Computer Science

CSC380: Principles of Data Science

Basic machine learning 1

Chicheng Zhang

- Probability
- Statistics

- Data Visualization
- Predictive modeling
- Clustering

Outline

- Introduction to Machine Learning
- Supervised Learning: Linear Regression
- Overfitting and underfitting
- Regularization in regression
- Feature Selection

Introduction to Machine Learning

What is machine learning (ML)?

- **Tom Mitchell** established Machine Learning Department at CMU (2006).

Machine Learning, Tom Mitchell, McGraw Hill, 1997.

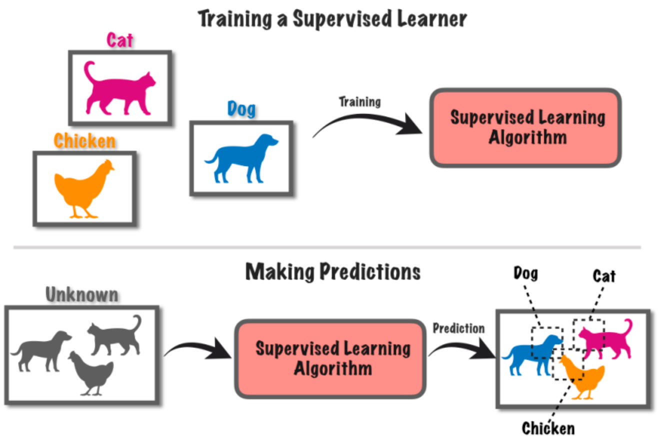
Machine Learning is the study of computer algorithms that improve automatically through experience. Applications range from datamining programs that discover general rules in large data sets, to information filtering systems that automatically learn users' interests.

This book provides a single source introduction to the field. It is written for advanced undergraduate and graduate students, and for developers and researchers in the field. No prior background in artificial intelligence or statistics is assumed.

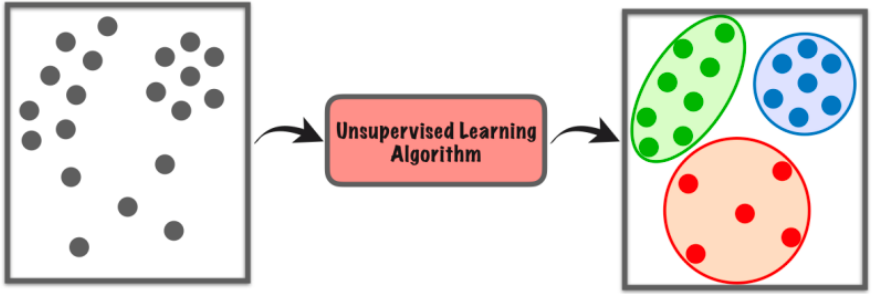
- In short: algorithms adapt to data
- A subfield of **Artificial Intelligence (AI)** – computers perform “intelligent” tasks.
- Classical AI vs ML: rule-driven approaches vs. data-driven approaches

Supervised vs Unsupervised Learning

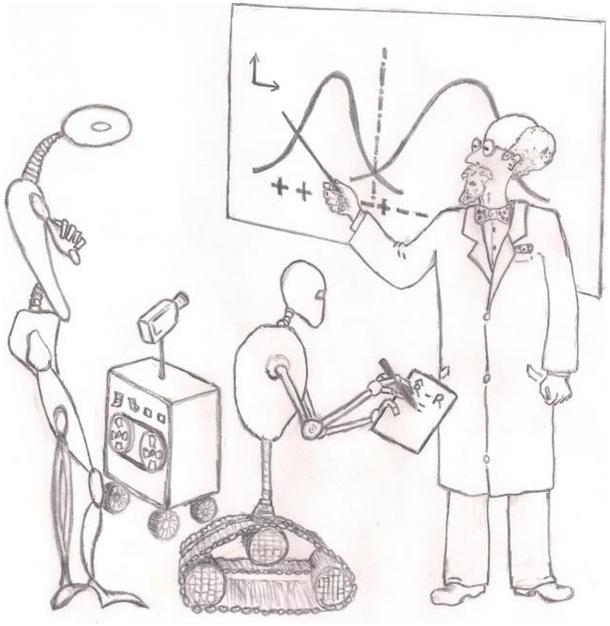
- **Supervised Learning** - Training data consist of inputs and outputs
  - Classification, regression, translation, …



- **Unsupervised Learning** – Training data only contain inputs
  - Clustering, dimensionality reduction, segmentation, …



Supervised Learning Basics



Picture from Samory Kpotufe

Supervised learning

- Training / test data: datasets comprised of ***labeled examples***: pairs of (feature, label)

training data

supervised learning algorithm

training

test data

, cat

function
("predictor")

cat

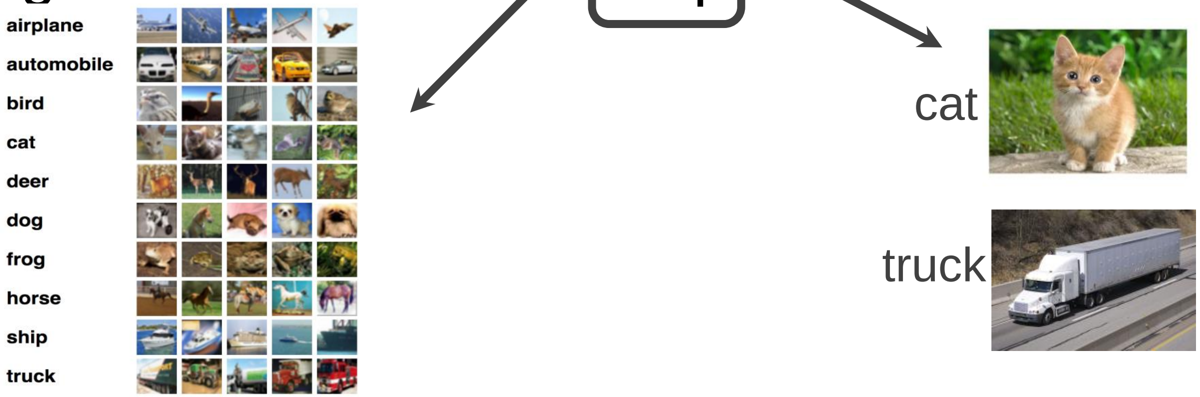
test

How should test data be chosen?

- Should test data be identical to training data? No
- Should test data be just ONE data point? No

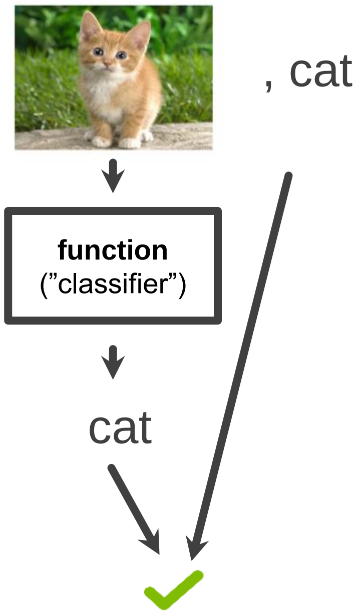
Supervised learning setup

- Key assumption: training and test data are drawn from the same *population*, or *data generating distribution* D
  - They are assumed to be IID samples: independent and identically distributed
- Training and test data are independent



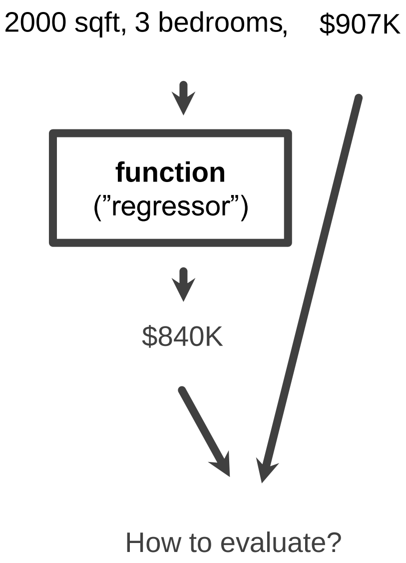
Supervised learning setup

- Scenario 1: classification



- Scenario 2: regression

(e.g. house price prediction)



- Loss function ℓ: measures the quality of prediction $\hat{y}$ respect to true label y

