Some symbolic tools for the Fox H-function

Le Chen

Department of Maathematics and Statistics

Auburn University

le.chen@auburn.edu, chenle02@gmail.com

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Contents

1 Introduction

In this note, we explain the code for checking the conditions of the Fox H-function [Fox61]. Here we follow the notation from Kilbas and Saigo [KS].

Let m, n, p, q be configure integers such that

$$0 \le m \le q \quad \text{and} \quad 0 \le n \le p.$$

Let $a_i, b_j \in \mathbb{C}$ and $\alpha_i, \beta_j \in \mathbb{R}_+$ be the parameters given below:

$\in (\mathbb{C}, \mathbb{R}_+)$	Front list	Rear list	
p	$(a_1, \alpha_1), \cdots, (a_n, \alpha_n)$	$(a_{n+1}, \alpha_{n+1}), \cdots, (a_p, \alpha_p)$	Upper list
q	$(b_1, \beta_1), \cdots, (b_m, \beta_m)$	$(b_{m+1}, \beta_{m+1}), \cdots, (b_q, \beta_q)$	Lower list

and denote

$$\mathcal{H}_{p,q}^{m,n}(s) := \frac{\prod_{i=1}^{n}\Gamma\left(1-a_i-\alpha_i s\right)}{\prod_{i=n+1}^{p}\Gamma\left(a_j+\alpha_i s\right)} \times \frac{\prod_{j=1}^{m}\Gamma\left(b_j+\beta_j s\right)}{\prod_{j=m+1}^{q}\Gamma\left(1-b_j-\alpha_j s\right)}. \tag{1}$$

Then the Fox H-function $H_{2,3}^{2,1}\left(z \,\middle|\, \begin{matrix} \cdots \\ \\ \cdots \end{matrix}\right)$ is defined by a Mellin-Barnes type integral of the form

$$H_{m,n}^{p,q}\left(z \,\middle|\, \begin{matrix} (a_1,\alpha_1),\cdots,(a_p,\alpha_p) \\ \\ (b_1,\beta_1),\cdots,(b_q,\beta_q) \end{matrix}\right) := \frac{1}{2\pi i}\int_{\mathcal{L}} H_{p,q}^{m,n}(s) z^{-s}\mathrm{d}s. \tag{2}$$

The basic assumption for the well-posedness of the Fox H-function is that two sets of poles do not overlap, i.e.,

$$\left\{b_{j\ell} = \frac{-b_j-\ell}{\beta_j}, \ell = 0,1,\cdots\right\} \bigcap \left\{a_{ik} = \frac{1-a_i+k}{\alpha_i}, k = 0,1,\cdots\right\} = \emptyset. \tag{3}$$

The contour $\mathcal{L}$ in (2) is given by one of the following three cases:

1. $\mathcal{L} = \mathcal{L}_{-\infty}$ is a left loop situated in a horizontal strip starting at point $-\infty + i\phi_1$ and terminating at point $-\infty + i\phi_2$ for some $-\infty < \phi_1 < \phi_2 < \infty$;
2. $\mathcal{L} = \mathcal{L}_{+\infty}$ is a right loop situated in a horizontal strip starting at point $+\infty + i\phi_1$ and terminating at point $\infty + i\phi_2$ for some $-\infty < \phi_1 < \phi_2 < \infty$;
3. $\mathcal{L} = \mathcal{L}_{i\gamma\infty}$ is a contour starting at point $\gamma - i\infty$ and terminating at point $\gamma + i\infty$ for some $\gamma \in (-\infty, \infty)$.

We need a set of conditions to ensure the convergence of the integral in (2). To explain this, we need to introduce some notation (following p. 2 of [KS]). First denote

$$a_1^* := \sum_{j=1}^{m}\beta_j - \sum_{i=n+1}^{p}\alpha_i,$$
$$a_2^* := \sum_{i=1}^{n}\alpha_i - \sum_{j=m+1}^{q}\beta_j.$$

The following two parameters play the most important role:

$$a^* := a_2^* + a_1^* = \sum_{i=1}^{n}\alpha_i - \sum_{i=n+1}^{p}\alpha_i + \sum_{j=1}^{m}\beta_j - \sum_{j=m+1}^{q}\beta_j;$$
$$\Delta := a_2^* - a_1^* = \sum_{j=1}^{q}\beta_j - \sum_{i=1}^{p}\alpha_i.$$

