

dm22s1

## Topic 10 : Classification2

### Part 01 : Classification2-Overview

Preparation

Data Handling

Exploring Data 1

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Exploring Data 2

Building Models

Prediction

Autumn Semester, 2022

#### Outline

- Decision Trees
- Naive Bayes

Wrap up

# Data Mining (Week 10)

Introduction

Motivating Example

## Preparation

Data Handling

Exploring Data 1

Exploring Data 2

Building Models

## Prediction

Regression  
1

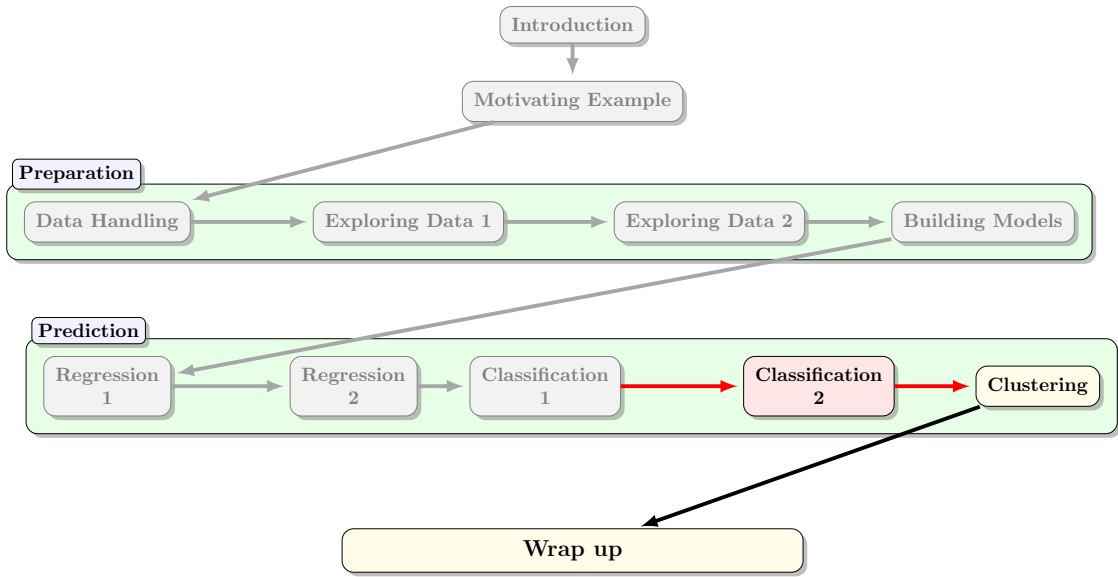
Regression  
2

Classification  
1

Classification  
2

Clustering

Wrap up



# Classification2-Overview — Summary

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1. Introduction	4
2. Classification Trees	6
3. Naive Bayes classification	21
4. Resources	31

# Outline

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# This Week's Aim

This week's aim is to introduce some more advanced techniques used for **classification**. Remember: you have already met *logistic regression* and *k nearest neighbours* in Topics 9 and 2.

The new approaches are:

- A technique that uses a series of questions to classify a data set (Decision Trees)
- A technique that uses probability directly to classify a data set (Naive Bayes)

These are two of the Top 10 algorithms in data mining (**WuKumarRossQuinlanEtAl2008**), each with its own strengths and weaknesses.

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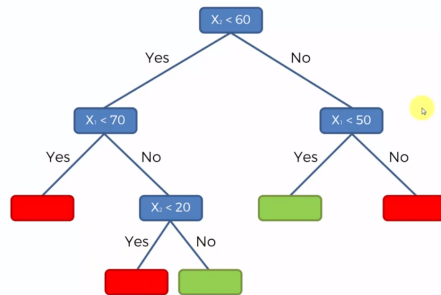
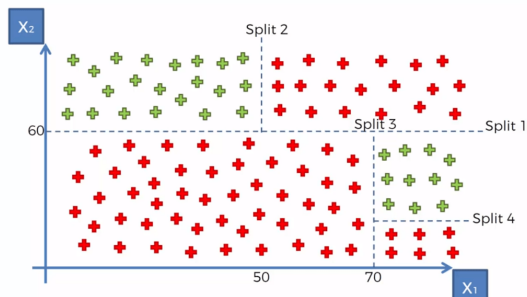
# Motivation