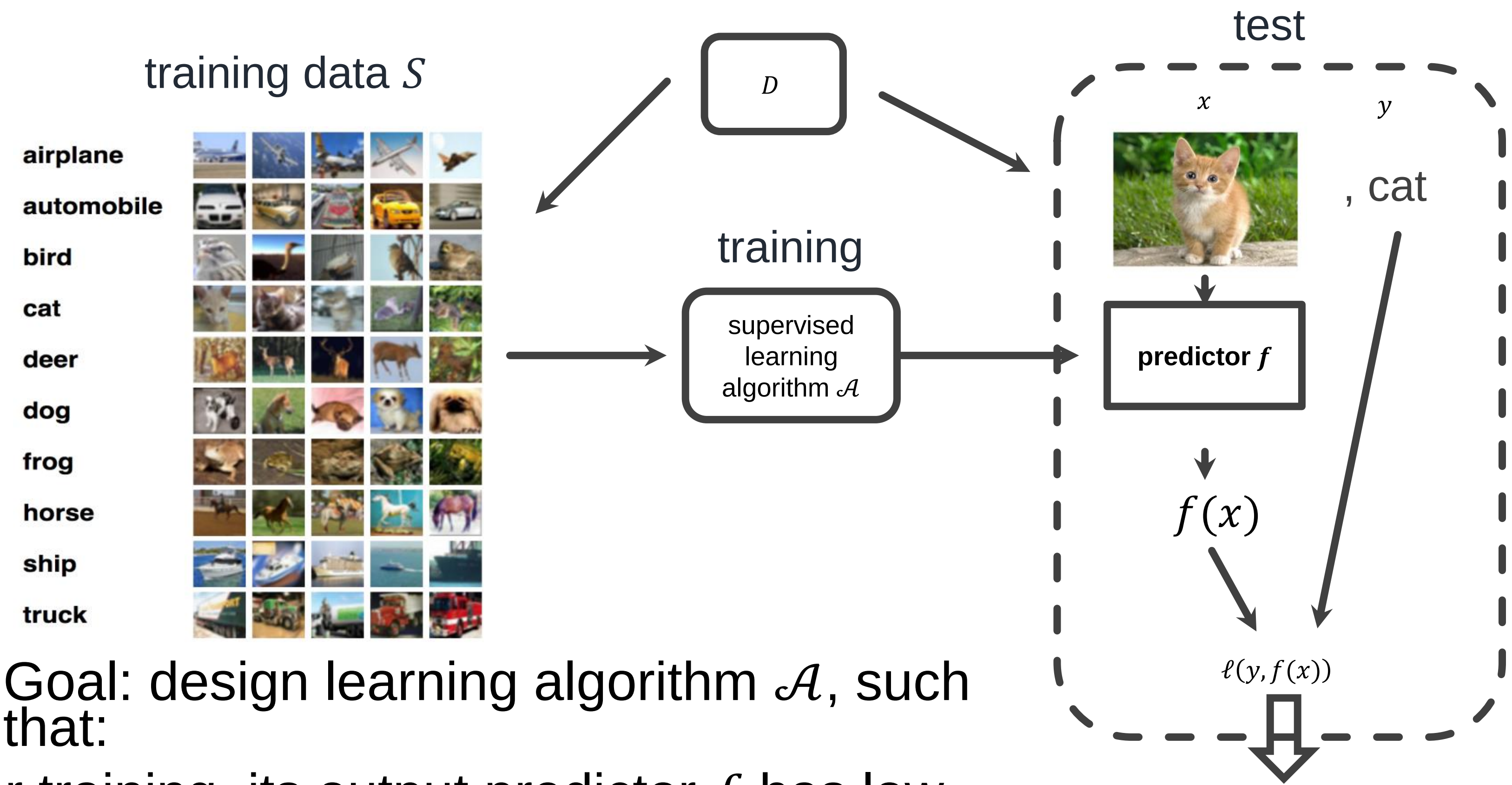
- Examples:
  - Classification error

  $\ell(y, \hat{y}) = 1$ if $y \neq \hat{y}$, and zero otherwise

  - Square loss

  $\ell(y, \hat{y}) = (y - \hat{y})^2$ - regression

Supervised learning setup in one figure



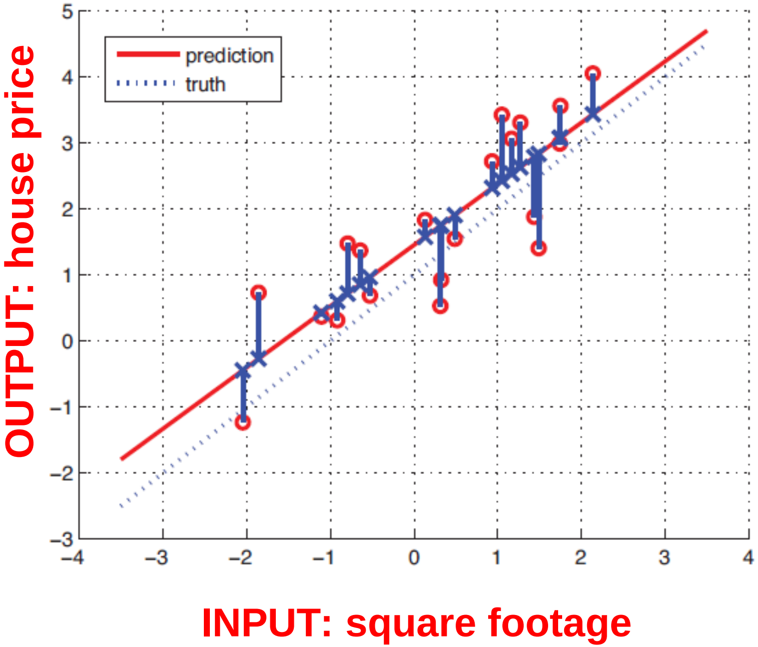
- Goal: design learning algorithm $\mathcal{A}$, such that:

after training, its output predictor f has low test error

Test error: average of $\ell(y, f(x))$ in test set

Supervised Learning: Linear Regression

Linear Regression



Regression Learn a function that predicts outputs from inputs,

$$y = f(x)$$

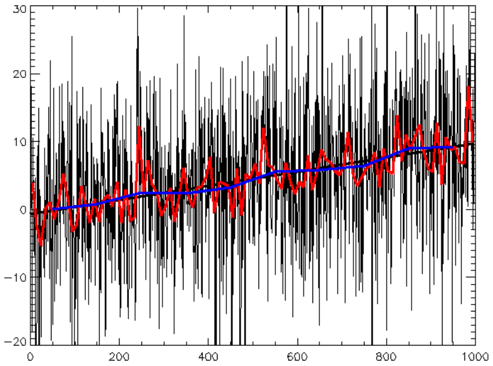
Outputs y are real-valued

Linear Regression As the name suggests, uses a *linear function*:

$$y = w^T x + b$$

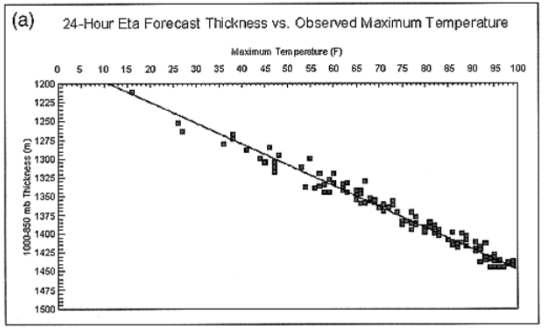
Linear Regression

Where is linear regression useful?



Trendlines

Stock Prediction

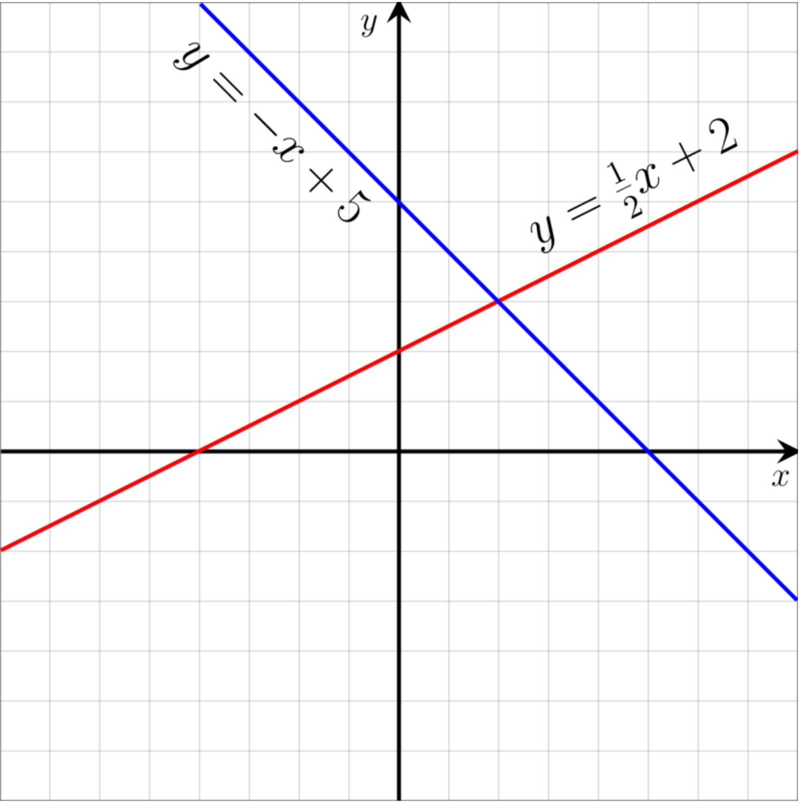


Climate Models

Massie and Rose (1997)

Used anywhere a linear relationship is assumed between continuous inputs / outputs

Line Equation



Recall the equation for a line has a *slope* and an *intercept*,

$$y = w \cdot x + b$$

Slope **Intercept**

- Intercept (b) indicates where line crosses y-axis
- Slope controls angle of line
- Positive slope (w) → Line goes up left-to-right
- Negative slope → Line goes down left-to-right

Math Interlude: inner product

Two vectors:

$$\vec{x} = \langle 2, -3 \rangle \qquad \mathbf{x} = \begin{bmatrix} 2 \\ -3 \end{bmatrix}$$

$$\vec{y} = \langle 5, 1 \rangle \qquad \mathbf{y} = \begin{bmatrix} 5 \\ 1 \end{bmatrix}$$

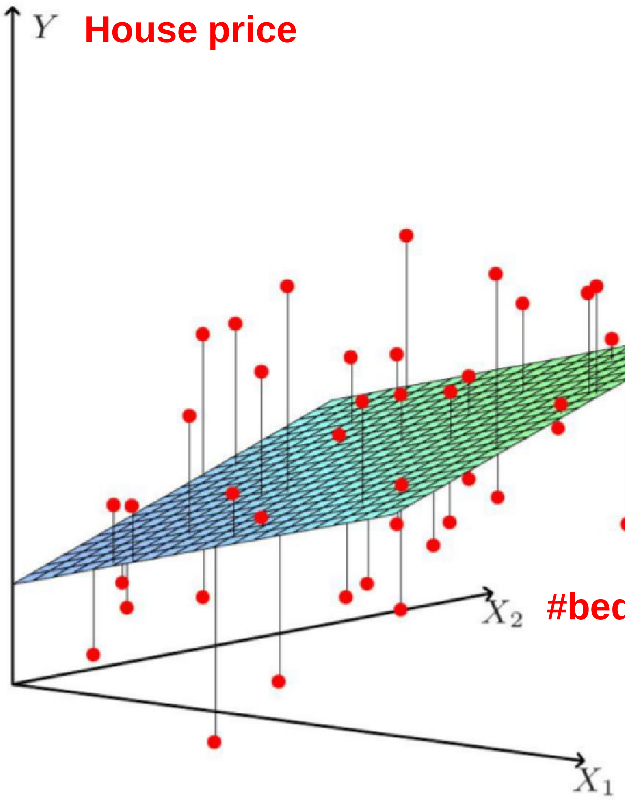
How to compute $\vec{x} \cdot \vec{y}$?

Multiply corresponding entries and add:

$$\vec{x} \cdot \vec{y} = \langle 2, -3 \rangle \cdot \langle 5, 1 \rangle = (2)(5) + (-3)(1) = 7$$

$$\mathbf{x}^T \mathbf{y} = \begin{bmatrix} 2 & -3 \end{bmatrix} \begin{bmatrix} 5 \\ 1 \end{bmatrix} = [7] \quad \text{(or just 7)} \quad (\text{so } \vec{x} \cdot \vec{y} \text{ becomes } \mathbf{x}^T \mathbf{y})$$

Linear regression in dimension more than 2



$$h(x) = w_1 \cdot x_1 + w_2 \cdot x_2 + b = w \cdot x + b$$

$y = w \cdot x + b$ is a hyperplane

Linear Regression

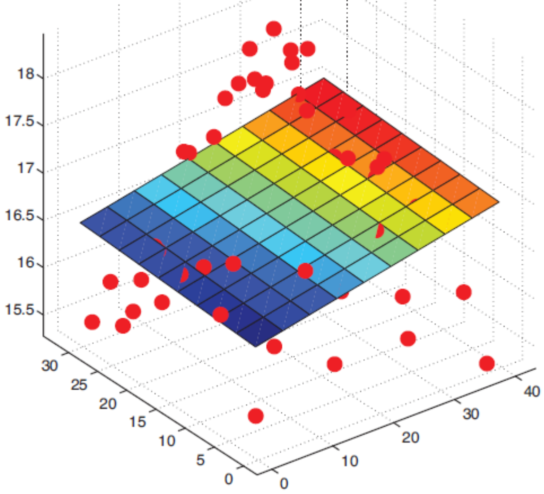
For D-dimensional input vector $x \in \mathbb{R}^D$ the plane equation,

$$y = w^T x + b$$

Sometimes we simplify this by including the intercept into the weight vector,

$$\widetilde{w} = \begin{pmatrix} w_1 \\ \vdots \\ w_D \\ b \end{pmatrix} \qquad \widetilde{x} = \begin{pmatrix} x_1 \\ \vdots \\ x_D \\ 1 \end{pmatrix} \qquad y = \widetilde{w}^T \widetilde{x}$$

[Image: Murphy, K. (2012)]



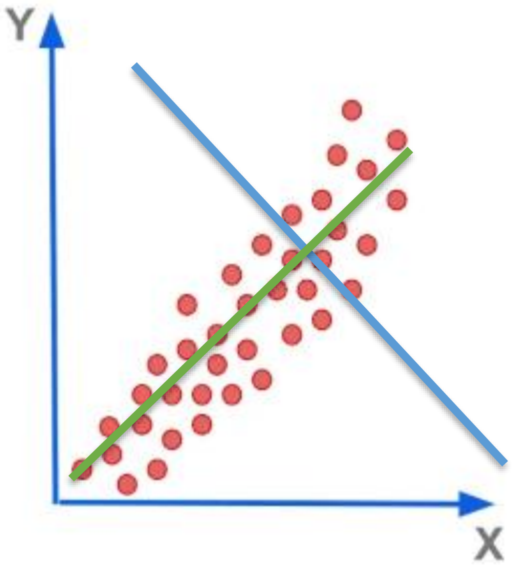
Since:

$$\widetilde{w}^T \widetilde{x} = \sum_{d=1}^{D} w_d x_d + b \cdot 1$$
$$= w^T x + b$$

Learning linear regression models

- Which line is a better predictor, blue or green?

