Outline

- Announcements
  - Homework #1 will be assigned this evening
- Inductive learning
- Decision Trees
Outline

- Announcements
  - Homework #1
- Inductive learning
- Decision Trees
Defining a task

Tasks:
- Predicting the stock market based on past price data
  - Input: A ticker symbol and a date
  - Output: Will the close higher or lower on the date? (classification)
    Or what will the price change be? (regression)
- Predicting outcomes of sporting events
  - Input: A game (two opponents, a date)
  - Output: which team will win (classification)

Not tasks:
- “Studying the relationship between weather and sports game outcomes.”
- “Applying neural networks to natural language processing.”
Inductive Learning

- **Given** examples of a function \((x, f(x))\)
- **Predict** function \(f(x)\) for new instances \(x\)
  - Discrete \(f(x)\): Classification
  - Continuous \(f(x)\): Regression
  - \(f(x) = \text{Probability}(x)\): Probability estimation

**Example:**
- \(x = \langle \text{Flight=United 102, FlightDate=May 26, Today=May 7} \rangle\)
- \(f(x) = \begin{cases} +1 & \text{if flight price will increase in the next week, or} \\ -1 & \text{otherwise} \end{cases} \)
Instances

- E.g. Four Days, in terms of weather:

<table>
<thead>
<tr>
<th>Sky</th>
<th>Temp</th>
<th>Humid</th>
<th>Wind</th>
<th>Water</th>
<th>Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunny</td>
<td>warm</td>
<td>normal</td>
<td>strong</td>
<td>warm</td>
<td>same</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>warm</td>
<td>same</td>
</tr>
<tr>
<td>rainy</td>
<td>cold</td>
<td>high</td>
<td>strong</td>
<td>warm</td>
<td>change</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>cool</td>
<td>change</td>
</tr>
</tbody>
</table>
Functions

“Days on which my friend Aldo enjoys his favorite water sport”

<table>
<thead>
<tr>
<th>Sky</th>
<th>Temp</th>
<th>Humid</th>
<th>Wind</th>
<th>Water</th>
<th>Forecast</th>
<th>f(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunny</td>
<td>warm</td>
<td>normal</td>
<td>strong</td>
<td>warm</td>
<td>same</td>
<td>1</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>warm</td>
<td>same</td>
<td>1</td>
</tr>
<tr>
<td>rainy</td>
<td>cold</td>
<td>high</td>
<td>strong</td>
<td>warm</td>
<td>change</td>
<td>0</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>cool</td>
<td>change</td>
<td>1</td>
</tr>
</tbody>
</table>
Inductive Learning!

- **Predict** the output for a new instance (**generalize!**)

<table>
<thead>
<tr>
<th>Sky</th>
<th>Temp</th>
<th>Humid</th>
<th>Wind</th>
<th>Water</th>
<th>Forecast</th>
<th>$f(x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunny</td>
<td>warm</td>
<td>normal</td>
<td>strong</td>
<td>warm</td>
<td>same</td>
<td>1</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
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<td>same</td>
<td>1</td>
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<tr>
<td>rainy</td>
<td>cold</td>
<td>high</td>
<td>strong</td>
<td>warm</td>
<td>change</td>
<td>0</td>
</tr>
<tr>
<td>sunny</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>cool</td>
<td>change</td>
<td>1</td>
</tr>
<tr>
<td>rainy</td>
<td>warm</td>
<td>high</td>
<td>strong</td>
<td>cool</td>
<td>change</td>
<td>?</td>
</tr>
</tbody>
</table>
General Inductive Learning Task

DEFINE:

- Set $X$ of Instances (of $n$-tuples $\mathbf{x} = \langle x_1, \ldots, x_n \rangle$)
  - E.g., days described by attributes (or features): Sky, Temp, Humidity, Wind, Water, Forecast
- Target function $f : X \rightarrow Y$, e.g.:
  - EnjoySport $X \rightarrow Y = \{0, 1\}$
  - HoursOfSport $X \rightarrow Y = \{0, 1, 2, 3, 4\}$
  - InchesOfRain $X \rightarrow Y = [0, 10]$

