

Lecture 8: Hypothesis testing part II

Statistical Methods for Data Science

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December 8 and December 12, 2022

Today

- 1 Test statistics and hypothesis tests
 - z-test
 - One-sample t-test
 - Two-sample t-test (Welch's t-test - unequal variances)
 - Paired t-test
 - Binomial test

Learning outcome

- 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 generalize the learning routine to new hypothesis tests
- Be able to compare two classifiers using the paired t-test and McNemar's test for different scenarios

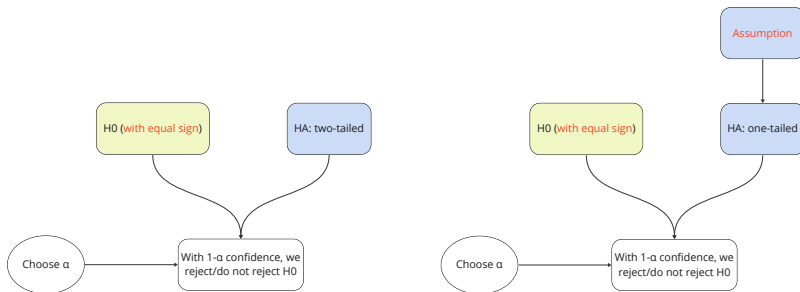
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Remark

Regarding α and one-tailed/two-tailed test



Remark (cont.)

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- 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

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- 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

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 - PDF/PMF: description of the PDF/PMF
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 - 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 6)

z-test

One-sample z-test

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Note: only two-tailed H_A is illustrated here.

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- Test statistic:

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- PDF: $f(z \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$
- Python: `stats.norm.pdf(z, 0, 1)`

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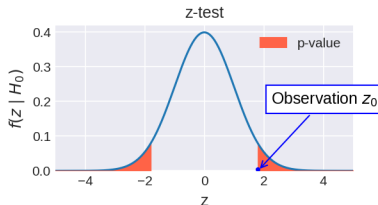
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- **p-value**

- Definition: $p = 2 \min(P(Z \leq z_0 | H_0), P(Z \geq z_0 | H_0))$
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- **Parameter of interest:** μ_X, μ_Y
- **Parameter estimate:** \bar{x}, \bar{y}
- **Hypotheses** H_0 and H_A : given c a constant

$$H_0 : \mu_X - \mu_Y = c$$

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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: $\bar{X} - \bar{Y} \sim \mathcal{N}(\mu_X - \mu_Y, \sigma_X^2/N_X + \sigma_Y^2/N_Y)$

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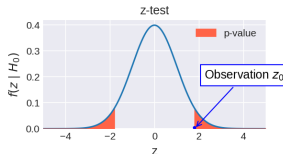
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One-sample t-test

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 - 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 outcomes contain one i.i.d. sample with **continuous numerical values**
- **Purpose**: to test if the mean of the outcomes differs from a predefined constant
- **Data**: x_1, \dots, x_N , e.g. blood pressure after taking a new drug
- **Random variable** and **assumption**: X_1, \dots, 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

$$H_0 : \mu = c$$

$$H_A : \mu \neq c$$

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

One-sample t-test (cont.)

- **Test statistic:**

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- **Null distribution:**

- Student's-t distribution with degrees of freedom $df = N - 1$
- Python: `stats.t.pdf(t, df = N - 1)`

One-sample t-test (cont.)

- **Test statistic:**

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

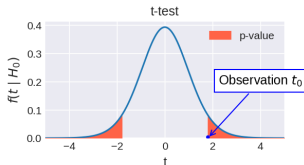
where $s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2}$ is the sample standard deviation

- **Null distribution:**

- Student's-t distribution with degrees of freedom $df = N - 1$
- Python: `stats.t.pdf(t, df = N - 1)`

- **p-value:**

- Definition: $p = 2 \min(P(T \leq t_0 | H_0), P(T \geq t_0 | H_0))$
- Python: `2 * min(stats.t.cdf(t_0, df = N - 1), 1 - stats.t.cdf(t_0, df = N - 1))`



Two-sample t-test (Welch's t-test - unequal variances)

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 drug D to patient sample \mathcal{X} and drug E to patient sample \mathcal{Y} 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 outcomes contain two i.i.d. samples with continuous numerical values
- **Purpose**: to test if two alternative options have different effects by testing if the means differ by a constant
- **Data**: x_1, \dots, x_{N_X} and y_1, \dots, y_{N_Y} , e.g. blood pressure measured after taking two different drugs
- **Random variable** and **assumption**: X_1, \dots, X_{N_X} , Y_1, \dots, 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

$$H_0 : \mu_X - \mu_Y = c$$

$$H_A : \mu_X - \mu_Y \neq c$$

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

Two-sample t-test (cont.)