house price



square footage

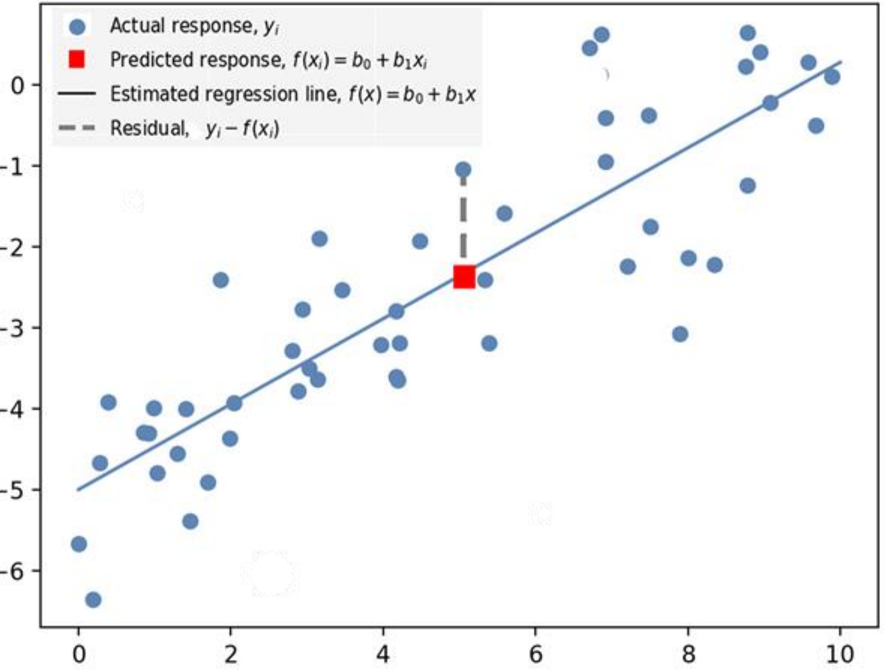
- green

Learning Linear Regression Models

There are at least two ways to think about fitting regression:

- **Intuitive** Find a plane/line that is close to data
- **Functional** Find a line that minimizes the *square* loss

Fitting Linear Regression



Intuition Find a line that is as *close as possible* to every training data point

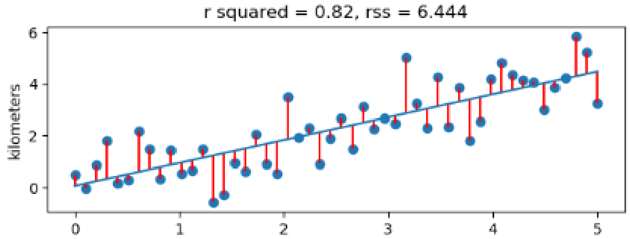
The distance from each point to the line is the **residual**

$$y - w^T x$$

https://www.activestate.com/resources/quick-reads/how-to-run-linear-regressions-in-python-scikit-learn/

Fitting linear regression

- Each point i induces a separate residual value $y_i - w \cdot x_i$



- We'd like to find w such that all $y_i - w \cdot x_i$ are small

- We can convert this to an optimization problem: find w that minimizes

$$\sum_{i=1}^{n} (y_i - w \cdot x_i)^2$$

- This is called the *least squares solution*

Math Interlude: optimization problems

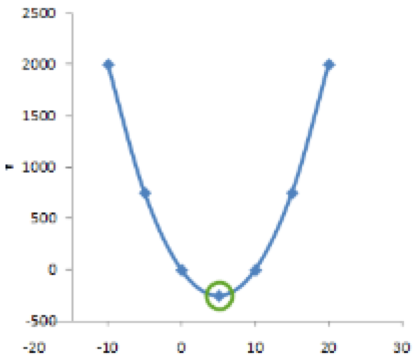
- The above is often written as: find

$$\text{argmin}_{w \in \mathrm{R}^d} \sum_{i=1}^{n} (y_i - w \cdot x_i)^2$$

w: Optimization variable

Objective function

- **Example** Find $\text{argmin}_x \; ax^2 + bx + c \; (a > 0)$
  - $x = -\frac{b}{2a}$



- *These are called unconstrained optimization problems*

Math Interlude: optimization problems

Example Suppose we have 2 data points (x=1, y=0) and (x=-1, y=1), find the least squares solution $\hat{w}$

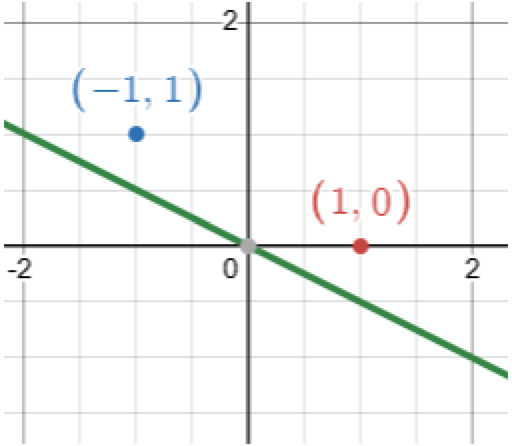
Solution the objective function of least squares is

$$(y_1 - w\, x_1)^2 + (y_2 - w\, x_2)^2$$

which is

$$w^2 + (1 + w)^2 = 2w^2 + 2w + 1$$

the minimizer is $\hat{w} = -\frac{b}{2a} = -\frac{1}{2}$



Why cannot the line fit perfectly?

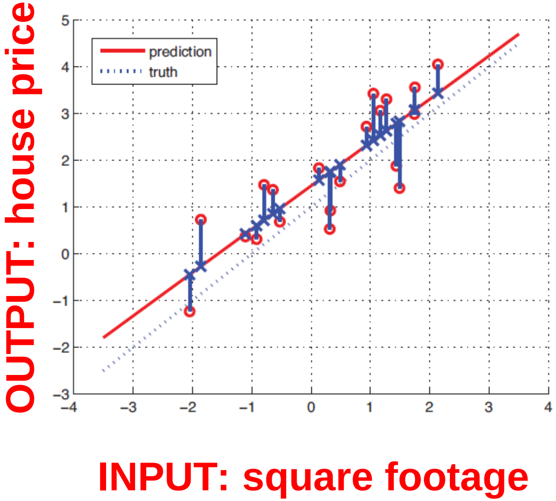
- Here, we only consider $y = w\, x$ without intercept

Announcements 3/31

- HW5 was out last Thursday (due 4/8)
- We will have quiz 8 this Wednesday (4/2)
- Participation bonuses are now fractional and unlimited in any one lecture

Linear regression

- Given training data $(x_i, y_i), i = 1, \ldots, n$, find a linear predictor w such that $w \cdot x$ can predict *future unseen* y's



- Ordinary least squares: find w that

minimizes average training loss

(aka mean square error, MSE)

$$\frac{1}{n}\sum_i (y_i - w \cdot x_i)^2$$

In-class exercise: training and test loss

- We have the following training data

Study hours (x)	Exam score (y)
1	2
3	6

- We fit a linear regression model $y = w \cdot x$ that minimizes mean square error. What is this model $\widehat{w}$?

- What is the average loss of model $\widehat{w}$ on training and test data?

Study hours (x)	Exam score (y)
4	7
5	10

In-class exercise: training and test loss

Solution

$\hat{w} = \text{argmin}_w \, (1w - 2)^2 + (3w - 6)^2$

Minimizer: $\hat{w} = -\frac{b}{2a} = 2$ $\quad 10w^2 - 40w + 40$

Study hours (x)	Exam score (y)
1	2
3	6

Training loss of $\hat{w}$:

$\frac{1}{2}((2-2)^2 + (6-6)^2) = 0$

size of training set

Study hours (x)	Exam score (y)	Predicted score
1	2	2
3	6	6

Test loss of $\hat{w}$:

$\frac{1}{2}((8-7)^2 + (10-10)^2) = 0.5$

size of test set

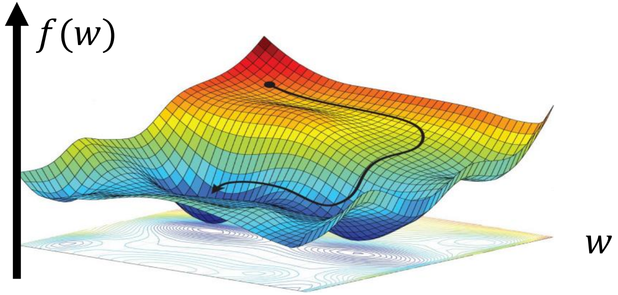
Study hours (x)	Exam score (y)	Predicted score
4	7	8
5	10	10

Usually, a trained model has smaller training loss than test loss

Math Interlude: optimization problems

- Unconstrained optimization problem: find

$$\text{argmin}_{w \in \mathbb{R}^d} f(w)$$



- Solutions can oftentimes be found in one of two ways:
  1. Closed form solutions
  2. Open-source or commercial optimization libraries (e.g. `cvxpy`, `scipy.optimize.minimize`)

Linear Regression in Scikit-Learn

Load your libraries,

For Evaluation

```
import matplotlib.pyplot as plt
import numpy as np
from sklearn import datasets, linear_model
from sklearn.metrics import mean_squared_error, r2_score
```

Load data,

```
# Load the diabetes dataset
diabetes_X, diabetes_y = datasets.load_diabetes(return_X_y=True)

# Use only one feature
diabetes_X = diabetes_X[:, np.newaxis, 2]
```

Samples total	442
Dimensionality	10
Features	real, -.2 < x < .2
Targets	integer 25 - 346

Train / Test Split:

```
diabetes_X_train = diabetes_X[:-20]
diabetes_X_test = diabetes_X[-20:]
```

```
diabetes_y_train = diabetes_y[:-20]
diabetes_y_test = diabetes_y[-20:]
```

Linear Regression in Scikit-Learn

Train (fit) and predict,

```
# Create linear regression object
regr = linear_model.LinearRegression()

# Train the model using the training sets
regr.fit(diabetes_X_train, diabetes_y_train)

# Make predictions using the testing set
diabetes_y_pred = regr.predict(diabetes_X_test)
```

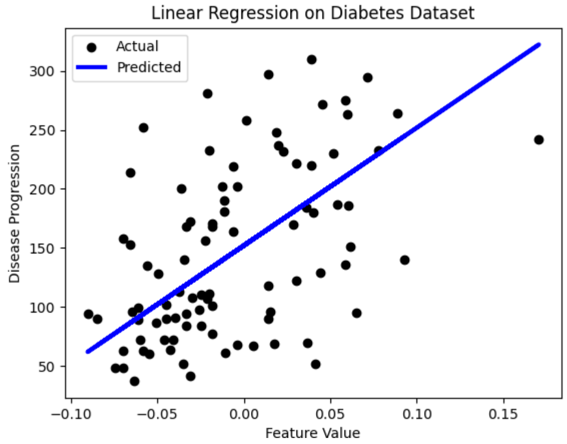
```
Coefficients: [998.57768914]

Intercept: 152.00335421448167

Mean squared error: 4061.83

Coefficient of determination (R^2): 0.23
```

Scale sensitive, a bit hard to interpret

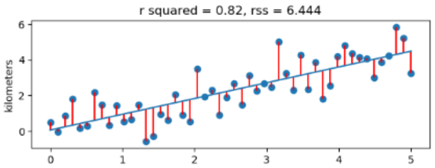
More interpretable

Plot regression line with the test set,

```
# Plot outputs
plt.scatter(diabetes_X_test, diabetes_y_test, color="black")
plt.plot(diabetes_X_test, diabetes_y_pred, color="blue", linewidth=3)

plt.xticks(())
plt.yticks(())

plt.show()
```



Coefficient of Determination R^2



Variance unexplained by Regression model

Residual Sum-of-Squares

$$R^2 = 1 - \frac{\text{RSS}}{\text{SS}} = 1 - \frac{\sum_{i=1}^{N} (y_i - w^T x_i)^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2}$$

