Classification:
Logistic Regression

Step 1: Function Set

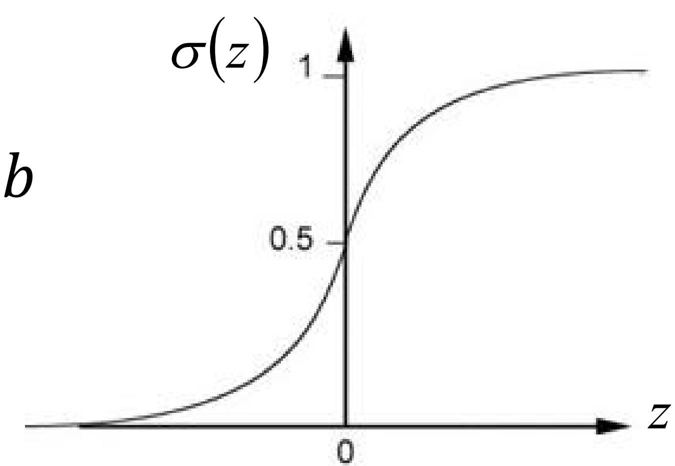
Function set: **Including all different w and b**

$$\begin{cases} z \geq 0 & \text{class 1} \\ z < 0 & \text{class 2} \end{cases}$$

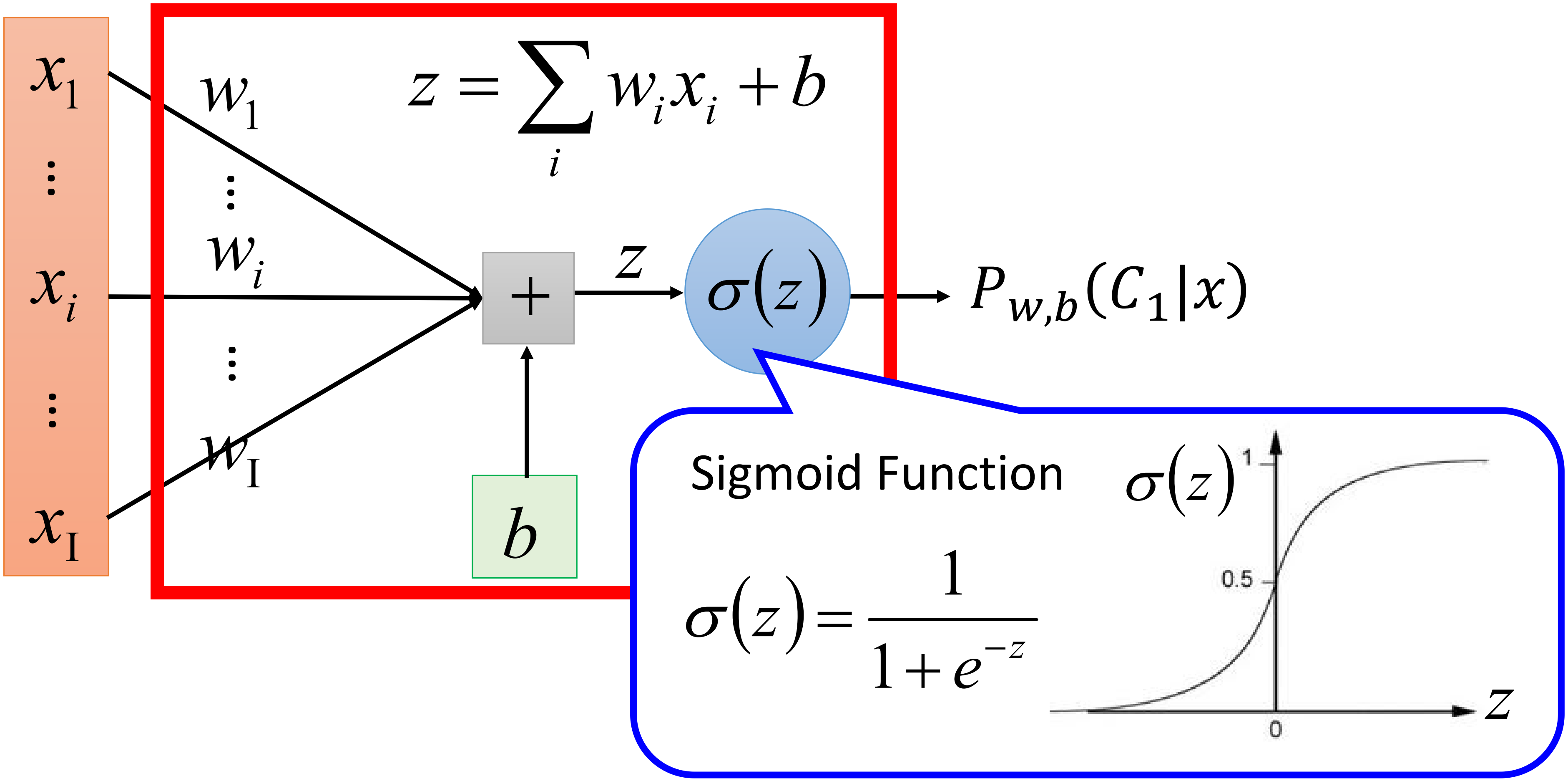
$$P_{w,b}(C_1|x) = \sigma(z)$$

$$z = w \cdot x + b = \sum_i w_i x_i + b$$

$$\sigma(z) = \frac{1}{1 + exp(-z)}$$



Step 1: Function Set



Step 2: Goodness of a Function

Training Data	x^1	x^2	x^3	……	x^N
	C_1	C_1	C_2		C_1

Assume the data is generated based on $f_{w,b}(x) = P_{w,b}(C_1|x)$

Given a set of w and b, what is its probability of generating the data?

$$L(w,b) = f_{w,b}(x^1) f_{w,b}(x^2) \left(1 - f_{w,b}(x^3)\right) \cdots f_{w,b}(x^N)$$

The most likely w* and b* is the one with the largest $L(w,b)$.

$$w^*, b^* = arg \max_{w,b} L(w,b)$$

$$\begin{array}{cccc} x^1 & x^2 & x^3 & \\ C_1 & C_1 & C_2 & \cdots\cdots \end{array} \quad \Rightarrow \quad \begin{array}{cccc} x^1 & x^2 & x^3 & \\ \hat{y}^1 = 1 & \hat{y}^2 = 1 & \hat{y}^3 = 0 & \cdots\cdots \end{array}$$

$\hat{y}^n$: 1 for class 1, 0 for class 2

$$L(w,b) = f_{w,b}(x^1) f_{w,b}(x^2) \left(1 - f_{w,b}(x^3)\right) \cdots$$

$$\boxed{w^*, b^* = arg \max_{w,b} L(w,b)} = \boxed{w^*, b^* = arg \min_{w,b} -lnL(w,b)}$$

$$-lnL(w,b)$$

$$= -\, lnf_{w,b}(x^1) \Rightarrow -\ \boxed{1}\ lnf(x^1) \cancel{+ \boxed{0}\ ln\left(1 - f(x^1)\right)}]$$

$$-lnf_{w,b}(x^2) \Rightarrow -\ \boxed{1}\ lnf(x^2) \cancel{+ \boxed{0}\ ln\left(1 - f(x^2)\right)}]$$

$$-ln\left(1 - f_{w,b}(x^3)\right) \Rightarrow -\ \cancel{\boxed{0}\ lnf(x^3) +}\ \boxed{1}\ ln\left(1 - f(x^3)\right)]$$

$$\vdots$$

Step 2: Goodness of a Function

$$L(w,b) = f_{w,b}(x^1) f_{w,b}(x^2)\left(1 - f_{w,b}(x^3)\right) \cdots f_{w,b}(x^N)$$

$$-lnL(w,b) = lnf_{w,b}(x^1) + lnf_{w,b}(x^2) + ln\left(1 - f_{w,b}(x^3)\right) \cdots$$

$\hat{y}^n$: 1 for class 1, 0 for class 2

$$= \sum_n \underbrace{-\left[\hat{y}^n lnf_{w,b}(x^n) + (1 - \hat{y}^n) ln\left(1 - f_{w,b}(x^n)\right)\right]}_{\text{Cross entropy between two Bernoulli distribution}}$$

Distribution p:

$p(x = 1) = \hat{y}^n$

$p(x = 0) = 1 - \hat{y}^n$

$\Longleftrightarrow$ cross entropy

Distribution q:

