

Lecture 11: Hypothesis testing

Statistical Methods for Data Science

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Today

1 Terminology

- Experiment and parameter of interest
- Null hypothesis and alternative hypothesis
- Test statistic
- Null distribution $f(s \mid H_0)$
- Significance level α , power and *p*-value

2 Example

3 *p*-hacking

4 Summary



Learning outcome

- Be able to explain the following terminology
 - Null hypothesis H_0 and alternative hypothesis H_A
 - Test statistic s
 - Null distribution $f(s | H_0)$
 - Significance level α and power
 - p -value
- Be able to design and interpret the one-sample z-test
- Be able to explain the concept of p -hacking

Today

1 Terminology

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Important example

If you control the diet of your ducks, they lose 2.1 kg after one month on average

- Company A has developed a drug D (aka. Duckyphanomin) to help duckies lose weight. They claim that **on average** the drug works better than diet control
- Company B has developed a drug E (aka. Everyduckyslim) and they claim that drug E is more effective than drug D **on average**

You NEED to help your chonker ducks lose weight. Which drug should you buy? Or should you just control their diet without drugs?

- If company A tested drug D on 30 ducks and the average weight loss after one month is 2.2 kg, would you buy drug D instead of regular diet control?
- What if company A tested drug D on 30 ducks and the average weight loss after one month is 2.3 kg? Would you buy drug D instead of regular diet control in this case?
- What if company A tested drug D on 100 ducks and the average weight loss after one month is 2.3 kg?
- Now company B tested drug E on 30 ducks and the average weight loss after one month is 2.5 kg, while drug D results in 2.3 kg weight loss with the same setup, would you buy drug E instead of drug D?

What would you do?

Hypothesis

- **Hypothesis:**
 - A proposed explanation for a phenomenon (Wikipedia)
 - An idea or explanation of something that is based on a few known facts but that has not yet been proved to be true or correct (Oxford dictionary)
- **Statistical hypothesis:** a proposed distribution that explains a set of random variables
- **Hypothesis testing in statistics:** we want to decide if it is likely that a random variable follows the proposed distribution
 - The test is based on sample statistics, which are computed from data
 - Hypothesis + data \rightarrow decision on rejecting or not rejecting the hypothesis

Hypothesis testing: a list to go through

- A default statement
- Experiment
- Data x , random variable X
- Parameter of interest θ
- Parameter estimate $\hat{\theta}$
- Null hypothesis H_0
- Alternative hypothesis H_A
- Test statistic s
- Null distribution $f(s \mid H_0)$
- Significance level α
- p -value

Experiment and parameter of interest

Experiment design

- Before formulating the statistical hypothesis, we need to propose a **default statement**: a “boring” and unsurprising claim that we would like to **test**, e.g.,
 - Drug D is **not more effective** than regular diet on average
 - Drug E works the same as drug D on average

In science, we are hoping for new discoveries and excitement, but we need to earn it by showing that the **trivial explanation** does not hold with evidence (**data**)

- Example 1: recall if you control the diet of your ducks, they lose 2.1 kg after one month on average
 - **A default statement**: drug D is not more effective than regular diet on average What experiments can we run to test if this statement is true?
 - **Experiment** (5 sec): give drug D to N chonker ducks and record the average weight loss after one month
 - **Data** and **random variable** (5 sec):
 - Data: x_i weight loss after one month for $i = 1, \dots, N$
 - Random variable: X_i i.i.d.
 - **Parameter of interest** (5 sec): the mean of the weight loss μ_D
 - **Parameter estimate** (5 sec): the sample mean $\hat{\mu}_D = \bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$

Then we test if \bar{x} is greater than diet control (2.1 kg)

Experiment design (cont.)