Total variance in dataset

Variance using avg. prediction

Where: $\bar{y} = \frac{1}{N} \sum_i y_i$ is the average output

Coefficient of Determination R^2

$$R^2 = 1 - \frac{\text{RSS}}{\text{SS}}$$

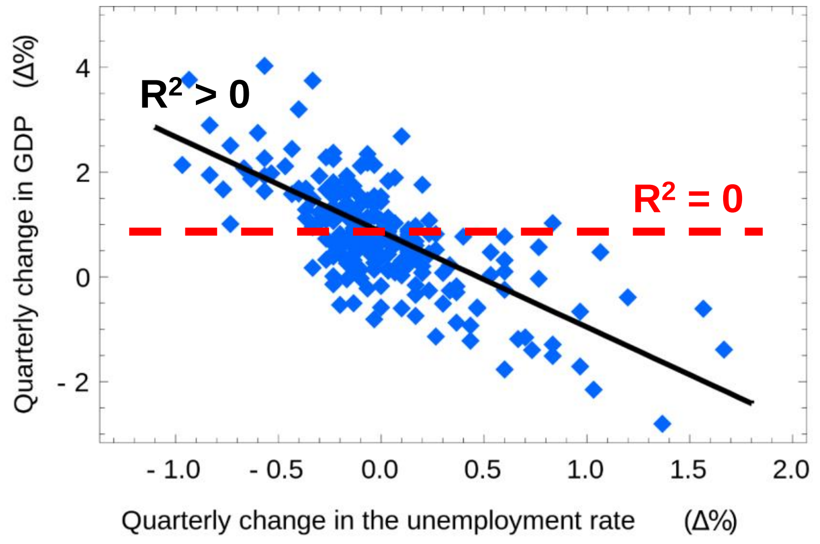
Variance unexplained by Regression model

Variance using avg. prediction

Maximum value R^2=1.0 means model explains *all variation* in the data

R^2=0 means model is as good as predicting average response

R^2<0 means model is worse than predicting average output (rare)



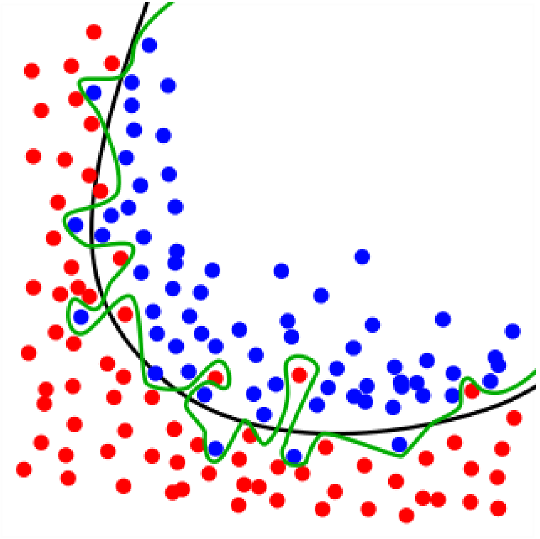
Overfitting and underfitting

Challenge in machine learning: generalization

Why not learn the most complex predictor that can work flawlessly for the training data and be done with it? (i.e., predicts every training data point correctly)

Problem: may not generalize to unseen data – called *overfitting* the training data.

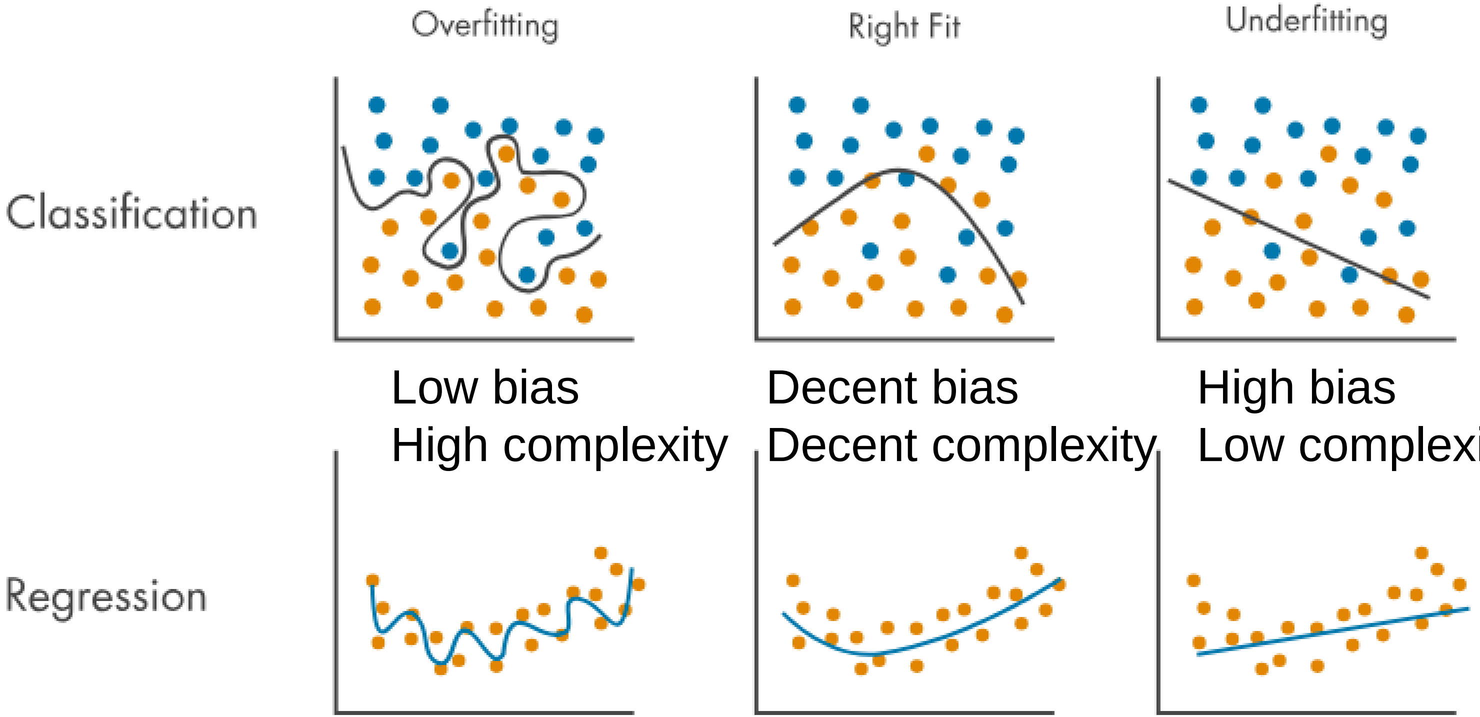
In other words, memorization is not generalization



Mitigation: Fit the training set but don't "over-do" it -- **regularization**.

green: may be sensitive to noise in training data
black: more robust and can generalize better

Overfitting and Underfitting



Low bias
High complexity

Decent bias
Decent complexity

High bias
Low complexity

Ideal: select a model that trades off bias & complexity, i.e.,
- sophisticated enough to capture meaningful patterns for accurate predictions,
- yet not so intricate that it overfits the data. **Low complexity** **Low bias**

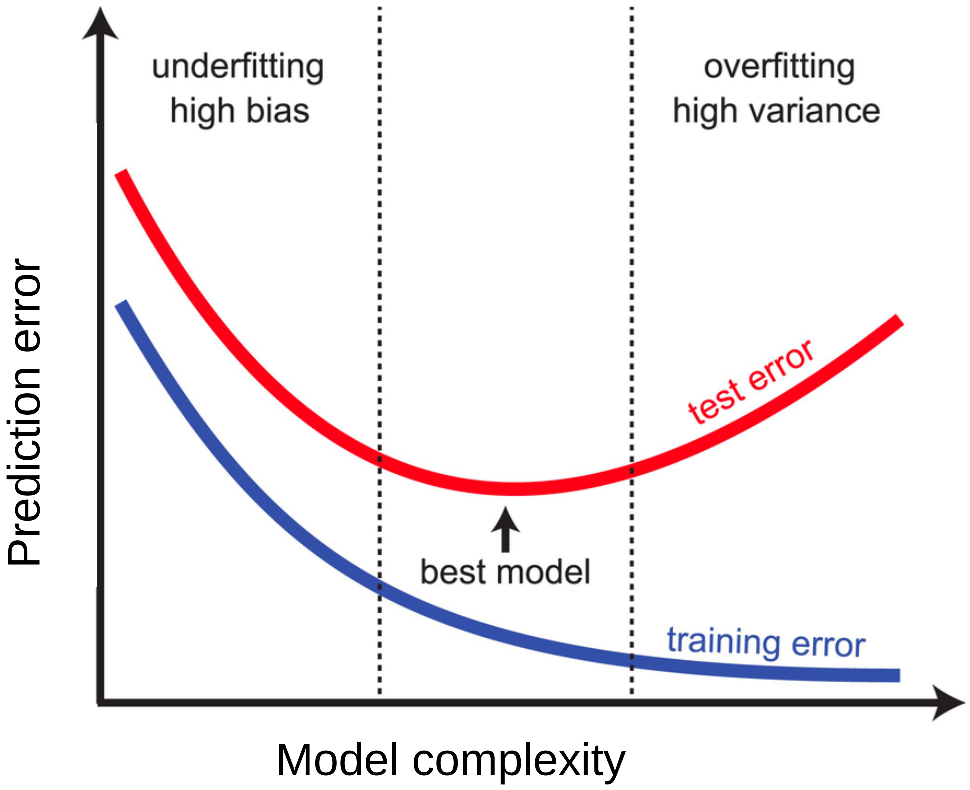
Model selection

Examples of model complexity:

- The number of features used for prediction (more features => more complex)

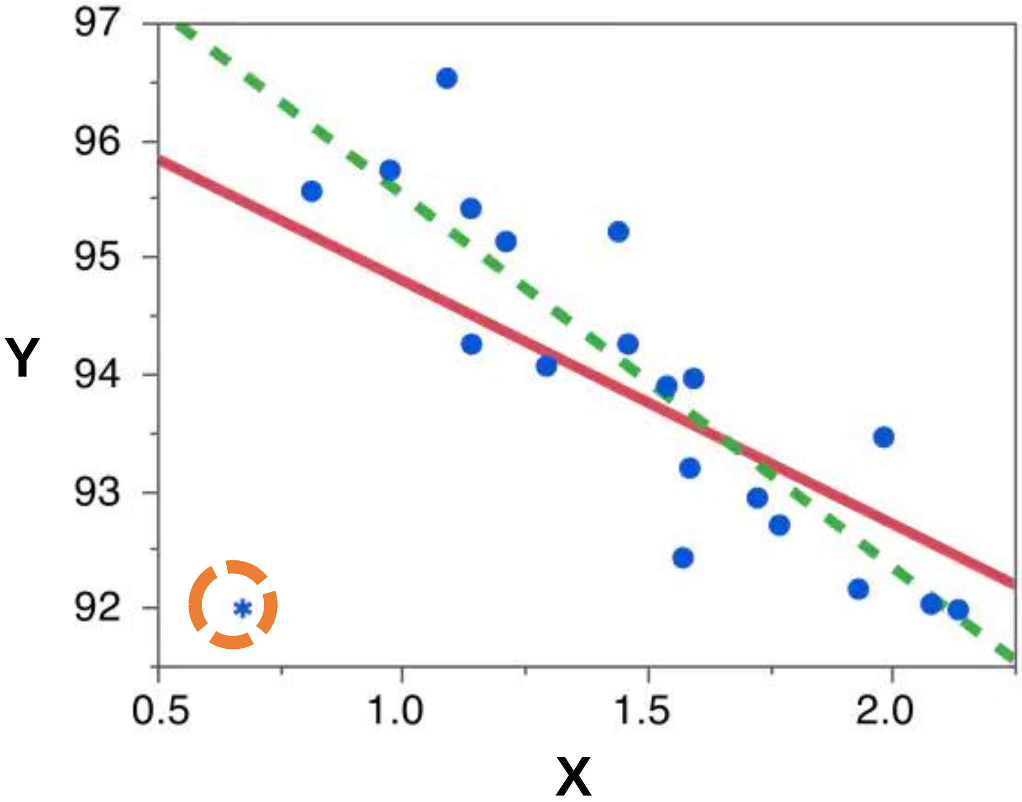
- The weight of the predictors used for prediction (higher weight => more complex)

Model selection: choosing model with “just right” complexity for data



Regularization in regression

Outliers in Linear Regression



Outlier "pulls" regression line away from inlier data, which results in overfitting