$q(x = 1) = f(x^n)$

$q(x = 0) = 1 - f(x^n)$

$$H(p,q) = -\sum_x p(x) ln\left(q(x)\right)$$

Step 2: Goodness of a Function

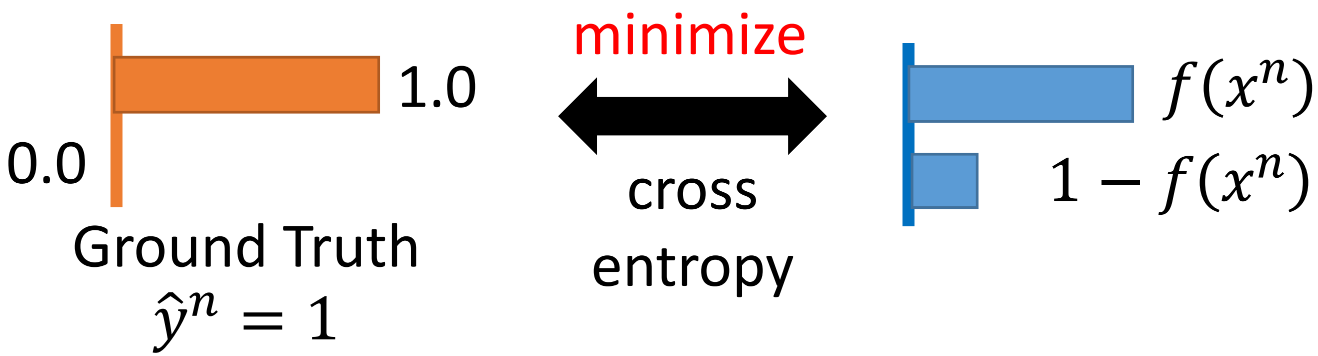
$$L(w,b) = f_{w,b}(x^1) f_{w,b}(x^2) \left(1 - f_{w,b}(x^3)\right) \cdots f_{w,b}(x^N)$$

$$-lnL(w,b) = lnf_{w,b}(x^1) + lnf_{w,b}(x^2) + ln\left(1 - f_{w,b}(x^3)\right) \cdots$$

$\hat{y}^n$: 1 for class 1, 0 for class 2

$$= \sum_n - \left[\hat{y}^n lnf_{w,b}(x^n) + (1 - \hat{y}^n) ln\left(1 - f_{w,b}(x^n)\right)\right]$$

Cross entropy between two Bernoulli distribution

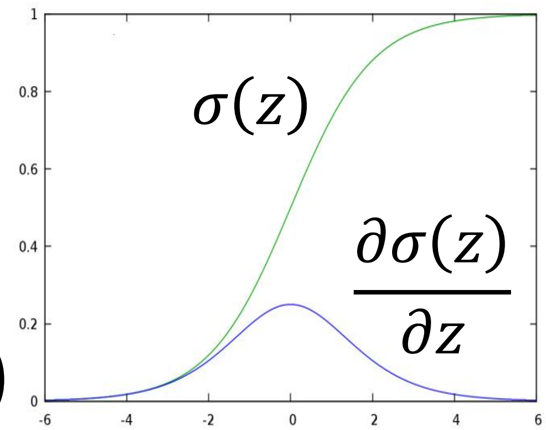


Step 3: Find the best function

$$\frac{-\ln L(w,b)}{\partial w_i} = \sum_n -\left[\hat{y}^n \overset{(1-f_{w,b}(x^n))x_i^n}{\boxed{\frac{\ln f_{w,b}(x^n)}{\partial w_i}}} + (1-\hat{y}^n)\frac{\ln\left(1-f_{w,b}(x^n)\right)}{\partial w_i}\right]$$

$$\frac{\partial \ln f_{w,b}(x)}{\partial w_i} = \frac{\partial \ln f_{w,b}(x)}{\partial z}\frac{\partial z}{\partial w_i} \qquad \frac{\partial z}{\partial w_i} = x_i$$

$$\frac{\partial \ln \sigma(z)}{\partial z} = \frac{1}{\sigma(z)}\frac{\partial \sigma(z)}{\partial z} = \frac{1}{\cancel{\sigma(z)}}\cancel{\sigma(z)}\left(1-\sigma(z)\right)$$



$$f_{w,b}(x) = \sigma(z)$$
$$= 1/1 + exp(-z)$$

$$z = w \cdot x + b = \sum_i w_i x_i + b$$

Step 3: Find the best function

$$\frac{-lnL(w,b)}{\partial w_i} = \sum_n -\left[\hat{y}^n \overset{(1-f_{w,b}(x^n))x_i^n}{\boxed{\frac{lnf_{w,b}(x^n)}{\partial w_i}}} + (1-\hat{y}^n)\overset{-f_{w,b}(x^n)x_i^n}{\boxed{\frac{ln\left(1-f_{w,b}(x^n)\right)}{\partial w_i}}}\right]$$

$$\frac{\partial ln\left(1-f_{w,b}(x)\right)}{\partial w_i} = \frac{\partial ln\left(1-f_{w,b}(x)\right)}{\partial z}\frac{\partial z}{\partial w_i} \qquad \frac{\partial z}{\partial w_i} = x_i$$

$$\frac{\partial ln\left(1-\sigma(z)\right)}{\partial z} = -\frac{1}{1-\sigma(z)}\frac{\partial \sigma(z)}{\partial z} = -\frac{1}{\cancel{1-\sigma(z)}}\sigma(z)\cancel{\left(1-\sigma(z)\right)}$$

$$f_{w,b}(x) = \sigma(z)$$
$$= 1/1 + exp(-z)$$

$$z = w \cdot x + b = \sum_i w_i x_i + b$$

Step 3: Find the best function

$$\frac{-lnL(w,b)}{\partial w_i} = \sum_n -\left[\hat{y}^n \overset{(1-f_{w,b}(x^n))x_i^n}{\boxed{\frac{lnf_{w,b}(x^n)}{\partial w_i}}} + (1-\hat{y}^n)\overset{-f_{w,b}(x^n)x_i^n}{\boxed{\frac{ln(1-f_{w,b}(x^n))}{\partial w_i}}}\right]$$

$$= \sum_n -\left[\hat{y}^n \underline{(1-f_{w,b}(x^n))x_i^n} - (1-\hat{y}^n)\underline{f_{w,b}(x^n)x_i^n}\right]$$

$$= \sum_n -\left[\hat{y}^n \cancel{-\hat{y}^n f_{w,b}(x^n)} - f_{w,b}(x^n) \cancel{+\hat{y}^n f_{w,b}(x^n)}\right] \underline{x_i^n}$$

$$= \sum_n -\left(\hat{y}^n - f_{w,b}(x^n)\right)x_i^n$$

Larger difference, larger update

$$w_i \leftarrow w_i - \eta \sum_n -\underline{\left(\hat{y}^n - f_{w,b}(x^n)\right)}x_i^n$$

Logistic Regression + Square Error

Step 1: $$f_{w,b}(x) = \sigma\left(\sum_i w_i x_i + b\right)$$

Step 2: Training data: $(x^n, \hat{y}^n)$, $\hat{y}^n$: 1 for class 1, 0 for class 2

$$L(f) = \frac{1}{2}\sum_n \left(f_{w,b}(x^n) - \hat{y}^n\right)^2$$

Step 3:

$$\frac{\partial\,(f_{w,b}(x)-\hat{y})^2}{\partial w_i} = 2\left(f_{w,b}(x) - \hat{y}\right)\frac{\partial f_{w,b}(x)}{\partial z}\frac{\partial z}{\partial w_i}$$

$$= 2\left(f_{w,b}(x) - \hat{y}\right)f_{w,b}(x)\left(1 - f_{w,b}(x)\right)x_i$$

$\hat{y}^n = 1$

If $f_{w,b}(x^n) = 1$ (close to target) ➡ $\partial L/\partial w_i = 0$

If $f_{w,b}(x^n) = 0$ (far from target) ➡ $\partial L/\partial w_i = 0$

Logistic Regression + Square Error

Step 1: $$f_{w,b}(x) = \sigma\left(\sum_i w_i x_i + b\right)$$

Step 2: Training data: $(x^n, \hat{y}^n)$, $\hat{y}^n$: 1 for class 1, 0 for class 2

$$L(f) = \frac{1}{2}\sum_n \left(f_{w,b}(x^n) - \hat{y}^n\right)^2$$

Step 3:

$$\frac{\partial\, (f_{w,b}(x) - \hat{y})^2}{\partial w_i} = 2\left(f_{w,b}(x) - \hat{y}\right) \frac{\partial f_{w,b}(x)}{\partial z} \frac{\partial z}{\partial w_i}$$

