

# Economics 103 – Statistics for Economists

Francis J. DiTraglia

University of Pennsylvania

Lecture # 9

# Discrete RVs – Part II

# Last Time

Random Variable (RV)

$$X: S \mapsto \mathbb{R}$$

Probability Mass Function (pmf)

$$p(x) = P(X = x)$$

Cumulative Distribution Function (CDF)

$$F(x_0) = P(X \leq x_0)$$

Expected Value (aka Expectation/Mean)

$$\mu = E[X] = \sum_{\text{all } x} x \cdot p(x)$$

# Today

## More About Expected Value

- ▶ Random Variables and Parameters
- ▶ Expectation of Functions
- ▶ Variance & Standard Deviation
- ▶ Variance of Bernoulli RV

## Binomial Random Variable

# Random Variables and Parameters

Notation:  $X \sim \text{Bernoulli}(p)$

Means  $X$  is a Bernoulli RV with  $P(X = 1) = p$  and  $P(X = 0) = 1 - p$ . The tilde is read “distributes as.”

## Parameter

Any constant that appears in the definition of a RV, here  $p$ .

## Important

Use RVs to model populations  $\implies$  this definition of parameter corresponds to the one from earlier in the semester: a “feature of the population (e.g. mean).”

# Constants Versus Random Variables

This is a crucial distinction that students sometimes miss:

## Random Variables

- ▶ Suppose  $X$  is a RV – the values it takes on are random
- ▶ A function  $g(X)$  of a RV is itself a RV as we'll learn today.

## Constants

- ▶  $\mu = E[X]$  is a constant (you should convince yourself of this)
- ▶ Realizations  $x$  are constants. What is random is *which* realization the RV takes on.
- ▶ Parameters are constants (e.g.  $p$  for Bernoulli RV)
- ▶ Sample size  $n$  is a constant

# The St. Petersburg Game

## How Much Would You Pay?



How much would you be willing to pay for the right to play the following game?

*Imagine a fair coin. The coin is tossed once. If it falls heads, you receive a prize of \$2 and the game stops. If not, it is tossed again. If it falls heads on the second toss, you get \$4 and the game stops. If not, it is tossed again. If it falls heads on the third toss, you get \$8 and the game stops, and so on. The game stops after the first head is thrown. If the first head is thrown on the  $x^{\text{th}}$  toss, the prize is  $\$2^x$*



$X =$  Trial Number of First Head

$x$	$2^x$	$p(x)$	$2^x \cdot p(x)$
-----	-------	--------	------------------

$$E[Y] = \sum_{\text{all } x} 2^x \cdot p(x) =$$

$X =$  Trial Number of First Head

$x$	$2^x$	$p(x)$	$2^x \cdot p(x)$
1	2	1/2	1
2	4	1/4	1
3	8	1/8	1

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1	2	$1/2$	1
2	4	$1/4$	1
3	8	$1/8$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n$	$2^n$	$1/2^n$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$

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$n$	$2^n$	$1/2^n$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$

$$E[Y] = \sum_{\text{all } x} 2^x \cdot p(x) = 1 + 1 + 1 + \dots$$

$X$  = Trial Number of First Head

$x$	$2^x$	$p(x)$	$2^x \cdot p(x)$
1	2	$1/2$	1
2	4	$1/4$	1
3	8	$1/8$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n$	$2^n$	$1/2^n$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$

$$E[Y] = \sum_{\text{all } x} 2^x \cdot p(x) = 1 + 1 + 1 + \dots = \infty$$

# Functions of Random Variables are Themselves Random Variables

## Example: Function of Bernoulli RV

Let  $Y = e^X$  where  $X \sim \text{Bernoulli}(p)$

Support of  $Y$

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Probability Mass Function for  $Y$



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Support of  $Y$

$$\{e^0, e^1\} = \{1, e\}$$

Probability Mass Function for  $Y$

$$p_Y(y) = \begin{cases} p & y = e \\ 1 - p & y = 1 \\ 0 & \text{otherwise} \end{cases}$$

## Expectation: Function of Bernoulli RV

Let  $Y = e^X$  where  $X \sim \text{Bernoulli}(p)$

### Probability Mass Function for $Y$

$$p_Y(y) = \begin{cases} p & y = e \\ 1 - p & y = 1 \\ 0 & \text{otherwise} \end{cases}$$

### Expectation of $Y = e^X$

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$$p_Y(y) = \begin{cases} p & y = e \\ 1 - p & y = 1 \\ 0 & \text{otherwise} \end{cases}$$

### Expectation of $Y = e^X$

$$\sum_{y \in \{1, e\}} y \cdot p_Y(y) = (1 - p) \cdot 1 + p \cdot e = 1 + p(e - 1)$$

