Thesis Contents

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Abstract

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13 Semiseparable

Define matrices $E_u(p)$ and $E_l(q)$ as following,

$$E_u(p) = \begin{cases} 1, & \text{if} \quad i \leqslant j - p, \\ 0, & \text{otherwise.} \end{cases} \quad \text{and} \quad E_l(q) = \begin{cases} 1, & \text{if} \quad i \geqslant j - q, \\ 0, & \text{otherwise.} \end{cases} . \tag{1}$$

i.e.

$$E_u(-1) = \begin{bmatrix} 1 & 1 & \cdots & \cdots & 1 \\ 1 & \ddots & \ddots & & \vdots \\ 0 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 1 \\ 0 & \cdots & 0 & 1 & 1 \end{bmatrix}, \quad E_u(0) = \begin{bmatrix} 1 & 1 & \cdots & \cdots & 1 \\ 0 & \ddots & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & \ddots & \ddots & 1 \\ 0 & \cdots & \cdots & 0 & 1 \end{bmatrix}, \quad E_u(1) = \begin{bmatrix} 0 & 1 & \cdots & \cdots & 1 \\ \vdots & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & \ddots & \vdots \\ \vdots & & & \ddots & 1 \\ 0 & \cdots & \cdots & \cdots & 0 \end{bmatrix}; \tag{2}$$

$$E_l(-1) = \begin{bmatrix} 1 & 1 & 0 & \cdots & 0 \\ 1 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & \ddots & 1 \\ 1 & \cdots & \cdots & 1 & 1 \end{bmatrix}, \quad E_l(0) = \begin{bmatrix} 1 & 0 & \cdots & \cdots & 0 \\ 1 & \ddots & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & \ddots & \ddots & 0 \\ 1 & \cdots & \cdots & 1 & 1 \end{bmatrix}, \quad E_l(1) = \begin{bmatrix} 0 & \cdots & \cdots & \cdots & 0 \\ 1 & \ddots & & & \vdots \\ \vdots & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & \ddots & \vdots \\ 1 & \cdots & \cdots & 1 & 0 \end{bmatrix}. \tag{3}$$

where $|p| \leqslant n - 1$ and $|q| \leqslant n - 1$.

Define the operations triu and tril,

$$\operatorname{triu}(A, p) = A \circ E_u(p) \tag{4}$$

$$\operatorname{tril}(A, q) = A \circ E_l(q) \tag{5}$$

i.e. $\operatorname{triu}(A, p)$ retains the entries of A above the p-th super-diagonal (inclusive) and makes the entries of A below the p-th super-diagonal (exclusive) 0.

define symmetric {1,1}-semiseparable matrix, S

$$S = \begin{cases} x_i y_j & \text{if } i \leqslant j \ ; \\ x_j y_i & \text{if } i \geqslant j. \end{cases} \tag{6}$$

$$= \operatorname{triu}\left(xy^{\mathrm{T}}\right) + \operatorname{tril}\left(yx^{\mathrm{T}}, -1\right) \tag{7}$$

$$= \operatorname{triu}\left(xy^{\mathrm{T}}, 1\right) + \operatorname{tril}\left(yx^{\mathrm{T}}\right) \tag{8}$$

$$= \begin{bmatrix} x_1 y_1 & x_1 y_2 & \cdots & x_1 y_n \\ x_1 y_2 & x_2 y_2 & \cdots & x_2 y_n \\ \vdots & \vdots & \ddots & \vdots \\ x_1 y_n & x_2 y_n & \cdots & x_n y_n \end{bmatrix} \tag{9}$$

14 Matrix (basic def)

Matrix-Matrix Multiplication

$$AB = C \tag{10}$$

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj} \tag{11}$$

Matrix-Vector Multiplication

$$Ax = b \tag{12}$$

$$b_i = \sum_{k=1}^{n} a_{ik} x_k \tag{13}$$

15 Algorithm (Appendix)

Backward Subsitution

$$Ux = b \tag{14}$$

Triangular Matrix

$$\begin{bmatrix} d_1 & u_1^1 & u_1^2 & \cdots & \cdots & u_1^{n-1} \\ & d_2 & u_2^1 & u_2^2 & \cdots & u_2^{n-2} \\ & & \ddots & \ddots & \ddots & \vdots \\ & & & d_{n-2} & u_{n-2}^1 & u_{n-2}^2 \\ & & & & d_{n-1} & u_{n-1}^1 \\ & & & & & d_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-2} \\ x_{n-1} \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{n-2} \\ b_{n-1} \\ b_n \end{bmatrix} \tag{15}$$

$$x_n = b_n / u_{nn} \tag{16}$$

$$x_i = \left(b_i - \sum_{j=i+1}^{n} u_{ij} x_j \right) \Big/ u_{ii} \tag{17}$$

$$d_n x_n = b_n \qquad \Rightarrow \qquad x_n = b_n / \, d_n \tag{18}$$

$$d_{n-1} x_{n-1} + u_{n-1}^1 x_n = b_{n-1} \qquad \Rightarrow \qquad x_{n-1} = \left(b_{n-1} - u_{n-1}^1 x_n \right) / \, d_{n-1} \tag{19}$$

$$d_{n-2} x_{n-2} + u_{n-2}^1 x_{n-1} + u_{n-2}^2 x_n = b_{n-2} \qquad \Rightarrow \qquad x_{n-2} = \left(b_{n-2} - u_{n-2}^1 x_{n-1} - u_{n-2}^2 x_n \right) / \, d_{n-2} \tag{20}$$

