Chapter 4 Expectations of functions of RVs

Example: Toss a die and win X^2 if X is # of spots.

$g(X)$

$$E(X^2) = \sum_x x^2 p_X(x) = 1^2 \cdot \frac{1}{6} + 2^2 \cdot \frac{1}{6} + \cdots + 6^2 \cdot \frac{1}{6}$$

$$= 15\tfrac{1}{6}$$

$E(X)$

$= \int x f(x)\,dx$

$\int g(x) f(x)\,dx$

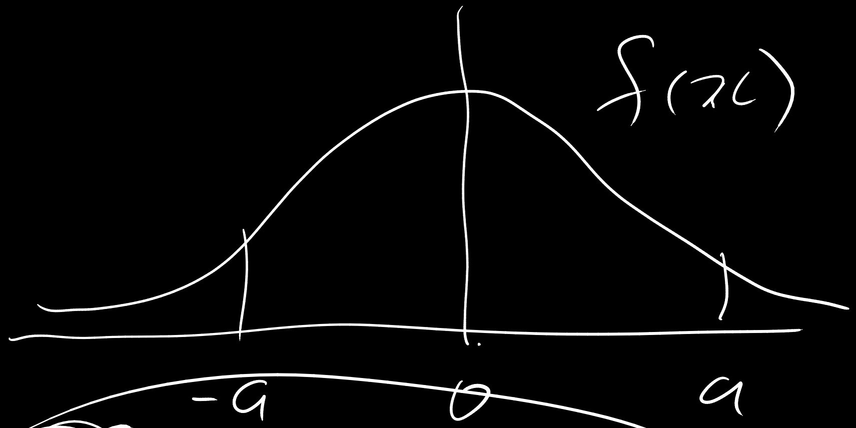
Note $E(X^2) \neq (E(X))^2$

$$(E(X))^2 = \left(1 \cdot \frac{1}{6} + 2 \cdot \frac{1}{6} + \cdots + 6 \cdot \frac{1}{6}\right)^2$$

$$= (3.5)^2 = 12\tfrac{1}{4}$$

$E(X^2) \neq \cancel{= (E(X))^2}$

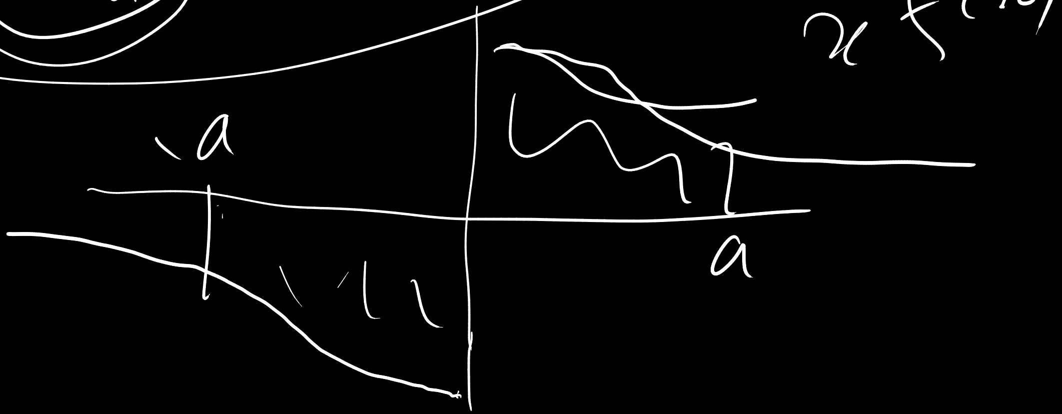
$$\lim_{a\to\infty}\int_{-a}^{a} f(x)\,dx$$



$E(X)$

$E(|X|) < \infty$

$$\lim_{a\to\infty}\int_{-a}^{a} x f(x)\,dx = 0$$



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In general: $E(g(X)) = \sum_{x} g(x)\, p_X(x)$

or

$= \int g(x) f_X(x)\, dx$

$\int |g(x)| f(x)\, dx < \infty$

Works for function of random vectors:

Let $Y = g(X_1, X_2, \ldots, X_k)$

with pmf $p(x_1, x_2, \ldots, x_k)$

then $E(Y) = E(g(X_1, \ldots, X_k)) = \sum_{x's} g(x_1, \ldots, x_k)\, p(x_1, \ldots, x_k)$

or $E(Y) = \int \left[\int \cdots \int g(x_1, \ldots, x_k) f(x_1, \ldots, x_k)\, dx_k \cdots dx_2 \right] dx_1$

if the integral (sum) with $|g|$ converges.

