

Supervised Learning via Decision Trees

Lecture 9



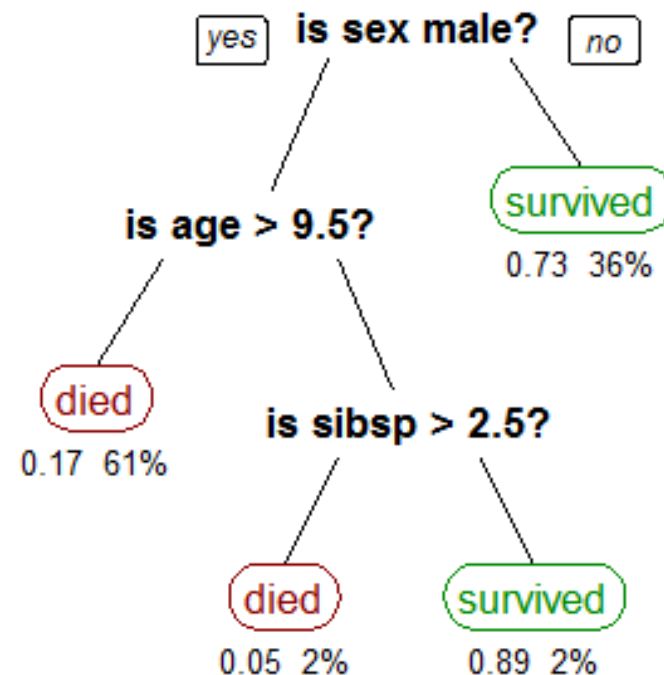
Outline

1. Learning via feature splits
2. ID3
 - Information gain
3. Extensions
 - Continuous features
 - Gain ratio
 - Ensemble learning



Decision Trees

- Sequence of decisions at *choice nodes* from root to a leaf node
 - Each choice node splits on a single feature
- Can be used for classification or regression
- **Explicit**, easy for humans to understand
- Typically very fast at testing/prediction time



https://en.wikipedia.org/wiki/Decision_tree_learning

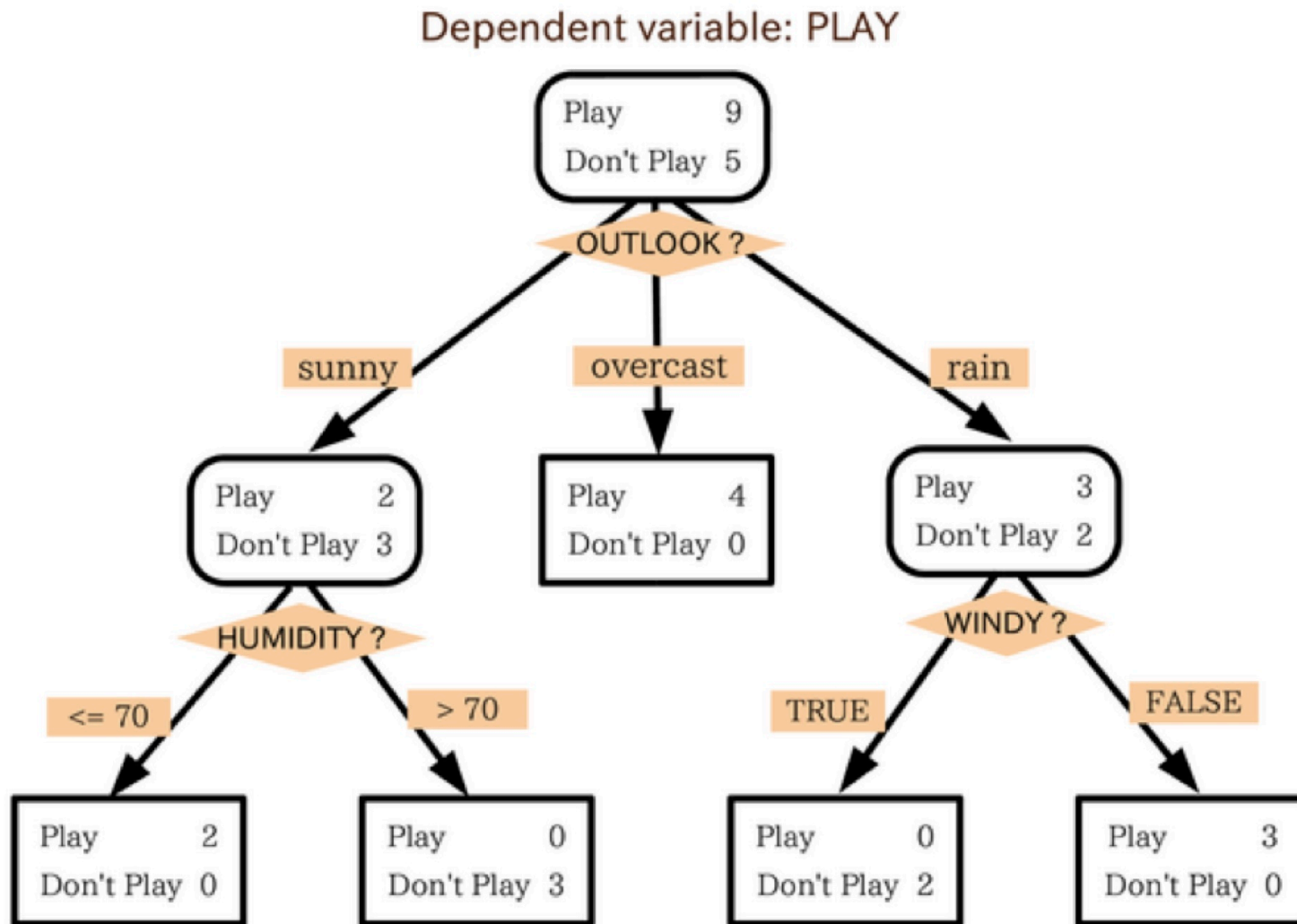


Input Data (Weather)

Outlook	Temperature	Humidity	Windy	Play
sunny	85	85	false	no
sunny	80	90	true	no
overcast	83	86	false	yes
rainy	70	96	false	yes
rainy	68	80	false	yes
rainy	65	70	true	no
overcast	64	65	true	yes
sunny	72	95	false	no
sunny	69	70	false	yes
rainy	75	80	false	yes
sunny	75	70	true	yes
overcast	72	90	true	yes
overcast	81	75	false	yes
rainy	71	91	true	no



Output Tree (Weather)



Training Issues

- Approximation
 - Optimal tree-building is NP-complete
 - Typically greedy, top-down
- Under/over-fitting
 - Occam's Razor vs. CC/SSN
 - Pruning, ensemble methods
- Splitting metric
 - **Information gain**, gain ratio, Gini impurity



Iterative Dichotomiser 3

- Invented by Ross Quinlan in 1986
 - Precursor to C4.5/5
- Categorical data only (can't split on numbers)
- Greedily consumes features
 - Subtrees cannot reconsider previous feature(s) for further splits
 - *Typically* produces shallow trees



ID3: Algorithm Sketch

- If all examples “same”, return $f(\text{examples})$
- If no more features, return $f(\text{examples})$
- $A = \text{“best” feature}$
 - For each distinct value of A
 - $\text{branch} = \text{ID3}(\text{attributes} - \{A\})$

Classification

- “same” = same class
- $f(\text{examples}) = \text{majority}$
- “best” = information gain

Now!

