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PRACTICAL INFORMATION

Today's lecture:

- inference for **one** and **two proportions**:¹
 - * similar breakdown of designs as for continuous data,
 - * mix of familiar z -type inference and new approaches,
 - * inference for 2 proportions continues in Session 8 (Two-way tables),
- **nonparametric methods** for one and two (continuous) samples
 - **sign test** and **rank-based tests**²:
 - * the sign test can be understood as a binomial test,³
 - * for rank-based tests, all calculations are based on statistical software (despite details about hand calculation of P -values in the textbook chapter).

Scheduling notes:

- second home assignment due tomorrow, Friday October 20 (anytime),
- information about **mid-term exam**:
 - * Tuesday October 24, 11:00am-12:00pm, AVC 287N,
 - * new course syllabus page posted (for mid-term),
 - * see (mid-term) exams from previous years for examples.

¹ PSLS 4e: Chapters 19-20; S: Chapter 8-9 (parts); IPS 7e: Chapter 8.

² PSLS Supplementary Chapter 27 on rank-based tests.

³ Despite the sign test not being covered in PSLS and S texts, it is still included in the course!

INFERENCE FOR PROPORTIONS – OVERVIEW

Basic assumption: binomial setting(s) \Rightarrow binomial distribution $B(n, p)$ for number of “successes”, where n = number of “trials” and p = probability of success.

Same **3 fundamental designs** as for quantitative data:

- **one sample** — one binomial distribution, parameter of interest is p ,
- **two independent samples** — two binomial distributions \Rightarrow focus on $p_1 - p_2$,⁴
- **two paired samples** — not in textbooks, but discussed as a sign test.⁵

Statistical inference:

- **estimation:** always use sample proportions,
- several approaches for **confidence intervals:**
 - * classical⁶ approximation of $B(n, p)$ by $N(np, \sqrt{np(1-p)})$,
 - * “plus four” (Wilson) adjustment of classical approach,
 - * “exact” based on binomial distribution (1-sample setting only),
- several approaches for **tests:**
 - * classical⁶ z -test approximation,
 - * exact based on binomial or other distributions.

⁴ $p_1 - p_2$ is the **risk difference**, rather than risk ratio or odds ratio (Epidemiology).

⁵ Two paired samples often lead to McNemar’s test or to κ (kappa)-calculations.

⁶ “Classical” (also “normal approximation”) refers to methods based on the standard normal (z) distribution.

CHOICE OF METHOD FOR PROPORTIONS

Issue: several methods exist for both CI and test across all designs \Rightarrow we need guidelines to choose a good method.

Principle: choice of method should be based on data dimensions, with separate guidelines for different inferential procedures (CI and test) and for different designs.

PSLS **guidelines:** ⁷

Design	Method	Conditions (all must be met)	(Notes)
1-sample (n, \hat{p})	classical CI	$n\hat{p} \geq 15; n(1-\hat{p}) \geq 15$	$n\hat{p} \sim \#$ positives $n(1-\hat{p}) \sim \#$ negatives
	“plus four” CI	$n \geq 10$	
	“exact” CI	no conditions	
$H_0 : p = p_0$	z -test	$np_0 \geq 10; n(1-p_0) \geq 10$	1-sample exact methods based on binomial distrib.
	exact test	no conditions	
2-sample indep. $(n_1, \hat{p}_1, n_2, \hat{p}_2)$	classical CI	$n_1\hat{p}_1 \geq 10; n_1(1-\hat{p}_1) \geq 10;$ $n_2\hat{p}_2 \geq 10; n_2(1-\hat{p}_2) \geq 10$	2-sample exact test (Fisher’s exact test) not in textbooks \rightarrow Session 8
	“plus four” CI	$n_1 \geq 5; n_2 \geq 5$	
$H_0 : p_1 = p_2$ (combined \hat{p})	z -test	$n_1\hat{p} \geq 5; n_1(1-\hat{p}) \geq 5;$ $n_2\hat{p} \geq 5; n_2(1-\hat{p}) \geq 5$	
	exact test	no conditions	

⁷ Same guidelines as in IPS 7e; the coverage in S is too limited to be of practical use.

