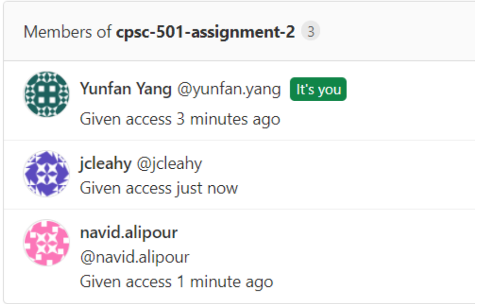
Yunfan Yang 30067857

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 so I can fix. :)



Members of **cpsc-501-assignment-2** 3

Yunfan Yang @yunfan.yang It's you
Given access 3 minutes ago

jcleahy @jcleahy
Given access just now

navid.alipour
@navid.alipour
Given access 1 minute ago

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`

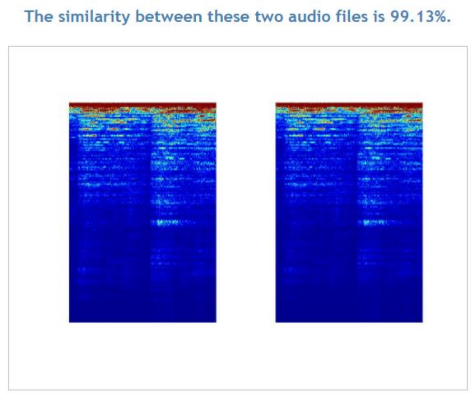
This is the baseline version of the program. It implements: read and write wave file, convolution with O(n^2) time complexity multiplication algorithm.

The full audio takes a really long time to convolute, 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



The similarity between these two audio files is 99.13%.

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: `c9fc0d2c8a3854b44c11a52c5684a7c9c77c09c6`

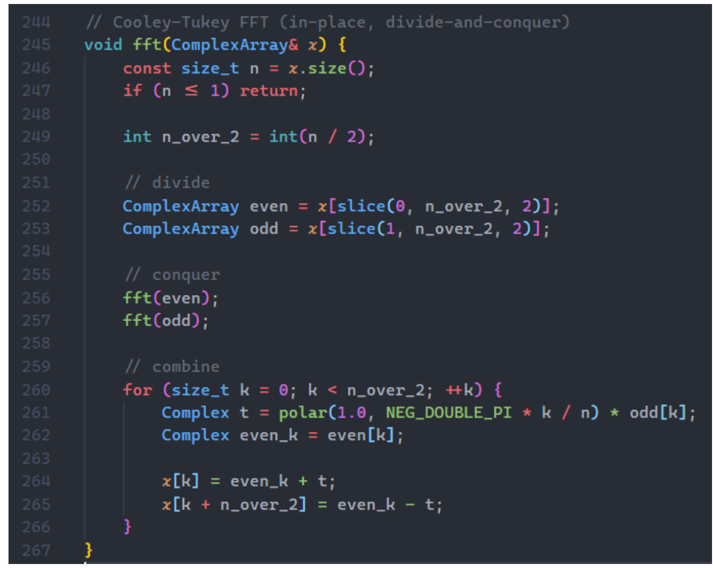
This is the optimized version of convolution algorithm, using Fast Fourier Transform to achieve O(n log n) time complexity.

The code is referenced from: Fast Fourier transform - Rosetta Code and https://stackoverflow.com/questions/466204/rounding-up-to-next-power-of-2.

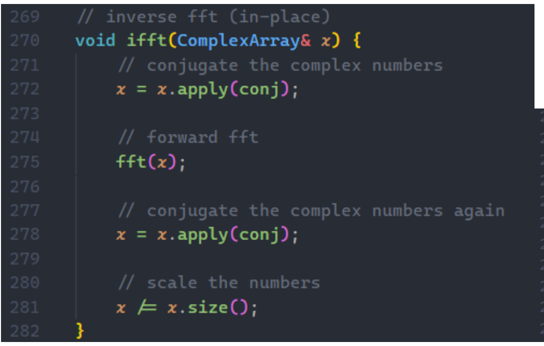
It implements: find the next closest n^2 number: `upper_power_of_two`, `fft` and `ifft`. Updated the convolution function adapting new fft and ifft functions.

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.