Regression

- “same” = $\text{std. dev.} < \epsilon$
- $f(\text{examples}) = \text{average}$
- “best” = $\text{std. dev. reduction}$

http://www.saedsayad.com/decision_tree_reg.htm



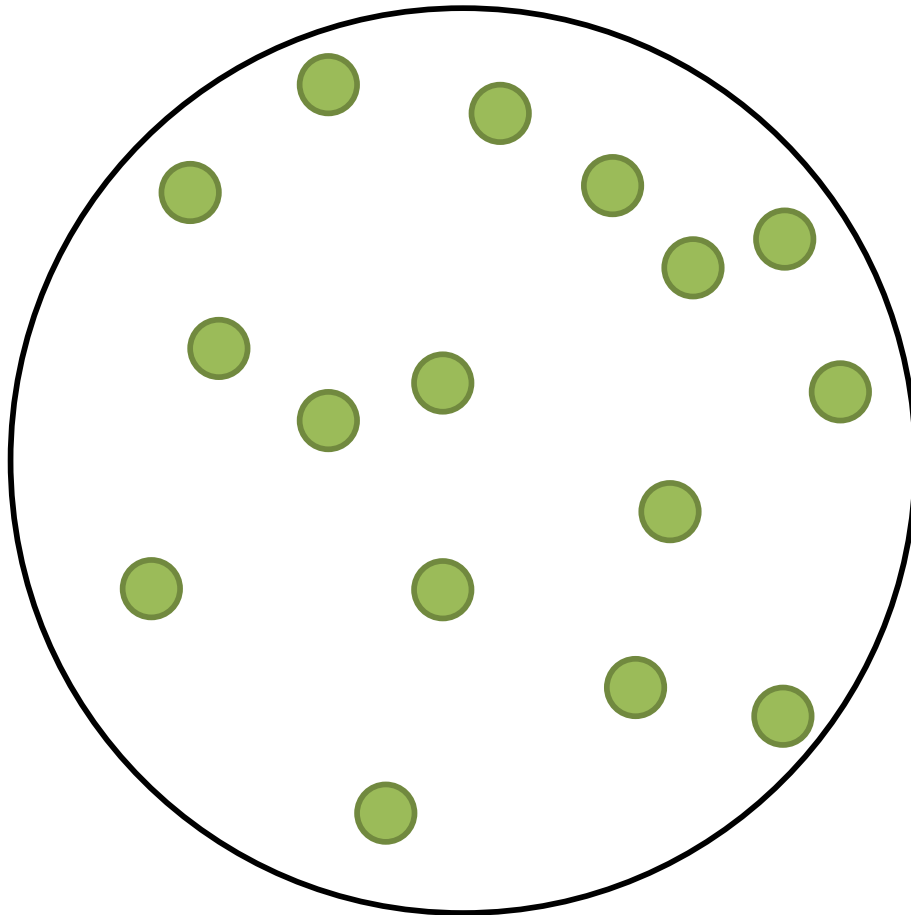
Shannon Entropy

- Measure of “impurity” or uncertainty
- Intuition: the less likely the event, the more information is transmitted