INFERENCE FOR 1 PROPORTION – DETAILS

- **Data:** X = number of “successes” in a binomial setting.
- **Model:** $X \sim B(n, p)$.
- **Estimation:** $\hat{p} = X/n$, $SE_{\hat{p}} = \sqrt{\hat{p}(1-\hat{p})/n}$.
- **Confidence intervals** for p with confidence level $1-\alpha$:
 - * **classical approx.:** $\hat{p} \pm z^* SE_{\hat{p}}$, $z^* = z_{1-\alpha/2}$,
 - * **plus four approx.:** $\tilde{p} \pm z^* SE_{\tilde{p}}$ (same formula, but add 2 successes and 2 failures⁸),
 - * **“exact”**⁹: based on binomial distribution (software only, usually the default),
- **Recommendations** — **“exact”**: always conservative (too wide); **classical**: may be very poor (too narrow) in small samples; **plus four**: generally good approximation,
- **Test** of $H_0: p = p_0$ (where p_0 is a known value), against one-/two-sided alternative H_a ,
 - * **classical**, approximate z -test: $z = (\hat{p} - p_0) / \sqrt{p_0(1-p_0)/n} \approx N(0,1)$ under H_0 ,
 - * **exact**: based on binomial distribution, e.g.,
 - $H_a: p > p_0$: $P = P(X \geq X_{\text{obs}})$,
 - $H_a: p \neq p_0$: $P = 2 \min\{P(X \geq X_{\text{obs}}), P(X \leq X_{\text{obs}})\}$,¹⁰
- **Recommendations:** **exact** generally preferable, but **classical** almost same in large samples.

⁸ This surprising method is usually referred to Agresti & Coull (1998), but other similar ideas exist.

⁹ Also referred to as the Clopper-Pearson CI/method; note that the CI is actually **not exact**.

¹⁰ Other formulae exist, but this is the simplest one; see Supplementary Exercise 8.85 (solution).

1 PROPORTION: APHID DROPS

Aphid landings on their feet or back:¹¹

- **Data:** 19 out of 20 aphids dropped at height 20 cm landed on their feet,
- **Model:** binomial setting $\sim B(20, p)$, where p = probability of feet landing,
- **Estimation:** $\hat{p} = 19/20 = 0.95$, $SE_{\hat{p}} = \sqrt{\frac{0.95 \cdot 0.05}{20}} = 0.049$,
- **95% CI for p :**
 - * **classical:** $0.95 \pm 1.96 \times 0.049 = (0.854, 1.046)$,
 - * **plus four:** $0.875 \pm 1.96 \times 0.068 = (0.743, 1.007)$,¹²
 - * **“exact”** (Minitab/Stata): $(0.751, 0.999)$,
- **Test** of $H_0: p = 0.5$ against $H_a: p > 0.5$:
 - * **classical:** $z = (0.95 - 0.5) / \sqrt{\frac{0.5(1-0.5)}{20}} = 4.025$, and $P = P(Z > 4.025) = 0.000028$,
 - * **exact** using $B(20, 0.5)$ and software/formula:
$$P = P(X \geq 19) = P(X = 19) + P(X = 20) = 0.000020,$$
- **Conclusion:** clear evidence of non-random landings,
 - * “plus four” and exact CIs similar and preferable (“classical” CI awful),
 - * exact test preferable (but z -test not too far off).

¹¹ Pea aphids drops were videotaped after release; Ribak et al. (2013), *Current Biology* 23, R102-103; PSLs 4e Ex. 19.6.

¹² $\tilde{p} = (19+2)/(20+4) = 0.875$, and $SE(\tilde{p}) = \sqrt{0.875(1-0.875)/24} = 0.068$.

INFERENCE FOR 2 INDEPENDENT PROPORTIONS – DETAILS

- **Data:** X and Y = number of “successes” in two independent binomial settings.
- **Model:** $X \sim B(n_1, p_1)$ and $Y \sim B(n_2, p_2)$, X and Y independent,
- **Estimation:**

$$\hat{p}_1 = X/n_1, \hat{p}_2 = Y/n_2, D = \hat{p}_1 - \hat{p}_2,$$

$$SE_D = \sqrt{\hat{p}_1(1-\hat{p}_1)/n_1 + \hat{p}_2(1-\hat{p}_2)/n_2}.$$
- **Confidence interval** for $p_1 - p_2$ with confidence level $1 - \alpha$:
 - * **classical** approx.: $\hat{p}_1 - \hat{p}_2 \pm z^* SE_D$, $z^* = z_{1-\alpha/2}$,
 - * **plus four** approx.: $\tilde{p}_1 - \tilde{p}_2 \pm z^* SE_{\tilde{D}}$ (same formula, but add 1 success and 1 failure in each sample!),

