

Introduction to Machine Learning

NPFL 054

<http://ufal.mff.cuni.cz/course/npfl054>

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Lecture #11

Statistical tests and applications in ML

Statistical hypothesis testing

- General principles of hypothesis testing
 - classical examples: Fisher's motivation, fair die, classifier accuracy
 - null hypothesis, test statistic, p-values, significance and confidence levels
 - rejecting the null hypothesis
 - confidence intervals
- Testing the mean of normal population
 - t-test and critical values
 - confidence interval for the mean (of normal distribution)
 - paired t-test

General principles of hypothesis testing

Example 1 – historical

Lady tasting tea – a famous example introduced by R. Fisher (1935)

The example is based on a real story. Fisher met a lady (Muriel Bristol) who claimed to be able to tell whether the tea or the milk was added first to a cup.

First we need to design an experiment to test her ability.

Then we need to meaningfully evaluate the result of the experiment.

Lady tasting tea – Experiment 1

The Lady is provided with 2 randomly ordered cups of tea – 1 prepared by first adding milk, the other prepared by first adding the tea. She should select the one prepared by first adding milk.

Result: The Lady selected the cup prepared by first adding milk.

What can we conclude from this experiment?

Lady tasting tea – Experiment 2

We repeat the Experiment 1 four times.

The Lady is provided with 4 pairs of 2 randomly ordered cups of tea – in each pair one cup is prepared by first adding milk, the other prepared by first adding the tea. From each pair she should select the one prepared by first adding milk.

Result: The Lady selected the 4 cups prepared by first adding milk.

What can we conclude from this experiment?

Obviously, the Experiment 2 is more convincing than the Experiment 1.

Lady tasting tea – Experiment 3 (Fisher's)

In fact, Fisher proposed to give her eight cups, four of each variety, in random order.

The Lady is provided with 8 randomly ordered cups of tea – 4 prepared by first adding milk, 4 prepared by first adding the tea. She should select the 4 cups prepared by first adding milk.

Result: The Lady selected the 4 cups prepared by first adding milk.

What can we conclude from this experiment?

Both Experiment 2 and Experiment 3 indicate that the results are probably not random. Which one is more convincing?

Fisher's experiment – random selection

Compute the probability of getting the observed result **if** the selection is random?

```
# the eight cups -- four T and four F
> cups = c(T,T,T,T,F,F,F,F)

# one million random experiments
> N = 10^6; s = numeric(N)
> for(i in 1:N) s[i] = sum(sample(cups, 4, rep=F))
> table(s)
s
 0      1      2      3      4
14433 228323 514215 228763 14266

# the probability of getting 4 T at random is
> mean(s == 4)
[1] 0.014266
```

Or, since the statistic has hypergeometric distribution, you can simply do

```
> dhyper(4,4,4,4)
[1] 0.01428571
```

Lady tasting tea

– interpretation and analysis of the experiments

How to interpret the three experiments in the framework of “statistical hypothesis testing” originally coined by R. Fisher?

- The **null hypothesis** H_0 is that the Lady has no such ability to recognize cups prepared by first adding milk.
 - null hypothesis means that she (hypothetically) does random selection
- The **test statistic** is a simple count of the number of successes in selecting the correct cups.
- The probability of getting the observed result (= the statistic value) at random is
 - 50 % in the Experiment 1
 - 6.25 % in the Experiment 2
 - 1.43 % in the Experiment 3

Rejecting the null hypothesis based on p-value

Assuming that the null hypothesis is true, the probability of getting the observed result in Experiment 3 is only 1.43%, which *could be considered as* a good reason to **reject the null hypothesis**.

P-value

In statistical tests, p-value is the probability of obtaining a test statistic result at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.

The null hypothesis is rejected if the p-value is small enough

So, we need to set a threshold for the p-value.

Test significance level α and confidence level $1 - \alpha$

Could we make wrong decision when rejecting the null hypothesis?

- Yes, in the example above there is 1.43 % chance of getting the result even if the Lady selected randomly!
- Such an error is called error of the first kind or “Type I Error”.

