

# Machine Learning for econometrics

## Statistical learning and regularized linear models

---

Matthieu Doutreligne

A lot of today's content is taken from the excellent [sklearn mooc](#) (Estève et al., 2022)

## Matthieu Doutreligne

- 2018: Master degree in statistical learning and artificial intelligence (Ensaie/MVA)
- 2018-2020: Data scientist at the French Ministry of Health (Drees)
- 2020-2023: PhD in statistics and informatics (SODA / scikit-learn inria team):

*Causal inference with machine learning applied to clinical data*

- Same time: Statistician during 5 years at Haute Autorité de santé (HAS)
- **2025-**: Data analyst at Insee (Département des Études Économiques)

**More from the **machine learning** than **economics** culture**

## Objectives

Important **concepts and methods** of machine learning...

Useful for **empirical work** in economics.

## Objectives

Important **concepts and methods** of machine learning...

Useful for **empirical work** in economics.

## Philosophy

- More **intuitions** than equations
- Basics and **references** for formal understanding
- Focus on practical skills: **coding** 

# Course syllabus

8 sessions, two teachers: Matthieu Doutreligne (MD), Bruno Crépon (BC)

## Sessions

- 1. Statistical learning and regularized linear models (MD)
- 2. Flexible models for tabular data (MD)
- 3. Reminders of potential outcomes and Directed Acyclic Graphs (MD)
- 4.a Event studies: Causal methods for panel data (MD)
- 4.b Double-lasso for statistical inference (BC)
- 5. Double machine learning: Neyman-orthogonality (BC)
- 6. Heterogeneous treatment effect (BC)
- 7. Oral presentations of the evaluation projects (MD + BC)

# Evaluation of the course

## Coding project

- Causal inference on a small dataset of your choice: several datasets provided.
- Objective: ask a sound causal question, discuss hypotheses and estimate a causal effect with a machine learning method, discuss the design and the results.

## Details

- Handing over a notebook with code and comments on a github: (Python, R or stata)
- Presenting your work in a 20-30 minutes oral during the last session.
- Details and datasets: <https://straymat.github.io/causal-ml-course/evaluation.html>
- Inscription: email sent to every students.

# Course resources for my four sessions

## Website

Detailed syllabus: <https://straymat.github.io/causal-ml-course/syllabus.html>

Slides: <https://straymat.github.io/causal-ml-course/slides.html>

Practical sessions: [https://straymat.github.io/causal-ml-course/practical\\_sessions.html](https://straymat.github.io/causal-ml-course/practical_sessions.html)

## Predictive inference in high dimensions

- Statistical learning basics
- Regularized linear models for predictive inference
- Practice with scikit-learn

## Predictive inference in high dimensions

- Statistical learning basics
- Regularized linear models for predictive inference
- Practice with scikit-learn

## Next two sessions

- Flexible models: Trees, Random Forests, Gradient Boosting and more scikit-learn
- Reminders of potential outcomes and Directed Acyclic Graphs

## Contents

Statistical learning framework .....	8
High estimation error means overfit .....	30
High approximation error means underfit .....	35
Sampling different training sets .....	72
Many features, few observations .....	79
Bibliography .....	100

# Statistical learning framework

---

## Goal

- Predict the value of an outcome based on one or more input variables.

# Statistical learning, ie. predictive inference

## Goal

- Predict the value of an outcome based on one or more input variables.

## Setting

- Data:  $n$  pairs of (features, outcome),  $(x_i, y_i) \in \mathcal{X} \times \mathcal{Y}$  identically and independently distributed (i.i.d.) from an unknown distribution  $P$ .
- Goal: find a function  $\hat{f} : \mathcal{X} \rightarrow \mathcal{Y}$  that approximates the true value of  $y$  ie. for a new pair  $(x, y)$ , we should have:

$$\hat{y} = \hat{f}(x) \approx y$$

# Statistical learning, ie. predictive inference

## Goal

- Predict the value of an outcome based on one or more input variables.

## Setting

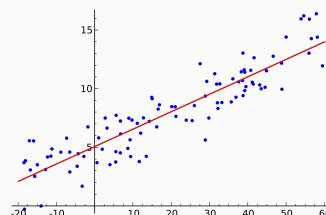
- Data:  $n$  pairs of (features, outcome),  $(x_i, y_i) \in \mathcal{X} \times \mathcal{Y}$  identically and independently distributed (i.i.d.) from an unknown distribution  $P$ .
- Goal: find a function  $\hat{f} : \mathcal{X} \rightarrow \mathcal{Y}$  that approximates the true value of  $y$  ie. for a new pair  $(x, y)$ , we should have:

$$\hat{y} = \hat{f}(x) \approx y$$

## Vocabulary: Fitting the model

Finding the appropriate model  $\hat{f}$  is called learning, training or fitting the model.

# Statistical learning, two classes of problems

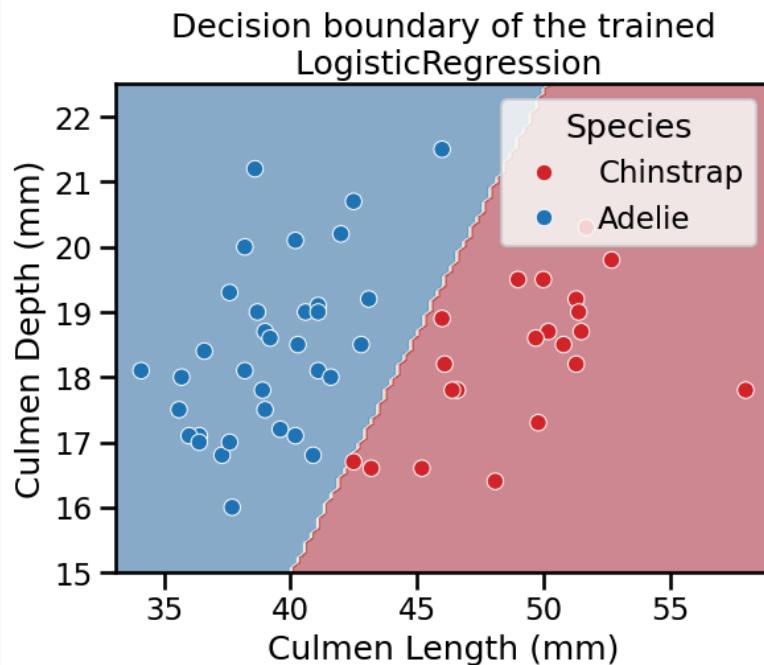


## Regression

- The outcome is continuous: eg. wage prediction
- The error is often measured by the mean squared error (MSE):

$$\text{MSE} = \mathbb{E} \left[ (Y - \hat{f}(X))^2 \right]$$

# Statistical learning, two classes of problems



## Classification

- Outcome is categorical: eg. diagnosis, loan default, ...
- Error is often measured with accuracy:

Misclassification rate =

$$\mathbb{E} \left[ \mathbf{1}(Y \neq \hat{f}(X)) \right]$$

with  $\hat{f} \in \{0, 1\}$  for binary classification

# Statistical learning framework

---

Motivation: why prediction?

# Why do we need prediction for ?

## Predictive inference

- Some problems in economics requires accurate prediction without a causal interpretation (Kleinberg et al., 2015), only knowledge of  $y$  (eg. stratifying on a risk score for loan, preventive care, ...)
- Reconstruct missing data: eg. imputation of missing values between two waves of a survey (eg. house prices, production of cultivation plots,...)

# Why do we need prediction for ?

## Predictive inference

- Some problems in economics requires accurate prediction without a causal interpretation (Kleinberg et al., 2015), only knowledge of  $y$  (eg. stratifying on a risk score for loan, preventive care, ...)
- Reconstruct missing data: eg. imputation of missing values between two waves of a survey (eg. house prices, production of cultivation plots,...)

## Statistical/causal inference

- Infer the effect of an intervention with a causal interpretation
- Powerful predictive models are used to regress “away” the relationship between the treatment/outcome and the confounders
  - > More on this in sessions on Double machine learning and Directed Acyclic Graphs.

# Do we need more than linear models?

Let:

- $p$  is the number of features
- $n$  is the number of observations

## Maybe no

- Low-dimensional data:  $n \gg p$
- No non-linearities, no or few interactions between features

# Do we need more than linear models?

Let:

- $p$  is the number of features
- $n$  is the number of observations

## Maybe no

- Low-dimensional data:  $n \gg p$
- No non-linearities, no or few interactions between features

## Maybe yes

- High-dimensional data: ie.  $p \gg n$
- Non-linearities, many interactions between features

# What high-dimension means: Is $p >> n$ common in economics?

⚠️  **$p$  can be greater than the number of columns in the dataset**

## Characteristics leading to high-dimensionality

- Categorical variables with high cardinality, eg. job title, diagnoses...
- Text data: eg. job description, medical reports...
- Technical regressors to handle non-linearities, eg. polynomials, splines, log, ...

# What high-dimension means, concrete example

- Population referencing individual files (INSEE):  $n = 19,735,576$ ;  $n_{\text{cols}} = 88$  🤪
- But many variables with cardinality: more than 555 pairs of (variable, category).
- Adding interaction of degree 2:  $\binom{p}{2} = \binom{555}{2} = \frac{555*554}{2} = 153735$  features 😭
- Adding interactions of any degree:  $2^p - p - 1 = 2^{555} - 554$  🤯

## Is this common? Yes

- Categorical with high cardinality or text data are increasingly common.
- Image data is high-dimensional by nature.
- Automation of data collection and storage leads to more datasets and more variables.

# Some problems where high dimensional data is common

## Some examples

- The US [Current Population Survey \(CPS\)](#) dataset has hundreds of variables, many of which are categorical
- The [Système National des Données de Santé \(SNDS\)](#) in France = healthcare claims : many hundreds of variables, many of which are categorical.

# Some problems where high dimensional data is common

## Some examples

- The US [Current Population Survey \(CPS\)](#) dataset has hundreds of variables, many of which are categorical
- The [Système National des Données de Santé \(SNDS\)](#) in France = healthcare claims : many hundreds of variables, many of which are categorical.

## Other area

- Country characteristics in cross-country wealth analysis,
- Housing characteristics in house pricing/appraisal analysis,
- Product characteristics at the point of purchase in demand analysis.

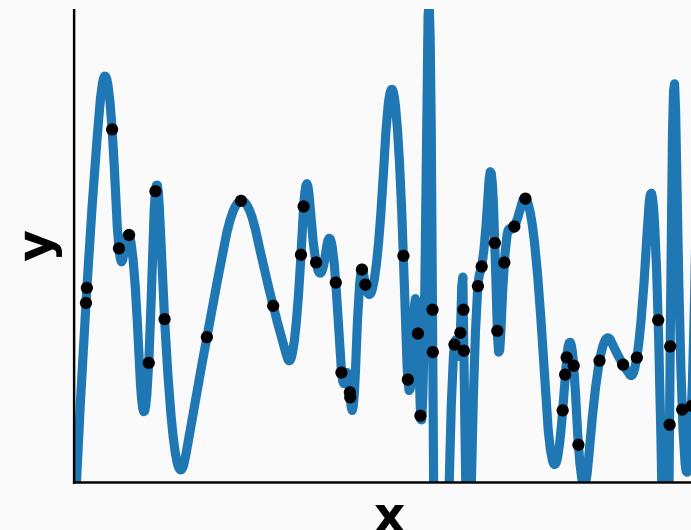
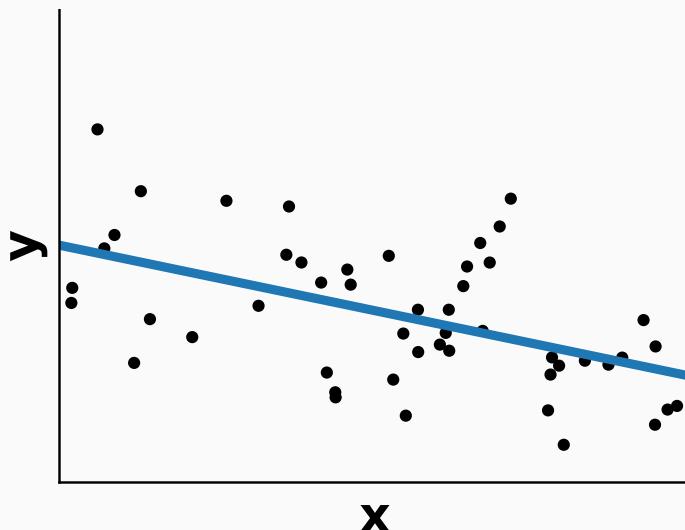
# Statistical learning framework

---

Statistical learning theory and intuitions

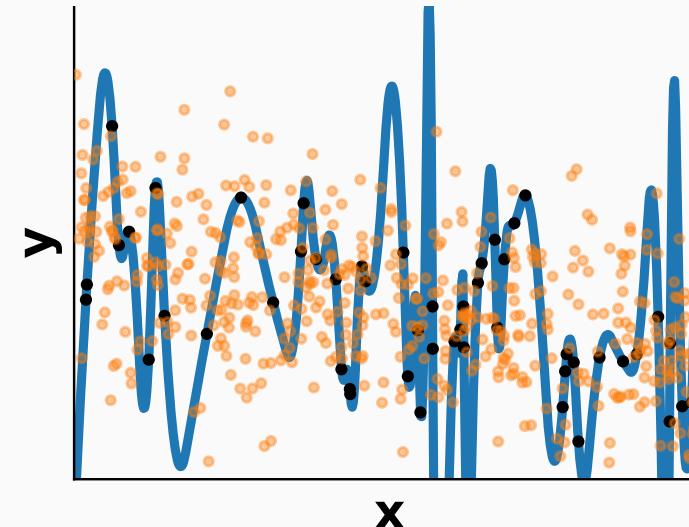
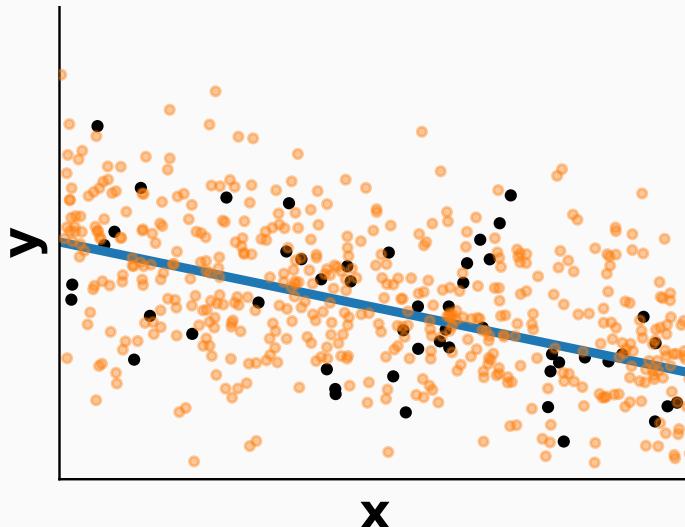
# Under vs. overfitting

Which data fit do you prefer?



# Under vs. overfitting

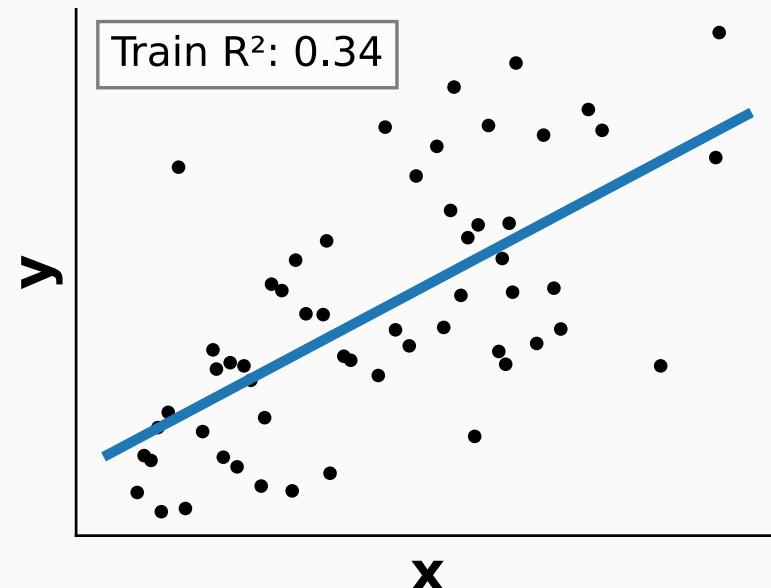
Which data fit do you prefer? (new data incoming)



- Answering this question might be hard.
- Goal: create models that generalize.
- The good way of framing the question is: **how will the model perform on new data?**

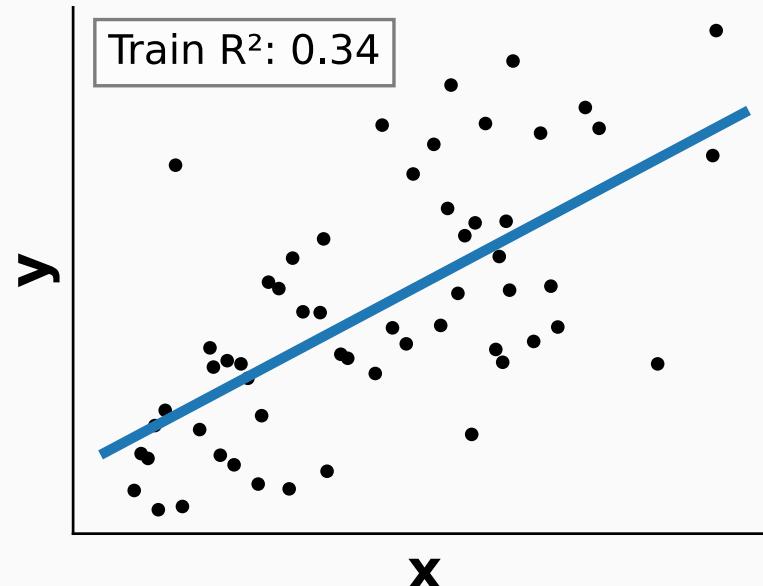
# Train vs test error: simple models

**Measure the errors on the training data => fitting**

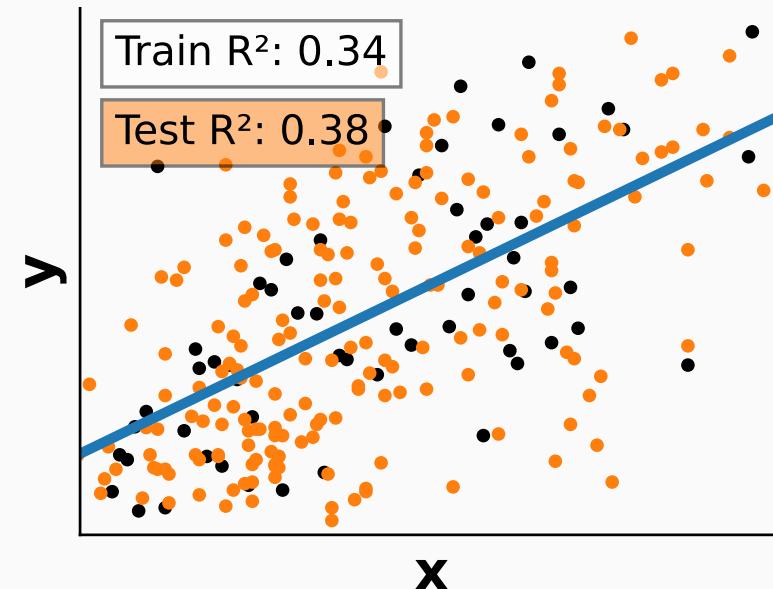


# Train vs test error: simple models

Measure the errors on the training data => fitting

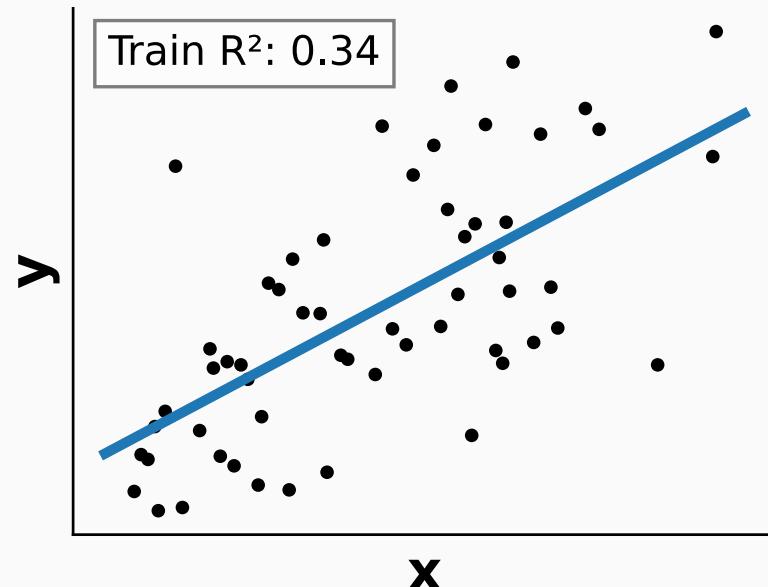


Measure the performances on test data => generalization

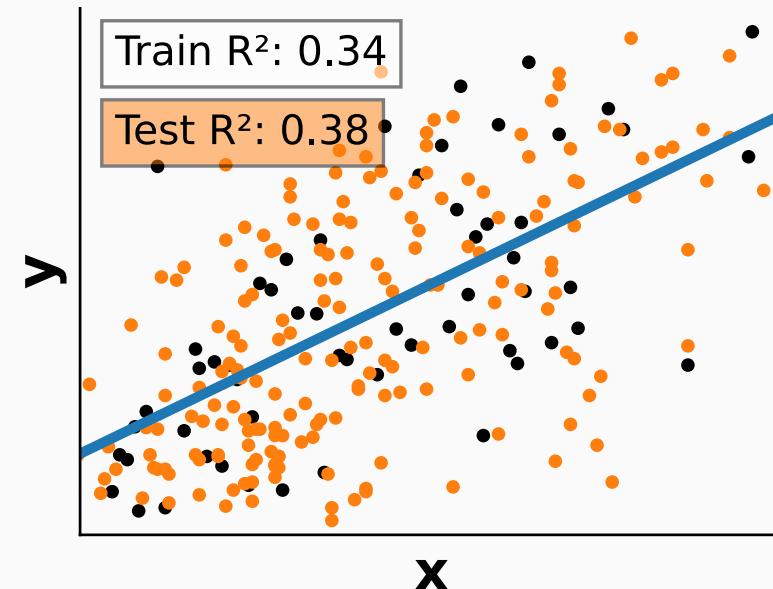


# Train vs test error: simple models

Measure the errors on the training data => fitting



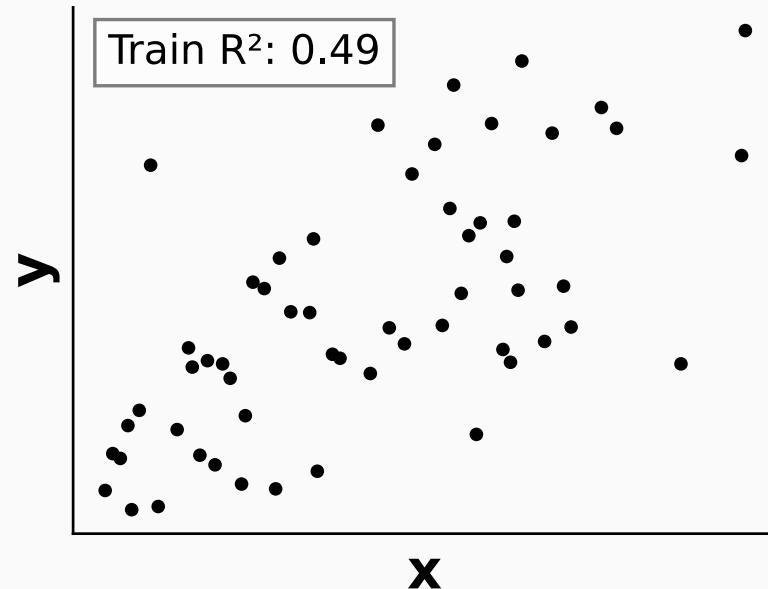
Measure the performances on test data => generalization



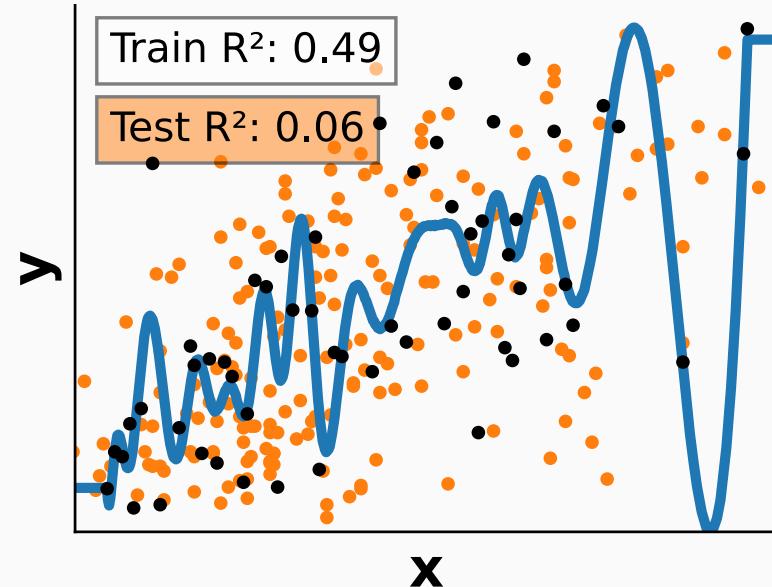
🎉 Here, no problem of overfitting: train vs test error are similar.