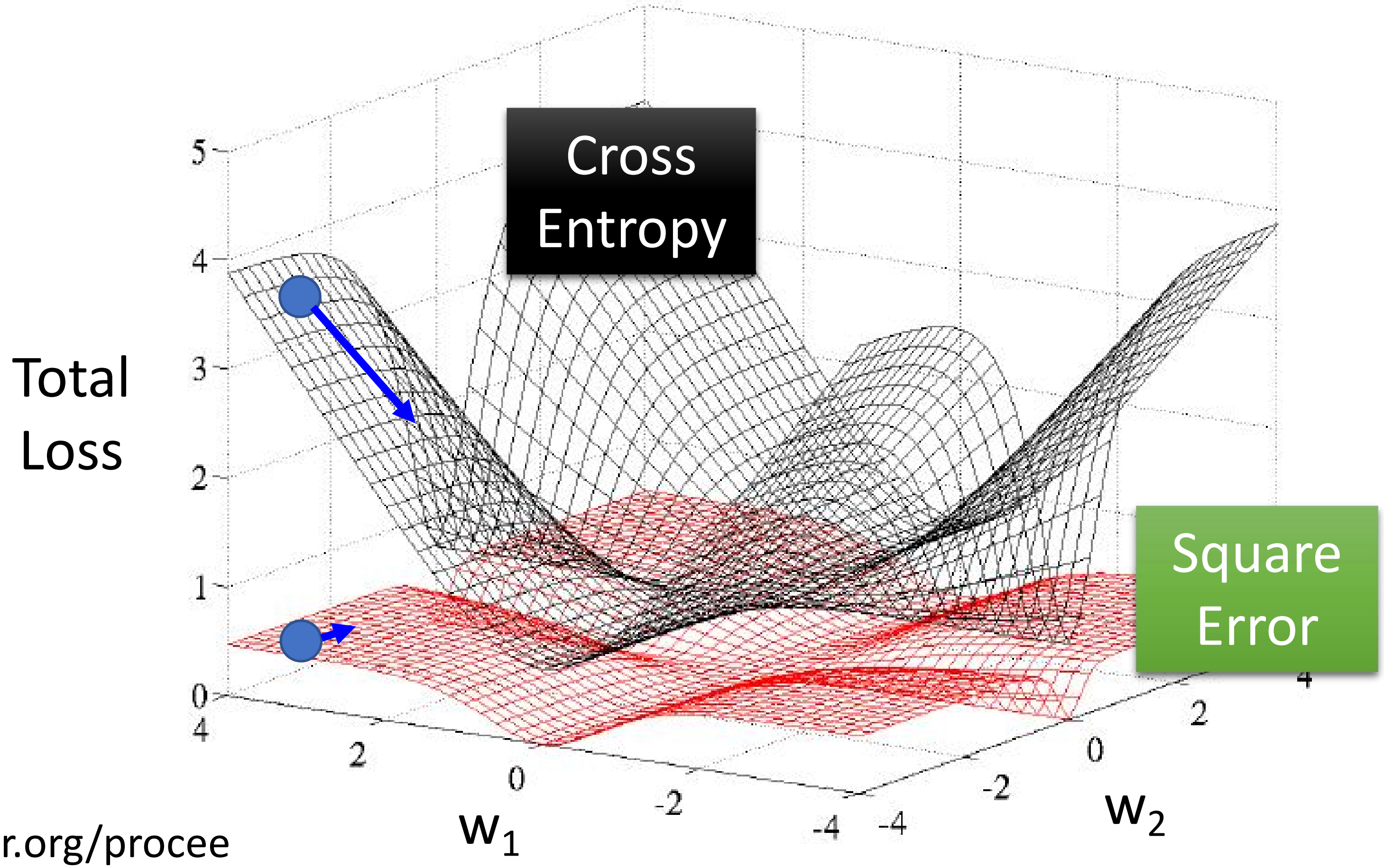
$$= 2\left(f_{w,b}(x) - \hat{y}\right) f_{w,b}(x)\left(1 - f_{w,b}(x)\right) x_i$$

$\hat{y}^n = 0$

If $f_{w,b}(x^n) = 1$ (far from target) ➡ $\partial L / \partial w_i = 0$

If $f_{w,b}(x^n) = 0$ (close to target) ➡ $\partial L / \partial w_i = 0$

Cross Entropy v.s. Square Error



http://jmlr.org/proceedings/papers/v9/glorot10a/glorot10a.pdf

Logistic Regression	***Linear Regression***
Step 1: $f_{w,b}(x) = \sigma\left(\sum_i w_i x_i + b\right)$ Output: between 0 and 1	$f_{w,b}(x) = \sum_i w_i x_i + b$ Output: any value
Step 2:	
Step 3:	

	Logistic Regression	***Linear Regression***
Step 1:	$f_{w,b}(x) = \sigma\left(\sum_i w_i x_i + b\right)$ Output: between 0 and 1	$f_{w,b}(x) = \sum_i w_i x_i + b$ Output: any value
Step 2:	Training data: $(x^n, \hat{y}^n)$ $\hat{y}^n$: 1 for class 1, 0 for class 2 $L(f) = \sum_n l(f(x^n), \hat{y}^n)$	Training data: $(x^n, \hat{y}^n)$ $\hat{y}^n$: a real number $L(f) = \frac{1}{2}\sum_n (f(x^n) - \hat{y}^n)^2$

Cross entropy:

$$l(f(x^n), \hat{y}^n) = -\left[\hat{y}^n \ln f(x^n) + (1 - \hat{y}^n) \ln\left(1 - f(x^n)\right)\right]$$

	Logistic Regression	**Linear Regression**
Step 1:	$f_{w,b}(x) = \sigma\left(\sum_i w_i x_i + b\right)$ Output: between 0 and 1	$f_{w,b}(x) = \sum_i w_i x_i + b$ Output: any value
Step 2:	Training data: $(x^n, \hat{y}^n)$ $\boxed{\hat{y}^n\text{: 1 for class 1, 0 for class 2}}$ $L(f) = \sum_n l(f(x^n), \hat{y}^n)$	Training data: $(x^n, \hat{y}^n)$ $\hat{y}^n$: a real number $L(f) = \frac{1}{2}\sum_n \left(f(x^n) - \hat{y}^n\right)^2$

Step 3:

Logistic regression: $w_i \leftarrow w_i - \eta \sum_n -\underline{\left(\hat{y}^n - f_{w,b}(x^n)\right)} x_i^n$

Linear regression: $w_i \leftarrow w_i - \eta \sum_n -\underline{\left(\hat{y}^n - f_{w,b}(x^n)\right)} x_i^n$

Discriminative v.s. Generative

$$P(C_1|x) = \sigma(w \cdot x + b)$$

directly find ***w*** and b

Find $\mu^1, \mu^2, \Sigma^{-1}$

$$w^T = (\mu^1 - \mu^2)^T \Sigma^{-1}$$

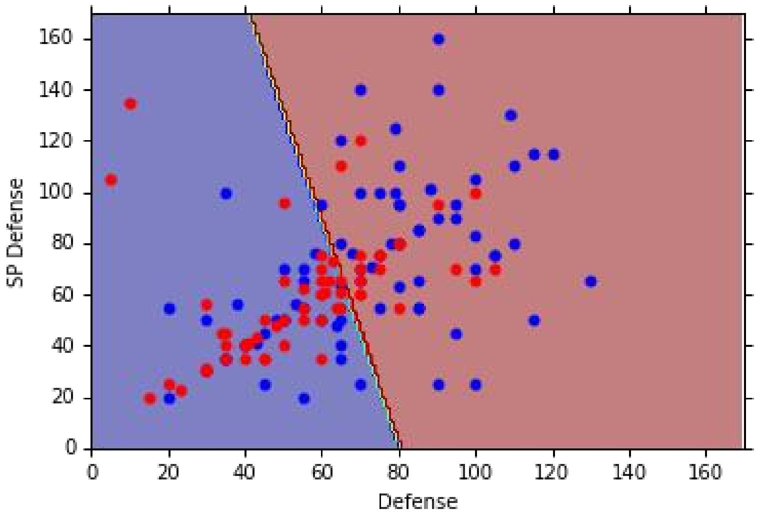
$$b = -\frac{1}{2}(\mu^1)^T(\Sigma^1)^{-1}\mu^1 + \frac{1}{2}(\mu^2)^T(\Sigma^2)^{-1}\mu^2 + ln\frac{N_1}{N_2}$$

Will we obtain the same set of w and b?

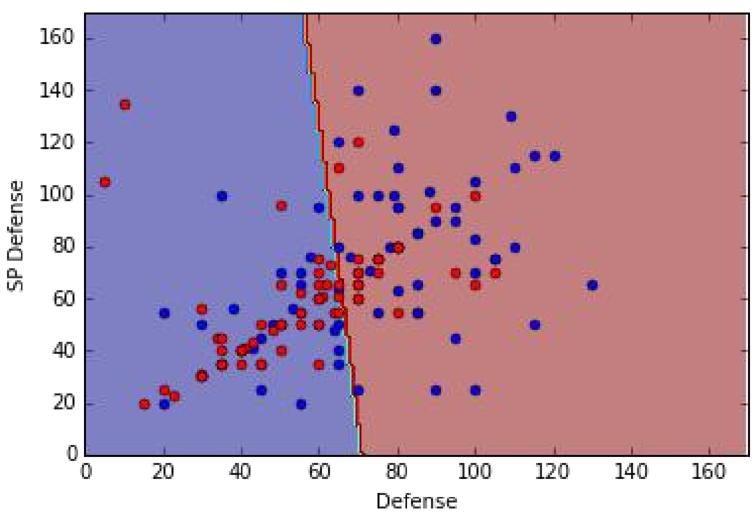
The same model (function set), but different function may be selected by the same training data.

