



Linear classifiers: Logistic regression

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Predicting sentiment by topic: *An intelligent restaurant review system*

It's a big day & I want to book a table at a nice Japanese restaurant

Seattle has many
★★★★★
sushi restaurants

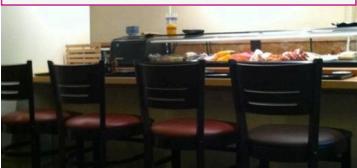


What are people
saying about
the food?
the ambiance?...





Positive reviews not positive about everything



Sample review:

Watching the chefs create incredible edible art made the experience very unique.

My wife tried their ramen and it was pretty forgettable.

All the sushi was delicious! Easily best sushi in Seattle.



Classifying sentiment of review

Easily best sushi in Seattle.

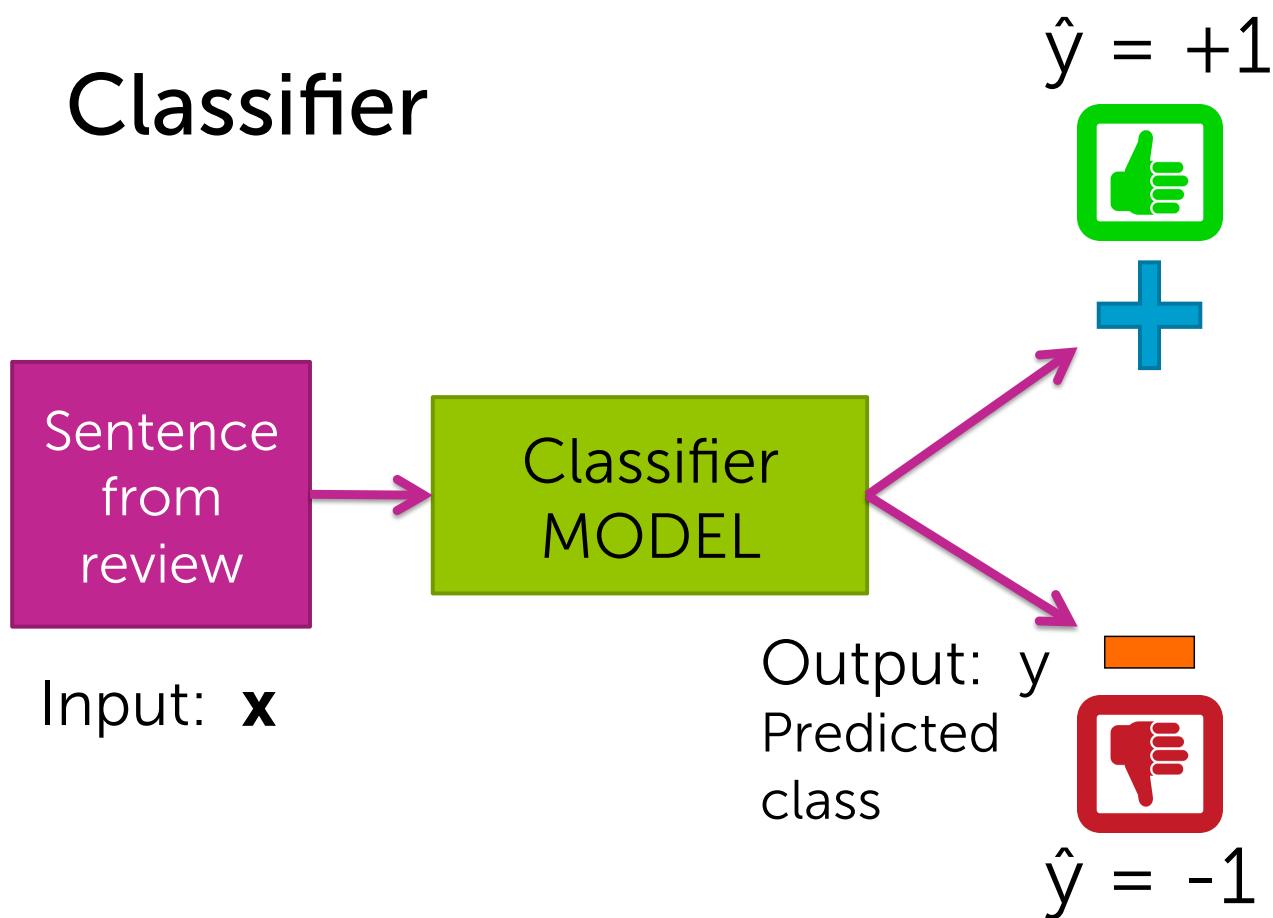


Sentence Sentiment
Classifier



Linear classifier: Intuition

Classifier



Note: we'll start talking about 2 classes, and address multiclass later

A (linear) classifier

- Will use training data to learn a weight or coefficient for each word

Word	Coefficient
good	1.0
great	1.5
awesome	2.7
bad	-1.0
terrible	-2.1
awful	-3.3
restaurant, the, we, where, ...	0.0
...	...

Scoring a sentence

Word	Coefficient
good	1.0
great	1.2
awesome	1.7
bad	-1.0
terrible	-2.1
awful	-3.3
restaurant, the, we, where, ...	0.0
...	...

Input \mathbf{x}_i :

Sushi was great,
the food was awesome,
but the service was terrible.

$$\begin{aligned} \text{Score}(x_i) &= 1.2 + 1.7 + (-2.1) = 0.8 > 0 \\ \Rightarrow y \hat{\text{ }} &= +1 \text{ positive review} \end{aligned}$$

Called a linear classifier, because output is weighted sum of input.



Word	Coefficient
...	...



Simple linear classifier

$\text{Score}(\mathbf{x})$ = weighted count of words in sentence

If $\text{Score}(\mathbf{x}) > 0$:

$\hat{y} = +1$

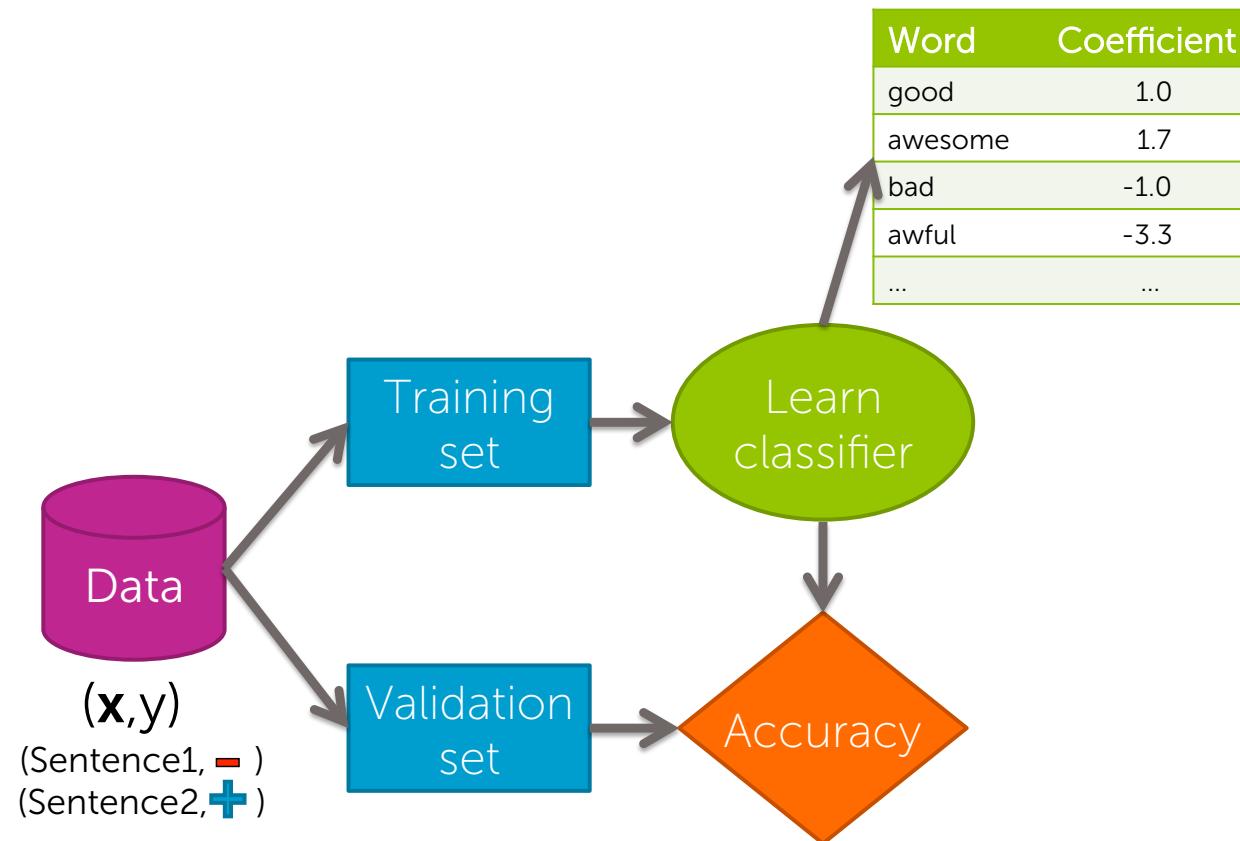
Else:

$\hat{y} = -1$

Sentence
from
review

Input: \mathbf{x}

Training a classifier = Learning the coefficients

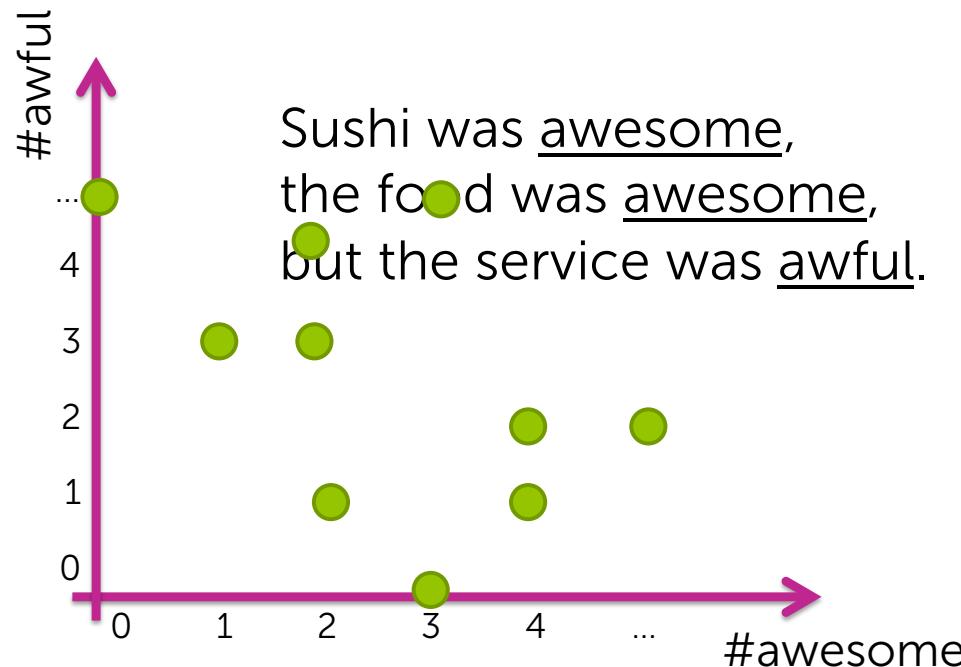


Decision boundaries

Suppose only two words had non-zero coefficient

Word	Coefficient
#awesome	1.0
#awful	-1.5

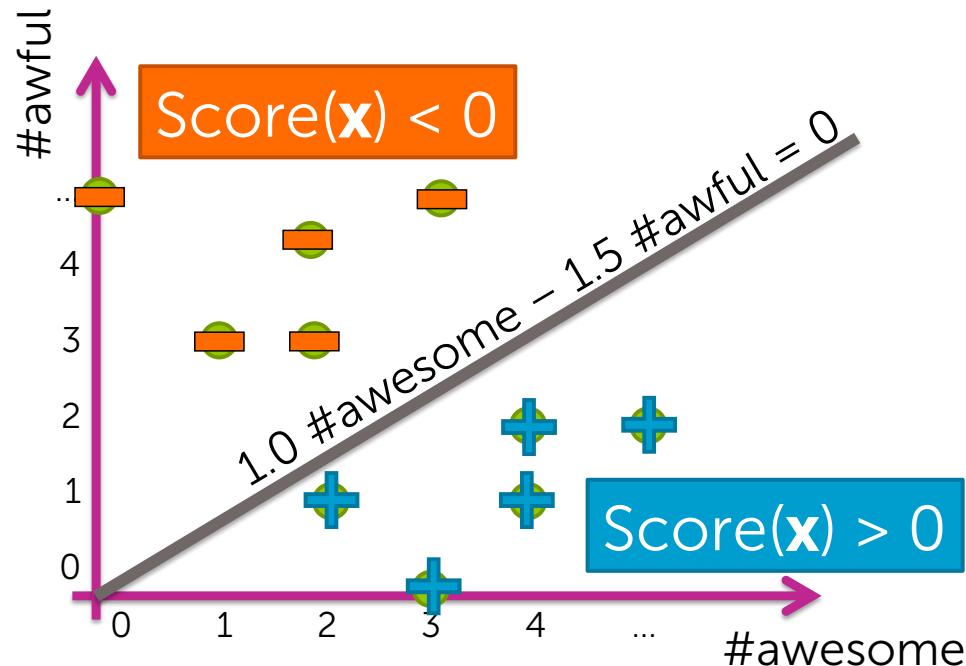
$$\text{Score}(x) = 1.0 \text{ #awesome} - 1.5 \text{ #awful}$$



