

# **Lecture 3: Non-Parametric Models**

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**COMP0088 Introduction to Machine Learning • UCL Computer Science • Autumn 2021**

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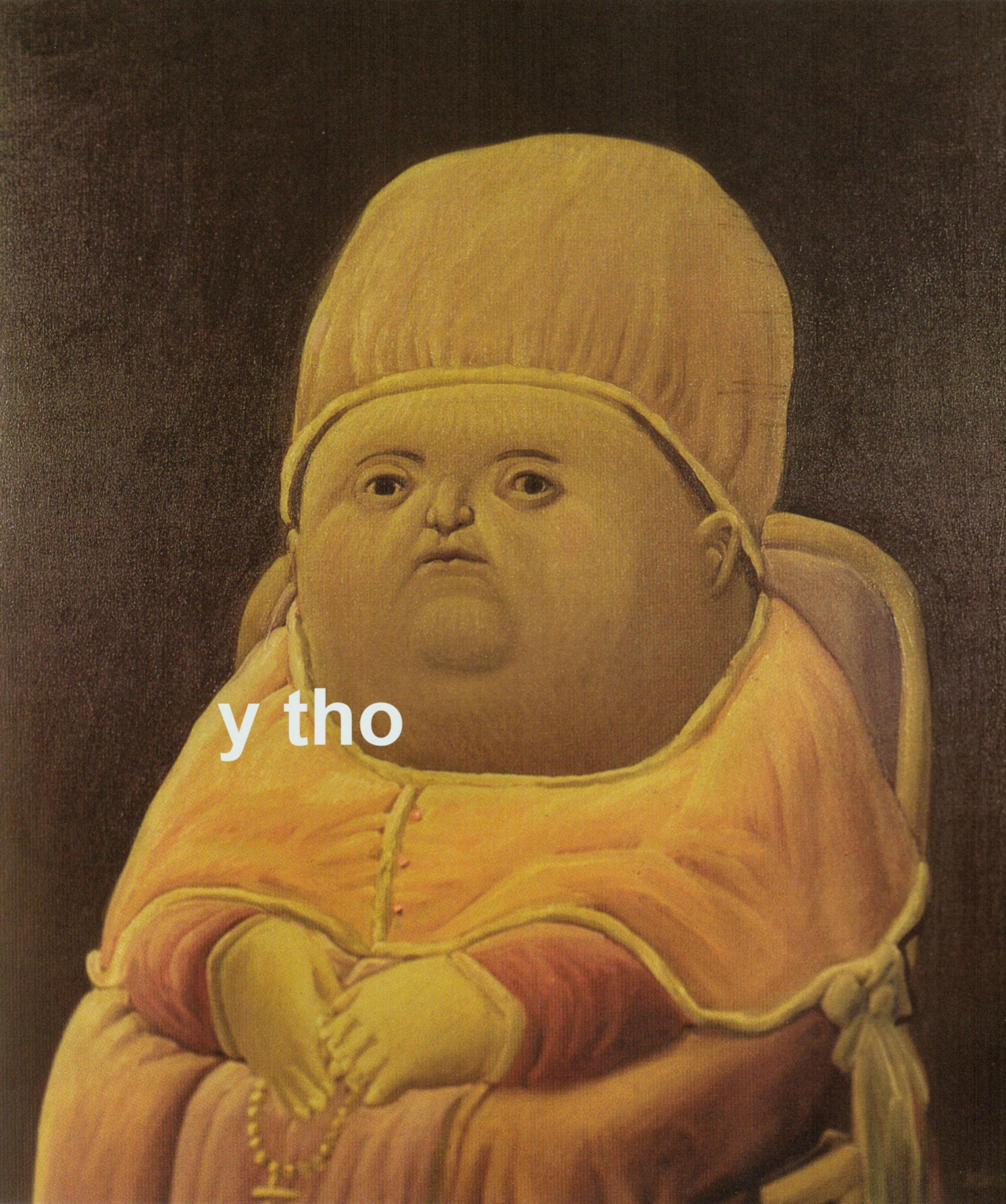
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# **3.1: Non What?**

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A painting of a baby with a large, round head and a serious expression. The baby is wearing a yellow cap and a yellow dress with a red sash. The background is dark.

y tho

# Unhelpful terminology strikes again

- Non-parametric models **do** have parameters
- The term refers to the fact that they don't assume an a prior parameter structure — or assume a parametric distribution
  - ie, that the data has a particular “shape”
  - Not doing this often makes them hard to interpret probabilistically
- One common rule of thumb:
  - A model is “non-parametric” if the number of parameters scales with the number of data points, rather than the number of feature dimensions

# Parameters are (often) efficient

- Parametric models distill the “shape” of the data into a compact form
- Having more data is (usually, up to a point) better
  - Improves estimation of parameter values
  - Cost of storage and evaluation remain the same
- For a non-parametric model, there can be a downside to having more data
  - Supports more complex & nuanced predictions
    - ▶ May or may not be desirable depending on the problem
  - But model may become correspondingly bigger and slower

# Partitioning feature space

- Though not necessarily true for all non-parametric models, the models we're looking at this week can be usefully understood as chopping up the feature space into disjoint regions
- Each region is then associated with a particular output value
  - For our cases, this will be a constant, although it could also be a function
- Regions are effectively independent: there's no prescribed meaning to adjacency or distance between them
- (cf. piecewise fitting examples in last week's basis expansion lecture)

# Classification vs Regression

- All this week's methods can be used for both
- But — because of partitioning — it's natural to think in terms of classification
- We'll focus on that, but point out differences for regression
  - Typically: different loss, aggregate by averaging

# **3.2: k-Nearest Neighbours**

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# Platonic ideal of a non-parametric model

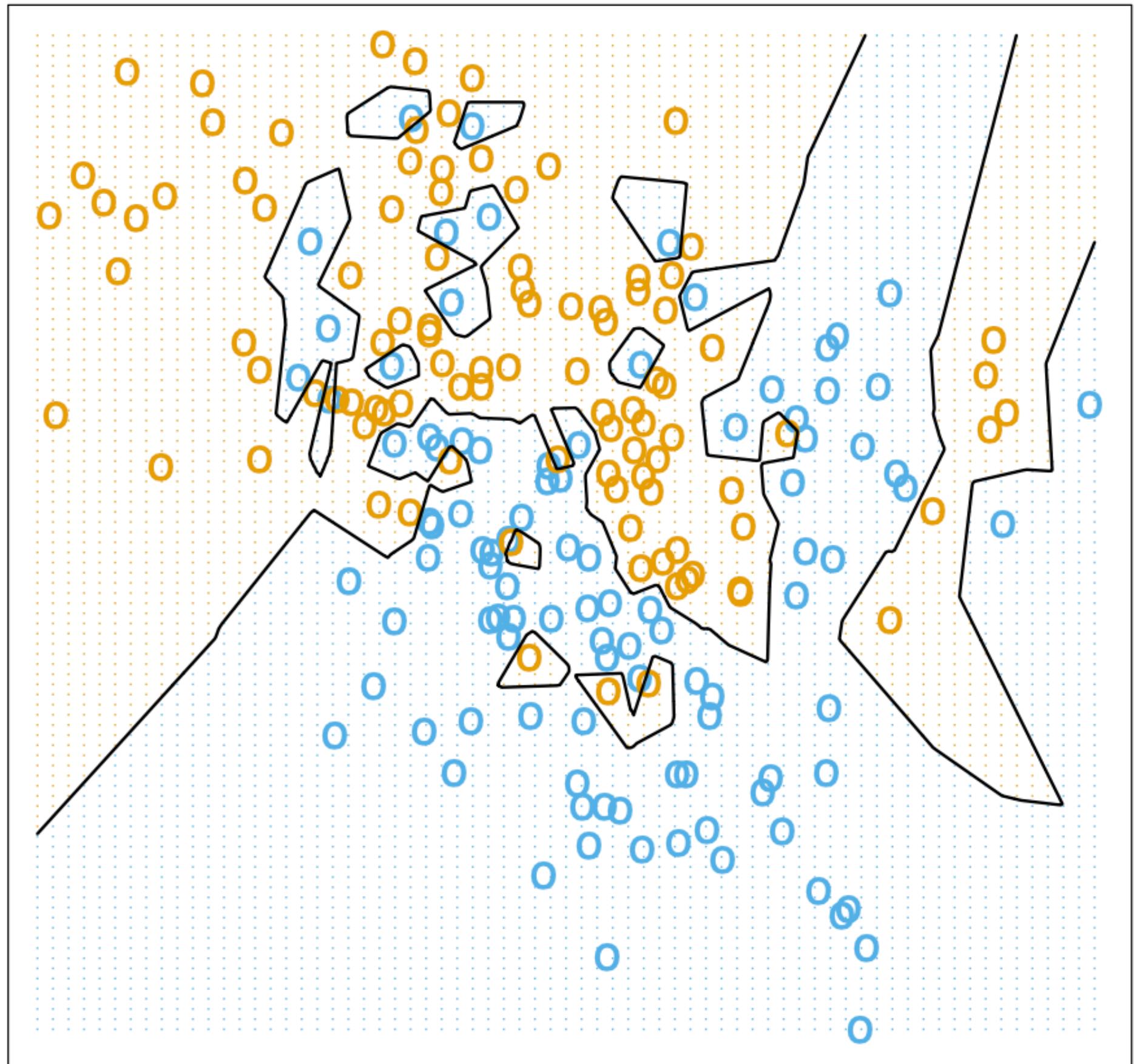
- Principle: the best estimate of the data distribution is the data itself
- Assume test data is “like” training data
  - This is really the weakest assumption for learning to be possible at all
- “Training” consists solely of memorising the training set
  - No attempt to summarise or distill or **model** it
- Prediction consists of comparing the test sample with **all** training samples and taking a vote or average of the  $k$  most similar ones

# What is “like”?

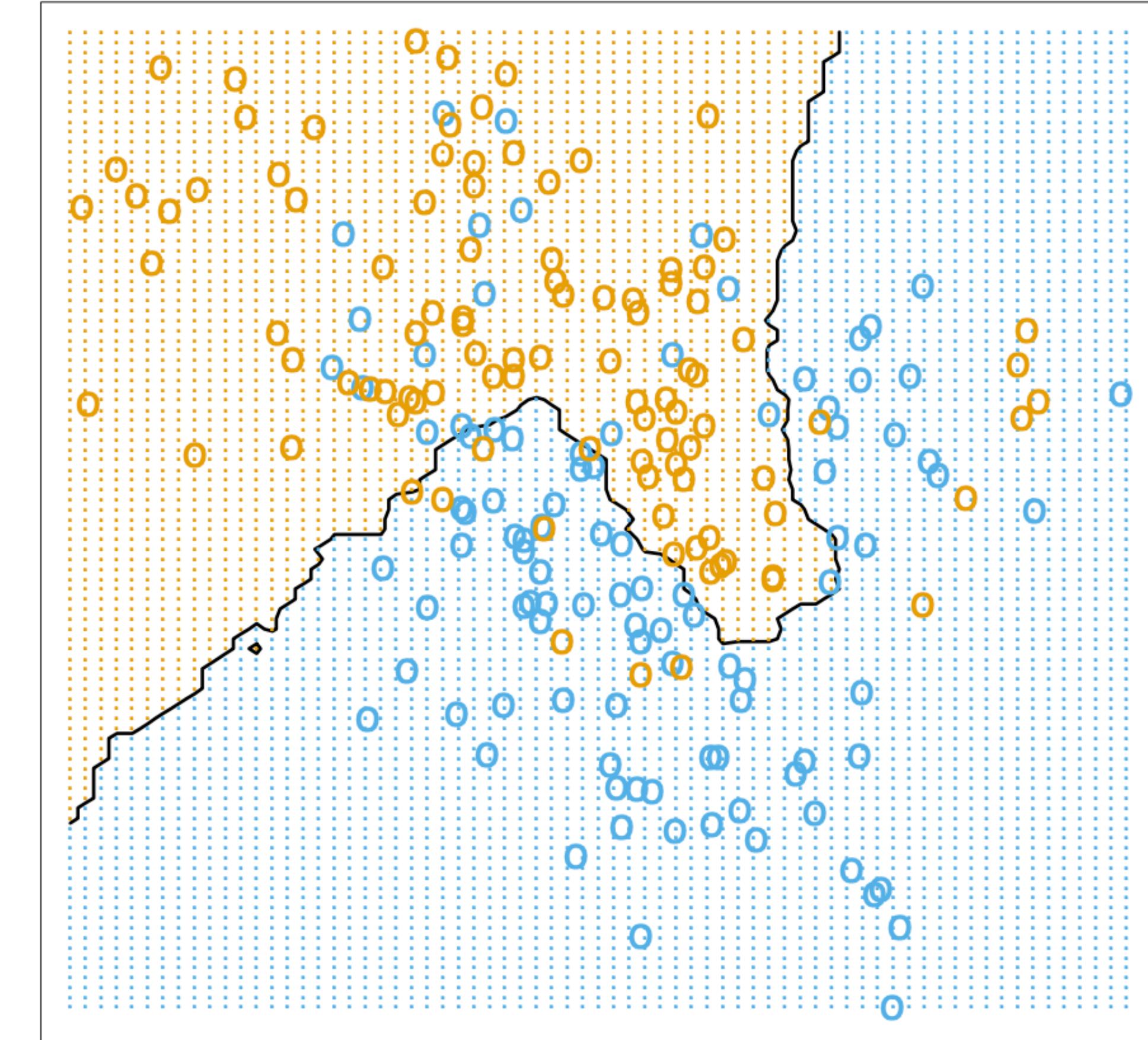
- Requires a distance (or similarity) metric
  - And a tie-break policy
- May lose value in high dimensions
- May be sensitive to scale disparities

# Consequences of k

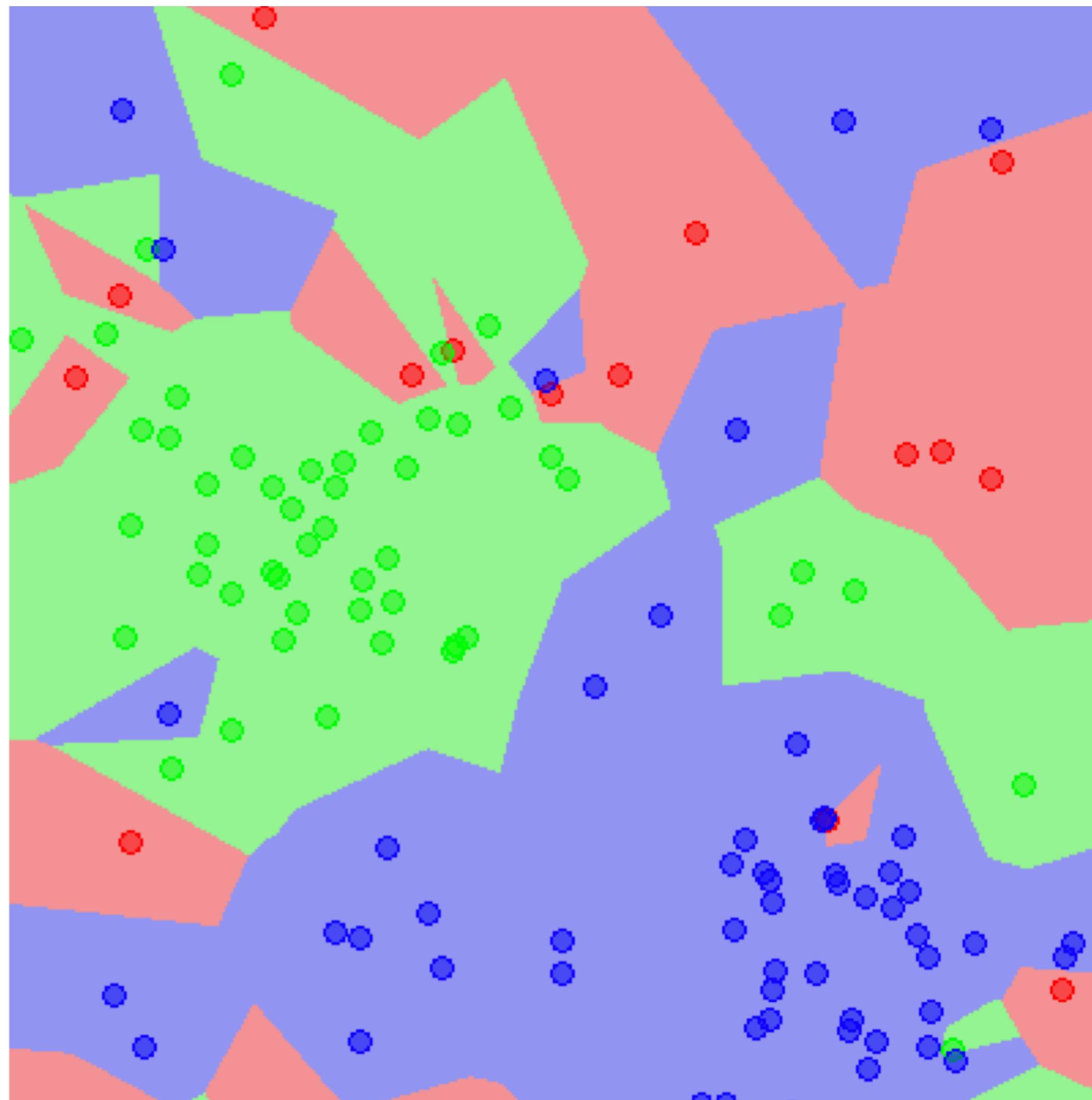
- With  $k=1$ , any bad data point contaminates a neighbourhood
- As  $k$  increases, boundaries become less “wiggly”
- If  $k=n$ , model reduces to **winner takes all** (or global average)
- In general increasing  $k$  reduces variance
  - But k-NN by its nature is sensitive to vagaries of data distribution



