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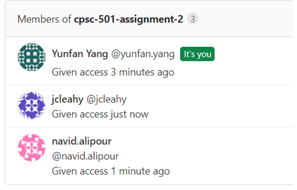
https://gitlab.cpsc.ucalgary.ca/yunfan.yang/cpsc-501-assignment-2/

The access to this repository has been granted to the TA and the professor.



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: `8f6c17866033a1326ec17acbe77a0a517f328efa`

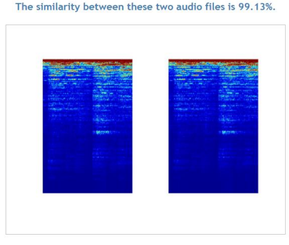
This is the baseline version of the program. It implements: read and write wave file, convolution with O(n^2) time complexity multiplication algorithm.

The full audio takes a really long time to convolute.

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



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%).

Algorithmic Optimization: FFT Program

Commit: `c9fc0d2c8a3854b44c11a52c5684a7c9c77c09c6`

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

The code is partially referenced from: Fast Fourier transform - Rosetta Code.

It implements: find the next closest n^2 number, fft and ifft, updated convolution function adapted fft and ifft.

The time is reduced from 407 seconds to 1.92 seconds, which is really significant.

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>*)
  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&)
```

As one can see, the function takes most of the time is fft, thus the following optimizations are focusing on reducing the time of this function.

Regression Testing

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `0678ecb72ed3a312b64431627424332c50eeace9`

In the vscode build task configuration file, the optimization tag −O2 is added to compile. Then run the build task and run the program.

```
5   5           "label": "C/C++: g++.exe build active file",
6   6           "command": "C:\\MinGW\\bin\\g++.exe",
7   7           "args": [
8   +               "-O2",
8   9               "-fdiagnostics-color=always",
9   10              "-pg",
10  11              "-g",
```

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `aa4af5687890fd17b5a094a3d7ab075670878715`

This optimization combines the two for-loops from the `fft` function into one.

```
260 260     for (size_t k = 0; k < n / 2; ++k) {
261 261         Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
262 262         x[k] = even[k] + t;
263     -     }
264     -
265     -     // for (size_t
266     -     for (size_t k = 0; k < n / 2; ++k) {
267     -         Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
268 263         x[k + n / 2] = even[k] - t;
269 264     }
270 265 }
```

Now, the time has reduced from 1.9 seconds to 233.33 miliseconds, which is also a significant improvement.

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `f9735ee1628c4b48bd3e4da1237dc2ea05b226a9`

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.

```
259 259     // combine
260 260     for (size_t k = 0; k < n / 2; ++k) {
261 261         Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
262     -       x[k] = even[k] + t;
263     -       x[k + n / 2] = even[k] - t;
    262 +       Complex even_k = even[k];
    263 +
    264 +       x[k] = even_k + t;
    265 +       x[k + n / 2] = even_k - t;
264 266     }
265 267 }
266 268
```

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `6116b4d04ffb1d0cc66d1a1ce48df70e0cb4544d`

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)

```
248 248     const size_t n = x.size();
249 249     if (n <= 1) return;
250 250
    251 +   int n_over_2 = int(n / 2);
    252 +
251 253     // divide
252     -   ComplexArray even = x[slice(0, n / 2, 2)];
253     -   ComplexArray odd = x[slice(1, n / 2, 2)];
    254 +   ComplexArray even = x[slice(0, n_over_2, 2)];
    255 +   ComplexArray odd = x[slice(1, n_over_2, 2)];
254 256
255 257     // conquer
256 258     fft(even);
257 259     fft(odd);
258 260
259 261     // combine
260     -   for (size_t k = 0; k < n / 2; ++k) {
    262 +   for (size_t k = 0; k < n_over_2; ++k) {
261 263         Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
262 264         Complex even_k = even[k];
263 265
264 266         x[k] = even_k + t;
265     -       x[k + n / 2] = even_k - t;
    267 +       x[k + n_over_2] = even_k - t;
266 268     }
267 269 }
268 270
```

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `6006b3dcff99b3d7aa885a9a7c7d8a7ceea4963a`

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.

```
13  13
14  14  // Constants
15  15  #define PI                 3.14159265358979
    16  +#define NEG_DOUBLE_PI       -2 * PI
16  17  #define TONE_FREQUENCY     440 // Frequency of tone to be created (A = 440 Hz)
17  18  #define SAMPLE_RATE        44100.0 //  Standard sample rate in Hz
18  19  #define BITS_PER_SAMPLE        16 //  Standard sample size in bits
    ↓
    ↑   @@ -260,7 +261,7 @@ void fft(ComplexArray& x) {
260 261
261 262     // combine
262 263     for (size_t k = 0; k < n_over_2; ++k) {
263     -       Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
    264 +       Complex t = polar(1.0, NEG_DOUBLE_PI * k / n) * odd[k];
264 265         Complex even_k = even[k];
265 266
266 267         x[k] = even_k + t;
```

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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: `bdb120a1879a1f831d47e0a5e00dd9e73a08486a`

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.

```
    // For each channel, FFT the input and output and multiply, and copy to output
    for (int r = 0; r < output.channels; r++) {
        cout << "IR complex array channel #" << r << endl;

        inputComplexArray.resize(complexArraySize, 0);
        IRComplexArray.resize(complexArraySize, 0);
        outputComplexArray.resize(complexArraySize, 0);

        // FFT input
        for (int t = 0; t < input.arraySize; t++) {
            inputComplexArray[t] = input.array[t];
        }
        fft(inputComplexArray);

        // FFT IR
        for (int t = 0; t < IR.numberOfSample; t++) {
            IRComplexArray[t] = IR.array[t * output.channels + r];
        }
        fft(IRComplexArray);

        // Multiplication
        outputComplexArray = inputComplexArray * IRComplexArray;
        ifft(outputComplexArray);
        cout << "output complex array ifft" << endl;

        // Copy real to output intertwined
        for (int t = 0; t < outputSample; t++) {
            output.array[t * output.channels + r] = outputComplexArray[t].real();
        }
        cout << "output complex array to real" << endl << endl;
    }
```

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: `2f49ffc380e9cad0b84236f40e9305c6092bed9a`

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.

```
330 330         fft(inputComplexArray);
331 331
332 332         // FFT IR
    333 +       int IRArrayIndex = r;
333 334         for (int t = 0; t < IR.numberOfSample; t++) {
334     -           IRComplexArray[t] = IR.array[t * output.channels + r];
    335 +           IRComplexArray[t] = IR.array[IRArrayIndex];
    336 +           IRArrayIndex += output.channels;
335 337         }
336 338         fft(IRComplexArray);
337 339
        @@ -341,8 +343,10 @@ WaveFile convolution(WaveFile input, WaveFile IR) {
341 343         cout << "output complex array ifft" << endl;
342 344
343 345         // Copy real to output intertwined
    346 +       int outputIndex = r;
344 347         for (int t = 0; t < outputSample; t++) {
345     -           output.array[t * output.channels + r] = outputComplexArray[t].real();
    348 +           output.array[outputIndex] = outputComplexArray[t].real();
    349 +           outputIndex += output.channels;
346 350         }
347 351         cout << "output complex array to real" << endl << endl;
348 352     }
```

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

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output.wav output_dry_stereo.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$
```

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.