# Yunfan Yang 30067857

<https://gitlab.cpsc.ucalgary.ca/yunfan.yang/cpsc-501-assignment-2/>

The access to this repository has been granted to the TA and the professor. Please let me know if it is not working by sending email to [yunfan.yang1@ucalgary.ca](mailto:yunfan.yang1@ucalgary.ca) so I can fix. :)

Graphical user interface, text, application, email

Description automatically generated

## Report

Part 1. Baseline Program + Optimizations

Part 2. Bonus Stereo Handling + Extra Optimization

## Compile and Run

For VS Code, the build task is configured. Press Ctrl+Shift+B or click Terminal > Run Build Task to compile the code. In terminal, enter the following command to compile:

g++ -O2 -pg -g convolve.cpp -o convolve

To run, follow the following format:

./convolve <input file name.wav> <IR file name.wav> <output file name.wav>

# Baseline Program

Commit: **8f6c17**866033a1326ec17acbe77a0a517f328efa

This is the baseline version of the program. It implements: read and write wave file, convolution with O(n^2) time complexity multiplication algorithm.

The full audio takes a really long time to convolute, in total of 407.87 seconds = 6.7 minutes. And the most time is spent on convolution function.

## Profiling

guitar\_dry.wav

% cumulative self self total

time seconds seconds calls s/call s/call name

100.00 407.87 407.87 1 **407.87** 407.87 convolution(WaveFile, WaveFile)

0.00 407.88 0.01 1 0.01 0.01 WaveFile::writeData()

0.00 407.88 0.00 12 0.00 0.00 WaveFile::nextIntLSB()

0.00 407.88 0.00 8 0.00 0.00 WaveFile::nextShortLSB()

0.00 407.88 0.00 5 0.00 0.00 WaveFile::nextIntLSB(int)

0.00 407.88 0.00 5 0.00 0.00 WaveFile::~WaveFile()

0.00 407.88 0.00 4 0.00 0.00 WaveFile::nextShortLSB(short)

0.00 407.88 0.00 3 0.00 0.00 WaveFile::WaveFile()

0.00 407.88 0.00 2 0.00 0.00 WaveFile::readHeader()

0.00 407.88 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 407.88 0.00 2 0.00 0.00 WaveFile::readData()

0.00 407.88 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 407.88 0.00 1 0.00 0.00 WaveFile::writeHeader()

0.00 **407.88** 0.00 1 0.00 0.01 WaveFile::write(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

## Comparison with sample output

Graphical user interface

Description automatically generated with medium confidence

The above is a comparison graph of the provided sample output on D2L with the output from my program. The files are highly identical (99.13%), and should sound no difference by human hearing.

# Algorithmic Optimization: FFT Program

Commit: **c9fc0d**2c8a3854b44c11a52c5684a7c9c77c09c6

This is the optimized version of convolution algorithm, using Fast Fourier Transform to achieve O(n log n) time complexity.

The code is referenced from: [Fast Fourier transform - Rosetta Code](https://rosettacode.org/wiki/Fast_Fourier_transform#C.2B.2B) and <https://stackoverflow.com/questions/466204/rounding-up-to-next-power-of-2>.

It implements: find the next closest n^2 number: **upper\_power\_of\_two**, **fft** and **ifft**. Updated the convolution function adapting new fft and ifft functions.

The time for the most time-spending part is changed from **convolution** to **fft**, and the time is reduced from 407 seconds (~6.7 min) to 1.92 seconds, which is a significant improvement. And the total timing is 5.92 seconds.

Since the most time-consuming part is **fft**, the following optimizations are mainly focusing on this function.