## Expectation: Function of Bernoulli RV

Let  $Y = e^X$  where  $X \sim \text{Bernoulli}(p)$

### Expectation of the Function

$$\sum_{y \in \{1, e\}} y \cdot p_Y(y) = (1 - p) \cdot 1 + p \cdot e = 1 + p(e - 1)$$

### Function of the Expectation

$$e^{E[X]} = e^p$$

$$E[g(X)] \neq g(E[X])$$

(Expected value of Function  $\neq$  Function of Expected Value)

## Expectation of a Function of a Discrete RV

Let  $X$  be a random variable and  $g$  be a function. Then:

$$E[g(X)] = \sum_{\text{all } x} g(x)p(x)$$

This is how we proceeded in the St. Petersburg Game Example

Your Turn: Calculate  $E[X^2]$



$X$  has support  $\{-1, 0, 1\}$ ,  $p(-1) = p(0) = p(1) = 1/3$ .



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$$E[X^2] = \sum_{\text{all } x} x^2 p(x) = \sum_{x \in \{-1, 0, 1\}} x^2 p(x)$$

## Your Turn: Calculate $E[X^2]$



$X$  has support  $\{-1, 0, 1\}$ ,  $p(-1) = p(0) = p(1) = 1/3$ .

$$\begin{aligned} E[X^2] &= \sum_{\text{all } x} x^2 p(x) = \sum_{x \in \{-1, 0, 1\}} x^2 p(x) \\ &= (-1)^2 \cdot (1/3) + (0)^2 \cdot (1/3) + (1)^2 \cdot (1/3) \end{aligned}$$

## Your Turn: Calculate $E[X^2]$



$X$  has support  $\{-1, 0, 1\}$ ,  $p(-1) = p(0) = p(1) = 1/3$ .

$$\begin{aligned} E[X^2] &= \sum_{\text{all } x} x^2 p(x) = \sum_{x \in \{-1, 0, 1\}} x^2 p(x) \\ &= (-1)^2 \cdot (1/3) + (0)^2 \cdot (1/3) + (1)^2 \cdot (1/3) \\ &= 1/3 + 1/3 \\ &= 2/3 \approx 0.67 \end{aligned}$$

# Linearity of Expectation

Holds for Continuous RVs as well, but proof is different.

Let  $X$  be a RV and  $a, b$  be constants. Then:

$$E[a + bX] = a + bE[X]$$

This is one of the most important facts in the course: the special case in which  $E[g(X)] = g(E[X])$  is  $g = a + bX$ .

## Proof: Linearity of Expectation For Discrete RV

$$E[a + bX] =$$

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$$\begin{aligned} E[a + bX] &= \sum_{\text{all } x} (a + bx)p(x) \\ &= \end{aligned}$$

## Proof: Linearity of Expectation For Discrete RV

$$\begin{aligned} E[a + bX] &= \sum_{\text{all } x} (a + bx)p(x) \\ &= \sum_{\text{all } x} p(x) \cdot a + \sum_{\text{all } x} p(x) \cdot bx \\ &= \end{aligned}$$

## Proof: Linearity of Expectation For Discrete RV

$$\begin{aligned}E[a + bX] &= \sum_{\text{all } x} (a + bx)p(x) \\&= \sum_{\text{all } x} p(x) \cdot a + \sum_{\text{all } x} p(x) \cdot bx \\&= a \sum_{\text{all } x} p(x) + b \sum_{\text{all } x} x \cdot p(x) \\&= \end{aligned}$$



## Proof: Linearity of Expectation For Discrete RV

$$\begin{aligned}E[a + bX] &= \sum_{\text{all } x} (a + bx)p(x) \\&= \sum_{\text{all } x} p(x) \cdot a + \sum_{\text{all } x} p(x) \cdot bx \\&= a \sum_{\text{all } x} p(x) + b \sum_{\text{all } x} x \cdot p(x) \\&= a + bE[X]\end{aligned}$$

# Variance and Standard Deviation of a RV

The Defs are the same for continuous RVs, but the method of calculating will differ.

## Variance (Var)

$$\sigma^2 = \text{Var}(X) = E[(X - \mu)^2] = E[(X - E[X])^2]$$

## Standard Deviation (SD)

$$\sigma = \sqrt{\sigma^2} = \text{SD}(X)$$

# Key Point

Variance and std. dev. are *expectations of functions of a RV*

It follows that:

1. Variance and SD are constants
2. To derive facts about them you can use the facts you know about expected value

# How To Calculate Variance for Discrete RV?

Remember: it's just a function of  $X$ !

$$\text{Recall that } \mu = E[X] = \sum_{\text{all } x} xp(x)$$

$$\text{Var}(X) = E[(X - \mu)^2] = \sum_{\text{all } x} (x - \mu)^2 p(x)$$

## Shortcut Formula For Variance

This is *not* the definition, it's a shortcut for doing calculations:

$$\text{Var}(X) = E[(X - \mu)^2] = E[X^2] - (E[X])^2$$

We'll prove this in an upcoming lecture.

