

CPSC 340: Machine Learning and Data Mining

MLE and MAP

Fall 2021

Admin

- Final exam format:
 - Online
 - 12 hour window: Dec 19 from 8:30am to 8:30pm
 - Will take around 2.5 hours to complete (not 12 hours!)
 - The official room will be available if you'd like to use it
 - More details on the exact format TBA
- Next week
 - Midterm break Wed-Fri
 - **No tutorials next week**

Last Time: Maximum Likelihood Estimation (MLE)

- Maximum likelihood estimation (MLE):
 - Define a likelihood function, probability of data given parameters: $p(D | w)$.
 - Choose parameters ‘w’ to maximize the likelihood.
- Gives naïve Bayes “counting” estimates we used.
- Typically easier to equivalently minimize negative log-likelihood (NLL).

$$\hat{w} \in \arg\max_w p(D|w) \equiv \arg\min_w -\log(p(D|w))$$

↑
"equivalent"

- This will turns product of probability over IID examples into sum over examples.

Minimizing the Negative Log-Likelihood (NLL)

- We use **log-likelihood** because it **turns multiplication into addition**:

$$\log(\alpha \beta) = \log(\alpha) + \log(\beta)$$

- More generally: $\log\left(\prod_{i=1}^n a_i\right) = \sum_{i=1}^n \log(a_i)$

- If data is ' n ' **IID** samples then $p(D|w) = \prod_{i=1}^n p(D_i|w)$

likelihood of
example i

and our MLE is $\hat{w} \in \operatorname{argmax}_w \prod_{i=1}^n p(D_i|w) \equiv \operatorname{argmin}_w - \sum_{i=1}^n \log(p(D_i|w))$

Least Squares is Gaussian MLE (Gory Details)

- Let's assume that $y_i = w^T x_i + \varepsilon_i$, with ε_i following standard normal:

$$p(\varepsilon_i) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\varepsilon_i^2}{2}\right)$$

also known
as "Gaussian"
distribution

- This leads to a Gaussian likelihood for example 'i' of the form:

$$p(y_i | x_i, w) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(w^T x_i - y_i)^2}{2}\right)$$

- Finding MLE (minimizing NLL) is least squares:

$$\begin{aligned} f(w) &= -\sum_{i=1}^n \log(p(y_i | w, x_i)) \\ &= -\sum_{i=1}^n \log\left(\frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(w^T x_i - y_i)^2}{2}\right)\right) \\ &= -\sum_{i=1}^n \left[\log\left(\frac{1}{\sqrt{2\pi}}\right) + \log\left(\exp\left(-\frac{(w^T x_i - y_i)^2}{2}\right)\right) \right] \end{aligned}$$

constant in 'w'

A

$$\begin{aligned} &\Rightarrow -\sum_{i=1}^n \left[(\text{constant}) - \frac{1}{2} (w^T x_i - y_i)^2 \right] \\ &= (\text{constant}) + \frac{1}{2} \sum_{i=1}^n (w^T x_i - y_i)^2 \\ &= (\text{constant}) + \frac{1}{2} \|Xw - y\|^2 \end{aligned}$$

operations cancel

Digression: “Generative” vs. “Discriminative”

- Notice, that we maximized conditional $p(y | X, w)$, not the likelihood $p(y, X | w)$.
 - We did MLE “conditioned” on the features ‘X’ being fixed (no “likelihood of X”).
 - This is called a “discriminative” supervised learning model.
 - A “generative” model (like naïve Bayes) would optimize $p(y, X | w)$.
- Discriminative probabilistic models:
 - Least squares, robust regression, logistic regression.
 - Can use complicated features because you don’t model ‘X’.
- Example of generative probabilistic models:
 - Naïve Bayes, linear discriminant analysis (makes Gaussian assumption).
 - Often need strong assumption because they model ‘X’.
- “Folk” belief: generative models are often better with small ‘n’.

Loss Functions and Maximum Likelihood Estimation

- So least squares is MLE under Gaussian likelihood.

If $p(y_i | x_i, w) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(w^T x_i - y_i)^2}{2}\right)$

then MLE of ' w ' is minimum of $f(w) = \frac{1}{2} \|Xw - y\|^2$

- With a Laplace likelihood you would get absolute error.

If $p(y_i | x_i, w) = \frac{1}{2} \exp(-|w^T x_i - y_i|)$

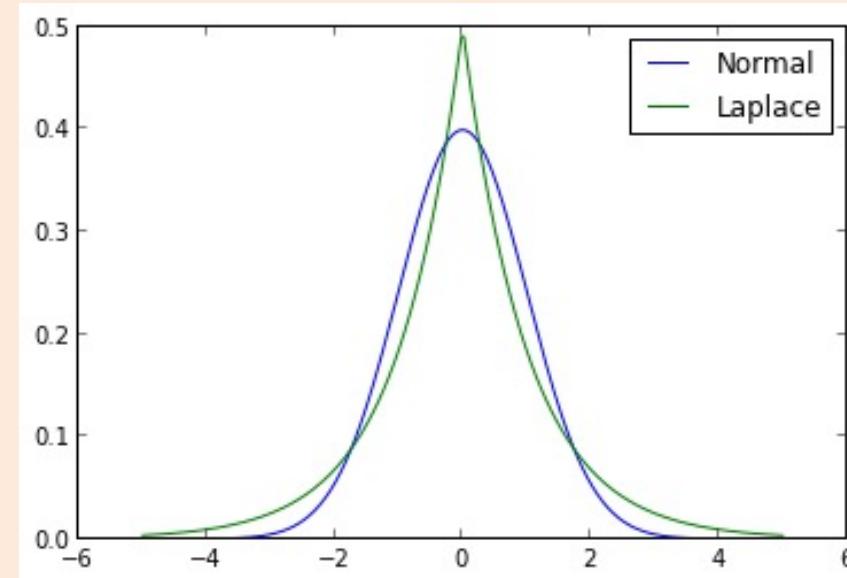
then MLE is minimum of $f(w) = \|Xw - y\|_1$

- Other likelihoods lead to different errors ("sigmoid" -> logistic loss).

bonus!