Need a way to *ignore* or to *down-weight* impact of outlier

https://www.jmp.com/en_us/statistics-knowledge-portal/what-is-multiple-regression/mlr-residual-analysis-and-outliers.html

Dealing with Outliers

Too many outliers can indicate many things: heavy-tailed data, corrupted data, bad data collection, …

A few ways to handle outliers…

This lecture: penalize extreme weights to avoid overfitting (Regularization)

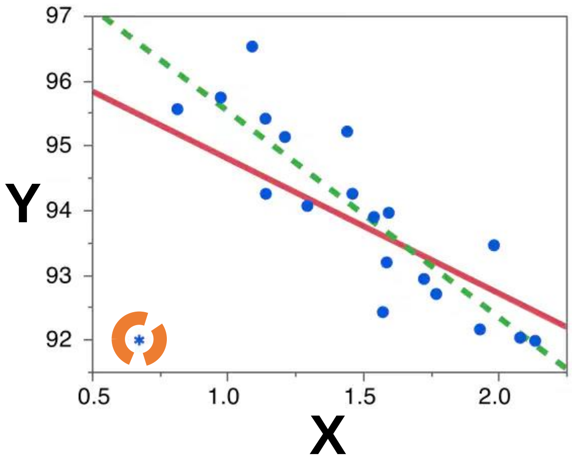
Regularization

Regularization helps avoid overfitting to training data…

$$\text{Model} = \text{argmin}_{\text{model}} \text{Loss}(\text{Model}, \text{Data}) + \lambda \cdot \text{Regularizer}(\text{Model})$$

Regularization Strength

Regularization Penalty



Red model is without regularization

Green model is with regularization

Regularized Least Squares

A couple regularizers are so common they have specific names

L2 Regularized Linear Regression

- Ridge Regression

L1 Regularized Linear Regression

- LASSO -- “Least Absolute Shrinkage and Selection Operator”

Regularized Least Squares

Ordinary least-squares estimation (no regularizer),

$$w^{\mathrm{OLS}} = \arg\min_{w} \sum_{i=1}^{N} (y_i - w^T x_i)^2$$

L2-regularized Least-Squares (Ridge)

Quadratic Penalty

$$w^{\mathrm{L2}} = \arg\min_{w} \sum_{i=1}^{N} (y_i - w^T x_i)^2 + \frac{\lambda}{2} \|w\|^2$$

$$||w||^2 = \sum_{j=1}^{d} w_j^2$$

L1-regularized Least-Squares (LASSO)

Absolute Value (L1) Penalty

$$w^{\mathrm{L1}} = \arg\min_{w} \sum_{i=1}^{N} (y_i - w^T x_i)^2 + \lambda |w|$$

$$|w| = \sum_{j=1}^{d} |w_j|$$

Scikit-Learn : L2 Regularized Regression

sklearn.linear_model.Ridge

class sklearn.linear_model.Ridge(*alpha=1.0, *, fit_intercept=True, normalize='deprecated', copy_X=True, max_iter=None, tol=0.001, solver='auto', positive=False, random_state=None*) ¶ [source]

alpha : *{float, ndarray of shape (n_targets,)}, default=1.0*

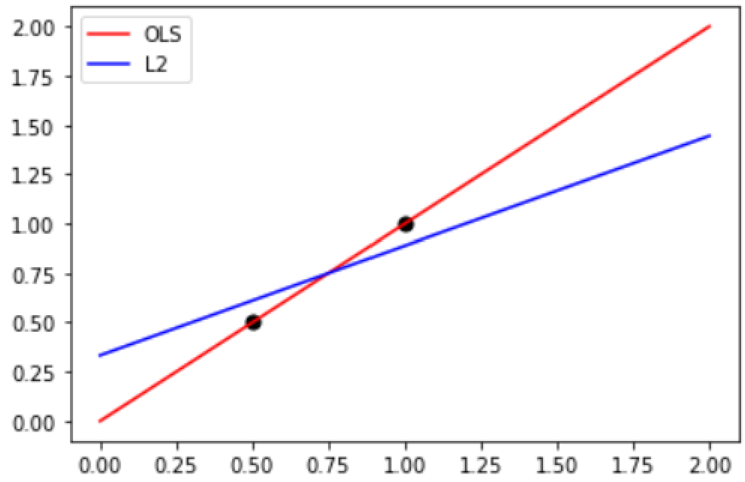
Regularization strength; must be a positive float. Regularization improves the conditioning of the problem and reduces the variance of the estimates. Larger values specify stronger regularization. Alpha corresponds to `1 / (2C)` in other linear models such as `LogisticRegression` or `LinearSVC`. If an array is passed, penalties are assumed to be specific to the targets. Hence they must correspond in number.

Alpha is what we have been calling λ

Scikit-Learn: L2 Regularized Regression

Define and fit OLS and L2 regression,

```
ols=linear_model.LinearRegression()
ols.fit(X_train, y_train)
ridge=linear_model.Ridge(alpha=0.1)
ridge.fit(X_train, y_train)
```



Plot results,

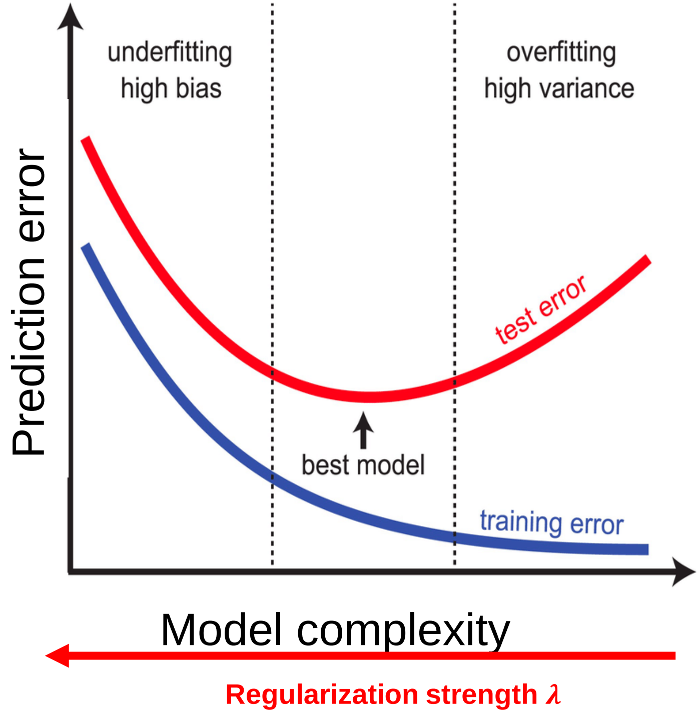
```
fig, ax = plt.subplots()
ax.scatter(X_train, y_train, s=50, c="black", marker="o")
ax.plot(X_test, ols.predict(X_test), color="red", label="OLS")
ax.plot(X_test, ridge.predict(X_test), color="blue", label="L2")

plt.legend()
plt.show()
```

L2 (Ridge) reduces impact of any single data point

Choosing Regularization Strength

We need to tune regularization strength to get the best performance…

$$w^{\mathrm{L2}} = \arg\min_{w} \sum_{i=1}^{N} (y_i - w^T x_i)^2 + \frac{\lambda}{2}\|w\|^2$$



High λ => learned w has small weights

increases bias & *decreases complexity*

Model selection: How should we properly tune λ?

Naïve idea: using training loss to choose regularization

How to choose a good λ?

First, we need set of candidate λ's

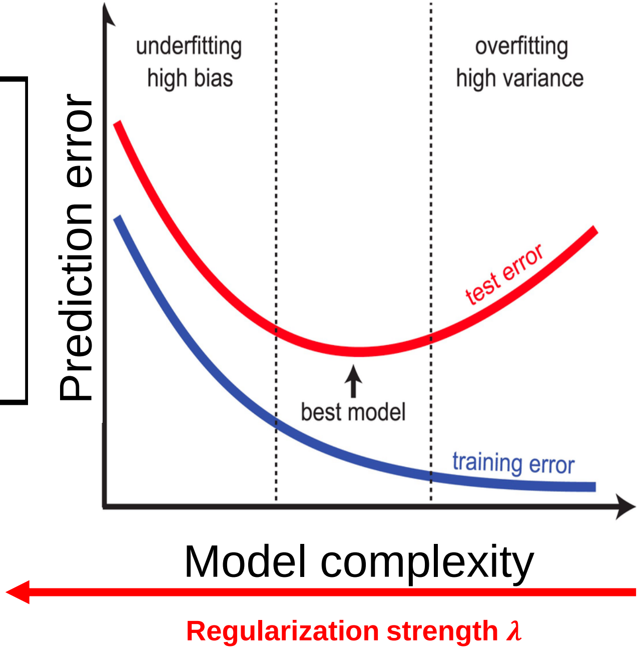
- e.g., geometric grid $\Lambda = \{0.1, 0.2, 0.4, .., 1000\}$

Is the following a good approach?

For each $\lambda \in \Lambda$:
    Train ridge estimator w_λ with regularization λ

Return: w_λ with the smallest training loss

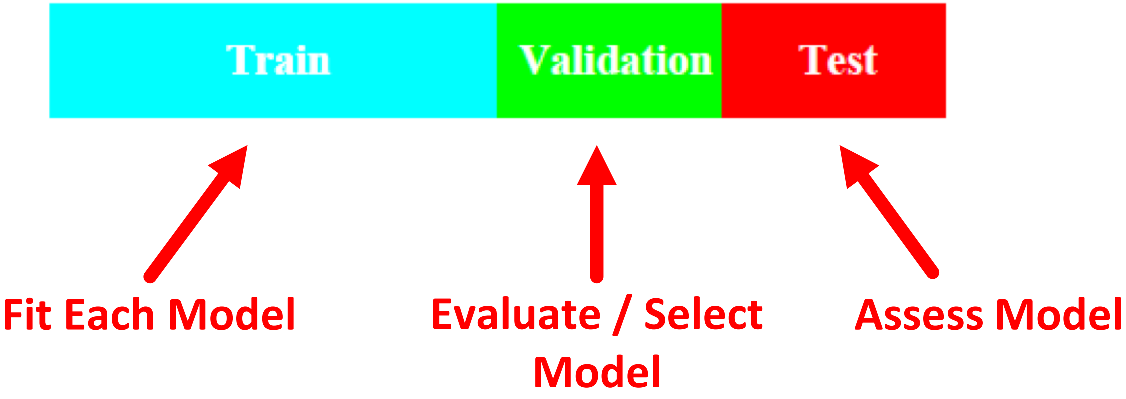
No – this likely always chooses the smallest λ which is prone to overfitting



Model Selection approach 1: hold-out validation set

How to choose a good $\lambda \in \Lambda$?

Partition data into Train-Validation-Test sets



- Ideally, Test set is kept in a "vault" and **only peek at it once final predictor is selected**
- Small dataset: 50% Training, 25% Validation, 25% Test (rule of thumb by statisticians)
- For large data (say a few thousands), 80-10-10 is usually fine.

