5 Continuous random variables

We deviate from the order in the book for this chapter, so the subsections in this chapter do not correspond to those in the text.

5.1 Densities of continuous random variable

Recall that in general a random variable X is a function from the sample space to the real numbers. If the range of X is finite or countable infinite, we say X is a discrete random variable. We now consider random variables whose range is not countably infinite or finite. For example, the range of X could be an interval, or the entire real line.

For discrete random variables the probability mass function is $f_X(x) = \mathbf{P}(X = x)$. If we want to compute the probability that X lies in some set, e.g., an interval $[a, b]$, we sum the pmf:

$$\mathbf{P}(a \leq X \leq b) = \sum_{x: a \leq x \leq b} f_X(x)$$

A special case of this is

$$\mathbf{P}(X \leq b) = \sum_{x: x \leq b} f_X(x)$$

For continuous random variables, we will have integrals instead of sums.

Definition 1. *A random variable X is continuous if there is a non-negative function $f_X(x)$, called the probability density function (pdf) or just density, such that*

$$\mathbf{P}(X \leq t) = \int_{-\infty}^{t} f_X(x)\, dx$$

Proposition 1. *If X is a continuous random variable with density $f(x)$, then*

1. $\mathbf{P}(X = x) = 0$ *for any* $x \in \mathbb{R}$.
2. $\mathbf{P}(a \leq X \leq b) = \int_a^b f(x)\, dx$
3. *For any subset C of $\mathbb{R}$,* $\mathbf{P}(X \in C) = \int_C f(x)\, dx$

4. $\int_{-\infty}^{\infty} f(x)\,dx = 1$

Proof. First we observe that subtracting the two equations

$$\mathbf{P}(X \le b) = \int_{-\infty}^{b} f_X(x)\,dx, \quad \mathbf{P}(X \le a) = \int_{-\infty}^{a} f_X(x)\,dx$$

gives

$$\mathbf{P}(X \le b) - \mathbf{P}(X \le a) = \int_{a}^{b} f_X(x)\,dx$$

and we have $\mathbf{P}(X \le b) - \mathbf{P}(X \le a) = \mathbf{P}(a < X \le b)$, so

$$\mathbf{P}(a < X \le b) = \int_{a}^{b} f_X(x)\,dx \tag{1}$$

Now for any n

$$\mathbf{P}(X = x) \le \mathbf{P}(x - 1/n < X \le x) = \int_{x-1/n}^{x} f_X(t)\,dt$$

As $n \to \infty$, the integral goes to zero, so $\mathbf{P}(X = x) = 0$.

Property 2 now follows from eq. (1) since

$$\mathbf{P}(a \le X \le b) = \mathbf{P}(a < X \le b) + \mathbf{P}(X = a) = \mathbf{P}(a < X \le b)$$

Note that since the probability X equals any single real number is zero, $\mathbf{P}(a \le X \le b)$, $\mathbf{P}(a < X \le b)$, $\mathbf{P}(a \le X < b)$, and $\mathbf{P}(a < X < b)$ are all the same.

Property 3 is easy if C is a disjoint union of intervals. For more general sets, it is not clear what $\int_C$ even means. This is beyond the scope of this course.

Property 4 is just the fact that $P(-\infty < X < \infty) = 1$. $\square$

Caution Often the range of X is not the entire real line. Outside of the range of X the density $f_X(x)$ is zero. So the definition of $f_x(x)$ will typically involves cases: in one region it is given by some formula, elsewhere it is simply 0. So integrals over all of $\mathbb{R}$ which contain $f_X(x)$ will reduce to intervals over a subset of $\mathbb{R}$. If you mistakenly integrate the formula over the entire real line you will of course get nonsense.

5.2 Catalog

As with discrete RV's, two continuous RV's defined on completely different probability spaces can have the same density. And there are certain densities that come up a lot. So we start a catalog of them.