$$\vdots \tag{21}$$

$$b_{n-k} = d_{n-k} x_{n-k} + u_{n-k}^1 x_{n-k+1} + u_{n-k}^2 x_{n-k+2} + \cdots u_{n-k}^k x_{n-k+k} \tag{22}$$

$$\Rightarrow \quad x_{n-k} = \left(b_{n-k} - u_{n-k}^1 x_{n-k+1} - u_{n-k}^2 x_{n-k+2} - \cdots u_{n-k}^k x_{n-k+k} \right) \Big/ \, d_{n-k} \tag{23}$$

$$= \left(b_{n-k} - \sum_{j=1}^{k} u_{n-k}^j x_{n-k+j} \right) \Big/ \, d_{n-k} \tag{24}$$

$$\tag{25}$$

$$x_i = \left(b_i - \sum_{j=1}^{n-i} u_i^j x_{i+j} \right) \Big/ \, d_i \tag{26}$$

$$x_i = \left(b_i - \sum_{j=i+1}^{n} u_{ij} x_j \right) \Big/ \, u_{ii} \tag{27}$$

Upper Banded Matrix

$$\begin{bmatrix} d_1 & b_1^1 & b_1^2 & \cdots & b_1^u & & & & \\ & d_2 & b_2^1 & b_2^2 & \cdots & b_2^u & & & \\ & & \ddots & \ddots & \ddots & & & \ddots & \\ & & & \ddots & \ddots & \ddots & & & b_{n-u}^u \\ & & & & \ddots & \ddots & & \ddots & \vdots \\ & & & & & & d_{n-2} & b_{n-2}^1 & b_{n-2}^2 \\ & & & & & & & d_{n-1} & b_{n-1}^1 \\ & & & & & & & & d_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ \vdots \\ x_{n-2} \\ x_{n-1} \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ \vdots \\ \vdots \\ b_{n-2} \\ b_{n-1} \\ b_n \end{bmatrix} \tag{28}$$

$$x_n = b_n / u_{nn} \tag{29}$$

$$x_i = \left(b_i - \sum_{j=i+1}^{n} u_{ij} x_j \right) \Big/ \, u_{ii} \tag{30}$$

$$d_n x_n = b_n \quad \Rightarrow \quad x_n = b_n / \, d_n \tag{31}$$

$$d_{n-1} x_{n-1} + u_{n-1}^1 x_n = b_{n-1} \quad \Rightarrow \quad x_{n-1} = \left(b_{n-1} - u_{n-1}^1 x_n \right) / \, d_{n-1} \tag{32}$$

$$d_{n-2} x_{n-2} + u_{n-2}^1 x_{n-1} + u_{n-2}^2 x_n = b_{n-2} \quad \Rightarrow \quad x_{n-2} = \left(b_{n-2} - u_{n-2}^1 x_{n-1} - u_{n-2}^2 x_n \right) / \, d_{n-2} \tag{33}$$

$$\vdots \tag{34}$$

$$b_{n-k} = d_{n-k} x_{n-k} + u_{n-k}^1 x_{n-k+1} + u_{n-k}^2 x_{n-k+2} + \cdots u_{n-k}^k x_{n-k+k} \tag{35}$$

$$\Rightarrow \quad x_{n-k} = \left(b_{n-k} - u_{n-k}^1 x_{n-k+1} - u_{n-k}^2 x_{n-k+2} - \cdots u_{n-k}^k x_{n-k+k} \right) \Big/ \, d_{n-k} \tag{36}$$

$$= \left(b_{n-k} - \sum_{j=1}^{k} u_{n-k}^j x_{n-k+j} \right) \Big/ \, d_{n-k} \tag{37}$$

$$\tag{38}$$

$$x_i = \left(b_i - \sum_{j=1}^{n-i} u_i^j x_{i+j} \right) \Big/ \, d_i \tag{39}$$

$$x_i = \left(b_i - \sum_{j=i+1}^{n} u_{ij} x_j \right) \Big/ \, u_{ii} \tag{40}$$

16 Apply on symmetric positive definite tridiagonal matrices

$$\longleftarrow \text{ cholesky } \mathcal{O}\left(\frac{1}{3}n^3\right)$$

$$\begin{aligned}
T &= U^{\mathrm{T}}U \\
U^{-1} &= \operatorname{triu}\left(xy^{\mathrm{T}}\right) \\
\left(U^{\mathrm{T}}\right)^{-1} &= \left(U^{-1}\right)^{\mathrm{T}} \\
&= \left(\operatorname{triu}\left(xy^{\mathrm{T}}\right)\right)^{\mathrm{T}} \\
&= \operatorname{tril}\left(yx^{\mathrm{T}}\right) \\
T^{-1} &= \left(U^{\mathrm{T}}U\right)^{-1} \\
&= \left(U^{-1}\right)\left(U^{\mathrm{T}}\right)^{-1} \\
&= \operatorname{triu}\left(xy^{\mathrm{T}}\right)\operatorname{tril}\left(yx^{\mathrm{T}}\right)
\end{aligned}$$

$$\begin{aligned}
\left(T^{-1}\right)_{i,j} &= \sum_{k=1}^{n}\left[\operatorname{triu}\left(xy^{\mathrm{T}}\right)\right]_{i,k}\left[\operatorname{tril}\left(yx^{\mathrm{T}}\right)\right]_{k,j} \\
&= \sum_{k=1}^{n}\left(\begin{cases} x_i y_k, & \text{if } i \leqslant j; \\ 0, & \text{if } i > j. \end{cases}\right)\left(\begin{cases} 0, & \text{if } k < j; \\ y_k x_j, & \text{if } k \geqslant j. \end{cases}\right) \\
&= \sum_{k=1}^{n}\left(x_i y_k \mathbb{1}_{\mathbb{Z}\cap[i,n]}(k)\right)\left(y_k x_j \mathbb{1}_{\mathbb{Z}\cap[j,n]}(k)\right) \\
&= x_i x_j \sum_{k=1}^{n} y_k^2\left(\mathbb{1}_{\mathbb{Z}\cap[i,n]}(k)\,\mathbb{1}_{\mathbb{Z}\cap[j,n]}(k)\right) \\
&= x_i x_j \sum_{k=1}^{n} y_k^2 \mathbb{1}_{\mathbb{Z}\cap[\max(i,j),n]}(k)
\end{aligned}$$