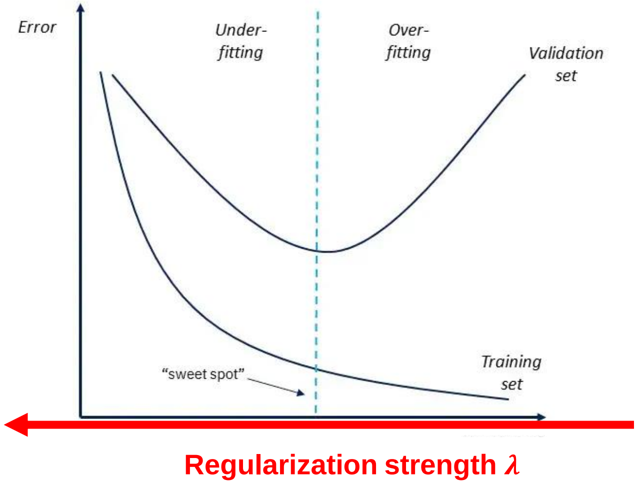
Model Selection approach 1: hold-out validation set

Key idea: use validation performance as a proxy of test performance

For each $\lambda \in \Lambda$:

- Train ridge estimator w_λ with training set with regularization λ
- measure performance e_λ of w_λ on validation set

Return $w_{\hat{\lambda}}$, $\hat{\lambda}$: the λ with the best e_λ value



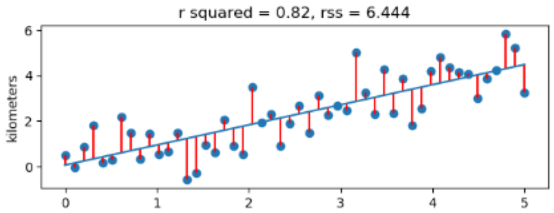
Model Selection for Linear Regression

A couple of common metrics for model selection…

Residual Sum-of-squared Errors The total squared residual error on the held-out validation set,

Lower the better

$$\mathrm{RSS} = \sum_{i=1}^{N} (y_i - w^T x_i)^2$$



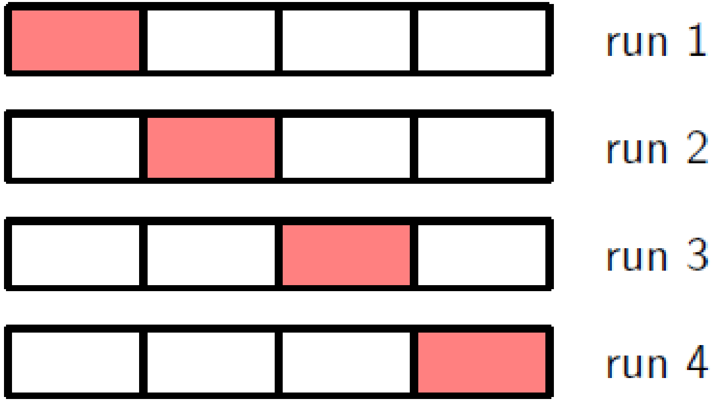
Coefficient of Determination Also called R-squared or R^2.

Higher the better

Model selection metrics are known as "goodness of fit" measures

Model Selection approach 2: cross-validation

Main idea: improve data efficiency by splitting the training / validation data in multiple ways



K-fold Cross Validation: Partition training data into K "chunks" and for each run select one chunk to be validation data

For each run, fit to training data (K-1 chunks) and measure performance on validation set. Average model performance across all runs.

$K = 5, 10$ are typical good choices

Source: Bishop, C. PRML

Cross-validation: formal description

For each $\lambda \in \Lambda$:

For $k \in \{1, \ldots, K\}$:

- Train ridge estimator f with $S \setminus \mathrm{fold}_k$
- measure performance $e_{\lambda,k}$ of f on fold_k

Compute average performance: $E_\lambda = \frac{1}{K} \sum_{k=1}^{K} e_{\lambda,k}$

Choose $\hat{\lambda}$:= best λ according to E_λ

Train $\hat{f}$ using S with hyperparameter $\hat{\lambda}$

What is the largest possible value of K?

$K = |S|$ -- this is called leave-one-out cross validation (LOOCV)

"Shrinkage" Feature Selection

Regularization down-weight features that are not useful for prediction…

Term	LS	Ridge
Intercept	2.465	2.452
lcavol	0.680	0.420
lweight	0.263	0.238
age	−0.141	−0.046
lbph	0.210	0.162
svi	0.305	0.227
lcp	−0.288	0.000
gleason	−0.021	0.040
pgg45	0.267	0.133

Quadratic penalty $\lambda \|w\|^2$ down-weights (shrinks) features that are not useful for prediction

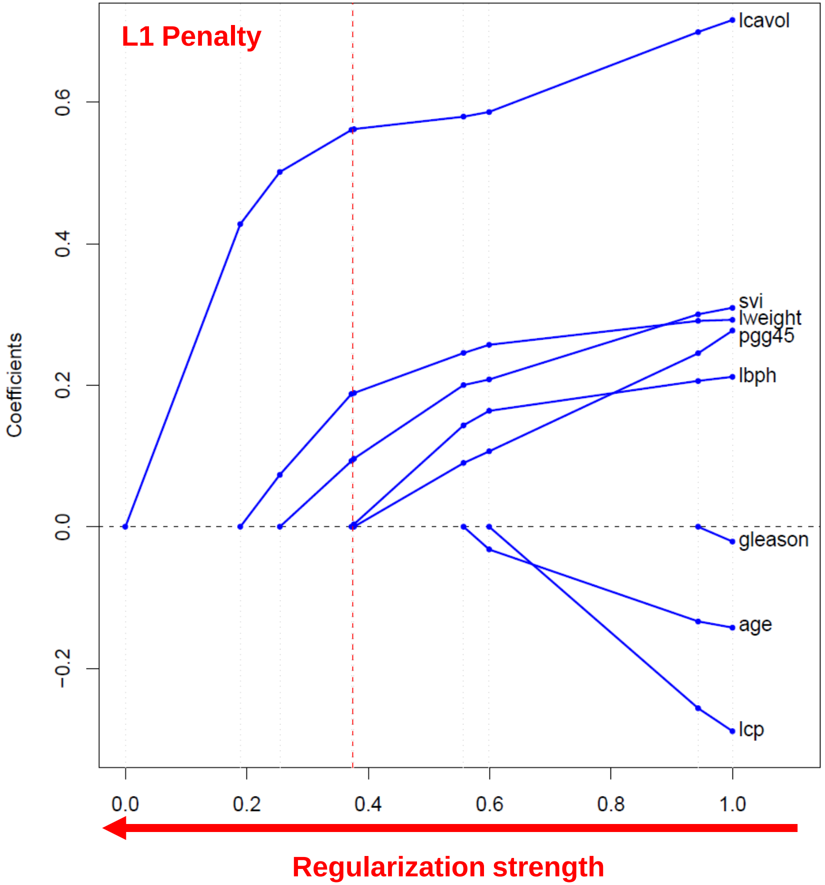
Example *Prostate Cancer Dataset* predicts prostate-specific cancer antigen with features: age, log-prostate weight (lweight), log-benign prostate hyperplasia (lbph), Gleason score (gleason), seminal vesical invasion (svi), etc.

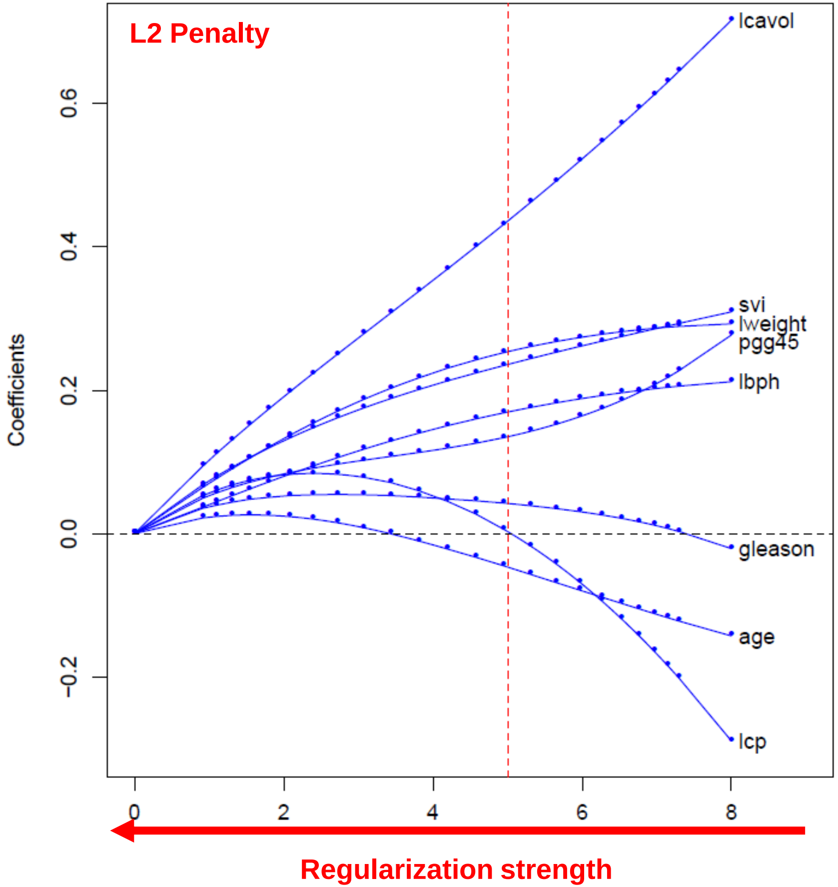
L2 regularization learns zero-weight for log capsular penetration (lcp)

[Source: Hastie et al. (2001)]

Feature Weight Profiles

L1 penalty more likely learns coefficients that are zero, thus induces sparsity





sklearn.linear_model.Lasso

class sklearn.linear_model.Lasso(*alpha=1.0*, ***, *fit_intercept=True*, *normalize='deprecated'*, *precompute=False*, *copy_X=True*, *max_iter=1000*, *tol=0.0001*, *warm_start=False*, *positive=False*, *random_state=None*, *selection='cyclic'*) ¶ [source]

Parameters:

alpha : *float, default=1.0*

Constant that multiplies the L1 term. Defaults to 1.0. `alpha = 0` is equivalent to an ordinary least square, solved by the `LinearRegression` object. For numerical reasons, using `alpha = 0` with the `Lasso` object is not advised. Given this, you should use the `LinearRegression` object.

fit_intercept : *bool, default=True*

Whether to calculate the intercept for this model. If set to False, no intercept will be used in calculations (i.e. data is expected to be centered).

precompute : *'auto', bool or array-like of shape (n_features, n_features), precompute*

Whether to use a precomputed Gram matrix to speed up calculations. The Gram matrix can also be passed as argument. For sparse input this option is always `False` to preserve sparsity.

copy_X : *bool, default=True*

If `True`, X will be copied; else, it may be overwritten.

Specialized methods for cross-validation…

sklearn.linear_model.LassoCV

class sklearn.linear_model.LassoCV(**, eps=0.001, n_alphas=100, alphas=None, fit_intercept=True, normalize='deprecated', precompute='auto', max_iter=1000, tol=0.0001, copy_X=True, cv=None, verbose=False, n_jobs=None, positive=False, random_state=None, selection='cyclic'*) [source]

Computes solution using coordinate descent

sklearn.linear_model.LassoLarsCV

class sklearn.linear_model.LassoLarsCV(**, fit_intercept=True, verbose=False, max_iter=500, normalize='deprecated', precompute='auto', cv=None, max_n_alphas=1000, n_jobs=None, eps=2.220446049250313e-16, copy_X=True, positive=False*) ¶ [source]

Uses *least angle regression* (LARS) to compute solution path

Their results are similar; LassoCV may be more stable

L1 Regression Cross-Validation

Perform L1 Least Squares (LASSO) 20-fold cross-validation,

```
model = LassoCV(cv=20).fit(X, y)
```

or

```
model = LassoLarsCV(cv=20, normalize=False).fit(X, y)
```

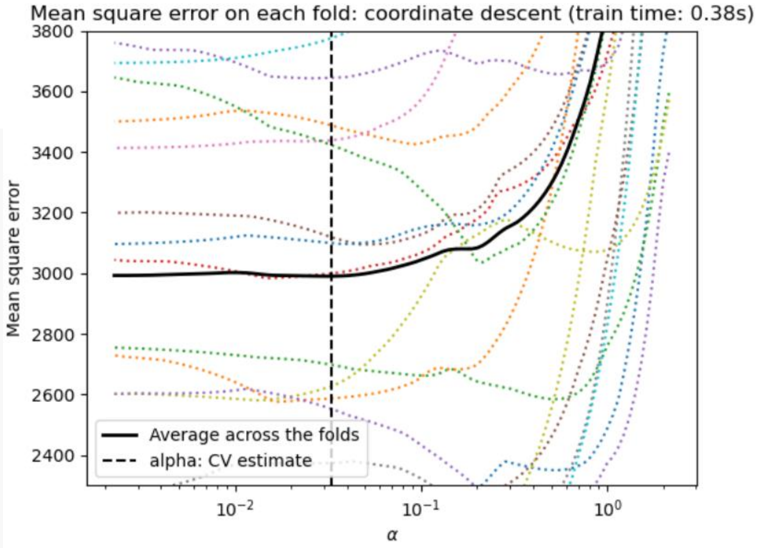
Plot solution path for range of alphas,

```
plt.figure()
ymin, ymax = 2300, 3800
plt.semilogx(model.alphas_ + EPSILON, model.mse_path_, ":")
plt.plot(
    model.alphas_ + EPSILON,
    model.mse_path_.mean(axis=-1),
    "k",
    label="Average across the folds",
    linewidth=2,
)
plt.axvline(
    model.alpha_ + EPSILON, linestyle="--", color="k", label="alpha: CV estimate"
)
```