Twenty Questions is a powerful way of learning (identifying something)

## Can it be used to predict categorical variables?

- Assume we have a set of  $l$  labels to assign to  $n_{\text{test}}$  data observations
- During training we repeatedly partition the training set using a sequence of ever finer rules
- The resulting decision tree generates a mapping from *attributes* of an item (the mapping is defined by a path from root to leaf) to conclusions about the item's target value (represented in the leaves).
- The rules which generate the binary splits are applied in a greedy fashion and are intended to reduce the *impurity* in each nodes' children as quickly as possible
- the algorithm proceeds top-down from the root (all data), recursively generating rules as it goes
- Prediction is simple: the rules are applied along the path from root to leaf. The predicted class value is either the most frequent value at the leaf, or the leaf's probability vector.

# Classification tree visualisation

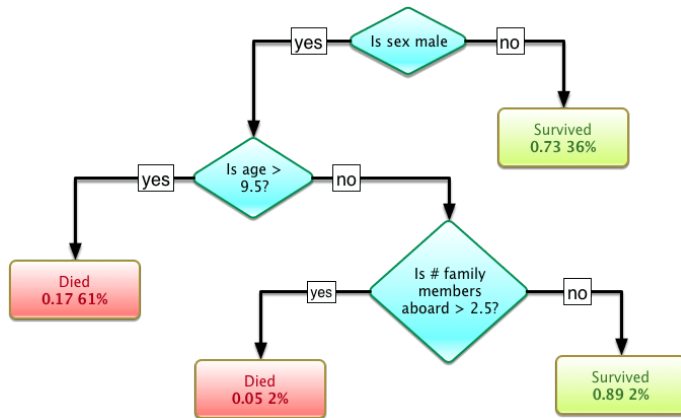


Source: <http://diamondclover.com/dtc.html>

Note how successive splits reduce the mixing between the red and green symbols.



# Classification tree example: Titanic survival



- First split is on Sex, as that attribute was the most important predictor of survival.
- Leaves show the probability of survival and the percentage of training observations in the leaf.
- Percentages sum to 100% (approximately), as the leaves partition the training data.
- Leaf colour indicates  $p(\text{survival}) \approx 1$  (green) or  $p(\text{survival}) \approx 0$  (red)

# Information Entropy: intuition

Probability	Information	Perceived as
Low	High	Surprising
High	Low	Unsurprising

## Example

If it is winter in Ireland, and Met Eireann forecast that tomorrow will have a temperature of 10 degrees C, nobody would pay much attention. If, on the other hand, they said it would be 40 degrees C, everyone would notice!

➤ (Information) entropy is the average amount of information conveyed by an event, when considering all possible events

## How information is measured

Information is measured in bits, and is computed from the probability  $P(x)$  using  $h(x) = -\log_2(P(x))$ .

# Information Entropy: Applied to classification

## Classification and entropy

- Given a set of observations with the same label, we wish to make membership of that set as unsurprising as possible as possible, given the training set.
- Can we partition a set of observations to achieve this, so that it is “obvious” that the label assignments are correct?

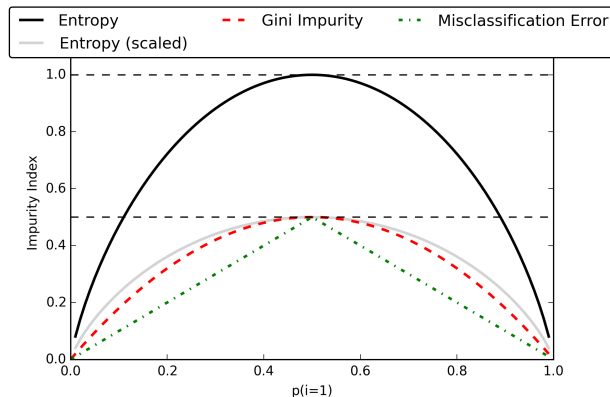
## Definition 1 ((Information) Entropy)

$$H(X) = - \sum_{i=1}^n P(x_i) \log_2(P(x_i))$$

where  $X = \{x_i\}$ . If all probabilities are equal ( $X$  is uniformly distributed),  $H(X) = 1$ . If they differ,  $H(X) < 1$ . Remember the weather forecasting example!

