

# Introduction to Statistical Modeling: Linear Regression

Introduction to Data Analysis with Python - Spring Semester 2026

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April 23, 2026

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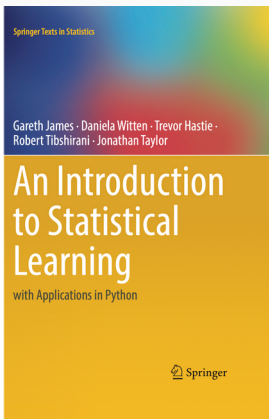
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## Other recommended resources

- [Think Python](#) by Allen Downey offers electronic resources [here](#) that will allow you to directly code there
- [Kaggle - Learn Python](#) is a more interactive guide
- [Invent your Own Computer Games with Python](#) by Al Sweigart

# Resources for this class



- This class follows **Chapter 3** of this book
- Refer to the book if you want to deepen today's topic
- It is a bit more mathematically intensive than this class!

An Introduction to Statistical Learning

# Homework Correction

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# Statistical Modeling Foundations

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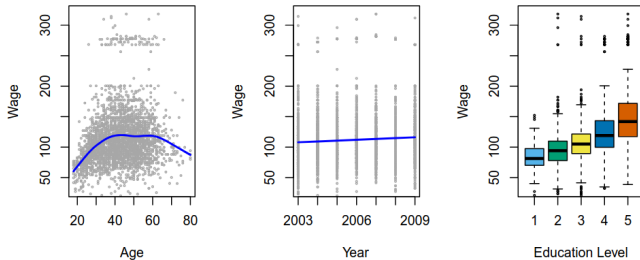
# What is a statistical model?

## Definition (Statistical Model)

A statistical model is a mathematical model that embodies a set of statistical assumptions concerning the generation of sample data (and similar data from a larger population).

Source: [Wikipedia](#)

# Example: Regression

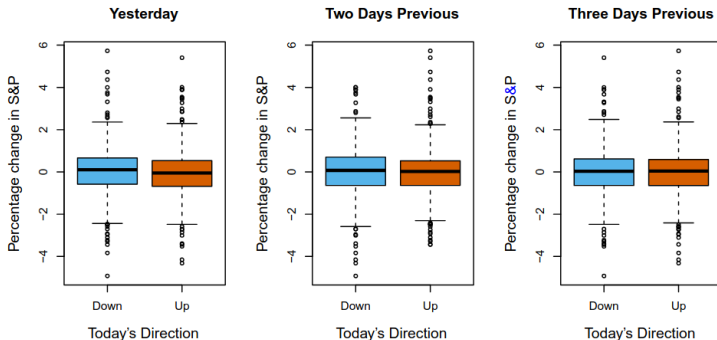


**FIGURE 1.1.** *Wage data, which contains income survey information for men from the central Atlantic region of the United States. Left: wage as a function of age. On average, wage increases with age until about 60 years of age, at which point it begins to decline. Center: wage as a function of year. There is a slow but steady increase of approximately \$10,000 in the average wage between 2003 and 2009. Right: Boxplots displaying wage as a function of education, with 1 indicating the lowest level (no high school diploma) and 5 the highest level (an advanced graduate degree). On average, wage increases with the level of education.*

Source: *An Introduction to Statistical Learning with Applications in Python.*

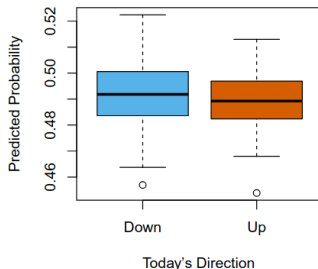


# Example: Classification



**FIGURE 1.2.** Left: *Boxplots of the previous day's percentage change in the S&P index for the days for which the market increased or decreased, obtained from the Smarket data.* Center and Right: *Same as left panel, but the percentage changes for 2 and 3 days previous are shown.*

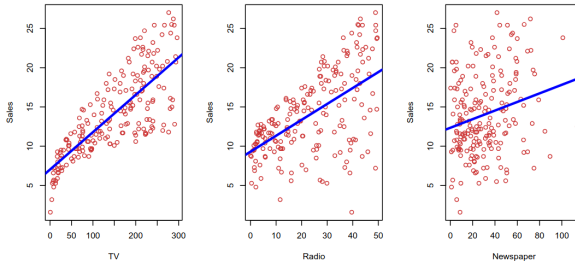
## Example: Classification



**FIGURE 1.3.** We fit a quadratic discriminant analysis model to the subset of the **Smarket** data corresponding to the 2001–2004 time period, and predicted the probability of a stock market decrease using the 2005 data. On average, the predicted probability of decrease is higher for the days in which the market does decrease. Based on these results, we are able to correctly predict the direction of movement in the market 60% of the time.

