

Advanced Statistical Computing Proejct

Hierarchical-block conditioning approximations for high-dimensional
multivariate normal probabilities

Hyunseok Yang, Kyeongwon Lee, Songhyun Kim

Department of Statistics, Seoul National University

December 8, 2019

1 Introduction

The computation of multivariate normal probability appears various fields. For instance, the inferences based on the central limit theorem, which holds when the sample size is large enough, is widely used in the social sciences and engineering as well as in the natural sciences. Recently, the dimensionality of data and models has been grown significantly, and in this respect, so does a need for the methodology to efficiently calculate high-dimensional multivariate normal probability.

Cao, Genton, Keyes, and Turkiyyah (2019) proposes new approaches to approximate high-dimensional multivariate normal probability

$$\Phi_n(\mathbf{a}, \mathbf{b}; 0, \mathbf{\Sigma}) = \int_a^b \frac{1}{\sqrt{(2\pi)^n |\mathbf{\Sigma}|}} \exp\left(-\frac{1}{2} \mathbf{x}^T \mathbf{\Sigma}^{-1} \mathbf{x}\right) d\mathbf{x}, \quad (1)$$

using the hierarchical matrix \mathcal{H} (Hackbusch, 2015) for the covariance matrix $\mathbf{\Sigma}$. The methods are based on two state-of-arts methods, among others, are the bivariate conditioning method (Trinh & Genz, 2015) and the hierarchical Quasi-Monte Carlo method (Genton, Keyes, & Turkiyyah, 2018). Specifically, Cao et al. (2019) generalize the bivariate conditioning method to a d -dimension and combine it with the hierarchical representation of the covariance matrix.

2 Multidimensional Conditioning Approximations

2.1 Quasi Monte Carlo Method

Error bound of $O(N^{-1/2})$ for monte carlo(MC) method which is guaranteed by central limit theorem is not enough for high dimensional multivariate random variable. Genz and Bretz (2009) claimed independent sample points is the reason of slow convergence. *Quasi-Monte Carlo*(QMC) methods uses deterministic sequences of sample points. Via employing low discrepancy sets for sequence, QMC is asymptotically efficient than MC. Since square root of prime numbers is irrational and linear independent over the rational numbers, K_N defined below is low-discrepancy sets.

$$K_N = \{i\mathbf{q} \bmod 1, i = 1, \dots, N\},$$

where $\mathbf{q} = \sqrt{\mathbf{p}}$ and \mathbf{p} is set of prime numbers. Selecting K_N shifted with $\Delta \sim U[0, 1]^n$ as sample points sequence, we have been implemented QMC.

$$L_N = \{\mathbf{z} + \Delta \bmod 1 : \mathbf{z} \in K_N\}$$

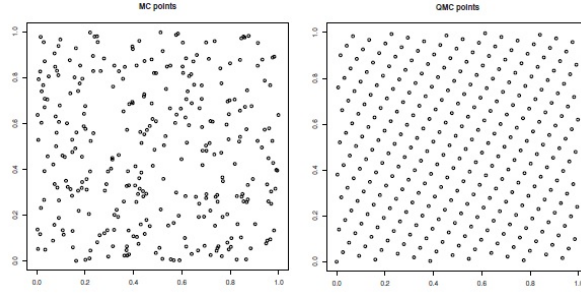


Figure 1: Comparison of MC and QMC sample points(Genz & Bretz, 2009)

Cholesky decomposition and few tranformation gives (2), and algorithm implemented (2) at $L_N \times ns$ times.

$$\begin{aligned} \Phi_n(\mathbf{a} \leq \mathbf{x} \leq \mathbf{b}; \Sigma) &= \Phi_n(a \leq \mathbf{L}\mathbf{y} \leq \mathbf{b}; I_n) \\ &= \int_{a_1 \leq l_{11}y_1 \leq b_1} \phi(y_1) \cdots \int_{a_n \leq l_{nn}y_n \leq b_n} \phi(y_n) d\mathbf{y} \\ &= \int_{\tilde{a}_1}^{\tilde{b}_1} \phi(y_1) \int_{\tilde{a}_2(y_1)}^{\tilde{b}_2(y_1)} \phi(y_2) \cdots \int_{\tilde{a}_n(y_1, \dots, y_{n-1})}^{\tilde{b}_n(y_1, \dots, y_{n-1})} \phi(y_n) d\mathbf{y} \\ \text{with } \tilde{a}_i(y_1, \dots, y_{i-1}) &= \frac{a_i - \sum_{j=1}^{i-1} l_{ij}y_j}{l_{ii}} \text{ and } (\tilde{b}_i(y_1, \dots, y_{i-1})) = \frac{b_i - \sum_{j=1}^{i-1} l_{ij}y_j}{l_{ii}} \end{aligned}$$

$$\begin{aligned}
&= \int_{\Phi(\tilde{a}_1)}^{\Phi(\tilde{b}_1)} \int_{\Phi(\tilde{a}_2(\Phi^{-1}(z_1)))}^{\Phi(\tilde{b}_2(\Phi^{-1}(z_1)))} \cdots \int_{\Phi(\tilde{a}_n(\Phi^{-1}(z_1), \dots, \Phi^{-1}(z_{n-1})))}^{\Phi(\tilde{b}_n(\Phi^{-1}(z_1), \dots, \Phi^{-1}(z_{n-1})))} d\mathbf{z}(y_i = \Phi^{-1}(z_i)) \\
&= (e_1 - d_1) \int_0^1 (e_2(w_1) - d_2(w_1)) \cdots \\
&\quad \int_0^1 (e_n(w_1, \dots, w_{n-1}) - d_n(w_1, \dots, w_{n-1})) \int_0^1 d\mathbf{w} \\
&\text{with } z_i = d_i + (e_i - d_i)w_i
\end{aligned} \tag{2}$$

Algorithm 1 Multivariate Normal Probability with Quasi Monte Carlo Method

```

1: procedure MVN( $\boldsymbol{\mu}, \boldsymbol{\Sigma}, \mathbf{a}, \mathbf{b}, ns, N$ )
2:    $\mathbf{L} = \text{cholesky}(\boldsymbol{\Sigma})$ 
3:    $\mathbf{a} = \mathbf{a} - \boldsymbol{\mu}; \mathbf{b} = \mathbf{b} - \boldsymbol{\mu}$ 
4:    $T = 0, N = 0, V = 0$ 
5:    $\mathbf{p} = \text{vector of primes less than } \frac{5n \log n + 1}{4}; \mathbf{q} = \sqrt{\mathbf{p}}$ 
6:    $\mathbf{P} = \mathbf{1}_{ns}$ 
7:    $ans = 0$ 
8:   for  $i = 1, \dots, ns$  do
9:      $I_i = 0, \boldsymbol{\Delta} \sim U(0, 1)^n$ 
10:    for  $j = 1, \dots, N$  do
11:       $\mathbf{X}[1 : n, j] = (j + 1)\mathbf{q} + \boldsymbol{\Delta}$ 
12:       $\mathbf{X}[1 : n, j] = 2|\mathbf{X}[1 : n, j] - \text{floor}(\mathbf{X}[1 : n, j])| - 1$ 
13:    end for
14:     $\text{sample} = \mathbf{O}_{n, N}$ 
15:     $\mathbf{s}, \mathbf{c}, \mathbf{d}, \mathbf{dc}, \mathbf{P} = \mathbf{0}_N$ 
16:    for  $j = 1, \dots, n$  do
17:      if  $j > 1$  then
18:         $c = \min(1, c + X[j - 1, :] \odot dc)$ 
19:         $\text{sample}[i - 1, 1 : N] = \Phi^{-1}(c)$ 
20:         $s = \text{sample}[1 : i - 1, 1 : N]^T L[1 : i - 1, i]$ 
21:      end if
22:       $\mathbf{P}^* = \Phi(\frac{b-s}{L[i, i]}) - \Phi(\frac{a-s}{L[i, i]})$ 
23:    end for
24:     $ans+ = \text{mean}(\mathbf{P})$ 
25:  end for
26:  return  $ans/ns$ 
27: end procedure