$$\left(T^{-1}\right)_{i,j} = \begin{cases} x_i x_j \sum_{k=j}^{n} y_k^2, & \text{if } i \leqslant j; \\ x_j x_i \sum_{k=i}^{n} y_k^2, & \text{if } i \geqslant j. \end{cases} \tag{41}$$

for $i = j$,

$$\left(T^{-1}\right)_{i,i} = x_i^2 \sum_{k=i}^{n} y_k^2 = x_j^2 \sum_{k=j}^{n} y_k^2 = \left(T^{-1}\right)_{j,j}$$

following the definition of {1,1}-Semiseparable matrix

$$S = \begin{cases} x_i y_j & \text{if } i \leqslant j \ ; \\ x_j y_i & \text{if } i \geqslant j. \end{cases} \tag{42}$$

$$= \operatorname{triu}\left(xy^{\mathrm{T}}\right) + \operatorname{tril}\left(yx^{\mathrm{T}}, -1\right) \tag{43}$$

$$\tag{44}$$

$$
\begin{aligned}
\left(T^{-1}\right)_{i,j} &= \begin{cases} x_i\left(x_j \sum_{k=j}^{n} y_k^2\right), & \text{if } i \leqslant j; \\ x_j\left(x_i \sum_{k=i}^{n} y_k^2\right), & \text{if } i \geqslant j. \end{cases} && (45) \\
&= \begin{cases} \tilde{x}_i \tilde{y}_j & \text{if } i \leqslant j \ ; \\ \tilde{x}_j \tilde{y}_i & \text{if } i \geqslant j. \end{cases} && (46) \\
&= \operatorname{triu}\left(\tilde{x}\tilde{y}^{\mathrm{T}}\right) + \operatorname{tril}\left(\tilde{y}\tilde{x}^{\mathrm{T}}, -1\right) && (47) \\
& && (48)
\end{aligned}
$$

where $\tilde{x}_i = x_i$ and $\tilde{y}_i = x_i \sum_{k=i}^{n} y_k^2$.

$$
\begin{aligned}
\tilde{x}_i &= x_i && (49) \\
\Rightarrow \tilde{x} &= x && (50) \\
\tilde{y}_i &= x_i \sum_{k=i}^{n} y_k^2 && (51) \\
\Rightarrow \tilde{y} &= \begin{bmatrix} x_1\left(\sum_{k=1}^{n} y_k^2\right) \\ x_2\left(\sum_{k=2}^{n} y_k^2\right) \\ \vdots \\ x_n\left(\sum_{k=n}^{n} y_k^2\right) \end{bmatrix} && (52) \\
&= x \circ \begin{bmatrix} y^{\mathrm{T}} y \\ y_{[2:n]}^{\mathrm{T}} y_{[2:n]} \\ \vdots \\ y_n^2 \end{bmatrix} && (53)
\end{aligned}
$$

$\mathbb{1}\mathbb{1} \leqslant$

17 28.06.2022 Meeting draft

17.1 Tridiagonal matrix (Upper)

$n = 2k$

$$
\begin{aligned}
U &= \begin{bmatrix}
d_1 & b_1^1 & b_1^2 & & & & & & & \\
 & d_2 & b_2^1 & b_2^2 & & & & & & \\
 & & d_3 & b_3^1 & b_3^2 & & & & & \\
 & & & d_4 & b_4^1 & b_4^2 & & & & \\
 & & & & \ddots & \ddots & \ddots & & & \\
 & & & & & \ddots & \ddots & \ddots & & \\
 & & & & & & d_{n-3} & b_{n-3}^1 & b_{n-3}^2 & \\
 & & & & & & & d_{n-2} & b_{n-2}^1 & b_{n-2}^2 \\
 & & & & & & & & d_{n-1} & b_{n-1}^1 \\
 & & & & & & & & & d_n
\end{bmatrix} \\
&= \begin{bmatrix}
\begin{bmatrix} d_1 & b_1^1 \\ & d_2 \end{bmatrix} & \begin{bmatrix} b_1^2 & \\ b_2^1 & b_2^2 \end{bmatrix} & & & \\
 & \begin{bmatrix} d_3 & b_3^1 \\ & d_4 \end{bmatrix} & \begin{bmatrix} b_3^2 & \\ b_4^1 & b_4^2 \end{bmatrix} & & \\
 & & \ddots & \ddots & \\
 & & & \begin{bmatrix} d_{2k-3} & b_{2k-3}^1 \\ & d_{2k-2} \end{bmatrix} & \begin{bmatrix} b_{2k-3}^2 & \\ b_{2k-2}^1 & b_{2k-2}^2 \end{bmatrix} \\
 & & & & \begin{bmatrix} d_{2k-1} & b_{2k-1}^1 \\ & d_{2k} \end{bmatrix}
\end{bmatrix} \\
&= \begin{bmatrix}
D_1 & B_1 & & & \\
 & D_2 & B_2 & & \\
 & & \ddots & \ddots & \\
 & & & D_{k-1} & B_{k-1} \\
 & & & & D_k
\end{bmatrix} \in \mathbb{R}^{2k \times 2k}
\end{aligned}
$$