- Example 2:
 - **A default statement**: drug E and drug D work the same on average
 - **Experiment** (5 sec): give drug D to N_D chonker ducks and record the average weight loss after one month; test drug E on another N_E chonker ducks and record the average weight loss after one month
 - **Data** and **random variable** (5 sec): data - x_i weight loss using drug D after one month for $i = 1, \dots, N_D$; random variable - X_i i.i.d.; likewise, we have data y_j and random variable Y_j for drug E
 - **Parameter of interest** (5 secs): the mean μ_D and μ_E for drug D and E, respectively
 - **Parameter estimate** (5 secs): the sample mean $\hat{\mu}_D = \bar{x} = \frac{1}{N_D} \sum_{i=1}^{N_D} x_i$ and $\hat{\mu}_E = \bar{y} = \frac{1}{N_E} \sum_{j=1}^{N_E} y_j$

Then we test if \bar{x} and \bar{y} are the same

Experiment design (cont.)

- We make our decision by observing data; if the evidence does not support the default statement, we **reject the statement**; otherwise, we **do not reject the statement**
- But we can never prove or accept the statement - we can only **reject** a statement by showing counterexamples
- Intuition: “If the statement is true, then the evidence should support the statement”, which is the same as (\Longleftrightarrow) “if the evidence does not support the statement, the statement is considered false” , which is not the same as (\nRightarrow) “if the evidence supports the statement, the statement must be true”

Null hypothesis and alternative hypothesis

Hypotheses H_0 and H_A

- **Statistical hypothesis**: a proposed **distribution** - a statement about the **parameter of interest**
- **Null hypothesis H_0** : the default statement translated into a mathematical expression
 - Example 1: drug D is not more effective than regular diet on average

$$H_0 : \mu_D = 2.1$$

- Example 2: drug E and drug D work the same on average (5 sec)

$$H_0 : \mu_D = \mu_E$$

- **Alternative hypothesis H_A** : an alternative hypothesis that is **complementary** (the opposite) to the null hypothesis
 - Example 2 (5 sec): drug E and drug D do not work the same on average (5 sec)

$$H_A : \mu_D \neq \mu_E$$

- Example 1 (5 sec): drug D is more effective than regular diet on average (5 sec)

$$H_A : \mu_D > 2.1$$

Hypotheses H_0 and H_A (cont.)

Questions:

- Question 1: Why are $H_A : \mu_D > 2.1$ and $H_0 : \mu_D = 2.1$ complementary to each other? What about $H_A : \mu_D < 2.1$?

Answer: One implicit assumption here is that μ_D will not be smaller than 2.1

Question 1.1: Do I need to make this assumption?

Answer: No

Question 1.2: Could you elaborate on that?

Answer: Yes

Question 1.3: When?

Answer: In a few slides

Okay

- Question 2: Can H_0 and H_A be ANYTHING I want? Like a magic mirror!?

Answer: No

Question 2.2: What are the choices for H_0 and H_A then?

Choices for H_0

- In this course, we only deal with null hypotheses **with an equal sign** in them - only one fixed choice for the distribution proposed by H_0
- **Null hypothesis H_0** : two cases
 - **One-sample test**: to test a data distribution against a theoretical probability distribution, i.e. for a given constant c

$$H_0 : \theta = c$$

For example, is this (binary) classifier more accurate than random? $H_0 : p = 50\%$

- **Two-sample test**: to test a data distribution against another data distribution, i.e.

$$H_0 : \theta_1 = \theta_2$$

For example, is classifier A better than classifier B? $H_0 : p_A = p_B$

- We have seen one-sample test and two-sample test in the Q-Q plot lecture
- In practice, you can narrow down your choice of hypotheses by looking at Q-Q plots

Choices for H_A

Given

$$H_0 : \theta = \beta$$

where β can be either a constant (one-sample test) or a parameter from another data distribution (two-sample test)

- **Alternative hypothesis** H_A : H_A can be **one-tailed** or **two-tailed**
 - **One-tailed:**

$$H_A : \theta > \beta$$

or

$$H_A : \theta < \beta$$

- **Two-tailed:**

$$H_A : \theta \neq \beta \iff \theta < \beta \text{ or } \theta > \beta$$

Summary: choices for H_0 and H_A

Putting everything together,

	One-sample test	Two-sample test
Two-tailed	$H_0 : \theta = c, H_A : \theta \neq c$	$H_0 : \theta_1 = \theta_2, H_A : \theta_1 \neq \theta_2$
One-tailed	$H_0 : \theta = c, H_A : \theta > c$	$H_0 : \theta_1 = \theta_2, H_A : \theta_1 > \theta_2$
	$H_0 : \theta = c, H_A : \theta < c$	$H_0 : \theta_1 = \theta_2, H_A : \theta_1 < \theta_2$

where $\theta, \theta_1, \theta_2$ are the parameters of interest and c is a constant