Source: *An Introduction to Statistical Learning with Applications in Python.*

# Regression: Example



**FIGURE 2.1.** The Advertising data set. The plot displays sales, in thousands of units, as a function of TV, radio, and newspaper budgets, in thousands of dollars, for 200 different markets. In each plot we show the simple least squares fit of sales to that variable, as described in Chapter 3. In other words, each blue line represents a simple model that can be used to predict sales using TV, radio, and newspaper, respectively.

Source: [An Introduction to Statistical Learning with Application in Python](#)

# Regression: Research Questions

1. Is there a relationship between advertising budget and sales?
2. How strong is the relationship between advertising budget and sales?
3. Which media are associated with sales?
4. How large is the association between each medium and sales?
5. How accurately can we predict future sales?
6. Is the relationship linear?
7. Is there synergy among the advertising media?

Source: [An Introduction to Statistical Learning with Application in Python](#)

# Predictors and dependent variables

- **Dependent variable:** the output you are trying to predict.
- **Predictor(s):** the variable(s) used to forecast the output.

# Statistical Modeling Foundations

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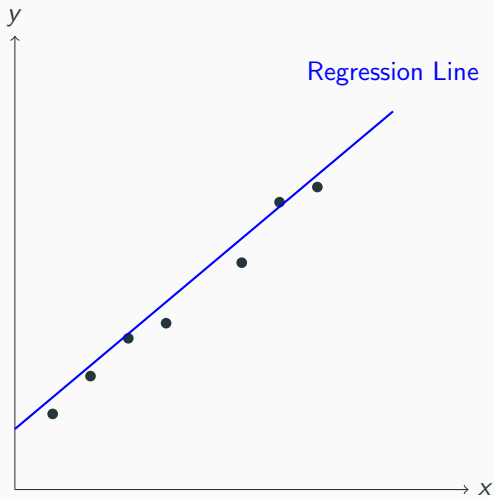
## Simple Linear Regression

# What is Simple Linear Regression?

- **Linear Regression** predicts a quantitative response assuming a **linear relationship** with the predictor(s).
- Single linear regression predicts the quantitative output  $Y$  on the basis of a **single** predictor variable  $X$ .
- Assumes linear relationship:

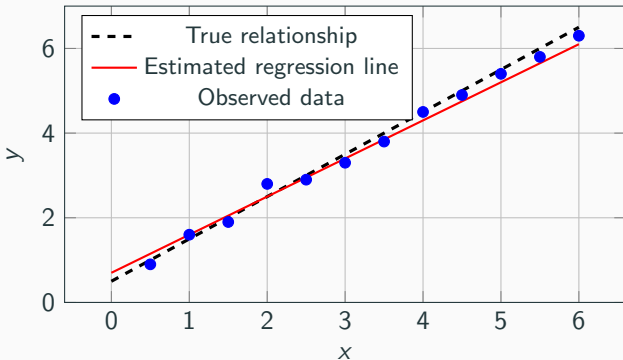
$$y = \beta_0 + \beta_1 x + \epsilon$$

- Parameters or coefficients:
  - $\beta_0$ : intercept (value of  $y$  when  $x = 0$ )
  - $\beta_1$ : slope (how much  $y$  changes for 1 unit increase in  $x$ )
- $\epsilon$ : error term





## True Line vs. Regression Line



**Figure 1:**

Comparison of the true relationship (black dashed line) and the estimated regression line (red). The regression line approximates the true line but is not perfectly identical due to random noise in the data. Readapted from

[An introduction to Statistical Learning with Python.](#)

# From Abstract X and Y to Real Data

Substitute the example values:

$$Y \longrightarrow \textit{sales}$$

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# From Abstract X and Y to Real Data

Substitute the example values:

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Apply the regression formula:

$$\textit{sales} = \beta_0 + \beta_1 \times \textit{TV}$$

## Problem

You cannot compute the above example without **knowing the values of the coefficients!**

# Estimating the coefficients

- Let's consider a sequence of data points

$$(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$$

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- The most common approach is minimizing the **least squares criterion**.