Uniform: (two parameters $a, b \in \mathbb{R}$ with $a < b$) The uniform density on $[a, b]$ is

$$f(x) = \begin{cases} \frac{1}{b-a}, & \text{if } a \leq x \leq b \\ 0, & \text{otherwise} \end{cases}$$

We have seen the uniform before. Previously we said that to compute the probability X is in some subinterval $[c, d]$ of $[a, b]$ you take the length of that subinterval divided by the length of $[a, b]$. This is of course what you get when you compute

$$\int_c^d f_X(x)\, dx = \int_c^d \frac{1}{b-a}\, dx = \frac{d-c}{b-a}$$

Exponential: (one real parameter $\lambda > 0$)

$$f(x) = \begin{cases} \lambda e^{-\lambda x}, & \text{if } x \geq 0 \\ 0, & \text{if } x < 0 \end{cases}$$

Check that its total integral is 1. Note that the range is $[0, \infty)$.

Normal: (two real parameters $\mu, \sigma > 0$)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)$$

The range of a normal RV is the entire real line. It is anything but obvious that the integral of this function is 1. Try to show it.

Cauchy:

$$f(x) = \frac{1}{\pi(1+x^2)}$$

Example: Suppose X is a random variable with an exponential distribution with parameter $\lambda = 2$. Find $\mathbf{P}(X \leq 2)$ and $P(X \leq 1 | X \leq 2)$.

Example: Suppose X has the Cauchy distribution. Find the number c with the property that $\mathbf{P}(X \geq c) = 1/4$.

Example: Suppose X has the density

$$f(x) = \begin{cases} c\,x(2-x) & \text{if } 0 \leq x \leq 2 \\ 0 & \text{otherwise} \end{cases}$$

where c is a constant. Find the constant c and then compute $\mathbf{P}(1/2 \leq X)$.

5.3 Expected value

A rigorous treatment of the expected value of a continuous random variable requires the theory of abstract Lebesgue integration, so our discussion will not be rigorous.

For a discrete RV X, the expected value is

$$\mathbf{E}[X] = \sum_x x f_X(x)$$

We will use this definition to derive the expected value for a continuous RV. The idea is to write our continuous RV as the limit of a sequence of discrete RV's.

Let X be a continuous RV. We will assume that it is bounded. So there is a constant M such that the range of X lies in $[-M, M]$, i.e., $-M \leq X \leq M$. Fix a positive integer n and divide the range into subintervals of width $1/n$. In each of these subintervals we "round" the value of X to the left endpoint of the interval and call the resulting RV X_n. So X_n is defined by

$$X_n(\omega) = \frac{k}{n}, \quad \textit{where } k \textit{ is the integer with} \quad \frac{k}{n} \leq X(\omega) < \frac{k+1}{n}$$

Note that for all outcomes ω, $|X(\omega) - X_n(\omega)| \leq 1/n$. So X_n converges to X pointwise on the sample space Ω. In fact it converges uniformly on Ω. The expected value of X should be the limit of $\mathbf{E}[X_n]$ as $n \to \infty$.

The random variable X_n is discrete. Its values are k/n with k running from $-Mn$ to $Mn - 1$ (or possibly a smaller set). So

$$\mathbf{E}[X_n] = \sum_{k=-Mn}^{Mn-1} \frac{k}{n} f_{X_n}(\frac{k}{n})$$

Now

$$f_{X_n}(\frac{k}{n}) = \mathbf{P}(X_n = \frac{k}{n}) = \mathbf{P}(\frac{k}{n} \le X(\omega) < \frac{k+1}{n}) = \int_{\frac{k}{n}}^{\frac{k+1}{n}} f_X(x)\,dx$$

So

$$\begin{aligned}
\mathbf{E}[X_n] &= \sum_{k=-Mn}^{Mn-1} \frac{k}{n} \int_{\frac{k}{n}}^{\frac{k+1}{n}} f_X(x)\,dx \\
&= \sum_{k=-Mn}^{Mn-1} \int_{\frac{k}{n}}^{\frac{k+1}{n}} \frac{k}{n} f_X(x)\,dx
\end{aligned}$$

When n is large, the integrals in the sum are over a very small interval. In this interval, x is very close to k/n. In fact, they differ by at most $1/n$. So the limit as $n \to \infty$ of the above should be

$$\sum_{k=-Mn}^{Mn-1} \int_{\frac{k}{n}}^{\frac{k+1}{n}} x\, f_X(x)\,dx = \int_{-M}^{M} x\, f_X(x)\,dx = \int_{-\infty}^{\infty} x\, f_X(x)\,dx$$