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p. 124 Corollary A

If X & Y are independent, then

$$E(g(X)h(Y)) = E(g(X)) \times E(h(Y))$$

provided $\uparrow$ and $\uparrow$ exist.

Special case: If X & Y are independent

$$E(XY) = E(X)E(Y)$$

if ↑ and ↑ exist.

$$f(x,y) = g(x)h(y)$$

Beware: 1) not true in general

2) converse not true

X & Y ind $\Rightarrow Cov(X,Y)=0$

$\overset{?}{\Leftarrow} (X,Y) \sim N$

<u>Linear combinations of R.V.'s</u>

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n$$

then $E(Y) = a + b_1E(X_1) + b_2E(X_2) + \cdots + b_nE(X_n)$

if ↑ ⋯ exist.

Example A (p. 126)

What is $E(Y)$ if $Y \sim Bin(n, p)$?

$$E(Y) = \sum_y \binom{n}{y} y \, p^y (1-p)^{n-y}$$

Easier: Use fact that $Y = X_1 + \cdots + X_n$

where X_i's are indep. $Bin(1, p)$

and $E(X_i) = p$

So $E(Y) = \sum_{i=1}^n E(X_i) = np$

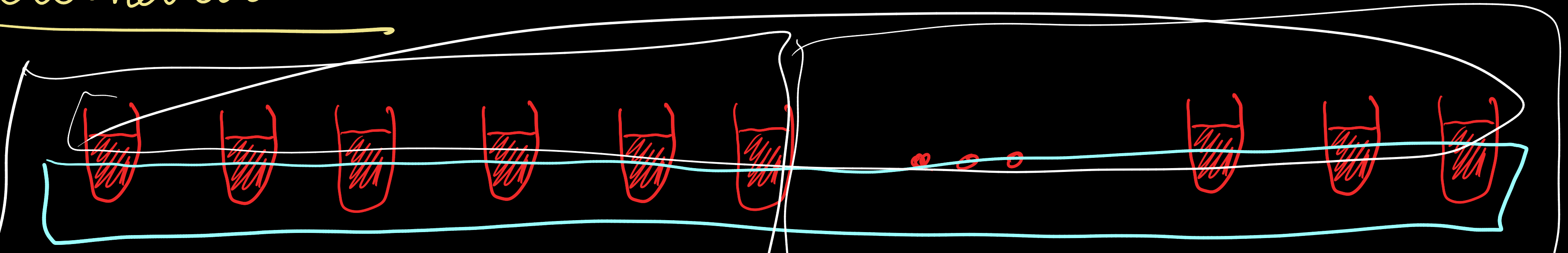
Example C p. 128

Group testing

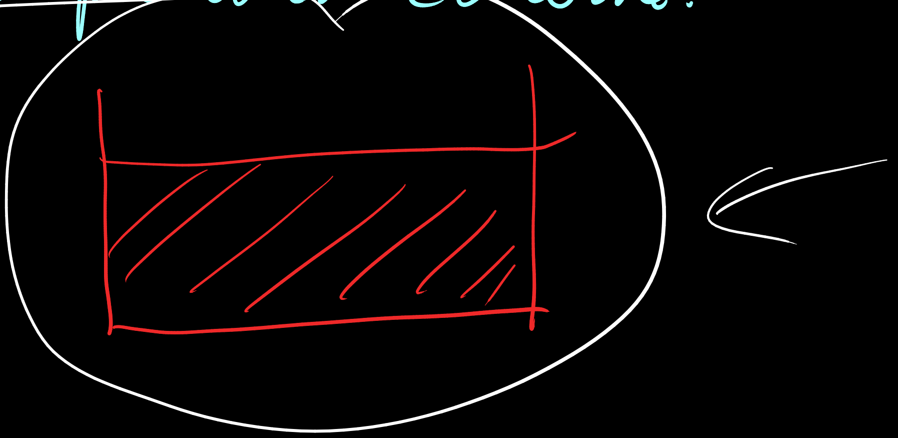
- n blood samples tested for rare disease

- If you test each individually will need n tests.