A decision tree recursively partitions a set so as to increase the purity (equivalently: reduce the mixing) of the set of observations  $X$  at each node as we move from the root to the leaves.

# Classification tree metrics for rule building



Let  $p_i$  be the probability of an item with label  $1 < i < J$  being chosen. Then the *GINI* impurity is  $1 - \sum_{i=1}^J p_i^2$ . Worst case (maximum impurity): labels are uniformly distributed (entropy of the set is maximum: each value of the label appears the same number of times in the set of observations at that node). We wish to minimise this entropy.

## Sidebar: Entropy and Information Gain

### Definition 2 (Entropy)

Entropy is a concept from *thermodynamics* and *information theory*. Here it measures the *impurity* of a collection of items. It ranges from 0 (only 1 item, possibly repeated) to 1 (equal numbers of each item type). Mathematically, it is defined for *one attribute*  $T$  as  $H(T) = - \sum_{j=1}^J p_j \log_2 p_j$ , in a collection of size  $N$  where there are  $J$  unique elements of  $T$ , hence  $p_j = \frac{n_j}{N}$  where there are  $n_j$  elements of type  $j$ . For *two attributes*  $T$  and  $X$ ,  $H(T, X) = \sum_{c \in X} P(c) E(c)$  where each  $c$  represents a level of the  $X$  attribute.

### Definition 3 (Information Gain)

Information Gain measures the decrease in entropy after a dataset is split on an attribute. It is defined as  $G(T, X) = H(T) - H(T, X)$ , where  $H(T)$  is the entropy at the parent node, and  $H(T, X)$  is the entropy after the split by candidate attribute  $X$ .

## Example: PlayTennis example data

outlook	temp	humidity	windy	play
sunny	hot	high	false	no
sunny	hot	high	true	no
overcast	hot	high	false	yes
rainy	mild	high	false	yes
rainy	cool	normal	false	yes
rainy	cool	normal	true	no
overcast	cool	normal	true	yes
sunny	mild	high	false	no
sunny	cool	normal	false	yes
rainy	mild	normal	false	yes
sunny	mild	normal	true	yes
overcast	mild	high	true	yes
overcast	hot	normal	false	yes
rainy	mild	high	true	no

*Source: Mitchell, Machine Learning, 1997.*

# PlayTennis example calculations

## Example 4 ( $H(\text{play})$ )

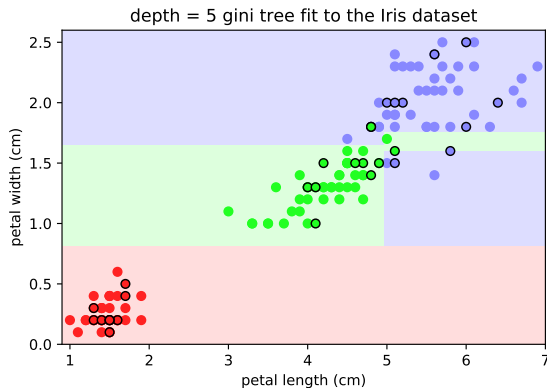
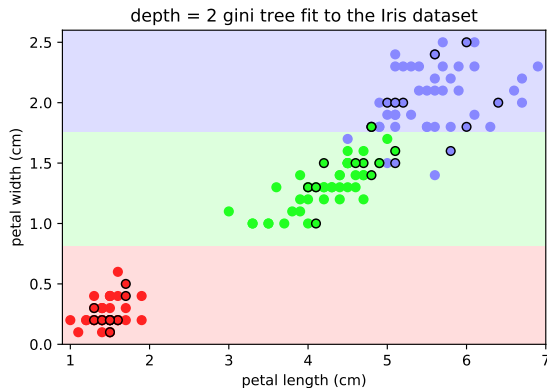
$$\begin{aligned}
 H(\text{play}) &= -(p(\text{play} = \text{yes}) \log_2 p(\text{play} = \text{yes}) + p(\text{play} = \text{no}) \log_2 p(\text{play} = \text{no})) \\
 &= H_{9,5} \\
 &= - \left( \frac{9}{14} \log_2 \left( \frac{9}{14} \right) + \frac{5}{14} \log_2 \left( \frac{5}{14} \right) \right) \approx 0.94
 \end{aligned}$$