The last equality comes from the fact that $f_X(x)$ is zero outside $[-M, M]$. So we make the following definition

Definition 2. *Let X be a continuous RV with density $f_X(x)$. The expected value of X is*

$$\mathbf{E}[X] = \int_{-\infty}^{\infty} x\, f_X(x)\,dx$$

provided

$$\int_{-\infty}^{\infty} |x|\, f_X(x)\,dx < \infty$$

(If this last integral is infinite we say the expected value of X is not defined.) The variance of X is

$$\sigma^2 = \mathbf{E}[(X-\mu)^2], \quad \mu = \mathbf{E}[X]$$

provided the expected value is defined.

End of September 30 lecture

Just as with discrete RV's, if X is a continuous RV and g is a function from $\mathbb{R}$ to $\mathbb{R}$, then we can define a new RV by $Y = g(X)$. How do we compute the mean of Y ? One approach would be to work out the density of Y and then use the definition of expected value. We have not yet seen how to find the density of Y, but for this question there is a shortcut just as there was for discrete RV.

Theorem 1. *Let X be a continuous RV, g a function from $\mathbb{R}$ to $\mathbb{R}$. Let $Y = g(X)$. Then*

$$\mathbf{E}[Y] = \mathbf{E}[g(X)] = \int_{-\infty}^{\infty} g(x)\, f_X(x)\, dx$$

Proof. Since we do not know how to find the density of Y, we cannot prove this yet. We just give a non-rigorous derivation. Let X_n be the sequence of discrete RV's that approximated X defined above. Then $g(X_n)$ are discrete RV's. They approximate $g(X)$. In fact, if the range of X is bounded and g is continous, then $g(X_n)$ will converge uniformly to $g(X)$. So $\mathbf{E}[g(X_n)]$ should converges to $\mathbf{E}[g(X)]$.

Now $g(X_n)]$ is a discrete RV, and by the law of the unconscious statistician

$$\mathbf{E}[g(X_n)] = \sum_x g(x)\, f_{X_n}(x) \tag{2}$$

Looking back at our previous derivation we see this is

$$\begin{aligned} \mathbf{E}[g(X_n)] &= \sum_{k=-Mn}^{Mn-1} g(\frac{k}{n}) \int_{\frac{k}{n}}^{\frac{k+1}{n}} f_X(x)\, dx \\ &= \sum_{k=-Mn}^{Mn-1} \int_{\frac{k}{n}}^{\frac{k+1}{n}} g(\frac{k}{n})\, f_X(x)\, dx \end{aligned}$$

which converges to

$$\int g(x)\, f_X(x)\, dx \tag{3}$$

$\square$

Just as in the discrete case, there is an application of this theorem that gives us a shortcut for computing the variance

Corollary 1. *If X is a continuous random variable with finite variance σ^2 and mean μ, then*

$$\sigma^2 = \mathbf{E}[X^2] - \mu^2 = \int_{-\infty}^{\infty} x^2 \, f_X(x) \, dx - \mu^2$$

Proof. By the theorem

$$\begin{aligned} \sigma^2 &= \mathbf{E}[(X-\mu)^2] = \int (x-\mu)^2 \, f_X(x) \, dx = \int [x^2 - 2\mu x + \mu)^2] \, f_X(x) \, dx \\ &= \int x^2 \, f_X(x) \, dx - 2\mu \int x \, f_X(x) \, dx + \mu^2 \int f_X(x) \, dx \\ &= \int x^2 \, f_X(x) \, dx - 2\mu^2 + \mu^2 = \int x^2 \, f_X(x) \, dx - \mu^2 \end{aligned}$$

□

Example: Find the mean and variance of the uniform distribution on $[a, b]$.

The mean is

$$\mu = \int_a^b x \, f(x) \, dx = \int_a^b \frac{x}{b-a} \, dx = \frac{1}{2} \frac{b^2 - a^2}{b-a} = \frac{a+b}{2} \tag{4}$$

For the variance we have to first compute

$$\mathbf{E}[X^2] = \int_a^b x^2 \, f(x) \, dx \tag{5}$$

We then subtract the square of the mean and find $\sigma^2 = (b-a)^2/12$.

Example: Find the mean and variance of the normal distribution.

