Role of dependence in portfolio credit modeling
Measures of dependence
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Monte Carlo simulation of copulas

Interest Rate and Credit Models

8. Modeling dependence and copulas

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Portfolio credit risk

- We now turn to the issues of modeling portfolios of credit risky assets.

- The central problem of portfolio credit risk modeling is understanding the impact of the dependence between credit events of the individual names on the portfolio as a whole.

- Exposure to portfolio credit risk is common in banking and insurance businesses.

- Various commonly traded structures such as *collateralized loan obligations* (CLOs) are exposed to portfolio credit risk.

- There is a class of credit derivatives, called *synthetic CDOs*, which are options on the portfolio losses in baskets of CDSs.

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Portfolio loss function

- Let us consider portfolio consisting of risky N names.
- We fix a time horizon T, and let l_i and τ_i denote the *loss given default* (LGD) (defined as par less the recovery value) and the default time for name i, respectively.
- Let $L(T)$ denote the total portfolio loss over the time horizon T. Thus

$$L(T) = \sum_{i=1}^{N} 1_{\tau_i \leq T} \, l_i.$$

- The expected loss is thus given by

$$E[L(T)] = \sum_{i=1}^{N} E[1_{\tau_i \leq T}] l_i$$
$$= \sum_{i=1}^{N} Q_i(T) \, l_i,$$

where $Q_i(T)$ is the default probability of name i.

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Portfolio loss function

- The expected loss can often be estimated from CDS markets (which allows us to infer risk-neutral default probabilities) or from rating (using historical probabilities).
- The primary driver of loss distributions is the dependence among the defaults of the individual names.
- Intuitively, higher dependence among the credit events lead to more extreme events with multiple defaults.
- At the same time, higher dependence increases the likelihood of events with few defaults.
- As an illustration, consider $N = 10$, with $l_i = 1$ and $Q_i(T) = 0.1$, for all i.

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Portfolio loss function

- If all names are completely independent:

$$P(L(T) = k) = \binom{N}{k}(0.1)^k(0.9)^{N-k}, \text{ where } n = 0, \ldots, 10.$$

  In particular,

$$P(L(T) = 0) = (0.9)^{10} = 0.349,$$
$$P(L(T) = N) = (0.1)^{10} = 10^{-10}.$$

- If all names are perfectly dependent (if one firm defaults, they all default):

$$P(L(T) = 0) = 0.9,$$
$$P(L(T) = k) = 0.0, \text{ for all } k = 1, \ldots, N-1,$$
$$P(L(T) = N) = 0.1.$$

- Consequently, more dependence implies higher probabilities of tail events.

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Pearson correlation coefficient

- Consider N random variables $X_1, \ldots, X_N$ with joint distribution $H(X_1, \ldots, X_N)$. Their Pearson correlation matrix ρ is defined by

$$\rho_{ij} = \frac{\text{Cov}(X_i, X_j)}{\sqrt{\text{Var}(X_i)}\sqrt{\text{Var}(X_i)}}.$$

- For example, if $X_i = 1_{\tau_i < T}$, then

$$E[X_i^2] = E[X_i]$$
$$= Q_i(T),$$

and so

$$\text{Cov}(X_i, X_j) = P(\tau_i < T, \tau_j < T) - Q_i(T)Q_j(T),$$
$$\text{Var}(X_i) = Q_i(T)S_i(T).$$

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Correlation coefficient

- The Pearson correlation coefficient is a flawed measure of dependence:
    - (i) It is not natural outside of Gaussian distributions.
    - (ii) It only measures linear relationships.
    - (iii) Perfectly dependent random variables do not necessarily have a correlation of 1.
    - (iv) For example, if $X \sim N(0, 1)$, then X and $Y \triangleq X^2$ are perfectly dependent, but their correlation coefficient is 0. The correlation coefficient between X and $Z \triangleq X^3$ is $3/\sqrt{15} \approx 0.775$.
    - (v) Correlation is not invariant under monotone transformations of the random variables.
- Some other measures include concordance measures such as Kendall's tau and Spearman's rho.

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Kendall's tau

- Let $\{(x_1, y_1), \ldots, (x_n, y_n)\}$ be a sample of observations from a pair of random variables X and Y with joint distribution $H(X, Y)$.

- Of the $\binom{n}{2}$ distinct pairs (x_i, y_i), (x_j, y_j), let c be the number of *concordant* pairs (if $x_i < x_j$ and $y_i < y_j$, or $x_i > x_j$ and $y_i > y_j$), and let d be the number of *discordant* pairs (if $x_i < x_j$ and $y_i > y_j$, or $x_i > x_j$ and $y_i < y_j$).