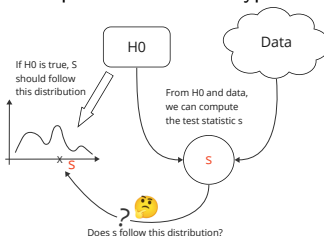
Note: this is the answer to question 1.1 (cf. page 14): if you choose the one-tailed test, then you are making the assumption

$H_A : \mu_D > 2.1$; if you choose the two-tailed test, then you are not making this assumption

Test statistic

Test statistic

- **Test statistic s** (random variable S): a (typically standardized) statistic computed from data
- **Purpose:** to determine how plausible the null hypothesis H_0 is by observing s



- What is needed for the expression of the test statistic?
 - Assumptions on random variables X_i 's
 - We only need the null hypothesis H_0 (not H_A) to express the test statistic

Disclaimer: in this course, we only deal with null hypothesis where we are able to express the PDF/PMF $f(s | H_0)$, i.e. H_0 with an equal sign in them

Test statistic (cont.)

Example 1. one-sample test (is drug D more effective than diet control)

- **Data:** x_1, \dots, x_N
- **Random variable:** X_1, \dots, X_N i.i.d. Gaussian with known σ
- **Parameter of interest:** μ_D
- **Parameter estimate:** $\bar{x} (\sim \mathcal{N}(\mu_D, \frac{\sigma^2}{N})$ - CLT)
- **Null hypothesis:** $H_0 : \mu_D = 2.1$
- **Test statistic:** $s = \text{standardized } \bar{x} \text{ assuming the null hypothesis}$
 - What are we trying to do here? - To decide if we can reject the null hypothesis - if the null hypothesis is true, we should be able to see evidence that supports it - if we do not see evidence, we reject the null hypothesis
 - What is "evidence"? It is the value of the test statistic s assuming the **data distribution described by the null hypothesis** (we need H_0 to compute s)
 - What is the **data distribution described by the null hypothesis**?
 - Gaussian distribution with (known) standard deviation σ and **mean $\mu_D = 2.1$**
 - **Assuming the null hypothesis:** data are assumed to be generated from the distribution described by the null hypothesis - $X_j \sim \mathcal{N}(2.1, \sigma^2)$
 - Recall: what is **standardization**?
 - Random variable X : $Y = \frac{X - \mu_X}{\sigma_X}$
 - Data x : $y = \frac{x - \mu_X}{\sigma_X}$
 - Why are we standardizing the statistic \bar{x} ? We want to use standard tools for our analysis

Standardize \bar{x} (15 sec)

$$s = z = \frac{\bar{x} - 2.1}{\sigma / \sqrt{N}}$$

Test statistic (cont.)

Example 2. two-sample test

- **Data:** x_1, \dots, x_{N_D} and y_1, \dots, y_{N_E}
- **Random variable:** X_1, \dots, X_{N_D} i.i.d. **Gaussian with known σ_D** ; Y_1, \dots, Y_{N_E} i.i.d. **Gaussian with known σ_E** ; X_i and Y_j independent
- **Parameter of interest:** μ_D, μ_E
- **Parameter estimate:** \bar{x}, \bar{y}
- **Null hypothesis:** $H_0 : \mu_D = \mu_E \iff H_0 : \mu_D - \mu_E = 0$
- **Test statistic:** standardized $\bar{x} - \bar{y}$ assuming the null hypothesis

$$z = \frac{\bar{x} - \bar{y}}{\sqrt{\sigma_D^2/N_D + \sigma_E^2/N_E}}$$

Note: \bar{x}, \bar{y} Gaussian (CLT); awesome properties of Gaussian from Lecture 6