“Heavy” Tails vs. “Light” Tails

- We know that L1-norm is more robust than L2-norm.
 - What does this mean in terms of probabilities?



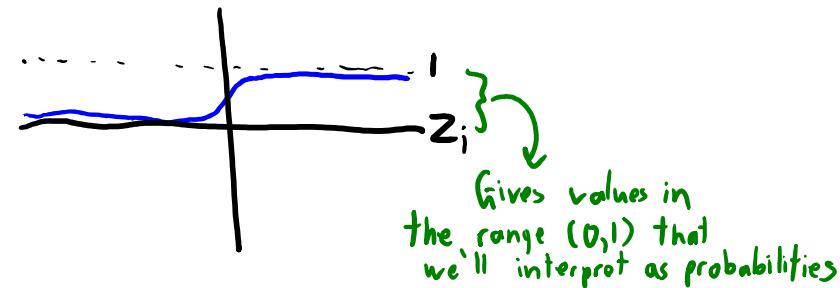
Here “tail” means
“mass of the
distribution away
from the mean.”

- Gaussian has “light tails”: assumes everything is close to mean.
- Laplace has “heavy tails”: assumes some data is far from mean.
- Student ‘t’ is even more heavy-tailed/robust, but NLL is non-convex.

Sigmoid: transforming $w^T x_i$ to a Probability

- Recall we got probabilities from binary linear models with **sigmoid**:
 1. The linear model $w^T x_i$ gives us a number in $z_i (-\infty, \infty)$.
 2. We'll map $z_i = w^T x_i$ to a probability with the **sigmoid function**.

$$h(z_i) = \frac{1}{1 + \exp(-z_i)}$$



- We can show that MLE with this model gives logistic loss.

Sigmoid: transforming $w^T x_i$ to a Probability

- We'll define $p(y_i = +1 | z_i) = h(z_i)$, where 'h' is the sigmoid function.

$$\begin{aligned} \text{So } p(y_i = -1 | z_i) &= 1 - p(y_i = +1 | z_i) \\ &= 1 - h(z_i) \quad \text{can show from} \\ &= h(-z_i) \quad \text{definition of 'h'} \end{aligned}$$

- With y_i in $\{-1, +1\}$, we can write both cases as $p(y_i | z_i) = h(y_i z_i)$.
- So we convert $z_i = w^T x_i$ into "probability of y_i " using:

$$\begin{aligned} p(y_i | w, x_i) &= h(y_i \underbrace{w^T x_i}_{z_i}) \\ &= \frac{1}{1 + \exp(-y_i w^T x_i)} \end{aligned}$$

- MLE with this likelihood is equivalent to minimizing logistic loss.

MLE Interpretation of Logistic Regression

- For IID regression problems the conditional NLL can be written:

$$\underbrace{-\log(p(y|X, w))}_{NLL} = -\log(\underbrace{\prod_{i=1}^n p(y_i|x_i, w)}_{IID \text{ assumption}}) = -\sum_{i=1}^n \log(p(y_i|x_i, w))$$

log turns product into sum

- Logistic regression assumes sigmoid($w^T x_i$) conditional likelihood:

$$p(y_i|x_i, w) = h(y_i w^T x_i) \quad \text{where} \quad h(z_i) = \frac{1}{1 + \exp(-z_i)}$$

- Plugging in the sigmoid likelihood, the NLL is the logistic loss:

$$NLL(w) = -\sum_{i=1}^n \log\left(\frac{1}{1 + \exp(-y_i w^T x_i)}\right) = \sum_{i=1}^n \log(1 + \exp(-y_i w^T x_i))$$

(since $\log(1) = 0$)

MLE Interpretation of Logistic Regression

- We just derived the logistic loss from the perspective of MLE.
 - Instead of “smooth convex approximation of 0-1 loss”, we now have that logistic regression is doing MLE in a probabilistic model.
 - The training and prediction would be the same as before.
 - We still minimize the logistic loss in terms of ‘w’.
 - But MLE justifies sigmoid for “probability that e-mail is important”:
- Similarly, NLL under the softmax likelihood is the softmax loss (for multi-class).

$$p(y_i | x_i, w) = \frac{1}{1 + \exp(-y_i w^T x_i)}$$

(pause)

Maximum Likelihood Estimation and Overfitting

- In our abstract setting with data D the MLE is:

$$\hat{w} \in \underset{w}{\operatorname{argmax}} \quad p(D|w)$$

- But conceptually MLE is a bit weird:
 - “Find the ‘w’ that makes ‘D’ have the highest probability given ‘w’.”
- And MLE often leads to overfitting:
 - Data could be very likely for some very unlikely ‘w’.
 - For example, a complex model that overfits by memorizing the data.
- What we really want:
 - “Find the ‘w’ that has the highest probability given the data D.”

Maximum a Posteriori (MAP) Estimation

- Maximum a posteriori (MAP) estimate maximizes the reverse probability:

$$\hat{w} \in \operatorname{argmax}_w p(w|D)$$

- This is what we want: the probability of ‘w’ given our data.

- MLE and MAP are connected by Bayes rule:

$$p(w|D) = \frac{p(D|w)p(w)}{p(D)} \propto p(D|w)p(w)$$

posterior likelihood prior

- So MAP maximizes the likelihood $p(D|w)$ times the prior $p(w)$:

- Prior is our “belief” that ‘w’ is correct before seeing data.
 - Prior can reflect that complex models are likely to overfit.

