

Data Science

Lecture 2-2: Data Science Fundamentals (Modeling)



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Date: Feb 2023

This lecture recaps **classification** and **regression** techniques for modeling data.

Classification

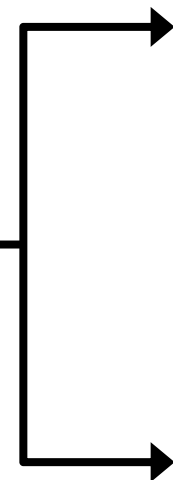
For this lecture, let us now use the following text classification task as an example: identifying **whether a text message is spam or ham (non-spam)**.

◆◆◆◆◆◆◆◆◆◆ PRIVATE!
Your 2020 Account won \$1,000,000
lottery! ◆◆◆◆◆◆◆◆◆◆ To claim
call 08719180248 ◆◆◆◆◆◆◆◆◆◆

Hi Yen-Chia, may we have our
meeting on 5/15 by just email
update to buy some time? if not,
zero worries if you need to talk.



Mail



Spam



Ham
(Non-spam)

Classification

To classify spam messages, we need examples: a **dataset** with **observations** (messages) and **labels** (spam or non-spam).

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lottery! ◆◆◆◆◆◆◆◆◆◆ To claim call 08719180248 ◆◆◆◆◆◆◆◆◆◆



Spam

Hi Yen-Chia, may we have our meeting on 5/15 by just email update to
buy some time? if not, zero worries if you need to talk.



Ham

Would you be willing to meet with me on 3/26 Thursday when I was in
TU Delft after (or before) giving the guest lecture (10:35am-11:50am)?



Ham



Observations



Labels

Classification

We can extract **features (information)** using human knowledge, which can help distinguish spam and ham messages.

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lottery! ◆◆◆◆◆◆◆◆◆◆ To claim call 08719180248 ◆◆◆◆◆◆◆◆◆◆



Spam

Number of special characters = 34

Number of digits = 22

Hi Yen-Chia, may we have our meeting on 5/15 by just email update to
buy some time? if not, zero worries if you need to talk.



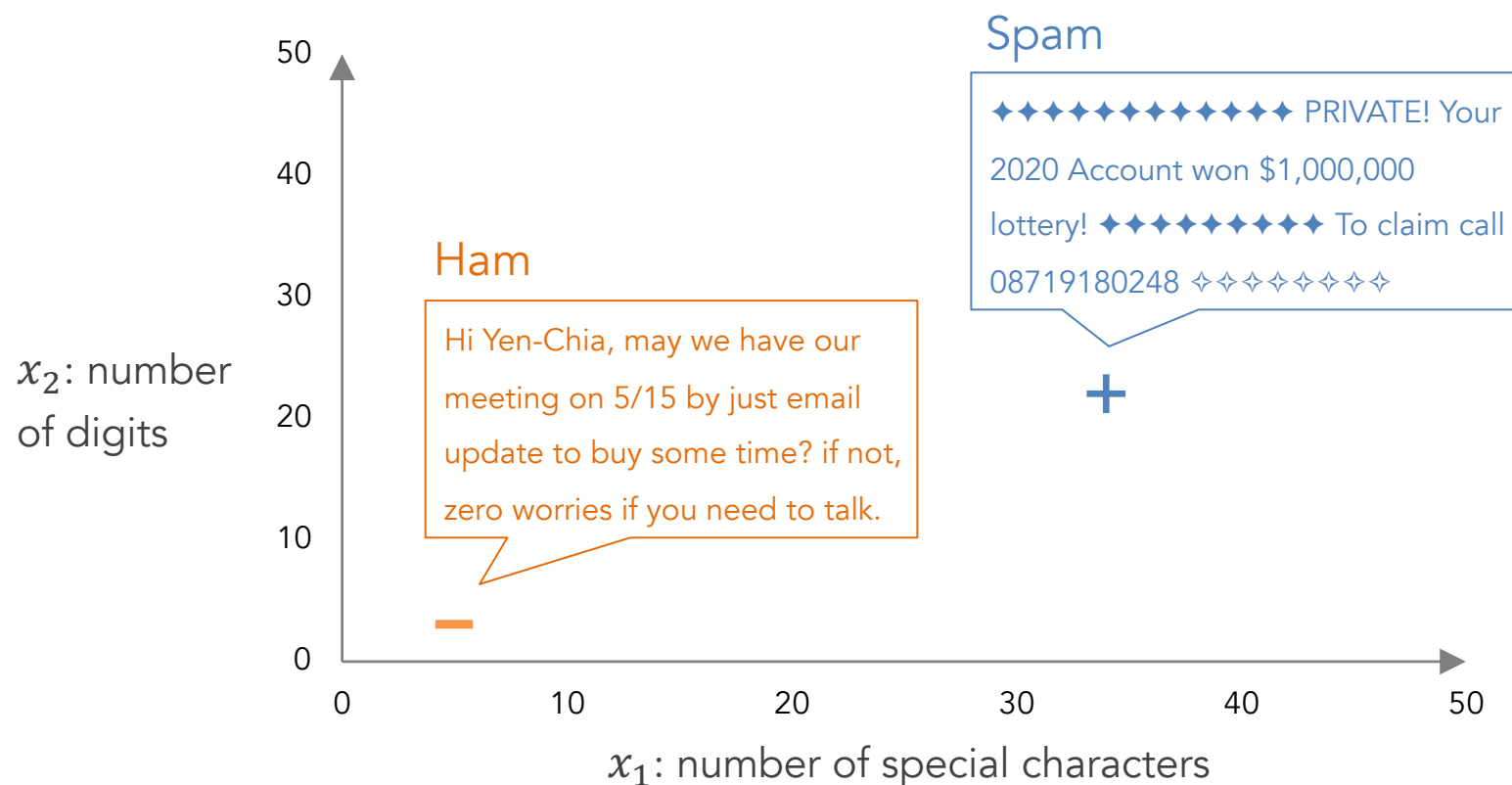
Ham

Number of special characters = 5

Number of digits = 3

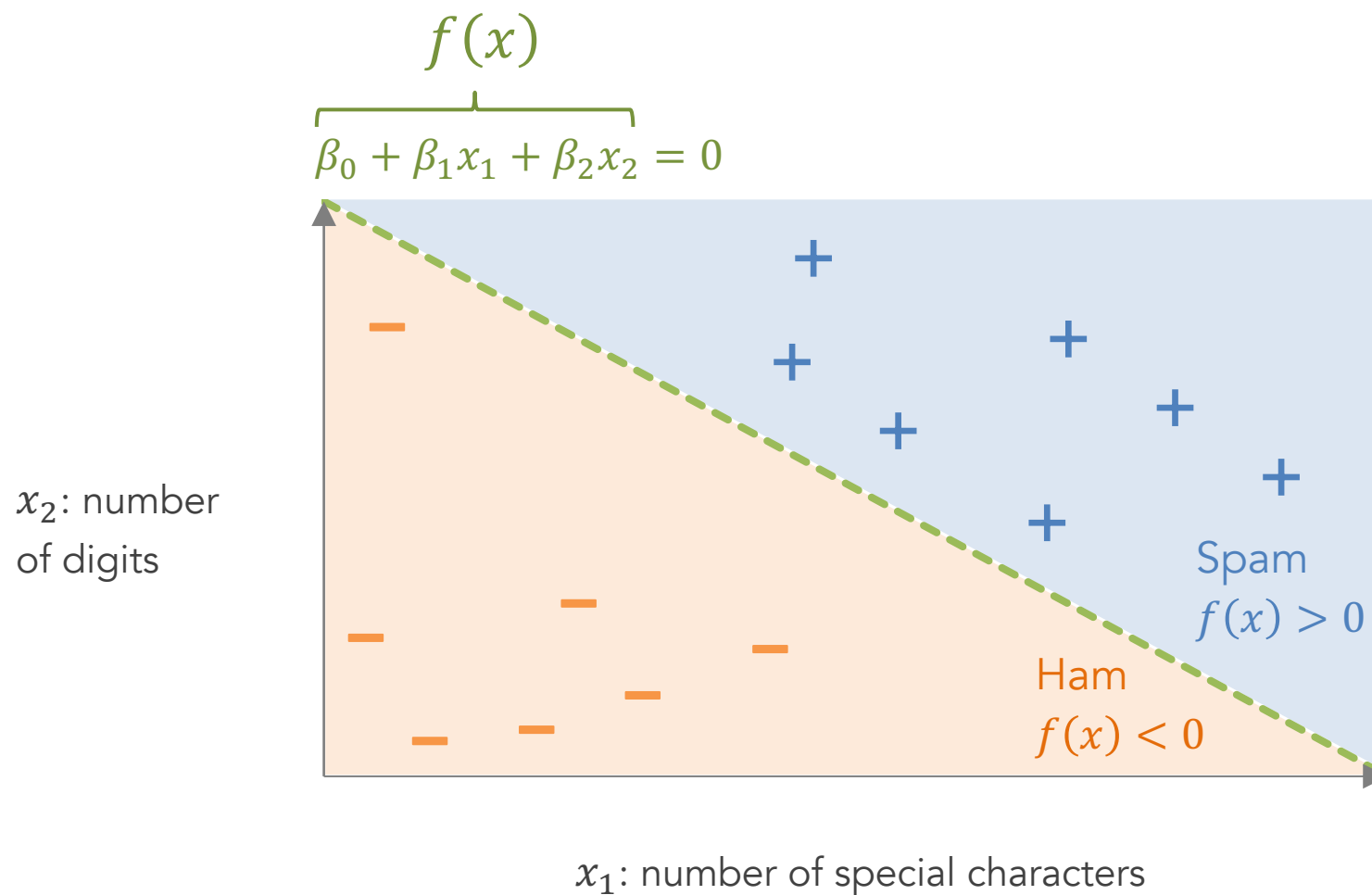
Classification

Using **features x** (which contains x_1 and x_2), we can represent each message **as one data point** on an p -dimensional space ($p = 2$ in this case).



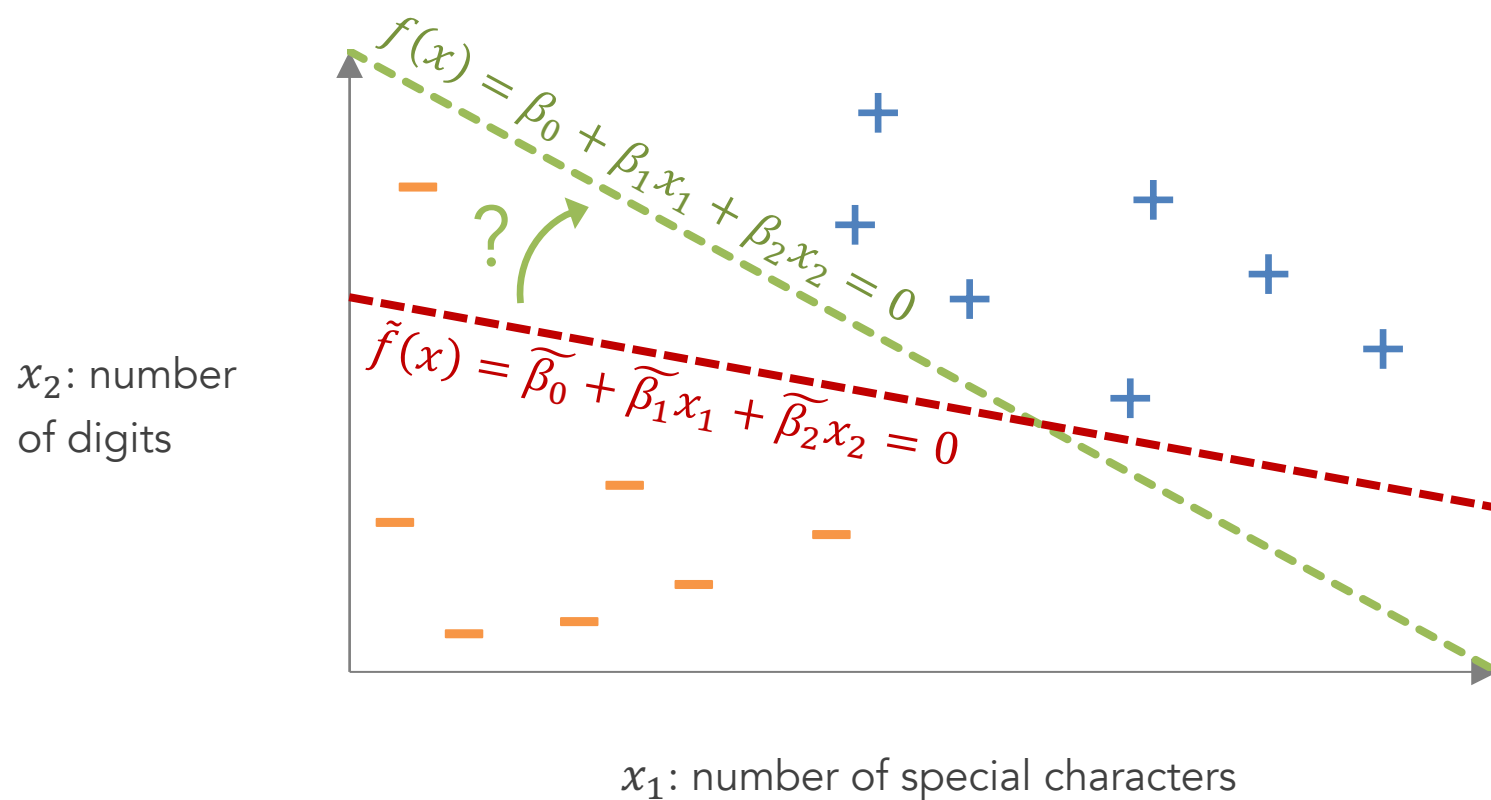
Classification

We can think of the model as a function f that can separate the observations into groups (i.e., class labels y) according to their features $x = \{x_1, x_2\}$.



