Classification: Probabilistic Generative Model

Classification

例子

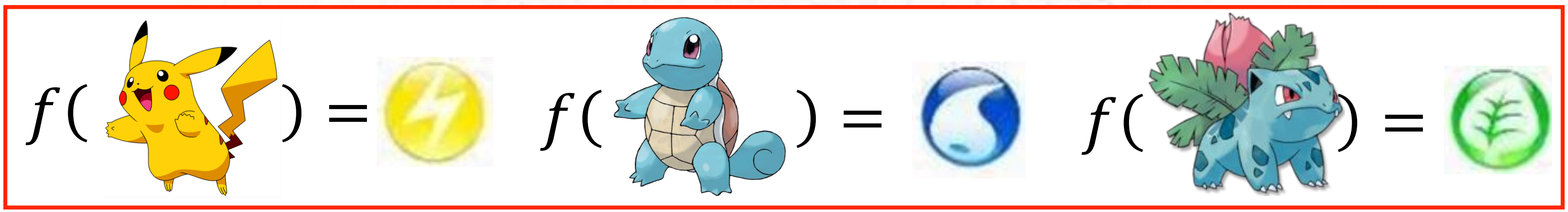
- Credit Scoring
  - Input: income, savings, profession, age, past financial history ……
  - Output: accept or refuse
- Medical Diagnosis
  - Input: current symptoms, age, gender, past medical history ……
  - Output: which kind of diseases
- Handwritten character recognition

Input: 

output: 金

- Face recognition
  - Input: image of a face, output: person

Example Application



寶可夢屬性分類案例

pokemon games (*NOT* pokemon cards or Pokemon Go)

Example Application

想要將寶可夢丟進 Function 中，就必須將寶可夢「數值化」=> 用 Vector 表示

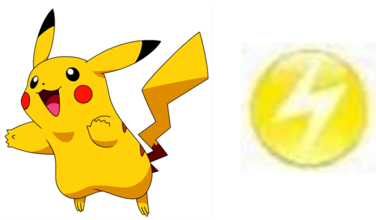
- **Total**: sum of all stats that come after this, a general guide to how strong a pokemon is 320
- **HP**: hit points, or health, defines how much damage a pokemon can withstand before fainting 35
- **Attack**: the base modifier for normal attacks (eg. Scratch, Punch) 55
- **Defense**: the base damage resistance against normal attacks 40
- **SP Atk**: special attack, the base modifier for special attacks (e.g. fire blast, bubble beam) 50
- **SP Def**: the base damage resistance against special attacks 50
- **Speed**: determines which pokemon attacks first each round 90

Can we predict the "type" of pokemon based on the information?

How to do Classification

- Training data for Classification

$(x^1, \hat{y}^1)$



$(x^2, \hat{y}^2)$

…… ……

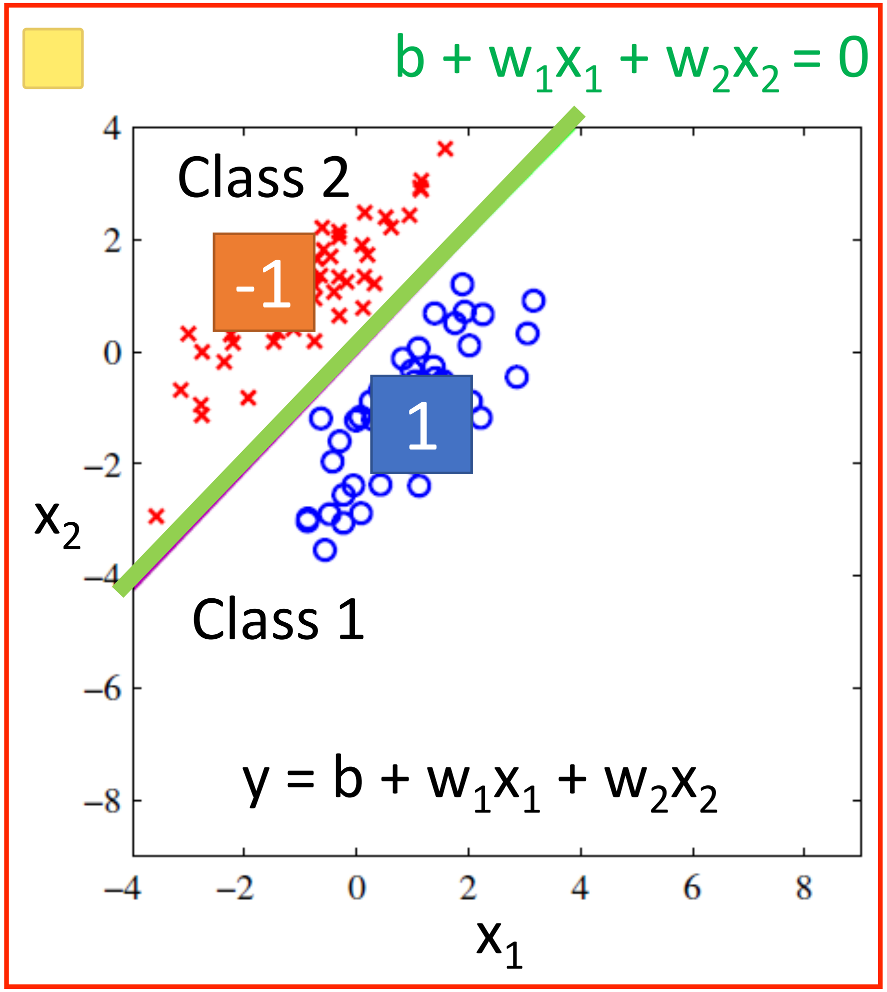
$(x^N, \hat{y}^N)$

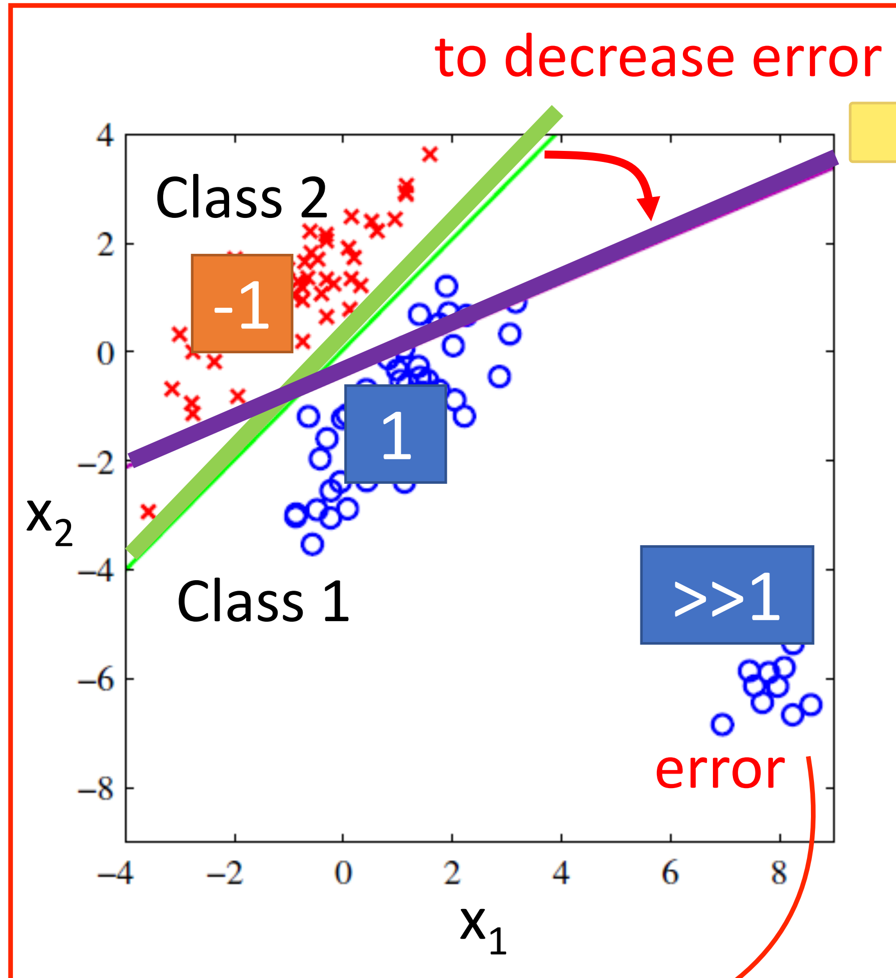
Classification as Regression?