Similar to a^*, we define

$$\xi := \sum_{i=1}^{n} a_i - \sum_{i=n+1}^{p} a_i + \sum_{j=1}^{m} b_j - \sum_{j=m+1}^{q} b_j.$$

Additionally, set

$$c^* := m + n - \frac{p+q}{2}.$$

In the critical cases, we need to use the following two parameters:

$$\delta := \prod_{i=1}^{p} \alpha_i^{-\alpha_i} \prod_{j=1}^{q} \beta_j^{\beta_j};$$
$$\mu := \sum_{j=1}^{q} b_j - \sum_{i=1}^{p} a_i + \frac{p-q}{2}$$

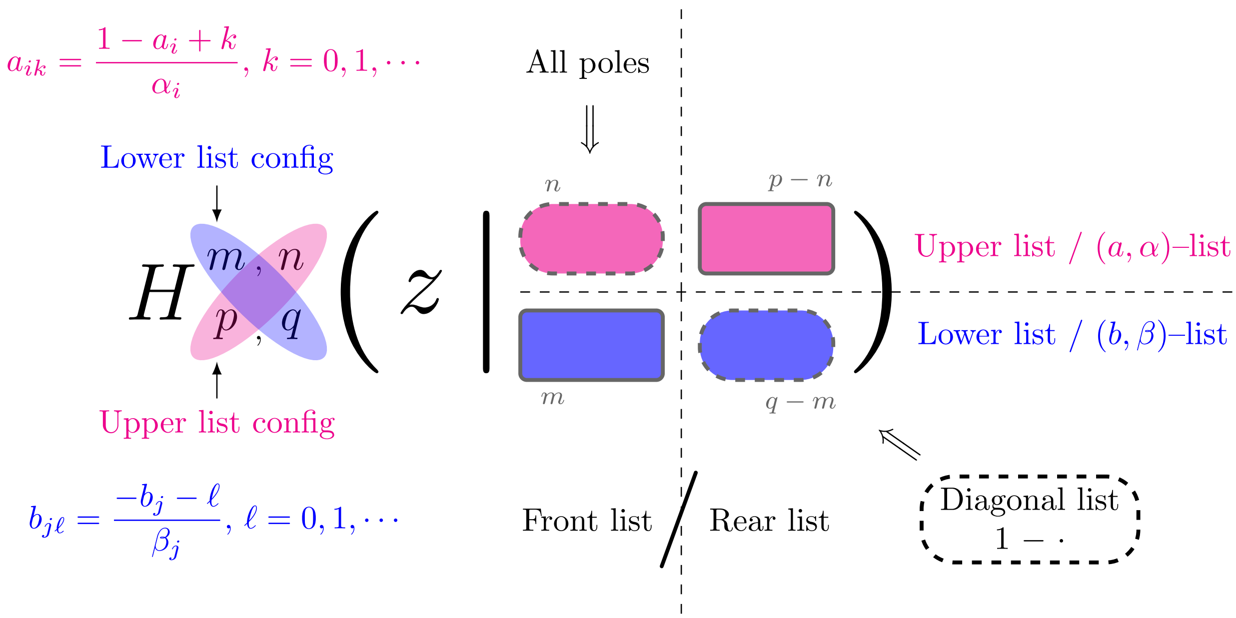


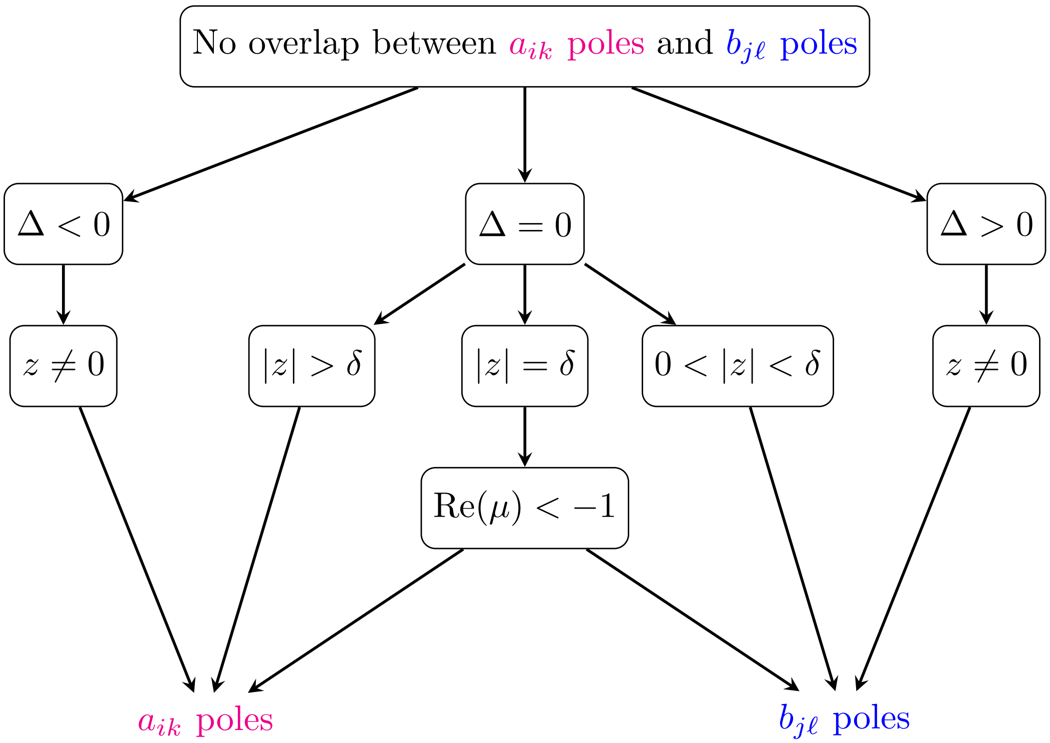
Figure 1: Diagram for the parameterization of the Fox H-function.

The well-posedness of the Fox H-function is given by Theorems 1.1 and 1.2 of [KS], which are summarized in the following figure 2:

2 Examples

2.1 Example `FoxH32-21.wls`

File content



$$H_{p,q}^{m,n}(z) = \sum_{i=1}^{n} \sum_{k=0}^{\infty} \operatorname*{Res}_{s=a_{ik}} \left[\mathcal{H}_{p,q}^{m,n}(s) z^{-s} \right] \qquad H_{p,q}^{m,n}(z) = \sum_{j=1}^{m} \sum_{\ell=0}^{\infty} \operatorname*{Res}_{s=b_{j\ell}} \left[\mathcal{H}_{p,q}^{m,n}(s) z^{-s} \right]$$

Figure 2: Well-posedness of the Fox H-function.

```
{
  (* Upper List *) {