# Train vs test error: flexible models

Measure the errors on the training data = fitting

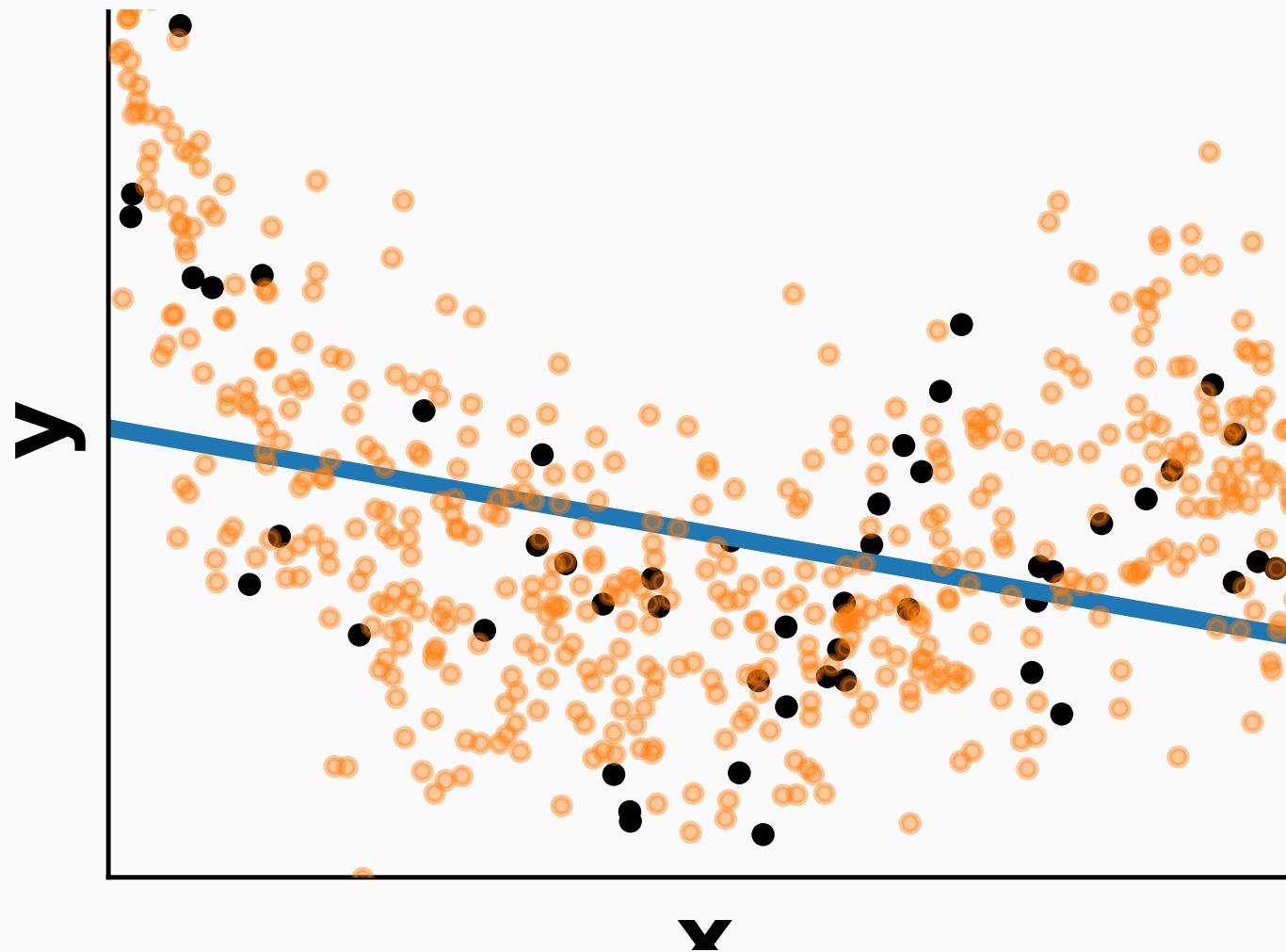


Measure the performances on test data = generalization



Overfitting: the model is too complex and captures noise.

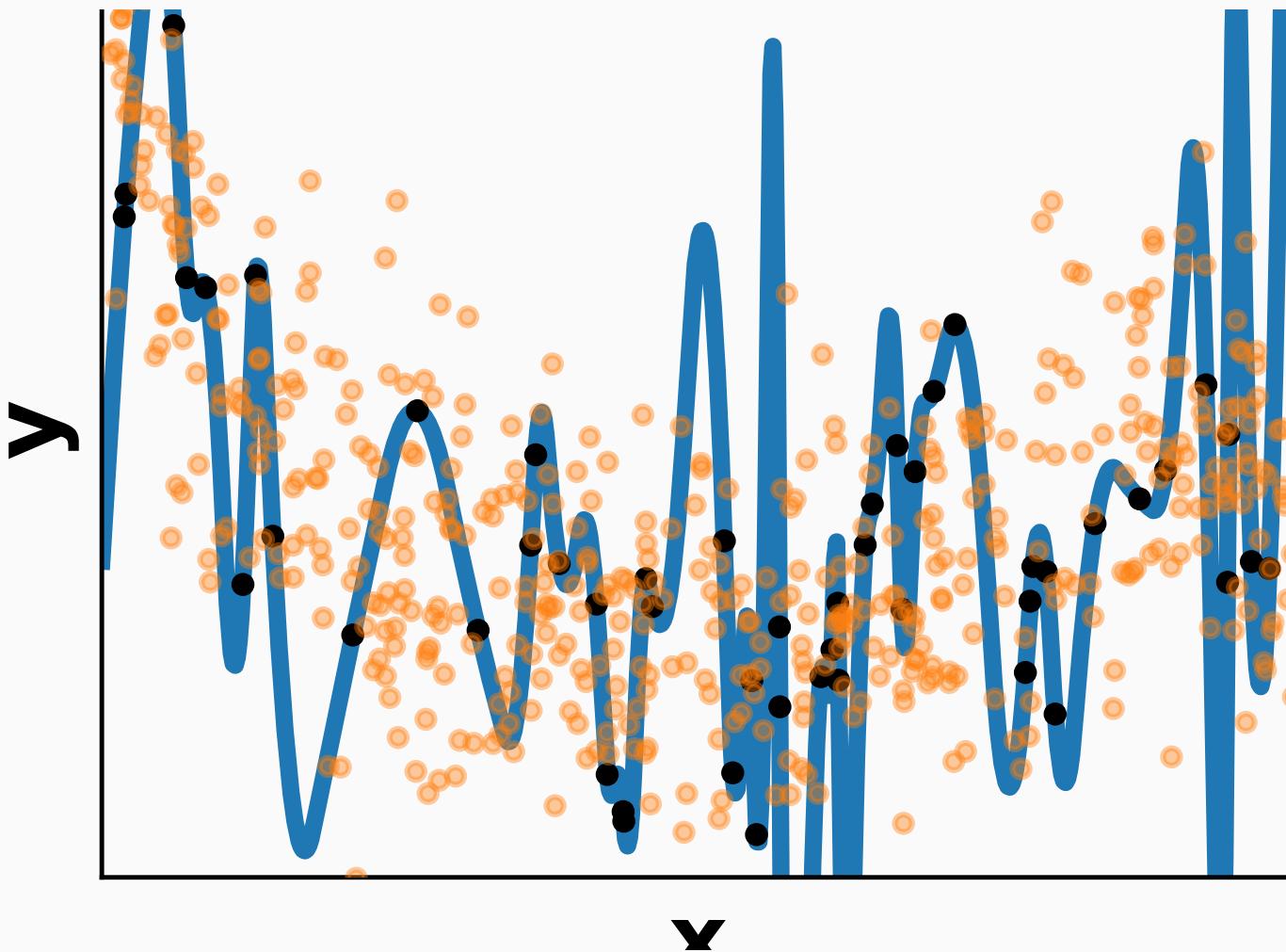
# How to choose the complexity of the model?



# How to choose the complexity of the model?

[

# How to choose the complexity of the model?



# How to choose the complexity of the model?

]

This trade-off is called **Bias variance trade-off**.

- Let's recover it in the context of statistical learning theory.

# Empirical Risk Minimization

## Loss function

A **loss function**  $\ell$  defines the proximity between the predicted value  $\hat{y} = f(x)$  and the true value  $y$ :  $\ell(f(x), y)$

# Empirical Risk Minimization

## Loss function

A **loss function**  $\ell$  defines the proximity between the predicted value  $\hat{y} = f(x)$  and the true value  $y$ :  $\ell(f(x), y)$

**Example, for continuous outcomes, the squared loss**

$$\ell(f(x), y) = (f(x) - y)^2$$

# Empirical Risk Minimization

## Loss function

A **loss function**  $\ell$  defines the proximity between the predicted value  $\hat{y} = f(x)$  and the true value  $y$ :  $\ell(f(x), y)$

**Example, for continuous outcomes, the squared loss**

$$\ell(f(x), y) = (f(x) - y)^2$$

## Risk minimization

We look into a (finite) family of candidate functions  $f \in \mathcal{F}$ ,

For the best possible function  $f^*$ , ie  $f$  minimizing the **risk or expected loss**

$$\mathcal{E}(f) = \mathbb{E}[(f(x) - y)^2]:$$

# Empirical Risk Minimization

## Loss function

A **loss function**  $\ell$  defines the proximity between the predicted value  $\hat{y} = f(x)$  and the true value  $y$ :  $\ell(f(x), y)$

**Example, for continuous outcomes, the squared loss**

$$\ell(f(x), y) = (f(x) - y)^2$$

## Risk minimization

We look into a (finite) family of candidate functions  $f \in \mathcal{F}$ ,

For the best possible function  $f^*$ , ie  $f$  minimizing the **risk or expected loss**

$\mathcal{E}(f) = \mathbb{E}[(f(x) - y)^2]$ :

$$f^* = \operatorname{argmin}_{f \in \mathcal{F}} \mathbb{E}[(f(x) - y)^2]$$

## Empirical risk minimization: estimation error

- In finite sample regimes, the expectation  $\mathbb{E}$  is not accessible since we only have access to a finite number of data pairs

## Empirical risk minimization: estimation error

- In finite sample regimes, the expectation  $\mathbb{E}$  is not accessible since we only have access to a finite number of data pairs
- In practice, we minimize the empirical risk or average loss  $R_{\text{emp}} = \sum_{i=1}^n (f(x_i) - y_i)^2$ :

$$\hat{f} = \operatorname{argmin}_{f \in \mathcal{F}} \sum_{i=1}^n (f(x_i) - y_i)^2$$

## Empirical risk minimization: estimation error

- In finite sample regimes, the expectation  $\mathbb{E}$  is not accessible since we only have access to a finite number of data pairs
- In practice, we minimize the empirical risk or average loss  $R_{\text{emp}} = \sum_{i=1}^n (f(x_i) - y_i)^2$ :

$$\hat{f} = \operatorname{argmin}_{f \in \mathcal{F}} \sum_{i=1}^n (f(x_i) - y_i)^2$$

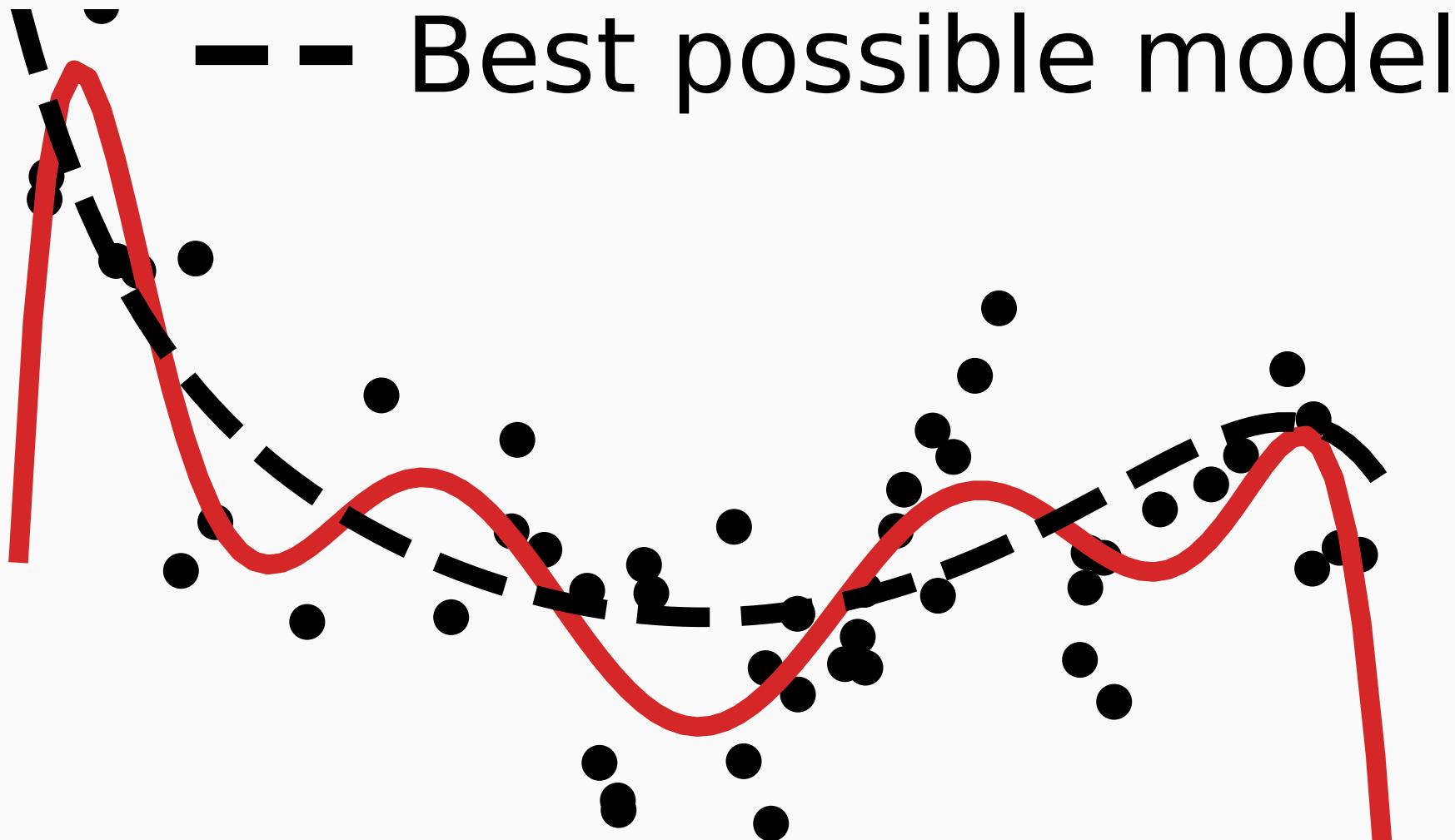
- This creates the estimation error, related to sampling noise:

$$\mathcal{E}(\hat{f}) - \mathcal{E}(f^\star) = \mathbb{E}\left[\left(\hat{f}(x) - y\right)^2\right] - \mathbb{E}\left[\left(f^\star(x) - y\right)^2\right] \geq 0$$

# Empirical risk minimization: estimation error illustration

High **estimation error** means overfit

## Empirical risk minimization: estimation error illustration



# Empirical risk minimization: estimation error illustration

, [

## **Model is too complex**

- The model is able to recover the true generative process
- But its flexibility captures noise

## **Too much noise**

## **Not enough data**

]

# Bayes error rate: Randomness of the problem



**Interesting problems exhibit randomness**

$$y = g(x) + e \text{ with } E(e|x) = 0 \text{ and } \text{Var}(e|x) = \sigma^2$$

# Bayes error rate: Randomness of the problem



## Interesting problems exhibit randomness

$y = g(x) + e$  with  $E(e|x) = 0$  and  $\text{Var}(e|x) = \sigma^2$



## $g(\cdot)$ is the best possible estimator

$g(\cdot)$  induces the Bayes error, the unavoidable error:

$$\mathcal{E}(g) = \mathbb{E}[(g(x) + e - g(x))^2] = \mathbb{E}[e^2] = \sigma^2$$

# Empirical risk minimization: approximation error

**In practice, the class of function in which the true function lies is unknown:**

$y \approx g(x)$  : Every model is wrong !

# Empirical risk minimization: approximation error

**In practice, the class of function in which the true function lies is unknown:**  
 $y \approx g(x)$  : Every model is wrong !

**One chooses the best possible function in the candidate family  $\mathcal{F}$**   
 $f^* \in \mathcal{F}$  eg. linear models, polynomials, trees, neural networks...

# Empirical risk minimization: approximation error

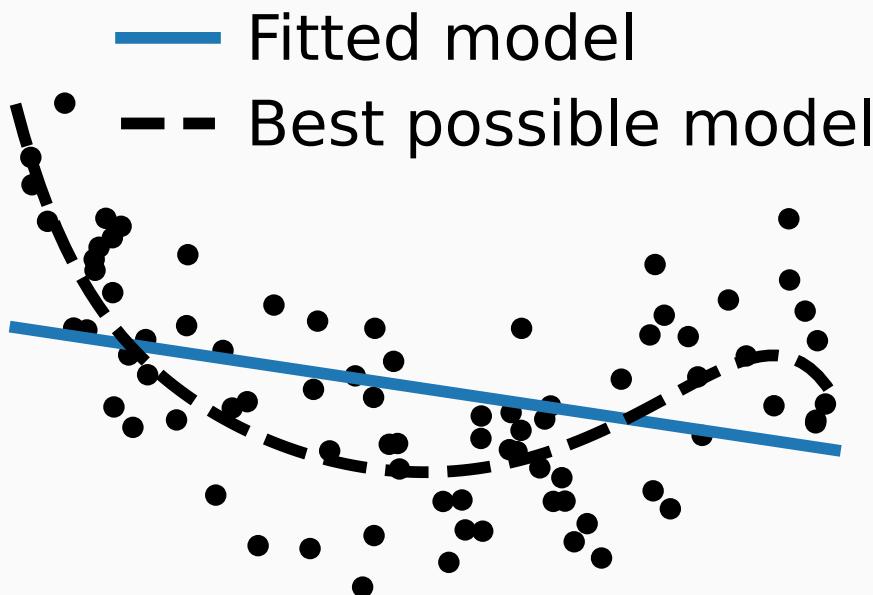
**In practice, the class of function in which the true function lies is unknown:**  
 $y \approx g(x)$  : Every model is wrong !

**One chooses the best possible function in the candidate family  $\mathcal{F}$**   
 $f^* \in \mathcal{F}$  eg. linear models, polynomials, trees, neural networks...

**This creates the approximation error:**

$$\mathcal{E}(f^*) - \mathcal{E}(g) = \mathbb{E}[(f^*(x) - y)^2] - \mathbb{E}[(g(x) - y)^2] \geq 0$$

## High approximation error means underfit



**Model is too simple for the data**

- its best fit does not approximate the true generative process
- Yet it captures little noise

**Low noise**

**Rapidly enough data to fit the model**

# Bias variance trade-off: Putting the pieces together

**Decomposition of the empirical risk of a fitted model  $\hat{f}$**

$$\mathcal{E}(\hat{f}) = \underbrace{\mathcal{E}(g)}_{\text{Bayes error}} + \underbrace{\mathcal{E}(f^*) - \mathcal{E}(g)}_{\text{approximation error}} + \underbrace{\mathcal{E}(\hat{f}) - \mathcal{E}(f^*)}_{\text{estimation error}}$$

# Bias variance trade-off: Putting the pieces together

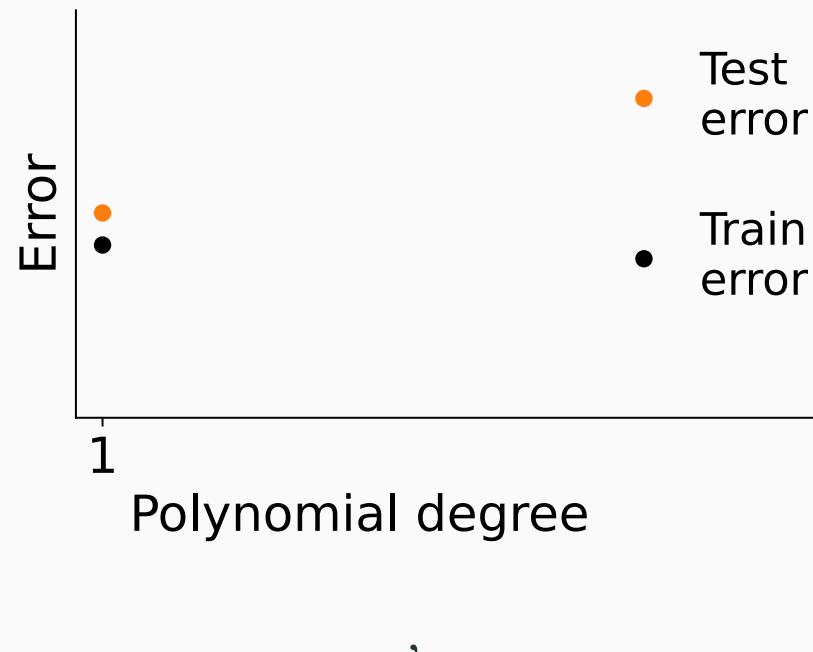
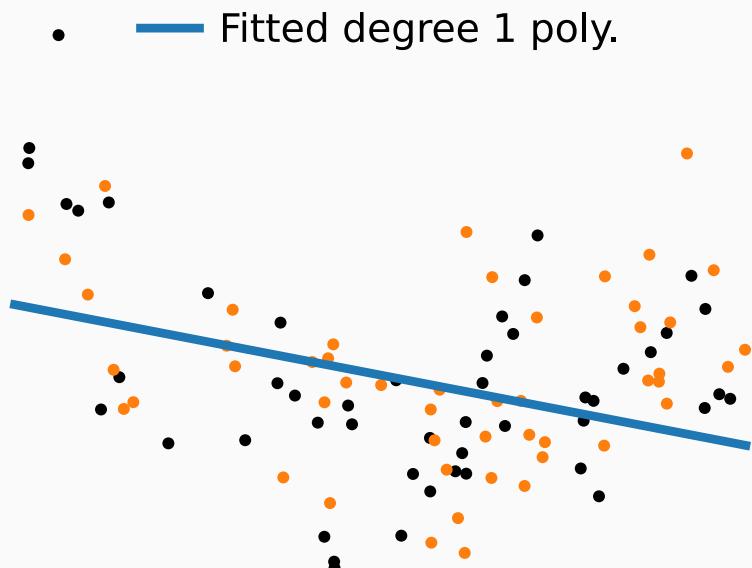
## Decomposition of the empirical risk of a fitted model $\hat{f}$

$$\mathcal{E}(\hat{f}) = \underbrace{\mathcal{E}(g)}_{\text{Bayes error}} + \underbrace{\mathcal{E}(f^*) - \mathcal{E}(g)}_{\text{approximation error}} + \underbrace{\mathcal{E}(\hat{f}) - \mathcal{E}(f^*)}_{\text{estimation error}}$$

### Controls on this trade-off

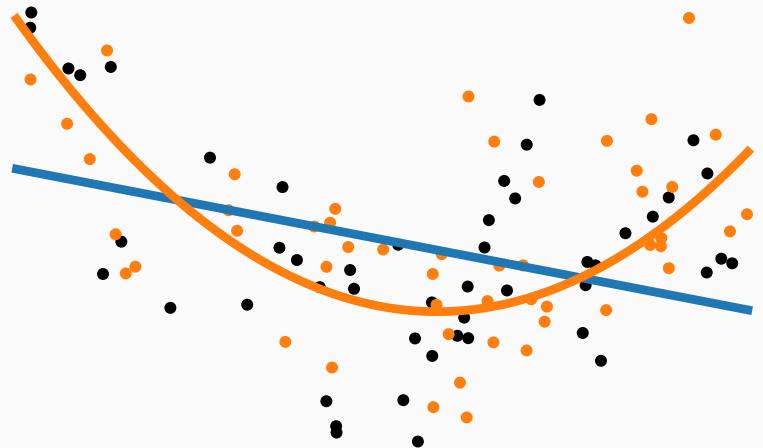
- Bigger candidate family (more complex models)  $\mathcal{F}$ : increases the estimation errors but decreases the approximation error.
- Smaller candidate family (simpler models): decreases the estimation error but increases the approximation error.
- Bigger sample size  $n$ : reduces estimation error and allows more complex models.