Binary classification as example

Training: Class 1 means the target is 1; Class 2 means the target is -1

Testing: closer to 1 → class 1; closer to -1 → class 2





Penalize to the examples that are “too correct” … (Bishop, P186)

Multiple class: Class 1 means the target is 1; Class 2 means the target is 2; Class 3 means the target is 3 …… problematic

解決 Classification 的思路

Ideal Alternatives

- Function (Model):

$$f(x)$$

$$x \Rightarrow \begin{cases} g(x) > 0 & \text{Output = class 1} \\ else & \text{Output = class 2} \end{cases}$$

- Loss function:

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

The number of times f get incorrect results on training data.

- Find the best function:
  - Example: Perceptron, SVM

Not Today

若 A, B 為樣本空間 Ω 中二事件, 且 $P(B)>0$。則在給定 B 發生之下, A 之條件機率, 以 $P(A|B)$ 表之, 定義為

$$P(A|B)=\frac{P(A\cap B)}{P(B)}。 \text{-----------------------------}(1)$$

在上述條件機率的定義中, B 成為新的樣本空間: $P(B|B)=1$。也就是原先的樣本空間 Ω 修正為 B。 所有事件發生之機率, 都要先將其針對與 B 的關係做修正。 例如, 若 A 與 B 為互斥事件,且 $P(B)>0$, 則因 $P(A\cap B)=0$, 故 $P(A|B)=0$; 若 $P(A)$ 亦為正, 則此時亦有 $P(B|A)=0$。

條件機率也可用來求非條件下的機率。由(1)式得

$$P(A\cap B)=P(A|B)P(B)。\text{-----------------------------}(2)$$

故若知道 $P(A|B)$ 及 $P(B)$。 則可得到 $P(A\cap B)$。當然亦有

$$P(A\cap B)=P(B|A)P(A), \text{-----------------------------}(3)$$

只要 $P(A)>0$。結合(2)式與(3)式, 得

$$P(A|B)=\frac{P(B|A)P(A)}{P(B)}。\text{-----------------------------}(4)$$

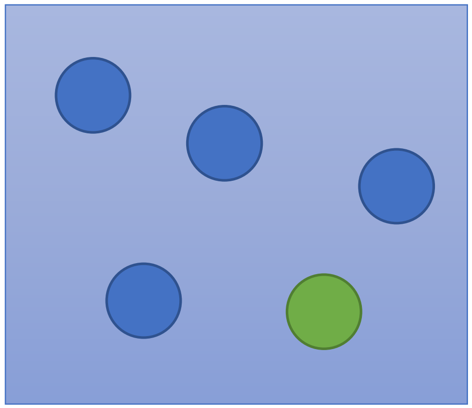
例如, A_1 , A_2 為樣本空間 Ω 中之一分割, 在給定一事件 B, 且 $P(B) > 0$, 則

$$P(A_1|B) = \frac{P(B|A_1)P(A_1)}{P(B|A_1)P(A_1) + P(B|A_2)P(A_2)}\ 。$$

Two Boxes

Box 1

$P(B_1) = 2/3$

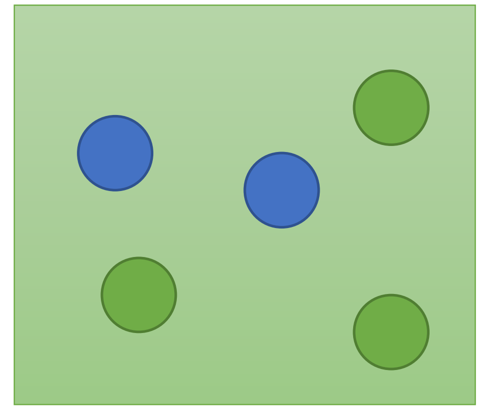


$P(\text{Blue}|B_1) = 4/5$

$P(\text{Green}|B_1) = 1/5$

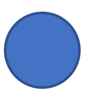
Box 2

$P(B_2) = 1/3$



$P(\text{Blue}|B_1) = 2/5$

$P(\text{Green}|B_1) = 3/5$

 from one of the boxes

Where does it come from? 由條件機率公式推得而來

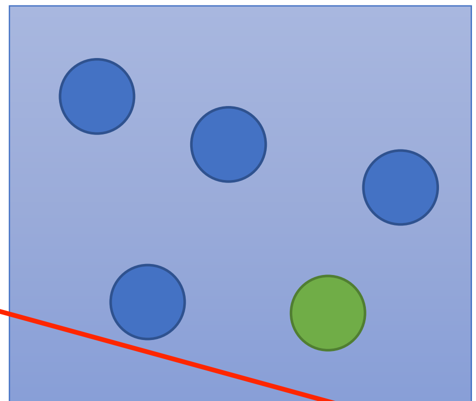
將 Box 換成 Class

$$\boxed{P(B_1 \mid \text{Blue}) = \frac{P(\text{Blue}|B_1)P(B_1)}{P(\text{Blue}|B_1)P(B_1) + P(\text{Blue}|B_2)P(B_2)}}$$

Two Classes

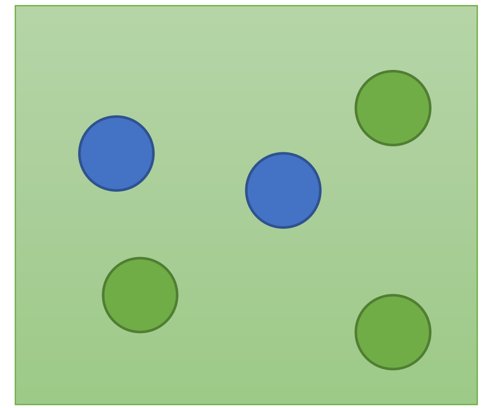
Estimating the Probabilities
From training data

Class 1



$\boxed{P(C_1)}$

Class 2



$\boxed{P(C_2)}$

有了這四個機率
就可以去計算：

$\boxed{P(x|C_1)}$

$\boxed{P(x|C_2)}$

Given an x, which class does it belong to

Given 一個 x 他屬於 class 1 的機率
解決 Classification 問題

$$\boxed{P(C_1|x)} = \frac{P(x|C_1)P(C_1)}{P(x|C_1)P(C_1) + P(x|C_2)P(C_2)}$$

Generative Model $\boxed{P(x)} = P(x|C_1)P(C_1) + P(x|C_2)P(C_2)$

Class 的「機率」稱為 Prior (容易計算)

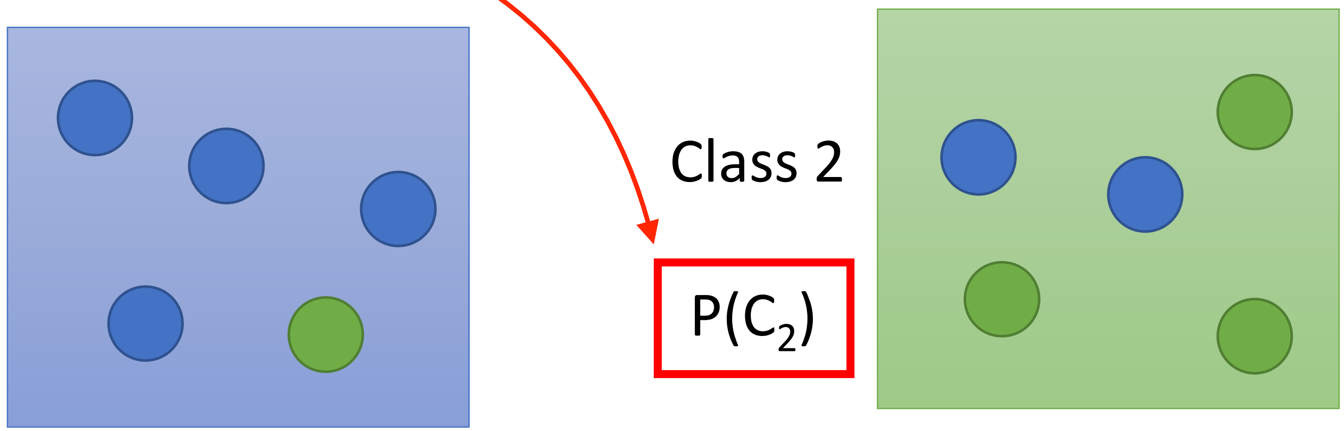
Prior

Class 1

$P(C_1)$

Class 2

$P(C_2)$



Water **Normal**

Water and Normal type with ID < 400 for training, rest for testing

Training: 79 Water, 61 Normal

例子：Training Data 有 79 隻水系寶可夢與 61 隻一般系寶可夢

$P(C_1) = 79 / (79 + 61) = 0.56$

$P(C_2) = 61 / (79 + 61) = 0.44$

Probability from Class

Given 一個 Class 要 Sample 出一隻寶可夢的「機率」稱為 Likelihood （難計算）

$P(x|C_1) = ?$ P( |Water) = ?