The null hypothesis should be only rejected when an error is very unlikely

- Therefore we choose a **significance level** α as a threshold for p-value
 - α is the test's probability of incorrectly rejecting the null hypothesis
- Then the null hypothesis will be only rejected when p-value $< \alpha$
- Usually, $\alpha = 5\%$ or 1% or 0.5% or something like that
- The corresponding value $1 - \alpha$ is called **confidence level**
 - which is the probability of not doing the error of the first kind

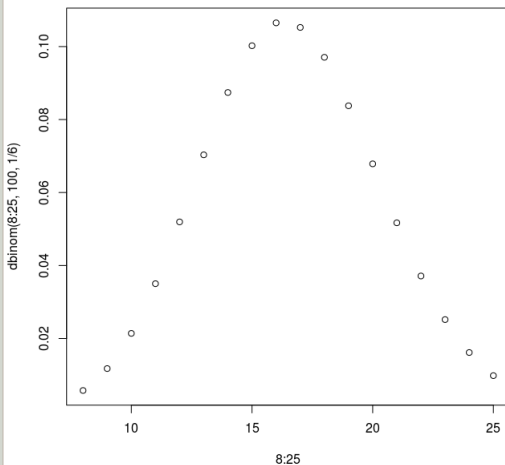
Remember: The significance level α is a property of the test itself, while p-value is derived from the observed data!

Česká terminologie

- significance level $\alpha = \textit{hladina významnosti testu}$
- confidence level $1 - \alpha = \textit{hladina spolehlivosti testu}$
- interval hodnot statistiky (e.g. t-values), které lze pozorovat s pravděpodobností (pouze) α se nazývá *kritický obor*
→ pokud statistika padne do kritického oboru, zamítáme H_0
- α je míra rizika, že uděláme chybu I. druhu, tj. že chybně zamítneme H_0 , ačkoliv ona platí
- p-value = p-hodnota = *dosažená hladina testu*

Example 2 – Is your die fair?

You have got only 10 sixes when rolling a die 100 times



Example 3 – Classifier accuracy

Example

Test sample size = 100; there are 73 correctly classified instances.

– **Is it possible that classifier accuracy is 76 %?**

Example 4 – men's height mean

Assume that the population of men's height is normally distributed with the known variance $\sigma^2 = 100$ and an unknown mean μ . In other words, the men's height will be represented by a continuous random variable X so that

$$X \sim N(\mu = ?, \sigma^2 = 100).$$

We have a sample of $n = 10$ men's heights:

```
> observation
[1] 174.7 178.0 195.9 181.0 181.6 197.5 184.9 167.6 173.4 175.8
```

Are we able to reliably estimate the mean of the population?

The best estimate is given by the **sample mean**:

```
> mean(observation)
[1] 181.04
```

Why do you believe that this estimate is the best one?

How confident are you about the estimated mean?

Men's height mean – test statistic distribution

The sample average $\bar{x} = \frac{1}{n} \sum x_i$ will be used as a **test statistic**.

- What is the distribution of the average represented by the random variable \bar{X} when we randomly sample the population?

Theorem

If X_1, \dots, X_n are independent and have the same distribution $N(\mu, \sigma^2)$, then

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad \text{has the distribution} \quad N\left(\mu, \frac{\sigma^2}{n}\right).$$

When we formulate a hypothesis about the population mean, we will know the hypothetical distribution of the statistic. Hence, we will be able to compute the probability of the observed statistic.

Men's height mean – first example hypothesis

Let us consider the following null hypothesis about the population mean
 $H_0 : \mu = 190$.

Under that assumption the distribution of the sample average is
 $\bar{X} \sim N(\mu = 190, \sigma^2 = 100/10)$. (orig. σ^2 is divided by the averaged sample size)

Then, what is the probability that $\bar{X} \leq 181.04$?

The answer is 0.23 %.

```
> pnorm(181.04, 190, sqrt(10))  
[1] 0.00230278  
>
```

Similarly, the probability that $\bar{X} \geq 198.96$ is also 0.23 %.