```

2.2 Conditioning Approximation

We can exploit Cholesky factors from LDL decomposition rather than dealing with original covariance matrix. Mendell and Elston (1974) and Kamakura (1989) developed conditioning method to calculate cdf of multivariate truncated normal distribution. Trinh and Genz (2015) employ bivariate blocking method for efficient calculation while accuracy is preserved

$$\Sigma = \begin{pmatrix} \Sigma_{1,1} & \mathbf{R}^T \\ \mathbf{R} & \hat{\Sigma} \end{pmatrix}, \text{ with } \mathbf{L} = \begin{pmatrix} \mathbf{I}_2 & \mathbf{O} \\ \mathbf{1} : \mathbf{M} & \mathbf{L} \end{pmatrix} \text{ and } \mathbf{D} = \begin{pmatrix} \mathbf{D}_1 & \mathbf{O} \\ \mathbf{O} & \hat{\mathbf{D}} \end{pmatrix},$$

where $\Sigma_{1,1}, \mathbf{D}_1$ is a 2×2 matrix. From $\mathbf{D}_1 = \Sigma_{1,1}$, $\mathbf{M} = \mathbf{R}\mathbf{D}_1^{-1}$, $\hat{\mathbf{D}} = \hat{\Sigma} - \mathbf{M}\mathbf{D}_1\mathbf{M}^T$, we can obtain bivariate LDL decomposition of Σ inductively.

With transformation $\mathbf{y} = \mathbf{L}\mathbf{x}$, $\mathbf{a} \leq \mathbf{x} \leq \mathbf{b}$ is transformed to $a_j - \sum_{m=1}^{j-1} l_{jm}x_m = \alpha_j \leq x_j \leq b_j - \sum_{m=1}^{j-1} l_{jm}x_m = \beta_j$ for $j = 1, \dots, n$. Then, with $k = \frac{n}{2}$ and $\mathbf{x}_{2k} = (x_{2k-1}, x_{2k})^T$

$$\begin{aligned} \Phi_n(\mathbf{a}, \mathbf{b}; \mathbf{0}, \Sigma) &= \frac{1}{\sqrt{|\mathbf{D}|}(2\pi)^n} \int_{\alpha_1}^{\beta_1} \int_{\alpha_2}^{\beta_2} e^{-\frac{1}{2}\mathbf{x}_2^T \mathbf{D}_1^{-1} \mathbf{x}_2} \\ &\quad \dots \int_{\alpha_{2k-1}}^{\beta_{2k-1}} \int_{\alpha_{2k}}^{\beta_{2k}} e^{-\frac{1}{2}\mathbf{x}_{2k}^T \mathbf{D}_1^{-1} \mathbf{x}_{2k}} \end{aligned} \quad (3)$$

Cao et al. (2019) generalizes bivariate method of Trinh and Genz (2015) to d -dimensional. Algorithms and details are following. When $s = \frac{m}{d}$ is integer, results of Algorithm 2, \mathbf{L}, \mathbf{D} can

Algorithm 2 LDL decomposition

```

1: procedure LDL( $\Sigma$ )
2:    $\mathbf{L} \leftarrow \mathbf{I}_m, \mathbf{D} \leftarrow \mathbf{O}_m$ 
3:   for  $i = 1 : d : m - d + 1$  do
4:      $\mathbf{D}[i : i + d - 1, i : i + d - 1] \leftarrow \Sigma[i : i + d - 1, i : i + d - 1]$ 
5:      $\mathbf{L}[i + d : m, i : i + d - 1] \leftarrow \Sigma[i + d : m, i : i + d - 1]\mathbf{D}^{-1}[i : i + d - 1, i : i + d - 1]$ 
6:      $\Sigma[i + d : m, i + d : m] \leftarrow \Sigma[i + d : m, i + d : m] - \mathbf{L}[i + d : m, i : i + d - 1]\mathbf{D}^{-1}[i : i + d - 1, i : i + d - 1]\Sigma[i + d : m, i + d : m]$ 
7:     if  $i + d < m$  then
8:        $\mathbf{D}[i + d : m, i + d : m] \leftarrow \Sigma[i + d : m, i + d : m]$ 
9:     end if
10:  end for
11:  return  $\mathbf{L}$  and  $\mathbf{D}$ 
12: end procedure

```

be written as

$$\mathbf{L} = \begin{pmatrix} \mathbf{I}_d & \mathbf{O}_d & \cdots & \mathbf{O}_d \\ \mathbf{L}_{2,1} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \mathbf{I}_d & \mathbf{O}_d \\ \mathbf{L}_{s,1} & \cdots & \mathbf{L}_{s,s-1} & \mathbf{I}_d \end{pmatrix}, \mathbf{D} = \begin{pmatrix} \mathbf{D}_1 & \mathbf{O}_d & \cdots & \mathbf{O}_d \\ \mathbf{O}_d & \ddots & \ddots & \vdots \\ \vdots & \ddots & \mathbf{D}_{s-1} & \mathbf{O}_d \\ \mathbf{O}_d & \cdots & \mathbf{O}_d & \mathbf{D}_s \end{pmatrix}$$

with d -dimensional identity matrix \mathbf{I}_d and d -dimensional zero matrix \mathbf{O}_d and d -dimensional positive-definite matrix $\mathbf{D}_1, \dots, \mathbf{D}_s$. Algorithm 2 is still valid when m is not multiple of d if we allow \mathbf{L}, \mathbf{D} to have non- d dimensional matrix block as last row.

As in (3), tranformation, $Y = LX$ provides m -dimensional multivariate normal prabability as the product of s d -dimensional multivariate normal probabilities as below.

$$\Phi_m(\mathbf{a}, \mathbf{b}; \mathbf{0}, \Sigma) = \int_{\alpha_1}^{\beta_1} \phi_d(\mathbf{y}_1; \mathbf{D}_1) \int_{\alpha_2}^{\beta_2} \phi_d(\mathbf{y}_2; \mathbf{D}_2) \cdots \int_{\alpha_s}^{\beta_s} \phi_d(\mathbf{y}_s; \mathbf{D}_s) d\mathbf{y}_s \cdots d\mathbf{y}_2 d\mathbf{y}_1, \quad (4)$$

where $\alpha_i = \mathbf{a}_i - \sum_{j=1}^{i-1} \mathbf{L}_{ij} \mathbf{y}_j, \beta_i = \mathbf{b}_i - \sum_{j=1}^{i-1} \mathbf{L}_{ij} \mathbf{y}_j$ Equation (4) is implemented as below.