20 validation error curves (dashed)

mean curve (solid)

alpha_ value chosen by cross validation



Quiz 8

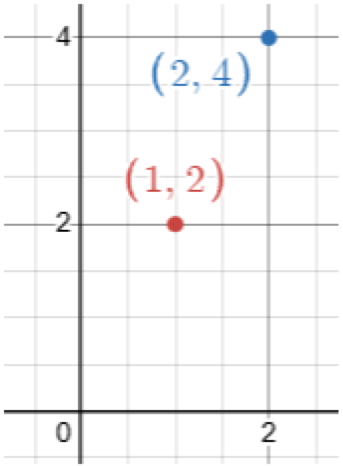
- Let's fit a linear regression model $y = w \cdot x$ on the following training data:

#bedrooms (x)	House price / 100K (y)
1	2
2	4

  - Draw the training data points in an x-y plane
  - Write down the mean square error as a function of w
  - Find $\hat{w}$ that minimizes the mean square error
  - Draw the line $y = \hat{w} \cdot x$

Quiz 8

Draw the training data points in an x-y plane



Write down the mean square error as a function of w

$$\frac{1}{2}\left((w \cdot 1 - 2)^2 + (w \cdot 2 - 4)^2\right)$$

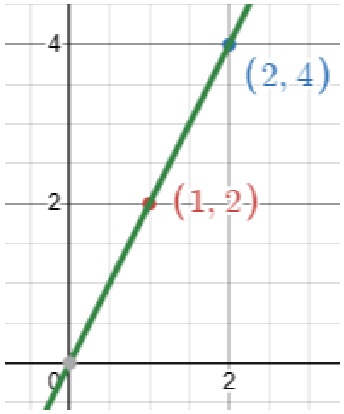
$$2.5w^2 - 10w + 20$$

Find $\hat{w}$ that minimizes the mean square error

$$\hat{w} = -\frac{b}{2a} = 2$$

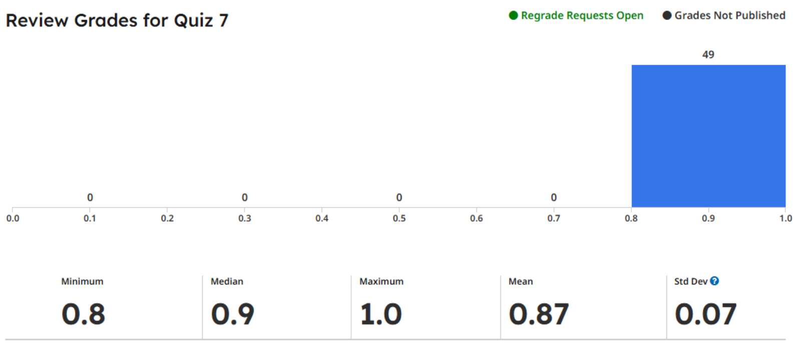
Interpretation: every additional bedroom will increase the house price by 200K

Draw the line $y = \hat{w} \cdot x$



Announcements 4/2

Quiz 7 graded



Note:

- normal distribution with mean 50 and stddev 0.5 is denoted as $N(50, 0.5^2)$ – *note the square*
- There is no such thing as $\frac{N(50,0.5^2)}{10}$ -- we can talk about the distribution of $\frac{X}{10}$ when $X \sim N(50, 0.5^2)$ though

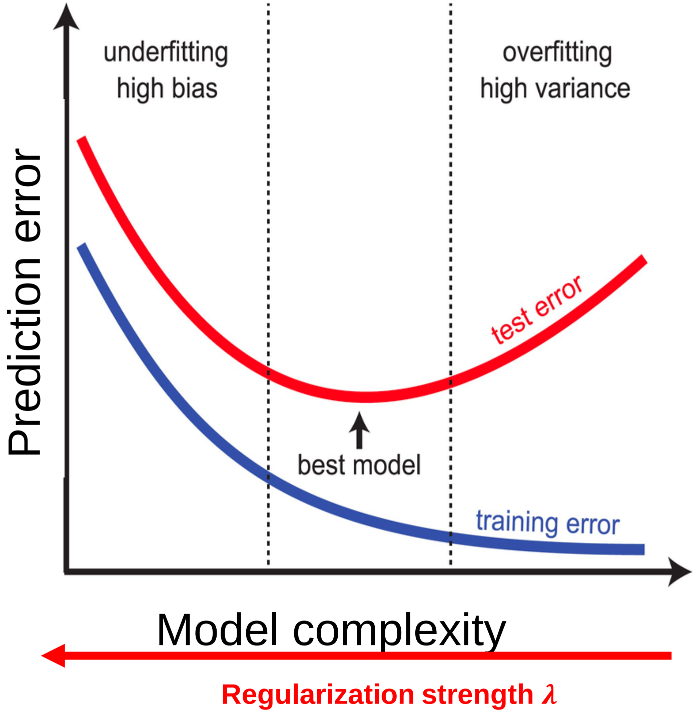
We are working on answering questions on Piazza..

Midterm grades will be capped at 100

Choosing Regularization Strength

We need to tune regularization strength to get the best performance…

$$w^{\mathrm{L2}} = \arg\min_w \sum_{i=1}^{N} (y_i - w^T x_i)^2 + \frac{\lambda}{2}\|w\|^2$$



High λ => learned w has small weights

increases bias & *decreases complexity*

Model selection: How should we properly tune λ?

L1 Regression Cross-Validation

Perform L1 Least Squares (LASSO) 20-fold cross-validation,

```
model = LassoCV(cv=20).fit(X, y)
```

or

```
model = LassoLarsCV(cv=20, normalize=False).fit(X, y)
```

Plot solution path for range of alphas,

```
plt.figure()
ymin, ymax = 2300, 3800
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    label="Average across the folds",
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plt.axvline(
    model.alpha_ + EPSILON, linestyle="--", color="k", label="alpha: CV estimate"
)
```
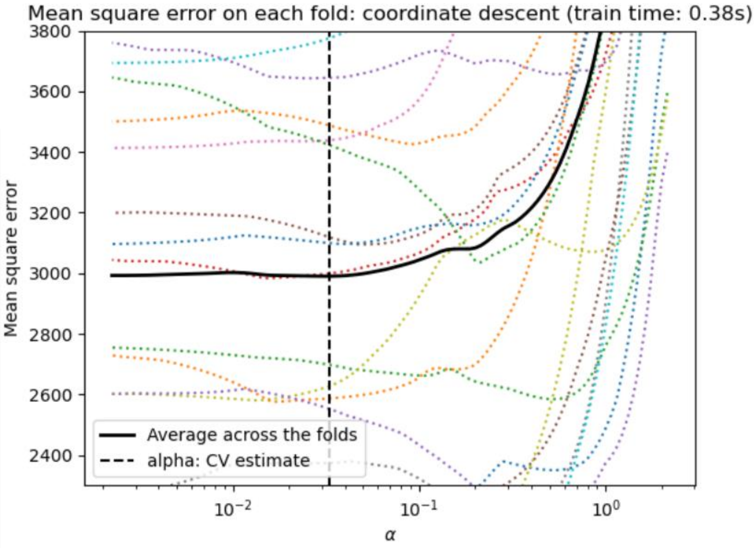

20 validation error curves (dashed)

mean curve (solid)

alpha_ value chosen by cross validation



Feature Selection

Feature selection

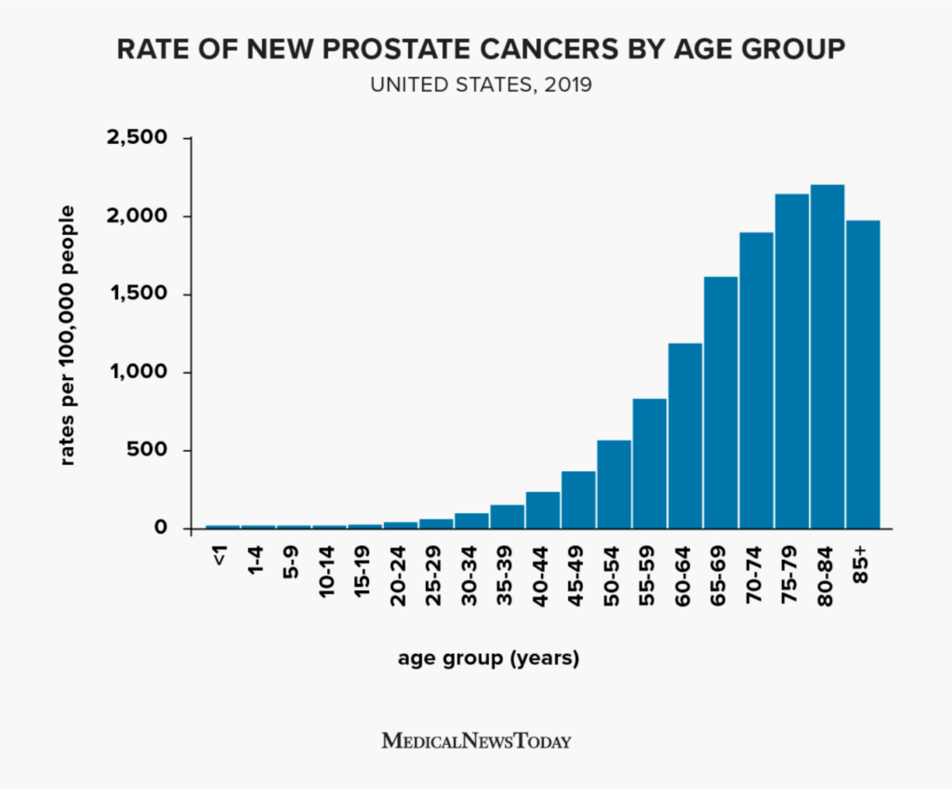
- Use only a few features to make predictions

- Benefits of using only a few features:
  - Model selection – trades off between bias and complexity
  - Interpretability – makes the model trustworthy by e.g. doctors and policy makers

E.g. cardiovascular disease risk

= 0 x physical activity + 3.5 x smoking + 2.8 x cholesterol + …

Rate of Prostate Cancer



https://www.medicalnewstoday.com/articles/age-range-for-prostate-cancer

Example: Prostate Cancer Dataset

Best LASSO model learns to ignore several features (age, lcp, gleason, pgg45).

Term	LS	Ridge	Lasso
Intercept	2.465	2.452	2.468
lcavol	0.680	0.420	0.533
lweight	0.263	0.238	0.169
age	−0.141	−0.046	
lbph	0.210	0.162	0.002
svi	0.305	0.227	0.094
lcp	−0.288	0.000	
gleason	−0.021	0.040	
pgg45	0.267	0.133	

Task: predict logarithm of prostate specific antigen (PSA).

Wait…Is **age** really not a significant predictor of prostate cancer? What's going on here?

