Lecture 8: Hypothesis testing part II

Statistical Methods for Data Science

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Today

Learning outcome

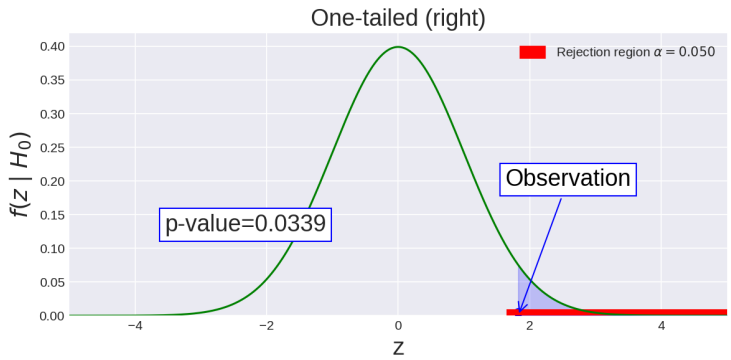
- Be able to explain the concept of *p*-hacking
- Be able to explain the following hypothesis tests
  - One-sample and two-sample z-test
  - One-sample and two-sample t-test
  - Paired t-test
  - Binomial test (exact, approximate)
  - McNemar's test (exact, approximate)

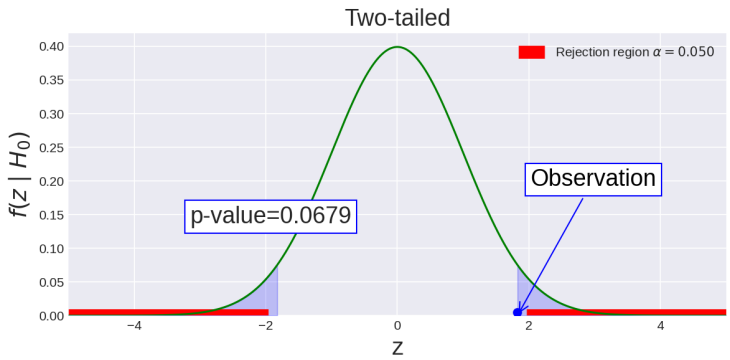
  For each of these tests, be able to describe the typical set up for the experiment, the general purpose of the test, data produced by the experiment, random variables, parameter of interest, null hypothesis, alternative hypothesis, test statistic, null distribution, the computation of *p*-value
- Be able to compare two classifiers using the paired t-test and McNemar's test for different scenarios

Today

Recall: one-tailed vs two-tailed tests

- *p*-value indicates how "surprising" the observation is
- "Surprising" observation usually means potential novelty
- In one of the examples from the previous lecture, we have shown that we reject the null hypothesis for the one-tailed test and 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 unconscious action
- *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

Today

Disclaimer

- Recall that in this course, we only consider H_0 **with an equal sign in them**, i.e. the **null distribution is fully specified**; the description of H_0 is based on this assumption
- For **symmetric null distributions**, e.g. **standard Gaussian distribution**, **student's t distribution**, **binomial distribution with** $p = 0.5$, etc, we only illustrate examples with the two-tailed alternative hypothesis H_A in this lecture without loss of generality; the one-tailed version can be easily derived
- For the **exact binomial test with** $p \neq 0.5$, the null distribution is not symmetric; in this case, the computation of the two-tailed p-value is not uniquely defined; in this lecture, we will not go into details for these cases; we will only look at the one-tailed tests for asymmetric binomial null distributions
- For each hypothesis test, the purpose of the Python code snippet is to provide a better understanding of the calculation; in practice, there are alternative libraries and built-in functions for these tests that might result in a more compact implementation

Disclaimer (cont.)

For each of the hypothesis tests we introduce, we present the following components:

- **Typical set up for the experiment**
  - **Test subjects**, e.g. the number of samples, the number of groups, etc
  - Description of the **experiment** and the **result**
  - Description of the **data type** produced in the result
- **Purpose**: the general purpose of the test
- **Data**: symbolic description of the data produced by the experiment
- **Random variable** and **assumption** corresponding to the data
- **Parameter of interest** and the **estimates**
- **Hypotheses** H_0 and H_A
- **Test statistic**
- **Null distribution**
  - PDF/PMF: description of the PDF/PMF
  - Python: code snippet of the PDF/PMF
- p-**value**
  - Definition: an expression of p-value in terms of a probability
  - Python: code snippet to illustrate the computation of the p-value (see page 10)

z-test

One-sample z-test

- **Typical set up for the experiment**:
  - **One sample** of independent test subjects, e.g. a sample of patients, a sample of customers, etc
  - Run the same experiment on each subject and collect the outcomes, e.g. give a new drug to a sample of patients and measure the effect on each individual patient; test a new web design on a sample of customers and record the time they spend on the web page, etc
  - The result contains one i.i.d. sample with **continuous numerical values**
- **Purpose**: to test if the mean of the result differs from a predefined constant
- **Data**: $x_1, \cdots, x_N$, e.g. blood pressure after taking a new drug
- **Random variable** and **assumption**: $X_1, \cdots, X_N$
  - X_i i.i.d.
  - X_i Gaussian or large N (CLT)
  - X_i standard deviation σ known
- **Parameter of interest**: μ
- **Parameter estimate**: $\bar{x}$, $\bar{X} \sim \mathcal{N}(\mu, \sigma^2/N)$
- **Hypotheses** H_0 and H_A: given c a constant

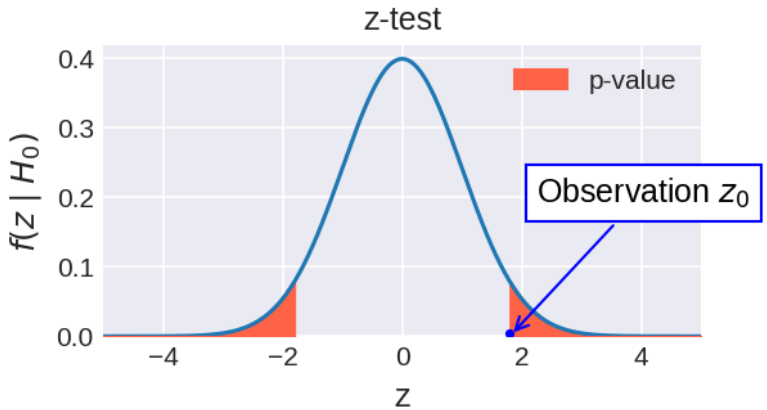
$$H_0: \quad \mu = c$$
$$H_A: \quad \mu \neq c$$

One-sample z-test (cont.)

