Decision Trees

Emily Fox & Carlos Guestrin
Machine Learning Specialization
University of Washington

Predicting potential loan defaults

What makes a loan risky?

Loan
Application

Credit
★★★★

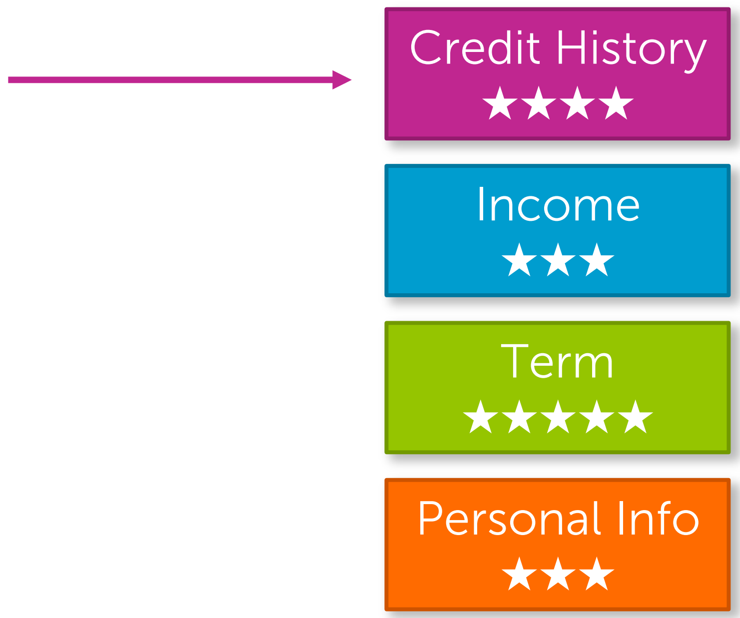
Income
★★★

Term
★★★★★

Personal Info
★★★

Credit history explained

Did I pay previous loans on time?



Example: excellent, good, or fair

Income

What's my income?

Example:
$80K per year

Credit History
★★★★

Income
★★★

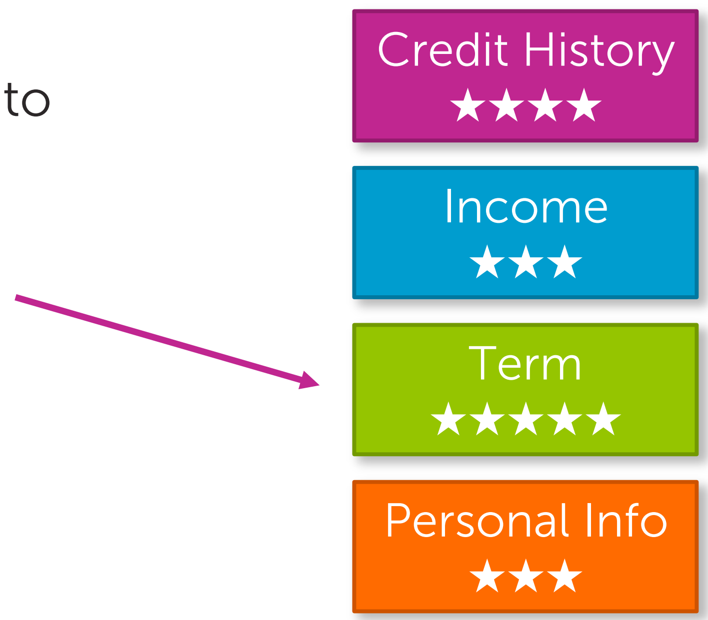
Term
★★★★★

Personal Info
★★★

Loan terms

How soon do I need to pay the loan?

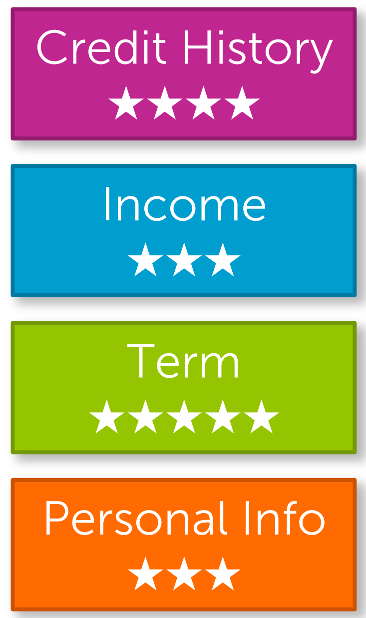
Example: 3 years, 5 years,…



Personal information

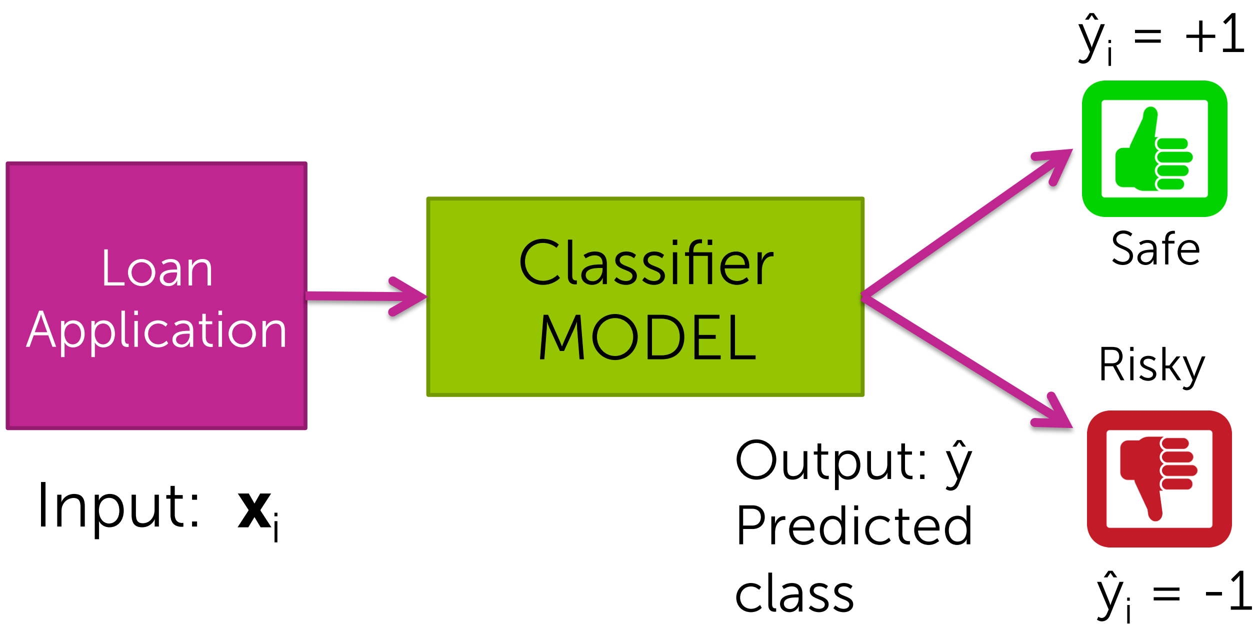
Age, reason for the loan, marital status,…

Example: Home loan for a married couple

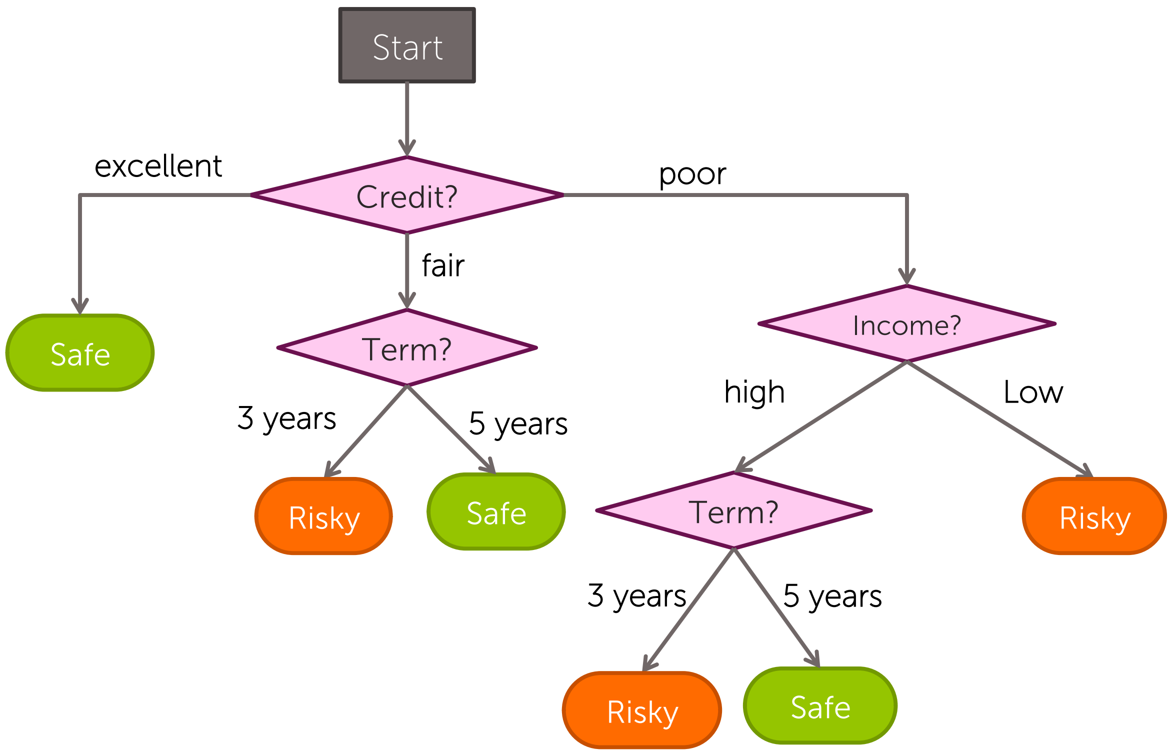


Intelligent application

Classifier review

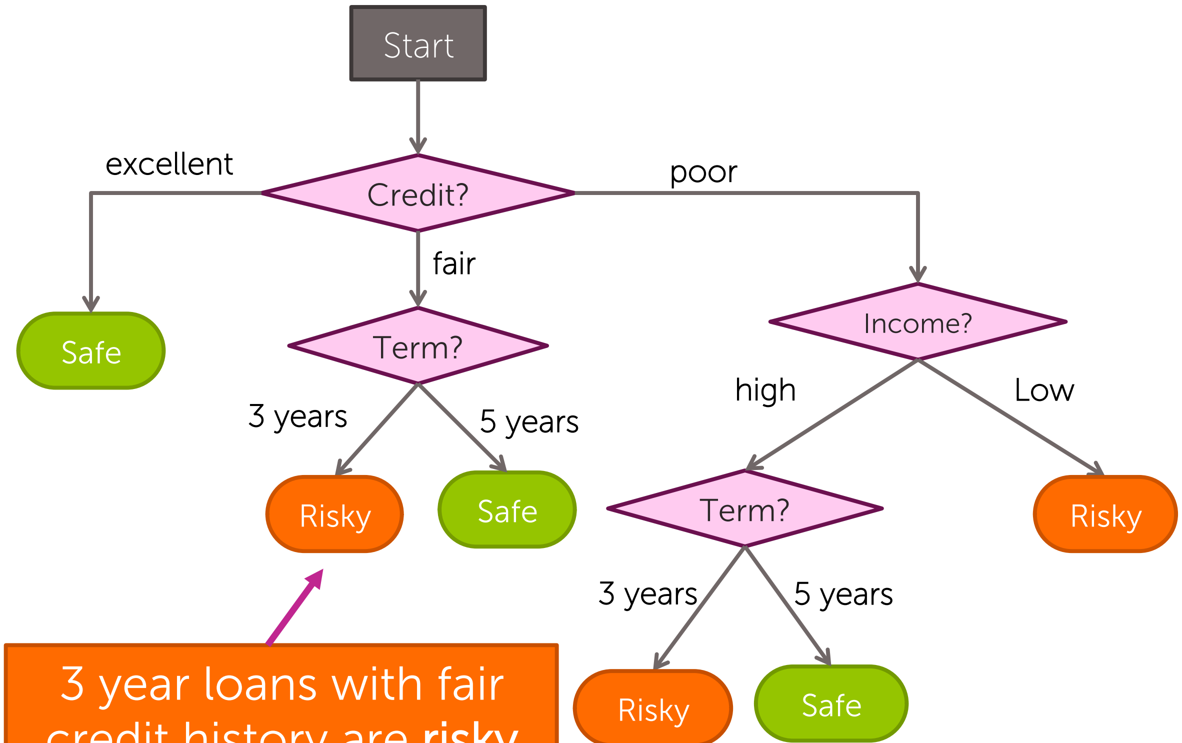


This module ... decision trees



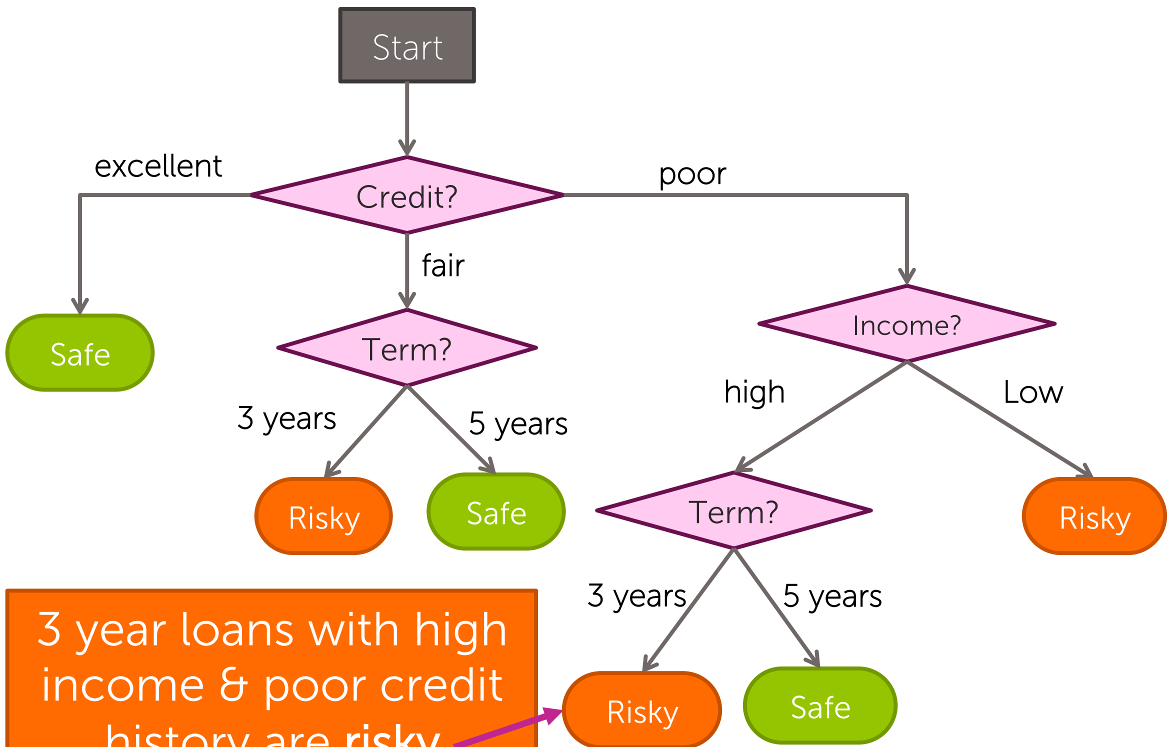
Decision trees: *Intuition*

What does a decision tree represent?



3 year loans with fair credit history are **risky**

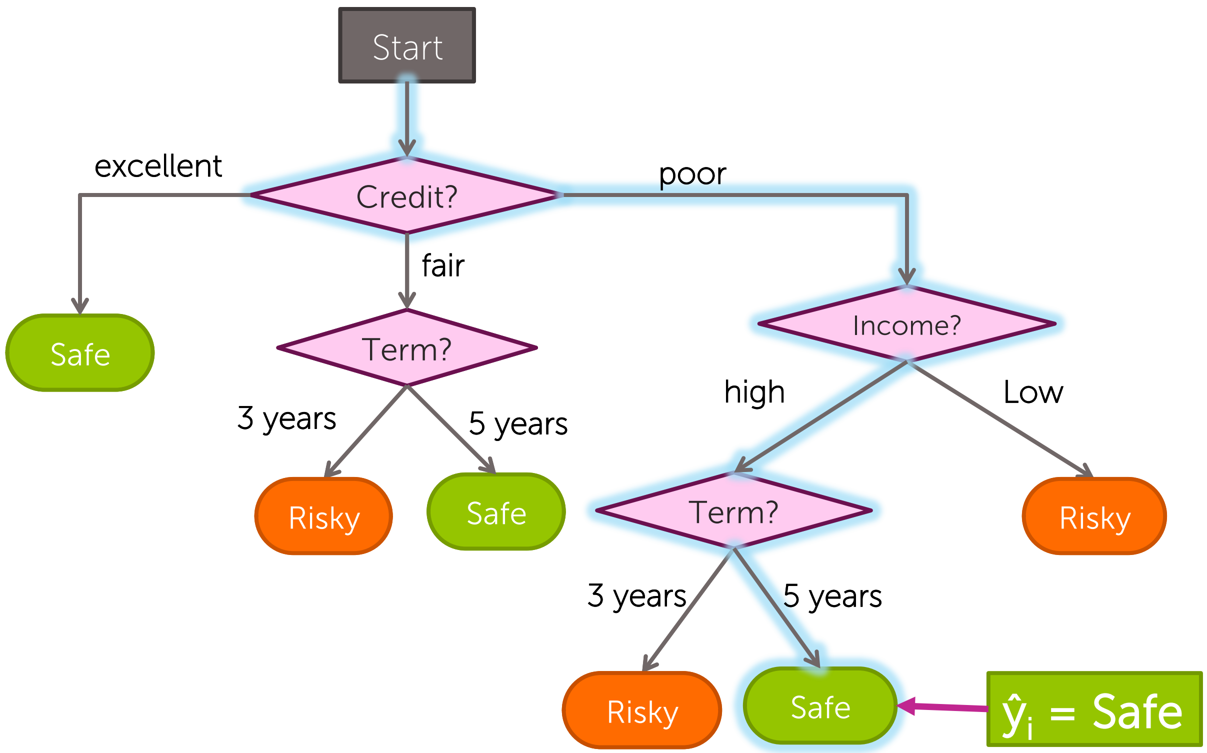
What does a decision tree represent?