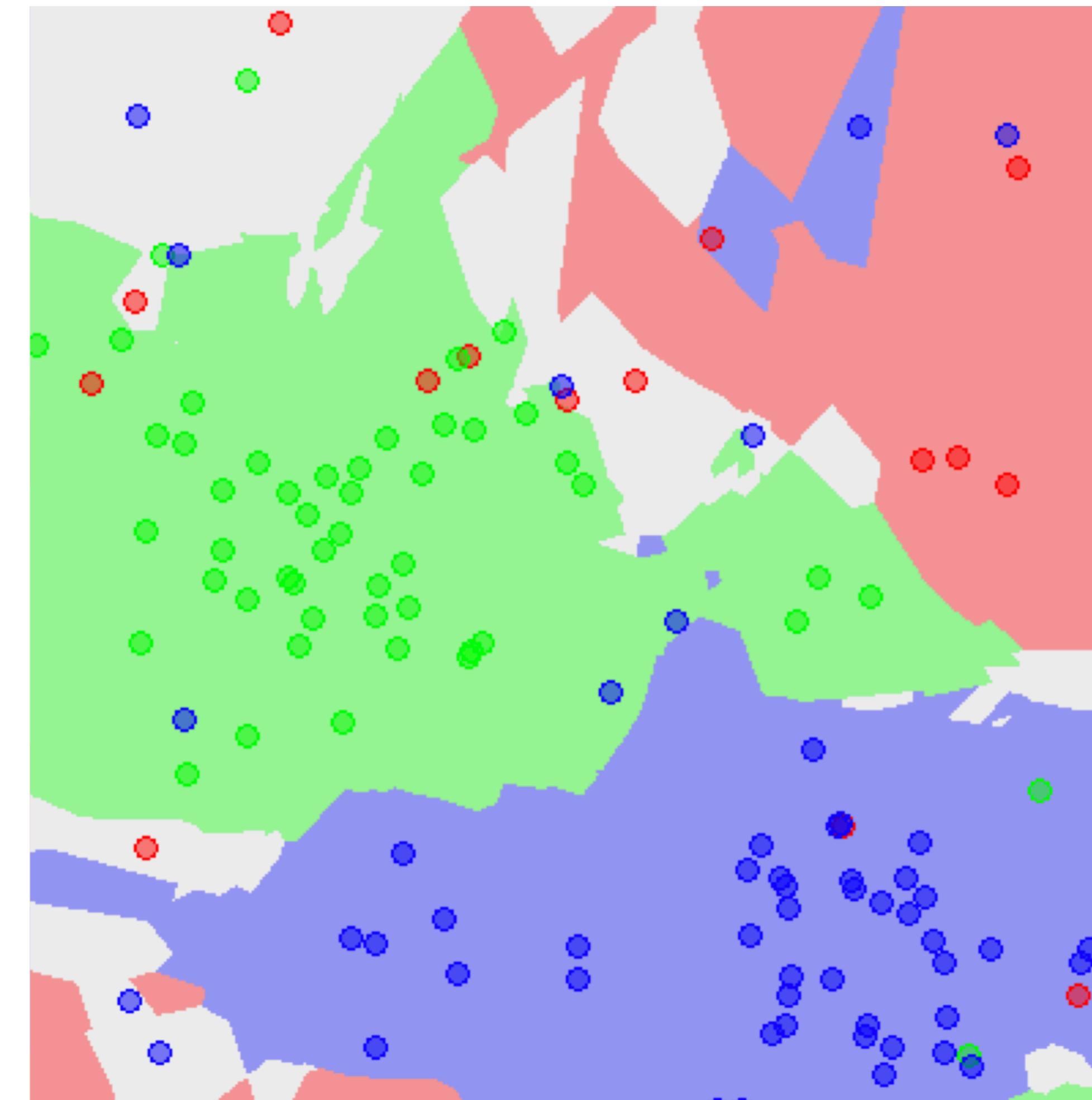
$k=1$



$k=15$



$k=1$



$k=3$

# Pros and cons

- Able to learn complex non-linear decision boundaries (or regression landscapes)
- Easy to understand and implement
- Need to choose  $k$
- Risks overfitting
- May be hard to interpret
- Vulnerable to differences in feature scaling and importance
- Potentially **very slow** to evaluate for large training sets

# Scope for improvement

- Data reduction
  - Many points may not contribute to boundary – prune them
- Dimensionality reduction
  - Drop or combine features – more on this in week 7
- Weighted averaging/voting
  - Nearest nearest neighbours contribute more

# **3.3: Decision Trees**

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# Choose your own adventure

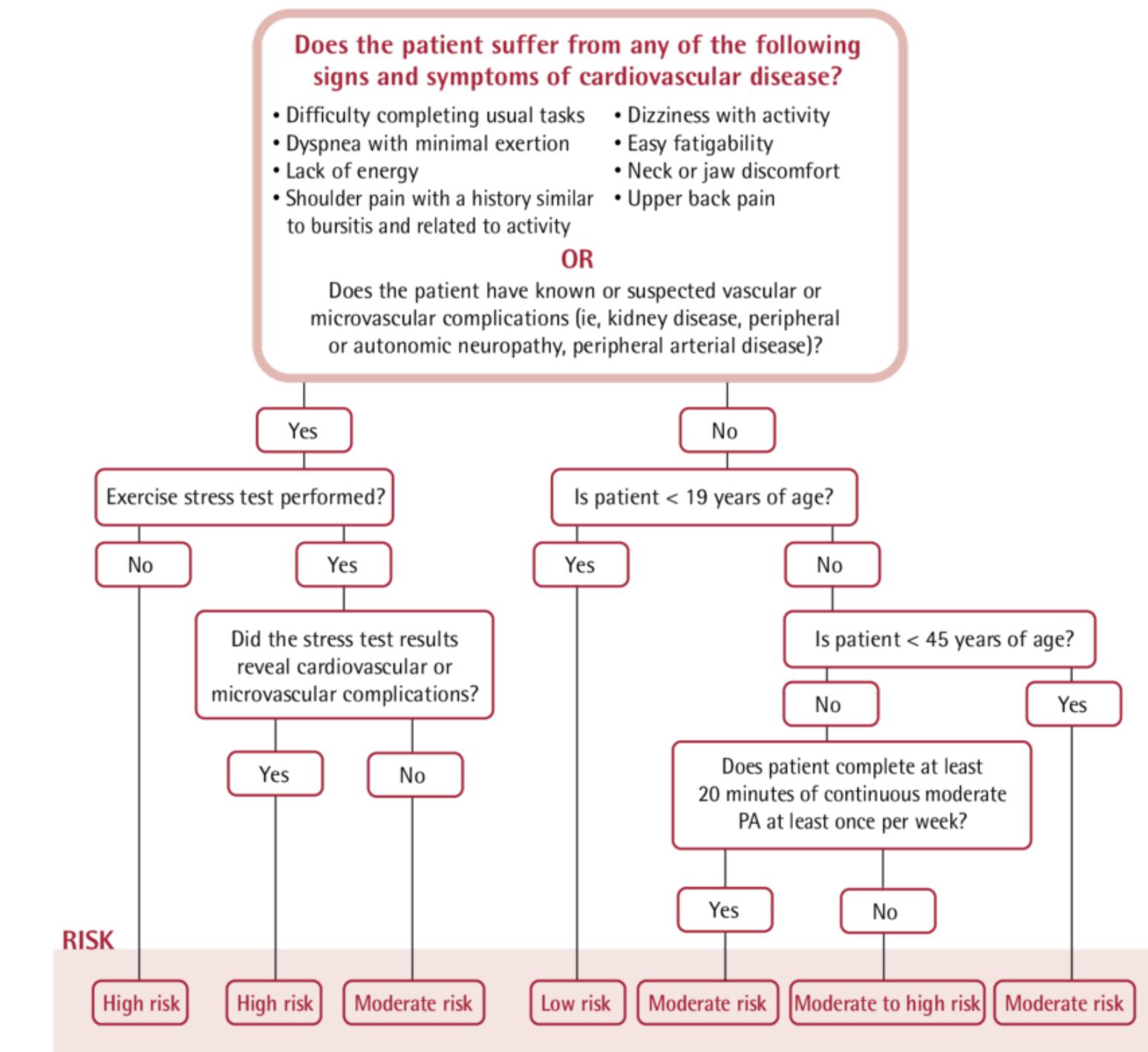
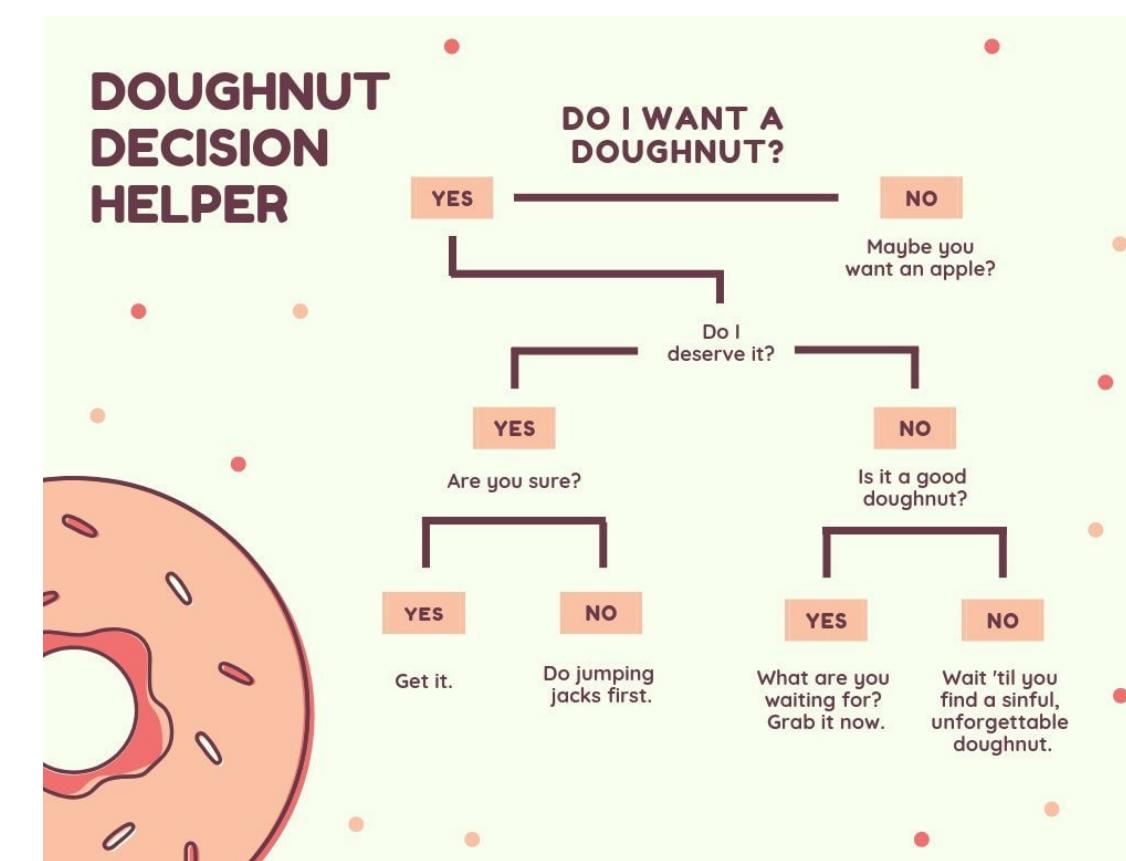
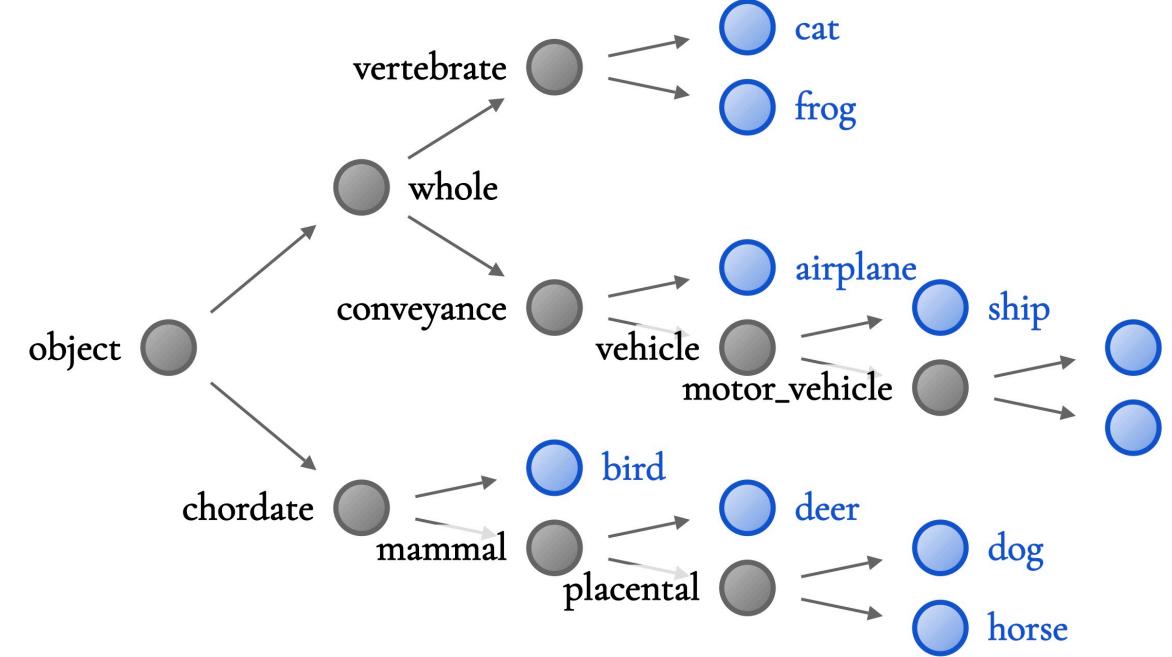
- Decision tree concept is ancient and familiar
    - Long predates ML as a way to encode procedural or diagnostic “knowledge”
  - Algorithms, forms, recipes, flowcharts, games
  - Natural graphical representation
    - Trees are graphs

Does the patient suffer from any of the following signs and symptoms of cardiovascular disease?