Recommendations — **classical**: may be very poor in small samples; **plus four**: generally good approximation,
- **Test** (approximate) of $H_0: p_1 = p_2 (= p)$, against one-/two-sided alternative H_a ,
 - * **estimate common value p** : $\hat{p} = (X + Y)/(n_1 + n_2)$ – total number of successes divided by the total number of trials,
 - * “pooled” standard error under H_0 : $SE_{D_p} = \sqrt{\hat{p}(1-\hat{p}) \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$,
 - * **test statistic**: $z = (D - 0)/SE_{D_p} = (\hat{p}_1 - \hat{p}_2)/SE_{D_p}$,
 - * **P -values** from $N(0,1)$ the usual way.

2 INDEPENDENT PROPORTIONS: ECHINACEA FOR COMMON COLD

Development of cold in Echinacea and control groups:¹³

- **Data:** after exposure, 88 out of 103 persons in control group, and 44 out of 48 in a treatment group developed a cold,
- **Estimation:**

tx :	$\hat{p}_1 = 44/48 = 0.917,$	$SE(\hat{p}_1) = 0.040,$
control :	$\hat{p}_2 = 88/103 = 0.854,$	$SE(\hat{p}_2) = 0.035,$
diff :	$\hat{p}_1 - \hat{p}_2 = 0.062,$	$SE(\hat{p}_1 - \hat{p}_2) = 0.053,$
	$\tilde{p}_1 - \tilde{p}_2 = 0.052,$	$SE(\tilde{p}_1 - \tilde{p}_2) = 0.055,$ ¹⁴
- **95% CI for $p_1 - p_2$:**
 - * **classical:** $0.062 \pm 1.96 \times 0.053 = (-0.041, 0.166),$
 - * **plus four:** $0.052 \pm 1.96 \times 0.055 = (-0.056, 0.160),$
- **Test of $H_0: p_1 = p_2$ against $H_a: p_1 \neq p_2$:**
 - * **classical:** $z = (\hat{p}_1 - \hat{p}_2)/SE_{D_p} = 0.062/0.058 = 1.075,$ ¹⁵ and $P = 2 \times P(Z > 1.075) = 0.282,$
 - * **alternative methods** → Session 8.

Conclusions:

- only little difference between confidence intervals despite violation of guideline for classical method,
- P -value so large that we can be confident there is no evidence against H_0 (despite only narrowly meeting the guideline); observed effect is in the **opposite direction** of what one might have hoped.

¹³ Experimental study on efficacy of Echinacea product against common cold; Turner et al. (2005), *New England Journal of Medicine* 353, 341-348.; PSLs 4e Exercise 20.3.

¹⁴ Calculations: $SE(\tilde{p}_1 - \tilde{p}_2) = \sqrt{(0.90 \cdot (1-0.90)/50 + 0.8476 \cdot (1-0.8476)/105)} = 0.055$, where we used the values $\tilde{p}_1 = (44+1)/(48+2) = 0.90$, and $\tilde{p}_2 = (88+1)/(103+2) = 0.8476$.

¹⁵ Calculations: $SE_{D_p} = \sqrt{0.874(1-0.874)(1/48 + 1/103)} = 0.058$, where pooled $\hat{p} = (44+88)/(48+103) = 0.874$.

NONPARAMETRIC (DISTRIBUTION-FREE) METHODS

- no parametric statistical model (involving particular distribution type),
- still assumptions of **i.i.d. samples** and possibly of particular features of distributions,
- **classical methods** — the only ones in the course syllabus!
 - * mostly based on **ranks**, that is, the **relative magnitude of observations**, where it does not matter how much $X_2 > X_1$, only that $X_2 > X_1$,
 - * analyses computable by hand (tedious for large data), but reference distributions require special tables or large-sample approximations,
 - * all methods in the course **available in Minitab/Stata/R**,
 - * **advantages**: no distribution assumptions, robust, “simple to use”...
 - * **disadvantages**:
some loss of information compared to good parametric model, problems with getting good estimates and confidence intervals (**what to estimate?**), not available beyond the very simplest designs,
- alternative: **modern, computer-intensive methods**:
 - * **resampling/permutation/bootstrap** methods,¹⁶
 - * very flexible and powerful, but **not** so simple to use.¹⁷

¹⁶ Recommended by PSLS/IPS; described in IPS Supplementary Chapter 16.