    (* Upper Front List *) {{1, α^(-1)}},
    (* Upper Rear List *)  {{Ceiling[β], β}}
  },
  (* Lower List *) {
    (* Lower Front List *) {{1/2, α/2}, {1, 1}},
    (* Lower Rear List *)  {{1, α/2}}
  }
}
```

Fox H-function

$$H_{2,3}^{2,1}\left(\cdot\;\middle|\;\begin{array}{c}\left(1,\frac{1}{\alpha}\right),(\lceil\beta\rceil,\beta)\\ \\ \left(\frac{1}{2},\frac{\alpha}{2}\right),(1,1),\left(1,\frac{\alpha}{2}\right)\end{array}\right)$$

$$H_{2,3}^{2,1}\left(\cdot\;\middle|\;\begin{array}{c|c}\left(1,\frac{1}{\alpha}\right) & (\lceil\beta\rceil,\beta)\\ \hline \left(\frac{1}{2},\frac{\alpha}{2}\right),(1,1) & \left(1,\frac{\alpha}{2}\right)\end{array}\right)$$

Summary

$$\begin{aligned}
a^* &= \frac{1}{\alpha} - \beta + 1 \\
\Delta &= \alpha - \frac{1}{\alpha} - \beta + 1 \\
\delta &= 2^{-\alpha}\left(\frac{1}{\alpha}\right)^{-1/\alpha}\left(2^{\alpha/2}\alpha^{\alpha/2} + \alpha^{\alpha}\right)\beta^{-\beta} \\
\mu &= 1 - \lceil\beta\rceil \\
a_1^* &= \frac{1}{2}(\alpha - 2\beta + 2) \\
a_2^* &= \frac{1}{\alpha} - \frac{\alpha}{2} \\
\xi &= \frac{3}{2} - \lceil\beta\rceil \\
c^* &= \frac{1}{2}
\end{aligned}$$