## Example 5 ( $H(\text{play}, \text{outlook})$ )

$$\begin{aligned}
 H(\text{play}, \text{outlook}) &= p(\text{outlook} = \text{sunny})H(\text{play} \& (\text{outlook} = \text{sunny})) + \dots \\
 &= p(\text{outlook} = \text{sunny})H_{3,2} + p(\text{outlook} = \text{overcast})H_{4,0} + \dots \\
 &\approx \frac{5}{14}0.97 + \frac{4}{14}0 + \frac{5}{14}0.97 \\
 &\approx 0.69
 \end{aligned}$$

When growing decision trees, at a given node we search over the attributes for splitting, and choose the one that gives the maximum information gain, until we reach a leaf, which has an entropy of zero.

# Classification tree examples: Iris Data



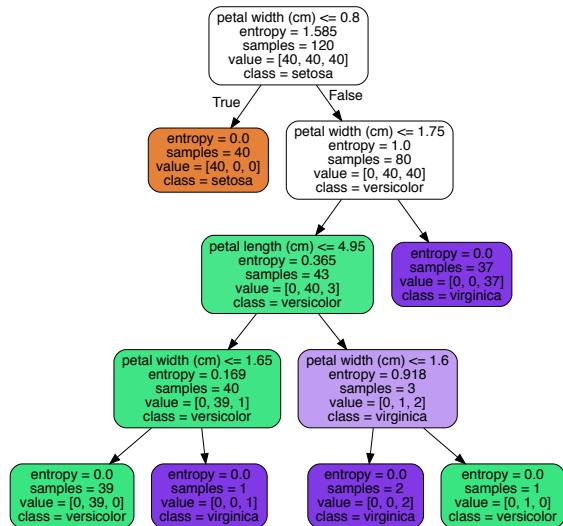
Note the rectangular regions (because each split is over one variable) and the greater complexity when the maximum depth of the tree increases.

Points within a dark circle represent test data, with the main colour of the point indicating its species label. The choice of metric (Gini impurity or Information Gain) makes only slight changes to fit.



# Classification tree view: Iris Data

Note that the leaf nodes are pure (entropy=0) and are coloured according to predicted value (species label): brown for *I. setosa*, green for *I. versicolor* and purple for *I. virginica*.



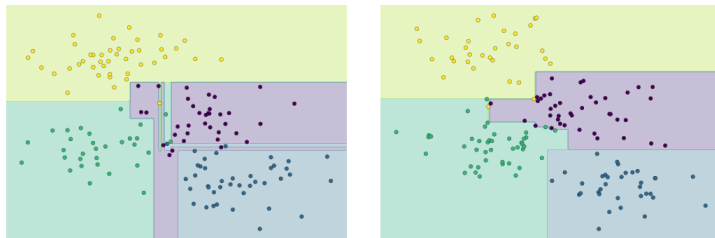
# Classification tree: Use for Prediction

Now that we have a decision tree, how do we use it to predict the label?