$$
X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{k-1} \\ X_k \end{bmatrix} \in \mathbb{R}^{2k \times 2} \qquad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{k-1} \\ Y_k \end{bmatrix} \in \mathbb{R}^{2k \times 2} \qquad Y^{\mathrm{T}} = \begin{bmatrix} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{bmatrix} \in \mathbb{R}^{2 \times 2k}
$$

$$
\begin{aligned}
XY^{\mathrm{T}} &= \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{k-1} \\ X_k \end{bmatrix} \begin{bmatrix} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{bmatrix} \\
&= \begin{bmatrix} X_1Y_1^{\mathrm{T}} & X_1Y_2^{\mathrm{T}} & \cdots & X_1Y_{k-1}^{\mathrm{T}} & x_1Y_k^{\mathrm{T}} \\ X_2Y_1^{\mathrm{T}} & X_2Y_2^{\mathrm{T}} & \cdots & X_2Y_{k-1}^{\mathrm{T}} & x_2Y_k^{\mathrm{T}} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ X_{k-1}Y_1^{\mathrm{T}} & X_{k-1}Y_2^{\mathrm{T}} & \cdots & X_{k-1}Y_{k-1}^{\mathrm{T}} & X_{k-1}Y_k^{\mathrm{T}} \\ X_kY_1^{\mathrm{T}} & X_kY_2^{\mathrm{T}} & \cdots & X_kY_{k-1}^{\mathrm{T}} & X_kY_k^{\mathrm{T}} \end{bmatrix} \\
&= X\begin{bmatrix} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{bmatrix} \\
&= \begin{bmatrix} XY_1^{\mathrm{T}} & XY_2^{\mathrm{T}} & \cdots & XY_{k-1}^{\mathrm{T}} & XY_k^{\mathrm{T}} \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
\operatorname{triu}(X_k) &\coloneqq X_k \\
\operatorname{triu}(Y_k^{\mathrm{T}}) &\coloneqq Y_k^{\mathrm{T}} \\
\operatorname{triu}(X_kY_k^{\mathrm{T}}) &= X_kY_k^{\mathrm{T}}
\end{aligned}
$$

$$
\begin{aligned}
\operatorname{triu}(XY^{\mathrm{T}}) &= \begin{bmatrix} \operatorname{triu}(X_1Y_1^{\mathrm{T}}) & X_1Y_2^{\mathrm{T}} & \cdots & X_1Y_{k-1}^{\mathrm{T}} & X_1Y_k^{\mathrm{T}} \\ 0_{2\times 2} & \operatorname{triu}(X_2Y_2^{\mathrm{T}}) & \cdots & X_2Y_{k-1}^{\mathrm{T}} & X_2Y_k^{\mathrm{T}} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0_{2\times 2} & 0_{2\times 2} & \cdots & \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) & X_{k-1}Y_k^{\mathrm{T}} \\ 0_{2\times 2} & 0_{2\times 2} & \cdots & 0_{2\times 2} & X_kY_k^{\mathrm{T}} \end{bmatrix} \\
&= \begin{bmatrix} \begin{bmatrix} \operatorname{triu}(X_1Y_1^{\mathrm{T}}) \\ 0_{2(k-1)\times 2} \end{bmatrix} & \begin{bmatrix} X_1Y_2^{\mathrm{T}} \\ \operatorname{triu}(X_2Y_2^{\mathrm{T}}) \\ 0_{2(k-2)\times 2} \end{bmatrix} & \cdots & \begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{2\times 2} \end{bmatrix} & XY_k^{\mathrm{T}} \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
U^{-1} &= \operatorname{triu}(XY^{\mathrm{T}}) \\
I &= U \operatorname{triu}(XY^{\mathrm{T}})
\end{aligned}
$$

$$
E_i = \begin{bmatrix} 0 & \cdots & 0 & I_{2\times 2} & 0 & \cdots & 0 \end{bmatrix}^{\mathrm{T}}
$$

k-th block column,

$$
\begin{aligned}
E_k &= U \operatorname{triu}(XY^{\mathrm{T}})E_k \\
&= UXY_k^{\mathrm{T}}
\end{aligned}
$$

$$
\begin{aligned}
X &\coloneqq U^{-1}E_k \\
E_k &= UXY_k^{\mathrm{T}} \\
&= UU^{-1}E_kY_k^{\mathrm{T}} \\
&= E_kY_k^{\mathrm{T}} \\
Y_k^{\mathrm{T}} &\coloneqq I_{2\times 2}
\end{aligned}
$$

$(k-1)$-th block column,

$$\begin{aligned}
E_{k-1} &= U \operatorname{triu}(XY^{\mathrm{T}})E_{k-1} \\
&= U \begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{2\times 2} \end{bmatrix}
\end{aligned}$$