Poles 1. First ten poles from upper front list

$$a_{i,k} = \begin{pmatrix} 0 & \alpha & 2\alpha & 3\alpha & 4\alpha & 5\alpha & 6\alpha & 7\alpha & 8\alpha & 9\alpha & 10\alpha \end{pmatrix}$$

2. First ten poles from lower front list

$$b_{j,\ell} = \begin{pmatrix} -\frac{1}{\alpha} & -\frac{3}{\alpha} & -\frac{5}{\alpha} & -\frac{7}{\alpha} & -\frac{9}{\alpha} & -\frac{11}{\alpha} & -\frac{13}{\alpha} & -\frac{15}{\alpha} & -\frac{17}{\alpha} & -\frac{19}{\alpha} & -\frac{21}{\alpha} \\ -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 & -11 \end{pmatrix}$$

2.2 Example `FoxH32-21-Y.wls`

File content

```
{
  (* Upper List *) {
    (* Upper Front List *) {{1, 1}},
    (* Upper Rear List *)  {{β + γ, β}}
  },
  (* Lower List *) {
    (* Lower Front List *) {{d/2, α/2}, {1, 1}},
    (* Lower Rear List *)  {{1, α/2}}
  }
}
```

Fox H-function

$$H_{2,3}^{2,1}\left(\cdot \;\middle|\; \begin{array}{l} (1,1)\,,(\beta+\gamma,\beta) \\ \\ \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1)\,,\left(1,\frac{\alpha}{2}\right) \end{array}\right)$$

$$H_{2,3}^{2,1}\left(\cdot \;\middle|\; \begin{array}{c|c} (1,1) & (\beta+\gamma,\beta) \\ \hline \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1) & \left(1,\frac{\alpha}{2}\right) \end{array}\right)$$

Summary

$$\begin{aligned} a^* &= 2-\beta \\ \Delta &= \alpha-\beta \\ \delta &= 2^{-\alpha}\left(2^{\alpha/2}\alpha^{\alpha/2}+\alpha^{\alpha}\right)\beta^{-\beta} \\ \mu &= \frac{1}{2}(-2\beta-2\gamma+d+1) \\ a_1^* &= \frac{1}{2}(\alpha-2\beta+2) \\ a_2^* &= 1-\frac{\alpha}{2} \\ \xi &= \frac{1}{2}(d-2(\beta+\gamma-1)) \\ c^* &= \frac{1}{2} \end{aligned}$$

Poles 1. First ten poles from upper front list

$$a_{i,k} = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}$$

2. First ten poles from lower front list

$$b_{j,\ell} = \begin{pmatrix} -\frac{d}{\alpha} & -\frac{d+2}{\alpha} & -\frac{d+4}{\alpha} & -\frac{d+6}{\alpha} & -\frac{d+8}{\alpha} & -\frac{d+10}{\alpha} & -\frac{d+12}{\alpha} & -\frac{d+14}{\alpha} & -\frac{d+16}{\alpha} & -\frac{d+18}{\alpha} & -\frac{d+20}{\alpha} \\ -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 & -11 \end{pmatrix}$$

2.3 Example `FoxH32-21-Z.wls`

File content

```
{
  (* Upper List *) {
    (* Upper Front List *) {{1, 1}},
    (* Upper Rear List *)  {{Ceiling[β], β}}
  },
  (* Lower List *) {
    (* Lower Front List *) {{d/2, α/2}, {1, 1}},
    (* Lower Rear List *)  {{1, α/2}}
  }
}
```

Fox H-function

$$H^{2,1}_{2,3}\left(\cdot \;\middle|\; \begin{array}{l} (1,1)\,,(\lceil\beta\rceil,\beta) \\ \\ \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1)\,,\left(1,\frac{\alpha}{2}\right) \end{array} \right)$$

$$H^{2,1}_{2,3}\left(\cdot \;\middle|\; \begin{array}{c|c} (1,1) & (\lceil\beta\rceil,\beta) \\ \hline \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1) & \left(1,\frac{\alpha}{2}\right) \end{array} \right)$$