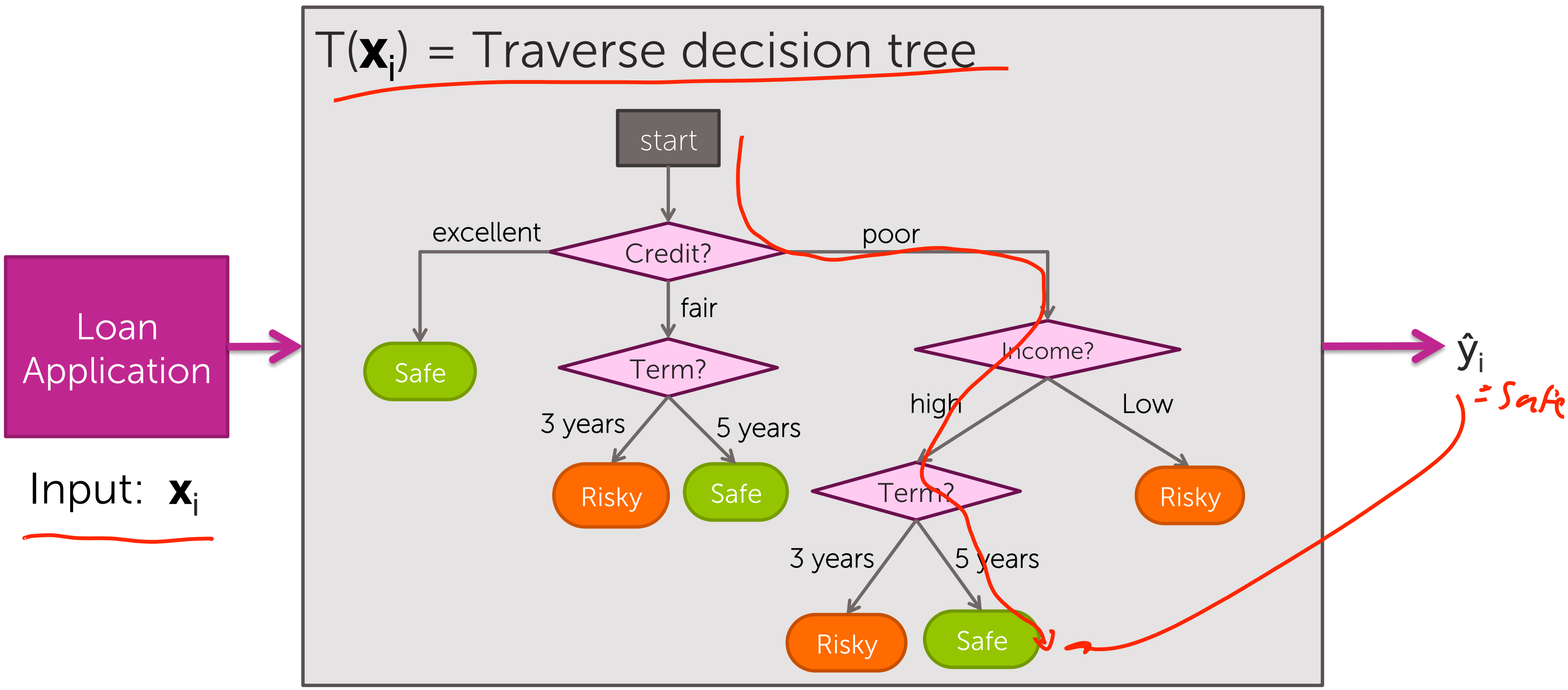
3 year loans with high income & poor credit history are **risky**

Scoring a loan application

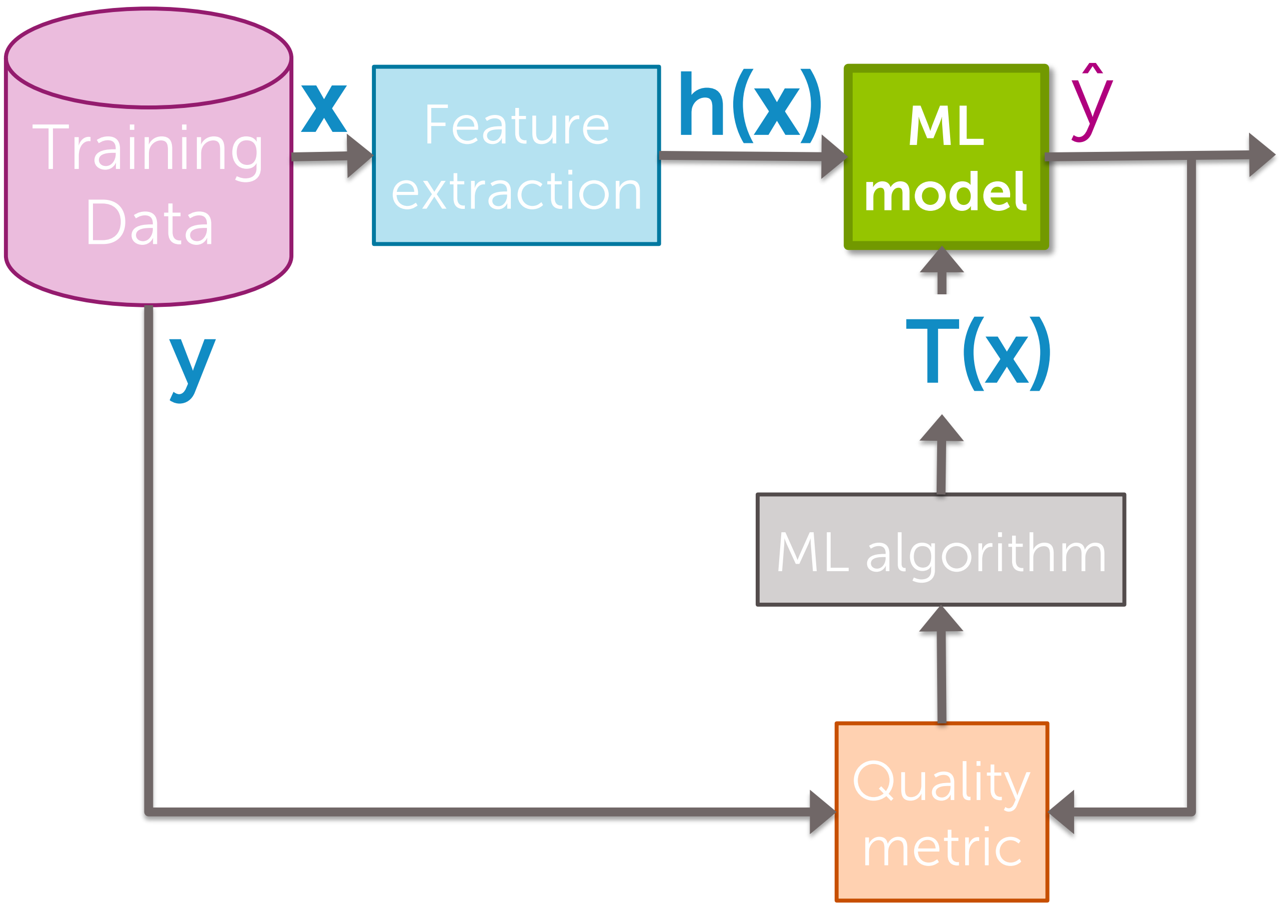
$\mathbf{x}_i$ = (Credit = poor, Income = high, Term = 5 years)



Decision tree model



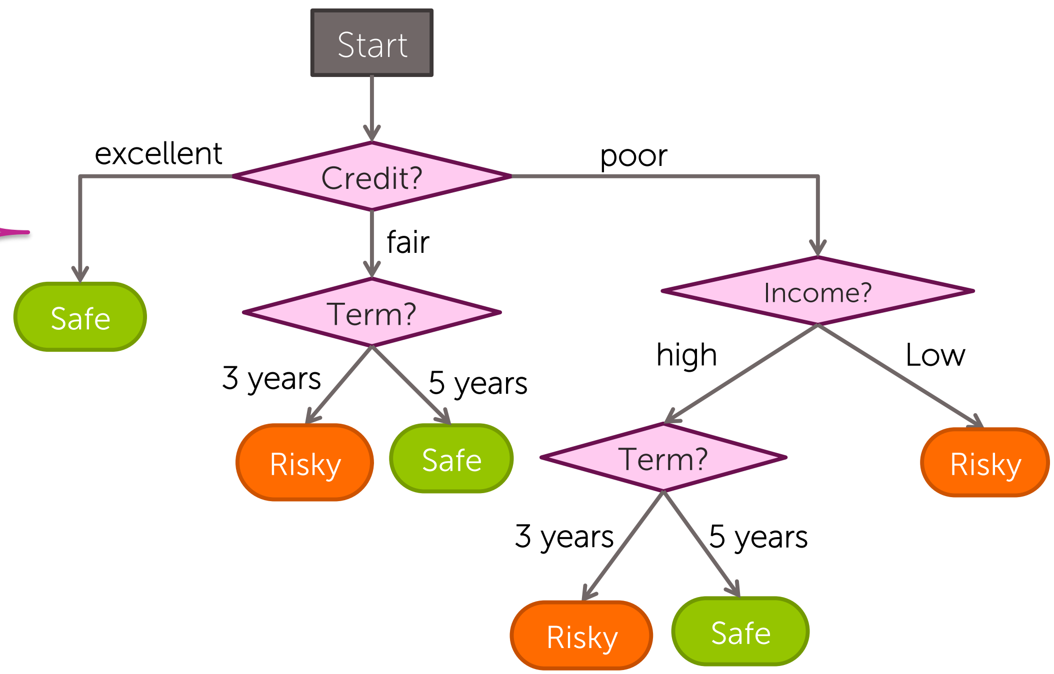
Decision tree learning task


Training Data
x
Feature extraction
h(x)
ML model
ŷ
y
T(x)
ML algorithm
Quality metric

Learn decision tree from data?

$h_1(x)$ $h_2(x)$ $h_3(x)$ Loan Status

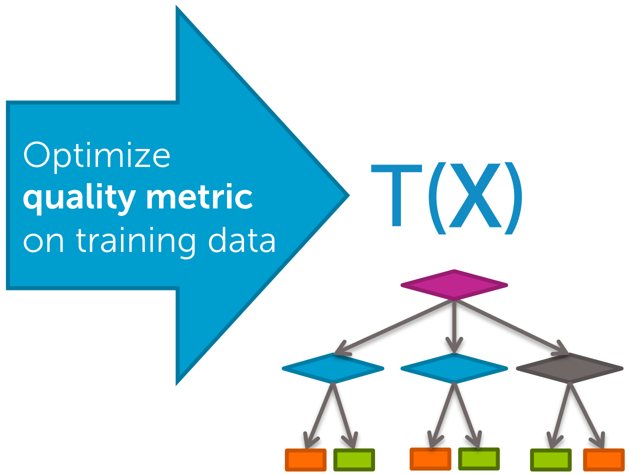
Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe



Decision tree learning problem

Training data: N observations ($\mathbf{x}_i$,y_i)

Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe



Quality metric: Classification error

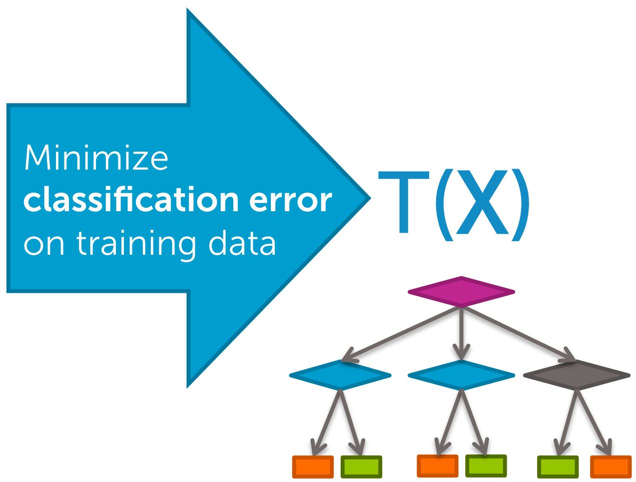
- Error measures fraction of mistakes

$$\text{Error} = \frac{\text{\# incorrect predictions}}{\text{\# examples}}$$

  – Best possible value : 0.0
  – Worst possible value: 1.0

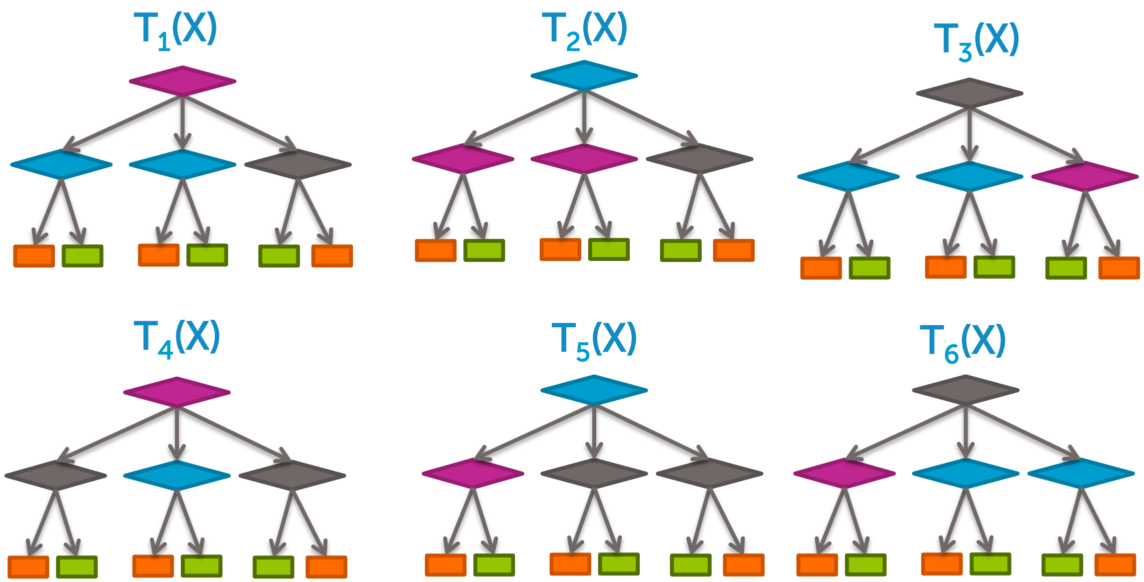
Find the tree with lowest classification error

Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe



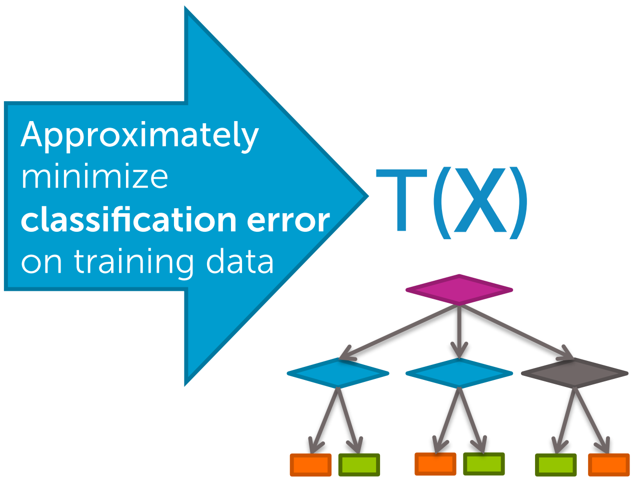
How do we find the best tree?

Exponentially large number of possible trees makes decision tree learning hard! *(NP-hard problem)*



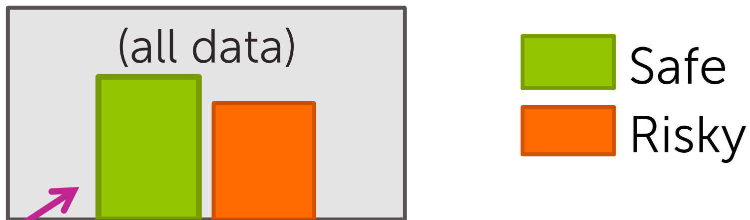
Simple (greedy) algorithm finds "good" tree

Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe



Greedy decision tree learning: *Algorithm outline*

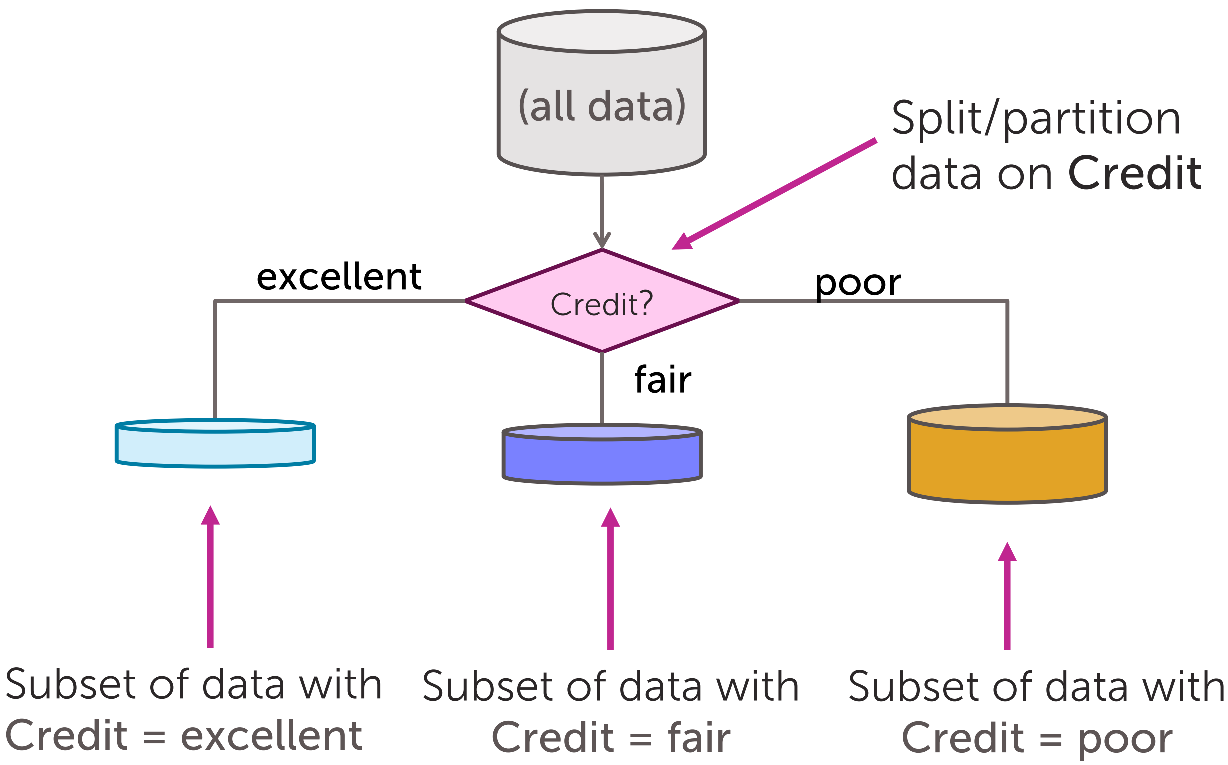
Step 1: Start with an empty tree



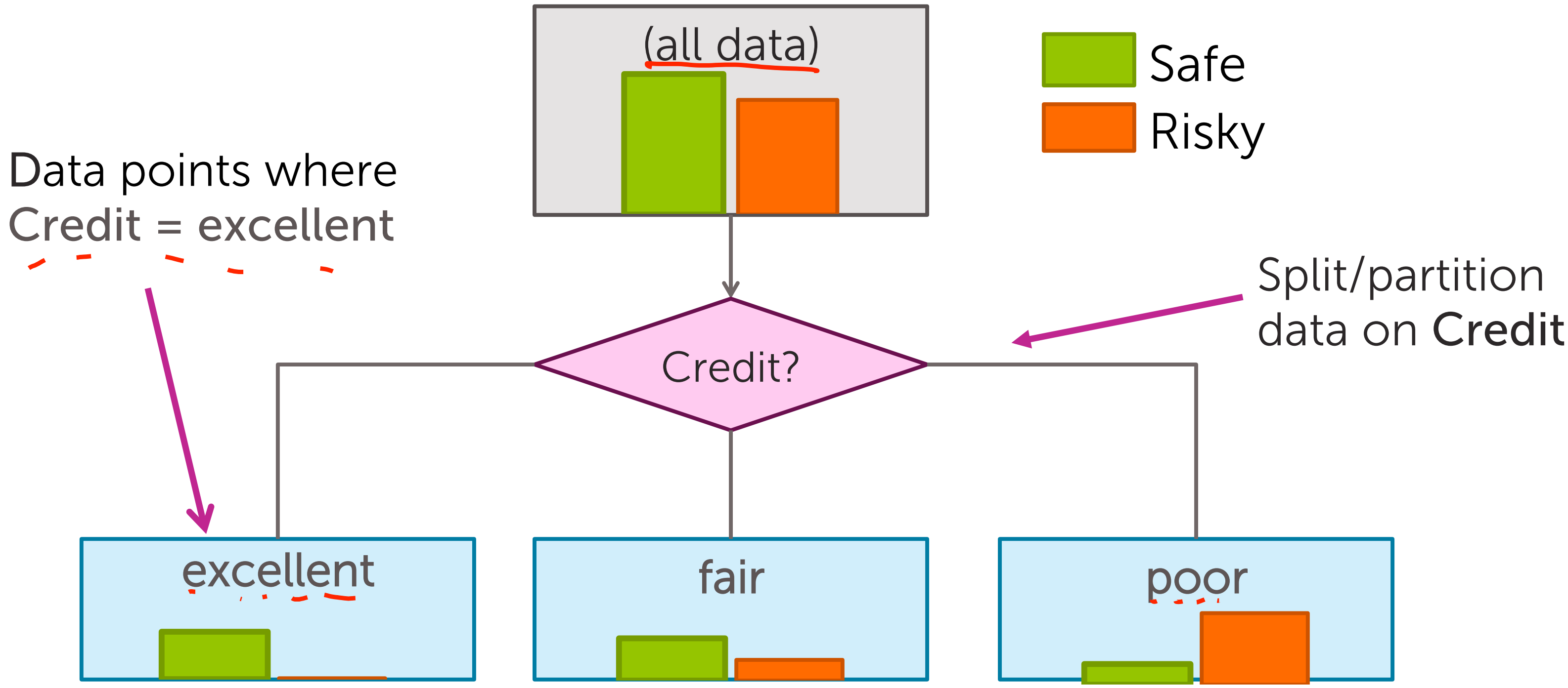
Histogram
of y values

All points in the
dataset

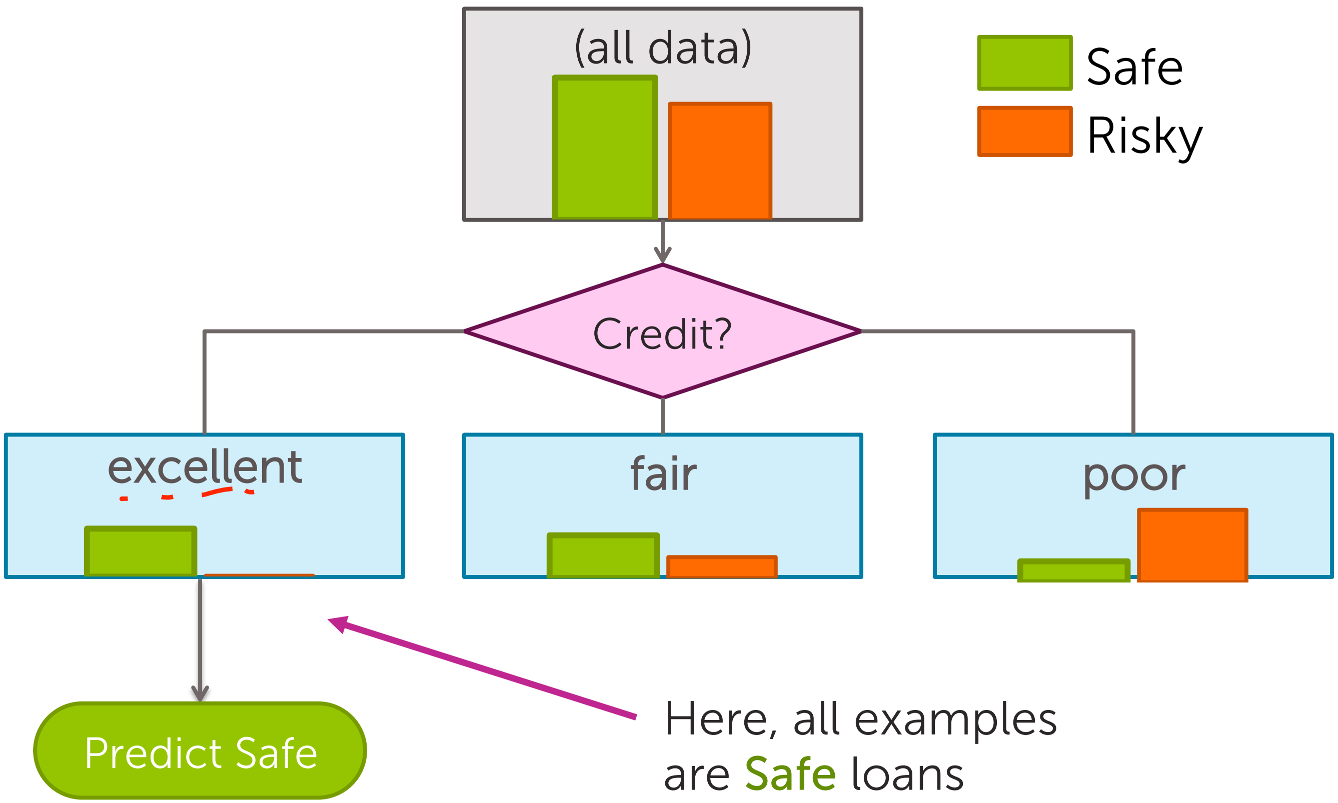
Step 2: Split on a feature



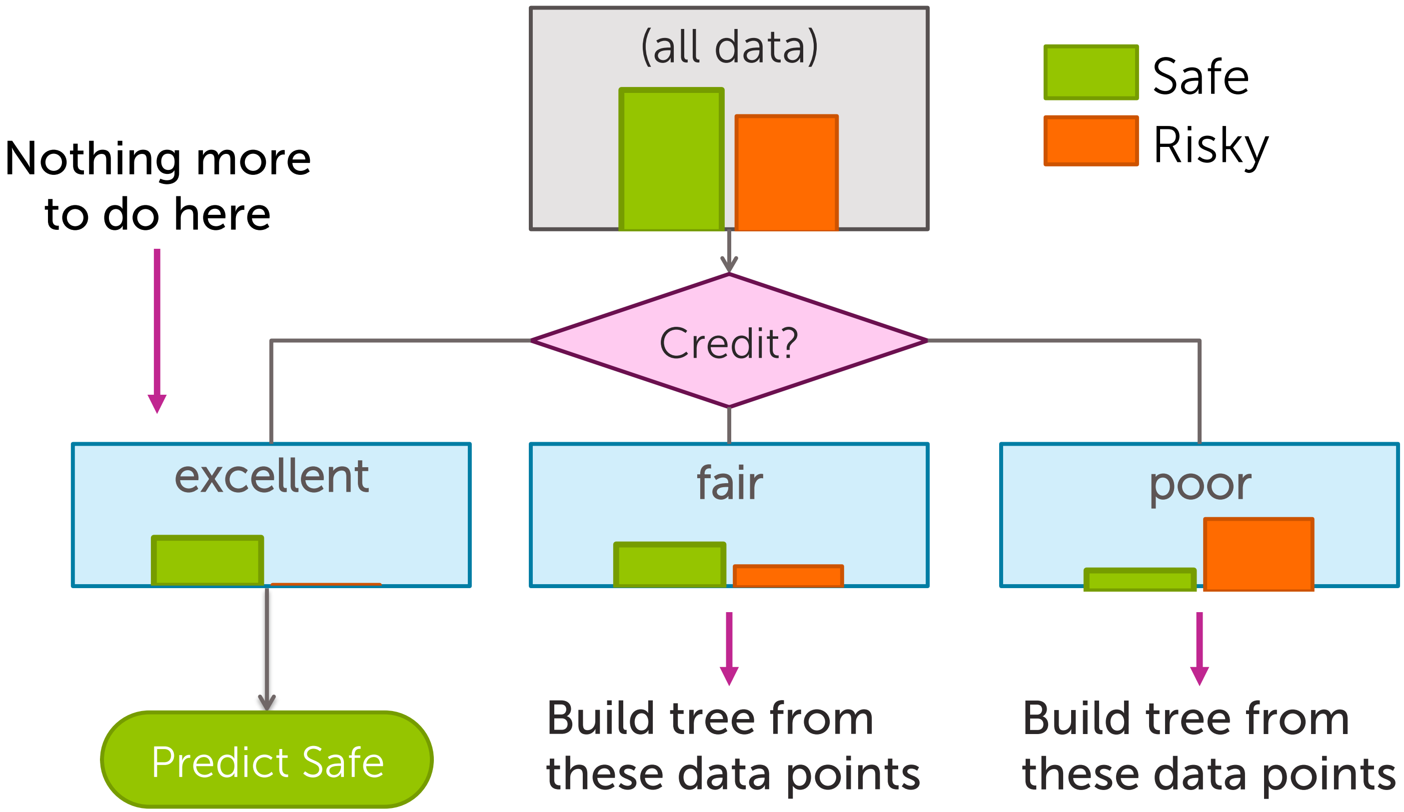
Feature split explained



Step 3: Making predictions



Step 4: Recursion



Greedy decision tree learning

- Step 1: Start with an empty tree
- Step 2: Select a feature to split data
- For each split of the tree:
  - Step 3: If nothing more to, make predictions
  - Step 4: Otherwise, go to Step 2 & continue (recurse) on this split

Problem 1: Feature split selection

Problem 2: Stopping condition

Recursion

Feature split learning

=

Decision stump learning

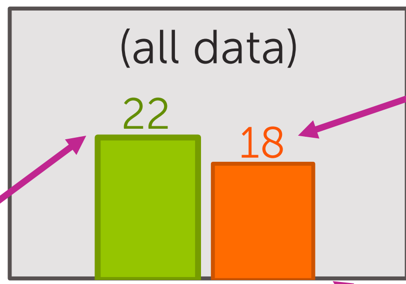
Start with the data

Assume N = 40, 3 features

Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe

Start with all the data

Loan status: Safe Risky

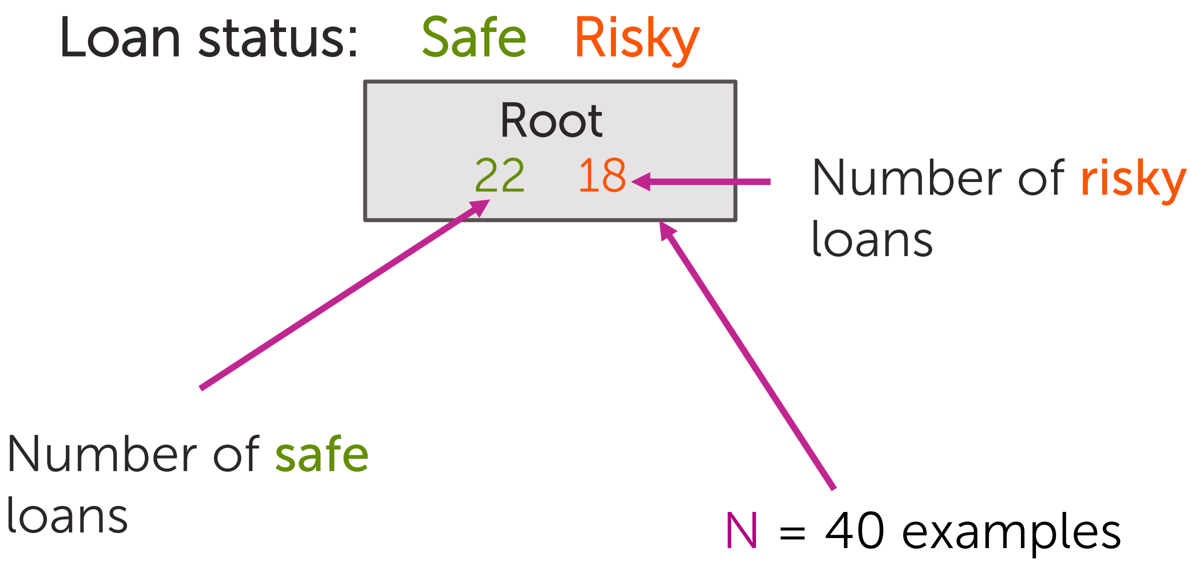


Number of Risky loans

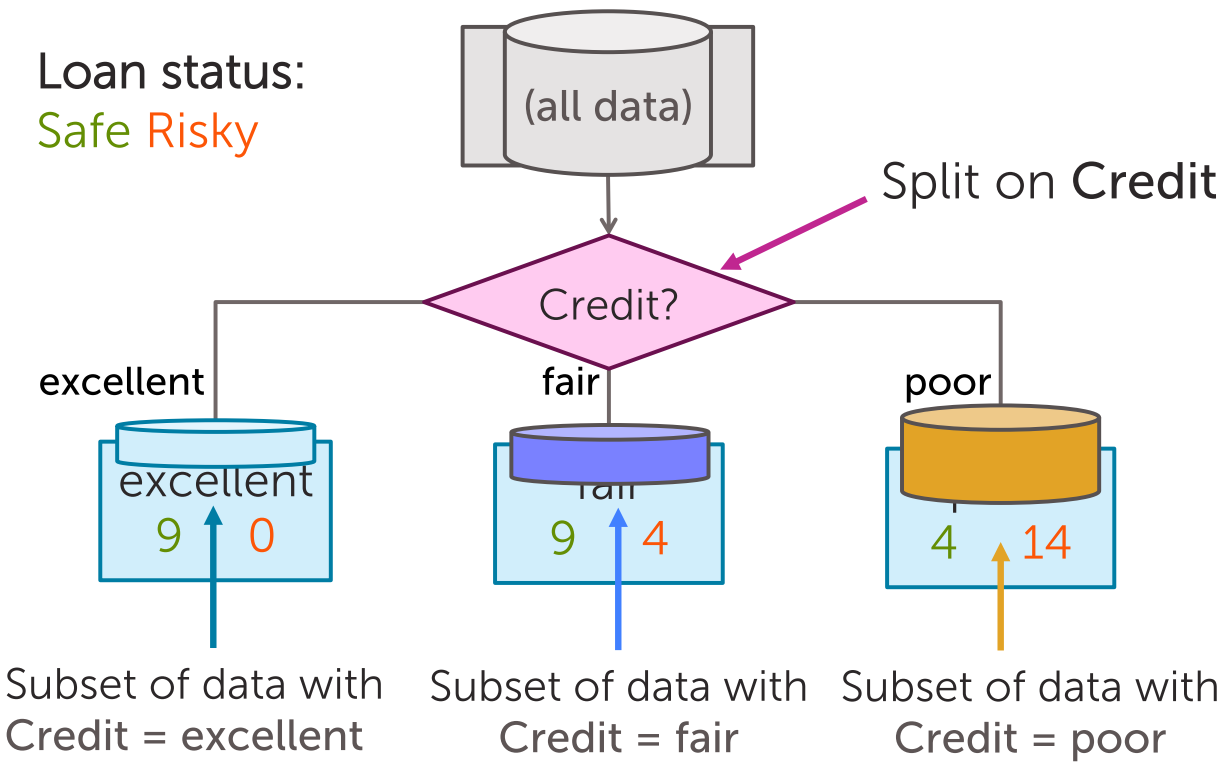
Number of Safe loans

N = 40 examples

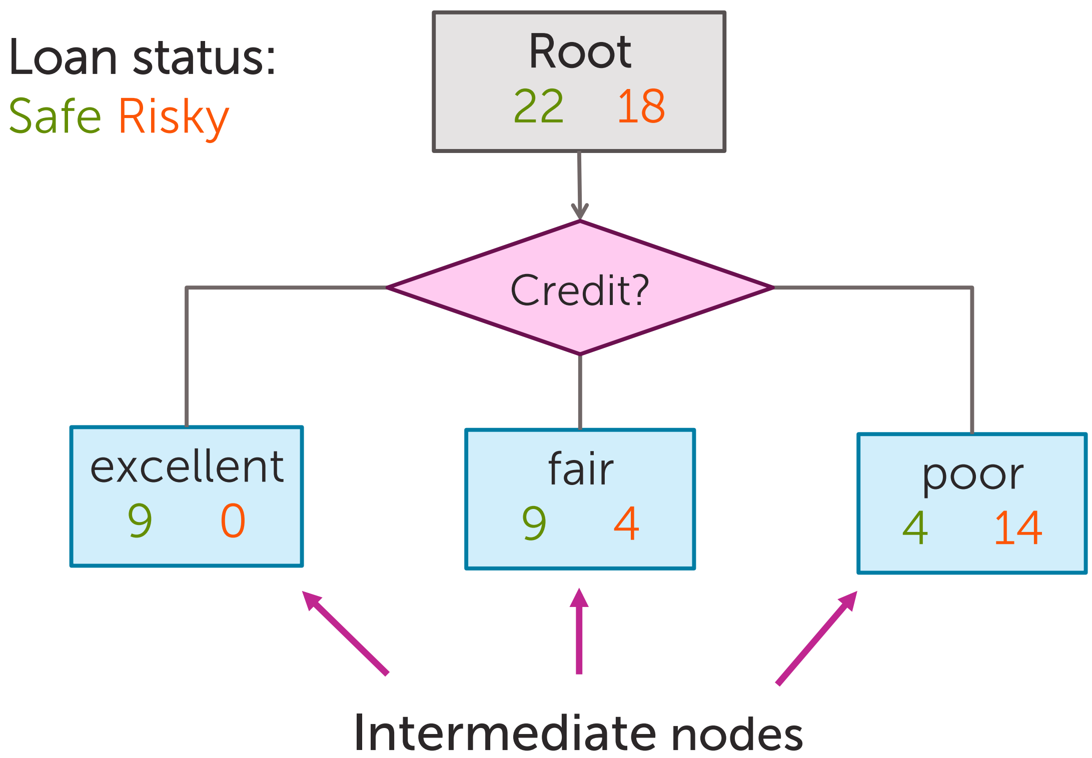
Compact visual notation: Root node



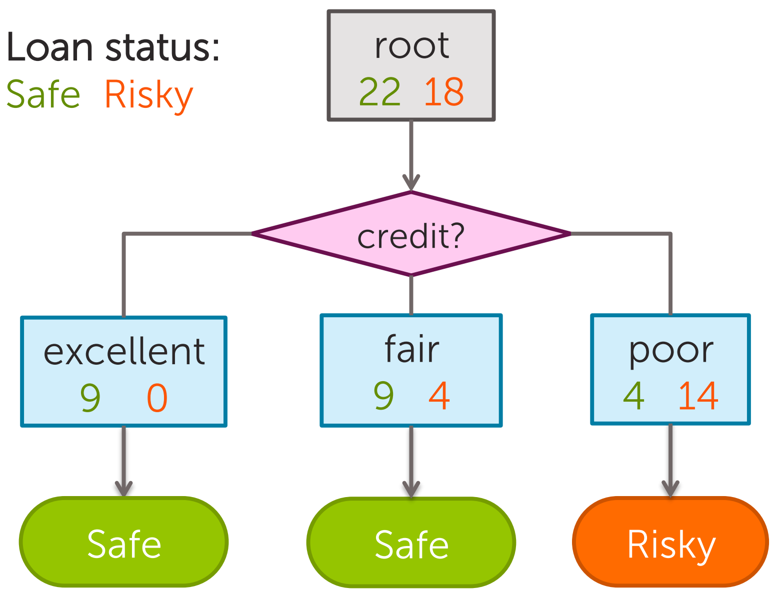
Decision stump: Single level tree



Visual Notation: Intermediate nodes



Making predictions with a decision stump

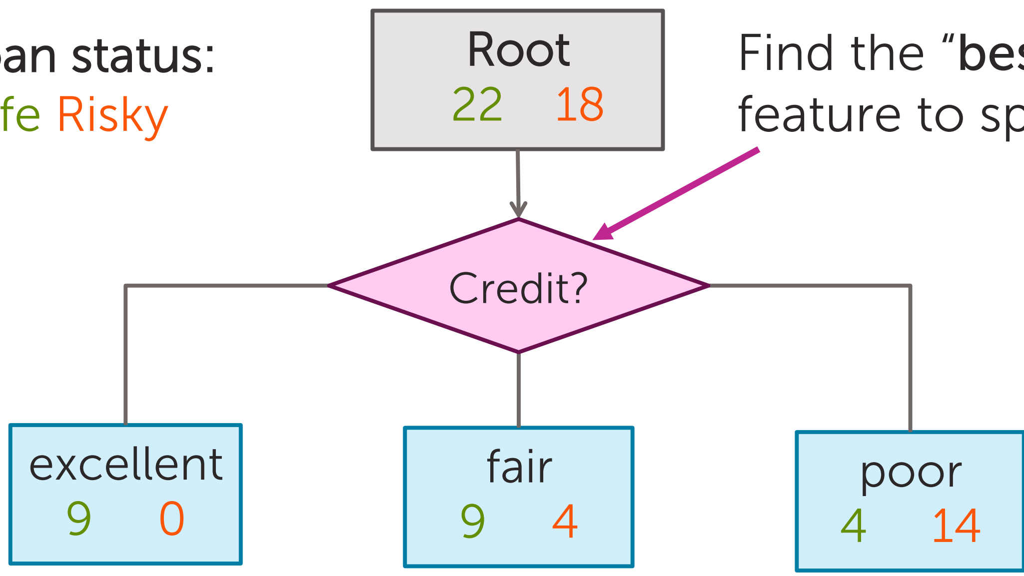


For each intermediate node,
set ŷ = **majority value**

Selecting best feature to split on

How do we learn a decision stump?

Loan status:
Safe Risky

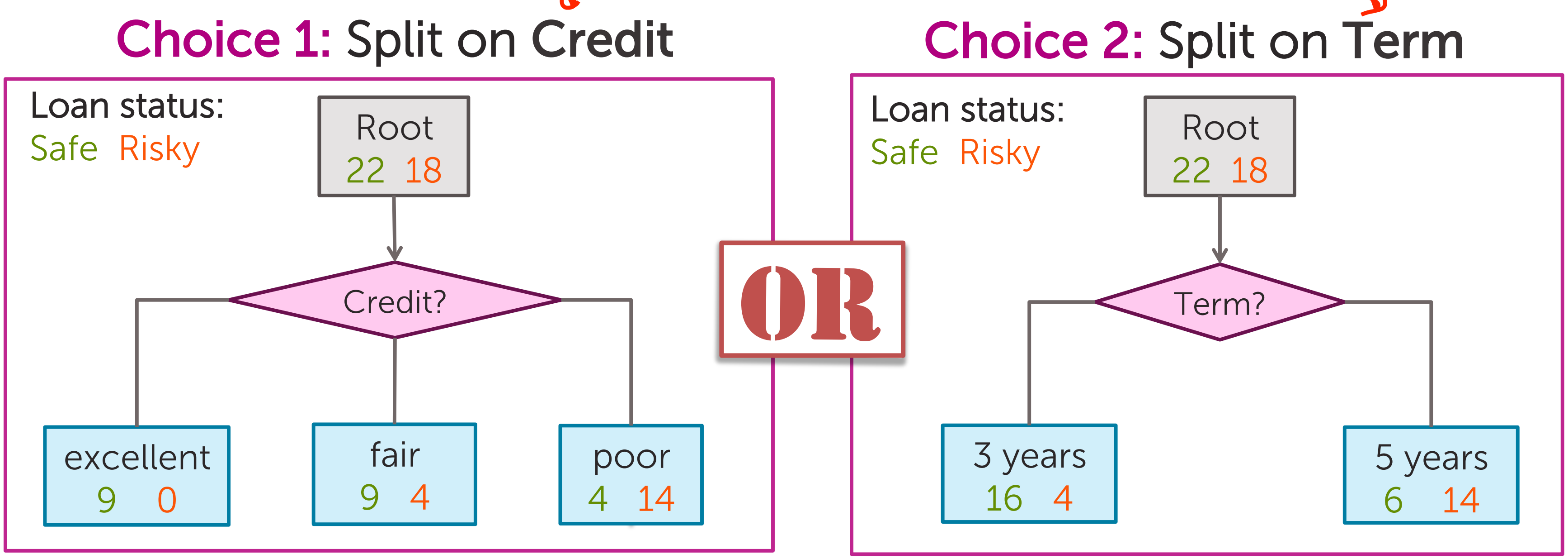


Find the "**best**" feature to split on!