Classification

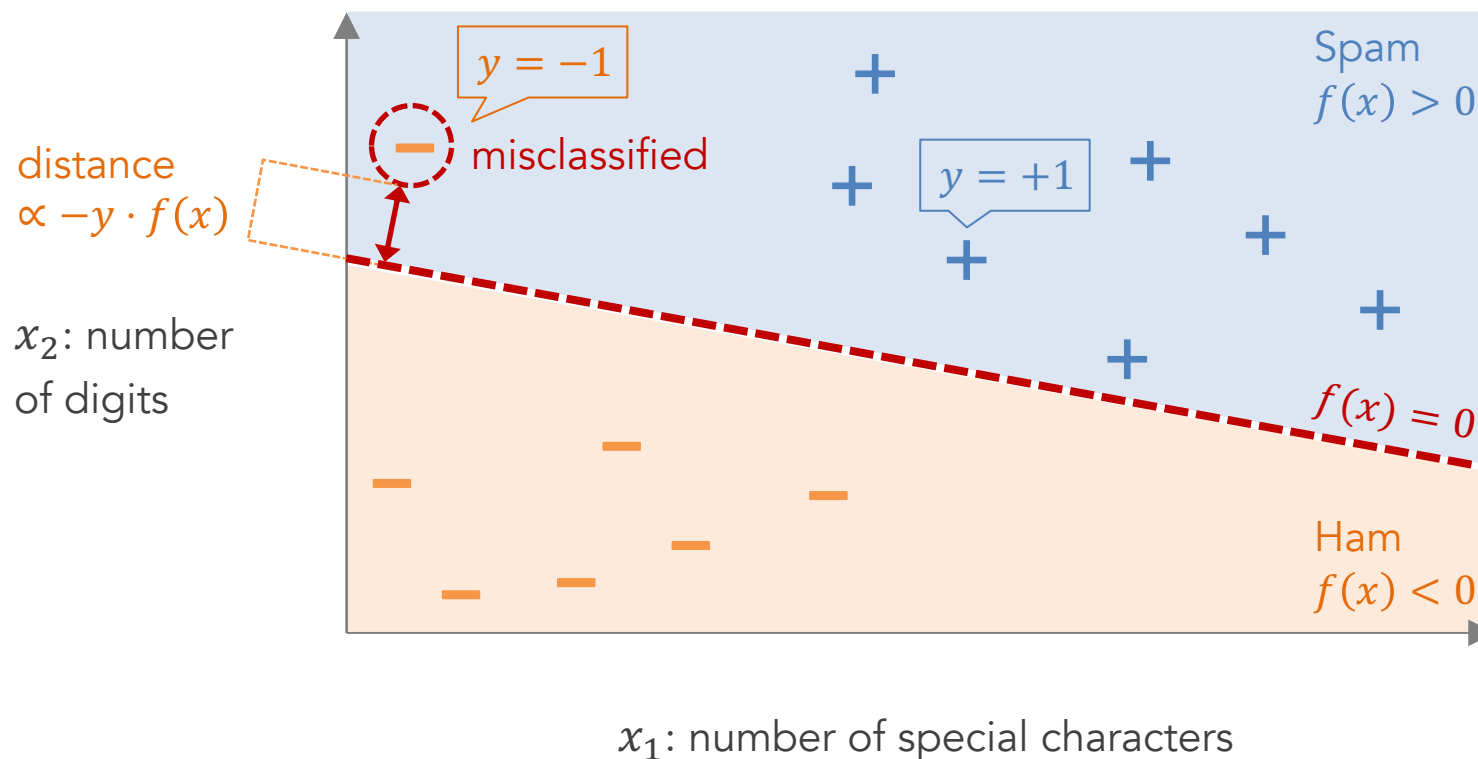
To find a good function f , we start from some f and **train it** until satisfied. We need something to tell us **which direction and magnitude** to update.



Classification

First, we need an error metric (i.e., cost or objective function). For example, we can use the **sum of distances** between the misclassified points and line f .

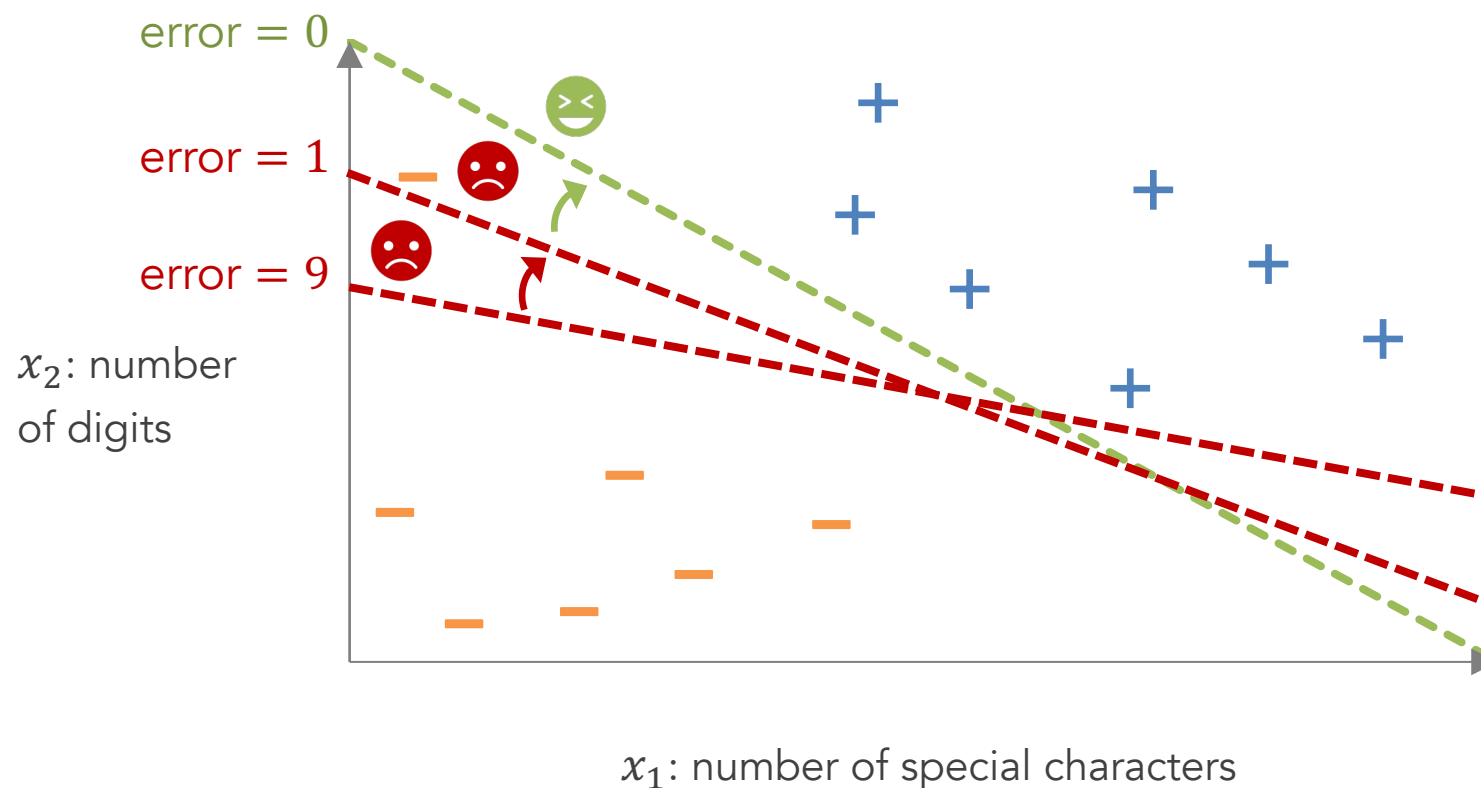
$$\text{error} = \sum -y \cdot f(x) \quad \text{for each misclassified point } x = \{x_1, x_2\}$$



Classification

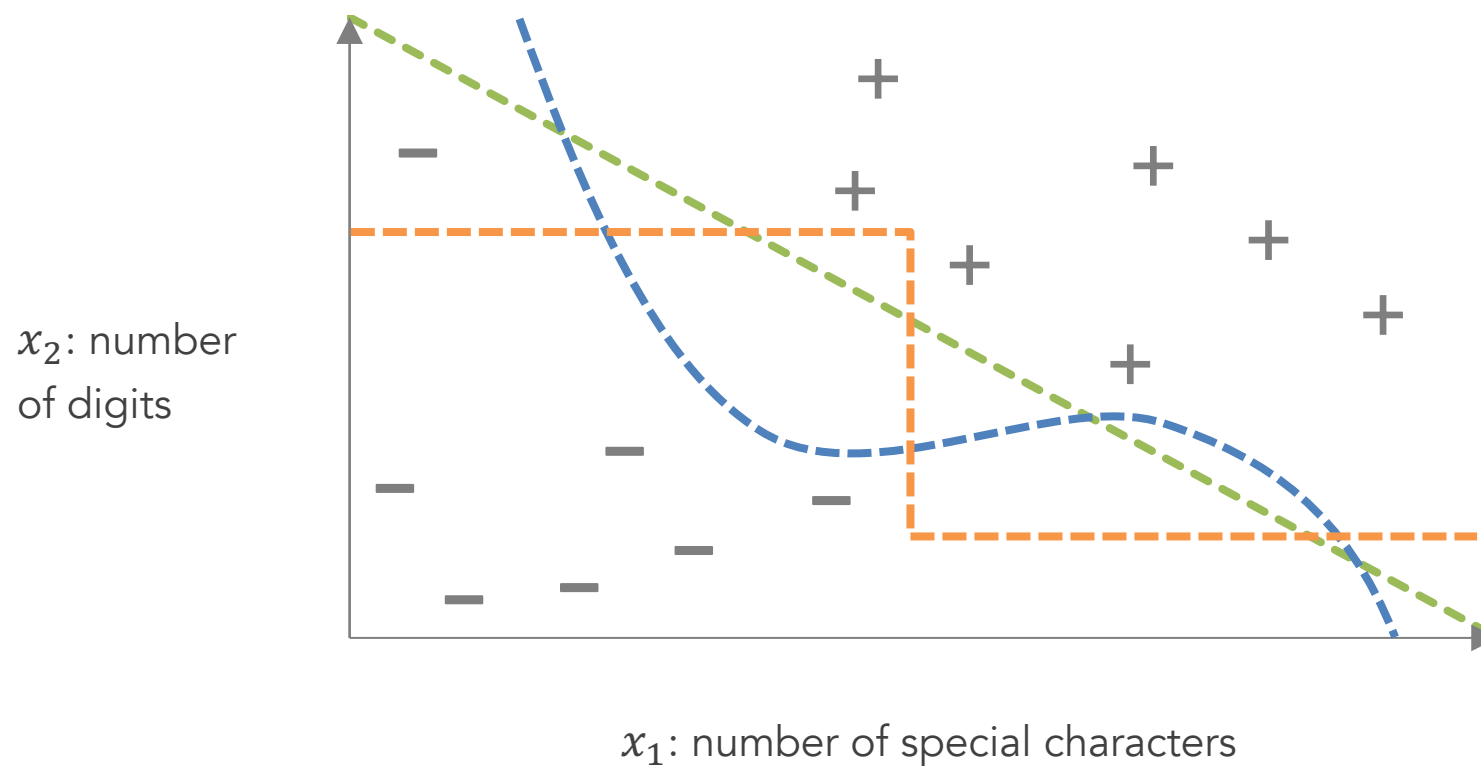
We can use gradient descent (an optimization algorithm) to **minimize the error** to train the model f iteratively. This example is the Perceptron algorithm.

$$\text{minimize error} = \sum -y \cdot f(x) \quad \text{for each misclassified point } x = \{x_1, x_2\}$$