Algorithm 3 d-dimensional conditioning algorithm

```

1: procedure CMVN( $\Sigma, \mathbf{a}, \mathbf{b}, d$ )
2:    $\mathbf{y} \leftarrow \mathbf{0}, P \leftarrow 1$ 
3:   for  $i = 1 : s$  do
4:      $j \leftarrow (i - 1)d$ 
5:      $\mathbf{g} \leftarrow \mathbf{L}[j + 1 : j + d, 1 : j] \mathbf{y}[1 : j]$ 
6:      $\alpha \leftarrow \mathbf{a}[j + 1 : j + d] - \mathbf{g}$ 
7:      $\beta \leftarrow \mathbf{b}[j + 1 : j + d] - \mathbf{g}$ 
8:      $\mathbf{D}' \leftarrow \mathbf{D}[j + 1 : j + d, j + 1 : j + d]$ 
9:      $P \leftarrow P \cdot \Phi_d(\alpha, \beta; \mathbf{0}, \mathbf{D}')$ 
10:     $\mathbf{y}[j + 1 : j + d] \leftarrow E[\mathbf{Y}']$ 
11:   end for
12:   return  $P$  and  $\mathbf{y}$ 
13: end procedure
```

2.3 Multidimensional Truncated Expectations

In algorithm 3 needs approximation of Φ_d and $E[Y']$. Φ_d is possibly obtained with quasi monte calro method proposed by Genz (1992), and Kan and Robotti (2017) provides methods to calculate $E[Y']$. The truncated expectation is expressed as

$$E(X^{e_j}) = \frac{1}{\Phi(\mathbf{a}, \mathbf{b}; \mu, \Sigma)} \int_{\mathbf{a}}^{\mathbf{b}} x_j \phi_d(\mathbf{x}; \mu, \Sigma) d\mathbf{x} = \frac{1}{\Phi(\mathbf{a}, \mathbf{b}; \mu, \Sigma)} F_j^d(\mathbf{a}, \mathbf{b}; \mu, \Sigma)$$

Theorem 1. (Kan & Robotti, 2017)

$$F_j^d(\mathbf{a}, \mathbf{b}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) = \mu_j \boldsymbol{\Phi}_d(\mathbf{a}, \mathbf{b}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) + \mathbf{e}_j^T \boldsymbol{\Sigma} \mathbf{c}$$

, where \mathbf{c} is a vector with l th component defined as

$$\begin{aligned} c_l &= \phi_1(a_l; \mu_l, \sigma_l^2) \Phi_{d-1}(\mathbf{a}_{-l}, \mathbf{b}_{-l}; \hat{\boldsymbol{\mu}}^1, \hat{\boldsymbol{\Sigma}}_l) \\ &\quad - \phi_1(b_l; \mu_l, \sigma_l^2) \Phi_{d-1}(\mathbf{a}_{-l}, \mathbf{b}_{-l}; \hat{\boldsymbol{\mu}}^2, \hat{\boldsymbol{\Sigma}}_l) \\ \hat{\boldsymbol{\mu}}_l^1 &= \mu_{-l} + \boldsymbol{\Sigma}_{-l,l} \frac{a_l - \mu_l}{\sigma_l^2}, \\ \hat{\boldsymbol{\mu}}_l^2 &= \mu_{-l} + \boldsymbol{\Sigma}_{-l,l} \frac{b_l - \mu_l}{\sigma_l^2}, \\ \hat{\boldsymbol{\Sigma}}_l &= \boldsymbol{\Sigma}_{-l,-l} - \frac{1}{\sigma_l^2} \boldsymbol{\Sigma}_{-l,l} \boldsymbol{\Sigma}_{l,-l} \end{aligned}$$

Proof. Derivative of the multivariate normal density satisfies below

$$-\frac{\partial \phi_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})}{\partial \mathbf{x}} = \boldsymbol{\Sigma}^{-1}(\mathbf{x} - \boldsymbol{\mu}) \phi_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) \quad (5)$$

With integration (5) from \mathbf{a} to \mathbf{b} ,

$$\mathbf{c} = \boldsymbol{\Sigma}^{-1} \begin{bmatrix} F_1^d - \mu_1 \Phi_{d-1} \\ F_2^d - \mu_1 \Phi_{d-1} \\ \vdots \\ F_d^d - \mu_1 \Phi_{d-1} \end{bmatrix} \quad (6)$$

Using the fact that

$$\begin{aligned} \phi_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})|_{x_j=a_j} &= \phi_1(a_j; \mu_j, \sigma_j^2) \phi_{n-1}(\mathbf{x}_{-j}; \hat{\boldsymbol{\mu}}_j^1, \hat{\boldsymbol{\Sigma}}_j^1) \\ \phi_n(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})|_{x_j=b_j} &= \phi_1(b_j; \mu_j, \sigma_j^2) \phi_{n-1}(\mathbf{x}_{-j}; \hat{\boldsymbol{\mu}}_j^2, \hat{\boldsymbol{\Sigma}}_j^1), \end{aligned}$$

(6) becomes

$$\begin{aligned} c_l &= \phi_1(a_l; \mu_l, \sigma_l^2) \Phi_{d-1}(\mathbf{a}_{-l}, \mathbf{b}_{-l}; \hat{\boldsymbol{\mu}}^1, \hat{\boldsymbol{\Sigma}}_l) \\ &\quad - \phi_1(b_l; \mu_l, \sigma_l^2) \Phi_{d-1}(\mathbf{a}_{-l}, \mathbf{b}_{-l}; \hat{\boldsymbol{\mu}}^2, \hat{\boldsymbol{\Sigma}}_l) \end{aligned}$$

□

Theorem 1 has same form with bivariate version of Trinh and Genz (2015) with $d = 2$ and it allows us to calculate $E[Y']$ in Algorithm 3 with $\boldsymbol{\Phi}$ which can be obtained with quasi monte carlo method proposed by Genz (1992)

2.4 Multidimensional Conditioning Approximation with Univariate Reordering

It is known that appropriate integration order on conditioning algorithm possibly improves estimation accuracy. Schervish (1984) originally proposed integral with shortest integration interval widths be the outermost integration variables to reduce overall variation of integrand and Gibson, Glasbey, and Elston (1994) suggested variables which have smallest expected values be the outermost integration variables. Since innermost integrals which have smaller variation have the most influence with this order, overall variance reduces. Trinh and Genz (2015) also employs this ordering, and Cao et al. (2019) generalized it to d -dimensional problem.

