Discrete Mathematics & Mathematical Reasoning
Chapter 7 (section 7.4): Random Variables, Expectation, and Variance

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Expected Value (Expectation) of a Random Variable

Recall: A **random variable** (**r.v.**), is a function $X : \Omega \to \mathbb{R}$, that assigns a real value to each outcome in a sample space Ω.

The **expected value**, or **expectation**, or mean, of a random variable $X : \Omega \to \mathbb{R}$, denoted by $E(X)$, is defined by:

$$E(X) = \sum_{s \in \Omega} P(s)X(s)$$

Here $P : \Omega \to [0, 1]$ is the underlying probability distribution on Ω.

Question: Let X be the r.v. outputing the number that comes up when a fair die is rolled. What is the expected value, $E(X)$, of X?

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Answer:

$$E(X) = \sum_{i=1}^{6} \frac{1}{6} \cdot i = \frac{21}{6} = \frac{7}{2}. \quad \square$$

A bad way to calculate expectation

The definition of expectation, $E(X) = \sum_{s \in \Omega} P(s)X(s)$, can be used directly to calculate $E(X)$. But sometimes this is horribly inefficient.

Example: Suppose that a biased coin, which comes up heads with probability p each time, is flipped 11 times consecutively.

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Bad way to answer this: Let's try to use the definition of $E(X)$ directly, with $\Omega = \{H, T\}^{11}$. Note that $|\Omega| = 2^{11} = 2048$.
So, the sum $\sum_{s \in \Omega} P(s)X(s)$ has 2048 terms!

This is clearly not a practical way to compute $E(X)$.

Is there a better way? Yes.

Better expression for the expectation

Recall $P(X = r)$ denotes the probability $P(\{s \in \Omega \mid X(s) = r\})$.
Recall that for a function $X : \Omega \to \mathbb{R}$,

$$range(X) = \{r \in \mathbb{R} \mid \exists s \in \Omega \text{ such that } X(s) = r\}$$

Theorem: For a random variable $X : \Omega \to \mathbb{R}$,

$$E(X) = \sum_{r \in range(X)} P(X = r) \cdot r$$

Proof: $E(X) = \sum_{s \in \Omega} P(s)X(s)$, but for each $r \in range(X)$, if we sum all terms $P(s)X(s)$ such that $X(s) = r$, we get $P(X = r) \cdot r$ as their sum. So, summing over all $r \in range(X)$ we get $E(X) = \sum_{r \in range(X)} P(X = r) \cdot r$. $\square$

So, if $|range(X)|$ is small, and if we can compute $P(X = r)$, then we need to sum a lot fewer terms to calculate $E(X)$.

Expected # of successes in n Bernoulli trials

Theorem: The expected # of successes in n (independent) Bernoulli trials, with probability p of success in each, is np.

Note: We'll see later that we do not need independence for this.

First, a proof which uses mutual independence: For $\Omega = \{H, T\}^n$, let $X : \Omega \rightarrow \mathbb{N}$ count the number of successes in n Bernoulli trials. Let $q = (1 - p)$. Then...

$$\begin{aligned} E(X) &= \sum_{k=0}^{n} P(X = k) \cdot k \\ &= \sum_{k=1}^{n} \binom{n}{k} p^k q^{n-k} \cdot k \end{aligned}$$

The second equality holds because, assuming mutual independence, $P(X = k)$ is the binomial distribution $b(k; n, p)$.

first proof continued

$$
\begin{aligned}
E(X) = \sum_{k=0}^{n} P(X=k)\cdot k = \sum_{k=1}^{n} \binom{n}{k} p^k q^{n-k} \cdot k = \\
&= \sum_{k=1}^{n} \frac{n!}{k!(n-k)!} p^k q^{n-k} \cdot k = \sum_{k=1}^{n} \frac{n!}{(k-1)!(n-k)!} p^k q^{n-k} \\
&= \sum_{k=1}^{n} n \cdot \frac{(n-1)!}{(k-1)!(n-k)!} p^k q^{n-k} = n \sum_{k=1}^{n} \binom{n-1}{k-1} p^k q^{n-k} \\
&= np \sum_{k=1}^{n} \binom{n-1}{k-1} p^{k-1} q^{n-k} = np \sum_{j=0}^{n-1} \binom{n-1}{j} p^j q^{n-1-j} \\
&= np(p+q)^{n-1} \\
&= np\,. \quad \square
\end{aligned}
$$

We will soon see this was an unnecessarily complicated proof.

Expectation of a geometrically distributed r.v.

Question: A coin comes up heads with probability $p > 0$ each time it is flipped. The coin is flipped repeatedly until it comes up heads. What is the expected number of times it is flipped?

Note: This simply asks: "What is the expected value $E(X)$ of a geometrically distributed random variable with parameter p?"