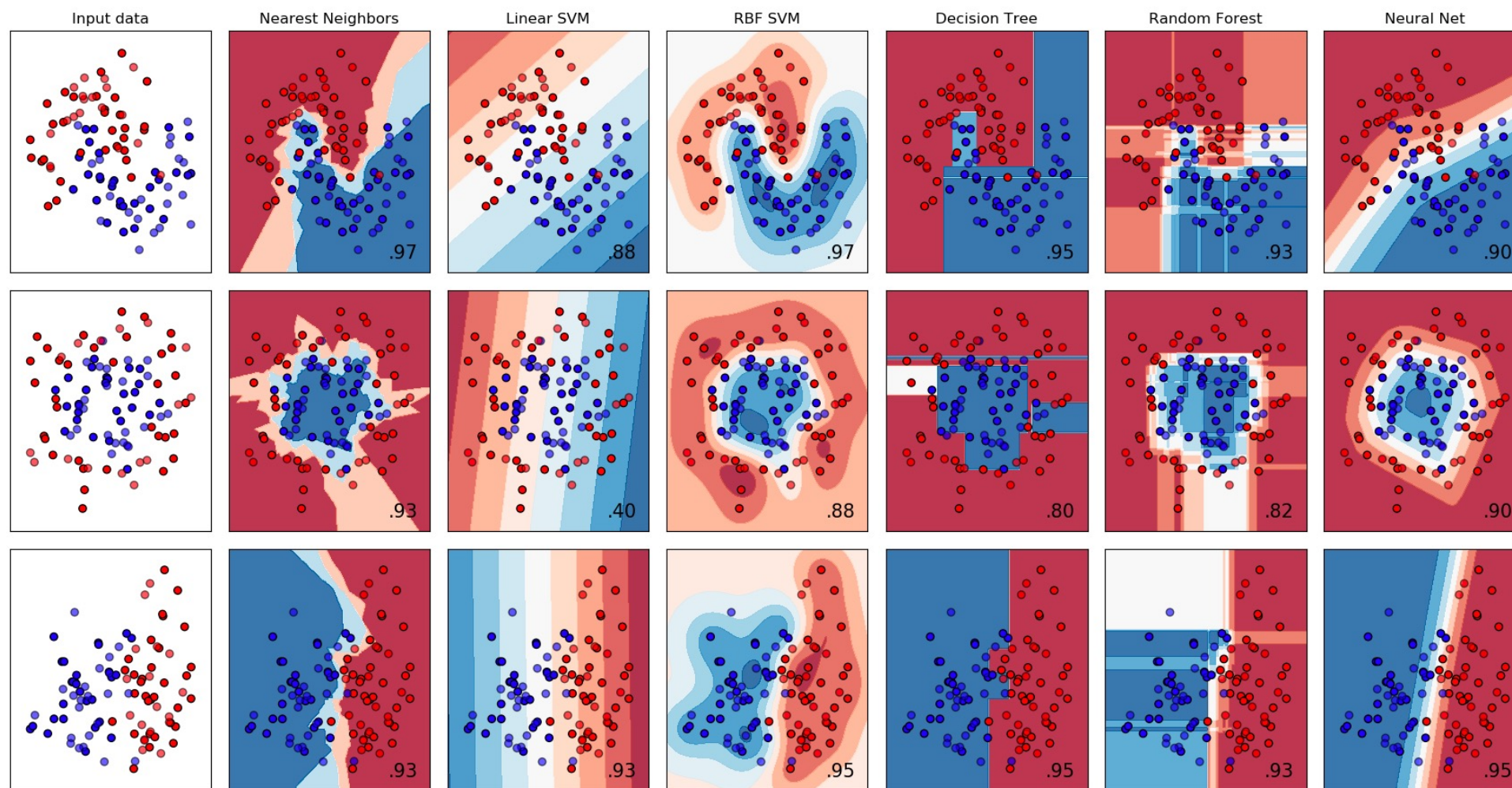
Classification

Depending on the needs, we can train **different models** (using different loss functions) with various shapes of decision boundaries.



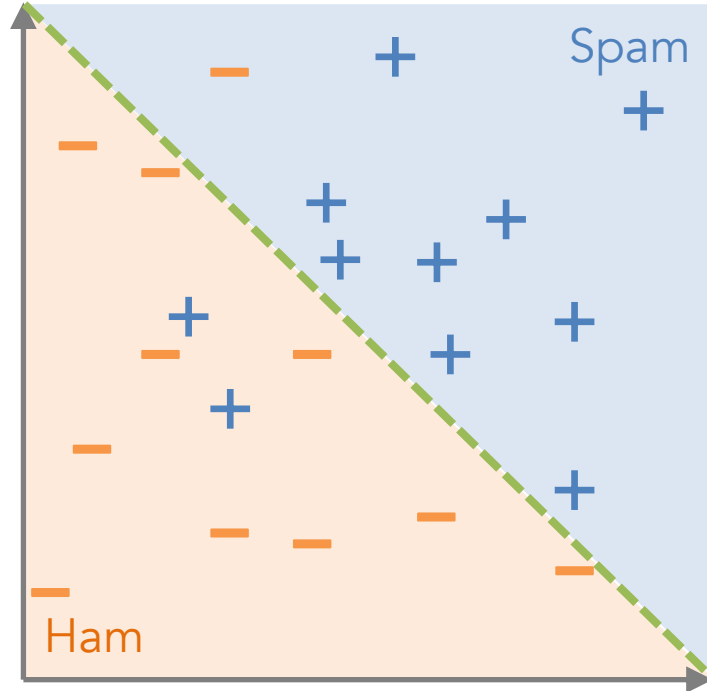
Classification

Depending on the needs, we can train **different models** (using different loss functions) with various shapes of decision boundaries.



Classification

To evaluate our classification model, we need to compute **evaluation metrics** to measure and quantify model performance, such as the **accuracy** of all data.



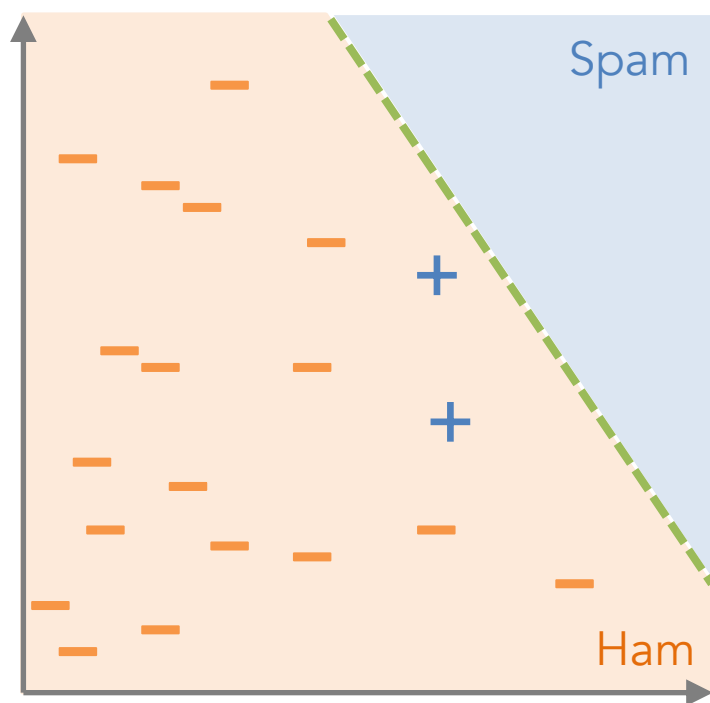
Accuracy for all data

$$= \frac{\text{\# of correctly classified points}}{\text{\# of all points}}$$

$$= \frac{19}{22} = 0.86$$

Classification

But what if **the dataset is imbalanced** (i.e., some classes have far less data)? In this case, the accuracy of all data is a bad evaluation metric.



Classify all data as non-spam

Accuracy for all data

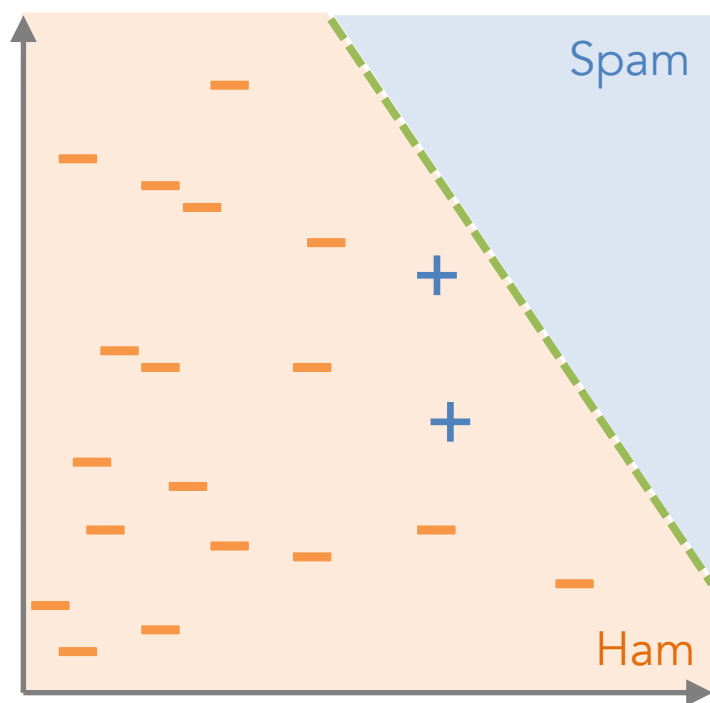
$$= \frac{\text{\# of correctly classified points}}{\text{\# of all points}}$$

$$= \frac{18}{20} = 0.9$$



Classification

Instead of computing the accuracy for all the data, we can compute **accuracy for each class**, which allows us to see the performance of different labels.



$$\text{Accuracy for spam} = \frac{0}{2} = 0$$

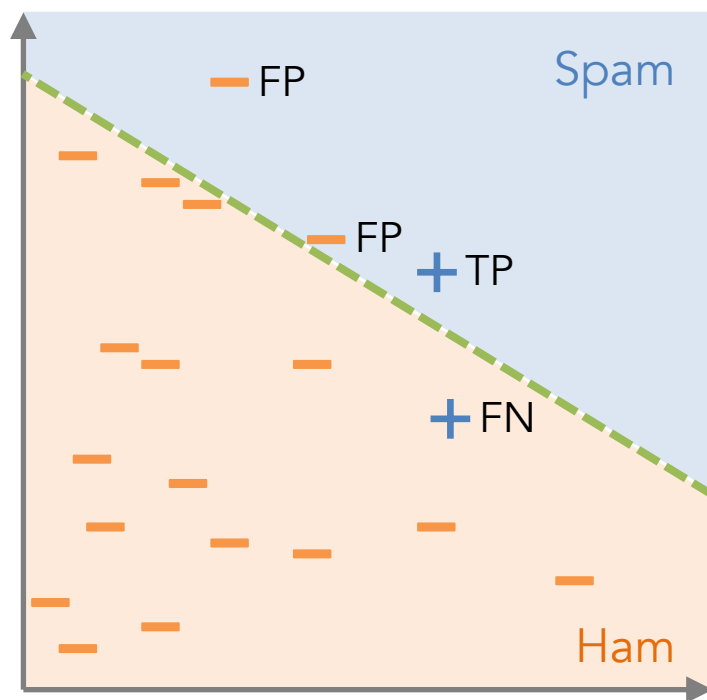
(true positive rate, recall, sensitivity)

$$\text{Accuracy for ham} = \frac{18}{18} = 1$$

(true negative rate, specificity)

Classification

If we care more about the positive class (e.g., spam), we can use **precision** and **recall**, with its best value at 1 and the worst value at 0.



TP = 1 (True Positive)

FP = 2 (False Positive)

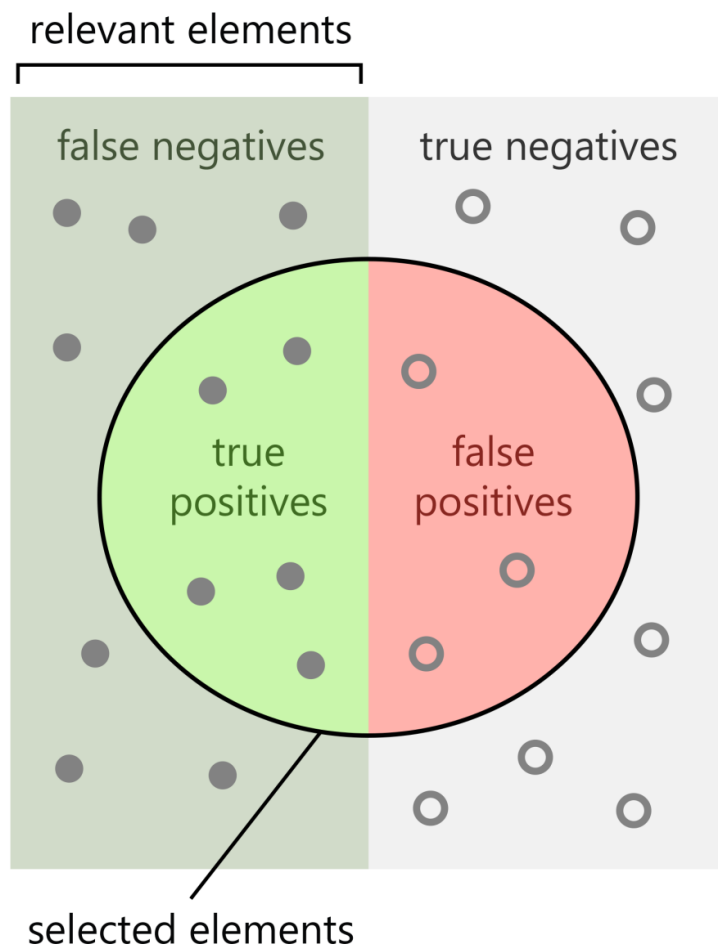
FN = 1 (False Negative)

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} = 0.33$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} = 0.5$$

Classification

Precision and recall can be aggregated into **F-score** as a general model performance, with its best value at 1 and worst value at 0.



