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# Hardy Z Software Program

## 5.1 Introduction

The contents of this section is more fully discussed in my book, *A Study of Riemann's Zeta Function*, Terrence P. Murphy.

The Hardy Z function,  $Z(t)$ , greatly simplifies the location of zeros of  $\zeta(s)$  (the zeta function) on the critical line ( $Re(s) = \frac{1}{2}$ ). We have

$$Z(t) = \zeta\left(\frac{1}{2} + it\right) e^{i\theta(t)},$$

where  $\theta(t)$  is given by the estimate

$$\theta(t) \approx \frac{t}{2} \log \frac{t}{2\pi} - \frac{\pi}{8} - \frac{t}{2} + \frac{1}{48t} + \frac{7}{5760t^3}.$$

The error in the approximation of  $\theta(t)$  is less than a very small fraction of the  $t^{-3}$  term and therefore approaches zero very rapidly for increasing  $t$ .

For  $t$  real,  $|Z(t)| = \left| \zeta\left(\frac{1}{2} + it\right) \right|$ . Thus,  $Z(t) = 0$  if and only if  $\zeta\left(\frac{1}{2} + it\right) = 0$ . Also, for  $t$  real,  $Z(t)$  is real. With  $Z(t)$  a smooth function along the critical line, that means that  $Z(t) = 0$  only if  $Z(t)$  changes sign in the immediate neighborhood of that zero.

Thus, the task of finding zeros of the zeta function on the critical line is reduced to finding sign changes of Hardy's  $Z$  function. In the simplest case, we know that one or more zeta zeros must exist *somewhere* in an interval on the critical line if  $Z(t)$  has different signs at the interval end points.

More often, the goal is to find zeta zeros with great accuracy. For that, we must estimate  $Z(t)$  efficiently and with a minimal error term. The Riemann-Siegel Formula provides a remarkably accurate and efficient method of computing  $Z(t)$ . For a given  $t$ , the Riemann-Siegel Formula requires just  $\mathcal{O}(t^{1/2})$  computation steps. We describe that formula next.

Fix any  $t > 0$  and let  $T = (t/2\pi)^{1/2}$ . Let  $N = [T]$  and  $p = \{T\}$  be the integral and fractional parts of  $T$ . Then, for the "main term"  $M(t)$

$$M(t) = 2 \sum_{n=1}^N n^{-1/2} \cos [\theta(t) - t \log n],$$

we have

$$Z(t) = M(t) + R,$$

where  $R$  is called the "remainder term". The Riemann Siegel Formula gives the following estimate:

$$R \approx R(K) = (-1)^{N-1} \left(\frac{t}{2\pi}\right)^{-1/4} \left[ \sum_{j=0}^K C_j \left(\frac{t}{2\pi}\right)^{-j/2} \right] \quad (K \in \mathbb{N}).$$

For  $K = 4$ , the five  $C_j$  terms are

$$\begin{aligned}
C_0 &= \Psi(p) = \frac{\cos[2\pi(p^2 - p - 1/16)]}{\cos(2\pi p)} \\
C_1 &= -\frac{\Psi^{(3)}(p)}{96\pi^2} \\
C_2 &= \frac{\Psi^{(6)}(p)}{18,432\pi^4} + \frac{\Psi^{(2)}(p)}{64\pi^2} \\
C_3 &= -\frac{\Psi^{(9)}(p)}{5,308,416\pi^6} - \frac{\Psi^{(5)}(p)}{3,840\pi^4} - \frac{\Psi^{(1)}(p)}{64\pi^2} \\
C_4 &= \frac{\Psi^{(12)}(p)}{2,038,431,744\pi^8} + \frac{11 \cdot \Psi^{(8)}(p)}{5,898,240\pi^6} - \frac{19 \cdot \Psi^{(4)}(p)}{24,676\pi^4} + \frac{\Psi(p)}{128\pi^2}.
\end{aligned}$$

It turns out the  $C_j$  terms are entire functions that can be expressed as power series. In our program, we use a table of power series coefficients developed by Gabcke (accurate to 50 decimal places) – an improvement on the coefficients developed by Haselgrove and shown in our book (accurate to 20 or less decimal places). With the Gabcke coefficients, we can compute the remainder term  $R(4)$  with great accuracy. Considering only the mathematical theory discussed above, the error in the approximation of  $Z(t)$  given by  $Z(t) = M(t) + R(4)$  is  $\leq |0.017t^{-11/4}|$  for  $t > 200$ .

