Some symbolic tools for the Fox H-function

Le Chen

Department of Maathematics and Statistics

Auburn University

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

November 12, 2023

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

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

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

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

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

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

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, let's denote (following p. 2 of [KS])

$$\begin{aligned} a^* &:= \sum_{i=1}^{n} \alpha_i - \sum_{i=n+1}^{p} \alpha_i + \sum_{j=1}^{m} \beta_j - \sum_{j=m+1}^{q} \beta_j; \\ \Delta &:= \sum_{j=1}^{q} \beta_j - \sum_{i=1}^{p} \alpha_i \\ \delta &:= \prod_{n=1}^{\infty} \cdots \end{aligned}$$

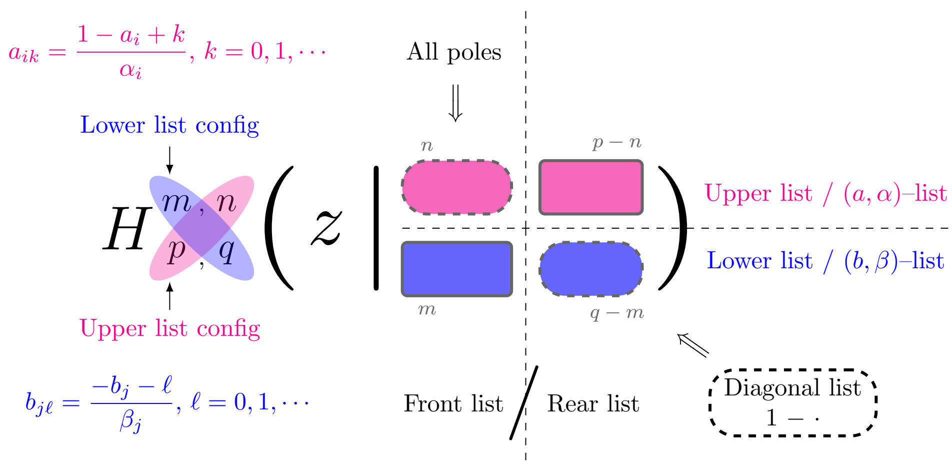

Figure 1: Diagram for the parameterization of the Fox H-function.

1 Example `FoxH32-21.wls`

File content

```
{
  (* 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5 Example `FoxH-Cos.wls`

File content

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

Fox H-function

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

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

Summary

$$a^* = 0$$
$$\Delta = -1$$
$$\delta = 0$$
$$\mu = -\frac{1}{2}$$
$$a_1^* = -\frac{1}{2}$$
$$a_2^* = \frac{1}{2}$$
$$\xi = \frac{1}{2}$$
$$c^* = 0$$

Poles 1. First ten poles from upper front list

$$a_{i,k} = \begin{pmatrix} 0 \\ 2 \\ 4 \\ 6 \\ 8 \\ 10 \\ 12 \\ 14 \\ 16 \\ 18 \\ 20 \end{pmatrix}$$

2. First ten poles from lower front list

$$b_{j,\ell} = \{\{\},\{\},\{\},\{\},\{\},\{\},\{\},\{\},\{\},\{\},\{\}\}$$

6 Example **`FoxH-Mittag-Leffler.wls`**

File content

```
{
  (* 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

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

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

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

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

7 Example `FoxH-Sin.wls`

File content

```
{
  (* Upper List *) {
    (* Upper Front List *) {},
    (* Upper Rear List *)  {}
  },
  (* Lower List *) {
    (* Lower Front List *) {{1/2, 1}},
    (* Lower Rear List *)  {{0, 1}}
  }
}
```

Fox H-function

$$H^{1,0}_{0,2}\left(\cdot \,\middle|\, \begin{array}{c} \\ \left(\tfrac{1}{2},1\right),(0,1) \end{array} \right)$$

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

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

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

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.