GIVEN:

- Training examples $D$
  - examples of the target function: $\langle \mathbf{x}, f(\mathbf{x}) \rangle$

FIND:

- A hypothesis $h$ such that $h(\mathbf{x})$ approximates $f(\mathbf{x})$. 
Another example: continuous attributes

Learn function from $\mathbf{x} = (x_1, \ldots, x_d)$ to $f(\mathbf{x}) \in \{0, 1\}$ given labeled examples $(\mathbf{x}, f(\mathbf{x}))$
Hypothesis Spaces

- Hypothesis space $H$ is a subset of all $f : X \rightarrow Y$ e.g.:
  - Linear separators
  - Conjunctions of constraints on attributes (humidity must be low, and outlook != rain)
  - Etc.

- In machine learning, we restrict ourselves to $H$
  - The subset aspect turns out to be important
Examples

- **Credit Risk Analysis**
  - $X$: Properties of customer and proposed purchase
  - $f(x)$: Approve (1) or Disapprove (0)

- **Disease Diagnosis**
  - $X$: Properties of patient (symptoms, lab tests)
  - $f(x)$: Disease (if any)

- **Face Recognition**
  - $X$: Bitmap image
  - $f(x)$: Name of person

- **Automatic Steering**
  - $X$: Bitmap picture of road surface in front of car
  - $f(x)$: Degrees to turn the steering wheel
When to use?

- Inductive Learning is appropriate for building a face recognizer
- It is not appropriate for building a calculator
  - You’d just write a calculator program

Question:
What general characteristics make a problem suitable for inductive learning?
Think/Pair/Share

What general characteristics make a problem suitable for inductive learning?
Think/Pair/Share

What general characteristics make a problem suitable for inductive learning?
Think/Pair/Share

What general characteristics make a problem suitable for inductive learning?

Share
Appropriate applications

- Situations in which:
  - There is no human expert
  - Humans can perform the task but can’t describe how
  - The desired function changes frequently
  - Each user needs a customized $f$
Outline

- Announcements
  - Homework #1
- Inductive learning
- Decision Trees
Task: Will I wait for a table?

<table>
<thead>
<tr>
<th>Example</th>
<th>Alt</th>
<th>Bar</th>
<th>Fri</th>
<th>Hun</th>
<th>Pat</th>
<th>Price</th>
<th>Rain</th>
<th>Res</th>
<th>Type</th>
<th>Est</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>Some</td>
<td>$$$</td>
<td>F</td>
<td>T</td>
<td>French</td>
<td>0–10</td>
<td>T</td>
</tr>
<tr>
<td>X₂</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>Full</td>
<td>$</td>
<td>F</td>
<td>F</td>
<td>Thai</td>
<td>30–60</td>
<td>F</td>
</tr>
<tr>
<td>X₃</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>Some</td>
<td>$</td>
<td>F</td>
<td>F</td>
<td>Burger</td>
<td>0–10</td>
<td>T</td>
</tr>
<tr>
<td>X₄</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>Full</td>
<td>$</td>
<td>F</td>
<td>F</td>
<td>Thai</td>
<td>10–30</td>
<td>T</td>
</tr>
<tr>
<td>X₅</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>Full</td>
<td>$$$</td>
<td>F</td>
<td>T</td>
<td>French</td>
<td>&gt;60</td>
<td>F</td>
</tr>
<tr>
<td>X₆</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>Some</td>
<td>$$</td>
<td>T</td>
<td>T</td>
<td>Italian</td>
<td>0–10</td>
<td>T</td>
</tr>
<tr>
<td>X₇</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>None</td>
<td>$</td>
<td>T</td>
<td>F</td>
<td>Burger</td>
<td>0–10</td>
<td>F</td>
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<tr>
<td>X₈</td>
<td>F</td>
<td>F</td>
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<td>T</td>
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<td>$$</td>
<td>T</td>
<td>T</td>
<td>Thai</td>
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<tr>
<td>X₉</td>
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<td>T</td>
<td>T</td>
<td>F</td>
<td>Full</td>
<td>$</td>
<td>T</td>
<td>F</td>
<td>Burger</td>
<td>&gt;60</td>
<td>F</td>
</tr>
<tr>
<td>X₁₀</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>Full</td>
<td>$$$</td>
<td>F</td>
<td>T</td>
<td>Italian</td>
<td>10–30</td>
<td>F</td>
</tr>
<tr>
<td>X₁₁</td>
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<td>F</td>
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<td>F</td>
<td>None</td>
<td>$</td>
<td>F</td>
<td>F</td>
<td>Thai</td>
<td>0–10</td>
<td>F</td>
</tr>
<tr>
<td>X₁₂</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>Full</td>
<td>$</td>
<td>F</td>
<td>F</td>
<td>Burger</td>
<td>30–60</td>
<td>T</td>
</tr>
</tbody>
</table>