Of course, the mathematical theory above does not account for the errors introduced by the real world of floating point calculations. For  $N$  as defined above,  $M(t)$  requires  $N$  floating point calculations of square root, cosine and logarithm, with associated sums and products. For larger  $t$  (and therefore larger  $N$ ), this requires a large number of quite accurate floating point calculations. We discuss further below the C compiler and specialized floating point library used in our program.

With our current compiler and environment, the results seem to be accurate to 5 decimal digits for  $t \leq 200$ , to at least 6 decimal digits for  $t > 200$ , to at least 10 decimal digits for  $t > 1000$ , to at least 12 decimal digits for  $t > 10,000$ , and to at least 28 decimal digits for  $t > 10,000,000,000$ . As you see, as  $t$  increases the accuracy increases.

## 5.2 Compiler Setup on Windows

We are using the gcc/mingw-64 C compiler on Windows 11, with the MPFR library (a C library for multiple-precision floating-point computations, with user-selectable precision and correct rounding). Our program runs with default floating point precision set to 256 bits (typically, a **double** floating point type in C has 64 bits).

We briefly discuss here how we installed the **gcc** compiler and the MPFR floating point library on our Windows system. If you do not have a Windows 10 or 11 system, a different setup will be needed. If you Google **gcc C compiler** and **MPFR library**, along with your computer system, you should find installation instructions.

**The following is to the best of my recollection. I make no warranties on any of the steps, methods or programs described below. Proceed at your own risk.**

- (1) Download the GUI installer from [www.msys2.org](http://www.msys2.org).
- (2) Run the installer. The GUI will ask for an install folder. The default of `c:\msys64` should be accepted.
- (3) When done, click Finish on the GUI.
- (4) A Unix-style terminal will now launch – all installations are done inside that terminal. Install the **gcc** compiler and a pre-selected group of supporting libraries (including MPFR) using the **pacman** installer program as follows.

```
pacman -S mingw-w64-ucrt-x86_64-toolchain
```

- (5) After the needed files are downloaded, respond 'Y' to "Proceed with installation".
- (6) When completed, exit the terminal (click the 'X' in the upper-right corner of the terminal, or type exit).
- (7) Next, you need to add `c:\msys64\ucrt64\bin` to your Windows (user) PATH. To do that, just Google how to add a directory to your PATH.
- (8) Now verify **gcc** was installed by typing the following at the Windows command prompt:

```
gcc --version
```

- (9) If a **gcc** version number is displayed (mine was 14.1.0), the installation is complete.

## 5.3 Making the Hardy Z Program on Windows

Once the compiler installation is complete, you can make the HardyZ.exe program.

- (1) Create a new directory `gcc` under your Documents directory. Then create a new directory `HardyZ` under the `gcc` directory. You then have: `Documents\gcc\HardyZ`.
- (2) Copy `hardyz.c`, `hardyz.h`, `computemain.c`, `computetheta.c`, `remainderMPFR.c`, `buildcoeff.c` and `makehardyz.bat` to the newly created `HardyZ` directory.
- (3) Open the Command prompt, change directory to `Documents\gcc\HardyZ` and run the `makehardyz.bat` batch file. The `hardyz.exe` program will be ready for use.

## 5.4 Using the Hardy Z Program

Our program is a command line program that takes the following command line parameters:



## 5.6 The Source Code for the Hardy Z Program

### 5.6.1 `hardyz.c`

This source code file is quite straightforward. We validate the user's command line input, save their choices and call the `ComputeAllHardyZ` function.

### 5.6.2 `remainderMPFR.c`

See the discussion above about the “remainder” term  $R$  in computing Hardy Z values. In our code, we call the `ComputeRemainderMPFR` function to compute the  $R(4)$  approximation of  $R$ . We use the Gabcke table of power series coefficients for the  $C_0$  through  $C_4$  terms.

In this source code file, we use the MPFR library (set to 256-bit by default and changeable by the “-b” command line parameter) for all floating point calculations.

### 5.6.3 `buildcoeff.c`

As part of the initialization process for the MPFR floating point system, we build an MPFR version of the Gabcke coefficients.

### 5.6.4 `computetheta.c`

This source code file uses the MPFR floating point library to compute the  $\theta(t)$  (theta) term in the Riemann-Siegel Formula.

