Copula modelling of serially correlated multivariate data with hidden structures

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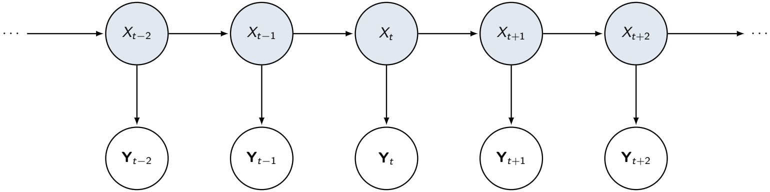
Hidden Markov Models: A Primer

- A hidden Markov model (HMM) pairs an observed time series $\{\mathbf{Y}_t\}_{t\geq 1} \subseteq \mathbb{R}^d$ with a Markov chain $\{X_t\}_{t\geq 1}$ on some state space $\mathcal{X}$, such that the distribution of $\mathbf{Y}_s \mid X_s$ is independent of $\mathbf{Y}_t \mid X_t$ for $s \neq t$:



- $\mathbf{Y}_{t,h}|\{X_t = k\} \sim f_{k,h}(\cdot|\lambda_{k,h})\ \forall h = 1, \ldots, d$
- $\{X_t\}$ is a Markov process (finite state space $\mathcal{X}$) with initial probability mass distribution $\{\pi_i\}_{i\in\mathcal{X}}$ and transition probabilities $\{\gamma_{i,j}\}_{i,j\in\mathcal{X}}$

Inferential aims for HMMs

- Typically, the chain $\{X_t\}_{t\geq 1}$ is partially or completely unobserved.
- The hidden states can correspond to a precise variable (occupancy data) or might be postulated (psychology, ecology, etc)
- Aim 1: Model the data generating mechanism Nasri et al. (2020)
- Aim 2: Decode (i.e., classify) or predict the X_t's from the observed data.

Examples

- A tri-axial accelerometer captures a shark's acceleration with respect to three positional axes depending on the shark's activity (resting, hunting, attacking). For short periods some of the sharks are filmed.
- Stock exchanges keep track of real-time prices for hundreds of stocks within an industry, depending on market conditions/states (stagnant, growing, shrinking).
- In-game team statistics like shots on goal and ball touches in a ~~soccer~~ football match are changing with the "momentum" of the team (defensive, offensive, passive) Ötting et al. (2021)

Fusion of Multiple Data Sources

- In the real-world applications above, various sensors capture multiple streams of data, which are "fused" into a multivariate time series $\{\mathbf{Y}_t\}_{t\geq 1}$
- In such situations, the components of any $\mathbf{Y}_t = (Y_{t,1}, \ldots, Y_{t,d})$ cannot be assumed independent (even conditional on X_t)
- The corresponding assumption for HMMs – that of contemporaneous conditional independence Zucchini et al. (2017) – is often violated
- Instead, it is common to assume that $\mathbf{Y}_t$ follows a multivariate Gaussian distribution, but this places limits on marginals and dependence structures
- What if the strength of dependence between the components of $\mathbf{Y}_t$ could be informative about the underlying state X_t?

Copulas

- Copula functions are used to model dependence between continuous random variables.
- If $Y_1, Y_2, \ldots Y_d$ are continuous r.v.'s with distribution functions (df) $F_1, \ldots, F_d$, there exists an unique copula function $C : [0,1]^d \to [0,1]$ such that

$$H(t_1, \ldots, t_d) = \mathbb{P}(Y_1 \le t_1, \ldots, Y_d \le t_d) = C(F_1(t), \ldots, F_d(t_d)).$$

- The copula bridges the marginal distributions of $Y_1, \ldots, Y_d$ with the joint distribution. It corresponds to a distribution on $[0,1]^d$ with uniform margins.
- This can be extended to conditional distributions and copulas:

$$\mathbb{P}(Y_1 \le t_1, \ldots, Y_d \le t_d | X) = C(F_1(t|X), \ldots, F_d(t_d|X)|X).$$

Copulas Within HMMs

- Our model consists of an HMM $\{(\mathbf{Y}_t, X_t)\}_{t\geq 1} \subseteq \mathbb{R}^d \times \mathcal{X}$ in which the state-dependent distributions are copulas:

$$\mathbf{Y}_t \mid (X_t = k) \sim H_k(\cdot) = \underbrace{C_k\Big(F_{k,1}(\cdot\,;\lambda_{k,1}), \ldots, F_{k,d}(\cdot\,;\lambda_{k,d}) \Big| \, \theta_k\Big)}_{\text{depends on the hidden state value } k}.$$