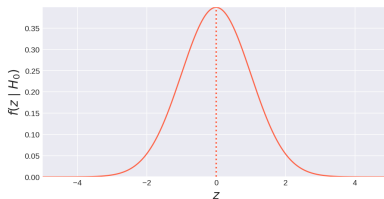
Null distribution $f(s \mid H_0)$

Null distribution

- **Null distribution $f(s | H_0)$:** the distribution of the **test statistic S** given the null hypothesis H_0
- **Example:**
 - **Data:** x_1, \dots, x_N
 - **Random variable:** X_1, \dots, X_N i.i.d. Gaussian with known σ
 - **Parameter of interest:** μ
 - **Parameter estimate:** \bar{x}
 - **Null hypothesis:** $H_0 : \mu = \mu_0$
 - **Test statistic:**

$$z = \frac{\bar{x} - \mu_0}{\sigma/\sqrt{N}}$$

- **Null distribution:** standard Gaussian distribution



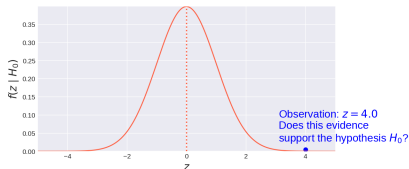
Significance level α , power and p -value

Significance level

Given a null hypothesis $H_0 : \mu = 2.1$ and the null distribution $f(s | H_0)$, we decide if we reject the hypothesis or not by observing data

- Run some experiments and collect data x_1, \dots, x_N
- Compute the test statistic from data, e.g.

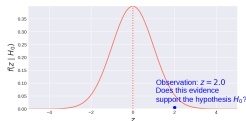
$$z = \frac{\bar{x} - 2.1}{\sigma/\sqrt{N}} = 4.0$$



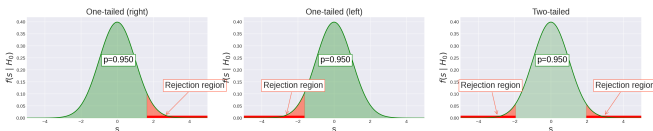
- Does this evidence support the hypothesis H_0 ? Probably not since it's so far away from the center?

Significance level (cont.)

- What about this observation?



- To be able to answer the question, you need to decide where you draw the line (quite literally) - define a **rejection region** by choosing a significance level
- Significance level α** : red area under the curve

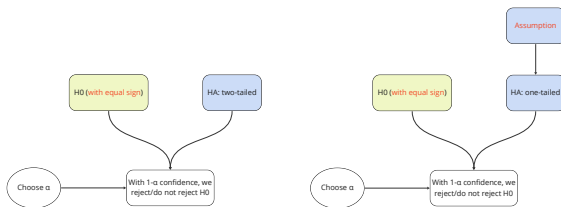
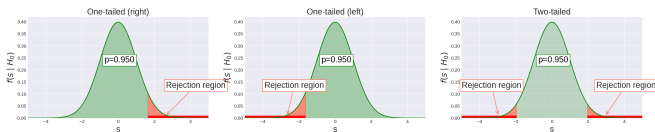


In these three images, $\alpha = 0.05$

- What is needed for choosing a meaningful α ?
 - Null distribution
 - H_A one-tailed or two-tailed

Significance level (cont.)

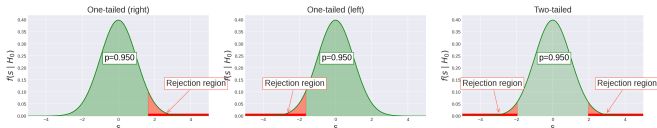
- Significance level $\alpha = 0.05$: red area under the curve



- More conservative \Rightarrow less probable to reject H_0 , which indicates a smaller rejection region
- Two-tailed H_A is more conservative

Interpretation of α

- $\alpha = P(\text{reject } H_0 \mid H_0 \text{ is true})$ - the probability of making such a mistake



- The rejection region indicates that H_0 is **unlikely**, but the probability is not zero
- It is possible that H_0 is true, but our observation happens to fall in the rejection region
- If H_0 is true and our observation falls in the rejection region, we will **mistakenly** reject H_0
- The probability of making this type of mistakes is α
- Similar to the confidence interval, $1 - \alpha$ is called the **confidence level** - “with 95% confidence, rejecting H_0 is the right thing to do”
- Define the significance level **before you run the experiments** so that you can't cheat!