Answer: $\Omega = \{H, TH, TTH, \ldots\}$, and $P(T^{k-1}H) = (1-p)^{k-1}p$. And clearly $X(T^{k-1}H) = k$. Thus $E(X) = \sum_{s \in \Omega} P(s)X(s) =$

$$E(X) = \sum_{k=1}^{\infty} (1-p)^{k-1} p \cdot k = p \sum_{k=1}^{\infty} k(1-p)^{k-1} = p \cdot \frac{1}{p^2} = \frac{1}{p}.$$

This is because: $\sum_{k=1}^{\infty} k \cdot x^{k-1} = \frac{1}{(1-x)^2}$, for $|x| < 1$. $\square$

Example: If $p = 1/4$, then the expected number of coin tosses before we see Heads for the first time is 4.

Linearity of Expectation (VERY IMPORTANT)

Theorem (Linearity of Expectation): For any random variables $X, X_1, \ldots, X_n$ on Ω, $E(X_1 + X_2 + \ldots + X_n) = E(X_1) + \ldots + E(X_n)$.

Furthermore, for any $a, b \in \mathbb{R}$,

$$E(a\,X + b) = a\,E(X) + b.$$

(In other words, the expectation function is a **linear function**.)

Proof:

$$E(\sum_{i=1}^{n} X_i) = \sum_{s\in\Omega} P(s) \sum_{i=1}^{n} X_i(s) = \sum_{i=1}^{n} \sum_{s\in\Omega} P(s) X_i(s) = \sum_{i=1}^{n} E(X_i).$$

$$E(aX + b) = \sum_{s\in\Omega} P(s)(aX(s) + b) = (a \sum_{s\in\Omega} P(s)X(s)) + b \sum_{s\in\Omega} P(s)$$

$$= aE(X) + b. \quad \square$$

Using linearity of expectation

Theorem: The expected # of successes in n (not necessarily independent) Bernoulli trials, with probability p of success in each trial, is np.

Easy proof, via linearity of expectation: For $\Omega = \{H, T\}^n$, let X be the r.v. counting the number of successes, and for each i, let $X_i : \Omega \rightarrow \mathbb{R}$ be the binary r.v. defined by:

$$X_i((s_1, \ldots, s_n)) = \begin{cases} 1 & \text{if } s_i = H \\ 0 & \text{if } s_i = T \end{cases}$$

Note that $E(X_i) = p \cdot 1 + (1 - p) \cdot 0 = p$, for all $i \in \{1, \ldots, n\}$.

Also, clearly, $X = X_1 + X_2 + \ldots + X_n$, so:

$$E(X) = E(X_1 + \ldots + X_n) = \sum_{i=1}^{n} E(X_i) = np. \quad \square$$

Note: this holds even if the n coin tosses are totally correlated.

Using linearity of expectation, continued

Hatcheck problem: At a restaurant, the hat-check person forgets to put claim numbers on hats.
n customers check their hats in, and they each get a random hat back when they leave the restuarant.
What is the expected number, $E(X)$, of people who get their correct hat back?

Answer: Let X_i be the r.v. that is 1 if the i'th customer gets their hat back, and 0 otherwise.
Clearly, $E(X) = E(\sum_i X_i)$.
Furthermore, $E(X_i) = P(i\text{'th person gets its hat back}) = 1/n$.
Thus, $E(X) = n \cdot (1/n) = 1$. $\square$

This would be much harder to prove without using the linearity of expectation.
Note: $E(X)$ doesn't even depend on n in this case.

Independence of Random Variables

Definition: Two random variables, X and Y, are called **independent** if for all $r_1, r_2 \in \mathbb{R}$:

$$P(X = r_1 \text{ and } Y = r_2) = P(X = r_1) \cdot P(Y = r_2)$$

Example: Two die are rolled. Let X_1 be the number that comes up on die 1, and let X_2 be the number that comes up on die 2. Then X_1 and X_2 are independent r.v.'s.

Theorem: If X and Y are independent random variables on the same space Ω. Then

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

We will not prove this in class. (The proof is a simple re-arrangement of the sums in the definition of expectation. See Rosen's book for a proof.)

Variance

The "variance" and "standard deviation" of a r.v., X, give us ways to measure (roughly) *"on average, how far off the value of the r.v. is from its expectation"*.

Variance and Standard Deviation

Definition: For a random variable X on a sample space Ω, the **variance** of X, denoted by $V(X)$, is defined by:

$$V(X) = E((X - E(X))^2) = \sum_{s \in \Omega} (X(s) - E(X))^2 P(s)$$

The **standard deviation** of X, denoted $\sigma(X)$, is defined by

$$\sigma(X) = \sqrt{V(X)}$$

Example, and a useful identity for variance

Example: Consider the r.v., X, such that $P(X = 0) = 1$, and the r.v. Y, such that $P(Y = -10) = P(Y = 10) = 1/2$.
Then $E(X) = E(Y) = 0$, but $V(X) = 0 = \sigma(X)$, whereas $V(Y) = 100$ and $\sigma(Y) = 10$. $\square$

Theorem: For any random variable X,

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

Proof:

$$\begin{aligned} V(X) &= E((X - E(X))^2) \\ &= E(X^2 - 2XE(X) + E(X)^2) \\ &= E(X^2) - 2E(X)E(X) + E(X)^2 \\ &= E(X^2) - E(X)^2. \quad \square \end{aligned}$$