Text

Description automatically generatedA screenshot of a computer

Description automatically generated with medium confidenceText

Description automatically generated

## Profiling

guitar\_dry.wav

% cumulative self self total

time seconds seconds calls s/call s/call name

33.78 2.00 2.00 3 0.67 **1.92** fft(std::valarray<std::complex<double> >&)

8.78 2.52 0.52 134217728 0.00 0.00 std::complex<double>& std::complex<double>::operator\*=<double>(std::complex<double> const&)

8.45 3.02 0.50 136314884 0.00 0.00 std::complex<double>::complex(double, double)

7.60 3.47 0.45 132120576 0.00 0.00 std::complex<double> std::polar<double>(double const&, double const&)

5.24 3.78 0.31 274505830 0.00 0.00 std::complex<double>::real[abi:cxx11]() const

4.56 4.05 0.27 12582906 0.00 0.00 void std::\_\_valarray\_copy\_construct<std::complex<double> >(std::complex<double> const\*, unsigned int, unsigned int, std::complex<double>\*)

4.05 4.29 0.24 400113869 0.00 0.00 std::valarray<std::complex<double> >::operator[](unsigned int)

3.89 4.52 0.23 272629760 0.00 0.00 std::complex<double>::imag[abi:cxx11]() const

3.38 4.72 0.20 66060288 0.00 0.00 std::complex<double> std::operator-<double>(std::complex<double> const&, std::complex<double> const&)

2.87 4.89 0.17 66060288 0.00 0.00 std::complex<double> std::operator+<double>(std::complex<double> const&, std::complex<double> const&)

2.70 5.05 0.16 66060288 0.00 0.00 std::complex<double>& std::complex<double>::operator-=<double>(std::complex<double> const&)

2.53 5.20 0.15 134217728 0.00 0.00 std::complex<double> std::operator\*<double>(std::complex<double> const&, std::complex<double> const&)

1.86 5.31 0.11 12582912 0.00 0.00 void std::\_\_valarray\_destroy\_elements<std::complex<double> >(std::complex<double>\*, std::complex<double>\*)

1.52 5.40 0.09 66060288 0.00 0.00 std::complex<double>& std::complex<double>::operator+=<double>(std::complex<double> const&)

1.18 5.47 0.07 37748722 0.00 0.00 std::\_Array<std::complex<double> >::\_Array(std::complex<double>\*)

1.01 5.53 0.06 138412032 0.00 0.00 operator new(unsigned int, void\*)

0.84 5.58 0.05 12582906 0.00 0.00 std::slice\_array<std::complex<double> >::slice\_array(std::\_Array<std::complex<double> >, std::slice const&)

0.84 5.63 0.05 12582906 0.00 0.00 std::valarray<std::complex<double> >::operator[](std::slice)

0.51 5.66 0.03 12582913 0.00 0.00 std::valarray<std::complex<double> >::size() const

0.51 5.69 0.03 12582906 0.00 0.00 std::slice::start() const

0.34 5.71 0.02 12582912 0.00 0.00 std::\_\_valarray\_release\_memory(void\*)

0.34 5.73 0.02 12582909 0.00 0.00 std::valarray<std::complex<double> >::~valarray()

0.34 5.75 0.02 12582909 0.00 0.00 std::complex<double>\* restrict std::\_\_valarray\_get\_storage<std::complex<double> >(unsigned int)

0.34 5.77 0.02 12582906 0.00 0.00 std::slice::size() const

0.34 5.79 0.02 12582906 0.00 0.00 std::slice::slice(unsigned int, unsigned int, unsigned int)

0.34 5.81 0.02 12582906 0.00 0.00 std::valarray<std::complex<double> >::valarray(std::slice\_array<std::complex<double> > const&)

0.34 5.83 0.02 2097152 0.00 0.00 std::complex<double>& std::complex<double>::operator/=<double>(std::complex<double> const&)

0.34 5.85 0.02 3 0.01 0.01 std::\_Array\_init\_ctor<std::complex<double>, false>::\_S\_do\_it(std::complex<double>\*, std::complex<double>\*, std::complex<double>)

0.34 5.87 0.02 2 0.01 0.02 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.17 5.88 0.01 1876071 0.00 0.00 std::complex<double>::operator=(double)

