



Logistic Regression

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based on the slides of Vibhav Gogate

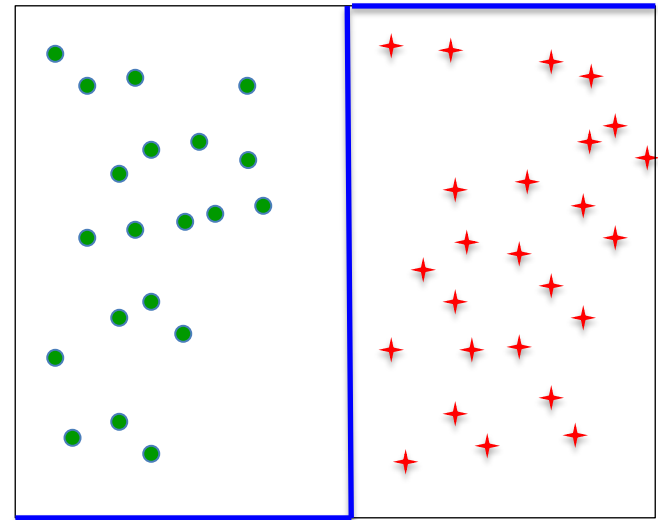
- Supervised learning via naive Bayes
 - Use MLE to estimate a distribution $p(x, y) = p(y)p(x|y)$
 - Classify by looking at the conditional distribution, $p(y|x)$
- Today: logistic regression

Logistic Regression



- Learn $p(Y|X)$ directly from the data
 - Assume a particular functional form, e.g., a linear classifier $p(Y = 1|x) = 1$ on one side and 0 on the other
 - Not differentiable...
 - Makes it difficult to learn
 - Can't handle noisy labels