How do we select the best feature?

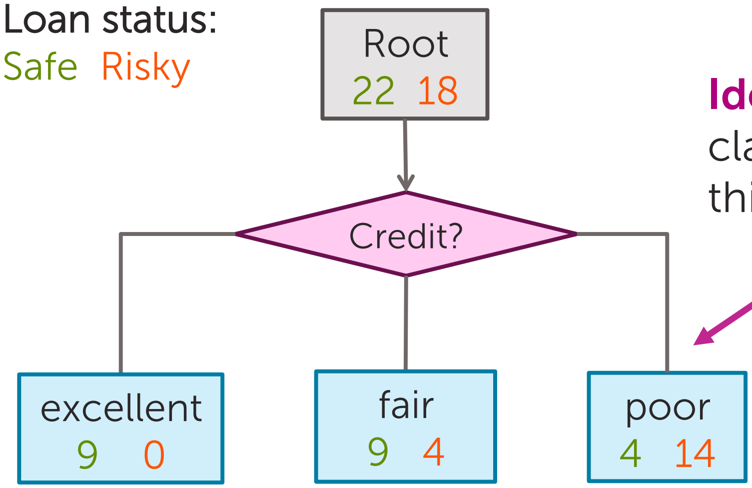
Intuitively, a better split is one that gives you lowest classification error.

Better?



How do we measure effectiveness of a split?

Loan status:
Safe Risky

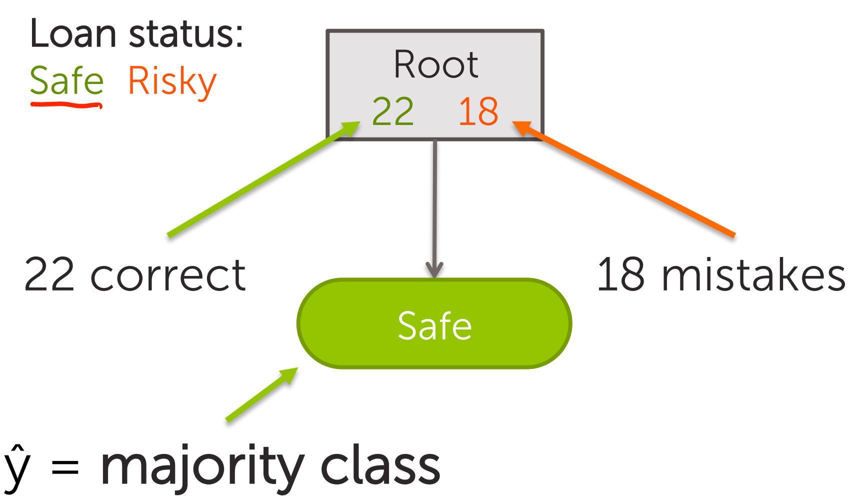


Idea: Calculate classification error of this decision stump

$$\text{Error} = \frac{\text{\# mistakes}}{\text{\# data points}}$$

Calculating classification error

- **Step 1:** $\hat{y}$ = class of majority of data in node
- **Step 2:** Calculate classification error of predicting $\hat{y}$ for this data

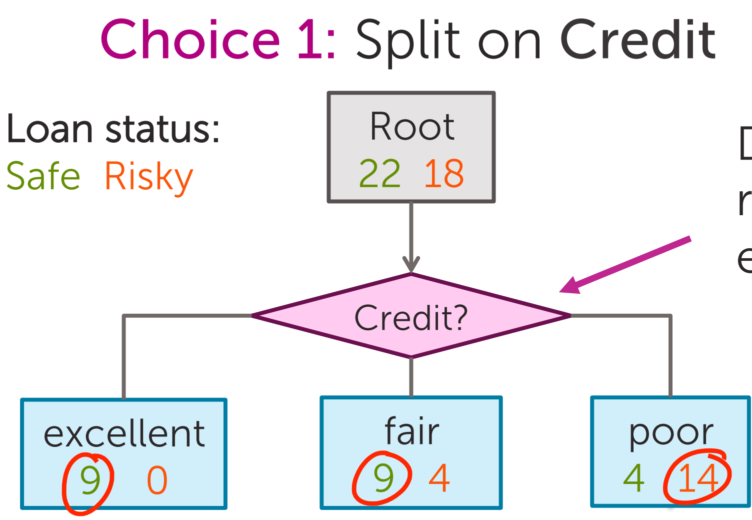


$$\text{Error} = \frac{18}{22+18}$$

$$= 0.45$$

Tree	Classification error
(root)	0.45

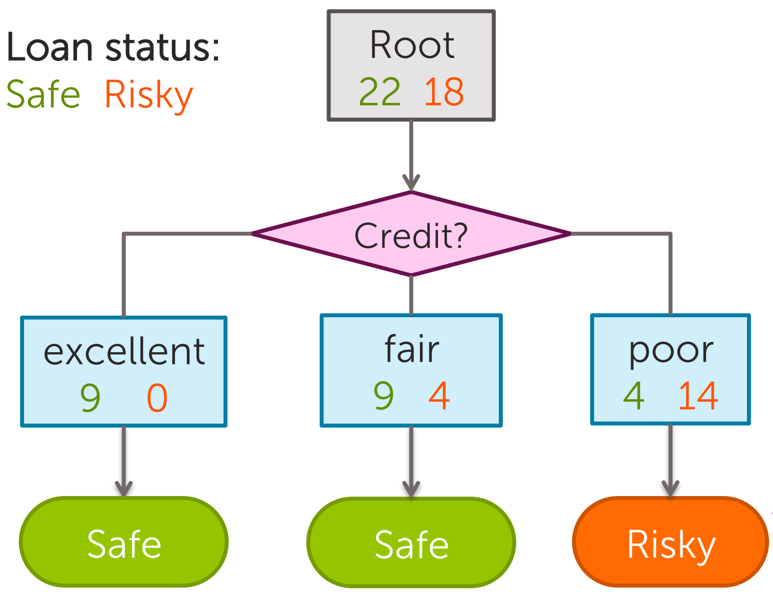
Choice 1: Split on **credit history?**



Does a split on Credit reduce classification error below 0.45?

How good is the split on **Credit?**

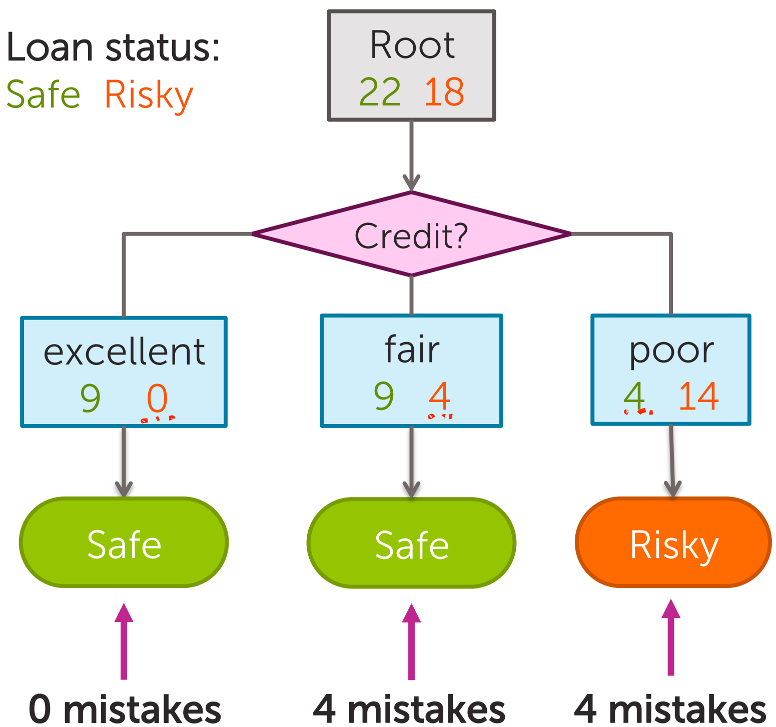
Choice 1: Split on **Credit**



Step 1: For each intermediate node, set ŷ = **majority value**

Split on **Credit**: Classification error

Choice 1: Split on **Credit**

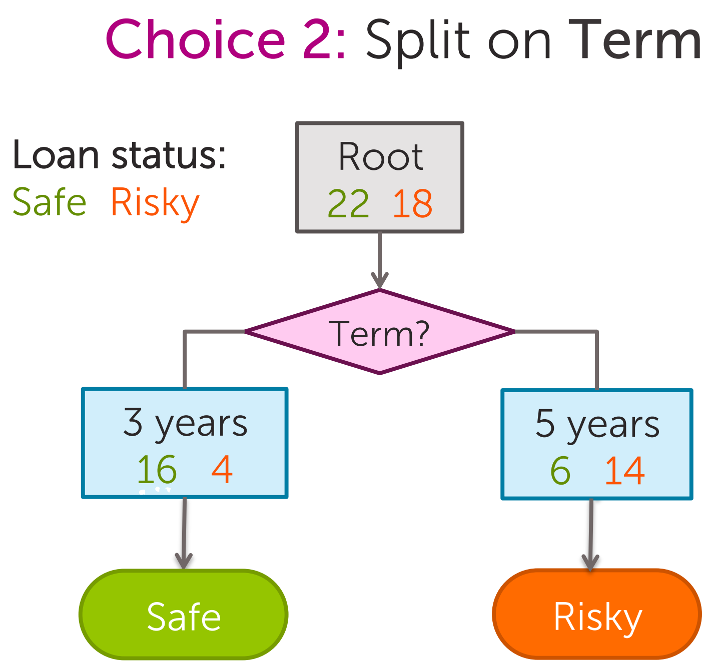


$$\text{Error} = \frac{4+4}{40}$$

$$= 0.20$$

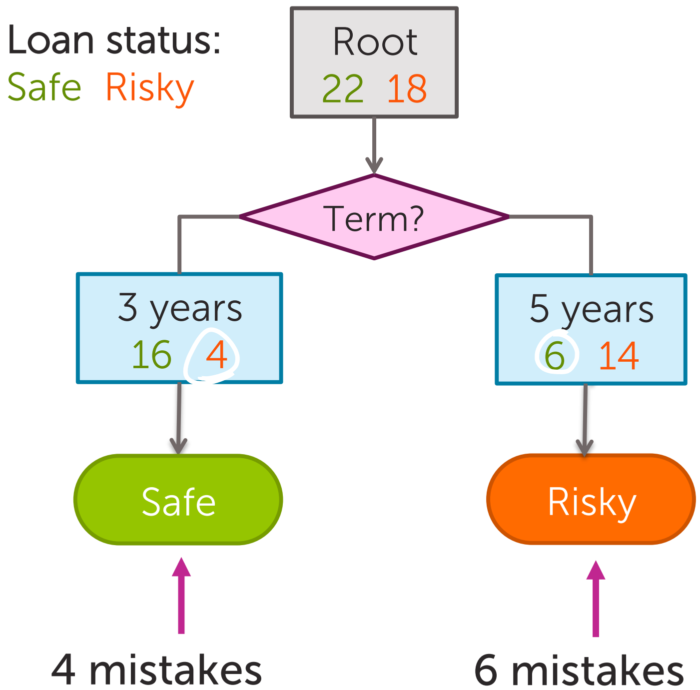
Tree	Classification error
(root)	0.45
Split on **credit**	0.2

Choice 2: Split on **Term**?



Evaluating the split on Term

Choice 2: Split on **Term**



$$\text{Error} = \frac{4+6}{40}$$

$$= 0.25$$

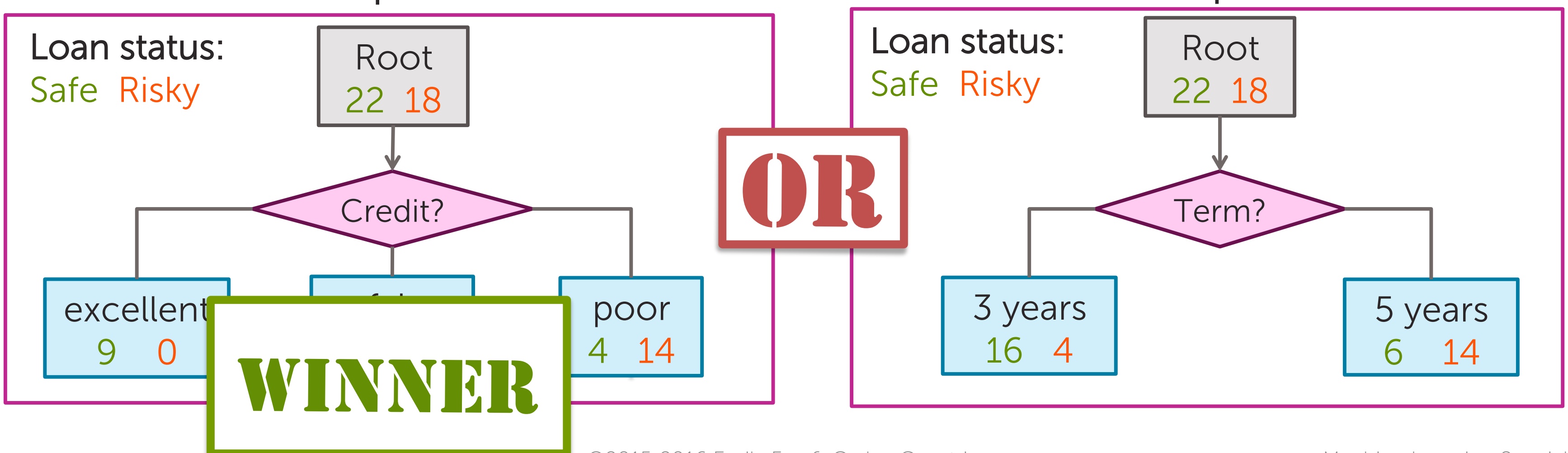
Tree	Classification error
(root)	0.45
Split on **credit**	0.2
Split on **term**	0.25

Choice 1 vs Choice 2

Tree	Classification error
(root)	0.45
split on **credit**	0.2
split on **loan term**	0.25

First split!

Choice 1: Split on **Credit** | Choice 2: Split on **Term**



Feature split selection algorithm

- Given a subset of data M (a node in a tree)
- For each feature $h_i(x)$: credit, term, income
  1. Split data of M according to feature $h_i(x)$
  2. Compute classification error split
- Chose feature $h^*(x)$ with lowest classification error credit

Greedy decision tree learning

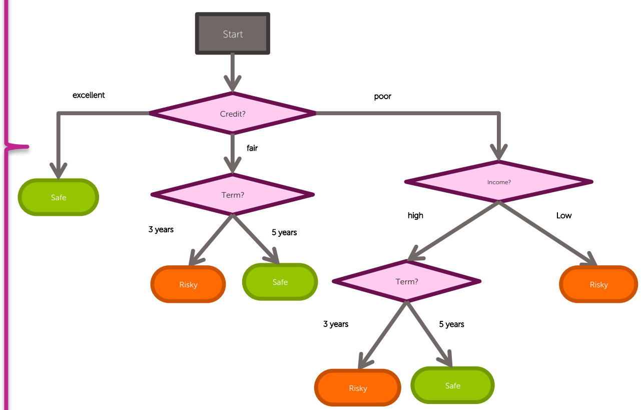
- Step 1: Start with an empty tree
- Step 2: Select a feature to split data
- For each split of the tree:
  - Step 3: If nothing more to, make predictions
  - Step 4: Otherwise, go to Step 2 & continue (recurse) on this split

Pick feature split leading to lowest classification error

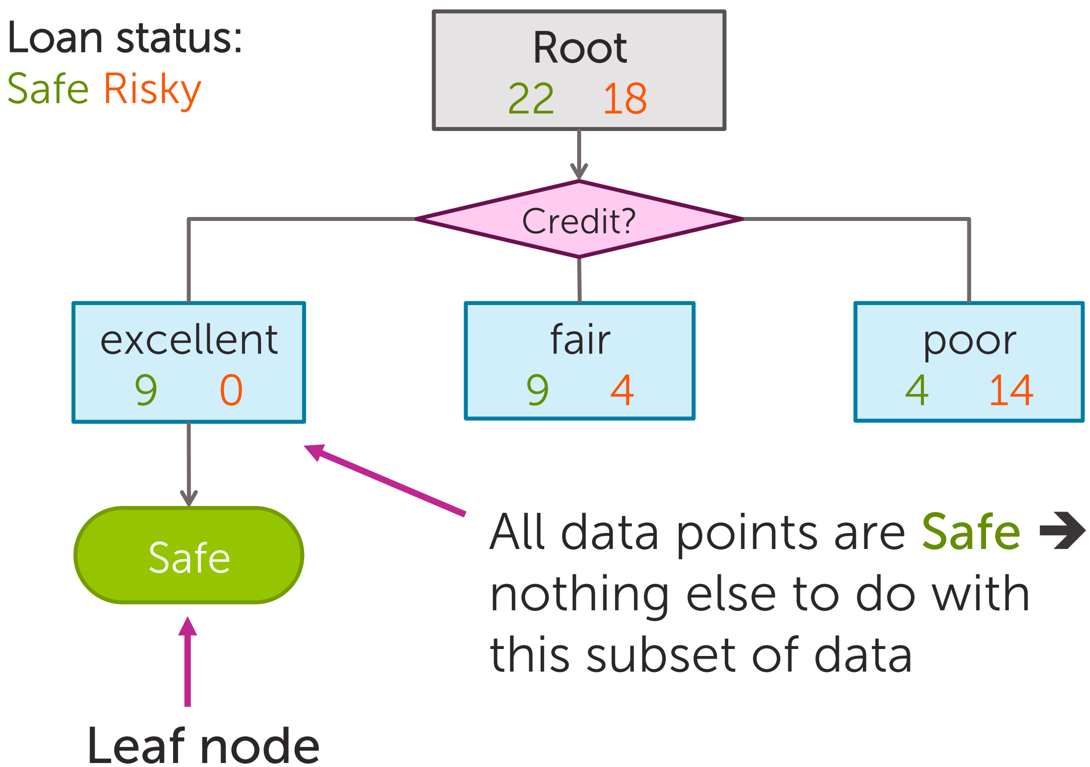
Decision Tree Learning:
Recursion & Stopping conditions

Learn decision tree from data?