- $C_k(\cdot, \ldots, \cdot \mid \theta_k)$ is a d-dimensional parametric copula
- $\{X_t\}_{t\geq 1}$ is a Markov process on finite state space $\mathcal{X} = \{1, 2, \ldots, K\}$ and K is known
- In this model, virtually all aspects of the state-dependent distributions are allowed to vary between states

Information in the dependence

- For a range of $\theta \in [0, 100)$, we simulated a bivariate time series of length $T = 100$ from the 2-state HMM

$$\mathbf{Y}_t \mid (X_t = k) \sim C_{\text{Frank}} \left(\mathcal{N}(0,1), \mathcal{N}(0,1) \mid (-1)^k \cdot |\theta| \right), \quad k = 1, 2$$

and then separately assessed the accuracy of a standard decoding algorithm, first assuming independent margins and then the true model:

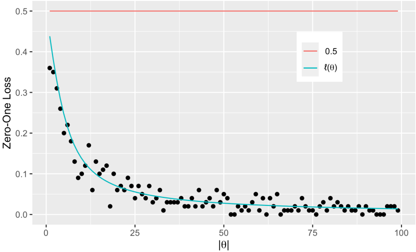


Figure: Zero-one losses for independent margins (red dots) and true model (blue dots)

Stronger Dependence Leads to Better Accuracy

- In fact, $\ell_{01}(\theta) = \frac{1}{2} - \frac{2}{\theta} \log\left(\cosh \frac{\theta}{4}\right) \to 0$ as $\theta \to \infty$
- Similar formulas hold for other radially symmetric copulas
- Much more generally, we have the following:

Theorem

Let $\nu_{t,k} = \mathbb{P}(X_t = k)$. The expected zero-one loss of the classifications made by local decoding is given by

$$\ell_{01}(\boldsymbol{\eta}) = 1 - \frac{1}{T} \sum_{t=1}^{T} \sum_{k=1}^{K} \nu_{t,k} \int_{\mathbb{R}^d} \mathbb{1}\left\{ \frac{\nu_{t,k} \cdot h_k(\mathbf{y})}{\max_{j \neq k} \nu_{t,j} \cdot h_j(\mathbf{y})} > 1 \right\} \mathrm{d}H_k(\mathbf{y}).$$

where $h_k(\mathbf{Y})$ is the joint density of $\mathbf{Y}|X = k$.

- Corollary: as the copula in any particular state approaches either of the Fréchet-Hoeffding bounds, the observations produced by that state will be detected with complete accuracy

Estimation with missing data

- Data consist in observed $\mathbf{Y}_{1:T}$ and missing $X_{1:T}$
- Parameters are $\eta = \{\lambda_{h,k}\}_{\substack{h=1:d \\ k=1:K}} \cup \{\theta_k\}_{k=1:K} \cup \{\gamma_{i,j}\}_{\substack{i=1:K \\ j=1:K}}$ $\cup\{\pi_j\}_{j=1:K}$.
- The complete-data log-likelihood for one trajectory of the copula HMM is given by

$$\ell_{\text{com}}\left(\boldsymbol{\eta} \mid \mathbf{y}_{1:T}, X_{1:T}\right) = \pi_{X_1} + \sum_{t=2}^{T} \log \gamma_{X_{t-1},X_t} + \sum_{h=1}^{d} \log f_{X_t,h}(y_{t,h}; \lambda_{X_t,h})$$
$$+ \sum_{t=1}^{T} \log c_{X_t}\left(F_{X_t,1}(y_{t,1}; \lambda_{X_t,1}), \ldots, F_{X_t,1}(y_{t,d}; \lambda_{X_t,d}) \mid \theta_{X_t}\right). \tag{1}$$

Inference for HMMs Via the EM Algorithm

- Without copula, the estimation is done via the EM algorithm (aka Baum-Welch)

E-step Compute $Q(\boldsymbol{\eta}|\boldsymbol{\eta}^{(s)}) = E[l_{com}(\boldsymbol{\eta}|\mathbf{Y}_{1:T}, X_{1:T})|\boldsymbol{\eta}^{(s)}, \mathbf{Y}_{1:T}]$

M-step Set $\boldsymbol{\eta}^{(s+1)} = \arg\max_{\boldsymbol{\eta}} Q(\boldsymbol{\eta}|\boldsymbol{\eta}^{(s)})$