- **Test statistic:**

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

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- **Null distribution:**

- Student's-t distribution with degrees of freedom df
- Python: `stats.t.pdf(t, df = df)`

Two-sample t-test (cont.)

- **Test statistic:**

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

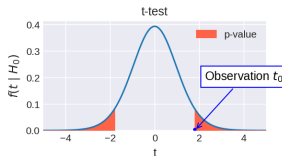
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- Python: `2 * min(stats.t.cdf(t_0, df= df), 1-stats.t.cdf(t_0, df= df))`



Paired t-test

Paired t-test

- Typical set up for the experiment:

Paired t-test

- **Typical set up for the experiment:**
 - Typically one sample of independent test subjects, e.g. one sample of independent patients; or two paired samples

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- Typically one sample of independent test subjects, e.g. one sample of independent patients; or two paired samples
- 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 a sample of patients **before** giving them a new drug (experiment A); measure the blood pressure of these patients **after** giving them the new drug (experiment B)

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- **Purpose:** to test if two alternative options have different effects by testing if the mean of their differences differs from a predefined constant

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- The outcomes contain two samples with **continuous numerical values**

- **Purpose:** to test if two alternative options have different effects by testing if the mean of their differences differs from a predefined constant

- **Data:** $x_1, \dots, x_N, y_1, \dots, y_N$

- **Random variable and assumption:** $X_1, \dots, X_N, Y_1, \dots, Y_N$

- $X_i - Y_i$ i.i.d.
- $X_i - Y_i \sim \mathcal{N}(\mu_{X-Y}, \sigma_{X-Y}^2)$ or large N (CLT)
- standard deviation unknown

Paired t-test

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- standard deviation unknown

- **Parameter of interest:** μ_{X-Y}

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- The outcomes contain two samples with **continuous numerical values**

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- **Random variable and assumption:** $X_1, \dots, X_N, Y_1, \dots, Y_N$

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- $X_i - Y_i \sim \mathcal{N}(\mu_{X-Y}, \sigma_{X-Y}^2)$ or large N (CLT)
- standard deviation unknown

- **Parameter of interest:** μ_{X-Y}

- **Parameter estimate:** $m_{X-Y} = \frac{1}{N} \sum_{i=1}^N (x_i - y_i)$

Paired t-test

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- standard deviation unknown

- **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

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

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

Paired t-test

- **Test statistic:**

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

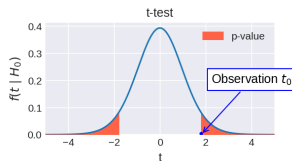
where $s_{X-Y} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - y_i - m_{X-Y})^2}$

- **Null distribution:**

- Student's-t distribution with degrees of freedom $N - 1$
- Python: `stats.t.pdf(t, df = N - 1)`

- **p-value:**

- Definition: $p = 2 \min(P(T \leq t_0 | H_0), P(T \geq t_0 | H_0))$
- Python: `2 * min(stats.t.cdf(t_0, df = N - 1), 1 - stats.t.cdf(t_0, df = N - 1))`



Exercise 1

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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 known constant

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- **Experiment:** let $N = 40$ people with insomnia take drug E and observe the amount of their sleep

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- **Experiment:** let $N = 40$ people with insomnia take drug E and observe the amount of their sleep
- **Data:** x_1, \dots, x_N the sleeping hours of people who have taken drug E; **random variable** X_1, \dots, X_N i.i.d.

Test 1: one-sample t-test

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- **Data:** x_1, \dots, x_N the sleeping hours of people who have taken drug E; **random variable** X_1, \dots, X_N i.i.d.
- **Parameter of interest:** the mean value μ ; **estimate:** sample mean

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

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- **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 known constant - say, it is 4.5 hours
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$$\hat{\mu} = \bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$$

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

Test 1: one-sample t-test

- **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 known constant - say, it is 4.5 hours
- **Experiment:** let $N = 40$ people with insomnia take drug E and observe the amount of their sleep
- **Data:** x_1, \dots, x_N the sleeping hours of people who have taken drug E; **random variable** X_1, \dots, 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 :** $H_0 : \mu = 4.5$
- **Significance level α :** set to 0.05

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's-t distribution with degrees 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

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

$$t_0 = \frac{\bar{x} - 4.5}{s/\sqrt{N}} = \frac{5.09 - 4.5}{1.172/\sqrt{40}} = 3.197$$

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

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 25

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, \dots, x_{N_X} sleeping hours of people with insomnia who have taken drug E; **random variable** X_1, \dots, X_{N_X} i.i.d.
 - y_1, \dots, y_{N_Y} sleeping hours of people with insomnia who have not taken drug E; **random variable** Y_1, \dots, Y_{N_Y} i.i.d.
 - X_i and Y_j independent, for $i = 1, \dots, N_X, j = 1, \dots, N_Y$

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 $\hat{\mu}_E = \bar{x} = \frac{1}{N_X} \sum_{i=1}^{N_X} x_i$
- 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 degrees 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

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

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

- **Null distribution:**
 - Student's-t distribution with degrees of freedom **df** (cf. page 29)
 - 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 25

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, \dots, z_N and x_1, \dots, x_N be the sleeping hours of people before and after taking drug E, respectively; **random variable** $X_1 - Z_1, \dots, X_N - Z_N$ 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's-t distribution with degrees 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 25
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

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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 twins of the first group (and they both have insomnia. Duh!). Would that be a problem? Can you still use the result somehow?