Significance level and power

- Contingency table:

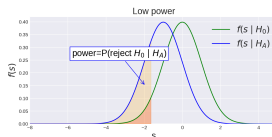
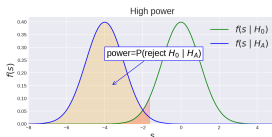
	$y = H_A$	$y = H_0$
$\hat{y} = \text{reject } H_0$	TP	FP (Type I error)
$\hat{y} = \text{do not reject } H_0$	FN (Type II error)	TN

- Significance level** α : incorrectly rejecting H_0

$$\alpha = P(\text{type I error})$$

- Power**: correctly rejecting H_0

$$\text{power} = P(\text{reject } H_0 | H_A) = 1 - P(\text{type II error})$$



- What is needed for computing power (20 sec)? $f(s | H_0)$, $f(s | H_A)$, α

p -value

- p -value:

- One-tailed:

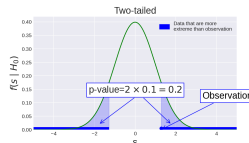
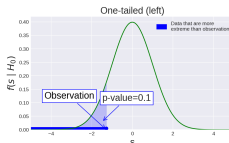
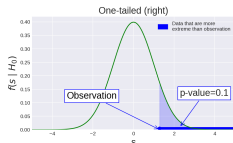
- Right tail: $p = P(S \geq s | H_0)$, e.g. $1 - \text{stats.norm.cdf}(s, 0, 1)$
- Left tail: $p = P(S \leq s | H_0)$, e.g. $\text{stats.norm.cdf}(s, 0, 1)$

- Two-tailed:

- $p = 2 \min(P(S \leq s | H_0), P(S \geq s | H_0))$, e.g. $2 * \min(\text{stats.norm.cdf}(s, 0, 1), 1 - \text{stats.norm.cdf}(s, 0, 1))$

Note: for example, if $f(s | H_0)$ is symmetric around zero and $s < 0$,

$$p = 2P(S \leq s | H_0)$$



- What is needed for computing the p -value? (10 sec)

- Null distribution
- Alternative hypothesis H_A to know one-tailed or two-tailed
- Observation - test statistic computed from data

Summary: steps for hypothesis testing

- Step 1 Make a default statement
- Step 2 Design an **experiment**
- Step 3 Describe the **data** generated from the experiment and the corresponding random variables
- Step 4 Describe the parameter of interest and their estimates
- Step 5 Translate the default statement into a statistical hypothesis and call it the **null hypothesis H_0**
- Step 6 Find the expression for the **test statistic s**
- Step 7 Find the expression for the **null distribution**
- Step 8 Define **an alternative hypothesis H_A** : one-tailed or two-tailed
- Step 9 Choose a **significance level α** (the tail), which defines the **rejection region**
- Step 10 Run experiments and collect **data**
- Step 11 Compute the test statistic from data
- Step 12 Compute the p -value
- Step 13 If $p\text{-value} < \alpha$, i.e. the test statistic falls in the rejection region of the null distribution, then we reject the hypothesis H_0 ; otherwise, we fail to reject H_0 .

Today

- 1 Terminology
- 2 Example
- 3 p -hacking
- 4 Summary

Example

Recall example: if you control the diet of your ducks, they lose 2.1 kg after one month on average. Company A has developed a drug D (Duckyphanomin!) to help ducks lose weight. They claim that on average the drug works better than diet control.

- Step 1 Make a default statement (5 secs): **drug D works the same as diet control**
- Step 2 Design an **experiment** (choose $N = 30$) (10 secs): **feed drug D to 30 chonker ducks and measure their weight loss after one month**
- Step 3 Describe the **data** and **random variables** along with assumptions about their distributions (5 secs): **weight loss** x_1, \dots, x_{30} ; X_1, \dots, X_{30} **i.i.d. Gaussian random variables** - let's make an additional assumption to simplify the problem - the standard deviation of X_i $\sigma = 0.6$ is known
- Step 4 Describe the parameter of interest and their estimates (10 secs): **the mean value** μ_D and $\hat{\mu}_D = \bar{x}$
- Step 5 Translate the default statement into a statistical hypothesis and call it the **null hypothesis** H_0 (10 secs): $H_0 : \mu_D = 2.1$
- Step 6 Find the expression for the **test statistic** s (60 secs):

$$s = z = \frac{\bar{x} - 2.1}{\sigma / \sqrt{30}}$$

- Step 7 Find the expression for the **null distribution** $f(s \mid H_0)$ (10 secs):

$$f(z \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$$

Example (cont.)