Generative v.s. Discriminative

<u>Generative</u>



<u>Discriminative</u>



All: hp, att, sp att, de, sp de, speed

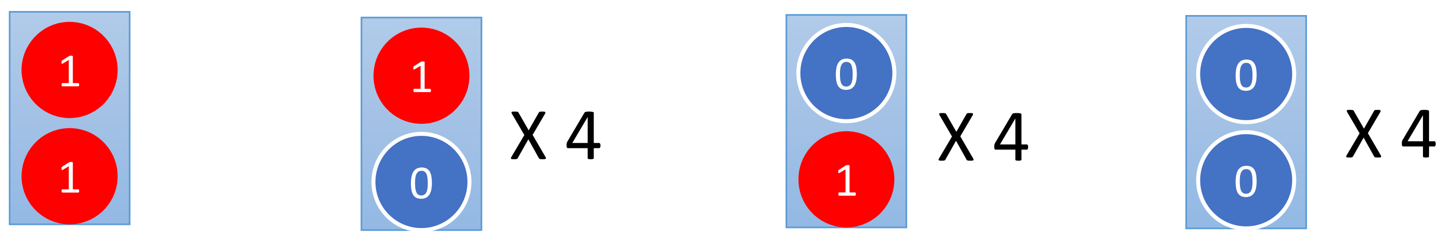
73% accuracy

79% accuracy

Generative v.s. Discriminative

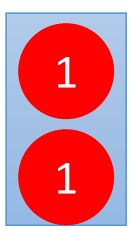
- Example

Training Data



Class 1 | Class 2 | Class 2 | Class 2

Testing Data



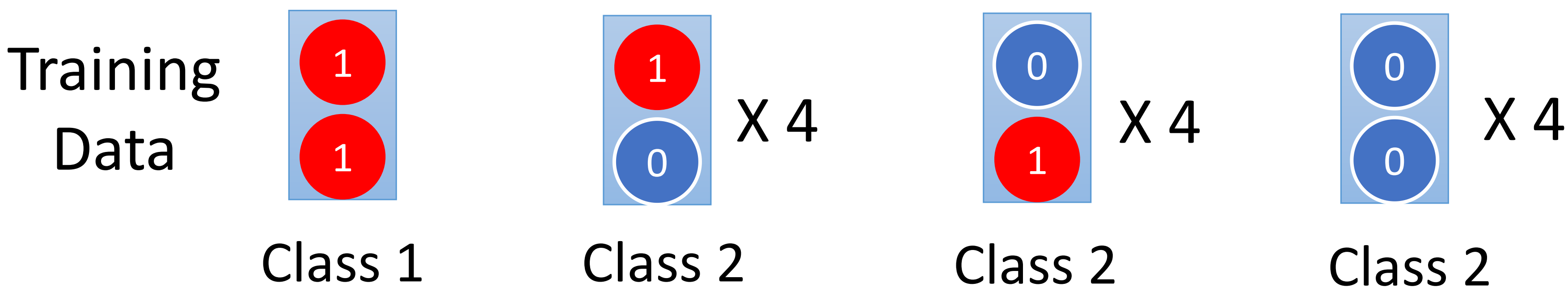
Class 1?
Class 2?

How about Naïve Bayes?

$$P(x|C_i) = P(x_1|C_i)P(x_2|C_i)$$

Generative v.s. Discriminative

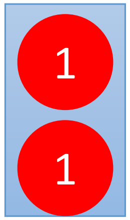
- Example



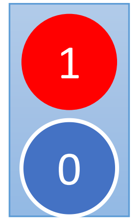
$$P(C_1) = \frac{1}{13} \qquad P(x_1 = 1|C_1) = 1 \qquad P(x_2 = 1|C_1) = 1$$

$$P(C_2) = \frac{12}{13} \qquad P(x_1 = 1|C_2) = \frac{1}{3} \qquad P(x_2 = 1|C_2) = \frac{1}{3}$$

Training Data

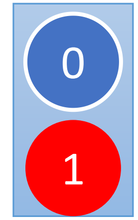


Class 1



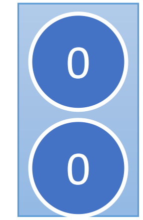
X 4

Class 2



X 4

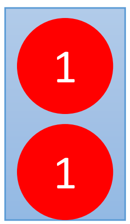
Class 2



X 4

Class 2

Testing Data



$$\overset{<0.5}{P(C_1|x)} = \frac{\overbrace{P(x|C_1)}^{1\times 1}\overbrace{P(C_1)}^{\frac{1}{13}}}{\underbrace{P(x|C_1)}_{1\times 1}\underbrace{P(C_1)}_{\frac{1}{13}}+\underbrace{P(x|C_2)}_{\frac{1}{3}\times\frac{1}{3}}\underbrace{P(C_2)}_{\frac{12}{13}}}$$

$$P(C_1) = \frac{1}{13} \qquad P(x_1 = 1|C_1) = 1 \qquad P(x_2 = 1|C_1) = 1$$

$$P(C_2) = \frac{12}{13} \qquad P(x_1 = 1|C_2) = \frac{1}{3} \qquad P(x_2 = 1|C_2) = \frac{1}{3}$$

Generative v.s. Discriminative

- Usually people believe discriminative model is better
- Benefit of generative model
  - With the assumption of probability distribution
    - less training data is needed
    - more robust to the noise
  - Priors and class-dependent probabilities can be estimated from different sources.

Multi-class Classification (3 classes as example)

C$_1$: w^1, b_1 $\quad z_1 = w^1 \cdot x + b_1$

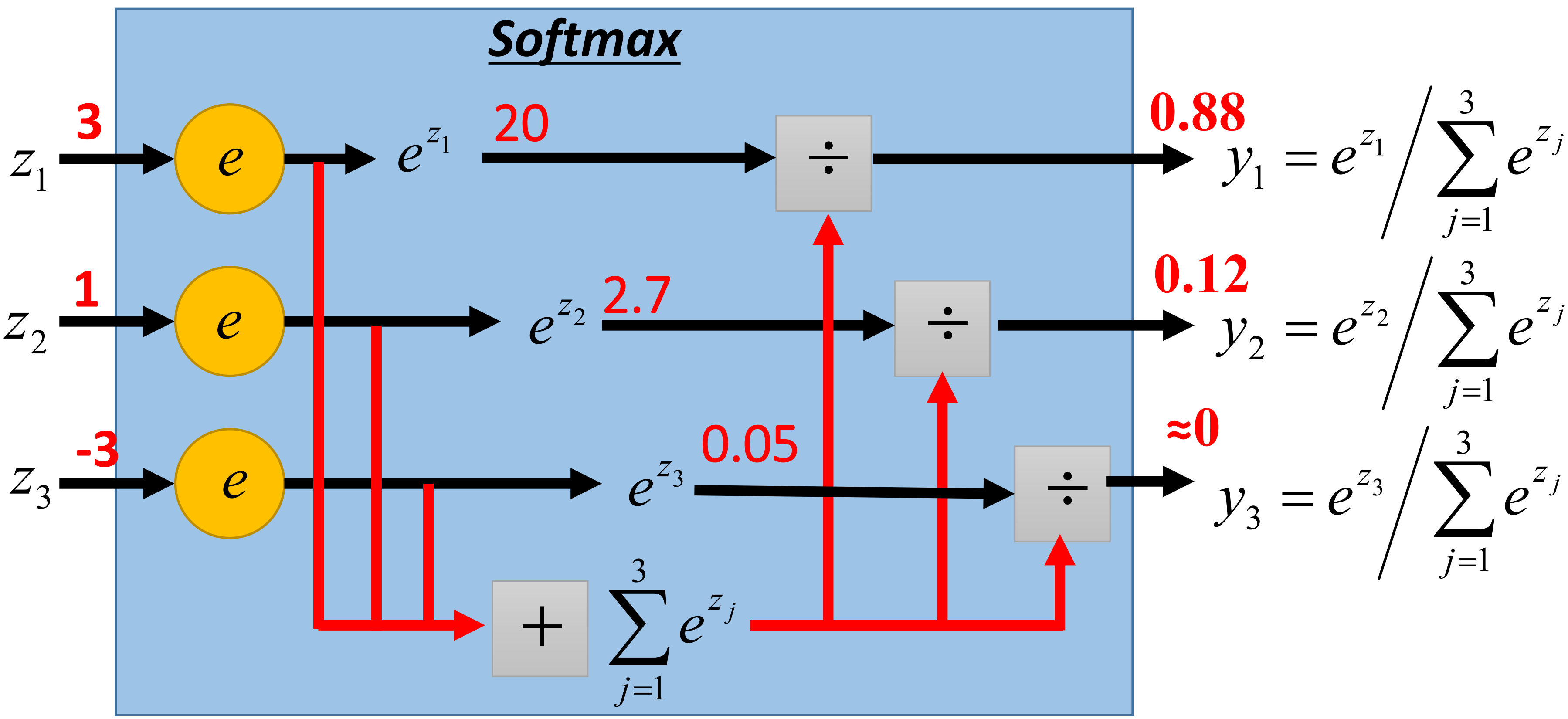
C$_2$: w^2, b_2 $\quad z_2 = w^2 \cdot x + b_2$