Decision boundary example

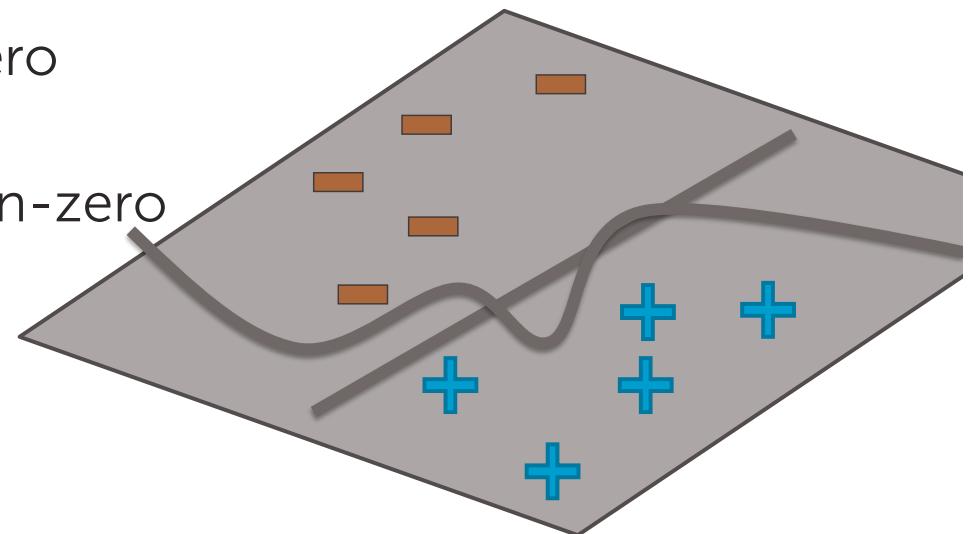
Word	Coefficient
#awesome	1.0
#awful	-1.5

$$\rightarrow \text{Score}(x) = 1.0 \text{ #awesome} - 1.5 \text{ #awful}$$

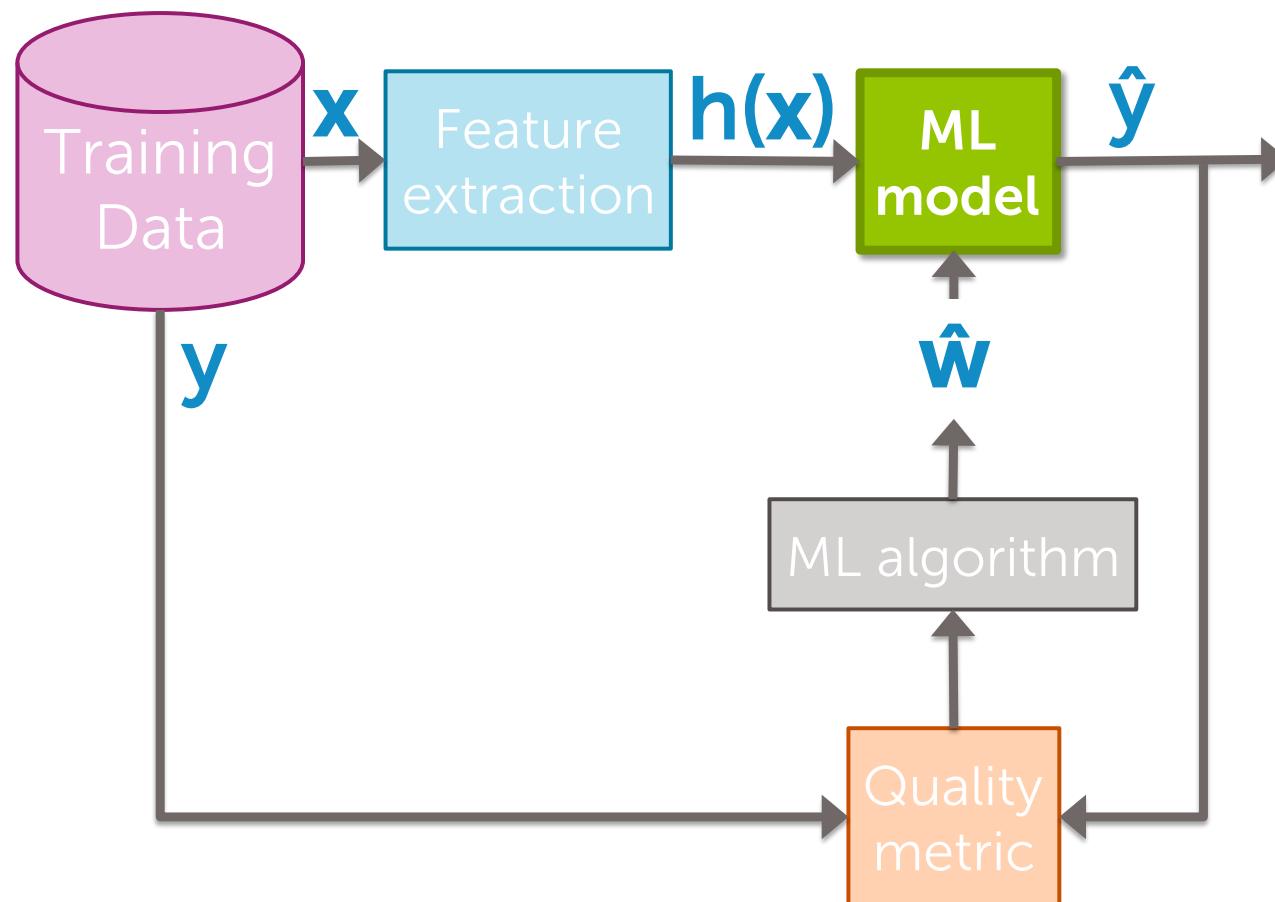


Decision boundary separates positive & negative predictions

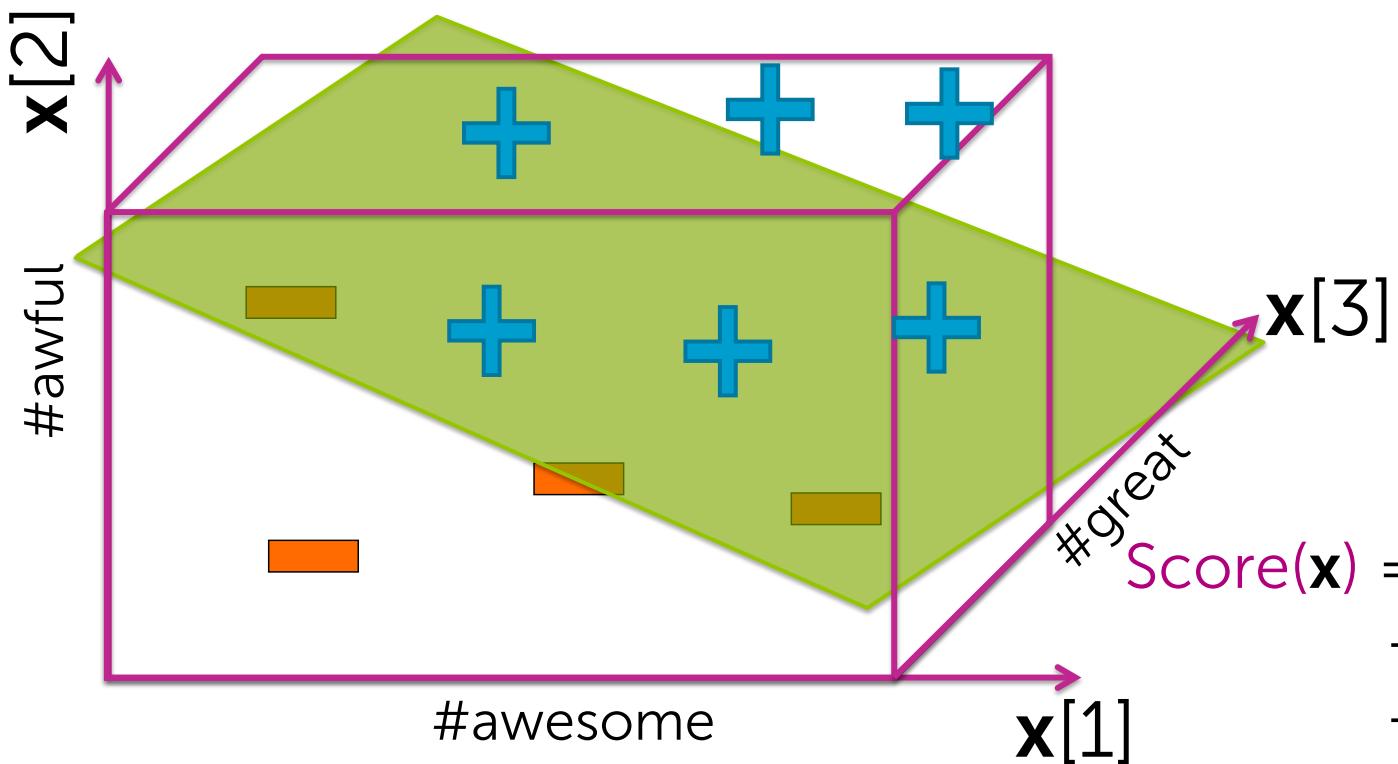
- For linear classifiers:
 - When 2 coefficients are non-zero
→ line
 - When 3 coefficients are non-zero
→ plane
 - When many coefficients are non-zero
→ hyperplane
- For more general classifiers
→ more complicated shapes



Linear classifier: Model



Coefficients of classifier



23

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$$\begin{aligned} \text{Score}(\mathbf{x}) = & w_0 \\ & + w_1 \#awesome \\ & + w_2 \#awful \\ & + w_3 \#great \end{aligned}$$

Machine Learning Specialization

General notation

Output: $y \leftarrow \{-1, +1\}$

Inputs: $\mathbf{x} = (\mathbf{x}[1], \mathbf{x}[2], \dots, \mathbf{x}[d])$



d-dim vector

Notational conventions:

$\mathbf{x}[j]$ = jth input (*scalar*)

$h_j(\mathbf{x})$ = jth feature (*scalar*)

\mathbf{x}_i = input of ith data point (*vector*)

$\mathbf{x}_i[j]$ = jth input of ith data point (*scalar*)

Simple hyperplane

Model: $\hat{y}_i = \text{sign}(\text{Score}(\mathbf{x}_i))$

$$\text{Score}(\mathbf{x}_i) = w_0 + w_1 x_i[1] + \dots + w_d x_i[d] = \mathbf{w}^\top \mathbf{x}_i$$

if $\text{Score}(\mathbf{x}_i) == 0$, can predict y hat either +1 or -1.

feature 1 = 1

feature 2 = $\mathbf{x}[1]$... e.g., #awesome

feature 3 = $\mathbf{x}[2]$... e.g., #awful

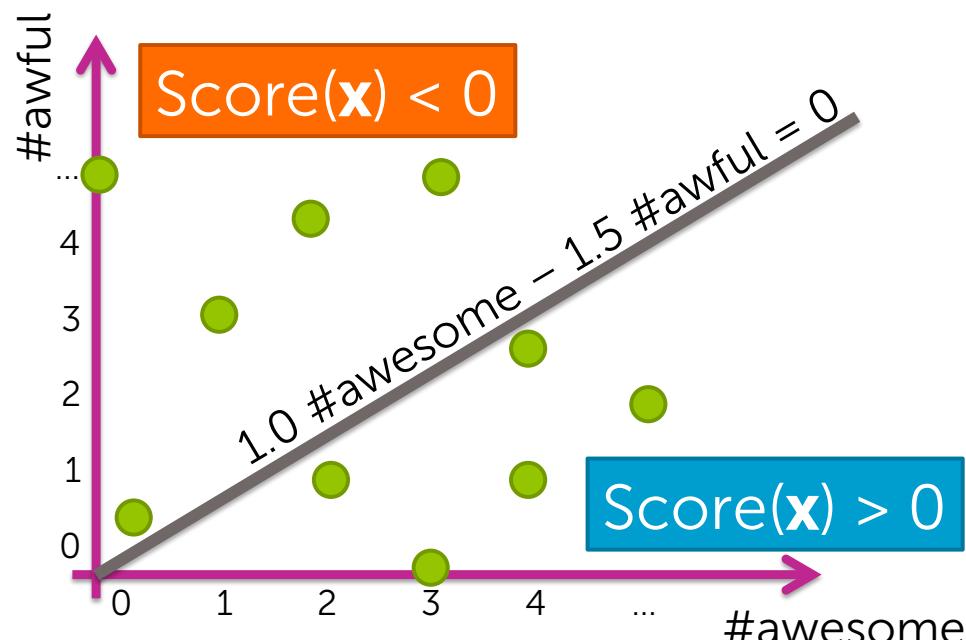
...