# Train vs test error: increasing complexity



# Train vs test error: increasing complexity

- Fitted degree 1 poly.
- Fitted degree 2 poly.



[

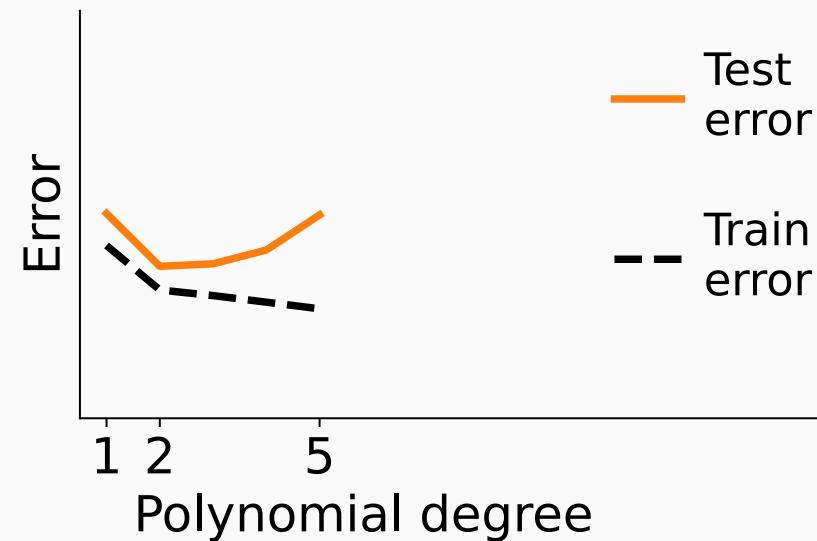
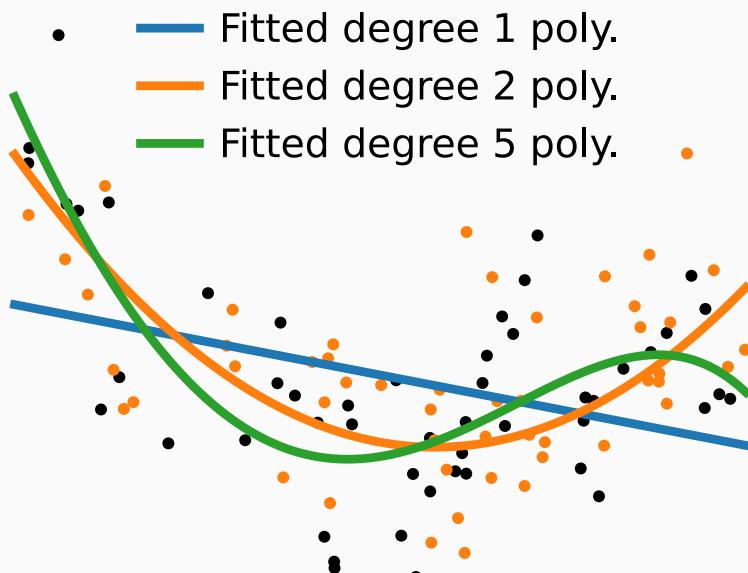
## Train vs test error: increasing complexity



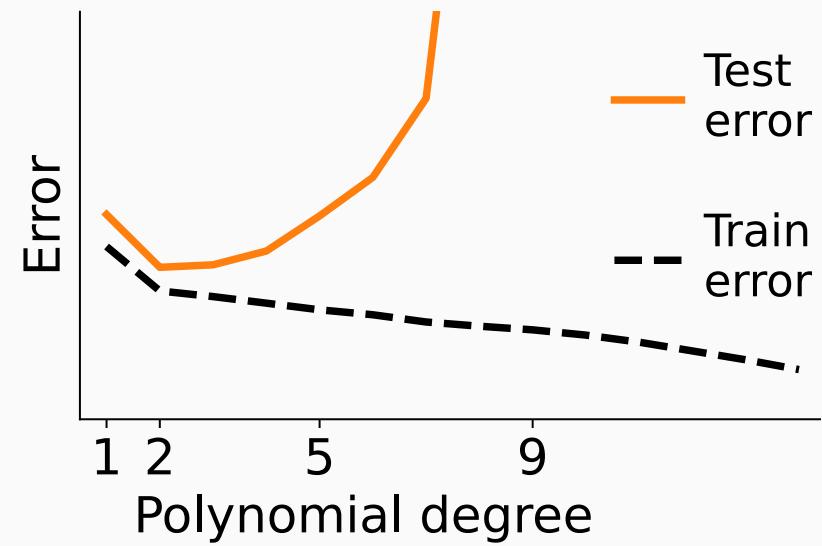
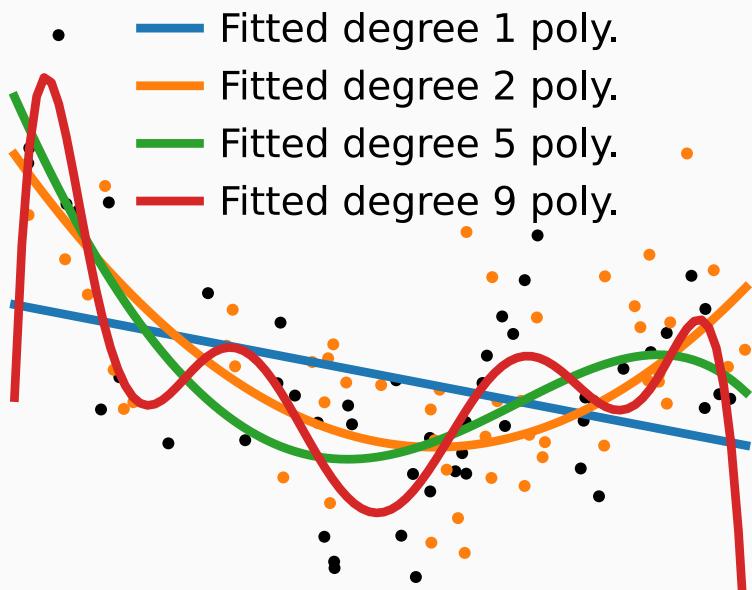
## Train vs test error: increasing complexity

]

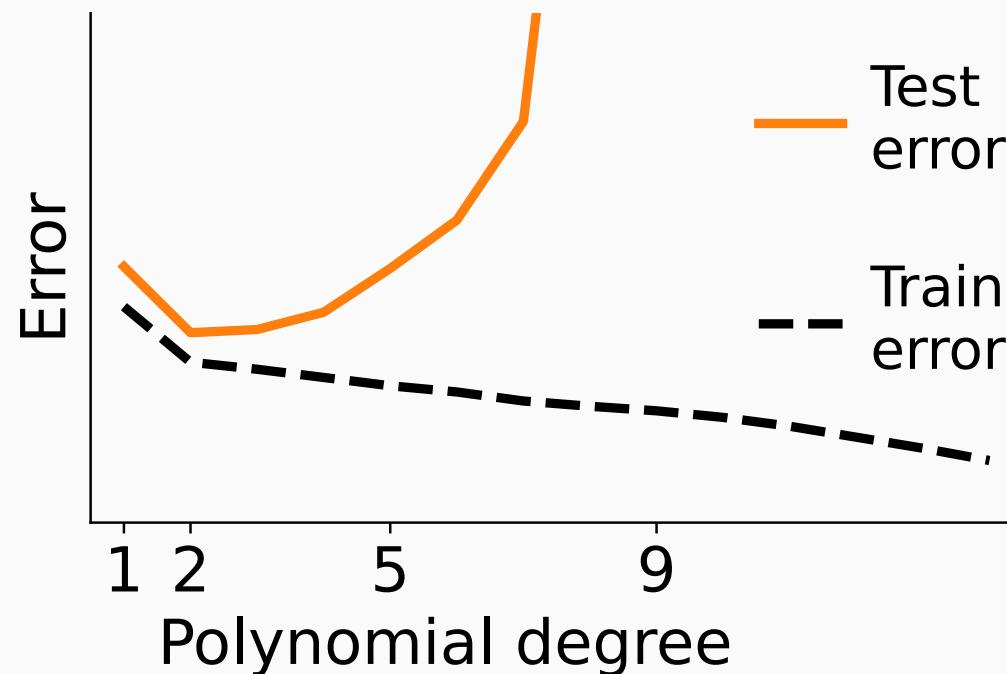
# Train vs test error: increasing complexity



# Train vs test error: increasing complexity

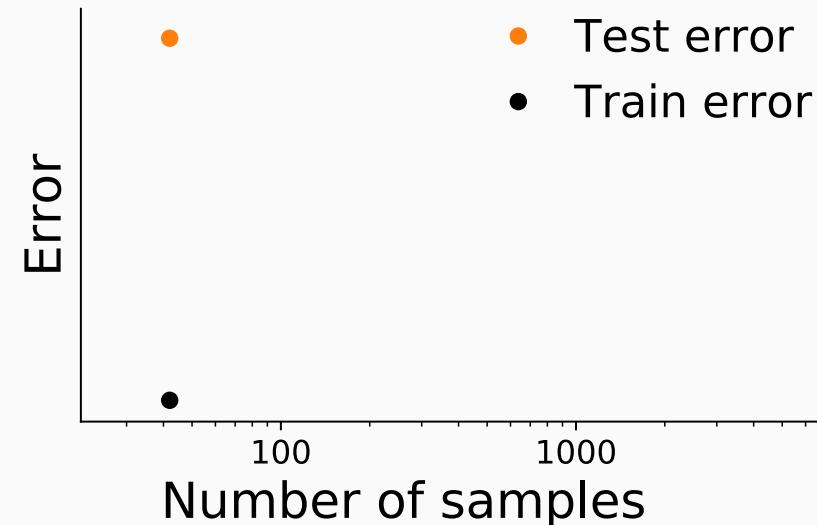
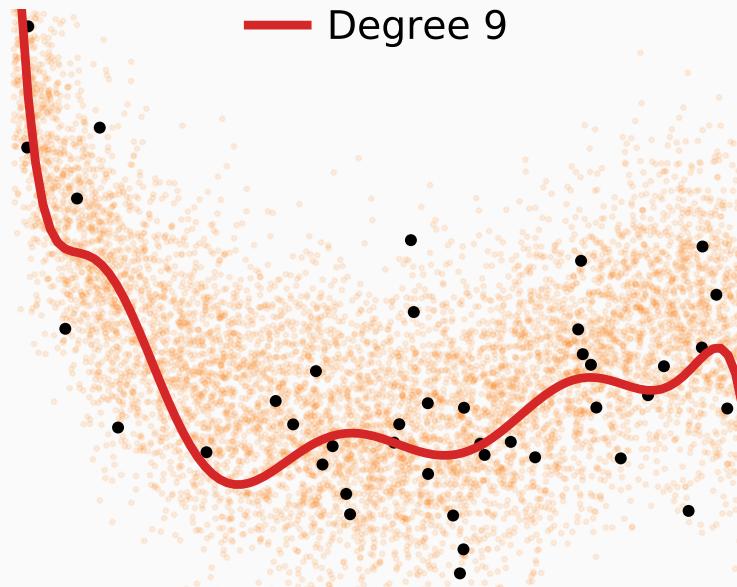


# Train vs test error: increasing complexity



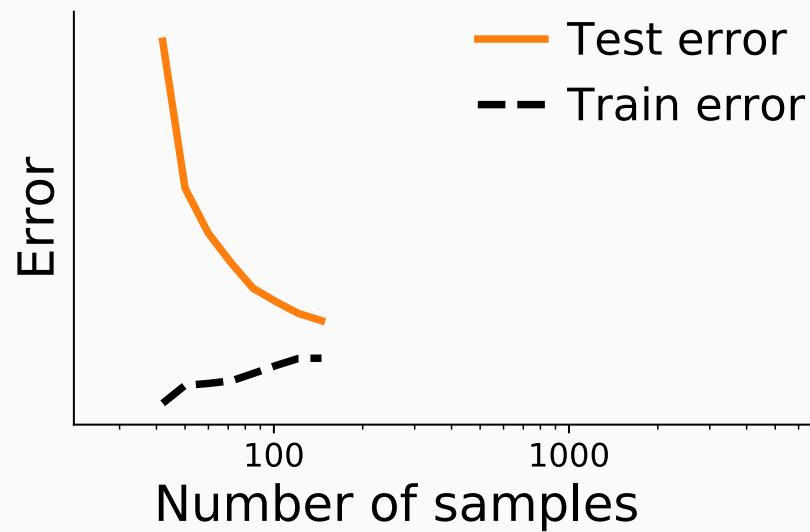
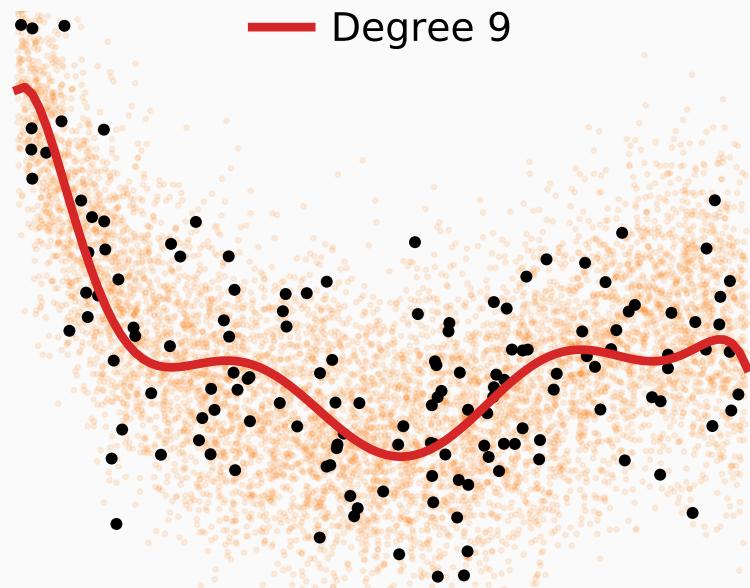
Underfit   Sweet Spot   Overfit

# Varying sample size with a candidate family ( $\mathcal{F}$ polynomials of degree 9)

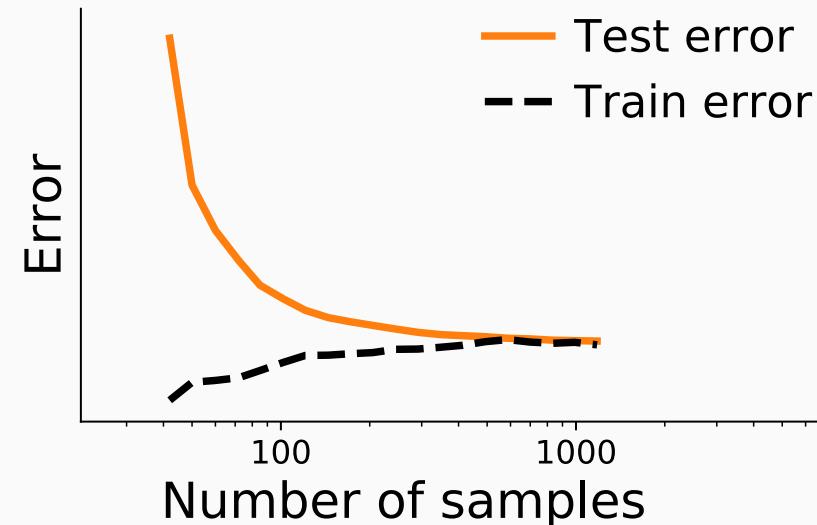
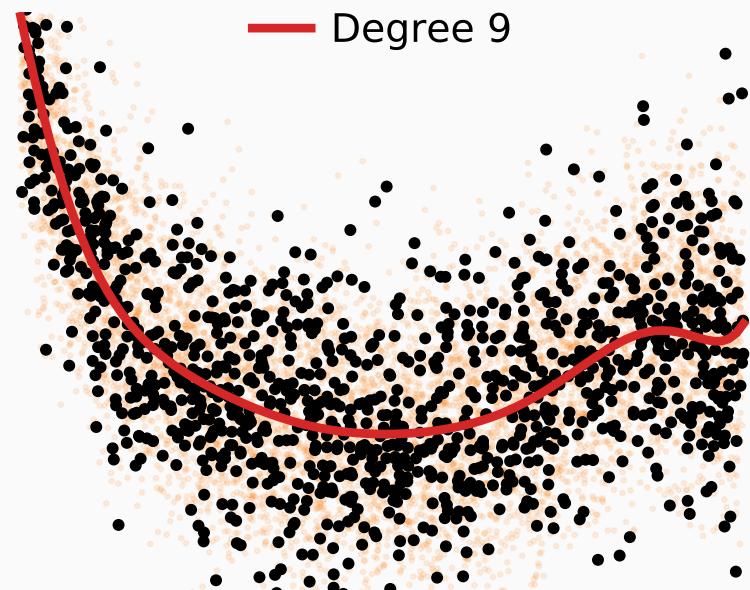


Overfit

# Varying sample size with a candidate family ( $\mathcal{F}$ polynomials of degree 9)

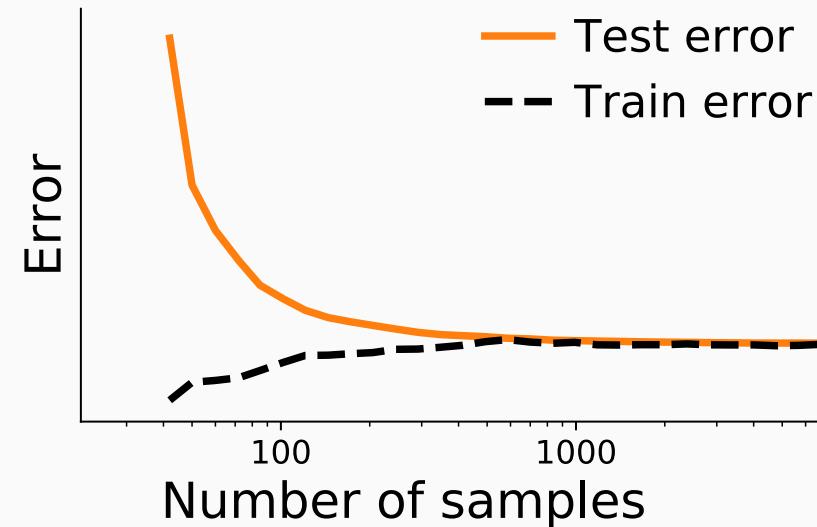
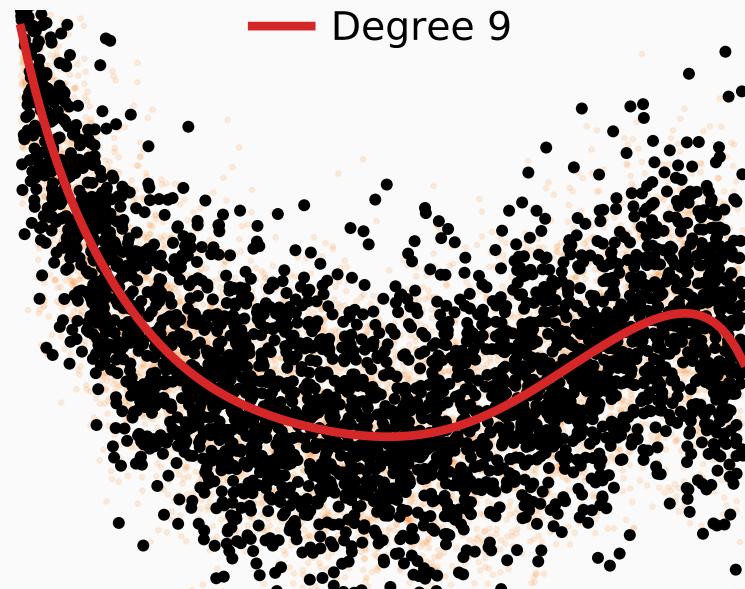


# Varying sample size with a candidate family ( $\mathcal{F}$ polynomials of degree 9)



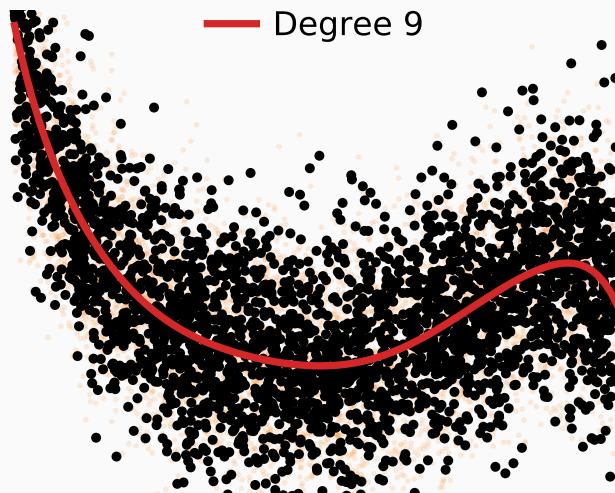
Sweet spot?

# Varying sample size with a candidate family ( $\mathcal{F}$ polynomials of degree 9)



Diminishing returns?

# Varying sample size with a candidate family ( $\mathcal{F}$ polynomials of degree 9)



— Degree 9

The error of the best model trained on unlimited data.

Here, the data is generated by a polynomial of degree 9.

We cannot do better.

Prediction is limited by noise: Bayes error.

Remaining of this session (and the next on predictive inference)

## Common model families suited to tabular data

### Today

- Regularized linear models: Lasso and Ridge
- Hands-on with scikit-learn

### Next session

- Practical model selection: Cross-validation
- Flexible models: Trees, Random Forests, Gradient Boosting
- Practical scikit-learn

**High approximation error  
means underfit**

---

Regularized linear models for predictive inference

## Reminder: Linear regression

$y$  is a linear combination of the features  $x \in \mathbb{R}^p$

$$Y_i = X_i^T \beta_0 + \varepsilon_i$$

- $\varepsilon$  the random error term (noise), often assumed  $\varepsilon_i \mid X \sim \mathcal{N}(0, \sigma^2)$
- $\beta_0 \in \mathbb{R}^{p \times 1}$  the *true* coefficients.