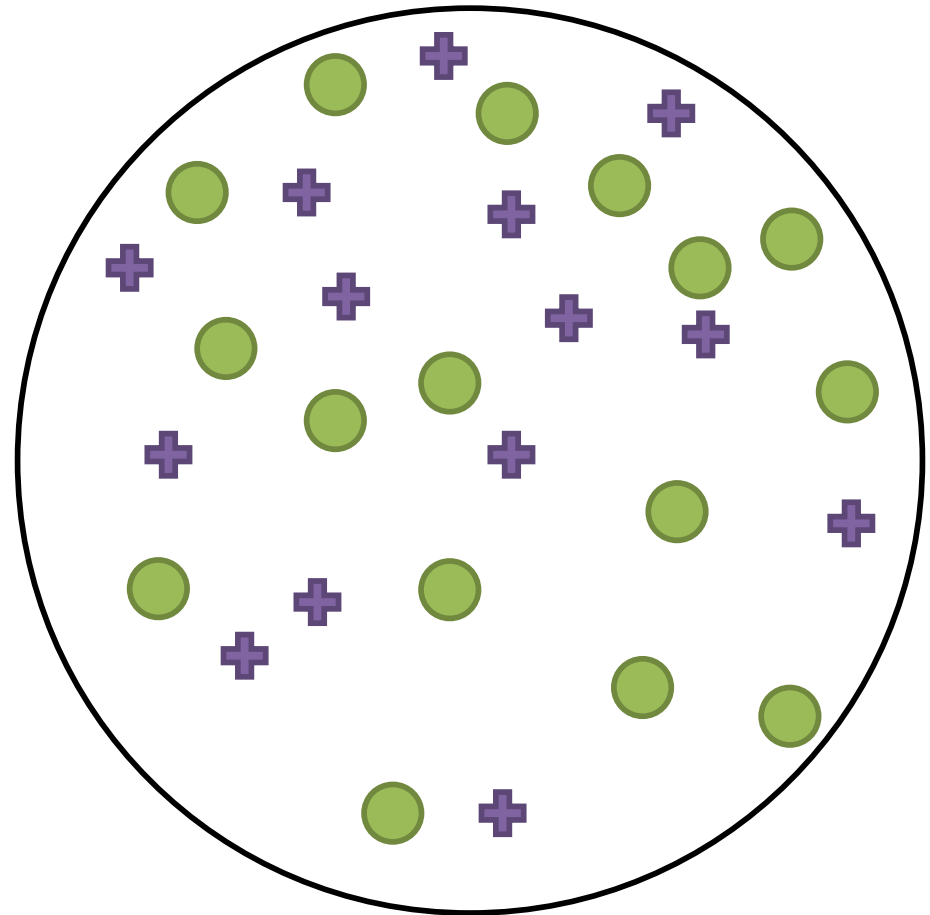


Entropy Range

Small



Large



Quantifying Entropy

$$H(X) = E[I(X)]$$

Expected value of information

$$\sum_i P(x_i) I(x_i) \quad \int P(x) I(x) dx$$



Intuition for Information

$$I(X) = \dots$$

$$I(X) \geq 0$$

- Shouldn't be negative

$$I(1) = 0$$

- Events that always occur communicate no information

$$I(X_1, X_2) = I(X_1) + I(X_2)$$

- Information from independent events are additive



Quantifying Information

$$I(X) = \log_b \frac{1}{P(X)} = -\log_b P(X)$$

Log Base = Units: 2=bit (**b**inary digit), 3=trit, e=nat

$$H(X) = -\sum_i P(x_i) \log_b P(x_i)$$

Log Base = Units: 2=shannon/bit



Example: Fair Coin Toss

$$I(\text{heads}) = \log_2\left(\frac{1}{0.5}\right) = \log_2 2 = 1 \text{ bit}$$

$$I(\text{tails}) = \log_2\left(\frac{1}{0.5}\right) = \log_2 2 = 1 \text{ bit}$$

$$\begin{aligned} H(\text{fair toss}) &= (0.5)(1) + (0.5)(1) = \\ &= 1 \text{ shannon} \end{aligned}$$



Example: Double Headed Coin

$$\begin{aligned} H(\text{double head}) &= (1) \cdot I(\text{head}) \\ &= (1) \cdot \log_2\left(\frac{1}{1}\right) \\ &= (1) \cdot (0) \\ &= 0 \text{ shannons} \end{aligned}$$



Exercise: Weighted Coin

Compute the entropy of a coin that will land on heads about 25% of the time, and tails the remaining 75%.

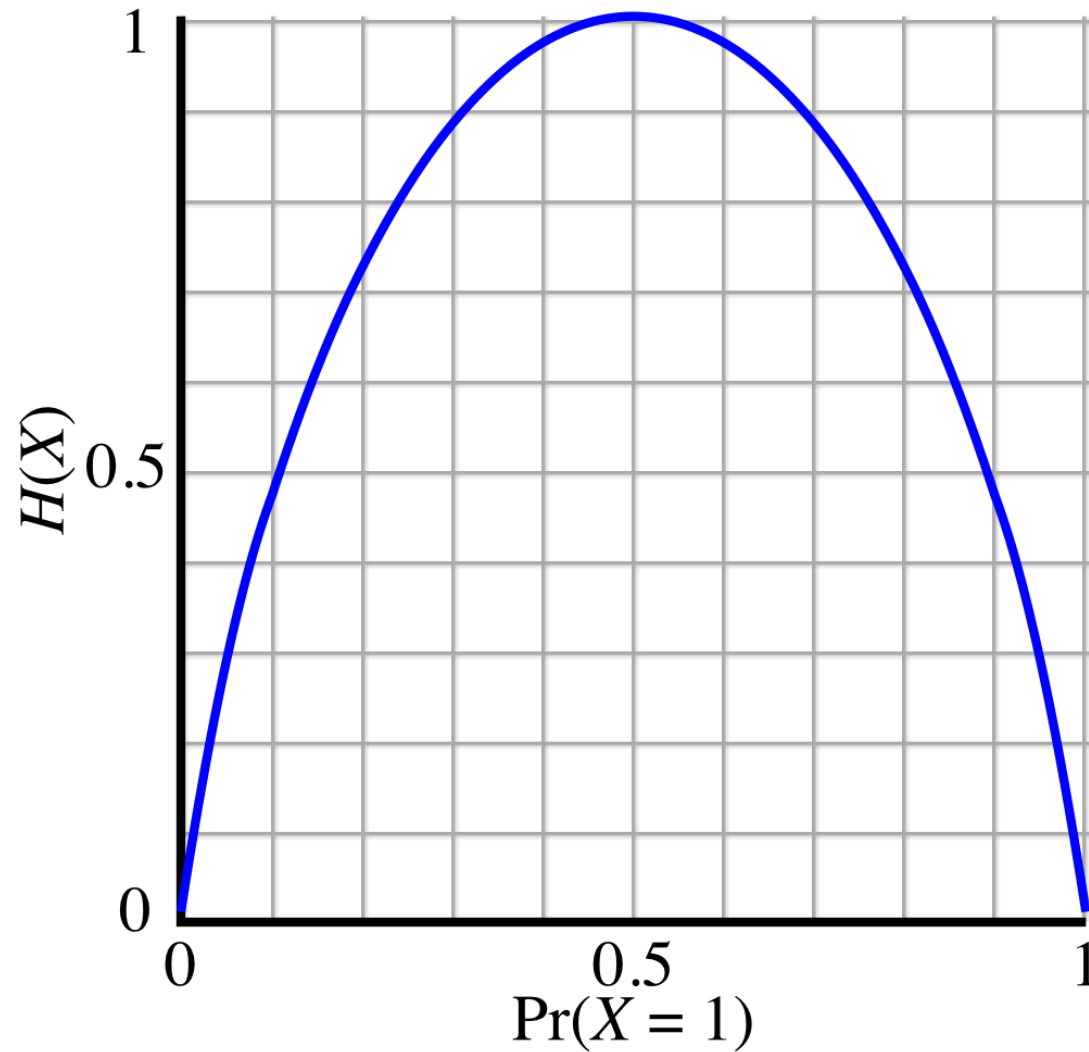


Answer

$$\begin{aligned} H(\text{weighted toss}) &= (0.25) \cdot I(\text{head}) + (0.75) \cdot I(\text{tails}) \\ &= (0.25) \cdot \log_2 \frac{1}{0.25} + (0.75) \cdot \log_2 \frac{1}{0.75} \\ &= 0.81 \text{ shannons} \end{aligned}$$