## Example: estimating the species of an iris plant

- Let Petal\_Width = 1.5cm and Petal\_Length = 5cm. The other (sepal) dimensions are ignored by the decision tree because they were not as useful for classification.
- The first split (Petal\_Width  $\leq 0.8$ ) is False so we take the *right* branch.
- The second split (Petal\_Width  $\leq 1.75$ ) is True so we take the *left* branch.
- The third split (Petal\_Length  $\leq 4.95$ ) is False so we take the *right* branch.
- The fourth split (Petal\_Width  $\leq 1.6$ ) is True so we take the *left* branch.
- We have reached a leaf (entropy = 0) and cannot split any further.
- Depending on where we stop, we would assign the prevalent label for that node (versicolor, versicolor, virginica or virginica if the max\_depth was 2, 3, 4 or 5, respectively).

# Be careful of overfitting...



- Given two very similar (generated) data sets, all leaves in each fitted decision tree are *pure*.
- The resulting trees look very different.
- This sensitivity to the noise in the data is characteristic of *overfitting* (high variance).
- Control by a) limiting depth or b) limiting number of leaves.

# Classification trees in python

```
1 tree = DecisionTreeClassifier(criterion=criterion, max_depth=treeDepth, random_state=0)
2 tree.fit(Xtrain, ytrain)
3 y_treeTest = tree.predict(Xtest)
4 print(accuracy_score(ytest, y_treeTest))
5 print(confusion_matrix(ytest, y_treeTest))
6 print(classification_report(ytest, y_treeTest, digits=3))
```

After creating the classifier object, fit the training data and then use the fit to predict yTest from xTest. I have also shown how to get some diagnostic output. Similar diagnostics can be obtained for other classifiers.

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# Rev. Bayes and his theorem



Rev. Thomas Bayes, 1702–1761

## Usage

Given  $P(E|H)$  (Probability of Evidence (attributes) given the Hypothesis (the known classes) in the *training* set), Bayes theorem shows how to invert this relationship to get  $P(H|E)$  (Probability of the Hypothesis (class) given the evidence (attributes) with an (unseen) *test case*).

## Bayes' Theorem

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (1)$$

where  $P(X|Y)$  is the conditional probability of  $X$  given that we know  $Y$  is true.

## Application to classification

By convention,  $A = H$  and  $B = E$ , where  $H$  is the **hypothesis** and  $E$  is the **evidence** in support of that hypothesis.

With this interpretation, the Bayes identity can be used to predict class probabilities (hypothesis) from features (evidence).

# Conditional probabilities and Bayes terminology

## Definition 6 (Conditional Probability)

If  $A$  and  $B$  are events, the Probability of  $A$ , given that  $B$  is true (has happened), written  $P(A|B)$  is defined as follows:

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \quad (2)$$

where  $P(A \cap B)$  is the probability that both  $A$  and  $B$  are true.

Given Bayes Theorem 1, we have

Term	Description
$P(A)$	Class prior; Prior probability
$P(B)$	Predictor prior; evidence
$P(A B)$	Posterior probability; Updated Class Prior
$P(B A)$	Likelihood

- In courtrooms,  $B$  might represent the available evidence in favour of guilt, and  $A$  might represent the verdict “is guilty”.
- In data mining,  $B$  might represent the features (derived from the **Data**) for a given instance and  $A$  might represent the *predicted label* for these features.
- If  $A$  and  $B$  are independent events,  $P(A \cap B) \equiv P(A)P(B)$ , so  $P(A|B) = P(A)$  and  $P(B|A) = P(B)$ .

# Extended and Bayes

➤ In practice, there would be multiple features/evidence so  $B = \{B_1, B_2, \dots, B_n\}$

## Definition 7 (Extended Bayes Theorem)

The **extended form**, when  $\{B_j\}$  partition  $B$ , so  $B = \cup_j B_j$  and  $B_p \cap B_q \equiv \emptyset$  unless  $p = q$ , is

$$P(A|\{B_i\}) = \frac{P(\{B_i\}|A)P(A)}{P(\{B_i\})} \quad (3)$$

which is the component-wise version of the standard Bayes Theorem.