Step 8 Define **an alternative hypothesis** H_A (10 secs):

$$H_A : \mu_D \neq 2.1 \text{ or } H_A : \mu_D > 2.1$$

One-tailed or two-tailed

- **Two-tailed (5 secs):** $H_A : \mu_D \neq 2.1$
- **One-tailed (5 secs):** $H_A : \mu_D > 2.1$

Step 9 Choose a **significance level** α (the tail), which defines the rejection region (5 secs): e.g. $\alpha = 0.05$

Step 10 Collect 30 ducks in 20 secs and feed them drugs - great job! Weights measured after one month x_1, \dots, x_{30}

Say $\frac{1}{30} \sum_{i=1}^{30} x_i = 2.2$

Step 11 Compute the test statistic from data (5 secs):

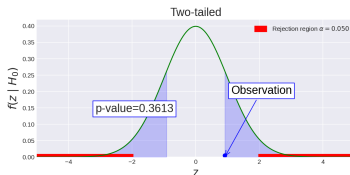
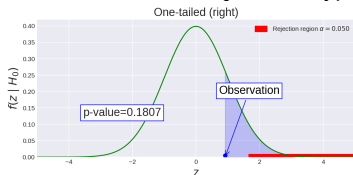
$$z_0 = \frac{2.2 - 2.1}{0.6/\sqrt{30}} = 0.91$$

Example (cont.)

Step 12 Compute the p -value (20 secs):

- For $H_A : \mu_D > 2.1$ (**one-tailed**): $p = P(Z \geq z_0 | H_0) = 0.1807 > \alpha$
- For $H_A : \mu_D \neq 2.1$ (**two-tailed**): $p = 2P(Z \geq z_0 | H_0) = 0.3613 > \alpha$

Step 13 If $p\text{-value} < \alpha$, i.e. the test statistic falls in the rejection region of the null distribution, then we reject the hypothesis H_0



Do not reject H_0 for both one-tailed and two-tailed H_A

What does it mean? - Based on this test, you will stick to diet control instead of buying Duckyphanomin

Example (cont.)

What if $\bar{x} = 2.3$?

Step 11 Compute the test statistic from data (5 secs):

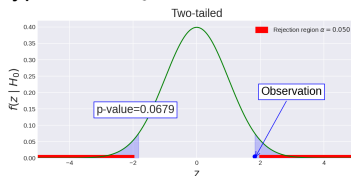
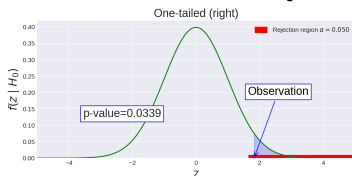
$$z_0 = \frac{2.3 - 2.1}{0.6/\sqrt{30}} = 1.826$$

Step 12 Compute the *p*-value (20 secs):

- **For $H_A : \mu_D > 2.1$ (one-tailed):** $p = P(Z \geq z_0 \mid H_0) = 0.0339 < \alpha$
- **For $H_A : \mu_D \neq 2.1$ (two-tailed):** $p = 2P(Z \geq z_0 \mid H_0) = 0.0679 > \alpha$

Example (cont.)

Step 13 If $p\text{-value} < \alpha$, i.e. the test statistic falls in the rejection region of the null distribution, then we reject the hypothesis H_0



Reject H_0 for one-tailed H_A ; do not reject H_0 for two-tailed H_A for the same confidence level $1 - \alpha = 95\%$

Note: the two-tailed test is more conservative - if the data passes a two-tailed test, it is more conclusive than one-tailed test for the same confidence level

Example (cont.)

What if $\bar{x} = 2.3$ with $N = 100$?