# Residual Sum of Squares (RSS) in Linear Regression

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- The **Residual Sum of Squares (RSS)** is:

$$RSS = e_1^2 + e_2^2 + e_3^2 + \dots + e_n^2$$

- Equivalent to:

$$RSS = (y_1 - \hat{\beta}_0 - \hat{\beta}_1 x_1)^2 + (y_2 - \hat{\beta}_0 - \hat{\beta}_1 x_2)^2 + \dots + (y_n - \hat{\beta}_0 - \hat{\beta}_1 x_n)^2$$

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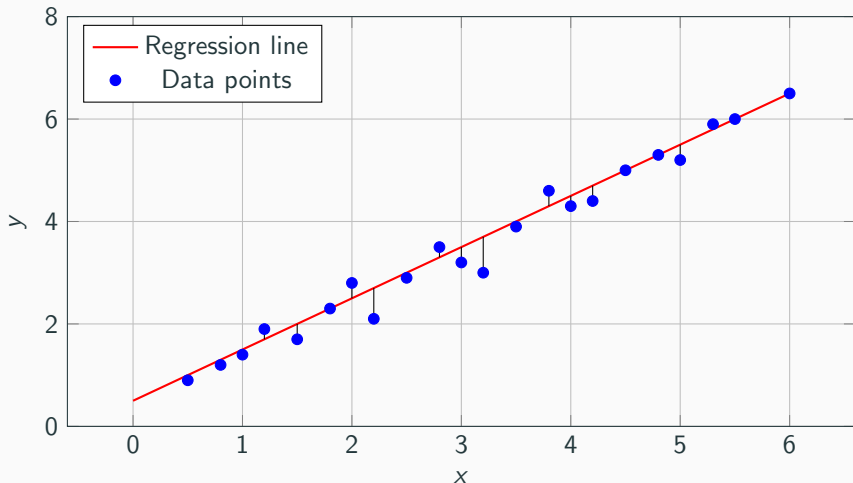
- Equivalent to:

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- To sum up:

$$\hat{\beta}_1 = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2}, \quad \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x}$$

## Residual Standard Error Visualization



**Figure 2:** Residual standard error: vertical distances from observed data points to the fitted regression line. Readapted from [Statistical Learning with Applications in Python](#).

It's not over yet!

Next step is **assessing the accuracy of the coefficients** that you estimated!

# Assessing the accuracy of the coefficients

- Let's recall the formula:

$$y = \beta_0 + \beta_1 x + \epsilon$$

- The error term  $\epsilon$  captures what we missed with this model
- Therefore, **it is important to know how well the estimated coefficients are estimated.**

# Mean Standard Error (SE)

How accurate is the sample mean  $\bar{\mu}$  as an estimate of  $\mu$ ?

- **Standard Error** measures how much a sample statistic (like the mean) would vary if we repeated the experiment multiple times.
- This means that it tells us how accurately a sample statistic represents the population value.

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- Example: Let  $\mu$  be the population mean, and  $\bar{\mu}$  be mean of a sample:

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- **Larger samples = smaller SE = more precise estimates**



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How close are  $\bar{\beta}_0$  and  $\bar{\beta}_1$  are to the true values  $\beta_0$  and  $\beta_1$ ?

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**Formulas:**

$$SE(\beta_0)^2 = s^2 \left( \frac{1}{n} + \frac{\bar{x}^2}{\sum (x_i - \bar{x})^2} \right)$$
$$SE(\beta_1)^2 = \frac{s^2}{\sum (x_i - \bar{x})^2}$$

Where:

- $s^2 = \frac{\sum (y_i - \hat{y}_i)^2}{n-2}$  is the residual variance ( $\text{Var}(\epsilon)$ )
- $x_i$  = independent variable values
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**Keep in mind:** Smaller standard error = more precise coefficient estimates

## Assessing the accuracy of the model

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The **error** of an observation is the deviation of the observed value from the true value of a quantity of interest (for example, a population mean).