How many selected items are relevant?

$$\text{Precision} = \frac{\text{true positives}}{\text{true positives} + \text{false positives}}$$

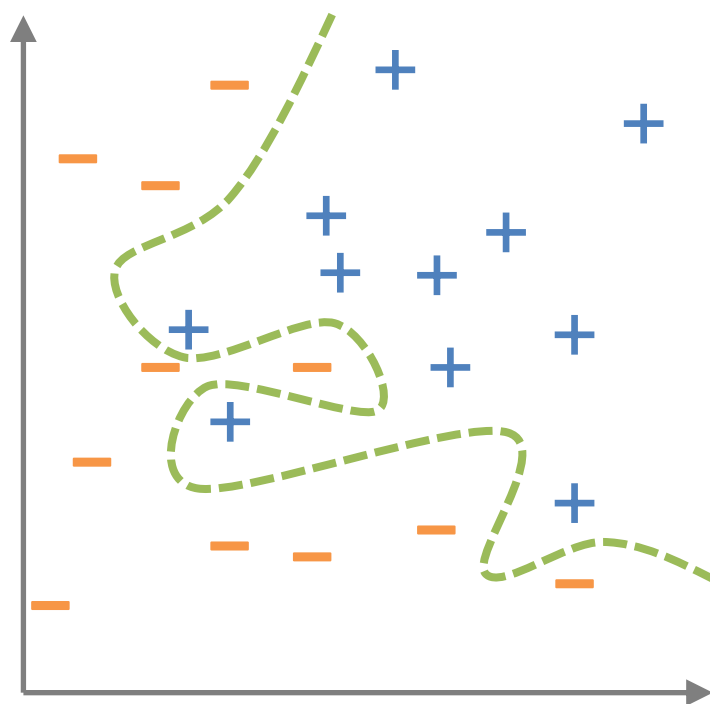
How many relevant items are selected?

$$\text{Recall} = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}}$$

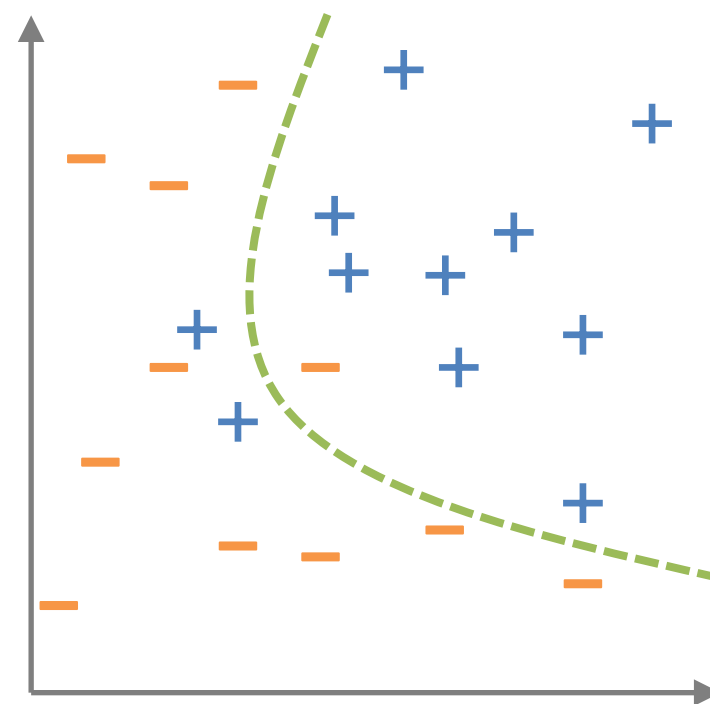
$$\text{F-score} = 2 \cdot \frac{\text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}}$$

Classification

We can train different types of models. But how do we know **which one is better**? Can we just pick an evaluation metric to determine which model is good?



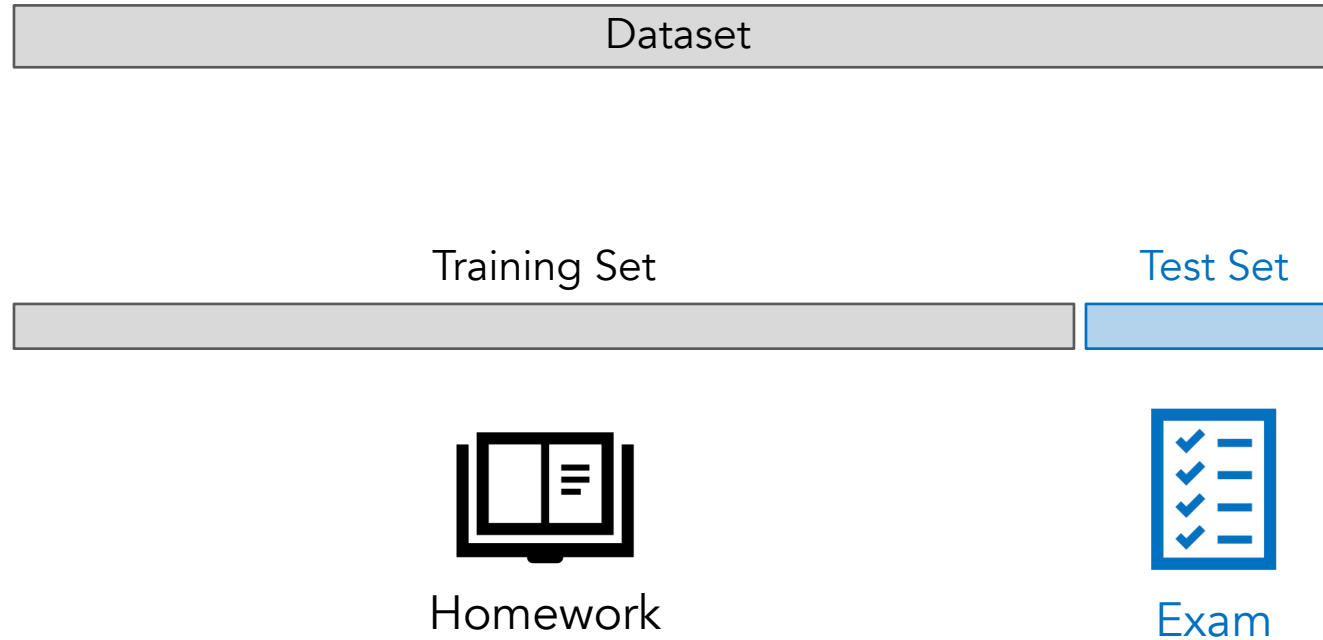
Model A



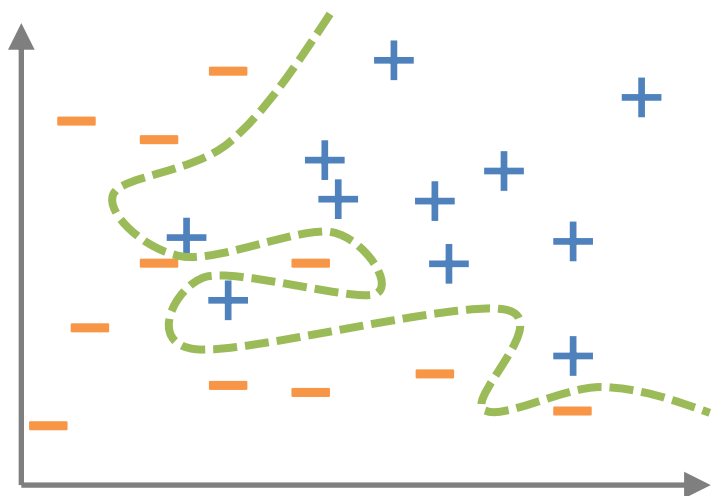
Model B

Classification

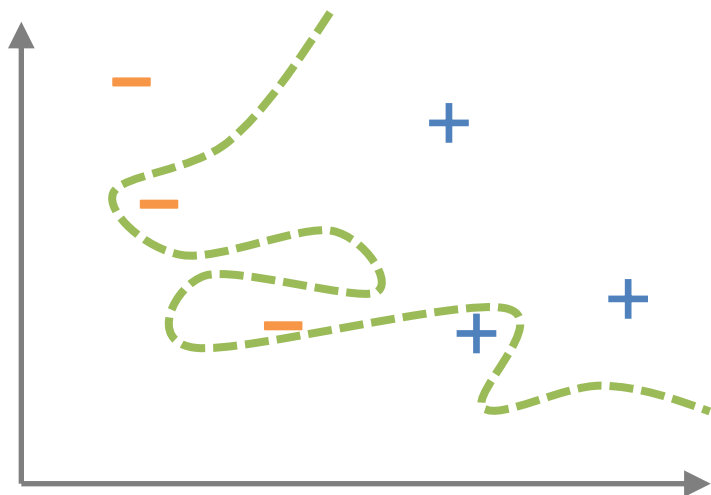
To choose models, we need a **test set**, which contains data that the models **have not yet seen before** during the training phase.