$$p(Y = 1|x) = 0$$



$$p(Y = 1|x) = 1$$

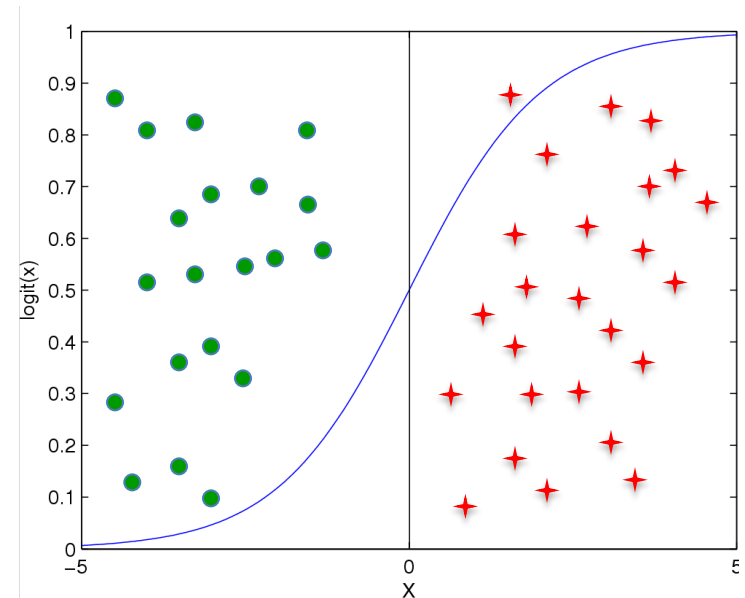
Logistic Regression



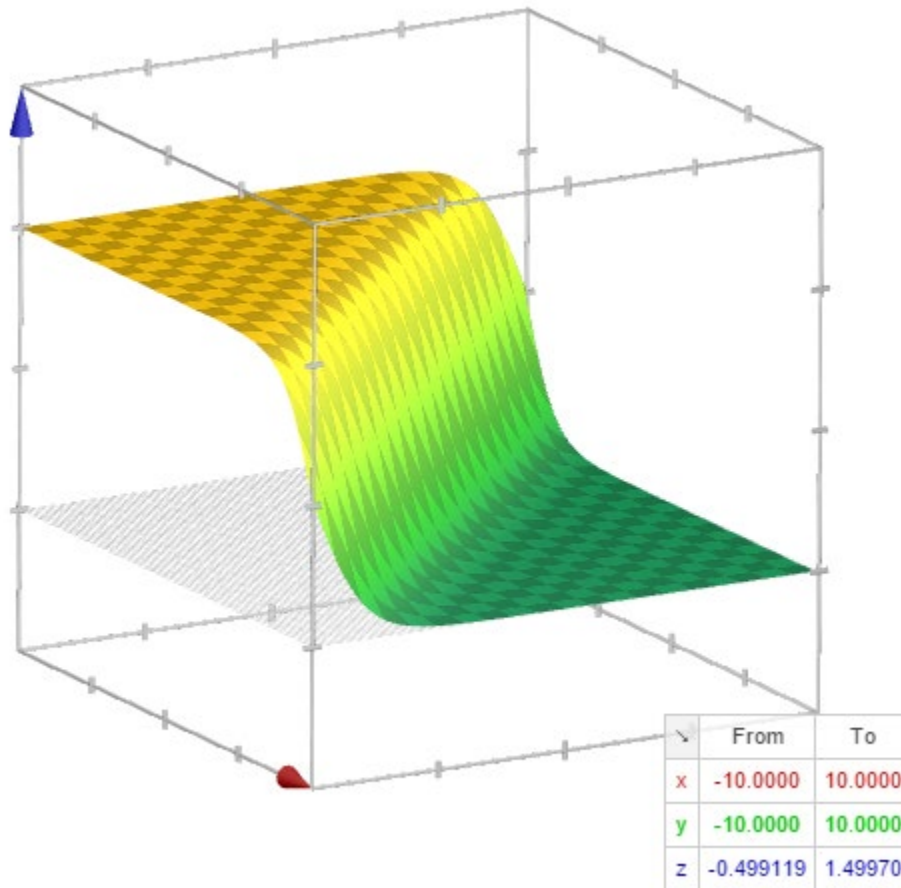
- Learn $p(y|x)$ directly from the data
- Assume a particular functional form

$$p(Y = -1|x) = \frac{1}{1 + \exp(w^T x + b)}$$

$$p(Y = 1|x) = \frac{\exp(w^T x + b)}{1 + \exp(w^T x + b)}$$



Logistic Function in m Dimensions



$$p(Y = -1|x) = \frac{1}{1 + \exp(w^T x + b)}$$

**Can be applied to
discrete and
continuous features**

Functional Form: Two classes



- Given some w and b , we can classify a new point x by assigning the label 1 if $p(Y = 1|x) > p(Y = -1|x)$ and -1 otherwise
 - This leads to a linear classification rule:
 - Classify as a 1 if $w^T x + b > 0$
 - Classify as a -1 if $w^T x + b < 0$

- To learn the weights, we maximize the **conditional likelihood**

$$(w^*, b^*) = \arg \max_{w, b} \prod_{i=1}^N p(y^{(i)} | x^{(i)}, w, b)$$

- This is not the same strategy that we used in the case of naive Bayes
 - For naive Bayes, we maximized the log-likelihood

Generative vs. Discriminative Classifiers

Generative classifier: (e.g., Naïve Bayes)

- Assume some **functional form** for $p(x|y), p(y)$
- Estimate parameters of $p(x|y), p(y)$ directly from training data
- Use Bayes rule to calculate $p(y|x)$
- This is a **generative model**
 - **Indirect** computation of $p(Y|X)$ through Bayes rule
 - As a result, **can also generate a sample of the data**,
$$p(x) = \sum_y p(y)p(x|y)$$

Discriminative classifiers: (e.g., Logistic Regression)

- Assume some **functional form for $p(y|x)$**
- Estimate parameters of $p(y|x)$ directly from training data
- This is a **discriminative model**
 - Directly learn $p(y|x)$
 - But **cannot obtain a sample of the data** as $p(x)$ is not available
 - Useful for discriminating labels

Learning the Weights



$$\begin{aligned}\ell(w, b) &= \ln \prod_{i=1}^N p(y^{(i)} | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \ln p(y^{(i)} | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} \ln p(Y = 1 | x^{(i)}, w, b) + \left(1 - \frac{y^{(i)} + 1}{2}\right) \ln p(Y = -1 | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} \ln \frac{p(Y = 1 | x^{(i)}, w, b)}{p(Y = -1 | x^{(i)}, w, b)} + \ln p(Y = -1 | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} (w^T x^{(i)} + b) - \ln(1 + \exp(w^T x^{(i)} + b))\end{aligned}$$