Algorithm 4 d -dimensional conditioning algorithm with univariate reordering

```

1: procedure RCMVN( $\Sigma, \mathbf{a}, \mathbf{b}, d$ )
2:    $\mathbf{y} \leftarrow \mathbf{0}, \mathbf{C} \leftarrow \Sigma$ 
3:   for  $i = 1 : m$  do
4:     if  $i > 1$  then
5:        $\mathbf{y}[i-1] \leftarrow \frac{\phi(a') - \phi(b')}{\Phi(b') - \Phi(a')}$ 
6:     end if
7:      $j \leftarrow \operatorname{argmin}_{i \leq j \leq m} \{ \Phi(\frac{\mathbf{b}[j] - \mathbf{C}[j, 1:i-1]\mathbf{y}[1:i-1]}{\sqrt{\Sigma[j,j] - \mathbf{C}[j, 1:i-1]\mathbf{C}^T[j, 1:i-1]}}) - \Phi(\frac{\mathbf{a}[j] - \mathbf{C}[j, 1:i-1]\mathbf{y}[1:i-1]}{\sqrt{\Sigma[j,j] - \mathbf{C}[j, 1:i-1]\mathbf{C}^T[j, 1:i-1]}}) \}$ 
8:      $\Sigma[:, (i, j)] \leftarrow \Sigma[:, (j, i)]; \Sigma[(i, j), :] \leftarrow \Sigma[(j, i), :]$ 
9:      $\mathbf{C}[:, (i, j)] \leftarrow \mathbf{C}[:, (j, i)]; \mathbf{C}[(i, j), :] \leftarrow \mathbf{C}[(j, i), :]$ 
10:     $\mathbf{a}[(i, j)] = \mathbf{a}[(j, i)]$ 
11:     $\mathbf{b}[(i, j)] = \mathbf{b}[(j, i)]$ 
12:     $\mathbf{C}[i, i] \leftarrow \sqrt{\Sigma[i, i] - \mathbf{C}[i, 1:i-1]\mathbf{C}^T[i, 1:i-1]}$ 
13:     $\mathbf{C}[j, i] \leftarrow \frac{\Sigma[j, i] - \mathbf{C}[j, 1:i-1]\mathbf{C}^T[j, 1:i-1]}{\mathbf{C}[i, i]}, \text{ for } j = i+1, \dots, m$ 
14:     $a' = \frac{\mathbf{a}[i] - \mathbf{C}[i, 1:i-1]\mathbf{y}[1:i-1]}{\mathbf{C}[i, i]}$ 
15:     $b' = \frac{\mathbf{b}[i] - \mathbf{C}[i, 1:i-1]\mathbf{y}[1:i-1]}{\mathbf{C}[i, i]}$ 
16:   end for
17:   return CMVN( $\Sigma, \mathbf{a}, \mathbf{b}, d$ ) as in Algorithm 3
18: end procedure

```

3 Hierarchical-Block Approximations

In this section, we suggest methods to solve the n -dimensional MVN problem with the hierarchical covariance matrix using the d -dimensional conditioning method with that of the Monte Carlo-based method for solving the m -dimensional MVN problems presented by the diagonal blocks.

3.1 Hierarchical Cholesky Decomposition

Hackbusch (2015) proposed hierarchical matrix and its cholesky decomposition method. We have applied low rank approximation to each block of its decomposition to make implementation efficiently and save storage while accuracy is preserved. $A = LU$ have the structure

$$\begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} = \begin{pmatrix} L_{11} & O \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} L_{11}^T & L_{12}^T \\ O & L_{22}^T \end{pmatrix}$$

with lower triangular matrix L_{11}, L_{22} . It leads to four tasks:

- (a) compute L_{11} via Cholesky decomposition of A_{11}
- (b) compute L_{12} from $L_{21}L_{11}^T = A_{21}$
- (c) low rank approximation of $L_{12} = UV^T$
- (d) compute L_{22} via Cholesky decomposition of $A_{22} - L_{21}L_{21}^T$

(a) and (d) is solved with hierarchical cholesky decomposition it self, and (b) is easy since it has triangular form. (c) is implemented with low-rank approximation of SVD, i.e. $A = UDV^T = \sum_{i=1}^n d_i u_i v_i^T \approx \sum_{i=1}^k d_i u_i v_i^T$. Hierarchical cholesky decomposition of $n \times n$ matrix into $m \times m$ blocks is implemented like below.

Algorithm 5 Hierarchical cholesky decomposition

```

1: procedure HCHOL( $A, n, m, rank$ )
2:   for  $i = 1 : \log_2(\frac{n}{m})$  do
3:      $nb = n/2^i$ 
4:      $x = 0, y = nb$ 
5:     for  $j = 1 : 2^{i-1}$  do
6:        $\mathbf{U}, \mathbf{D}, \mathbf{V} = \text{lowrankSVD}(A[xbegin + 1 : xbegin + nb, ybegin + 1 : ybegin + nb], rank)$ 
7:        $\mathbf{A}[x + 1 : x + nb, y + 1 : y + rank] = \mathbf{U}\mathbf{D}$ 
8:        $\mathbf{A}[x + 1 : x + nb, y + rank + 1 : y + nb] = \mathbf{O}$ 
9:        $\mathbf{A}[y + 1 : y + nb, x + 1 : x + rank] = \mathbf{V}\mathbf{D}$ 
10:       $\mathbf{A}[y + 1 : y + nb, x + rank + 1 : x + nb] = \mathbf{O}$ 
11:       $x += 2nb, y += 2nb$ 
12:     end for
13:   end for
14: end procedure

```

3.2 The Hierarchical-Block Conditioning Method

Let $\phi_m(\mathbf{x}; \Sigma)$ be a pdf of the m -dimensional normal distribution $N(\mathbf{0}, \Sigma)$ and $(\mathbf{B}, \mathbf{UV}^T)$ be the hierarchical Cholesky decomposition of the covariance matrix Σ . Then, we can express (1) as

$$\Phi_n(\mathbf{a}, \mathbf{b}; \mathbf{0}, \Sigma) = \int_{\mathbf{a}'_1}^{\mathbf{b}'_1} \phi_m(\mathbf{x}_1; \mathbf{B}_1 \mathbf{B}_1^T) \cdots \int_{\mathbf{a}'_r}^{\mathbf{b}'_r} \phi_r(\mathbf{x}_r; \mathbf{B}_r \mathbf{B}_r^T) d\mathbf{x}_r \cdots d\mathbf{x}_1. \quad (7)$$

Where \mathbf{a}' , \mathbf{b}' , $i = 1, \dots, r$, are the corresponding segments of the updated \mathbf{a} and \mathbf{b} . Specifically, we can compute n -dimensional MVN problem using hierarchical structure as algorithm 6.