feature $d+1 = \mathbf{x}[d]$... e.g., #ramen

Decision boundary: effect of changing coefficients

Input	Coefficient	Value
	w_0	0.0
#awesome	w_1	1.0
#awful	w_2	-1.5

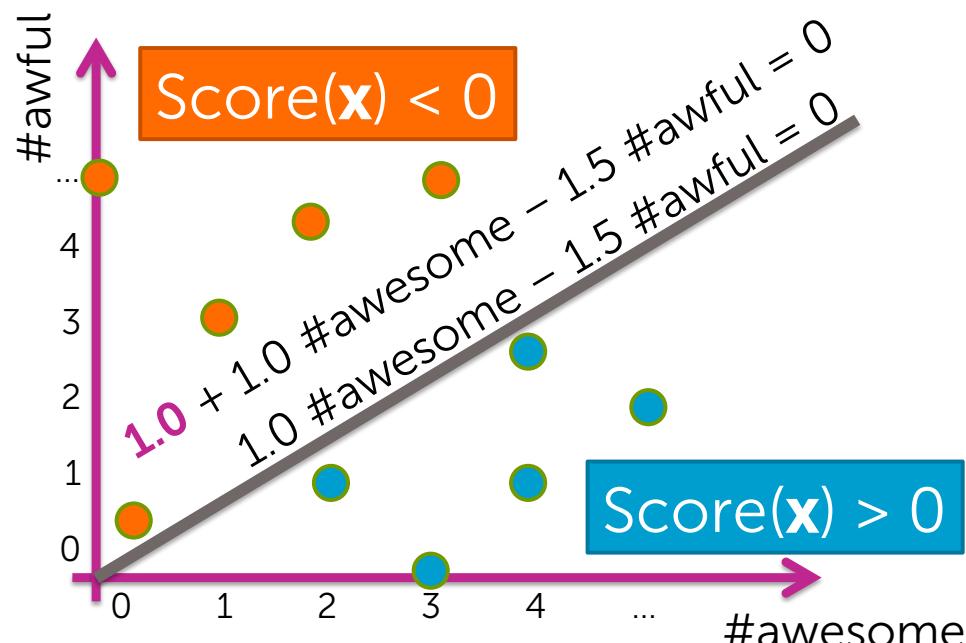
$$\rightarrow \text{Score}(x) = 1.0 \text{ #awesome} - 1.5 \text{ #awful}$$



Decision boundary: effect of changing coefficients

Input	Coefficient	Value
	w_0	1.0
#awesome	w_1	1.0
#awful	w_2	-1.5

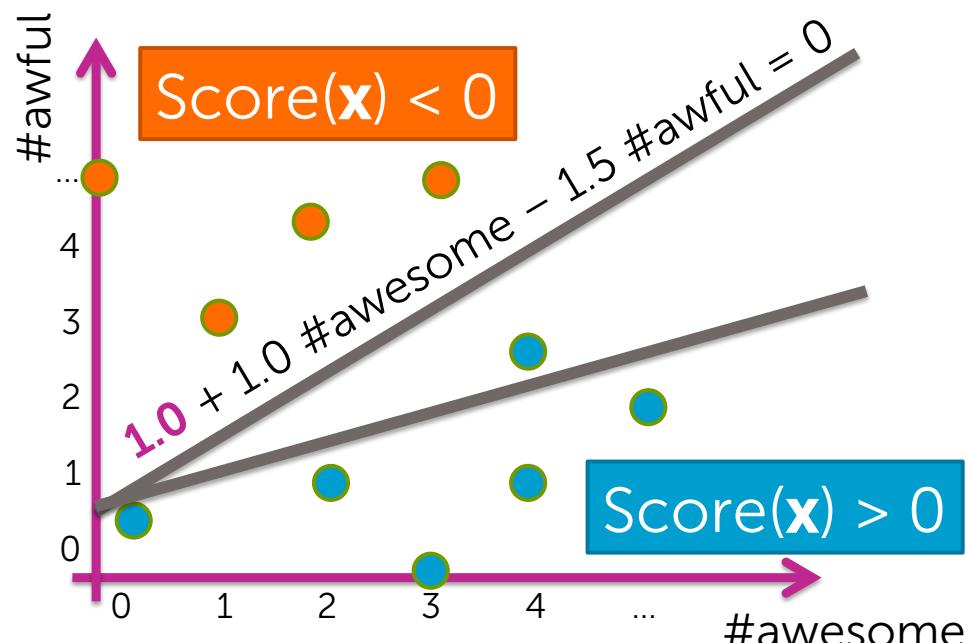
$$\rightarrow \text{Score}(x) = 1.0 \text{ #awesome} - 1.5 \text{ #awful}$$



Decision boundary: effect of changing coefficients

Input	Coefficient	Value
	w_0	1.0
#awesome	w_1	1.0
#awful	w_2	-3.0

$$\rightarrow \text{Score}(x) = 1.0 + 1.0 \text{ #awesome} - 3.0 \text{ #awful}$$



More generic features... D-dimensional hyperplane

Model: $\hat{y}_i = \text{sign}(\text{Score}(\mathbf{x}_i))$

$$\text{Score}(\mathbf{x}_i) = w_0 h_0(\mathbf{x}_i) + w_1 h_1(\mathbf{x}_i) + \dots + w_D h_D(\mathbf{x}_i)$$

$$= \sum_{j=0}^D w_j h_j(\mathbf{x}_i) = \mathbf{w}^\top \mathbf{h}(\mathbf{x}_i)$$

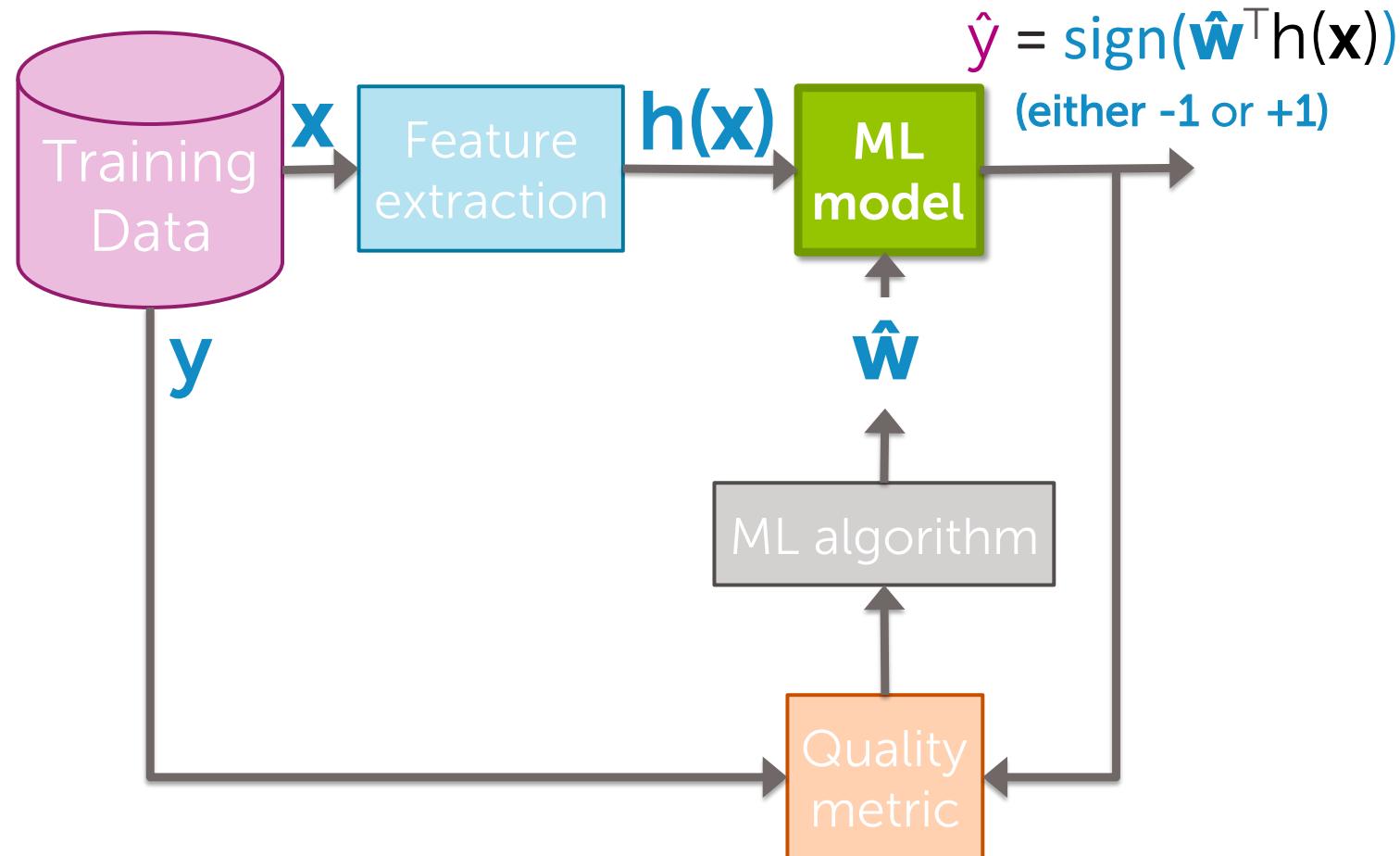
feature 1 = $h_0(\mathbf{x})$... e.g., 1

feature 2 = $h_1(\mathbf{x})$... e.g., $\mathbf{x}[1] = \text{\#awesome}$

feature 3 = $h_2(\mathbf{x})$... e.g., $\mathbf{x}[2] = \text{\#awful}$
or, $\log(\mathbf{x}[7]) \mathbf{x}[2] = \log(\#\text{bad}) \times \#\text{awful}$
or, tf-idf("awful")

...

feature $D+1 = h_D(\mathbf{x})$... some other function of $\mathbf{x}[1], \dots, \mathbf{x}[d]$

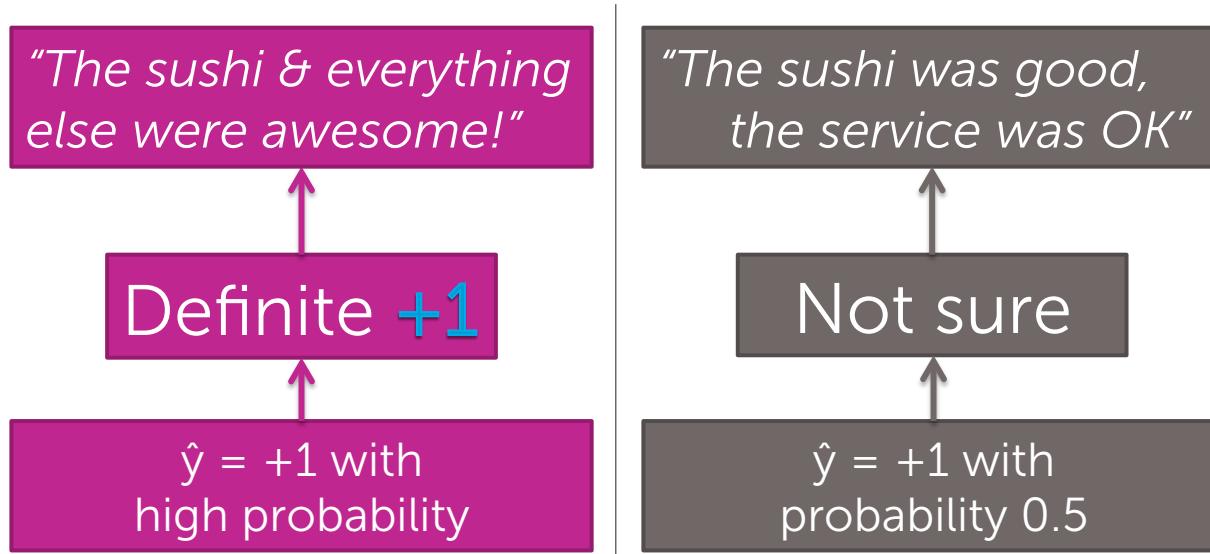




Are you sure about the prediction?
Class probability

How confident is your prediction?

- Thus far, we've outputted a prediction **+1** or **-1**
- But, how sure are you about the prediction?