The **residual** is the difference between the observed value and the estimated value of the quantity of interest (for example, a sample mean).

Source: [Wikipedia](#)

# Assessing the accuracy of the model

- Residual Standard Error (RSE)
- Coefficient of Determination (R-Squared)

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- The **smaller** your RSE, the better your model.

The **coefficient of determination**, denoted as  $r^2$ , is the proportion of the variation in the dependent variable that is predictable from the independent variable(s).

Source: [Wikipedia](#)

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$$1 - \frac{\text{Residual Sum of Squares}}{\text{Total Sum of Squares}}$$

- $R^2 = 1$ : the regression predictions perfectly fit the data
- $R^2 = 0$ : the regression does not fit the data

**Table 1:** Linear Regression of Wage on Age: Key Statistics

Measure	Value	Meaning
Mean Standard Error (SEM)	50	Average variation of sample mean wage
Standard deviation of $b_0$ (SE $b_0$ )	300	Intercept (2000) varies $\pm 300$ due to sampling
Standard deviation of $b_1$ (SE $b_1$ )	20	Slope (150) varies $\pm 20$ ; uncertainty in slope
Residual Standard Error (RSS)	12,000	Difference between observed and predicted wages
0.85	85% of wage variation explained by age; higher $\rightarrow$ better model fit	

# Statistical Modeling Foundations

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## Multiple Linear Regression

What happens when we have more than one predictor?

# What is multiple linear regression?

- Models the relationship between a dependent variable  $Y$  and multiple independent variables  $X_1, X_2, \dots, X_p$ :

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p + \varepsilon$$

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where:

- $Y$  = dependent variable (outcome)
- $X_1, X_2, \dots, X_p$  = independent variables (predictors)
- $\beta_0$  = intercept
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## Remember

The coefficient  $\beta_i$  represents the change in  $Y$  for a one-unit increase in  $X_i$  (*remember single linear regression!*), **holding other variables constant.**

# From Abstract X and Y to Real Data

Substitute the example values:

$$Y \longrightarrow \textit{sales}$$

$$X_1 \longrightarrow \textit{TV}$$

$$X_2 \longrightarrow \textit{radio}$$

$$X_3 \longrightarrow \textit{newspaper}$$

# From Abstract X and Y to Real Data

Substitute the example values:

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Apply the regression formula:

$$\textit{sales} = \beta_0 + \beta_1 \times \textit{TV} + \beta_2 \times \textit{radio} + \beta_3 \times \textit{newspaper}$$

## Problem: Correlation

### Remember

Correlation among predictors can be problematic: low correlation is desired.

# Estimating the coefficients

- **Minimizing least squares** as in simple linear regression

$$\text{RSS} = \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

where:

- $y_i$  = actual value of the  $i$ -th observation
- $\hat{y}_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip}$  = predicted value
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$$\sum_{i=1}^n \left( y_i - \hat{\beta}_0 - \hat{\beta}_1 \times x_{i1} - \hat{\beta}_2 \times x_{i2} - \dots - \hat{\beta}_n \times x_{in} \right)$$

# Evaluation of Linear Regression

- We handled the most important evaluation metrics in class
- Some more advanced metrics (p-value, t-test, confidence intervals...) not handled in this course, due to its limited scope
- If you are interested in them (for example if you have prior knowledge of statistics), you can find supplementary materials about them

## Some assumptions of Linear Regression

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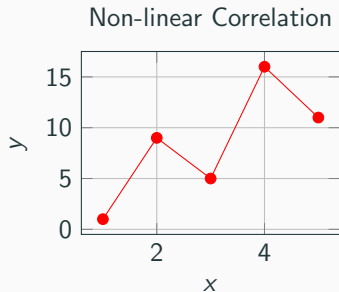
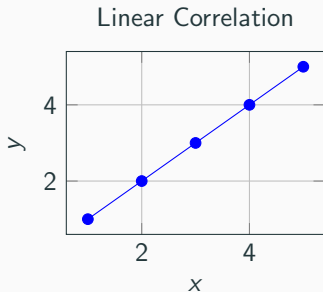