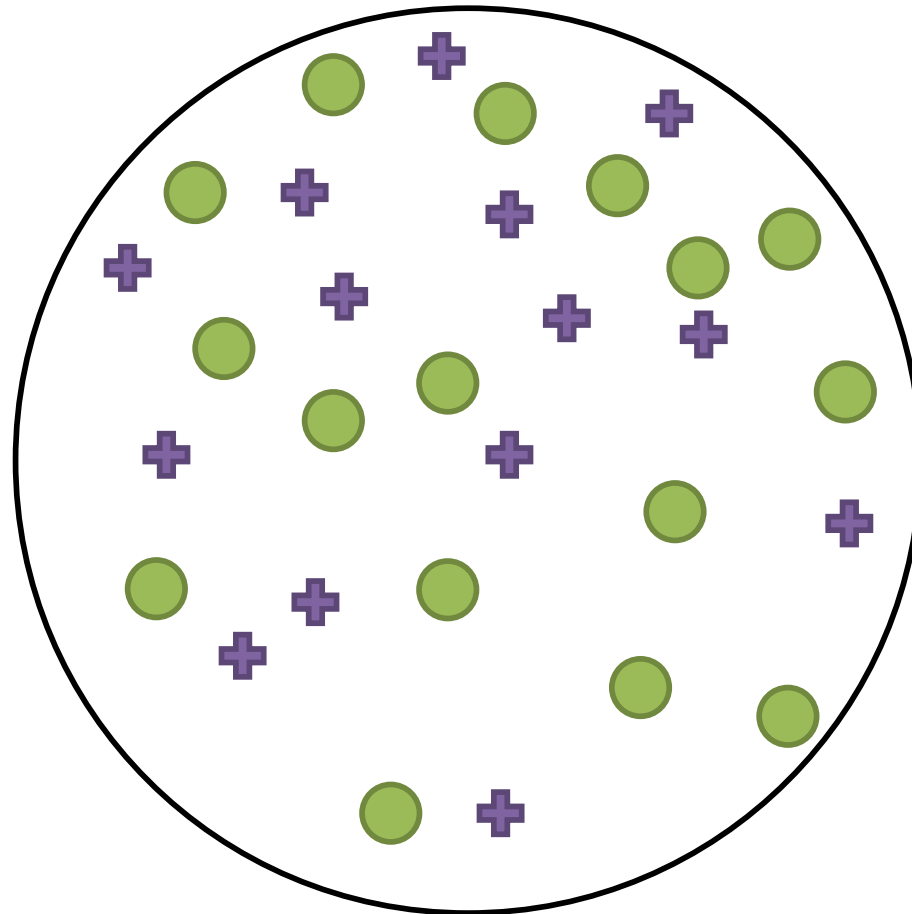


Entropy vs. P



Exercise

Calculate the entropy of the following data



Answer

$$\begin{aligned} H(\text{data}) &= \frac{16}{30} \cdot I(\text{green circle}) + \frac{14}{30} \cdot I(\text{purple cross}) \\ &= \frac{16}{30} \cdot \log_2 \frac{30}{16} + \frac{14}{30} \cdot \log_2 \frac{30}{14} \\ &= 0.99679 \text{ shannons} \end{aligned}$$



Bounds on Entropy

$$H(X) \geq 0$$

$$H(X) = 0 \iff \exists x \in X (P(x) = 1)$$

$$H_b(X) \leq \log_b(|\mathcal{X}|)$$

$|\mathcal{X}|$ denotes the number of elements in the range of X

$$H_b(X) = \log_b(|\mathcal{X}|) \iff X \text{ has a uniform distribution over } |\mathcal{X}|$$



Information Gain

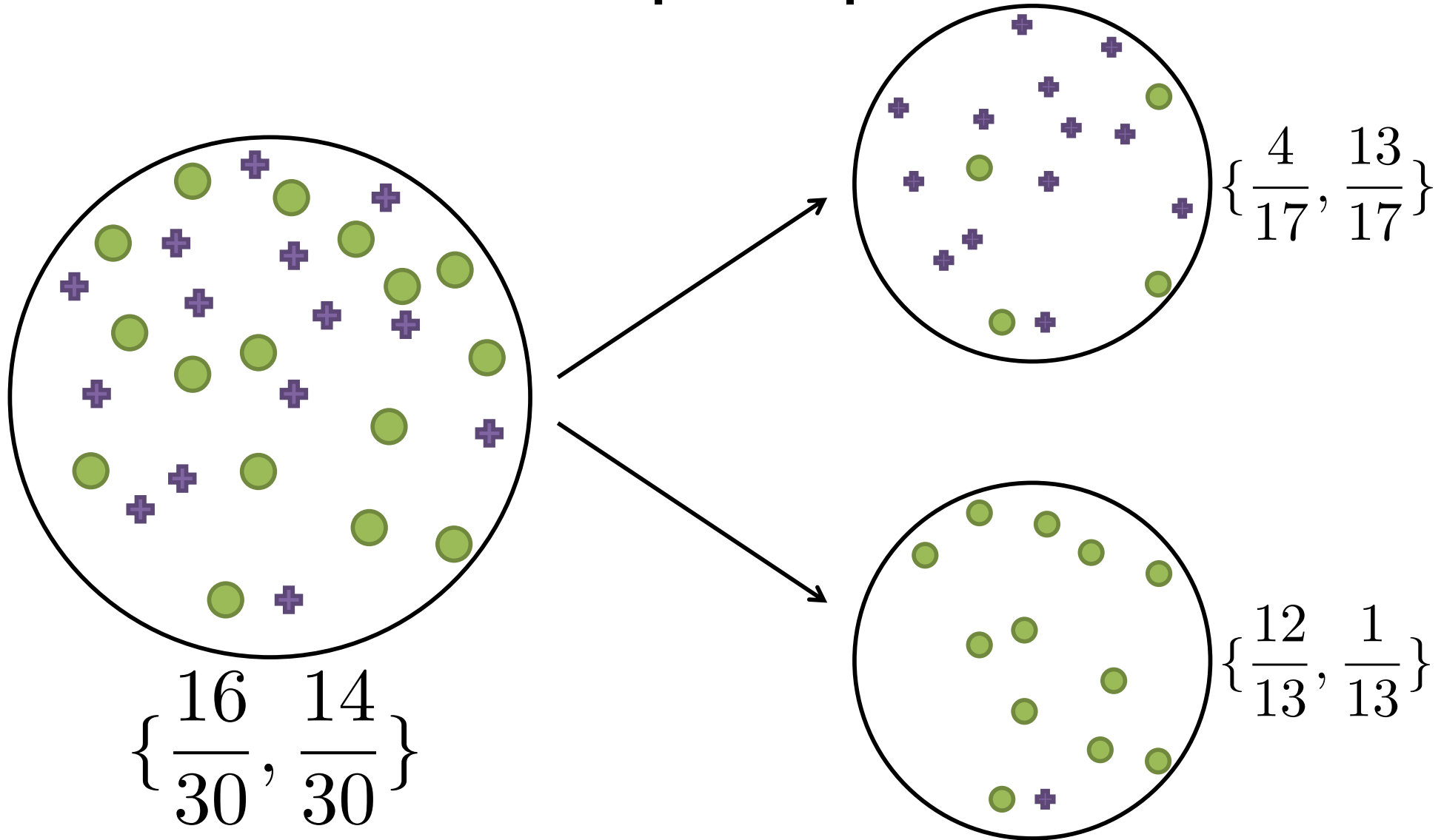
To use entropy for a splitting metric, we consider the **information gain** of an action as the resulting change in entropy

$$\begin{aligned} \text{IG}(T, a) &= H(T) - H(T|a) \\ &= H(T) - \sum_i \frac{|T_i|}{|T|} H(T_i) \end{aligned}$$