## Variance of Bernoulli RV – via the Shortcut Formula

Step 1 –  $E[X]$

$$\mu = E[X] = \sum_{x \in \{0,1\}} p(x) \cdot x = (1-p) \cdot 0 + p \cdot 1 = p$$

## Variance of Bernoulli RV – via the Shortcut Formula

Step 1 –  $E[X]$

$$\mu = E[X] = \sum_{x \in \{0,1\}} p(x) \cdot x = (1-p) \cdot 0 + p \cdot 1 = p$$

Step 2 –  $E[X^2]$

$$E[X^2] = \sum_{x \in \{0,1\}} x^2 p(x) = 0^2(1-p) + 1^2 p = p$$

## Variance of Bernoulli RV – via the Shortcut Formula

Step 1 –  $E[X]$

$$\mu = E[X] = \sum_{x \in \{0,1\}} p(x) \cdot x = (1-p) \cdot 0 + p \cdot 1 = p$$

Step 2 –  $E[X^2]$

$$E[X^2] = \sum_{x \in \{0,1\}} x^2 p(x) = 0^2(1-p) + 1^2 p = p$$

Step 3 – Combine with Shortcut Formula

$$\sigma^2 = \text{Var}[X] = E[X^2] - (E[X])^2 = p - p^2 = p(1-p)$$



## Variance of Bernoulli RV – Without Shortcut

You will fill in the missing steps on Problem Set 5.

$$\begin{aligned}\sigma^2 &= \text{Var}(X) = \sum_{x \in \{0,1\}} (x - \mu)^2 p(x) \\ &= \sum_{x \in \{0,1\}} (x - p)^2 p(x) \\ &\vdots \\ &= p(1 - p)\end{aligned}$$

## Variance of a Linear Function



Suppose  $X$  is a random variable with  $\text{Var}(X) = \sigma^2$  and  $a, b$  are constants. What is  $\text{Var}(a + bX)$ ?

- (a)  $\sigma^2$
- (b)  $a + \sigma^2$
- (c)  $b\sigma^2$
- (d)  $a + b\sigma^2$
- (e)  $b^2\sigma^2$

## Variance and SD are *NOT* Linear

$$\text{Var}(a + bX) = b^2\sigma^2$$

$$\text{SD}(a + bX) = |b|\sigma$$

These should look familiar from the related results for sample variance and std. dev. that you worked out on an earlier problem set.

## Variance of a Linear Transformation

$$\text{Var}(a + bX) = E \left[ \{(a + bX) - E(a + bX)\}^2 \right]$$

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$$\begin{aligned}\text{Var}(a + bX) &= E \left[ \{(a + bX) - E(a + bX)\}^2 \right] \\ &= E \left[ \{(a + bX) - (a + bE[X])\}^2 \right]\end{aligned}$$

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## Variance of a Linear Transformation

$$\begin{aligned}\text{Var}(a + bX) &= E \left[ \{(a + bX) - E(a + bX)\}^2 \right] \\&= E \left[ \{(a + bX) - (a + bE[X])\}^2 \right] \\&= E \left[ (bX - bE[X])^2 \right] \\&= E[b^2(X - E[X])^2] \\&= b^2 E[(X - E[X])^2] \\&= b^2 \text{Var}(X) = b^2 \sigma^2\end{aligned}$$

The key point here is that variance is defined in terms of expectation and expectation is linear.

# Binomial Random Variable

What we get if we sum a bunch of indep. Bernoulli RVs



## Question

Suppose we flip a fair coin 3 times. What is the probability that we get exactly 2 heads?



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Three basic outcomes make up this event:  $\{HHT, HTH, THH\}$ .



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## Answer

Three basic outcomes make up this event:  $\{HHT, HTH, THH\}$ .

Each of these has probability  $1/8 = 1/2 \times 1/2 \times 1/2$  so, since

basic outcomes are mutually exclusive we sum to get  $3/8 = 0.375$

## A More Complicated Example

### Question

Suppose we flip an *unfair* coin 3 times, where the probability of heads is  $1/3$ . What is the probability that we get exactly 2 heads?

### Answer

The basic outcomes of the experiment are no longer equally likely, but those with exactly two heads *remain so*

$$P(HHT) = (1/3)^2(1 - 1/3) = 2/27$$

$$P(THH) = 2/27$$

$$P(HTH) = 2/27$$

Summing gives  $2/9 \approx 0.22$

## Starting to see a pattern?

Suppose we flip an unfair coin 4 times, where the probability of heads is  $1/3$ . What is the probability that we get exactly 2 heads?