MAP Estimation and Regularization

- From Bayes rule, the MAP estimate with IID examples D_i is:

$$\hat{w} \in \arg\max_w p(w|D) \equiv \arg\max_w \prod_{i=1}^n [p(D_i|w)] p(w)$$

- By again taking the negative of the logarithm as before we get:

$$\hat{w} \in \arg\min_w -\sum_{i=1}^n [\underbrace{\log(p(D_i|w))}_{\text{loss}}] - \underbrace{\log(p(w))}_{\text{regularizer}}$$

- So we can view the negative log-prior as a regularizer:
 - Many regularizers are equivalent to negative log-priors.

L2-Regularization and MAP Estimation

- We obtain L2-regularization under an independent Gaussian assumption:

Assume each w_j comes from a Gaussian with mean 0 and variance $\frac{1}{\lambda}$

- This implies that:

$$p(w) = \prod_{j=1}^d p(w_j) \propto \prod_{j=1}^d \exp\left(-\frac{\lambda}{2} w_j^2\right) = \exp\left(-\frac{\lambda}{2} \sum_{j=1}^d w_j^2\right)$$

independence Gaussian assumption $e^\alpha e^\beta = e^{\alpha + \beta}$

- So we have that:

$$-\log(p(w)) = -\log\left(\exp\left(-\frac{\lambda}{2}\|w\|^2\right)\right) + (\text{constant}) = \frac{\lambda}{2}\|w\|^2 + (\text{constant})$$

- With this prior, the MAP estimate with IID training examples would be

$$\hat{w} \in \arg\min -\log(p(y|x, w)) - \log(p(w)) \equiv \arg\min_w - \sum_{i=1}^n [\log(p(y_i|x_i, w))] + \frac{\lambda}{2}\|w\|^2$$

MAP Estimation and Regularization

- MAP estimation gives link between probabilities and loss functions.
 - Gaussian likelihood ($\sigma = 1$) + Gaussian prior gives L2-regularized least squares.

If $p(y_i | x_i, w) \propto \exp\left(-\frac{(w^T x_i - y_i)^2}{2}\right)$ $p(w_j) \propto \exp\left(-\frac{\lambda}{2} w_j^2\right)$

then MAP estimation is equivalent to minimizing $f(w) = \frac{1}{2} \|Xw - y\|^2 + \frac{\lambda}{2} \|w\|^2$

- Laplace likelihood ($\sigma = 1$) + Gaussian prior give L2-regularized robust regression:

If $p(y_i | x_i, w) \propto \exp\left(-|w^T x_i - y_i|\right)$ $p(w) \propto \exp\left(-\frac{\lambda}{2} w_j^2\right)$

then MAP estimation is equivalent to minimizing $f(w) = \|Xw - y\|_1 + \frac{\lambda}{2} \|w\|^2$

- As 'n' goes to infinity, effect of prior/regularizer goes to zero.
- Unlike with MLE, the choice of σ changes the MAP solution for these models.

Summarizing the past few slides

- Many of our **loss functions and regularizers have probabilistic interpretations.**
 - Laplace likelihood leads to absolute error.
 - Laplace prior leads to L1-regularization.
- The choice of **likelihood** corresponds to the choice of **loss**.
 - Our assumptions about how the y_i -values can come from the x_i and ‘w’.
- The choice of **prior** corresponds to the choice of **regularizer**.
 - Our assumptions about which ‘w’ values are plausible.

bonus!

Regularizing Other Models

- We can view priors in other models as regularizers.
- Remember the problem with MLE for naïve Bayes:
 - The MLE of $p(\text{'lactase'} = 1 \mid \text{'spam'})$ is: $\text{count(spam,lactase)}/\text{count(spam)}$.
 - But this caused problems if $\text{count(spam,lactase)} = 0$.
- Our solution was Laplace smoothing:
 - Add “+1” to our estimates: $(\text{count(spam,lactase)}+1)/(\text{counts(spam)}+2)$.
 - This corresponds to a “Beta” prior so Laplace smoothing is a regularizer.

(pause)

bonus!

Why do we care about MLE and MAP?

- Unified way of thinking about many of our tricks?
 - Probabilistic interpretation of logistic loss.
 - Laplace smoothing and L2-regularization are doing the same thing.
- Remember our two ways to reduce overfitting in complicated models:
 - Model averaging (ensemble methods).
 - Regularization (linear models).
- “Fully”-Bayesian methods (CPSC 440, 532W) combine both of these.
 - Average over all models, weighted by posterior (including regularizer).
 - Can use extremely-complicated models without overfitting.

bonus!

Losses for Other Discrete Labels

- MLE/MAP gives loss for classification with basic labels:
 - Least squares and absolute loss for regression.
 - Logistic regression for binary labels {"spam", "not spam"}.
 - Softmax regression for multi-class {"spam", "not spam", "important"}.
- But MLE/MAP lead to losses with other discrete labels (bonus):
 - Ordinal: {1 star, 2 stars, 3 stars, 4 stars, 5 stars}.
 - Counts: 602 'likes'.
 - Survival rate: 60% of patients were still alive after 3 years.
 - Unbalanced classes: 99.9% of examples are classified as +1.
- Define likelihood of labels, and use NLL as the loss function.
- We can also use ratios of probabilities to define more losses (bonus):
 - Binary SVMs, multi-class SVMs, and “pairwise preferences” (ranking) models.

End of Part 3: Key Concepts

- Linear models predict based on linear combination(s) of features:

$$w^T x_i = w_1 x_{i1} + w_2 x_{i2} + \dots + w_d x_{id}$$

- We model non-linear effects using a change of basis:

- Replace d-dimensional x_i with k-dimensional z_i and use $v^T z_i$.
 - Examples include polynomial basis and (non-parametric) RBFs.

