Hypothesis Testing and statistical preliminaries

Stony Brook University

CSE545, Spring 2019

Hypothesis Testing:

- Random Variables
- Distributions
- Hypothesis Testing Framework

Comparing Variables:

- Simple Linear Regression, Correlation, Multiple Linear Regression,
- Comparing Variables and Hypothesis Testing
- Regularized Linear Regression
- Multiple Hypothesis Testing

Random Variables

X: A mapping from Ω to $\mathbb{R}$ that describes the question we care about in practice.

↓

"sample space", set of all possible outcomes.

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Example: **Ω** = 5 coin tosses = $\{<HHHHH>, <HHHHT>, <HHHTH>, <HHHTH> \ldots\}$

We may just care about how many tails? Thus,

$X(<HHHHH>) = 0$

$X(<HHHTH>) = 1$

$X(<TTTHT>) = 4$

$X(<HTTTT>) = 4$

X only has 6 possible values: 0, 1, 2, 3, 4, 5

What is the probability that we end up with $k = 4$ tails?

$\mathbf{P}(X = k) := \mathbf{P}(\ \{\omega : X(\omega) = k\}\ )$ where $\omega \in \mathbf{\Omega}$

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X(ω) = 4 for 5 out of 32 sets in **Ω**. Thus, assuming a fair coin, $\mathbf{P}(X = 4) = 5/32$

(Not a "variable", but a function that we end up notating a lot like a variable)

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Random Variables

$\mathbf{X}$: A mapping from $\mathbf{\Omega}$ to $\mathbb{R}$ that describes the question we care about in practice.

Example: $\mathbf{\Omega}$ = inches of snowfall = $[0, \infty) \subseteq \mathbb{R}$

$\mathbf{X}$ is a *continuous random variable* if it can take on an infinite number of values between any two given values.

X amount of inches in a snowstorm

$\mathbf{X}(\omega) = \omega$

What is the probability we receive (at least) a *inches?*

$\mathbf{P}(X \geq a) := \mathbf{P}(\ \{\omega : X(\omega) \geq a\}\ )$

What is the probability we receive between a *and* b *inches?*

$\mathbf{P}(a \leq X \leq b) := \mathbf{P}(\ \{\omega : a \leq X(\omega) \leq b\}\ )$

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$\mathbf{X}(\omega) = \omega$

$\mathbf{P}(X = i) := 0$, for all $i \in \mathbf{\Omega}$

(probability of receiving exactly i inches of snowfall is zero)

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X(ω) = ω

P(X = i) := 0, for all i ∈ **Ω**

(probability of receiving exactly i inches of snowfall is zero)

How to model?

s?

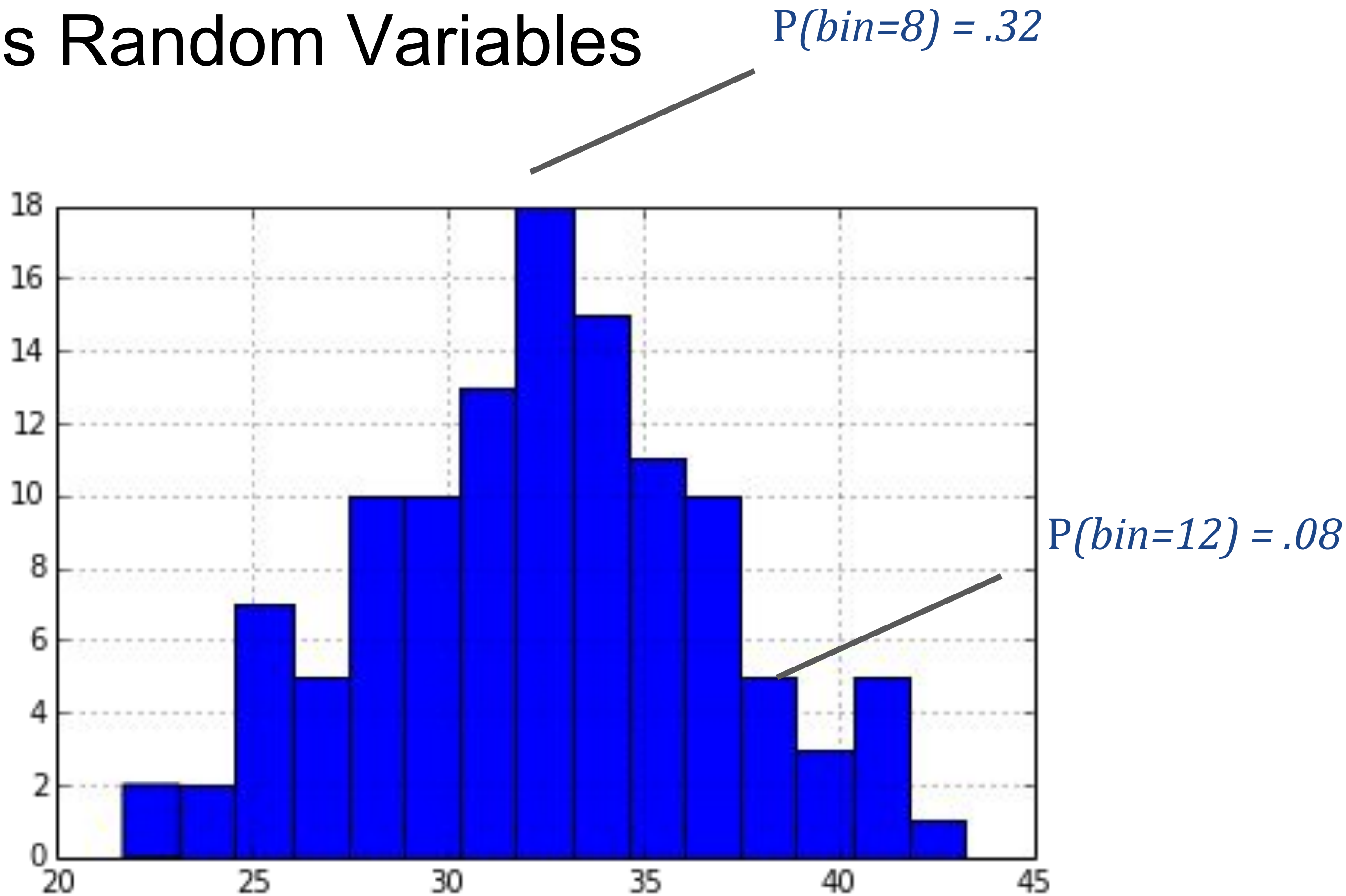
inches?

Continuous Random Variables

Discretize them!
(group into discrete bins)

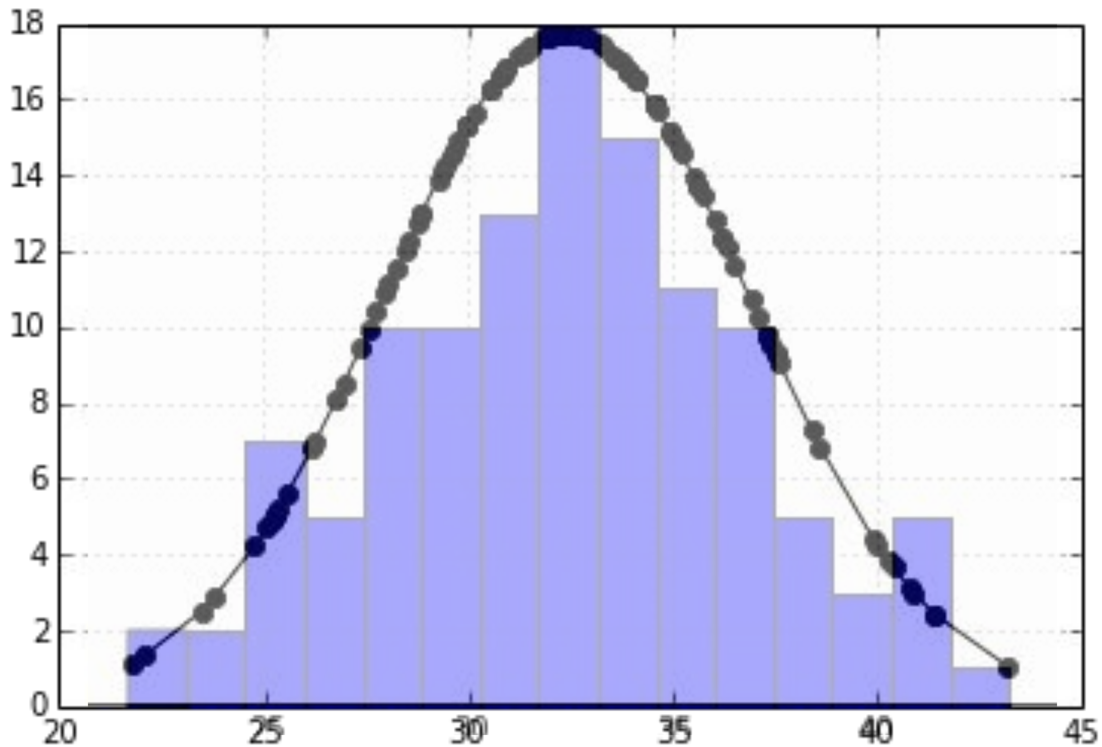
How to model?

Continuous Random Variables



But aren't we throwing away information?

Continuous Random Variables



Continuous Random Variables

X is a *continuous random variable* if it can take on an infinite number of values between any two given values.

X is a *continuous random variable* if there exists a function *fx* such that:

$$f_X(x) \geq 0, \text{for all } x \in X,$$

$$\int_{-\infty}^{\infty} f_X(x)dx = 1, \quad \text{and}$$

$$\mathrm{P}(a < X < b) = \int_a^b f_X(x)dx$$

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***fx* : "probability density function" (pdf)**

