

Economics 103 – Statistics for Economists

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Lecture 15

Sampling Distributions and Estimation – Part II

Unbiased means “Right on Average”

Bias of an Estimator

Let $\hat{\theta}_n$ be a sample estimator of a population parameter θ_0 . The *bias* of $\hat{\theta}_n$ is $E[\hat{\theta}_n] - \theta_0$.

Unbiased Estimator

A sample estimator $\hat{\theta}_n$ of a population parameter θ_0 is called *unbiased* if $E[\hat{\theta}_n] = \theta_0$

A Different Estimator of the Population Variance

$$\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2$$

$$E[\hat{\sigma}^2] = E \left[\frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2 \right] = \frac{1}{n} E \left[\sum_{i=1}^n (X_i - \bar{X})^2 \right] = \frac{(n-1)\sigma^2}{n}$$

Bias of $\hat{\sigma}^2$

$$E[\hat{\sigma}^2] - \sigma^2 = \frac{(n-1)\sigma^2}{n} - \sigma^2 = \frac{(n-1)\sigma^2}{n} - \frac{n\sigma^2}{n} = -\sigma^2/n$$

Procedure versus Result of the Procedure

Procedure = Random Variable

- ▶ X_1, \dots, X_n represents **procedure of taking a random sample**.
- ▶ $\bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$ represents **procedure of taking sample mean**

Sampling Dist. = Probabilistic Behavior of Procedure

If I repeat the procedure of taking the mean of a random sample over and over for many samples, what relative frequencies do I get **for the sample means?**

Result of Procedure = Constant

- ▶ x_1, \dots, x_n is the **result of sampling**, the observed data.
- ▶ $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ is the **result of taking sample mean**

Procedure? Long-Run Relative Frequencies?

Why would I advise you not to play the lottery?

- ▶ You may sometimes win, but if you play the lottery many times, on average you will lose money.
- ▶ Let X be a random variable representing lottery winnings. I am arguing that $E[X] - \text{Cost of Ticket} < 0$

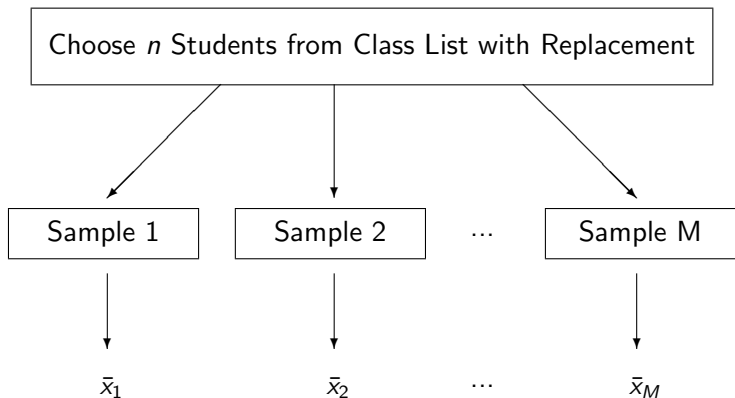
Procedure = Random Variable

Making a habit of playing the lottery. Expectation is negative.

Result of that Procedure = Constant

How much you win in a *particular* lottery. Could be greater than or less than cost of ticket in any *individual* instance.

Sampling Distribution of $\bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$



Repeat M times \rightarrow get M different sample means

Sampling Dist: long run relative frequencies of the \bar{x}_i

Height of Econ 103 Students

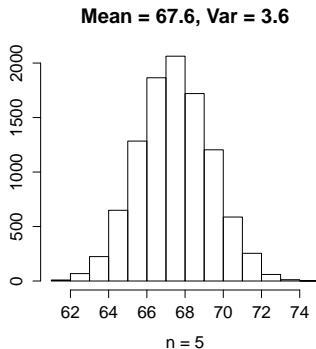
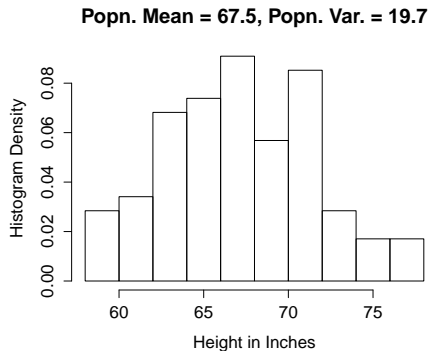


Figure : Left: Population, Right: Sampling distribution of \bar{X}_5

How Large is the Average Family?



How many brothers and sisters are in your family, including yourself?

The average number of children per family was about 2.0 twenty years ago.

What's Going On Here?

Biased Sample!