- Regression is supervised learning with continuous labels.

- Logical error measure for regression is squared error:

$$f(w) = \frac{1}{2} \|X_w - y\|^2$$

- Can be solved as a system of linear equations.

End of Part 3: Key Concepts

- Gradient descent finds local minimum of smooth objectives.
 - Converges to a global optimum for convex functions.
 - Can use smooth approximations (Huber, log-sum-exp)
- Stochastic gradient methods allow huge/infinite ‘n’.
 - Though very sensitive to the step-size.
- Kernels let us use similarity between examples, instead of features.
 - Lets us use some exponential- or infinite-dimensional features.
- Feature selection is a messy topic.
 - Classic method is forward selection based on L0-norm.
 - L1-regularization simultaneously regularizes and selects features.

End of Part 3: Key Concepts

- We can reduce over-fitting by using regularization:

$$f(w) = \frac{1}{2} \|Xw - y\|^2 + \frac{\lambda}{2} \|w\|^2$$

- Squared error is not always right measure:
 - Absolute error is less sensitive to outliers.
 - Logistic loss and hinge loss are better for binary y_i .
 - Softmax loss is better for multi-class y_i .
- MLE/MAP perspective:
 - We can view loss as log-likelihood and regularizer as log-prior.
 - Allows us to define losses based on probabilities.

The Story So Far...

- Part 1: Supervised Learning.
 - Methods based on **counting and distances**.
- Part 2: Unsupervised Learning.
 - Methods based on **counting and distances**.
- Part 3: Supervised Learning (just finished).
 - Methods based on **linear models and gradient descent**.
- Part 4: Unsupervised Learning (next time).
 - Methods based on **linear models and gradient descent**.

Summary

- Maximum likelihood estimate viewpoint of common models.
 - Objective functions are equivalent to maximizing $p(y, X | w)$ or $p(y | X, w)$.
- MAP estimation directly models $p(w | X, y)$.
 - Gives probabilistic interpretation to regularization.
- Losses for weird scenarios are possible using MLE/MAP:
 - Ordinal labels, count labels, censored labels, unbalanced labels.
- Next time:
 - What ‘parts’ are your personality made of?

bonus!

Discussion: Least Squares and Gaussian Assumption

- Classic **justifications for the Gaussian assumption** underlying least squares:
 - Your **noise might really be Gaussian**. (It probably isn't, but maybe it's a good enough approximation.)
 - The **central limit theorem** (CLT) from probability theory. (If you add up enough IID random variables, the estimate of their mean converges to a Gaussian distribution.)
- I think the CLT justification is wrong as we've never assumed that the x_{ij} are IID across 'j' values. We only assumed that the examples x_i are IID across 'i' values, so the CLT implies that our estimate of 'w' would be a Gaussian distribution under different samplings of the data, but this says nothing about the distribution of y_i given $w^T x_i$.
- On the other hand, there are reasons ***not*** to use a Gaussian assumption, like it's sensitivity to outliers. This was (apparently) what lead Laplace to propose the Laplace distribution as a more robust model of the noise.
- The "student t" distribution (published anonymously by Gosset while working at the Guiness beer company) is even more robust, but doesn't lead to a convex objective.

bonus!

Binary vs. Multi-Class Logistic

- How does multi-class logistic generalize the binary logistic model?
- We can re-parameterize softmax in terms of (k-1) values of z_c :

$$p(y|z_1, z_2, \dots, z_{k-1}) = \frac{\exp(z_y)}{1 + \sum_{c=1}^{k-1} \exp(z_c)} \quad \text{if } y \neq k \quad \text{and} \quad p(y|z_1, z_2, \dots, z_{k-1}) = \frac{1}{1 + \sum_{c=1}^{k-1} \exp(z_c)} \quad \text{if } y = k$$

- This is due to the “sum to 1” property (one of the z_c values is redundant).
- So if $k=2$, we don’t need a z_2 and only need a single ‘ z ’.
- Further, when $k=2$ the probabilities can be written as:

$$p(y=1|z) = \frac{\exp(z)}{1 + \exp(z)} \quad p(y=2|z) = \frac{1}{1 + \exp(z)}$$

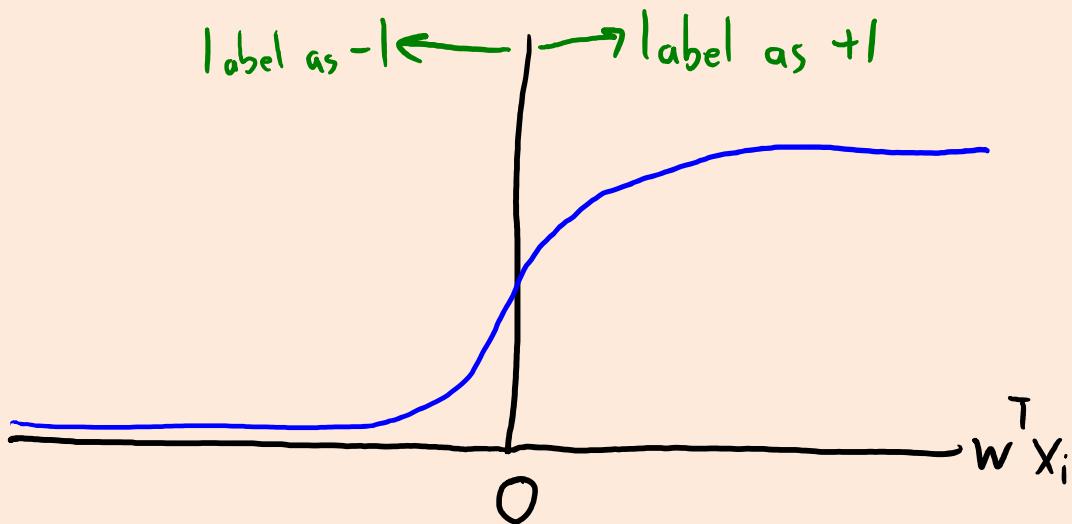
- Renaming ‘2’ as ‘-1’, we get the **binary logistic regression** probabilities.

bonus!