# Linearity

- **Linear relationship** between the dependent and independent variable(s)

# Linearity

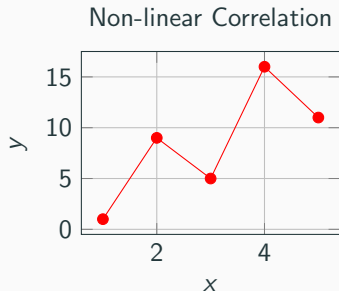
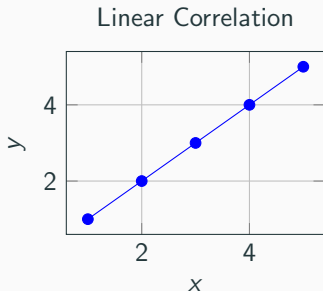
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**Figure 3:** Left: Linear correlation. Right: Non-linear correlation.

# Linearity

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**Figure 3:** Left: Linear correlation. Right: Non-linear correlation.

- **How to check:** With a scatterplot.

## No multicollinearity

- In multiple linear regression, independent variables must be **not too highly correlated with each other**.

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**Figure 4:** From last week's lab: a heatmap representing correlation values.

# Homoscedasticity

- **Homoscedasticity** means that the variance of the errors is roughly the same across all values of the predictor(s) in your regression model.

# Homoscedasticity

- **Homoscedasticity** means that the variance of the errors is roughly the same across all values of the predictor(s) in your regression model.
- **How to check** (intuitively, without formal tests): Plot the residuals and look for (approximately) even variance.



## Other limitations

- Linear regression involves other limitations and assumptions, **not treated in this course due to its more limited scope.**

How can you elaborate a meaningful data analysis pipeline that involves linear regression?

## Handling data for Linear Regression

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- Golden rule: **garbage in, garbage out**
- Some data quality standards to always check for:
  - Missing values
  - Missing features (e.g., the demographics info for the patients are not fully present)
  - Duplicates
  - Imbalanced datasets
- One main question: **Do I have the necessary data to answer my research question?**

For example, for linear regression you will only need **numerical variables**.

# Data splitting

- Core concept of ML: **data splitting**
- train and test set; eventually **evaluation** set

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- Core concept of ML: **data splitting**
- train and test set; eventually **evaluation** set
- **Why splitting?**
  - Allows you to **test the model on unseen data**
  - Prevents overfitting
  - Ensures generalization

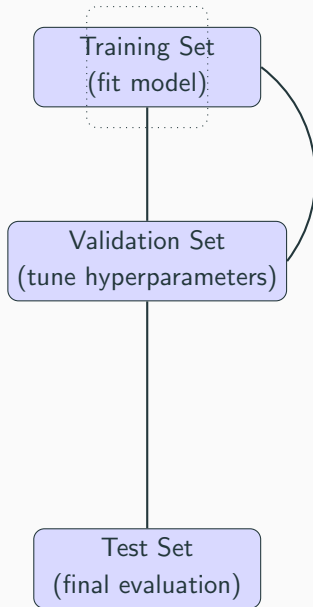
# Usual splits

- train: the model is **trained** on the training set
- test: the model is tested on the **test set**, which consists of unseen data
- eval: testing **during training** for hyperparameter finetuning and other adjustments

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Repeatedly testing the model on the test set to adjust parameters can lead to the model **memorizing patterns from the test set** and thus to misleading results, hence the necessity of an **evaluation set**.





# Common splits

- 70% train, 15% test, 15% eval
- 80% train, 10% test, 10% eval
- The best proportion is very **dataset-dependent**: you will have to **experiment with the data** to find it.

# Adapt to your own research question

- Elaborate a **public policy research question** related to your own studies and knowledge
- This way, **errors in your model will still be meaningful.**
- Example:
  - I evaluate **wage** in relation to **age**: this is meaningful!
  - I evaluate **wage** in relation to **height**: I might detect some patterns (for example, due to biases in my samples), but this research question makes no sense!
- This seems obvious, yes; but I am sure you can think of several field-specific examples, and of correlation that people who do not study public policies do not know!