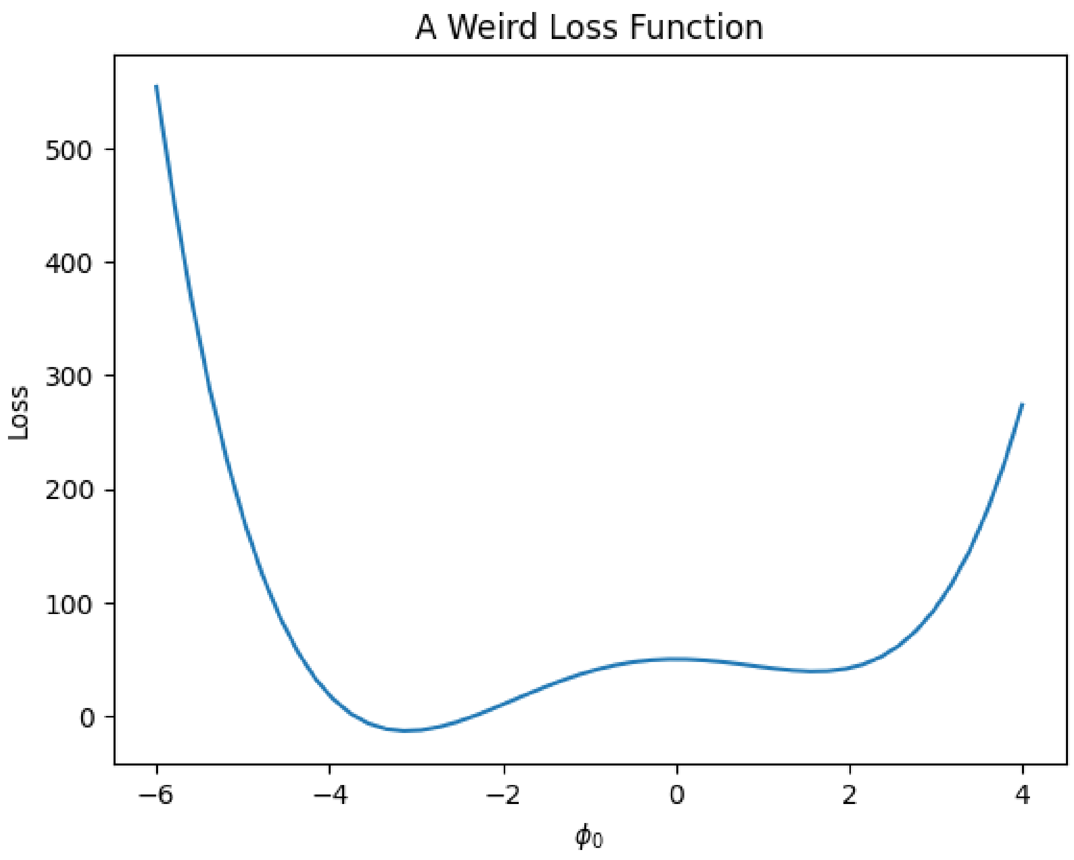
Comparing Models with Different Training Samples

- How far apart are the models of these samples?