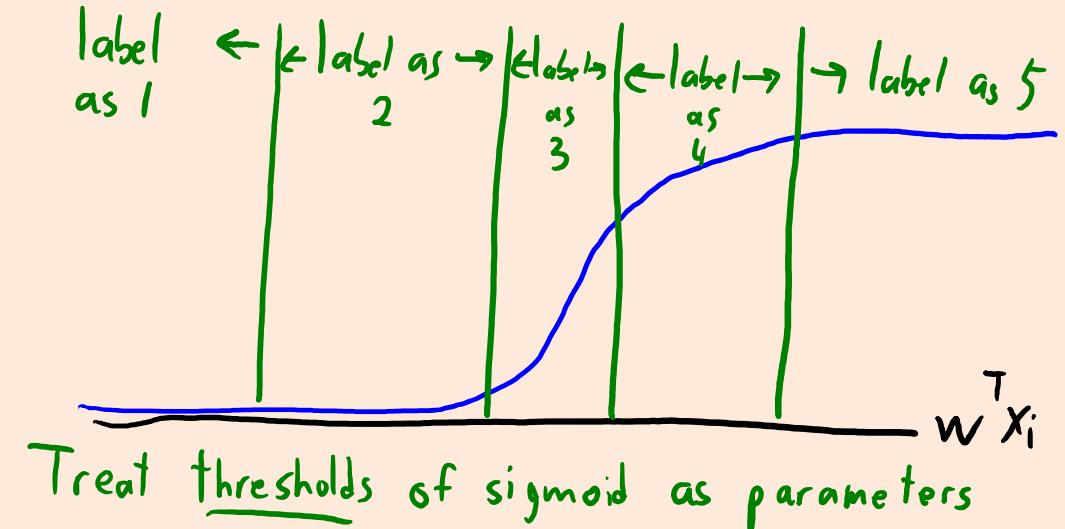
Ordinal Labels

- **Ordinal data:** categorical data where the **order matters**:
 - Rating hotels as {‘1 star’, ‘2 stars’, ‘3 stars’, ‘4 stars’, ‘5 stars’}.
 - Softmax would ignore order.
- Can use ‘ordinal logistic regression’.

Logistic regression



Ordinal logistic regression



Treat thresholds of sigmoid as parameters

bonus!

Count Labels

- Count data: predict the number of times something happens.
 - For example, $y_i = "602"$ Facebook likes.
- Softmax requires finite number of possible labels.
- We probably don't want separate parameter for '654' and '655'.
- Poisson regression: use probability from Poisson count distribution.
 - Many variations exist, a lot of people think this isn't the best likelihood.

Censored Survival Analysis (Cox Partial Likelihood)

bonus!

- Censored survival analysis:
 - Target y_i is last time at which we know person is alive.
 - But some people are still alive (so they have the same y_i values).
 - The y_i values (time at which they die) are “censored”.
 - We use $v_i=0$ if they are still alive and otherwise we set $v_i = 1$.
- Cox partial likelihood assumes “instantaneous” rate of dying depends on x_i but not on total time they’ve been alive (not that realistic). Leads to likelihood of the “censored” data of the form:

$$P(y_i, v_i | x_i, w) = \exp(v_i w^\top x_i) \exp(-y_i \exp(w^\top x_i))$$

- There are many extensions and alternative likelihoods.

bonus!

Other Parsimonious Parameterizations

- Sigmoid isn't the way to model a binary $p(y_i \mid x_i, w)$:
 - Probit (uses CDF of normal distribution, very similar to logistic).
 - Noisy-Or (simpler to specify probabilities by hand).
 - Extreme-value loss (good with class imbalance).
 - Cauchit, Gosset, and many others exist...

Unbalanced Training Sets

- Consider the case of binary classification where your training set has 99% class -1 and **only 1% class +1**.
 - This is called an “**unbalanced**” training set
- Question: is this a problem?
- Answer: it depends!
 - If these **proportions are representative of the test set proportions**, and you care about both types of errors equally, then “no” it’s not a problem.
 - You can get 99% accuracy by just always predicting -1, so ML can only help with the 1%.
 - But it’s a **problem if the test set is not like the training set** (e.g. your data collection process was biased because it was easier to get -1’s)
 - It’s also a **problem if you care more about one type of error**, e.g. if mislabeling a +1 as a -1 is much more of a problem than the opposite
 - For example if +1 represents “tumor” and -1 is “no tumor”

Unbalanced Training Sets

- This issue comes up a lot in practice!
- How to fix the problem of unbalanced training sets?
 - Common strategy is to build a “**weighted**” model:
 - Put higher weight on the training examples with $y_i=+1$.