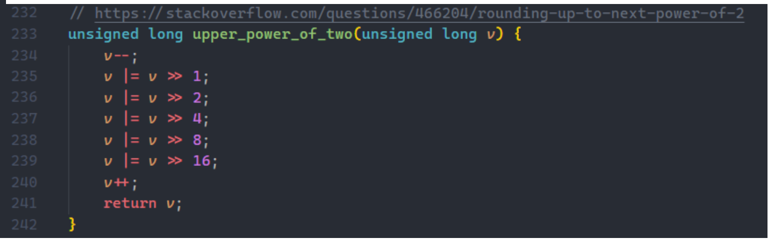
Since the most time-consuming part is `fft`, the following optimizations are mainly focusing on this function.



```
// Cooley-Tukey FFT (in-place, divide-and-conquer)
void fft(ComplexArray& x) {
    const size_t n = x.size();
    if (n <= 1) return;

    int n_over_2 = int(n / 2);

    // divide
    ComplexArray even = x[slice(0, n_over_2, 2)];
    ComplexArray odd = x[slice(1, n_over_2, 2)];

    // conquer
    fft(even);
    fft(odd);

    // combine
    for (size_t k = 0; k < n_over_2; ++k) {
        Complex t = polar(1.0, NEG_DOUBLE_PI * k / n) * odd[k];
        Complex even_k = even[k];

        x[k] = even_k + t;
        x[k + n_over_2] = even_k - t;
    }
}
```



```
// inverse fft (in-place)
void ifft(ComplexArray& x) {
    // conjugate the complex numbers
    x = x.apply(conj);

    // forward fft
    fft(x);

    // conjugate the complex numbers again
    x = x.apply(conj);

    // scale the numbers
    x /= x.size();
}
```

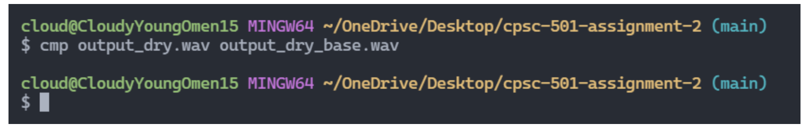


```
// https://stackoverflow.com/questions/466204/rounding-up-to-next-power-of-2
unsigned long upper_power_of_two(unsigned long v) {
    v--;
    v |= v >> 1;
    v |= v >> 2;
    v |= v >> 4;
    v |= v >> 8;
    v |= v >> 16;
    v++;
    return v;
}
```

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



```
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)
$ 
```

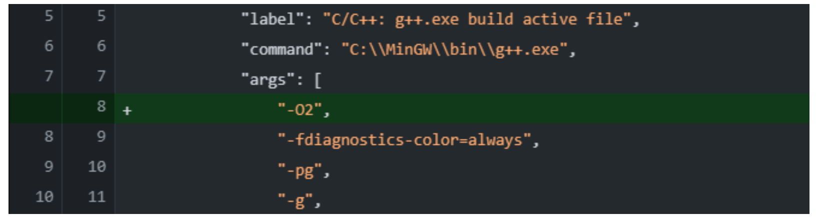
To testing the correctness, compare the new output file with the original base version output file. There is nothing prints after the compare command, which indicates that the two files are identical.

Optimization: Compiler

Commit: `0678ecb72ed3a312b64431627424332c50eeace9`

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.

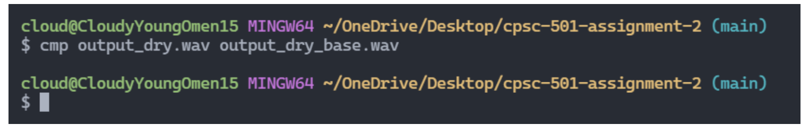


```
            "label": "C/C++: g++.exe build active file",
            "command": "C:\\MinGW\\bin\\g++.exe",
            "args": [
+               "-O2",
                "-fdiagnostics-color=always",
                "-pg",
                "-g",
```