  - Difficulty completing usual tasks
  - Dyspnea with minimal exertion
  - Lack of energy
  - Shoulder pain with a history similar to bursitis and related to activity
  - Dizziness with activity
  - Easy fatigability
  - Neck or jaw discomfort
  - Upper back pain

OR

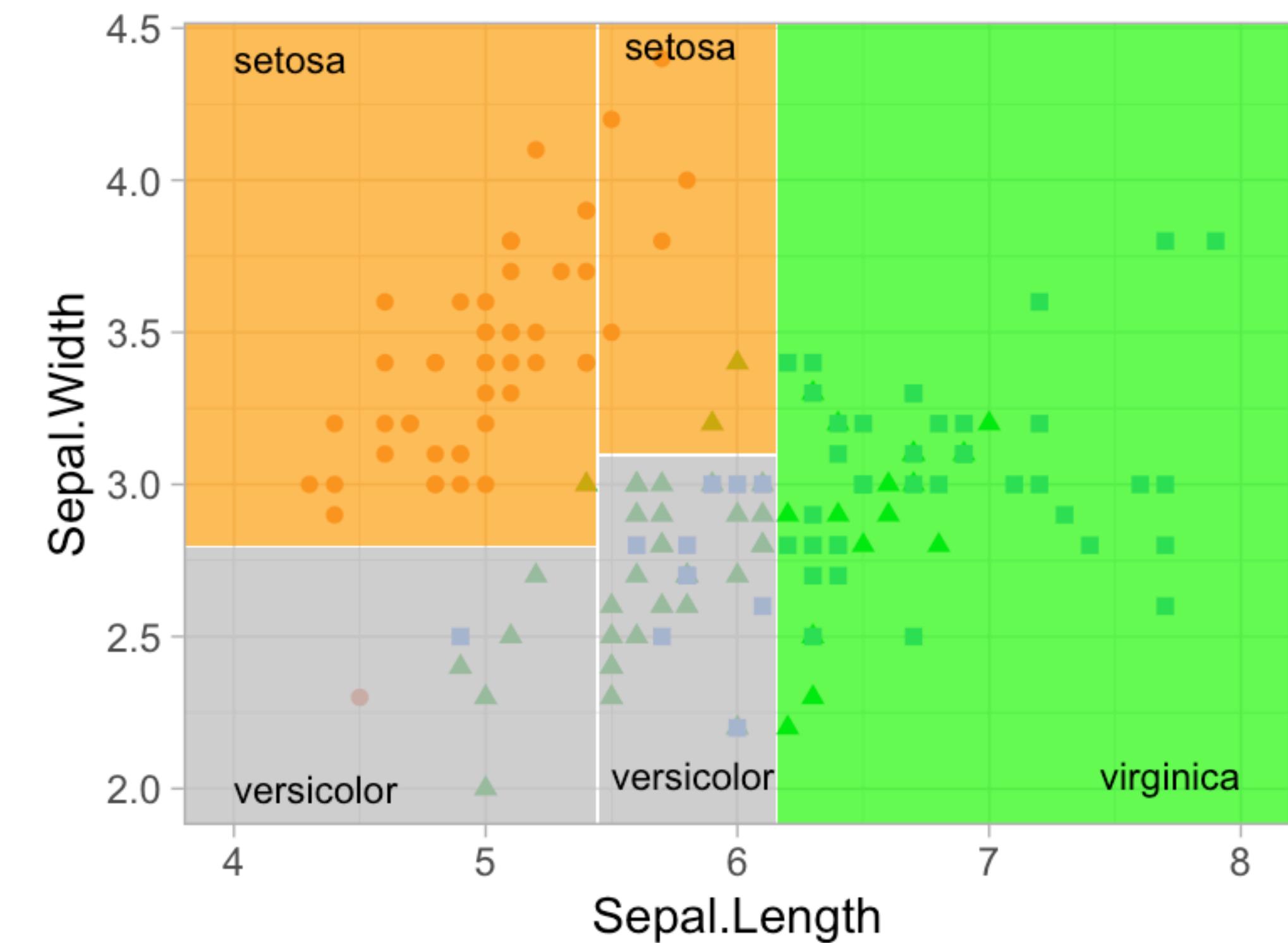
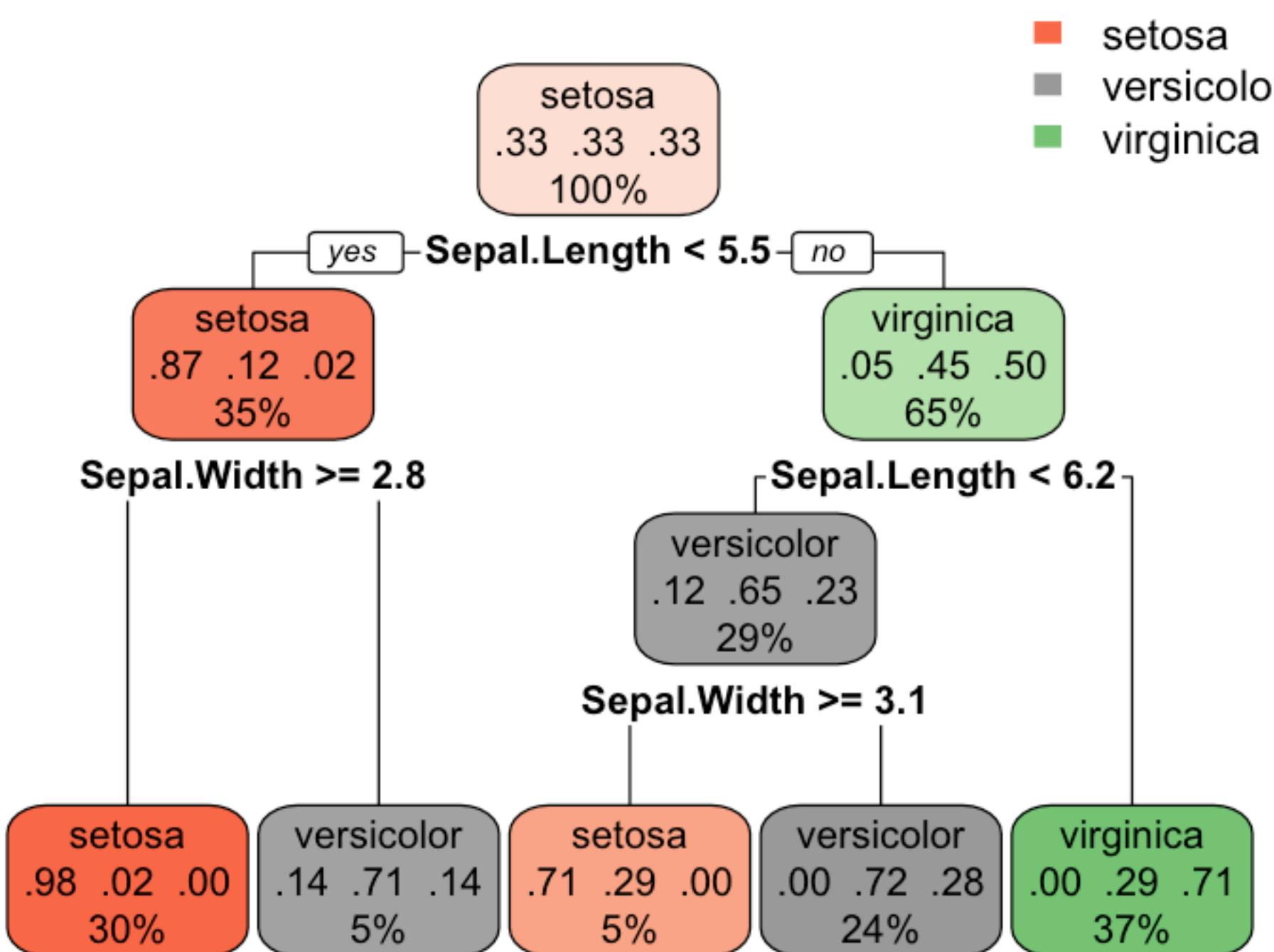
Does the patient have known or suspected vascular or microvascular complications (ie, kidney disease, peripheral or autonomic neuropathy, peripheral arterial disease)?



# Garden of forking paths

- In a classic flowchart choices are free form, posed in natural language
- Decision could depend on any arbitrary question
  - How long until the bus arrives?
  - Napoleon Solo or Ilya Kuryakin?
  - If I asked the other guard which door had the tiger, what would he say?
- For ML we want to learn from the data, so limit to questions about features
  - Usually to simple equalities or inequalities on feature values: is  $x_5 \geq 2.4$ ?
  - Splits don't have to be binary, but we almost always restrict them to be so
    - ▶ A multi-way decision can always be represented as a sequence of binary ones

- Tree represents a recursive partitioning of the feature space
- Each decision splits the current subspace into disjoint parts
- So an alternative visualisation (for 2D features, at least) is something like:



# How to grow a tree?

- Recursively
- Greedily
  - Potentially suboptimal, but avoids combinatorial explosion
- By brute force
  - Check each feature value present in subset
  - Can instead use systematic search if training data really large
- But how to choose?
  - General principle: minimise (weighted) sum of child node losses
  - Optionally: halt if weighted sum of child losses is no less than loss of unsplit parent

# Loss functions for classification trees

- For the current region of input space,  $R$ , define:

$$p_k = \frac{1}{n_R} \sum_{i \in R} \mathbf{1}(y_i = k)$$

- ie, proportion of examples in  $R$  that are of class  $k$
- Then the prediction for all examples in  $R$  is:

$$\hat{y}_R = \operatorname{argmax}_k p_k$$

- ie, we just predict the most common class in  $R$

# Loss functions for classification trees

- Misclassification error (equivalent to 0-1 loss discussed last week)

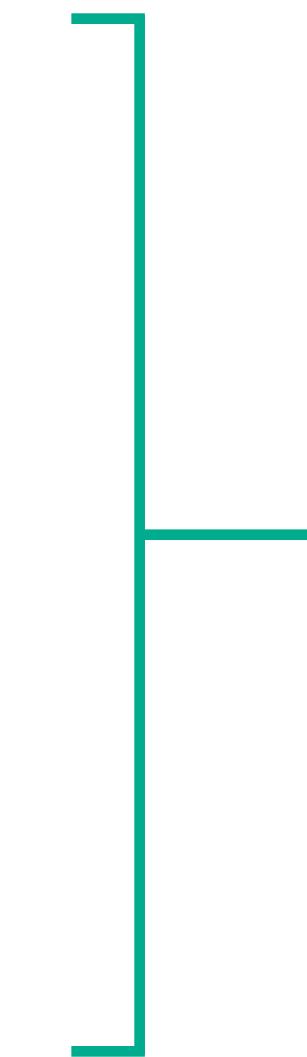
$$\frac{1}{n_R} \sum_{i \in R} \mathbf{1}(y_i \neq \hat{y}_R)$$

- [Cross-]Entropy

$$-\sum_{k \in R} p_k \log p_k$$

- Gini Impurity

$$\sum_{k \in R} p_k(1 - p_k)$$



NB: don't depend  
on the prediction!

# Loss functions for classification trees

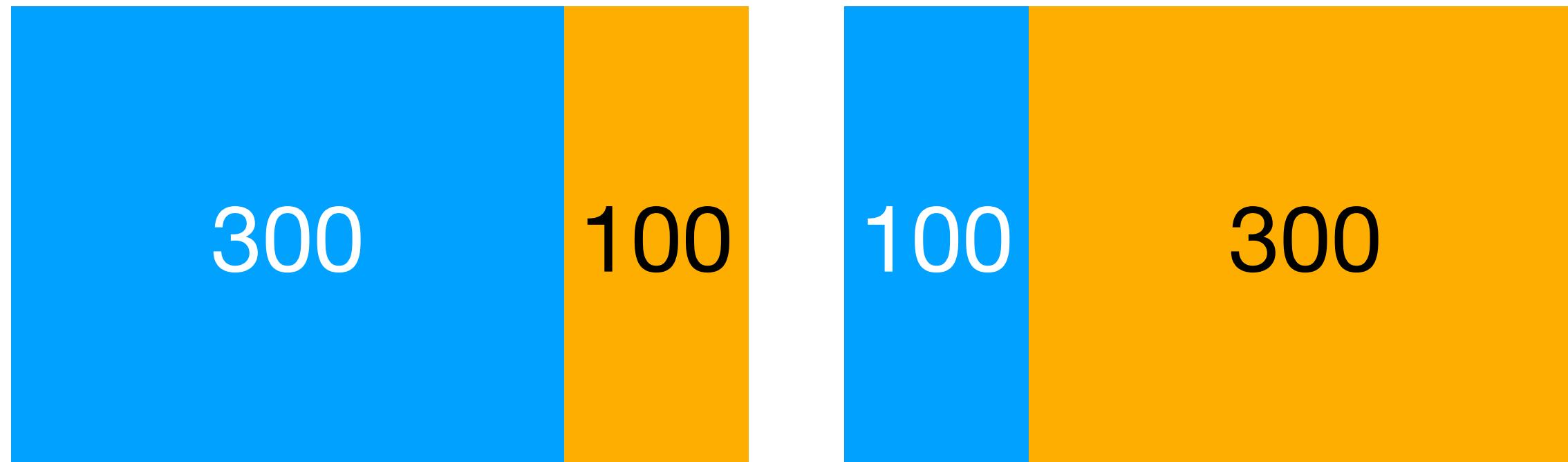
- All three losses will be zero for a **pure** node (ie, containing only one class)
  - Pure nodes are good, because we can stop recursing
- Cross-entropy and Gini impurity are differentiable
  - We are only considering brute force optimisation here but gradient-based methods may be used in other contexts
- Cross-entropy and Gini impurity are also more sensitive to node probabilities
  - example from Hastie:  $[400, 400] \rightarrow \{[300, 100], [100, 300]\}$  vs  $\{[400, 200], [200, 0]\}$
  - both splits have the same misclassification error: 0.25
  - but second creates a pure node, which is probably preferable – Gini & Cross-Entropy are both lower in this case

Parent



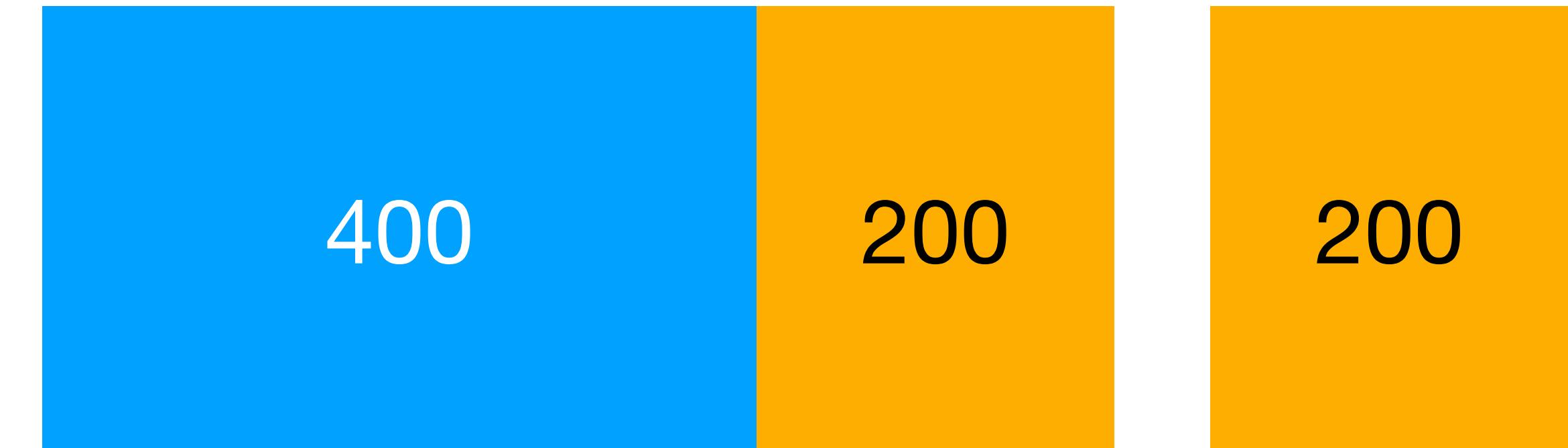
Misclassification: 0.5  
Gini: 0.5  
Entropy: 0.693

Split Option 1



Misclassification: 0.25  
Gini: 0.375  
Entropy: 0.56

Split Option 2



Misclassification: 0.25  
Gini: 0.333  
Entropy: 0.477

# Regression trees

- Predict mean of all samples in node
- Typically use a mean-squared error loss to choose splits

# Limiting tree growth

- Growing without bounds might eventually produce a tree with a node for every training sample
  - Roughly equivalent to 1-Nearest Neighbour
  - Unlikely to get to this point if there's any local structure at all
  - But still may overfit significantly
- Limits can be imposed (as a kind of regularisation) on:
  - Maximum tree depth
  - Maximum overall nodes in tree
  - Minimum number of data points in node
  - Minimum improvement in loss