Algorithm 6 Hierarchical-block conditioning algorithm

```

1: procedure HBMV( $a, b, \Sigma, d$ )
2:    $\mathbf{x} \leftarrow \mathbf{0}$  and  $P \leftarrow 1$ 
3:    $[\mathbf{B}, \mathbf{UV}] \leftarrow \text{choldecomp\_hmatrix}(\Sigma)$ 
4:   for  $i = 1 : r$  do
5:      $j \leftarrow (i - 1)m$ 
6:     if  $i > 1$  then
7:        $o_r \leftarrow \text{row offset of } \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T$ 
8:        $o_c \leftarrow \text{column offset of } \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T$ 
9:        $l \leftarrow \text{dim}(\mathbf{U}_{i-1} \mathbf{V}_{i-1}^T)$ 
10:       $\mathbf{g} \leftarrow \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T \mathbf{x}[o_c + 1 : o_c + l]$ 
11:       $\mathbf{a}[o_r + 1 : o_r + l] = \mathbf{a}[o_r + 1 : o_r + l] - \mathbf{g}$ 
12:       $\mathbf{b}[o_r + 1 : o_r + l] = \mathbf{a}[o_r + 1 : o_r + l] - \mathbf{g}$ 
13:    end if
14:     $\mathbf{a}_i \leftarrow \mathbf{a}[j + 1 : j + m]$ 
15:     $\mathbf{b}_i \leftarrow \mathbf{b}[j + 1 : j + m]$ 
16:     $P = P * \Phi_m(\mathbf{a}_i, \mathbf{b}_i; \mathbf{0}, \mathbf{B}_i \mathbf{B}_i^T)$ 
17:     $\mathbf{x}[j + 1 : j + m] \leftarrow \mathbf{B}_i^{-1} E(\mathbf{X}_i)$ 
18:  end for
19: end procedure

```

Note the probabilities $\Phi_m(\mathbf{a}_i, \mathbf{b}_i; \mathbf{0}, \mathbf{B}_i \mathbf{B}_i^T)$ can be computed using Quasi-Monte Carlo method (HBMV, Method 1 in Cao et al. (2019)), d -dimensional conditioning algorithm (HCMVN, Method 2 in Cao et al. (2019)) or with d -dimensional conditioning algorithm with univariate reordering (HRCMVN, Method 3 in Cao et al. (2019)). These methods are more effective and easily parallelizable than the classical methods.

3.3 Computational Complexity

For a clearer comparison of the complexities, we decompose the complexity of Algorithm 6 into three parts and list the complexity for each part in Table 1, where $M(\cdot)$ denotes the complexity of the QMC simulation in the given dimension.

	MVN prob	Trunc exp	Upd limits
HMVN	$\frac{n}{m}M(m)$	$2nM(m) + O(nm^2)$	$O(mn + kn\log(n/m))$
HCMVN	$\frac{n}{d}M(d) + O(m^2n)$	$2nM(d) + O(nd^2)$	$O(mn + kn\log(n/m))$
HRCMVN	$\frac{n}{d}M(d) + O(m^2n)$	$2nM(d) + O(nd^2)$	$O(mn + kn\log(n/m))$

Table 1: Complexity decomposition of the HMVN, HCMVN, and HRCMVN

The three parts of the complexity are the calculation of the MVN probability (MVN prob), the calculation of the truncated expectations (Trunc exp), and the update of the integration limits with truncated expectations (Upd limits). The latter two share the same asymptotic order in all three complexity terms. The updating cost is independent of the method. The complexity of the univariate reordering is $O(m^2n)$, the same as the complexity of computing the MVN probabilities in HCMVN, resulting in an identical major complexity component for HCMVN and HRCMVN. Since HCMVN and HRCMVN perform the QMC simulation in d -dimensions, these two methods are not greatly affected by the choice of m .

4 Block Reordering

Summarizing the previous computations, the cdf value for n -dimensioned multivariate normal variable comprises of m multiplications of d -dimensional integrals. The idea arose from the construction of hierarchical Cholesky decomposition of covariance matrix, which enables concentration of high correlation values in the block diagonal area. As a consequence, correlation within blocks(or, group of compositions) are high while correlation between blocks(between groups) are low. Recall the RCMVN algorithm(3) : as computing each d -dimensional integral values, integration variables were arranged in order of increasing order of CMVN probability values, from outer to inner. Trinh and Genz (2015) discovered that this reordering improves overall accuracy. In this sense, the authors adopted block reordering procedure. Briefly speaking, this procedure permutes the block of LDL-decomposed covariance matrix, in order of RCMVN probability values of each blocks. On the top left corner, the block with minimal probability value get its place. Algorithm 7 is the block reordering algorithm introduced in Cao et al. (2019).

Here, sort function arranges elements in the vector 'ind' in an increasing order based on \mathbf{P} . Also, G means the intrinsic geometry of data. In practice, we set the geometry as 2D isotropic exponential covariance model, assuming data observation occurred in unit square grd, indices arranged based on Morton order of level 1. The paper implemented the comparison between computing HMVN, HCMVN, HRCMVN values with or without block reordering procedure. Commonly, block reordering procedure places on the way before implementing hierar-

Algorithm 7 Blockwise reordering

```
1: procedure BLOCKREORDER( $G, \rho, a, b, m, ind$ )
2:    $G, \rho, a, b, m, ind$  given,  $\mathbf{P} \leftarrow \mathbf{0}$ 
3:   for  $i = 1 : m : n - m + 1$  do
4:      $\mathbf{s} \leftarrow ind[i : i + m - 1]$ 
5:      $\mathbf{A} \leftarrow \rho(G, \mathbf{s})$ 
6:      $a' \leftarrow a[\mathbf{s}]$ 
7:      $b' \leftarrow b[\mathbf{s}]$ 
8:      $\mathbf{P} \leftarrow [\mathbf{P}, RCMVN(\mathbf{A}, a', b', 1).P]$ 
9:   end for
10:  sort( $ind, \mathbf{P}, m$ )
11:  return  $ind$ 
12: end procedure
```

chical decomposition. For example, one can derive Algorithm 8 as a HCMVN procedure with block reordering.

Algorithm 8 Hierarchical-block conditioning algorithm with Block Reordering

```
procedure HCMVN_BR0( $a, b, \Sigma, d$ )
   $\mathbf{x} \leftarrow \mathbf{0}, P \leftarrow 1, ind \leftarrow [1, \dots, n]$ 
   $[\mathbf{B}, \mathbf{UV}] \leftarrow choldecomp\_hmatrix(\Sigma)$ 
   $\mathbf{B} \leftarrow \text{Blockreorder}(G, \rho, a, b, m, ind)$ 
  for  $i = 1 : r$  do
     $j \leftarrow (i - 1)m$ 
    if  $i > 1$  then
       $o_r \leftarrow \text{row offset of } \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T$ 
       $o_c \leftarrow \text{column offset of } \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T$ 
       $l \leftarrow \text{dim}(\mathbf{U}_{i-1} \mathbf{V}_{i-1}^T)$ 
       $\mathbf{g} \leftarrow \mathbf{U}_{i-1} \mathbf{V}_{i-1}^T \mathbf{x}[o_c + 1 : o_c + l]$ 
       $\mathbf{a}[o_r + 1 : o_r + l] = \mathbf{a}[o_r + 1 : o_r + l] - \mathbf{g}$ 
       $\mathbf{b}[o_r + 1 : o_r + l] = \mathbf{b}[o_r + 1 : o_r + l] - \mathbf{g}$ 
    end if
     $\mathbf{a}_i \leftarrow \mathbf{a}[j + 1 : j + m]$ 
     $\mathbf{b}_i \leftarrow \mathbf{b}[j + 1 : j + m]$ 
     $P = P * \Phi_m(\mathbf{a}_i, \mathbf{b}_i; \mathbf{0}, \mathbf{B}_i \mathbf{B}_i^T)$ 
     $\mathbf{x}[j + 1 : j + m] \leftarrow \mathbf{B}_i^{-1} E(\mathbf{X}_i)$ 
  end for
end procedure
```

Block reordering aims for improving accuracy rather than shortening computation time. According to the simulation result introduced in Cao et al. (2019), the extra time used for running block reordering is relatively small compared with the total time costs.