Learning the Weights



$$\begin{aligned}\ell(w, b) &= \ln \prod_{i=1}^N p(y^{(i)} | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \ln p(y^{(i)} | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} \ln p(Y = 1 | x^{(i)}, w, b) + \left(1 - \frac{y^{(i)} + 1}{2}\right) \ln p(Y = -1 | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} \ln \frac{p(Y = 1 | x^{(i)}, w, b)}{p(Y = -1 | x^{(i)}, w, b)} + \ln p(Y = -1 | x^{(i)}, w, b) \\ &= \sum_{i=1}^N \frac{y^{(i)} + 1}{2} (w^T x^{(i)} + b) - \ln(1 + \exp(w^T x^{(i)} + b))\end{aligned}$$

This is concave in w and b : take derivatives and solve!

Learning the Weights



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No closed form solution ☹️

- Can apply gradient **ascent** to maximize the conditional likelihood

$$\frac{\partial \ell}{\partial b} = \sum_{i=1}^N \left[\frac{y^{(i)} + 1}{2} - p(Y = 1 | x^{(i)}, w, b) \right]$$

$$\frac{\partial \ell}{\partial w_j} = \sum_{i=1}^N x_j^{(i)} \left[\frac{y^{(i)} + 1}{2} - p(Y = 1 | x^{(i)}, w, b) \right]$$

- Can define priors on the weights to prevent overfitting
 - Normal distribution, zero mean, identity covariance

$$p(w) = \prod_j \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{w_j^2}{2\sigma^2}\right)$$

- “Pushes” parameters towards zero
- Regularization
 - Helps avoid very large weights and overfitting

- The log-MAP objective with this Gaussian prior is then

$$\ln \prod_{i=1}^N p(y^{(i)} | x^{(i)}, w, b) p(w) p(b) = \left[\sum_i^N \ln p(y^{(i)} | x^{(i)}, w, b) \right] - \frac{\lambda}{2} \|w\|_2^2$$

- Quadratic penalty: drives weights towards zero
- Adds a negative linear term to the gradients
- Different priors can produce different kinds of regularization