Exercise 2

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- Solution:
 - The two-sample test is the two-sample t-test (cf. page 28); cannot use the result as 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 $(x_1, y_1), \dots, (x_N, y_N)$, 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 $(x_1, y_1), \dots, (x_N, y_N)$

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- Discrete distribution

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- Applies to discrete numerical data - the number of success from n independent Bernoulli trials with probability of success p

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where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$ is the binomial coefficient (choose k from n)

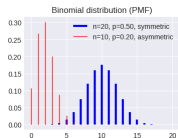
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- Shape
 - When $p = 0.5$, the PMF is symmetric
 - When $p \neq 0.5$, the PMF is asymmetric



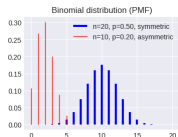
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 - When $p \neq 0.5$, the PMF is asymmetric



- Parameters: p and n ; n is typically known

(exact) Binomial test

- Typical set up for the experiment:

(exact) Binomial test

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 - One sample of independent test subjects, e.g. one sample of independent patients

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- **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

(exact) Binomial test (cont.)

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

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

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- Binomial distribution with parameters N and π

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- Binomial distribution with parameters N and π
- Python: `stats.binom.pmf(k, N, π)`

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- As discussed in the remarks (cf. page 6), we only introduce the following scenarios:

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- **Null distribution:**

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- Binomial distribution with parameters N and π
- Python: `stats.binom.pmf(k, N, π)`
- As discussed in the remarks (cf. page 6), we only introduce the following scenarios:
 - One-tailed (left) binomial test with any $\pi \in (0, 1)$

(exact) Binomial test (cont.)

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

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 - One-tailed (right) binomial test with any $\pi \in (0, 1)$

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- **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
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- As discussed in the remarks (cf. page 6), 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

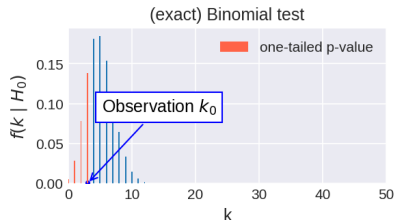
- Hypotheses H_0 and H_A :

$$H_0 : p = \pi$$

$$H_A : p < \pi$$

- p -value:

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



(exact) One-tailed (right) binomial test

- Hypotheses H_0 and H_A :

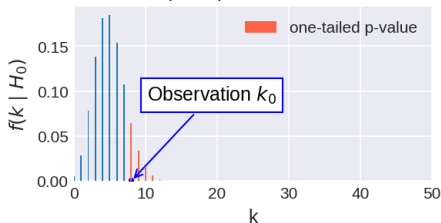
$$H_0 : p = \pi$$

$$H_A : p > \pi$$

- p -value:

- Definition: $P(K \geq k_0 \mid H_0)$
- Python: `1 - stats.binom.cdf(k_0, n = N, p = π) + stats.binom.pmf(k_0, n = N, p = π)`

(exact) Binomial test



(exact) Two-tailed binomial test

- Hypotheses H_0 and H_A :

$$H_0 : p = 0.5$$

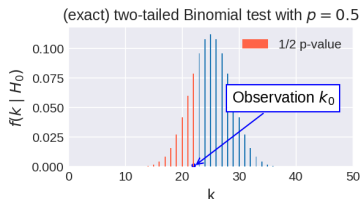
$$H_A : p \neq 0.5$$

- p -value:

- Definition: $2 \min(P(K \leq k_0 | H_0), P(K \geq k_0 | H_0))$

- Python:

- `c = stats.binom.cdf(k0, n = N, p = 0.5)`
- `2 * min(c, 1 - c + stats.binom.pmf(k0, n = N, p = 0.5))`



(large N) Binomial test

Same set up as page 41, but with large N

- **Test statistic:**

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

- **Null distribution:** standard normal distribution

- PDF: $f(z | H_0) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$
- Python: `stats.norm.pdf(z, 0, 1)`

- **p-value:**

- Definition: $p = 2 \min(P(Z \leq z_0 | H_0), P(Z \geq z_0 | H_0))$
- Python: `2 * min(stats.norm.cdf(z_0, 0, 1), 1-stats.norm.cdf(z_0, 0, 1))`