- Then *Kendall's tau* is defined as

$$\widehat{\tau}_{X, Y} = \frac{c - d}{c + d}.$$

- The probabilistic version of this sample definition is

$$\tau_K(X, Y) = P((X_1 - X_2)(Y_1 - Y_2) > 0) - P((X_1 - X_2)(Y_1 - Y_2) < 0),$$

where (X_1, Y_1) and (X_2, Y_2) are independent pairs of random variables drawn from H.

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Spearman's rho

- We consider three pairs (X_1, Y_1), (X_2, Y_2) and (X_3, Y_3) of independent pairs of random variables drawn from the joint distribution H.

- Their Spearman' rho is defined by

$$\rho_S(X, Y) = 3\big(\mathsf{P}((X_1 - X_2)(Y_1 - Y_3) > 0) - \mathsf{P}((X_1 - X_2)(Y_1 - Y_3) < 0)\big).$$

- Spearman's rho is thus the difference of the probability of concordance and the probability of discordance for the vectors of random variables (X_1, Y_1) and (X_2, Y_3).

- These two pairs have the same margins, but the former has joint distribution H while the components of the latter are independent.

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Definition of a copula

- Copulas are devices for constructing joint (multivariate) probability distributions out of marginal (univariate) probability distributions.
- To motivate the definition, we consider uniformly distributed random variables $U_i \in [0, 1]$, $i = 1, \ldots, N$.
- Their joint distribution is a function $C : [0, 1]^N \to [0, 1]$ such that

$$C(u_1, \ldots, u_N) = P(U_1 \leq u_1, \ldots, U_N \leq u_N).$$

- Note that C satisfies the following conditions:
    (i)

$$C(u_1, \ldots, 0, \ldots, u_N) = 0,$$
$$C(1, \ldots, 1, u_i, 1, \ldots, 1) = u_i.$$

    (ii) *Volume monotonicity condition*, which is elementary but somewhat cumbersome to write down.

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Definition of a copula

- We shall formulate the volume monotonicity condition explicitly in the $N = 2$ case only, see [2] or [3] for the general case.
- Namely, if $N = 2$, it reads as follows: for $a_1 \leq b_1$ and $a_2 \leq b_2$,

$$C(b_1, b_2) - C(a_1, b_2) - C(b_1, a_2) + C(a_1, a_2) \geq 0.$$

- This is a consequence of the fact that $P(a_1 \leq U_1 \leq b_1, a_2 \leq U_2 \leq b_2) \geq 0$, i.e.

$$\begin{aligned}
0 &\leq \int_{a_1}^{b_1} \int_{a_2}^{b_2} dC(u_1, u_2) \\
&= C(b_1, b_2) - C(a_1, b_2) - C(b_1, a_2) + C(a_1, a_2),
\end{aligned}$$

where

$$dC(u_1, u_2) \triangleq \frac{\partial^2 C(u_1, u_2)}{\partial u_2 \partial u_2} \, du_1 \, du_2.$$

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Definition of a copula

- *Definition*: Any function $C : [0, 1]^N \to [0, 1]$ satisfying conditions (i) and (ii) is called a *copula*.
- A copula with $N = 2$ is called a *bivariate copula*.

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Examples of copulas

● The independence copula is defined by

$$C(u_1, \ldots, u_N) = \prod_{i=1}^{N} u_i.$$

● The dependence copula is defined by

$$C(u_1, \ldots, u_N) = \min_i u_i.$$

● The anti-dependence copula can be defined for $N = 2$:

$$C(u_1, u_2) = \max(u_1 + u_2 - 1, 0).$$

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Joint probability distributions and copulas

- Consider N continuous random variables $X_1, \ldots, X_N$ with monotone increasing marginal probability distributions $F_1(x), \ldots, F_N(x)$, i.e. $F_i(x) = P(X_i \leq x)$, for $i = 1, \ldots, N$.

- Let $H(X_1, \ldots, X_N)$ denote their joint probability distribution, i.e.

$$H(x_1, \ldots, x_N) = P(X_1 \leq x_1, \ldots, X_N \leq x_N).$$

- For each i, consider the random variable $U_i = F_i(X_i)$. Clearly, $U_i \in [0, 1]$.

- Since

$$
\begin{aligned}
P(U_i \leq u) &= P(X_i \leq F_i^{-1}(u)) \\
&= F_i(F_i^{-1}(u)) \\
&= u,
\end{aligned}
$$

U_i is uniformly distributed on $[0, 1]$.