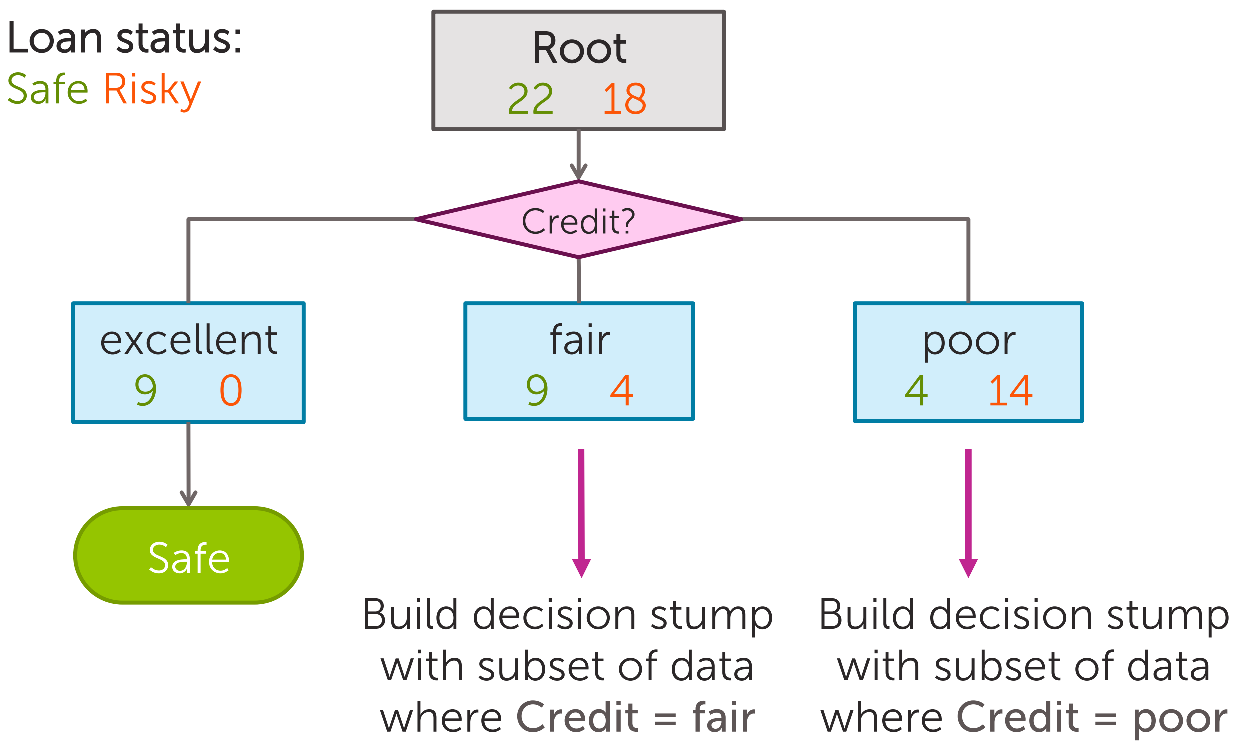
Credit	Term	Income	y
excellent	3 yrs	high	safe
fair	5 yrs	low	risky
fair	3 yrs	high	safe
poor	5 yrs	high	risky
excellent	3 yrs	low	risky
fair	5 yrs	low	safe
poor	3 yrs	high	risky
poor	5 yrs	low	safe
fair	3 yrs	high	safe



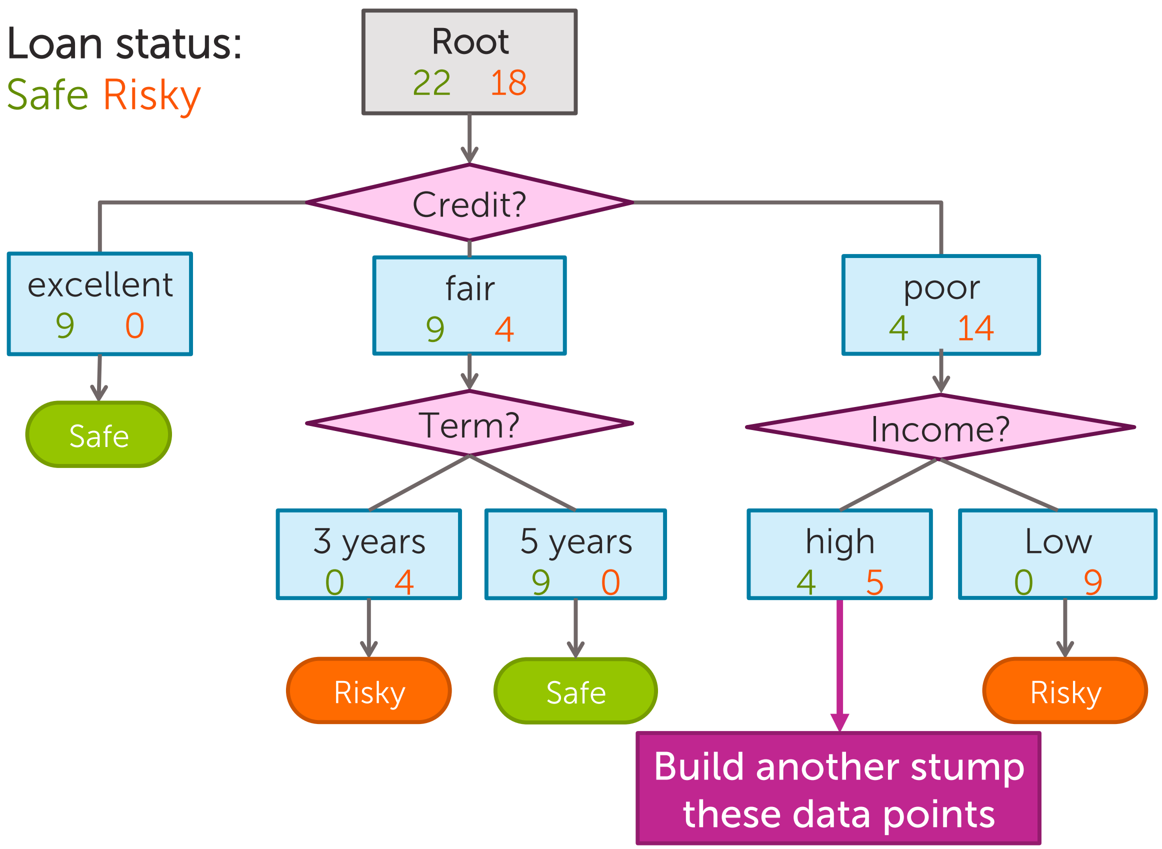
We've learned a decision stump, what next?



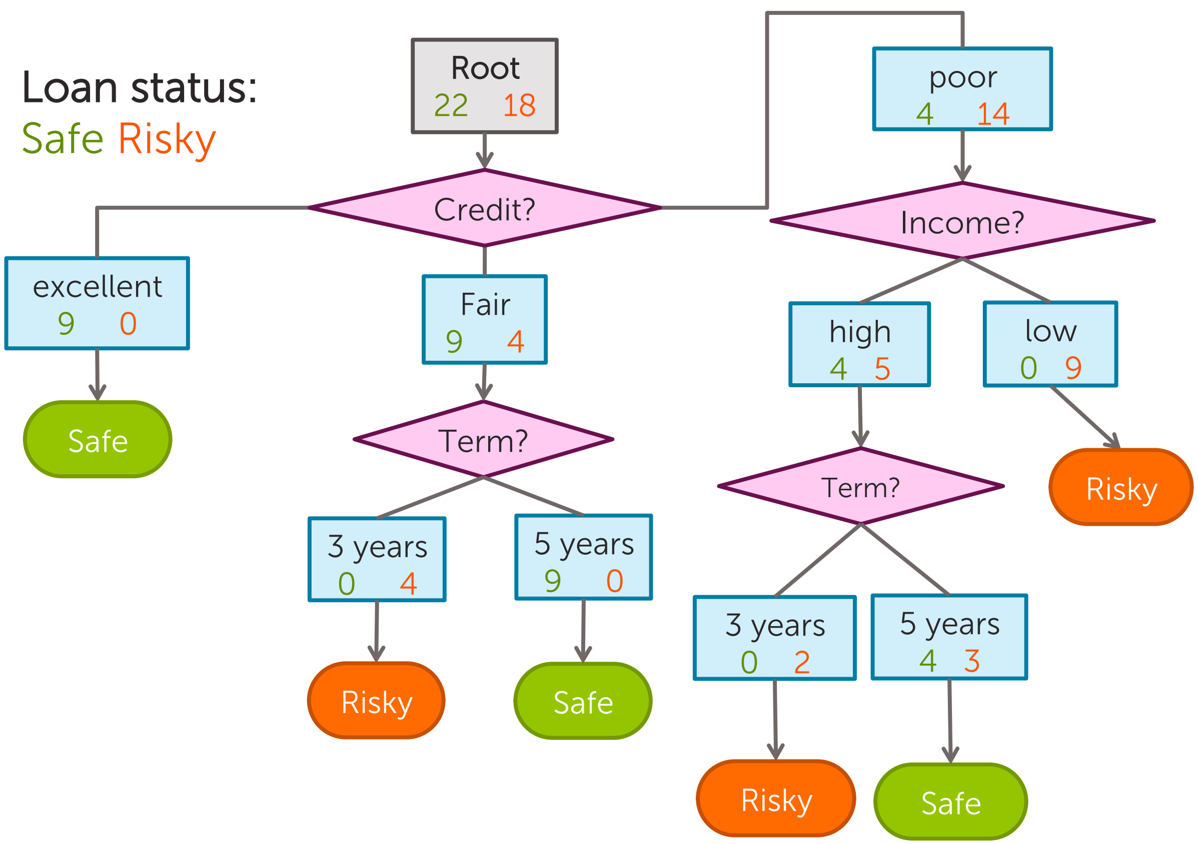
Tree learning = Recursive stump learning



Second level



Final decision tree



Simple greedy decision tree learning

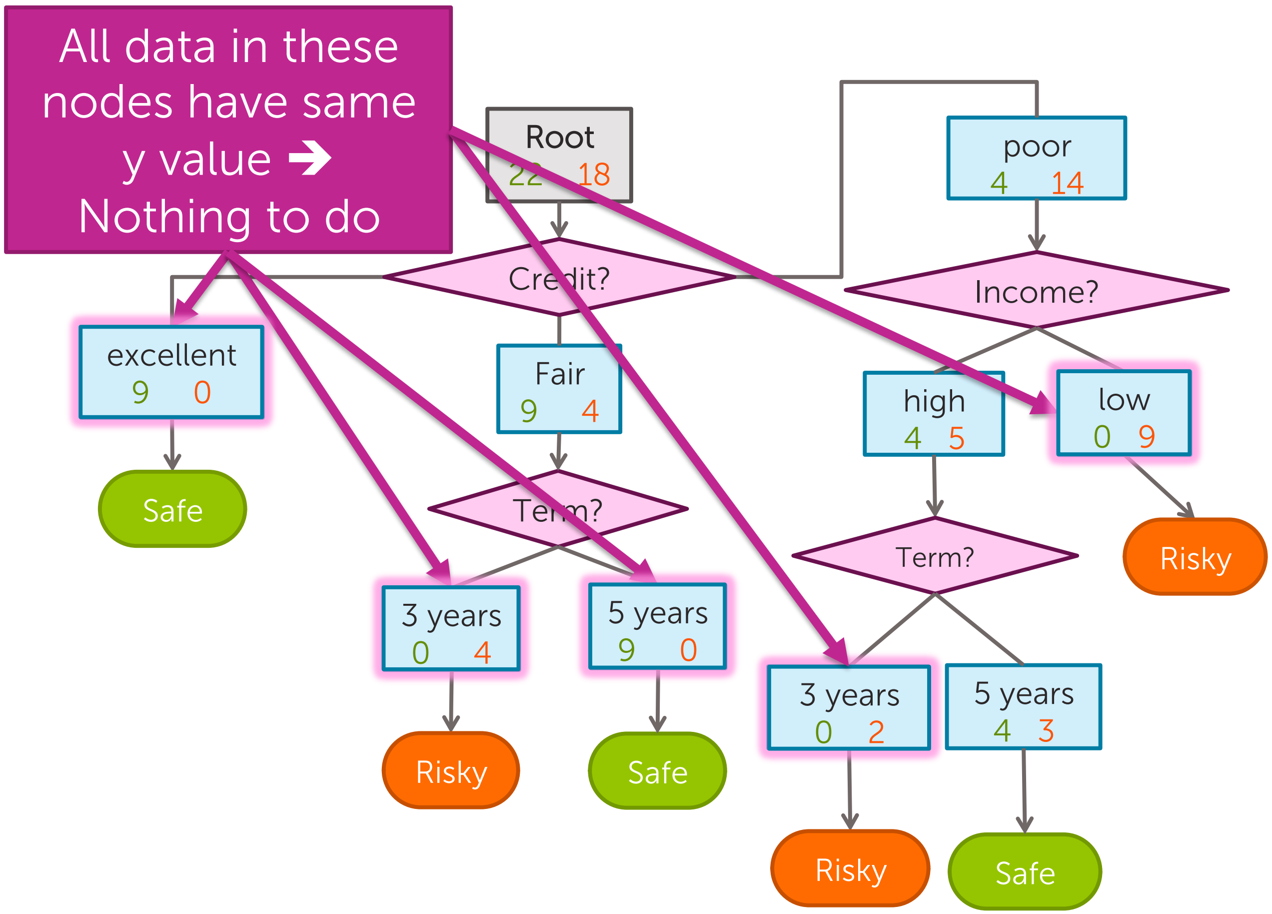
Pick best feature to split on

Learn decision stump with this split

For each leaf of decision stump, recurse

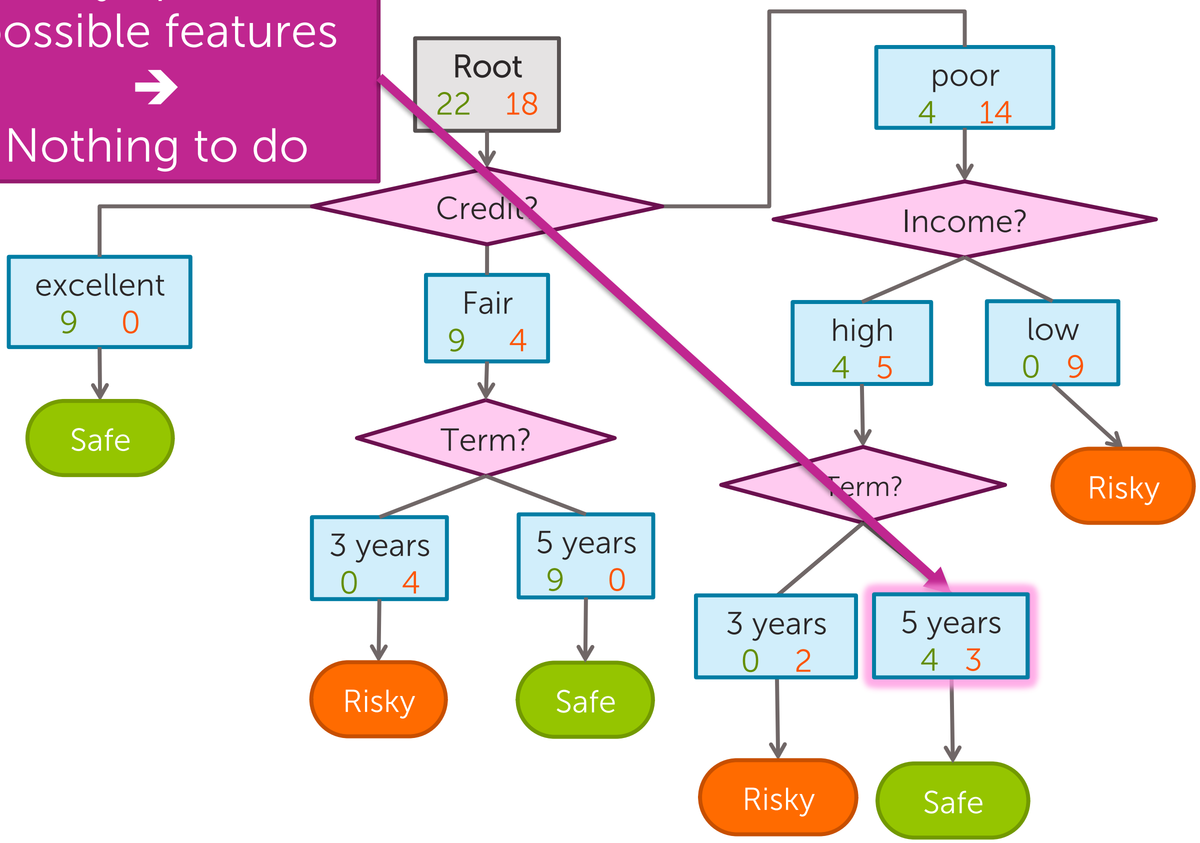
When do we stop???

Stopping condition 1: All data agrees on y



Stopping condition 2: Already split on all features

Already split on all possible features
➔
Nothing to do



Greedy decision tree learning

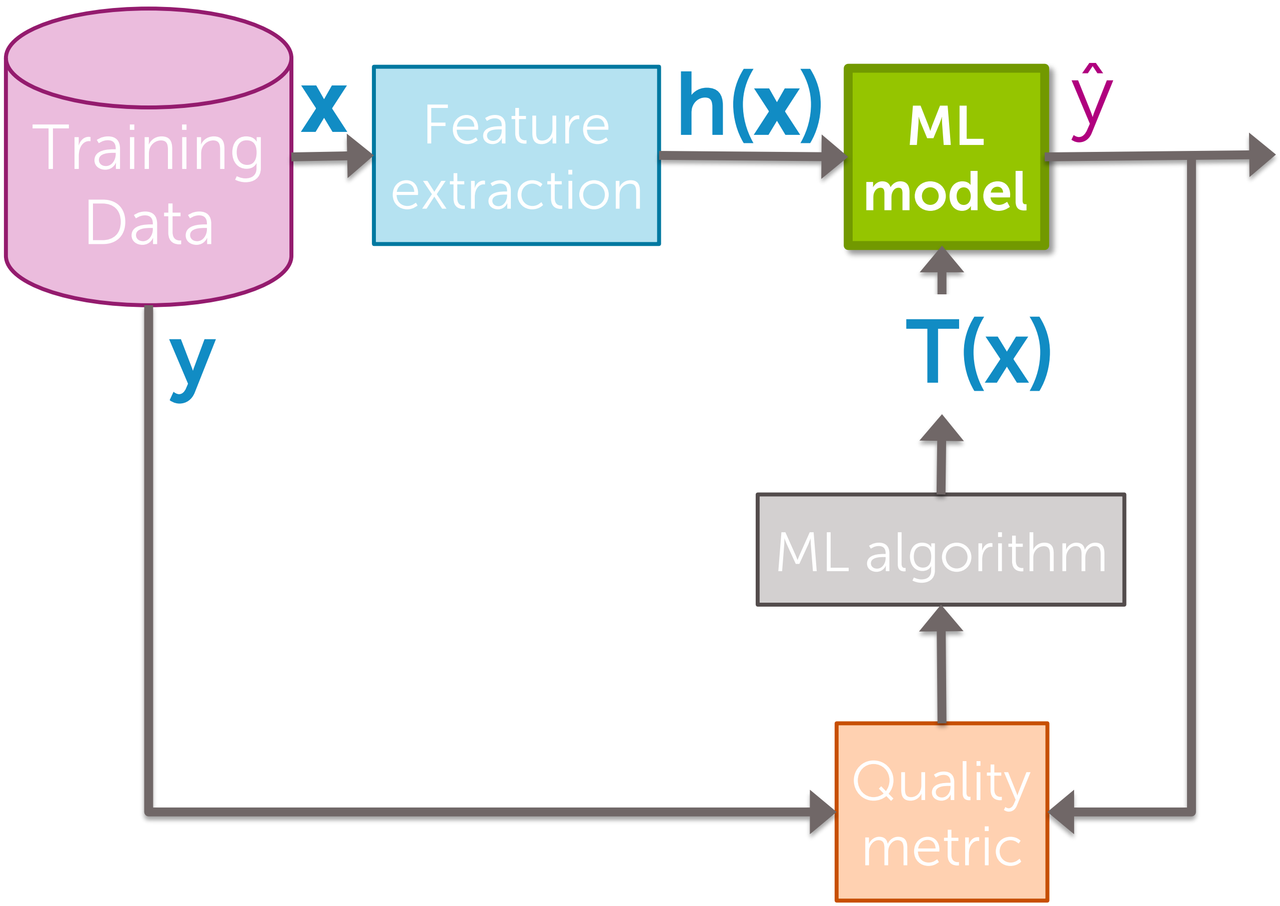
- Step 1: Start with an empty tree
- Step 2: Select a feature to split data
- For each split of the tree:
  - Step 3: If nothing more to, make predictions
  - Step 4: Otherwise, go to Step 2 & continue (recurse) on this split