¹⁷ Minitab 19-21 includes features for 1 and 2 samples under Calc-Resampling, rather than in the Stat menu.

1 SAMPLE: SIGN TEST

Example (Visual receptive fields, 6L–11):

- neural activity at 9 recordings of both Spontaneous activity (SA) and Response (R),
- analyze differences (R–SA) (ordered): -7.5 -2.5 12.5 13.3 14.2 16.7 26.7 34.2 44.2.

Sign test for **null hypothesis** H_0 : median = known value (m_0):

- **Model**: X_1, \dots, X_n i.i.d. from continuous distribution,
- **Test procedure**:
 - * test statistic: Y = number of X 's $> m_0$,
 - * disregard X 's = m_0 , let n_1 = number of X 's $\neq m_0$,
 - * **under H_0** : $Y \sim B(n_1, 0.5) \Rightarrow$ corresponds to **testing $H_0: p=0.5$** in the binomial distribution $B(n_1, p)$ for Y ,
 - * **P -values** from binomial distribution, e.g. $P = P(Y \geq Y_{\text{obs}})$ for H_a : median $> m_0$,¹⁸
- **Confidence interval** for the median: in Minitab/Stata.

Example — interest is in testing H_0 : median = 0 vs. H_a : median > 0 :

- no differences = 0; out of 9 differences, 7 are > 0 ,
- $P = P(Y \geq 7) = 0.090$, where $Y \sim B(9, 0.5)$,
- cannot reject H_0 : no evidence of higher activity for R by the test.

¹⁸ Also the alternative hypotheses have equivalent binomial formulations, e.g. here H_a : $p > 0.5$.

McNEMAR'S TEST

= sign test for paired binary data¹⁹ (or paired proportions); **note**: not in course curriculum.

Example: Varicose veins and overweight:

- 122 pairs of brothers, one overweight and one normal weight, with records of presence or absence of varicose veins,

Group	var. veins	
	+ (1)	- (0)
normal wt	23	99
overwt	30	92

Normal weight	Overweight	
	+ var. veins (1)	- var. veins (0)
+ var. veins (1)	19	4
- var. veins (0)	11	88

- hypothesis of interest: same proportion of varicose veins among normal weight and overweight persons? — observed proportions:

$$\text{normal weight: } \hat{p} = 23/122 = 0.19,$$

$$\text{overweight: } \hat{p} = 30/122 = 0.25.$$

Test procedure:

- code each “success” as 1, and each “failure” as 0,
- compute differences D_i (e.g. normal weight – overweight) within each pair i :
 - * $D_i = 0$: same outcome (either 1 or 0) in both pair members,
 - * $D_i = 1$: success in first pair member, failure in second,
 - * $D_i = -1$: failure in first pair member, success in second,
- disregard all $D_i = 0$; let $n_1 = \# (D_i = 1 \text{ or } D_i = -1)$; assume $Y = \# (D_i = 1) \sim B(n_1, p)$; and test $H_0 : p = 0.5$ against $H_a : p \neq 0.5$,
- **example:** $Y_{\text{obs}} = 4$; $Y \sim B(15, p)$; and $P = 2 \times P(Y \leq 4) \approx 2 \cdot (0 + 0 + 0.0003 + 0.014 + 0.042) = 0.12$ (binomial table); **conclusion:** no statistical evidence against H_0 .

¹⁹ Different versions of McNemar's test exist; the one described here gives an exact P -value based on the binomial distribution, and is generally recommended.

RANKS

Values/numbers x_1, \dots, x_n .

- **order values** by increasing magnitude:

$$x_{(1)} \leq x_{(2)} \leq \dots x_{(n)}, \quad \text{where } \text{rank}(x_{(i)}) = i$$

i.e., rank = i when value is the i th smallest among all values,

- **ties** (several values equal): use average rank among all tied values,
- it is sometimes possible to assign ranks, even if data only partially observed (**left-/right-censored**: smaller/greater than or equal to a cut-off).

Example (constructed data):

data	2.2	3.1	1.9	2.2	2.0	5.0
ordered data	1.9	2.0	2.2	2.2	3.1	5.0
ranks	1	2	3.5 ^a	3.5 ^a	5	6

^a average rank computed as: $3.5 = (3 + 4)/2$

- the value 5.0 is much larger than the others but that is not reflected (strongly) in the ranks,
- if an additional observation was partially observed and only known to be > 5 (i.e., right-censored at 5), then its rank would be 7,
- sum of ranks = 21 (generally, among n values the sum of ranks equals $n(n+1)/2$).