C$_3$: w^3, b_3 $\quad z_3 = w^3 \cdot x + b_3$

Probability:

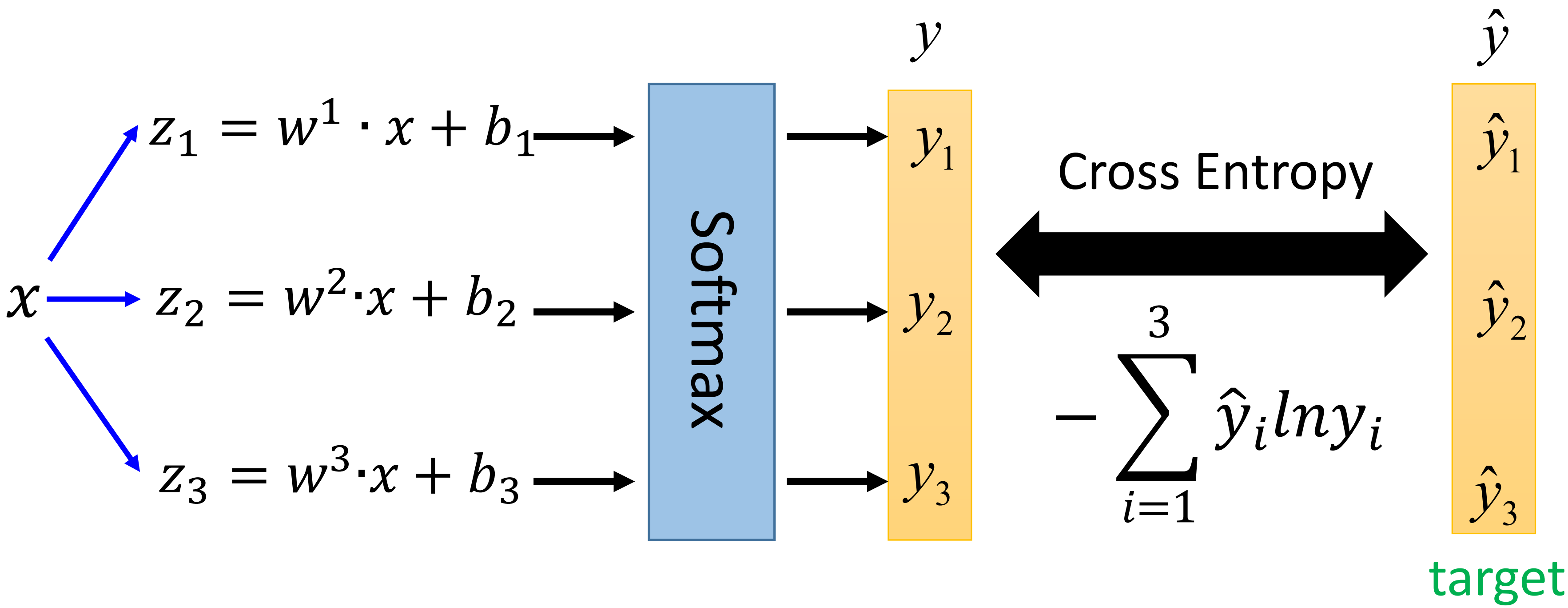
- $1 > y_i > 0$
- $\sum_i y_i = 1$

$$y_i = P(C_i \mid x)$$



Multi-class Classification (3 classes as example)

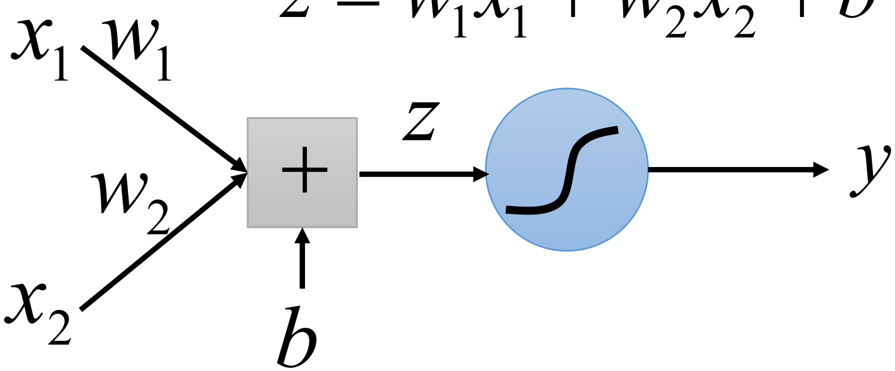
[Bishop, P209-210]



If x ∈ class 1	If x ∈ class 2	If x ∈ class 3
$\hat{y} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\hat{y} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$\hat{y} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$
$-ln y_1$	$-ln y_2$	$-ln y_3$

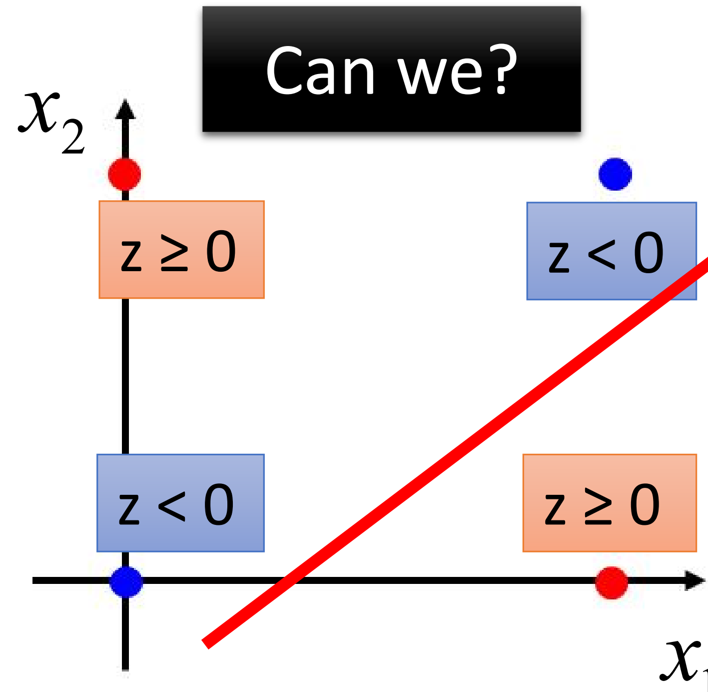
Limitation of Logistic Regression

$$z = w_1 x_1 + w_2 x_2 + b$$



$$\begin{cases} Class1 & y \geq 0.5 \quad (z \geq 0) \\ Class2 & y < 0.5 \quad (z < 0) \end{cases}$$