# Pruning

- Pre-emptively stopping growth can lead to underfitting
  - Eg, if best choice at later node made possible by weak choice earlier
- An alternative is to grow the tree to full depth and then iteratively prune the least beneficial branches

# Pros and cons

- Fast to evaluate
- Easy to understand and visualise
- Potentially interpretable
- Non-smooth
  - Basically a discrete method that we can fudge for regression
- Non-additive
  - Basically: they don't learn diagonals
- High variance
  - Minor data differences that alter early splits can result in very different structures

# **3.4: Ensembles & Random Forests**

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# Fighting variance with aggregation

- Experimental measurements are often noisy
- We might take multiple readings and average them to reduce this
- Similarly, we can often mitigate model variance by fitting multiple models and aggregating their predictions
  - Obviously, models must be different — can't use a deterministic learning algorithm repeatedly on the same task, something must change
  - Each model may be wrong in a different way, but some of that averages out
- There are a number of ways to do this, including methods that throw together a whole bunch of completely dissimilar models
- We will focus on two structured approaches: **boosting** and **bagging**

# Boosting

- Boosting combines multiple **weak learners** to improve the performance
- Training is sequential
  - Learner  $k+1$  is contingent on learners  $1 \dots k$
- Each new learner is trained on a different task
  - Task is modified at each step to address weaknesses in the ensemble so far
- There are several variants, but the most popular is probably AdaBoost, which we will describe in detail in §3.5

# Bagging

- Bagging combines multiple **strong learners** to reduce the variance
- The learners are trained independently — potentially in parallel
- All learners learn the same task — but training on different randomised subsets of the training data
- Bagging is a contraction of “bootstrap aggregation”
  - The “bootstrap” comes from statistics — it is a tactic to improve estimates about a population for which there is limited data by resampling that data with replacement
- Easily the most popular bagging method is Random Forests, which we’ll discuss shortly

# Meta-algorithms

- Bagging and boosting do not prescribe a particular model or learning algorithm for their ensemble members
- They are (families of) “meta-algorithms”, which specify how to combine other models for improved results
- It is possible to use them to aggregate many different kinds of machine learning model
- However, decision trees are probably the most common choice for both
  - NB: they are “weak” in one and “strong” in the other because of different hyperparameterisation

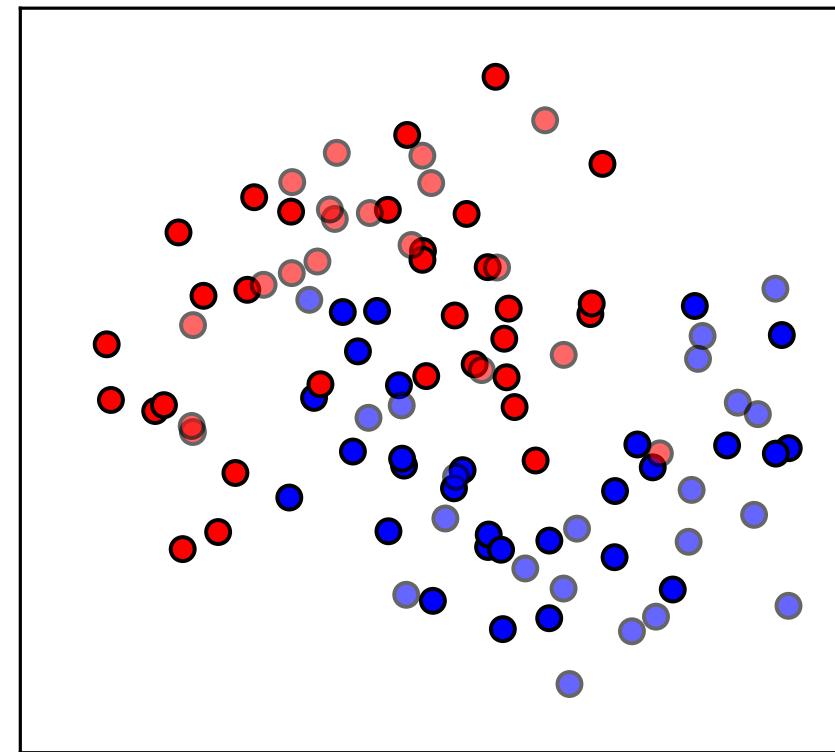
# Random forests

- Decision trees are (or can be) able to fit complex decision functions
- But they are high variance and prone to overfitting
- We can combat this by aggregating over an ensemble of trees — a **forest**
- Fun fact: “random forest” is a registered trademark!
  - The algorithm itself is public domain
  - The circumstances where you would care about this are rare
  - ...but still, it’s a bit weird

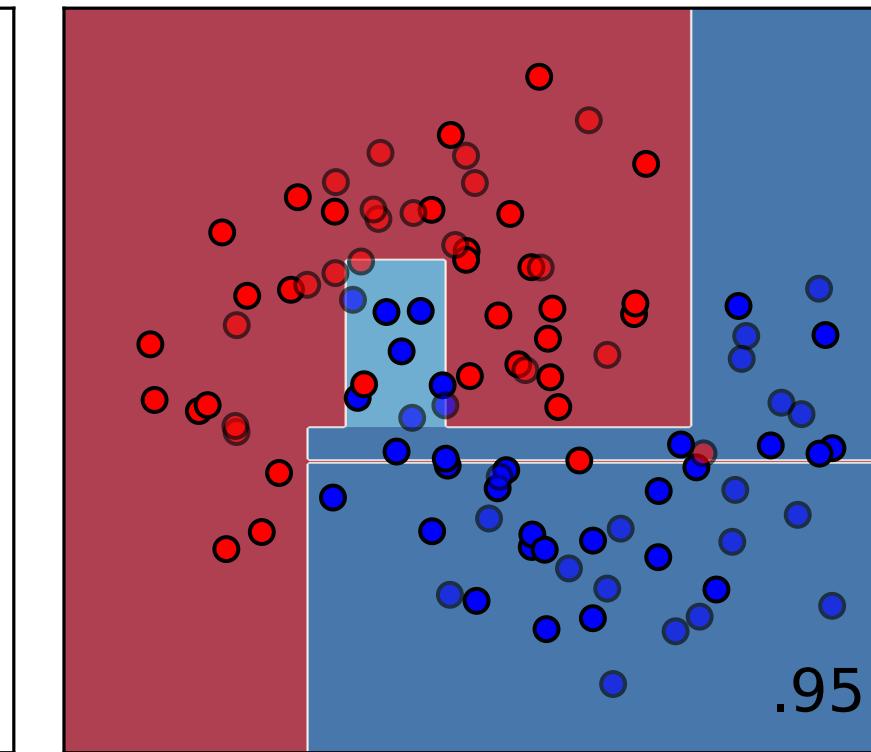
# Diversification

- Fitting decision trees is deterministic, so we need to vary it somehow
- One way is bagging: fitting to bootstrap samples of the training data
  - Randomly resample from the training set with replacement
  - Any given sample may appear once, multiple times or not at all
  - Each bootstrap sample is a different approximation of the true distribution
- Random forests add a further source of variation by randomly selecting different feature subsets for each tree
- **Extremely randomised trees** is an alternative approach that randomises the fitting procedure to increase the diversity of the ensemble, instead of bootstrapping the data

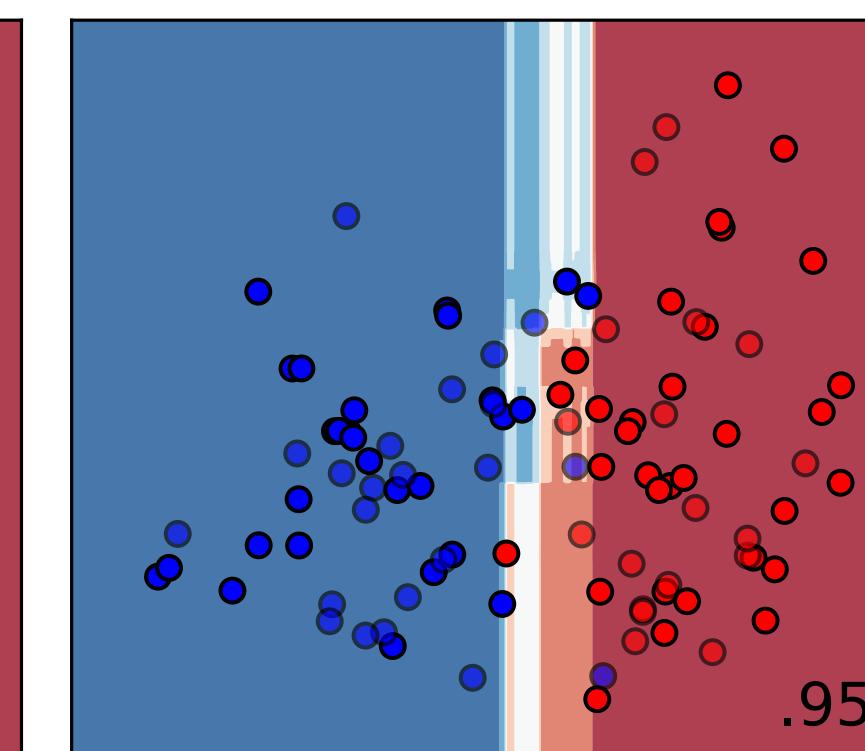
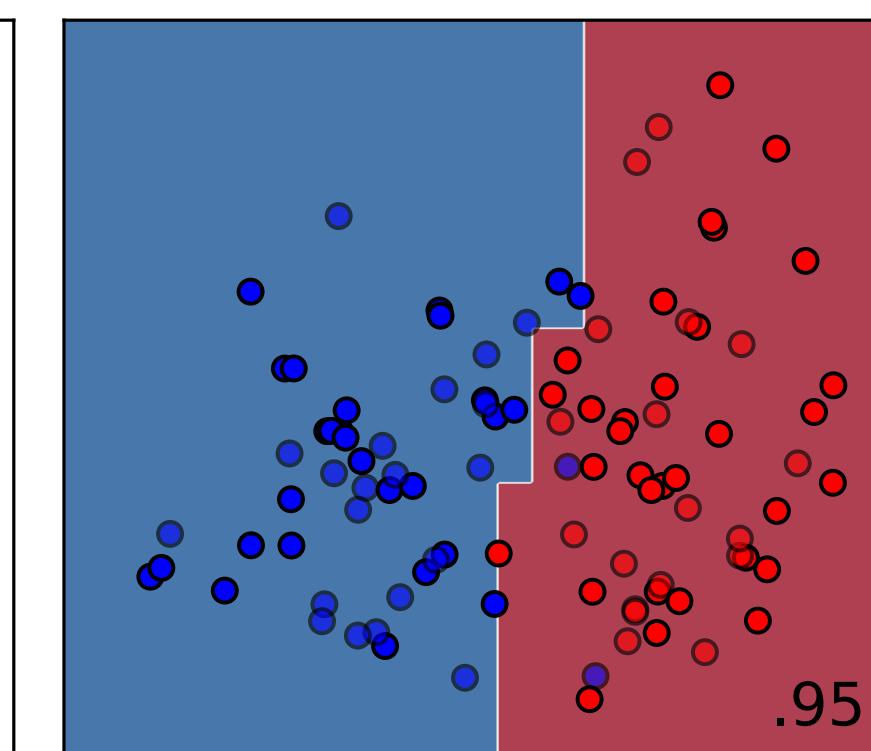
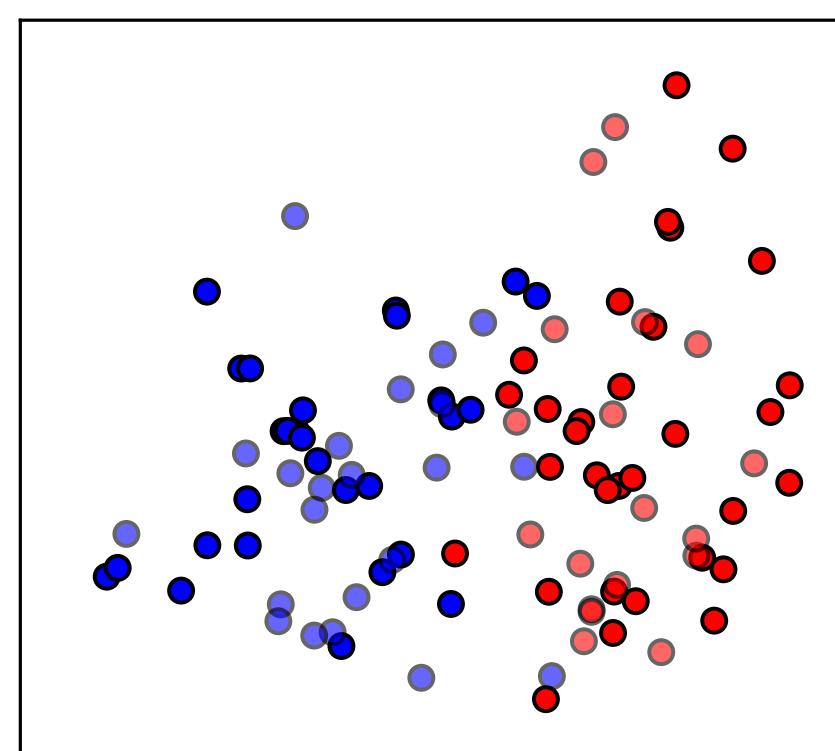
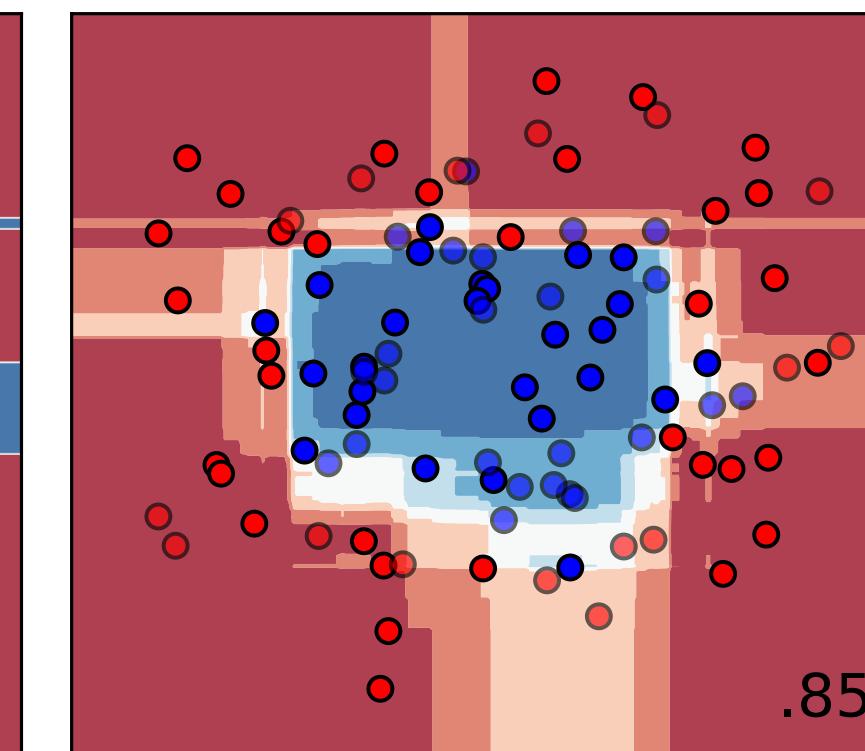
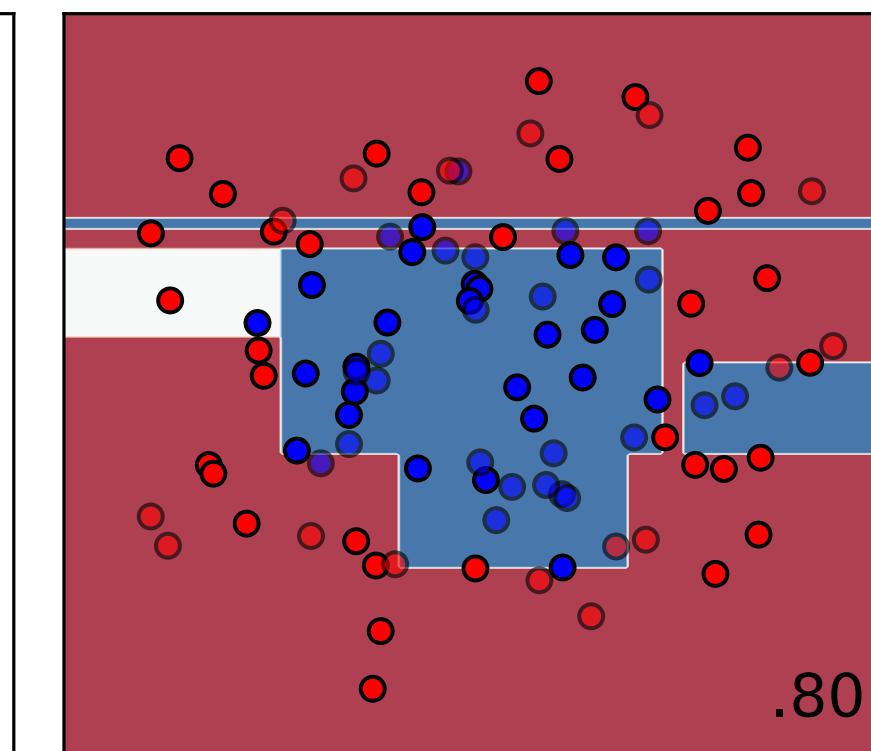
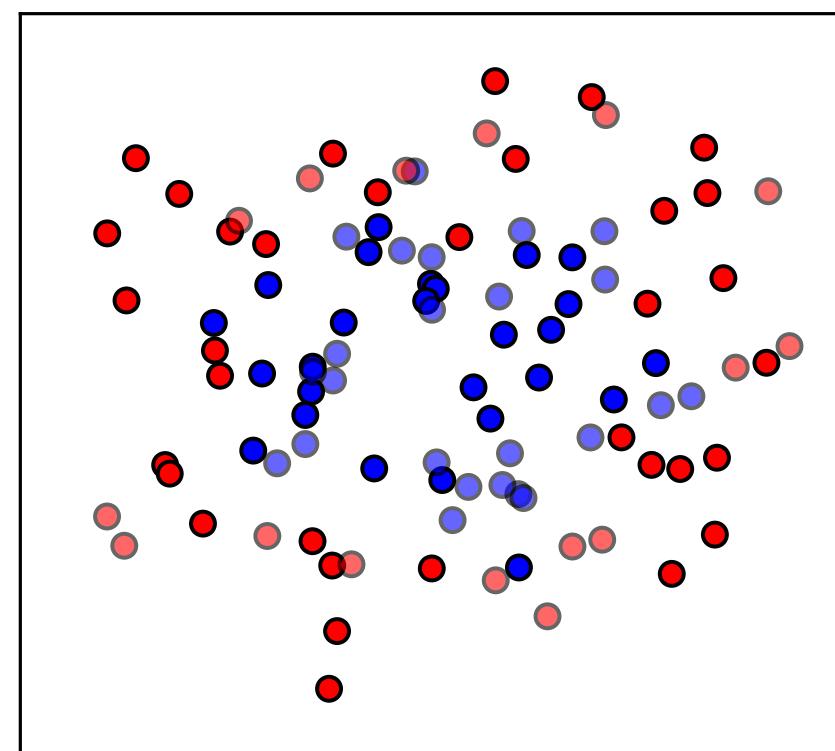
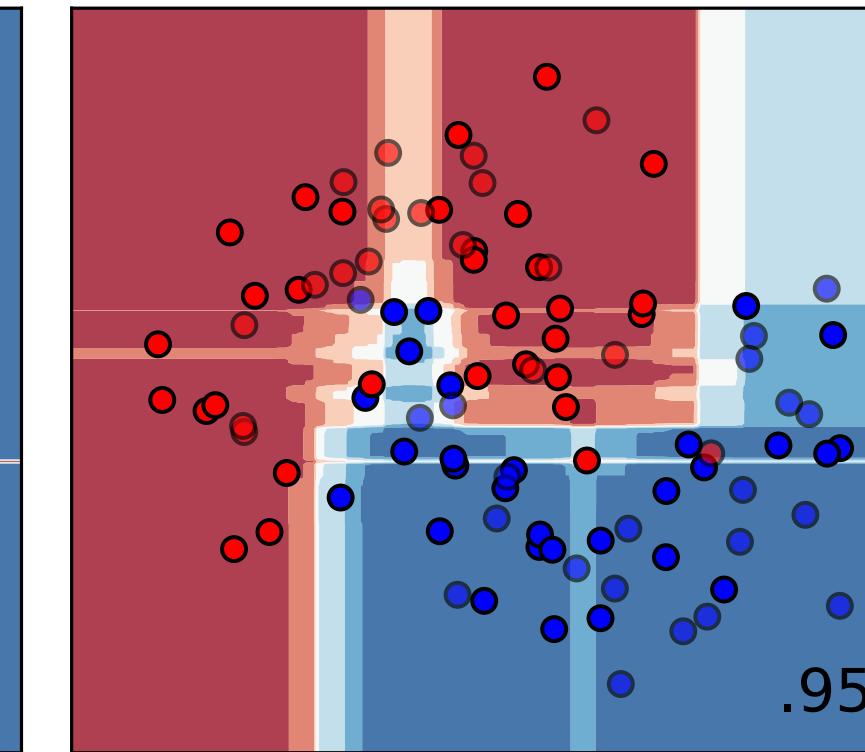
Input data