Step 11 Compute the test statistic from data (5 secs):

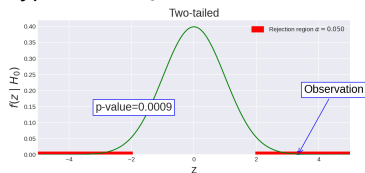
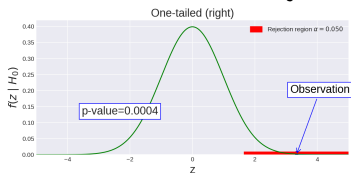
$$z_0 = \frac{2.3 - 2.1}{0.6/\sqrt{100}} = 3.33$$

Step 12 Compute the *p*-value (20 secs):

- **For $H_A : \mu_D > 2.1$ (one-tailed):** $p = P(Z \geq z_0 \mid H_0) = 0.0004 < \alpha$
- **For $H_A : \mu_D \neq 2.1$ (two-tailed):** $p = 2P(Z \geq z_0 \mid H_0) = 0.0009 < \alpha$

Example (cont.)

Step 13 If $p\text{-value} < \alpha$, i.e. the test statistic falls in the rejection region of the null distribution, then we reject the hypothesis H_0



Reject H_0 for both one-tailed and two-tailed H_A

Note:

- With more data, it becomes more certain that we should reject H_0 in favor of H_A given the observation $\bar{x} = 2.3$

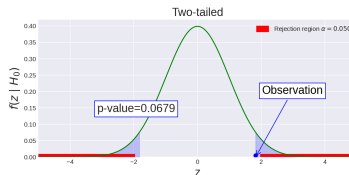
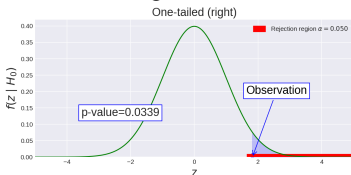
This test is called **one-sample z-test** (one of the established tests you choose from)

Today

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- 2 Example
- 3 p -hacking**
- 4 Summary

Recall: one-tailed vs two-tailed tests

- p -value indicates how “surprising” the observation is
- In this context, “surprising” observations usually mean potential novelty
- In one of the examples, we have shown that we reject the null hypothesis for the one-tailed test but we fail to reject the null hypothesis for the two-tailed test given the same significance level



- In this example, if we use the two-tailed test, we will not claim that we have observed potential novelty with the experiment, whereas if we use the one-tailed test, we claim that we do observe potential novelty
- The conclusion we draw depends on which test we conduct

Variation of the *p*-value

- *p*-value is computed from data
- Data is random - ***p*-value is random**
- With the same experiment set up, if we switch to a different sample, *p*-value will be different

p-hacking

- Many factors can result in a different *p*-value
- *p*-hacking refers to situations where researchers are **trying multiple things until they get the desired result**
- This action can be a conscious decision, a subconscious decision or even an accident
- *p*-hacking can be tricky to identify
- Suggestions to avoid *p*-hacking, e.g. one should always **report effect sizes and confidence intervals**
- Reference:
 - <https://www.nature.com/news/scientific-method-statistical-errors-1.14700>
 - Why Most Published Research Findings Are False?

p-hacking (cont.)



What should I do!?

- Be honest and explicit about your assumptions
- Be “conservative”
- Be skeptical about your result - **don't let go of any doubt!**
- Assume the first success is always **too good to be true** - **try to prove yourself wrong** - be a proper scientist

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Summary

So far:

- Data types and data containers
- Descriptive data analysis: descriptive statistics, visualization
- Probability distributions, events, random variables, PMF, PDF, parameters
- CDF, Q-Q plot, how to compare two distributions (data vs theoretical, data vs data)
- Modeling
- Parameter estimation: maximum likelihood estimation (MLE) and maximum a posteriori estimation (MAP)
- Classification, multinomial naive Bayes classifier, Gaussian naive Bayes classifier
- Central limit theorem, interval estimation
- Clustering, cluster tendency
- Centroid clustering, k-means, parameter estimation, SSE, Silhouette score
- Gaussian Mixture Models, AIC/BIC
- The EM algorithm
- Hypothesis test

Next:

- More examples and test statistics

Before next lecture:

- Steps for hypothesis testing





Screw diet! I'm perfect $p = 100\%$!

That's not how p -value works...