0.17 5.89 0.01 1 0.01 0.01 WaveFile::writeData()

0.17 5.90 0.01 1 0.01 0.02 void std::\_\_valarray\_copy<std::complex<double>, std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > >(std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.17 5.91 0.01 operator delete(void\*)

0.17 5.92 0.01 cos

0.00 5.92 0.00 12582909 0.00 0.00 std::\_\_valarray\_get\_memory(unsigned int)

0.00 5.92 0.00 12582906 0.00 0.00 std::slice::stride() const

0.00 5.92 0.00 12582906 0.00 0.00 std::\_Array<std::complex<double> >::begin() const

0.00 5.92 0.00 12582906 0.00 0.00 void std::\_\_valarray\_copy\_construct<std::complex<double> >(std::\_Array<std::complex<double> >, unsigned int, unsigned int, std::\_Array<std::complex<double> >)

0.00 5.92 0.00 8388608 0.00 0.00 std::valarray<std::complex<double> >::operator[](unsigned int) const

0.00 5.92 0.00 4194304 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::operator[](unsigned int) const

0.00 5.92 0.00 4194304 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::operator[](unsigned int) const

0.00 5.92 0.00 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

0.00 5.92 0.00 2097152 0.00 0.00 std::complex<double> std::\_\_multiplies::operator()<std::complex<double> >(std::complex<double> const&, std::complex<double> const&) const

0.00 5.92 0.00 2097152 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::operator[](unsigned int) const

0.00 5.92 0.00 2097152 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::operator[](unsigned int) const

0.00 5.92 0.00 12 0.00 0.00 WaveFile::nextIntLSB()

0.00 5.92 0.00 8 0.00 0.00 WaveFile::nextShortLSB()

0.00 5.92 0.00 5 0.00 0.00 WaveFile::nextIntLSB(int)

0.00 5.92 0.00 5 0.00 0.00 WaveFile::~WaveFile()

0.00 5.92 0.00 4 0.00 0.00 WaveFile::nextShortLSB(short)

0.00 5.92 0.00 3 0.00 0.00 WaveFile::WaveFile()

0.00 5.92 0.00 3 0.00 0.01 std::valarray<std::complex<double> >::resize(unsigned int, std::complex<double>)

0.00 5.92 0.00 3 0.00 0.00 std::valarray<std::complex<double> >::valarray()

0.00 5.92 0.00 3 0.00 0.01 void std::\_\_valarray\_fill\_construct<std::complex<double> >(std::complex<double>\*, std::complex<double>\*, std::complex<double>)

0.00 5.92 0.00 2 0.00 0.00 WaveFile::readHeader()

0.00 5.92 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 5.92 0.00 2 0.00 0.00 WaveFile::readData()

0.00 5.92 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 5.92 0.00 2 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::size() const

0.00 5.92 0.00 2 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::size() const

0.00 5.92 0.00 2 0.00 0.00 std::valarray<std::complex<double> >::apply(std::complex<double> (\*)(std::complex<double> const&)) const

0.00 5.92 0.00 2 0.00 0.00 std::\_RefFunClos<std::\_ValArray, std::complex<double> >::\_RefFunClos(std::valarray<std::complex<double> > const&, std::complex<double> (\*)(std::complex<double> const&))

0.00 5.92 0.00 2 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::\_Expr(std::\_RefFunClos<std::\_ValArray, std::complex<double> > const&)

0.00 5.92 0.00 2 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::\_FunBase(std::valarray<std::complex<double> > const&, std::complex<double> (\*)(std::complex<double> const&))

0.00 5.92 0.00 2 0.00 0.02 std::valarray<std::complex<double> >& std::valarray<std::complex<double> >::operator=<std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&)

0.00 5.92 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 5.92 0.00 1 0.00 0.00 upper\_power\_of\_two(unsigned long)