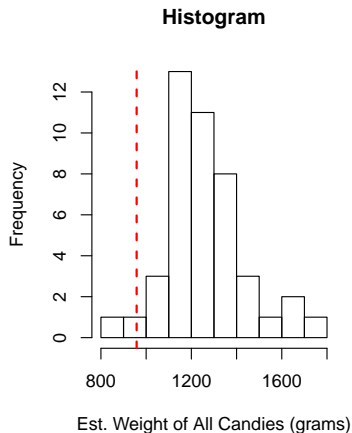
- ▶ Zero children \Rightarrow didn't send any to college
- ▶ Sampling by *children* so large families **oversampled**

Candy Weighing: 44 Estimates, Each With $n = 5$

$$\hat{\theta} = 20 \times (X_1 + \dots + X_5)$$

Summary of Sampling Dist.	
Overestimates	42
Exactly Correct	0
Underestimates	2
$E[\hat{\theta}]$	1269 grams
$SD(\hat{\theta})$	189 grams

Actual Mass: $\theta_0 = 958$ grams



What was in the bag?

100 Candies Total:

- ▶ 20 Fun Size Snickers Bars (large)
- ▶ 30 Reese's Miniatures (medium)
- ▶ 50 Tootsie Roll "Midgees" (small)

So What Happened?

Not a random sample! The Snickers bars were *oversampled*.

Could we have avoided this? How?



Let $X_1, X_2, \dots, X_n \sim iid$ mean μ , variance σ^2 and define $\bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$. True or False:

\bar{X}_n is an unbiased estimator of μ

- (a) True
- (b) False

TRUE!



Let $X_1, X_2, \dots, X_n \sim iid$ mean μ , variance σ^2 . True or False:

X_1 is an unbiased estimator of μ

(a) True

(b) False

TRUE!

How to choose between two unbiased estimators?

Suppose $X_1, X_2, \dots, X_n \sim iid$ with mean μ and variance σ^2

$$E[\bar{X}_n] = E\left[\frac{1}{n} \sum_{i=1}^n X_i\right] = \frac{1}{n} \sum_{i=1}^n E[X_i] = \mu$$

$$E[X_1] = \mu$$

$$Var(\bar{X}_n) = Var\left(\frac{1}{n} \sum_{i=1}^n X_i\right) = \frac{1}{n^2} \sum_{i=1}^n Var(X_i) = \sigma^2/n$$

$$Var(X_1) = \sigma^2$$

Efficiency - Compare Unbiased Estimators by Variance

Let $\hat{\theta}_1$ and $\hat{\theta}_2$ be unbiased estimators of θ_0 . We say that $\hat{\theta}_1$ is *more efficient* than $\hat{\theta}_2$ if $\text{Var}(\hat{\theta}_1) < \text{Var}(\hat{\theta}_2)$.

Mean-Squared Error

Except in very simple situations, unbiased estimators are hard to come by. In fact, in many interesting applications there is a *tradeoff* between **bias** and **variance**:

- ▶ Low bias estimators often have a high variance
- ▶ Low variance estimators often have high bias

Mean-Squared Error (MSE): Squared Bias plus Variance

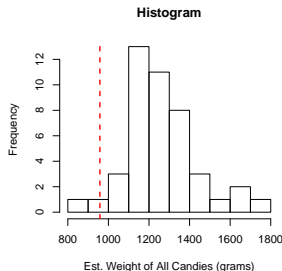
$$MSE(\hat{\theta}) = \text{Bias}(\hat{\theta})^2 + \text{Var}(\hat{\theta})$$

Root Mean-Squared Error (RMSE): $\sqrt{\text{MSE}}$

Calculate MSE for Candy Experiment



$E[\hat{\theta}]$	1269 grams
θ_0	958 grams
$SD(\hat{\theta})$	189 grams



$$\begin{aligned}\text{Bias} &= 1269 \text{ grams} - 958 \text{ grams} \\ &= 311 \text{ grams}\end{aligned}$$

$$\begin{aligned}\text{MSE} &= \text{Bias}^2 + \text{Variance} \\ &= (311^2 + 189^2) \text{ grams}^2 \\ &= 1.3244 \times 10^5 \text{ grams}^2\end{aligned}$$

$$\text{RMSE} = \sqrt{\text{MSE}} = 364 \text{ grams}$$

Finite Sample versus Asymptotic Properties of Estimators

Finite Sample Properties

For *fixed sample size n* what are the properties of the sampling distribution of $\hat{\theta}_n$? (E.g. bias and variance.)

Asymptotic Properties

What happens to the sampling distribution of $\hat{\theta}_n$ *as the sample size n gets larger and larger?* (That is, $n \rightarrow \infty$).

Why Asymptotics?

Law of Large Numbers

Make precise what we mean by “bigger samples are better.”

Central Limit Theorem

As $n \rightarrow \infty$ *pretty much any* sampling distribution is well-approximated by a normal random variable!

Consistency

Consistency

If an estimator $\hat{\theta}_n$ (which is a RV) *converges* to θ_0 (a constant) as $n \rightarrow \infty$, we say that $\hat{\theta}_n$ *is consistent for θ_0* .