Decision Tree



Random Forest



# Pros and cons

- Easy to use
- Good performance with reduced variance and less overfitting
- Uninterpretable
  - Sacrifices clear decision structure of single trees
- Strong learners can be slower to train
- Hyperparameters
  - Number of trees
  - Tree depth
  - Feature subsetting

# **3.5: AdaBoost**

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# Adaptive boosting

- Probably most popular boosting meta-algorithm
- Combines weak learners to build a strong learner
- We'll focus on the binary classification case
  - Extends to multiclass and regression but in slightly fiddly ways that would be distracting here
- Different labelling convention: classes are  $\{-1, 1\}$  rather than  $\{0, 1\}$ 
  - Gives a neat way of calculating update direction:  $y\hat{y}$  or  $yf(\mathbf{x}) \leftarrow \text{"margin"}$
  - Makes the final aggregation simpler: we'll want to make a weighted sum where opposing classifications have **magnitude** in the relevant direction, rather than zeroing out the negative ones

# Weak learners

- There isn't really a set definition of "weakness"
- Must perform better than chance — otherwise nothing learned at all
  - Performance constraint for classic Adaboost is actually  $> 50\%$
  - This is one of the obstacles to extending to multiclass
- But might be only a bit better
- Weak learners can be cheap to train, making for efficient ensembles
- It is possible to boost strong learners, but less worthwhile

# Decision stumps

- The classic weak learner used for AdaBoost
- A decision tree of depth 1
  - ie, just a single split with no recursion
- Fast to train
- But very weak
  - Individual stump performance likely to be terrible for almost all problems

# Sample weighting

- Each learner is chosen to minimise a **weighted** misclassification error

$$\epsilon = \sum_i w_i \mathbf{1}(y_i \neq \hat{y}_i)$$

- Weights define the importance attached to each observation
- All weights are initially equal, set to 1/n

# Predictor weighting

- After a learner is fitted, it is assigned a prediction weight ( $\alpha$ ) based on its weighted prediction error:

$$\alpha = \frac{1}{2} \log \left( \frac{1 - \epsilon}{\epsilon} \right)$$

- Note the error is for the predictions of this learner alone, not the whole ensemble
- Information accumulates in the loss weights  $w_i$

# Sample re-weighting

- The weights are adjusted according to predictions
  - Two different formulations are common, using only errors or all predictions:

$$w_i \leftarrow w_i e^{\alpha \mathbf{1}(y_i \neq \hat{y}_i)}$$

$$w_i \leftarrow w_i e^{-\alpha \hat{y}_i y_i}$$

- Either way, we then normalise adjusted weights to sum to 1:

$$w_i = \frac{w_i}{\sum_j w_j}$$

- Overall effect is to upweight wrongly classified samples, downweight correct

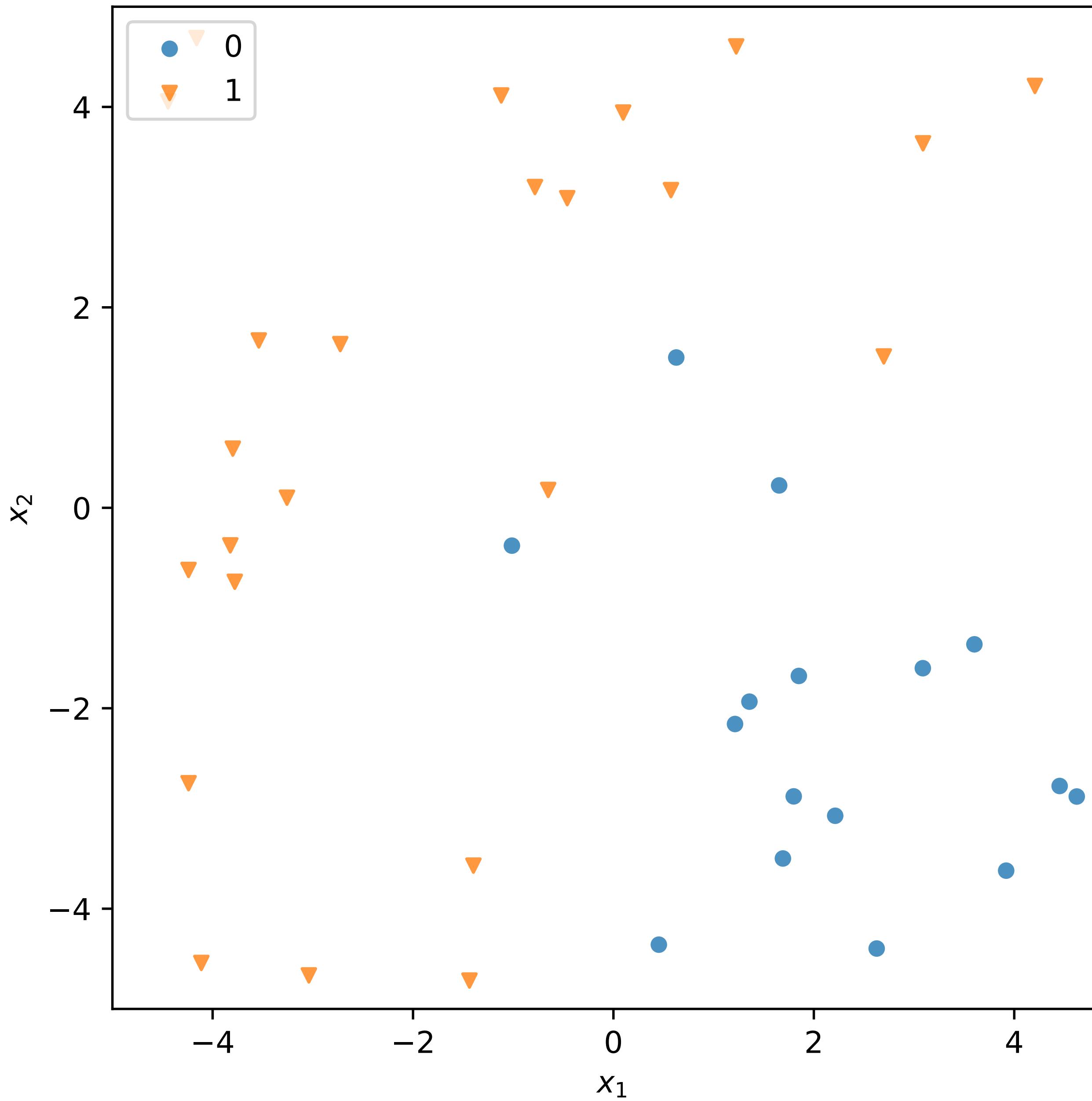
# Ensemble prediction

- Having trained  $k$  learners,  $h_1 \dots h_k$ , each with associated weight  $\alpha_1 \dots \alpha_k$ , an unseen test sample  $\mathbf{x}$  can be predicted as:

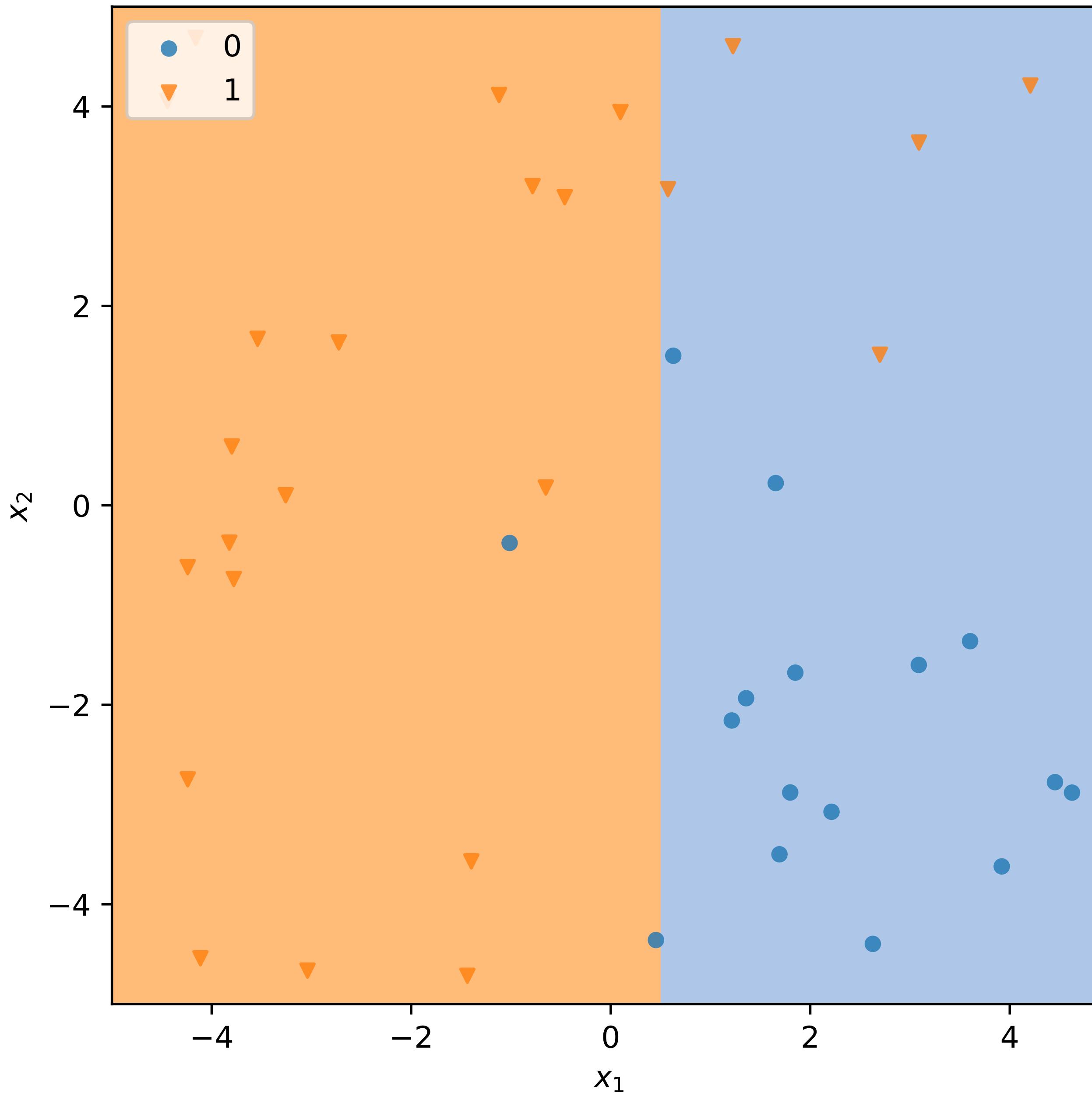
$$\hat{y} = \operatorname{sgn} \sum_{t=1}^k \alpha_t h_t(\mathbf{x})$$