0.00 5.92 0.00 1 0.00 1.99 ifft(std::valarray<std::complex<double> >&)

0.00 5.92 0.00 1 0.00 0.00 WaveFile::writeHeader()

0.00 5.92 0.00 1 0.00 0.01 WaveFile::write(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 5.92 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::size() const

0.00 5.92 0.00 1 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::size() const

0.00 5.92 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::\_Expr(std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > const&)

0.00 5.92 0.00 1 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::\_BinBase(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

0.00 5.92 0.00 1 0.00 0.00 std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >::\_BinClos(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

0.00 5.92 0.00 1 0.00 0.02 std::valarray<std::complex<double> >& std::valarray<std::complex<double> >::operator=<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > >(std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> > const&)

0.00 5.92 0.00 1 0.00 0.02 std::valarray<std::complex<double> >::operator/=(std::complex<double> const&)

0.00 5.92 0.00 1 0.00 0.02 void std::\_Array\_augmented\_\_\_divides<std::complex<double> >(std::\_Array<std::complex<double> >, unsigned int, std::complex<double> const&)

0.00 **5.92** 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::\_\_fun<std::\_\_multiplies, std::complex<double> >::result\_type> std::operator\*<std::complex<double> >(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Optimization: Compiler

Commit: **0678ec**b72ed3a312b64431627424332c50eeace9

File: .vscode/tasks.json

In this optimization, the compiler O2 level optimization is applied. In the vscode build task configuration file, the optimization tag **-O2** is added to the command line arguments. When compiling the code, the optimization is applied by the compiler. The new total timing is 5.87 seconds.

Text

Description automatically generated

## Profiling

% cumulative self self total

time seconds seconds calls s/call s/call name

33.05 1.94 1.94 3 0.65 **1.90** fft(std::valarray<std::complex<double> >&)

9.88 2.52 0.58 136314884 0.00 0.00 std::complex<double>::complex(double, double)

8.69 3.03 0.51 132120576 0.00 0.00 std::complex<double> std::polar<double>(double const&, double const&)

8.52 3.53 0.50 274505830 0.00 0.00 std::complex<double>::real[abi:cxx11]() const

6.47 3.91 0.38 134217728 0.00 0.00 std::complex<double>& std::complex<double>::operator\*=<double>(std::complex<double> const&)

5.62 4.24 0.33 400113869 0.00 0.00 std::valarray<std::complex<double> >::operator[](unsigned int)

4.26 4.49 0.25 12582906 0.00 0.00 void std::\_\_valarray\_copy\_construct<std::complex<double> >(std::complex<double> const\*, unsigned int, unsigned int, std::complex<double>\*)

3.75 4.71 0.22 272629760 0.00 0.00 std::complex<double>::imag[abi:cxx11]() const

2.90 4.88 0.17 12582912 0.00 0.00 void std::\_\_valarray\_destroy\_elements<std::complex<double> >(std::complex<double>\*, std::complex<double>\*)

2.73 5.04 0.16 66060288 0.00 0.00 std::complex<double> std::operator+<double>(std::complex<double> const&, std::complex<double> const&)

2.39 5.18 0.14 66060288 0.00 0.00 std::complex<double>& std::complex<double>::operator+=<double>(std::complex<double> const&)

2.21 5.31 0.13 134217728 0.00 0.00 std::complex<double> std::operator\*<double>(std::complex<double> const&, std::complex<double> const&)

1.87 5.42 0.11 66060288 0.00 0.00 std::complex<double>& std::complex<double>::operator-=<double>(std::complex<double> const&)

0.85 5.47 0.05 138412032 0.00 0.00 operator new(unsigned int, void\*)

0.85 5.52 0.05 66060288 0.00 0.00 std::complex<double> std::operator-<double>(std::complex<double> const&, std::complex<double> const&)

0.85 5.57 0.05 12582906 0.00 0.00 std::valarray<std::complex<double> >::valarray(std::slice\_array<std::complex<double> > const&)