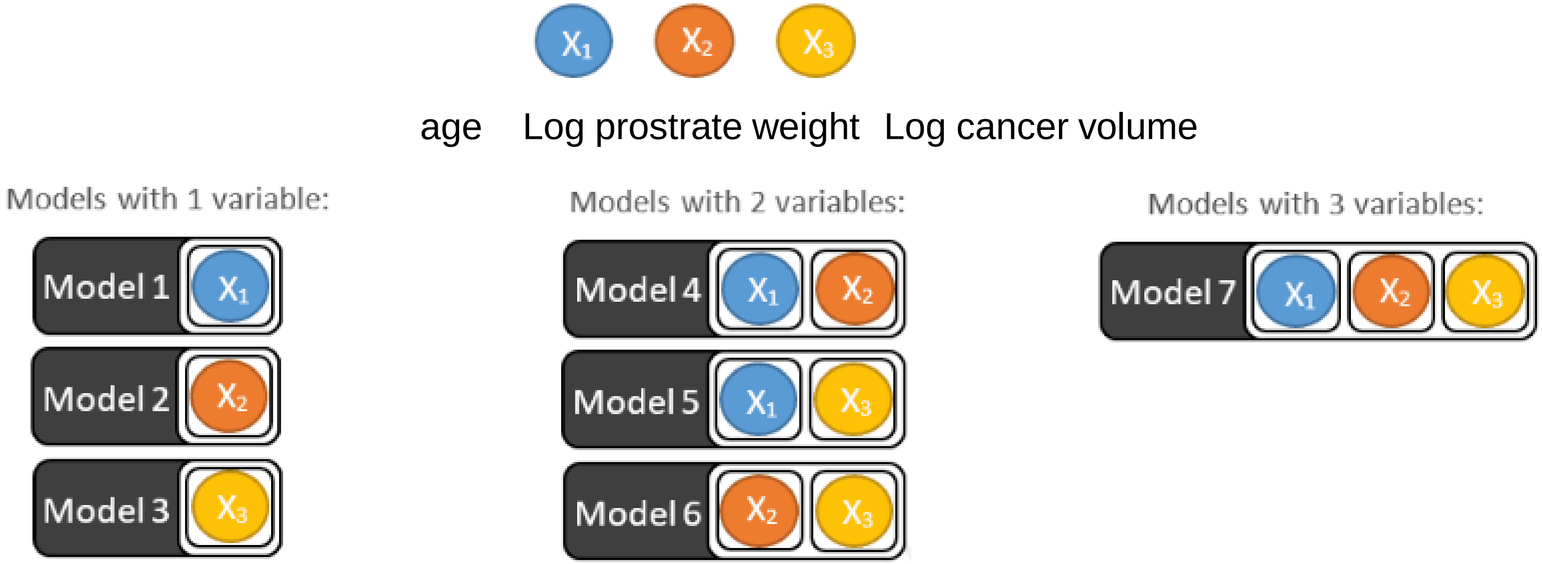
Age is highly correlated with other factors and thus *not significant* in the presence of those factors

Best-Subset Selection

The optimal strategy for p features looks at models over *all possible combinations* of features,

```
For k in 1,…,p:
  subset = Compute all subset of k-features (p-choose-k)
  For kfeat in subset:
    model = Train model on kfeat features
    score = Evaluate model using cross-validation
Choose the model with best cross-validation score
```

Best-Subset Selection



Feature Selection: Prostate Cancer Dataset

Best subset works well

reasonably good test error, low standard deviation, and only based on two features!

Term	LS	Best Subset	Ridge	Lasso
Intercept	2.465	2.477	2.452	2.468
lcavol	0.680	0.740	0.420	0.533
lweight	0.263	0.316	0.238	0.169
age	−0.141		−0.046	
lbph	0.210		0.162	0.002
svi	0.305		0.227	0.094
lcp	−0.288		0.000	
gleason	−0.021		0.040	
pgg45	0.267		0.133	
Test Error	0.521	0.492	0.492	0.479
Std Error	0.179	0.143	0.165	0.164

[Source: Hastie et al. (2001)]

Best-Subset Selection : Prostate Cancer Dataset

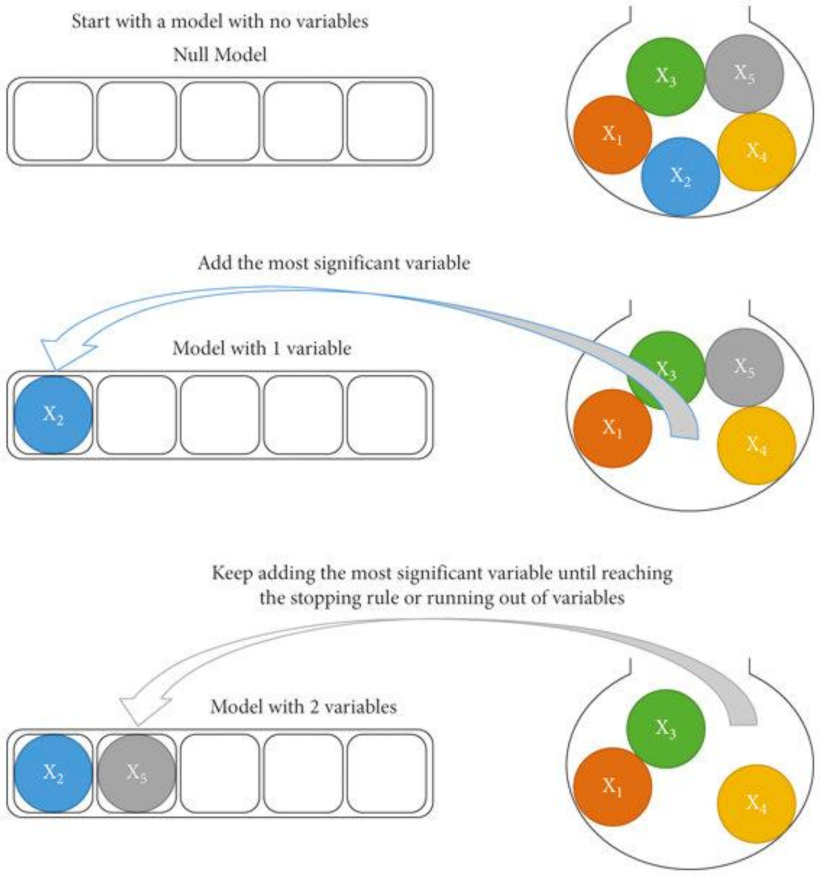
Time complexity

- Data have 8 features, there are 8-choose-k subsets for each k=1,…,8 for a total of 255 models
- Using 10-fold cross-val requires 10 x 255 = 2,550 training runs!
- In general, $O(2^p)$ time complexity

This is undesirable even for moderate p (e.g. $p = 20$)

Instead, we can use greedy algorithms to reduce time cost

Forward Sequential Selection

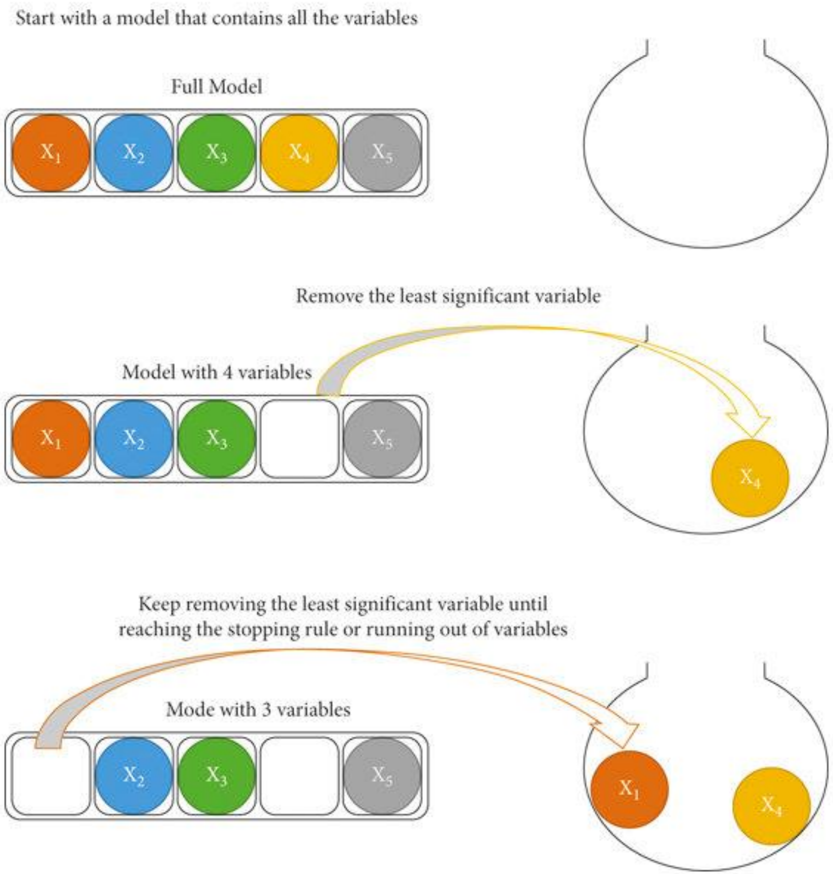


Forward Sequential Selection

An efficient method that adds the most predictive feature one-by-one

```
featSel = empty
featUnsel = All features
For iter in 1,…,p:
  For kfeat in featUnsel:
    thisFeat = featSel + kfeat
    model = Train model on thisFeat features
    score = Evaluate model using cross-validation
  featSel = featSel + best scoring feature
  featUnsel = featUnsel – best scoring feature
Choose the model with best cross-validation score
```

Backward Sequential Selection



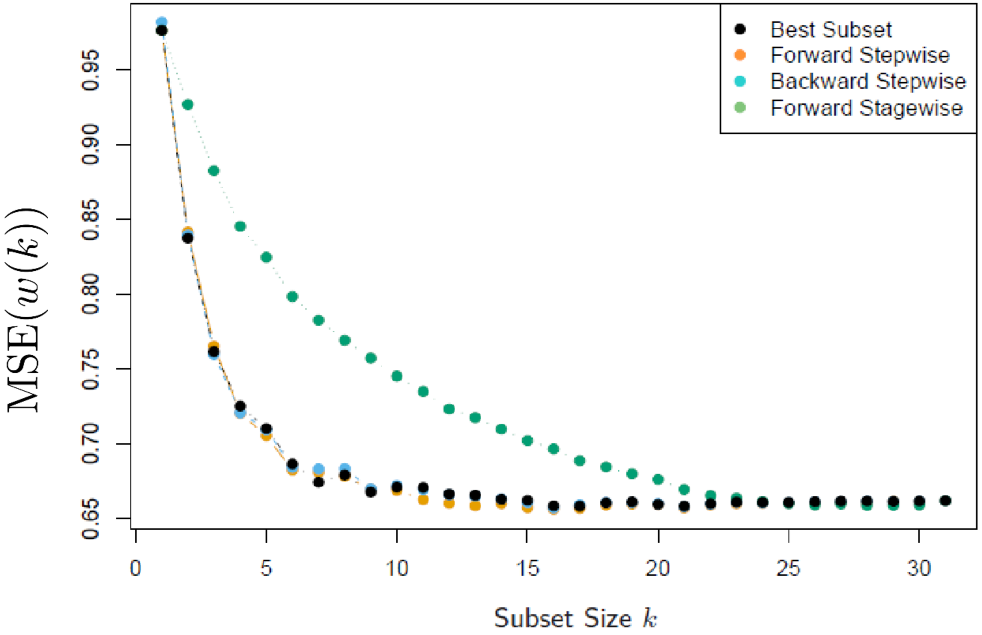
Backward Sequential Selection

Backwards approach starts with *all* features and removes one-by-one

```
featSel = All features
For iter in 1,…,p:
  For kfeat in featSel:
    thisFeat = featSel - kfeat
    model = Train model on thisFeat features
    score = Evaluate model using cross-validation
  featSel = featSel – worst scoring feature
Choose the model with best cross-validation score
```

Comparing Feature Selection Methods

Sequential selection is greedy, but often performs well…



Example Feature selection on data with p=30 features with pairwise correlations (0.85). True feature weights are all zero except for 10 features, with weights drawn from N(0,6.25).

Sequential selection with p features takes $O(p^2)$ time, compared to exponential time for best subset

Sequential feature selection available in Scikit-Learn under:
`feature_selection.SequentialFeatureSelector`