- **Test statistic**:

$$z_0 = \frac{\bar{x} - c}{\sigma/\sqrt{N}}$$

- **Null distribution**: standard normal distribution
  - PDF: $f(z \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$
  - Python: stats.norm.pdf(z, 0, 1)
- ***p*-value**
  - Definition: $p = 2\min\left(P(Z \leq z_0 \mid H_0), P(Z \geq z_0 \mid H_0)\right)$
  - Python: $2 * \min$ (stats.norm.cdf(z_0, 0, 1), 1-stats.norm.cdf(z_0, 0, 1))



Two-sample z-test

- **Typical set up for the experiment**:
  - **Two samples** of independent test subjects, where the two samples $\mathcal{X}$ and $\mathcal{Y}$ letters with a calligraphic font are typically used to denote sets are independent from one another, e.g. two samples of independent patients, two samples of independent customers, etc
  - Run two sets of experiments A and B on the test subjects from the two samples $\mathcal{X}$ and $\mathcal{Y}$, respectively, and collect the outcomes, e.g. give different drugs to the two samples of patients and measure the effect on each individual patient; test two web designs on two samples of customers and record the time they spend on the web page, etc
  - The result contains two i.i.d. samples with **continuous numerical values**
- **Purpose**: to test if two alternative options have different effects by testing if the mean of the result from one sample differs from the mean of the other sample
- **Data**: $x_1, \cdots, x_{N_X}$ and $y_1, \cdots, y_{N_Y}$, e.g. blood pressure measured after taking two different drugs
- **Random variable** and **assumption**: $X_1, \cdots, X_{N_X}$, $Y_1, \cdots, Y_{N_Y}$
  - X_i and Y_j independent
  - X_i i.i.d.; Y_j i.i.d.
  - X_i Gaussian or large N_X; Y_j Gaussian or large N_Y
  - X_i and Y_j have known standard deviation σ_X and σ_Y, respectively
- **Parameter of interest**: μ_X, μ_Y
- **Parameter estimate**: $\bar{x}$, $\bar{y}$
- **Hypotheses** H_0 and H_A: given c a constant

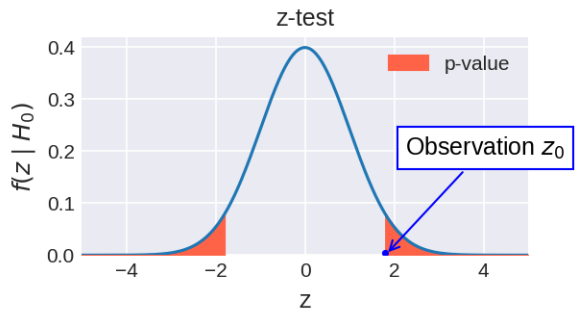
$$H_0: \quad \mu_X - \mu_Y = c$$
$$H_A: \quad \mu_X - \mu_Y \neq c$$

Two-sample z-test (cont.)

- **Test statistic**:

$$z_0 = \frac{\bar{x} - \bar{y} - c}{\sqrt{\frac{\sigma_X^2}{N_X} + \frac{\sigma_Y^2}{N_Y}}}$$

  Hint: $\bar{X} - \bar{Y} \sim \mathcal{N}\left(\mu_X - \mu_Y, \sigma_X^2/N_X + \sigma_Y^2/N_Y\right)$
- **Null distribution**: standard normal distribution
  - PDF: $f(z \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$
  - Python: stats.norm.pdf(z, 0, 1)
- ***p*-value**
  - Definition: $p = 2\min\left(P(Z \leq z_0 \mid H_0), P(Z \geq z_0 \mid H_0)\right)$
  - Python: $2 * \min$(stats.norm.cdf(z_0, 0, 1), 1-stats.norm.cdf(z_0, 0, 1))



One-sample t-test

One-sample t-test

- **Typical set up for the experiment** (same as the one-sample z-test):
  - One sample of independent test subjects, e.g. a sample of patients, a sample of customers, etc
  - Run the same experiment on each subject and collect the outcomes, e.g. give a new drug to a sample of patients and measure the effect on each individual patient; test a new web design on a sample of customers and record the time they spend on the web page, etc
  - The result contains one i.i.d. sample with **continuous numerical values**
- **Purpose**: to test if the mean of the result differs from a predefined constant
- **Data**: $x_1, \cdots, x_N$, e.g. blood pressure after taking a new drug
- **Random variable** and **assumption**: $X_1, \cdots, X_N$
  - X_i i.i.d.
  - X_i Gaussian or large N
  - X_i standard deviation σ **unknown**
- **Parameter of interest**: μ
- **Parameter estimate**: $\bar{x}$
- **Hypotheses** H_0 and H_A: given c a constant

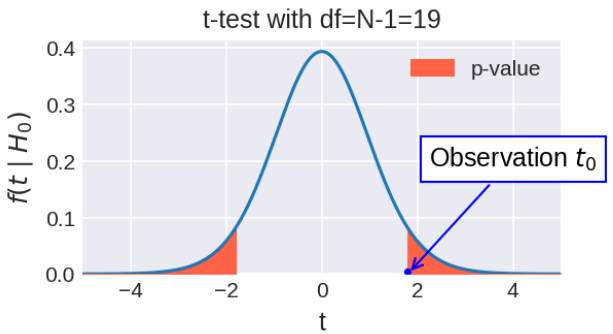
$$H_0: \quad \mu = c$$
$$H_A: \quad \mu \neq c$$

One-sample t-test (cont.)

- **Test statistic**:

$$t_0 = \frac{\bar{x} - c}{s/\sqrt{N}}$$

  where $s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$ is the sample standard deviation
- **Null distribution**:
  - Student-t distribution with degree of freedom $df = N - 1$
  - Python: stats.t.pdf($t, df = N - 1$)
- ***p*-value**:
  - Definition: $p = 2\min\left(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)\right)$
  - Python: $2 * \min\left(\text{stats.t.cdf}(t_0, df = N - 1),\ \text{1-stats.t.cdf}(t_0, df = N - 1)\right)$



Two-sample t-test

Two-sample t-test

- **Typical set up for the experiment** (same as the two-sample z-test):
  - Two samples of independent test subjects, where the two samples $\mathcal{X}$ and $\mathcal{Y}$ are independent from one another, e.g. two samples of independent patients, two samples of independent customers, etc
  - Run two sets of experiments A and B on the test subjects from the two samples $\mathcal{X}$ and $\mathcal{Y}$, respectively, and collect the outcomes, e.g. give different drugs to the two samples of patients and measure the effect on each individual patient; test two web designs on two samples of customers and record the time they spend on the web page, etc
  - The result contains two i.i.d. samples with **continuous numerical values**
- **Purpose**: to test if two alternative options have different effects by testing if the mean of the result from one sample differs from the mean of the other sample
- **Data**: $x_1, \cdots, x_{N_X}$ and $y_1, \cdots, y_{N_Y}$, e.g. blood pressure measured after taking two different drugs
- **Random variable** and **assumption**: $X_1, \cdots, X_{N_X}$, $Y_1, \cdots, Y_{N_Y}$
  - X_i and Y_j independent
  - X_i i.i.d.; Y_j i.i.d.
  - X_i Gaussian or large N_X; Y_j Gaussian or large N_Y
  - X_i and Y_j have **unknown** standard deviation σ_X and σ_Y, respectively
- **Parameter of interest**: μ_X, μ_Y
- **Parameter estimate**: $\bar{x}$, $\bar{y}$
- **Hypotheses** H_0 and H_A: given c a constant