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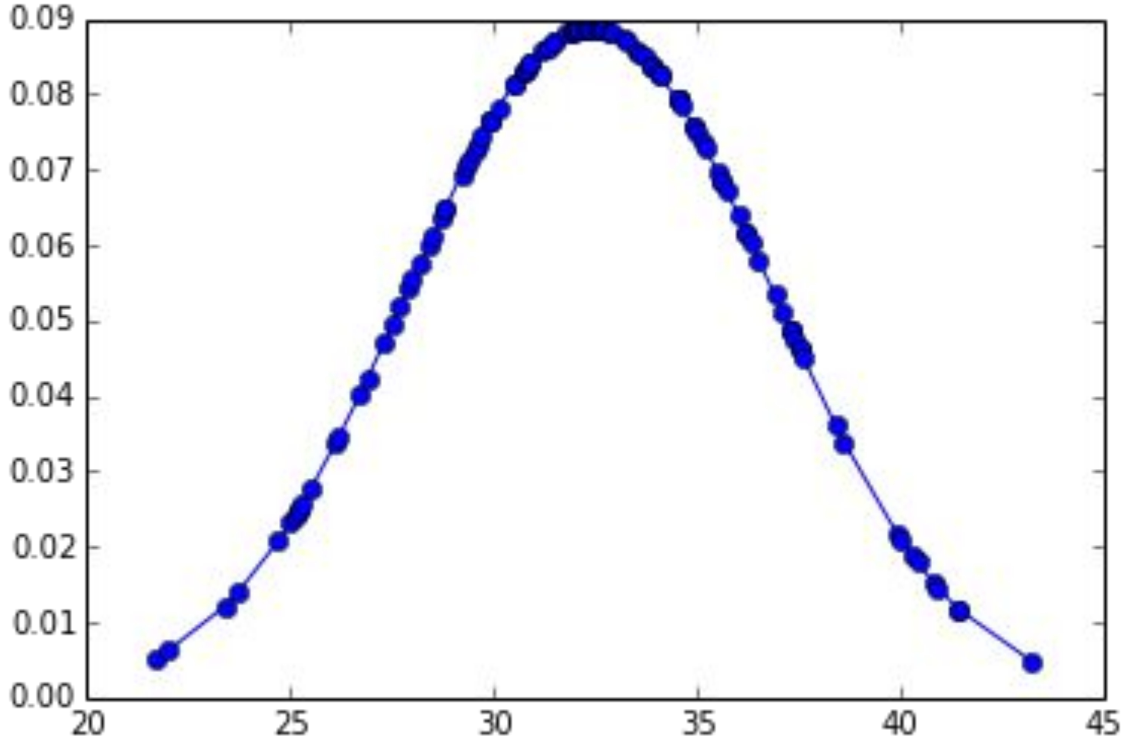
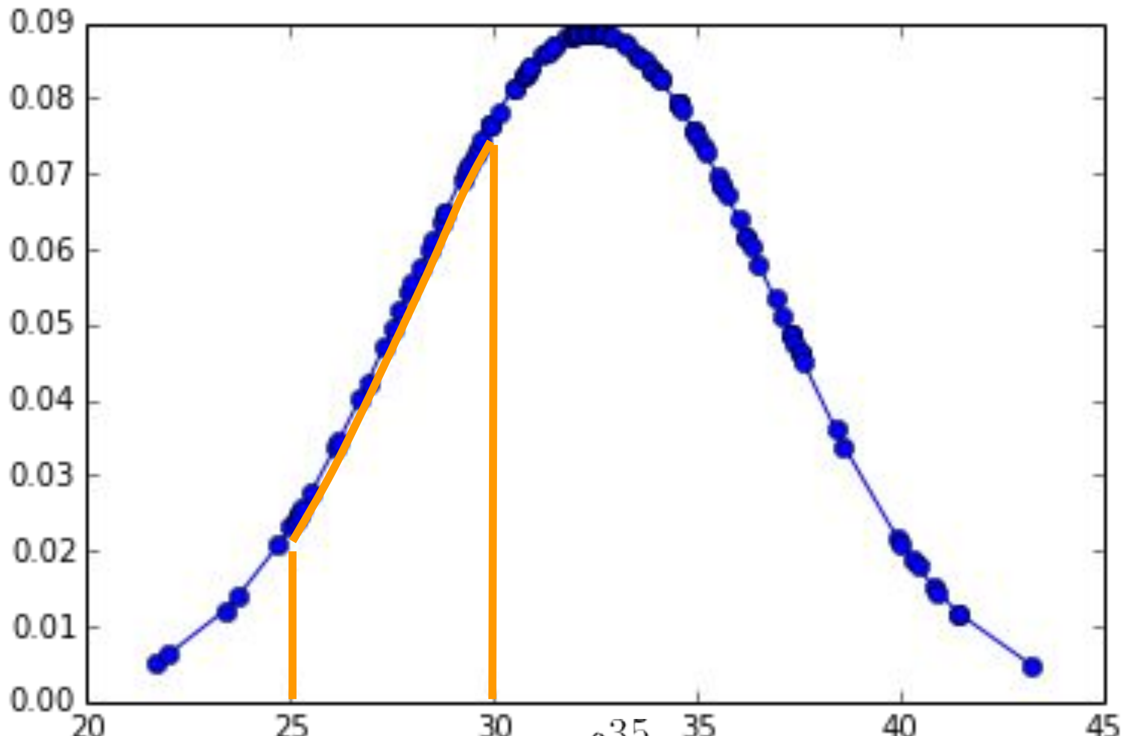


Continuous Random Variables

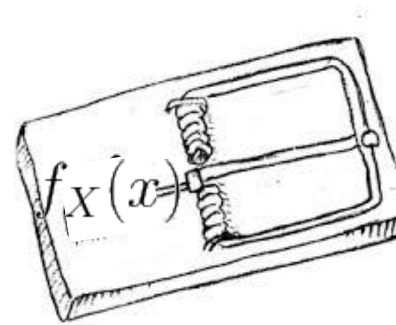


$$P(25 < X < 35) = \int_{25}^{35} fx(x)dx$$

Continuous Random Variables

Common Trap

- $f_X(x)$ does not yield a probability
  - $\int_a^b f_X(x)dx$ does
  - x may be anything ($\mathbb{R}$)
    - thus, $f_X(x)$ may be > 1



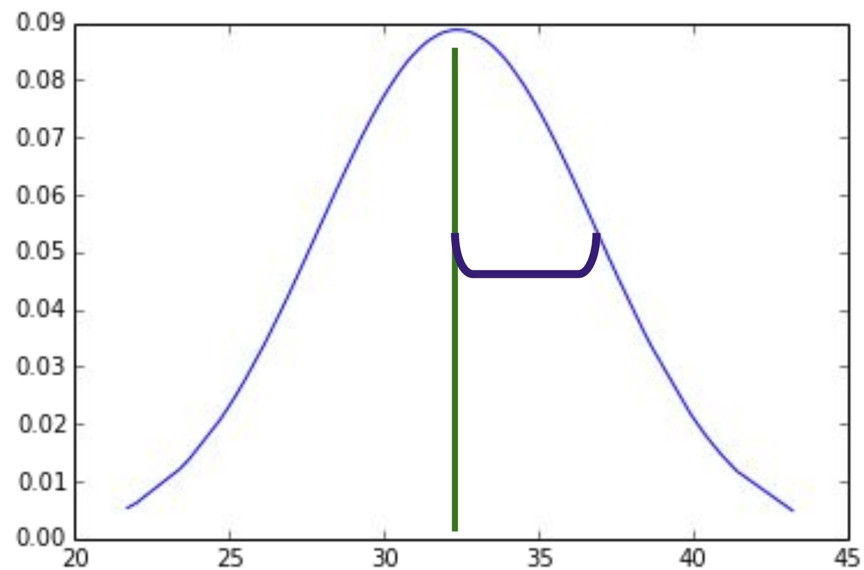
Continuous Random Variables

A Common Probability Density Function

Continuous Random Variables

Common *pdfs*: Normal(μ, σ^2)

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



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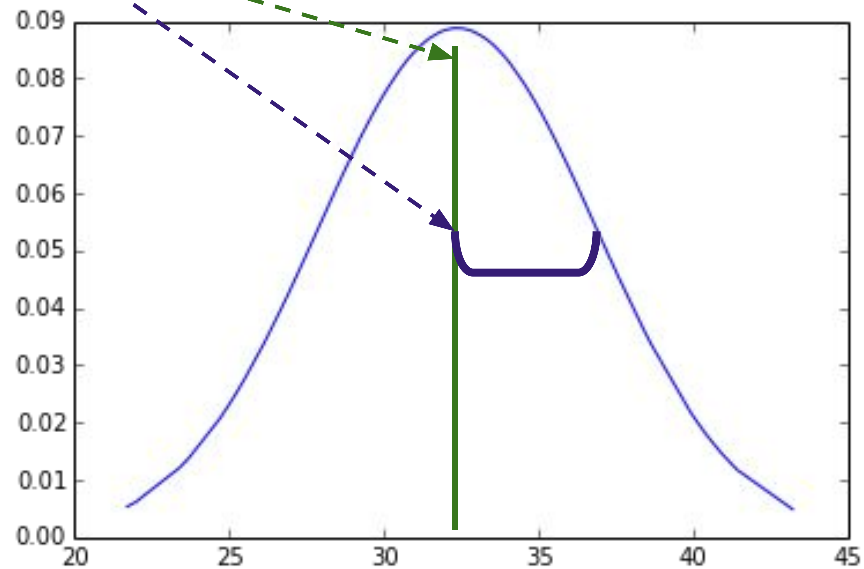

μ: mean (or "center")

= expectation

σ^2: variance,

σ: standard deviation

Continuous Random Variables

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Credit: Wikipedia

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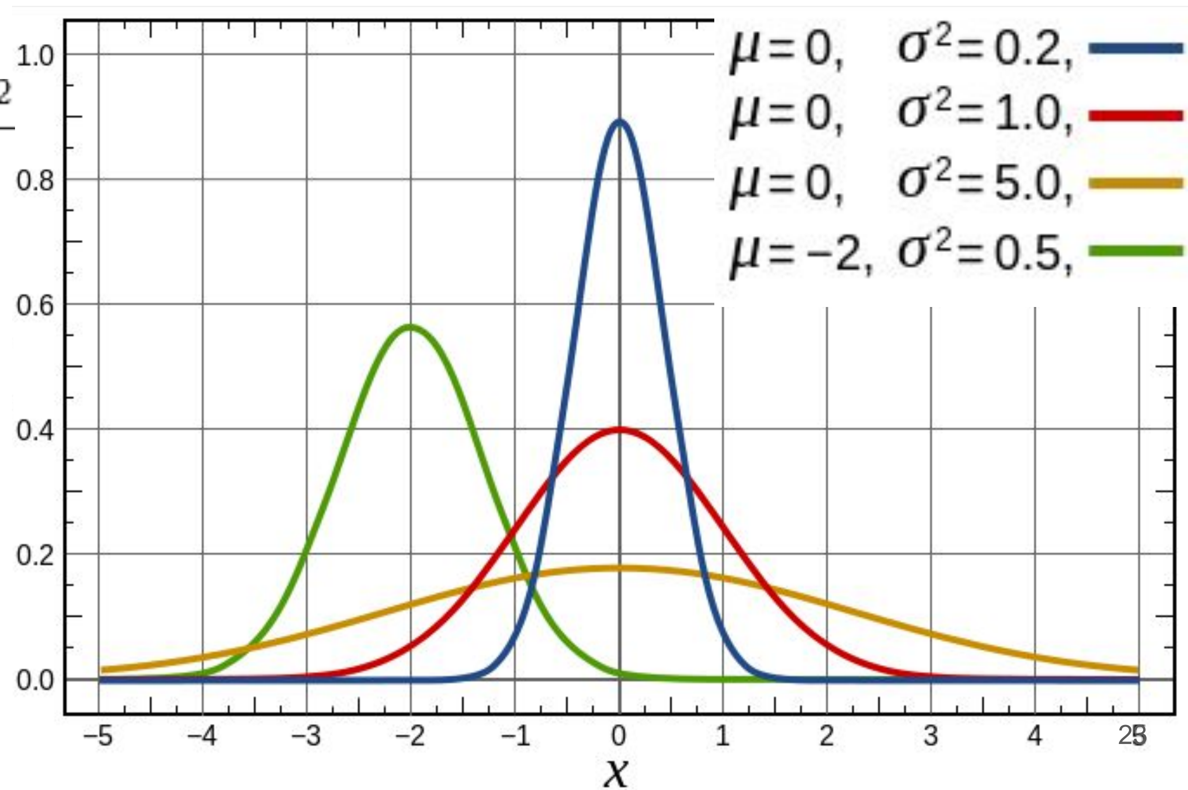

