# A Note on Bivariate Distributions That Are Conditionally Normal

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# ABSTRACT

It is possible for a non-Normal bivariate distribution to have conditional distribution functions that are Normal in both directions. This article presents several examples, with graphs, including a counterintuitive bimodal joint density. The graphs simultaneously display the joint density and the conditional density functions, which appear as Gaussian curves in the threedimensional plots.

Key words: Bivariate Normal distribution; Conditional probability; Bimodality.

#### 1. INTRODUCTION

It is well known that the pair of marginal distributions does not uniquely determine a bivariate distribution; for example, a bivariate distibution with Normal marginals need not be jointly Normal (Feller, 1966, p. 69). In contrast, the *conditional* distribution functions uniquely deterimine a joint density function (Arnold and Press, 1989). A natural question then arises: must a bivariate distribution with Normal conditional distributions be jointly Normal? The answer is no; in fact, the joint distribution thus specified must fall in a parametric exponential family that we show includes such oddities as bimodal densities and a distribution with constant conditional means but nonconstant conditional variances. This paper presents a simple expression for the distributional result derived in Castillo and Galambos (1987); we then graph some examples of bivariate density functions.

In general, a multivariate distribution on the variables  $(x_1, \dots, x_n)$  may be characterized by its joint distribution or the conditional distributions of  $(x_i|x_j, \text{ all } j \neq i)$  for all *i*. For many models, one can specify the set of conditional distributions but cannot directly identify the joint distribution; Brook (1964) and Besag (1974) connect these two specifications for nearestneighbour and Gibbs distributions, and show that the set of conditional distributions for all  $x_i$  determines the joint distribution. In addition, the set of conditional distributions is constrained by the requirement that they be consistent; that is, a single joint distribution should exist that reduces to each conditional distribution. Even in the bivariate case, interesting complications arise, as in the example of this paper.

Dawid (1979) and others stress the importance of identifying models by their conditional distributions; our work may be of practical importance because we expand the class of multivariate distributions that can be simply specified by conditionals. The supply of tractable joint distributions is limited, and it may be useful, for example, to model a bimodal joint density using only conditional normal densities (see Figure 3).

# 2. PARAMETRIC FAMILY

Let  $x_1$  and  $x_2$  be two jointly-distributed random variables, for which  $x_1$  is

normally distributed given  $x_2$  and vice-versa. Then their joint distribution, after location and scale transformations in each variable, can be written:

$$f(x_1, x_2) \propto \exp(-\frac{1}{2} [Ax_1^2 x_2^2 + x_1^2 + x_2^2 - 2Bx_1 x_2 - 2C_1 x_1 - 2C_2 x_2]), \quad (1)$$

whence the conditional distributions are:

$$\begin{aligned} x_1 | x_2 &\sim N(\frac{Bx_2 + C_1}{Ax_2^2 + 1}, \frac{1}{Ax_2^2 + 1}), \\ x_2 | x_1 &\sim N(\frac{Bx_1 + C_2}{Ax_1^2 + 1}, \frac{1}{Ax_1^2 + 1}). \end{aligned}$$

The only restrictions for (1) to be a probability density function are that  $A \ge 0$ , and if A = 0, then |B| < 1. One can see that the conditional variances are constant if and only if A = 0, in which case the conditional mean functions are linear and the joint distribution is Gaussian.

This result can be extended to the general multivariate problem of variables  $x_1, \dots, x_n$  whose conditional distributions  $(x_i|x_j, \text{ all } j \neq i)$  are Gaussian for all *i*. The resulting joint density must be of the form:

$$f(x_1,\cdots,x_n)\propto \exp(-\frac{1}{2}[\sum A_k x_1^{k_1}\cdots x_n^{k_n}]).$$

The summation is taken over all  $3^n$  values of the exponents defined by each  $k_i$  attaining the values 0, 1, or 2. The coefficients  $A_k$  are allowed to take on any real values for which the joint density function has a finite integral.

# 3. EXAMPLES

We illustrate the diversity of this distributional family with graphs of three bivariate densities that clearly differ from joint normality. Consider for simplicity the symmetric subfamily in which A = 1, B = 0,  $C_1 = C_2 = C$ , with conditional distributions

$$x_1|x_2 \sim N\left(\frac{C}{1+x_2^2}, \frac{1}{1+x_2^2}\right),$$

and similarly for  $x_2|x_1$ . Figures 1-3 illustrate the corresponding joint densities for the values C = 0, 1, 4. Note that the grid lines in the graphs, which are just unnormalized conditional density functions, are clearly Gaussian. Figure 1 shows a joint density with zero conditional means that differs from a Gaussian by having nonconstant conditional variances. The distribution shown in Figure 2 is amusing in that  $(x_1|x_2) \sim N(1/(x_2^2 + 1), 1/(x_2^2 + 1))$ and vice-versa, so that the conditional mean equals the conditional variance at all points. Figure 3 presents a counterintuitive example of a bimodal joint density with bimodal marginals but Gaussian conditional densities. It is easily shown that, within this subfamily, the joint density is bimodal if and only if C > 2.

# REFERENCES

- Arnold, B. C., and Press, S. J. (1989). Compatible conditional distributions. Journal of the American Statistical Association 84, 152-156.
- Besag, J. (1974). Spatial interaction and the statistical analysis of lattice systems. Journal of the Royal Statistics Society, Series B 36, 192-225.
- Brook, D. (1964). On the distinction between the conditional probabil-

ity and the joint probability approaches in the specification of nearestneighbour systems. *Biometrika* 51, 481-483.

- Castillo, E. and Galambos, J. (1987). Bivariate distributions with normal conditionals. In Proceedings of the International Association of Science and Technology for Development (International Symposium on Simulation Modelling and Development, Cairo, Egypt). Anaheim, CA: Acta Press, 59-62.
- Dawid, A. P. (1979). Conditional independence in statistical theory. Journal of the Royal Statistics Society, Series B 41, 1-31.
- Feller, W. (1966). An Introduction to Probability Theory and Its Applications, Volume 2. New York: Wiley.





Figure 2.  $f(x_1, x_2) \propto \exp(-\frac{1}{2}[x_1^2 x_2^2 + x_1^2 + x_2^2 - 2x_1 - 2x_2])$ 



Figure 3.  $f(x_1, x_2) \propto \exp(-\frac{1}{2}[x_1^2 x_2^2 + x_1^2 + x_2^2 - 8x_1 - 8x_2])$ 