Conclusion

Assuming that the null hypothesis is true, the probability of obtaining the test statistic \bar{x} as extreme or more extreme as the one that was actually observed is only 0.46 % (= the p-value). Hence, with the significance level $\alpha = 5\%$ we will reject the hypothesis.

Men's height mean – second example hypothesis

Let us consider the following null hypothesis about the population mean

$$H_0 : \mu = 180.$$

Under that assumption the distribution of the sample average is

$$\bar{X} \sim N(\mu = 180, \sigma^2 = 100/10). \quad (\text{orig. } \sigma^2 \text{ is divided by the averaged sample size})$$

Then, what is the probability that $\bar{X} \geq 181.04$?

The answer is 37.1 %.

```
> 1 - pnorm(181.04, 180, sqrt(10))  
[1] 0.3711244  
>
```

Similarly, the probability that $\bar{X} \leq 178.96$ is also 37.1 %.

Conclusion

We will not reject the hypothesis. Assuming that the null hypothesis is true, the probability of obtaining the test statistic \bar{x} as extreme or more extreme as the one that was actually observed is 74.2 %. If we rejected the hypothesis, we would take the 74.2 % risk of doing the error of the first kind.

Men's height mean – confidence interval

Obviously, hypothesized values of μ that are relatively close to the observed \bar{x} *would not be rejected*. On the other hand, values that are too far from the observed \bar{x} *would be rejected*.

Question: What is the interval of all possibly hypothesized values of μ that would NOT be rejected?

- to determine this interval you need to know or choose a required significance level α
- this interval is called **confidence interval** for the population mean with the confidence level $1 - \alpha$

Statistical tests – first little summary

Statistical tests are used to test a hypothesis about a population

Always we observe only a sample (often only a small one) of the population. Then we should make a decision according to this observation. Having the observed data we compute a test statistic.

The value of the test statistic can be

- in contradiction with the hypothesis
→ then we **reject** the hypothesis
- NOT in contradiction with the hypothesis
→ then we **do not reject** the hypothesis

Example 5 – Confidence interval for the mean of normal population *with known variance* σ^2

Example exercise

Given the confidence level 99 %, find the confidence interval for the men's height population mean based on the given observation. The given assumptions are:

- the men's height population variance $\sigma^2 = 100$
- the observed sample mean $\bar{x} = 181.04$
- the observed sample size $n = 10$

The confidence interval contains all possible values of the population mean that could not be rejected if hypothesized at the given confidence level.

To generally derive how to compute the confidence interval we will use standardized normal distribution and its critical values.

Expected value and variance – basic properties

For any random variables X, Y and any $a, b \in \mathbb{R}$ the following holds true:

- $E(a + bX) = a + bEX$
- $E(X + Y) = EX + EY$
- if X and Y are independent, then $E(XY) = EXEY$

Variance of a random variable is defined by

$$\text{var } X = E(X - EX)^2.$$

If a random variable X has finite variance, then the following holds true:

- $\text{var } X = EX^2 - (EX)^2$
- $\text{var}(a + bX) = b^2 \text{var } X$
- $\sqrt{\text{var}(a + bX)} = |b| \sqrt{\text{var } X}$

Standardized random variable

Definition

If a random variable X has non-zero finite variance, then $Z = \frac{X - EX}{\sqrt{\text{var } X}}$ is called *standardized* random variable.

Note: If Z is standardized, then $EZ = 0$ and $\text{var } Z = 1$.

Standardized normal distribution – notation

If $X \sim N(\mu, \sigma^2)$ then standardized variable $Z = \frac{X - EX}{\sqrt{\text{var } X}} = \frac{X - \mu}{\sigma}$ has the distribution $N(0, 1)$. Usual notation for standardized normal distribution is

- φ for the density,
- Φ for the distribution function,
- Φ^{-1} for the quantile function.

Quantiles and critical values

Definition

Quantile function of a random variable X is defined as

$$F_X^{-1}(\alpha) = \inf\{x : F(x) \geq \alpha\},$$

where F_X is the distribution function of X and $\alpha \in (0, 1)$.

Value $F^{-1}(\alpha)$ is called α -quantile.

