Topic 4: Sufficiency, and MVUEs

Ethan P. Marzban   University of California, Santa Barbara   PSTAT 120B

Outline

1. Sufficiency

2. MVUEs

Sufficiency

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Leadup

- Perhaps you've noticed that certain quantities arise repeatedly in the context of estimating certain parameters.
- For example, when estimating a *population* mean μ (using either the method of moments or maximum likelihood estimation), the *sample* mean $\overline{Y}_n$ appears often.
- When estimating the population variance of a zero-mean distribution, the quantity $\sum_{i=1}^{n} Y_i^2$ arises frequently.
- As such, let's take a brief break from estimation and return back to the general notion of a **statistic**.

Statistics

Definition (Statistic)

Given a random sample $\vec{\boldsymbol{Y}} = \{Y_i\}_{i=1}^n$, a **statistic** T is simply a function of $\vec{\boldsymbol{Y}}$:

$$T := T(\vec{\boldsymbol{Y}}) = T(Y_1, \cdots, Y_n)$$

- Example: sample mean $\overline{Y}_n := \frac{1}{n} \sum_{i=1}^n Y_i$
- Example: sample variance $S_n^2 \frac{1}{n-1} \sum_{i=1}^n (Y_i - \overline{Y}_n)^2$
- Example: sample maximum $Y_{(n)}$

Statistics as Data Reduction

- A statistic, inherently, is a form of *data reduction*.
- That is, we take a sample $\vec{\boldsymbol{Y}}$ consisting of n elements (i.e. observations) and *reduce* it to a single quantity (like the mean, variance, maximum, etc.).
  - Again, this is just a more heuristic way of saying that a statistic is a *function* of our sample!
- For this reason, statistics are sometimes referred to as **summary statistics**, as they *summarize* our sample in some way (e.g. summarize where the "center" of our sample is, summarize how "spread out" our sample is, etc.)

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Leadup

- Intuitively (as was mentioned at the beginning of this lecture), the sample mean seems like a pretty good proxy for the population mean.
- Conversely, the sample variance might not give us a lot of information about the population mean (unless we have a very specific distribution).
- So, our intuition is telling us that the sample mean is doing a better job of summarizing information about μ (the population mean) than the sample variance.
- Can we make this more explicit?

Leadup

- Well, the answer is "yes" and we've actually taken some pretty good steps to making our intuition more explicit, by way of estimation!
- Said differently, used as an estimator for μ, $\overline{Y}_n$ possess *many* more desirable properties than, say, S_n^2.
  - For example, $\overline{Y}_n$ is an unbiased estimator for μ whereas S_n^2 is, in general, not.
  - Similarly, $\overline{Y}_n$ is a consistent estimator for μ whereas S_n^2 is, in general, not.
- But let's see if there's perhaps a *different* way to quantify our intuitions.

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Example

- This is all very abstract - let's make things more concrete.
- Specifically, suppose $Y_1, \cdots, Y_n \overset{\text{i.i.d.}}{\sim} \text{Bern}(\theta)$.
  - In other words, you can imagine Y_i to be the outcome of tossing a coin once and observing whether it landed on heads or tails, where θ represents the probability the coin will lands "heads" on any particular toss.
- One statistic we could consider is $U := \sum_{i=1}^{n} Y_i$.
  - In words, U denotes the number of heads in the n coin tosses.
- Does U capture the maximal amount of information about θ? That is, can we gain any further information about θ by looking at other statistics?

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Example

- Here is one way to answer this question: let's look at the distribution of $(Y_1, \cdots, Y_n \mid U)$.
- Before we do, let's convince ourselves that examining this distribution is a good idea.
- If the distribution of $(Y_1, \cdots, Y_n \mid U)$ does not depend on θ, then, in essence, U will have captured all of the necessary information about θ.
    - Remember that the distribution of $(X \mid Y)$ can be interpreted as our beliefs on X after knowing Y.
    - Saying that the distribution of $(Y_1, \cdots, Y_n \mid U)$ doesn't depend on θ means, after knowing U, our beliefs on $(Y_1, \cdots, Y_n)$ no longer depend on θ.