$$H_0: \quad \mu_X - \mu_Y = c$$
$$H_A: \quad \mu_X - \mu_Y \neq c$$

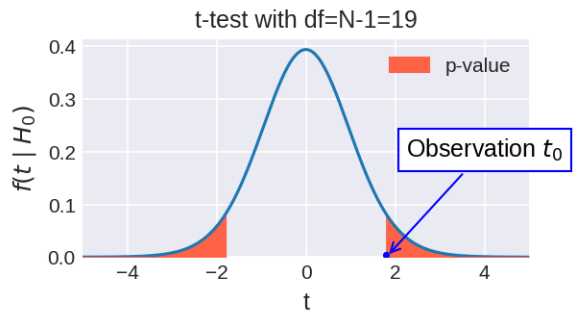
Two-sample t-test (cont.)

- **Test statistic**:

$$t_0 = \frac{\bar{x} - \bar{y} - c}{\sqrt{\frac{s_X^2}{N_X} + \frac{s_Y^2}{N_Y}}}$$

  with degree of freedom $df = \frac{(s_X^2/N_X + s_Y^2/N_Y)^2}{(\frac{s_X^2}{N_X})^2/(N_X-1) + (\frac{s_Y^2}{N_Y})^2/(N_Y-1)}$

- **Null distribution**:
  - Student-t distribution with degree of freedom df
  - Python: stats.t.pdf($t, df = df$)
- ***p*-value**:
  - Definition: $p = 2\min\left(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)\right)$
  - Python: $2 * \min$(stats.t.cdf(t_0, df=df), 1-stats.t.cdf(t_0, df=df))



Paired t-test

Paired t-test

- **Typical set up for the experiment**:
  - One sample of independent test subjects, e.g. one sample of independent patients
  - Run two sets of experiments A and B on all subjects from the sample and collect the outcomes, e.g. measure the blood pressure of the patients **before** giving them a new drug (experiment A); measure the blood pressure of the patients **after** giving them the new drug (experiment B)
  - The result contains two samples with **continuous numerical values**
- **Purpose**: to test if two alternative options have different effects by testing if the mean of the difference between two results differs from a predefined constant
- **Data**: $x_1, \cdots, x_N$, $y_1, \cdots, y_N$
- **Random variable** and **assumption**: $X_1, \cdots, X_N$, $Y_1, \cdots, Y_N$
  - $X_i - Y_i$ i.i.d.
  - $X_i - Y_i \sim \mathcal{N}\left(\mu_{X-Y}, \sigma^2_{X-Y}\right)$ with unknown standard deviation
- **Parameter of interest**: μ_{X-Y}
- **Parameter estimate**: $m_{X-Y} = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)$
- **Hypotheses** H_0 and H_A: given c a constant

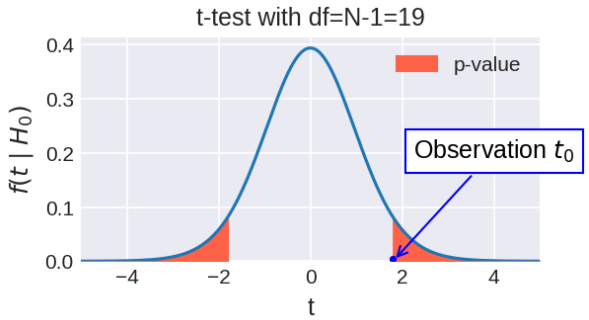
$$H_0: \quad \mu_{X-Y} = c$$
$$H_A: \quad \mu_{X-Y} \neq c$$

Paired t-test

- **Test statistic**:

$$t_0 = \frac{m_{X-Y} - c}{s_{X-Y}/\sqrt{N}}$$

  where $s_{X-Y} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - y_i - m_{X-Y})^2}$
- **Null distribution**:
  - Student-t distribution with degree of freedom $N-1$
  - Python: stats.t.pdf($t, df = N-1$)
- ***p*-value**:
  - Definition: $p = 2\min\left(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)\right)$
  - Python: $2 * \min$(stats.t.cdf($t_0, df = N-1$), 1-stats.t.cdf($t_0, df = N-1$))



Exercise 1

- A company claims that a new drug E they have developed can increase the average sleeping hours of people with insomnia. Design three different hypothesis tests to test this statement.

Let's design experiments for running the one-sample t-test, two sample t-test and paired t-test

Test 1: one-sample t-test

- **Statement**: drug E does not increase the average sleeping hours of people with insomnia; for the one-sample t-test, the average sleeping hours of people with insomnia is a constant - we need to know it in advance - 4.5 hours
- **Experiment**: let $N = 40$ people with insomnia take drug E and observe their amount of sleep
- **Data**: $x_1, \cdots, x_N$ the sleeping hours of people who have taken drug E; **random variable** $X_1, \cdots, X_N$ i.i.d.
- **Parameter of interest**: the mean value μ; **estimate**: sample mean

$$\hat{\mu} = \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

- **Null hypothesis** H_0: $H_0 : \mu = 4.5$

Test 1: one-sample t-test (cont.)

- **Test statistic**:

$$t_0 = \frac{\bar{x} - 4.5}{s/\sqrt{N}}$$

  where $s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$
- **Null distribution**:
  - Student-t distribution with degree of freedom $df = N - 1$
  - Python: stats.t.pdf$(t, df = N - 1)$
- **Alternative hypothesis** H_A: $H_A : \mu \neq 4.5$ - two tailed test
- **Significance level** α: set to 0.05

Test 1: one-sample t-test (cont.)

- Run the experiment and collect data

```
# Data in this example is generated using the following command
N = 40
x = stats.norm.rvs(loc=5.2, scale=1.2, size=N, random_state=1)
>> x = [7.14921444 4.4658923  4.5661939  3.91243765
        6.23848916 2.43815356 7.29377412 4.28655172
        5.58284692 4.90075555 6.95452952 2.72783115
        4.81309936 4.73913477 6.56052333 3.88013048
        4.99308615 4.1465699  5.2506565  5.89937826
        3.87925699 6.57366845 6.28190886 5.80299321
        6.28102714 4.37952657 5.05253173 4.07707668
        4.8785343  5.83642656 4.3700071  4.72389577
        4.37539276 4.18575323 4.39450464 5.18480248
        3.85922758 5.48129884 7.19176261 6.09045299]
```

$\Rightarrow \bar{x} = 5.092$

Test 1: one-sample t-test (cont.)