☹️ Model A

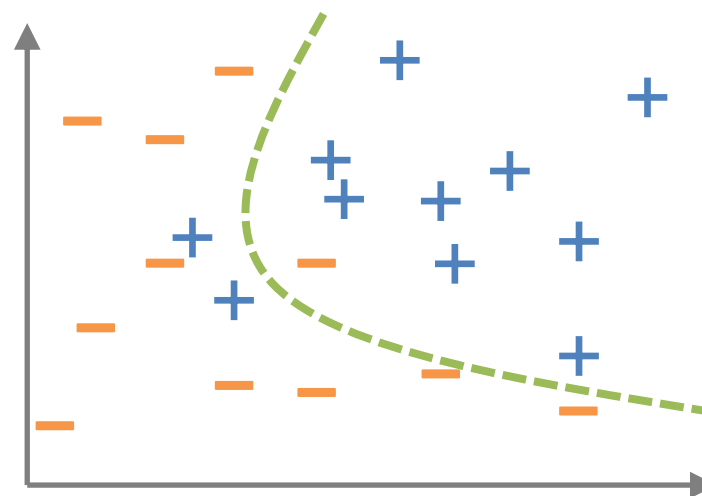


Training Accuracy = 1

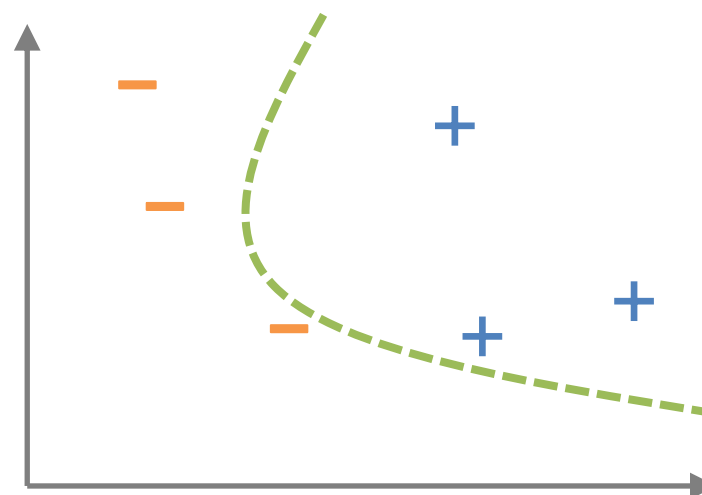


Testing Accuracy = 0.5

😊 Model B



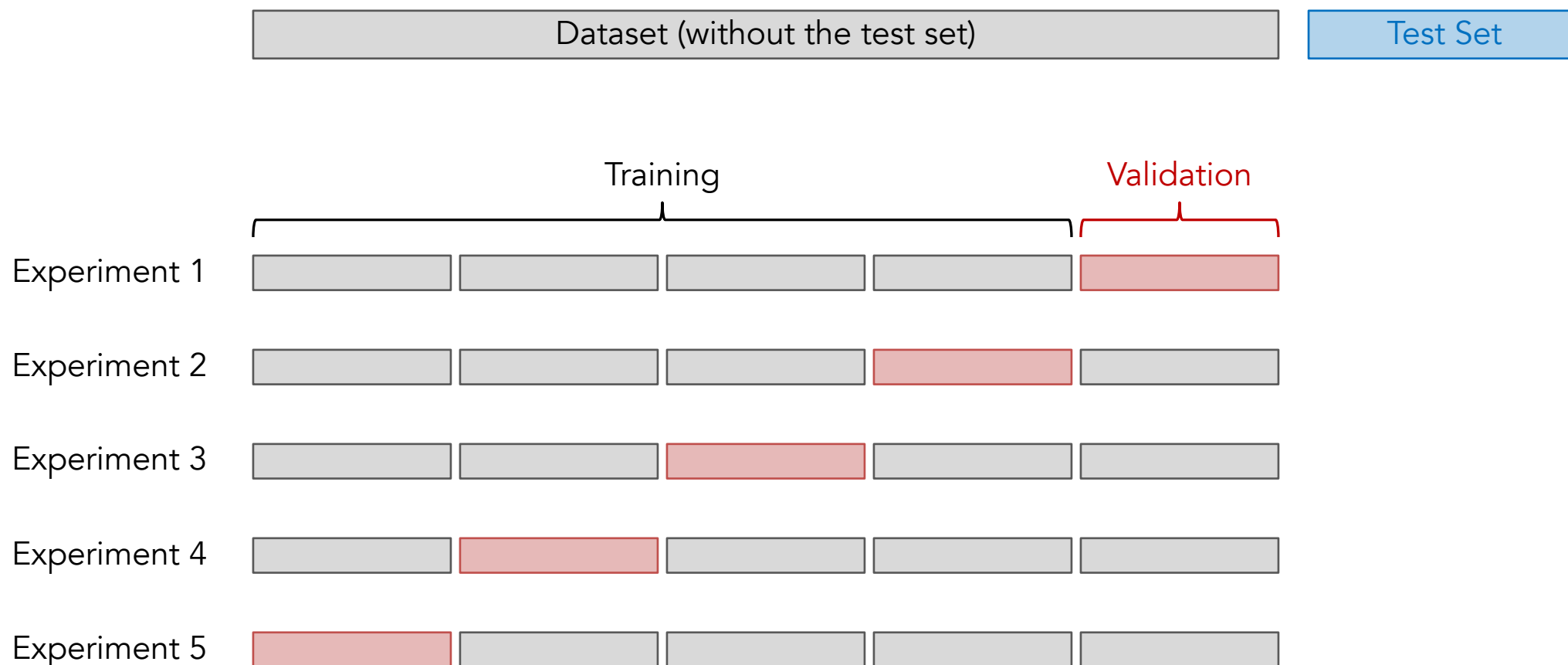
Training Accuracy = 0.86



Testing Accuracy = 1

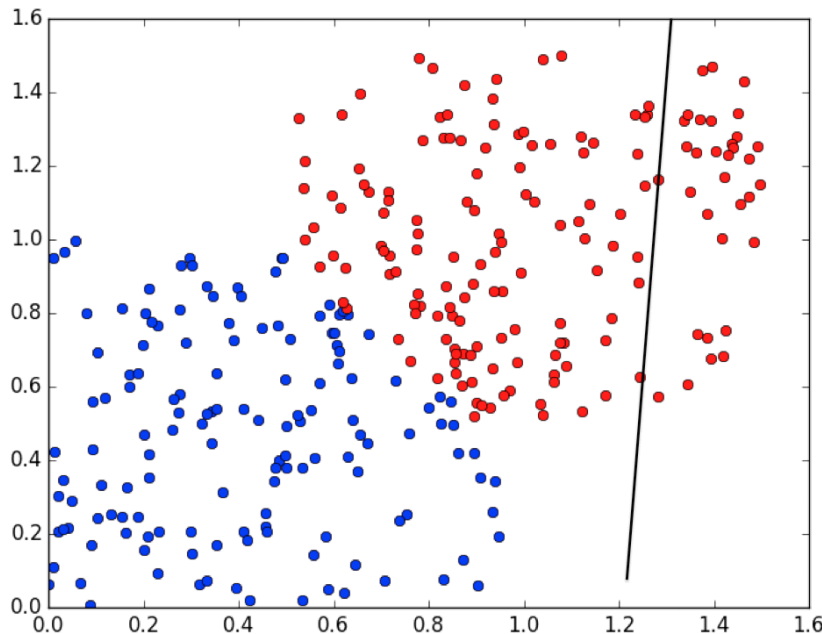
Classification

To **tune hyper-parameters** for a model, we use **cross-validation** to divide the dataset into folds and use each fold for validation.

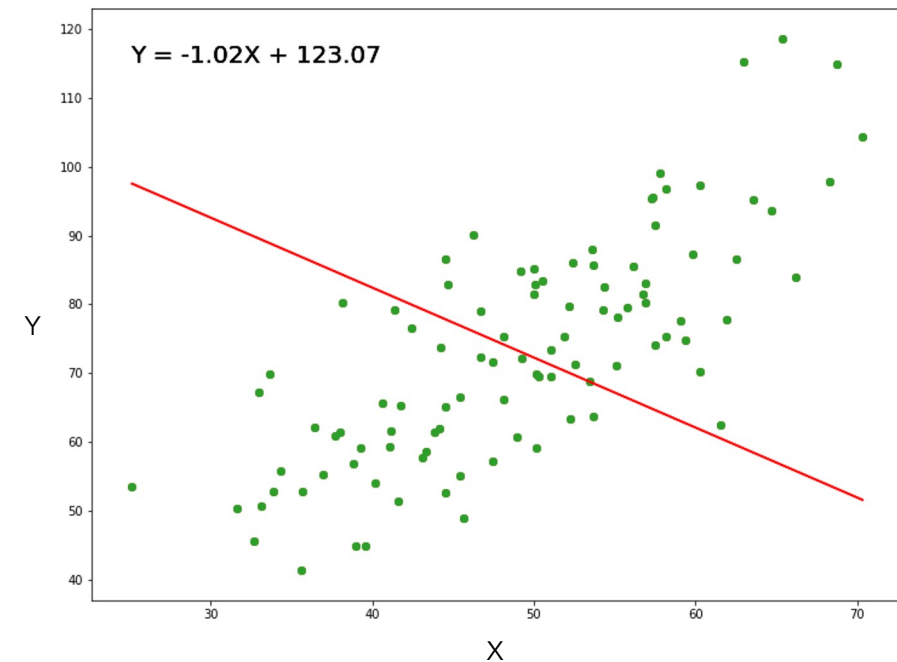


Regression

Unlike classification (which separates data into categories), **regression** fits a function that maps features x to a **continuous variable y** (i.e., the response).



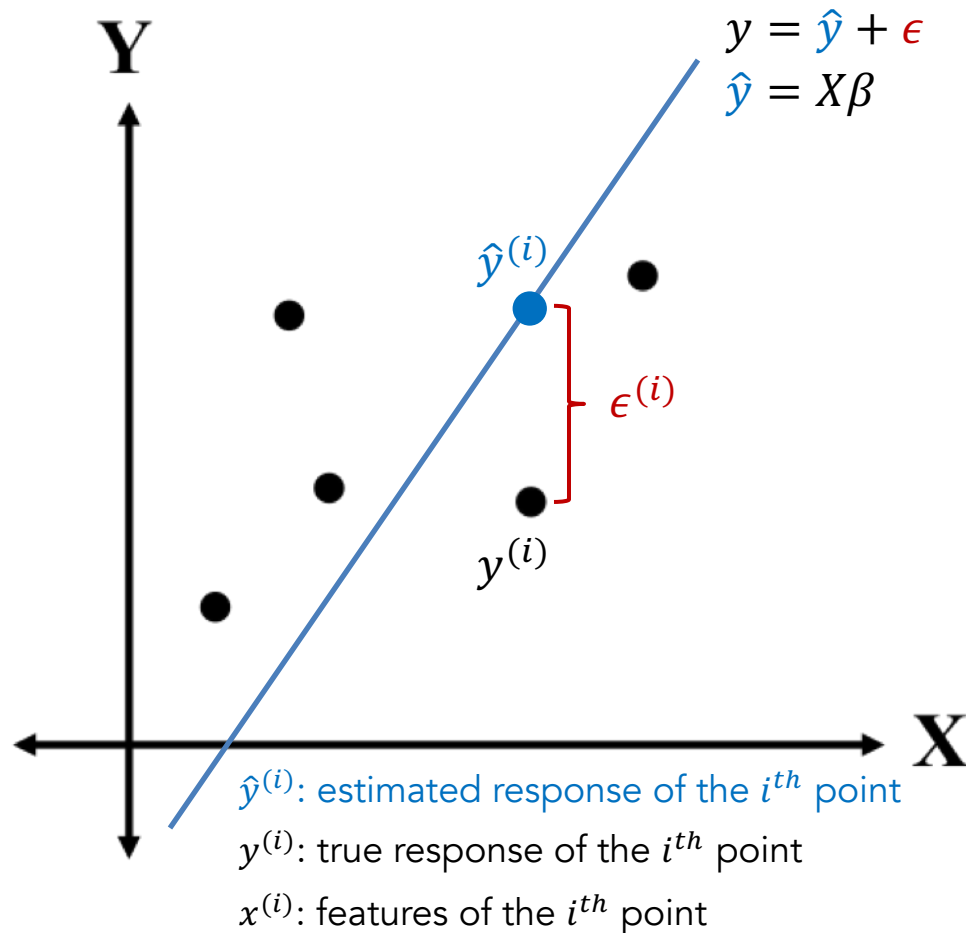
- [Classification] How can we fit a function that separates data points into different groups?



- [Regression] How can we fit a function that maps features (input) to a continuous variable (output)?

Regression

Linear regression fits a linear function f that maps x to y using some **error metric**, which can best describe the linear relationship between variables x and y .



y : true response (in vector form)

\hat{y} : **estimated response** (in vector form)

X : predictors/features (in matrix form)

β : coefficient (in vector form)

ϵ : **error/noise/residual** (in vector form)

$$X = [\mathbf{1} \quad x_1] = \begin{bmatrix} 1 & x_1^{(1)} \\ \vdots & \vdots \\ 1 & x_1^{(n)} \end{bmatrix} \quad \begin{array}{l} \beta_0: \text{intercept} \\ \beta_1: \text{slope} \\ x_1: \text{first predictor} \end{array}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix}$$

$$\hat{y} = X\beta = \beta_0 + \beta_1 x_1 = \begin{bmatrix} \hat{y}^{(1)} \\ \vdots \\ \hat{y}^{(n)} \end{bmatrix}$$

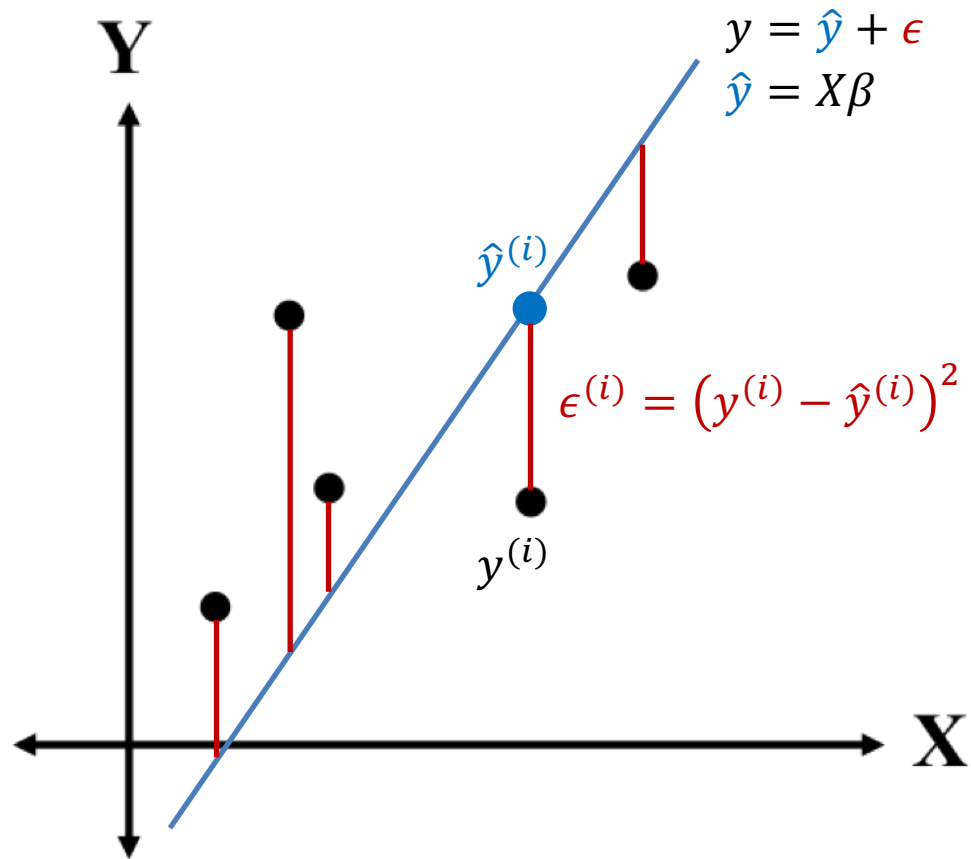
Regression

We use the vector and matrix forms to simplify equations.

$$\begin{aligned} X &= [\mathbf{1} \quad \boxed{x_1} \quad \cdots \quad x_p] = \boxed{\begin{bmatrix} 1 & x_1^{(1)} & \cdots & x_p^{(1)} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_1^{(n)} & \cdots & x_p^{(n)} \end{bmatrix}} \\ \beta &= \boxed{\begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{bmatrix}} \\ \hat{y} &= f(x) = X\beta = [\mathbf{1} \quad x_1 \quad \cdots \quad x_p] \cdot \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{bmatrix} = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p = \boxed{\begin{bmatrix} \hat{y}^{(1)} \\ \vdots \\ \hat{y}^{(n)} \end{bmatrix}} \end{aligned}$$

Regression

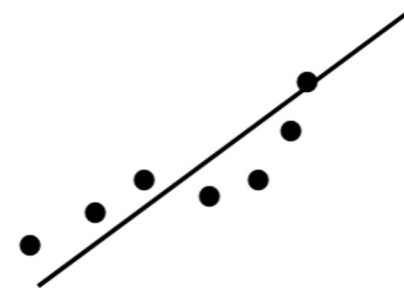
Usually, we assume that the error ϵ is IID (independent and identically distributed) and follows a normal distribution with zero mean and some variance σ^2 .