- Sample weights  $w_i$  are used only in training and discarded afterwards

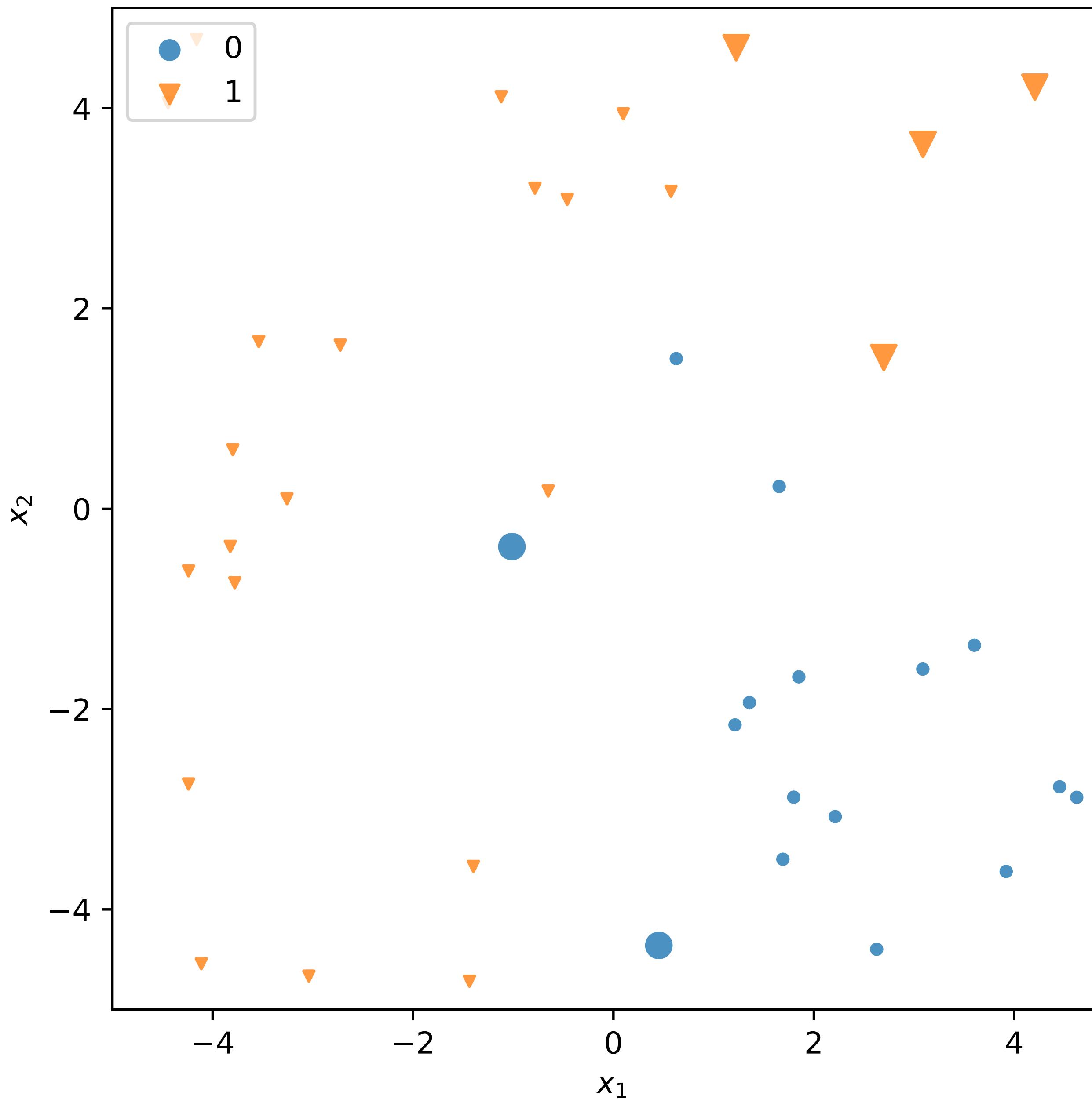
Weighted Samples 1



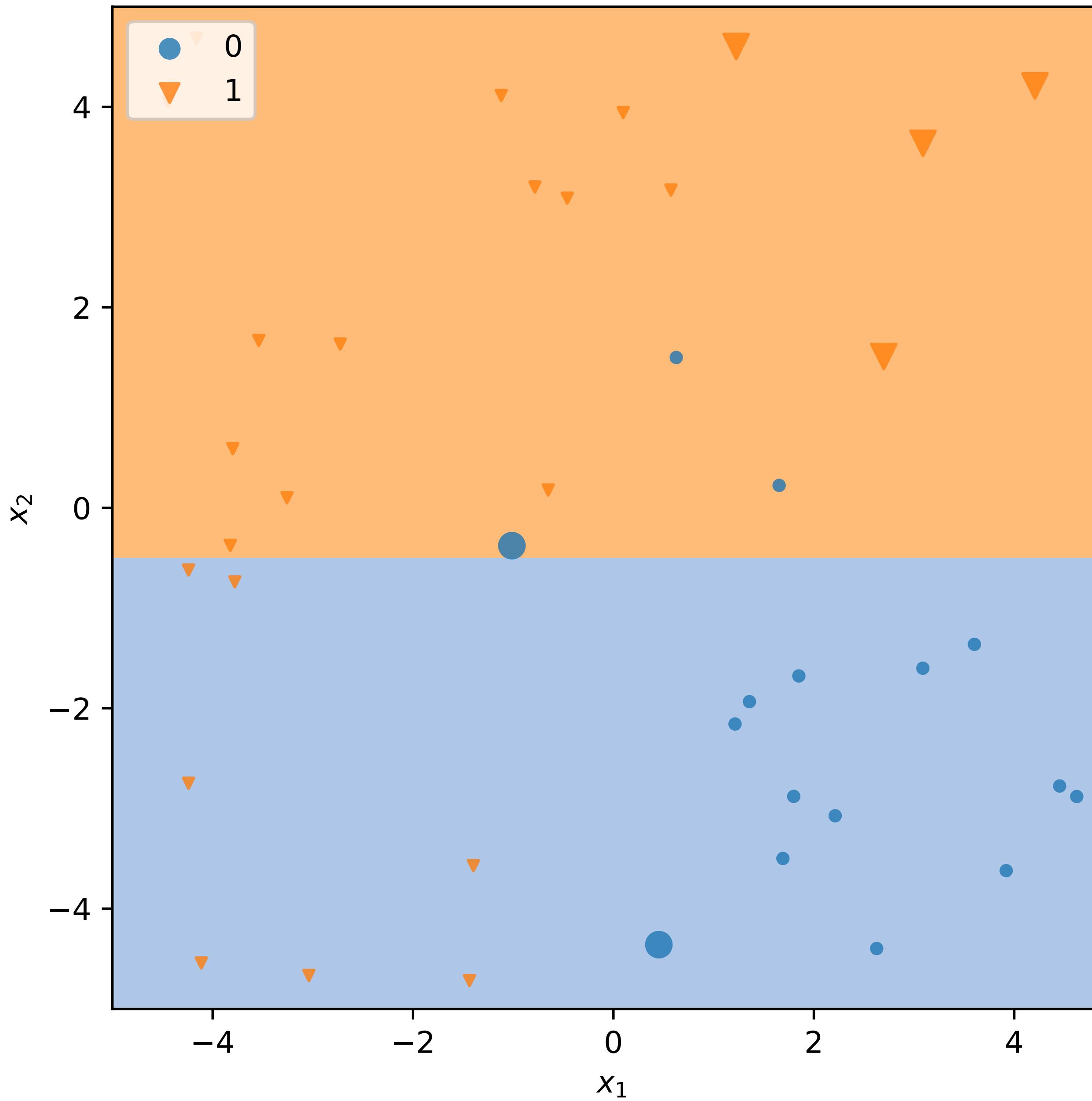
Decision Stump 1



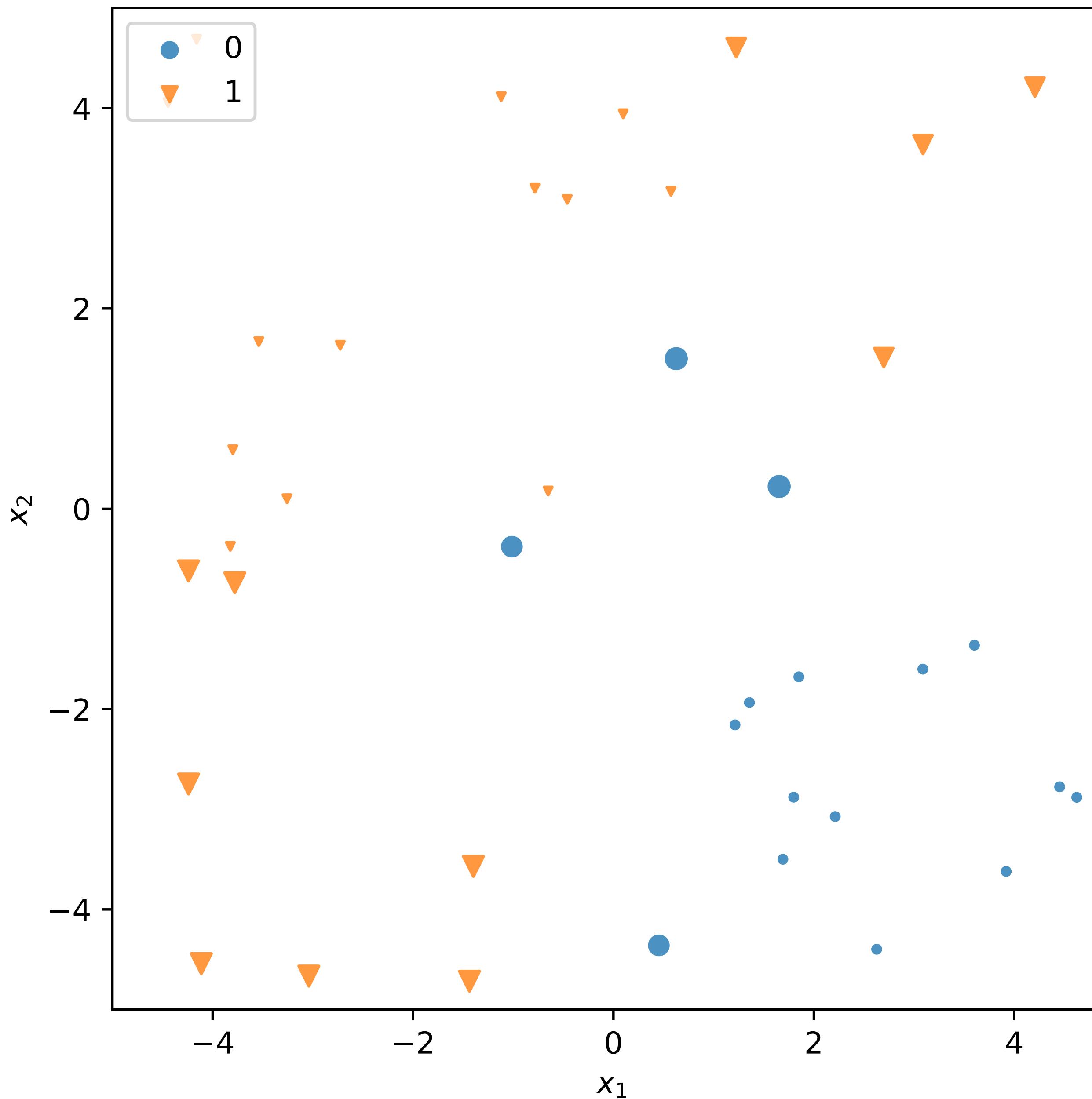
### Weighted Samples 2



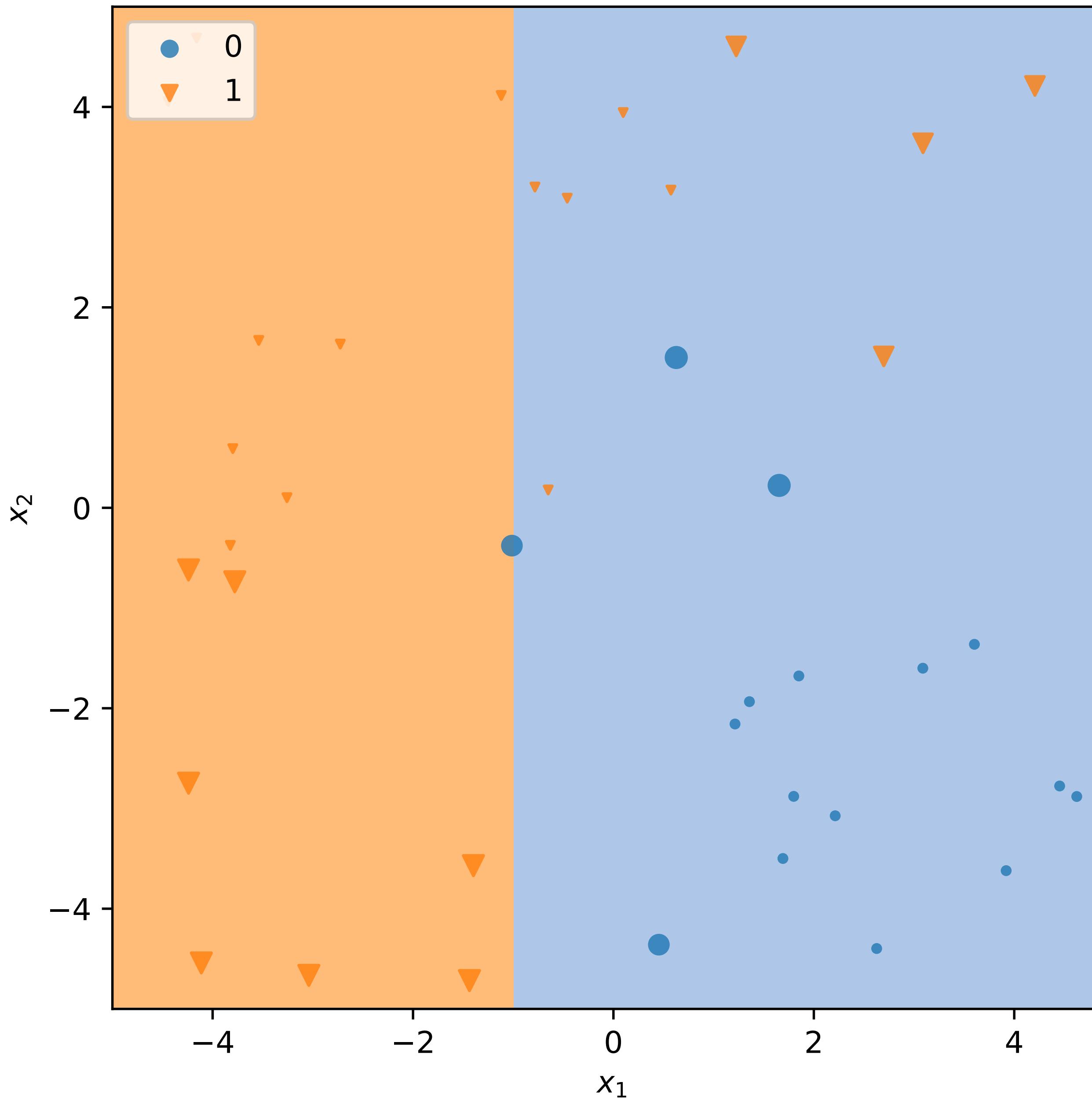
Decision Stump 2



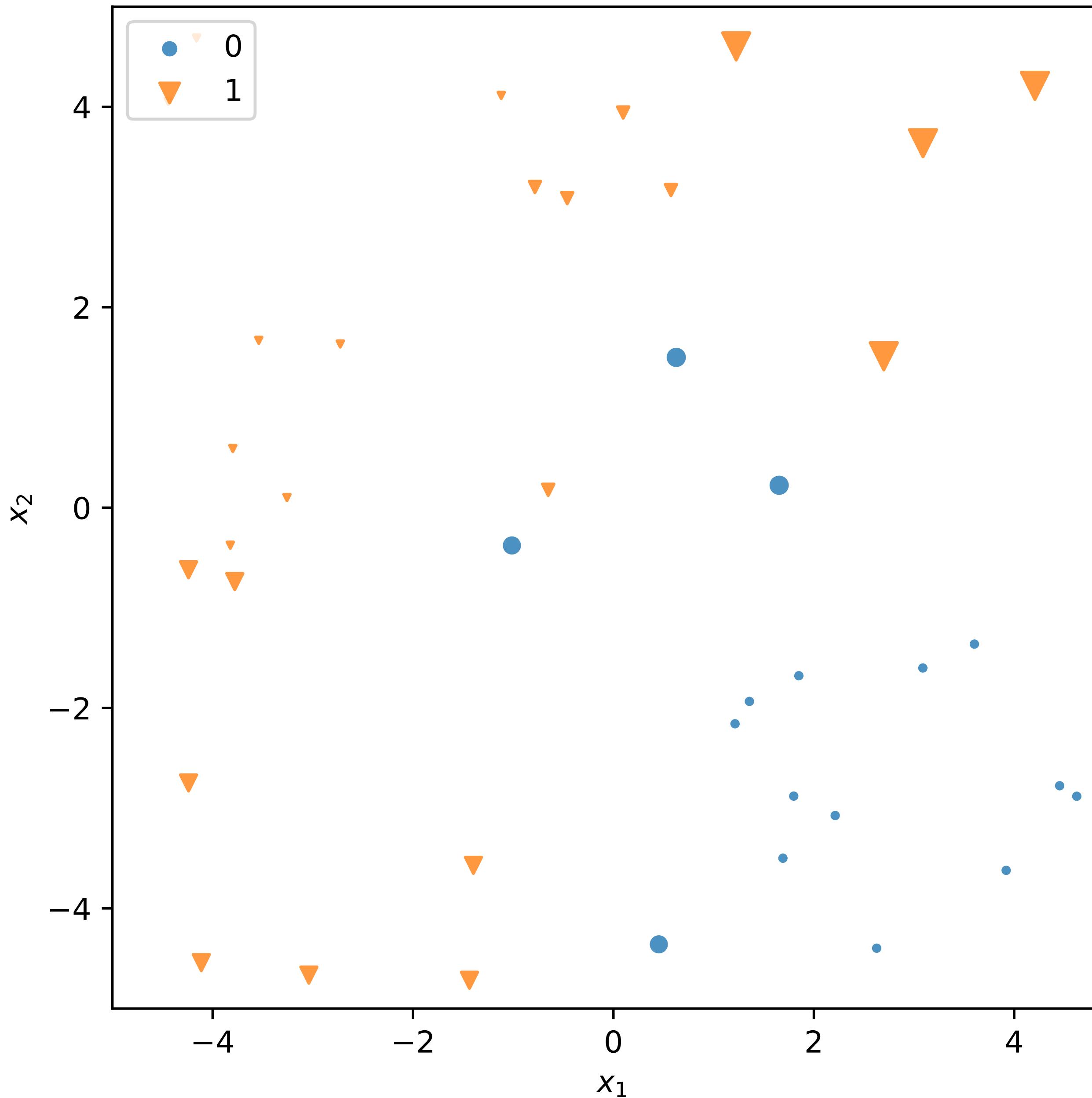
### Weighted Samples 3



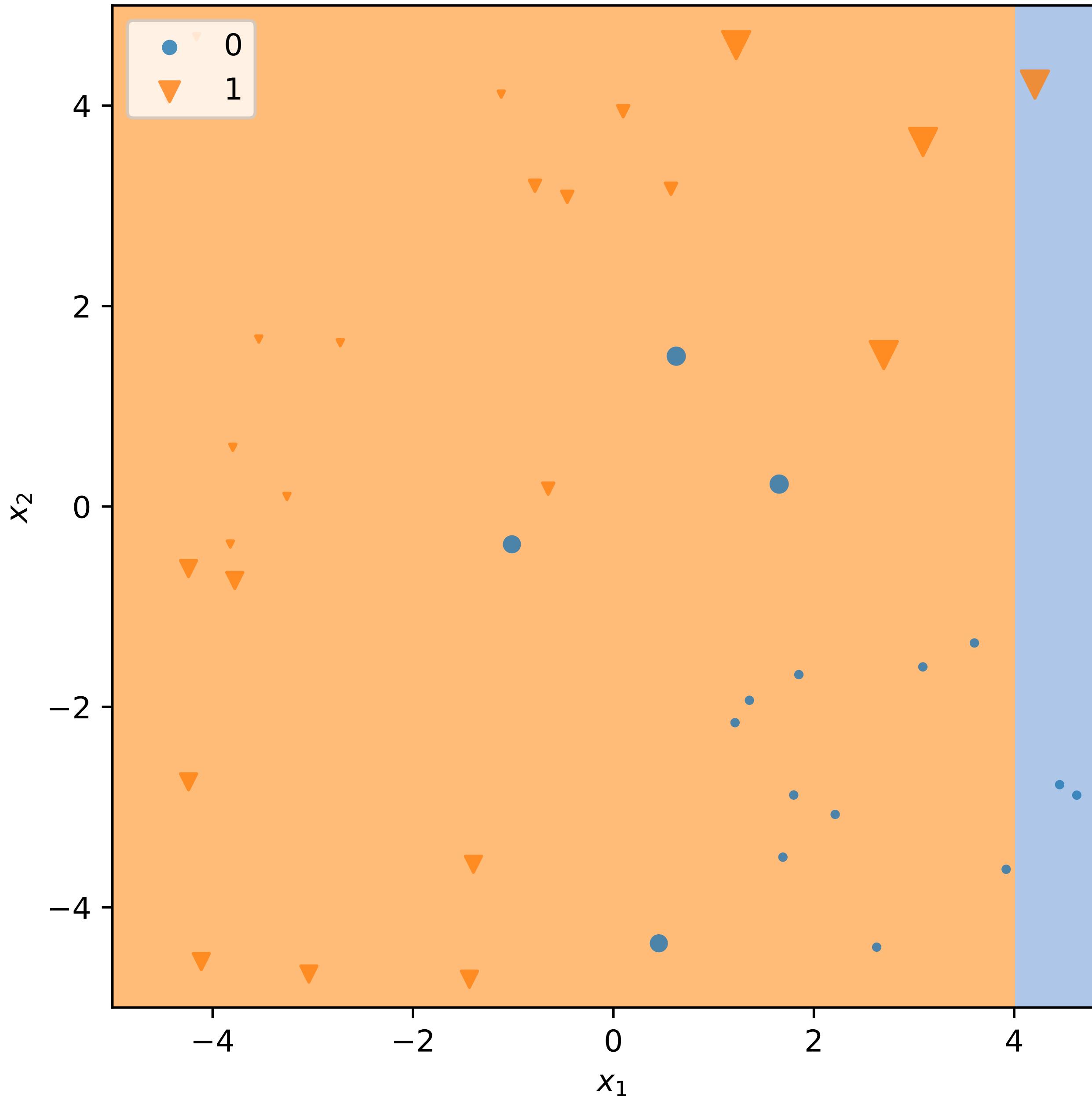
Decision Stump 3



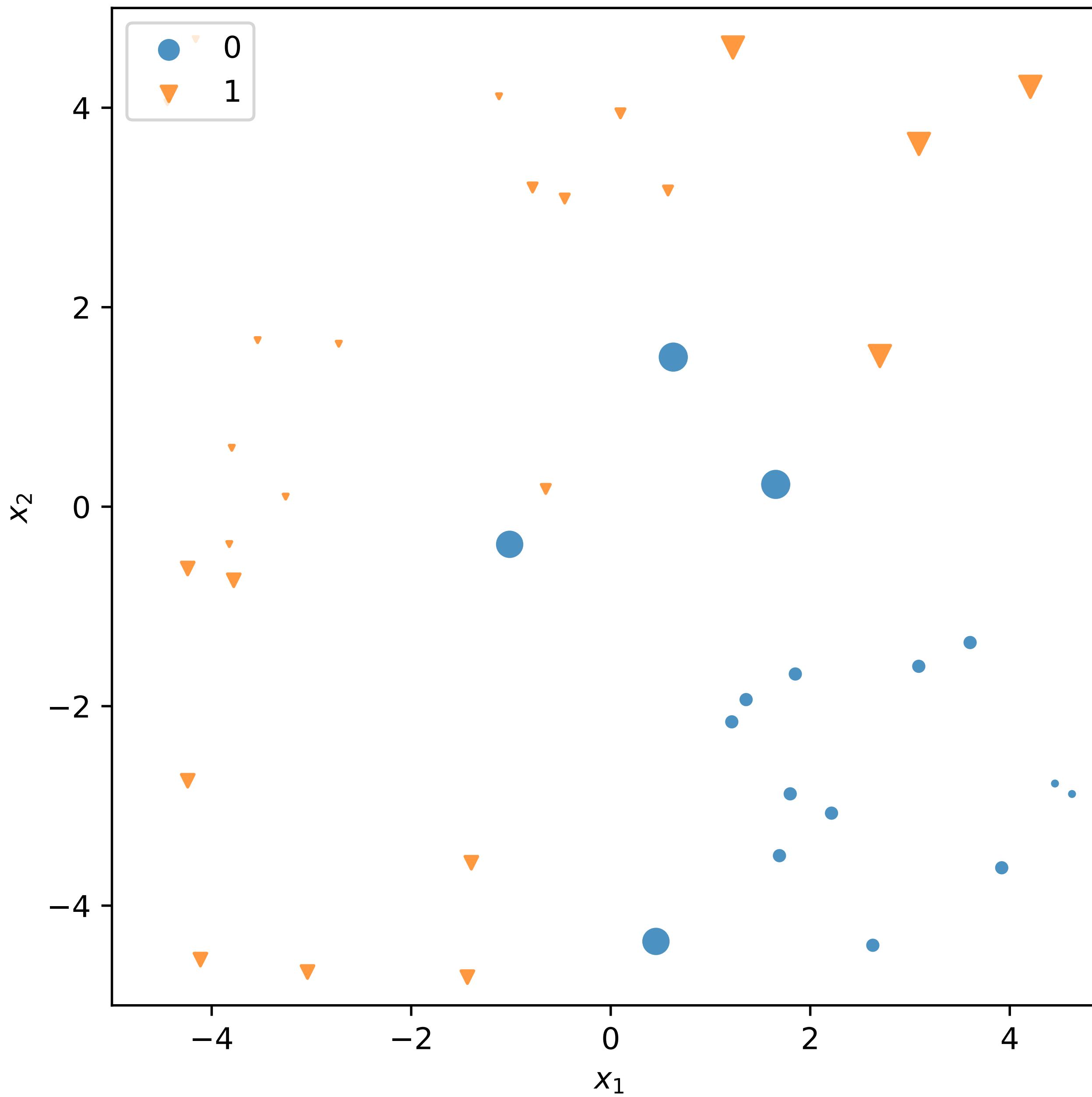
### Weighted Samples 4



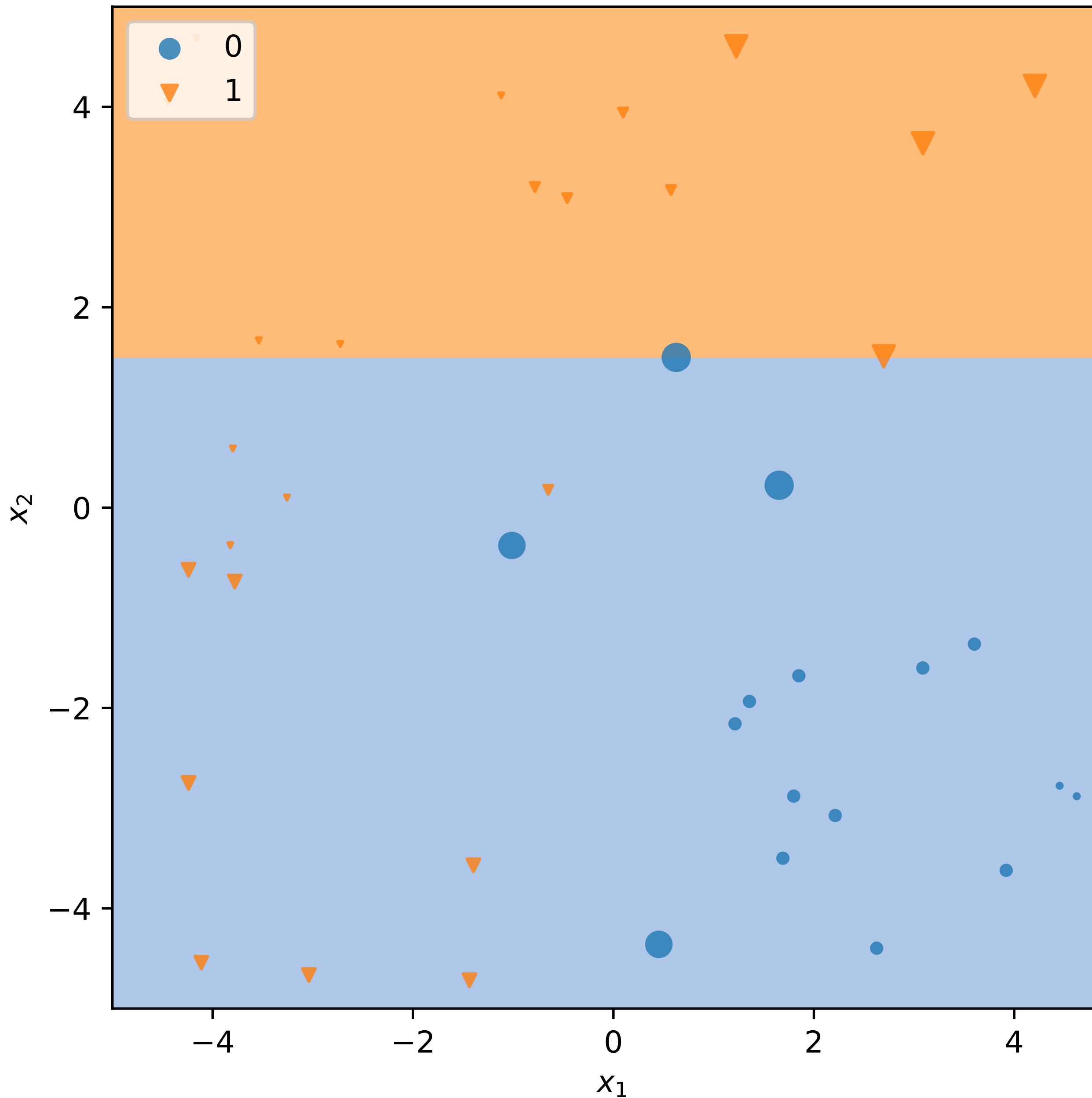
Decision Stump 4



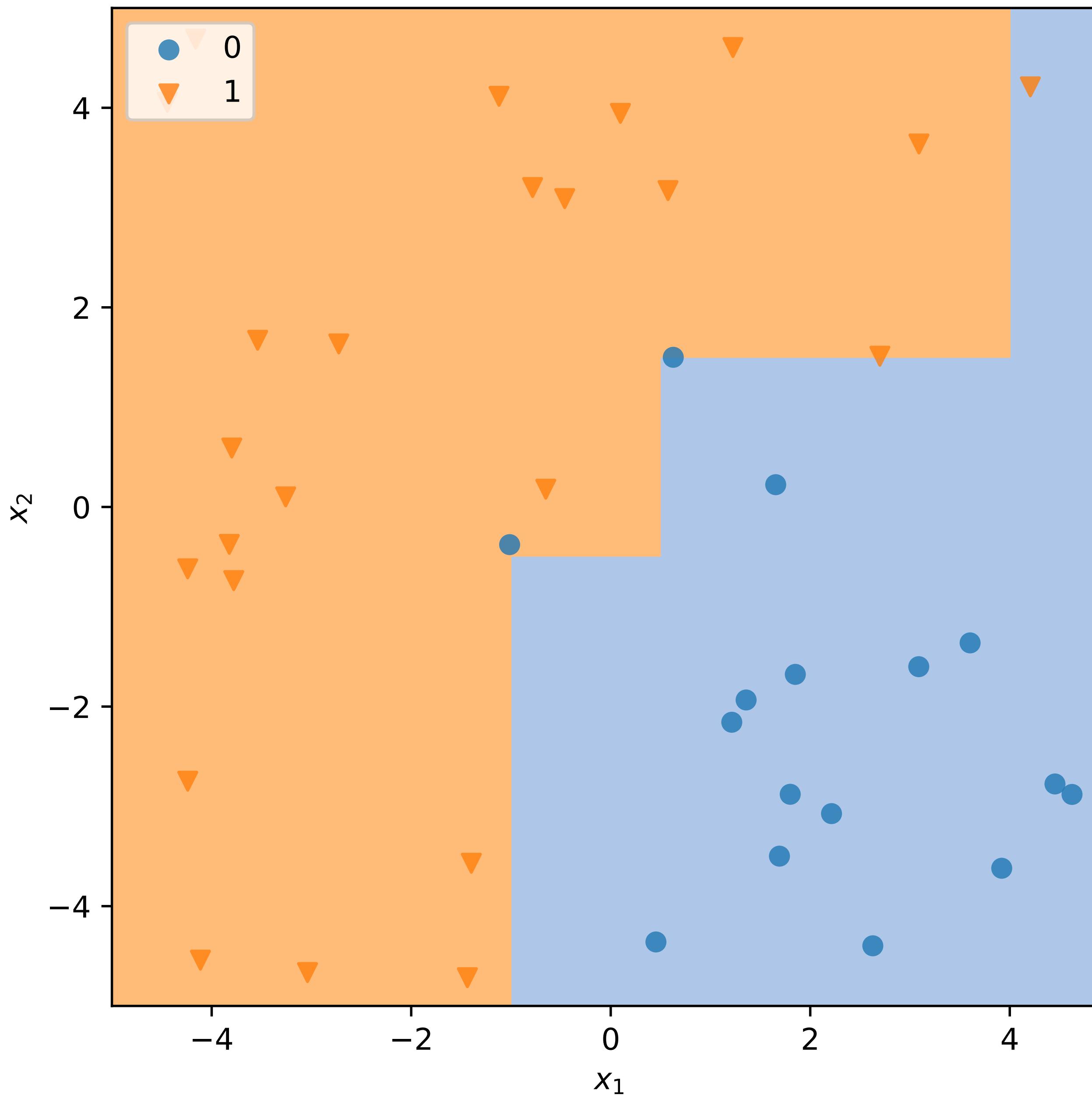
### Weighted Samples 5



Decision Stump 5



AdaBoost Combined



# Why does it work?

- AdaBoost performs a forward stagewise fit of an additive prediction model

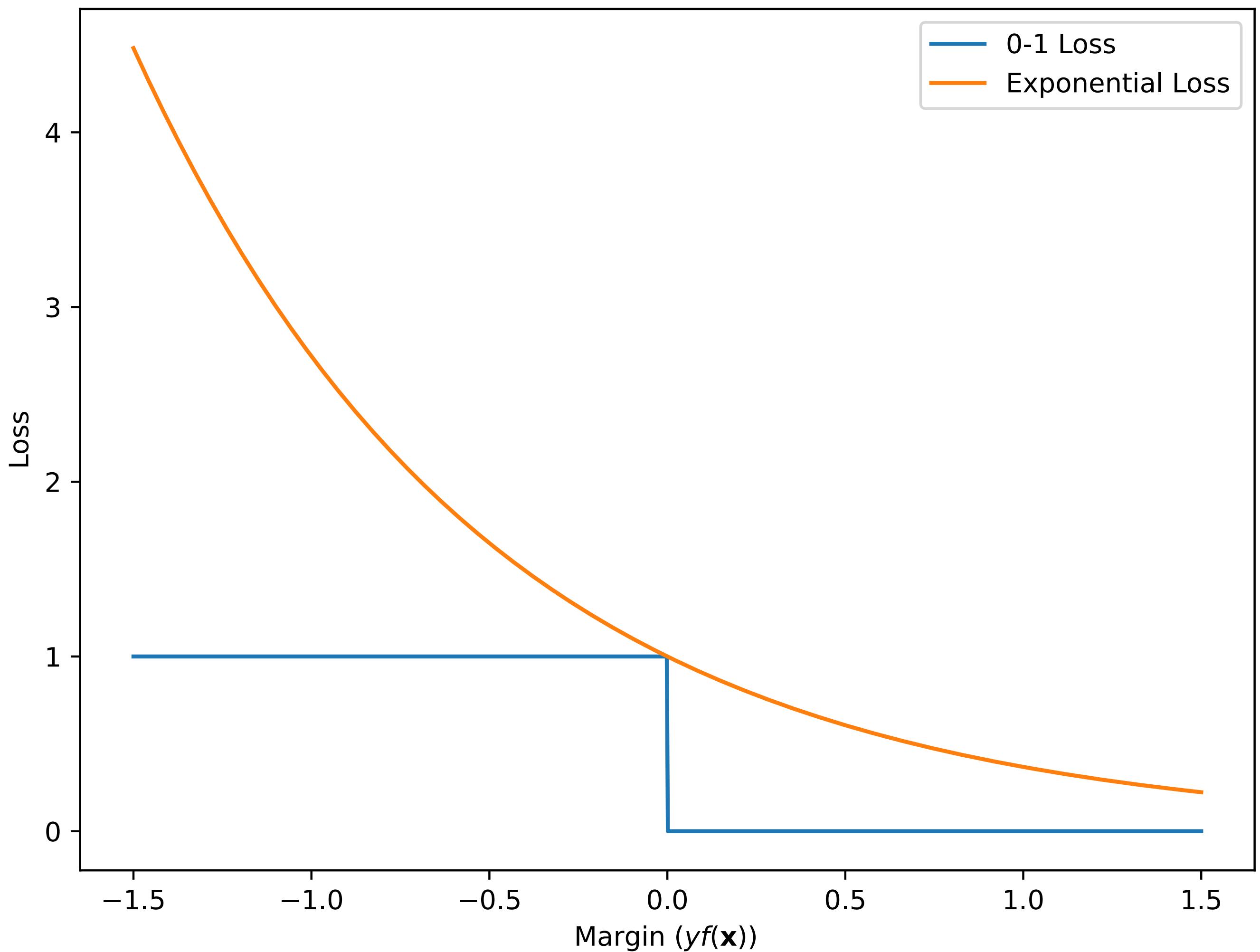
$$\hat{y} = \operatorname{sgn} \sum_{t=1}^k \alpha_t h_t(\mathbf{x}) = \operatorname{sgn} f_k(\mathbf{x})$$

- To minimise the exponential loss

$$L(y, f(\mathbf{x})) = e^{-yf(\mathbf{x})}$$

# Exponential loss

- (Another) smooth proxy for 0-1 loss
- Sensitive to margin
- More negative margin = more firmly wrong = higher loss



# Adding a learner

- Given existing ensemble

$$f_{k-1}(\mathbf{x}) = \sum_{t=1}^{k-1} \alpha_t h_t(\mathbf{x})$$

- Choose optimal weight  $\alpha_k$  and classifier  $h_k$  to add such that

$$\alpha_k, h_k = \operatorname{argmin}_{\alpha, h} \sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))}$$

# Justifying the weights

$$\sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))}$$

# Justifying the weights

$$\sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))}$$

Split sum in exponent to product

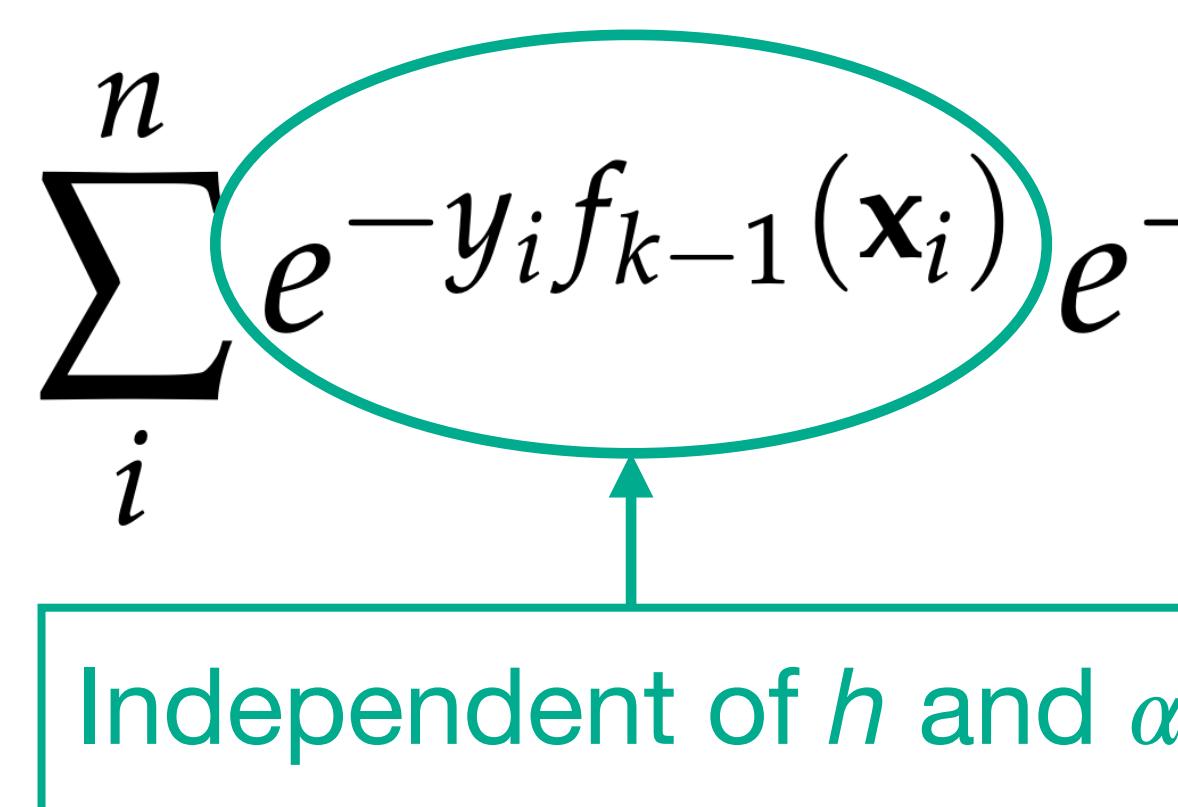
# Justifying the weights

$$\begin{aligned} & \sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))} \\ &= \sum_i^n e^{-y_i f_{k-1}(\mathbf{x}_i)} e^{-y_i \alpha h(\mathbf{x}_i)} \end{aligned}$$

# Justifying the weights

$$\begin{aligned} & \sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))} \\ &= \sum_i^n e^{-y_i f_{k-1}(\mathbf{x}_i)} e^{-y_i \alpha h(\mathbf{x}_i)} \end{aligned}$$

Independent of  $h$  and  $\alpha$



# Justifying the weights

$$\begin{aligned} & \sum_i^n e^{-y_i(f_{k-1}(\mathbf{x}_i) + \alpha h(\mathbf{x}_i))} \\ &= \sum_i^n e^{-y_i f_{k-1}(\mathbf{x}_i)} e^{-y_i \alpha h(\mathbf{x}_i)} \\ &= \sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)} \end{aligned}$$

where:  $w_i = e^{-y_i f_{k-1}(\mathbf{x}_i)}$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

Separate the correct  
and incorrect cases  
into separate sums

assume:  $\alpha > 0$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)} \quad \text{assume: } \alpha > 0$$
$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$