Classification of examples is positive (T) or negative (F)
Decision Trees!

One possible representation for hypotheses
E.g., here is the “true” tree for deciding whether to wait:

```
Patrons?
  None  Some  Full
    F     T     WaitEstimate?
       /  \   /  \  >60
      30-60 10-30
    Alternate?  Hungry?
      No  Yes  No  Yes
    Reservation?  Fri/Sat?  Alternate?
      T  F  T  T
        No  Yes  No  Yes
      Bar?
        T  F  T  T
          No  Yes  No  Yes
            F  T
```
Expressiveness of D-Trees

Decision trees can express any function of the input attributes. E.g., for Boolean functions, truth table row $\rightarrow$ path to leaf:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A xor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>F</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>T</td>
<td>F</td>
</tr>
</tbody>
</table>

Trivially, there is a consistent decision tree for any training set w/ one path to leaf for each example (unless $f$ nondeterministic in $x$) but it probably won’t generalize to new examples.

Prefer to find more compact decision trees.
A learned decision tree

Decision tree learned from the 12 examples:

Substantially simpler than “true” tree—a more complex hypothesis isn’t justified by small amount of data
Inductive Bias

- To learn, we **must** prefer some functions to others

**Selection bias**
- use a **restricted** hypothesis space, e.g.:
  - linear separators
  - 2-level decision trees

**Preference bias**
- use the whole concept space, but state a **preference** over concepts, e.g.:
  - *Lowest-degree* polynomial that separates the data
  - *shortest* decision tree that fits the data
Decision Tree Learning (ID3)

Aim: find a small tree consistent with the training examples

Idea: (recursively) choose “most significant” attribute as root of (sub)tree

```plaintext
function DTL(examples, attributes, default) returns a decision tree

    if examples is empty then return default
    else if all examples have the same classification then return the classification
    else if attributes is empty then return MODE(examples)
    else
        best ← CHOOSE-ATTRIBUTE(attributes, examples)
        tree ← a new decision tree with root test best
        for each value \( v_i \) of best do
            examples_i ← \{elements of examples with best = \( v_i \}\}
            subtree ← DTL(examples_i, attributes − best, MODE(examples))
            add a branch to tree with label \( v_i \) and subtree subtree
        return tree
```
Recap

- Inductive learning
  - Goal: generate a **hypothesis** — a function from **instances** described by **attributes** to an output — using **training examples**.
  - Requires **inductive bias**
    - a restricted **hypothesis space**, or preferences over hypotheses.

- Decision Trees
  - Simple representation of hypotheses, recursive learning algorithm
  - Prefer smaller trees!
Choosing an attribute

Idea: a good attribute splits the examples into subsets that are (ideally) “all positive” or “all negative”

Patrons? is a better choice—gives information about the classification
Think/Pair/Share

How should we choose which attribute to split on next?