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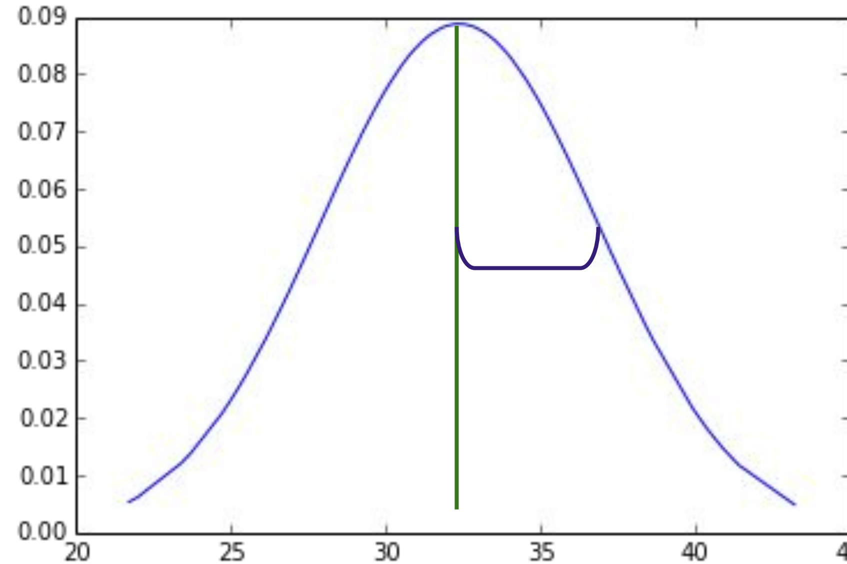
Continuous Random Variables

Common *pdf*s: Normal(μ, σ^2)

$X \sim \text{Normal}(\mu, \sigma^2)$, examples in real life:

- height
- intelligence/ability
- measurement error
- averages (or sum) of lots of random variables



Continuous Random Variables

Common *pdf*s: Normal(0, 1) ("standard normal")

How to "standardize" any normal distribution:

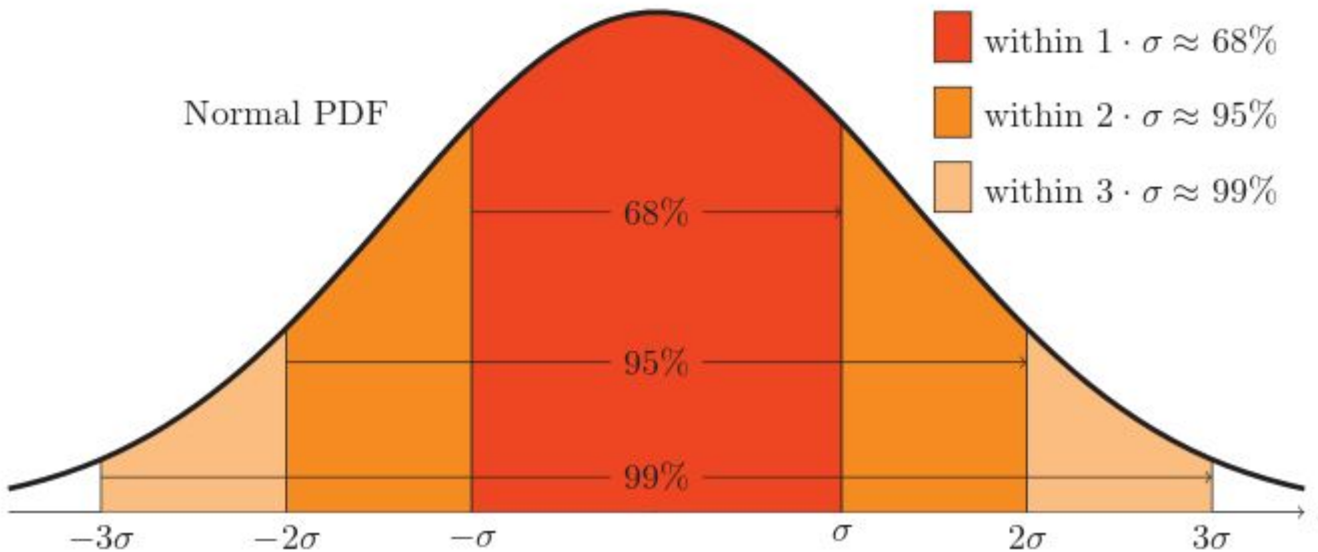
1. subtract the mean, μ (aka "mean centering")
2. divide by the standard deviation, σ

$z = (x - \mu) / \sigma$, (aka "z score")

Continuous Random Variables

Common *pdfs*: $\text{Normal}(0, 1)$

$$P(-1 \leq Z \leq 1) \approx .68, \quad P(-2 \leq Z \leq 2) \approx .95, \quad P(-3 \leq Z \leq 3) \approx .99$$



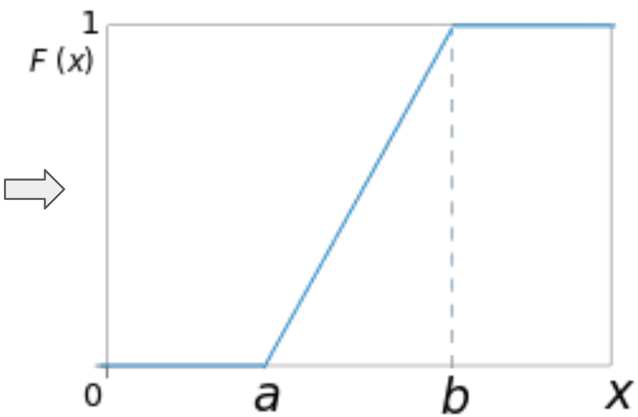
Credit: MIT Open Courseware: Probability and Statistics

Cumulative Distribution Function

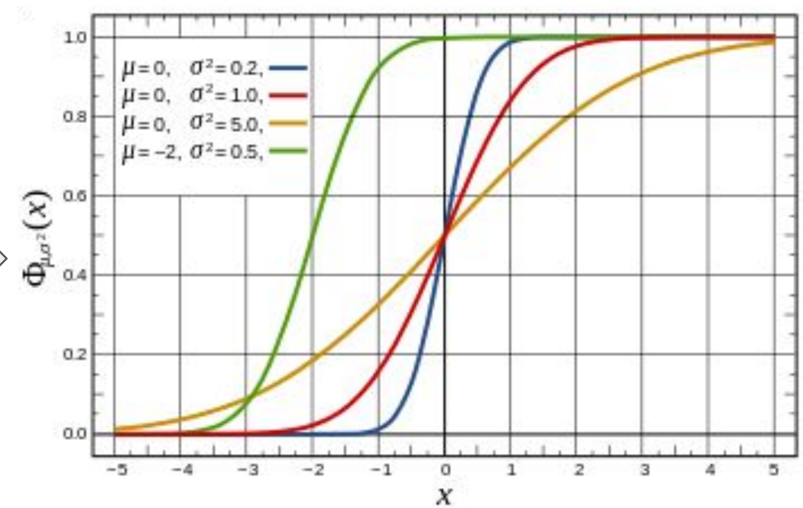
For a given random variable X, the *cumulative distribution function* (CDF), *Fx:* $\mathbb{R} \rightarrow [0, 1]$, is defined by:

$$F_X(x) = \mathrm{P}(X \leq x)$$

Uniform ⇨



Normal ⇨



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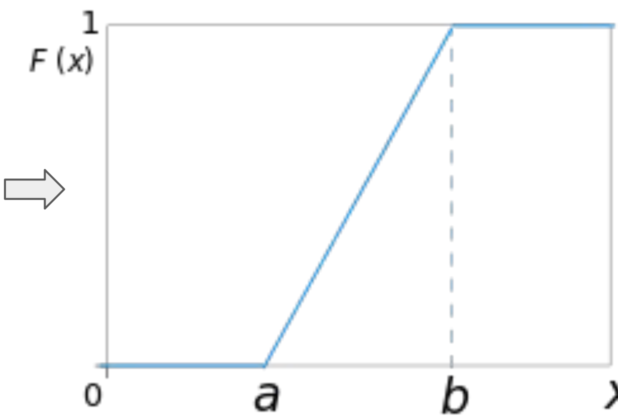

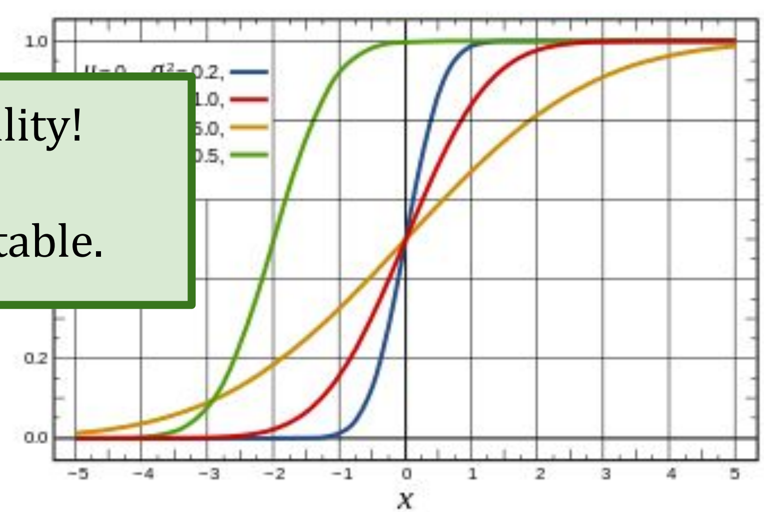

Pro: $F_X(x)$ yields a probability!

Con: Not intuitively interpretable.

Random Variables, Revisited

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Discrete Random Variables

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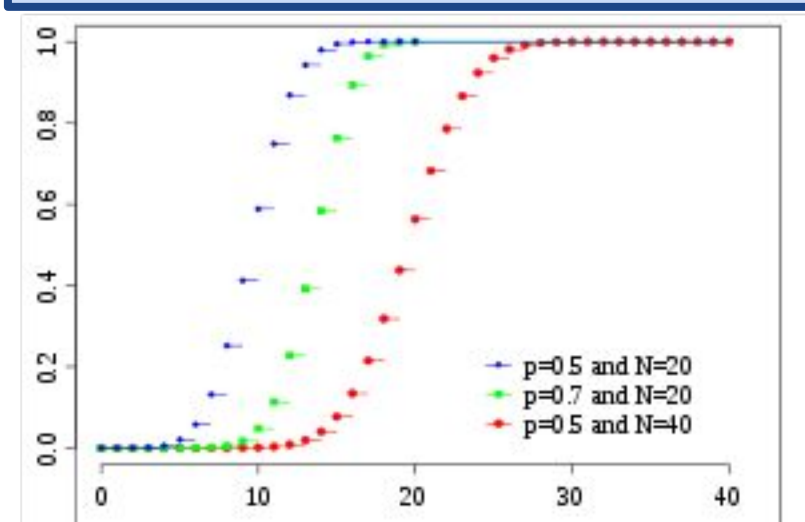

Binomial (n, p)

(like normal)

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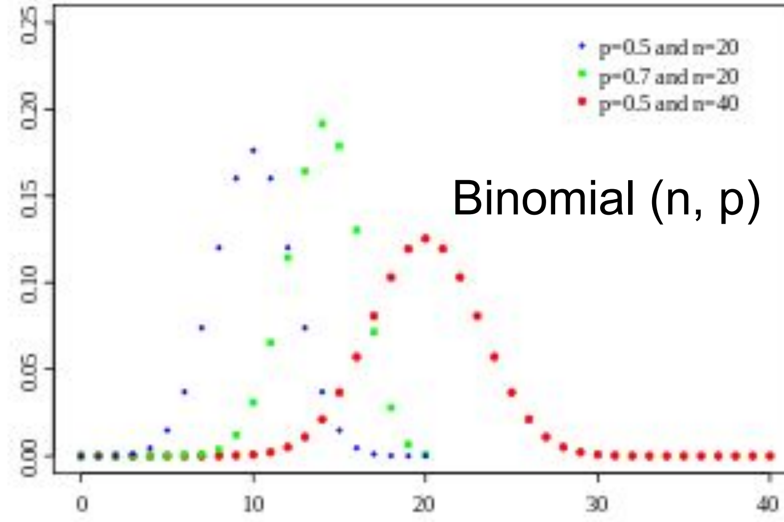
Discrete Random Variables