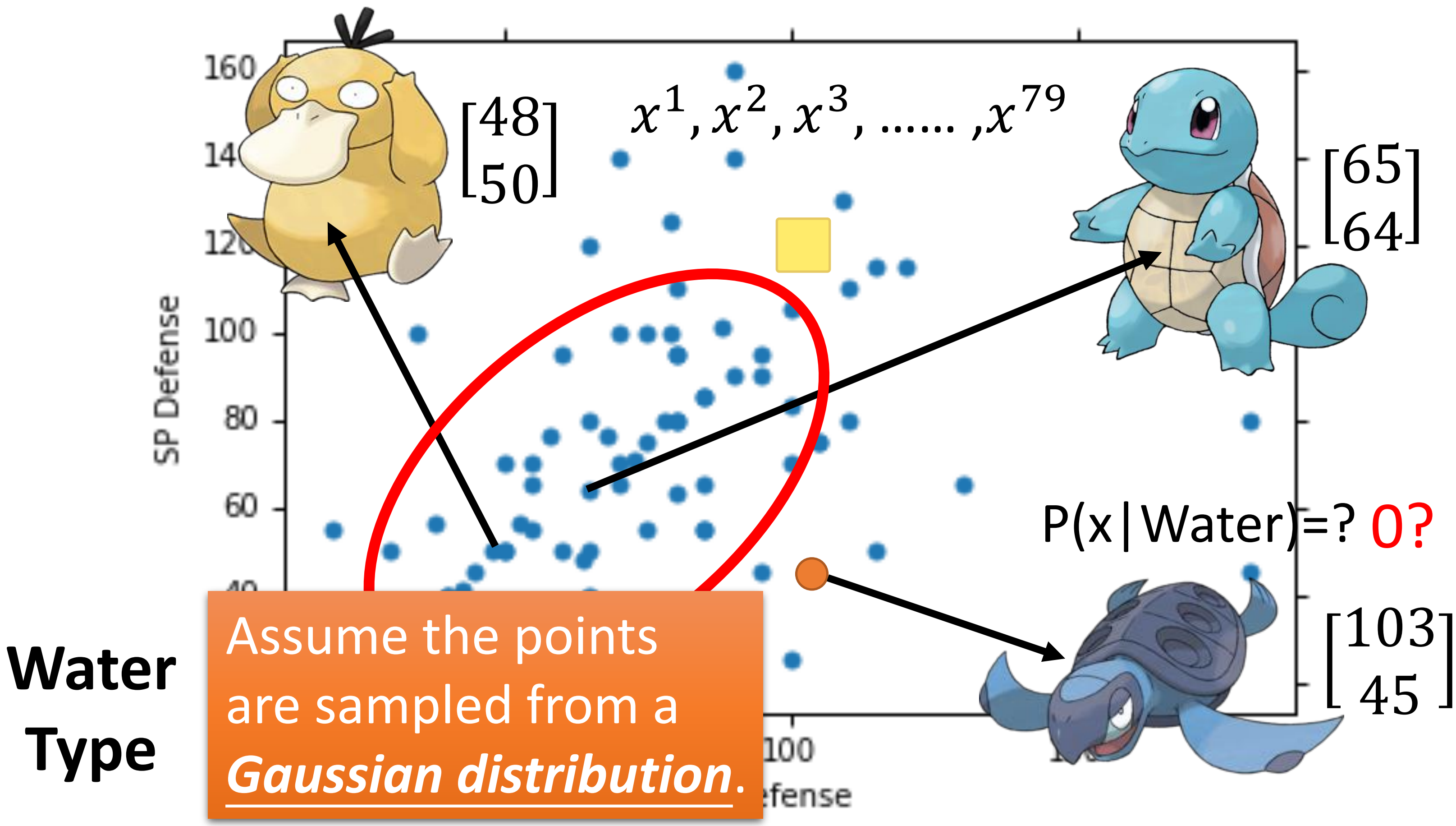
Each Pokémon is represented as a vector by its attribute. → feature

Water Type

79 in total

Probability from Class - Feature

- Considering **Defense** and **SP Defense**



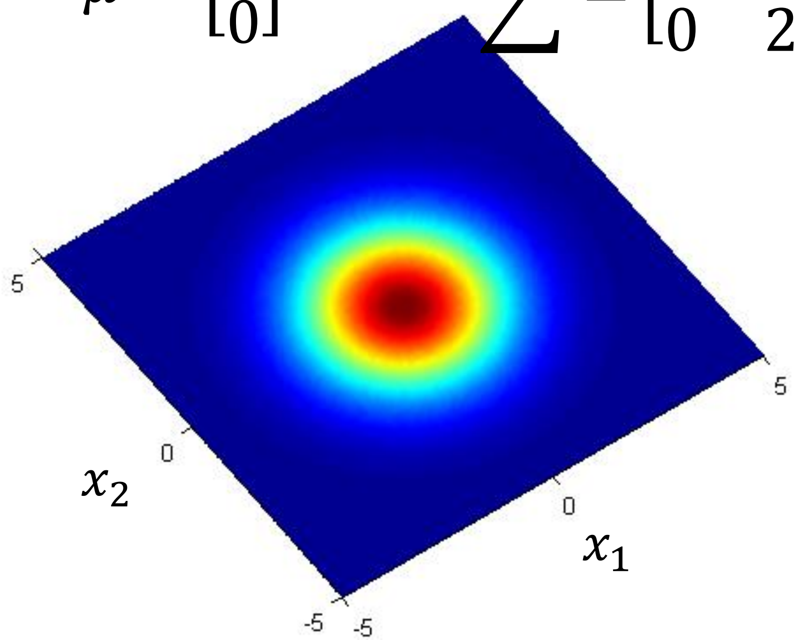
Gaussian Distribution

$$f_{\mu,\Sigma}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)\right\}$$

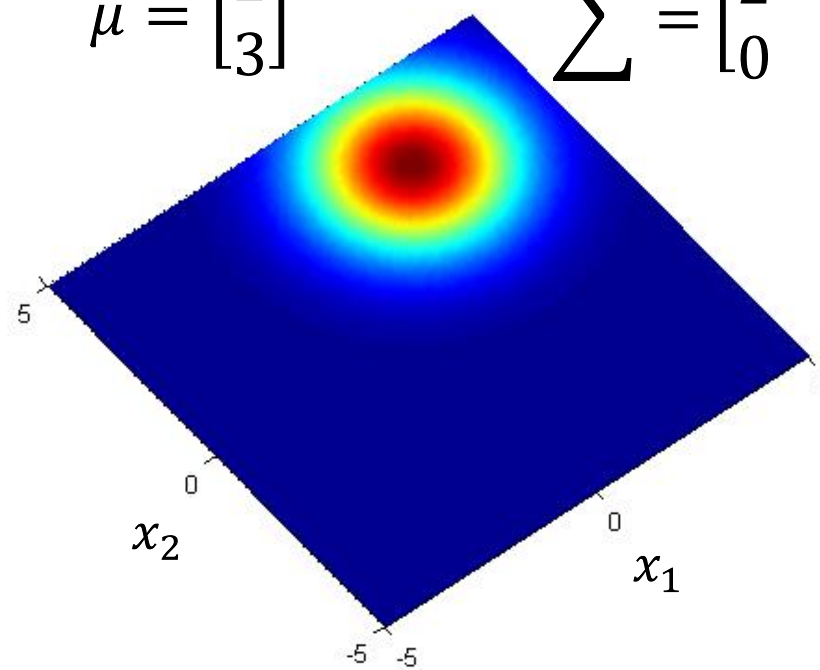
Input: vector x, output: probability of sampling x