Priors as Regularization

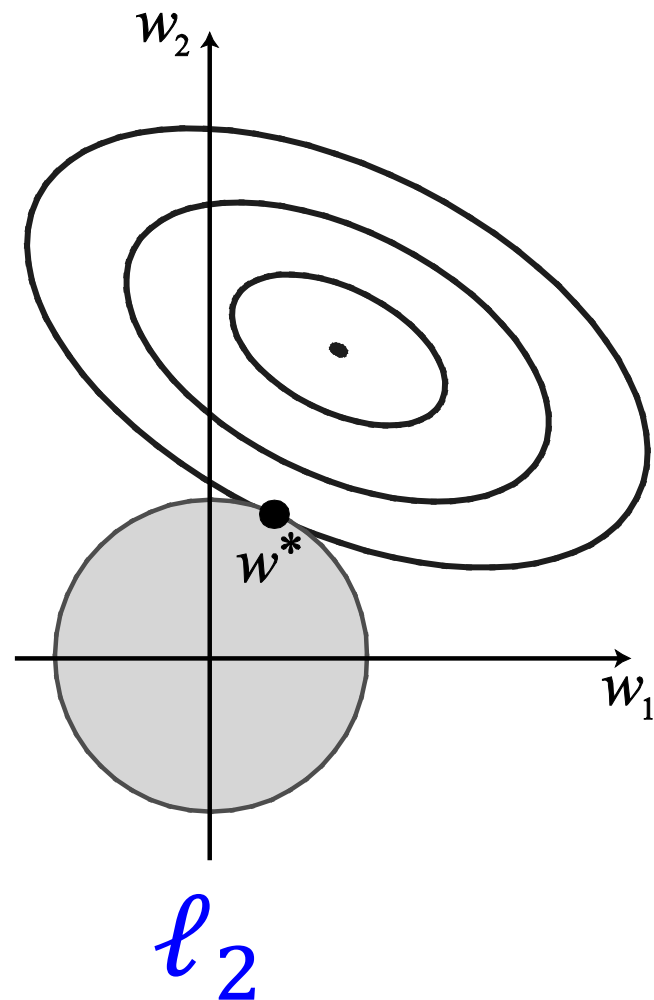
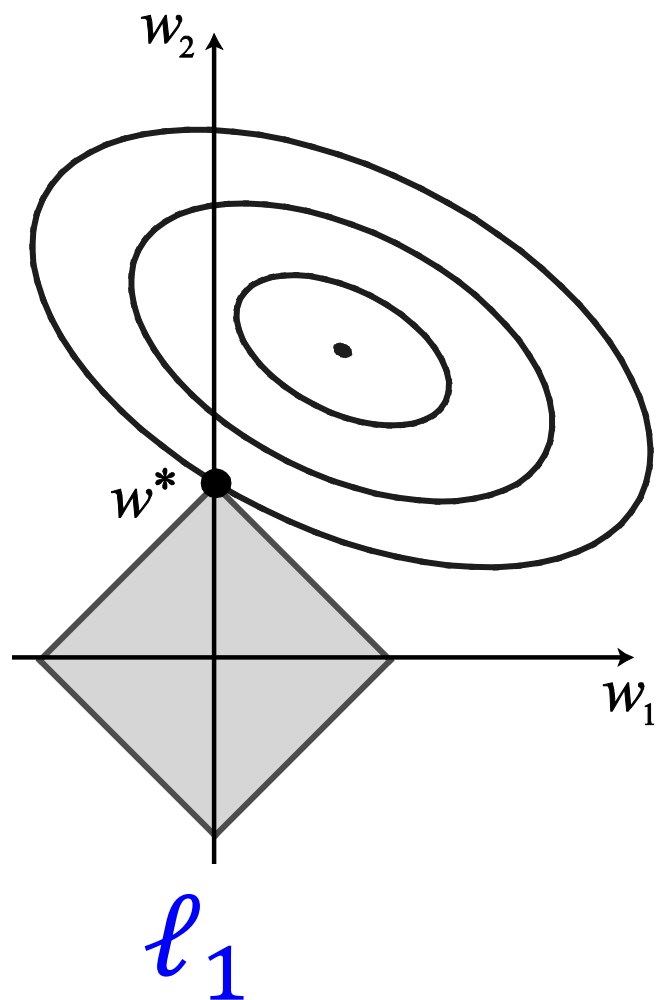


- The log-MAP objective with this Gaussian prior is then

$$\ln \prod_{i=1}^N p(y^{(i)} | x^{(i)}, w, b) p(w) p(b) = \left[\sum_i^N \ln p(y^{(i)} | x^{(i)}, w, b) \right] - \frac{\lambda}{2} \|w\|_2^2$$