Binomial (n, p)

For a given random variable X, the *cumulative distribution function* (CDF), *Fx:* $\mathbb{R} \to [0, 1]$, is defined by:

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For a given *discrete* random variable X, *probability mass function* (*pmf*), *fx:* $\mathbb{R} \to [0, 1]$, is defined by:

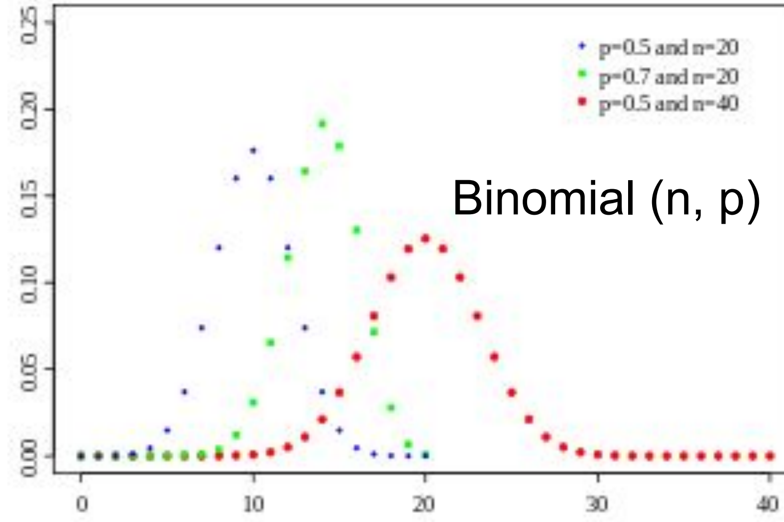
$$f_X(x) = \mathrm{P}(X = x)$$

X is a *discrete random variable* if it takes only a countable number of values.

$$\sum_i f_X(x) = 1$$

$$F_X(f) = \mathrm{P}(X \leq x) = \sum_{x_i \leq x} f_X(x)$$

Discrete Random Variables



Binomial (n, p)

Two Common **Discrete** Random Variables

- Binomial(n, p)

$$f_X(x) = \binom{n}{x} p^x (1-p)^{n-x}, \text{ if } 0 \leq x \leq n \text{ (0 otherwise)}$$

  example: number of heads after n coin flips (p, probability of heads)

- Bernoulli(p) = Binomial(1, p)

  example: one trial of success or failure

Hypothesis Testing

Hypothesis -- something one asserts to be true.

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Classical Approach:

H_0: *null hypothesis* -- some “default” value; “null”: nothing changes

H_1: the alternative -- the opposite of the null => a change or difference

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H_1: the alternative -- the opposite of the null => a change or difference

Goal: Use probability to determine if we can:

"reject the null" (H_0) in favor of H_1.

"There is less than a 5% chance that the null is true"
(i.e. 95% chance that alternative is true).

Hypothesis Testing

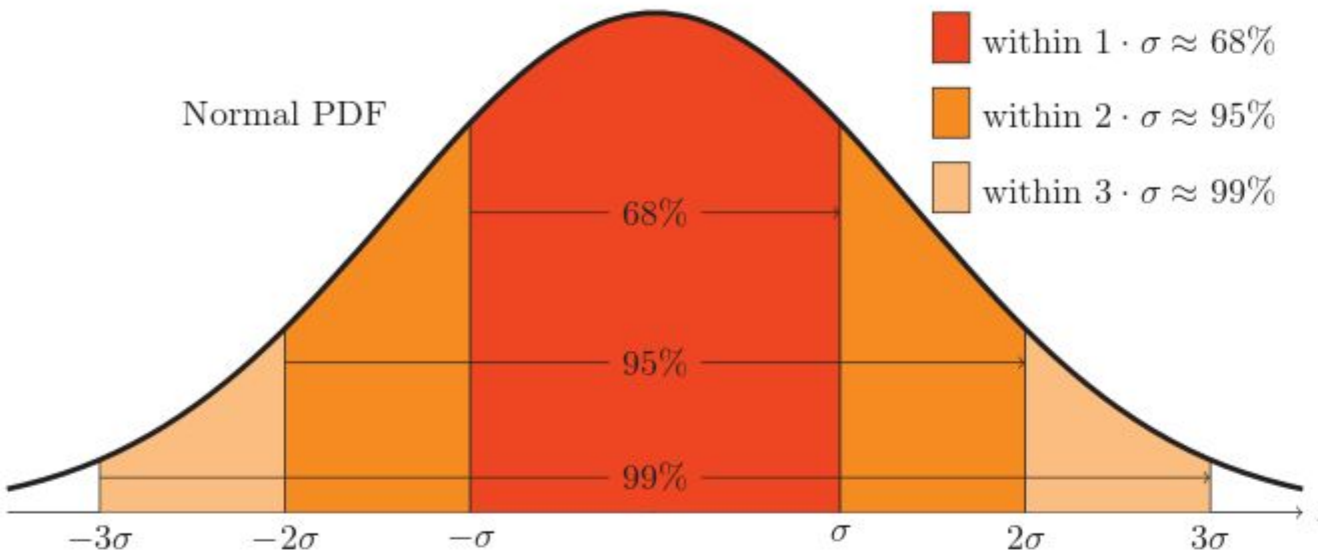
Example: Hypothesize a coin is biased.

H_0: the coin is not biased
(i.e. flipping n times results in a Binomial(n, 0.5))

H_1: the coin is biased (i.e. flipping n times does not result in a Binomial(n, 0.5))

Hypothesis Testing

More formally: Let X be a random variable and let R be the range of X. $R_{reject} \subset R$ is the *rejection region.* If $X \in R_{reject}$ then we reject the null.



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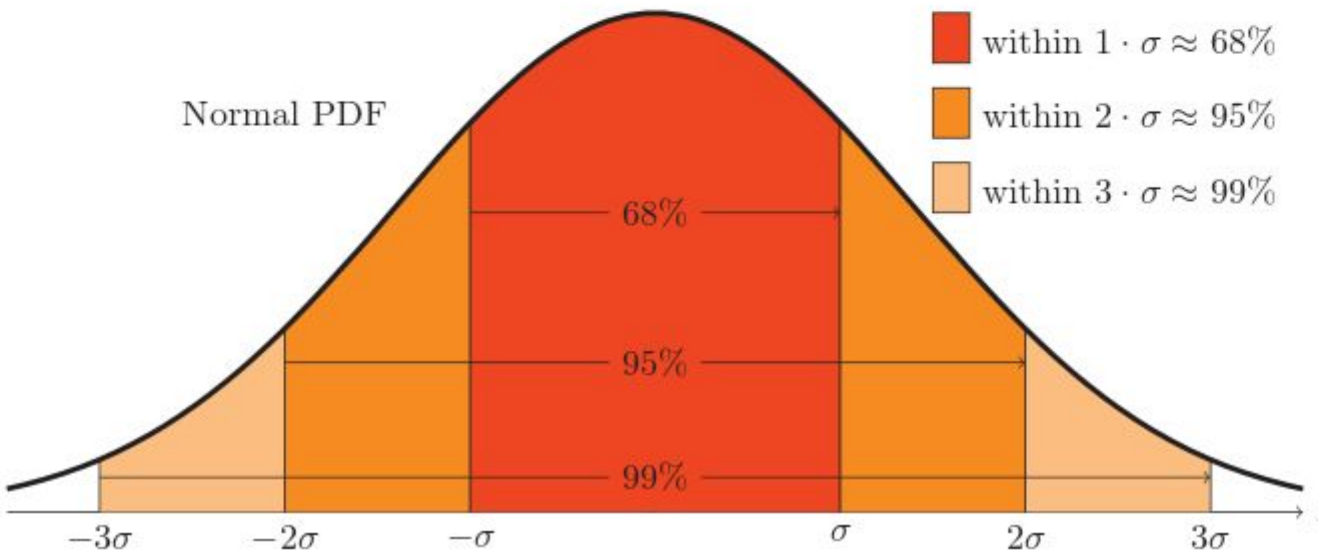
alpha : size of rejection region (e.g. 0.05, 0.01, .001)



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In the biased coin example,

if n = 1000, then then $R_{reject} = [0, 469] \cup [531, 1000]$

Hypothesis Testing

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A general framework for answering (yes/no) questions!

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- *Is my deep predictive model better than the state of the art?*

Hypothesis Testing

Why?

A general framework for answering (yes/no) questions!

- *Are height and baldness related?*
- *Is my deep predictive model better than the state of the art?*
- *Is the heat index of a community related to poverty?*
- *Is the heat index of a community related to poverty* ***controlling for education rates?***
- *Does my website receive a higher average number of monthly visitors?*

Hypothesis Testing

Failing to "reject the null" does not mean the null is true.

Why?

A general framework for answering (yes/**maybe**) questions!

- *Are height and baldness related?*
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Hypothesis Testing

Failing to "reject the null" does not mean the null is true.
However, if the sample is large enough, it may be enough to say that the effect size (correlation, difference value, etc…) is not very meaningful.

Why?

A general framework for answering (yes/**maybe**) questions!

- *Are height and baldness related?*
- *Is my deep predictive model better than the state of the art?*
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Hypothesis Testing

Important logical question:

Does failure to reject the null mean the null is true?

Hypothesis Testing

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Does failure to reject the null mean the null is true?

Thought experiment: If we have infinite data, can the null ever be true?

Statistical Considerations in Big Data

1. Average multiple models (ensemble techniques)
2. Correct for multiple tests (Bonferonni's Principle)
3. Smooth data
4. "Plot" data (or figure out a way to look at a lot of it "raw")
5. Interact with data
6. Know your "real" sample size
7. Correlation is not causation
8. Define metrics for success (set a baseline)
9. Share code and data
10. The problem should drive solution

(http://simplystatistics.org/2014/05/22/10-things-statistics-taught-us-about-big-data-analysis/)

Measures for Comparing Random Variables

- Distance metrics
- **Linear Regression**
- Pearson Product-Moment Correlation
- Multiple Linear Regression
- (Multiple) Logistic Regression
- Ridge Regression (L2 Penalized)
- Lasso Regression (L1 Penalized)

Linear Regression

Finding a linear function based on *X* to best yield *Y*.

X = "covariate" = "feature" = "predictor" = "regressor" = "independent variable"

Y = "response variable" = "outcome" = "dependent variable"

Regression: $$r(x) = \mathrm{E}(Y|X = x)$$

goal: estimate function r

The **expected** value of *Y*, given that the random variable *X* is equal to some specific value, *x*.