Example: Find the mean of the Cauchy distribution

The gamma function is defined by

$$\Gamma(w) = \int_0^{\infty} x^{w-1} \, e^{-x} \, dx \tag{6}$$

The gamma distribution has range $[0, \infty)$ and depends on two parameters $\lambda > 0, w > 0$. The density is

$$f(x) = \begin{cases} \frac{\lambda^w}{\Gamma(w)} \, x^{w-1} \, e^{-\lambda x} & \text{if } x \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

In one of the homework problems we compute its mean and variance. You should find that they are

$$\mu = \frac{w}{\lambda}, \quad \sigma^2 = \frac{w}{\lambda^2} \tag{8}$$

Example: Let X be exponential with parameter λ. Let $Y = X^2$. Find the mean and variance of Y.

5.4 Cumulative distribution function

In this section X is a random variable that can be either discrete or continuous.

Definition 3. *The cumulative distribution function (cdf) of the random variable X is the function*

$$F_X(x) = \mathbf{P}(X \leq x)$$

Why introduce this function? It will be a powerful tool when we look at functions of random variables and compute their density.

Example: Let X be uniform on $[-1, 1]$. Compute the cdf.

GRAPH !!!!!!!!!!!!!!!!!!!!

Example: Let X be a discrete RV whose pmf is given in the table.

x	2	3	4	5	6
$f_X(x)$	1/8	1/8	3/8	2/8	1/8

GRAPH !!!!!!!!!!!!!!!!!!!!

Example: Compute cdf of exponential distribution.

End of September 30 lecture

Theorem 2. *Let X be a continuous RV with pdf $f(x)$ and cdf $F(x)$. Then they are related by*

$$\begin{aligned} F(x) &= \int_{-\infty}^{x} f(t)\,dt, \\ f(x) &= F'(x) \end{aligned}$$

Proof. The first equation is immediate from the def of the cdf. To get the second equation, differentiate the first equation and remember that the fundamental theorem of calculus says

$$\frac{d}{dx}\int_{a}^{x} f(t)\,dt = f'(x)$$

$\square$

Theorem 3. *For any random variable the cdf satisfies*

1. *$F(x)$ is non-decreasing, $0 \leq F(x) \leq 1$.*
2. *$\lim_{x\to-\infty} F(x) = 0$, $\lim_{x\to\infty} F(x) = 1$.*
3. *$F(x)$ is continuous from the right.*
4. *For a continuous random variable the cdf is continuous.*
5. *For a discrete random variable the cdf is piecewise constant. The points where it jumps is the range of X. If x is a point where it has a jump, then the height of the jump is $\mathbf{P}(X = x)$.*

Proof. 1 is obvious ....

To prove 2, let $x_n \to \infty$. Assume that x_n is increasing. Let $E_n = \{X \leq x_n\}$. Then E_n is in increasing sequence of events. By the continuity of the probability measure,

$$\mathbf{P}(\cup_{n=1}^{\infty} E_n) = \lim_{n\to\infty} \mathbf{P}(E_n)$$

Since $x_n \to \infty$, every outcome is in E_n for large enough n. So $\cup_{n=1}^\infty E_n = \Omega$. So

$$\lim_{n\to\infty} F(x_n) = \lim_{n\to\infty} \mathbf{P}(E_n) = 1 \tag{9}$$

The proof that the limit as $x \to -\infty$ is 0 is similar.

GAP

$\square$

Now consider a continuous random variable X with density f. Then

$$F(x) = \mathbf{P}(X \le x) = \int_{-\infty}^{x} f(t)\, dt$$

So given the density we can compute the cdf by doing the above integral. Differentiating the above we get

$$F'(x) = f(x)$$

So given the cdf we can compute the density by differentiating.

Theorem 4. *Let $F(x)$ be a function from $\mathbb{R}$ to $[0,1]$ such that*

1. *$F(x)$ is non-decreasing.*
2. *$\lim_{x\to-\infty} F(x) = 0$, $\lim_{x\to\infty} F(x) = 1$.*
3. *$F(x)$ is continuous from the right.*

Then $F(x)$ is the cdf of some random variable, i.e., there is a probability space $(\Omega, \mathcal{F}, \mathbf{P})$ and a random variable X on it such that $F(x) = \mathbf{P}(X \le x)$.
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The proof of this theorem is way beyond the scope of this course.