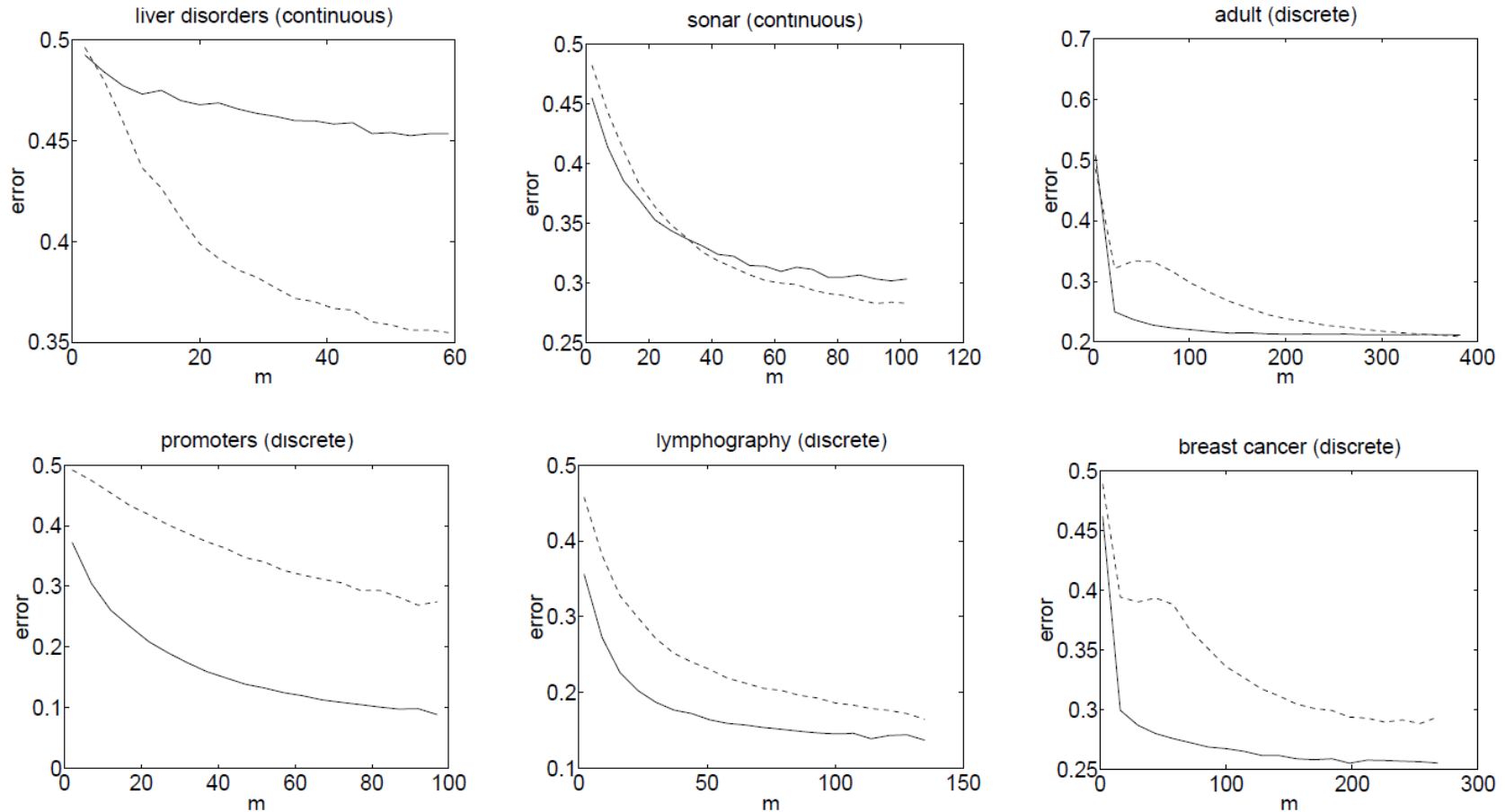
- Quadratic penalty: drives weights towards zero
 - Adds a negative linear term to the gradients
 - Different priors can produce different kinds of regularization
- Sometimes called an ℓ_2 regularizer
-
- A red arrow originates from the text 'Sometimes called an l2 regularizer' and points upwards and to the left towards the
- $-\frac{\lambda}{2} \|w\|_2^2$
- term in the equation above.

Regularization



- Non-asymptotic analysis (for Gaussian NB)
 - Convergence rate of parameter estimates as size of training data tends to infinity ($n = \#$ of attributes in X)
 - Naïve Bayes needs $O(\log n)$ samples
 - NB converges quickly to its (perhaps less helpful) asymptotic estimates
 - Logistic Regression needs $O(n)$ samples
 - LR converges more slowly but makes no independence assumptions (typically less biased)

NB vs. LR (on UCI datasets)



— Naïve bayes
..... Logistic Regression

Sample size m

- Suppose that $y \in \{1, \dots, R\}$, i.e., that there are R different class labels
- Can define a collection of weights and biases as follows
 - Choose a vector of biases and a matrix of weights such that for $y \neq R$

$$p(Y = k|x) = \frac{\exp(b_k + \sum_i w_{ki}x_i)}{1 + \sum_{j < R} \exp(b_j + \sum_i w_{ji}x_i)}$$

and

$$p(Y = R|x) = \frac{1}{1 + \sum_{j < R} \exp(b_j + \sum_i w_{ji}x_i)}$$