$(k-1)$-th block row of $(k-1)$-th block column,

$$E_i^{\mathrm{T}} E_j = \begin{cases} I_{2\times 2}, & \text{if } i = j \ ; \\ 0_{2\times 2}, & \text{otherwise.} \end{cases}$$

$$\begin{aligned}
E_{k-1}^{\mathrm{T}} E_{k-1} = I_{2\times 2} &= E_{k-1}^{\mathrm{T}} U \begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{2\times 2} \end{bmatrix} \\
&= \begin{bmatrix} 0_{2\times 2(k-2)} & D_{k-1} & B_{k-1} \end{bmatrix} \begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{2\times 2} \end{bmatrix} \\
&= D_{k-1} \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\
Y_{k-1}^{\mathrm{T}} &\coloneqq (D_{k-1}X_{k-1})^{-1}
\end{aligned}$$

$$\begin{aligned}
D_{k-1} &= \operatorname{triu}(D_{k-1}) \\
D_{k-1}^{-1} &= \operatorname{triu}(D_{k-1}^{-1}) \\
Y_{k-1}^{\mathrm{T}} &\coloneqq (D_{k-1}X_{k-1})^{-1} \\
D_{k-1} \operatorname{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) &= D_{k-1} \operatorname{triu}(X_{k-1}(D_{k-1}X_{k-1})^{-1}) \\
&= D_{k-1} \operatorname{triu}(X_{k-1}X_{k-1}^{-1}D_{k-1}^{-1}) \\
&= D_{k-1} \operatorname{triu}(D_{k-1}^{-1}) \\
&= D_{k-1}D_{k-1}^{-1} \\
&= I_{2\times 2}
\end{aligned}$$

$$\begin{aligned}
X &\coloneqq U^{-1}E_k \\
E_k &= UX \\
E_k^{\mathrm{T}} E_k = I_{2\times 2} &= E_k^{\mathrm{T}} UX \\
&= \begin{bmatrix} 0_{2\times 2(k-1)} & D_k \end{bmatrix} X \\
&= D_k X_k \\
Y_k^{\mathrm{T}} &\coloneqq I_{2\times 2} \\
&\coloneqq (D_k X_k)^{-1}
\end{aligned}$$

$$\begin{aligned}
X &\coloneqq U^{-1}E_k \\
Y_i^{\mathrm{T}} &\coloneqq (D_i X_i)^{-1}
\end{aligned}$$

$n = 2k+1$

$$U = \begin{bmatrix} \begin{bmatrix} d_1 \end{bmatrix} & \begin{bmatrix} b_1^1 & b_1^2 \end{bmatrix} & & & & & \\ & \begin{bmatrix} d_2 & b_2^1 \\ & d_3 \end{bmatrix} & \begin{bmatrix} b_2^2 & \\ b_3^1 & b_3^2 \end{bmatrix} & & & & \\ & & \ddots & & \ddots & & \\ & & & & \begin{bmatrix} d_{2k-2} & b_{2k-2}^1 \\ & d_{2k-1} \end{bmatrix} & \begin{bmatrix} b_{2k-2}^2 & \\ b_{2k-1}^1 & b_{2k-1}^2 \end{bmatrix} \\ & & & & & \begin{bmatrix} d_{2k} & b_{2k}^1 \\ & d_{2k+1} \end{bmatrix} \end{bmatrix}$$

$$= \begin{bmatrix} \tilde{D}_1 & \tilde{B}_1 & & & \\ & D_2 & B_2 & & \\ & & \ddots & \ddots & \\ & & & D_k & B_k \\ & & & & D_{k+1} \end{bmatrix} \in \mathbb{R}^{(2k+1)\times(2k+1)}$$

$$\begin{aligned} X &\coloneqq U^{-1} E_{k+1} \\ Y_i^{\mathrm{T}} &\coloneqq (D_i X_i)^{-1} \text{ for } i = 2, \ \cdots, \ k+1 \\ Y_1^{\mathrm{T}} &\coloneqq (D_1 X_1)^{+} = (D_1 X_1)^{\mathrm{T}} (D_1 X_1 (D_1 X_1)^{\mathrm{T}})^{-1} \end{aligned}$$

17.2 Banded matrix (Upper)

$n = ku + r,\ 0 \le r < u$

$$U = \begin{bmatrix} d_1 & b_1^1 & b_1^2 & \cdots & b_1^u & & & \\ & d_2 & b_2^1 & b_2^2 & \cdots & b_2^u & & \\ & & \ddots & \ddots & \ddots & \cdots & \ddots & \\ & & & \ddots & \ddots & \ddots & \cdots & b_{n-u}^u \\ & & & & \ddots & \ddots & \ddots & \vdots \\ & & & & & \ddots & \ddots & b_{n-2}^2 \\ & & & & & & \ddots & b_{n-1}^1 \\ & & & & & & & d_n \end{bmatrix}$$

$r = 0,\ n = ku,$

$$U = \begin{bmatrix} D_1 & B_1 & & & \\ & D_2 & B_2 & & \\ & & \ddots & \ddots & \\ & & & D_{k-1} & B_{k-1} \\ & & & & D_k \end{bmatrix} \in \mathbb{R}^{ku \times ku},$$

$$D_i \in \mathbb{R}^{u\times u},\ B_i \in \mathbb{R}^{u\times u} \text{ for } i = 1,\ 2,\ \cdots,\ k.$$

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_k \end{bmatrix} \in \mathbb{R}^{ku\times u} \qquad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_k \end{bmatrix} \in \mathbb{R}^{ku\times u} \qquad Y^{\mathrm{T}} = \begin{bmatrix} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_k^{\mathrm{T}} \end{bmatrix} \in \mathbb{R}^{u\times ku}$$

$$\begin{aligned} X_i,\ Y_i^{\mathrm{T}} &\in \mathbb{R}^{u\times u},\ \text{for } i = 1,\ 2,\ \cdots,\ k \\ X &\coloneqq U^{-1}E_k \\ Y_i^{\mathrm{T}} &\coloneqq (D_i X_i)^{-1} \end{aligned}$$