- The complete-data log-likelihood is written in terms of the state membership indicators $U_{k,t} = \mathbb{1}_{X_t=k}$ and $V_{j,k,t} = \mathbb{1}_{X_{t-1}=j, X_t=k}$
- In the **E-Step**, these indicators are estimated by the conditional probabilities $\hat{u}_{k,t} = \mathbb{P}\left(X_t = k \mid \mathbf{Y}_{1:T} = \mathbf{y}_{1:T}\right)$ and $\hat{v}_{j,k,t} = \mathbb{P}\left(X_{t-1} = j, X_t = k \mid \mathbf{Y}_{1:T} = \mathbf{y}_{1:T}\right)$, which are computed based on current parameter estimates
- This only requires evaluating the state-dependent densities at each of the observations $\mathbf{y}_1, \ldots, \mathbf{y}_T$ (this is “OK”)

The M-Step stalls

- In the **M-Step**, the resulting complete-data log-likelihood is maximized with respect to all parameters in the model simultaneously
  - Only for the simplest univariate models do the state-dependent MLEs exist in closed form; otherwise, one must resort to numerical methods (this is hard!)
  - Evaluating a copula density $c_k(\cdot, \ldots, \cdot \mid \theta_k)$ in high dimensions is slow
  - When the state-dependent distributions in an HMM are copulas, performing the M-Step directly requires the evaluation of

$$\underset{\{\theta_k\},\{\lambda_{k,h}\}}{\operatorname{argmax}} \left\{ \sum_{k=1}^{K} \sum_{t=1}^{T} \hat{u}_{k,t} \left[\log c_k\left(F_{k,1}(y_{t,1}; \lambda_{k,1}), \ldots, F_{k,d}(y_{t,d}; \lambda_{k,d}) \,\middle|\, \theta_k \right) + \sum_{h=1}^{d} \log f_{k,h}(y_{t,h}; \lambda_{k,h}) \right] \right\}$$

  - This is very unstable (and slow)

Divide and conquer

- Likelihood-based inference for copulas is easier when the goal is to estimate θ alone in the presence of known margins
- Why not perform inference on the marginal distributions first, and then on the copula itself?
- In the context of iid data, this is exactly the inference functions for margins (IFM) approach of Joe and Xu (1996):
  - First estimate each λ_h by its "marginal MLE" $\hat{\lambda}_h$ given $\{Y_{t,h}\}_{t\geq 1}$, for $h \in \{1, \ldots, d\}$
  - Then estimate θ assuming fixed marginals $F_1(\cdot; \hat{\lambda}_1), \ldots, F_d(\cdot; \hat{\lambda}_d)$
- The IFM estimator is consistent and asymptotically normal.

EM + IFM → EFM

- Replace the M-Step in the EM algorithm with an IFM iteration to create an "EFM algorithm"

- For $T \in \{100, 1000, 5000\}$ and $d \in \{2, 5, 10\}$, we simulated a d-dimensional time series of length T from the 2-state HMM

$$\mathbf{Y}_t \mid (X_t = 1) \sim C_{\text{Frank}} \left((\mathcal{N}(\mu_{1,h} = -h, 1))_{h=1}^{d} \mid \theta_1 = 3 \right)$$
$$\mathbf{Y}_t \mid (X_t = 2) \sim C_{\text{Clayton}} \left((\mathcal{N}(\mu_{2,h} = h, 1))_{h=1}^{d} \mid \theta_2 = 3 \right)$$

and estimated $\boldsymbol{\eta} = (\mu_{1,1}, \ldots, \mu_{2,d}, \theta_1, \theta_2)$ using both approaches

- Applied to the basic EM algorithm, R's `optim` with `L-BFGS-B` (i.e., quasi-Newton with box constraints) typically fails as soon as $d \geq 3$
  - The procedure is extremely sensitive to initial values and requires $\hat{\boldsymbol{\eta}}^{(0)} \approx \boldsymbol{\eta}$ just to avoid overflow
  - This kind of tuning is very tedious or impossible in high dimensions

Does This Work?

- We keep track of the time (in seconds) until the algorithm converges, and the L_2 error of the resulting estimate, $\epsilon = \|\boldsymbol{\eta} - \hat{\boldsymbol{\eta}}\|_2$
  - We used the `lbfgsb3c` package, which is more stable than `optim`

	$d = 2$	$d = 5$	$d = 10$
$T = 100$	111.9 s, $\epsilon = 0.14$	123.4 s, $\epsilon = 299.98$	111.8 s, $\epsilon > 10^9$
$T = 1000$	166.6 s, $\epsilon = 0.63$	169.5 s, $\epsilon > 10^{11}$	418.23 s, $\epsilon = 725.06$
$T = 5000$	?	?	?