## Reminder: Linear regression

$y$  is a linear combination of the features  $x \in \mathbb{R}^p$

$$Y_i = X_i^T \beta_0 + \varepsilon_i$$

- $\varepsilon$  the random error term (noise), often assumed  $\varepsilon_i \mid X \sim \mathcal{N}(0, \sigma^2)$
- $\beta_0 \in \mathbb{R}^{p \times 1}$  the *true* coefficients.

Usually, we assume that the errors are normally distributed and independent of  $X_i$ :

$$\varepsilon_i \sim \mathcal{N}(0, \sigma^2) \text{ and } \varepsilon_i \perp\!\!\!\perp X_i$$

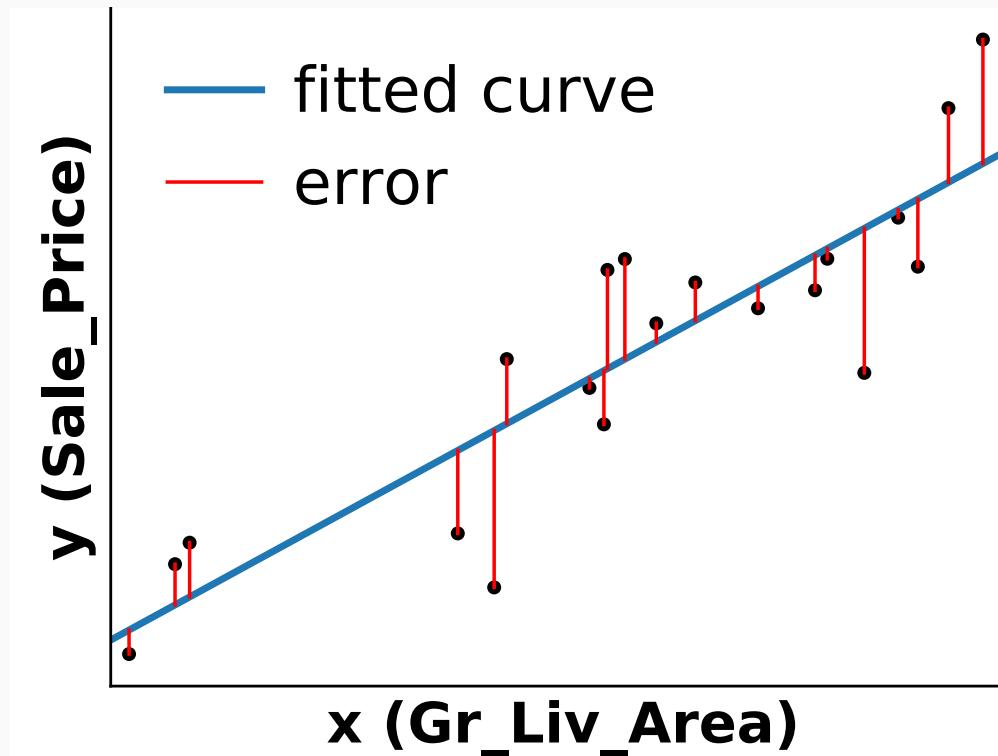
Model are typically fitted by linear algebra methods (Hastie, 2009).

## Reminder: Linear regression

$y$  is a linear combination of the features  $x \in \mathbb{R}^p$

$$Y_i = X_i^T \beta_0 + \varepsilon_i$$

## Reminder: Linear regression



## Common metrics

- Mean Squared Error:  $MSE = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2$

# Reminder: Linear regression

## Common metrics

- Mean Squared Error:  $MSE = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2$
- R-squared, :  $R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \bar{Y})^2}{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}$  where  $\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i$

The proportion of variance explained by the model (perfect fit:  $R^2 = 1$ )

# Reminder: Linear regression

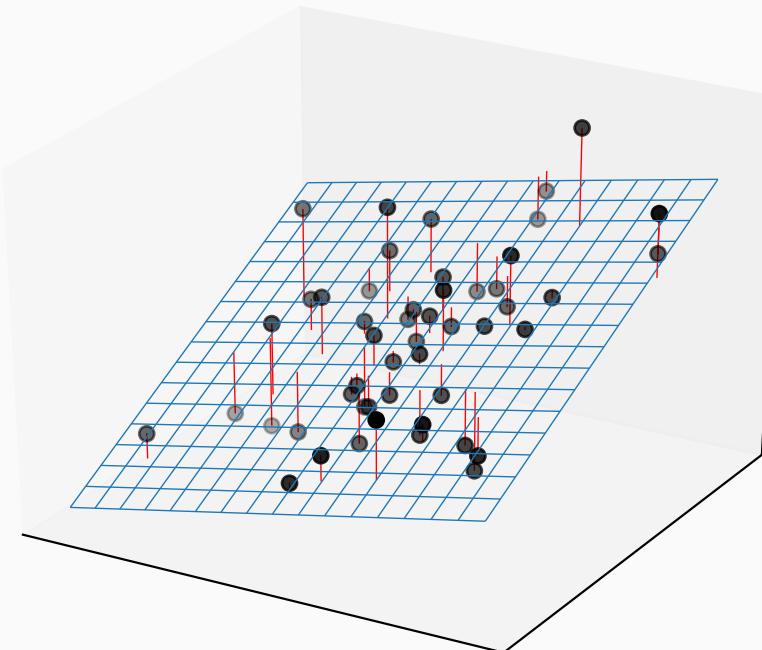
## Common metrics

- Mean Squared Error:  $MSE = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2$
- R-squared, :  $R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \bar{Y})^2}{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}$  where  $\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i$

The proportion of variance explained by the model (perfect fit:  $R^2 = 1$ )

- Mean absolute error:  $MAE = \frac{1}{n} \sum_{i=1}^n |Y_i - \hat{Y}_i|$

# Linear regression: Illustration in two dimensions



## Reminder: logistic regression for classification

The logit of the probability of the outcome is a linear combination of the features  $X_i \in \mathbb{R}^p$ :

$$\ln\left(\frac{p(Y_i=1|X_i)}{p(Y_i=0|X_i)}\right) = X_i^T \beta_0$$

## Reminder: logistic regression for classification

## Reminder: logistic regression for classification

The logit of the probability of the outcome is a linear combination of the features  $X_i \in \mathbb{R}^p$ :

$$\ln\left(\frac{p(Y_i=1|X_i)}{p(Y_i=0|X_i)}\right) = X_i^T \beta_0$$

Taking exponential of both sides, we get:

$$p(Y_i = 1|X_i, \beta_0) \stackrel{\text{def}}{=} p(X_i, \beta_0) = \frac{1}{1 + \exp(-X_i^T \beta_0)}$$

The statistical model is a Bernoulli :  $B(p(x, \beta_0))$

## Reminder: logistic regression for classification

## Reminder: logistic regression for classification

The logit of the probability of the outcome is a linear combination of the features  $X_i \in \mathbb{R}^p$ :

$$\ln\left(\frac{p(Y_i=1|X_i)}{p(Y_i=0|X_i)}\right) = X_i^T \beta_0$$

Taking exponential of both sides, we get:

$$p(Y_i = 1|X_i, \beta_0) \stackrel{\text{def}}{=} p(X_i, \beta_0) = \frac{1}{1 + \exp(-X_i^T \beta_0)}$$

The statistical model is a Bernoulli :  $B(p(x, \beta_0))$

## Reminder: logistic regression for classification

Model fitted by maximum likelihood with iterative optimization (Hastie, 2009): eg. coordinate descents (liblinear), second order descent (Newton's method), gradient descent (SAG)...

# Reminder: classification, logistic regression

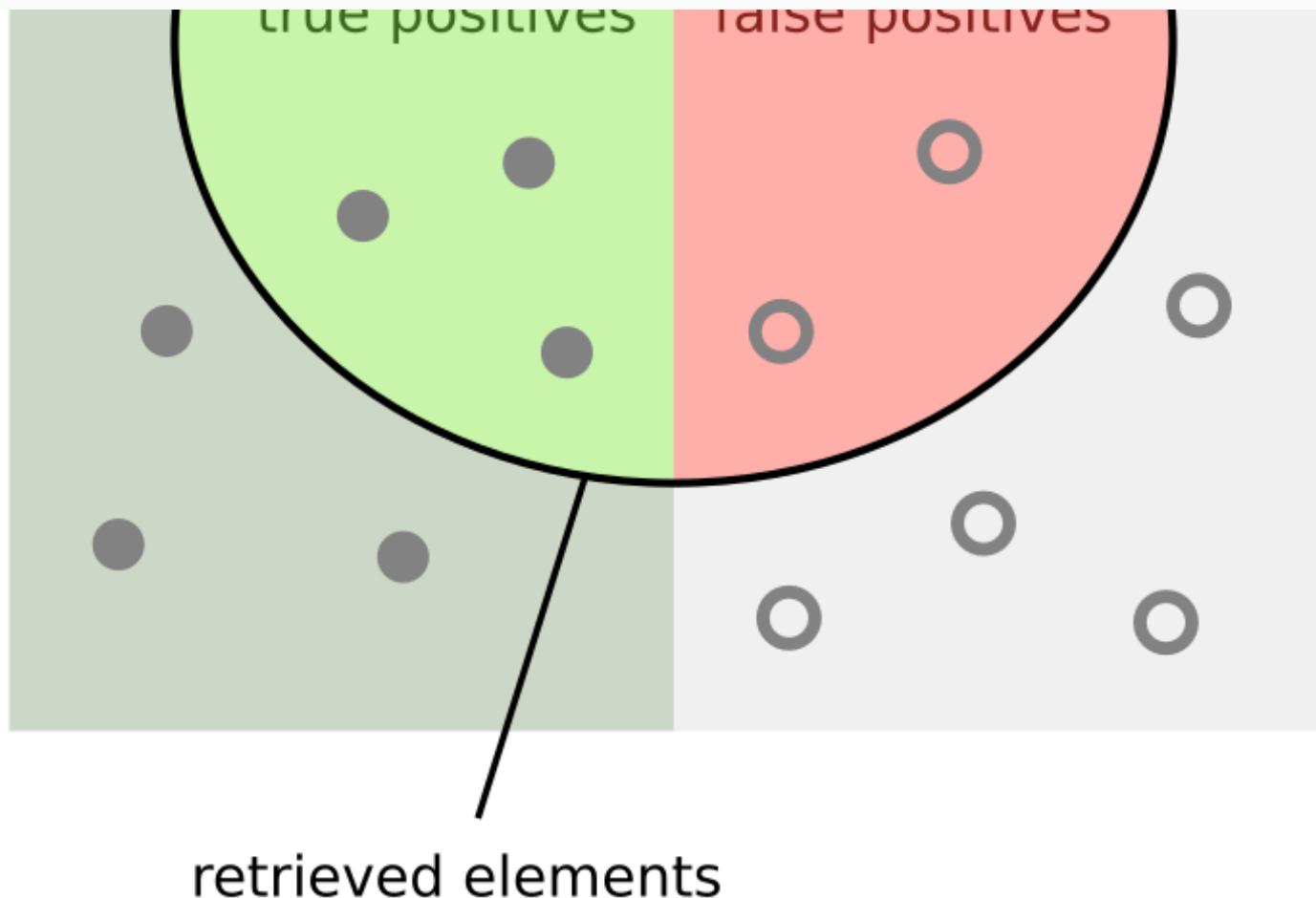
[

## Common metrics

- Accuracy =  $\frac{1}{n} \sum_{i=1}^n \mathbb{1}(Y_i = \hat{Y}_i)$
- Precision: Precision =  $\frac{\text{TP}}{\text{TP} + \text{FP}}$
- Recall: Recall =  $\frac{\text{TP}}{\text{TP} + \text{FN}}$
- Brier score loss: BSL =  $\frac{1}{n} \sum_{i=1}^n (Y_i - p_i)^2$

], [

## Reminder: classification, logistic regression



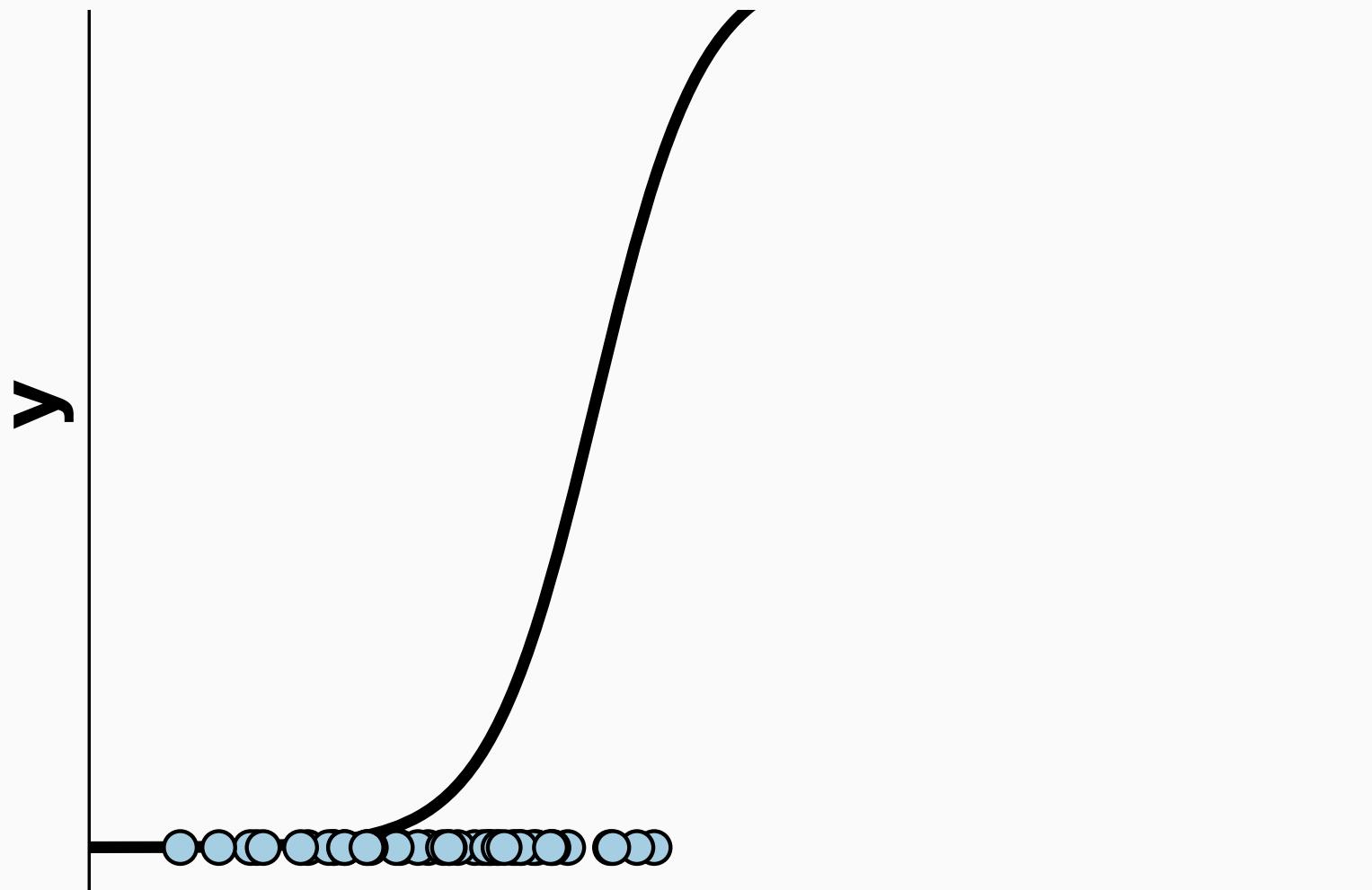
## Reminder: classification, logistic regression

]

# Logistic regression: Illustrations

[

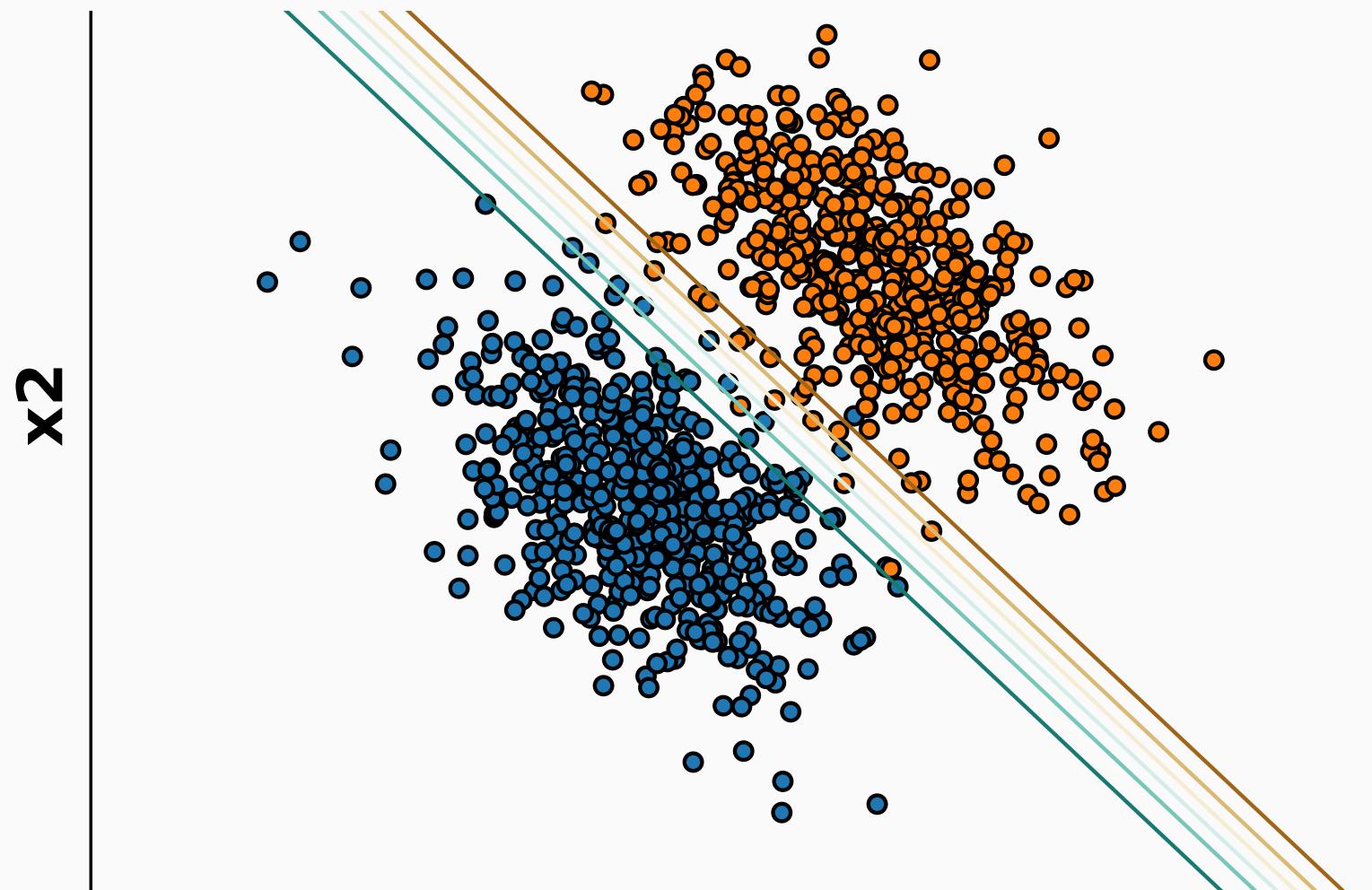
# Logistic regression: Illustrations



# Logistic regression: Illustrations

Logistic regression in one dimension. ], [

# Logistic regression: Illustrations



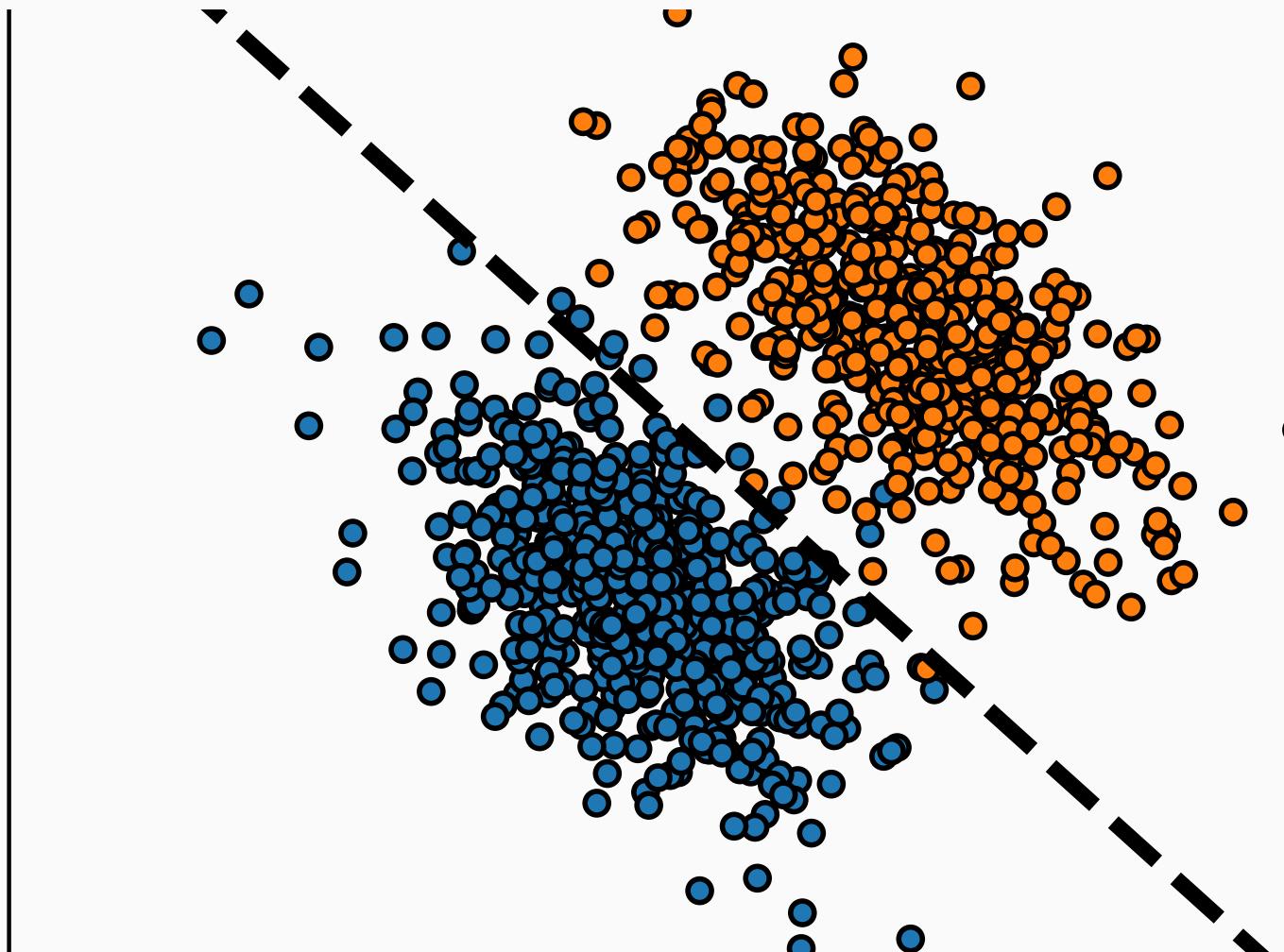
# Logistic regression: Illustrations

Logistic regression in two dimensions. ]