Think

Start

End
Think/Pair/Share

How should we choose which attribute to split on next?

Pair

Start

End
Think/Pair/Share

How should we choose which attribute to split on next?

Share
Information

Information answers questions

The more clueless I am about the answer initially, the more information is contained in the answer

Scale: 1 bit = answer to Boolean question with prior \( \langle 0.5, 0.5 \rangle \)

Information in an answer when prior is \( \langle P_1, \ldots, P_n \rangle \) is

\[
H(\langle P_1, \ldots, P_n \rangle) = \sum_{i=1}^{n} P_i \log_2 P_i
\]

(also called entropy of the prior)
Entropy

The entropy $H(V)$ of a Boolean random variable $V$ as the probability of $V = 0$ varies from 0 to 1.
Using Information

Suppose we have \( p \) positive and \( n \) negative examples at the root
\[
\Rightarrow H\left(\frac{p}{p+n}, \frac{n}{p+n}\right) \text{ bits needed to classify a new example}
\]
E.g., for 12 restaurant examples, \( p = n = 6 \) so we need 1 bit

An attribute splits the examples \( E \) into subsets \( E_i \), each of which (we hope) needs less information to complete the classification

Let \( E_i \) have \( p_i \) positive and \( n_i \) negative examples
\[
\Rightarrow H\left(\frac{p_i}{p_i+n_i}, \frac{n_i}{p_i+n_i}\right) \text{ bits needed to classify a new example}
\]
\[
\Rightarrow \textbf{expected} \text{ number of bits per example over all branches is}
\]
\[
\frac{p_i + n_i}{p + n} H\left(\frac{p_i}{p_i+n_i}, \frac{n_i}{p_i+n_i}\right)
\]

For \( Patrons? \), this is 0.459 bits, for \( Type \) this is (still) 1 bit
\[
\Rightarrow \text{choose the attribute that minimizes the remaining information needed}
\]
Measuring Performance

How do we know that $h \approx f$? (Hume’s Problem of Induction)

1) Use theorems of computational/statistical learning theory

2) Try $h$ on a new test set of examples
   (use same distribution over example space as training set)

Learning curve = % correct on test set as a function of training set size
What the learning curve tells us

Learning curve depends on
  - realizable (can express target function) vs. non-realizable
    non-realizability can be due to missing attributes
    or restricted hypothesis class (e.g., thresholded linear function)
  - redundant expressiveness (e.g., loads of irrelevant attributes)
Overfitting is due to “noise”

- **Sources of noise:**
  - Erroneous training data
    - concept variable incorrect (annotator error)
    - Attributes mis-measured
  - Much more significant:
    - Irrelevant attributes
    - Target function not realizable in attributes
Irrelevant attributes

- If many attributes are noisy, information gains can be spurious, e.g.:
  - 20 noisy attributes
  - 10 training examples
  - Expected # of different depth-3 trees that split the training data perfectly using only noisy attributes: 13.4
Not realizable

- In general:
  - We can’t measure all the variables we need to do perfect prediction.
  - \( \Rightarrow \) Target function is not uniquely determined by attribute values
Not realizable: Example

<table>
<thead>
<tr>
<th>Humidity</th>
<th>EnjoySport</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90</td>
<td>0</td>
</tr>
<tr>
<td>0.87</td>
<td>1</td>
</tr>
<tr>
<td>0.80</td>
<td>0</td>
</tr>
<tr>
<td>0.75</td>
<td>0</td>
</tr>
<tr>
<td>0.70</td>
<td>1</td>
</tr>
<tr>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>0.65</td>
<td>1</td>
</tr>
<tr>
<td>0.63</td>
<td>1</td>
</tr>
</tbody>
</table>

**Decent hypothesis:**
Humidity > 0.70 → No
Otherwise → Yes

**Overfit hypothesis:**
Humidity > 0.89 → No
Humidity > 0.80
^ Humidity <= 0.89 → Yes
Humidity > 0.70
^ Humidity <= 0.80 → No
Humidity <= 0.70 → Yes
Overfitting in Decision Trees