Note: 0.5-quantile $F^{-1}(0.5)$ is called *median*.

Definition

Critical value of the standard normal distribution is defined as $z(\alpha) = \Phi^{-1}(1 - \alpha)$.

Note: If $Z \sim N(0, 1)$, then

- $\Pr\{Z > z(\alpha)\} = \alpha$
- $\Pr\{|Z| > z(\alpha/2)\} = \alpha$

Computing confidence interval

Example exercise

Given the confidence level 99 %, find the confidence interval for the men's height population mean based on the given observation. The given assumptions are:

- the men's height population variance $\sigma^2 = 100$
- the observed sample mean $\bar{x} = 181.04$
- the observed sample size $n = 10$

The confidence interval contains all possible values of the population mean that could not be rejected if hypothesized at the given confidence level.

Idea of the solution

The confidence interval is a symmetric interval around the observed sample mean \bar{x} . Hence, we are looking for the confidence interval radius r so that the null hypothesis $H_0 : \mu = \mu_0$ is rejected if and only if $|\bar{x} - \mu_0| > r$.

Then the confidence interval will be given by $(\bar{x} - r, \bar{x} + r)$.

Assuming that $H_0 : \mu = \mu_0$ is valid, we have $\bar{X} - \mu_0 \sim N(0, \sigma^2/n)$.

Since the significance level α , which is the probability of incorrectly rejecting the null hypothesis, is given, we should choose the confidence interval radius r so that

$$\Pr\{|\bar{X} - \mu_0| > r\} = \alpha,$$

and after standardization

$$\Pr\left\{\left|\frac{\bar{X} - \mu_0}{\sigma/\sqrt{n}}\right| > \frac{r}{\sigma/\sqrt{n}}\right\} = \alpha,$$

which means that $\frac{r}{\sigma/\sqrt{n}} = z(\alpha/2)$, and thus $r = \frac{\sigma}{\sqrt{n}} z(\alpha/2)$.

Therefore the confidence interval for the population mean μ is

$$\left(\bar{x} - \frac{\sigma}{\sqrt{n}} z(\alpha/2), \bar{x} + \frac{\sigma}{\sqrt{n}} z(\alpha/2)\right),$$

and $\Pr\left\{\bar{X} - \frac{\sigma}{\sqrt{n}} z(\alpha/2) < \mu < \bar{X} + \frac{\sigma}{\sqrt{n}} z(\alpha/2)\right\} = 1 - \alpha$.

Example 6 – testing the classifier accuracy mean

You have two models, **A** and **B**, and for each of them 10 results – accuracies obtained from 10-fold cross-validation experiment.

```
> A.acc
[1] 0.853 0.859 0.863 0.871 0.832 0.848 0.863 0.860 0.850 0.849
> mean(A.acc)
[1] 0.8548

> B.acc
[1] 0.851 0.848 0.862 0.871 0.835 0.836 0.860 0.859 0.841 0.843
> mean(B.acc)
[1] 0.8506
```

The average accuracy of **A** is 85.48 %, while the average accuracy of **B** is only 85.06 %.

Question: Is model A *really* better than model B?

Using t-distribution as the principle of t-test

What if you do NOT know the variance?

When we get k different results from the cross-validation experiment, we can assume that the values are (approximately) normally distributed. Then we use t-test.