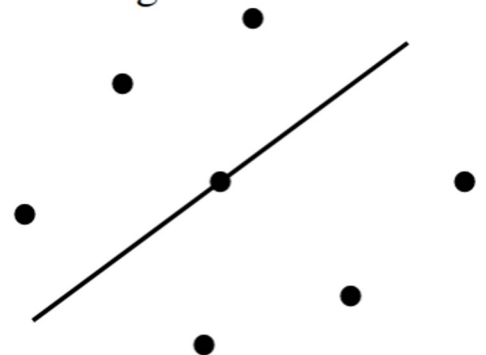
$$\epsilon \sim \text{iid } N(0, \sigma^2)$$

$$\text{total errors} = \sum_{i=1}^n (y^{(i)} - \hat{y}^{(i)})^2$$

Small σ^2

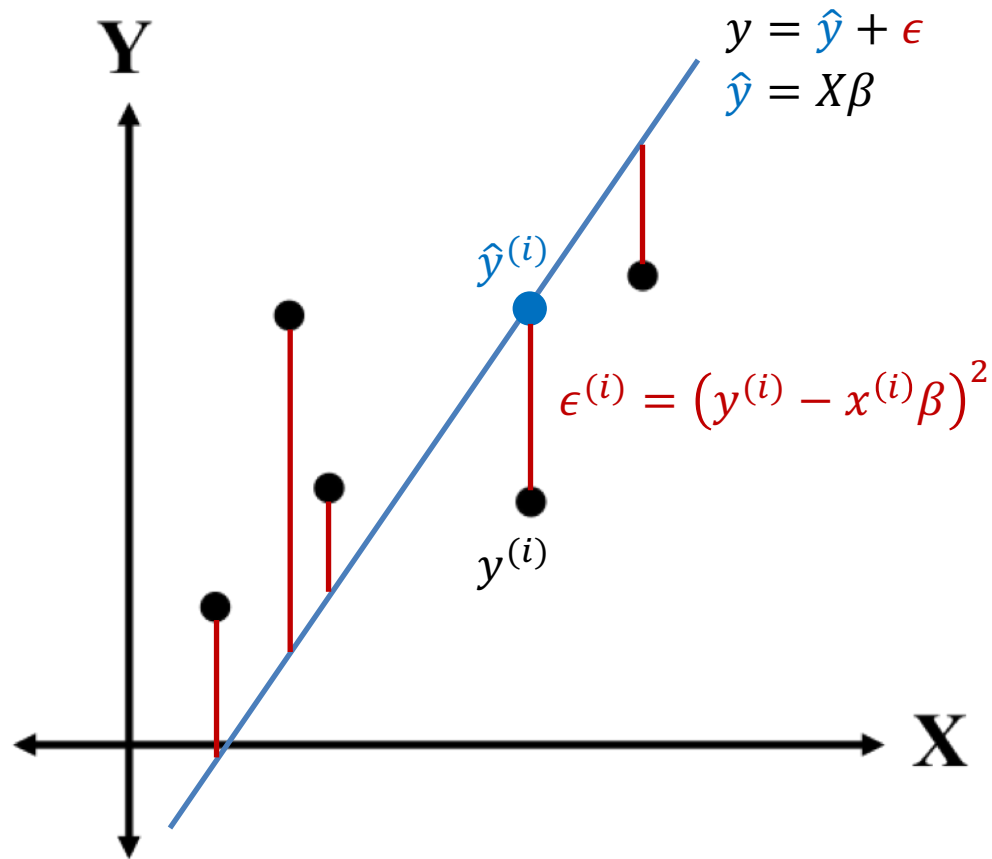


Large σ^2

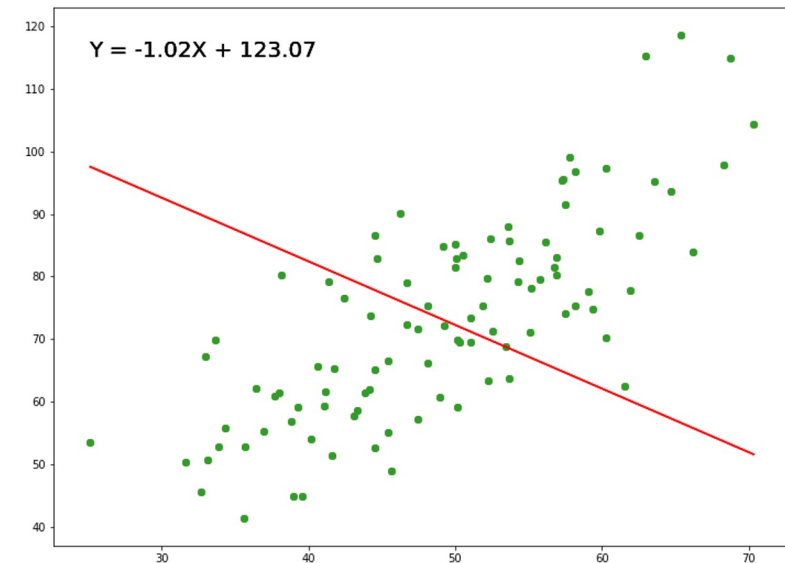


Regression

To find the optimal coefficient β , we need to **minimize the error** (the sum of squared errors) using gradient descent or taking the derivative of its matrix form.

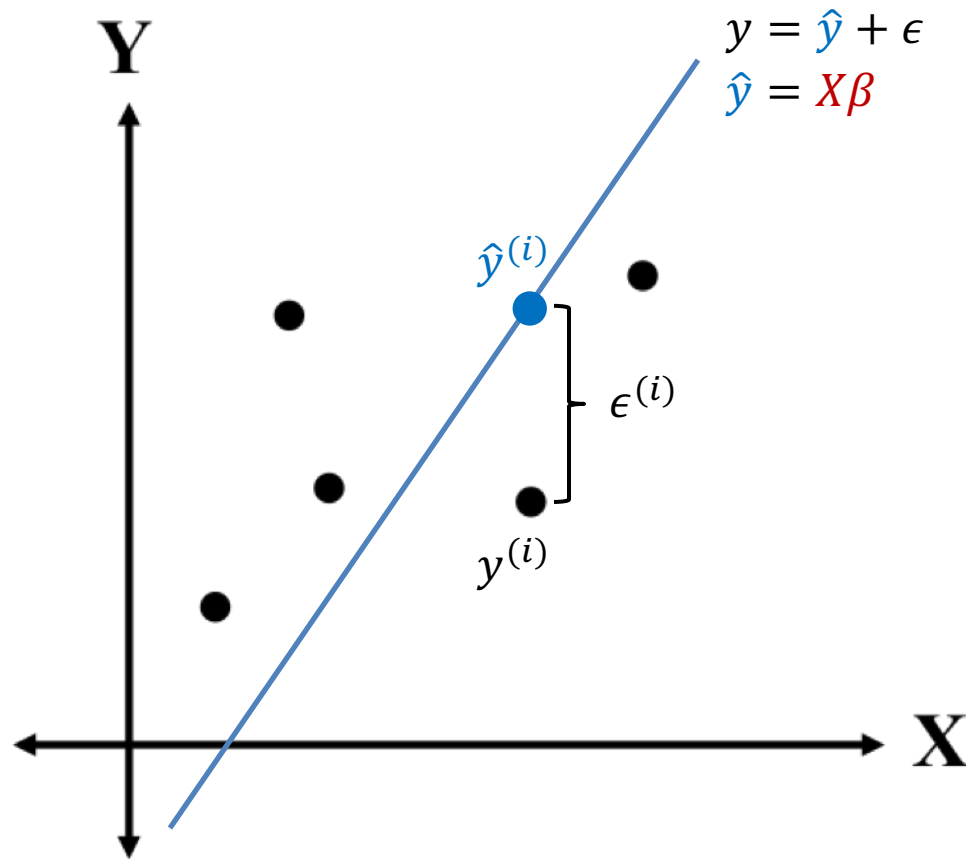


$$\begin{aligned}\min_{\beta} \sum_{i=1}^n \epsilon^{(i)} &= \min_{\beta} \sum_{i=1}^n (y^{(i)} - x^{(i)}\beta)^2 \\ &= \min_{\beta} (y - X\beta)^T (y - X\beta)\end{aligned}$$



Regression

We can generalize linear regression to have **multiple predictors** (i.e., multiple linear regression) and keep the original mathematical representation.



$x_j^{(i)}$: the j^{th} predictor of the i^{th} data point

$y^{(i)}$: response of the i^{th} data point

$\hat{y}^{(i)}$: estimated response of the i^{th} data point

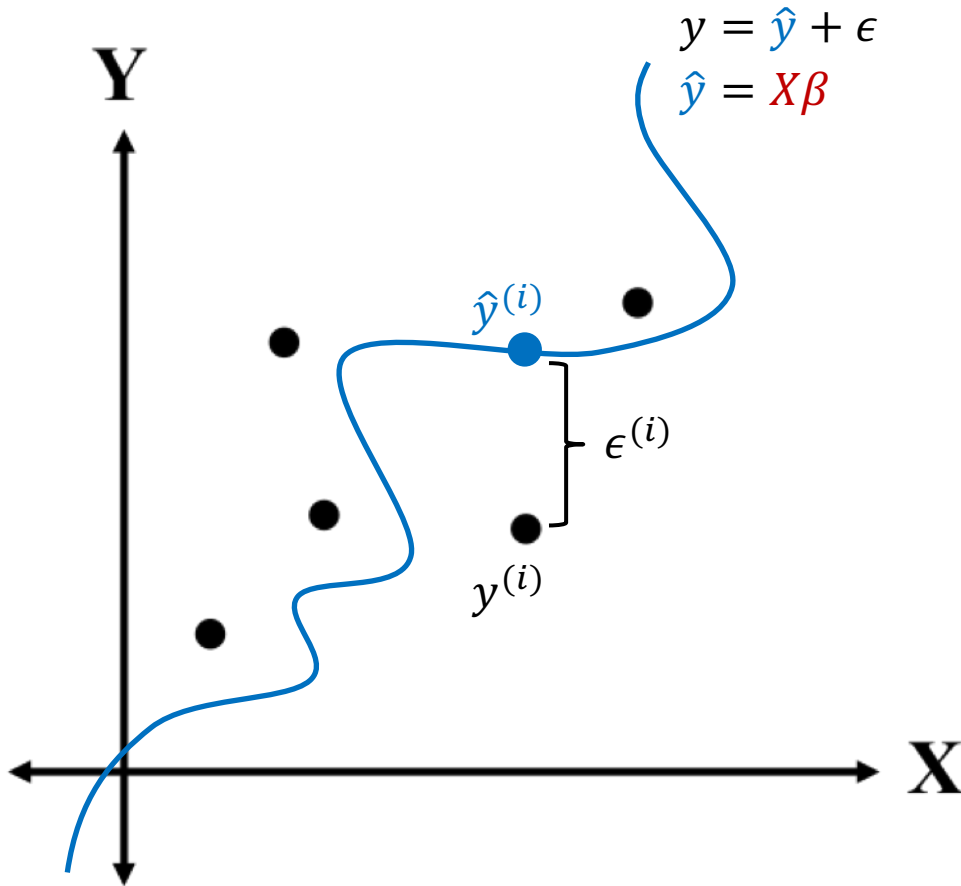
$$X = [\mathbf{1} \quad x_1 \quad \cdots \quad x_p] = \begin{bmatrix} 1 & x_1^{(1)} & \cdots & x_p^{(1)} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_1^{(n)} & \cdots & x_p^{(n)} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{bmatrix}$$

$$\hat{y} = X\beta = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p = \begin{bmatrix} \hat{y}^{(1)} \\ \vdots \\ \hat{y}^{(n)} \end{bmatrix}$$

Regression

We can model a **non-linear relationship** using polynomial functions with degree k . The example below uses one predictor x_1 .



y : true response (in vector form)

\hat{y} : estimated response (in vector form)

X : predictors/features (in matrix form)

β : coefficient (in vector form)

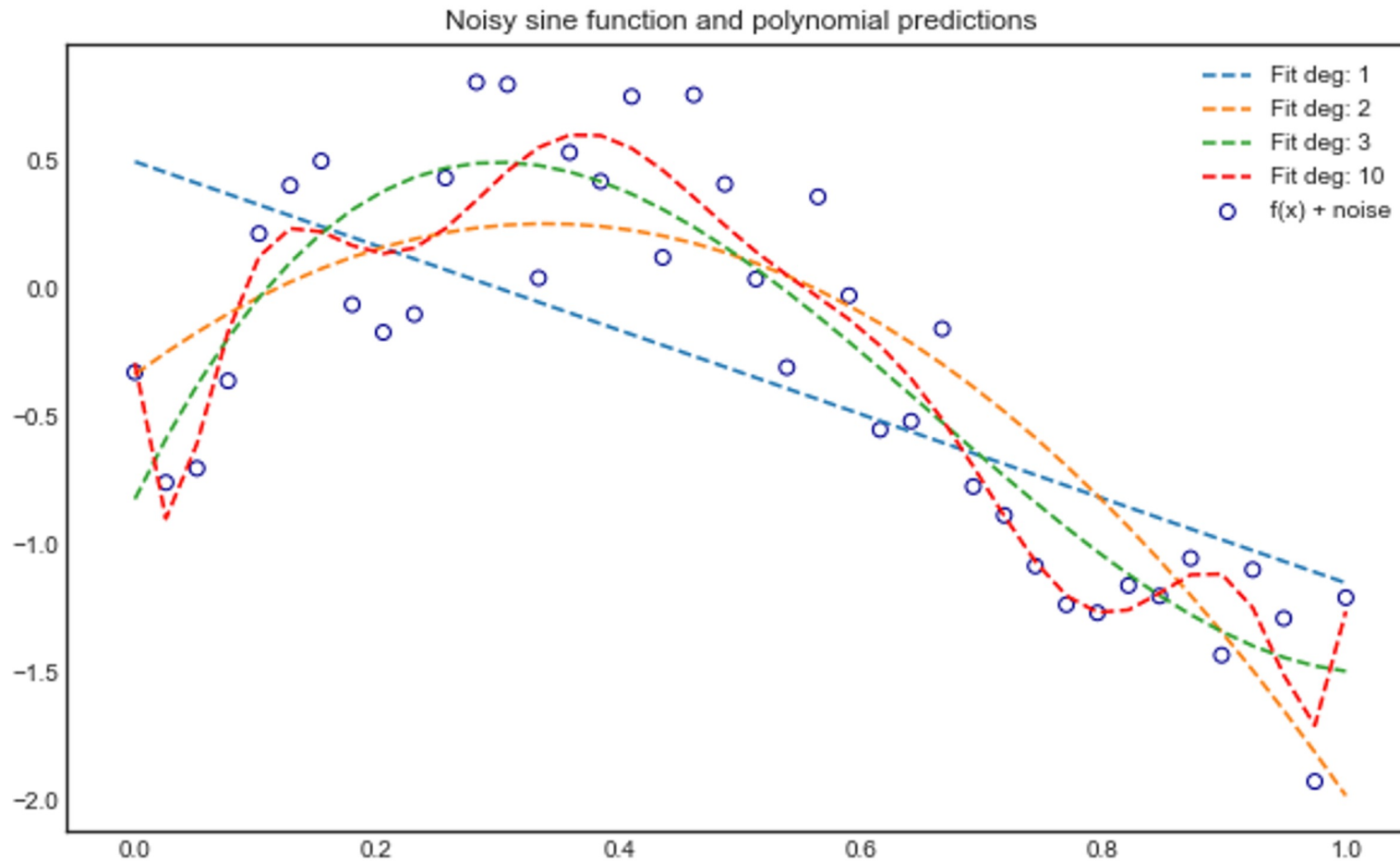
$$X = [\mathbf{1} \quad x_1 \quad (x_1)^2 \quad \cdots \quad (x_1)^k]$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}$$

$$\hat{y} = X\beta = \beta_0 + \beta_1 x_1 + \beta_2 (x_1)^2 + \cdots + \beta_k (x_1)^k$$