Add incorrect cases to  
this sum...

# Optimal classifier

$$\begin{aligned} & \sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)} \\ &= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i \end{aligned}$$

...and subtract the same weight from those same cases in this sum



# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$

$$= e^{-\alpha} \sum_1^n w_i + (e^{\alpha} - e^{-\alpha}) \sum_i^n w_i \mathbf{1}(y_i \neq h(\mathbf{x}_i))$$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$

$$= e^{-\alpha} \sum_1^n w_i + (e^{\alpha} - e^{-\alpha}) \sum_i^n w_i \mathbf{1}(y_i \neq h(\mathbf{x}_i))$$

Don't depend on  $h$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$

$$= e^{-\alpha} \sum_1^n w_i + (e^{\alpha} - e^{-\alpha}) \sum_i^n w_i \mathbf{1}(y_i \neq h(\mathbf{x}_i))$$

$$h_k = \operatorname{argmin}_h \sum_i^n w_i \mathbf{1}(y_i \neq h_k(\mathbf{x}))$$

# Optimal classifier

$$\sum_i^n w_i e^{-y_i \alpha h(\mathbf{x}_i)}$$

assume:  $\alpha > 0$

$$= e^{-\alpha} \sum_{y_i=h(\mathbf{x}_i)} w_i + e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i$$

$$= e^{-\alpha} \sum_1^n w_i + (e^{\alpha} - e^{-\alpha}) \sum_i^n w_i \mathbf{1}(y_i \neq h(\mathbf{x}_i))$$

$$h_k = \operatorname{argmin}_h \sum_i^n w_i \mathbf{1}(y_i \neq h_k(\mathbf{x}))$$

ie: optimal classifier is just  
the one that minimises  
the weighted error

# Optimal prediction weight

$$\alpha_k = \operatorname{argmin}_{\alpha} e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i + e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

# Optimal prediction weight

$$\alpha_k = \operatorname{argmin}_{\alpha} e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i + e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

Differentiate and set to zero

# Optimal prediction weight

$$\alpha_k = \operatorname{argmin}_{\alpha} e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i + e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

$$\frac{d(\dots)}{d\alpha} = e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i - e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i = 0$$

# Optimal prediction weight

$$\alpha_k = \operatorname{argmin}_{\alpha} e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i + e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

$$\frac{d(\dots)}{d\alpha} = e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i - e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i = 0$$

$$e^{\alpha_k} \sum_{y_i \neq h(\mathbf{x}_i)} w_i = e^{-\alpha_k} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

# Optimal prediction weight

$$\alpha_k = \operatorname{argmin}_{\alpha} e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i + e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