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Sklar's theorem

- The function

$$C(u_1, \ldots, u_N) = H(F_1^{-1}(u_1), \ldots, F_N^{-1}(u_N))$$

  defines a copula.

- Conversely, given a copula C, the function

$$H(x_1, \ldots, x_N) = C(F_1(x_1), \ldots, F_N(x_N))$$

  defines a joint probability function with marginals $F_1, \ldots, F_N$.

- The last two statements form the content of *Sklar's theorem*.

- Actually, Sklar's theorem is a bit more general than what we formulated above.

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Gaussian copula

- Consider an N-dimensional Gaussian distribution Φ_ρ with correlation matrix ρ.
- A random vector Z distributed according to Φ_ρ has zero mean and each of its components has variance one.
- The Gaussian copula is defined by

$$C_\rho(u_1, \ldots, u_N) = \Phi_\rho(N^{-1}(u_1), \ldots, N^{-1}(u_N)),$$

where $N(x)$ is the standard uniform Gaussian distribution function.

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Gaussian copula

- Explicitly, in the bivariate case,

$$C_\rho(u_1, u_2) = \frac{1}{2\pi\sqrt{1 - \rho_{12}^2}} \int_{-\infty}^{N^{-1}(u_1)} \int_{-\infty}^{N^{-1}(u_2)} \exp\left\{-\frac{s^2 - 2\rho_{12}su + u^2}{2(1 - \rho_{12}^2)}\right\} dsdu.$$

- Note that the correlation matrix ρ is the driver of dependence for the Gaussian copula.
- This is one of the reason's of the popularity of the Gaussian copula: its dependence parameters are the correlation coefficients between the random variables (which are not necessarily Gaussian).

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Student t copula

- Let Z be a random vector distributed according to Φ_ρ, and let Y be a scalar random variable distributed according to the χ^2-distribution with ν degrees of freedom, $S \sim \chi^2_\nu$.

- The Student t copula $C_{\nu,\rho}$ with ν degrees of freedom is defined as the copula corresponding to the N-dimensional random variable $X = \sqrt{\nu/S} Z$,

$$C_{\nu,\rho}(u_1, \ldots, u_n) = t_{\nu,\rho}(t_\nu^{-1}(u_1), \ldots, t_\nu^{-1}(u_N)),$$

where $t_{\nu,\rho}$ is the distribution of $\sqrt{\nu/S} Z$, and t_ν is the distribution of $\sqrt{\nu/S} Z_1$.

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Student t copula

- Explicitly, in the bivariate case,

$$C_{\nu,\rho}(u_1, u_2) = \frac{1}{2\pi\sqrt{1-\rho_{12}^2}} \int_{-\infty}^{t_\nu^{-1}(u_1)} \int_{-\infty}^{t_\nu^{-1}(u_2)} \left(1 + \frac{s^2 - 2\rho_{12}su + u^2}{\nu(1-\rho_{12}^2)}\right)^{-\frac{\nu+2}{2}} ds\,du.$$

- The Student t copula has fatter tails than the Gaussian copula (the smaller ν, the fatter the tails).
- It is used to model situations where tail events are believed to play a role.

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Archimedean copulas

- These are simple copulas that have interesting properties but (so far) little use in finance.
- A function $\phi : [0, 1] \to [0, \infty)$ is called a *copula generator* if it satisfies the properties:
    - (i) It is monotone decreasing,
    - (ii) $\phi(0) = \infty$,
    - (iii) $\phi(1) = 0$.
- Given a copula generator, and Archimedean copula is defined by

$$C(u_1, \ldots, u_N) = \phi^{-1}(\phi(u_1) + \ldots + \phi(u_N)).$$

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Archimedean copulas

- Below are some of the more popular Archimedean copulas.
- *Independence copula*:
$$\phi(u) = -\log u.$$

- *Clayton copula*: for $\theta > 0$,

$$\phi(u) = u^{-\theta} - 1,$$
$$C_{Clayton}(u_1, \ldots, u_N) = (u_1^{-\theta} + \ldots u_N^{-\theta} - N + 1)^{-1/\theta}.$$

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Archimedean copulas

- *Gumbel copula*: for $\theta > 1$,

$$\phi(u) = (-\log u)^{\theta},$$
$$C_{Gumbel}(u_1, \ldots, u_N) = \exp\left\{ -\left((-\log u_1)^{\theta} + \ldots + (-\log u_N)^{\theta}\right)^{1/\theta}\right\}.$$