$$f(w) = \sum_{i=1}^n v_i \log(1 + \exp(-y_i w^T x_i))$$

Make this weight bigger
for under-represented class

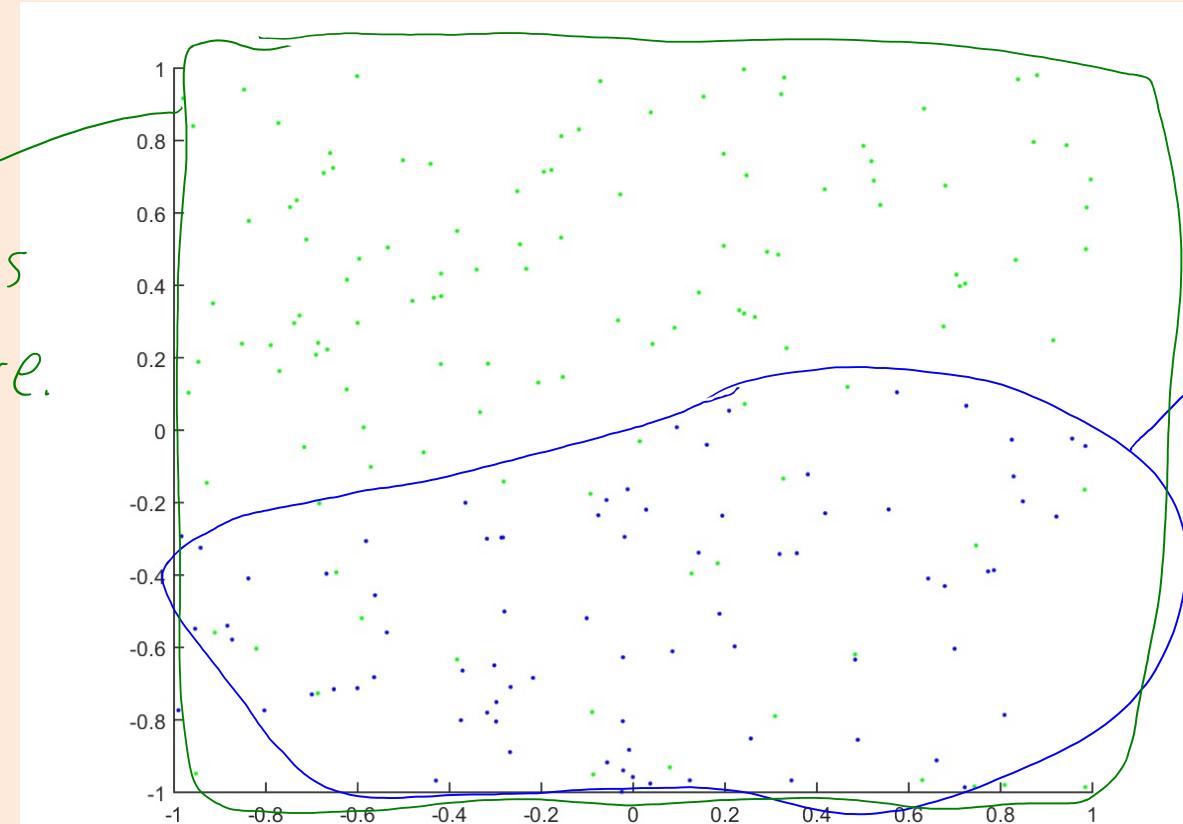
- This is equivalent to replicating those examples in the training set.
- You could also subsample the majority class to make things more balanced.
- Bootstrap: create a dataset of size ‘n’ where $n/2$ are sampled from +1, $n/2$ from -1.
- Another approach is to try to make “fake” data to fill in minority class.
- Another option is to change to an **asymmetric loss function** (next slides) that penalizes one type of error more than the other.
- Some discussion of different methods [here](#).

bonus!

Unbalanced Data and Extreme-Value Loss

- Consider binary case where:
 - One class overwhelms the other class ('unbalanced' data).
 - Really important to find the minority class (e.g., minority class is tumor).

"majority" class
is everywhere.



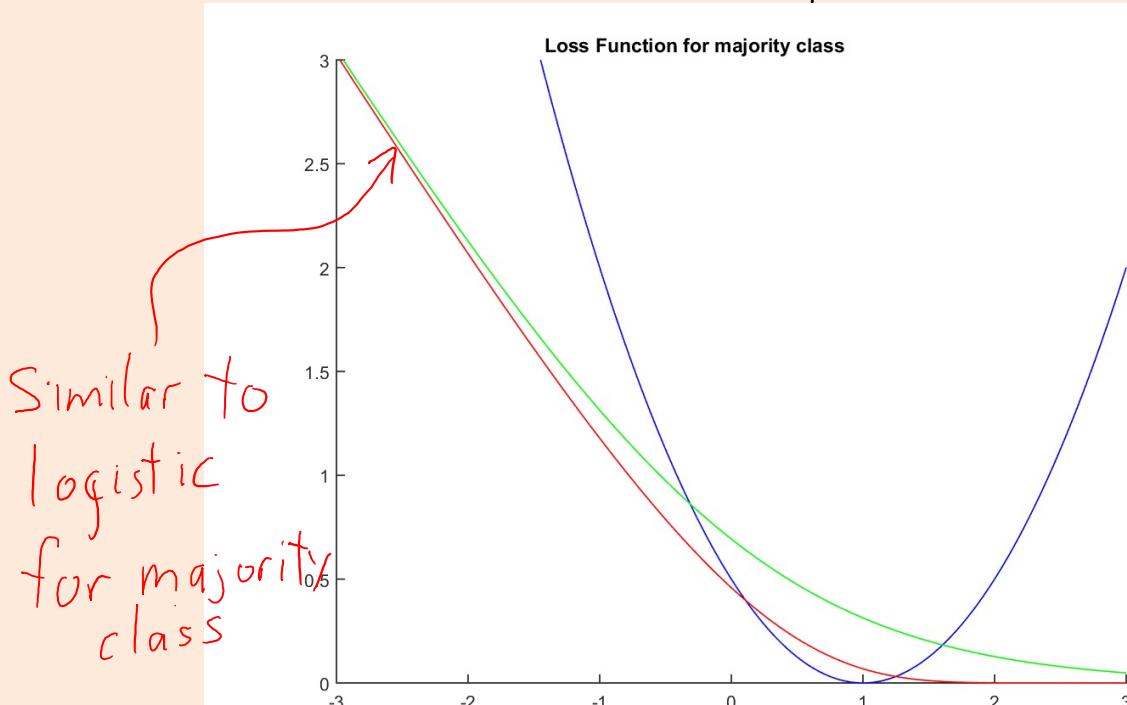
bonus!

