

# SDS 384 11: Theoretical Statistics

## Lecture 10: U Statistics cont.

---

Purnamrita Sarkar  
Department of Statistics and Data Science  
The University of Texas at Austin

- We will see many interesting examples of U statistics.
- Interesting properties
  - Unbiased (done)
  - Reduces variance (done)
  - Concentration (via McDiarmid) (done)
  - Asymptotic variance (done)
  - Asymptotic distribution (today)

# Normal Convergence of U statistics-proof

- Trick: find some  $\hat{U}$  such that  $\hat{U}$  is asymptotically equivalent to  $U$ .
- Make sure  $\hat{U}$  is easy to analyze.

## Theorem

If  $X_n \xrightarrow{d} X$  and  $|Y_n - X_n| \xrightarrow{P} 0$ , then  $Y_n \xrightarrow{d} X$ .

- In our case we will use  $\hat{U}$  as a sum of functions of  $X_i$
- Then use CLT on  $\hat{U}$
- We will find the functions using Hájek projections.

# Hájek Projections – Setup

- Let  $\{X_1, \dots, X_n\}$  be independent random vectors.
- Consider a linear space  $\mathcal{S}$  of random variables.
  - E.g.  $\mathcal{S}$  can be the set of all random variables of the form

$$\sum_{i=1}^n g_i(X_i)$$

- $g_i$  are arbitrary measurable functions  $g_i : \mathbb{R}^d \rightarrow \mathbb{R}$  with  $E[g_i(X_i)^2] < \infty$ , for  $i \in [n]$
- $ES^2 < \infty, \forall S \in \mathcal{S}$
- Consider a random variable  $T$  with  $E[T^2] < \infty$

# Hájek projections

- Define by the projection  $\hat{S} = \arg \inf_{S \in \mathcal{S}} E[(T - S)^2]$

## Theorem

*$\hat{S}$  is a projection of  $T$  onto a linear space  $\mathcal{S}$  with finite second moments, iff,  $\hat{S} \in \mathcal{S}$  and*

$$E[(T - \hat{S})S] = 0, \quad \text{For every } S \in \mathcal{S}. \quad \text{Orthogonality}$$

*Every two projections of  $T$  onto  $\mathcal{S}$  are equal a.s. If  $\mathcal{S}$  contains the constant variables, then  $E[T] = E[\hat{S}]$  and  $\text{cov}(T - \hat{S}, S) = 0$  for every  $S \in \hat{\mathcal{S}}$ .*

## Proof.

- First note that

$$E(T - S)^2 = E[(T - \hat{S})^2] + 2E[(T - \hat{S})(\hat{S} - S)] + E[(S - \hat{S})^2]$$

- If the orthogonality condition is satisfied, then the middle term is zero.
- So  $E(T - S)^2 \geq E(T - \hat{S})^2$ , and this inequality is strict unless  $E(\hat{S} - S)^2 = 0$ . This proves uniqueness.



# Hájek projections-converse

## Proof.

- For any number  $\alpha$

$$E(T - \hat{S} - \alpha S)^2 = E[(T - \hat{S})^2] - 2\alpha E[(T - \hat{S})S] + \alpha^2 E[S^2]$$

- If  $\hat{S}$  is the projection, then  $\forall \alpha$  and  $\forall S \in \mathcal{S}$ ,

$$\alpha^2 E[S^2] - 2\alpha E[(T - \hat{S})S] \geq 0$$

- So for  $\alpha > 0$ ,  $E[(T - \hat{S})S] \leq \alpha E[S^2]/2$
- for  $\alpha < 0$ ,  $E[(T - \hat{S})S] \geq -|\alpha| E[S^2]/2$
- So the orthogonality condition must hold.



## Hájek projections-proos cont.

- If constants are in  $\mathcal{S}$ , then the orthogonality condition with  $S = 1$  gives  $E[T] = E[\hat{S}]$ .
- So,  $\text{cov}(T - \hat{S}, S) = E[(T - \hat{S})S] - E[T - \hat{S}]E[S] = 0$
- The first term is zero using orthogonality.
- The second term is zero because  $E[T] = E[\hat{S}]$ .
- Hájek projections do not always exist, i.e. the  $\inf_{S \in \mathcal{S}}$  may not be achievable.
- However it is typically easy to establish existence directly



# Projections and asymptotic equivalence

- By the orthogonality, we have  $E[T^2] = E[(T - \hat{S})^2] + E[\hat{S}^2]$
- If  $\mathcal{S}$  contains constants, then  $E[T] = E[\hat{S}]$
- So  $\text{var}(T) = \text{var}(T - \hat{S}) + \text{var}(\hat{S})$
- So if  $\mathcal{S}$  has constants, and  $\text{var}(T) = \text{var}(\hat{S})$ , then  $\hat{S} = T$  a.s.
- What if the variances are not equal, but almost (or asymptotically) equal?

# Projections and asymptotic equivalence

## Theorem

*Consider linear spaces of random variables with finite second moment  $S_n$  that contains constants. Let  $T_n$  be random variables with projections  $\hat{S}_n$  onto  $S_n$ . If  $\text{var}(T_n)/\text{var}(S_n) \rightarrow 1$ , then,*

$$\frac{T_n - E[T_n]}{sd(T_n)} - \frac{\hat{S}_n - E[\hat{S}_n]}{sd(\hat{S}_n)} \xrightarrow{P} 0,$$

*where  $sd(X)$  is  $\sqrt{\text{var}(X)}$ .*

# Projections and asymptotic equivalence-proof

## Proof.

- We will prove convergence in second mean.