- Compute the test statistic t_0 from data:
  - First, estimate the **nuisance parameter** - the parameter that is **not the parameter of interest**: standard deviation

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} = 1.172$$

  - Then compute the test statistic

$$t_0 = \frac{\bar{x} - 4.5}{s/\sqrt{N}} = \frac{5.09 - 4.5}{1.32/\sqrt{40}} = 3.197$$

Test 1: one-sample t-test (cont.)

- Compute the p-value:

$$p = 2\min(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)) = 0.003$$

- $p < \alpha$: reject H_0

Example implementation in Python: **stats.ttest_1samp(x, 4.5)**

- x is specified on page 29

Test 2: two-sample t-test

- **Statement**: drug E does not increase the average sleeping hours of people with insomnia
- **Experiment**: let $N_X = 40$ people with insomnia take drug E and observe their amount of sleep; observe the sleeping hours of $N_Y = 50$ people with insomnia without taking drug E
- **Data**:
  - $x_1, \cdots, x_{N_X}$ sleeping hours of people with insomnia who have taken drug E; **random variable** $X_1, \cdots, X_{N_X}$ i.i.d.
  - $y_1, \cdots, y_{N_Y}$ sleeping hours of people with insomnia who have not taken drug E; **random variable** $Y_1, \cdots, Y_{N_Y}$ i.i.d.
  - X_i and Y_j independent, for $i = 1, \cdots, N_X$, $j = 1, \cdots, N_Y$

Test 2: two-sample t-test (cont.)

- **Parameter of interest**:
  - The mean value of the sleeping hours of people with insomnia after taking drug E μ_E; **estimate**: sample mean $\hat{\mu}_E = \bar{x} = \frac{1}{N_X}\sum_{i=1}^{N} x_i$
  - The mean value of the sleeping hours of people with insomnia without taking drug E μ_0; **estimate**: sample mean $\hat{\mu}_0 = \bar{y} = \frac{1}{N_Y}\sum_{i=1}^{N_Y} y_i$
- **Null hypothesis** H_0: $H_0 : \mu_E - \mu_0 = 0$
- **Test statistic**:

$$t_0 = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_X^2}{N_X} + \frac{s_Y^2}{N_Y}}}$$

with degree of freedom $df = \frac{(s_X^2/N_X + s_Y^2/N_Y)^2}{(\frac{s_X^2}{N_X})^2/(N_X-1) + (\frac{s_Y^2}{N_Y})^2/(N_Y-1)}$, where

$s_X = \sqrt{\frac{1}{N_X-1}\sum_{i=1}^{N_X}(x_i - \bar{x})^2}$ and $s_Y = \sqrt{\frac{1}{N_Y-1}\sum_{i=1}^{N_Y}(y_i - \bar{y})^2}$

Test 2: two-sample t-test (cont.)

- **Null distribution**:
  - Student-t distribution with degree of freedom $df =$ **df** (cf. page 33)
  - Python: stats.t.pdf($t, df =$ **df**)
- **Alternative hypothesis** H_A: $H_A : \mu_E - \mu_0 \neq 0$ - two tailed test
- **Significance level** α: set to 0.05

Test 2: two-sample t-test (cont.)

- Run the experiment and collect data: x is the same data as page 29

```
# Data y in this example is generated using the following command
y = stats.norm.rvs(loc=4.5, scale=0.9, size=50, random_state=2)
>> y = [4.12491794 4.44935986 2.57742351 5.97624373 2.88590797
        3.74242737 4.95259328 3.37924072 3.547843   3.68189315
        4.99630864 6.56298721 4.53738545 3.4938671  4.98515249
        3.96345627 4.48278255 5.5575011  3.82691615 4.50812273
        3.7097029  4.35920925 4.73091341 3.61009886 4.19506023
        4.28743437 3.92611049 3.43114894 3.2209045  4.36185432
        4.25784874 6.50823011 2.30870918 4.60145385 4.83340008
        5.72367048 4.95167149 3.74020767 4.50000879 4.98811731
        4.21784262 5.19391056 2.81871841 6.0580662  5.82091021
        4.1978904  5.0502067  4.54317353 3.75377824 4.5789392 ]
```

  Parameter estimate:
  - **Parameter of interest**: $\bar{x} = 5.092$, $\bar{y} = 4.374$
  - **Nuisance parameter**:

$$s_X = \sqrt{\frac{1}{N_X - 1}\sum_{i=1}^{N_X}(x_i - \bar{x})^2} = 1.172, \quad s_Y = \sqrt{\frac{1}{N_Y - 1}\sum_{i=1}^{N_Y}(y_i - \bar{y})^2} = 0.946$$

Test 2: two-sample t-test (cont.)

- Compute the test statistic t_0 from data:
  - Then compute the test statistic

$$t_0 = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_X^2}{N_X} + \frac{s_Y^2}{N_Y}}} = 3.142$$

- Compute the p-value:

$$p = 2\min(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)) = 0.002$$

- $p < \alpha$: reject H_0

Test 2: two-sample t-test (cont.)

- In this two-sample t-test, we do not assume equal variance for X_i and Y_j; this type of two-sample t-test is also called **Welch's t-test**
- Example implementation in Python:

  stats.ttest_ind(x, y, equal_var=False)

  where equal_var=False means we do not assume equal variance for x and y

Test 3: paired t-test

- **Statement**: drug E does not increase the average sleeping hours of people with insomnia
- **Experiment**: let $N = 40$ people with insomnia take drug E and observe their amount of sleep before and after taking drug E
- **Data**: let $z_1, \cdots, z_N$ and $x_1, \cdots, x_N$ be the sleeping hours of people before and after taking drug E, respectively; **random variable** $X_1 - Z_1, \cdots, X_N - Z_N$ i.i.d.
- **Parameter of interest**: the mean value of the difference μ_{X-Z}; **estimate**: sample mean $\hat{\mu}_{X-Z} = \frac{1}{N}\sum_{i=1}^{N} x_i - z_i$
- **Null hypothesis** H_0: $H_0 : \mu_{X-Z} = 0$

Test 3: paired t-test (cont.)

- **Test statistic**:

$$t_0 = \frac{\hat{\mu}_{X-Z}}{s_{X-Z}/\sqrt{N}}$$

  where $s_{X-Z} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - z_i - \hat{\mu}_{X-Z})^2}$
- **Null distribution**:
  - Student-t distribution with degree of freedom $df = N - 1$
  - Python: stats.t.pdf$(t, df = N - 1)$
- **Alternative hypothesis H_A**: $H_A : \mu_{X-Z} \neq 0$ - two tailed test
- **Significance level α**: set to 0.05

Test 3: paired t-test (cont.)