0.68 5.61 0.04 12582909 0.00 0.00 std::\_\_valarray\_get\_memory(unsigned int)

0.51 5.64 0.03 12582906 0.00 0.00 std::slice::slice(unsigned int, unsigned int, unsigned int)

0.51 5.67 0.03 sin

0.34 5.69 0.02 37748722 0.00 0.00 std::\_Array<std::complex<double> >::\_Array(std::complex<double>\*)

0.34 5.71 0.02 12582909 0.00 0.00 std::valarray<std::complex<double> >::~valarray()

0.34 5.73 0.02 12582906 0.00 0.00 std::slice::size() const

0.34 5.75 0.02 12582906 0.00 0.00 std::slice\_array<std::complex<double> >::slice\_array(std::\_Array<std::complex<double> >, std::slice const&)

0.34 5.77 0.02 12582906 0.00 0.00 void std::\_\_valarray\_copy\_construct<std::complex<double> >(std::\_Array<std::complex<double> >, unsigned int, unsigned int, std::\_Array<std::complex<double> >)

0.34 5.79 0.02 2097152 0.00 0.00 std::complex<double>& std::complex<double>::operator/=<double>(std::complex<double> const&)

0.17 5.80 0.01 12582912 0.00 0.00 std::\_\_valarray\_release\_memory(void\*)

0.17 5.81 0.01 12582909 0.00 0.00 std::complex<double>\* restrict std::\_\_valarray\_get\_storage<std::complex<double> >(unsigned int)

0.17 5.82 0.01 12582906 0.00 0.00 std::\_Array<std::complex<double> >::begin() const

0.17 5.83 0.01 4194304 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::operator[](unsigned int) const

0.17 5.84 0.01 2097152 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::operator[](unsigned int) const

0.17 5.85 0.01 1 0.01 0.01 WaveFile::writeData()

0.17 5.86 0.01 operator delete(void\*)

0.17 5.87 0.01 cos

0.00 5.87 0.00 12582913 0.00 0.00 std::valarray<std::complex<double> >::size() const

0.00 5.87 0.00 12582906 0.00 0.00 std::slice::start() const

0.00 5.87 0.00 12582906 0.00 0.00 std::slice::stride() const

0.00 5.87 0.00 12582906 0.00 0.00 std::valarray<std::complex<double> >::operator[](std::slice)

0.00 5.87 0.00 8388608 0.00 0.00 std::valarray<std::complex<double> >::operator[](unsigned int) const

0.00 5.87 0.00 4194304 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::operator[](unsigned int) const

0.00 5.87 0.00 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

0.00 5.87 0.00 2097152 0.00 0.00 std::complex<double> std::\_\_multiplies::operator()<std::complex<double> >(std::complex<double> const&, std::complex<double> const&) const

0.00 5.87 0.00 2097152 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::operator[](unsigned int) const

0.00 5.87 0.00 1876071 0.00 0.00 std::complex<double>::operator=(double)

0.00 5.87 0.00 12 0.00 0.00 WaveFile::nextIntLSB()

0.00 5.87 0.00 8 0.00 0.00 WaveFile::nextShortLSB()

0.00 5.87 0.00 5 0.00 0.00 WaveFile::nextIntLSB(int)

0.00 5.87 0.00 5 0.00 0.00 WaveFile::~WaveFile()

0.00 5.87 0.00 4 0.00 0.00 WaveFile::nextShortLSB(short)

0.00 5.87 0.00 3 0.00 0.00 WaveFile::WaveFile()

0.00 5.87 0.00 3 0.00 0.00 std::\_Array\_init\_ctor<std::complex<double>, false>::\_S\_do\_it(std::complex<double>\*, std::complex<double>\*, std::complex<double>)

0.00 5.87 0.00 3 0.00 0.00 std::valarray<std::complex<double> >::resize(unsigned int, std::complex<double>)