Unbalanced Data and Extreme-Value Loss

- Extreme-value distribution:

$$p(y_i = +1 | \hat{y}_i) = 1 - \exp(-\exp(\hat{y}_i)) \quad [+1 \text{ is majority class}] \quad \xrightarrow{\text{asymmetric}}$$

To make it a probability, $p(y_i = -1 | \hat{y}_i) = \exp(-\exp(\hat{y}_i))$



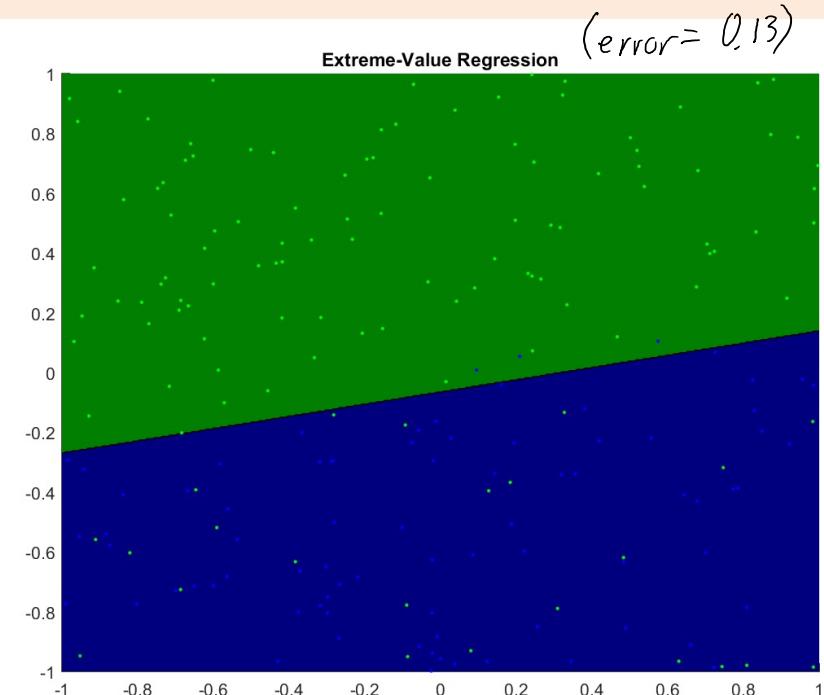
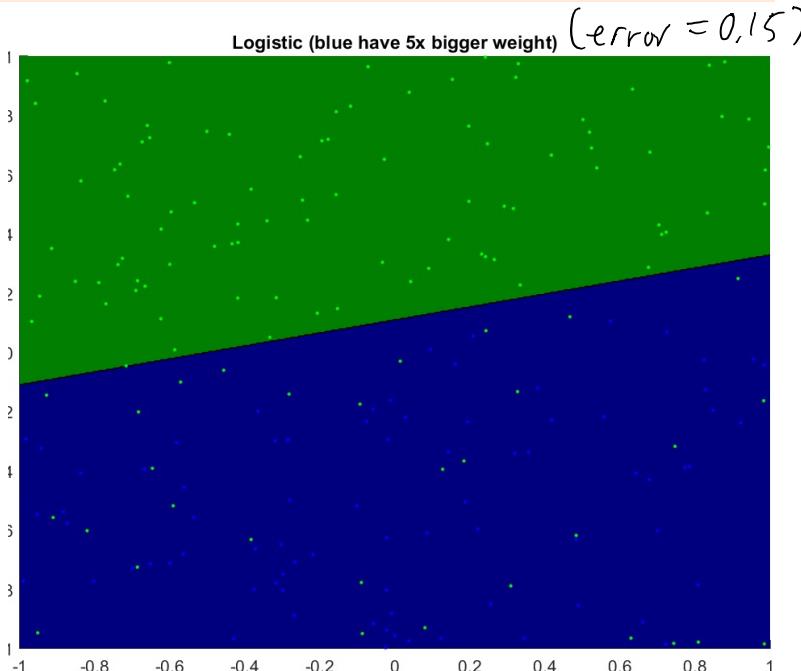
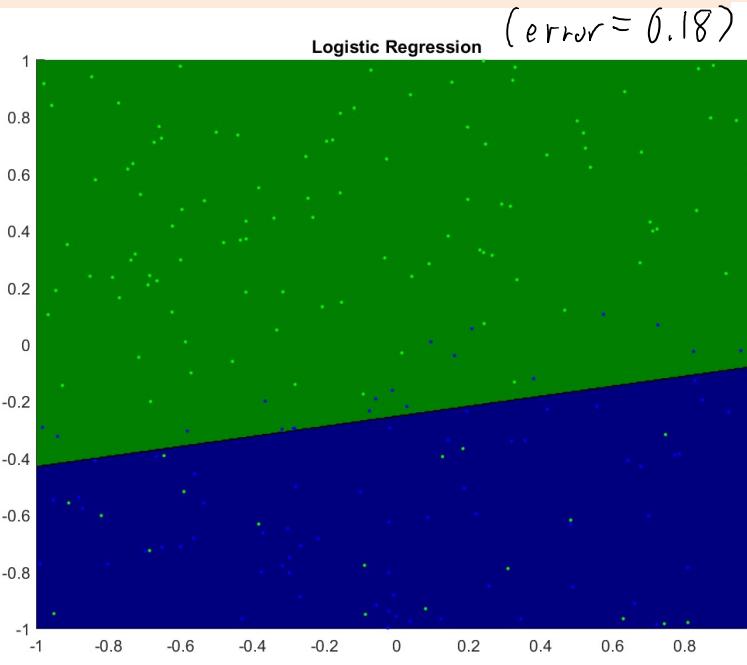
bonus!