Summary

$$
\begin{aligned}
a^* &= 2-\beta \\
\Delta &= \alpha-\beta \\
\delta &= 2^{-\alpha}\left(2^{\alpha/2}\alpha^{\alpha/2}+\alpha^{\alpha}\right)\beta^{-\beta} \\
\mu &= \frac{1}{2}(-2\lceil\beta\rceil+d+1) \\
a_1^* &= \frac{1}{2}(\alpha-2\beta+2) \\
a_2^* &= 1-\frac{\alpha}{2} \\
\xi &= \frac{1}{2}(-2\lceil\beta\rceil+d+2) \\
c^* &= \frac{1}{2}
\end{aligned}
$$

Poles 1. First ten poles from upper front list

$$
a_{i,k} = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}
$$

2. First ten poles from lower front list

$$
b_{j,\ell} = \begin{pmatrix} -\frac{d}{\alpha} & -\frac{d+2}{\alpha} & -\frac{d+4}{\alpha} & -\frac{d+6}{\alpha} & -\frac{d+8}{\alpha} & -\frac{d+10}{\alpha} & -\frac{d+12}{\alpha} & -\frac{d+14}{\alpha} & -\frac{d+16}{\alpha} & -\frac{d+18}{\alpha} & -\frac{d+20}{\alpha} \\ -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 & -11 \end{pmatrix}
$$

2.4 Example `FoxH32-21-Z-Star.wls`

File content

```
{
  (* Upper List *) {
    (* Upper Front List *) {{1, 1}},
    (* Upper Rear List *)  {{1, β}}
  },
  (* Lower List *) {
    (* Lower Front List *) {{d/2, α/2}, {1, 1}},
    (* Lower Rear List *)  {{1, α/2}}
  }
}
```

Fox H-function

$$
H_{2,3}^{2,1}\left(\cdot \,\middle|\, \begin{matrix} (1,1)\,,(1,\beta) \\ \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1)\,,\left(1,\frac{\alpha}{2}\right) \end{matrix} \right)
$$

$$H^{2,1}_{2,3}\left(\cdot\,\middle|\,\begin{array}{c|c}(1,1) & (1,\beta)\\ \hline \left(\frac{d}{2},\frac{\alpha}{2}\right),(1,1) & \left(1,\frac{\alpha}{2}\right)\end{array}\right)$$

Summary

$$\begin{aligned}
a^* &= 2-\beta\\
\Delta &= \alpha-\beta\\
\delta &= 2^{-\alpha}\left(2^{\alpha/2}\alpha^{\alpha/2}+\alpha^{\alpha}\right)\beta^{-\beta}\\
\mu &= \frac{d-1}{2}\\
a_1^* &= \frac{1}{2}(\alpha-2\beta+2)\\
a_2^* &= 1-\frac{\alpha}{2}\\
\xi &= \frac{d}{2}\\
c^* &= \frac{1}{2}
\end{aligned}$$

Poles **1. First ten poles from upper front list**

$$a_{i,k}=\begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}$$

2. First ten poles from lower front list

$$b_{j,\ell}=\begin{pmatrix} -\frac{d}{\alpha} & -\frac{d+2}{\alpha} & -\frac{d+4}{\alpha} & -\frac{d+6}{\alpha} & -\frac{d+8}{\alpha} & -\frac{d+10}{\alpha} & -\frac{d+12}{\alpha} & -\frac{d+14}{\alpha} & -\frac{d+16}{\alpha} & -\frac{d+18}{\alpha} & -\frac{d+20}{\alpha}\\ -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 & -11 \end{pmatrix}$$

2.5 Example `FoxH-Sin.wls`

File content

```
(* (2.9.7) and (2.9.9) of Kilbas & Saigo 04 *)
{
  (* Upper List *) {
    (* Upper Front List *) {},
    (* Upper Rear List *)  {}
  },
  (* Lower List *) {
    (* Lower Front List *) {{1/2, 1}},
    (* Lower Rear List *)  {{0, 1}}
  }
}
```

Fox H-function

$$H_{0,2}^{1,0}\left(\cdot \;\middle|\; \begin{matrix} \\ \left(\frac{1}{2},1\right),(0,1) \end{matrix}\right)$$

$$H_{0,2}^{1,0}\left(\cdot \;\middle|\; \begin{array}{c|c} & \\ \hline \left(\frac{1}{2},1\right) & (0,1) \end{array}\right)$$