Linear models are not suited to all data

[

Linear models are not suited to all data

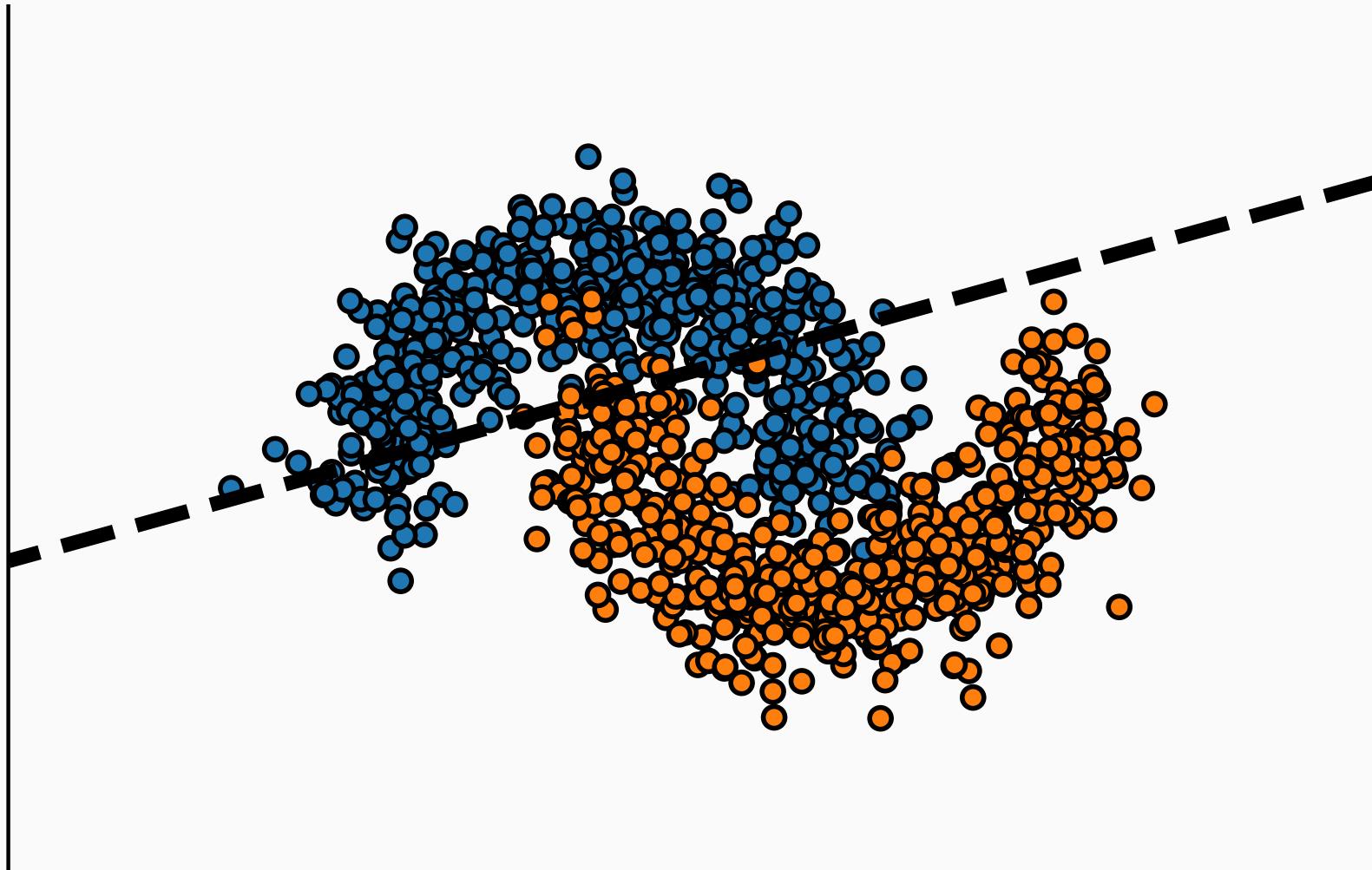


Linear models are not suited to all data

Almost linearly separable data. ],

[

Linear models are not suited to all data



Linear models are not suited to all data

Data not linearly separable. ]

## Pros

- Converge quickly
- Hard to beat when  $n_{\text{features}}$  is large but we still have  $n_{\text{samples}} \gg n_{\text{features}}$
- Linear models work well if
  - ▶ the classes are (almost) linearly separable
  - ▶ or the outcome is (almost) linearly related to the features.

# Linear model pros and cons

## Cons

Sometimes

- the best decision boundary to separate classes is not well approximated by a straight line.
- there are important non-linear relationships between the features and the outcome.

# Linear model pros and cons

## Cons

Sometimes

- the best decision boundary to separate classes is not well approximated by a straight line.
- there are important non-linear relationships between the features and the outcome.

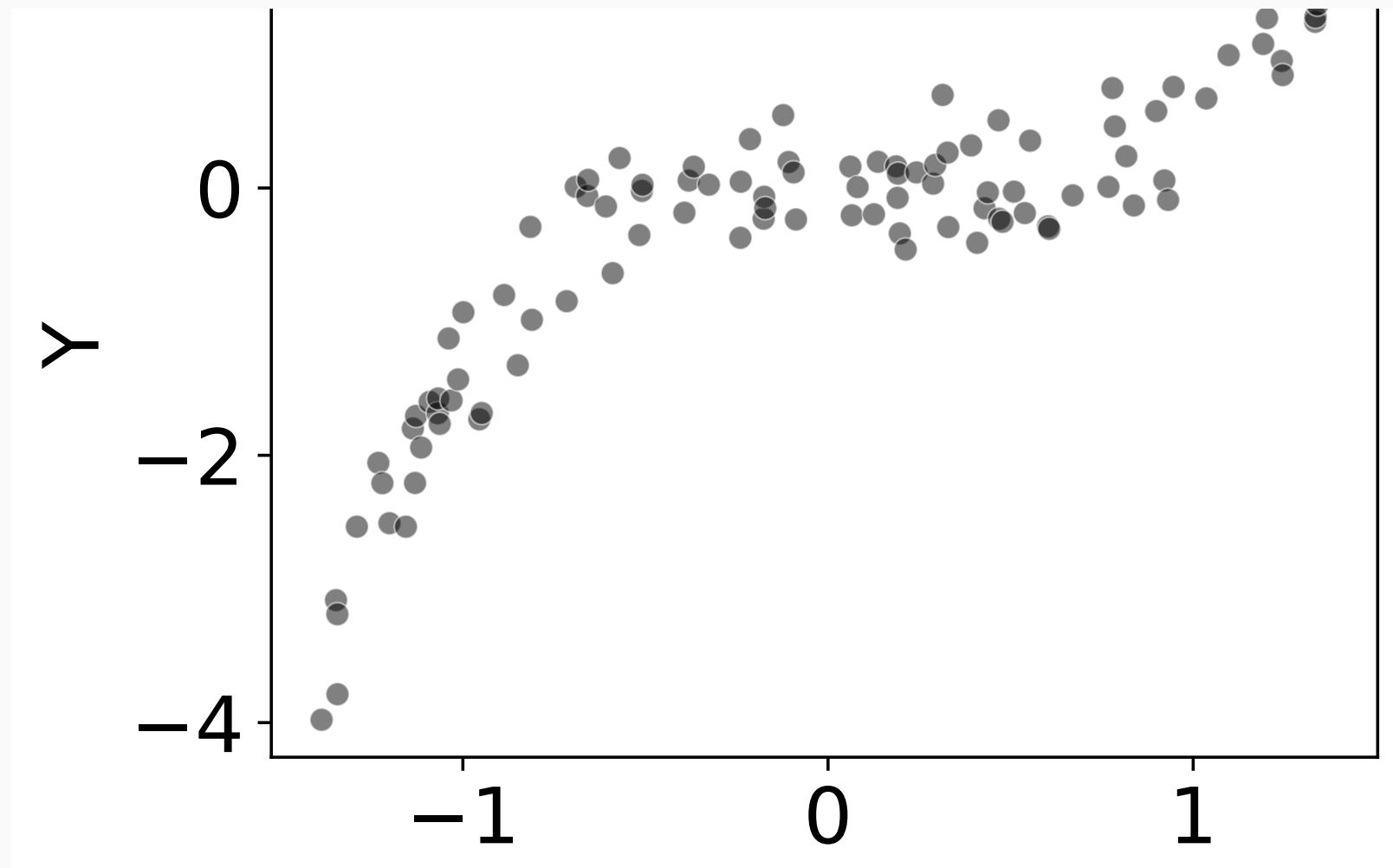


Either use non-linear models, or perform transformations on the data, to engineer new features.

## Transformation of the features: Example

[

## Transformation of the features: Example



## Transformation of the features: Example

], [

**Non-linear relationship between the features and the outcome**

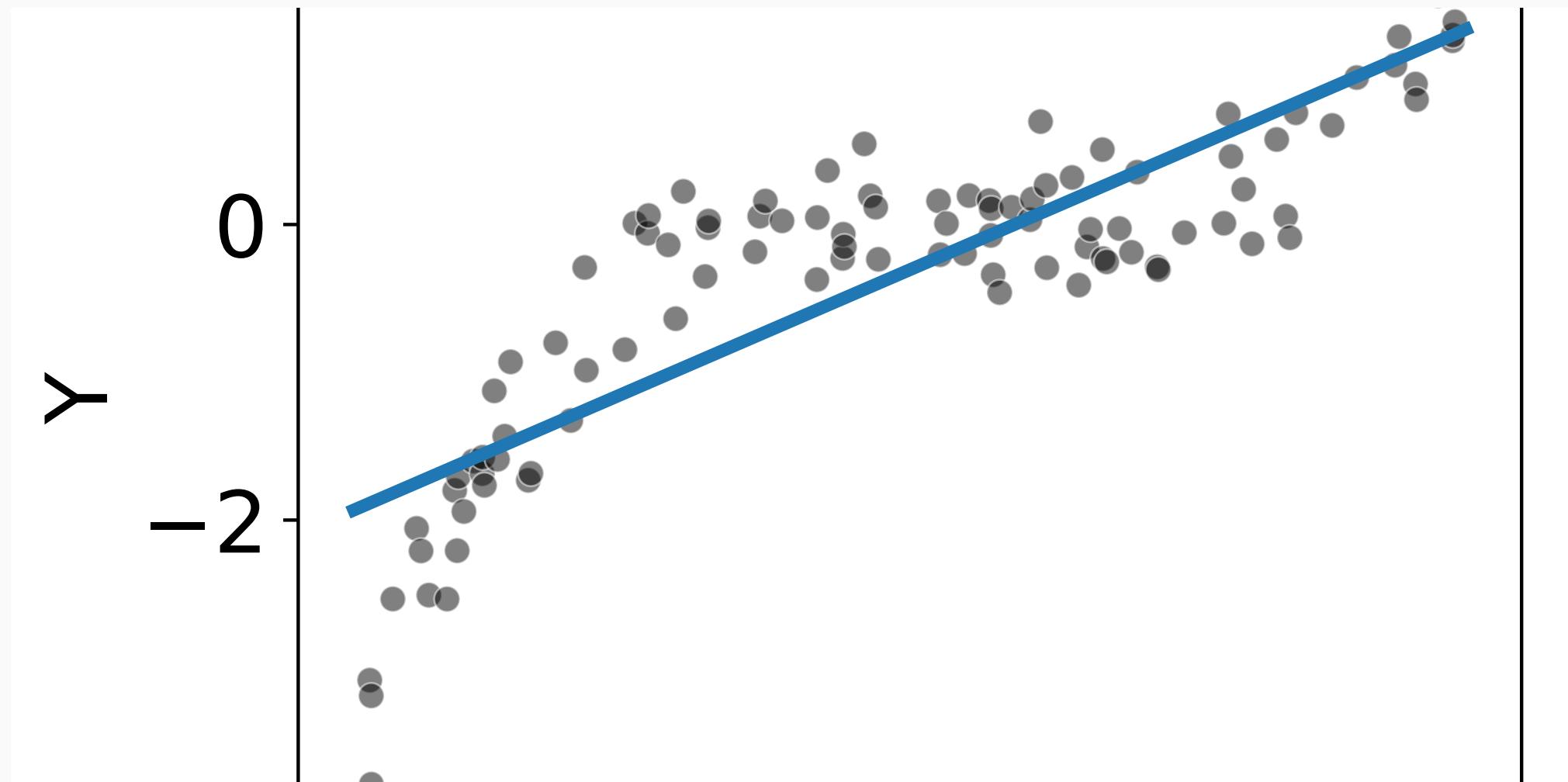
True data generating process:

$$Y = X^3 - 0.5 \times X^2 + \varepsilon ]$$

## Transformation of the features: Example

[

## Transformation of the features: Example



## Transformation of the features: Example

], [

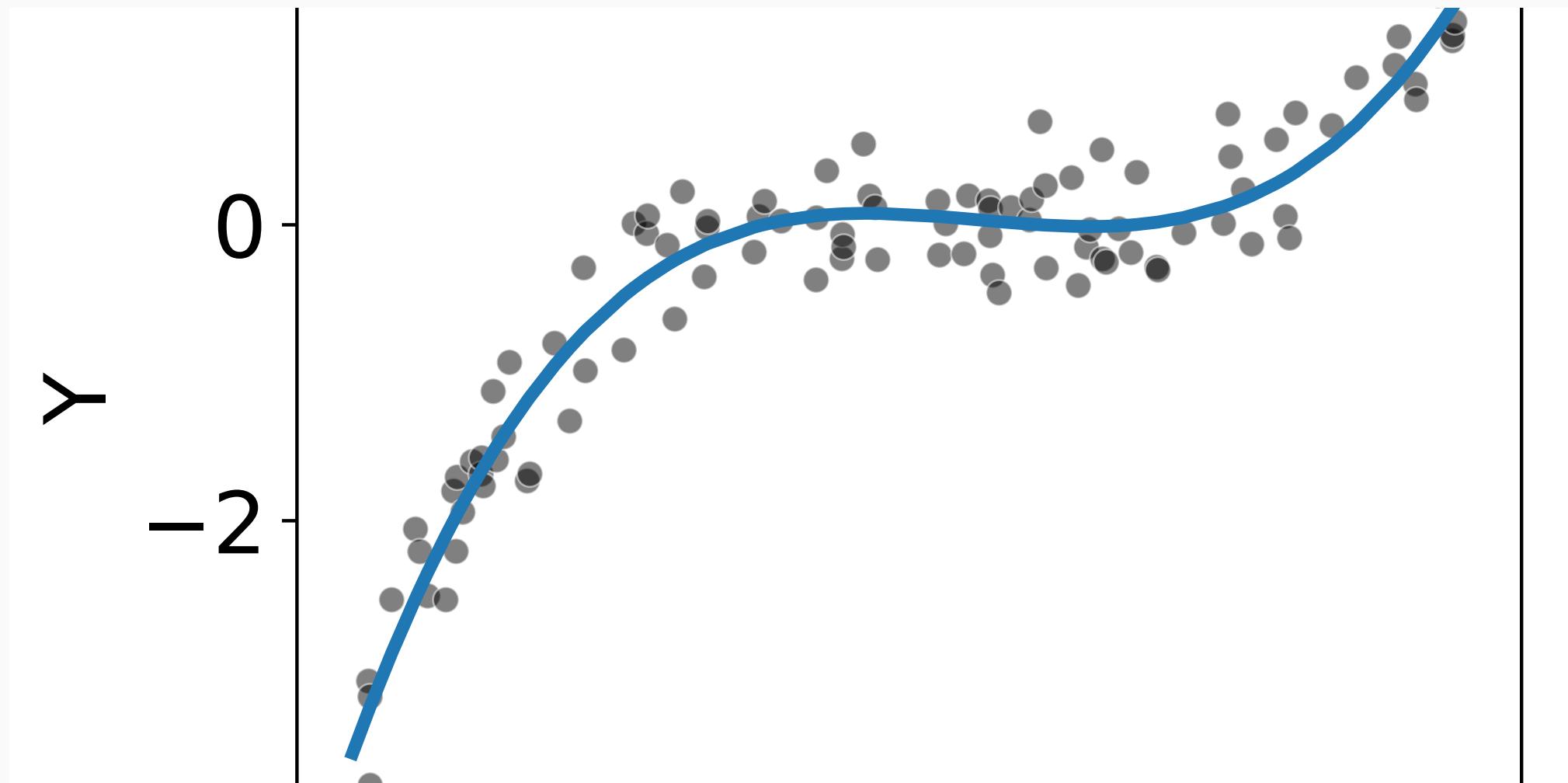
Vanilla linear regression fails to capture the relationship.

],

## Transformation of the features: Example

[

## Transformation of the features: Example



## Transformation of the features: Example

], [

Solution:

- Expand the feature space with polynomials of the features:

$$X = [X, X^2, X^3]$$

- Run a linear regression on the new feature space.

$$Y = [X, X^2, X^3]^T \hat{\beta}$$

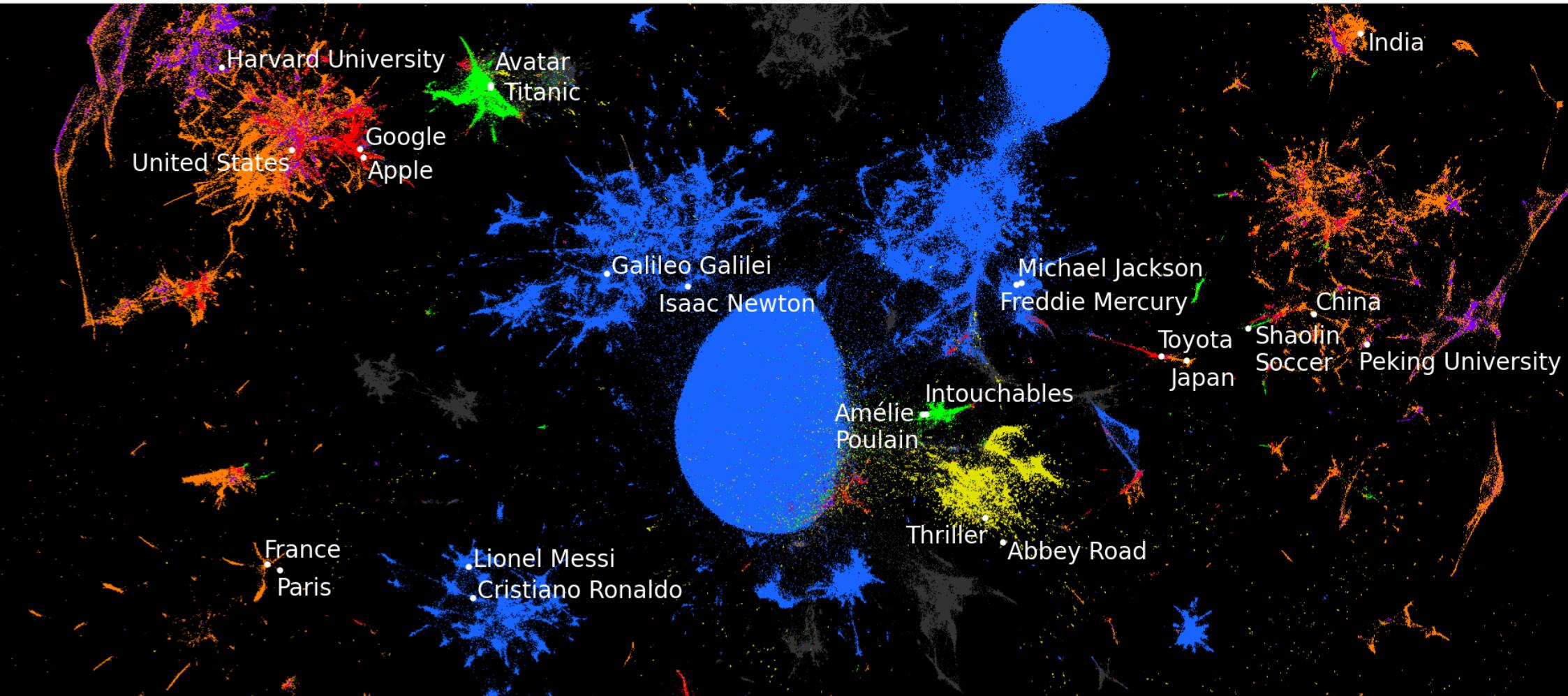
## **Feature expansion increase the family of models**

- Linear model can underfit : when n\_features small or the problem is not linearly separable.
- Feature expansion is an easy way to capture non-linear relationships.
- Different feature expansions exists: polynomial, log, splines, embeddings, kernels,  
...

## KEN (Cvetkov-Iliev et al., 2023): Relational Data Embeddings

[Easy to use with [skrub library](#)], [

# KEN (Cvetkov-Iliev et al., 2023): Relational Data Embeddings



]

But Linear models can also overfit!

## When

- $p$  is large
- Many uninformative features

But Linear models can also overfit!

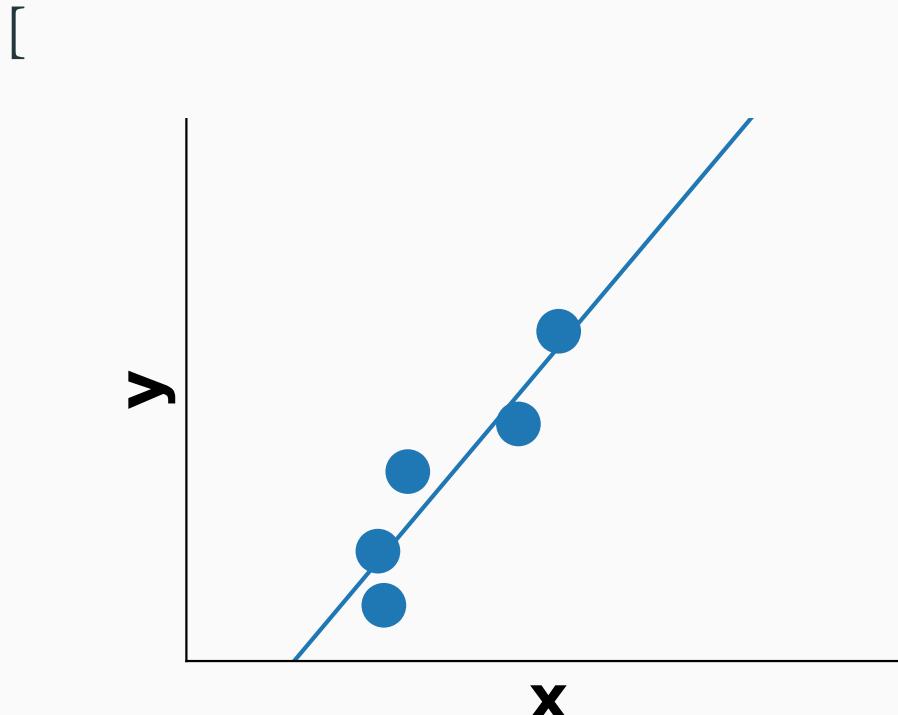
## When

- $p$  is large
- Many uninformative features

## Solution

- Used regularized linear models: penalize extreme weights
- Statistically, this allows biased models but with lower variance.
- We will see: Lasso and Ridge but this is a general principle in machine learning.

## Many features, few observations: illustration in 1D



, [

- Few observations with respect to the number of features.