Alternative:



take 1/2 of each sample and combine:



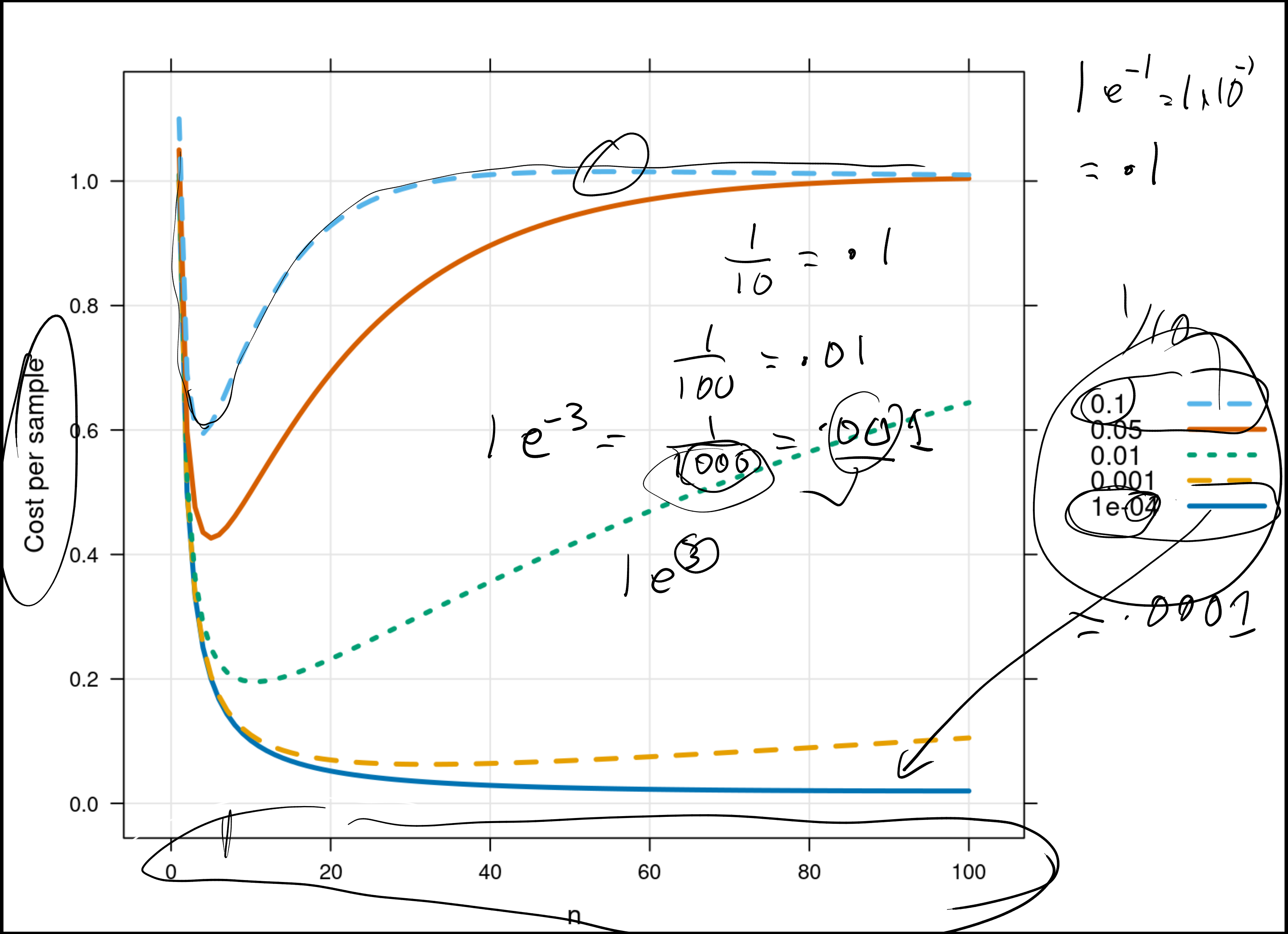
Then test.

If negative - done - all okay

If positive - test n samples.

Let p = probability of a positive.

$$E(\text{Tests}) = 1 \times \underbrace{(1-p)^n}_{\text{pr all negative}} + (n+1)\underbrace{\left(1-(1-p)^n\right)}_{\text{prob. at least 1 positive}}$$



Cost per sample
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
n
0.1
0.05
0.01
0.001
1e-04
1 e-1 = 1 x 10-1
= .1
1/10 = .1
1/100 = .01
1 e-3 = 1/1000 = .001
1 e3
1/10
= .0001

```r
df <- expand.grid(n = 1:100, p = c(.0001,.001, .01, .05, .1))
head(df)
dim(df)
df <- within(df,
             {
               Etests <- 1* (1-p)^n + (n + 1) * (1 - (1 - p)^n)
               Cost_per_sample <- Etests/n
             }
             )

library(latticeExtra)
trellis.par.set(superpose.line = list(lwd=3, lty = 1:3))
xyplot(Cost_per_sample ~ n, df,
       groups = p, type = 'l',
       ylab = "Cost per sample",
       auto.key = list(reverse.rows = T)) +
  layer_(panel.grid(h=-1, v = -1))
```

~~Tidyverse~~

Example D: Illustrates how

$$E\left(\sum_{i=1}^{n} X_i\right) = \sum_{i=1}^{n} E(X_i)$$

does not require independence

DNA Sequences: formed from 4 letters A C T G

If random & each letter with = prob.

$$\underbrace{A\,T\,C\,A\,A\,T\,C\,G\,A\,G\,T \cdots\quad T\,A\,A}$$

- Suppose length $= N$
- and each letter has $p = 1/4$

How many ATGC do you expect?