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Linear Regression (univariate version): $r(x) = \beta_0 + \beta_1 x$

goal: find β_0, β_1 such that $r(x) \approx \mathrm{E}(Y|X = x)$

Linear Regression

Simple Linear Regression $$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

$$\text{where } \mathbf{E}(\epsilon_i | X_i) = 0 \; and \; \mathbf{V}(\epsilon_i | X_i) = \sigma^2$$

more precisely

$$r(x) = \beta_0 + \beta_1 x$$

Linear Regression

intercept slope error

Simple Linear Regression

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expected variance

Linear Regression

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expected variance

Estimated intercept and slope

$$\hat{r}(x) = \hat{\beta}_0 + \hat{\beta}_1 x \qquad \hat{Y}_i = \hat{r}(X_i)$$

Residual: $\hat{\epsilon}_i = Y_i - \hat{Y}_i$

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Residual: $\hat{\epsilon}_i = Y_i - \hat{Y}_i$

Least Squares Estimate. Find $\hat{\beta}_0$ and $\hat{\beta}_1$ which minimizes the *residual sum of squares:*

$$RSS = \sum_{i=1}^{n} \hat{\epsilon}_i^2 = \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{n} (Y_i - \beta_0 - \beta_1 X_i)^2$$

Linear Regression

via Gradient Descent

Start with $\hat{\beta}_0$ = $\hat{\beta}_1$ = 0

Repeat until convergence:

Calculate all $\hat{Y}_i$

$$\hat{\beta}_0 = \hat{\beta}_0 - \alpha(\sum_{i=1}^{n} \hat{Y}_i - Y_i)$$

$$\hat{\beta}_1 = \hat{\beta}_1 - \alpha(\sum_{i=1}^{n} X_i(\hat{Y}_i - Y_i))$$

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Learning rate

Based on derivative of *RSS*

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Start with $\hat{\beta}_0 = \hat{\beta}_1 = 0$

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Calculate all $\hat{Y}_i$

$$\hat{\beta}_0 = \hat{\beta}_0 - \alpha(\sum_{i=1}^{n} \hat{Y}_i - Y_i)$$

$$\hat{\beta}_1 = \hat{\beta}_1 - \alpha(\sum_{i=1}^{n} X_i(\hat{Y}_i - Y_i))$$

via Direct Estimates (normal equations)

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

$$\hat{\beta}_0 = \bar{Y} - \hat{\beta}_1 \bar{X}$$

Least Squares Estimate. Find $\hat{\beta}_0$ and $\hat{\beta}_1$ which minimizes the *residual sum of squares:*

$$RSS = \sum_{i=1}^{n} \hat{\epsilon}_i^2 = \sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 = \sum_{i=1}^{n}(Y_i - \beta_0 - \beta_1 X_i)^2$$

Pearson Product-Moment Correlation

Covariance

$$Cov(X,Y) = \mathbf{E}(XY) - \mathbf{E}(X)\mathbf{E}(Y)$$
$$= \mathbf{E}\left((X - \bar{X})(Y - \bar{Y})\right)$$

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Correlation

$$r = r_{X,Y} = \frac{Cov(X,Y)}{s_X s_Y}$$

$$= \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i-\bar{X}}{s_X}\right)\left(\frac{Y_i-\bar{Y}}{s_Y}\right)$$

via Direct Estimates (normal equations)

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sum_{i=1}^{n}(X_i-\bar{X})^2}$$

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$$\hat{\beta}_0 = \bar{Y} - \hat{\beta}_1\bar{X}$$

If one standardizes *X* and *Y* (i.e. subtract the mean and divide by the standard deviation) before running linear regression, then:

$\hat{\beta}_0 = 0$ and $\hat{\beta}_1 = r$ --- *i.e.* $\hat{\beta}_1$ *is the Pearson correlation!*

Measures for Comparing Random Variables

- Distance metrics
- Linear Regression
- Pearson Product-Moment Correlation
- Multiple Linear Regression
- (Multiple) Logistic Regression
- Ridge Regression (L2 Penalized)
- Lasso Regression (L1 Penalized)

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Multiple Linear Regression

Suppose we have multiple X that we'd like to fit to Y at once:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_m X_{m1} + \epsilon_i$$

If we include and $X_{oi} = 1$ for all i (i.e. adding the intercept to X), then we can say:

$$Y_i = \sum_{j=0}^{m} \beta_j X_{ij} + \epsilon_i$$

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Or in vector notation across all i:

$$Y = X\beta + \epsilon$$

where β and ϵ are vectors and X is a matrix.

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Estimating β :

$$\hat{\beta} = (X^T X)^{-1} X^T Y$$

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Suppose we have multiple independent variables that we'd like to fit to our dependent variable: $Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_m X_{m1} + \epsilon_i$

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To test for significance of individual coefficient, *j*:

$$t = \frac{\hat{\beta}_j}{SE(\hat{\beta}_j)} = \frac{\hat{\beta}_j}{\sqrt{\frac{s^2}{\sum_{i=1}^{n}(X_{ij} - \bar{X}_j)^2}}}$$

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Multiple Linear Regression

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_m X_{m1} + \epsilon_i$$

$$s^2 = \frac{RSS}{df}$$

To test for significance of individual coefficient, j:

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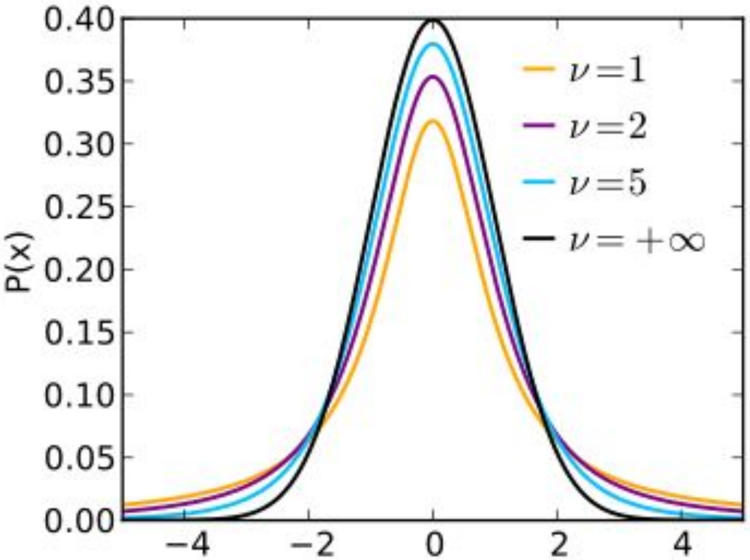
T-Test for significance of hypothesis:

1) Calculate t
2) Calculate degrees of freedom:

$$df = N - (m+1)$$

3) Check probability in a *t* distribution:



t

$\beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_m X_{m1} + \epsilon_i$

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T-Test for significance of hypothesis:

1) Calculate t
2) Calculate degrees of freedom:

$$df = N - (m+1)$$

3) Check probability in a t distribution: ($df = v$)

Hypothesis Testing

Important logical question:

Does failure to reject the null mean the null is true?

Thought experiment: If we have infinite data, can the null ever be true?

Type I, Type II Errors

		True state of nature	
		H_0	H_A
Our	Reject H_0	Type I error	correct decision
decision	'Accept' H_0	correct decision	Type II error

(Orloff & Bloom, 2014)

Power

significance level ("p-value") = P(type I error) = **P(Reject H_0 | H_0)**
(probability we are incorrect)

power = 1 - P(type II error) = **P(Reject H_0 | H_1)**
(probability we are correct)

	H_0	H_A
Reject H_0	**P(Reject H_0 | H_0)**	**P(Reject H_0 | H_1)**

		True state of nature	
		H_0	H_A
Our decision	Reject H_0	Type I error	correct decision
	'Accept' H_0	correct decision	Type II error

(Orloff & Bloom, 2014)

Multi-test Correction

If alpha = .05, and I run 40 variables through significance tests, then, by chance, how many are likely to be significant?

Multi-test Correction

How to fix?

Multi-test Correction

How to fix?

What if all tests are independent?
=> "Bonferroni Correction" (α/m)

Better Alternative: False Discovery Rate
(Bejamini Hochberg)

Logistic Regression

What if $Y_i \in \{0, 1\}$? (i.e. we want "classification")

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$$p_i \equiv p_i(\beta) \equiv \mathbf{P}(Y_i = 1 | X = x) = \frac{e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}{1 + e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}$$

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Note: this is a probability here.

In simple linear regression we wanted an expectation:

$$r(x) = \mathrm{E}(Y | X = x)$$

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Note: this is a probability here.

In simple linear regression we wanted an expectation:

$$r(x) = \mathrm{E}(Y | X = x)$$

(i.e. if $p > 0.5$ we can confidently predict $Y_i = 1$)

Logistic Regression

What if $Y_i \in \{0, 1\}$? (i.e. we want "classification")

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$$logit(p_i) = log\left(\frac{p_i}{1 - p_i}\right) = \beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}$$

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$$logit(p_i) = log\left(\frac{p_i}{1 - p_i}\right) = \beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}$$

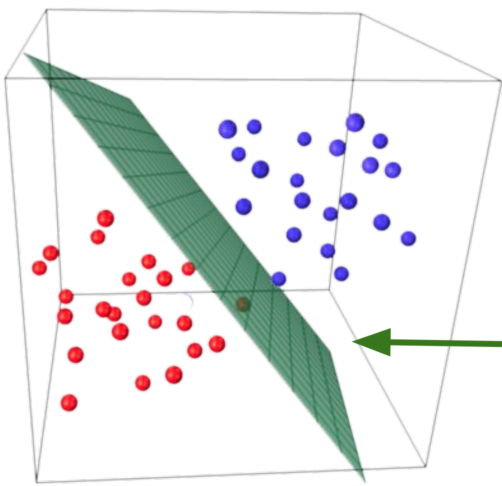
$P(Y_i = 0 \mid X = x)$

Thus, 0 is class 0 and 1 is class 1.

Logistic Regression

What if $Y_i \in \{0, 1\}$? (i.e. we want "classification")

$$p_i \equiv p_i(\beta) \equiv \mathbf{P}(Y_i = 1 | X = x) = \frac{e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}{1 + e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}$$



$$logit(p_i) = log\left(\frac{p_i}{1 - p_i}\right) = \beta_0 + \sum_{j=1}^{m} \boxed{\beta_j x_{ij}}$$

We're still learning a linear *separating hyperplane*, but fitting it to a *logit* outcome.

(https://www.linkedin.com/pulse/predicting-outcomes-probabilities-logistic-regression-konstantinidis/)

Logistic Regression

What if $Y_i \in \{0, 1\}$? (i.e. we want "classification")

$$p_i \equiv p_i(\beta) \equiv \mathbf{P}(Y_i = 1 | X = x) = \frac{e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}{1 + e^{\beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}}}$$

$$logit(p_i) = log\left(\frac{p_i}{1 - p_i}\right) = \beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}$$

To estimate β, one can use *reweighted least squares:*

set $\hat{\beta}_0 = ... = \hat{\beta}_m = 0$ (remember to include an intercept)

1. Calculate p_i and let W be a diagonal matrix where element$(i, i) = p_i(1 - p_i)$.
2. Set $z_i = logit(p_i) + \frac{Y_i - p_i}{p_i(1 - p_i)} = X\hat{\beta} + \frac{Y_i - p_i}{p_i(1 - p_i)}$
3. Set $\hat{\beta} = (X^T W X)^{-1} X^T W z$ //weighted lin. reg. of Z on Y.
4. Repeat from 1 until $\hat{\beta}$ converges.

(Wasserman, 2005; Li, 2010)

Uses of linear and logistic regression

1. Testing the relationship between variables given other variables. β is an "effect size" -- a score for the magnitude of the relationship; can be tested for significance.