## Side note: Prosecutor's Fallacy

Note that  $P(A|B) \neq P(B|A)$  in general. If the ratio  $\frac{P(A)}{P(B)}$  is not close to 1, lawyers can mislead jurors regarding guilt or innocence.



# Naive Extended Bayes

## Definition 8 (Naive Bayes)

If the features  $B$  are assumed to be independent of each other, it can be shown that

$$P(B) = P(B_1 \cap B_2 \cap \dots B_n) = \prod_i P(B_i) \quad (4)$$

$$P(B|A_j) = \prod_k P(B_i|A_j) \quad (5)$$

The naïve form of Bayes theorem becomes

$$P(A_j|B) = \frac{\prod_i P(B_i|A_j)P(A_j)}{\prod_i P(B_i)} \quad (6)$$

# Naive Bayes classifier

## Definition 9 (Naive Bayes classifier)

The Naive Bayes algorithm predicts a class, given a set of set of features, using probability principles. It is naive because it assumes the features are statistically independent (rarely true in practice). The training data is used to estimate the probabilities and likelihood. Bayes theorem is used to predict the observation's membership of each class (associated with a label). It is then assigned to the class for which its conditional probability is greatest.

## Interpretation

- Both the simple and extended Bayes Theorem provide a formula to flip between “B given A” (data given labels) to “A given B” (labels given data).
- From the Training set, we can calculate
  - $P(A_j)$  (prior probability of each class label),
  - $P(B_i)$  (the predictor prior) and
  - $P(B_i|A_j)$  (the evidence that the feature valued  $B_i$  predicts the class label  $A_j$ ).
- From this, we can use the naive version of the extended Bayes Theorem 6 to predict  $P(A_j|B)$ , the posterior probability of class label  $A_j$  given all the evidence from the features  $B$ .

# Overview of Naïve Bayes algorithm

- In the *Training Phase*, the method precomputes various probabilities  $P(A_j)$  and conditional probabilities  $P(B_k|A_j)$ .
- In the *Prediction Phase*
  - the extended form of Bayes' Theorem 6 is used to compute the posterior class probabilities  $P(A_j|B)$  for the given observation.
  - according to the *Maximum A Posteriori* (MAP) criterion, the observation is assigned to the class with the highest probability from  $P(A_j|B)$ .
- One of the features of Naïve Bayes (with  $P(A|B)$ ), like decision trees (with  $P(A \cap B)$ ), is the direct role played by probability
- When training Naïve Bayes, it is convenient to compute a table of *marginal counts*, as seen in the next slidei, and to use these for prediction.

# Fruit classification example

## Example: Fruit classification

Type	Long	¬Long	Sweet	¬Sweet	Yellow	¬Yellow	Total
Banana	400	100	350	150	450	50	500
Orange	0	300	150	150	300	0	300
Other	100	100	150	50	50	150	200
Total	500	500	650	350	800	200	1000

Source: [stackoverflow](#)

## Fruit classification : Precalculations

$$P(\langle \text{Fruit} \rangle) = \text{Total}_{\langle \text{Fruit} \rangle} / \text{Total}_{*}$$

$$P(\langle \text{Feature} \rangle) = \text{Total}_{\langle \text{Feature} \rangle} / \text{Total}_{*}$$

$$P(\langle \text{Feature} \rangle \mid \langle \text{Fruit} \rangle) = \langle \text{Fruit}, \text{Feature} \rangle / \text{Total}_{\langle \text{Fruit} \rangle}$$

$$\rightarrow P(\text{Other}) = 200/1000 = 0.2$$

$$\rightarrow P(\text{Sweet}) = 650/1000 = 0.65$$

$$\rightarrow P(\text{Sweet} \mid \text{Other}) = 150/200 = 0.75$$

# Fruit classification example: prediction

Given observation: Long=L, Sweet=S, Yellow=Y fruit, which is it?