The shape of the function determines by **mean** $\boldsymbol{\mu}$ and **covariance matrix** $\boldsymbol{\Sigma}$

$$\mu = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \sum = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$$



$$\mu = \begin{bmatrix} 2 \\ 3 \end{bmatrix} \quad \sum = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$$



https://blog.slinuxer.com/tag/pca

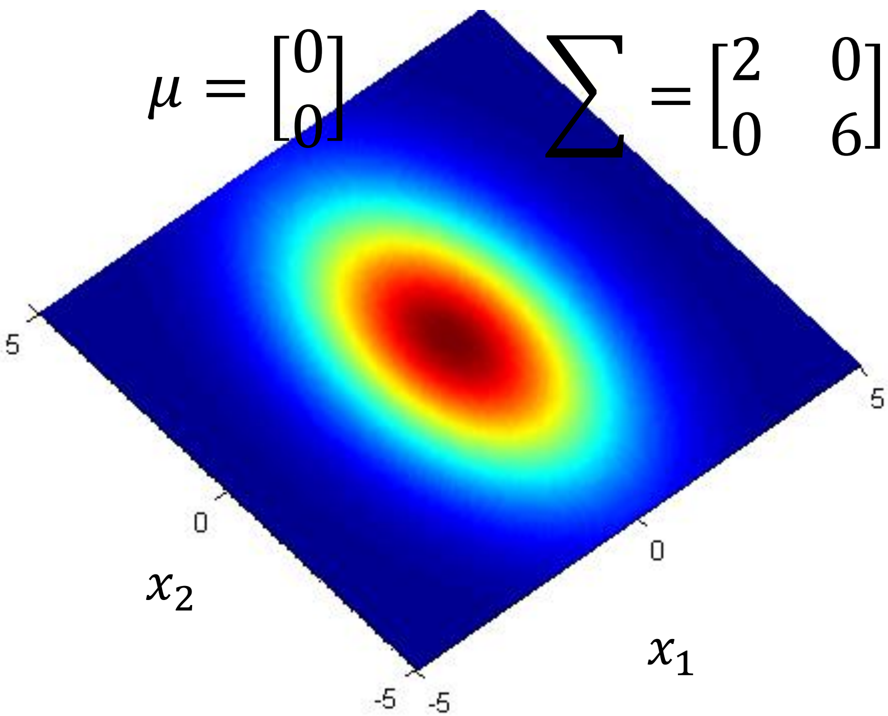
Gaussian Distribution

$$f_{\mu,\Sigma}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)\right\}$$

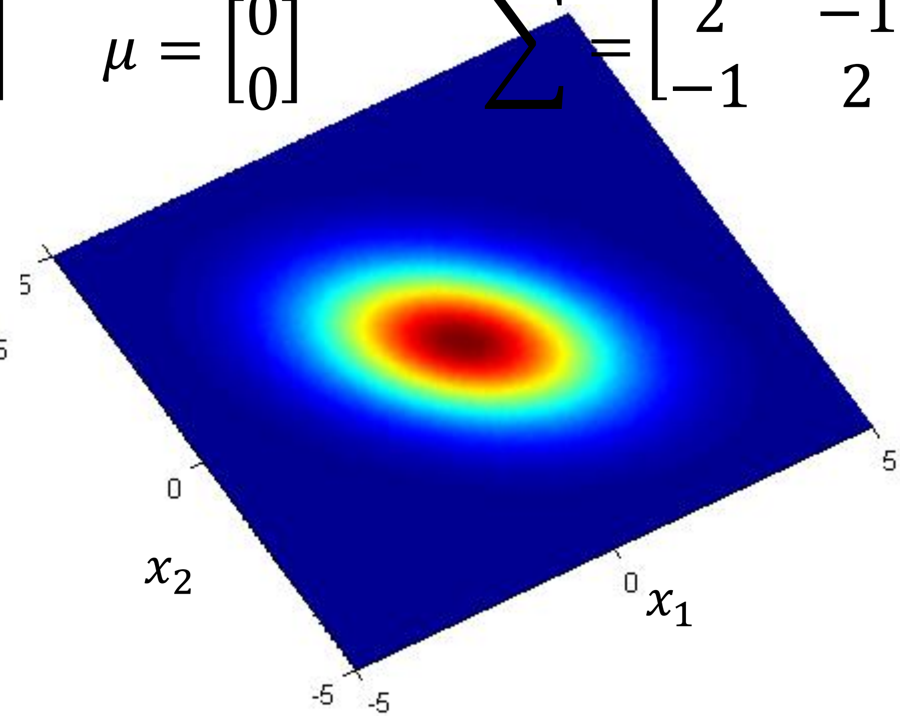
Input: vector x, output: probability of sampling x

The shape of the function determines by **mean $\boldsymbol{\mu}$** and **covariance matrix $\boldsymbol{\Sigma}$**

$$\mu = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \sum = \begin{bmatrix} 2 & 0 \\ 0 & 6 \end{bmatrix}$$



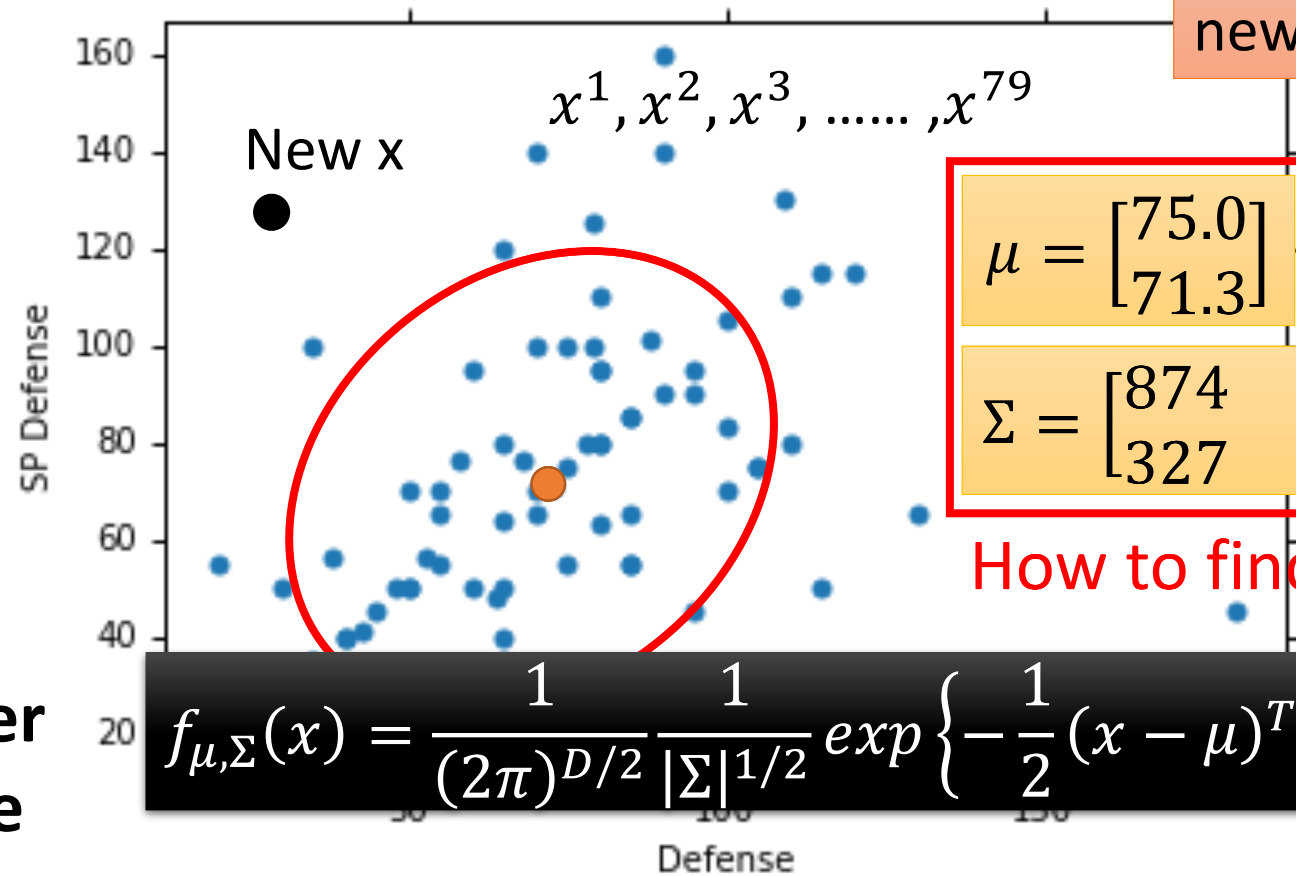
$$\mu = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \sum = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$



Probability from Class

Assume the points are sampled from a Gaussian distribution

Find the Gaussian distribution behind them → Probability for new points



New x

$x^1, x^2, x^3, \ldots\ldots, x^{79}$

$$\mu = \begin{bmatrix} 75.0 \\ 71.3 \end{bmatrix}$$

$$\Sigma = \begin{bmatrix} 874 & 327 \\ 327 & 929 \end{bmatrix}$$

How to find them?