0.00 5.87 0.00 3 0.00 0.00 std::valarray<std::complex<double> >::valarray()

0.00 5.87 0.00 3 0.00 0.00 void std::\_\_valarray\_fill\_construct<std::complex<double> >(std::complex<double>\*, std::complex<double>\*, std::complex<double>)

0.00 5.87 0.00 2 0.00 0.00 WaveFile::readHeader()

0.00 5.87 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 5.87 0.00 2 0.00 0.00 WaveFile::readData()

0.00 5.87 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 5.87 0.00 2 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::size() const

0.00 5.87 0.00 2 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::size() const

0.00 5.87 0.00 2 0.00 0.00 std::valarray<std::complex<double> >::apply(std::complex<double> (\*)(std::complex<double> const&)) const

0.00 5.87 0.00 2 0.00 0.00 std::\_RefFunClos<std::\_ValArray, std::complex<double> >::\_RefFunClos(std::valarray<std::complex<double> > const&, std::complex<double> (\*)(std::complex<double> const&))

0.00 5.87 0.00 2 0.00 0.00 std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> >::\_Expr(std::\_RefFunClos<std::\_ValArray, std::complex<double> > const&)

0.00 5.87 0.00 2 0.00 0.00 std::\_FunBase<std::valarray<std::complex<double> >, std::complex<double> const&>::\_FunBase(std::valarray<std::complex<double> > const&, std::complex<double> (\*)(std::complex<double> const&))

0.00 5.87 0.00 2 0.00 0.02 std::valarray<std::complex<double> >& std::valarray<std::complex<double> >::operator=<std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&)

0.00 5.87 0.00 2 0.00 0.02 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 5.87 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 5.87 0.00 1 0.00 0.00 upper\_power\_of\_two(unsigned long)

0.00 5.87 0.00 1 0.00 1.97 ifft(std::valarray<std::complex<double> >&)

0.00 5.87 0.00 1 0.00 0.00 WaveFile::writeHeader()

0.00 5.87 0.00 1 0.00 0.01 WaveFile::write(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 5.87 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::size() const

0.00 5.87 0.00 1 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::size() const

0.00 5.87 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> >::\_Expr(std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > const&)

0.00 5.87 0.00 1 0.00 0.00 std::\_BinBase<std::\_\_multiplies, std::valarray<std::complex<double> >, std::valarray<std::complex<double> > >::\_BinBase(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

0.00 5.87 0.00 1 0.00 0.00 std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >::\_BinClos(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

0.00 5.87 0.00 1 0.00 0.02 std::valarray<std::complex<double> >& std::valarray<std::complex<double> >::operator=<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > >(std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> > const&)

0.00 5.87 0.00 1 0.00 0.03 std::valarray<std::complex<double> >::operator/=(std::complex<double> const&)

0.00 5.87 0.00 1 0.00 0.02 void std::\_\_valarray\_copy<std::complex<double>, std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> > >(std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 5.87 0.00 1 0.00 0.03 void std::\_Array\_augmented\_\_\_divides<std::complex<double> >(std::\_Array<std::complex<double> >, unsigned int, std::complex<double> const&)

0.00 **5.87** 0.00 1 0.00 0.00 std::\_Expr<std::\_BinClos<std::\_\_multiplies, std::\_ValArray, std::\_ValArray, std::complex<double>, std::complex<double> >, std::\_\_fun<std::\_\_multiplies, std::complex<double> >::result\_type> std::operator\*<std::complex<double> >(std::valarray<std::complex<double> > const&, std::valarray<std::complex<double> > const&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Optimization: Jamming

Commit: **aa4af5**687890fd17b5a094a3d7ab075670878715

This optimization combines the two for-loops from the **fft** function into one. The two for-loops have the same counter so they can be combined.