Banana - B

$$P(B|L, S, Y) =$$

$$\frac{P(L|B)P(S|B)P(Y|B)P(B)}{P(L)P(S)P(Y)}$$

$$= \frac{0.8 \times 0.7 \times 0.9 \times 0.5}{0.5 \times 0.65 \times 0.8}$$

$$= 0.97$$

Orange - O

$$P(O|L, S, Y) =$$

$$\frac{P(L|O)P(S|O)P(Y|O)P(O)}{P(L)P(S)P(Y)}$$

$$= \frac{0.0 \times 0.5 \times 1.0 \times 0.3}{0.5 \times 0.65 \times 0.8}$$

$$= 0$$

Other = R

$$P(R|L, S, Y) =$$

$$\frac{P(L|R)P(S|R)P(Y|R)P(R)}{P(L)P(S)P(Y)}$$

$$= \frac{0.5 \times 0.75 \times 0.25 \times 0.2}{0.5 \times 0.65 \times 0.8}$$

$$= 0.07$$

➤ According to the MAP criterion, the observation (mystery fruit) is a banana!

Given the 3 binary-valued attributes, there are  $2^3 = 8$  possible combinations - Naïve Bayes will classify each of these 8 combinations as one of the 3 fruit classes.

# Naïve Bayes Classifier summary

- Advantages
  - Conceptually simple and easy to implement
  - Fast and scalable
  - Variants exist for numeric (Gaussian-), binary (Bernoulli-) and multi-class (multinomial-) featured Naïve Bayes
  - Particularly good for text classification and email spam detection
- Disadvantages
  - Ignores feature relationships
  - Be careful of zero-valued conditional probabilities and numerical underflow
  - Prone to underfitting (high bias)
- For prediction  $F(X) \rightarrow Y$ 
  - Most classifiers are **discriminative**—they learn  $P(Y|X)$ : “Given data  $X$ , what class  $Y$  is it?”
  - Naïve Bayes is **generative**—it learns  $P(X|Y)$  and  $P(Y)$ : “Given classes  $Y$ , what data fits each class, and how often do those classes occur?”
- Implementations exist in `sklearn`: `from sklearn.naive_bayes import GaussianNB, etc.`

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# Summary

- Classification is one of the main tasks in data mining, and is a mature and well-studied field
  - k-nearest-neighbours is conceptually simple (based on voting) and the lack of a model (lazy learning) means it responds better to data drift
  - Logistic regression is an extension of linear regression and benefits from its strengths
  - Decision trees learn a representation that is often easily interpretable, but works better with linear boundaries
  - Naïve Bayes offers a probability-based generative model, able to work from data summaries, ideal for text and email classification
- More advanced classifiers have their own advantages, especially in relation to high dimensional data:
  - Ensemble methods were state of the art (2000-2012, say) and sacrifice interpretability for good performance with high dimensional data
  - SVM was state of the art (1985-2000, say) and is still extremely effective for very high dimensional problems like document classification



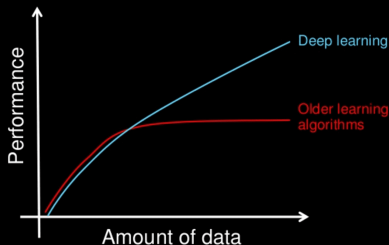
## Other considerations

- KNN uses *lazy* learning, all other techniques above use *eager* learning (derive model from training data)
- Naive Bayes uses *generative* learning to learn how the data was generated, all other techniques above use *discriminative* learning to derive the function that assigns class labels
- For KNN and Decision Trees, the representation grows with the size of the data - that is not generally true in all other techniques above

Classification is sometimes confused with clustering - will cover clustering next week.

# But is that the last word on Classification?

## Why deep learning



How do data science techniques scale with amount of data?

Source: Andrew Ng, *Why Deep Learning*

## Learning from big data

- Traditional classification algorithms eventually run out of steam as data size increases
- Shallow neural networks had been discounted in the 1980s and 1990s when trained with small data
- Deep learning to the rescue!
- Kernel SVM and logistic regression lead nicely to perceptron models, hence ANNs, hence **deep learning**
- Deep learning requires lots of data but the models can scale better to take account of extra data

Deep Learning will probably be covered in semester 2...

# General References

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