$r \ne 0,\ n = ku + r,$

$$U = \begin{bmatrix} \tilde{D}_1 & \tilde{B}_1 & & & \\ & D_2 & B_2 & & \\ & & \ddots & \ddots & \\ & & & D_k & B_k \\ & & & & D_{k+1} \end{bmatrix} \in \mathbb{R}^{(ku+r)\times(ku+r)},$$

$$\begin{aligned} &\tilde{D}_1 \in \mathbb{R}^{r\times r},\ \tilde{B}_1 \in \mathbb{R}^{r\times u}; \\ &D_i \in \mathbb{R}^{u\times u},\ B_i \in \mathbb{R}^{u\times u} \text{ for } i = 2,\ \cdots,\ k+1. \end{aligned}$$

$$X = \begin{bmatrix} \tilde{X}_1 \\ X_2 \\ \vdots \\ X_{k+1} \end{bmatrix} \in \mathbb{R}^{(ku+r)\times u} \quad Y = \begin{bmatrix} \tilde{Y}_1 \\ Y_2 \\ \vdots \\ Y_{k+1} \end{bmatrix} \in \mathbb{R}^{(ku+r)\times u} \quad Y^{\mathrm{T}} = \begin{bmatrix} \tilde{Y}_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k+1}^{\mathrm{T}} \end{bmatrix} \in \mathbb{R}^{u\times(ku+r)}$$

$$
\begin{aligned}
\tilde{X}_1 &\in \mathbb{R}^{r\times u} \\
\tilde{Y}_1^{\mathrm{T}} &\in \mathbb{R}^{u\times r} \\
X_i,\ Y_i^{\mathrm{T}} &\in \mathbb{R}^{u\times u} \text{ for } i = 2,\ \cdots,\ k+1 \\
X &\coloneqq U^{-1}E_{k+1} \\
\tilde{Y}_1^{\mathrm{T}} &\coloneqq (D_1X_1)^{+} = (D_1X_1)^{\mathrm{T}}(D_1X_1(D_1X_1)^{\mathrm{T}})^{-1} \\
\mathrm{triu}(D_1X_1\tilde{Y}_1^{\mathrm{T}}) &= I_{r\times r} \\
Y_i^{\mathrm{T}} &\coloneqq (D_iX_i)^{-1} \text{ for } i = 2,\ \cdots,\ k+1
\end{aligned}
$$

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18.1 Notation

This notes use Householder notation and start indexing at one.

$$\begin{aligned}
\text{Scalars, lower case Greek letters: } & \alpha,\ \beta,\ \gamma,\ \chi,\ etc. \\
\text{Vectors, lower case Roman letter: } & a,\ b,\ c,\ x,\ etc. \\
\text{Matrix, upper case Roman letter: } & A,\ B,\ C,\ X,\ etc.
\end{aligned}$$

18.2 Repersentation

Matrix & Vector

$$\begin{aligned}
x &= \begin{bmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{bmatrix} \in \mathbb{R}^n \\
A &= \left[\begin{array}{c|c|c|c} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{1n} \end{array}\right] \\
&= \left[\begin{array}{c|c|c|c} a_1 & a_2 & \cdots & a_n \end{array}\right] \in \mathbb{R}^{m\times n}
\end{aligned}$$

Block Matrix & Block Vector

$$\begin{aligned}
x &= \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^{kn},\ x_i \in \mathbb{R}^k \\
A &= \left[\begin{array}{c|c|c|c} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{1n} \end{array}\right] \\
&= \left[\begin{array}{c|c|c|c} A_1 & A_2 & \cdots & A_n \end{array}\right] \in \mathbb{R}^{lm\times kn},\ A_{ij} \in \mathbb{R}^{l\times k}
\end{aligned}$$

18.3 Content

Consider an upper banded matrix $U \in \mathbb{R}^{n\times n}$,

$$
U = \begin{bmatrix}
\alpha_1 & \beta_1^1 & \beta_1^2 & \cdots & \beta_1^u & & & \\
 & \alpha_2 & \beta_2^1 & \beta_2^2 & \cdots & \beta_2^u & & \\
 & & \ddots & \ddots & & \ddots & & \\
 & & & & & & \beta_{n-u}^u & \\
 & & & & & & \vdots & \\
 & & & & & \ddots & \beta_{n-2}^2 & \\
 & & & & & & \beta_{n-1}^1 & \\
 & & & & & & \alpha_n &
\end{bmatrix}. \tag{54}
$$

Then try to show that its inverse can be repersent as the upper triangular part of an outer product, *i.e.* ,

$$
U^{-1} = \mathrm{triu}(XY^{\mathrm{T}}) \tag{55}
$$

Let $X,\ Y \in \mathbb{R}^{n\times u}$, consider the following cases of n,

Case 1, $n = ku$

then (54) can be repersent as a block upper bidiagonal matrix,

$$
\begin{array}{c}
 & \overset{r}{\longleftrightarrow} & \overset{u}{\longleftrightarrow} & \cdots\cdots & \overset{u}{\longleftrightarrow} \\
\begin{array}{c} r\updownarrow \\ \\ u\updownarrow \\ \\ \vdots \\ \\ u\updownarrow \end{array} &
\multicolumn{4}{c}{
\left[\begin{array}{ccccccccc}
d_1 \cdots b_1^{r-1} & b_1^r \cdots\cdots b_1^u & & & & & \\
\ddots \quad \vdots & \vdots \qquad\quad \ddots & & & & & \\
d_r & b_r^1 \cdots\cdots\cdots b_r^u & & & & & \\
 & d_{1+r} \cdots\cdots b_{1+r}^{u-1} & b_{r+1}^u & & & & \\
 & \ddots \qquad \vdots & \vdots \quad \ddots & & & & \\
 & d_{u+r} & b_{u+r}^1 \cdots\cdots b_{u+r}^u & & & & \\
 & & \ddots & \vdots & \vdots & \ddots & \\
 & & & & d_{n-u+1} \cdots\cdots b_{n-u+1}^u & & \\
 & & & & \ddots \qquad \vdots & & \\
 & & & & d_n & &
\end{array}\right]}
\end{array}
$$