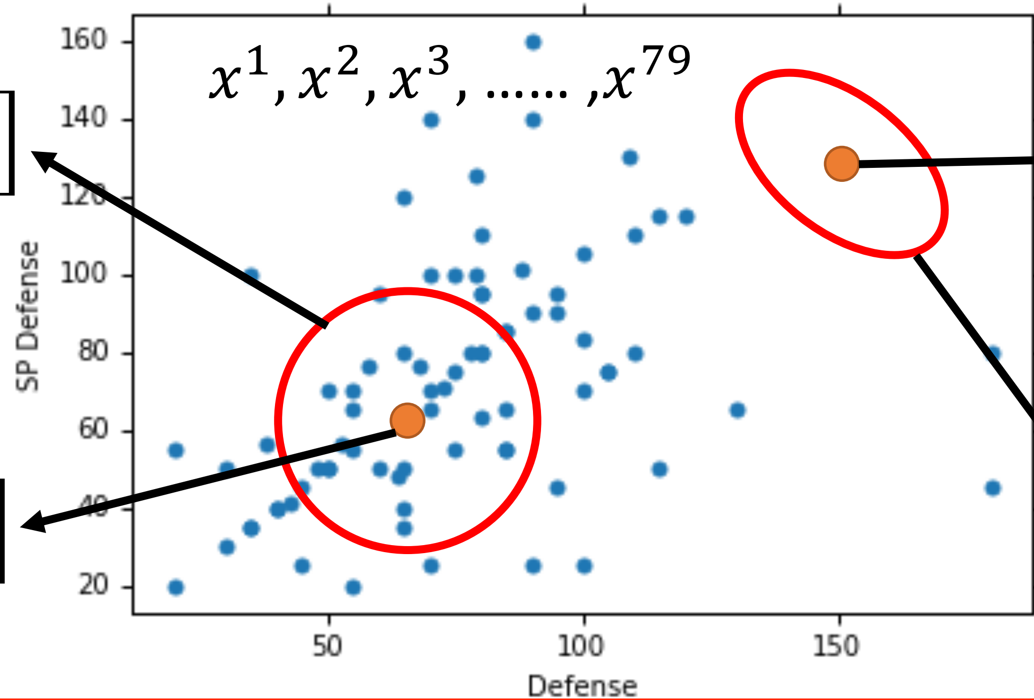
Water Type

$$f_{\mu,\Sigma}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)\right\}$$

Maximum Likelihood

$$f_{\mu,\Sigma}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu)\right\}$$

$$\sum = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix} \qquad \mu = \begin{bmatrix} 75 \\ 75 \end{bmatrix}$$



$$\mu = \begin{bmatrix} 150 \\ 140 \end{bmatrix} \qquad \sum = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

The Gaussian with any mean μ and covariance matrix Σ can generate these points. → Different Likelihood

Likelihood of a Gaussian with mean μ and covariance matrix Σ

= the probability of the Gaussian samples $x^1, x^2, x^3, \ldots\ldots, x^{79}$

$$\boxed{L(\mu,\Sigma) \;= f_{\mu,\Sigma}(x^1) f_{\mu,\Sigma}(x^2) f_{\mu,\Sigma}(x^3) \ldots\ldots f_{\mu,\Sigma}(x^{79})}$$

Maximum Likelihood

We have the "Water" type Pokémons: $x^1, x^2, x^3, \ldots\ldots, x^{79}$

We assume $x^1, x^2, x^3, \ldots\ldots, x^{79}$ generate from the Gaussian (μ^*, Σ^*) with the ***maximum likelihood***

$$L(\mu,\Sigma) = f_{\mu,\Sigma}(x^1) f_{\mu,\Sigma}(x^2) f_{\mu,\Sigma}(x^3) \ldots\ldots f_{\mu,\Sigma}(x^{79})$$

$$f_{\mu,\Sigma}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)\right\}$$

$$\boxed{\mu^*, \Sigma^* = arg \max_{\mu,\Sigma} L(\mu,\Sigma)}$$

窮舉所有的 Mean 與 Covariance Matrix (Sigma) 使 Likelihood 最大

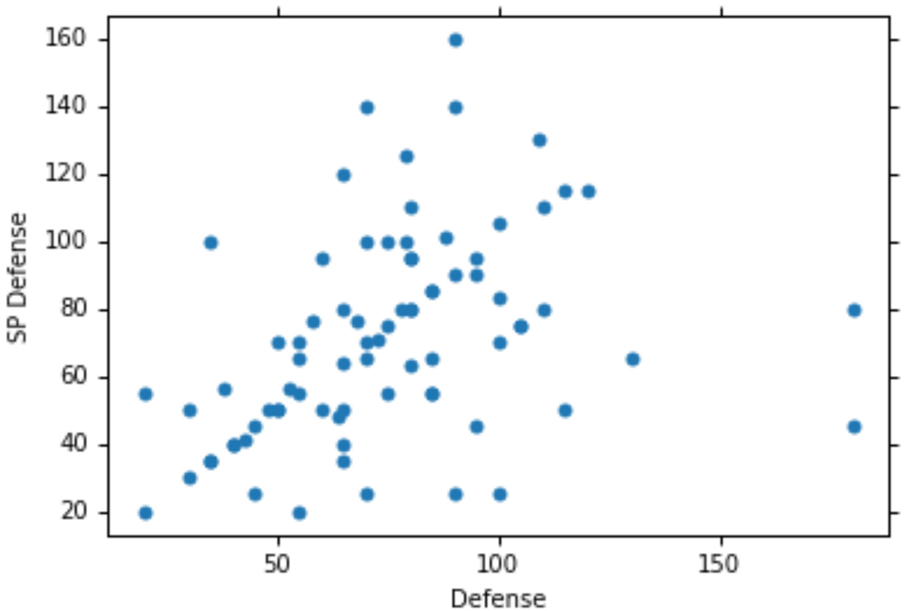
$$\boxed{\mu^* = \frac{1}{79}\sum_{n=1}^{79} x^n \qquad \Sigma^* = \frac{1}{79}\sum_{n=1}^{79}(x^n-\mu^*)(x^n-\mu^*)^T}$$

average

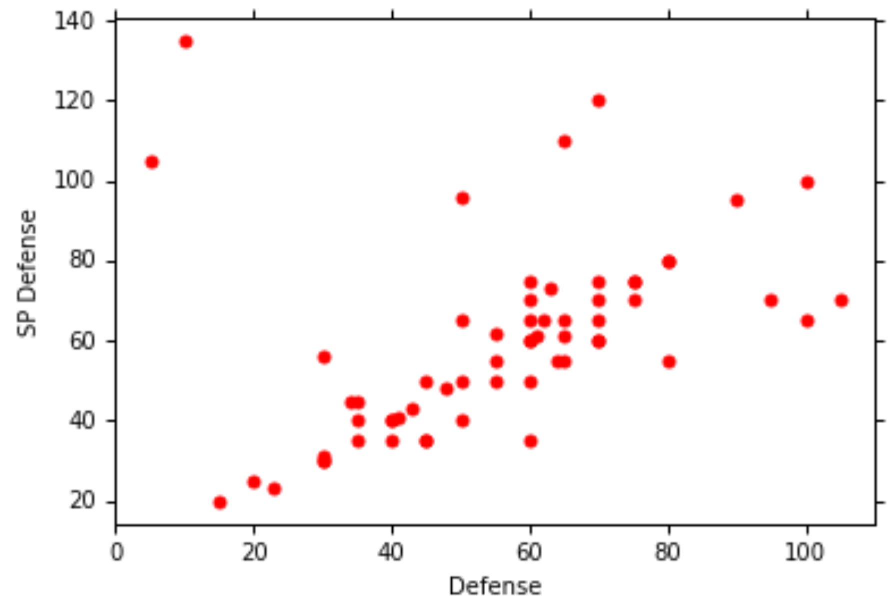
有 Maximum Likelihood 的 Gaussian Distribution 公式

Maximum Likelihood

Class 1: Water



Class 2: Normal



$$\mu^1 = \begin{bmatrix} 75.0 \\ 71.3 \end{bmatrix} \quad \Sigma^1 = \begin{bmatrix} 874 & 327 \\ 327 & 929 \end{bmatrix}$$

$$\mu^2 = \begin{bmatrix} 55.6 \\ 59.8 \end{bmatrix} \quad \Sigma^2 = \begin{bmatrix} 847 & 422 \\ 422 & 685 \end{bmatrix}$$