- Run the experiment and collect data: x is the same data as page 29

```
# Data z in this example is generated using the following command
N = 40
z = stats.norm.rvs(loc=4.5, scale=0.9, size=N, random_state=0)
>> z = [6.08764711 4.86014149 5.38086419 6.51680388 6.18080219
        3.62044991 5.35507958 4.36377851 4.40710303 4.86953865
        4.62963921 5.80884616 5.18493395 4.60950751 4.89947691
        4.80030689 5.84467117 4.31535756 4.78176093 3.73131383
        2.20230917 5.08825674 5.27799258 3.83205148 6.54277916
        3.19107089 4.54118267 4.33153453 5.87950129 5.82242289
        4.63945268 4.84034627 3.70099283 2.71728318 4.18687907
        4.64071407 5.60726161 5.58214186 4.15140586 4.22792752]
```

  Parameter estimate:
  - **Parameter of interest**: $\Rightarrow \hat{\mu}_{X-Z} = 0.311$
  - **Nuisance parameter**: $s_{X-Z} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - z_i - \hat{\mu}_{X-Z})^2} = 1.313$

Test 3: paired t-test (cont.)

- Compute the test statistic t_0 from data:

$$t_0 = \frac{\hat{\mu}_{X-Z}}{s_{X-Z}/\sqrt{N}} = 1.499$$

- Compute the p-value:

$$p = 2\min(P(T \leq t_0 \mid H_0), P(T \geq t_0 \mid H_0)) = 0.142$$

- $p > \alpha$: fail to reject H_0

Example implementation in Python: **stats.ttest_rel(x, z)**

Exercise 2

- One of the tests you have designed is a two-sample test. After the experiments, you realized the test subjects being selected in the second group are parents or siblings of the first group. Would that be a problem? Can you still use the result somehow?
- Solution:
  - The two-sample test is the two-sample t-test (cf. page 32); cannot use the result as it is since the two samples are not independent
  - As a potential solution, we can match related subjects in the first group and the second group to create a paired data set $(x_1, y_1), \cdots, (x_N, y_N)$, i.e. x_i and y_i in each pair are related to each other
  - Apply the paired t-test on the new data set $(x_1, y_1), \cdots, (x_N, y_N)$

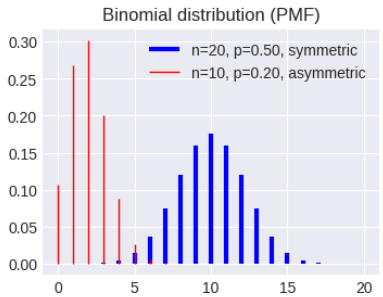
Binomial test

Binomial distribution

- Discrete distribution
- Applies to discrete numerical data - the number of success from n independent Bernoulli trials with probability of success p
- PMF:
  - Equation

$$f_X(k \mid n, p) = P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}, \ k = 0, \cdots, n, \ p \in [0, 1]$$

    where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$ is the binomial coefficient (n choose k)
  - Shape
    - When $p = 0.5$, the PMF is symmetric
    - When $p \neq 0.5$, the PMF is asymmetric



- Parameters: p and n; n is typically known

(exact) Binomial test

- **Typical set up for the experiment**:
  - One sample of independent test subjects, e.g. one sample of independent patients
  - Run the same experiment on all subjects from the sample and collect the outcomes, e.g. give a new drug to a sample of patients and measure how many patients are cured
  - The result contains one sample with **nominal categorical values with two categories**, which is then summarized into one **discrete numerical value** - the number of "success"
- **Purpose**: to test if the proportion of "success" differs from a predefined constant
- **Data**: N independent Bernoulli trials with k_0 "success", e.g. the number of cured patients within the sample of size N
- **Random variable** and **assumption**: $K \sim Binomial(N, p)$ with known N and unknown success rate p
- **Parameter of interest**: p
- **Parameter estimate**: $\hat{p} = \frac{k_0}{N}$
- **Null hypothesis**: given π a constant,

$$H_0 : p = \pi$$

(exact) Binomial test (cont.)

- **Test statistic**: k_0
- **Null distribution**:

$$P(X = k) = \binom{N}{k} \pi^k (1 - \pi)^{N-k}$$

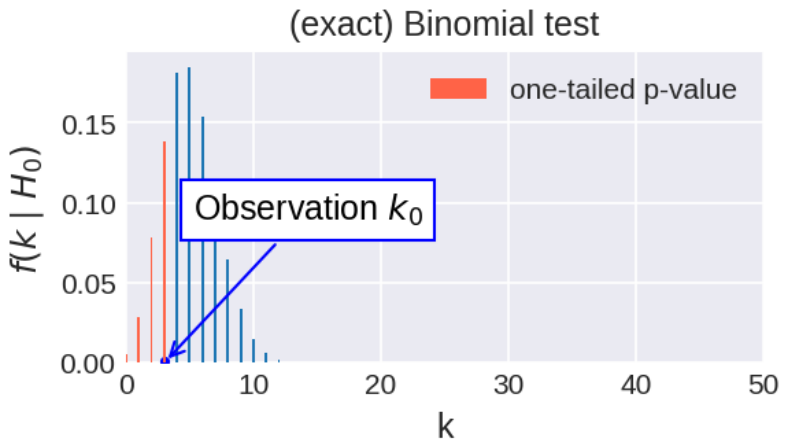
  - Binomial distribution with parameters N and π
  - Python: stats.binom.pmf(k, N, π)
- As discussed in the disclaimer (cf. page 10), we only introduce the following scenarios:
  - One-tailed (left) binomial test with any $\pi \in (0, 1)$
  - One-tailed (right) binomial test with any $\pi \in (0, 1)$
  - Two-tailed binomial test with $\pi = 0.5$, where the null distribution is symmetric

(exact) One-tailed (left) binomial test

- **Hypotheses** H_0 and H_A:

$$H_0: \quad p = \pi$$
$$H_A: \quad p < \pi$$

- p-**value**:
  - Definition: $p = P(K \leq k_0 \mid H_0)$
  - Python: stats.binom.cdf(k_0, n=N, p=π)