Input Feature		Label
x_1	x_2	
0	0	Class 2
0	1	Class 1
1	0	Class 1
1	1	Class 2



Limitation of Logistic Regression

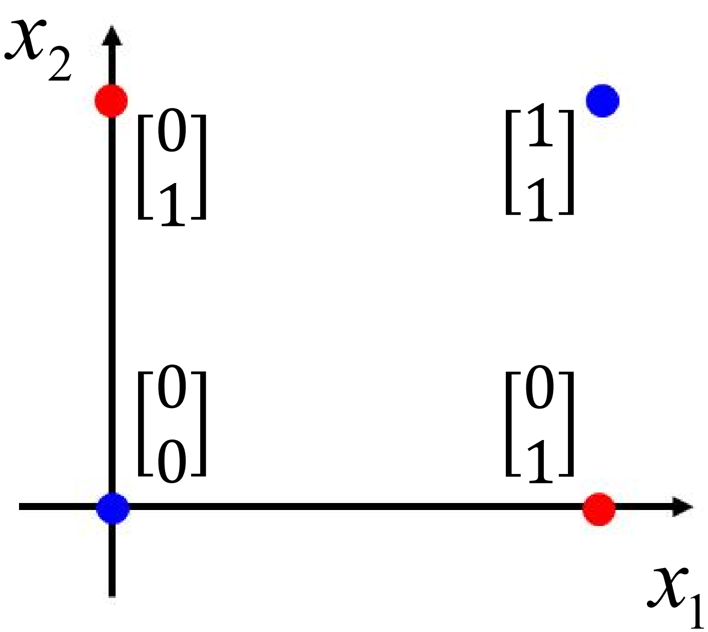
- ***Feature transformation***

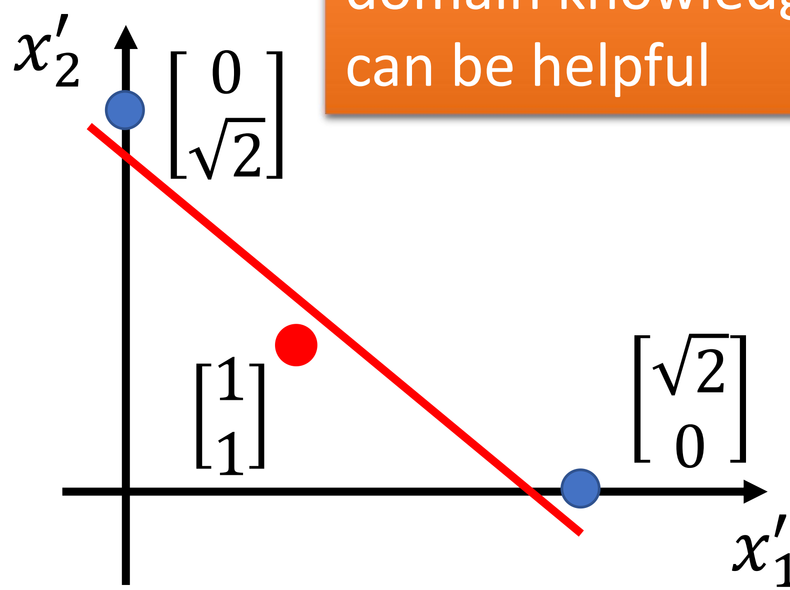
x_1': distance to $\begin{bmatrix} 0 \\ 0 \end{bmatrix}$

x_2': distance to $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \longrightarrow \begin{bmatrix} x_1' \\ x_2' \end{bmatrix}$$

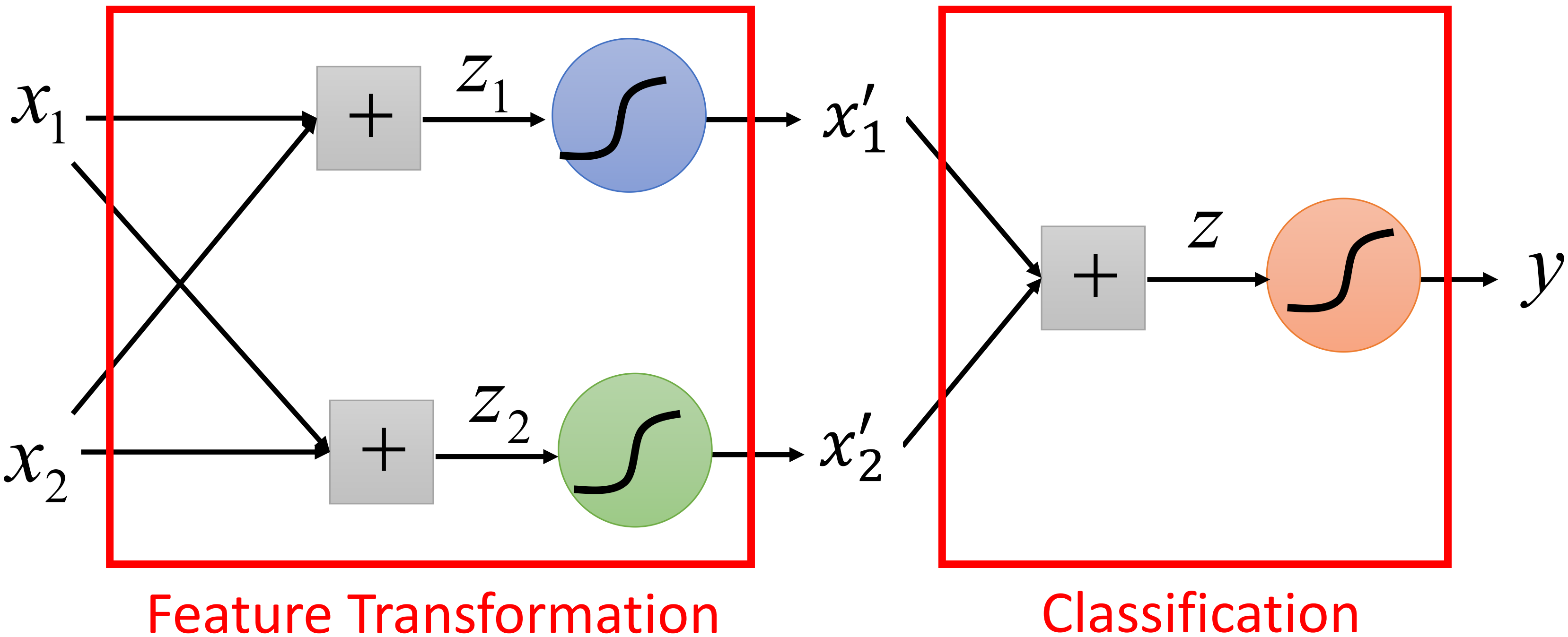
Not always easy ….. domain knowledge can be helpful