Unbalanced Data and Extreme-Value Loss

- **Extreme-value distribution:**

$$p(y_i = +1 | \hat{y}_i) = 1 - \exp(-\exp(\hat{y}_i)) \quad [+1 \text{ is majority class}] \quad \xrightarrow{\text{asymmetric}}$$

To make it a probability, $p(y_i = -1 | \hat{y}_i) = \exp(-\exp(\hat{y}_i))$



bonus!

Loss Functions from Probability Ratios

- We've seen that loss functions can come from probabilities:
 - Gaussian => squared loss, Laplace => absolute loss, sigmoid => logistic.
- Most other loss functions can be derived from probability ratios.
 - Example: sigmoid => hinge.

$$p(y_i | x_i, w) = \frac{1}{1 + \exp(-y_i w^T x_i)} = \frac{\exp(\frac{1}{2} y_i w^T x_i)}{\exp(\frac{1}{2} y_i w^T x_i) + \exp(-\frac{1}{2} y_i w^T x_i)} \propto \exp(\frac{1}{2} y_i w^T x_i)$$

*Same normalizing constant
for $y_i = +1$ and $x_i = -1$*

bonus!

Loss Functions from Probability Ratios

- We've seen that loss functions can come from probabilities:
 - Gaussian => squared loss, Laplace => absolute loss, sigmoid => logistic.
- Most other loss functions can be derived from probability ratios.
 - Example: sigmoid => hinge.

$$p(y_i | x_i, w) \propto \exp\left(\frac{1}{2} y_i w^T x_i\right)$$

To classify y_i correctly, it's sufficient to have $\frac{p(y_i | x_i, w)}{p(-y_i | x_i, w)} > \beta$ for some ' β ' > 1

Notice that normalizing constant doesn't matter:

$$\frac{\exp\left(\frac{1}{2} y_i w^T x_i\right)}{\exp\left(-\frac{1}{2} y_i w^T x_i\right)} > \beta$$

bonus!

Loss Functions from Probability Ratios

- We've seen that loss functions can come from probabilities:
 - Gaussian => squared loss, Laplace => absolute loss, sigmoid => logistic.
- Most other loss functions can be derived from probability ratios.
 - Example: sigmoid => hinge.

$$p(y_i | x_i, w) \propto \exp\left(\frac{1}{2} y_i w^T x_i\right)$$

We need: $\frac{\exp(\frac{1}{2} y_i w^T x_i)}{\exp(-\frac{1}{2} y_i w^T x_i)} \geq \beta$

Take \log :

$$\log\left(\frac{\exp(\frac{1}{2} y_i w^T x_i)}{\exp(-\frac{1}{2} y_i w^T x_i)}\right) \geq \log(\beta) \iff \frac{1}{2} y_i w^T x_i + \frac{1}{2} y_i w^T x_i \geq \log(\beta)$$

$$y_i w^T x_i \geq 1 \quad (\text{if we choose } \log(\beta) = 1)$$

bonus!

Loss Functions from Probability Ratios

- We've seen that loss functions can come from probabilities:
 - Gaussian => squared loss, Laplace => absolute loss, sigmoid => logistic.
- Most other loss functions can be derived from probability ratios.
 - Example: sigmoid => hinge.

$$p(y_i | x_i, w) \propto \exp\left(\frac{1}{2} y_i w^T x_i\right)$$

We need: $\frac{\exp(\frac{1}{2} y_i w^T x_i)}{\exp(-\frac{1}{2} y_i w^T x_i)} \geq \beta$

Or equivalently:

$$y_i w^T x_i \geq 1 \quad (\text{for } \beta = \exp(1))$$

Define a loss function by amount of constraint violation:

$$\max \{ 0, 1 - y_i w^T x_i \}$$

We get SVMs by looking at regularized average loss:
 $f(w) = \sum_{i=1}^n \max\{0, 1 - y_i w^T x_i\} + \frac{1}{2} \|w\|^2$

bonus!

Loss Functions from Probability Ratios

- General approach for defining losses using probability ratios:
 - Define constraint based on probability ratios.
 - Minimize violation of logarithm of constraint.
- Example: softmax => multi-class SVMs.

Assume: $p(y_i = c | x_i, w) \propto \exp(w_c^T x_i)$

Want: $\frac{p(y_i | x_i, w)}{p(y_i = c' | x_i, w)} \geq \beta$ for all c' and some $\beta > 1$

For $\beta = \exp(1)$ equivalent to

$$w_{y_i}^T x_i - w_{c'}^T x_i \geq 1 \quad \text{for all } c' \neq y_i$$

Option 1: penalize all violations:

$$\sum_{c'=1}^K \max\{0, 1 - w_{y_i}^T x_i + w_{c'}^T x_i\}$$

Option 2: penalize only max violation:

$$\max_{c' \neq c} \left\{ \max\{0, 1 - w_{y_i}^T x_i + w_{c'}^T x_i\} \right\}$$

Supervised Ranking with Pairwise Preferences

bonus!

- Ranking with pairwise preferences:

- We aren't given any explicit y_i values.
- Instead we're given list of objects (i,j) where $y_i > y_j$.

Assume $p(y_i | X, w) \propto \exp(w^T x_i)$ is probability that object ' i ' has highest rank.

Want: $\frac{p(y_i | X, w)}{p(y_j | X, w)} \geq \beta$ for all preferences (i, j)

For $\beta = \exp(1)$ equivalent to

$$w^T x_i - w^T x_j \geq 1$$

for preferences (i, j)

→ We can use $f(w) = \sum_{(i,j) \in R} \max\{0, 1 - w^T x_i + w^T x_j\}$

This approach can also be used to define losses for total/partial orderings. (but this information is hard to get)