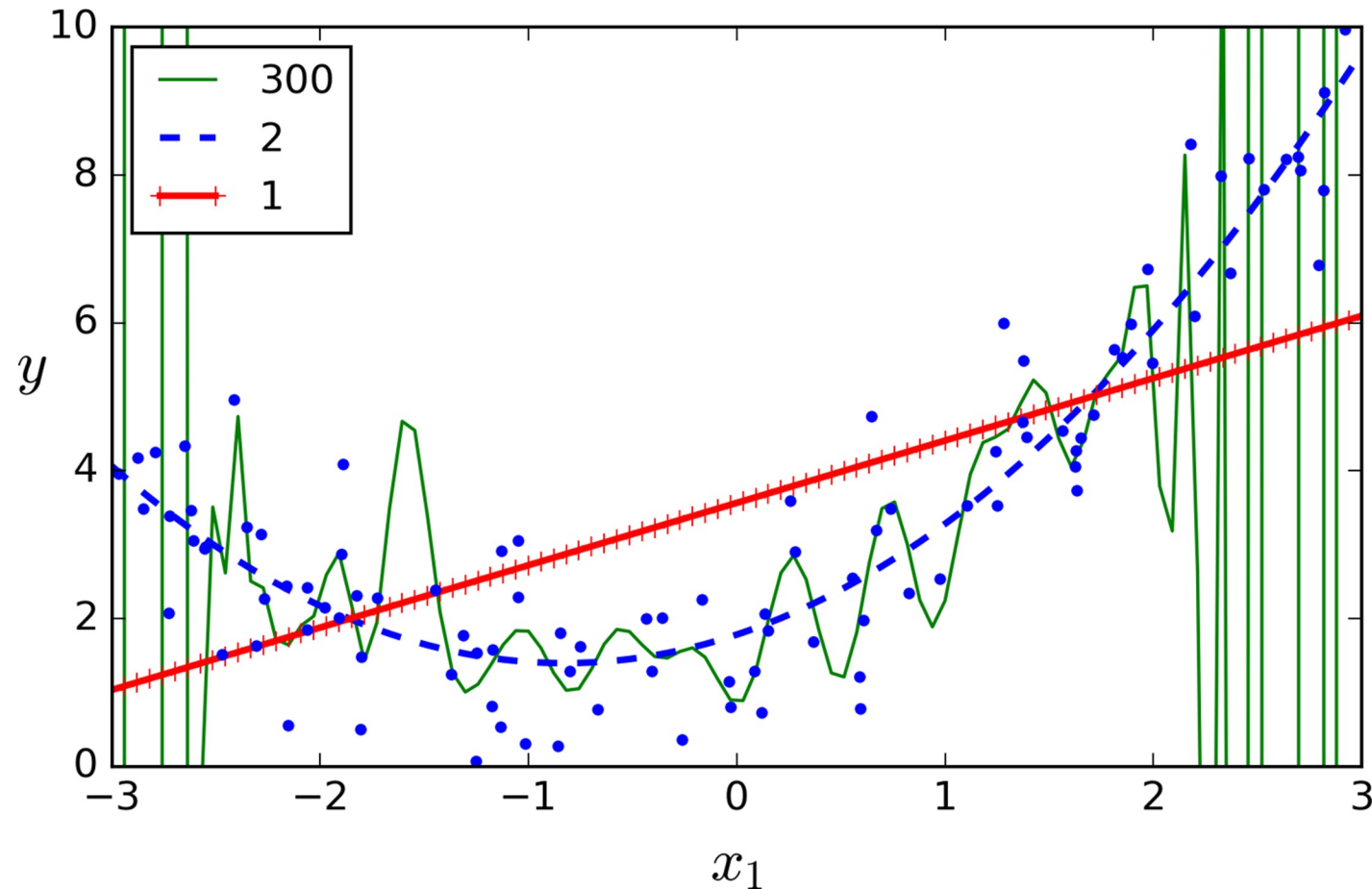
Regression

Here is an example of applying linear and polynomial regression to the data that is created using a sine function with some random noise.



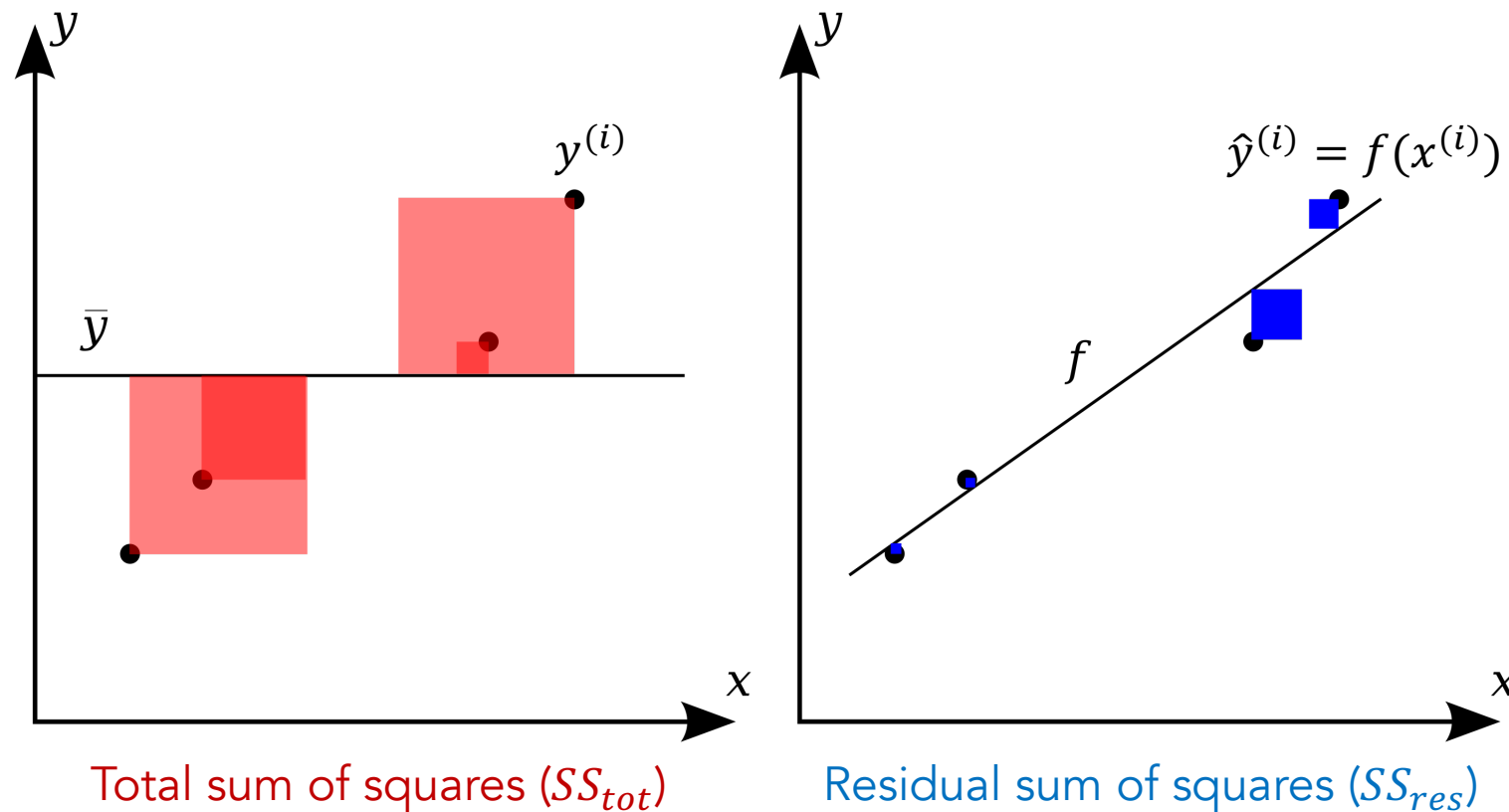
Regression

Using too complex/simple models can lead to **overfitting/underfitting**, which means the model fits the training set well but generalizes poorly on the test set.



Regression

To evaluate regression models, one common metric is the **coefficient of determination (R-squared, R^2)**. There exist other metrics such as AIC (Akaike's Information Criterion) that is based on likelihood, which is not covered in this lecture.

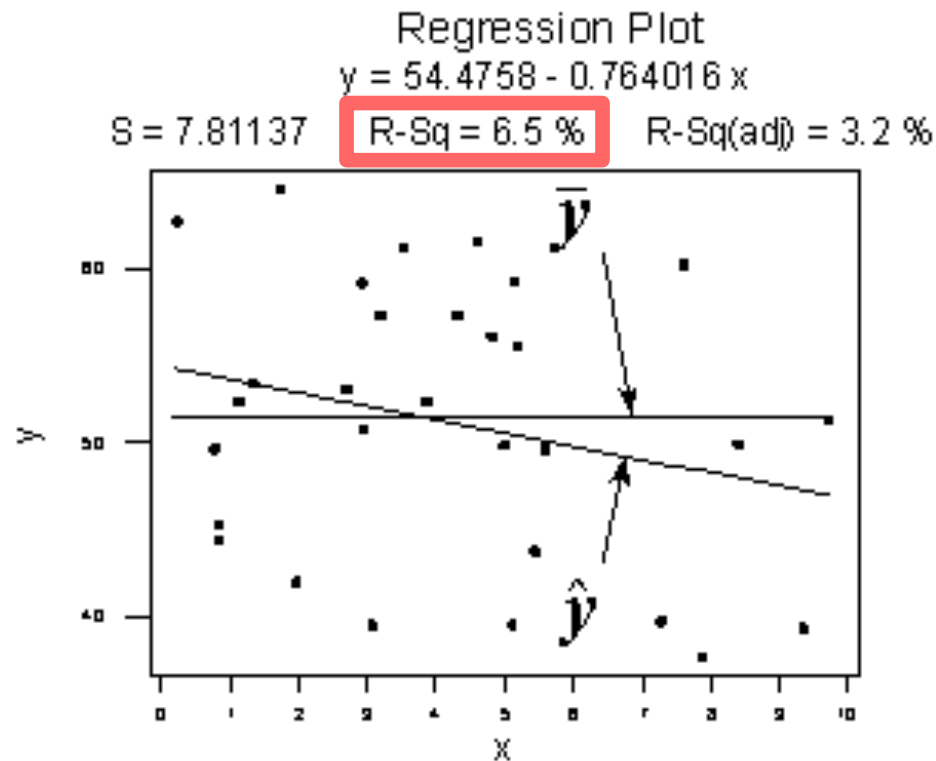


Unexplained Variation

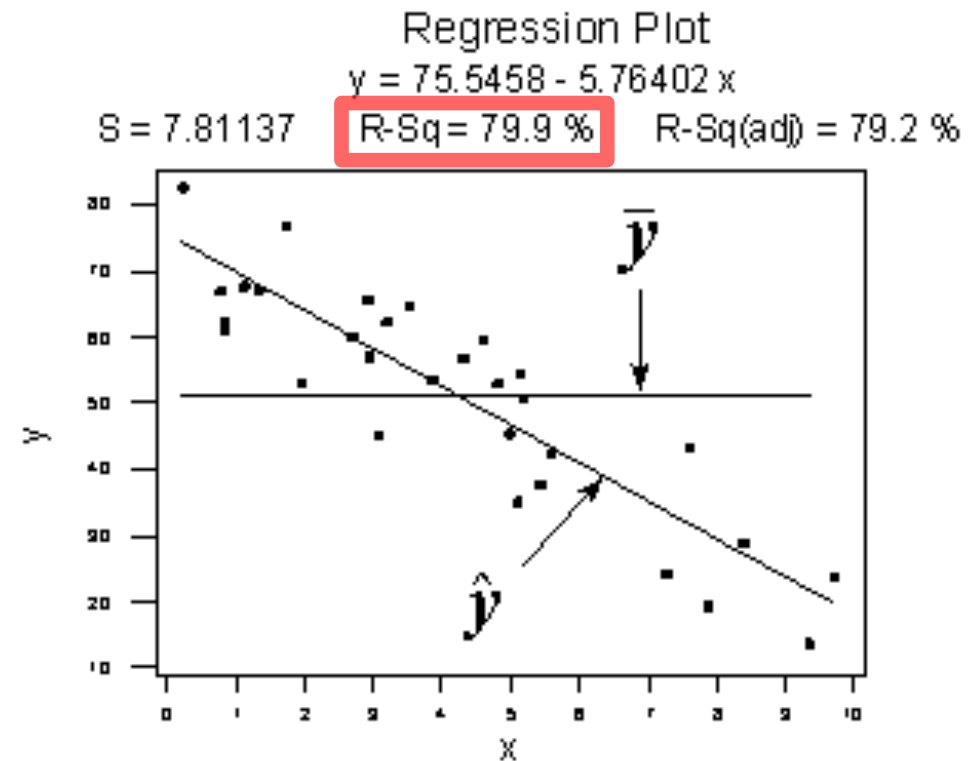
$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$
$$SS_{res} = \sum_i (y^{(i)} - \hat{y}^{(i)})^2$$
$$SS_{tot} = \sum_i (y^{(i)} - \bar{y})^2$$

Regression

For simple/multiple linear regression, R^2 equals the square of Pearson correlation coefficient r between the true y and the estimated $\hat{y} = f(X)$.