Average Entropy of the children



Example Split



Example Information Gain

$$H_1 = \frac{4}{17} \log_2 \frac{17}{4} + \frac{13}{17} \log_2 \frac{17}{13} \sim 0.79$$

$$H_2 = \frac{12}{13} \log_2 \frac{13}{12} + \frac{1}{13} \log_2 \frac{13}{1} \sim 0.39$$

$$\text{IG} = H(T) - \left(\frac{17}{30} H_1 + \frac{13}{30} H_2 \right)$$

$$= 0.99679 - 0.62$$

$$= 0.38 \text{ shannons}$$



Exercise

Consider the following dataset. Compute the information gain for each of the non-target attributes. Decide which attribute is the best to split on.

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



$H(C)$

$$\begin{aligned} H(C) &= -(0.5) \log_2 0.5 - (0.5) \log_2 0.5 \\ &= 1 \text{ shannon} \end{aligned}$$

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



IG(C,X)

$$H(C|X) = \frac{3}{4} \left[\frac{2}{3} \log_2 \frac{3}{2} + \frac{1}{3} \log_2 \frac{3}{1} \right] + \frac{1}{4} [0]$$
$$= 0.689 \text{ shannons}$$

$$IG(C, X) = 1 - 0.689 = 0.311 \text{ shannons}$$

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



IG(C, Y)

$$H(C|Y) = \frac{1}{2}[0] + \frac{1}{2}[0]$$
$$= 0 \text{ shannons}$$

$$IG(C, Y) = 1 - 0 = 1 \text{ shannon}$$

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



IG(C,Z)

$$H(C|Y) = \frac{1}{2} [1] + \frac{1}{2} [1]$$

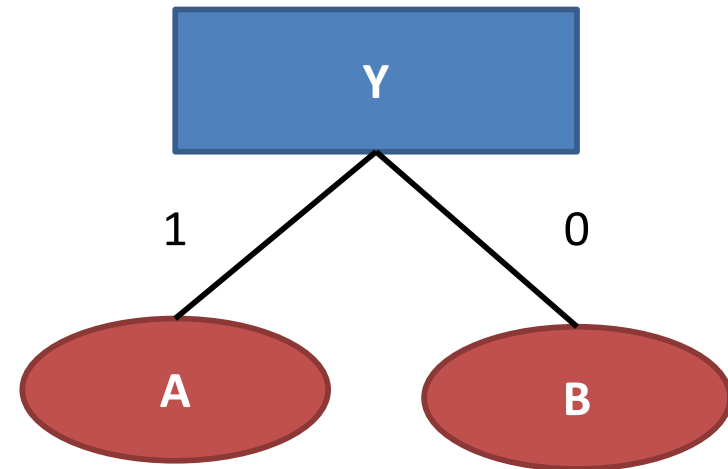
$$= 1 \text{ shannons}$$

$$IG(C, Z) = 1 - 1 = 0 \text{ shannons}$$

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



Feature Split Choice



IG:

0.311

1.0

0.0

X	Y	Z	Class
1	1	1	A
1	1	0	A
0	0	1	B
1	0	0	B



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Example

No Surfacing	Flippers?		Fish?
Yes	Yes		Yes
Yes	Yes		Yes
Yes	No		No
No	Yes		No
No	Yes		No



0. Preliminaries

No Surfacing	Flippers?	Fish?
Yes	Yes	Yes
Yes	Yes	Yes
Yes	No	No
No	Yes	No
No	Yes	No

- Examples not the same class
- Features remain
- $H(\text{Fish?}) = 0.971$

$$\frac{2}{5} \log_2 \frac{5}{2} + \frac{3}{5} \log_2 \frac{5}{3}$$



1a: No Surfacing

No Surfacing	Flippers?	Fish?
Yes	Yes	Yes
Yes	Yes	Yes
Yes	No	No
No	Yes	No
No	Yes	No

- $H(\text{Fish?} \mid \text{No Surfacing}) = 0.55$

$$\frac{3}{5} \left(\frac{2}{3} \log_2 \frac{3}{2} + \frac{1}{3} \log_2 \frac{3}{1} \right)$$

- $IG(\text{Fish?}, \text{No Surfacing}) = 0.42$



1b: Flippers?

No Surfacing	Flippers?	Fish?
Yes	Yes	Yes
Yes	Yes	Yes
Yes	No	No
No	Yes	No
No	Yes	No