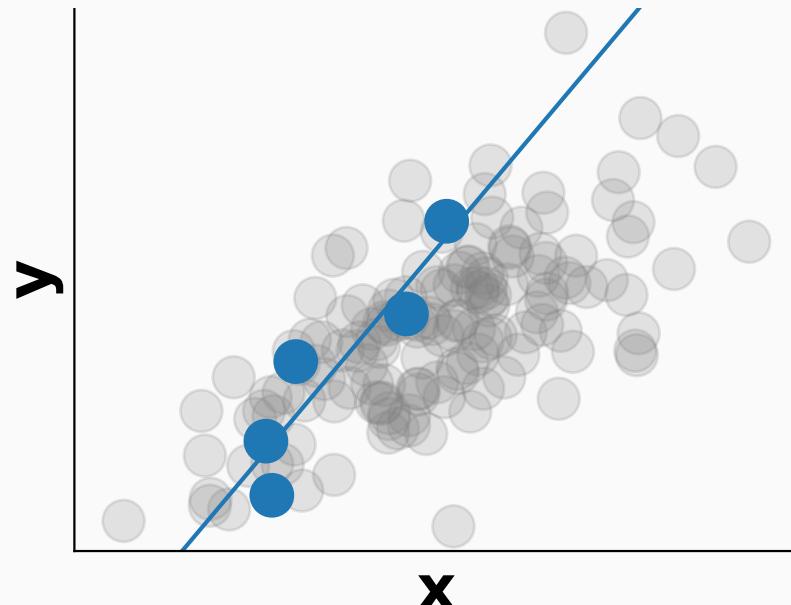
## Many features, few observations: illustration in 1D

- Fit a linear model without regularization.

],

# Many features, few observations: illustration in 1D

[



], [

- Few observations with respect to the number of features.

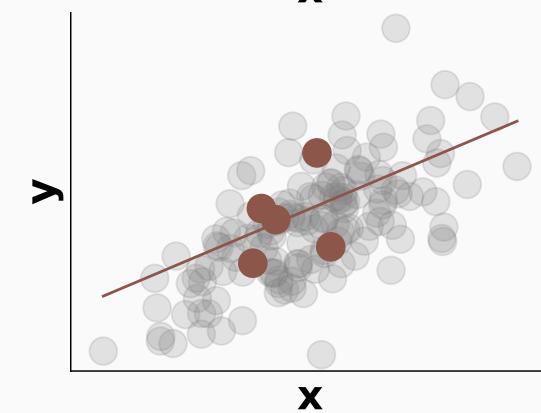
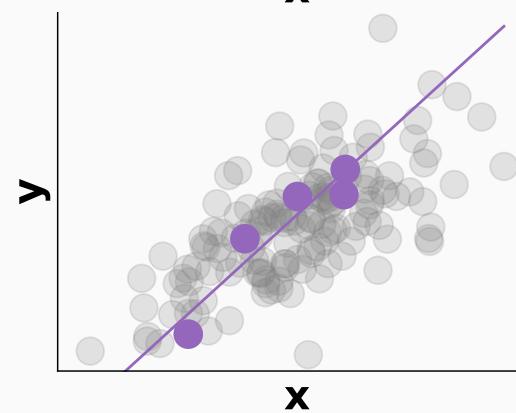
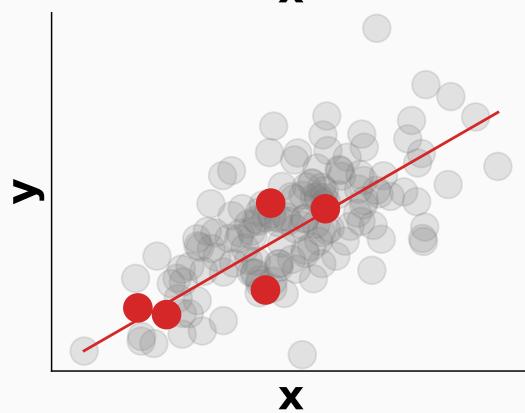
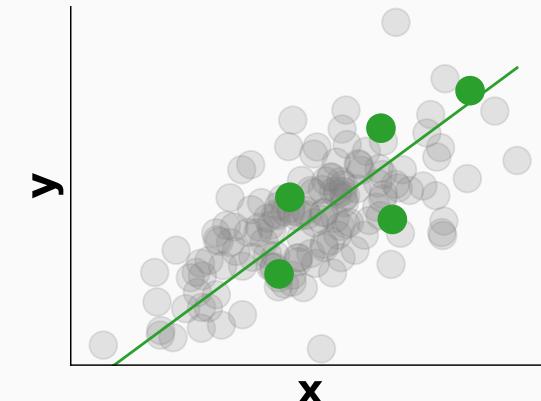
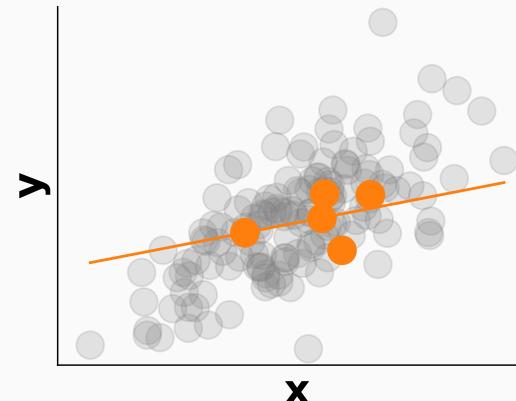
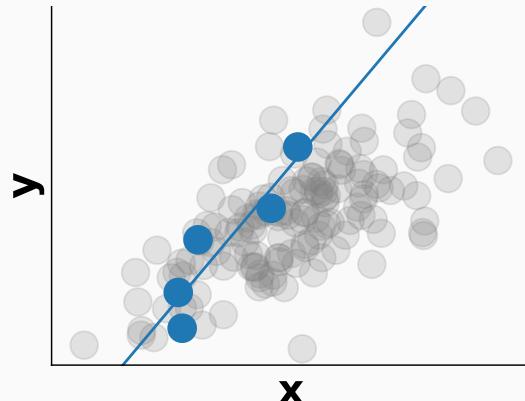
## Many features, few observations: illustration in 1D

- Fit a linear model without regularization.
- Linear model can overfit if data is noisy.

],

Many features, few observations: illustration in 1D

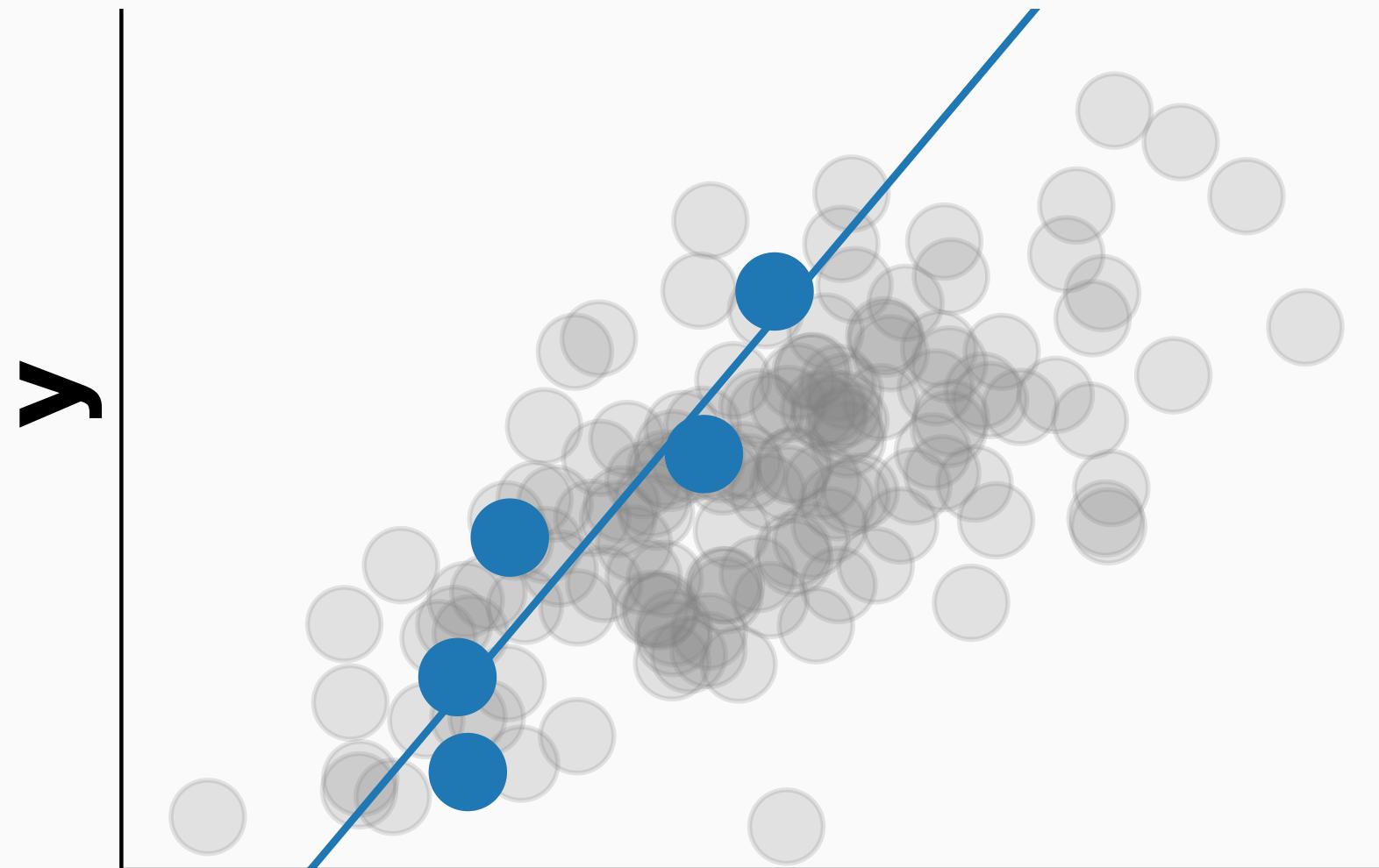
## Sampling different training sets



# Bias variance trade-off with Lasso

[

# Bias variance trade-off with Lasso

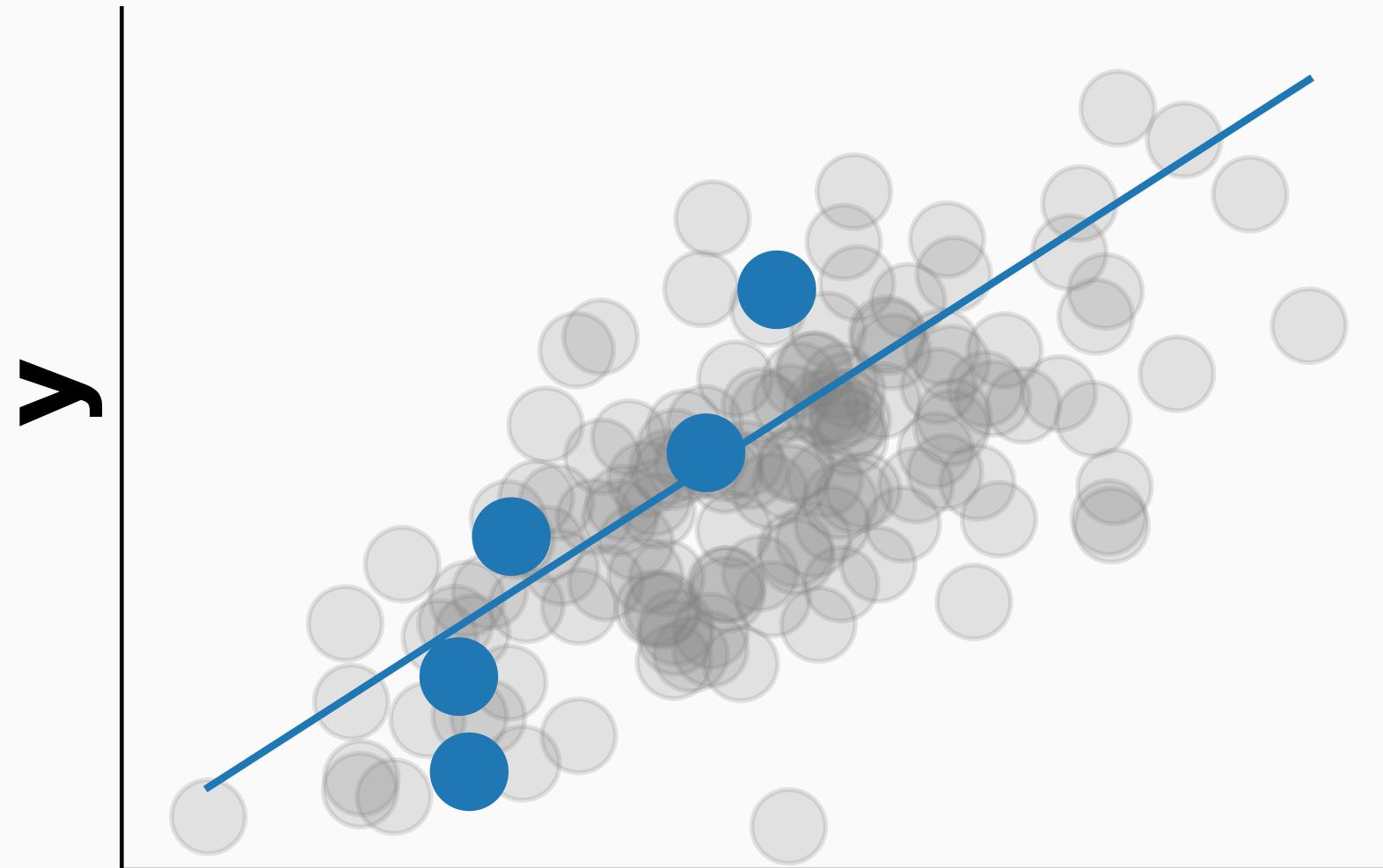


# Bias variance trade-off with Lasso

Linear regression (no regularization)

High variance, no bias. ], [

# Bias variance trade-off with Lasso

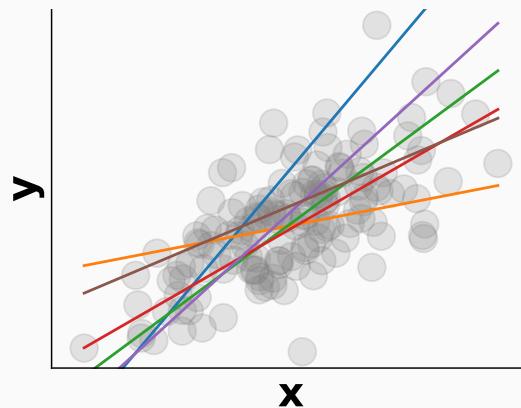


# Bias variance trade-off with Lasso

Lasso (regularization): Shrink some coefficients of  $\beta$ .

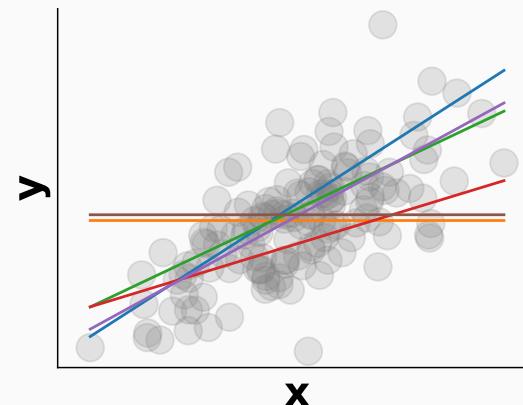
Lower variance, but bias. ],

# Bias variance trade-off with Lasso

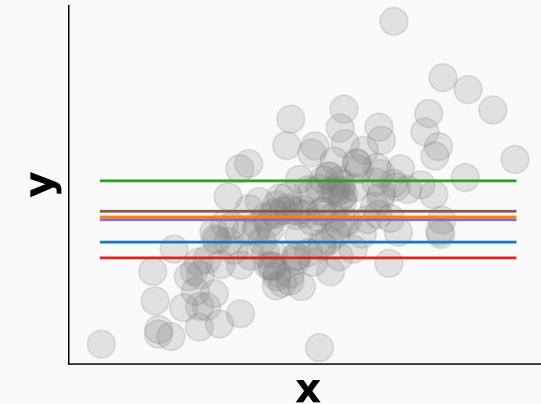


Too much variance

Not enough regularization



Best trade-off



Too much bias

Too much regularization

## Many features, few observations

Assumption 1: Linear model with high dimension

$$Y = X\beta_0 + \varepsilon, \quad \varepsilon \perp\!\!\!\perp X \text{ and } X \in \mathbb{R}^{n \times p} \text{ with } n \ll p$$

Assumption 2: (approximate) sparsity

- The true  $\beta_0$  is sparse: ie. many coefficients are zero or very close to zero.

## Objective function of the Lasso

The lasso puts a constraint of amplitude  $t$  on the  $L_1$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p |\beta_j| \leq t$$

## Objective function of the Lasso

The lasso puts a constraint of amplitude  $t$  on the  $L_1$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p |\beta_j| \leq t$$

This is equivalent to the following optimization problem (using lagrangian multiplier):

$$\min_{\beta} \frac{1}{n} \sum ((y_i - \beta^T x_i)^2) + \alpha \sum (|\beta_j|)$$

## Objective function of the Lasso

The lasso puts a constraint of amplitude  $t$  on the  $L_1$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p |\beta_j| \leq t$$

This is equivalent to the following optimization problem (using lagrangian multiplier):

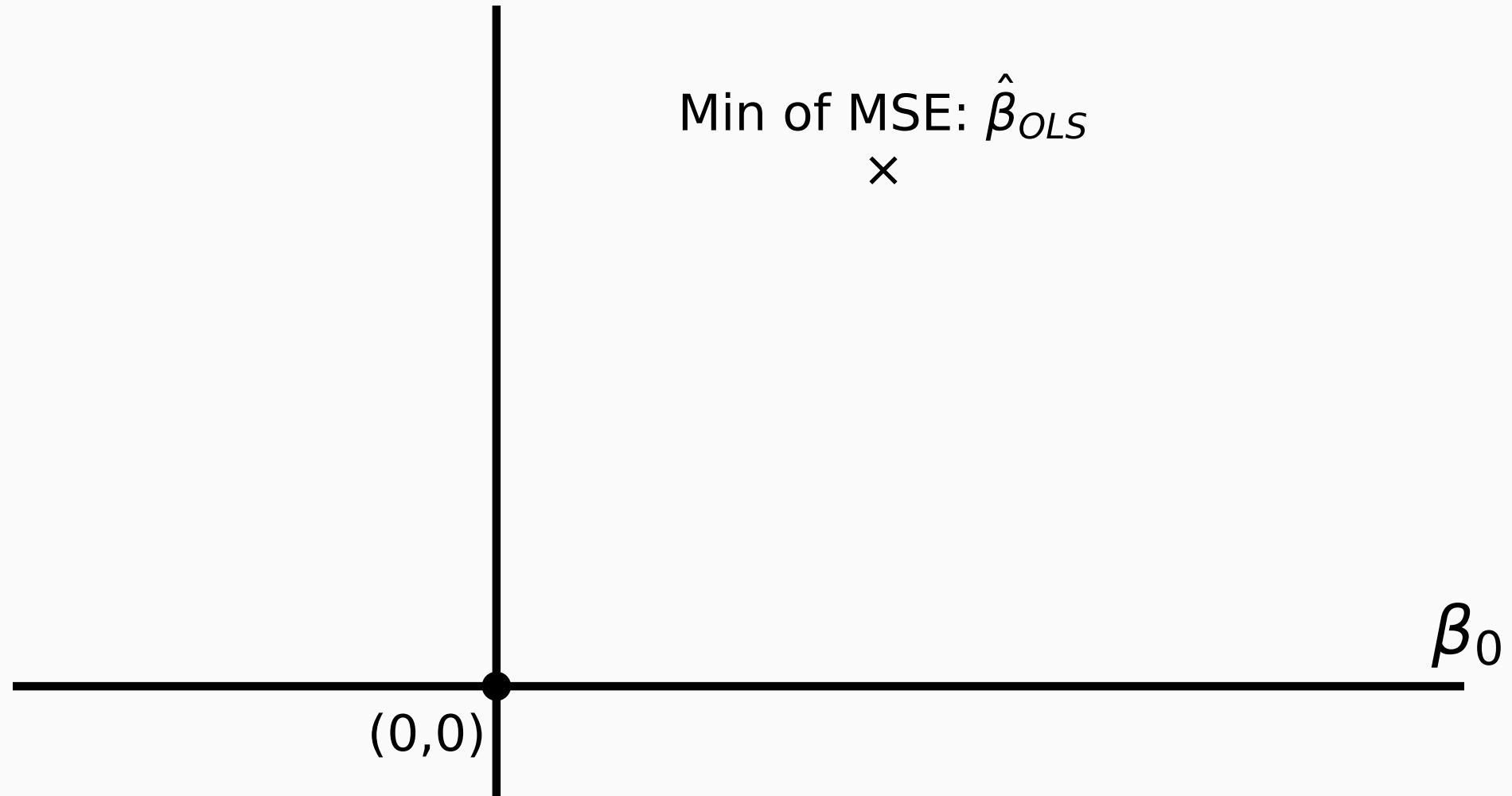
$$\min_{\beta} \frac{1}{n} \sum ((y_i - \beta^T x_i)^2) + \alpha \sum (|\beta_j|)$$

This penalty discourages large weights and can shrink certain weights to exactly *zero* (not clear yet why).

# Why does Lasso shrink some coefficients to zero?

[

# Why does Lasso shrink some coefficients to zero?



# Why does Lasso shrink some coefficients to zero?

], [

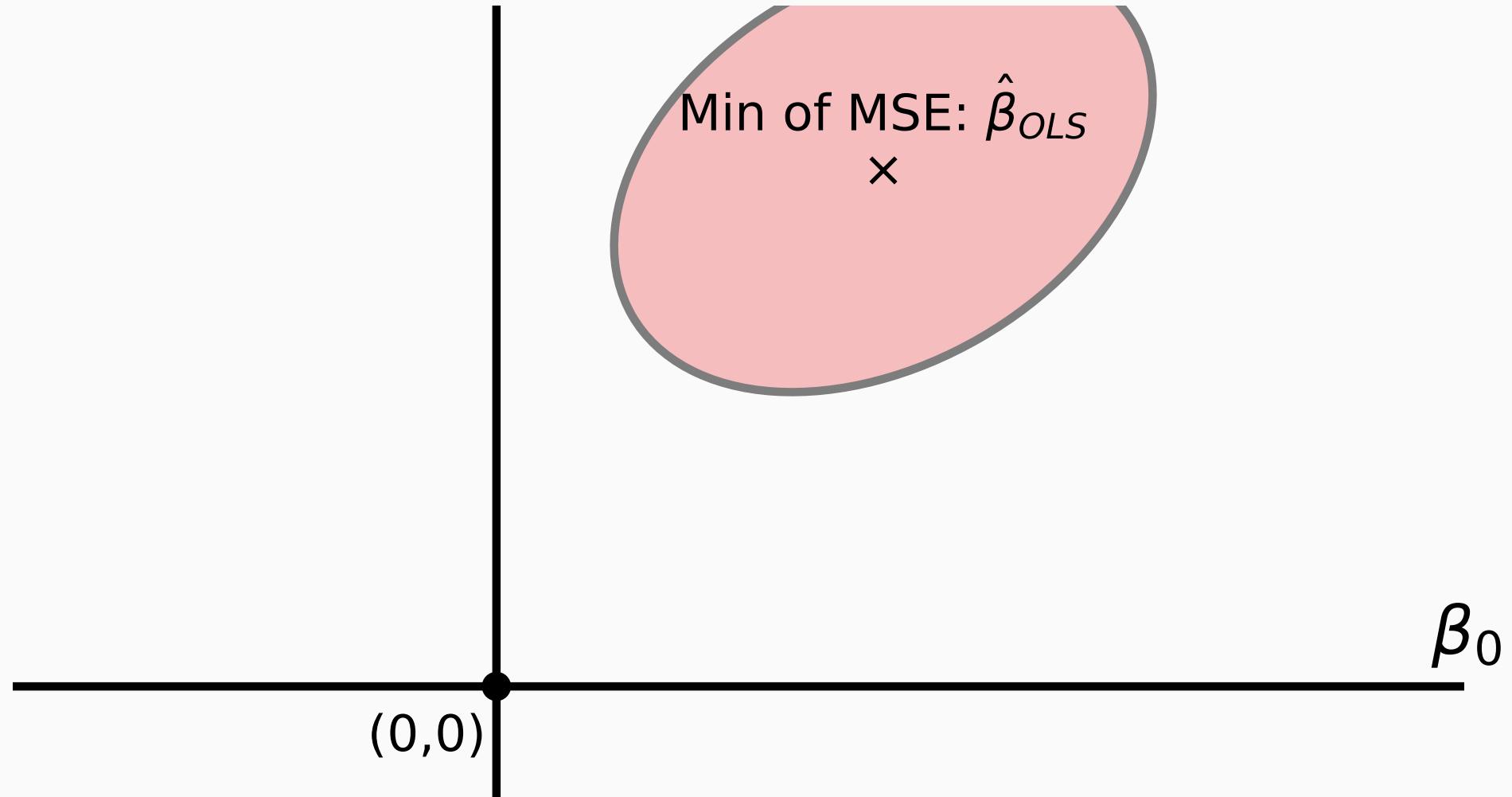
MSE as a function of the coefficients.