Consider adding a noisy training example:
*Sunny, Hot, Normal, Strong, PlayTennis=No*
What effect on tree?
Avoiding Overfitting

**Approaches**

- Stop splitting when information gain is low or when split is not statistically significant.
- Grow full tree and then **prune** it when done
Reduced-Error Pruning

Split data into training and validation set

Do until further pruning is harmful:

1. Evaluate impact on validation set of pruning each possible node (plus those below it)
2. Greedily remove the one that most improves validation set accuracy
Effect of Reduced Error Pruning

![Graph showing the effect of reduced error pruning on accuracy and size of tree.](image)
C4.5 Algorithm

- Builds a decision tree from labeled training data
- Generalizes simple “ID3” tree by
  - Prunes tree after building to improve generality
  - Allows missing attributes in examples
  - Allowing continuous-valued attributes
Rule post pruning

- Used in C4.5
- Steps
  1. Build the decision tree
  2. Convert it to a set of logical rules
  3. Prune each rule independently
  4. Sort rules into desired sequence for use
Converting A Tree to Rules

```
Outlook
  /    \
Sunny  Overcast
  /      \
High    Normal
  /    \
No     Yes

Rain
  /    \
Wind
  /    \
Strong  Weak
  /    \
No     Yes
```
IF (Outlook = Sunny) AND (Humidity = High) THEN PlayTennis = No

IF (Outlook = Sunny) AND (Humidity = Normal) THEN PlayTennis = Yes

...
Other Odds and Ends

- Unknown Attribute Values?
Unknown Attribute Values

What if some examples are missing values of $A$?
Use training example anyway, sort through tree

- If node $n$ tests $A$, assign most common value of $A$
  among other examples sorted to node $n$

- Assign most common value of $A$ among other examples
  with same target value

- Assign probability $p_i$ to each possible value $v_i$ of $A$
  Assign fraction $p_i$ of example to each descendant in tree

Classify new examples in same fashion
Odds and Ends

• Unknown Attribute Values?

• Continuous Attributes?
Decision Tree Boundaries

Decision trees divide the feature space into axis-parallel rectangles, and label each rectangle with one of the $K$ classes.
Learning Parity with Noise

When learning exclusive-or (2-bit parity), all splits look equally good. If extra random boolean features are included, they also look equally good. Hence, decision tree algorithms cannot distinguish random noisy features from parity features.

<table>
<thead>
<tr>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

$J=4$ $x_1$ $2$ $2$ $2$ $2$

$J=4$ $x_2$ $2$ $2$ $2$ $2$

$J=4$ $x_3$ $2$ $2$ $2$ $2$
Decision Trees Bias

- How to solve 2-bit parity:
  - Two step look-ahead, or
  - Split on pairs of attributes at once

- For $k$-bit parity, why not just do $k$-step look ahead? Or split on $k$ attribute values?

  $=>$ Parity functions are among the “victims” of the decision tree’s inductive bias.
Now we have choices

- Re-split continuous attributes?
- Handling unknown variables?
- Prune or not?
- Stopping criteria?
- Split selection criteria?
- Use look-ahead?

- In homework #2: one choice for each
- In practice, how to decide? An instance of Model Selection
  - In general, we could also select an H other than decision trees
Think/Pair/Share

We can do model selection using a 70% train, 30% validation split of our data. But can we do better?

Think

Start

End
Think/Pair/Share

We can do model selection using a 70% train, 30% validation split of our data. But can we do better?
Think/Pair/Share

We can do model selection using a 70% train, 30% validation split of our data. But can we do better?

Share
Take away about decision trees

- Used as classifiers
- Supervised learning algorithms (ID3, C4.5)
- Good for situations where
  - Inputs, outputs are discrete
  - “We think the true function is a small tree”