Let I_n = event ATGC starts at position n

$$P(I_n) = \frac{1}{4} \times \frac{1}{4} \times \frac{1}{4} \times \frac{1}{4} = \frac{1}{256}$$

$$= E(I_n)$$

if $I_n = \begin{cases} 1 & \text{if ATGC starts at position } n \\ 0 & \text{otherwise} \end{cases}$

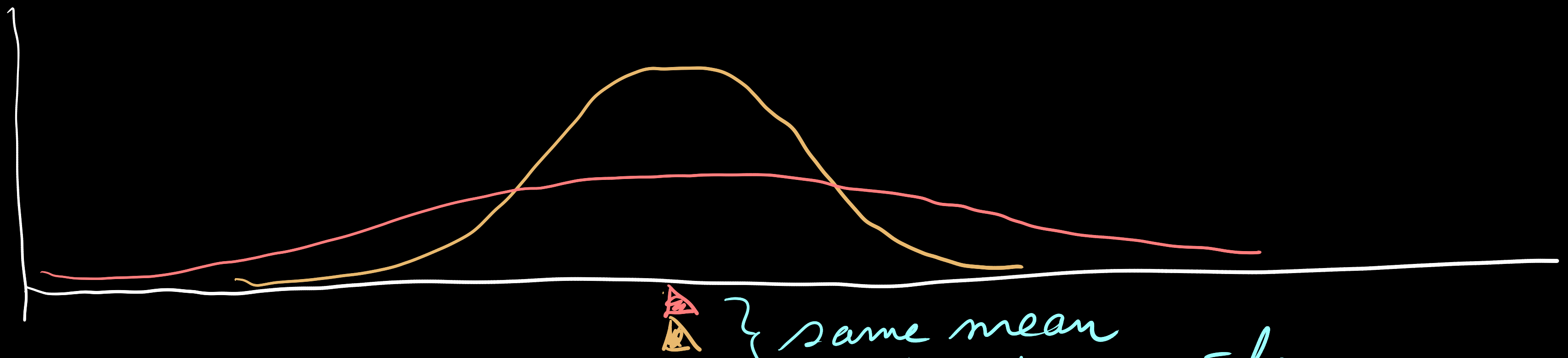
$$E(\#\text{ of sequences}) = E\left(\sum_{n=1}^{N-3} I_n\right) = \sum_{n=1}^{N-3} E(I_n)$$

$$= (N-3) \times \frac{1}{256}$$

Variance and Standard Deviation

Mean = "location parameter" ← one of many e.g median, min, max

Next we need a "spread" parameter



} same mean different spreads

Variance: Average squared distance from the mean

$$Var(X) = E[(X-\mu_X)^2] \text{ if } E \text{ exists.}$$ in squared units

$$SD(X) = \sqrt{Var(X)}$$ in original units

Facts about variance.

$$Var(X) = E(X^2) - (E(X))^2$$

also a useful way to calculate $Var(X)$

Proof

$$
\begin{aligned}
E[(X-\mu_X)^2] &= E(X^2 - 2\mu_X X + \mu_X^2) \\
&= E(X^2) - 2\mu_X E(X) + \mu_X^2 \\
&= E(X^2) - 2E(X)E(X) + (E(X))^2 \\
&= E(X^2) - (E(X))^2
\end{aligned}
$$

Corollary: $E(X^2) = E(X)^2$ iff $Var(X) = 0$

Fact: $Var(X) = 0$ iff X is a constant
i.e. $P(X = c) = 1$

Fact: If $Var(X) < \infty$ (i.e. exists)
and $Y = a + bX$
then $Var(Y) = b^2 Var(X)$

Chebyshev's Inequality: Prob & spread

Let X have mean μ and variance σ^2

Then for any $t \geq 0$:

$$P(|X-\mu| \geq t) \leq \sigma^2/t^2$$

Proof: Use Markov's inequality on $Y = (X-\mu)^2$