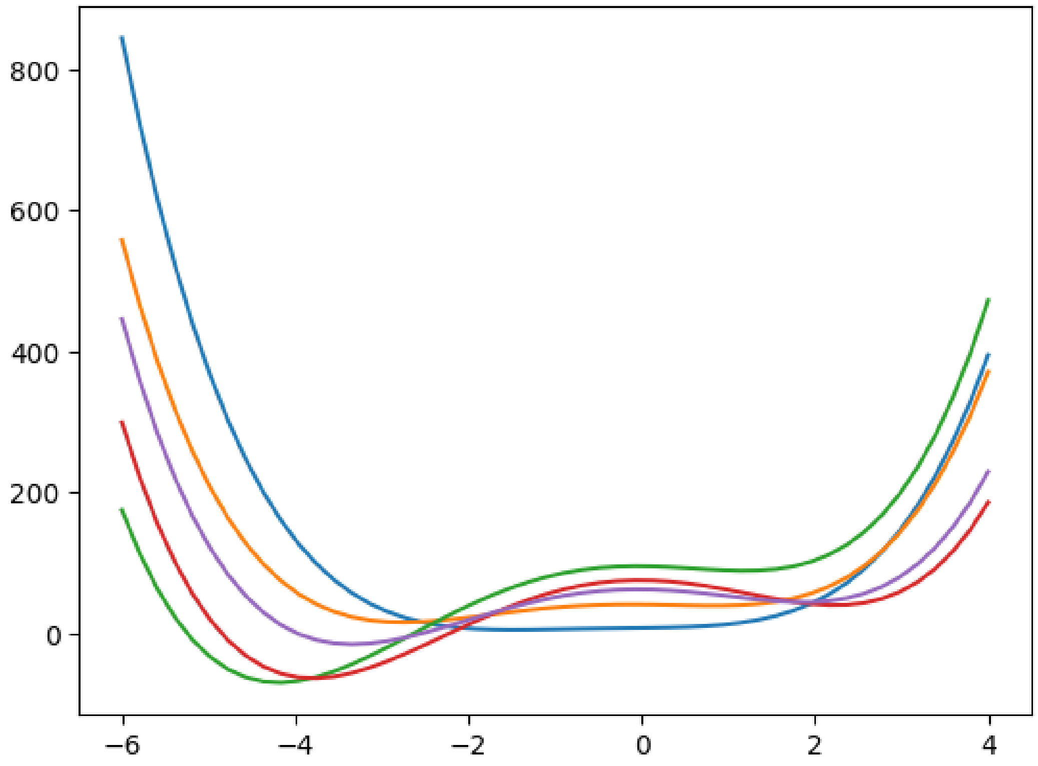
- Where do they agree and disagree?



A Weird Loss Function



Local Minima vs Samples of the Training Set



Stochastic Gradient Descent

Idea: Run gradient descent with "mini batches" instead of the full training set.

- E.g. pick a random partition of data into 10 equal-sized batches.
- One epoch = running through all the data once.
  - Vanilla gradient → one parameter update.
  - Stochastic gradient descent → one parameter update per mini batch.

Variation in Sampled Gradients

- Expected mini batch gradient = whole training set gradient.
  - On average, they agree.
  - But with noise from sampling.

- But remember, just taking one step with each mini batch.
  - Not optimizing to mini batch minimum loss.

Local Minima vs Stochastic Gradient Descent

- When far from a local minima, mini batches tend to agree on gradient direction.

- When close to a local minima, mini batches disagree more.
  - Sampling noise.
  - Explore the flat area around the minima.

Speed of Stochastic Gradient Descent

- How fast is this compared to vanilla gradient descent?

Any questions?