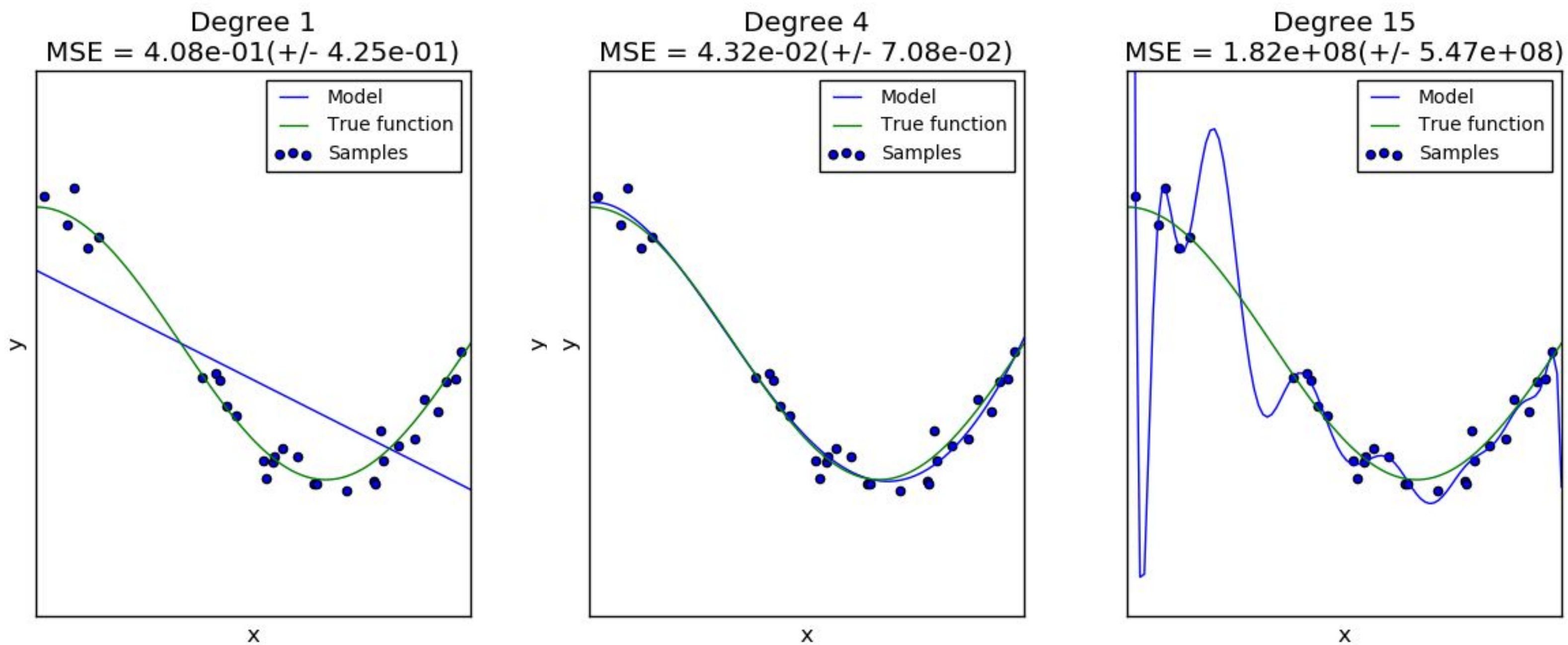
2. Building a predictive model that generalizes to new data. $\hat{Y}$ is an estimate value of Y given X.

Uses of linear and logistic regression

1. Testing the relationship between variables given other variables. β is an "effect size" -- a score for the magnitude of the relationship; can be tested for significance.

2. Building a predictive model that generalizes to new data. $\hat{Y}$ is an estimate value of Y given X. However, unless $|X| <<< observatations$ then the model might "overfit".

Overfitting (1-d non-linear example)



Underfit
High Bias

Overfit
High Variance

(image credit: Scikit-learn; in practice data are rarely this clear)

Overfitting (5-d linear example)

$Y \quad = \qquad\qquad X$

Y
1
1
0
0
1

0.5	0	0.6	1	0	0.25
0	0.5	0.3	0	0	0
0	0	1	1	1	0.5
0	0	0	0	1	1
0.25	1	1.25	1	0.1	2

Overfitting (5-d linear example)

Y = X

Y
1
1
0
0
1

0.5	0	0.6	1	0	0.25
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0	0	1	1	1	0.5
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0.25	1	1.25	1	0.1	2

$$logit(Y) = 1.2 + -63*X_1 + 179*X_2 + 71*X_3 + 18*X_4 + -59*X_5 + 19*X_6$$

Overfitting (5-d linear example)

Do we really think we found something generalizable?

$Y = X$

1
1
0
0
1

0.5	0	0.6	1	0	0.25
0	0.5	0.3	0	0	0
0	0	1	1	1	0.5
0	0	0	0	1	1
0.25	1	1.25	1	0.1	2

$$logit(Y) = 1.2 + -63*X_1 + 179*X_2 + 71*X_3 + 18*X_4 + -59*X_5 + 19*X_6$$

Overfitting (2-d linear example)

Do we really think we found something generalizable?

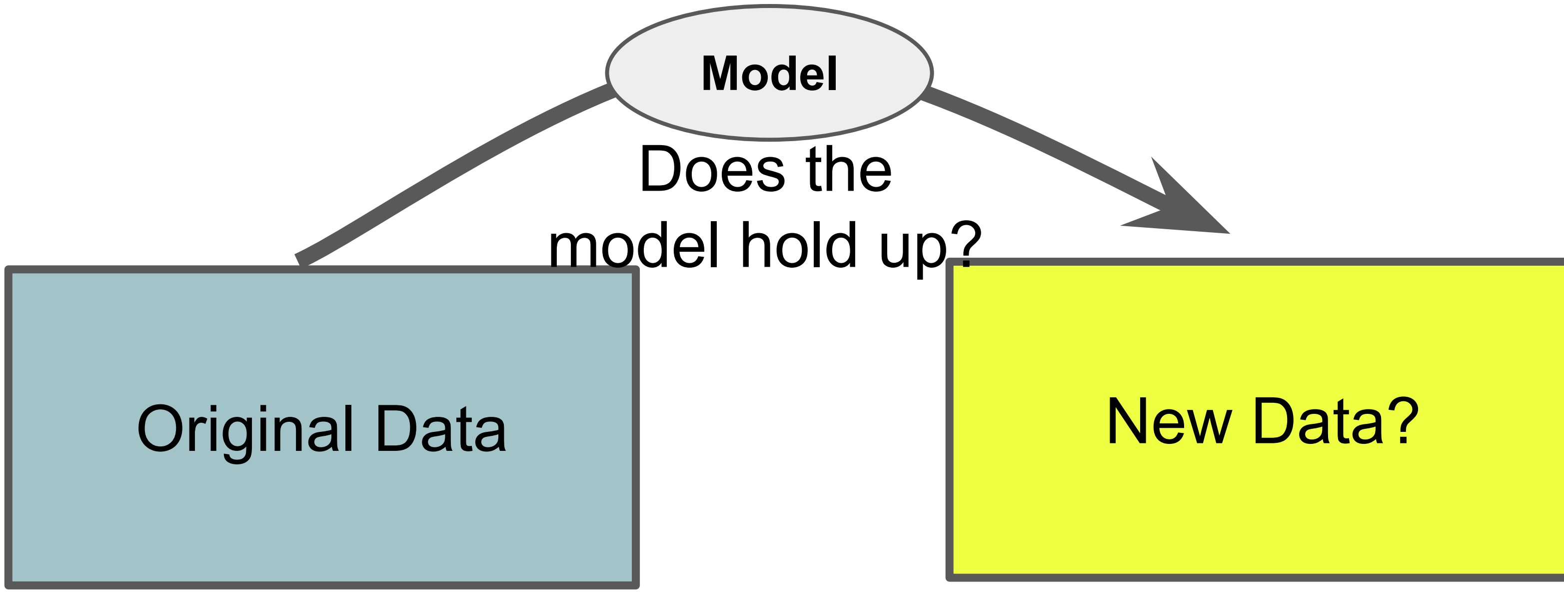
$Y \quad = \qquad\qquad X$

1		0.5	0
1		0	0.5
0		0	0
0		0	0
1		0.25	1

What if only 2 predictors?

$$logit(Y) = 0 + 2*X_1 + 2*X_2$$

Common Goal: Generalize to new data



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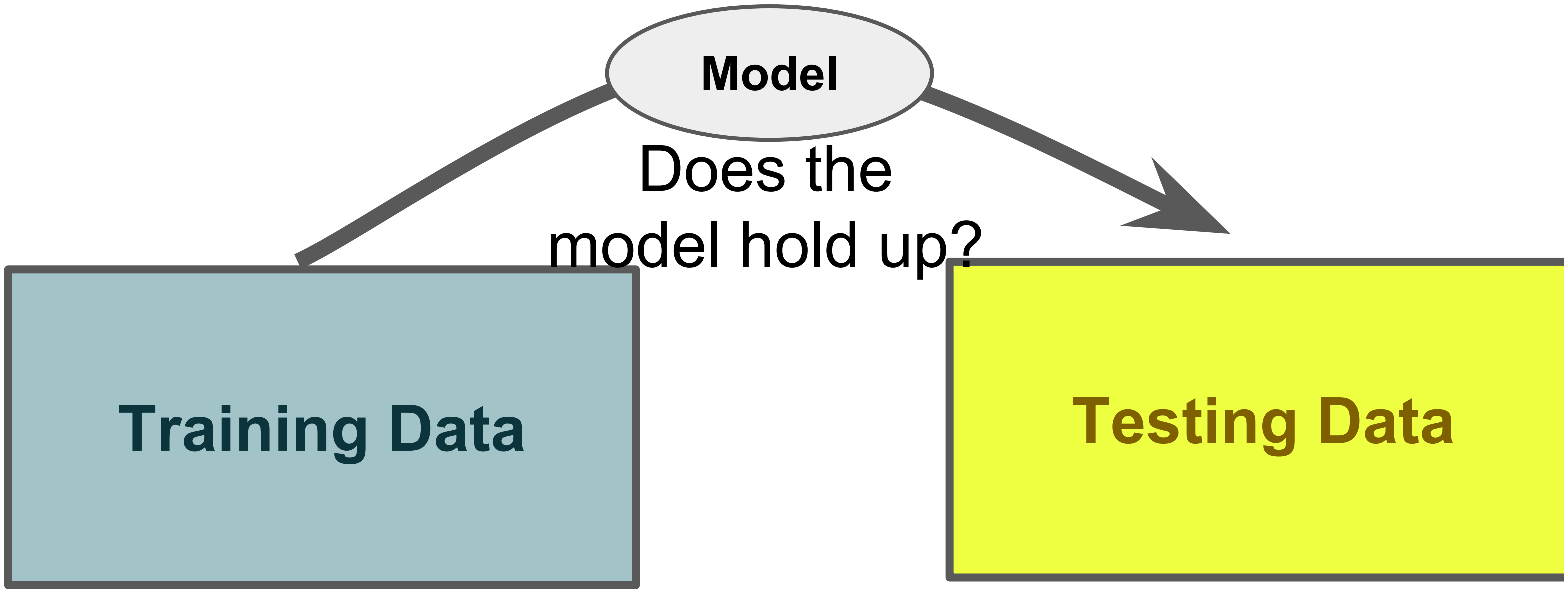