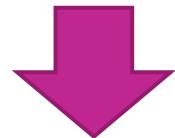




Basics of probabilities – quick review

Basic probability

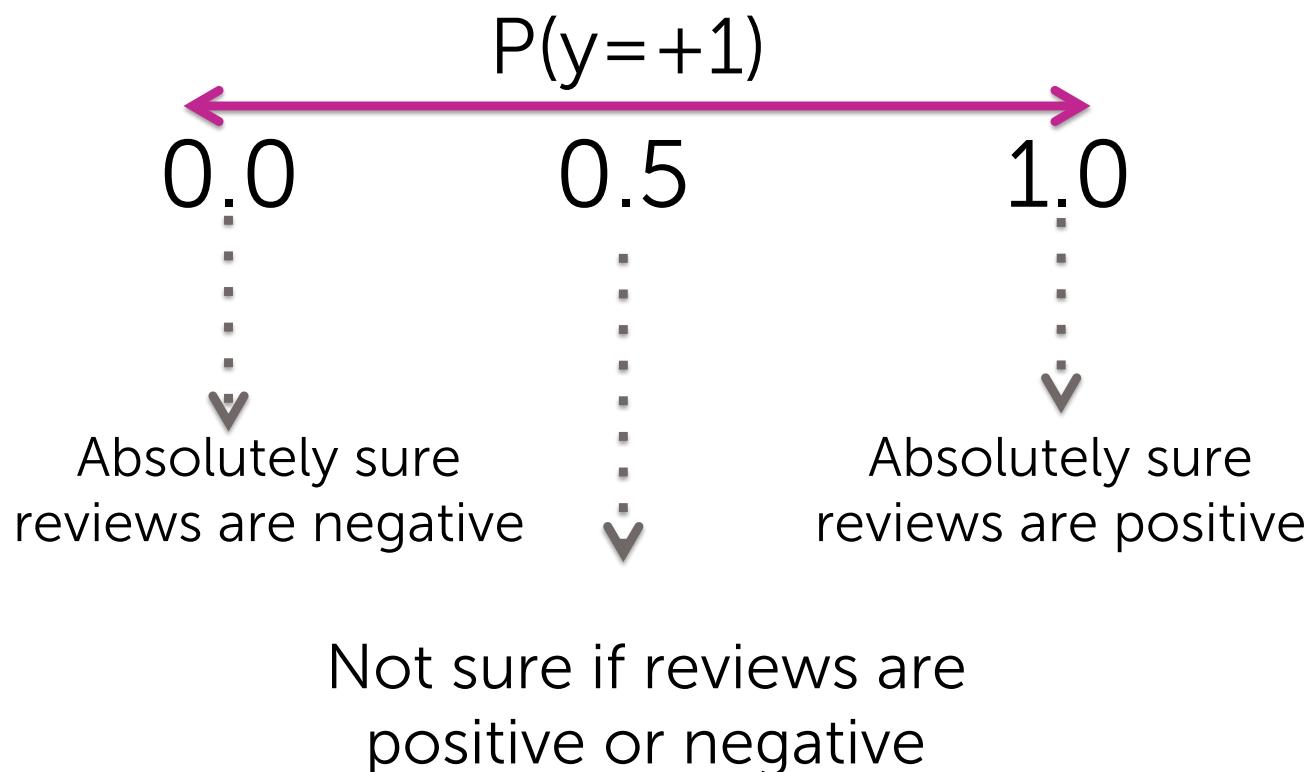
Probability a review is positive is 0.7



$x =$ review text	$y =$ sentiment
All the sushi was delicious! Easily best sushi in Seattle.	+1
The sushi & everything else were awesome!	+1
My wife tried their ramen, it was pretty forgettable.	-1
The sushi was good, the service was OK	+1
...	...

I expect 70% of rows
to have $y = +1$
(Exact number will vary
for each specific dataset)

Interpreting probabilities as degrees of belief



Key properties of probabilities

Property	Two class (e.g., y is +1 or -1)	Multiple classes (e.g., y is dog, cat or bird)
Probabilities always between 0 & 1	$0 \leq P(y=+1) \leq 1$ $0 \leq P(y=-1) \leq 1$	$0 \leq P(y=\text{dog}) \leq 1$ $0 \leq P(y=\text{cat}) \leq 1$ $0 \leq P(y=\text{bird}) \leq 1$
Probabilities sum up to 1	$P(y=+1) + P(y=-1) = 1$	$P(y=\text{dog}) + P(y=\text{cat}) + P(y=\text{bird}) = 1$

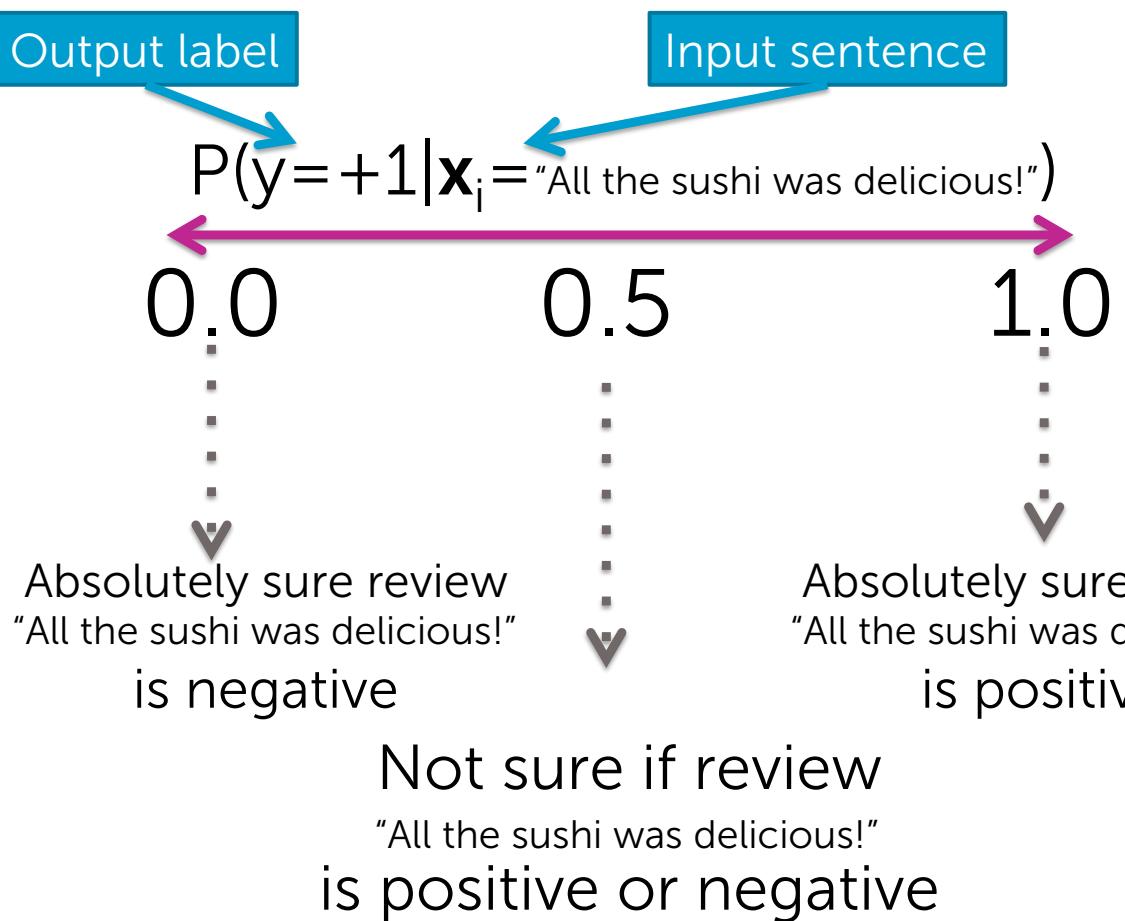
Conditional probability

Probability a review with
3 "awesome" and 1 "awful" is positive is 0.9

x = review text	y = sentiment
All the sushi was delicious! Easily best sushi in Seattle.	+1
Sushi was awesome & everything else was awesome! The service was awful , but overall awesome place!	+1
My wife tried their ramen, it was pretty forgettable.	-1
The sushi was good, the service was OK	+1
...	...
awesome ... awesome ... awful ... awesome	+1
...	...
awesome ... awesome ... awful ... awesome	-1
...	...
...	...
awesome ... awesome ... awful ... awesome	+1

I expect 90% of rows with reviews containing 3 "awesome" & 1 "awful" to have $y = +1$
(Exact number will vary for each specific dataset)

Interpreting conditional probabilities



Key properties of conditional probabilities

Property	Two class (e.g., y is +1 or -1, x_i is review text)	Multiple classes (e.g., y is dog, cat or bird, x_i is image)
Conditional probabilities always between 0 & 1	$0 \leq P(y=+1 \text{ given } x_i) \leq 1$ $0 \leq P(y=-1 \text{ given } x_i) \leq 1$	$0 \leq P(y=\text{dog} \text{ given } x_i) \leq 1$ $0 \leq P(y=\text{cat} \text{ given } x_i) \leq 1$ $0 \leq P(y=\text{bird} \text{ given } x_i) \leq 1$
Conditional probabilities sum up to 1 over y , but not over x	$P(y=+1 \text{ given } x_i) + P(y=-1 \text{ given } x_i) = 1$ But, $\Sigma(\text{Sum}) \text{ over } x \text{ of } P(y=+1 \text{ given } x_i) \neq 1$ $\Sigma \text{ over } i, i=1 \rightarrow N, P(y=+1 \text{ given } x_i) \neq 1$	$P(y=\text{dog} \text{ given } x_i) + P(y=\text{cat} \text{ given } x_i) + P(y=\text{bird} \text{ given } x_i) = 1$

How confident is your prediction?

"The sushi & everything else were awesome!"

Definite +1

$$P(y=+1|x=\text{"The sushi & everything else were awesome!"}) = 0.99$$

"The sushi was good, the service was OK"

Not sure

$$P(y=+1|x=\text{"The sushi was good, the service was OK"}) = 0.55$$

Many classifiers provide a degree of certainty:

Output label

$$P(y|x)$$

Input sentence

Extremely useful in practice

Goal: Learn conditional probabilities from data

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

$\mathbf{x}[1] = \#awesome$	$\mathbf{x}[2] = \#awful$	$y = \text{sentiment}$
2	1	+1
0	2	-1
3	3	-1
4	1	+1
...

Optimize **quality metric**
on training data

Find best model \hat{P}
by finding best $\hat{\mathbf{w}}$

Useful for
predicting \hat{y}

Sentence
from
review

Input: \mathbf{x}

Predict most likely class

$\hat{P}(y|x)$ = estimate of class probabilities

If $\hat{P}(y=+1|x) > 0.5$:

$\hat{y} = +1$

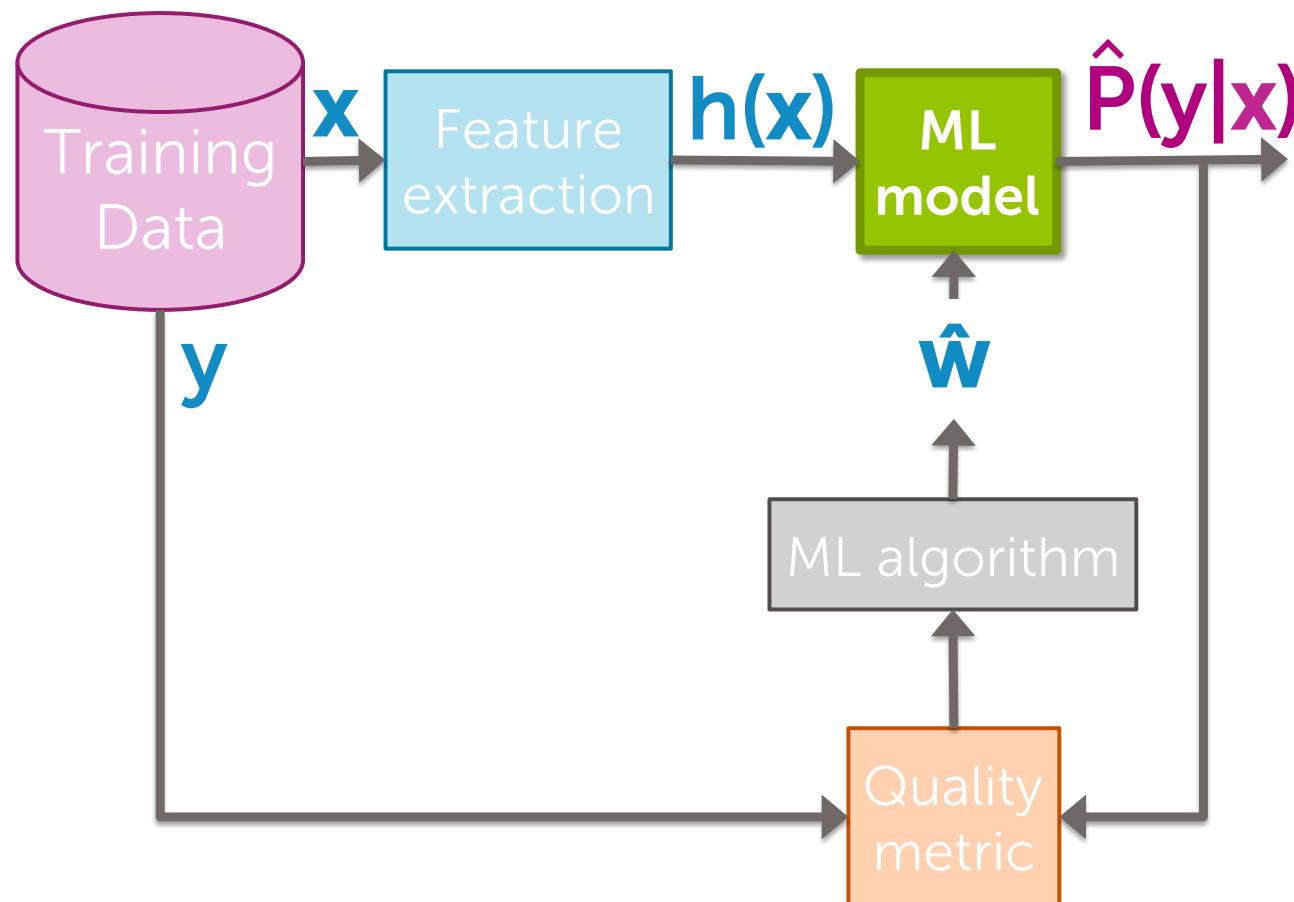
Else:

$\hat{y} = -1$

- Estimating $\hat{P}(y|x)$ improves **interpretability**:
 - Predict $\hat{y} = +1$ **and** tell me how sure you are