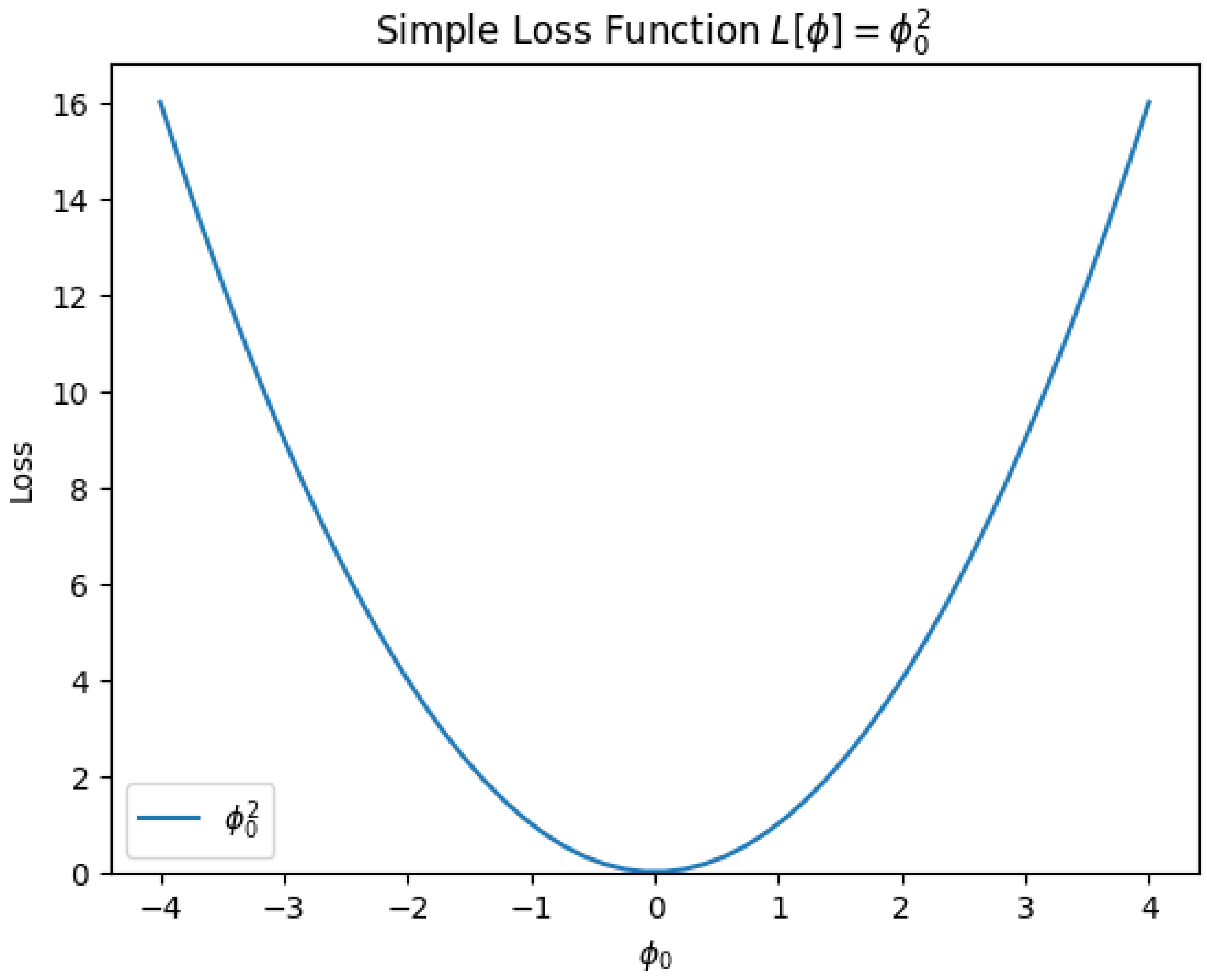
Gradient Descent as a Universal Algorithm

- What's the catch?

How do we pick Learning Rate?

- Remember, $\alpha = 1$ gives an infinite loop.

- Also, be impatient.



Really Bad Linear Regression

- $f(x) = f_1\left(f_2\left(f_3\left(f_4(x)\right)\right)\right)$

- $f_1(x) = a_1 x + b_1$
- $f_2(x) = a_2 x + b_2$
- $f_3(x) = a_3 x + b_3$
- $f_4(x) = a_4 x + b_4$

- $f(x)$ is just a linear function?

Really Bad Linear Regression (part 2)

- $f(x) = f_1\left(f_2\left(f_3\left(f_4(x)\right)\right)\right)$

- $f_1(x) = a_1x + b_1$
- $f_2(x) = a_2x + b_2$
- $f_3(x) = a_3x + b_3$
- $f_4(x) = a_4x + b_4$

- $f(x)$ is just a linear function?

- Initialize all parameters to zero.

- What are the gradients?

Really Bad Linear Regression (part 3)

- $f(x) = f_1\left(f_2\left(f_3\left(f_4(x)\right)\right)\right)$

- $f_1(x) = a_1 x + b_1$
- $f_2(x) = a_2 x + b_2$
- $f_3(x) = a_3 x + b_3$
- $f_4(x) = a_4 x + b_4$

- $f(x)$ is just a linear function?

- Initialize all parameters to 100.

- What are the gradients?

Really Bad Linear Regression (part 4)

- $f(x) = f_1\left(f_2\left(f_3\left(f_4(x)\right)\right)\right)$

- $f_1(x) = a_1 x + b_1$
- $f_2(x) = a_2 x + b_2$
- $f_3(x) = a_3 x + b_3$
- $f_4(x) = a_4 x + b_4$

- $f(x)$ is just a linear function?

- We will see both these problems with neural networks if we use the wrong initialization.

Any questions?