A screenshot of a computer

Description automatically generated with medium confidence

Now, the time has reduced from 1.9 seconds to 233.33 miliseconds, which is also a significant improvement. The new total timing is 0.79 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

88.61 0.70 0.70 3 **233.33** 233.33 fft(std::valarray<std::complex<double> >&)

5.06 0.74 0.04 \_\_muldc3

1.27 0.75 0.01 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

1.27 0.76 0.01 \_fu1\_\_\_ZSt4cout

1.27 0.77 0.01 \_fu21\_\_\_ZSt4cout

1.27 0.78 0.01 \_fu45\_\_\_ZSt4cout

1.27 0.79 0.01 \_fu9\_\_\_ZSt4cout

0.00 0.79 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 0.79 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 0.79 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 0.79 0.00 2 0.00 5.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 0.79 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 **0.79** 0.00 1 0.00 243.33 ifft(std::valarray<std::complex<double> >&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Optimization: Minimize Array Reference

Commit: **f9735e**e1628c4b48bd3e4da1237dc2ea05b226a9

This optimization replace all the occurrence of **even[k]** reference with a variable, for **fft** function. Thus, the access to **even[k]** would only be once.

A screenshot of a computer

Description automatically generated with medium confidence

The timing for fft is reduced to 196.67 miliseconds, and the total timing is now 0.62 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

95.16 0.59 0.59 3 196.67 **196.67** fft(std::valarray<std::complex<doubsle> >&)

1.61 0.60 0.01 \_fu1\_\_\_ZSt4cout

1.61 0.61 0.01 \_fu21\_\_\_ZSt4cout

1.61 0.62 0.01 \_fu45\_\_\_ZSt4cout

0.00 0.62 0.00 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

0.00 0.62 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 0.62 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 0.62 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 0.62 0.00 2 0.00 0.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 0.62 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 **0.62** 0.00 1 0.00 196.67 ifft(std::valarray<std::complex<double> >&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Optimization: Minimize work

Commit: **6116b4**d04ffb1d0cc66d1a1ce48df70e0cb4544d

This optimization replaces all **n/2** in the for-loop with a variable, for **fft** function, so the program would not need to do division every time. (It also replaced complex arrays which is outside of for-loop)

Text

Description automatically generated

The fft timing is 156 miliseconds, and the total timing is now 0.52 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

90.38 0.47 0.47 3 156.67 **156.67** fft(std::valarray<std::complex<double> >&)

1.92 0.48 0.01 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

1.92 0.49 0.01 \_fu1\_\_\_ZSt4cout

1.92 0.50 0.01 \_fu45\_\_\_ZSt4cout

1.92 0.51 0.01 \_fu9\_\_\_ZSt4cout

1.92 0.52 0.01 sin

0.00 0.52 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 0.52 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 0.52 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 0.52 0.00 2 0.00 5.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 0.52 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 **0.52** 0.00 1 0.00 166.67 ifft(std::valarray<std::complex<double> >&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Optimization: Constant

Commit: **6006b3**dcff99b3d7aa885a9a7c7d8a7ceea4963a

This optimization replace **-2 \* PI** with a defined constant, for **fft** function, so the program would not need to dynamically compute the value for each iteration of the for-loop in the runtime.

Text

Description automatically generated

The fft timing is 136 miliseconds, and the total timing is now 0.47 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

87.23 0.41 0.41 3 136.67 **136.67** fft(std::valarray<std::complex<double> >&)

4.26 0.43 0.02 \_\_muldc3

2.13 0.44 0.01 \_fu1\_\_\_ZSt4cout

2.13 0.45 0.01 \_fu21\_\_\_ZSt4cout

2.13 0.46 0.01 \_fu45\_\_\_ZSt4cout

2.13 0.47 0.01 \_fu9\_\_\_ZSt4cout

0.00 0.47 0.00 4194304 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

0.00 0.47 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 0.47 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 0.47 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 0.47 0.00 2 0.00 0.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 0.47 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

0.00 **0.47** 0.00 1 0.00 136.67 ifft(std::valarray<std::complex<double> >&)

## Regression Testing

Text

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

# Bonus: Handle Stereo

Commit: **bdb120**a1879a1f831d47e0a5e00dd9e73a08486a

It implements: produce a stereo wave file with multiple channels, given a mono input and a stereo IR. Theoretically this program supports ambiguous number of channels for IR instead of only 2.