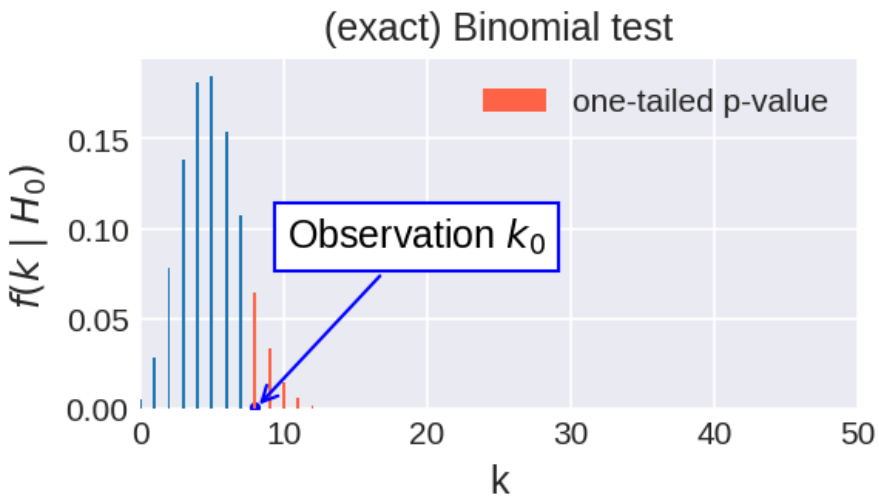


(exact) One-tailed (right) binomial test

- **Hypotheses** H_0 and H_A:

$$H_0: \quad p = \pi$$
$$H_A: \quad p > \pi$$

- ***p*-value**:
  - Definition: $p = P(K \geq k_0 \mid H_0)$
  - Python: $1 - \text{stats.binom.cdf}(k_0, n = N, p = \pi) + \text{stats.binom.pmf}(k_0, n = N, p = \pi)$

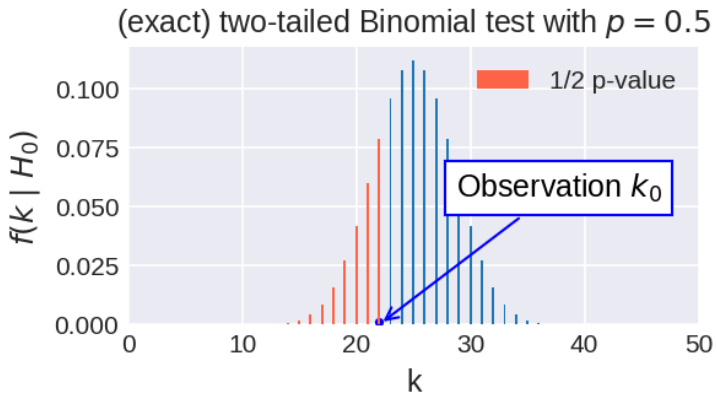


(exact) Two-tailed binomial test

- **Hypotheses** H_0 and H_A:

$$H_0: \quad p = 0.5$$
$$H_A: \quad p \neq 0.5$$

- ***p*-value**:
  - Definition: $p = 2\min\left(P(K \leq k_0 \mid H_0), P(K \geq k_0 \mid H_0)\right)$
  - Python:
    - $c =$ stats.binom.cdf$(k_0, n = N, p = 0.5)$
    - $2 * \min\left(c, 1 - c +$ stats.binom.pmf$(k_0, n = N, p = 0.5)\right)$



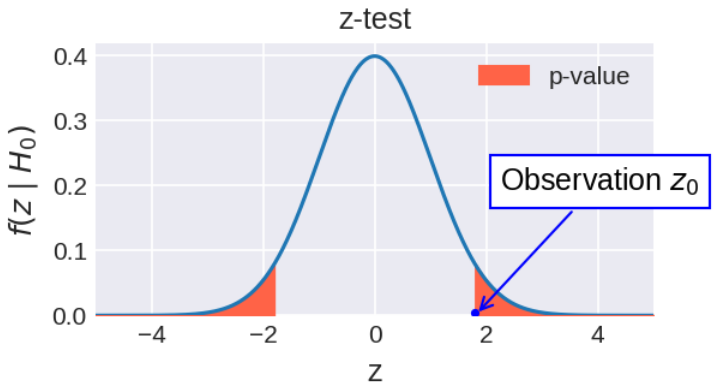
(large N) Binomial test

Same set up as page 45, but with large N

- **Test statistic**:

$$z_0 = \frac{k_0 - N\pi}{\sqrt{N\pi(1-\pi)}}$$

- **Null distribution**: standard normal distribution
  - PDF: $f(z \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$
  - Python: stats.norm.pdf(z, 0, 1)
- ***p*-value**:
  - Definition: $p = 2\min\left(P(Z \leq z_0 \mid H_0), P(Z \geq z_0 \mid H_0)\right)$
  - Python: $2 * \min$(stats.norm.cdf(z_0, 0, 1), 1-stats.norm.cdf(z_0, 0, 1))



McNemar's test

McNemar's test

- **Typical set up for the experiment**:
  - **One sample** of independent test subjects, e.g. one sample of independent patients
  - Within the sample, there are two **groups**; each subject belongs to one and only one group, e.g. within the sample of patients, we have one group with high blood pressure and another group with normal blood pressure
  - Run two sets of experiments A and B on all test subjects from the sample and collect the outcomes, e.g. measure the blood pressure (hight or normal) of the patients **before** giving them a new drug (experiment A); measure the blood pressure (hight or normal) of the patients **after** giving them the new drug (experiment B)
  - The result contains one sample with **nomimal categorical values with two categories** measured from each test subject, e.g. high blood pressure and normal blood pressure
- **Purpose**: to test if an action have different effects on two different **groups**
- **Data**: N independent Bernoulli trials with outcomes $x_1, \cdots, x_N$ and $y_1, \cdots, y_N$ for the two experiments, respectively; $x_i, y_i \in \{0, 1\}$

	$x_i = 0$	$x_i = 1$	
$y_j = 0$	n_{00}	n_{10}	$n_{00} + n_{10}$
$y_j = 1$	n_{01}	n_{11}	$n_{01} + n_{11}$
	$n_{00} + n_{01}$	$n_{10} + n_{11}$	N

  where n_{mn} is the count of $x_i = m$ and $y_j = n$
- **Random variable** and **assumption**: i.i.d. $X_i \sim Bernoulli(p_X)$ and i.i.d. $Y_i \sim Bernoulli(p_Y)$

McNemar's test (cont.)

Example

- A company is trying to determine the effectiveness of a drug on lowering blood pressure
- The company tested the drug on a sample of 229 **independent** patients
- There are **two groups** within this sample: a high blood pressure group (105 patients) and a normal blood pressure group (124 patients); each patient belongs to one and only one of these two groups
- The blood pressure of each patient is measured **before** (to determine the group) and **after** (to determine the effect) taking the drug
- The data is summarized as follows:

	Before (high blood pressure)	Before (normal blood pressure)	
After (high blood pressure)	90	15	105
After (normal blood pressure)	22	102	124
	112	117	229

(small discordance $n_{01} + n_{10}$) McNemar's test (cont.)