5 Numerical Examples

In this section, we show you the results of implementing and experimenting with the methods described above. The implementation was done in julia=1.2.0. Code is made available in the github repository¹.

5.1 Cholesky Factorization

The *chol* function from **LinearAlgebra** package, the *dpotrf* from **LAPACK** package, and hierarchical cholesky decomposition which suggested by Hackbusch (2015) are implemented. Exponential covariance matrix, $\Sigma_{ij} = \exp(-\|\mathbf{s}_i - \mathbf{s}_j\|/\beta)$ is set with $\beta = 0.3$. n points, $\mathbf{s}_1, \dots, \mathbf{s}_n$ is evenly distributed over unique square with Morton's order which defined recursively as described in figure 2.

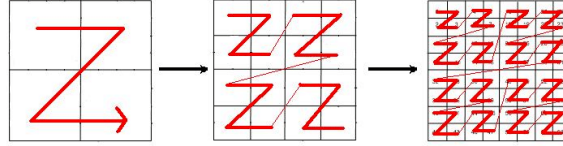


Figure 2: Morton's order(Salem & Arab, 2016)

With various n , three Cholesky methods are applied and results are below table 2. In low rank approximation at algorithm 5, rank is about $n^{1/4}$.

n	256	1024	4096	16384
chol	0.001s	0.0097s	0.414s	156.3s
dpotrf	0.0007s	0.0132s	0.431s	154.1s
hierarchical cholesky	0.153s	0.076s	0.916s	37.3s
Error of hierarchical cholesky	1.06e-7	9.97e-7	1.11e-3	1.87e-3

Table 2: Excution times for Cholesky factorization

Hierarchical cholesky decomposition is more efficient than other classical cholesky method with large dimension. Hierarchical cholesky decomposition provides $\Sigma \approx L_H L_H^T$. Its relative error is defined as $\frac{\|\Sigma - L_H L_H^T\|_2}{\|\Sigma\|_2}$, and table 2 ensures accuracy of hierarchical cholesky decomposition proposed by Hackbusch (2015).

¹https://github.com/kw-lee/AdvStatComp_HDP

5.2 Multivariate Normal Probabilities

To implement `*MVN` functions, we need to calculate n -dimensional normal probability (1),

$$\Phi_n(a, b; 0, \Sigma) = \int_a^b \frac{1}{\sqrt{(2\pi)^n |\Sigma|}} \exp\left(-\frac{1}{2} \mathbf{x}^T \Sigma^{-1} \mathbf{x}\right) d\mathbf{x},$$

numerically. We implement `mvn`, the function that calculate multivariate normal probabilities using Richtmyer Quasi-Monte Carlo(QMC) method proposed by Genz and Bretz (2009). It is well-known that QMC methods is more effective than classical Monte Carlo(MC) method. Varying sample size N and dimension d , two Monte Carlo methods are compared and results are below table 3. We generate N samples from $N(0, I_d)$ and set $\mathbf{a}_i = -\infty$ and $\mathbf{b}_i = 0$, i.e. true probabilities are $1/2^d$ s, and repeat 20 times. Relative errors and computation times of each method are formulated.

(n, d)	4	8	12	16	20
Classical Monte Carlo					
500	12.2%	56.8%	161.9%	100.0%	100.0%
	0.294ms	0.016ms	0.018ms	0.019ms	0.019ms
1000	9.5%	50.6%	193.8%	100.0%	100.0%
	0.046ms	0.041ms	0.028ms	0.028ms	0.034ms
1500	8.9%	38.7%	150.2%	100.0%	100.0%
	0.055ms	0.046ms	0.042ms	0.048ms	0.045ms
2000	5.4%	26.5%	102.4%	100.0%	100.0%
	0.070ms	0.065ms	0.072ms	0.058ms	0.055ms
2500	5.1%	32.0%	100.1%	100.0%	100.0%
	0.073ms	0.092ms	0.081ms	0.083ms	0.076ms
Richtmyer Quasi-Monte Carlo					
500	0.0%	0.0%	0.0%	0.0%	0.0%
	0.058ms	0.003ms	0.006ms	0.006ms	0.011ms
1000	0.0%	0.0%	0.0%	0.0%	0.0%
	0.003ms	0.009ms	0.013ms	0.017ms	0.020ms
1500	0.0%	0.0%	0.0%	0.0%	0.0%
	0.006ms	0.011ms	0.016ms	0.019ms	0.030ms
2000	0.0%	0.0%	0.0%	0.0%	0.0%
	0.011ms	0.012ms	0.013ms	0.025ms	0.036ms
2500	0.0%	0.0%	0.0%	0.0%	0.0%
	0.009ms	0.022ms	0.033ms	0.038ms	0.056ms

Table 3: Richtmyer Quasi-Monte Carlo and classical Monte Carlo

Note QMC is superior to MC in every criterion. All the multivariate normal distribution

probabilities required in the next algorithms are calculated using the `mvn` function.

5.3 d-dimensional Conditioning Algorithm without/with Reordering

Haar distribution is defined with a uniform distribution in the unitary $N \times N$ matrices group, $U(N)$. Stewart (1980) provides how to sample from Haar distribution with theorem 2

Theorem 2. *Stewart (1980) Let the independent vectors x_1, \dots, x_n be distributed $N(0, \sigma^2 \mathbf{I})$. For $j = 1, 2, \dots, n-1$, let \mathbf{H}_{x_j} be the Householder transformation that reduces x_j to $r_{jj}e_1$, where r_{ij} is obtained in QR decomposition of $[x_1, \dots, x_n]$ Let $\mathbf{H}_j = \text{diag}(\mathbf{I}_{j-1}, \bar{\mathbf{H}}_j)$. Let $\mathbf{D} = \text{diag}(\text{sign}(r_{11}), \dots, \text{sign}(r_{nn}))$. Then the product $\mathbf{Q} = \mathbf{D}\mathbf{H}_1 \cdots \mathbf{H}_{n-1}$ follows Haar Distribution.*

We simulate 250 MVN problems with various values of m and d . $\Sigma = \mathbf{Q}\mathbf{J}\mathbf{Q}^T$ is simulated with $\mathbf{Q} \sim \text{Haar distribution}$ and $\mathbf{J} = \text{diag}(j_i)$ where $j_1, \dots, j_m \sim U(0, 1)$. Integration limits $a_i = -\infty$ and $b_i \sim (U, m)$ for $i = 1 \dots m$ are chosen. Estimated value is compared with approximated value obtained via quasi monte carlo method with a sample size of 10^4 , which ensures error below 10^{-4} , and relative error and spent time is formulated below.