], )

# Why does Lasso shrink some coefficients to zero?

[

# Why does Lasso shrink some coefficients to zero?



# Why does Lasso shrink some coefficients to zero?

], [

MSE as a function of the coefficients.

The MSE surface is an ellipsoid in  $\beta$ :

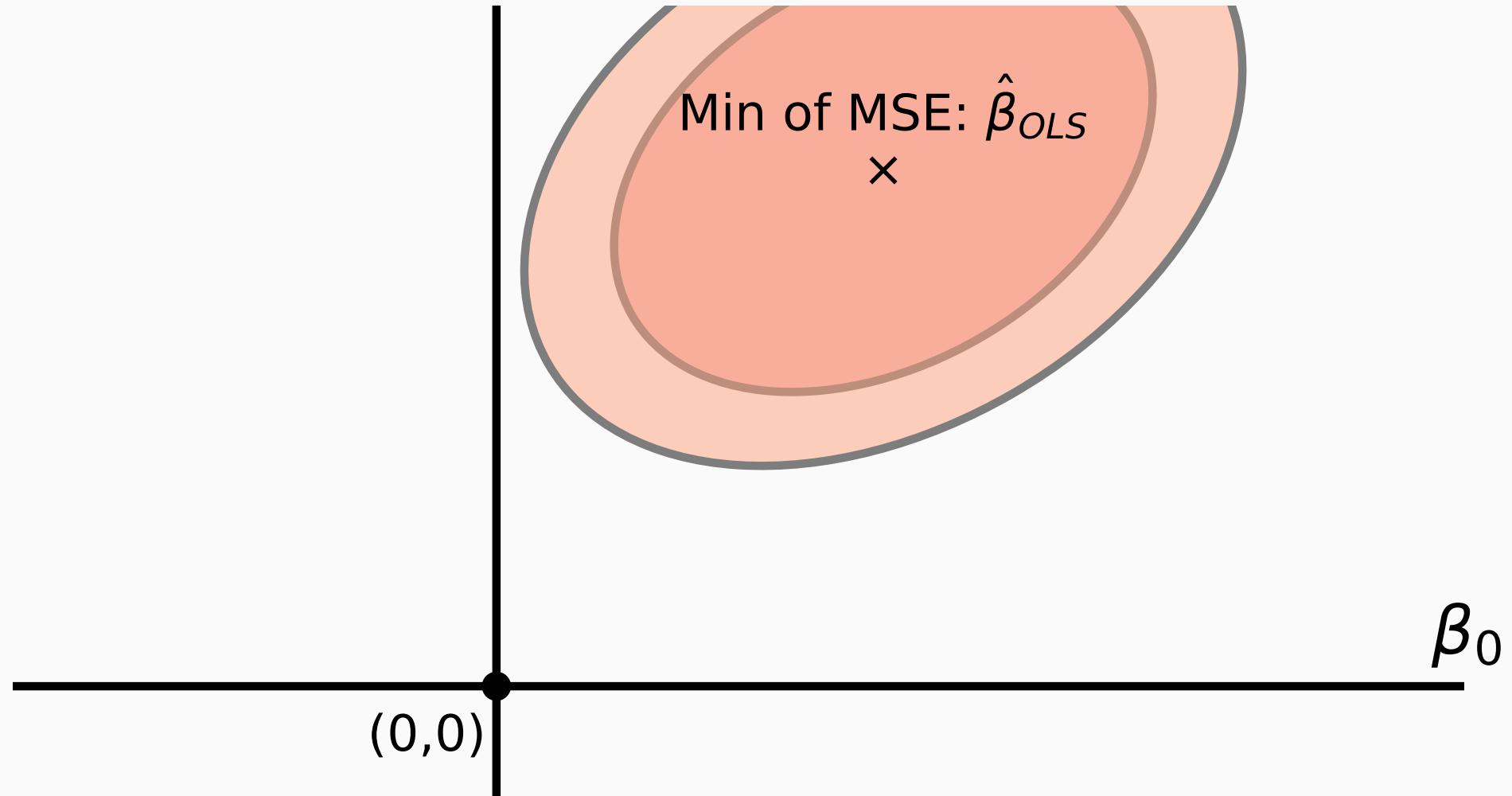
Every point on the ellipsoid edge has the same MSE.

], )

# Why does Lasso shrink some coefficients to zero?

[

# Why does Lasso shrink some coefficients to zero?



# Why does Lasso shrink some coefficients to zero?

], [

MSE as a function of the coefficients.

The MSE surface is an ellipsoid in  $\beta$ :

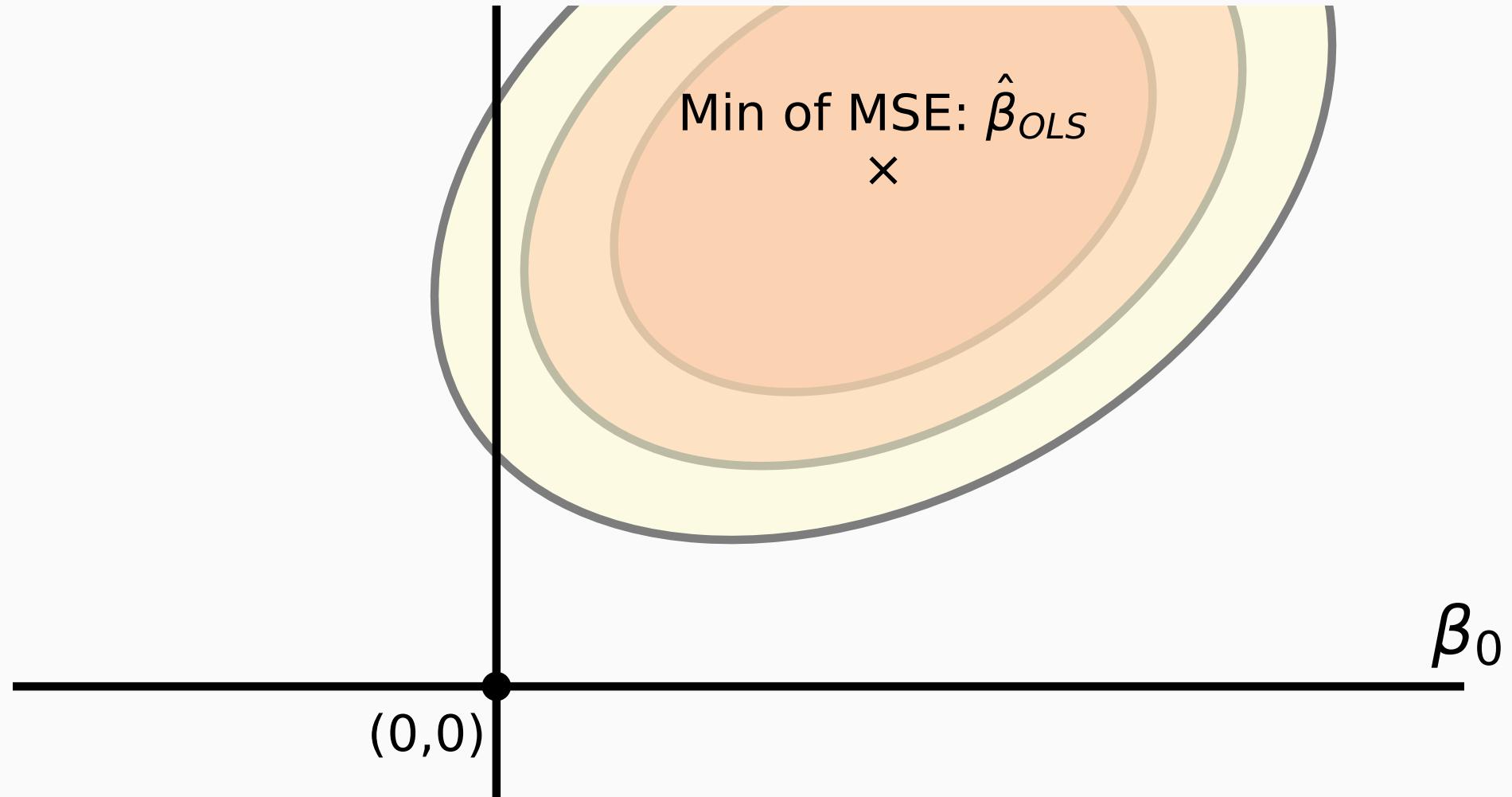
Every point on the ellipsoid edge has the same MSE.

], )

# Why does Lasso shrink some coefficients to zero?

[

# Why does Lasso shrink some coefficients to zero?



# Why does Lasso shrink some coefficients to zero?

], [

MSE as a function of the coefficients.

The MSE surface is an ellipsoid in  $\beta$ :

Every point on the ellipsoid edge has the same MSE.

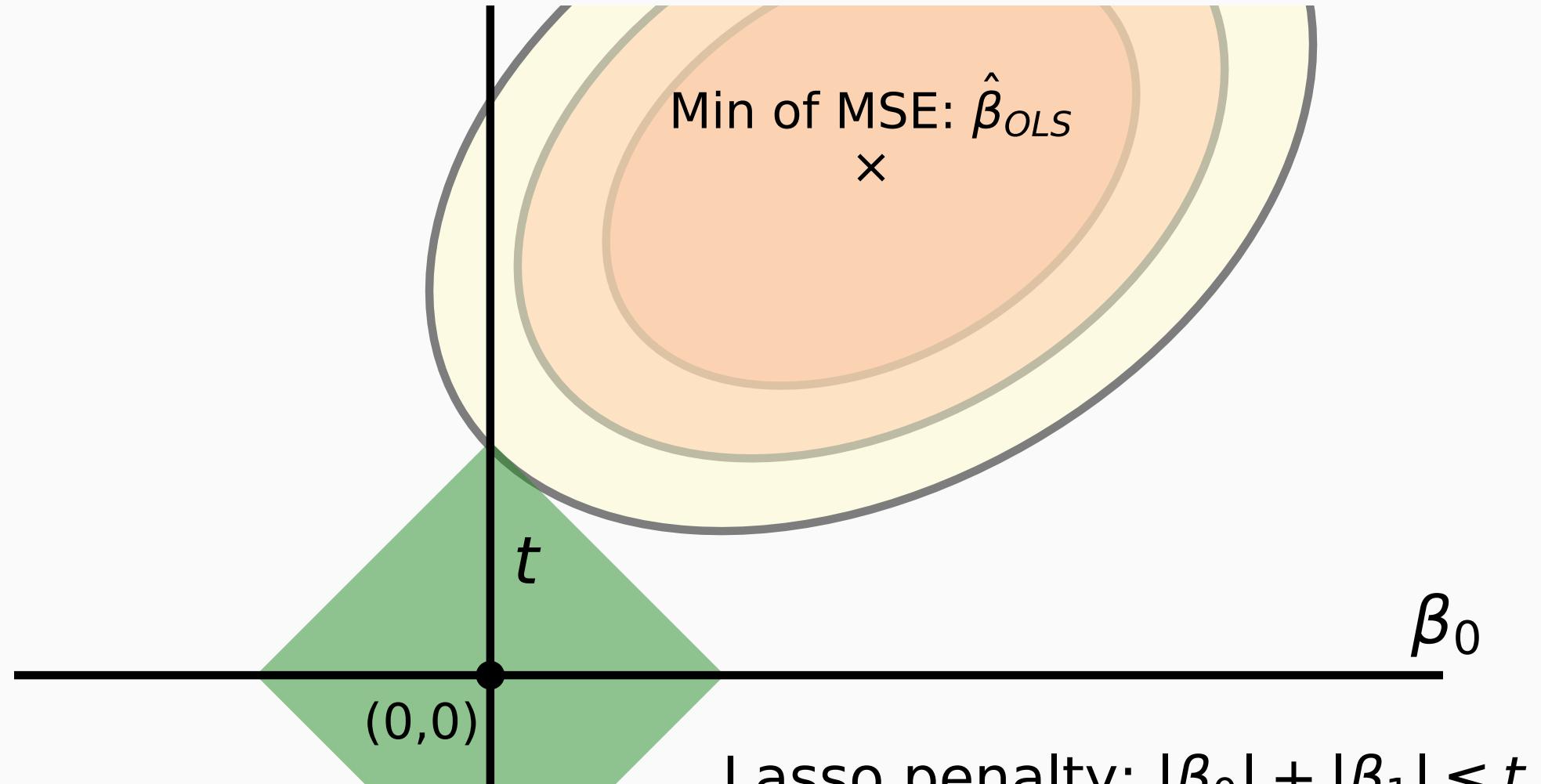
Moving away from OLS solution

], )

# Why does Lasso shrink some coefficients to zero?

[

# Why does Lasso shrink some coefficients to zero?



Lasso penalty:  $|\beta_0| + |\beta_1| < t$

# Why does Lasso shrink some coefficients to zero?

], [

MSE as a function of the coefficients.

The MSE surface is an ellipsoid in  $\beta$ :

Every point on the ellipsoid edge has the same MSE.

Moving away from OLS solution

Until the ellipsoid respects the lasso penalty (green diamond). ], )

## Another regularized linear model: Ridge

Ridge puts a constraint of amplitude  $t$  on the  $L_2$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p \beta_j^2 \leq t$$

## Another regularized linear model: Ridge

Ridge puts a constraint of amplitude  $t$  on the  $L_2$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p \beta_j^2 \leq t$$

This is equivalent to the following optimization problem (using lagrangian multiplier):

$$\min_{\beta} \frac{1}{n} \sum ((y_i - \beta^T x_i)^2) + \alpha \sum (\beta_j^2)$$

## Another regularized linear model: Ridge

Ridge puts a constraint of amplitude  $t$  on the  $L_2$  norm of the coefficients:

$$\min_{\beta} \frac{1}{n} \sum_i^n ((y_i - \beta^T x_i)^2) \text{ st. } \sum_1^p \beta_j^2 \leq t$$

This is equivalent to the following optimization problem (using lagrangian multiplier):

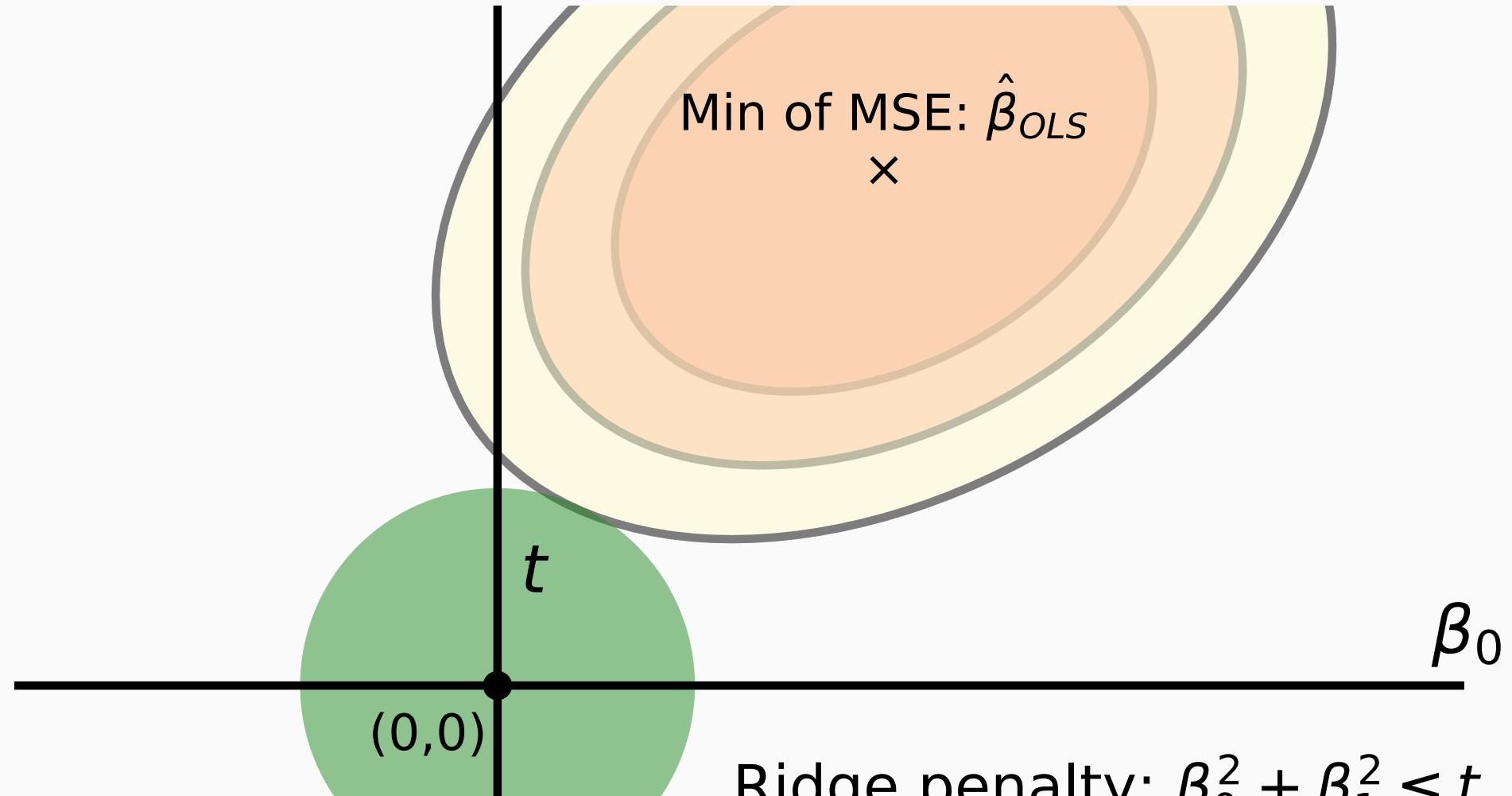
$$\min_{\beta} \frac{1}{n} \sum ((y_i - \beta^T x_i)^2) + \alpha \sum (\beta_j^2)$$

This penalty shrinks the coefficients towards zero and each other.

# Illustration of Ridge penalty

[

# Illustration of Ridge penalty



## Illustration of Ridge penalty

], [

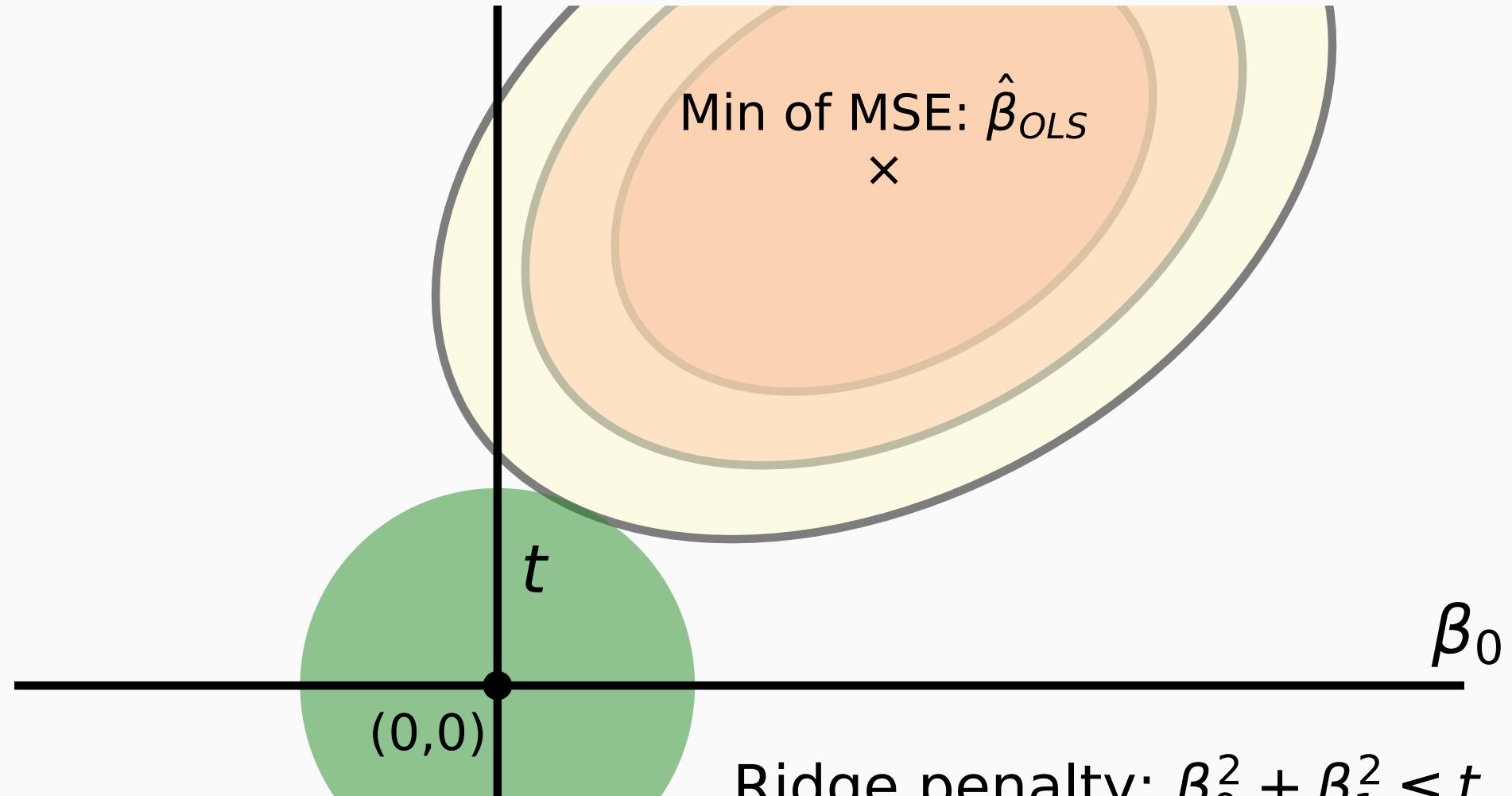
The first contact between the ellipsoid and the circle is the solution of Ridge.

], )

# Illustration of Ridge penalty

[

# Illustration of Ridge penalty



# Illustration of Ridge penalty

], [

The first contact between the ellipsoid and the circle is the solution of Ridge.