- **Parameter of interest**: **discordance**

$$p = \min\left(P(X_i = 0, Y_i = 1 \mid X_i \neq Y_i), P(X_i = 1, Y_i = 0 \mid X_i \neq Y_i)\right)$$

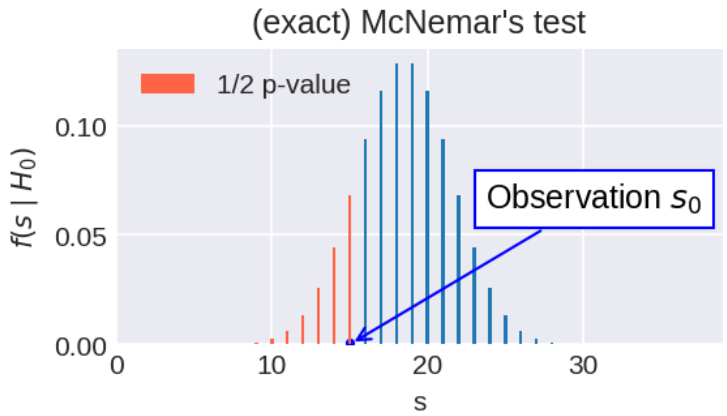
- **Parameter estimate**: $\hat{p} = \frac{\min(n_{01}, n_{10})}{n_{01}+n_{10}}$
- **Hypotheses** H_0 and H_A:

$$\begin{aligned} H_0 : &\quad p = 0.5 \\ H_A : &\quad p \neq 0.5 \end{aligned}$$

  - H_0: the drug does not have any effect on blood pressure control
  - H_1: the drug has effect on blood pressure control

(small discordance $n_{01} + n_{10}$) McNemar's test (cont.)

- **Test statistic**: $s_0 = \min(n_{01}, n_{10})$
- **Null distribution**:
  - Binomial distribution with parameters $(n_{01} + n_{10}, 0.5)$
  - Python: stats.binom.pmf(s, $n_{01} + n_{10}$, 0.5)
- *p*-**value**:
  - Definition: $p = 2P(S \leq s_0 \mid H_0)$
  - Python: $2 *$ stats.binom.cdf($s_0, n_{01} + n_{10}, 0.5$)



(large discordance $n_{01} + n_{10}$) McNemar's test

Same set up as page 52, but with large $n_{01} + n_{10}$, e.g. $n_{01} + n_{10} > 25$

- **Parameter of interest**: **discordance** (note: it is different from the previous definition (cf. page 54)) $p_{01} = P(X = 0, Y = 1)$ and $p_{10} = P(X = 1, Y = 0)$
- **Parameter estimate**: $\hat{p}_{01} = \frac{n_{01}}{N}$ and $\hat{p}_{10} = \frac{n_{10}}{N}$
- **Hypotheses** H_0 and H_A:

$$H_0 : \quad p_{01} = p_{10}$$
$$H_A : \quad p_{01} \neq p_{10}$$

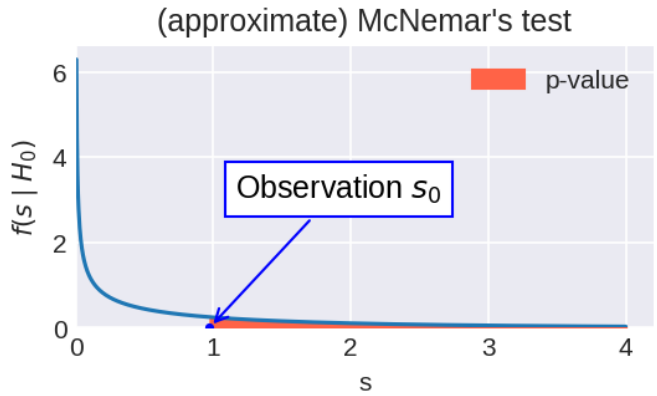
- **Test statistic**:

$$s_0 = \frac{(|n_{01} - n_{10}| - 1)^2}{n_{01} + n_{10}}$$

Note: "-1" is called the continuity correction (https://en.wikipedia.org/wiki/Continuity_correction)

(large discordance $n_{01} + n_{10}$) McNemar's test (cont.)

- **Null distribution**:
  - Chi-squared distribution with $df = 1$
  - Python: stats.chi2.pdf(s, $df = 1$)
- ***p*-value**:
  - Definition: $P(S \geq s_0 \mid H_0)$
  - Python: 1-stats.chi2.cdf(s_0, $df = 1$)



Exercise 3

- Run both the exact McNemar's test and the approximate McNemar's test on the data set provided on page 53

Test 1: exact McNemar's test

- **Data**: contingency table
  - n_{01}: high blood pressure $\overset{\text{take drug}}{\rightarrow}$ normal blood pressure
  - n_{10}: normal blood pressure $\overset{\text{take drug}}{\rightarrow}$ high blood pressure
  - We want to test if there is a difference between $\frac{n_{01}}{n_{01}+n_{10}}$ and $\frac{n_{10}}{n_{01}+n_{10}}$
- **Parameter estimate**: $\hat{p} = \frac{\min(n_{01}, n_{10})}{n_{01}+n_{10}}$
- **Hypotheses** H_0 and H_A:

$$H_0: \quad p = 0.5$$
$$H_A: \quad p \neq 0.5$$

- **Significance level** α: 0.05
- **Collected data**: $n_{01} = 22$, $n_{10} = 15$
- **Test statistic**: $s_0 = \min(n_{01}, n_{10}) = \min(22, 15) = 15$

Test 1: exact McNemar's test (cont.)

- **Null distribution**:
  - Binomial distribution with parameters $(n_{01} + n_{10}, 0.5)$
  - Python: stats.binom.pmf(s, $n_{01} + n_{10}$, 0.5)
- **p-value**: $2P(S \leq 15 \mid H_0) = 0.3239$
- p-value $> \alpha$: fail to reject H_0

Example implementation in Python:

```
from statsmodels.stats import contingency_tables
contingency_tables.mcnemar(table=[[n00, n10], [n01, n11]],
                           exact=True)
```

Args:

- table: the contingency table
- exact=True: exact test

Test 2: approximate McNemar's test

- **Data**: contingency table
  - n_{01}: high blood pressure $\overset{\text{take drug}}{\rightarrow}$ normal blood pressure
  - n_{10}: normal blood pressure $\overset{\text{take drug}}{\rightarrow}$ high blood pressure
  - We want to test if there is a difference between $\frac{n_{01}}{N}$ and $\frac{n_{10}}{N}$
- **Parameter estimate**: $\hat{p}_{01} = \frac{n_{01}}{N}$ and $\hat{p}_{10} = \frac{n_{10}}{N}$
- **Hypotheses** H_0 and H_A:

$$\begin{aligned} H_0 : &\quad p_{01} = p_{10} \\ H_A : &\quad p_{01} \neq p_{10} \end{aligned}$$

- **Significance level**: $\alpha = 0.05$
- **Collected data**: $n_{01} = 22$, $n_{10} = 15$, $n_{00} = 90$, $n_{11} = 102$
- **Test statistic**:

$$s_0 = \frac{(|n_{01} - n_{10}| - 1)^2}{n_{01} + n_{10}} = \frac{(|22 - 15| - 1)^2}{22 + 15} = 0.973$$

Test 2. approximate McNemar's test (cont.)