$$
\begin{array}{c c}
 & \begin{array}{ccccccccc} \multicolumn{3}{c}{\overset{u}{\longleftrightarrow}} & \multicolumn{3}{c}{\overset{u}{\longleftrightarrow}} & \cdots\cdots & \multicolumn{2}{c}{\overset{u}{\longleftrightarrow}} \end{array} \\
U = & \begin{bmatrix}
\alpha_1 & \cdots & \beta_1^{u-1} & \beta_1^{u} & & & & & & & \\
 & \ddots & \vdots & \vdots & \ddots & & & & & & \\
 & & \alpha_u & \beta_u^{1} & \cdots & \beta_u^{u} & & & & & \\
 & & & \alpha_{u+1} & \cdots & \beta_{u+1}^{u-1} & \beta_{u+1}^{u} & & & & \\
 & & & & \ddots & \vdots & \vdots & \ddots & & & \\
 & & & & & \alpha_{2u} & \beta_{2u}^{1} & \cdots & \beta_{2u}^{u} & & \\
 & & & & & & & \ddots & & \ddots & \\
 & & & & & & & & \alpha_{(k-1)u+1} & \cdots & \beta_{(k-1)u+1}^{u-1} \\
 & & & & & & & & & \ddots & \vdots \\
 & & & & & & & & & & \alpha_{ku}
\end{bmatrix}
\end{array}
$$

$$
= \begin{bmatrix}
D_1 & B_1 & & & \\
 & D_2 & B_2 & & \\
 & & \ddots & \ddots & \\
 & & & D_{k-1} & B_{k-1} \\
 & & & & D_k
\end{bmatrix} \in \mathbb{R}^{ku\times ku},\ D_i,\ B_i \in \mathbb{R}^{u\times u} \text{ for } i = 1,\ 2,\ \ldots,\ k. \tag{56}
$$

Repersent the n-dimensional identity matrix $I_{n\times n}$ in block form,

$$
I_{n\times n} = I_{ku\times ku} = \operatorname{diag}(\underbrace{I_{u\times u},\ I_{u\times u},\ \cdots,\ I_{u\times u}}_{k}) = \left[\ E_1 \mid E_2 \mid \cdots \mid E_k\ \right].
$$

then, its block columns E_i for $i = 1,\ 2,\ \ldots,\ k$ satisfies

$$
\begin{aligned}
E_i &\in \mathbb{R}^{ku\times u} \\
E_i^{\mathrm{T}} E_j &= \begin{cases} I_{u\times u}, & \text{if } i = j\ ; \\ 0_{u\times u}, & \text{otherwise.} \end{cases}.
\end{aligned}
$$

To find X and Y such that (55) holds, let

$$
X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{k-1} \\ X_k \end{bmatrix} \in \mathbb{R}^{ku\times u},\ Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{k-1} \\ Y_k \end{bmatrix} \in \mathbb{R}^{ku\times u},\ X_i,\ Y_i \in \mathbb{R}^{u\times u} \text{ for } i = 1,\ 2,\ \ldots,\ k,
$$

and let X_k and Y_k^{T} be upper triangular matrix, then $\operatorname{triu}(X_k Y_k^{\mathrm{T}}) = X_k Y_k^{\mathrm{T}}$.
For the outer product form,

$$
\begin{aligned}
Y^{\mathrm{T}} &= \left[\begin{array}{c|c|c|c|c} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{array}\right] \in \mathbb{R}^{u\times ku} \\
XY^{\mathrm{T}} &= \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{k-1} \\ X_k \end{bmatrix} \left[\begin{array}{c|c|c|c|c} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{array}\right] \\
&= \left[\begin{array}{c|c|c|c|c}
X_1Y_1^{\mathrm{T}} & X_1Y_2^{\mathrm{T}} & \cdots & X_1Y_{k-1}^{\mathrm{T}} & x_1Y_k^{\mathrm{T}} \\
X_2Y_1^{\mathrm{T}} & X_2Y_2^{\mathrm{T}} & \cdots & X_2Y_{k-1}^{\mathrm{T}} & x_2Y_k^{\mathrm{T}} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
X_{k-1}Y_1^{\mathrm{T}} & X_{k-1}Y_2^{\mathrm{T}} & \cdots & X_{k-1}Y_{k-1}^{\mathrm{T}} & X_{k-1}Y_k^{\mathrm{T}} \\
X_kY_1^{\mathrm{T}} & X_kY_2^{\mathrm{T}} & \cdots & X_kY_{k-1}^{\mathrm{T}} & X_kY_k^{\mathrm{T}}
\end{array}\right] \\
&= X\left[\begin{array}{c|c|c|c|c} Y_1^{\mathrm{T}} & Y_2^{\mathrm{T}} & \cdots & Y_{k-1}^{\mathrm{T}} & Y_k^{\mathrm{T}} \end{array}\right] \\
&= \left[\begin{array}{c|c|c|c|c} XY_1^{\mathrm{T}} & XY_2^{\mathrm{T}} & \cdots & XY_{k-1}^{\mathrm{T}} & XY_k^{\mathrm{T}} \end{array}\right] \in \mathbb{R}^{ku\times ku},
\end{aligned}
$$