(m, d)	1	2	4	8	16
Without univariate reordering					
16	3.7%	3.5%	3.6%	3.8%	2.9%
	0.029ms	0.201ms	0.431ms	0.676ms	1.372ms
32	2.4%	2.9%	2.9%	3.3%	2.7%
	0.001ms	0.390ms	0.833ms	1.283ms	2.545ms
64	1.9%	2.1%	2.1%	1.8%	1.9%
	0.004ms	0.762ms	1.686ms	2.545ms	5.004ms
128	1.3%	1.5%	1.3%	1.2%	1.4%
	0.024ms	1.505ms	3.333ms	5.146ms	10.548ms
With univariate reordering					
16	3.3%	3.1%	3.3%	3.6%	2.7%
	0.007ms	0.203ms	0.439ms	0.680ms	1.363ms
32	2.3%	2.6%	2.6%	3.2%	2.6%
	0.004ms	0.393ms	0.841ms	1.289ms	2.544ms
64	2.0%	2.1%	2.1%	1.9%	1.9%
	0.014ms	0.773ms	1.695ms	2.552ms	5.022ms
128	1.2%	1.5%	1.4%	1.2%	1.4%
	0.097ms	1.593ms	3.462ms	5.268ms	10.7861ms

Table 4: Errors and execution times of the d-dimensional conditioning method

Estimation error tended to decrease as d increases with each m since larger d implies less

discarded correlation information. Spent time grows to a linear fashion with m while it grows exponentially with d .

5.4 Hierarchical-Block Approximations

In this section, we implement three methods in the section 3 and compare their performance

- M1, $\text{HBMV}()$: Calculate multivariate normal probabilities using hierarchical-block approximation
- M2, $\text{HCMV}()$: Calculate multivariate normal probabilities using hierarchical-block conditioning approximation
- M3, $\text{HRCMV}()$: Calculate multivariate normal probabilities using hierarchical-block conditioning approximation with univariate reordering

We use 20 as the sample size instead of 250 as in Table 4 because the covariance structure is fixed, leading to a much smaller standard deviation for the estimators. We simulate two spatial problems with various values of m and n .

1. Constant covariance matrix: $k(x_i, x_j) = \theta + (1 - \theta)\delta_{ij}$ for some $|\theta| < 1$.
2. 1D exponential covariance matrix: $k(x_i, x_j) = \exp(-d_{ij}/\beta)$ for some $\beta > 0$, where d_{ij} is the distance between x_i and x_j .

We set the integration limits $a_i = -\infty$ and $b_i \sim (U, n)$ for $i = 1 \dots, n$, $\theta = 0.7$, $d_{ij} = 1$, and $\beta = 10$ as in Cao et al. (2019). Estimated value is compared with approximated value obtained via QMC with a sample size of 10^4 . In this simulation, we fix $d = 4$ for HCMV and HRCMV . Table 5 and Figure 3 are errors and execution times under the constant covariance structure and 1D exponential covariance structure respectively.

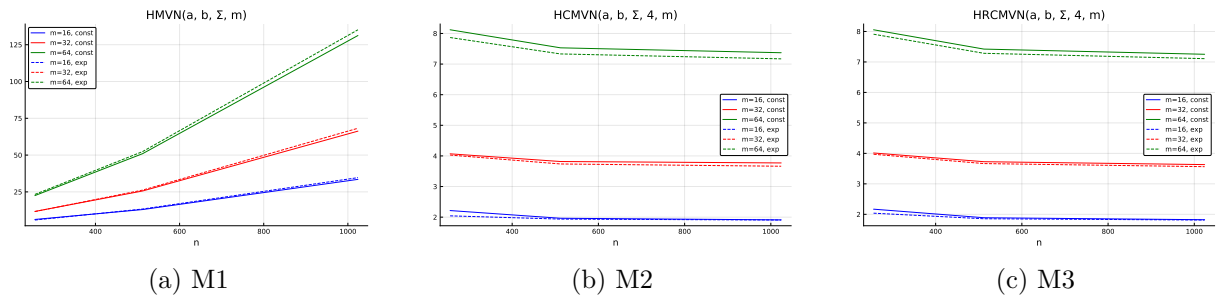


Figure 3: Execution time (seconds) under the constant covariance structure and 1D exponential covariance structure

m	16			32			64		
n	256	512	1024	256	512	1024	256	512	1024
Constant covariance structure									
M1	8.22%	7.11%	8.66%	8.94%	7.88%	6.68%	10.58%	8.05%	9.78%
M2	8.37%	7.08%	8.60%	8.91%	7.77%	6.61%	10.58%	8.26%	9.91%
M3	8.51%	7.10%	8.70%	9.51%	7.92%	7.00%	10.68%	7.94%	9.63%
1D exponential covariance matrix									
M1	2.87%	0.00%	0.01%	0.07%	1.31%	0.00%	2.65%	0.27%	0.57%
M2	3.28%	0.01%	0.90%	0.07%	1.31%	0.01%	2.65%	0.28%	0.57%
M3	4.73%	0.09%	2.11%	2.17%	1.90%	0.16%	3.72%	1.25%	0.66%

Table 5: Relative errors under the constant covariance structure and 1D exponential covariance structure

Note the execution times of M2 and M3 are significantly smaller than of M1 even their performances are similar.

Next, we give simulation with a 2D exponential covariance matrix using morton's order for indexing the sample points on the plane. We fix $m = 8$ for the 2D covariance structure and examine the effectiveness of our algorithm varying $d = 1, 2, 4$. To test the sensitivity with respect to the correlation strength, we perform the estimation under $\beta = 0.3, 0.1$, and 0.03 , representing strong, medium, and weak correlation strengths. We set n to 16, 64, 256 and other settings are same as above. Table 6 presents the results.

n	<i>compress</i>	<i>mvn</i>	HMVN	HCMVN ₁	HCMVN ₂	HCMVN ₄
$\beta = 0.3$						
16	0.89	0.00ppm	53.68ppm	2139.98ppm	1723.46ppm	276.37ppm
64	0.56	0.00ppm	143.88ppm	167.26ppm	167.69ppm	169.31ppm
256	0.28	0.00ppm	215.10ppm	213.41ppm	213.41ppm	213.41ppm
$\beta = 0.1$						
16	0.89	0.00ppm	0.00ppm	0.84ppm	0.60ppm	0.02ppm
64	0.56	0.00ppm	0.00ppm	1.61ppm	0.09ppm	0.01ppm
256	0.28	0.00ppm	0.00ppm	0.02ppm	0.02ppm	0.02ppm
$\beta = 0.03$						
16	0.89	0.00ppm	0.00ppm	0.00ppm	0.00ppm	0.00ppm
64	0.42	0.00ppm	0.00ppm	0.00ppm	0.00ppm	0.00ppm
256	0.20	0.00ppm	0.00ppm	0.00ppm	0.00ppm	0.00ppm

Table 6: Relative errors and efficiency of the two-level hierarchical-block conditioning methods