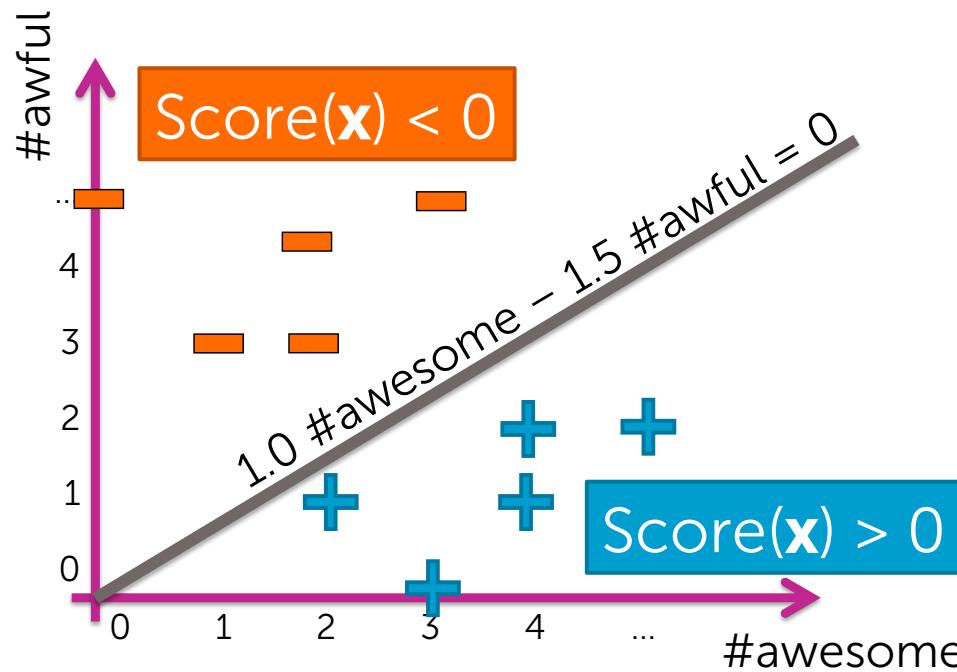


Predicting class probabilities with generalized linear models



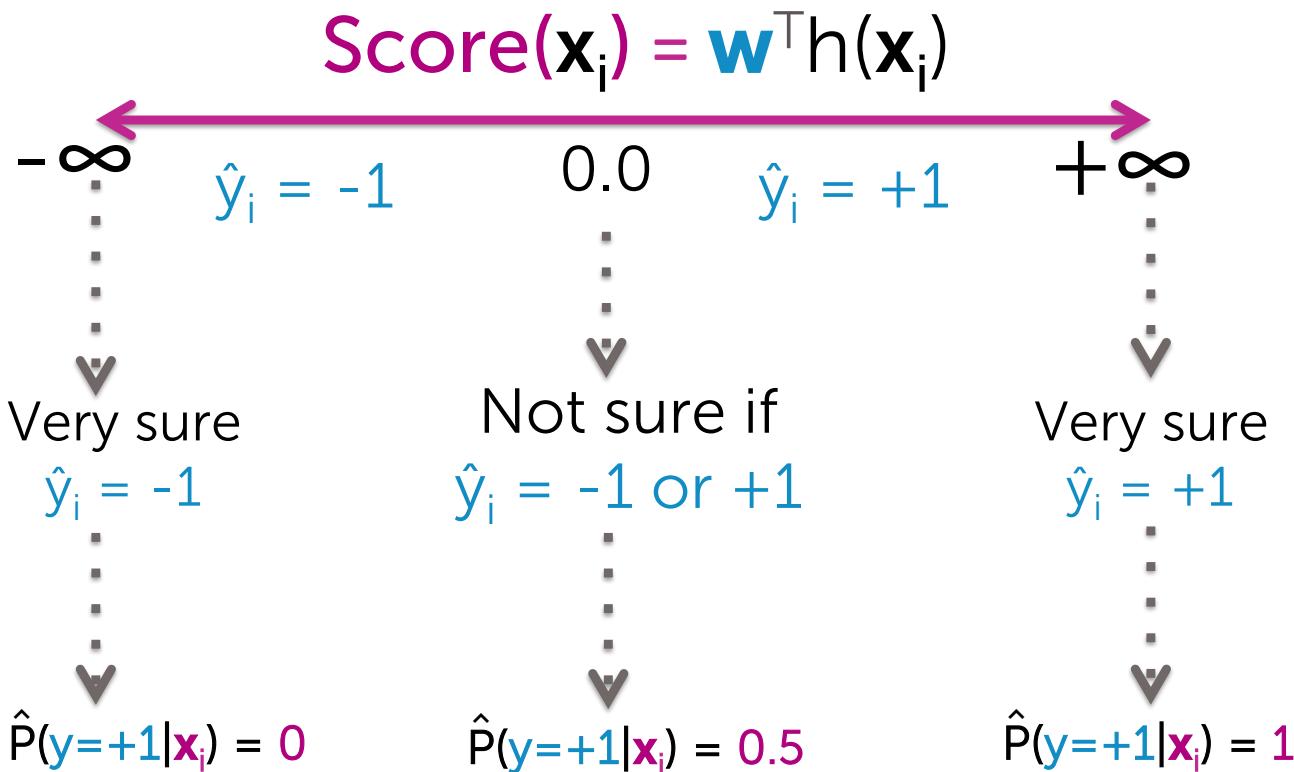
Thus far, we focused on decision boundaries

$$\begin{aligned}\text{Score}(\mathbf{x}_i) &= w_0 h_0(\mathbf{x}_i) + w_1 h_1(\mathbf{x}_i) + \dots + w_D h_D(\mathbf{x}_i) \\ &= \mathbf{w}^\top \mathbf{h}(\mathbf{x}_i)\end{aligned}$$

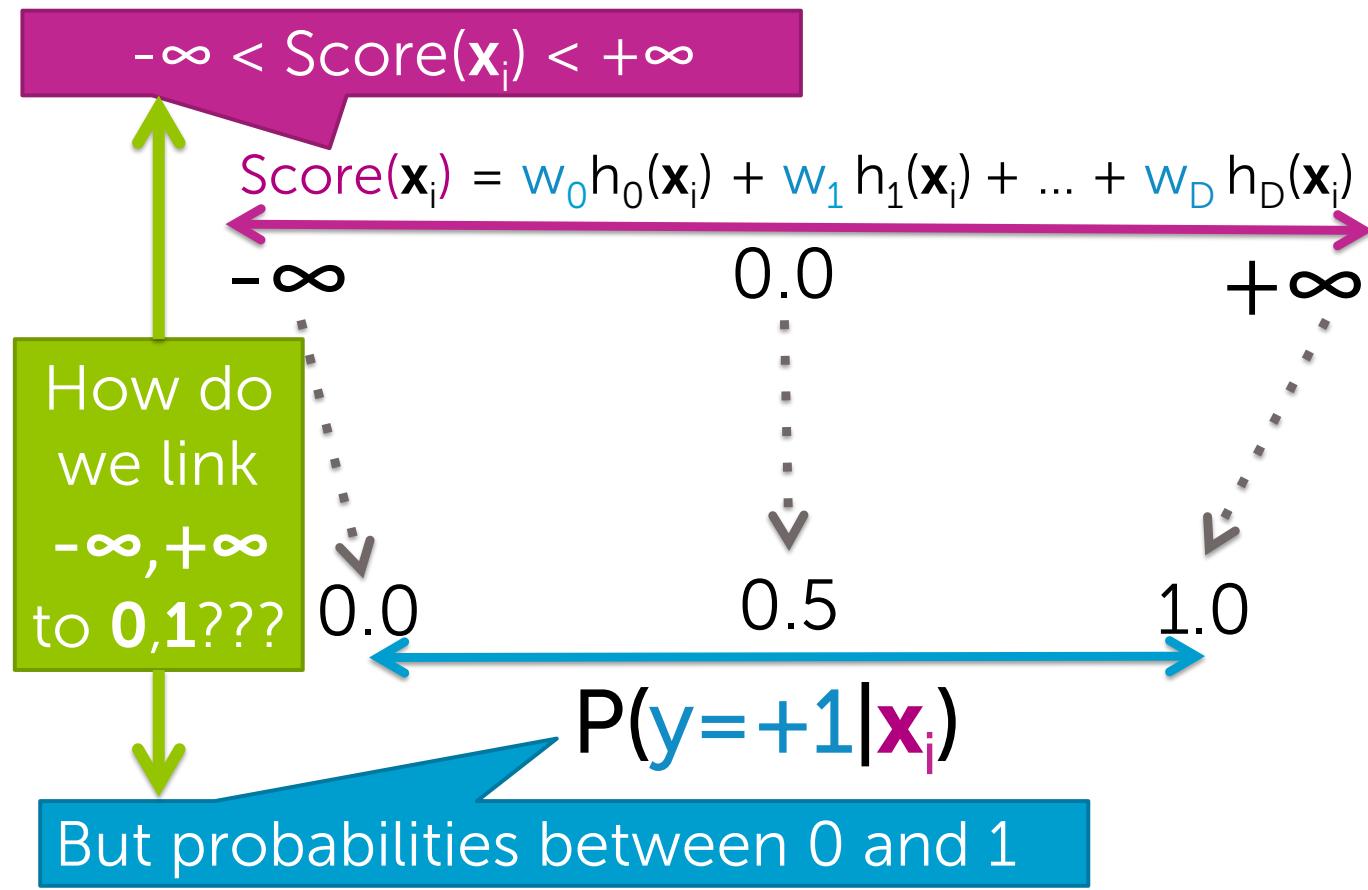


Relate
Score(\mathbf{x}_i) to
 $\hat{P}(y=+1|\mathbf{x}, \hat{\mathbf{w}})$?

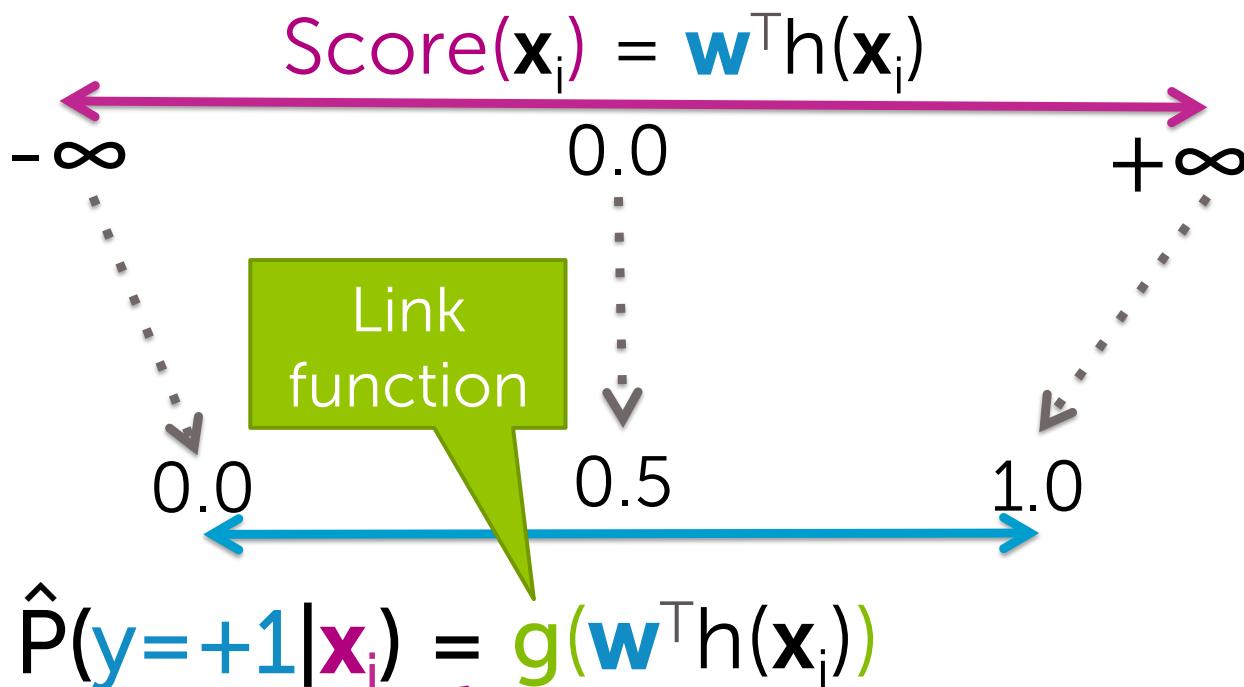
Interpreting $\text{Score}(\mathbf{x}_i)$