HHTT    TTHH

HTHT    THTH

HTTH    THHT

Six equally likely, mutually exclusive  
basic outcomes make up this event:

$$\binom{4}{2} (1/3)^2 (2/3)^2$$

# Binomial Random Variable

Let  $X$  = the sum of  $n$  independent Bernoulli trials, each with probability of success  $p$ . Then we say that:  $X \sim \text{Binomial}(n, p)$

## Parameters

$p$  = probability of “success,”  $n$  = # of trials

## Support

$\{0, 1, 2, \dots, n\}$

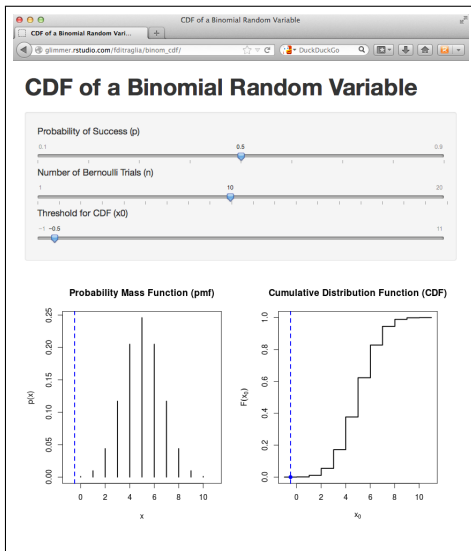
## Probability Mass Function (pmf)

$$p(x) = \binom{n}{x} p^x (1 - p)^{n-x}$$



[http://glimmer.rstudio.com/fditraglia/binom\\_cdf/](http://glimmer.rstudio.com/fditraglia/binom_cdf/)

Try playing around with all three sliders. If you set the second to 1 you get a Bernoulli.



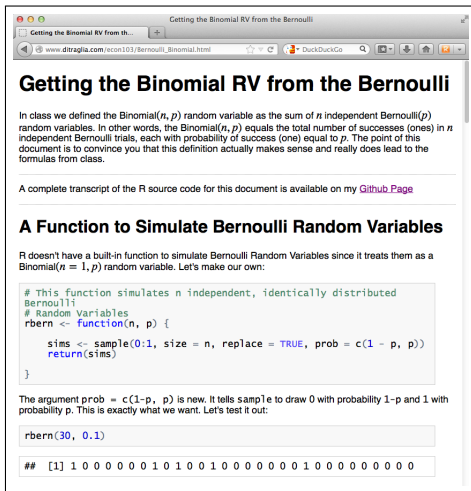
Don't forget this!

A Binomial Random Variable counts up the *total* number of successes (ones) in  $n$  independent Bernoulli trials, each with probability of success  $p$ .

We'll learn more about the Binomial RV in the coming lectures...

[http://fditraglia.github.com/Econ103Public/Rtutorials/Bernoulli\\_Binomial.html](http://fditraglia.github.com/Econ103Public/Rtutorials/Bernoulli_Binomial.html)

Source Code on my [Github Page](#)



The screenshot shows a web browser window with the title "Getting the Binomial RV from the Bernoulli". The address bar shows the URL "www.ditraglia.com/econ103/Bernoulli\_Binomial.html". The page content includes a title "Getting the Binomial RV from the Bernoulli", a paragraph explaining the Binomial random variable as the sum of independent Bernoulli trials, a link to a GitHub page for the R source code, a section titled "A Function to Simulate Bernoulli Random Variables", a paragraph explaining the need for a custom R function, a code block for the function, a paragraph explaining the 'prob' argument, and a code block for a test run.

## Getting the Binomial RV from the Bernoulli

In class we defined the  $\text{Binomial}(n, p)$  random variable as the sum of  $n$  independent  $\text{Bernoulli}(p)$  random variables. In other words, the  $\text{Binomial}(n, p)$  equals the total number of successes (ones) in  $n$  independent Bernoulli trials, each with probability of success (one) equal to  $p$ . The point of this document is to convince you that this definition actually makes sense and really does lead to the formulas from class.

A complete transcript of the R source code for this document is available on my [Github Page](#)

## A Function to Simulate Bernoulli Random Variables

R doesn't have a built-in function to simulate Bernoulli Random Variables since it treats them as a  $\text{Binomial}(n = 1, p)$  random variable. Let's make our own:

```
# This function simulates n independent, identically distributed
# Bernoulli
# Random Variables
rbern <- function(n, p) {
  sims <- sample(0:1, size = n, replace = TRUE, prob = c(1 - p, p))
  return(sims)
}
```

The argument `prob = c(1-p, p)` is new. It tells `sample` to draw 0 with probability  $1-p$  and 1 with probability  $p$ . This is exactly what we want. Let's test it out:

```
rbern(30, 0.1)
```

```
## [1] 1 0 0 0 0 0 0 1 0 1 0 0 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
```