- *Frank copula*: for $\theta \in \mathbb{R}$,

$$\phi(u) = -\log \frac{e^{-\theta u} - 1}{e^{-\theta} - 1},$$
$$C_{Frank}(u_1, \ldots, u_N) = -\frac{1}{\theta} \log\left(1 + \frac{(e^{-\theta u_1} - 1)\ldots(e^{-\theta_N u} - 1)}{(e^{-\theta} - 1)^{N-1}}\right).$$

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Copulas and dependence measures

- Let (X, Y) be a vector of continuous random variables with copula C. Then
  - Kendall's tau is given by

$$\tau_K(X, Y) = 4 \iint_{[0,1]^2} C(u, v) dC(u, v) - 1.$$

  (i) Spearman's rho is given by

$$\rho_S(X, Y) = 12 \iint_{[0,1]^2} uv dC(u, v) - 3$$
$$= 12 \iint_{[0,1]^2} C(u, v) du dv - 3.$$

  (ii) Note that these results do not depend on the marginals of X and Y.

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Copulas and dependence measures

- For Clayton's copula,

$$\tau_K = \frac{\theta}{\theta + 2} \, .$$

- For Gumbel's copula,

$$\tau_K = 1 - \frac{1}{\theta} \, .$$

- For Gaussian and Student t copulas, the following relation holds:

$$\rho = 2 \sin(\pi \rho_S / 6) \, .$$

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Tail dependence

- The concept of tail dependence relates to the amount of dependence in the upper right quadrant tail or lower left quadrant tail of a bivariate distribution.
- This concept is relevant for the study of dependence between tail ($\equiv$ extreme) events.
- One can prove that tail dependence between two continuous random variables X and Y is a copula property.
- As a result, the amount of tail dependence is invariant under strictly increasing transformations of X and Y.

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Tail dependence

● Consider a bivariate copula is such that the limit

$$\lim_{u \to 1} (1 - 2u + C(u, u))/(1 - u) \triangleq \lambda_U$$

exists.

● Then C has *upper tail dependence* if $0 < \lambda_U \leq 1$, and no upper tail dependence if $\lambda_U = 0$

● Similarly, if

$$\lim_{u \to 0} C(u, u)/u \triangleq \lambda_L.$$

exists, then C has *lower tail dependence* if $0 < \lambda_L \leq 1$, and no lower tail dependence if $\lambda_L = 0$.

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Tail dependence

- The definition is justified by the following calculation:

$$\lambda_U = \lim_{u \to 1} P(U_1 > u | U_2 > u)$$
$$= \lim_{u \to 1} P(U_2 > u | U_1 > u).$$

However,

$$\lim_{u \to 1} P(U_1 > u | U_2 > u) = \lim_{x \to \infty} P(X > x | Y > x).$$

- This shows that λ_U measures the co-dependence of X and Y at the right tail: $\lambda_U > 0$ if and only if the conditional probabilities $P(X > x | Y > x)$ and $P(Y > x | X > x)$ are positive for large values of x.
- A similar argument can be made for λ_L.

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Tail dependence

- For the bivariate Gaussian copula, $|\rho_{12}| < 1$,

$$\lambda_U = 0,$$
$$\lambda_L = 0.$$

- For the bivariate Student t copula, $|\rho_{12}| < 1$,

$$\lambda_U = 2t_{\nu+1}(-\sqrt{\nu+1}\sqrt{(1-\rho_{12})/(1+\rho_{12})}),$$
$$\lambda_L = \lambda_U.$$

- For the bivariate Clayton copula, $\theta > 0$,

$$\lambda_U = 0,$$
$$\lambda_L = 2^{1/\theta}$$

- For the bivariate Gumbel copula, $\theta > 1$,

$$\lambda_U = 2 - 2^{1/\theta},$$
$$\lambda_L = 0.$$

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Marshall-Olkin copula

- Consider a two-component system where the components are subject to shocks, which are fatal to one or both components.
- We assume that these shocks arrive at times T_1, T_2, and T_{12} as independent Poisson processes, with intensities of λ_1, λ_2, and λ_{12}, respectively.
- In credit applications, the components are credit names, and λ_1, λ_2, and λ_{12} are default intensities.
- The shared shock λ_{12} can be interpreted as global shock, that affects multiple names simultaneously.
- Let $\tau_1 = \min(T_1, T_{12})$ and $\tau_2 = \min(T_2, T_{12})$ denote the lifetimes of the two components.