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Example

- Alright, let's go!
- Specifically, we examine $\mathbb{P}(Y_1 = y_1, \cdots, Y_1 = y_n \mid U = u)$.
- We're conditioning on an event with nonzero probability, meaning we can invoke the definition of conditional probability to write

$$\mathbb{P}(Y_1 = y_1, \cdots, Y_1 = y_n \mid U = u) = \frac{\mathbb{P}(Y_1 = y_1, \cdots, Y_1 = y_n, U = u)}{\mathbb{P}(U = u)}$$

- Since $Y_1, \cdots, Y_n \overset{\text{i.i.d.}}{\sim} \text{Bern}(\theta)$, we know that $U := (\sum_{i=1}^{n} Y_i) \sim \text{Bin}(n, p)$, meaning

$$\mathbb{P}(U = u) = \binom{n}{u} p^u (1 - p)^{n-u}$$

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Example

- What about the numerator, $\mathbb{P}(Y_1 = y_1, \cdots, Y_1 = y_n, U = u)$?
- Well, if $\sum_{i=1}^{n} y_i \neq u$, the probability is zero.
  - Here's how we can think through this: say $n = 3$, and $y_1 = 1,\ y_2 = 0,\ y_3 = 3$. (That is, the first coin landed heads, the second landed tails, and the third landed tails).
  - What's the probability of the first coin landing heads, the second landing tails, the third landing tails, <u>and</u> observing a total number of heads that is not equal to 1 (i.e. $1 + 0 + 0$)?
  - The answer is zero!

Example

- If $\sum_{i=1}^{n} y_i = u$, the event we're taking the probability of is

$$\{Y_1 = y_1, \cdots, Y_n = y_n, U = u\}$$

  which is just the probability of an independent sequences of zeros and ones with a total of u ones and $(n - u)$ zeroes.
- That is,
$$\mathbb{P}(Y_1 = y_1, \cdots, Y_n = y_n, U = u) = \theta^u (1 - \theta)^{n-u}$$
- So, in all,

$$\mathbb{P}(Y_1 = y_1, \cdots, Y_n = y_n, U = u) = \begin{cases} \theta^u (1 - \theta)^{n-u} & \text{if } \sum_{i=1}^{n} y_i = u \\ 0 & \text{otherwise} \end{cases}$$

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Example

- Therefore, dividing by $\mathbb{P}(U = u) = \binom{n}{u}\theta^u(1-\theta)^{n-u}$, we have

$$\mathbb{P}(Y_1 = y_1, \cdots, Y_n = y_n, U = u) = \begin{cases} \frac{1}{\binom{n}{u}} & \text{if } \sum_{i=1}^n y_i = u \\ 0 & \text{otherwise} \end{cases}$$

- So, does this distribution depend on θ?
- Nope! So, after conditioning on $U := \sum_{i=1}^n Y_i$, we have removed all dependency on θ - said differently, U has captured all of the necessary information about θ.

Sufficiency

Definition (Sufficiency)

Let $Y_1, \cdots, Y_n$ denote a random sample from a distribution with parameter θ. A statistic $U := g(Y_1, \cdots, Y_n)$ is said to be **sufficient** for θ if the conditional distribution $(Y_1, \cdots, Y_n \mid U)$ does not depend on θ.

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Sufficiency

- Now, we almost never use the definition of sufficiency.
- Firstly, it only allows us to check whether a given statistic is sufficient - not how to actually *find* a sufficient statistic.
- Furthermore, it requires us to find conditional distributions which are, in general, not particularly easy to find.
- As such, in practice, we rely more heavily on the following theorem:

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Factorization Theorem

Theorem (Factorization Theorem)

Let U be a statistic based on the random sample $\vec{\mathbf{Y}} = (Y_1, \cdots, Y_n)$. Then U is a sufficient statistic for the estimation of a parameter θ if and only if the likelihood $\mathcal{L}_{\vec{\mathbf{Y}}}(\theta)$ factors as

$$\mathcal{L}_{\vec{\mathbf{Y}}}(\theta) = g(U, \theta) \times h(\vec{\mathbf{Y}})$$

where $g(U, \theta)$ is a function of only U and θ (and possibly fundamental constants) and $h(\vec{\mathbf{Y}})$ does *not* depend on θ.

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Example

Example

Let $Y_1, \cdots, Y_n \overset{\text{i.i.d.}}{\sim} \text{Bern}(\theta)$, where $\theta \in (0, 1)$ is an unknown parameter. Show that $U := \sum_{i=1}^{n} Y_i$ is a sufficient statistic for θ.

- We've actually already shown this using the definition of sufficiency (at the start of today's lecture) - let's show this again, this time using the Factorization Theorem.

Solution

$$
\begin{aligned}
\mathcal{L}_{\vec{\mathbf{Y}}}(\theta) &= \prod_{i=1}^{n} p(Y_i; \theta) = \prod_{i=1}^{n} \left[\theta^{Y_i} (1 - \theta)^{1 - Y_i} \right] \\
&= \theta^{\sum_{i=1}^{n} Y_i} \cdot (1 - \theta)^{n - \sum_{i=1}^{n} Y_i} \\
&= \underbrace{\left[\theta^{\sum_{i=1}^{n} Y_i} \cdot (1 - \theta)^{n - \sum_{i=1}^{n} Y_i} \right]}_{:= g(\sum_{i=1}^{n} Y_i \ , \theta)} \times \underbrace{[1]}_{:= h(\vec{\mathbf{Y}})}
\end{aligned}
$$

where $g(U, \theta) = \theta^{U} \cdot (1 - \theta)^{n - U}$ and $h(\vec{\mathbf{Y}}) = 1$. Therefore, by the Factorization Theorem, $U := \sum_{i=1}^{n} Y_i$ is a sufficient statistic for θ.

