EECS 126

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1 Conditional Expectation

Notice that $E[X|Y]$ is a random variable, but $E[X|Y=y]$ is a number. We can call $E[X|Y]$ a function $g(Y)$, where then $E[X|Y=y] = g(y)$ is just a value in the function.

2 Moment Generating Functions

Definition 1

The **moment generating function** (also known as a transform) associated with a RV X, is a function $M_X(s)$ of a scalar parameter s defined by $M_X(s) = E(e^{sX})$.

the simpler notation $M(S)$ can be used whenever the underlying random variable X is clear from context. In more detail, when X is a discrete random variable, the corresponding MGF is given by

$$M(s) = \sum_x e^{sx} p_X(x).$$

Analogously, when continuous, we just replace the summation with an integral to get

$$M(s) = \int_{-\infty}^{\infty} e^{sx} f_X(x)dx.$$

Just an example so that I know what the reference is here:

Example 2 (Discrete Example)

Let

$$p_X(x) = \begin{cases} \frac{1}{2} & x = 2 \\ \frac{1}{6} & x = 3 \\ \frac{1}{3} & x = 5. \end{cases}$$

Then the corresponding transform is

$$M(s) = E(e^{sx}) = \frac{1}{2} + \frac{1}{6}e^{3s} + \frac{1}{3}e^{5s}.$$

Example 3 (Continuous Example)
Let X be an exponential RV with parameter λ:

$$f_X(x) = \lambda e^{-\lambda x} \qquad x \geq 0.$$

Then,

$$\begin{aligned}
M(s) &= \lambda \int_0^\infty e^{sx} e^{-\lambda x} dx \\
&= \lambda \int_0^\infty e^{(s-\lambda)x} dx \\
&= \lambda \left(\frac{e^{(s-\lambda)x}}{s-\lambda} \right|_0^\infty \\
&= \frac{\lambda}{\lambda - s}.
\end{aligned}$$

Notice, in above examples, that MGF is a **function** of parameter s, and not a number. We can also find MGF's for functions of X:

Proposition 4 (MGF of Linear Function of RV)
Let $Y = aX + b$. Then,

$$M_Y(s) = E(e^{s(aX+b)}) = e^{sb} E(e^{saX}) = e^{sb} M_X(sa).$$

From our previous example, we see that $M_X(s) = \frac{1}{1-s}$ where X is the exponential distribution

2.1 Moments

Now that we've established what a moment generating function is, now it's time to understand what is being generated.

Let's do a generic MGF

$$M(s) = \int_{-\infty}^{\infty} e^{sx} f_X(x) dx.$$

Now, we take the derivative of this.

$$\begin{aligned}
\frac{d}{ds} M(s) &= \frac{d}{ds} \int_{-\infty}^{\infty} e^{sx} f_X(x) dx \\
&= \int_{-\infty}^{\infty} \frac{d}{ds} e^{sx} f_X(x) dx \\
&= \int_{-\infty}^{\infty} x e^{sx} f_X(x) dx.
\end{aligned}$$

When $s = 0$, we have that this evaluates to $\int_{-\infty}^{\infty} x f_X(x) dx = E(X)$. If we differentiate n times, then we will get

$$\left(\frac{d^n}{ds^n} M(s) \right|_{s=0} = \int_{-\infty}^{\infty} x^n f_X(x) dx = E(X^n).$$

2.2 Inversion

Proposition 5 (Inversion Property)
The MGF $M_X(s)$ associated with an RV X uniquely determines the CDF of X, assuming that $M_X(s)$ is finite for all s in some interval $[-a, a]$ for positive a.

2.3 Sum of Independent Random Variables

Proposition 6

Addition of independent random variables corresponds to multiplication of transforms.

Proof. Let $Z = X + Y$. $M_Z(s) = E(e^{sZ}) = E(e^{s(X+Y)}) = E(e^{sX}e^{sY})$. Since X, Y are independent, e^{sX} and e^{sY} are independent random variables for any fixed s. Thus, $E(e^{sX}e^{sY}) = E(e^{sX})E(e^{sY}) = M_X(s)M_Y(s)$. $\square$

We can further extend this; if $X_1, \dots, X_n$ is a collection of independent random variables and $Z = X_1 + \cdots + x_n$, then $M_Z(s) = M_{X_1}(s) \cdots M_{X_n}(s)$.

3 σ-algebra

Definition 7 (σ-algebra)

Given a sample space Ω, a set $\mathcal{F} \subseteq 2^\Omega$ is a σ-algebra if:

1. $\Omega \in \mathcal{F}$
2. If any event A is in $\mathcal{F}$, then its complement $\Omega \setminus A$ is also in $\mathcal{F}$.
3. For countably many events $A_1, A_2, \dots, A_n, \dots \in \mathcal{F}$, their union $A = \bigcup_{i=1}^\infty A_i \in \mathcal{F}$.