Lower Correlation



Higher Correlation

Regression

R^2 increases as we add more predictors (because the optimization always want to decrease the residual sum of squares) and thus is **not a good metric for model selection**. We need the adjusted R^2 , which considers the number of predictors.

$$R^2_{adj} = 1 - \frac{SS_{res}/df_{res}}{SS_{tot}/df_{tot}}$$

$$df_{res} = n - p - 1$$

$$df_{tot} = n - 1$$

$$SS_{res} = \sum_i (y^{(i)} - \hat{y}^{(i)})^2$$

$$SS_{tot} = \sum_i (y^{(i)} - \bar{y})^2$$

p : number of features/predictors

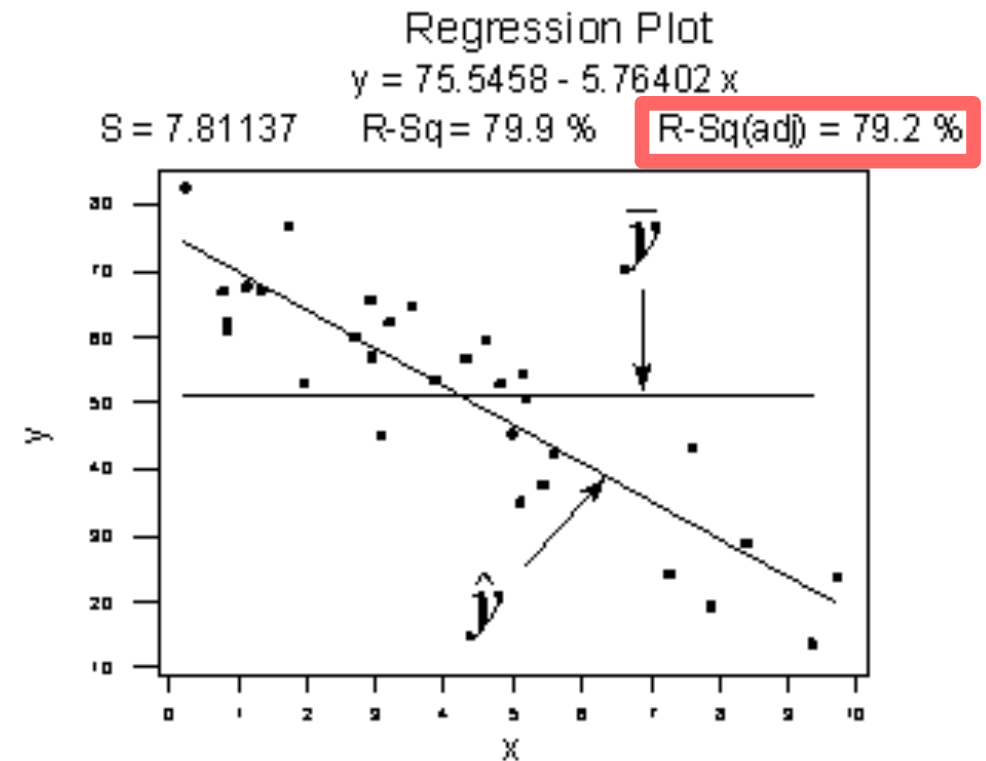
R^2_{adj} : adjusted value of R^2

df_{res} : residual degree of freedom

df_{tot} : total degree of freedom

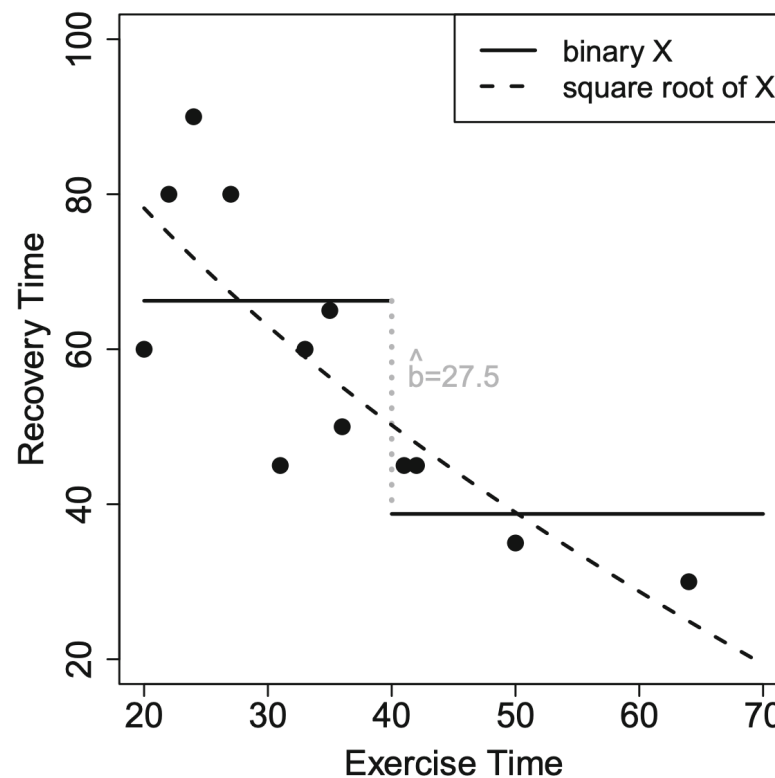
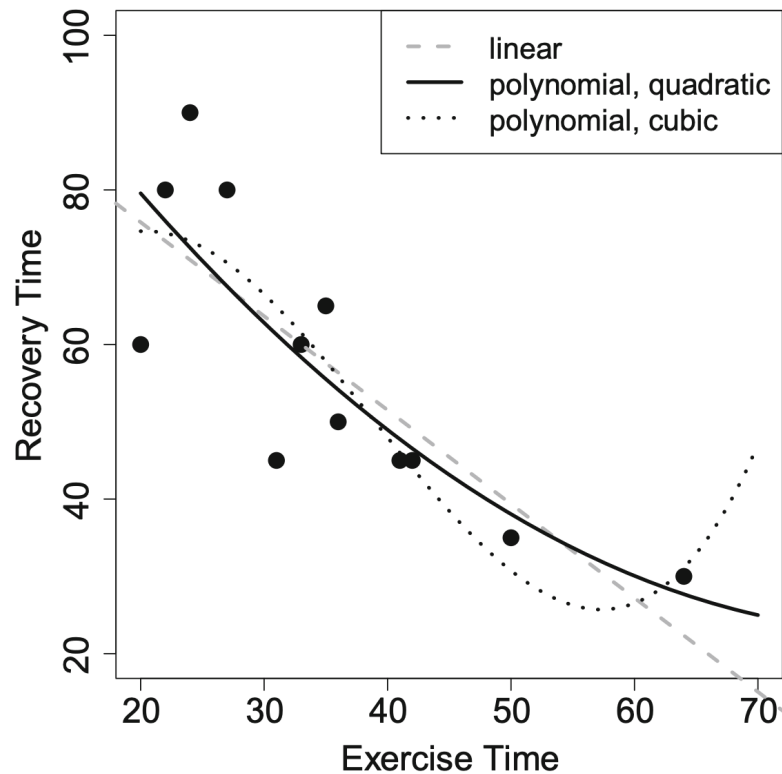
SS_{res} : residual sum of squares

SS_{tot} : total sum of squares



Regression

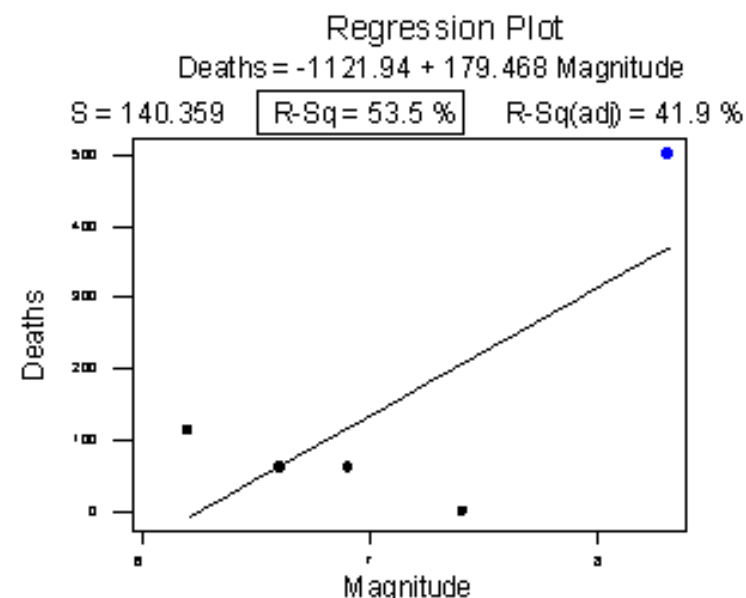
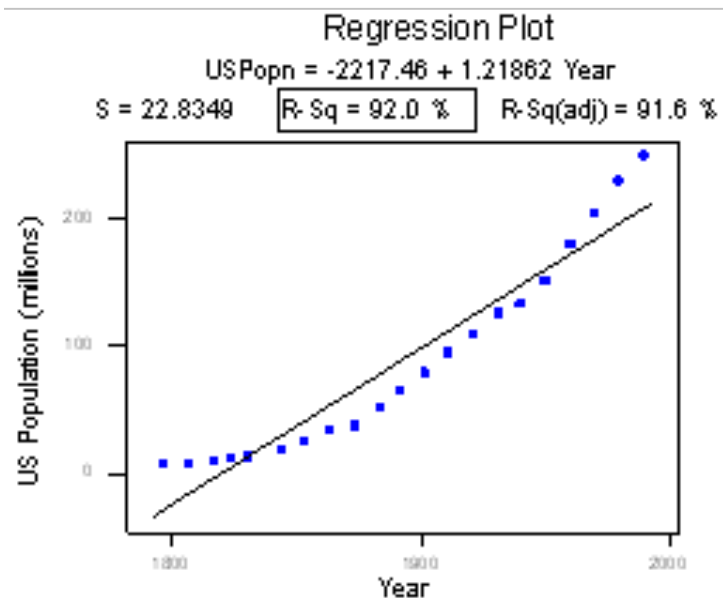
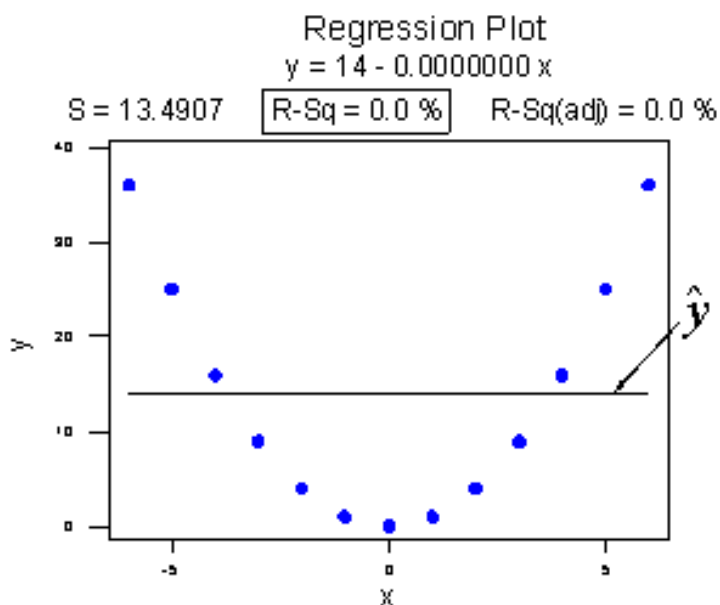
In the example below, R^2 is larger for the model with more predictors (i.e., the **cubic model** that has three predictors). The **adjusted R^2** , which considers the number of predictors (model complexity), favors the **square-root model**.



	R^2	R^2_{adj}
Linear	0.6584	0.6243
Quadratic	0.6787	0.6074
Cubic	0.7151	0.6083
Square root	0.6694	0.6363

Regression

Be careful when using and explaining R^2 in your findings. A bad R^2 does not always mean no pattern in the data. A good R^2 does not always mean that the function fits the data well. And R^2 can be greatly affected by outliers.



Take-Away Messages

- Classification outputs discrete labels, while regression outputs continuous values.
- Precision, recall, and F-score are common metrics for evaluating classification models.
- R-squared is a common evaluation metric for regression models.
- Feature engineering is an important step for models that do not use deep learning techniques.
- To train and update a model iteratively, you need a loss function to measure errors.
- Generally, it is a good practice to divide datasets into different parts for model training and testing.
- A model can perform extremely well on the training set but badly on the test set (i.e., overfitting).
- Cross-validation is a good technique to prevent overfitting.



Questions?