Example

Example

Let $Y_1, \cdots, Y_n \overset{\text{i.i.d.}}{\sim} \text{Exp}(\theta)$, where $\theta > 0$ is an unknown parameter. Propose a sufficient statistic for θ, and show that it is sufficient.

- We'll do this one on the board.

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Questions (to be answered together)

- **Question:** are sufficient statistics unique?
- **Question:** do sufficient statistics always exist?

- Let's discuss!

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MVUEs

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Leadup

- Alright, let's dip our toes back into the realm of estimation.
- Recall that, a few lectures ago, I tried to convince everyone that one notion of an "ideal" estimator should be unbiased and with as little variance as possible.
- Let's run with this idea a bit!
- Indeed, we have the notion of a **Minimum Variance Unbiased Estimator** (MVUE) as a sort of "gold-standard" estimator.
- As the name suggests, an MVUE is an estimator that is unbiased and possesses the smallest possible variance.

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Leadup

- "Smallest possible variance.-" is it possible to get an unbiased estimator with zero variance?
- It turns out (and the reasoning behind *why* is outside the scope of this course) the answer is, in general, "no."
- Indeed, there exists a lower bound for the variance of *any* unbiased estimator, called the **Cramér-Rao Lower Bound** (CRLB).

Cramér-Rao Lower Bound

Theorem (Cramér-Rao Lower Bound)

Consider an i.i.d. sample $Y_1, \cdots, Y_n$ from a distribution with unknown parameter θ. Under appropriate "regularity conditions", every unbiased estimator $\widehat{\theta}$ obeys the inequality

$$\mathrm{Var}(\widehat{\theta}) \geq \frac{1}{\mathcal{I}_n(\theta)}$$

where

$$\mathcal{I}_n(\theta) = \mathbb{E}\left[-\frac{\partial^2}{\partial \theta^2} \ell_{\vec{\mathbf{Y}}}(\theta) \right]$$

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Some Terminology

- The Cramér-Rao Lower Bound refers to the lower bound on the variance, $[\mathcal{I}_n(\theta)]^{-1}$.
- The term $\mathcal{I}_n(\theta)$ is referred to as the **Fisher Information** of the sample $\vec{\boldsymbol{Y}}$. Note that the fisher information is the expectation of the negative second-derivative of the log-likelihood of the sample.
- Note that the CRLB is not a strict inequality, meaning that certain estimators actually achieve the lower bound. An estimator that achieves the CRLB (i.e. an estimator satisfying $\mathrm{Var}(\widehat{\theta}) = [\mathcal{I}_n(\theta)]^{-1}$) is said to be a **efficient** estimator.

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A Note

- The Cramér-Rao Lower Bound only applies to *unbiased* estimators. It is possible to construct *biased* estimators that have variance smaller than the CRLB (a very popular example of such an estimator, used throughout a wide array of different disciplines, is the so-called "James-Stein estimator")

Example

Example

Let $Y_1, \cdots, Y_n \overset{\text{i.i.d.}}{\sim} \text{Exp}(\theta)$, where $\theta > 0$ is an unknown parameter.

(a) Find the lowest attainable variance by an unbiased estimator for θ.

(b) Is the estimator $\widehat{\theta}_n := \overline{Y}_n$ an efficient estimator for θ?

Solutions

- Part (a) is essentially just asking us to compute the CRLB.
- From previous work, we have that the log-likelihood of the sample is given by

$$\ell_{\vec{\mathbf{Y}}}(\theta) = -n \ln(\theta) - \frac{1}{\theta} \sum_{i=1}^{n} Y_i + \sum_{i=1}^{n} \ln \mathbb{1}_{\{Y_i \geq 0\}}$$

- We now take the first and second derivatives:

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Solutions

$$\frac{\partial}{\partial\theta}\ell_{\vec{\mathbf{Y}}}(\theta) = -\frac{n}{\theta} + \frac{1}{\theta^2}\sum_{i=1}^{n} Y_i$$

$$\frac{\partial^2}{\partial\theta^2}\ell_{\vec{\mathbf{Y}}}(\theta) = \frac{n}{\theta^2} - \frac{2}{\theta^3}\sum_{i=1}^{n} Y_i$$

$$-\frac{\partial^2}{\partial\theta^2}\ell_{\vec{\mathbf{Y}}}(\theta) = -\frac{n}{\theta^2} + \frac{2}{\theta^3}\sum_{i=1}^{n} Y_i$$