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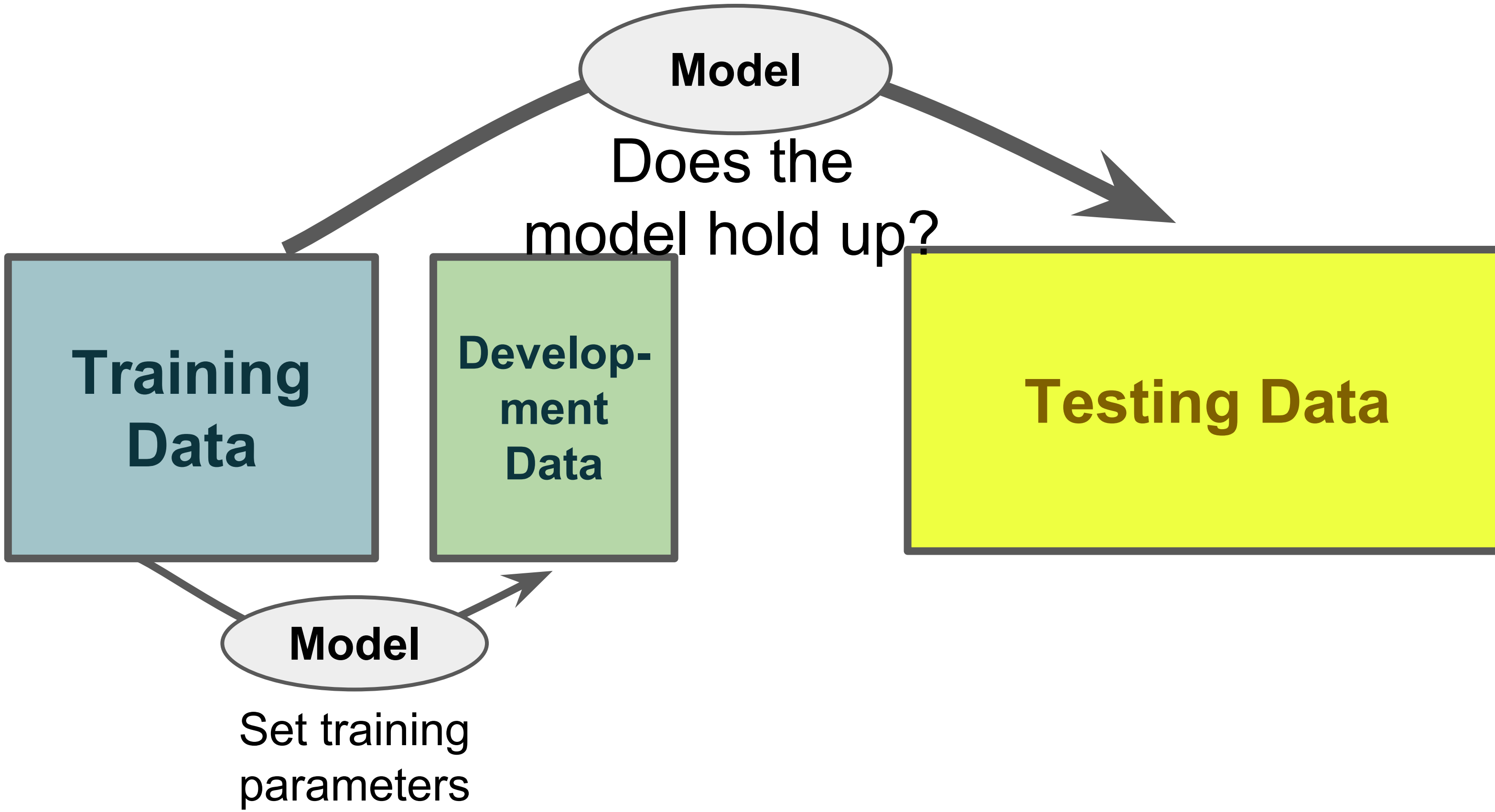


Feature Selection / Subset Selection

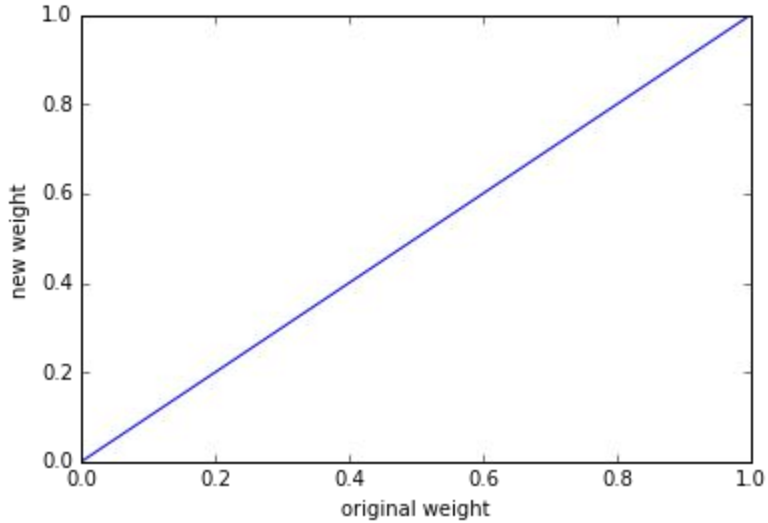
(bad) solution to overfit problem

Use less features based on Forward Stepwise Selection:

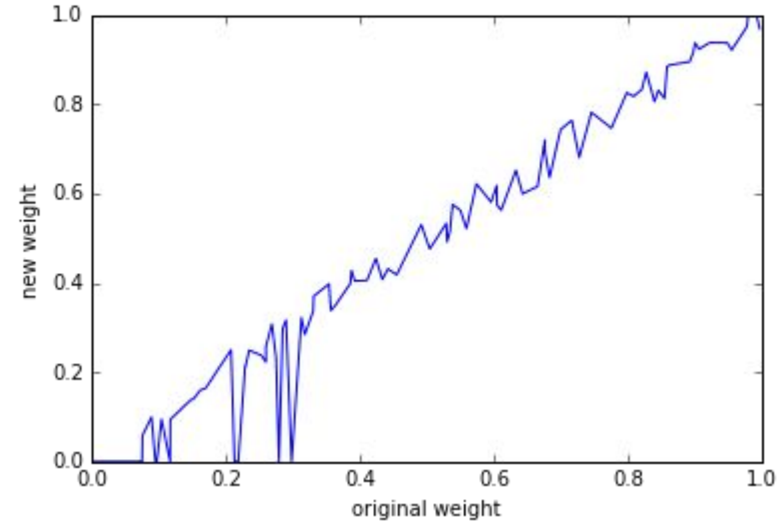
- start with current_model just has the intercept (mean)
  remaining_predictors = all_predictors

```
for i in range(k):
   #find best p to add to current_model:
   for p in remaining_prepdictors
      refit current_model with p
       #add best p, based on RSS_p to current_model
   #remove p from remaining predictors
```

Regularization (Shrinkage)



No selection (weight=beta)



forward stepwise

Why just keep or discard features?

Regularization (L2, Ridge Regression)

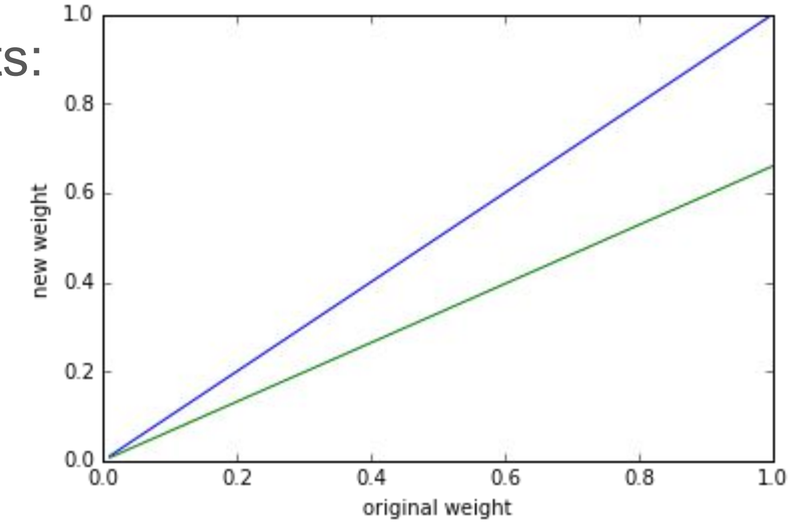
Idea: Impose a penalty on size of weights:

Ordinary least squares objective:

$$\hat{\beta} = argmin_{\beta}\{\sum_{i=1}^{N}(y_i - \sum_{j=1}^{m} x_{ij}\beta_j)^2\}$$

Ridge regression:

$$\hat{\beta}^{ridge} = argmin_{\beta}\{\sum_{i=1}^{N}(y_i - \sum_{j=1}^{m} x_{ij}\beta_j)^2 + \lambda \sum_{j=1}^{m} \beta_j^2\}$$



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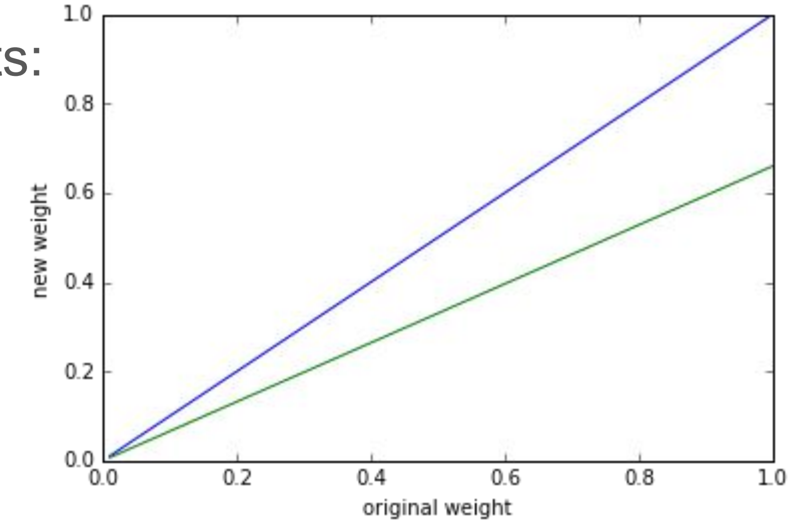

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$$\lambda||\beta||_2^2$$

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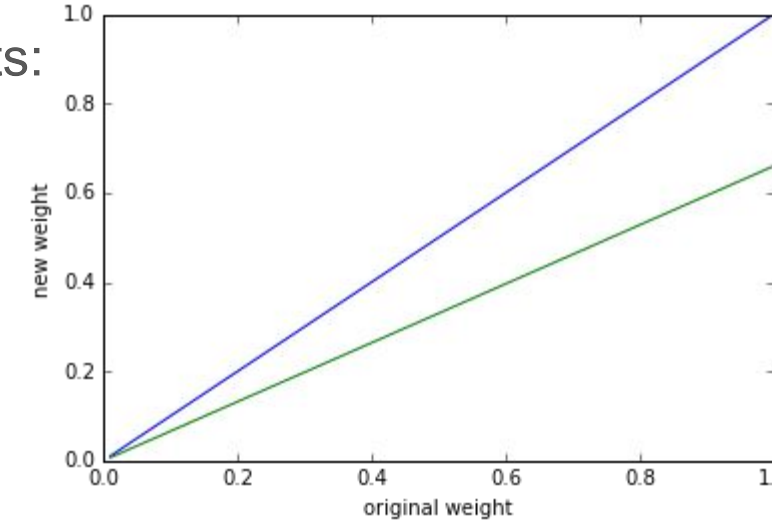