5.5 Function of a random variable

Let X be a continuous random variable and $g : \mathbb{R} \to \mathbb{R}$. Then $Y = g(X)$ is a new random variable. We want to find its density. This is not as easy as in the discrete case. In particular $f_Y(y)$ is not $\sum_{x:g(x)=y} f_X(x)$.

KEY IDEA: Compute the cdf of Y and then differentiate it to get the pdf of Y.

Example: Let X be uniform on $[0,1]$. Let $Y = X^2$. Find the pdf of Y.

!!!!!!! GAP

Example: Let X be uniform on $[-1,1]$. Let $Y = X^2$. Find the pdf of Y.

!!!!!!! GAP

Example: Let X be uniform on $[0,1]$. Let $\lambda > 0$. $Y = -\frac{1}{\lambda}\ln(X)$. Show Y has an exponential distribution.

!!!!!!! GAP

Example: The "standard normal" distribution is the normal distribution with $\mu = 0$ and $\sigma = 1$. Let X have a normal distribution with parameters μ and σ. Show that $Z = (X - \mu)/\sigma$ has the standard normal distribution.

!!!!!!! GAP

Proposition 2. *(How to write a general random number generator) Let X be a continuous random variable with values in $[a,b]$. Suppose that the cdf $F(x)$ is strictly increasing on $[a,b]$. Let U be uniform on $[0,1]$. Let $Y = F^{-1}(U)$. Then X and Y are identically distributed.*

Proof.

$$\mathbf{P}(Y \leq y) = \mathbf{P}(F^{-1}(U) \leq y) = \mathbf{P}(U \leq F(y)) = F(y) \tag{10}$$

□

Application: My computer has a routine to generate random numbers that are uniformly distributed on $[0,1]$. We want to write a routine to generate numbers that have an exponential distribution with parameter λ.

How do you simulate normal RV's? Not so easy since the cdf cannot be explicitly computed. More on this later.

5.6 More on expected value

Recall that for a discrete random variable that only takes on values in $0, 1, 2, \cdots$, we showed in a homework problem that

$$E[X] = \sum_{k=0}^{\infty} P(X > k) \tag{11}$$

There is a similar result for non-negative continuous random variables.

Theorem 5. *Let X be a non-negative continuous random variable with cdf $F(x)$. Then*

$$\mathbf{E}[X] = \int_0^\infty [1 - F(x)]\, dx \tag{12}$$

provided the integral converges.

Proof. We use integration by parts on the integral. Let $u(x) = 1 - F(x)$ and $dv = dx$. So $du = -f dx$ and $v = x$. So

$$\int_0^\infty [1 - F(x)]\, dx = x(1 - F(x))|_{x=0}^\infty + \int_0^\infty x\, f(x)\, dx = \mathbf{E}[X] \tag{13}$$

Note that the boundary term at ∞ is zero since $F(x) \to 1$ as $x \to \infty$. ☐

We can use the above to prove the law of the unconscious statistician for a special case. We assume that $X \geq 0$ and that the function g is from $[0, \infty)$ into $[0, \infty)$ and it strictly increasing. Note that this implies that g has an inverse. Then

$$\begin{aligned}
\mathbf{E}[Y] &= \int_0^\infty [1 - F_Y(x)]\, dx = \int_0^\infty [1 - \mathbf{P}(Y \leq x)]\, dx && (14)\\
&= \int_0^\infty [1 - \mathbf{P}(g(X) \leq x)]\, dx = \int_0^\infty [1 - \mathbf{P}(X \leq g^{-1}(x))]\, dx && (15)\\
&= \int_0^\infty [1 - F_X(g^{-1}(x))]\, dx && (16)
\end{aligned}$$

Now we do a change of variables. Let $s = g^{-1}(x)$. So $x = g(s)$ and $dx = g'(s) ds$. So above becomes

$$\int_0^\infty [1 - F_X(s)]\, g'(s)\, ds \tag{17}$$

Now integrate this by parts to get

$$[1 - F_X(s)]\, g(s)|_{s=0}^\infty + \int_0^\infty g(s)\, f(s)\, ds \tag{18}$$

which proves the theorem in this special case.