- The Fisher Information is just the expectation of this last quantity:

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Solutions

$$
\begin{aligned}
\mathcal{I}_n(\theta) &= \mathbb{E}\left[-\frac{\partial^2}{\partial\theta^2}\ell_{\vec{\mathbf{Y}}}(\theta)\right] \\
&= \mathbb{E}\left[-\frac{n}{\theta^2} + \frac{2}{\theta^3}\sum_{i=1}^{n} Y_i\right] \\
&= -\frac{n}{\theta^2} + \frac{2}{\theta^3}\sum_{i=1}^{n}\mathbb{E}[Y_i] = -\frac{n}{\theta^2} + \frac{2n}{\theta^2} = \frac{n}{\theta^2}
\end{aligned}
$$

- The CRLB is just the reciprocal of this last quantity: θ^2/n.

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Solutions

- So, in other words, *any* unbiased estimator for θ (in the context of the exponential distribution) will have variance greater than or equal to θ^2/n.
- To answer part (b), first note that $\widehat{\theta}_n := \overline{Y}_n$ is an unbiased estimator for θ. Hence, we simply need to check whether or not its variance attains the CRLB:

$$\mathrm{Var}(\widehat{\theta}_n) = \mathrm{Var}(\overline{Y}_n) = \frac{\mathrm{Var}(Y_1)}{n} = \frac{\theta^2}{n}$$

- Since this is exactly equal to the CRLB, we conclude that $\overline{Y}_n$ is a efficient estimator for θ.

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Solutions

- Finally, let's try and tie the notion of efficiency back to our initial discussions on MVUEs.
- First note: perhaps counterintuitively, it's possible that the MVUE in a given situation *won't* be efficient. We won't worry too much about why that is, for the purposes of this class.
- I would, however, like to stress that we would like to construct an unbiased estimator that has as low variance as possible.
- So, given an estimator $\widehat{\theta}_1$ for a parameter θ, is it possible to "improve" (i.e. obtain a new estimator $\widehat{\theta}_2$ with a lower variance than $\widehat{\theta}_1$?) Yes!

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Rao-Blackwell Theorem

Theorem (Rao-Blackwell Theorem)

Let $\widehat{\theta}_1$ be an unbiased estimator for θ with finite variance. If U is a sufficient statistic for θ, define $\widehat{\theta}_2 := \mathbb{E}[\widehat{\theta}_1 \mid U]$. Then, for all θ,

$$\mathbb{E}[\widehat{\theta}_2] = \theta \qquad \text{and} \qquad \mathrm{Var}(\widehat{\theta}_2) \leq \mathrm{Var}(\widehat{\theta}_1)$$

- So, given an initial unbiased estimator $\widehat{\theta}_1$ and a sufficient statistic U, we can "improve" (or, at least, never do worse) by conditioning our unbiased estimator on our sufficient statistic.

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Rao-Blackwell Theorem

- Now, in practice, using the Rao-Blackwell theorem can be a bit tricky, mainly due to the intractability of some of the conditional expectations it requires us to compute.
  - I walk you through one particular example in problem 4 of your HW05
- However, the Rao-Blackwell Theorem can be used to tell us that the following procedure generally gives us an MVUE:
- Say we have a sufficient statistic U that best summarizes our data. Additionally, say we have an estimator $\widehat{\theta} := h(U)$ that is unbiased for θ. Then, typically, $\widehat{\theta}$ will be an MVUE.

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Rao-Blackwell Theorem

- Of course, there are some details missing. For one, it turns out that even among sufficient statistics, some are "better" at capturing the information about a parameter than others. (These are called **minimal sufficient statistics**, which we won't cover in this course.)
  - So, it's really a function of a *minimal* sufficient statistic that will give us the MVUE in a given situation.
  - But, again, for the purposes of this class, we won't concern ourselves with this too much.
- Indeed, in general, constructing MVUEs can be a pain! But, it's useful to at least know about their existence, and how sufficiency and the Rao-Blackwell theorem tie into constructing them.

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Rao-Blackwell Theorem

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Example

Example

Let $Y_1, \cdots, Y_n \stackrel{\text{i.i.d.}}{\sim} \text{Unif}[0, \theta]$, where $\theta > 0$ is an unknown parameter.

(a) Show that $Y_{(n)}$ is a sufficient statistic for θ. (It turns out that this is a *minimal* sufficient statistic for θ, but you do not need to show that.)

(b) Find an MVUE for θ.

- Try this on your own, and feel free to ask me about it during Office Hours!

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