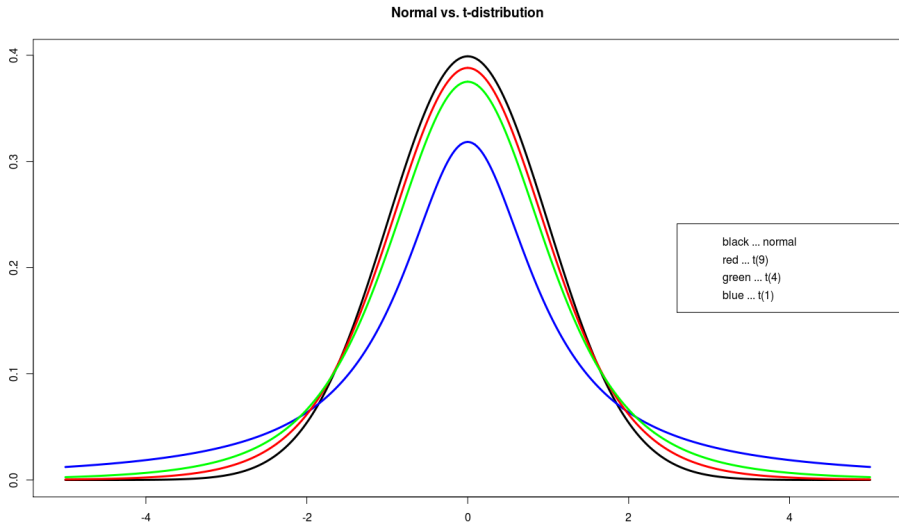
Theorem

If x_1, \dots, x_n is a random sample of size n selected from a normally distributed population, then

$$T = \frac{\bar{X} - \mu}{S} \sqrt{n} \sim t_{n-1},$$

where n is the sample size, \bar{X} is the sample mean, S is the sample standard deviation, μ is the population mean, T is called t-statistic, and t_{n-1} stands for t-distribution with $n - 1$ degrees of freedom.

Normal vs. t-distribution



Using t-test – practical procedure

First, compute **t-value** $T = \frac{\bar{X} - \mu}{S} \sqrt{n}$.

Then compare the t-value with the critical value $t_k(\alpha)$.

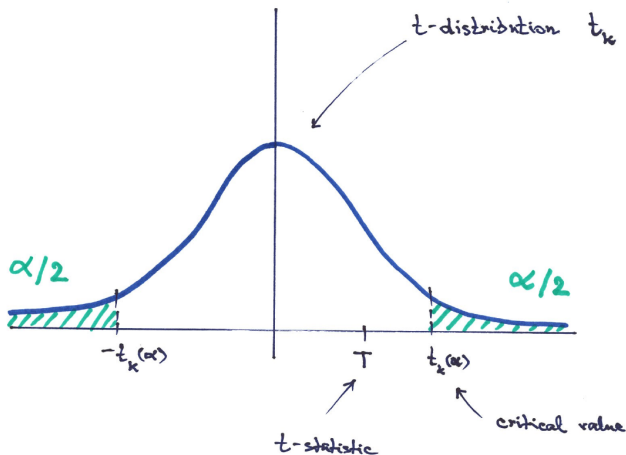
Definition

Critical value $t_k(\alpha)$ of the t-distribution t_k is defined by the equation $\Pr\{|T| \geq t_k(\alpha)\} = \alpha$, where α is the test significance level.

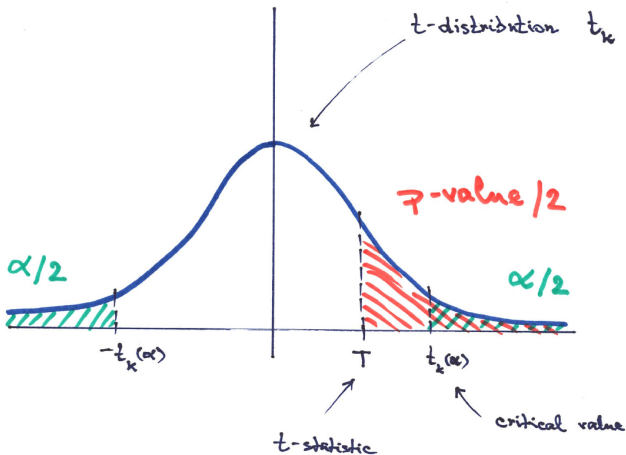
Therefore $\Pr\{-t_{n-1}(\alpha) < \frac{\bar{X} - \mu}{S} \sqrt{n} < t_{n-1}(\alpha)\} = 1 - \alpha$

Note: Critical value corresponds to a given significance level and determines the boundary between those samples resulting in a test statistic that leads to rejecting the null hypothesis and those that lead to a decision not to reject the null hypothesis. If the calculated value from the statistical test is greater than the critical value, then the null hypothesis is rejected in favour of the alternative hypothesis, and vice versa.