Pick feature split leading to lowest classification error

Stopping conditions 1 & 2

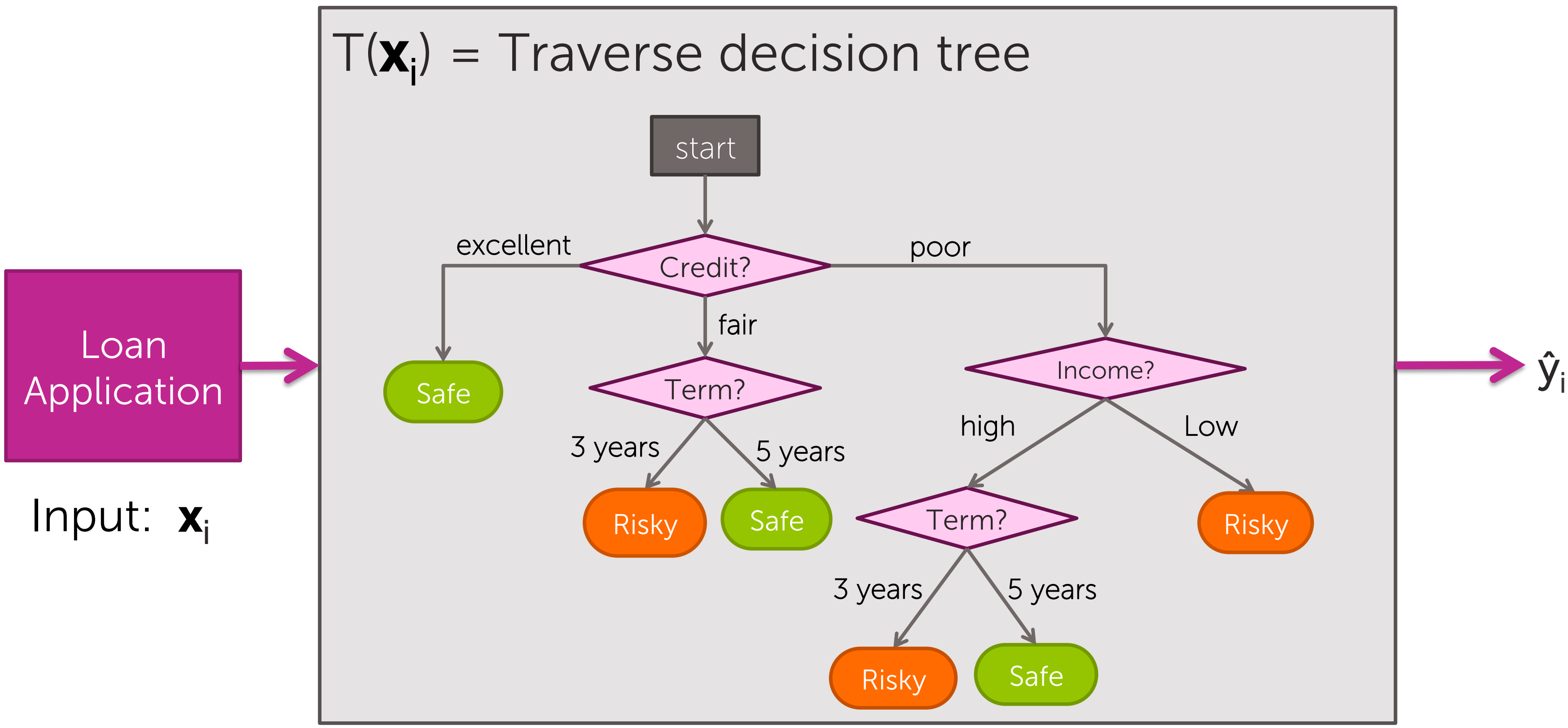
Recursion

Predictions with decision trees



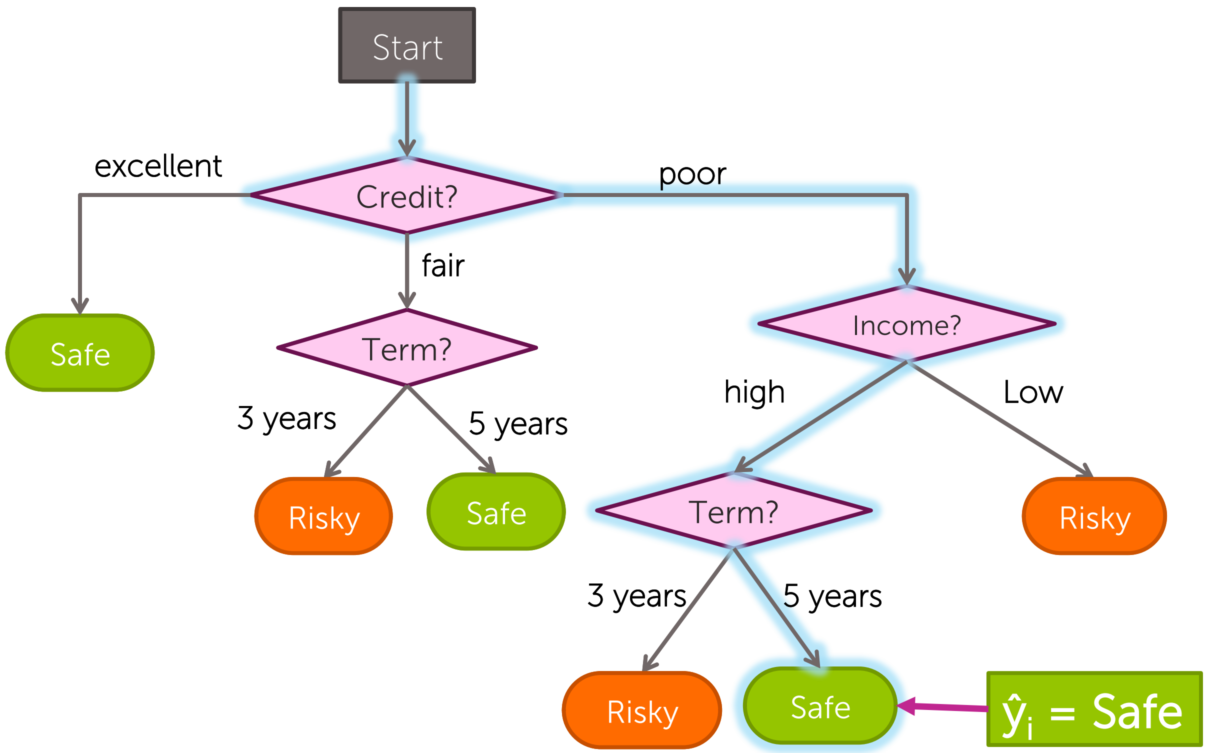
Training Data
x
Feature extraction
h(x)
ML model
ŷ
y
T(x)
ML algorithm
Quality metric

Decision tree model



Traversing a decision tree

$\mathbf{x}_i$ = (Credit = poor, Income = high, Term = 5 years)



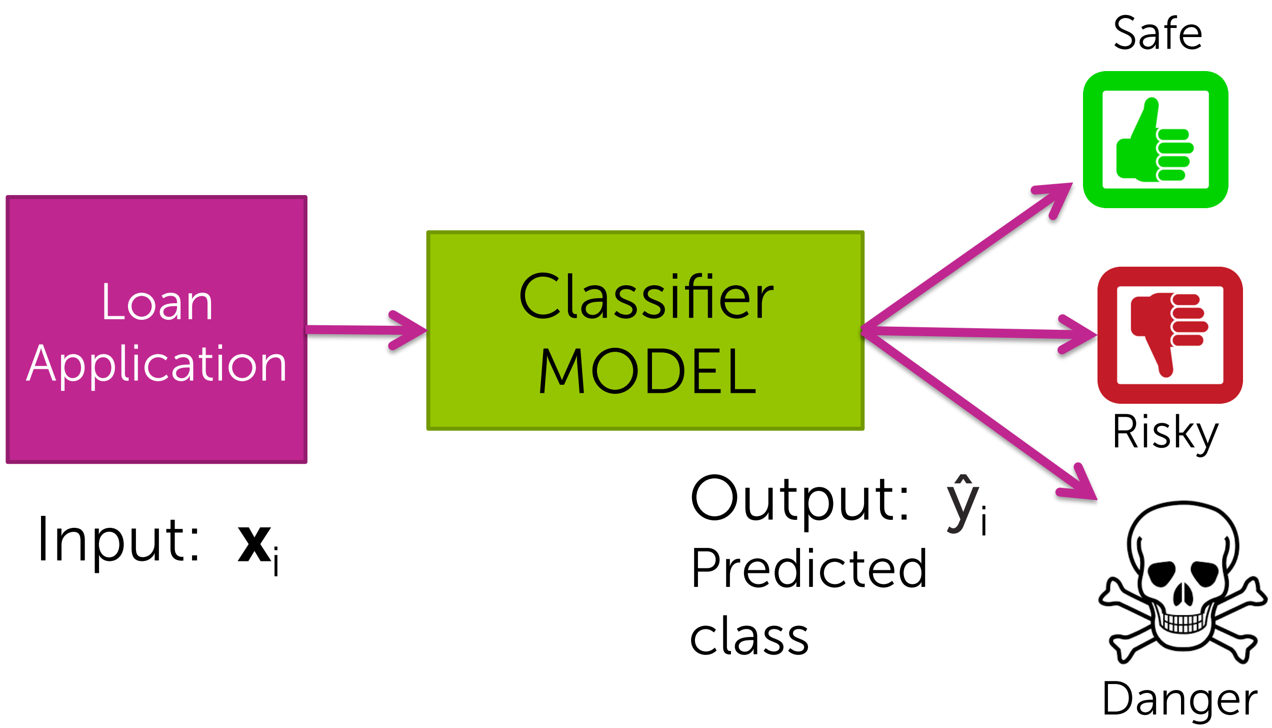
Decision tree prediction algorithm

predict(tree_node, input)

- If current tree_node is a leaf:
  - return majority class of data points in leaf
- else:
  - next_note = child node of tree_node whose feature value agrees with input
  - return predict(next_note, input)

Multiclass classification & predicting probabilities

Multiclass prediction



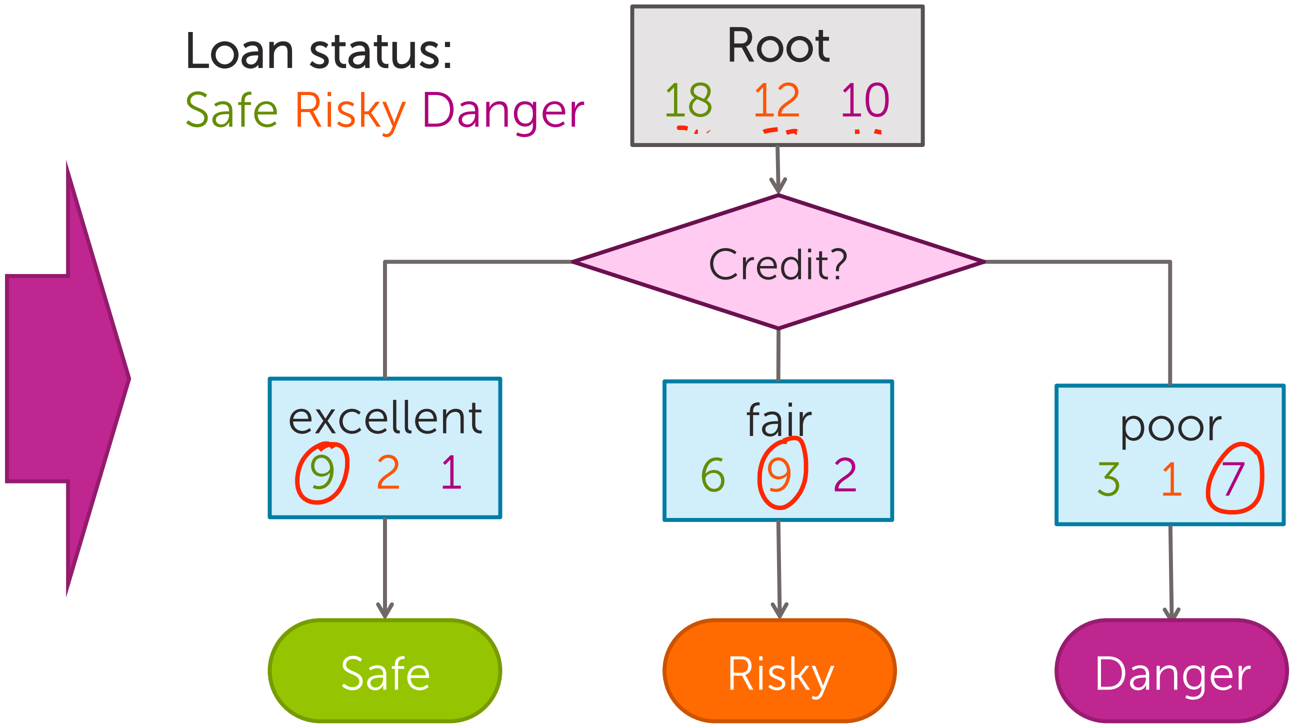
Input: $\mathbf{x}_i$

Output: $\hat{y}_i$
Predicted
class

Multiclass decision stump

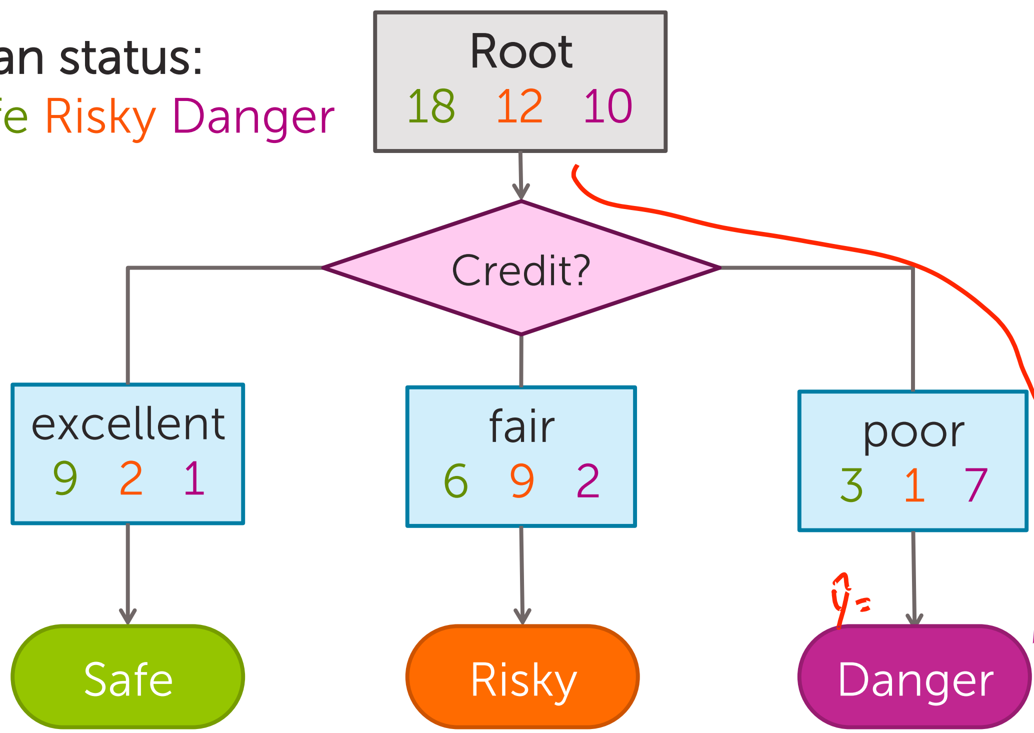
N = 40,
1 feature,
3 classes

Credit	y
excellent	safe
fair	risky
fair	safe
poor	danger
excellent	risky
fair	safe
poor	danger
poor	safe
fair	safe
…	…



Predicting probabilities with decision trees

Loan status:
Safe Risky Danger



$$P(y = \textbf{danger} \mid \mathbf{x}) = \frac{7}{3 + 1 + 7} = 0.64$$

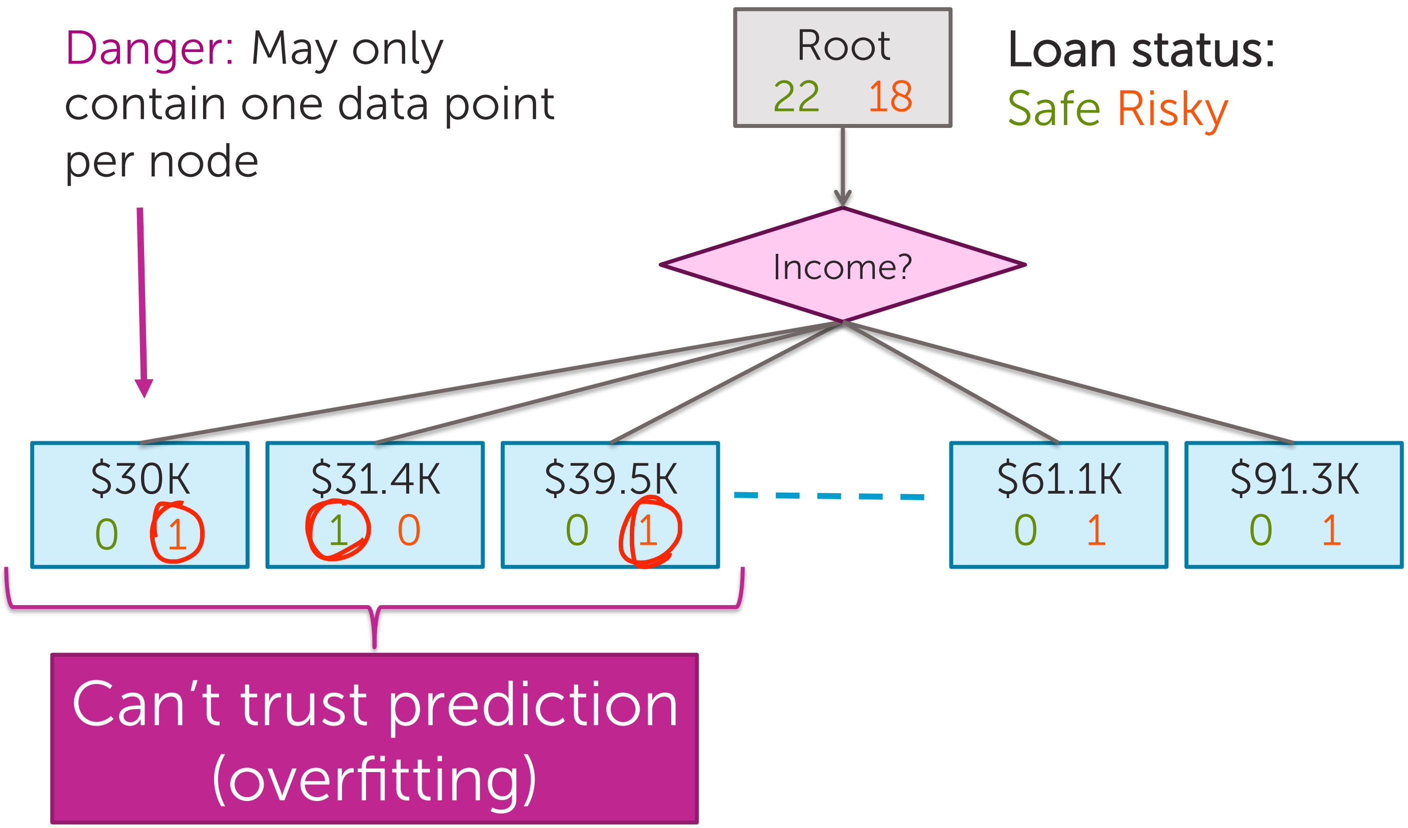
Decision tree learning:
Real valued features

How do we use real values inputs?

Income	Credit	Term	y
$105 K	excellent	3 yrs	Safe
$112 K	good	5 yrs	Risky
$73 K	fair	3 yrs	Safe
$69 K	excellent	5 yrs	Safe
$217 K	excellent	3 yrs	Risky
$120 K	good	5 yrs	Safe
$64 K	fair	3 yrs	Risky
$340 K	excellent	5 yrs	Safe
$60 K	good	3 yrs	Risky

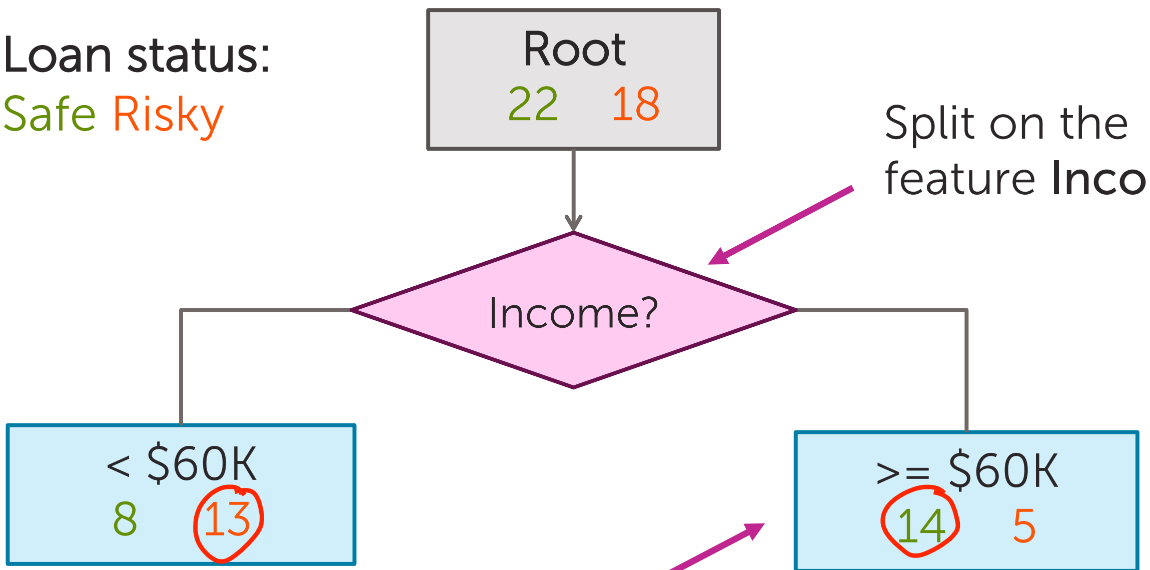
Split on each numeric value?