2 SAMPLES: WILCOXON–MANN–WHITNEY TEST

Wilcoxon rank sum test (PSLS/IPS terminology, also often Mann–Whitney test):

- **Model:** X_1, \dots, X_{n_1} and Y_1, \dots, Y_{n_2} independent and i.i.d. samples from distributions Dist_X and Dist_Y , respectively,
- **Hypotheses** — two possible setups:
 - (1) $H_0: \text{Dist}_X = \text{Dist}_Y$ (same distribution), $H_a: \text{Dist}_X \neq \text{Dist}_Y$,²⁰
 - (2) assuming “ $\text{Dist}_X = \text{Dist}_Y + \Delta$ ” (distributions differ only in position): $H_0: \Delta = 0$ (corresponding to $\text{median}_X = \text{median}_Y$) vs. one- or two-sided alternatives H_a ,
- **Test procedure:**
 - * **rank all observations** as if a single sample,
 - * **test statistic:** W = sum of ranks for X -sample,
 - * **under H_0 :** distribution of W has **no easy form**
 - **tabulated** in special tables for small n_1, n_2 , when there are **no ties**,
 - **software** may give exact values, or use different types of **approximations** (in Minitab/Stata/R), with improving accuracy for increasing sample size,
- **Confidence interval** for $\text{median}_X - \text{median}_Y$ (**valid under Δ -assumption**) → software,
- recommended to check for similar spread and skewness in the two **distributions of ranks**.²¹

²⁰ More specific wording of H_a : Dist_X is systematically larger than Dist_Y , or vice versa (for a two-sided H_a); see Chapter 27 of PSLS.

²¹ Fagerland & Sandvik (2009), *Statistics in Medicine* 28, 1487-1497.

EXAMPLE FOR 2-SAMPLE W-M-W TEST

Parasite burdens of calves in Lithuania:

pasture	Data values									
safe	0	8	8	10	26	34	38	44	46	
infected	20	30	30	36	50	52	54	70	70	100
both	0	8	8	10	20	26	30	30	34	36
samples	38	44	46	50	52	54	70	70	100	
	Ranks									
blue ~	1	2.5	2.5	4	5	6	7.5	7.5	9	10
safe	11	12	13	14	15	16	17.5	17.5	19	

Nonparametric analysis:

- **Model:** two independent samples, assume also that distributions differ only in position (Δ -assumption),
- **test statistic:** W = sum of ranks in safe sample = **61** (or 129 for infected sample),
- approximate **P-value** = 0.020 (Minitab/R) or 0.018 (Stata),
- **95% CI** for median difference (infected–safe): (6.0, 46.0).

Normal distribution analysis (from Lecture 6):

- **Estimation:** $\hat{\mu}_1 = 51.2$, $\hat{\mu}_2 = 23.8$, $SE(\hat{\mu}_1 - \hat{\mu}_2) = \sqrt{s_1^2/10 + s_2^2/9} = 9.59$,
- **test statistic:** $t = (\hat{\mu}_1 - \hat{\mu}_2)/SE(\hat{\mu}_1 - \hat{\mu}_2) = 2.86$; **P-value** = 0.011, from $t(16)$,
- **95% CI** for mean difference (infected–safe): (7.1, 47.8).

1 SAMPLE: WILCOXON'S SIGNED RANK TEST

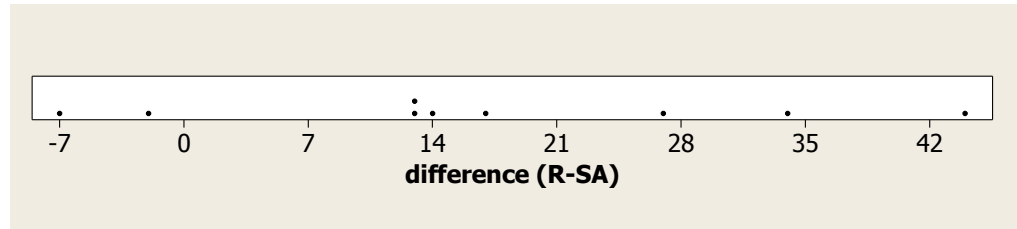
Wilcoxon's test for null hypothesis H_0 : median = known value (m_0):