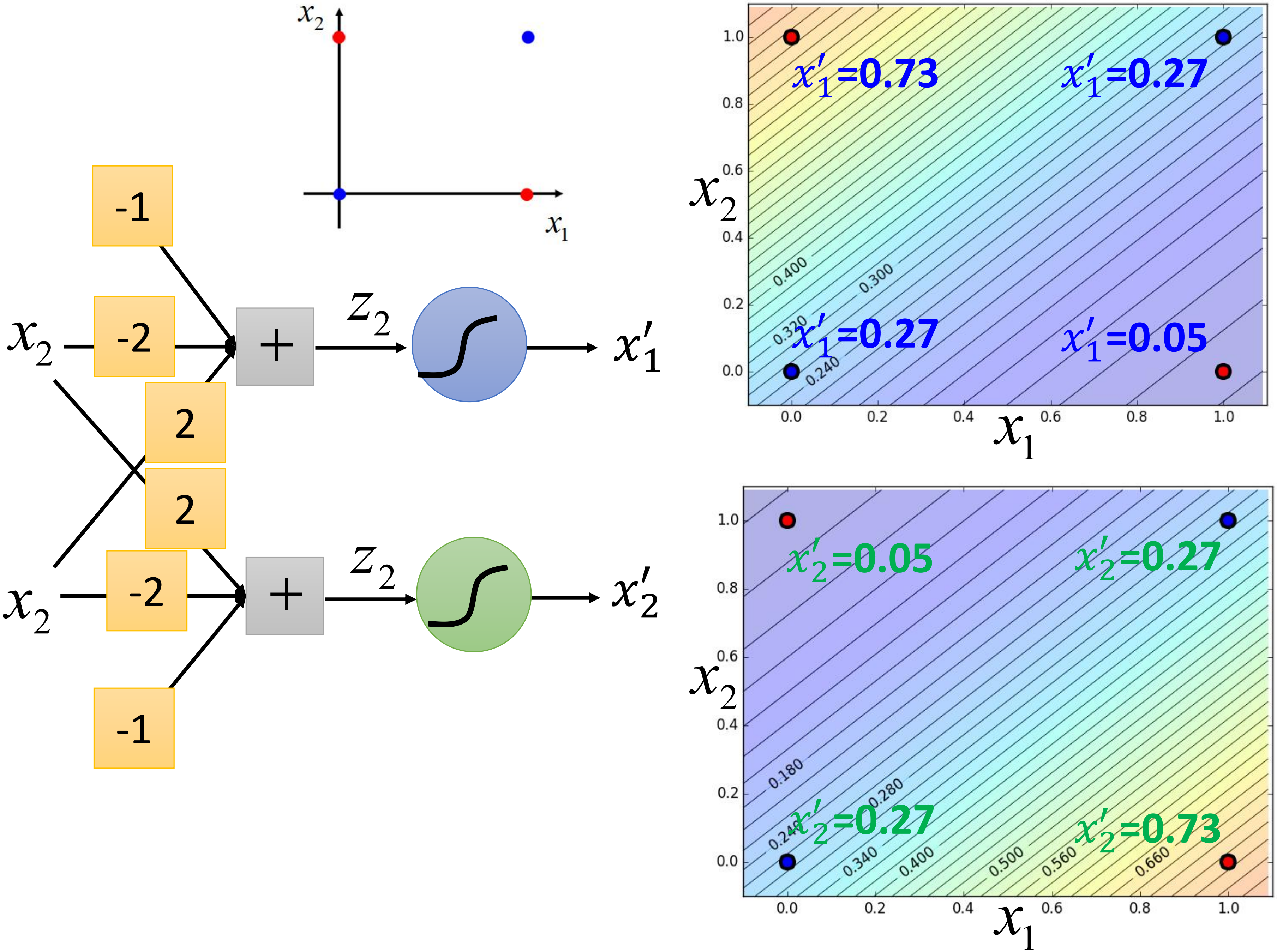


Limitation of Logistic Regression

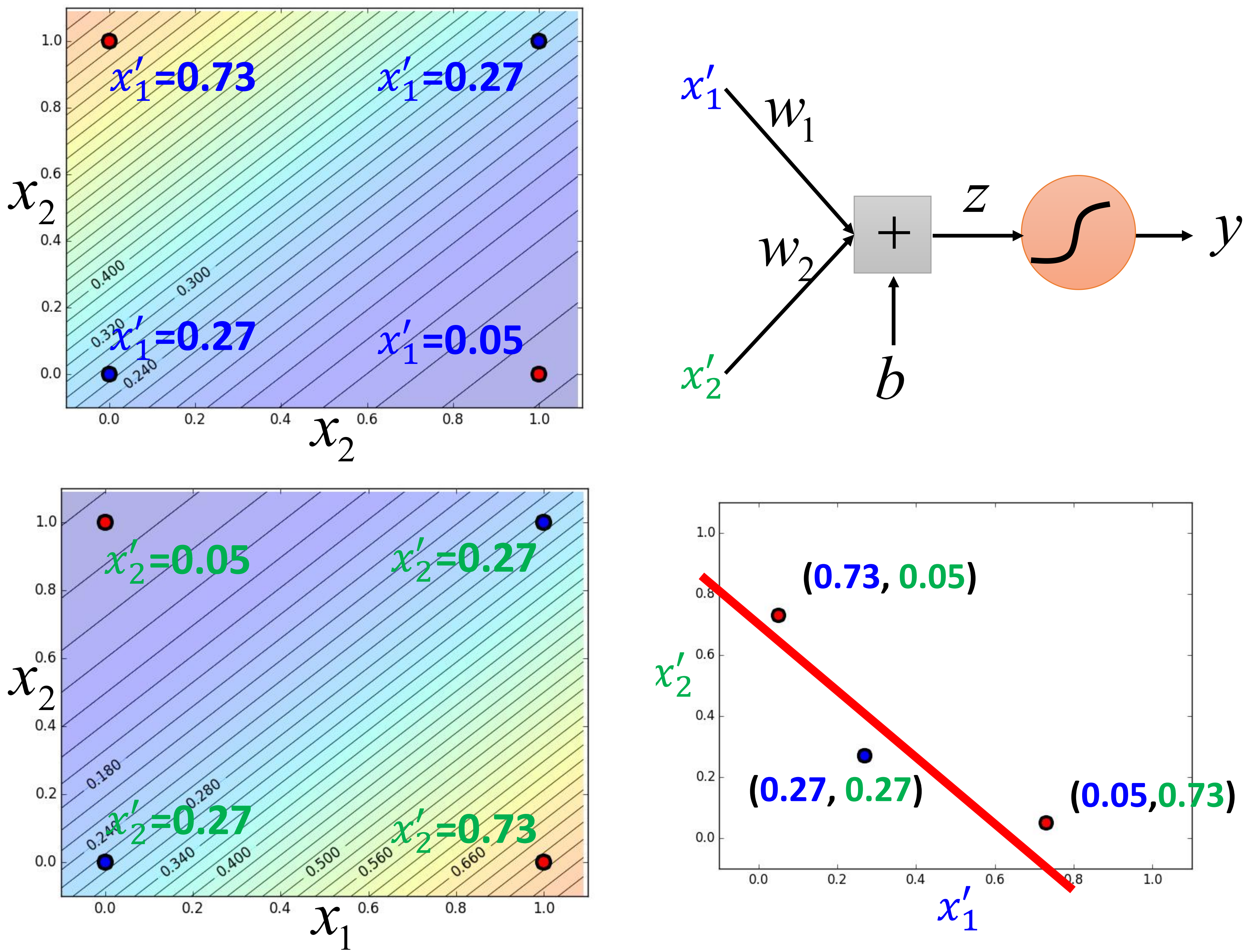
- Cascading logistic regression models



(ignore bias in this figure)



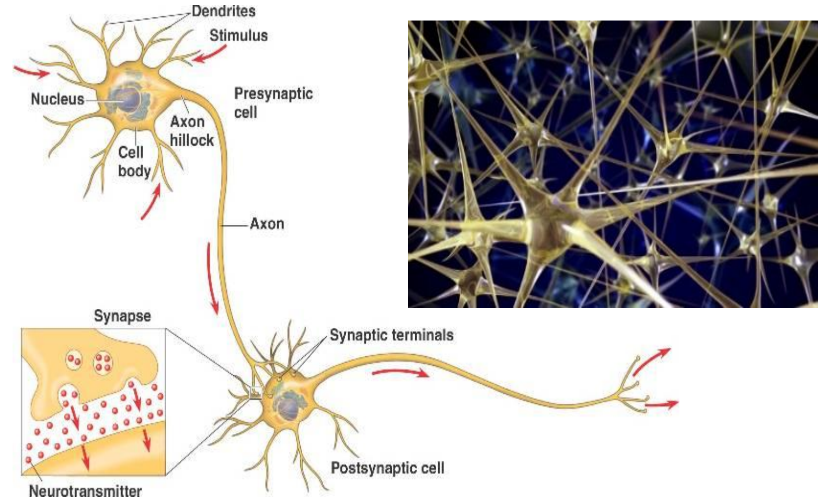
x_2
x_1
-1
x_2
-2
2
2
x_2
-2
-1
+
+
z_2
z_2
x'_1
x'_2
x'_1=0.73
x'_1=0.27
x'_1=0.27
x'_1=0.05
0.400
0.300
0.320
0.240
x'_2=0.05
x'_2=0.27
x'_2=0.27
x'_2=0.73
0.180
0.280
0.240
0.340
0.400
0.500
0.560
0.660
0.0
0.2
0.4
0.6
0.8
1.0