and its the upper triangular componnent,

$$
\begin{aligned}
\mathrm{triu}(XY^{\mathrm{T}}) &= \left[\begin{array}{c|c|c|c|c}
\mathrm{triu}(X_1Y_1^{\mathrm{T}}) & X_1Y_2^{\mathrm{T}} & \cdots & X_1Y_{k-1}^{\mathrm{T}} & X_1Y_k^{\mathrm{T}} \\
0_{u\times u} & \mathrm{triu}(X_2Y_2^{\mathrm{T}}) & \cdots & X_2Y_{k-1}^{\mathrm{T}} & X_2Y_k^{\mathrm{T}} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
0_{u\times u} & 0_{u\times u} & \cdots & \mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) & X_{k-1}Y_k^{\mathrm{T}} \\
0_{u\times u} & 0_{u\times u} & \cdots & 0_{u\times u} & X_kY_k^{\mathrm{T}}
\end{array}\right] \\
&= \left[\begin{array}{c|c|c|c|c}
\mathrm{triu}(X_1Y_1^{\mathrm{T}}) & X_1Y_2^{\mathrm{T}} & & X_{1:k-2}Y_{k-1}^{\mathrm{T}} & \\
0_{(k-2)u\times u} & \mathrm{triu}(X_2Y_2^{\mathrm{T}}) & \cdots & \mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) & XY_k^{\mathrm{T}} \\
0_{u\times u} & 0_{(k-2)u\times u} & & 0_{u\times u} &
\end{array}\right] .zz
\end{aligned}
\tag{57}
$$

From (55),

$$
I_{n\times n} = U\,\mathrm{triu}(XY^{\mathrm{T}}). \tag{58}
$$

For X and Y_k, from (57), the k-th block column of (58) can be written as,

$$
\begin{aligned}
E_k &= U\,\mathrm{triu}(XY^{\mathrm{T}})E_k \\
E_k &= UXY_k^{\mathrm{T}}
\end{aligned}
\tag{59}
$$

Define that

$$
X \coloneqq U^{-1}E_k; \tag{60}
$$

$$
Y_k^{\mathrm{T}} \coloneqq I_{u\times u}, \tag{61}
$$

which can be shown that (59) holds for the defined (60) and (61) through

$$
\begin{aligned}
UXY_k^{\mathrm{T}} &= UU^{-1}E_kI_{u\times u} \\
&= I_{n\times n}E_kI_{u\times u} \\
&= E_kI_{u\times u} \\
&= E_k,\ \text{as required.}
\end{aligned}
$$

Then, for Y_{k-1}, forming the $(k-1)$-th block column of (58) from (57) first,

$$\begin{aligned} E_{k-1} &= U\,\mathrm{triu}(XY^{\mathrm{T}})E_{k-1} \\ &= U\begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{u\times u} \end{bmatrix}. \end{aligned}$$

Focusing on the $(k-1)$-th block row of $(k-1)$-th block column,

$$\begin{aligned} E_{k-1}^{\mathrm{T}}E_{k-1} &= E_{k-1}^{\mathrm{T}}U\begin{bmatrix} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ 0_{u\times u} \end{bmatrix} \\ I_{u\times u} &= \left[\begin{array}{c|c|c} 0_{u\times(k-2)u} & D_{k-1} & B_{k-1} \end{array}\right]\left[\begin{array}{c} X_{1:k-2}Y_{k-1}^{\mathrm{T}} \\ \hline \mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) \\ \hline 0_{u\times u} \end{array}\right] \\ I_{u\times u} &= D_{k-1}\,\mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}). \end{aligned} \tag{62}$$

Define that

$$Y_{k-1}^{\mathrm{T}} \coloneqq (D_{k-1}X_{k-1})^{-1}, \tag{63}$$

and notice that $D_{k-1} \in \mathbb{R}^{u\times u}$ is a upper triangular, therefore

$$\begin{aligned} D_{k-1} &= \mathrm{triu}(D_{k-1}); \\ D_{k-1}^{-1} &= \mathrm{triu}(D_{k-1}^{-1}). \end{aligned} \tag{64}$$

With the fact (64), (62) holds for the defined (63) as,

$$\begin{aligned} D_{k-1}\,\mathrm{triu}(X_{k-1}Y_{k-1}^{\mathrm{T}}) &= D_{k-1}\,\mathrm{triu}(X_{k-1}(D_{k-1}X_{k-1})^{-1}) \\ &= D_{k-1}\,\mathrm{triu}(X_{k-1}X_{k-1}^{-1}D_{k-1}^{-1}) \\ &= D_{k-1}\,\mathrm{triu}(D_{k-1}^{-1}) \\ &= D_{k-1}D_{k-1}^{-1} \\ &= I_{u\times u}, \text{ as required.} \end{aligned}$$

Similar ideas can be use to redefine Y_k^{T} in (61), from (60),

$$\begin{aligned} E_k &= UX \\ E_k^{\mathrm{T}}E_k &= E_k^{\mathrm{T}}UX \\ I_{u\times u} &= E_k^{\mathrm{T}}UX \\ &= \left[\begin{array}{c|c} 0_{u\times(k-1)u} & D_k \end{array}\right]\left[\begin{array}{c} X_{1:k-1} \\ \hline X_k \end{array}\right] \\ &= D_kX_k \\ I_{u\times u} &= (D_kX_k)^{-1}, \end{aligned}$$

following that

$$\begin{aligned} Y_k^{\mathrm{T}} &:= I_{u \times u} \\ &:= (D_k X_k)^{-1}. \end{aligned}$$

In summary, for $U \in \mathbb{R}^{ku \times ku}$, (55) holds the following definitions of X and Y:

$$\begin{aligned} X &:= U^{-1} E_k \\ Y_i^{\mathrm{T}} &:= (D_i X_i)^{-1} \end{aligned}$$