- **Null distribution**:
  - Chi-squared distribution with $df = 1$
  - Python: stats.chi2.pdf(s, $df = 1$)
- **p-value**: $P(S \geq s_0 \mid H_0) = P(S \geq 0.973 \mid H_0) = 0.324$
- p-value $> \alpha$: fail to reject H_0

Example implementation in Python:

```
from statsmodels.stats import contingency_tables
contingency_tables.mcnemar(table=[[n00, n10], [n01, n11]],
                           exact=False,
                           correction=True)
```

Args:

- table: the contingency table
- exact=False: approximate test
- correction=True: continuity correction (cf. page 56)

Today

K-fold cross validation

- **Classifiers**: A and B
- **Data**: evaluation metric; **continuous numerical data**, e.g. accuracies $p_1^A, \cdots, p_K^A$ and $p_1^B, \cdots, p_K^B$ on the K validation sets

	fold 1	fold 2	$\cdots$	fold K
classifier A	p_1^A	p_2^A	$\cdots$	p_K^A
classifier B	p_1^B	p_2^B	$\cdots$	p_K^B
$p_i^A - p_i^B$	$p_1^A - p_1^B$	$p_2^A - p_2^B$	$\cdots$	$p_K^A - p_K^B$

- **Random variable** and **assumption**: $P_1^A, \cdots, P_K^A$, $P_1^B, \cdots, P_K^B$
  - $P_i^A - P_i^B$ i.i.d.
  - $P_i^A - P_i^B \sim \mathcal{N}\left(\mu_{A-B}, \sigma_{A-B}^2\right)$ with unknown standard deviation
- **Parameter of interest**: μ_{A-B}
- **Parameter estimate**: $m_{A-B} = \frac{1}{K}\sum_{i=1}^K \left(p_i^A - p_i^B\right)$
- **Hypotheses** H_0 and H_A:

$$H_0: \quad \mu_{A-B} = 0$$
$$H_A: \quad \mu_{A-B} \neq 0$$

- **Test statistic**: $t = \frac{m_{A-B}}{s_{A-B}/\sqrt{K}}$, where $s_{A-B} = \sqrt{\frac{1}{K-1}\sum_{i=1}^K \left(p_i^A - p_i^B - m_{A-B}\right)^2}$
- **Hypothesis test**: paired t-test

Training-validation split and leave-one-out cross validation

- **Classifiers**: A and B
- **Data**: classifiers A and B tested on the validation data; the outcome x_i^A and x_i^B can be either correct (0) or incorrect (1); **nominal categorical data** with two categories correct or incorrect

	classifier A correct	classifier A incorrect
classifier B correct	n_{00}=count(A correct, B correct)	n_{10}=count(A incorrect, B correct)
classifier B incorrect	n_{01}=count(A correct, B incorrect)	n_{11}=count(A incorrect, B incorrect)

- **Random variable** and **assumption**: $X_i^A \sim Bernoulli(p_A), X_i^B \sim Bernoulli(p_B)$
- **Test statistic**:
  - Small discordance (e.g. $n_{01} + n_{10} < 25$): $s_0 = \min(n_{01}, n_{10})$
  - Large discordance: $s_0 = \frac{(|n_{01} - n_{10}| - 1)^2}{n_{01} + n_{10}}$
- **Hypothesis test**: McNemar's test
- **Note**: why McNemar's test? - One consideration while developing hypothesis test is to have a reasonably low type I error

Exercise 4

- You have a labeled data set $\mathcal{D} = \{(x_1, y_1), \cdots, (x_N, y_N)\}$
- You developed two classifiers using the 10-fold validation
- Construct a table of the resulting F1 scores for these two classifiers
- Design a hypothesis test to compare these two classifiers

Exercise 5

- You have a labeled data set $\mathcal{D} = \{(x_1, y_1), \cdots, (x_N, y_N)\}$
- You developed two classifiers using the training-validation split
- Construct a table of the results for these two classifiers
- Design a hypothesis test to compare these two classifiers

Today

What is A/B testing?

- A/B testing refers to the methodology for testing two variants of the same type of product
- It is widely used for improving marketing strategies
- Example:
  - **Web design**: a company would like to increase the number of their subscribers by testing a new design for the "subscribe" button on their web page
  - **Product pricing**: a company would like to introduce a new product to the market; they compare two potential prices to see which one maximizes their sales while maintaining a reasonable margin

Today

Summary

So far:

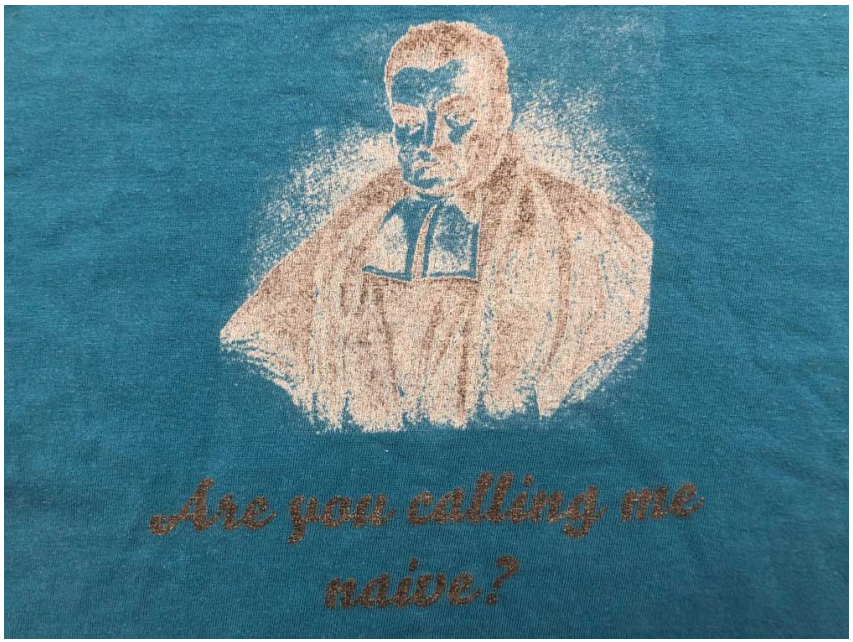
- Data types and data containers
- Descriptive data analysis: descriptive statistics, visualization
- Probability distributions, events, random variables, PMF, PDF, parameters
- CDF, Q-Q plot, how to compare two distributions (data vs theoretical, data vs data)
- Modeling
- Parameter estimation: maximum likelihood estimation (MLE) and maximum a posteriori estimation (MAP)
- Classification, multinomial naive Bayes classifier, Gaussian naive Bayes classifier
- Central limit theorem, interval estimation
- Hypothesis tests, comparison of two classifiers

Next:

- Unsupervised learning, clustering, k-means, Gaussian Mixture Models

Before next lecture:

- Gaussian distribution
- The Bayes' rule



I heard my name again!