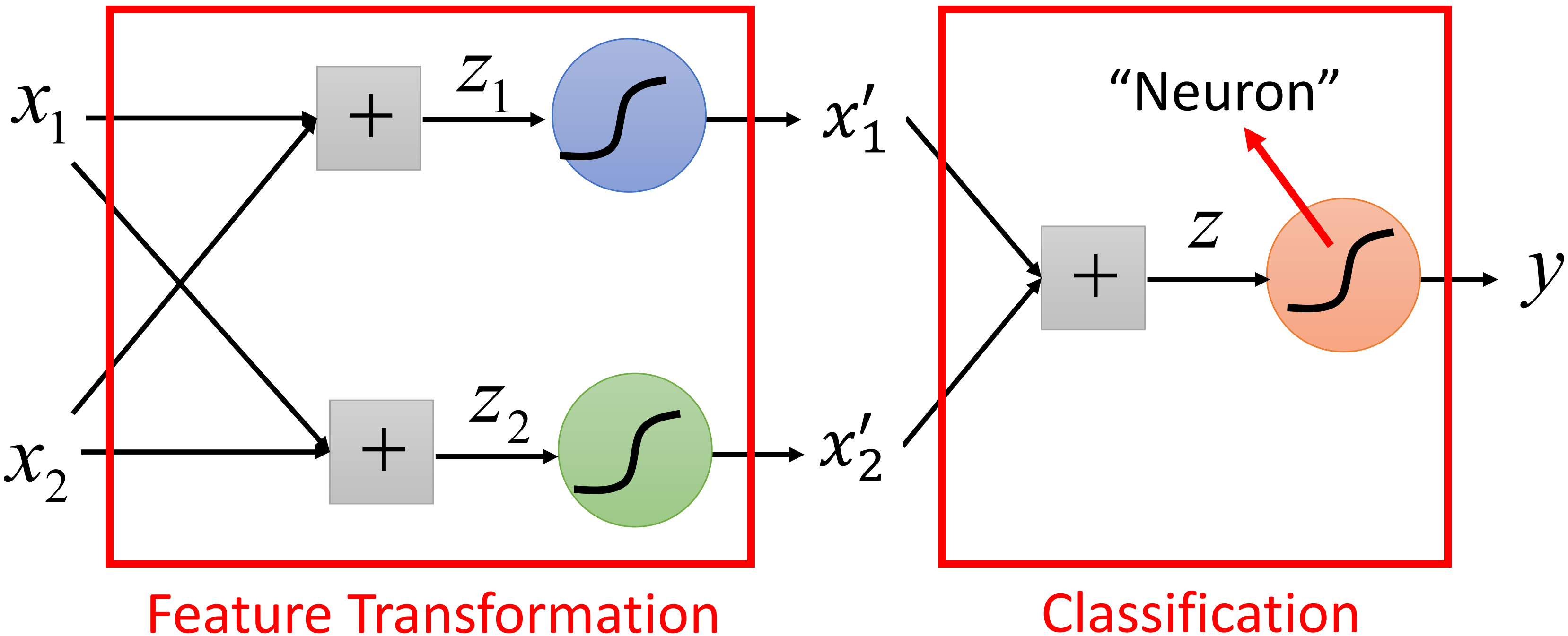


x'1=0.73
x'1=0.27
x'1=0.27
x'1=0.05
x2
x2
x'2=0.05
x'2=0.27
x'2=0.27
x'2=0.73
x2
x1
x'1
w1
x'2
w2
+
z
y
b
(0.73, 0.05)
(0.27, 0.27)
(0.05,0.73)
x'2
x'1

Deep Learning!

All the parameters of the logistic regressions are jointly learned.





Neural Network

Reference

- Bishop: Chapter 4.3

Appendix

Three Steps

x^1	x^2	x^3	……	x^n
$\hat{y}^1$	$\hat{y}^2$	$\hat{y}^3$		$\hat{y}^n$

$\hat{y}^n = class\ 1, class\ 2$

- Step 1. Function Set (Model)

x feature → If $P(C_1|x) > 0.5$, output: y = class 1
Otherwise, output: y = class 2 → y class

$$P(C_1|x) = \sigma(w \cdot x + b)$$

w and b are related to $N_1, N_2, \mu^1, \mu^2, \Sigma$

- Step 2. Goodness of a function

$$L(f) = \sum_n \delta(f(x^n) \neq \hat{y}^n) \quad \Rightarrow \quad L(f) = \sum_n l(f(x^n) \neq \hat{y}^n)$$

- Step 3. Find the best function: gradient descent

Step 2: Loss function

$$f_{w,b}(x) = \begin{cases} z \geq 0 & +1 \\ z < 0 & -1 \end{cases}$$

Ideal loss:

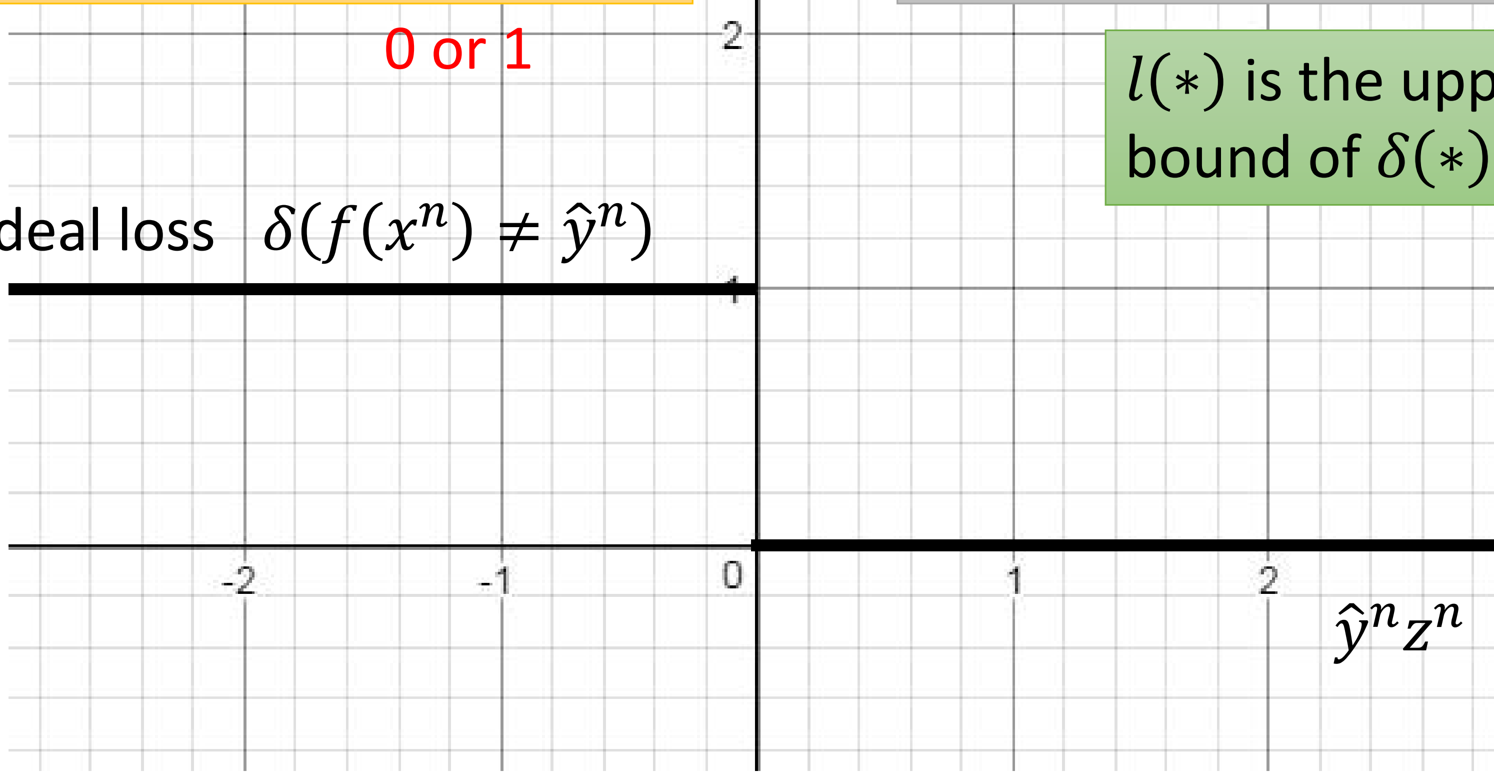
$$L(f) = \sum_n \delta(f(x^n) \neq \hat{y}^n)$$

0 or 1

Approximation:

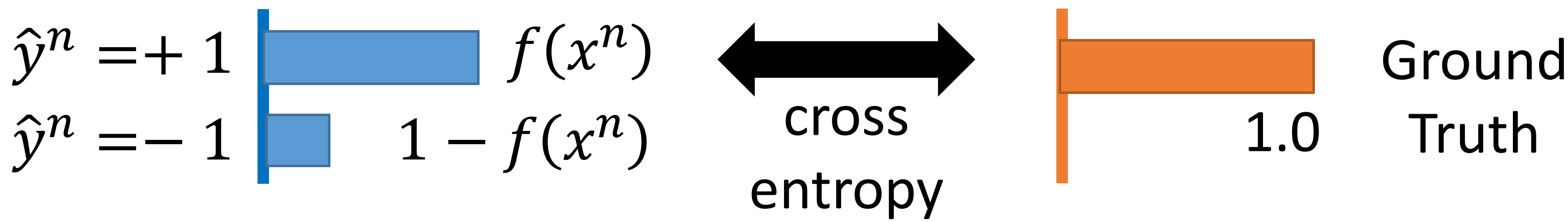
$$L(f) = \sum_n l(f(x^n), \hat{y}^n)$$

$l(*)$ is the upper bound of $\delta(*)$



Step 2: Loss function

$l(f(x^n), \hat{y}^n)$: cross entropy



If $\hat{y}^n = +1$:

$$l(f(x^n), \hat{y}^n) = -\ln f(x^n) = -\ln \sigma(z^n) = -\ln \frac{1}{1 + exp(-z^n)}$$

$$= \ln\left(1 + exp(-z^n)\right) = \underline{\ln\left(1 + exp(-\hat{y}^n z^n)\right)}$$

If $\hat{y}^n = -1$:

$$l(f(x^n), \hat{y}^n) = -\ln\left(1 - f(x^n)\right)$$

$$= -\ln\left(1 - \sigma(x^n)\right) = -\ln \frac{exp(-z^n)}{1 + exp(-z^n)} = -\ln \frac{1}{1 + exp(z^n)}$$

$$= \ln\left(1 + exp(z^n)\right) = \underline{\ln\left(1 + exp(-\hat{y}^n z^n)\right)}$$

Step 2: Loss function

$l(f(x^n), \hat{y}^n)$: cross entropy

$$l(f(x^n), \hat{y}^n) = \ln\left(1 + exp(-\hat{y}^n z^n)\right)$$