### 5.6.5 `computemain.c`

This source code file is “central control” for computing the Hardy Z values. The `ComputeAllHardyZ` function is the entry point. In that function, we

- (1) Initialize the MPFR floating point system.
- (2) Begin the loop computing Hardy Z values. If no “-c” command line parameter is entered, the loop ends after the first Hardy Z computation. Otherwise we loop the number of times requested in the “-c” command line parameter. After each loop iteration, we increment  $t$  by either 1 (the default value) or the amount requested in the “-i” command line parameter.
- (3) Inside the loop, we: (1) compute the  $N$  and  $p$  variables of the Riemann-Siegel Formula, (2) call the `ComputeRemainderMPFR` function to compute the  $R(4)$  approximated remainder term, (3) call the `ComputeMain` function to compute the main term, and (4) print the results to **stdout**.
- (4) Also inside the loop, if the user has requested the use of multiple threads via the “-k” command line parameter, we compute each Hardy Z value in an assigned thread.
- (5) After exiting the loop, we close down the MPFR system.

As mentioned above, in the `ComputeMain` function we compute the “main” term of the Riemann-Siegel formula. In that function, we

- (1) Using the passed parameter  $t$ , compute  $\theta(t)$ .
- (2) Using the passed parameter  $N$ , loop  $n = 1$  to  $N$  times, computing  $n^{-1/2} \cos [\theta(t) - t \log n]$  in each loop and summing those computed values in a `Main` variable.
- (3) At the end of the loop, multiply the `Main` variable by 2 and return that result.

For the  $n$ th argument of cosine in the above formula, let  $A(n) = \theta(t) - t \log n$ . There are multiple choices for calculating  $A(n)$ . We use the following idea in our approach

$$\begin{aligned} A(n) - A(n-1) &= [\theta(t) - t \log n] - [\theta(t) - t \log(n-1)] \\ &= t \log(n-1) - t \log n = t [\log(n-1) - \log(n)] \\ A(n) &= A(n-1) + t [\log(n-1) - \log(n)]. \end{aligned}$$

Note that  $[\log(n-1) - \log(n)]$  is a very small negative number that gets smaller as  $n$  gets larger. When multiplied by  $t$ , the product is therefore much smaller than  $t$ . The alternative, computing  $t \log n$  (for larger  $n$ ) will produce a product much larger than  $t$ . Our approach keep an intermediate variable smaller than  $t$ , which *may* have accuracy benefits in our floating point calculations. To test the standard calculation method (i.e., computing  $t \log n$ ), use the “-d” command line parameter, setting the value to any positive integer  $\leq 30,030$  that is evenly divisible by 7.

We keep intermediate variables smaller in one other way. Before passing  $A(n)$  to the cosine function, we use the `mpfr_fmod` function to set  $A(n)$  to the remainder obtained by dividing  $A(n)$  by  $2\pi$ . This is justified because the cosine function is  $2\pi$  periodic. No doubt, the `mpfr_cos` function will otherwise do the same thing. To bypass using the `mpfr_fmod` function, use the “-d” command line parameter, setting the value to any positive integer  $\leq 30,030$  that is evenly divisible by 5.

## 5.7 Performance of the Hardy Z Program

To give a general idea of the performance of the Hardy Z program, I will list the time it takes on my computer to do several different calculations. My computer is a Windows 11 computer, with an Intel Core i7-14700 (2.10 Ghz) processor and 32.0 GB of memory.

t	Count	Increment	MPFR bits	Threads	Time (Seconds)
1,234.5678	10	0.10	256	1	0.005
1,234.5678	100	0.10	256	1	0.042
9,871,234.5678	10	0.10	256	1	0.090
9,871,234.5678	10	0.10	<b>512</b>	1	0.133
9,871,234.5678	100	0.10	256	1	0.881
6,789,871,234.5678	10	0.10	256	1	2.325
6,789,871,234.5678	10	0.10	<b>512</b>	1	3.178
6,789,871,234.5678	100	0.10	256	1	22.90
416,789,871,234.5678	10	0.10	256	1	16.34
416,789,871,234.5678	8	0.10	256	1	13.01
416,789,871,234.5678	8	0.10	256	8	1.717

Consider the last  $t$  number above. A single calculation of the “main” term (i.e., Count = 1) involves  $N$  iterations through a loop computing  $n^{-1/2} \cos [\theta(t) - t \log n]$  where  $N = 256,554$ .

In my limited testing, I have not seen differences when comparing the ”-b 256” results (MPFR bits) with the ”-b 512” results until you get past at least 60 decimal places.

## 5.8 Other Notes

I should mention that the **gcc** compiler is licensed from Free Software Foundation, Inc. The license is described at:

<https://gcc.gnu.org/onlinedocs/libstdc++/manual/license.html>

The (also generous) license for the MPFR floating point software is shown at:

<https://www.mpfr.org/>