Location: the convolution method.

There is a for-loop for channels. Each channel, retrieve the corresponding number from array. For example, when total channel is 2: for the first channel, get numbers at index at 0,2,4,6,etc; for the second channel, get 1,3,5,7,etc. Then convert the number into complex array and FFT the complex array, and then multiply input and IR, as before. Then, when copying back the real number to the double array, write the first channel numbers into index 0,2,4,6,etc; and write the second channel ones into 1,3,5,7,etc. Finally, the file would have 2 channels and it is a stereo wave file.

Text

Description automatically generated

The timing for fft increases to 186 miliseconds because there are more IR arrays to handle and more output arrays to reverse. The total timing is now 1.26 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

88.89 1.12 1.12 6 186.67 186.67 fft(std::valarray<std::complex<double> >&)

3.17 1.16 0.04 \_\_muldc3

1.59 1.18 0.02 8388608 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

1.59 1.20 0.02 \_fu11\_\_\_ZSt4cout

1.59 1.22 0.02 \_fu7\_\_\_ZSt4cout

0.79 1.23 0.01 2 5.00 201.67 ifft(std::valarray<std::complex<double> >&)

0.79 1.24 0.01 \_fu19\_\_\_ZSt4cout

0.79 1.25 0.01 \_fu39\_\_\_ZSt4cout

0.79 1.26 0.01 sin

0.00 1.26 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 1.26 0.00 4 0.00 5.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 1.26 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 1.26 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 **1.26** 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

# Optimization: Strength reduction

Commit: **2f49ff**c380e9cad0b84236f40e9305c6092bed9a

Replace the index calculation multiplication (which is expensive) with addition (which is cheaper).

The time should have no difference for mono file with before. The time will be n times more for stereo file with n channels.

Text

Description automatically generated

The new total timing is now 1.18 seconds.

## Profiling

% cumulative self self total

time seconds seconds calls ms/call ms/call name

92.37 1.09 1.09 6 181.67 181.67 fft(std::valarray<std::complex<double> >&)

2.54 1.12 0.03 \_fu7\_\_\_ZSt4cout

1.69 1.14 0.02 8388608 0.00 0.00 std::complex<double> std::conj<double>(std::complex<double> const&)

1.69 1.16 0.02 \_\_muldc3

0.85 1.17 0.01 \_fu39\_\_\_ZSt4cout

0.85 1.18 0.01 cos

0.00 1.18 0.00 11 0.00 0.00 \_\_gcc\_deregister\_frame

0.00 1.18 0.00 4 0.00 5.00 void std::\_\_valarray\_copy<std::complex<double>, std::\_RefFunClos<std::\_ValArray, std::complex<double> > >(std::\_Expr<std::\_RefFunClos<std::\_ValArray, std::complex<double> >, std::complex<double> > const&, unsigned int, std::\_Array<std::complex<double> >)

0.00 1.18 0.00 2 0.00 191.67 ifft(std::valarray<std::complex<double> >&)

0.00 1.18 0.00 2 0.00 0.00 WaveFile::read(std::\_\_cxx11::basic\_string<char, std::char\_traits<char>, std::allocator<char> >)

0.00 1.18 0.00 2 0.00 0.00 WaveFile::WaveFile(WaveFile const&)

0.00 **1.18** 0.00 1 0.00 0.00 convolution(WaveFile, WaveFile)

## Regression Test

A picture containing text

Description automatically generatedText

Description automatically generated with medium confidence

To testing the correctness, compare the new output file with the original base version output file. Testing is applied for both mono and stereo wave files.

There is nothing prints after the compare command, which indicates that the two files are identical.