Random vectors

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Definition 4.1 (Random vector)**.** A random vector $\boldsymbol{X} \colon \Omega \to \mathbb{R}^n$ is a tuple of random variables $X_i \colon \Omega \to \mathbb{R}$.

Definition 4.2 (Joint cumulative distribution function)**.** The joint cumulative distribution function of a random vector $\boldsymbol{X}$ is the map $F_{\boldsymbol{X}} \colon \mathbb{R}^n \to [0,1]$, given as

$$F_{\boldsymbol{X}}(\boldsymbol{s}) = P(X_1 \leq s_1, \ldots, X_n \leq s_n).$$

Definition 4.3 (Joint probability mass function)**.** If X_i are discrete random variables, their joint probability mass function is the map $p_{\boldsymbol{X}} \colon \mathbb{R}^n \to [0,1]$,

$$p_{\boldsymbol{X}}(\boldsymbol{s}) = P(X_1 = s_1, \ldots, X_n = s_n).$$

Definition 4.4 (Joint probability density function)**.** Suppose that

$$F_{\boldsymbol{X}}(\boldsymbol{s}) = \int_{-\infty}^{s_n} \cdots \int_{-\infty}^{s_1} f_{\boldsymbol{X}}(t_1, \ldots, t_n) \, dt_1 \ldots \, dt_n,$$

then $f_{\boldsymbol{X}} \colon \mathbb{R}^n \to [0,1]$ is the probability density function corresponding to the joint cumulative distribution function $F_{\boldsymbol{X}}$.

Remark. If $f_{\boldsymbol{X}}$ is continuous, then

$$f_{\boldsymbol{X}} = \frac{\partial F_{\boldsymbol{X}}(t_1, \ldots, t_n)}{\partial t_1 \ldots \partial t_n}.$$

Definition 4.5 (Joint moment generating function)**.** Let $\boldsymbol{X}$ be a random vector. Then, its joint moment generating function is defined as

$$M_{\boldsymbol{X}}(\boldsymbol{t}) = E\left[e^{\boldsymbol{t}^\top \boldsymbol{X}}\right] = E\left[e^{t_1 X_1 + \cdots + t_n X_n}\right].$$

Remark. If $X_1, \ldots, X_n$ are independent, then

$$M_{\boldsymbol{X}}(\boldsymbol{t}) = \prod M_{X_i}(t_i).$$

Theorem 4.1. *If X and Y are independent continuous random variables, then the probability density function of their sum is the convolution $f_{X+Y} = f_X * f_Y$,*

$$f_{X+Y}(x) = \int_{\mathbb{R}} f_X(x - t)\, f_Y(t)\, dt.$$

Example. When X and Y are identical and uniform on $[0, 1]$, then

$$f_{X+Y}(x) = \int_0^1 f(x - t)\, dt = \begin{cases} x, & \text{if } a \in [0, 1], \\ 2 - x, & \text{if } a \in [1, 2], \\ 0, & \text{otherwise .} \end{cases}$$

Also,

$$M_{X+Y}(t) = (M(t))^2 = \frac{1}{t^2}(e^t - 1)^2.$$

Definition 4.6 (Conditional distribution)**.** Let X and Y be two discrete random variables. We write

$$P(X = s \mid Y = t) = \frac{P(X = s, Y = t)}{P(Y = t)}$$

for $P(Y = t) > 0$. We also have

$$P(X \le s \mid Y = t) = \sum_{r \le s} P(X = r \mid Y = t).$$

If X and Y are continuous random variables, then the conditional distribution of X given $Y = t$ is described as

$$F_{X \mid Y=t}(r) = \int_{-\infty}^s \frac{f_{X,Y}(r, t)}{f_Y(t)}\, dr.$$

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Example. Consider two continuous random variables X and Y which have a joint probability mass function
$$f_{X,Y}(s,t) = \begin{cases} \alpha t, & \text{if } 0 < t < s < 1, \\ 0, & \text{otherwise.} \end{cases}$$

First normalize, by demanding
$$\iint_{\mathbb{R}^2} f_{X,Y}(s,t)\, dt\, ds = \int_0^1 \int_0^s \alpha t\, dt\, ds = 1,$$

whence $\alpha = 6$. Thus,
$$E\left[Y \mid X = s\right] = \int_{\mathbb{R}} t \cdot \frac{f_{X,Y}(s,t)}{f_X(s)}\, dt.$$

Now,
$$f_X(s) = \int_{\mathbb{R}} f_{X,Y}(s,t)\, dt = \int_0^s 6t\alpha\, dt = 3s^2$$

for $0 < s < 1$, and simply 3 for $s \geq 1$. Thus,
$$E\left[Y \mid X = s\right] = \int_0^s t \cdot \frac{6t}{3s^2}\, dt = \frac{2}{3}s,$$

in the region $0 < s < 1$. For $s \geq 1$, the expectation becomes $2/3$. Also,
$$\mathrm{Var}[Y \mid X = s] = E\left[Y^2 \mid X = s\right] - E\left[Y \mid X = s\right]^2.$$

The first term is
$$E\left[Y^2 \mid X = s\right] = \int_0^s t^2 \cdot \frac{6t}{3s^2}\, dt = \frac{1}{2}s^2.$$

Thus,
$$\mathrm{Var}[Y \mid X = s] = \frac{1}{2}s^2 - \frac{4}{9}s^2 = \frac{1}{18}s^2.$$

Note that
$$f_Y(t) = \int_{\mathbb{R}} f_{X,Y}(s,t)\, ds = \int_t^1 6t\alpha\, ds = 6t(1-t)$$

in the region $0 < t < 1$. Thus,
$$F_Y(t) = \int_0^t 6t'(1-t')\, dt' = t^2(3 - 2t)$$

for $0 < t < 1$. $F_Y(t) = 1$ for $t \geq 1$.

Theorem 4.2. *For discrete or continuous random variables X and Y,*
$$E\left[E\left[X \mid Y\right]\right] = E\left[X\right].$$

Proof.
$$E\left[E\left[X \mid Y\right]\right] = \sum_n E\left[X \mid Y = n\right] P(Y = n) = \sum_{nm} m P(X = m, Y = n).$$

Reordering the summations, we get
$$\sum_m m \sum_n P(X = m, Y = n) = \sum_m m P(X = m) = E\left[X\right].$$

The proof for discrete random variables is analogous, switching the sums for integrals.   □