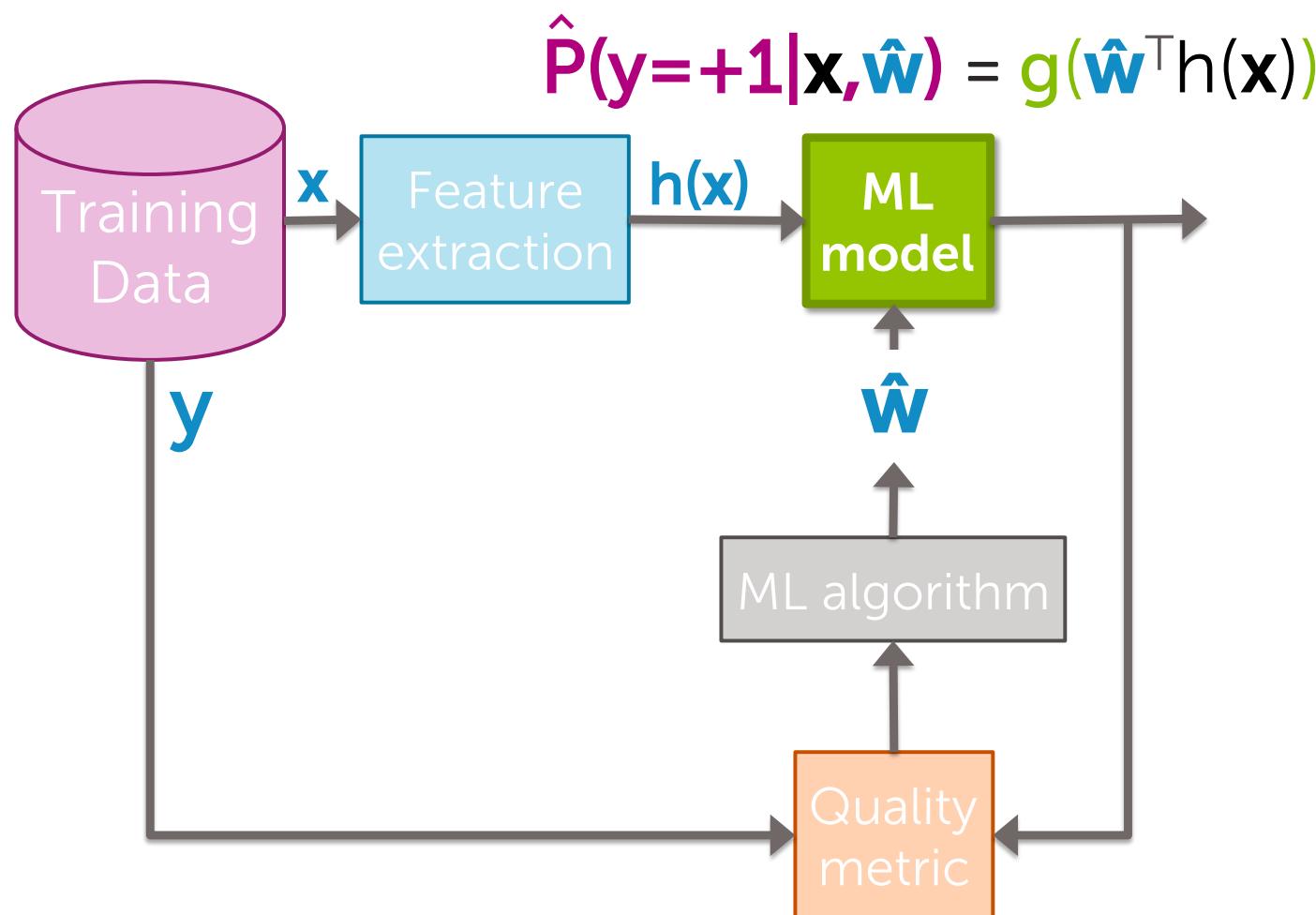
Why not just use regression to build classifier?



Link function: squeeze real line into [0,1]



Generalized linear model

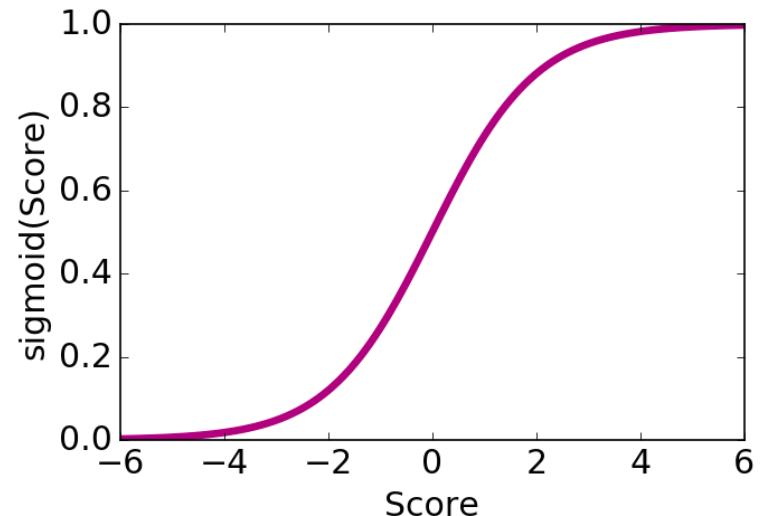


Logistic regression classifier: linear score with logistic link function

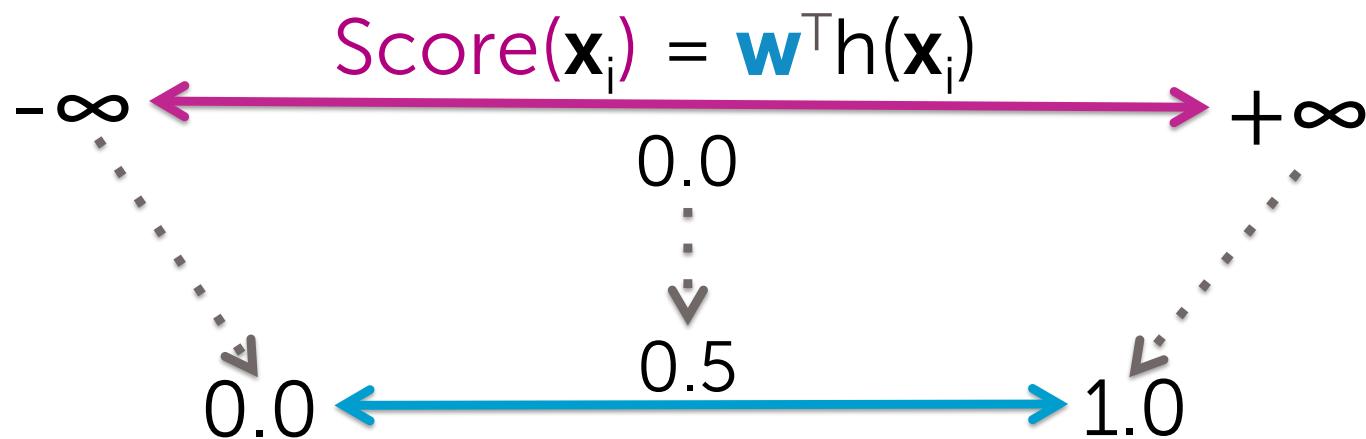
Logistic function (sigmoid, logit)

$$\text{sigmoid}(\text{Score}) = \frac{1}{1 + e^{-\text{Score}}}$$

Score	$-\infty$	-2	0.0	+2	$+\infty$
sigmoid(Score)					



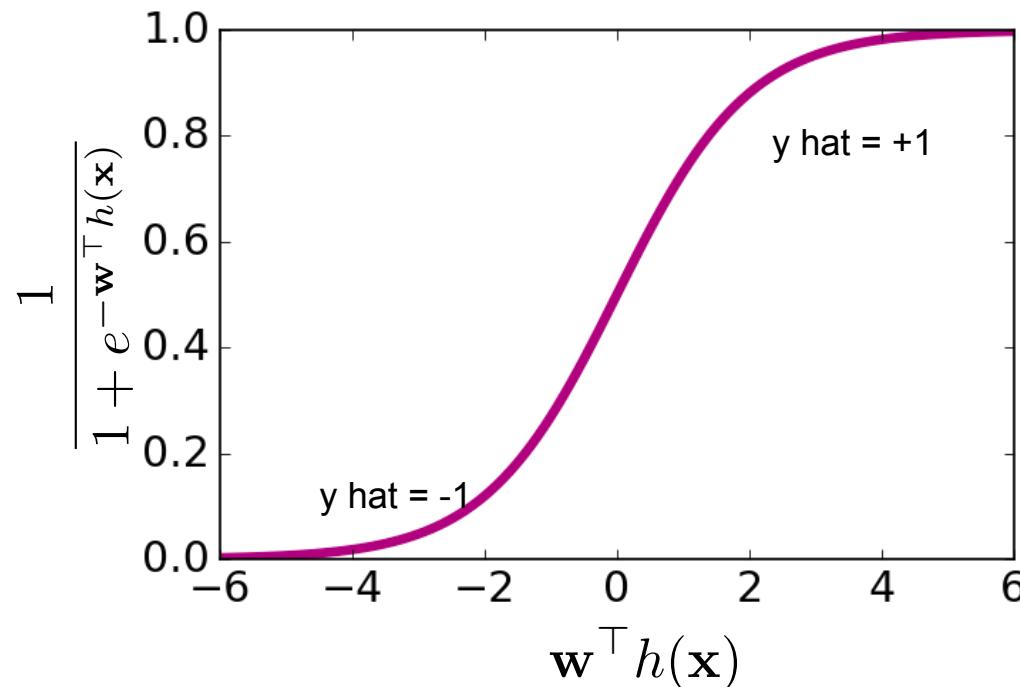
Logistic regression model



$$P(y=+1|\mathbf{x}_i, \mathbf{w}) = \text{sigmoid}(\text{Score}(\mathbf{x}_i))$$

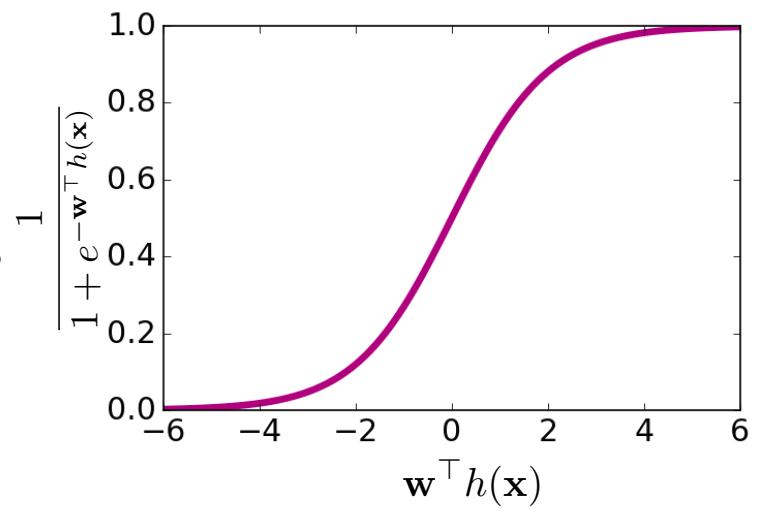
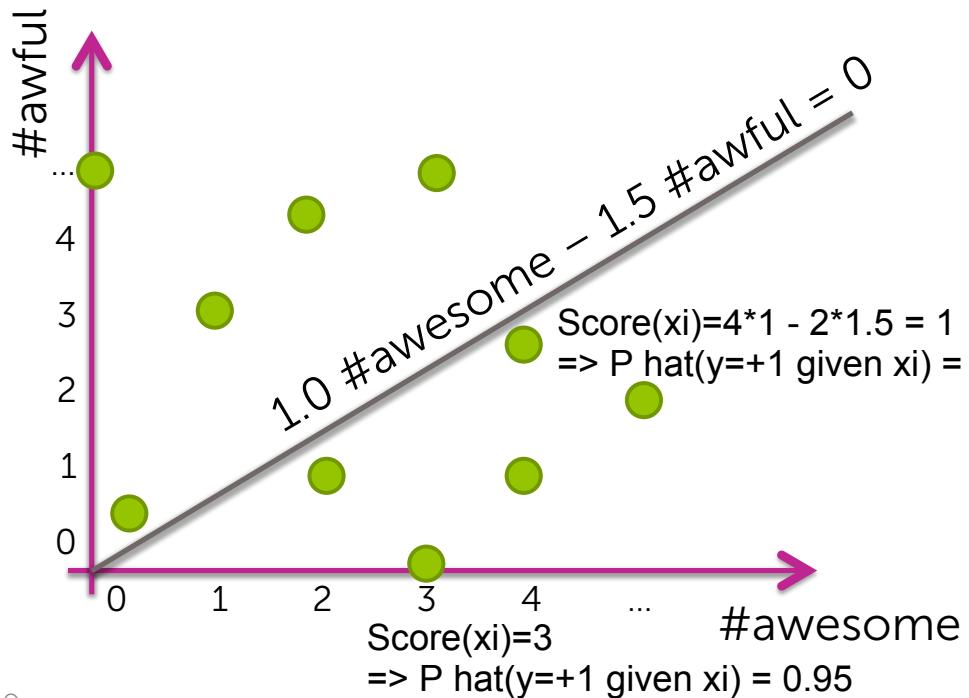
Understanding the logistic regression model

$$P(y = +1 \mid \mathbf{x}, \mathbf{w}) = \frac{1}{1 + e^{-\mathbf{w}^\top h(\mathbf{x})}}$$



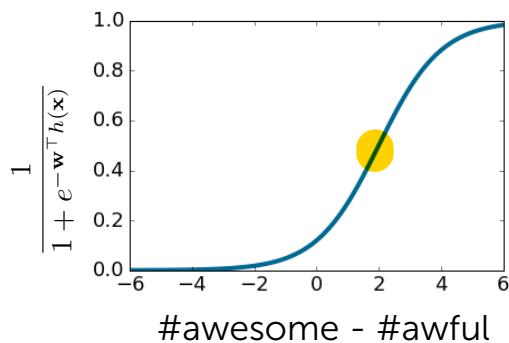
Score(\mathbf{x}_i)	$P(y=+1 \mathbf{x}_i, \mathbf{w})$
-2	$0.12 < 0.5 \Rightarrow y \text{ hat} = -1$
0	0.5
2	$0.88 > 0.5 \Rightarrow y \text{ hat} = +1$
4	$0.98 \Rightarrow y \text{ hat} = +1$