Now we can do classification ☺

$$f_{\mu^1,\Sigma^1}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma^1|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)\right\}$$

$$\mu^1 = \begin{bmatrix} 75.0 \\ 71.3 \end{bmatrix} \quad \Sigma^1 = \begin{bmatrix} 874 & 327 \\ 327 & 929 \end{bmatrix}$$

P(C1)
= 79 / (79 + 61) =0.56

likelihood prior

posterior

$$\boxed{P(C_1|x)} = \frac{\boxed{P(x|C_1)}\boxed{P(C_1)}}{P(x|C_1)P(C_1) + \boxed{P(x|C_2)}\boxed{P(C_2)}}$$

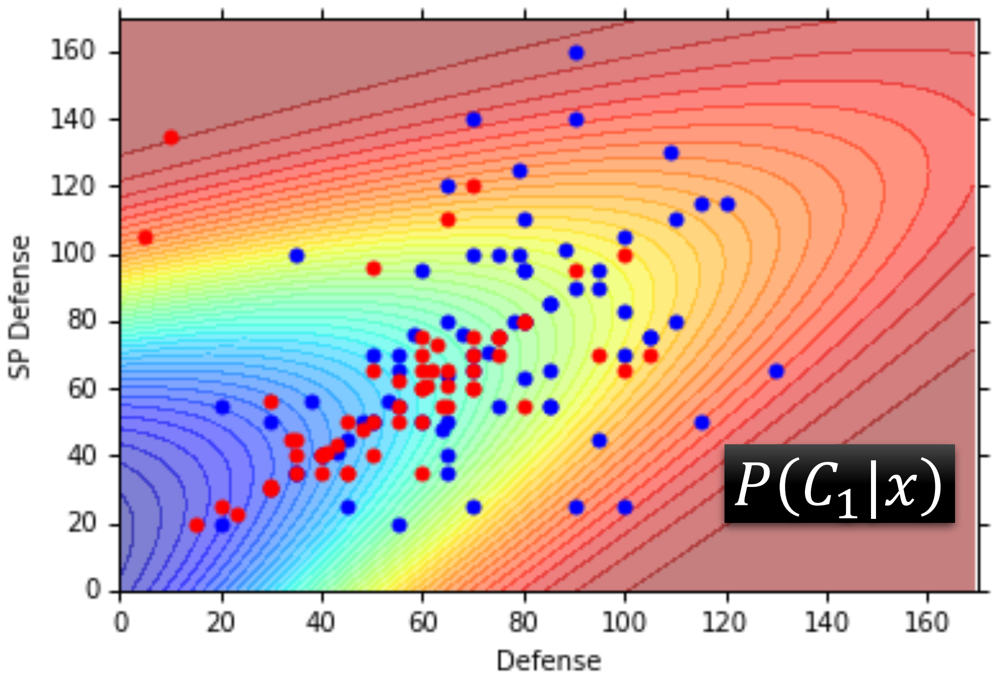
likelihood prior

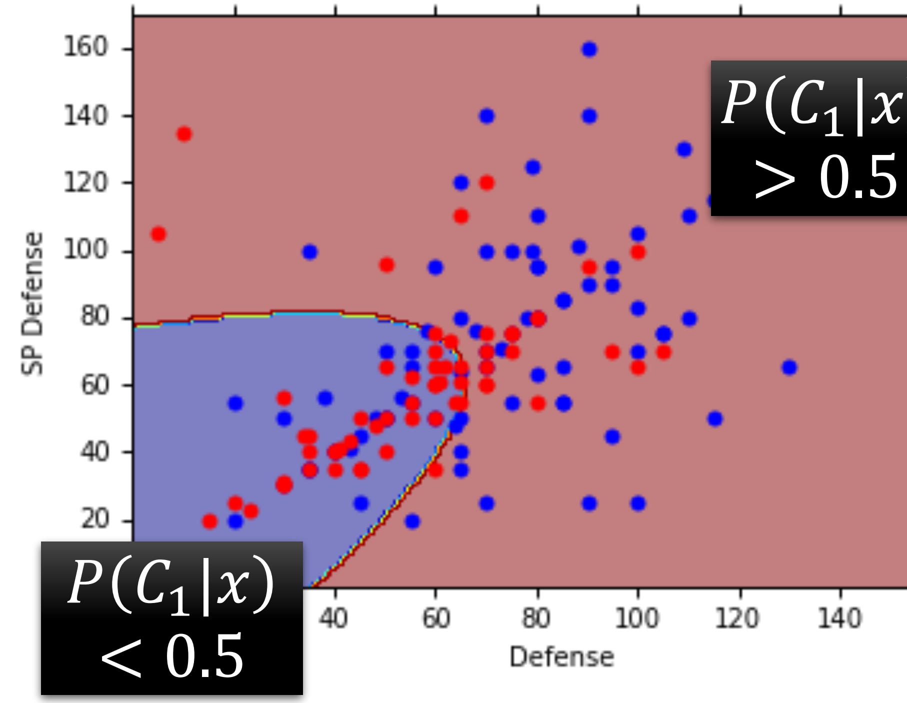
$$f_{\mu^2,\Sigma^2}(x) = \frac{1}{(2\pi)^{D/2}} \frac{1}{|\Sigma^2|^{1/2}} exp\left\{-\frac{1}{2}(x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)\right\}$$

$$\mu^2 = \begin{bmatrix} 55.6 \\ 59.8 \end{bmatrix} \quad \Sigma^2 = \begin{bmatrix} 847 & 422 \\ 422 & 685 \end{bmatrix}$$

P(C2)
= 61 / (79 + 61)
=0.44

If $P(C_1|x) > 0.5$ ➡ x belongs to class 1 (Water)

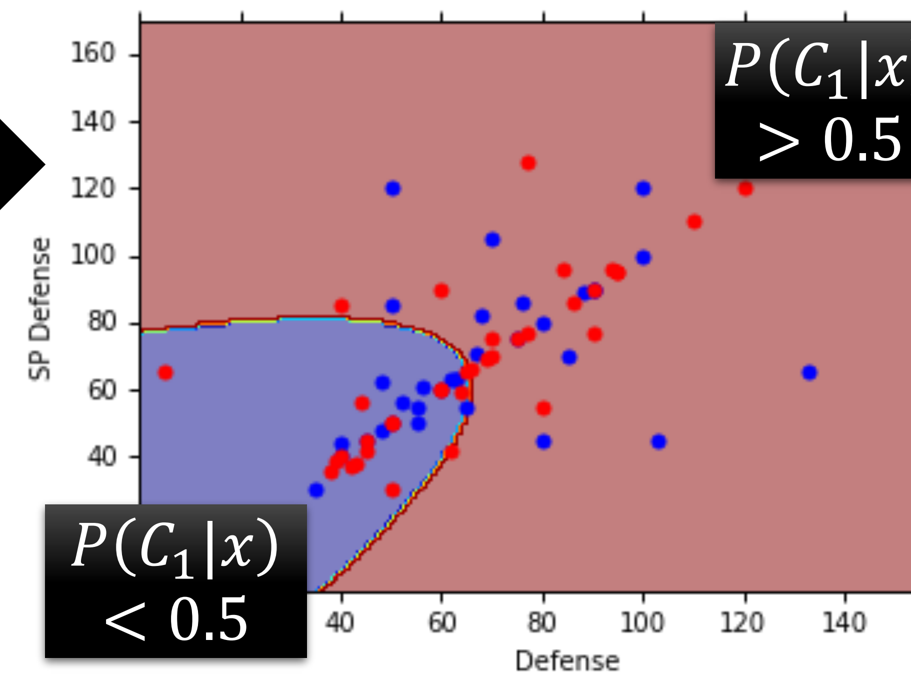




Blue points: C_1 (Water), Red points: C_2 (Normal)