- Let  $D_n = \frac{T_n - E[T_n]}{\text{sd}(T_n)} - \frac{\hat{S}_n - E[\hat{S}_n]}{\text{sd}(\hat{S}_n)}$

- $E[D_n] = 0$

- So the variance calculation gives:

$$\begin{aligned}\text{var}(D_n) &= 2 - 2 \frac{\text{cov}(T_n, \hat{S}_n)}{\text{sd}(T_n)\text{sd}(\hat{S}_n)} \\ &= 2 - 2 \frac{\text{cov}(T_n - \hat{S}_n, \hat{S}_n) + \text{var}(\hat{S}_n)}{\text{sd}(T_n)\text{sd}(\hat{S}_n)} \\ &= 2 - 2 \frac{\text{var}(\hat{S}_n)}{\text{sd}(T_n)\text{sd}(\hat{S}_n)} \rightarrow 0\end{aligned}$$



# How to get a Hájek projection

- Let  $\{X_1, \dots, X_n\}$  be independent random vectors.
- Consider a linear space  $\mathcal{S}$  of random variables.
  - E.g.  $\mathcal{S}$  can be the set of all random variables of the form  $\sum_{i=1}^n g_i(X_i)$ .
  - $g_i$  are arbitrary measurable functions  $g_i : \mathbb{R}^d \rightarrow \mathbb{R}$  with  $E[g_i(X_i)^2] < \infty$ , for  $i \in [n]$

## Theorem

*The Hájek projection of an arbitrary random variable  $T(X_1, \dots, X_n)$  with finite second moment onto  $\mathcal{S}$  is given by*

$$\hat{S} = \sum_{i=1}^n E[T|X_i] - (n-1)E[T].$$

# How to get a Hájek projection

## Proof.

- First note that  $\hat{S} \in \mathcal{S}$
- All that remains is to check the orthogonality condition.
- 

$$\begin{aligned} E[(T - \hat{S})S] &= E[(T - \hat{S}) \sum_i g_i(X_i)] \\ &= \sum_i E[(T - \hat{S})g_i(X_i)] \\ &= \sum_i E_{X_i} E[(T - \hat{S})g_i(X_i)|X_i] \\ &= \sum_i E g_i(X_i) E[T - \hat{S}|X_i] \end{aligned}$$

- But  $E[\hat{S}|X_i] = E[\sum_j E[T|X_j]|X_i] - (n-1)E[T] = E[T|X_i]$ . □

## What if $X_i$ 's are iid?

- If  $X_1, \dots, X_n$  are iid,
- So in this case,
$$E[T|X_i = x] = E[T(X_1, \dots, X_{i-1}, x, X_i, \dots)]$$
$$= E[T(x, X_2, \dots, X_n)]$$
- Thus the Hájek projections can be computed by taking a projection on a smaller set  $\mathcal{S}' \subset \mathcal{S}$
- $\mathcal{S}'$  contains random variables of the form  $\sum_{i=1}^n g(X_i)$  where  $g$  is some arbitrary measurable function with  $E[g(X_i)^2] < \infty$

# Normal Convergence of U statistics-proof

- Recall  $U := \frac{1}{\binom{n}{r}} \sum_{S \in \mathcal{I}_r} h(X_S)$
- Define the Hájek projection as

$$\begin{aligned}\hat{U} &:= \sum_{i=1}^n E[U - \theta | X_i] \\ &= \frac{1}{\binom{n}{r}} \sum_{i=1}^n \sum_{S \in \mathcal{I}_r} E[h(X_S) - \theta | X_i]\end{aligned}$$

- Note that

$$E[h(X_S) - \theta | X_i = x] = \begin{cases} E[h(x, X_2, \dots, X_r)] - \theta =: g(x) & \text{When } i \in S \\ 0 & \text{o.w.} \end{cases}$$

# Normal Convergence of U statistics-proof

- Define the Hájek projection as

$$\begin{aligned}\hat{U} &:= \sum_{i=1}^n E[U - \theta | X_i] \\&= \frac{1}{\binom{n}{r}} \sum_{i=1}^n \sum_{S \in \mathcal{I}_r} E[h(X_S) - \theta | X_i] \\&= \frac{1}{\binom{n}{r}} \sum_{i=1}^n \sum_{S \in \mathcal{I}_r: X_i \in S} E[h(X_S) - \theta | X_i] \\&= \frac{1}{\binom{n}{r}} \sum_{i=1}^n \binom{n-1}{r-1} g(X_i) \\&= \frac{r}{n} \sum_{i=1}^n g(X_i)\end{aligned}$$



# Normal Convergence of U statistics-proof

- Ok. So we got a projection. Now we need to move to asymptotics
- So let us calculate the variance of  $\hat{U}$

$$\begin{aligned}\text{var}(\hat{U}) &= \frac{r^2}{n} \text{var}(g(X_1)) \\ &= \frac{r^2}{n} \text{var}(E[h(X_S)|X_1]) = \frac{r^2}{n} \xi_1\end{aligned}$$

- Now CLT gives,  $\sqrt{n}(\hat{U} - \theta) \xrightarrow{d} N(0, r^2 \xi_1)$

## Normal Convergence of U statistics-proof

- $\sqrt{n}\hat{U} \xrightarrow{d} N(0, r^2\xi_1)$
- We already proved  $\frac{\text{var}(U)}{\text{var}(\hat{U})} \rightarrow 1$
- So  $\sqrt{n}(\hat{U} - (U - \theta)) \xrightarrow{P} 0$
- So  $\sqrt{n}(U - \theta) \xrightarrow{d} N(0, r^2\xi_1)$