Summary

$$\begin{aligned} a^* &= 0 \\ \Delta &= 2 \\ \delta &= \text{ComplexInfinity} \\ \mu &= -\frac{1}{2} \\ a_1^* &= 1 \\ a_2^* &= -1 \\ \xi &= \frac{1}{2} \\ c^* &= 0 \end{aligned}$$

Poles **1. First ten poles from upper front list**

$$a_{i,k} = \{\}$$

2. First ten poles from lower front list

$$b_{j,\ell} = \begin{pmatrix} -\frac{1}{2} & -\frac{3}{2} & -\frac{5}{2} & -\frac{7}{2} & -\frac{9}{2} & -\frac{11}{2} & -\frac{13}{2} & -\frac{15}{2} & -\frac{17}{2} & -\frac{19}{2} & -\frac{21}{2} \end{pmatrix}$$

2.6 Example `FoxH-Cos.wls`

File content

```
(* (2.9.8) and (2.9.10) of Kilbas & Saigo 04 *)
{
  (* Upper List *) {
    (* Upper Front List *) {},
    (* Upper Rear List *)  {}
  },
  (* Lower List *) {
    (* Lower Front List *) {{0, 1}},
    (* Lower Rear List *)  {{1/2,1}}
  }
}
```

Fox H-function

$$H_{0,2}^{1,0}\left(\cdot \,\middle|\, \begin{matrix} \\ (0,1),\left(\frac{1}{2},1\right) \end{matrix}\right)$$

$$H_{0,2}^{1,0}\left(\cdot \,\middle|\, \begin{array}{c|c} & \\ \hline (0,1) & \left(\frac{1}{2},1\right) \end{array}\right)$$

Summary

$$\begin{aligned} a^* &= 0 \\ \Delta &= 2 \\ \delta &= \text{ComplexInfinity} \\ \mu &= -\frac{1}{2} \\ a_1^* &= 1 \\ a_2^* &= -1 \\ \xi &= -\frac{1}{2} \\ c^* &= 0 \end{aligned}$$

Poles 1. First ten poles from upper front list

$$a_{i,k} = \{\}$$

2. First ten poles from lower front list

$$b_{j,\ell} = \begin{pmatrix} 0 & -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 \end{pmatrix}$$

2.7 Example `FoxH-Mittag-Leffler.wls`

File content

```
(* (2.9.27) of Kilbas and Saigo 04 *)
{
  (* Upper List *) {
    (* Upper Front List *) {{0, 1}},
    (* Upper Rear List *)  {}
  },
  (* Lower List *) {
    (* Lower Front List *) {{0, 1}},
    (* Lower Rear List *)  {{1 - μ, ρ}}
  }
}
```

Fox H-function

$$H_{1,2}^{1,1}\left(\cdot\ \middle|\ \begin{array}{l}(0,1)\\ \\ (0,1)\,,(1-\mu,\rho)\end{array}\right)$$

$$H_{1,2}^{1,1}\left(\cdot\ \middle|\ \begin{array}{c|c}(0,1) & \\ \hline (0,1) & (1-\mu,\rho)\end{array}\right)$$

Summary

$$\begin{aligned}
a^* &= 2-\rho\\
\Delta &= \rho\\
\delta &= \text{ComplexInfinity}\\
\mu &= \frac{1}{2}-\mu\\
a_1^* &= 1\\
a_2^* &= 1-\rho\\
\xi &= \mu-1\\
c^* &= \frac{1}{2}
\end{aligned}$$

Poles **1. First ten poles from upper front list**

$$a_{i,k}=\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \end{pmatrix}$$

2. First ten poles from lower front list

$$b_{j,\ell}=\begin{pmatrix} 0 & -1 & -2 & -3 & -4 & -5 & -6 & -7 & -8 & -9 & -10 \end{pmatrix}$$

References

[Fox61] Charles Fox. The G and H functions as symmetrical Fourier kernels. *Trans. Amer. Math. Soc.*, 98:395–429, 1961.

[KS] Anatoly A. Kilbas and Megumi Saigo. *H-transforms*, volume 9 of *Analytical Methods and Special Functions*. Chapman & Hall/CRC, Boca Raton, FL. Theory and applications.