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Lecture 3. 14.10.2014 (half-hour:problems)

3. Distributions and distribution functions

The distribution function $F(x) := P(X \leq x)$ of X is a Lebesgue-Stieltjes measure function; it determines the corresponding Lebesgue-Stieltjes measure by (denoting this also by F to save letters – μ_F is the other common notation)

$$F((a, b]) = F(b) - F(a)$$

(and hence we can extend from such intervals to general Borel sets). Now

$$F(x) = P(X \leq x) = P(X \in (-\infty, x]) = P(X^{-1}(-\infty, x]),$$

or (taking $a = -\infty, b = x$ above)

$$F((-\infty, x]) = P(X^{-1}(-\infty, x]).$$

Extending as above,

$$F(B) = P(X^{-1}(B))$$

for any Borel set B. We may write the RHS as the composite $(P \circ X)(B)$. We thus then have

$$F = P \circ X^{-1} :$$

F, the distribution of X, is the *image measure* of the probability measure P under the inverse map X^{-1} (or more briefly, 'under X').

Expectations

In Lecture 2, we defined $E[X]$ as $\int_\Omega X dP$, and similarly $E[g(X)] = \int_\Omega g(X) dP$, for Borel measurable g.

In your first course on Probability and/or Statistics, you defined

$$E[g(X)] := \int_{-\infty}^{\infty} g(x) dF(x),$$

at least in the two main cases:

$$\int_{-\infty}^{\infty} g(x) f(x) dx \quad \text{(density case, density } f\text{)}; \quad \sum_n g(x_n) f(x_n) \quad \text{(discrete case)}$$

(we now know that there is no need to handle these separately, we can handle them together – and, that we must restrict to the case of *absolute* convergence in all sums and integrals).

It seems that we now have two different ways of defining $E[g(X)]$ – as a P-integral over the sample space Ω or as an F-integral over the line. As one might expect, these two are the same. This follows from the transformation formula for integrals in Measure Theory; see SP L7.

The discrete case.

If X takes (finitely or) countably many values x_n, write

$$f(x_n) := P(X = x_n) \qquad (n = 1, 2, \ldots).$$

Then the distribution function

$$F(x) = \sum_{n : x_n \leq x} f(x_n)$$

is a jump-function, increasing by $f(x_n)$ at x_n and constant elsewhere.

The Lebesgue decomposition.

The discrete and density cases are not exhaustive – though they are all one usually encounters in practice in Statistics. We quote: the general distribution function F has a *Lebesgue decomposition*

$$F = c_{ac} F_{ac} + c_d F_d + c_s F_s,$$

where the constants c_i are non-negative and sum to 1 (the RHS is called a *mixture*), F_{ac} is an *absolutely continuous* distribution, F_d is a *discrete* distribution (with density f, say), and F_s is a *continuous singular* distribution (no jumps, but increases only on a Lebesgue-null set). We will not encounter such F_s in practice, so we do not discuss them further.

This reduces the number of components on the right to two. Actually, we will only encounter one at a time here – usually the density case (see below)

Discrete v. continuous.

Statistics is dominated by the density case: normal, chi-square, Student t, Fisher F, uniform, exponential, Gamma, Beta etc. But the discrete case also occurs – e.g., the *Poisson* distribution. The density case corresponds to *measurement* data, the discrete case to *count* data. Mathematically, the density case involves *integrals*, the discrete case *sums*. We have chosen our notation $f(.)$ to fit both cases. This is more than a formal analogy: distributions with densities are absolutely continuous w.r.t. *Lebesgue measure*; discrete ones are absolutely continuous w.r.t. *counting measure* (SP L4).