Logistic regression → Linear decision boundary

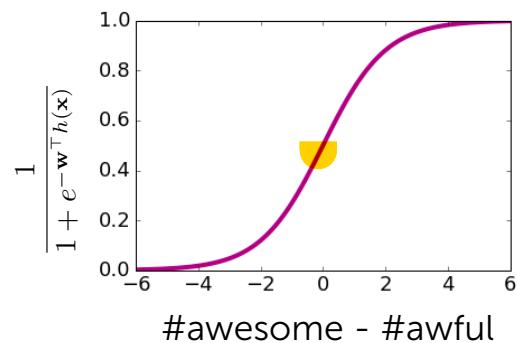


Effect of coefficients on logistic regression model

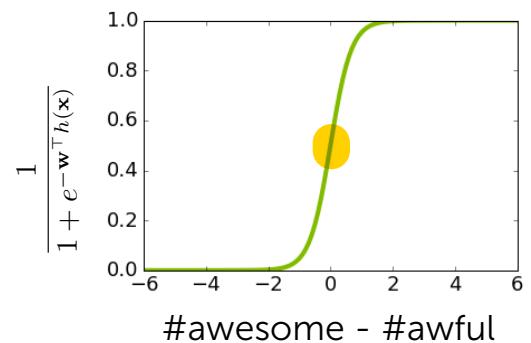
w_0	-2
$w_{\text{#awesome}}$	+1
$w_{\text{#awful}}$	-1



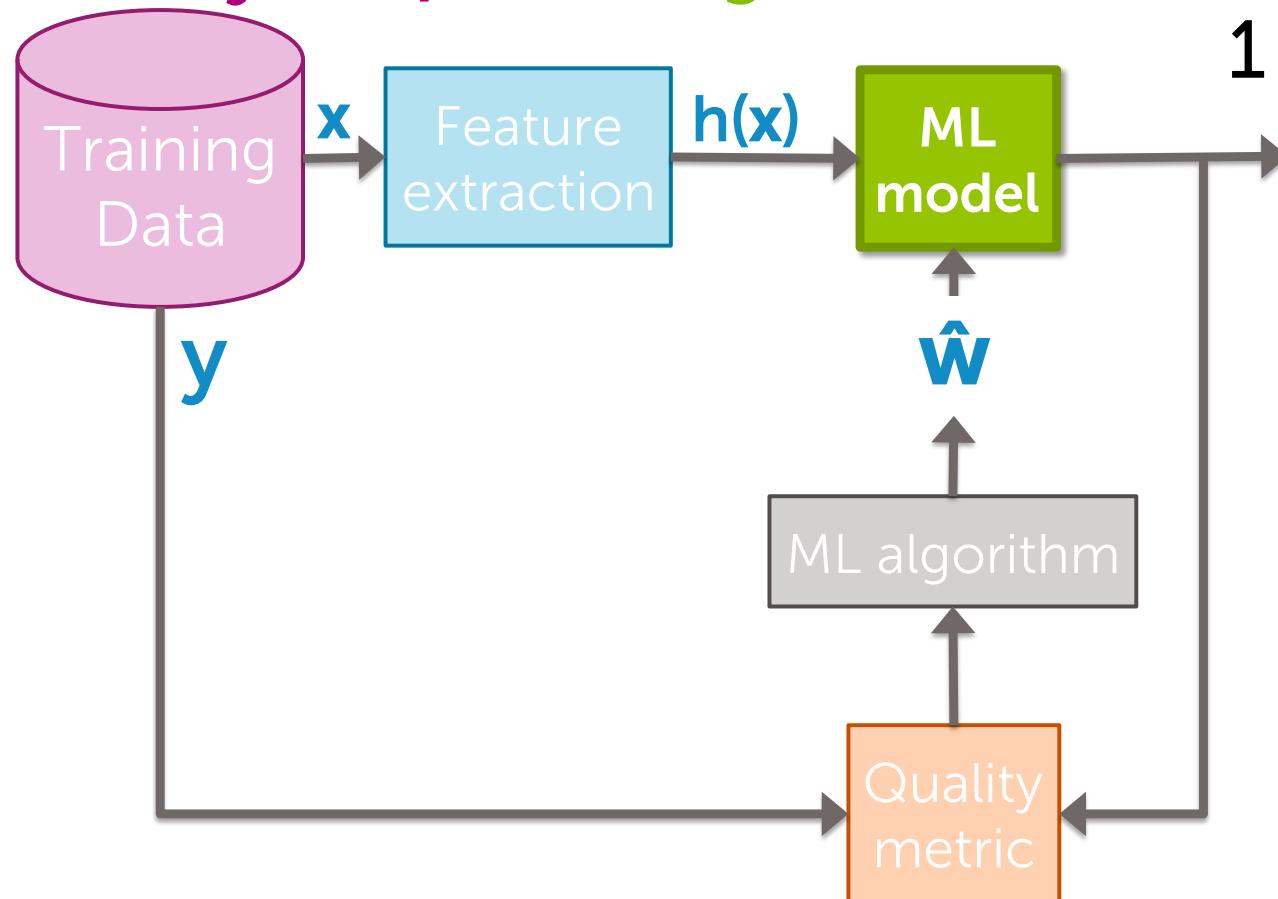
w_0	0
$w_{\text{#awesome}}$	+1
$w_{\text{#awful}}$	-1



w_0	0
$w_{\text{#awesome}}$	+3
$w_{\text{#awful}}$	-3



$$\hat{P}(y=+1|x, \hat{w}) = \text{sigmoid}(\hat{w}^T h(x)) = \frac{1}{1 + e^{-\hat{w}^T h(x)}}$$

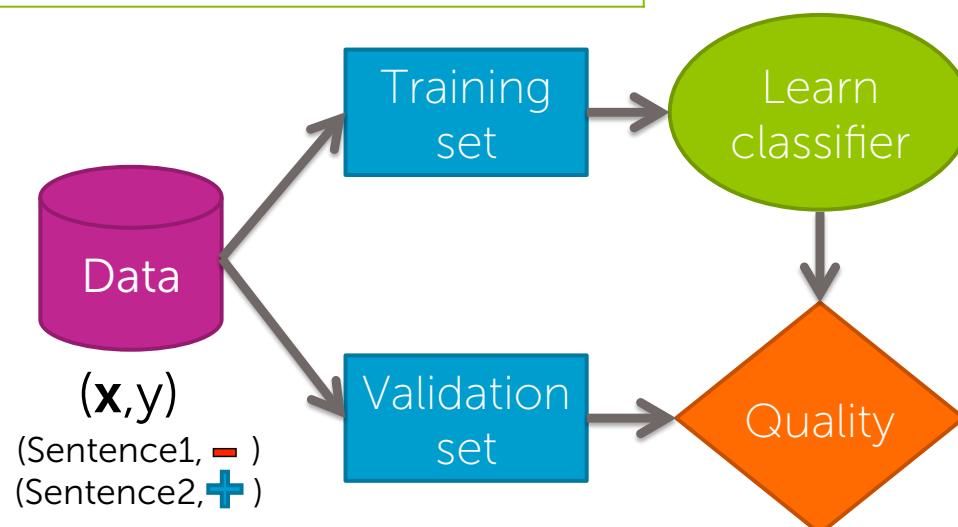


Overview of learning logistic regression model

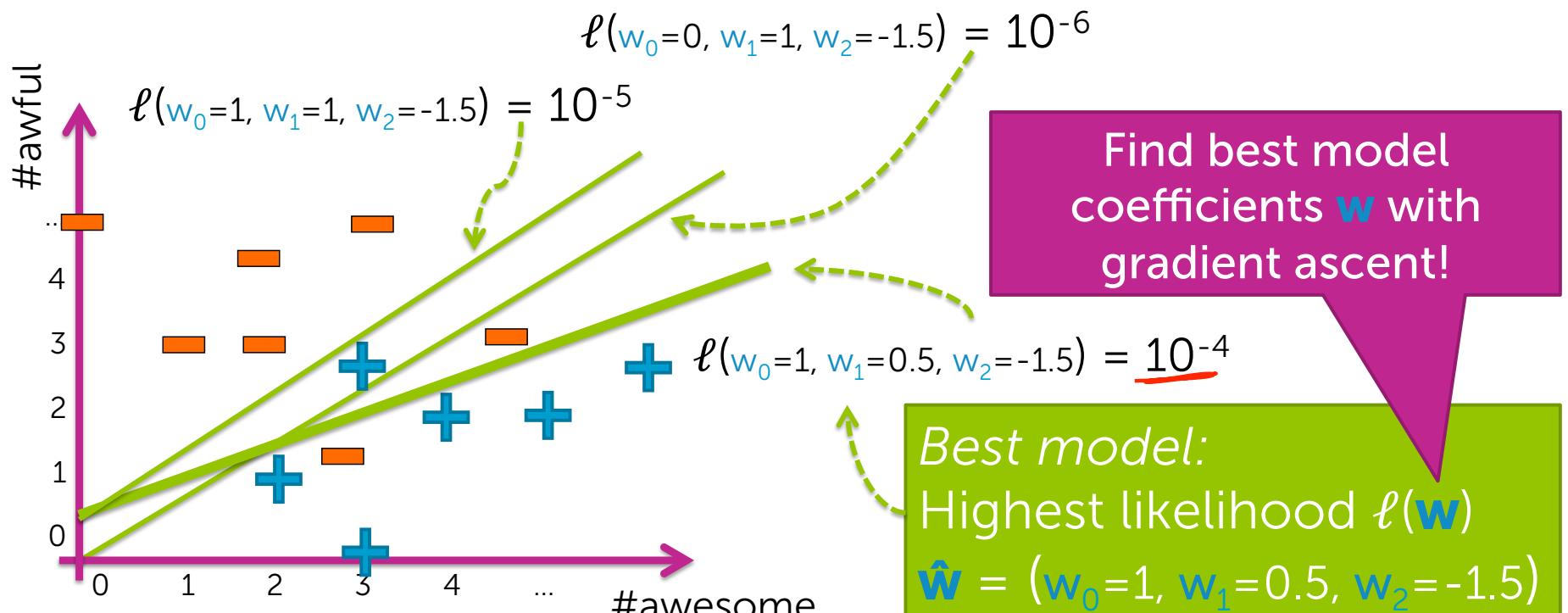
Training a classifier = Learning the coefficients

Word	Coefficient	Value
	\hat{w}_0	-2.0
good	\hat{w}_1	1.0
awesome	\hat{w}_2	1.7
bad	\hat{w}_3	-1.0
awful	\hat{w}_4	-3.3
...

$$\hat{P}(y=+1|x, \hat{w}) = \frac{1}{1 + e^{-\hat{w}^T h(x)}}$$



Find “best” classifier =
Maximize quality metric over all possible w_0, w_1, w_2
Likelihood $\ell(w)$



Encoding categorical inputs

Categorical inputs

- Numeric inputs:
 - #awesome, age, salary,...
 - Intuitive when multiplied by coefficient
 - e.g., **1.5 #awesome**

Numeric value, but should be interpreted as category
(98195 not about 9x larger than 10005)



Gender
(Male, Female,...)



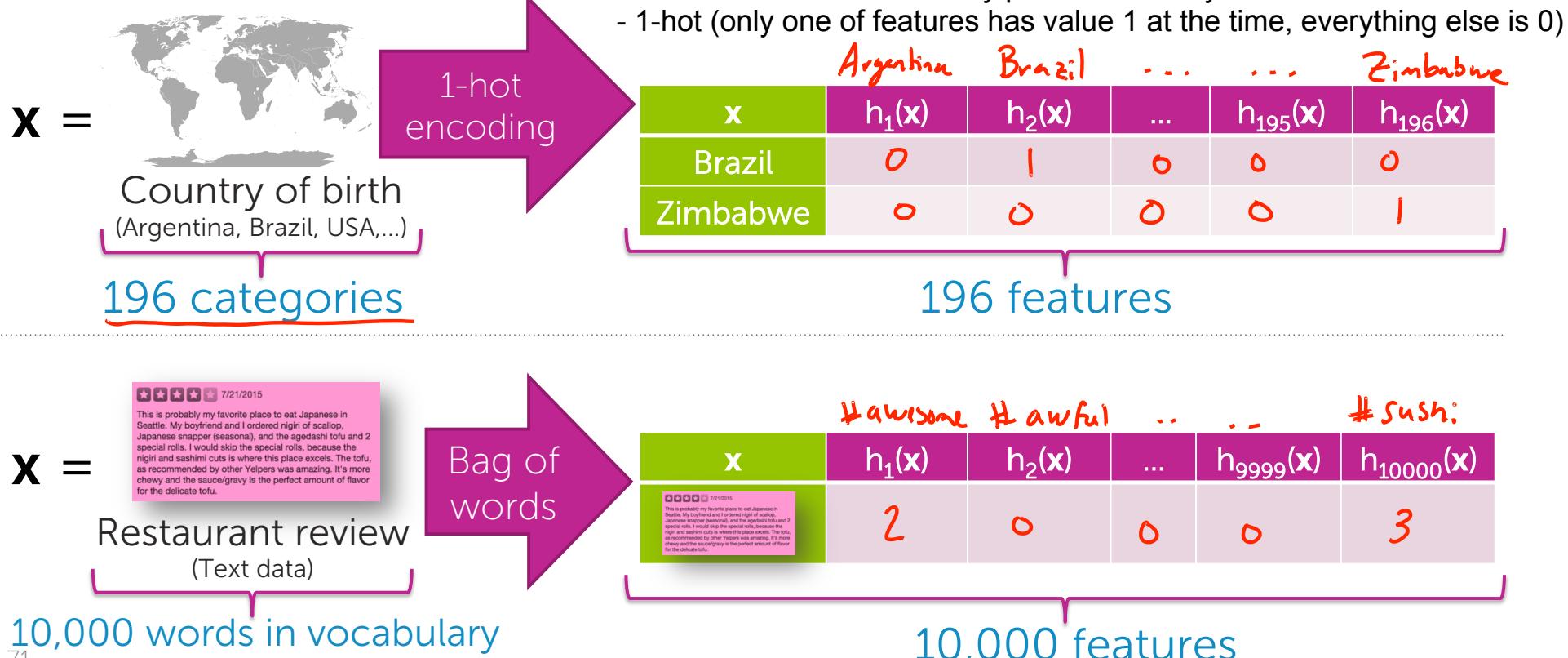
Country of birth
(Argentina, Brazil, USA,...)