Danger: May only contain one data point per node



Alternative: Threshold split

Loan status:
Safe Risky

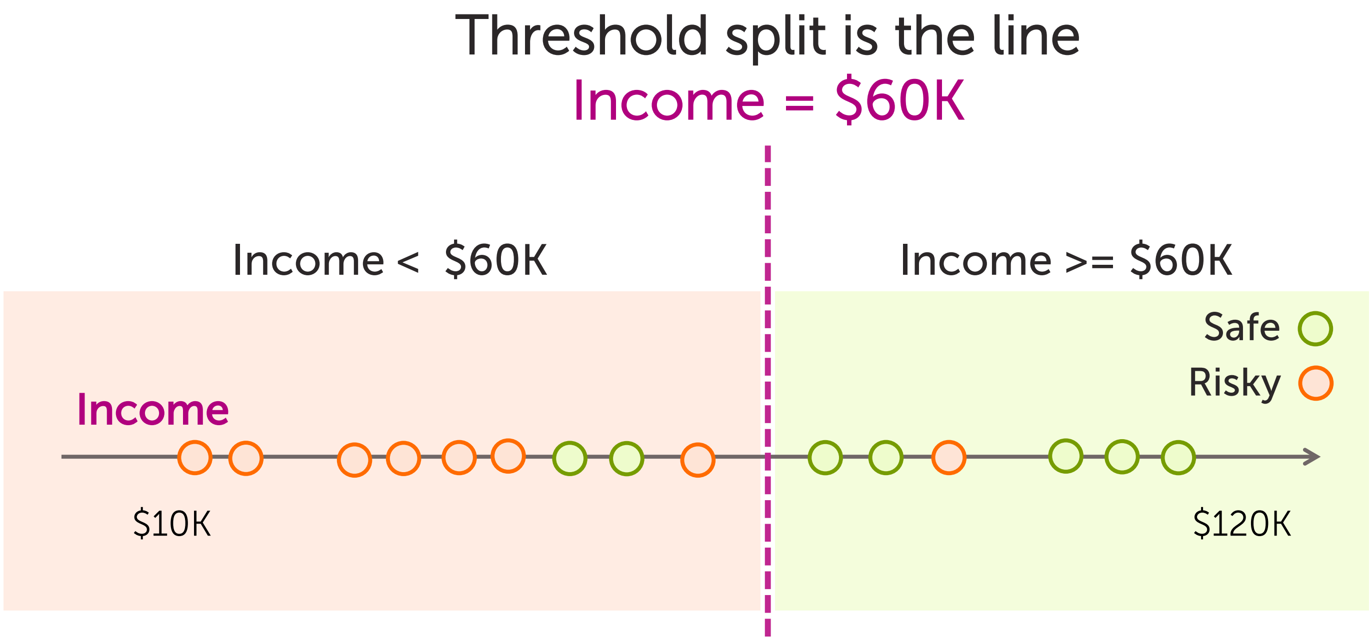


Split on the feature **Income**

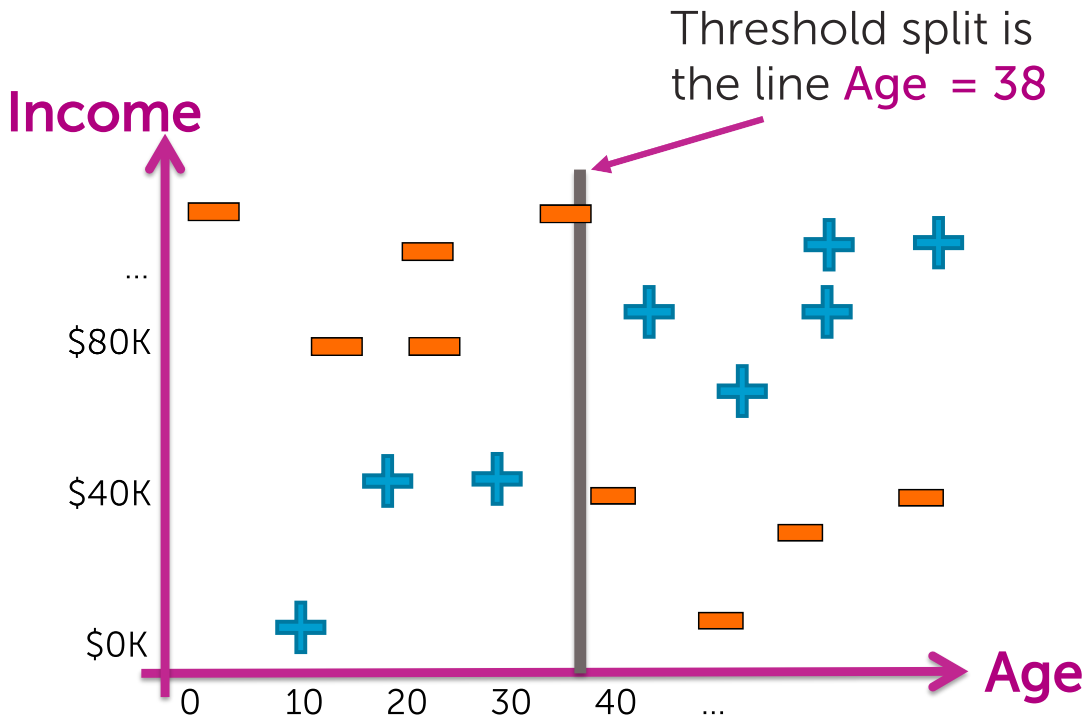
Subset of data with **Income >= $60K**

Many data points ➔ lower chance of overfitting

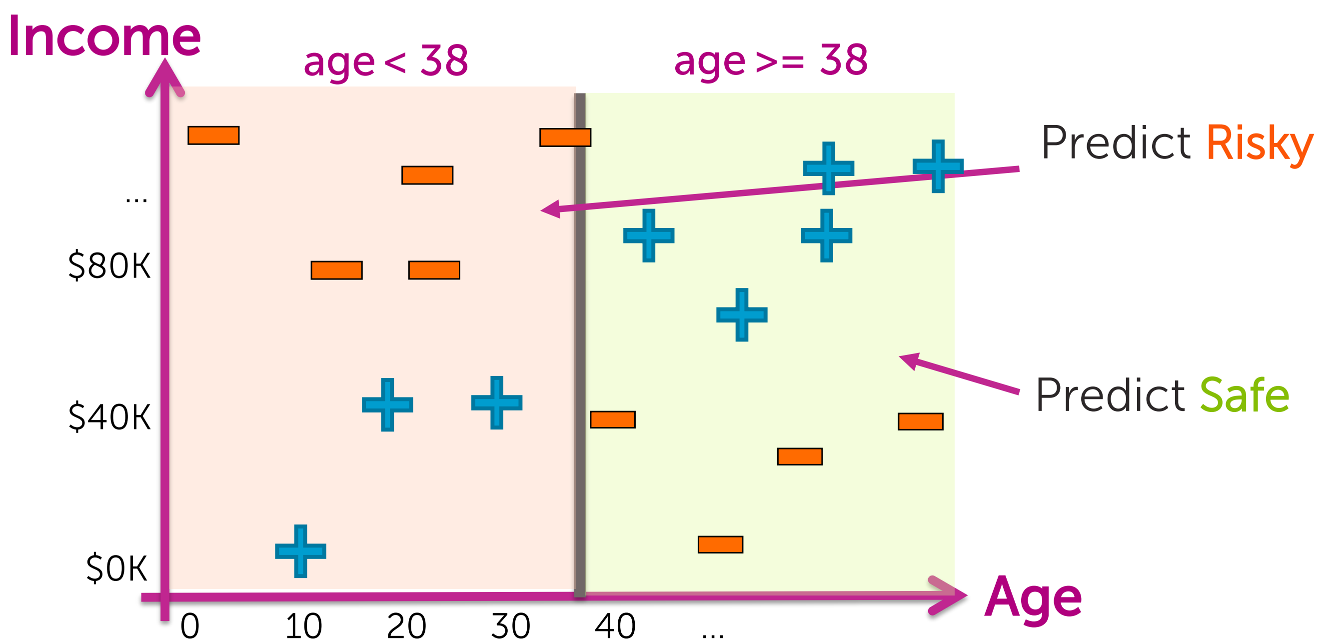
Threshold splits in 1-D



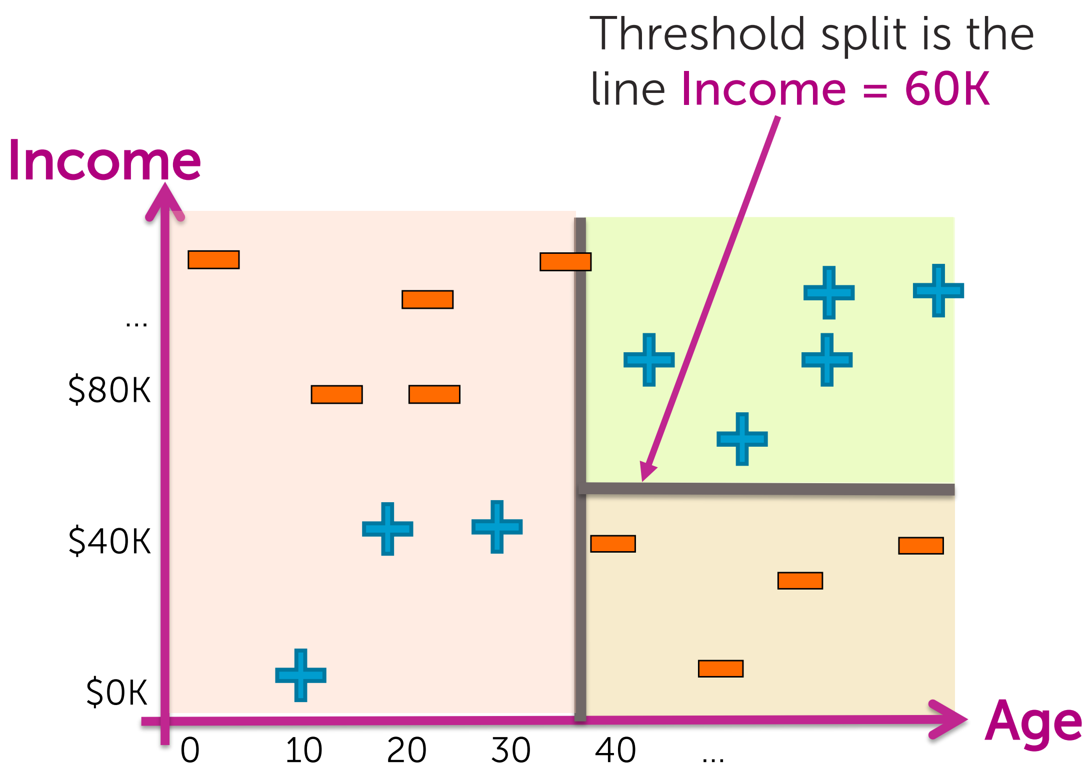
Visualizing the threshold split



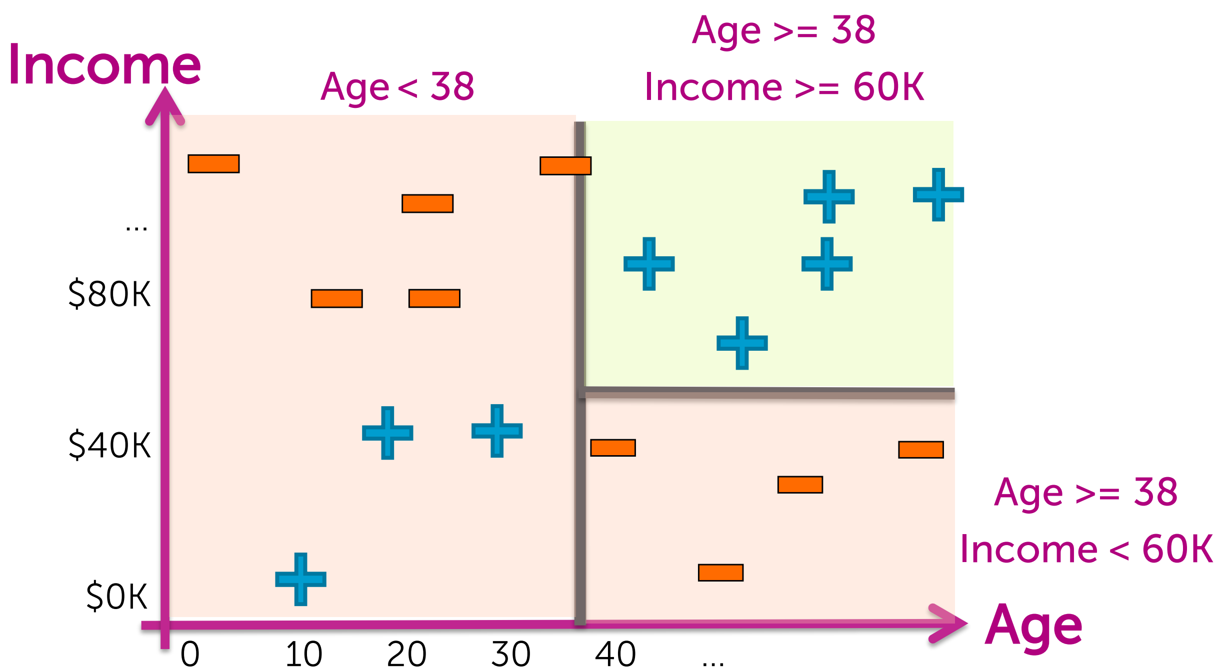
Split on Age >= 38

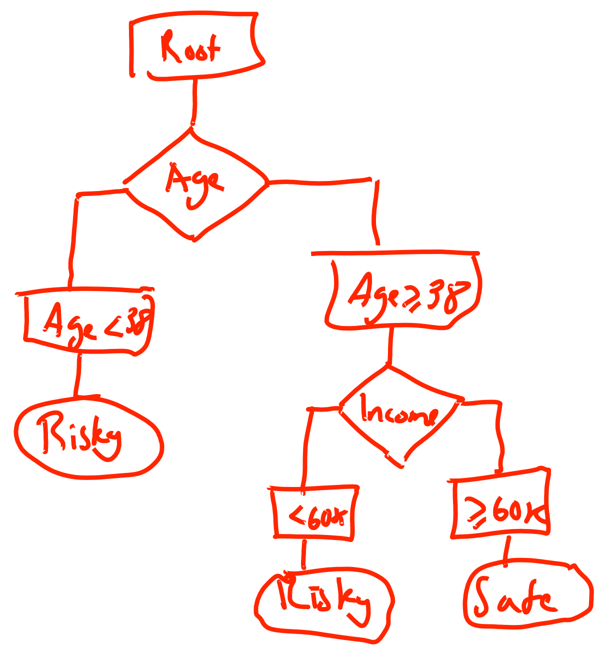


Depth 2: Split on Income >= $60K



Each split partitions the 2-D space

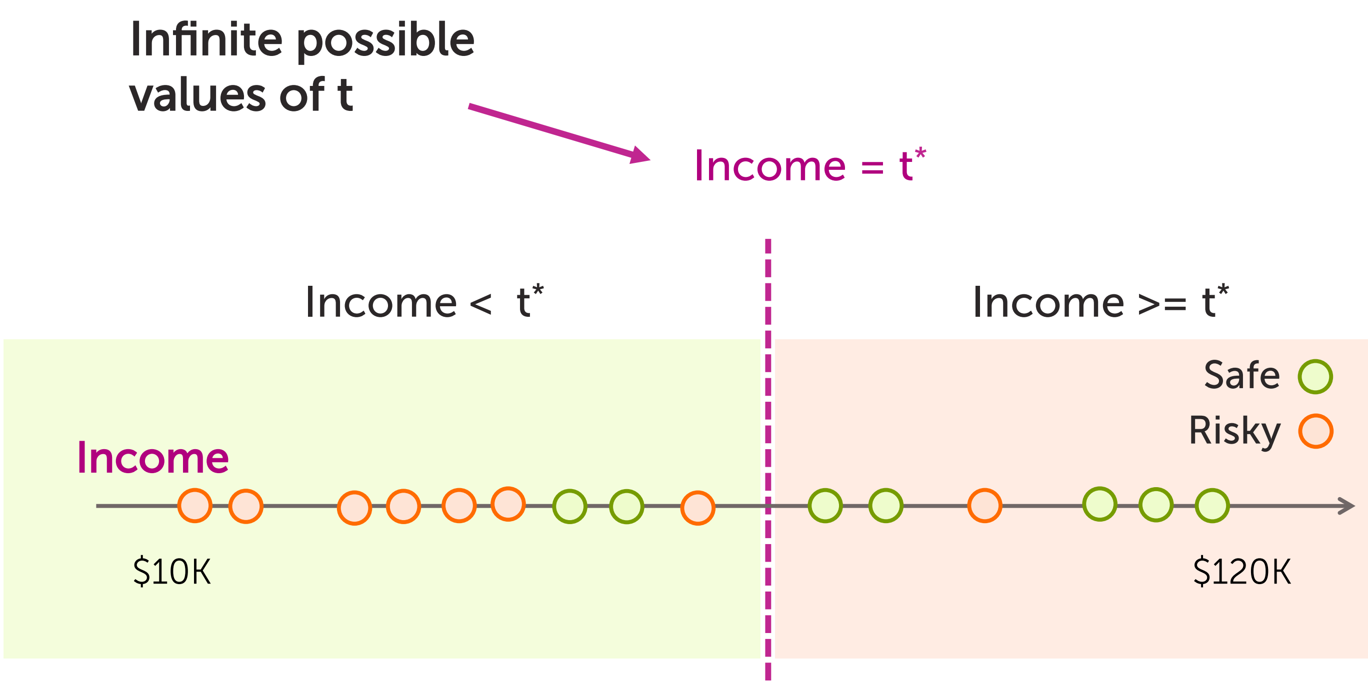




Finding the best threshold split

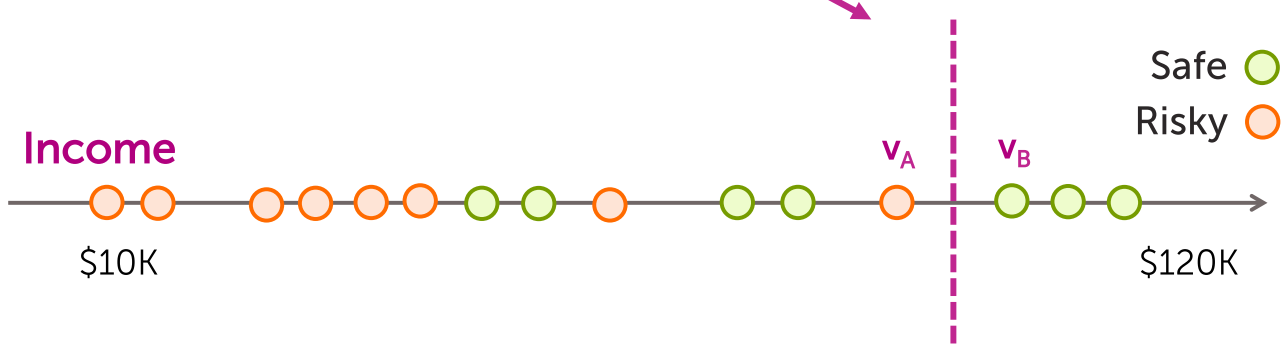
OPTIONAL

Finding the best threshold split



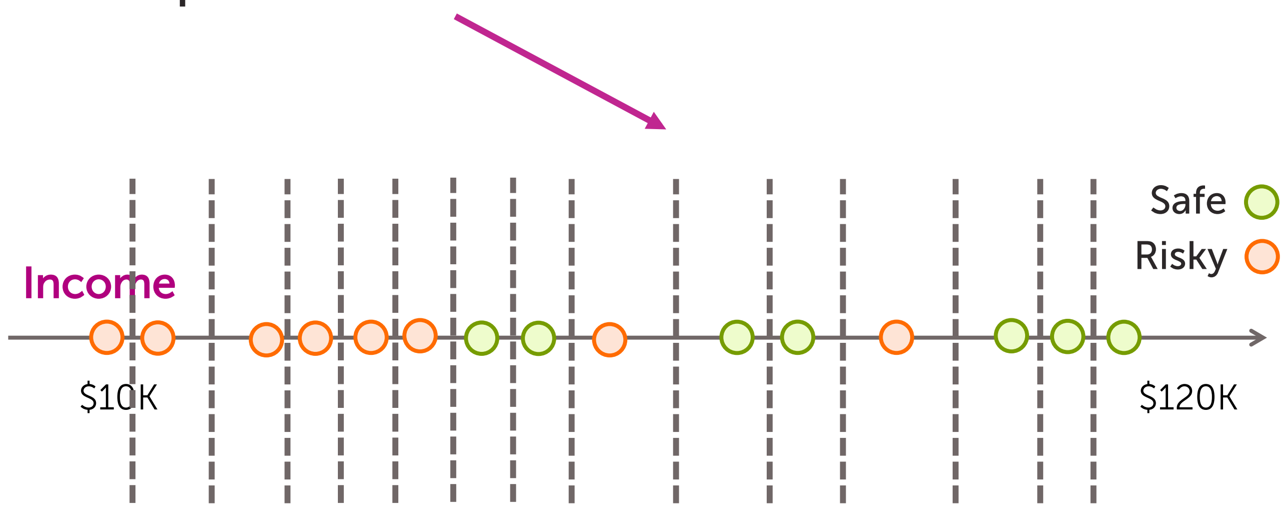
Consider a threshold between points

Same classification error for any threshold split between v_A and v_B



Only need to consider mid-points

Finite number of splits to consider



Threshold split selection algorithm

Income

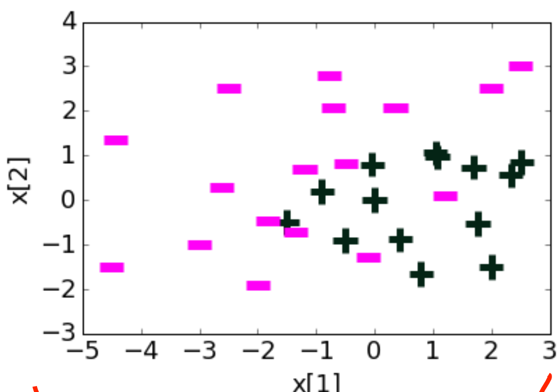
- Step 1: Sort the values of a feature $h_j(\mathbf{x})$:

  Let $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \ldots \mathbf{v}_N\}$ denote sorted values
- Step 2:
  - For i = 1 … N-1
    - Consider split $t_i = (\mathbf{v}_i + \mathbf{v}_{i+1}) / 2$
    - Compute classification error for treshold split $h_j(\mathbf{x}) >= \mathbf{t}_i$
  - Chose the $\mathbf{t}^*$ with the lowest classification error

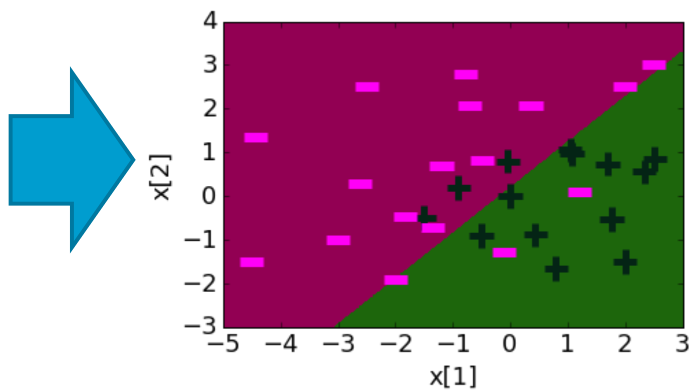
Decision trees vs logistic regression: *Example*

Logistic regression

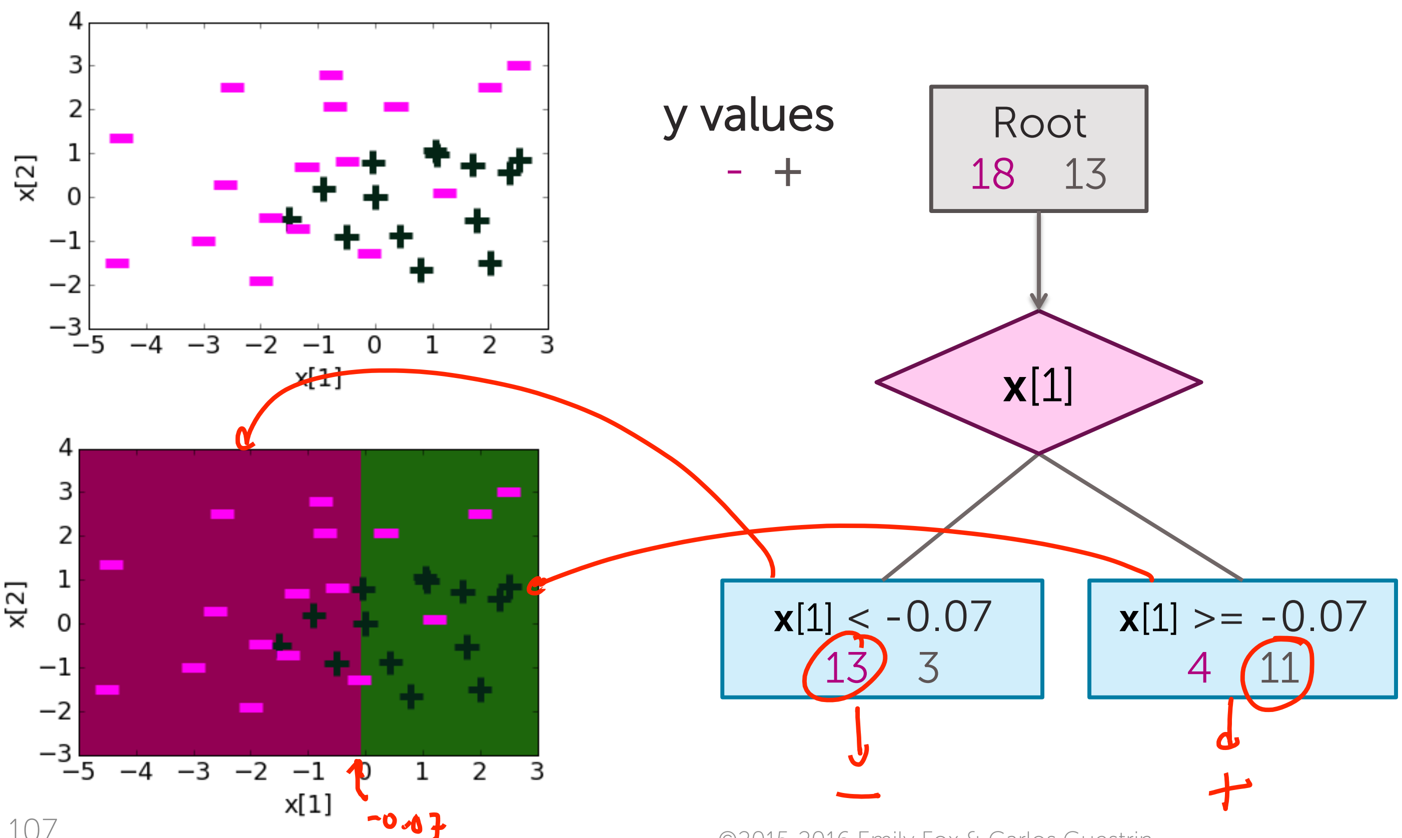
Feature	Value	Weight Learned
$h_0(\mathbf{x})$	1	0.22
$h_1(\mathbf{x})$	$\mathbf{x}[1]$	1.12
$h_2(\mathbf{x})$	$\mathbf{x}[2]$	-1.07



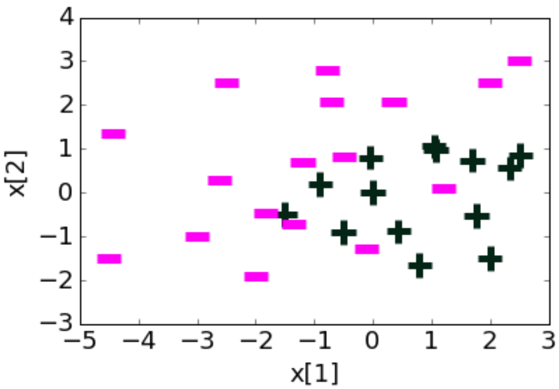
data



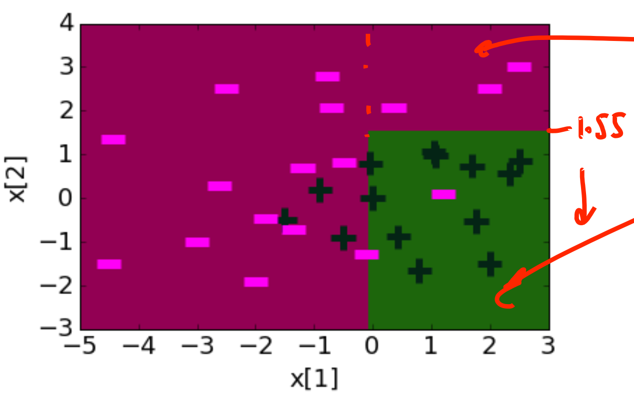
Depth 1: Split on **x**[1]



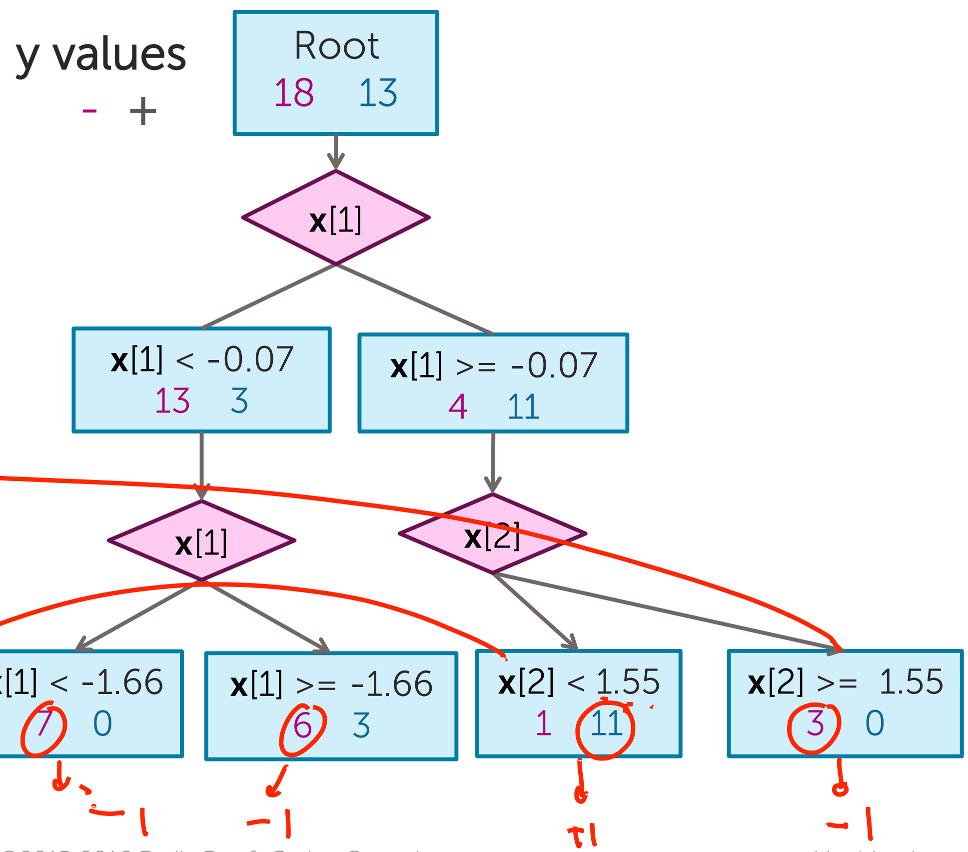
Depth 2



x[2]
x[1]



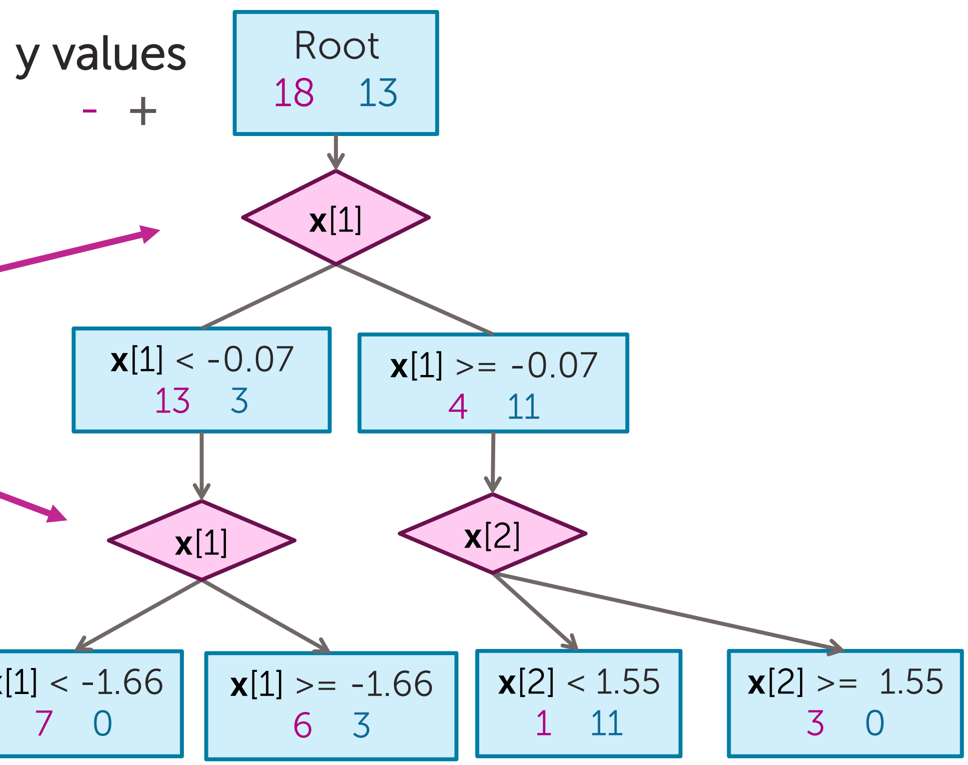
x[2]
x[1]
1.55



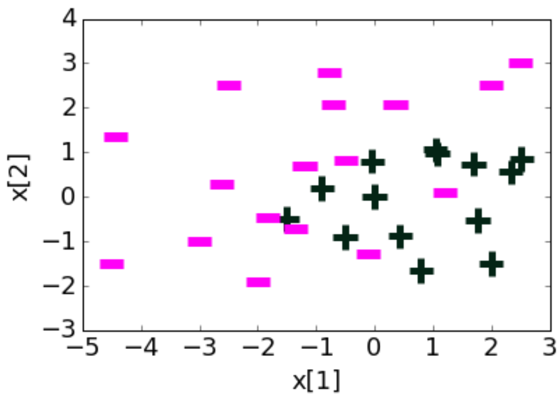
y values
- +
Root
18 13
x[1]
x[1] < -0.07
13 3
x[1] >= -0.07
4 11
x[1]
x[2]
x[1] < -1.66
7 0
x[1] >= -1.66
6 3
x[2] < 1.55
1 11
x[2] >= 1.55
3 0
-1
-1
+1
-1

Threshold split caveat

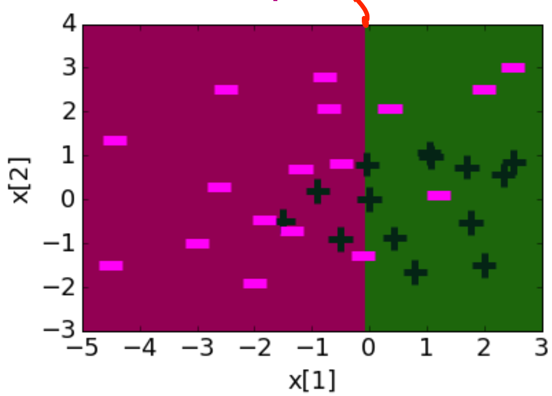
For threshold splits, same feature can be used multiple times



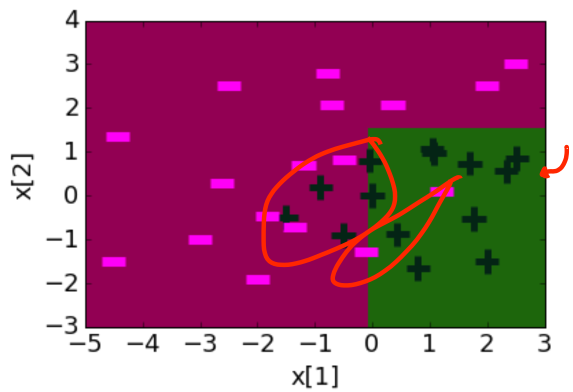
Decision boundaries



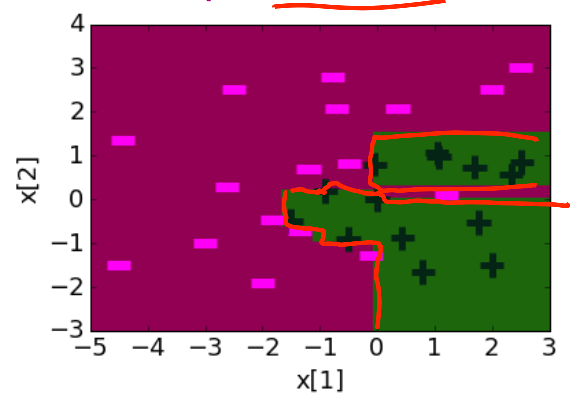
Depth 1



Depth 2

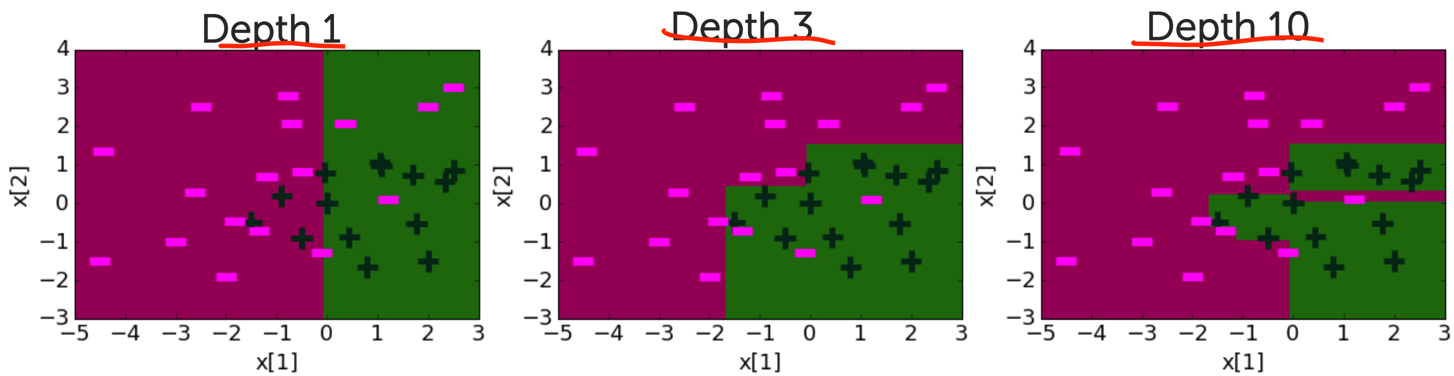


Depth 10

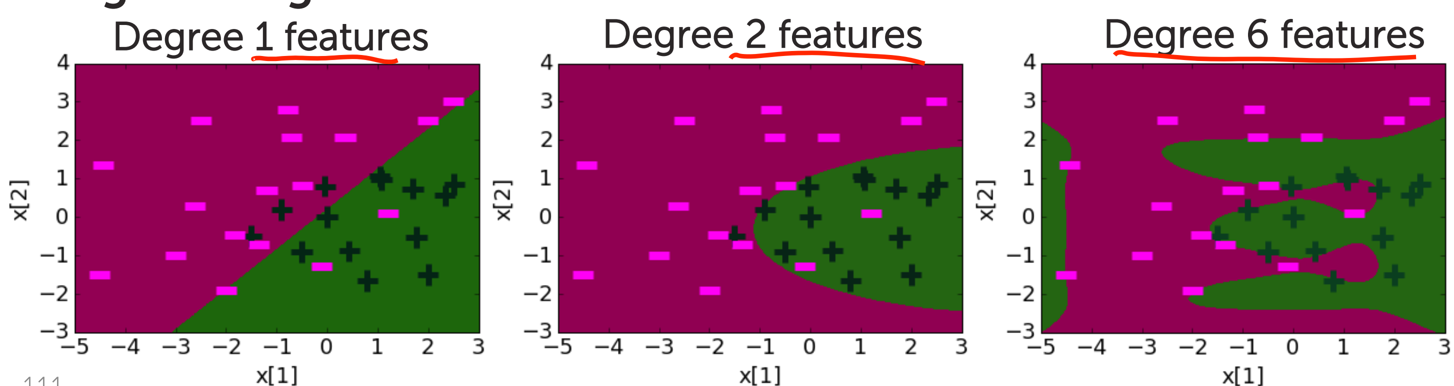


Comparing decision boundaries

Decision Tree



Logistic Regression



Summary of decision trees

What you can do now

- Define a decision tree classifier
- Interpret the output of a decision trees
- Learn a decision tree classifier using greedy algorithm
- Traverse a decision tree to make predictions
  - Majority class predictions
  - Probability predictions
  - Multiclass classification

Thank you to Dr. Krishna Sridhar

Dr. Krishna Sridhar

Staff Data Scientist, Dato, Inc.