How's the results? Model 的表現不好

Testing data: 47% accuracy



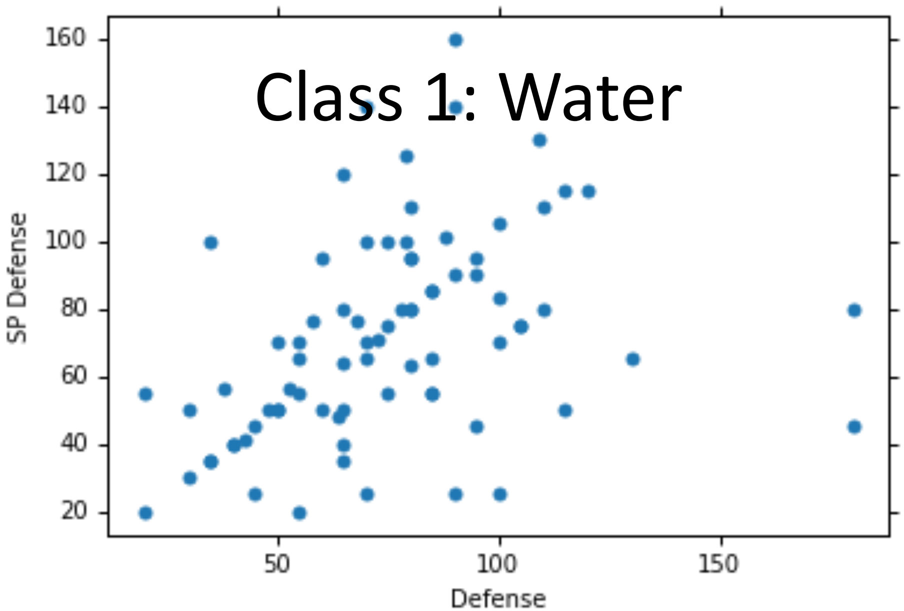
All: total, hp, att, sp att, de, sp de, speed (7 features)

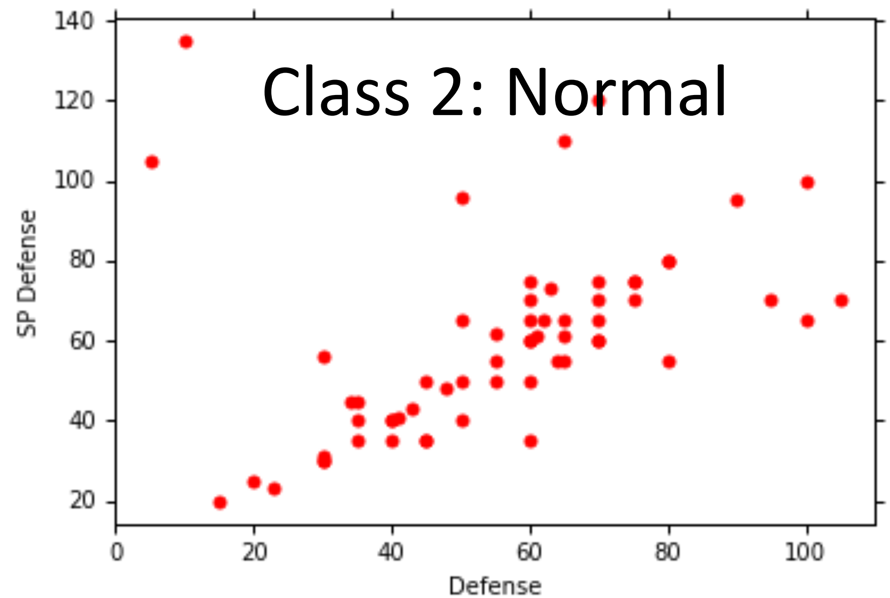
μ^1, μ^2: 7-dim vector

Σ^1, Σ^2: 7 x 7 matrices

54% accuracy … ☹

Modifying Model





$$\mu^1 = \begin{bmatrix} 75.0 \\ 71.3 \end{bmatrix} \quad \Sigma^1 = \begin{bmatrix} 874 & 327 \\ 327 & 929 \end{bmatrix} \qquad \mu^2 = \begin{bmatrix} 55.6 \\ 59.8 \end{bmatrix} \quad \Sigma^2 = \begin{bmatrix} 847 & 422 \\ 422 & 685 \end{bmatrix}$$

將兩個 Class 的 Gaussian Distribution 的 Covariance Matrix 設為相同的 => 減少 Model 的參數量 => 避免 Overfitting

The same Σ

Less parameters

Modifying Model

Ref: Bishop, chapter 4.2.2

- Maximum likelihood

兩個 Gaussian Distribution 使用各自的 Mean 但是使用共同的 Covariance Matrix

"Water" type Pokémons:

$x^1, x^2, x^3, \ldots\ldots, x^{79}$

"Normal" type Pokémons:

$x^{80}, x^{81}, x^{82}, \ldots\ldots, x^{140}$

μ^1 $\qquad$ Σ $\qquad$ μ^2

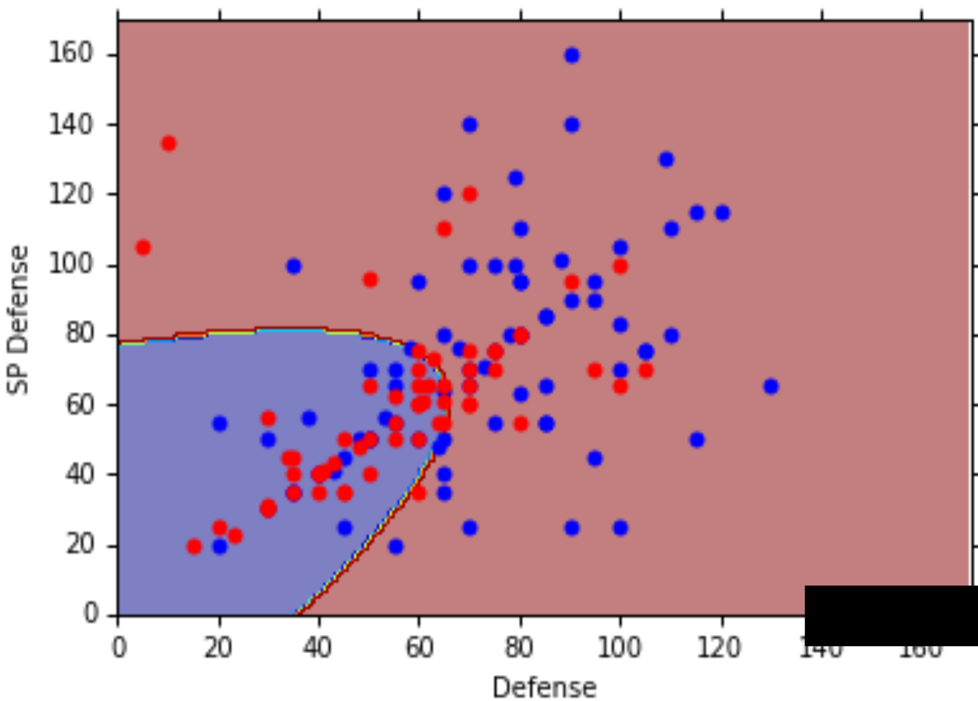
Find μ^1, μ^2, Σ maximizing the likelihood $L(\mu^1, \mu^2, \Sigma)$

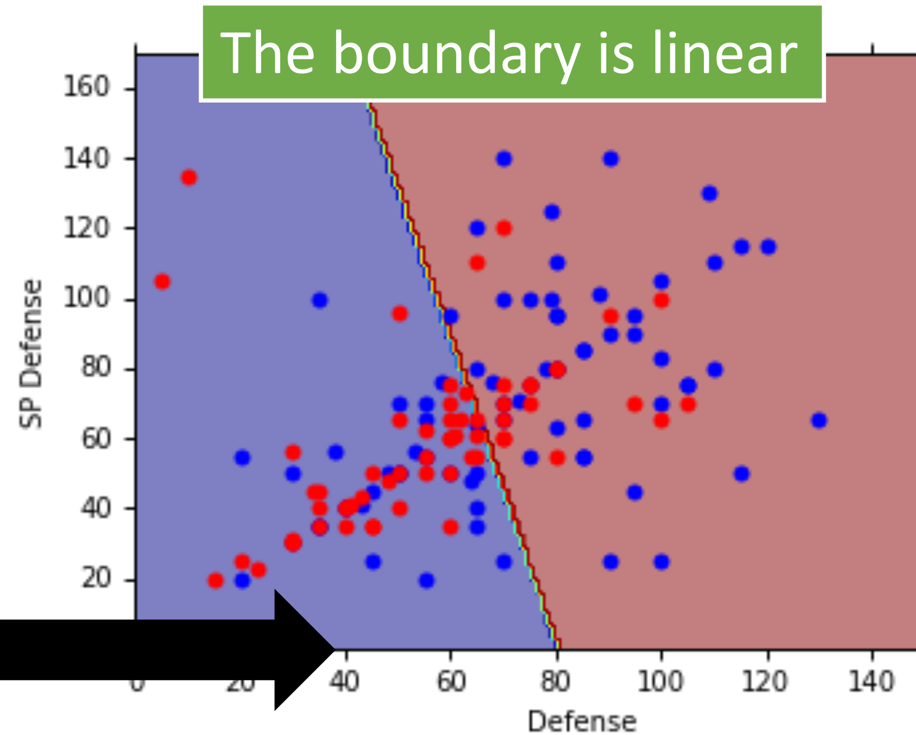
$$L(\mu^1, \mu^2, \Sigma) = f_{\mu^1,\Sigma}(x^1) f_{\mu^1,\Sigma}(x^2) \cdots f_{\mu^1,\Sigma}(x^{79}) \times f_{\mu^2,\Sigma}(x^{80}) f_{\mu^2,\Sigma}(x^{81}) \cdots f_{\mu^2,\Sigma}(x^{140})$$