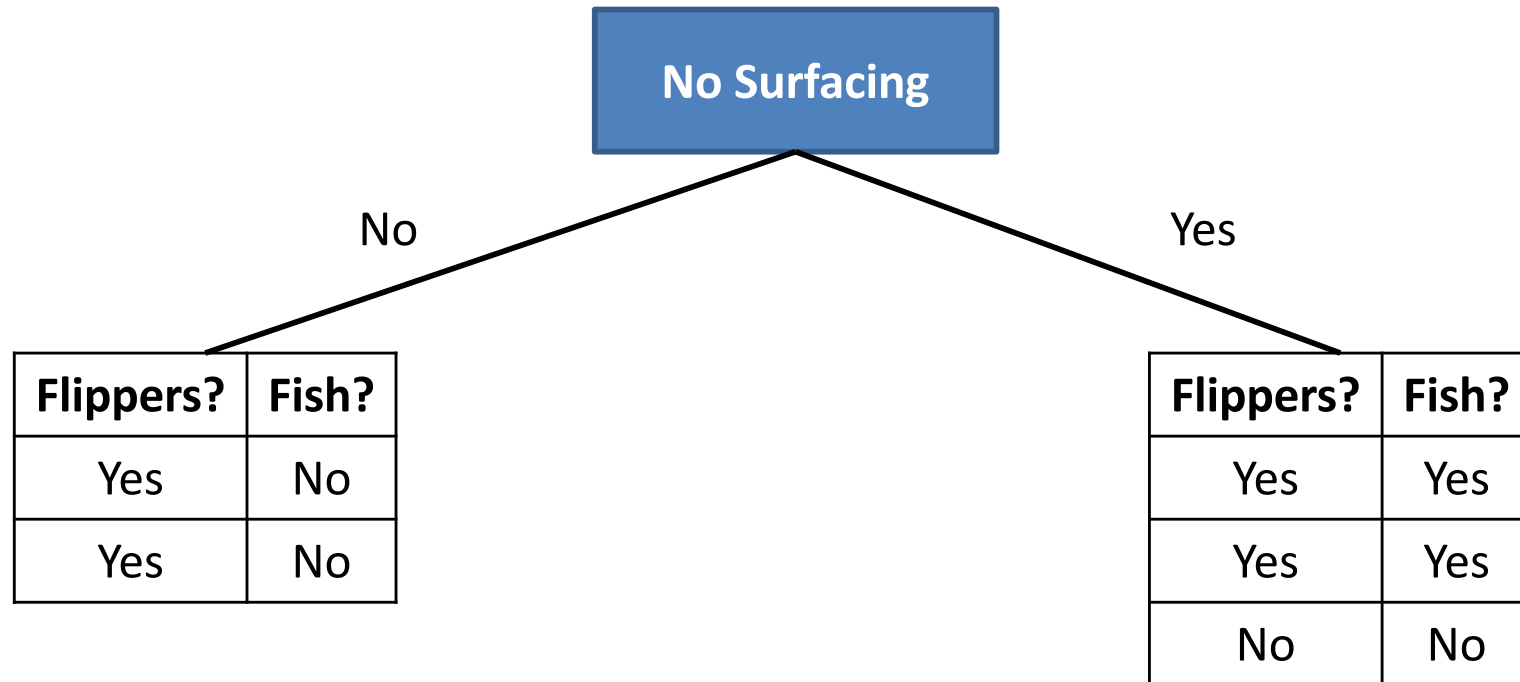
- $H(\text{Fish?} \mid \text{Flippers?}) = 0.8$

$$\frac{4}{5}(1) + \frac{1}{5}(0)$$

- $IG(\text{Fish?}, \text{Flippers}) = 0.17$



2: Split on No Surfacing



- Recurse(left)



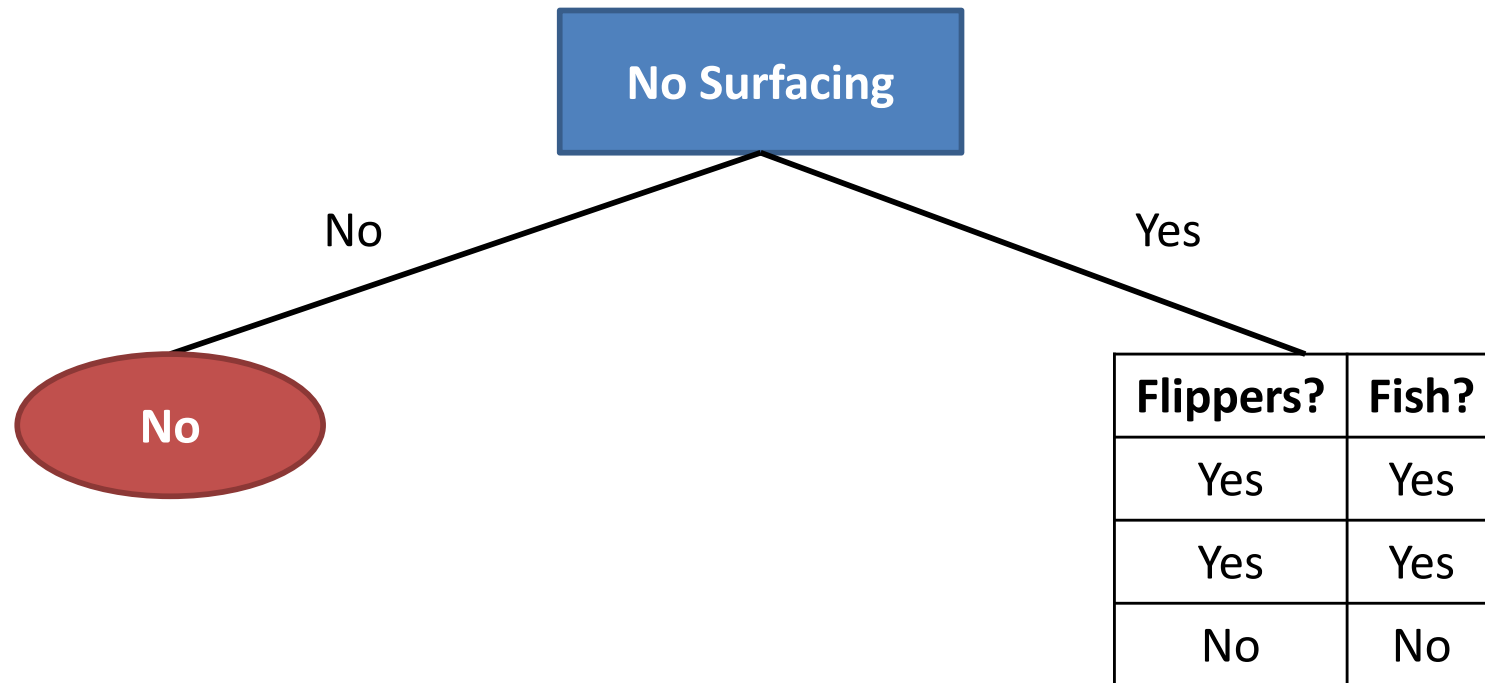
2. Left

Flippers?	Fish?
Yes	No
Yes	No

- Examples the same class!
 - Return class leaf node



2: Split on No Surfacing



- Recurse(right)