Zipcode
(10005, 98195,...)

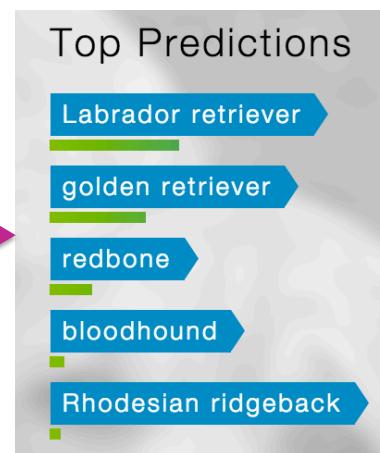
How do we multiply category by coefficient???
Must convert categorical inputs into numeric features

Encoding categories as numeric features



Multiclass classification using 1 versus all

Multiclass classification



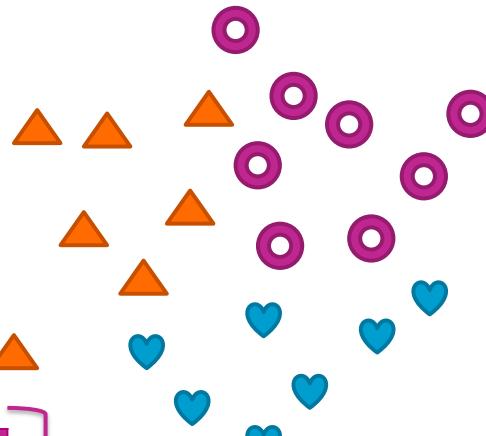
Input: x
Image pixels

Output: y
Object in image

Multiclass classification formulation

- C possible classes:
 - y can be 1, 2, ..., C
- N datapoints:

Data point	$x[1]$	$x[2]$	y
\mathbf{x}_1, y_1	2	1	▲
\mathbf{x}_2, y_2	0	2	♥
\mathbf{x}_3, y_3	3	3	○
\mathbf{x}_4, y_4	4	1	○



Learn:

$$\hat{P}(y=\triangle | \mathbf{x})$$

$$\hat{P}(y=\heartsuit | \mathbf{x})$$

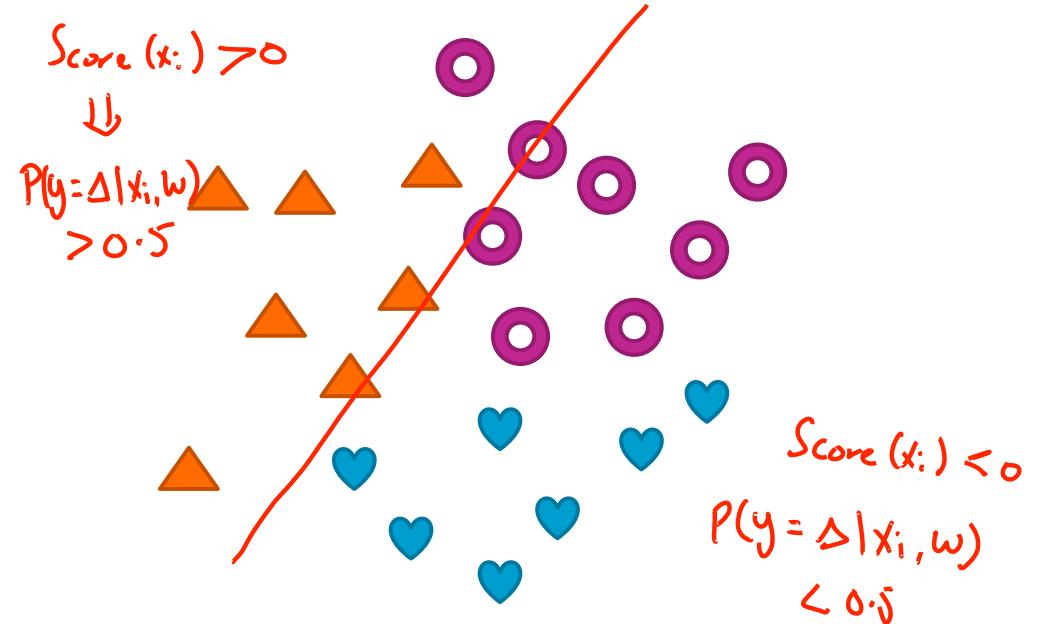
$$\hat{P}(y=\circlearrowleft | \mathbf{x})$$

1 versus all: Estimate $\hat{P}(y=\Delta|x)$ using 2-class model

+1 class: points with $y_i = \Delta$
-1 class: points with $y_i = \heartsuit$ OR \circ

Train classifier: $\hat{P}(\Delta|y=+1|x)$

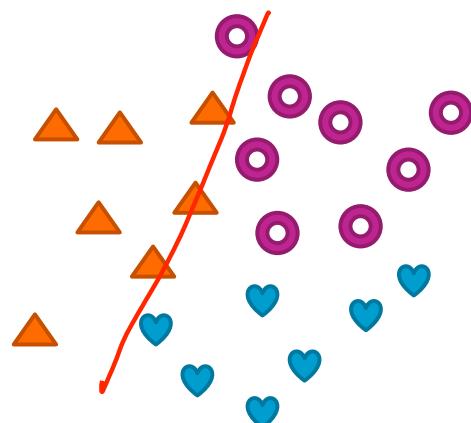
Predict: $\hat{P}(y=\Delta|x_i) = \hat{P}(\Delta|y=+1|x_i)$



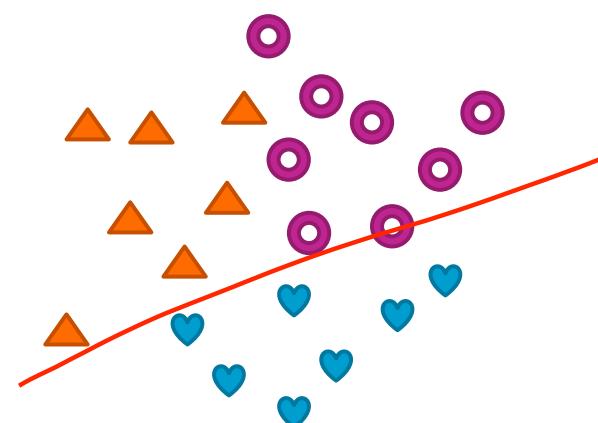
1 versus all: simple multiclass classification using C 2-class models

- 1 versus all for each of the classes
- w is different for each case
- What do we output? As a prediction, whatever class has the highest probability wins

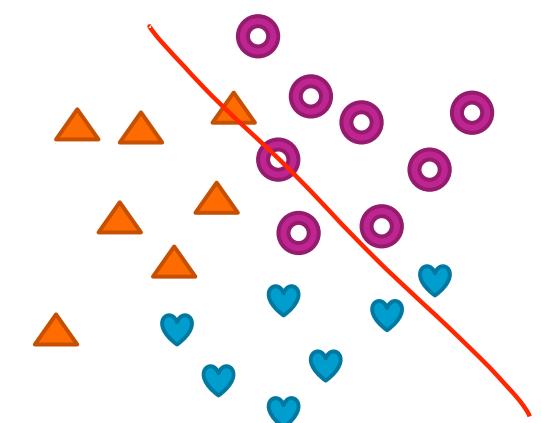
$$\hat{P}(y=\triangle | \mathbf{x}_i) = \hat{P}_\Delta(y=+1 | \mathbf{x}_i, w)$$



$$\hat{P}(y=\heartsuit | \mathbf{x}_i) = \hat{P}_\heartsuit(y=+1 | \mathbf{x}_i, w)$$



$$\hat{P}(y=\circlearrowleft | \mathbf{x}_i) = \hat{P}_\circlearrowleft(y=+1 | \mathbf{x}_i, w)$$



Multiclass training

$\hat{P}_c(y=+1|x)$ = estimate of
1 vs all model for each class



Input: \mathbf{x}_i

→ Predict most likely class

$\text{max_prob} = 0; \hat{y} = 0$

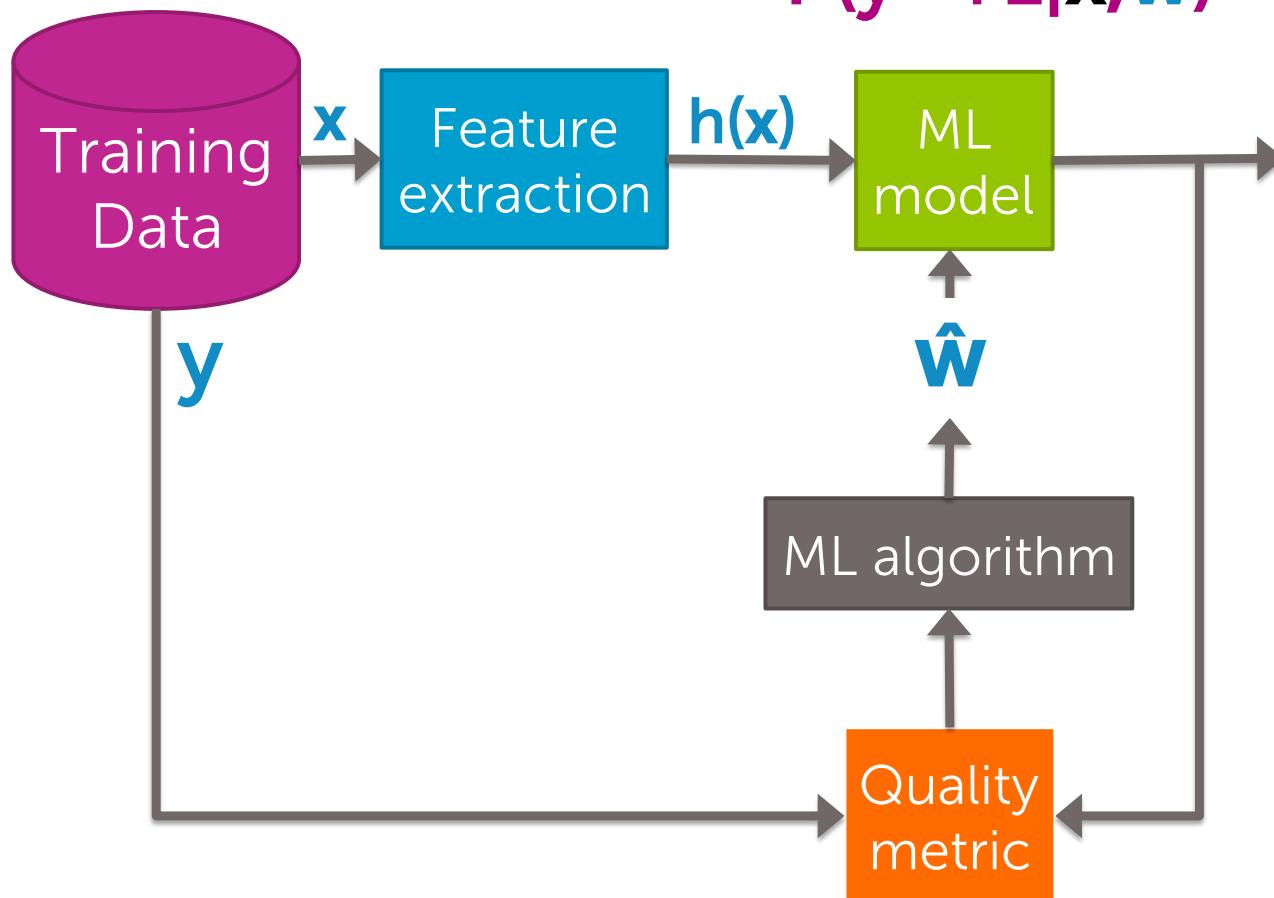
For $c = 1, \dots, C$:

If $\hat{P}_c(y=+1|\mathbf{x}_i) > \text{max_prob}$:

$\hat{y} = c$

$\text{max_prob} = \hat{P}_c(y=+1|\mathbf{x}_i)$

Summary of logistic regression classifier



$$\hat{P}(y=+1|x, \hat{w}) = \frac{1}{1 + e^{-\hat{w}^T h(x)}}$$



What you can do now...

- Describe decision boundaries and linear classifiers
- Use class probability to express degree of confidence in prediction
- Define a logistic regression model
- Interpret logistic regression outputs as class probabilities
- Describe impact of coefficient values on logistic regression output
- Use 1-hot encoding to represent categorical inputs
- Perform multiclass classification using the 1-versus-all approach