

Handout 19: Cramér-Rao Lower Bound

Consider a random variable X with a probability density function $f(\theta; x)$ with one univariate parameter θ . We can define a random variable V , called the **score**, as the derivative of the logarithm of the density of X .¹ We see that this has a nice form by applying the chain rule:

$$\begin{aligned} V &= \frac{\partial}{\partial \theta} [\log(f(\theta; X))] \\ &= \frac{1}{f(\theta; X)} \cdot \frac{\partial}{\partial \theta} [f(\theta; X)]. \end{aligned}$$

The score measures the sensitivity of the data to the parameter θ . However, because it can be positive or negative, on average it turns out that the score will have an expected value of zero:

$$\begin{aligned} \mathbb{E}V &= \int f(\theta; x) \cdot \frac{1}{f(\theta; x)} \cdot \frac{\partial}{\partial \theta} [f(\theta; x)] dx \\ &= \int \frac{\partial}{\partial \theta} f(\theta; x) dx = \frac{\partial}{\partial \theta} \int f(\theta; x) dx = \frac{\partial}{\partial \theta} [1] = 0. \end{aligned}$$

This holds for any value of θ .

Because the positive and negative scores cancel each other out, in order to use the score as a measurement of the relationship between the parameter θ and a value of the data X , we need to look at the square of the score. The expected value of this is called the **Fisher information**, commonly denoted by $\mathcal{I}(\theta)$:

$$\mathcal{I}(\theta) = \mathbb{E}[V^2 | \theta] = \text{Var}(V^2 | \theta).$$

The Fisher information serves as a measurement of how much information about θ is provided by the data X . The Fisher information can change for different values of θ , but does not depend on the data X , which has been integrated out.

Now, let $T = t(X)$ be a point estimator for the parameter θ with expectation $\mathbb{E}T = \psi(\theta)$. In other words, if T is unbiased, we would have $\psi(\theta) = \theta$ for all values of θ . Let's look at the covariance of T and V , note that this is equal to just $\mathbb{E}[VT]$ since the expected value of V is zero.² This has, by construction, a nice form:

$$\begin{aligned} \text{Cov}(V, T) &= \int \left[f(\theta; x) \times t(x) \times \frac{1}{f(\theta; x)} \times \frac{\partial}{\partial \theta} [f(\theta; x)] \right] dx \\ &= \frac{\partial}{\partial \theta} \left[\int t(x) f(\theta, x) dx \right] = \frac{\partial}{\partial \theta} \mathbb{E}T = \psi'(\theta). \end{aligned}$$

Next, we need to use the **Cauchy-Schwartz Inequality**, which for probability spaces says that covariance of two random variables is always less in absolute value than the square-root of the product of their variances.³ Applying this to T and V shows that:

¹ The important point is that the score tells us how much the density f changes at a point x with respect to θ . The logarithm is there to make the score measure the relative change rather than the absolute change, which can also be seen through the application of the chain-rule.

² Recall that the covariance in general would be $\mathbb{E}[(V - \mathbb{E}V)(T - \mathbb{E}T)]$.

³ The more general form says that the squared inner product $|\langle u, v \rangle|^2$ is less than $\langle u, u \rangle \cdot \langle v, v \rangle$. Applying this to the integration with density f yields the probabilistic version.

$$\begin{aligned}
\text{Var}(T) \cdot \text{Var}(V) &\geq |\text{Cov}(V, T)|^2 \\
\text{Var}(T) \cdot \mathcal{I}(\theta) &\geq |\psi'(\theta)|^2 \\
\text{Var}(T) &\geq \frac{|\psi'(\theta)|^2}{\mathcal{I}(\theta)}.
\end{aligned}$$

Which implies, in the unbiased case, that the variance of T can never be less than the inverse of the Fisher information. So, this provides a bound on the best that we can hope to do in terms of estimating the parameter θ from the data X . This result is called the **Cramér-Rao** lower bound.

The **efficiency** of an unbiased estimator, written $e(\hat{\theta})$, provides a measurement of how far away the variance of the estimator is away from the Cramér-Rao bound. Namely, we have:

$$e(\hat{\theta}) = \frac{\mathcal{I}(\theta)^{-1}}{\text{Var}(\hat{\theta})}.$$

We say that an estimator is **efficient** if it has an efficiency of 1. Another way to state the Cramér-Rao bound is to simply say that the efficiency is never greater than 1.

Under some regularity conditions—in particular, that the logarithm of the density function f is twice-differentiable—the Fisher information can be written in a somewhat simplified form:

$$\mathcal{I}(\theta) = -\mathbb{E} \left[\frac{\partial^2}{\partial \theta^2} \log f(\theta; x) \right].$$

Typically, squaring the log density requires having a number of cross terms, whereas the second derivative removes a number of terms, simplifying the calculation. This is the version that we will use on the worksheet.

It is possible to extend the result above to the case where X and θ are vectors. The extension for a vector X , which includes the important case of a random sample of size n , is fairly trivial. We just replace all of the single integrals above with n -dimensional integrals over \mathbb{R}^n . Generalizing to a vector value for θ is a bit more work, requiring some vector calculus that goes beyond the prerequisites for this course. The general idea, however, is very similar.