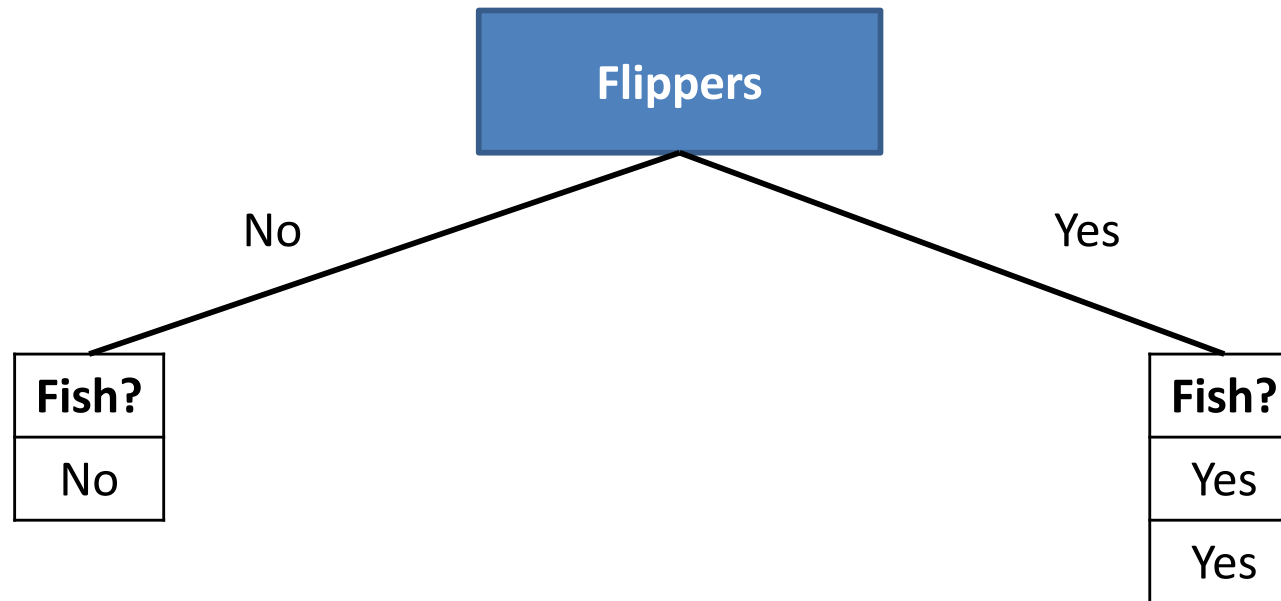
2. Right

Flippers?	Fish?
Yes	Yes
Yes	Yes
No	No

- Examples not the same class
- One feature remaining
 - Split!



3. Split on Flippers



- Recurse(left)



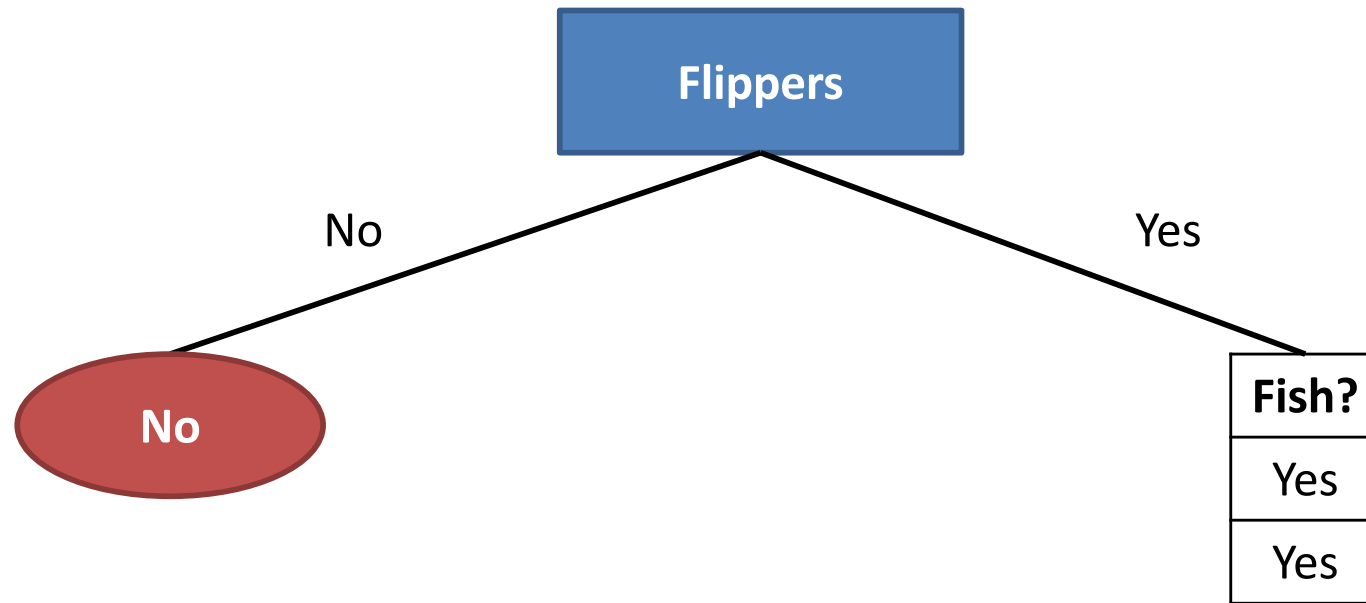
3. Left

Fish?
No

- Examples the same class!
 - Return class leaf node



3. Split on Flippers



- Recurse(right)