Table: EM Algorithm

	$d = 2$	$d = 5$	$d = 10$
$T = 100$	5.1 s, $\epsilon = 2.9$	3.0 s, $\epsilon = 0.94$	4.2 s, $\epsilon = 0.58$
$T = 1000$	34.4 s, $\epsilon = 0.57$	22.9 s, $\epsilon = 0.60$	34.4 s, $\epsilon = 0.80$
$T = 5000$	172.6 s, $\epsilon = 0.13$	106.2 s, $\epsilon = 0.12$	168.7 s, $\epsilon = 0.19$

Table: EFM Algorithm

Numerical stability

- R has no problem with the EFM algorithm
- The algorithm is considerably less sensitive to starting values than the vanilla EM algorithm, and terminates much faster
- It is theoretically justified based on adapting theory for ES (Elashoff and Ryan, 2004) and M-estimation for HMMs (Jensen, 2011)

Occupancy Data

- The ability to detect whether a room is occupied using sensor data (such as temperature and CO_2 levels) can potentially reduce unnecessary energy consumption by automatically controlling HVAC and lighting systems, without the need for motion detectors
- Consider three publicly-available labelled datasets presented by Candanedo and Feldheim (2016) which contain multivariate time series of four environmental measurements (light, temperature, humidity, CO_2) and one derived metric (the humidity ratio)
- Data contain binary indicators for whether the room was occupied or not at the time of measurement

Occupancy Data

- Several common families of parametric copulas (the Frank, Clayton, Gumbel, Joe, and Gauss families), and for each we carried out a goodness-of-fit test based on the pseudo-observations using the multiplier bootstrap method (Kojadinovic et al., 2011)
- The parametric family based on the lowest corresponding Cramér-von Mises test statistic is selected.
- This process yielded a Clayton copula for State 1 and a Frank copula for State 2

State	Frank	Clayton	Gumbel	Joe	Gauss
1	0.356	**0.255**	0.423	0.770	0.345
2	**0.018**	0.433	0.038	0.206	0.045

Table: Cramér-von Mises test statistics based on pseudo-observations computed from unoccupied (Row 1) and occupied (Row 2) subsets.

Occupancy Data

- Denote the unoccupied state as '1' and the occupied state as '2'

$$\mathbf{Y}_t \mid (X_t = 1) \sim C_{\text{Clayton}}\left(\mathcal{N}(\mu_{1,1}, \sigma^2_{1,1}), \mathcal{N}(\mu_{1,2}, \sigma^2_{1,2}) \mid \theta_1\right)$$
$$\mathbf{Y}_t \mid (X_t = 2) \sim C_{\text{Frank}}\left(\mathcal{N}(\mu_{2,1}, \sigma^2_{2,1}), \mathcal{N}(\mu_{2,2}, \sigma^2_{2,2}) \mid \theta_2\right).$$

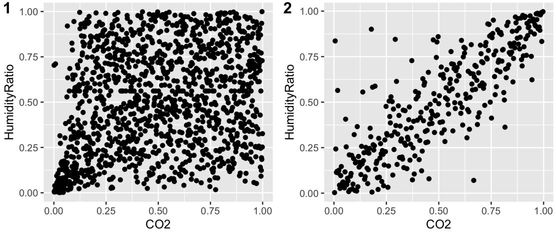


Figure: Pseudo-observations computed from unoccupied (Panel 1) and occupied (Panel 2) subsets.

Occupancy Data

Copula Model	Train	Test 1	Test 2
Independence	0.895	0.846	0.680
Clayton/Frank	0.899	0.852	0.696

Table: Overall state classification accuracy for the training dataset and the two test datasets using either the independence or Clayton/Frank copula.

Summary

- When using HMMs to model multivariate time series, ignoring the dependence between observed components can lead to...
  - Inaccurate state classifications
  - Failure to understand the true data-generating process
- The "copula-within-HMM" model integrates state-dependent copulas in order to capture joint information from the observed data, thereby addressing both problems
- The complexity of this model prohibits an application of the standard EM algorithm
- Our IFM-based refinement is faster and much more stable.

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Paper available on my homepage: `http://www.utstat.toronto.edu/craiu/`