$$\frac{d(\dots)}{d\alpha} = e^{\alpha} \sum_{y_i \neq h(\mathbf{x}_i)} w_i - e^{-\alpha} \sum_{y_i = h(\mathbf{x}_i)} w_i = 0$$

$$e^{\alpha_k} \sum_{y_i \neq h(\mathbf{x}_i)} w_i = e^{-\alpha_k} \sum_{y_i = h(\mathbf{x}_i)} w_i$$

Take log of both sides

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

$$2\alpha_k = \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right) - \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = \log \left( \frac{\sum_{y_i = h(\mathbf{x}_i)} w_i}{\sum_{y_i \neq h(\mathbf{x}_i)} w_i} \right)$$

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

$$2\alpha_k = \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right) - \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = \log \left( \frac{\sum_{y_i = h(\mathbf{x}_i)} w_i}{\sum_{y_i \neq h(\mathbf{x}_i)} w_i} \right)$$

Denominator is just the weighted error rate,  $\epsilon$

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

Weights sum to 1, so  
so numerator is  $1 - \epsilon$

$$2\alpha_k = \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right) - \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = \log \left( \frac{\sum_{y_i = h(\mathbf{x}_i)} w_i}{\sum_{y_i \neq h(\mathbf{x}_i)} w_i} \right)$$

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

$$2\alpha_k = \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right) - \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = \log \left( \frac{\sum_{y_i = h(\mathbf{x}_i)} w_i}{\sum_{y_i \neq h(\mathbf{x}_i)} w_i} \right)$$

$$\alpha_k = \frac{1}{2} \log \left( \frac{1 - \epsilon}{\epsilon} \right)$$

# Optimal prediction weight

$$\alpha_k + \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = -\alpha_k + \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right)$$

$$2\alpha_k = \log \left( \sum_{y_i = h(\mathbf{x}_i)} w_i \right) - \log \left( \sum_{y_i \neq h(\mathbf{x}_i)} w_i \right) = \log \left( \frac{\sum_{y_i = h(\mathbf{x}_i)} w_i}{\sum_{y_i \neq h(\mathbf{x}_i)} w_i} \right)$$

$$\alpha_k = \frac{1}{2} \log \left( \frac{1 - \epsilon}{\epsilon} \right)$$

NB: we assumed  $\alpha > 0$ , which requires  $\epsilon < 0.5$   
If learners are less accurate than 50% then  
they will make performance worse

# Notes

- AdaBoost is efficient and easy to use
  - Relatively turnkey — need to choose  $k$ , but not super critical
  - Pruning can improve efficiency and also reduce overfitting
- 
- This concept of taking a weighted sum over classifiers will crop up again when we talk about neural networks
  - Next week we'll see a model that is both linear and non-parametric, which uses basis expansion in new and exciting ways, and which depends crucially on the margin  $y f(\mathbf{x})$