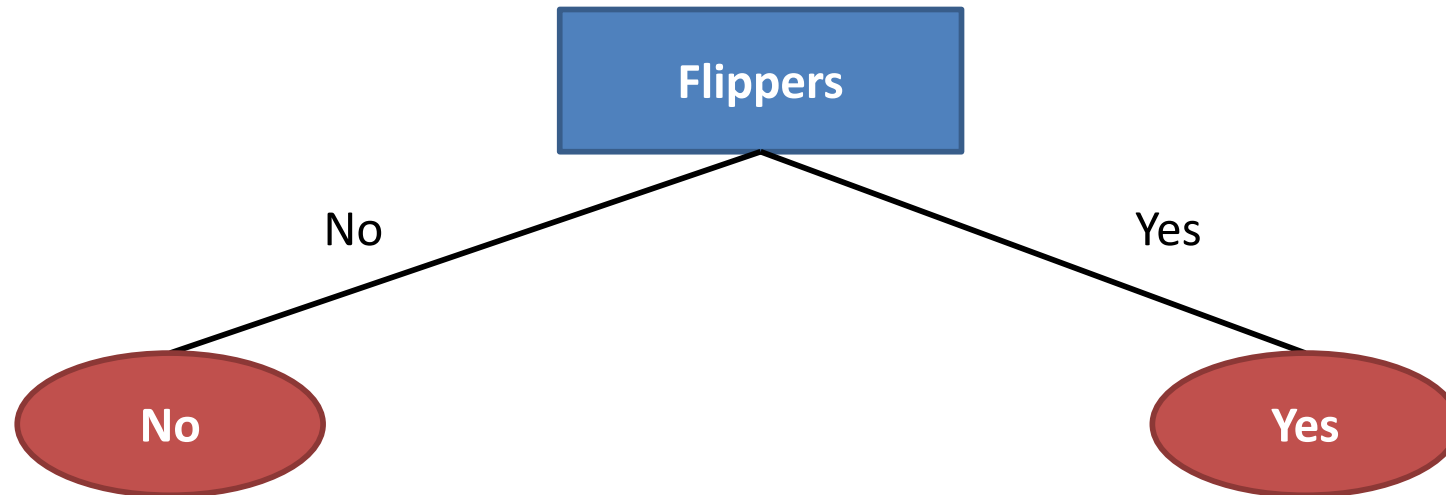
3. Right

Fish?
Yes
Yes

- Examples the same class!
 - Return class leaf node



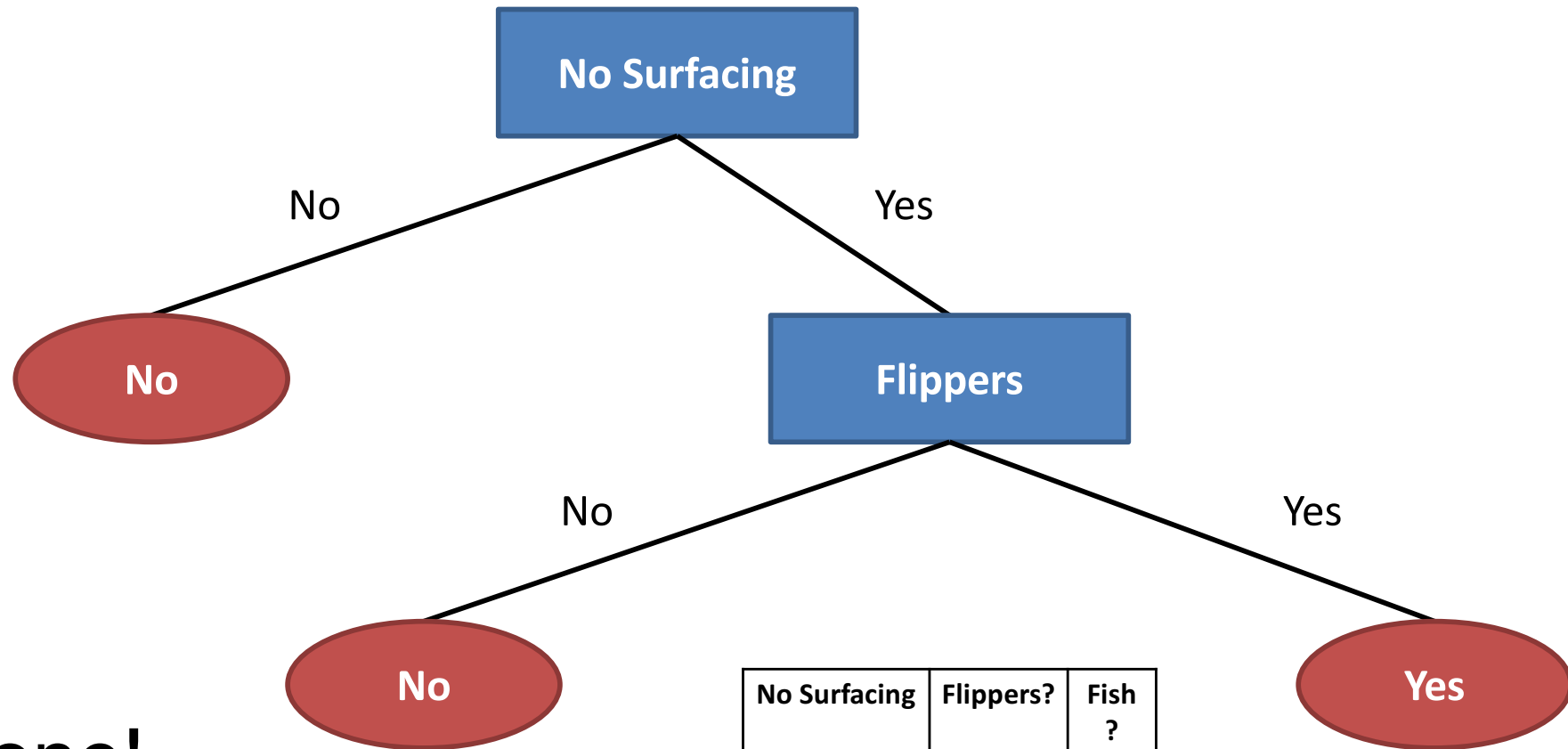
3. Split on Flippers



- Return!



2: Split on No Surfacing



- Done!

No Surfacing	Flippers?	Fish ?
Yes	Yes	Yes
Yes	Yes	Yes
Yes	No	No
No	Yes	No
No	Yes	No



Additional Base Case

- What to do given the following example input to ID3?
 - No additional features upon which to split
- For classification, majority vote

Fish?
Yes
Yes
No
No
No

No



Extensions

- Generalization
- Continuous features
- Ensemble learning



Generalization

- Information gain biases towards features with many distinct values
 - Consider the value of CC/SSN
- Approaches to mediate
 - Gain ratio is a metric that divides each IG term by “SplitInfo”, which is large for features with many partitions (used in C4.5)
 - There are several pruning techniques that replace subtrees



Continuous Features

- You can always discretize/bin yourself
 - Run the risk of suboptimal depending on tree location
- Simple approach: binary splits, whereby left is \leq threshold
- Consider each distinct value a threshold, calculate gain
 - Computationally expensive for large numbers of values
- C4.5 penalizes similar to large distinct sets



Ensemble Learning

- The **Random Forest** algorithm is an exemplar of using multiple trees
 - Each tree is trained via bootstrapped data (i.e. sampled with replacement)
 - Each choice node feature is selected from a random subset of overall
 - Decisions are bagged (i.e. aggregated over many trees)
 - Can use a validation set to weight via expected accuracy of each tree



Checkup

- ML task(s)?
 - Classification: binary/multi-class?
- Feature type(s)?
- Implicit/explicit?
- Parametric?
- Online?



Summary: ID3/Decision Trees

- Practicality
 - Easy, generally applicable
 - Need know nothing about the underlying process
 - Very popular, easy to understand
- Efficiency
 - Training: relatively fast, batch
 - Testing: typically very fast
- Performance
 - Possible to get stuck in suboptimal trees
 - Methods to help, hard in general