μ^1 and μ^2 is the same

$$\Sigma = \frac{79}{140}\Sigma^1 + \frac{61}{140}\Sigma^2$$

Modifying Model





The same covariance matrix

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

54% accuracy → 73% accuracy

解決 Machine Learning 問題的三步驟！

Three Steps

- Function Set (Model): Prior 與 Likelihood 就「參數」

$x \Rightarrow$

$$P(C_1|x) = \frac{P(x|C_1)P(C_1)}{P(x|C_1)P(C_1) + P(x|C_2)P(C_2)}$$

If $P(C_1|x) > 0.5$, output: class 1

Otherwise, output: class 2

- Goodness of a function:
  - The mean μ and covariance Σ that maximizing the likelihood (the probability of generating data)
- Find the best function: easy

Probability Distribution

- You can always use the distribution you like ☺

$$P(x|C_1) = P(x_1|C_1)\ P(x_2|C_1) \quad \cdots\cdots \quad P(x_k|C_1) \quad \cdots\cdots$$

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \\ \vdots \\ x_K \end{bmatrix}$$

1-D Gaussian

For binary features, you may assume they are from Bernoulli distributions.

If you assume all the dimensions are independent, then you are using *Naive Bayes Classifier*.

Posterior Probability

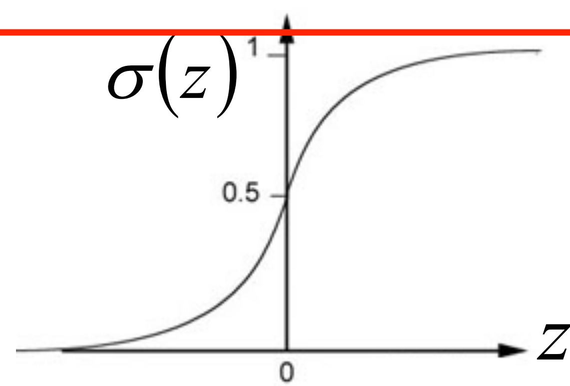
關鍵：Posterior Probability 可以轉為 Sigmoid Function (z)

$$P(C_1|x) = \frac{P(x|C_1)P(C_1)}{P(x|C_1)P(C_1) + P(x|C_2)P(C_2)}$$

$$= \frac{1}{1 + \frac{P(x|C_2)P(C_2)}{P(x|C_1)P(C_1)}} = \frac{1}{1 + exp(-z)} = \sigma(z)$$

Sigmoid function

$$z = ln \frac{P(x|C_1)P(C_1)}{P(x|C_2)P(C_2)}$$



Warning of Math

Posterior Probability

$$P(C_1|x) = \sigma(z)$$ sigmoid $$z = ln\frac{P(x|C_1)P(C_1)}{P(x|C_2)P(C_2)}$$

$$z = ln\frac{P(x|C_1)}{P(x|C_2)} + ln\boxed{\frac{P(C_1)}{P(C_2)}} \Rightarrow \frac{\frac{N_1}{N_1+N_2}}{\frac{N_2}{N_1+N_2}} = \frac{N_1}{N_2}$$

$$P(x|C_1) = \frac{1}{(2\pi)^{D/2}}\frac{1}{|\Sigma^1|^{1/2}}exp\left\{-\frac{1}{2}(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)\right\}$$

$$P(x|C_2) = \frac{1}{(2\pi)^{D/2}}\frac{1}{|\Sigma^2|^{1/2}}exp\left\{-\frac{1}{2}(x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)\right\}$$

$$z = \boxed{ln\frac{P(x|C_1)}{P(x|C_2)}} + ln\boxed{\frac{P(C_1)}{P(C_2)}} = \frac{N_1}{N_2}$$

$$P(x|C_1) = \frac{1}{(2\pi)^{D/2}}\frac{1}{|\Sigma^1|^{1/2}}exp\left\{-\frac{1}{2}(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)\right\}$$

$$P(x|C_2) = \frac{1}{(2\pi)^{D/2}}\frac{1}{|\Sigma^2|^{1/2}}exp\left\{-\frac{1}{2}(x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)\right\}$$

$$ln\frac{\cancel{\frac{1}{(2\pi)^{D/2}}}\boxed{\frac{1}{|\Sigma^1|^{1/2}}}\boxed{exp\left\{-\frac{1}{2}(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)\right\}}}{\cancel{\frac{1}{(2\pi)^{D/2}}}\boxed{\frac{1}{|\Sigma^2|^{1/2}}}\boxed{exp\left\{-\frac{1}{2}(x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)\right\}}}$$

$$= \boxed{ln\frac{|\Sigma^2|^{1/2}}{|\Sigma^1|^{1/2}}}\boxed{exp\left\{-\frac{1}{2}[(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1) - (x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)]\right\}}$$

$$= ln\frac{|\Sigma^2|^{1/2}}{|\Sigma^1|^{1/2}} - \frac{1}{2}[(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1) - (x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)]$$

$$z = \boxed{ln\frac{P(x|C_1)}{P(x|C_2)}} + ln\boxed{\frac{P(C_1)}{P(C_2)}} = \frac{N_1}{N_2}$$

$$= ln\frac{|\Sigma^2|^{1/2}}{|\Sigma^1|^{1/2}} - \frac{1}{2}\left[\underline{(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)} - \underline{(x-\mu^2)^T(\Sigma^2)^{-1}(x-\mu^2)}\right]$$

$$(x-\mu^1)^T(\Sigma^1)^{-1}(x-\mu^1)$$

$$= x^T(\Sigma^1)^{-1}x \underline{- x^T(\Sigma^1)^{-1}\mu^1 - (\mu^1)^T(\Sigma^1)^{-1}x} + (\mu^1)^T(\Sigma^1)^{-1}\mu^1$$

$$= x^T(\Sigma^1)^{-1}x \underline{- 2(\mu^1)^T(\Sigma^1)^{-1}x} + (\mu^1)^T(\Sigma^1)^{-1}\mu^1$$

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

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

$$\boxed{\begin{aligned} z = ln\frac{|\Sigma^2|^{1/2}}{|\Sigma^1|^{1/2}} &- \frac{1}{2}x^T(\Sigma^1)^{-1}x + (\mu^1)^T(\Sigma^1)^{-1}x - \frac{1}{2}(\mu^1)^T(\Sigma^1)^{-1}\mu^1 \\ &+ \frac{1}{2}x^T(\Sigma^2)^{-1}x - (\mu^2)^T(\Sigma^2)^{-1}x + \frac{1}{2}(\mu^2)^T(\Sigma^2)^{-1}\mu^2 + ln\frac{N_1}{N_2} \end{aligned}}$$

End of Warning

$$P(C_1|x) = \sigma(z)$$

$$z = \cancel{ln\frac{|\Sigma^2|^{1/2}}{|\Sigma^1|^{1/2}}} \cancel{-\frac{1}{2}x^T(\Sigma^1)^{-1}x} + (\mu^1)^T(\Sigma^1)^{-1}x - \frac{1}{2}(\mu^1)^T(\Sigma^1)^{-1}\mu^1$$
$$\cancel{+\frac{1}{2}x^T(\Sigma^2)^{-1}x} - (\mu^2)^T(\Sigma^2)^{-1}x + \frac{1}{2}(\mu^2)^T(\Sigma^2)^{-1}\mu^2 + ln\frac{N_1}{N_2}$$

$$\Sigma_1 = \Sigma_2 = \Sigma$$

$$z = \underbrace{(\mu^1 - \mu^2)^T\Sigma^{-1}}_{\boldsymbol{w^T}}x \underbrace{- \frac{1}{2}(\mu^1)^T\Sigma^{-1}\mu^1 + \frac{1}{2}(\mu^2)^T\Sigma^{-1}\mu^2 + ln\frac{N_1}{N_2}}_{\mathrm{b}}$$

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

How about directly find ***w*** and b?

In generative model, we estimate $N_1, N_2, \mu^1, \mu^2, \Sigma$

Then we have ***w*** and b