Critical value $t_k(\alpha)$ of the t-distribution t_k



Comparing critical value $t_k(\alpha)$ with t-statistic T



$$|T| \leq t_k(\alpha) \\ \Rightarrow p\text{-value} \geq \alpha$$

Confidence interval for the mean μ using t-test

- If \bar{x} is the sample mean of a sample of the size n randomly chosen from a normally distributed population and α is a significance level, then **confidence interval** for the population mean μ is

$$\left(\bar{x} - \frac{S}{\sqrt{n}} t_{n-1}(\alpha), \bar{x} + \frac{S}{\sqrt{n}} t_{n-1}(\alpha) \right)$$

- The probability that the (true) population mean μ lies inside the confidence interval is equal to $1 - \alpha$, which is called **confidence level**.

$$\Pr \left\{ \bar{X} - \frac{S}{\sqrt{n}} t_{n-1}(\alpha) < \mu < \bar{X} + \frac{S}{\sqrt{n}} t_{n-1}(\alpha) \right\} = 1 - \alpha$$

Example 6 – checking the confidence interval

To test if the difference between the models **A** and **B** is **statistically significant** we will check **confidence intervals** for the mean accuracy.

```
### Could the true mean of A accuracy be 0.8506?  
> t.test(A.acc, mu=0.8506)  
    One Sample t-test  
  
data:  A.acc  
t = 1.2195, df = 9, p-value = 0.2537  
alternative hypothesis: true mean is not equal to 0.8506  
95 percent confidence interval:  
 0.8470088 0.8625912  
sample estimates:  
mean of x  
 0.8548
```

We cannot reject the null hypothesis that the mean of A accuracy is equal to 0.8506. The t-test says that the true mean of A accuracy could be between 0.847 and 0.863, which is the confidence interval at the significance level $\alpha = 5\%$.

Similarly, you can check the confidence interval for the mean accuracy of classifier B:

```
### Could the true mean of B accuracy be 0.8548?  
> t.test(B.acc, mu = 0.8548)  
  
One Sample t-test  
  
data: B.acc  
t = -1.0974, df = 9, p-value = 0.301  
alternative hypothesis: true mean is not equal to 0.8548  
95 percent confidence interval:  
 0.8419418 0.8592582  
sample estimates:  
mean of x  
 0.8506
```

When you get k different results from the cross-validation experiment, what can you conclude then?

① One Sample t-test

– to test if the mean of a (normally distributed) population is equal to a given value

② Paired Two-Sample t-test

– to test if the difference of the means of two populations is equal to zero (or to another given value)
– assuming that the given samples contain paired individuals

Example 7 – paired t-test

Using the same input data as in Example 6

```
### Could the true mean of the difference be equal to zero?
> t.test(A.acc, B.acc, paired=T)

      Paired t-test

data:  A.acc and B.acc
t = 2.6296, df = 9, p-value = 0.02738
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 0.0005868378 0.0078131622
sample estimates:
mean of the differences
                0.0042
```

This test says that we can reject the null hypothesis that the mean of the difference between A accuracy and B accuracy is equal to 0.

Because the paired t-test shows that the true mean of the difference could be between (approximately) 0.00058 and 0.0078, which is the confidence interval at the significance level $\alpha = 5\%$.

Homework exercises

Go through all **examples** in this presentation and make sure that you understand them!

Compute the **confidence intervals** for men's height population mean at confidence levels 90 %, 95 %, and 99 % (the exercise from page 17 – Example 4).

What would change IF you do not know the variance?

- Compute the confidence intervals again!

Go through the **tutorial** posted for the lab session and make sure that you are able to successfully do all the exercises!

Summary – examination requirements

You should understand and should be able to practically use

- general principles of statistical tests
 - significance and confidence levels, critical values, p-values
- confidence intervals for the mean of normal distributions
 - you do not have to know the proofs
- practical use of t-test for population mean, paired t-test

Note: Example 5 in this presentation is not obligatory; its purpose is to show how to derive the formula for confidence intervals. However, on pages 20–22 you can find important mathematical notation and definitions.