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Marshall-Olkin copula

● The joint survival probability is given by

$$P(\tau_1 > t_1, \tau_2 > t_2) = P(T_1 > t_1)P(T_2 > t_2)P(T_{12} > \max(t_1, t_2))$$
$$= \exp(-\lambda_1 t_1 - \lambda_2 t_2 - \lambda_{12} \max(t_1, t_2)).$$

● The marginal survival probabilities are

$$P(\tau_1 > t_1) = \exp(-(\lambda_1 + \lambda_{12})t_1),$$
$$P(\tau_2 > t_1) = \exp(-(\lambda_2 + \lambda_{12})t_2).$$

● We now find the copula C_{MO} for this distribution.

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- To this end, we express $P(\tau_1 > t_1, \tau_2 > t_2)$ in terms of $P(\tau_1 > t_1)$ and $P(\tau_2 > t_2)$.
- Since
$$\max(t_1, t_2) = t_1 + t_2 - \min(t_1, t_2),$$
we have
$$P(\tau_1 > t_1, \tau_2 > t_2) = P(\tau_1 > t_1)P(\tau_2 > t_2) \min(\exp(\lambda_{12}t_1), \exp(\lambda_{12}t_2)).$$

- Set
$$u_1 = P(\tau_1 > t_1),$$
$$u_2 = P(\tau_2 > t_2),$$
and
$$\alpha_1 = \lambda_{12}/(\lambda_1 + \lambda_{12}),$$
$$\alpha_2 = \lambda_{12}/(\lambda_2 + \lambda_{12}).$$

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- Then

$$\exp(\lambda_{12}t_1) = u_1^{-\alpha_1},$$
$$\exp(\lambda_{12}t_2) = u_2^{-\alpha_2}.$$

- This leads to the following copula:

$$C_{MO}(u_1, u_2) = u_1 u_2 \min(u_1^{-\alpha_1}, u_2^{-\alpha_2})$$
$$= \min(u_1^{1-\alpha_1} u_2, u_1 u_2^{1-\alpha_2}).$$

- Note that the Marshall-Olkin copula is an example of a *survival copula*, which expresses the *joint survival probability* in terms of *marginal survival probabilities*.
- This is unlike the copulas discussed above, which express the joint event probabilities in terms of marginal event probabilities.

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Marshall-Olkin copula

- The Marshall-Olkin copula can be extended to more than two names in a straightforward manner.
- However, its complexity increases with the number of components.
- There are different kinds of shared shocks: some will affect all names, some will affect only subsets (like those in a particular industry).
- In practice, the specification of these shocks and their intensities is impractical, as the combinatorics get complicated, and the Marshall-Olkin copula is not used often in practice.
- Elements of the MO copula approach, specifically the idea of shared shocks, are used in combination with other models.

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Algorithm for simulating Gaussian copula

- Consider the N-dimensional Gaussian distribution $N(0, \rho)$ with mean 0 and correlation matrix ρ.
- Find the Cholesky decomposition of ρ, i.e. $\rho = LL^{\mathrm{T}}$, where L is an $N \times N$-dimensional lower triangular matrix.
- Then repeat the following steps a desired number of times:
  - (i) *Step 1*. Simulate N independent samples $Z_1, \ldots, Z_N$ from $N(0, 1)$.
  - (ii) *Step 2*. Calculate $X_1 = LZ_1, \ldots, X_N = LZ_N$.
  - (iii) *Step 3*. Convert this sample to a correlated N-dimensional uniform vector $U_1 = N(X_1), \ldots, U_N = N(X_N)$.
- Then $(U_1, \ldots, U_N) \sim C_\rho$.

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Algorithm for simulating Student t copula

- The algorithm is similar to the one above (Gaussian copula).
- Sampling from a χ^2-distribution can be done by standard acceptance-rejection techniques or by numerically inverting the cumulative distribution function
- Find the Cholesky decomposition L of ρ, and repeat the following steps:
    (i) *Step 1.* Simulate N independent samples $Z_1, \ldots, Z_N$ from from $N(0, 1)$.
    (ii) *Step 2.* Simulate a random variate S from χ^2_ν independent of $Z_1, \ldots, Z_N$.
    (iii) *Step 3.* Calculate $Y = LZ$.
    (iv) *Step 4.* Set $X = \sqrt{\nu/S}Y$.
    (v) *Step 5.* Set $U_i = t(X_i)$, for $i = 1, \ldots, N$.
- Then $(U_1, \ldots, U_N) \sim C_{\nu\rho}$.

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