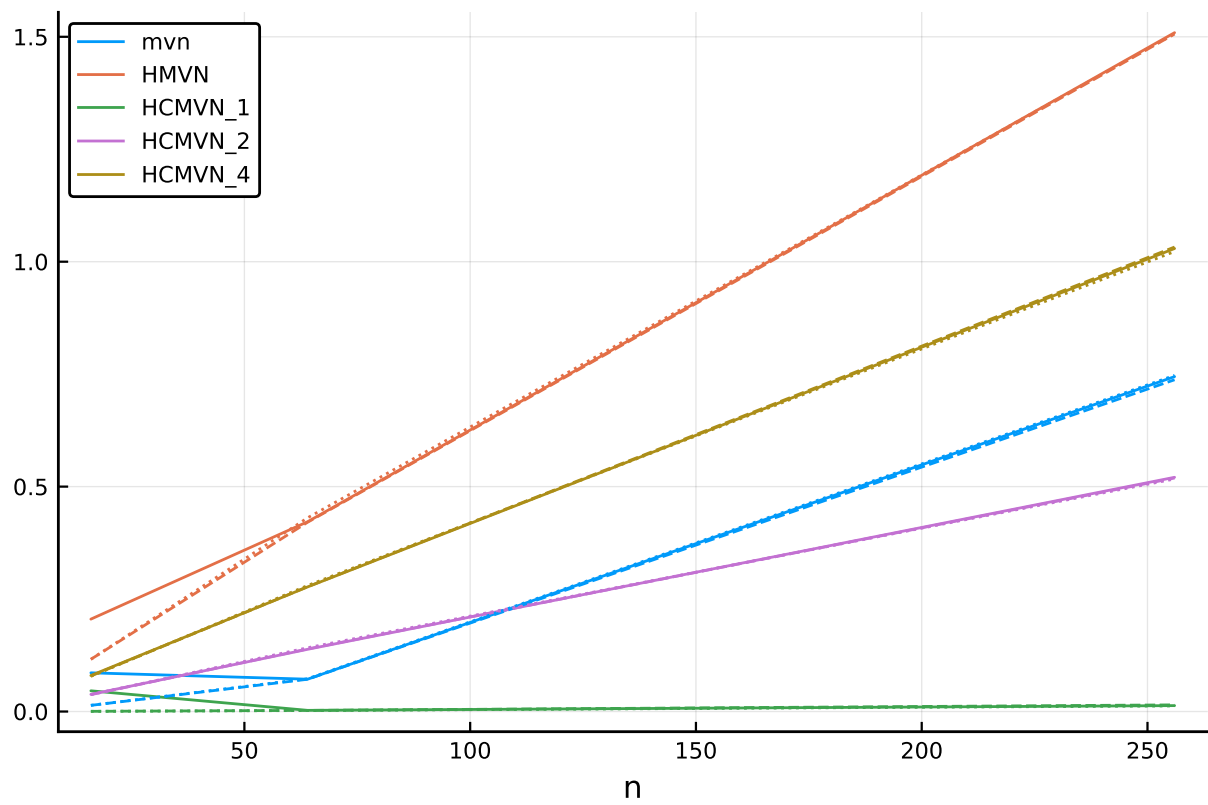


Figure 4: Execution time (seconds) under the constant covariance structure and 2D exponential covariance structure; solid line: $\beta = 0.3$, dashed line: $\beta = 0.1$, dotted line: $\beta = 0.03$

In Table 6, HCMVN_d denotes HCMVN function with d and

$$\text{compress} = \frac{\text{Total memory size of the } \mathcal{H} \text{ matrix}}{\text{Memory size of the covariance matrix } \Sigma}.$$

In this experiment, Cao et al. (2019) mentioned

It is worth mentioning that the correlation strength is essentially increased when n increases while β remains unchanged because the samples are from the unit hypercube. Also the increase of d will reduce the estimation error but is still unable to reach a satisfactory level. The method, when used without a reordering strategy, does not produce sufficiently accurate results. This motivated the development of the reordering strategy described in the next section

with extremely large size simulation. But, in our experiment, this phenomenon could not be found due to restriction of the computing resource.

6 Conclusion

So far, our group comprehended the method of d -dimensional conditioning and reproduced the result by writing and implementing code using Julia. In terms of computing, our group reproduced all the procedures mentioned in the paper such as CMVN, RCMVN, HCMVN, HRCMVN, and block reordering. The numbers including running time, error rate, etc were not exactly in line with the paper. The computing environment of our group and the authors are not the same. By using distinct programming language, possessing different computers with unequal quality of CPUs, etc.

In the paper, computation was done by setting covariance structure by 2D or 1D exponential spatial model along with Morton ordering, which is feasible to take advantage of hierarchical decomposition for covariance matrix. Although the paper suggested that in the case of completely random, non-hierarchical method might show better performance in terms of computing time, it seems rational that the hierarchical decomposition method is effective approach for the case of smooth covariance function. The procedure of d -dimensional conditioning and block reordering scheme improved accuracy of estimated value under the exponential covariance structure, with negligible amount of computing time and cost. The integrated value is computed by multiplying truncated expectation values, computed based on the principle of Quasi-Monte Carlo simulation. Hence, it remains further topic of research to delve into the methodology of estimating the truncated expectations of multivariate normal random variables.

References

- Cao, J., Genton, M. G., Keyes, D. E., & Turkiyyah, G. M. (2019). Hierarchical-block conditioning approximations for high-dimensional multivariate normal probabilities. *Statistics and Computing*, 29(3), 585–598.
- Genton, M. G., Keyes, D. E., & Turkiyyah, G. (2018). Hierarchical decompositions for the computation of high-dimensional multivariate normal probabilities. *Journal of Computational and Graphical Statistics*, 27(2), 268–277.
- Genz, A. (1992). Numerical computation of multivariate normal probabilities. *Journal of computational and graphical statistics*, 1(2), 141–149.
- Genz, A., & Bretz, F. (2009). *Computation of multivariate normal and t probabilities* (Vol. 195). Springer Science & Business Media.
- Gibson, G., Glasbey, C., & Elston, D. (1994). Monte carlo evaluation of multivariate normal integrals and sensitivity to variate ordering. *Advances in Numerical Methods and Applications*, 120–126.
- Hackbusch, W. (2015). *Hierarchical matrices: algorithms and analysis* (Vol. 49). Springer.
- Kamakura, W. A. (1989). The estimation of multinomial probit models: A new calibration algorithm. *Transportation Science*, 23(4), 253–265.
- Kan, R., & Robotti, C. (2017). On moments of folded and truncated multivariate normal distributions. *Journal of Computational and Graphical Statistics*, 26(4), 930–934.
- Mendell, N. R., & Elston, R. (1974). Multifactorial qualitative traits: genetic analysis and prediction of recurrence risks. *Biometrics*, 41–57.
- Salem, F. K. A., & Arab, M. A. (2016). Comparative study of space filling curves for cache oblivious tu decomposition. *arXiv preprint arXiv:1612.06069*.
- Schervish, M. J. (1984). Algorithm as 195: Multivariate normal probabilities with error bound. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, 33(1), 81–94.
- Stewart, G. W. (1980). The efficient generation of random orthogonal matrices with an application to condition estimators. *SIAM Journal on Numerical Analysis*, 17(3), 403–409.
- Trinh, G., & Genz, A. (2015). Bivariate conditioning approximations for multivariate normal probabilities. *Statistics and Computing*, 25(5), 989–996.