What does it mean for a *RV* to converge to a *constant*?

For this course we'll use *MSE Consistency*:

$$\lim_{n \rightarrow \infty} \text{MSE}(\hat{\theta}_n) = 0$$

This makes sense since $\text{MSE}(\hat{\theta}_n)$ is a *constant*, so this is just an ordinary limit from calculus.

Law of Large Numbers (aka Law of Averages)

Let $X_1, X_2, \dots, X_n \sim iid$ mean μ , variance σ^2 . Then the sample mean

$$\bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$$

is consistent for the population mean μ .

Law of Large Numbers (aka Law of Averages)

Let $X_1, X_2, \dots, X_n \sim iid$ mean μ , variance σ^2 .

$$E[\bar{X}_n] = E\left[\frac{1}{n} \sum_{i=1}^n X_i\right] = \mu$$

$$Var(\bar{X}_n) = Var\left(\frac{1}{n} \sum_{i=1}^n X_i\right) = \sigma^2/n$$

$$\begin{aligned} \text{MSE}(\bar{X}_n) &= \text{Bias}(\bar{X}_n)^2 + \text{Var}(\bar{X}_n) \\ &= (E[\bar{X}_n] - \mu)^2 + \text{Var}(\bar{X}_n) \\ &= 0 + \sigma^2/n \\ &\rightarrow 0 \end{aligned}$$

Hence \bar{X}_n is consistent for μ

Important!

An estimator *can* be biased but still consistent, as long as the bias disappears as $n \rightarrow \infty$

$$\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2$$

Bias of $\hat{\sigma}^2$

$$E[\hat{\sigma}^2] - \sigma^2 = \frac{(n-1)\sigma^2}{n} - \sigma^2 = -\sigma^2/n \rightarrow 0$$



Suppose $X_1, X_2, \dots, X_n \sim \text{iid } N(\mu, \sigma^2)$. What is the sampling distribution of \bar{X}_n ?

- (a) $\chi^2(n)$
- (b) $t(n)$
- (c) $F(n, n)$
- (d) $N(\mu, \sigma^2/n)$
- (e) Not enough information to determine.

But still, how can something random
converge to something constant?

Sampling Distribution of \bar{X}_n Collapses to μ

Look at an example where we can directly calculate not only the mean and variance of the sampling distribution of \bar{X}_n , but the *sampling distribution itself*:

$$X_1, X_2, \dots, X_n \sim \text{iid } N(\mu, \sigma^2) \Rightarrow \bar{X}_n \sim N(\mu, \sigma^2/n)$$

Sampling Distribution of \bar{X}_n Collapses to μ

$$X_1, X_2, \dots, X_n \sim \text{iid } N(\mu, \sigma^2) \Rightarrow \bar{X}_n \sim N(\mu, \sigma^2/n).$$

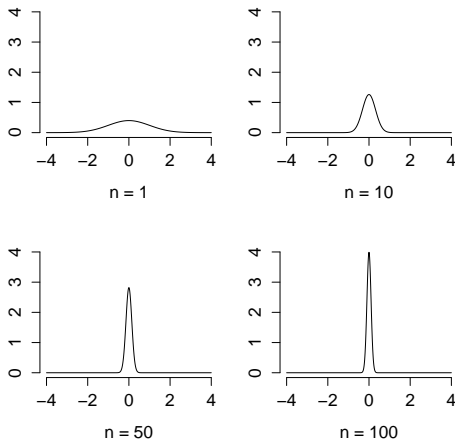
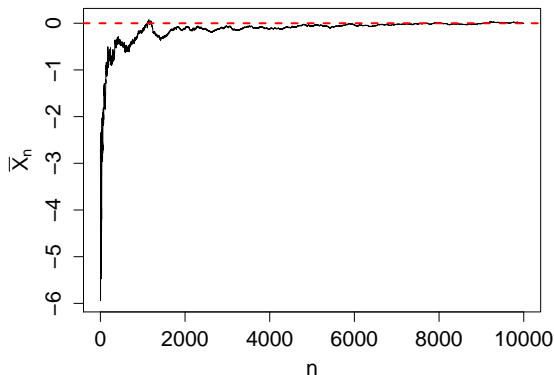


Figure : Sampling Distributions for \bar{X}_n where $X_i \sim \text{iid } N(0, 1)$

Another Visualization: Keep Adding Observations



n	\bar{X}_n
1	-2.69
2	-3.18
3	-5.94
4	-4.27
5	-2.62
10	-2.89
20	-5.33
50	-2.94
100	-1.58
500	-0.45
1000	-0.13
5000	-0.05
10000	0.00

Figure : Running sample means: $X_i \sim \text{iid } N(0, 100)$

Important!

Although I showed two examples involving normal RVs, the LLN holds IN GENERAL!