- **Model:** X_1, \dots, X_n i.i.d. sample from a continuous, **symmetric** distribution,
— **note:** the assumed symmetry is an **extra assumption** compared to the sign test,
- **Alternative hypotheses** H_a : either one- or two-sided,
- **Test procedure:**
 - * let $R_i = X_i - m_0$, and disregard observations with $R_i = 0$
 - * rank the $|R_i|$'s, and let $S_i = \text{rank of } |R_i|$,
 - * **idea:** if, for example, true median $> m_0$, then there will be both **more and larger ranks** for observations $> m_0$,
 - * **test statistic:** $W^+ = \text{sum of } S_i\text{'s for positive observations (i.e., } R_i > 0, \text{ corresponding to } X_i > m_0)$,
 - * **under H_0 :** distribution of W^+ has **no easy form**
 - **tabulated** in special tables for small n , when there are **no ties**,
 - **software** may give exact values (e.g., R), or use different types of **approximations** (Minitab/Stata), with improving accuracy for increasing sample size,
- **Confidence interval** for the median: in Minitab/R.

EXAMPLE FOR 1-SAMPLE WILCOXON TEST

Visual receptive fields (6L–11):

- dotplot for differences (R–SA):



- data values (X_i) and ranks (S_i ; blue $\sim X_i > 0$):

X_i	-7.5	-2.5	12.5	13.3	14.2	16.7	26.7	34.2	44.2
$ R_i $	7.5	2.5	12.5	13.3	14.2	16.7	26.7	34.2	44.2
S_i	2	1	3	4	5	6	7	8	9

- assume the distribution (of differences) to be symmetric about its median,
- H_0 : median = 0 vs. H_a : median > 0,
- $W^+ = 3 + 4 + 5 + 6 + 7 + 8 + 9 = 42$, $W^- = 3$,
- **P-value**: 0.012 (Minitab) / 0.021 (Stata) / 0.010 (R),
- **95% CI for median** (Minitab/R): (3.3, 30.5),
- Wilcoxon test is significant and preferable here (assumed symmetry seems ok).

Summary — comparison Wilcoxon vs. sign test:

Wilcoxon test is stronger (in fact, the sign test is quite weak), but additionally assumes the distribution to be symmetric.

MID-TERM EXAM PRACTICAL INFO

- **mark: optional** for 15% of course mark; that is, you decide **after you have received your mark** if you want to use it or not (**if you use it**, you final exam will be shorter),
- **all aids (books and notes) are allowed**, but no computers/computing devices (to be discussed),²²
- **duration: 1 hour, without extensions!**

One question/assignment with possible types of (sub)questions (possibly involving multiple choice):

- choice of statistical model and analysis —
 - * carry out analysis when calculations manageable (see below),
 - * or base analysis on Minitab print + extra calculations,
 - * or outline analysis if calculations not manageable,
- probability calculations manageable (see below).

Calculations manageable by hand (calculator):

- simple probabilities (e.g., $1-p$, $(1-p)^n$, simple binomial),
- probabilities in normal distribution (incl. standardization to $N(0, 1)$),
- z/t -tests and CIs (given estimates or calculated statistics),
- one-sample proportion (**note:** two-sample proportions not included),
- no data entry into calculator or large summations.

²² If no computers are allowed, you must bring a calculator and statistical tables; I will have a couple of extra tables and calculators, in case you forget.

SUMMARY NOTES

Key words and concepts:

- proportion data — modelled by binomial distributions,
 - * always **estimate** by sample proportions,
 - * **CI methods for proportions**:
 - classical (based on z -distribution), “plus four”, “exact” (1-sample only),
 - choice between methods, based on n and \hat{p} ,
 - * **test methods for proportions**:
 - classical (based on z -distribution), exact (based on binomial or other distributions),
 - choice between methods, based on n and \hat{p} ,
- **nonparametric tests**:
 - * characterized by no distribution (normality) assumptions,
 - * often focusing on **median**(s) instead of mean(s),
 - * many methods exist — the VHM 801 course covers:
 - **sign test** for 1-sample → test of $H_0 : p = 0.5$ in $B(n, p)$,
 - **rank-based tests** for 1 sample (Wilcoxon signed rank) and 2 independent samples (Mann-Whitney): all calculations by software, beware of assumptions for the test/model about distribution shape.