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$$\lambda||\beta||_2^2$$

In Matrix Form:

$$\text{RSS}(\lambda) = (y - X\beta)^T(y - X\beta) + \lambda\beta^T\beta$$

$$\hat{\beta}^{ridge} = (X^TX + \lambda I)^{-1}X^Ty$$

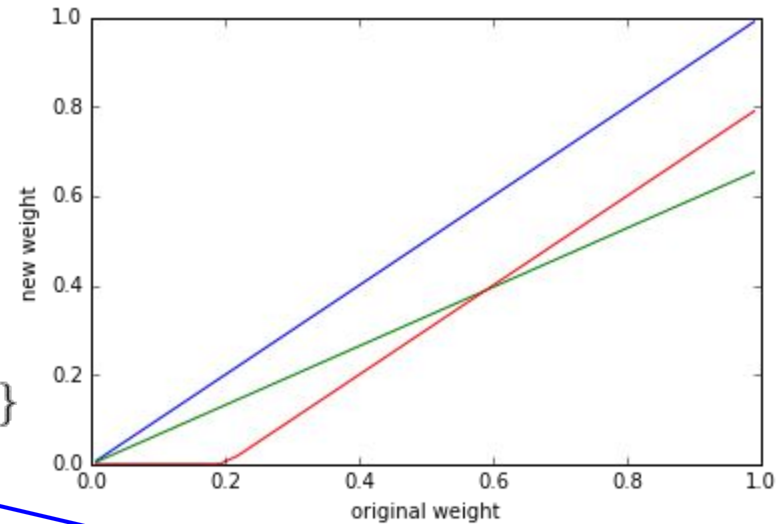
I: *m* x *m* identity matrix

Regularization (L1, The "Lasso")

Idea: Impose a penalty and zero-out some weights

The Lasso Objective:

$$\hat{\beta}^{lasso} = argmin_{\beta}\{\frac{1}{2}\sum_{i=1}^{N}(Y_i - \sum_{j=1}^{m} x_{ij}\beta_j)^2 + \lambda\sum_{j=1}^{m}|\beta_j|\}$$



$$\lambda||\beta||_1$$

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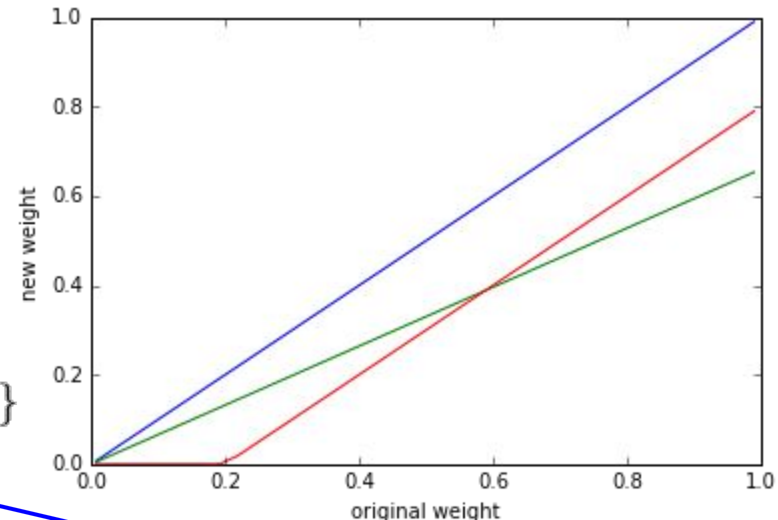
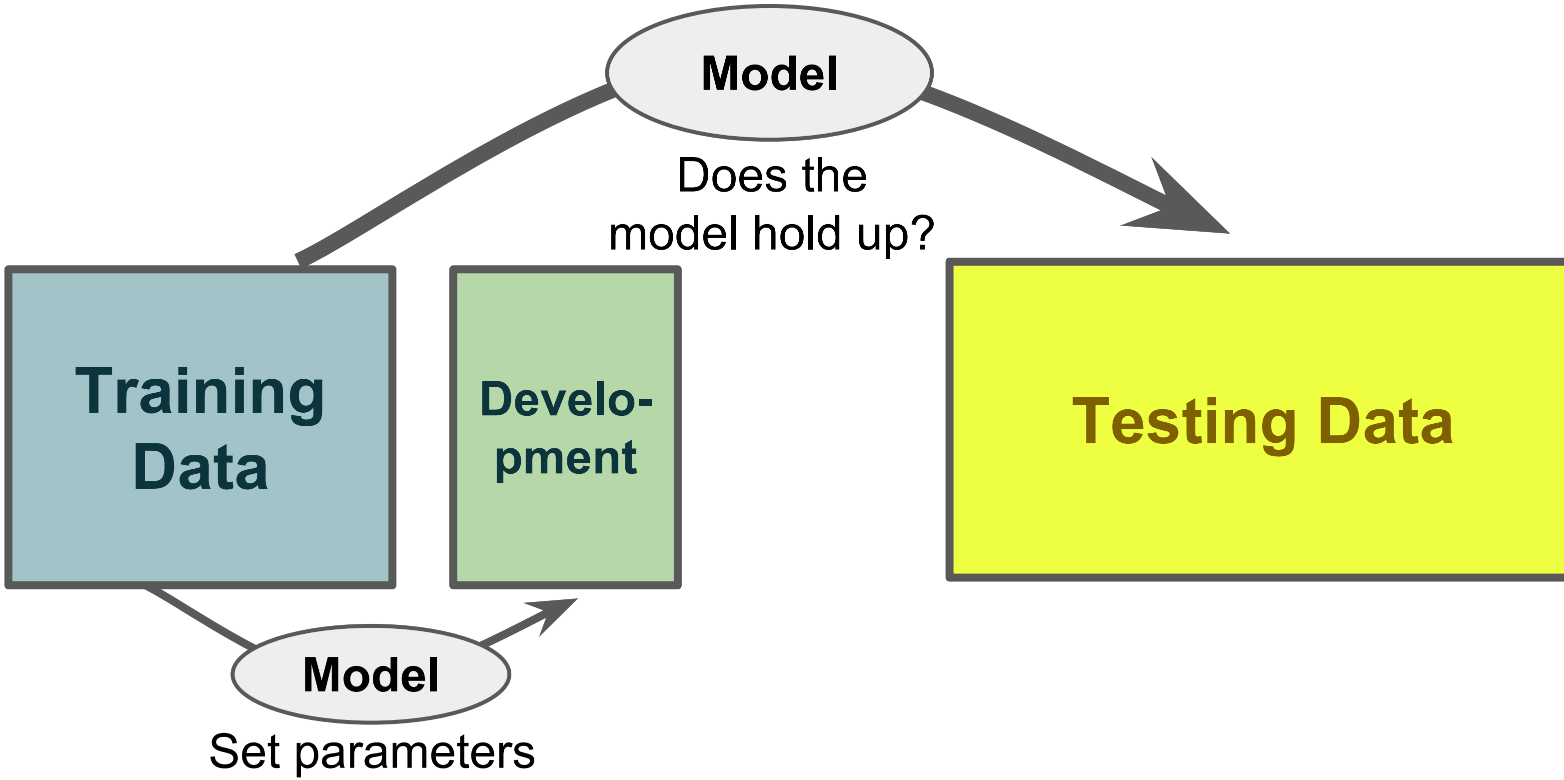


$$\lambda||\beta||_1$$

No closed form matrix solution, but often solved with coordinate descent.

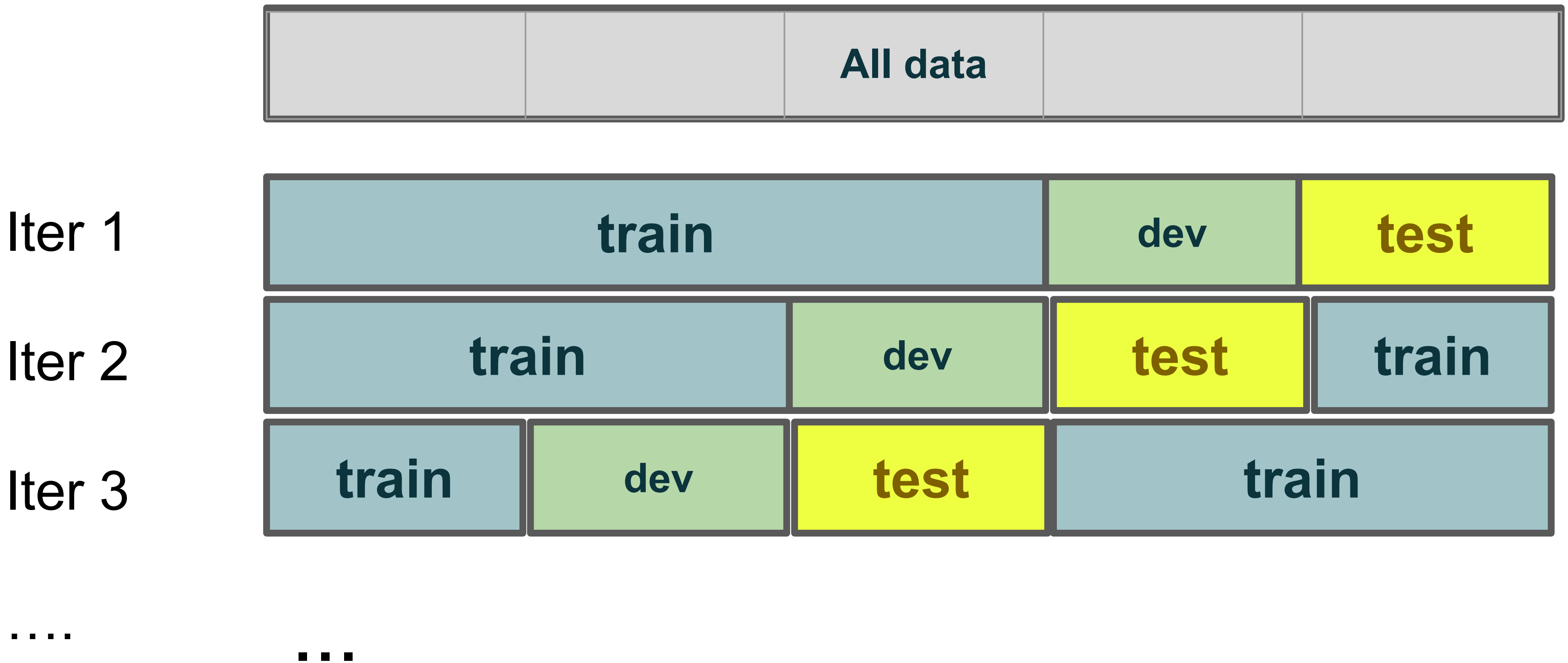
Application: p ≅ n or p >> n (p: features; n: observations)

Common Goal: Generalize to new data



N-Fold Cross-Validation

Goal: Decent estimate of model accuracy



Summary

Hypothesis Testing:

A framework for deciding which differences/relationships matter.

- Random Variables
- Distributions
- Hypothesis Testing Framework

Comparing Variables:

Metrics to quantify the difference or relationship between variables.

- Simple Linear Regression, Correlation, Multiple Linear Regression,
- Comparing Variables and Hypothesis Testing
- Regularized Linear Regression
- Multiple Hypothesis Testing