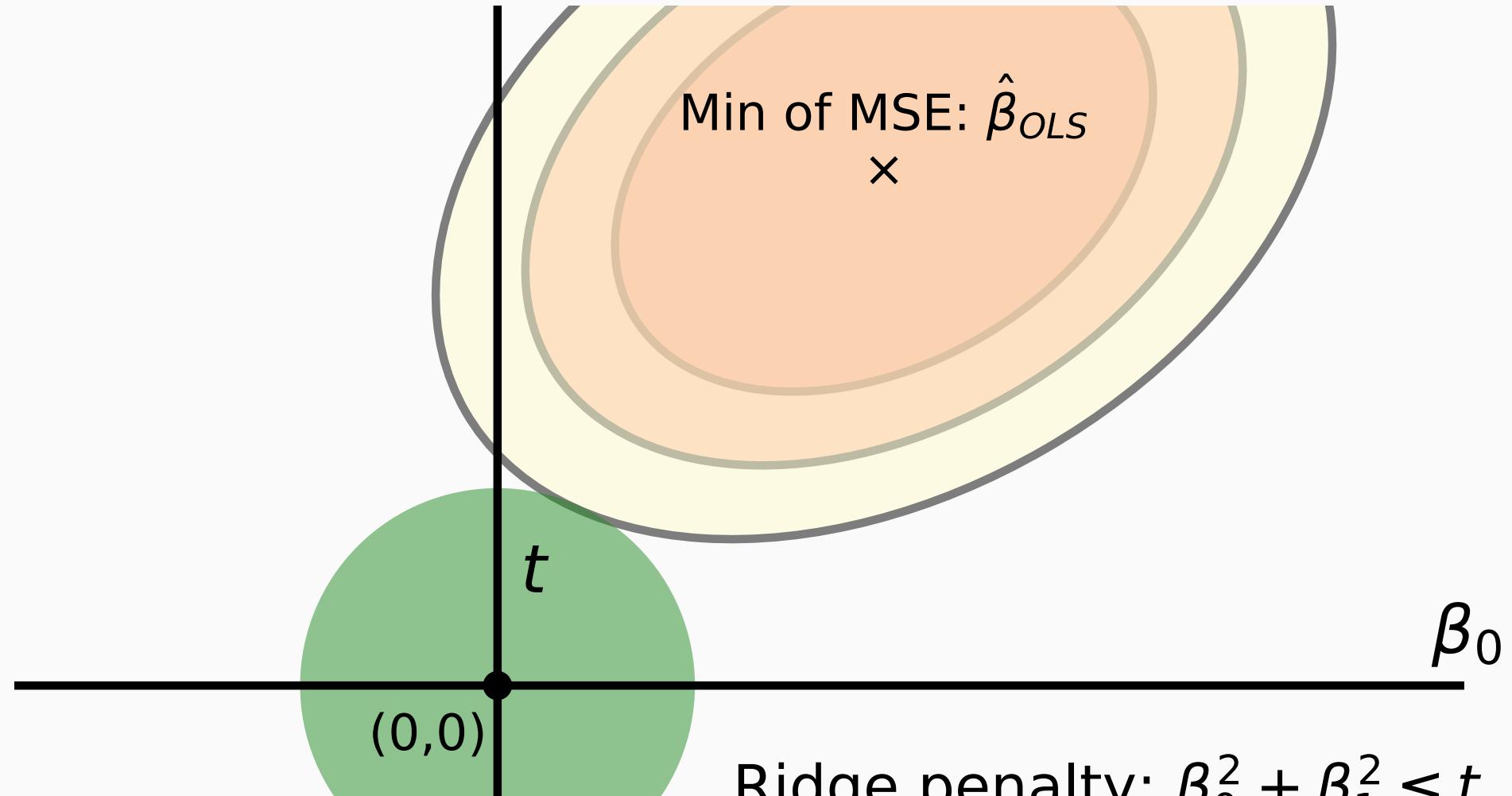
Few chances than lasso to cross an axis.

], )

# Illustration of Ridge penalty

[

# Illustration of Ridge penalty



# Illustration of Ridge penalty

], [

The first contact between the ellipsoid and the circle is the solution of Ridge.

Few chances than lasso to cross an axis.

Ridge insure smaller coefficients, but no exact zeros. ], )

## Why rescale?

- The penalty term in the Lasso and Ridge is sensitive to the scale of the features.
- If the features are not on the same scale, the regularization will not be applied uniformly.
- The coefficients of the model will be biased towards the features with the largest scale.

## Why rescale?

- The penalty term in the Lasso and Ridge is sensitive to the scale of the features.
- If the features are not on the same scale, the regularization will not be applied uniformly.
- The coefficients of the model will be biased towards the features with the largest scale.

## How to rescale?

- Gaussian hypothesis? Standard scaling:  $X = \frac{X - \text{mean}(X)}{\text{std}(X)}$
- Non Gaussian? MinMax scaling:  $X = \frac{X - \min(X)}{\max(X) - \min(X)}$

## Log likelihood for Lasso classification



Log likelihood for vanilla logistic regression

$$p_{i,\beta} = \mathbb{P}[Y_i | X_i, \beta] = \frac{1}{1 + \exp(-\beta^T X_i)}$$

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \log \left[ p_{i,\beta}^{y_i} (1 - p_{i,\beta})^{1-y_i} \right]$$

$$= \frac{1}{n} \sum_{i=1}^n [(y_i \beta^T X_i) - \log(1 + \exp(\beta^T X_i))]$$

# Regularized linear models for classification

## Log likelihood for Lasso classification

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \left[ (y_i \beta^T X_i - \log[1 + \exp(\beta^T X_i)]) - \lambda \sum_{j=1}^p |\beta_j| \right]$$



Log likelihood for vanilla logistic regression

$$p_{i,\beta} = \mathbb{P}[Y_i | X_i, \beta] = \frac{1}{1 + \exp(-\beta^T X_i)}$$

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \log \left[ p_{i,\beta}^{y_i} (1 - p_{i,\beta})^{1-y_i} \right]$$

$$= \frac{1}{n} \sum_{i=1}^n [(y_i \beta^T X_i - \log[1 + \exp(\beta^T X_i)])]$$

# Regularized linear models for classification

## Log likelihood for Lasso classification

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \left[ (y_i \beta^T X_i - \log[1 + \exp(\beta^T X_i)]) - \lambda \sum_{j=1}^p |\beta_j| \right]$$

## Log likelihood for Lasso classification

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \left[ (y_i \beta^T X_i - \log[1 + \exp(\beta^T X_i)]) - \lambda \sum_{j=1}^p |\beta_j| \right]$$



Log likelihood for vanilla logistic regression

$$p_{i,\beta} = \mathbb{P}[Y_i | X_i, \beta] = \frac{1}{1 + \exp(-\beta^T X_i)}$$

$$L(\beta) = \frac{1}{n} \sum_{i=1}^n \log \left[ p_{i,\beta}^{y_i} (1 - p_{i,\beta})^{1-y_i} \right]$$

$$= \frac{1}{n} \sum_{i=1}^n [(y_i \beta^T X_i - \log[1 + \exp(\beta^T X_i)])]$$

# How to choose lambda?

## Theoretical guarantees

- See (Chernozhukov et al., 2024, Chap 3.2)

# How to choose lambda?

## Theoretical guarantees

- See (Chernozhukov et al., 2024, Chap 3.2)  but assumptions are hard to check.

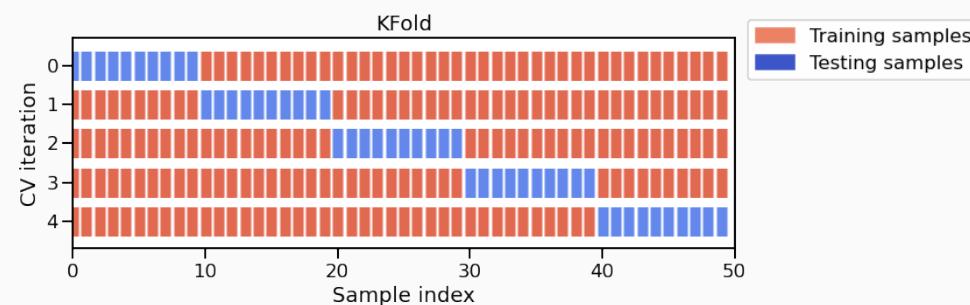
# How to choose lambda?

## Theoretical guarantees

- See (Chernozhukov et al., 2024, Chap 3.2)

## In practice

Use cross-validation: repeated train/test splits.



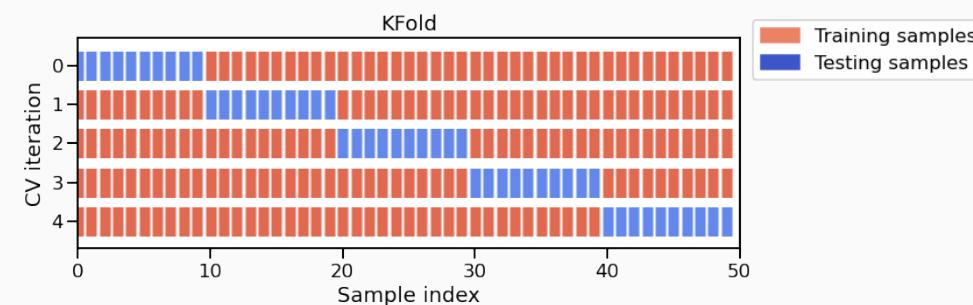
# How to choose lambda?

## Theoretical guarantees

- See (Chernozhukov et al., 2024, Chap 3.2)

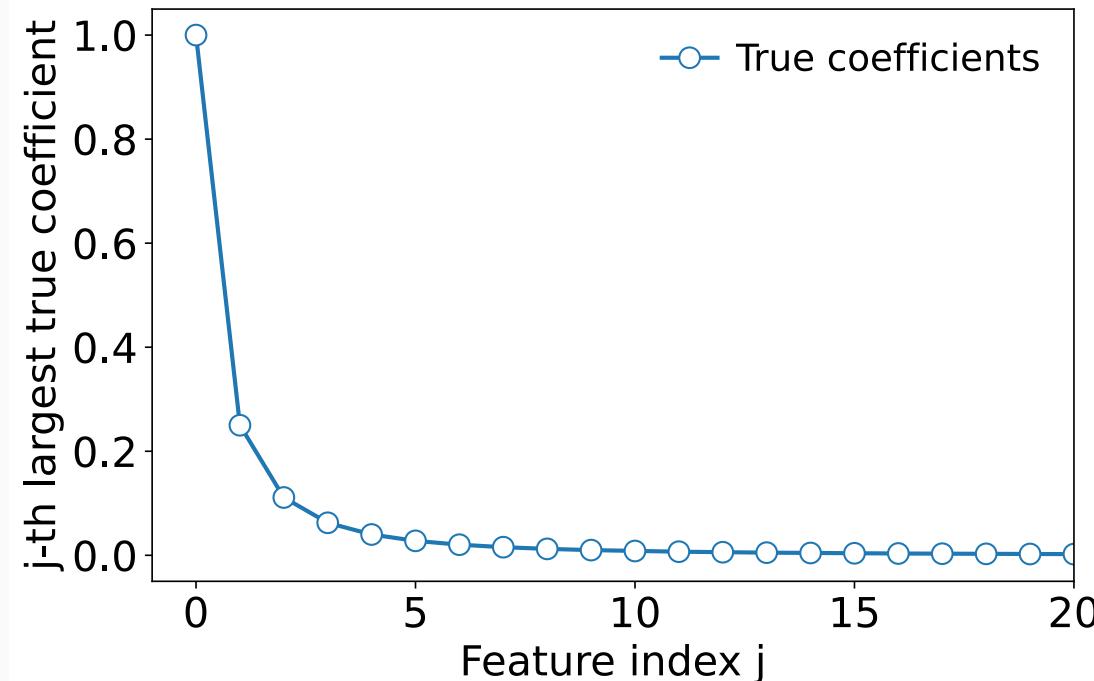
## In practice

Use cross-validation: repeated train/test splits.

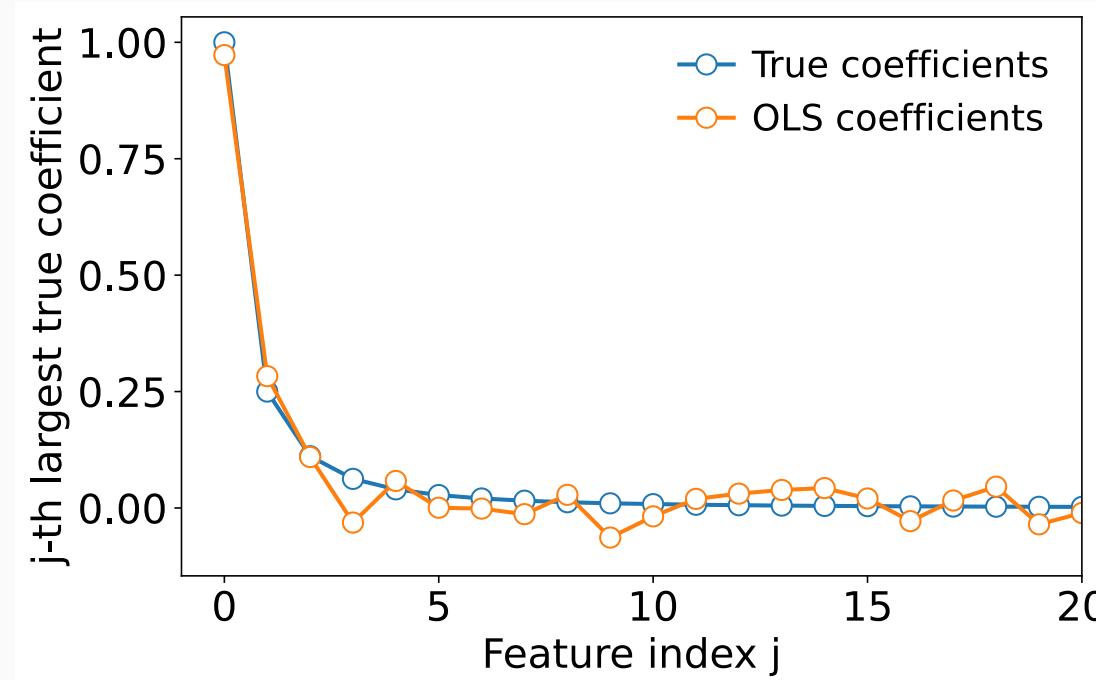


We will look into that in more details in the next session.

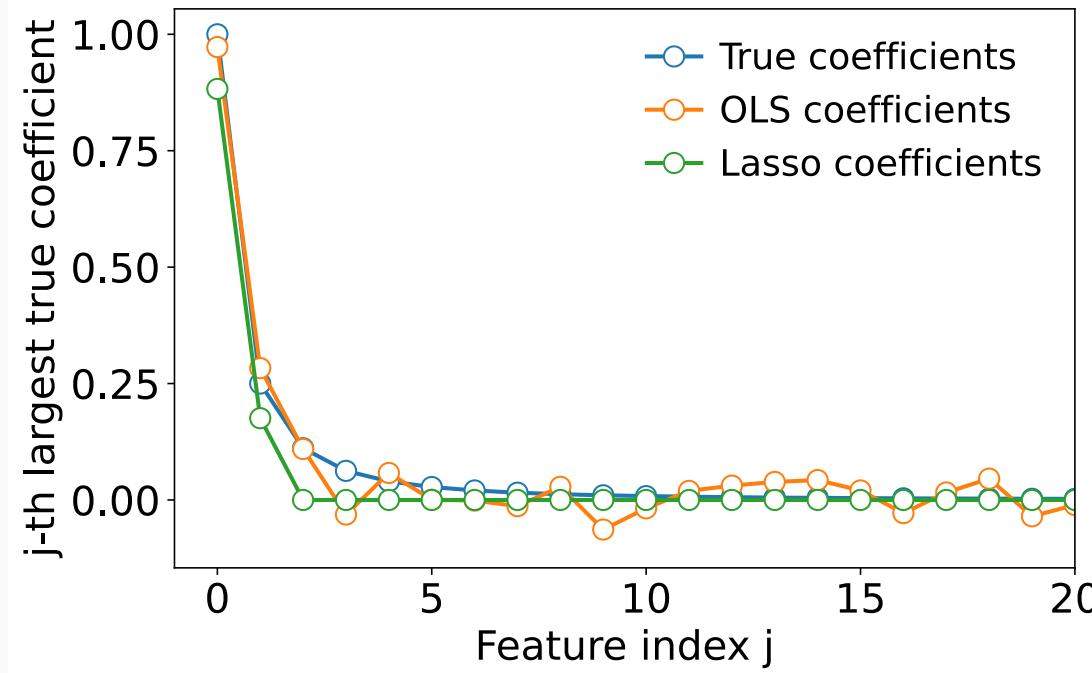
# OLS Post-Lasso: fixing excessive shrinkage of coefficients



# OLS Post-Lasso: fixing excessive shrinkage of coefficients



# OLS Post-Lasso: fixing excessive shrinkage of coefficients



Lasso is good for true zero coefficients (on the right)

But not so good for true non-zeros coefficients (on the left)

## OLS Post-Lasso

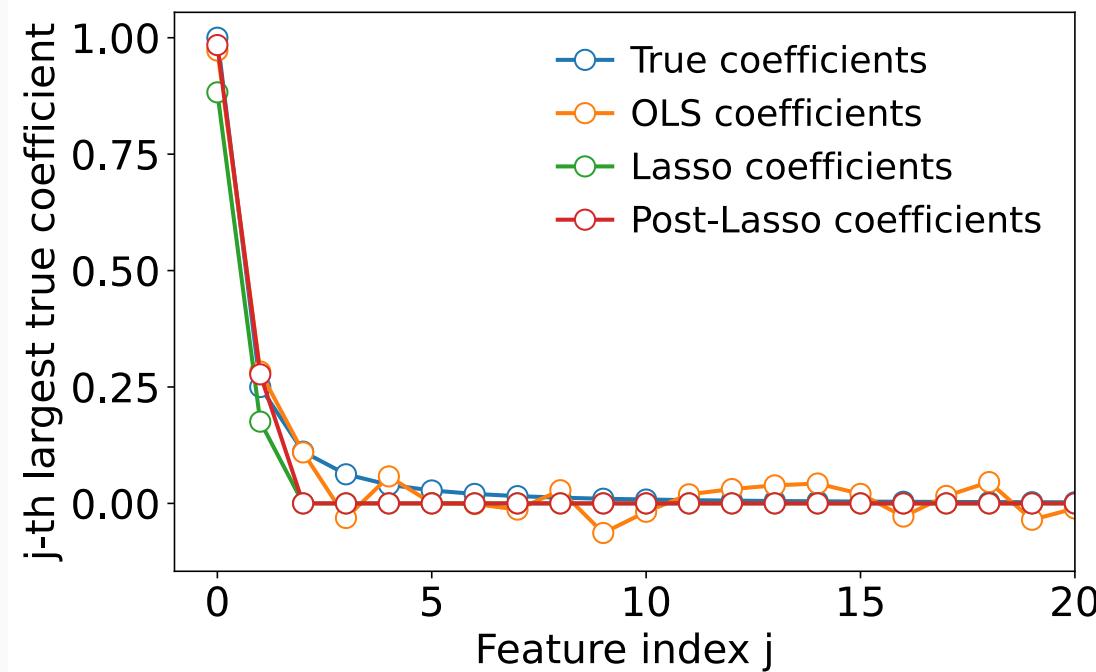
- 💡 Fit an OLS on the features selected by the Lasso (Belloni & Chernozhukov, 2013)

# OLS Post-Lasso

# OLS Post-Lasso



Fit an OLS on the features selected by the Lasso (Belloni & Chernozhukov, 2013)

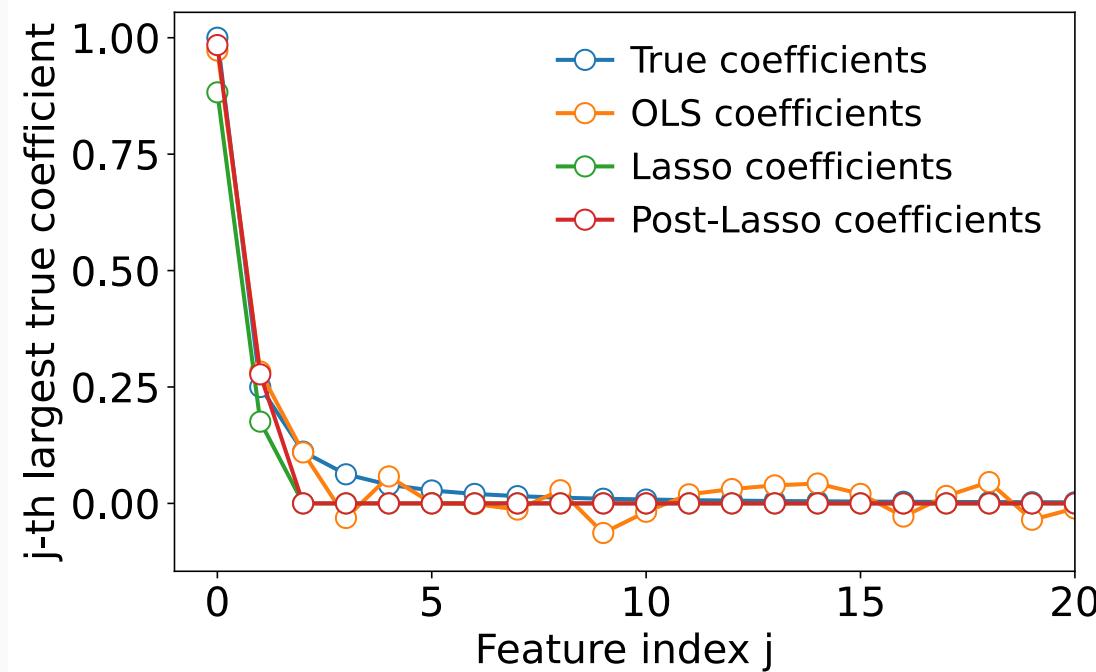


# OLS Post-Lasso

# OLS Post-Lasso



Fit an OLS on the features selected by the Lasso (Belloni & Chernozhukov, 2013)



⚠ Cross-validation should apply to the full procedure: Lasso + OLS, not only to the Lasso.

## **High bias = underfitting**

- systematic prediction errors
- the model prefers to ignore some aspects of the data
- misspecified models

## **High variance = overfitting**

- prediction errors without obvious structure
- small change in the training set, large change in model
- unstable models

# Take home messages: Lasso and Ridge

## Lasso

- L1 penalty: sparsity
- Feature selection
- Unstable for correlated features

## Ridge

- L2 penalty: shrinkage
- No feature selection
- Stable for correlated features

# Short introduction to scikit-learn

- url: [https://straymat.github.io/causal-ml-course/practical\\_sessions.html](https://straymat.github.io/causal-ml-course/practical_sessions.html)

Many features, few observations

---

# Python hands-on: Common pitfalls in the interpretation of coefficients of linear models

To your notebooks  !

- url: [https://straymat.github.io/causal-ml-course/practical\\_sessions.html](https://straymat.github.io/causal-ml-course/practical_sessions.html)

# Bibliography

## Bibliography

*Belloni, A., & Chernozhukov, V. (2013). Least squares after model selection in high-dimensional sparse models.*

*Chernozhukov, V., Hansen, C., Kallus, N., Spindler, M., & Syrgkanis, V. (2024). Applied causal inference powered by ML and AI. Arxiv Preprint Arxiv:2403.02467. <https://causalml-book.org/>*

*Cvetkov-Iliev, A., Allauzen, A., & Varoquaux, G. (2023). Relational data embeddings for feature enrichment with background information. Machine Learning, 112(2), 687–720.*

*Estève, L., Lemaitre, G., Grisel, O., Varoquaux, G., Amor, A., Lilian, Rospars, B., Schmitt, T., Liu, L., Kinoshita, B. P., hackmd-deploy, ph4ge, Steinbach, P., Boucaud, A., Muite, B., Boisberranger, J. du, Notter, M., Pierre, P., S., ... parmentelat. (2022). INRIA/scikit-learn-mooc: Third MOOC session. Zenodo. <https://doi.org/10.5281/zenodo.7220307>*

# Bibliography

*Hastie, T. (2009, ). The elements of statistical learning: data mining, inference, and prediction.*  
*Springer.*

*Kleinberg, J., Ludwig, J., Mullainathan, S., & Obermeyer, Z. (2015). Prediction policy problems.*  
American Economic Review, 105(5), 491–495.

# Bibliography

---

Supplementary materials

# Statistical model for lasso: approximate sparsity

## Definition: Approximate sparsity

The sorted absolute values of the coefficients decay quickly.

$$|\beta|_{(j)} < Aj^{-a} \quad a > \frac{1}{2}$$

for each  $j$ , where the constants  $a$  and  $A$  do not depend on the sample size  $n$ .