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



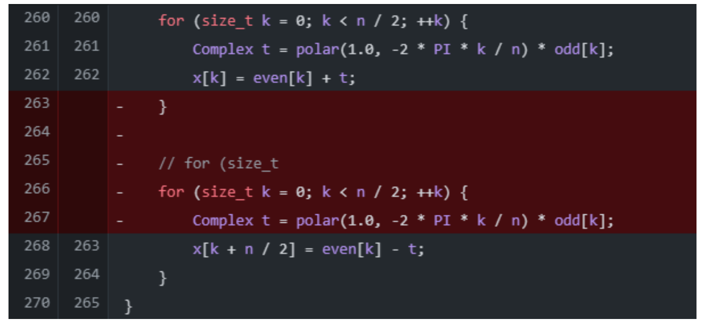
```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

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. The two for-loops have the same counter so they can be combined.



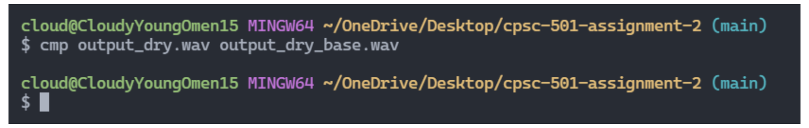
```
        for (size_t k = 0; k < n / 2; ++k) {
            Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
            x[k] = even[k] + t;
-       }
-
-       // for (size_t
-       for (size_t k = 0; k < n / 2; ++k) {
-           Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
            x[k + n / 2] = even[k] - t;
        }
    }
```

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



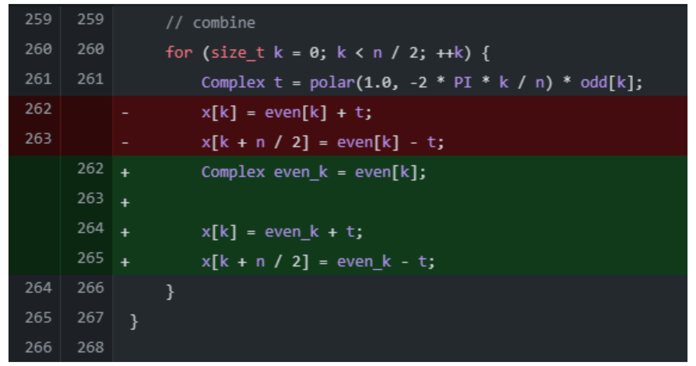
```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

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.



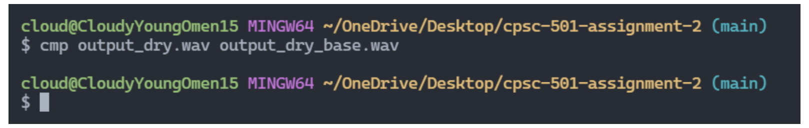
```
      // combine
      for (size_t k = 0; k < n / 2; ++k) {
          Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
-         x[k] = even[k] + t;
-         x[k + n / 2] = even[k] - t;
+         Complex even_k = even[k];
+
+         x[k] = even_k + t;
+         x[k + n / 2] = even_k - t;
      }
  }
```

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



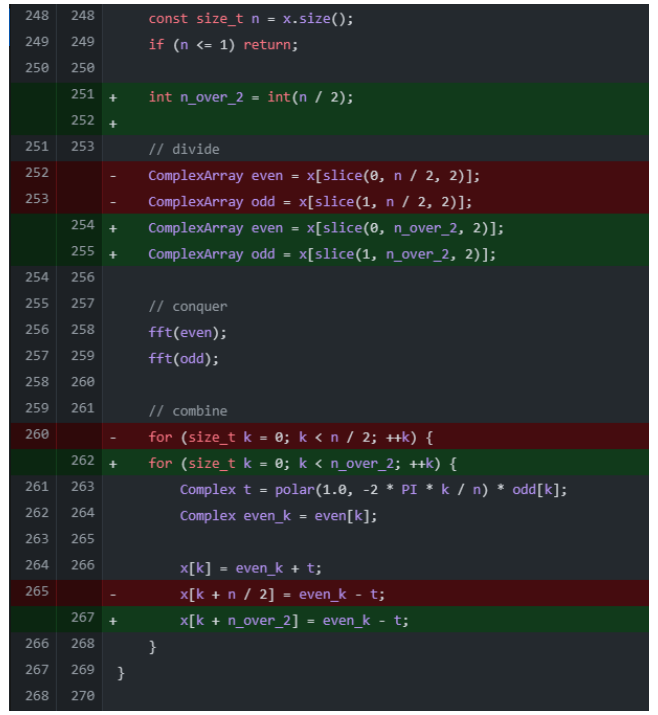
```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

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)



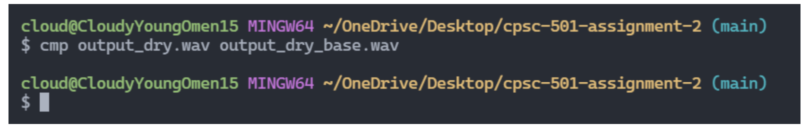
```
      const size_t n = x.size();
      if (n <= 1) return;

+     int n_over_2 = int(n / 2);
+
      // divide
-     ComplexArray even = x[slice(0, n / 2, 2)];
-     ComplexArray odd = x[slice(1, n / 2, 2)];
+     ComplexArray even = x[slice(0, n_over_2, 2)];
+     ComplexArray odd = x[slice(1, n_over_2, 2)];

      // conquer
      fft(even);
      fft(odd);

      // combine
-     for (size_t k = 0; k < n / 2; ++k) {
+     for (size_t k = 0; k < n_over_2; ++k) {
          Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
          Complex even_k = even[k];

          x[k] = even_k + t;
-         x[k + n / 2] = even_k - t;
+         x[k + n_over_2] = even_k - t;
      }
  }

```

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



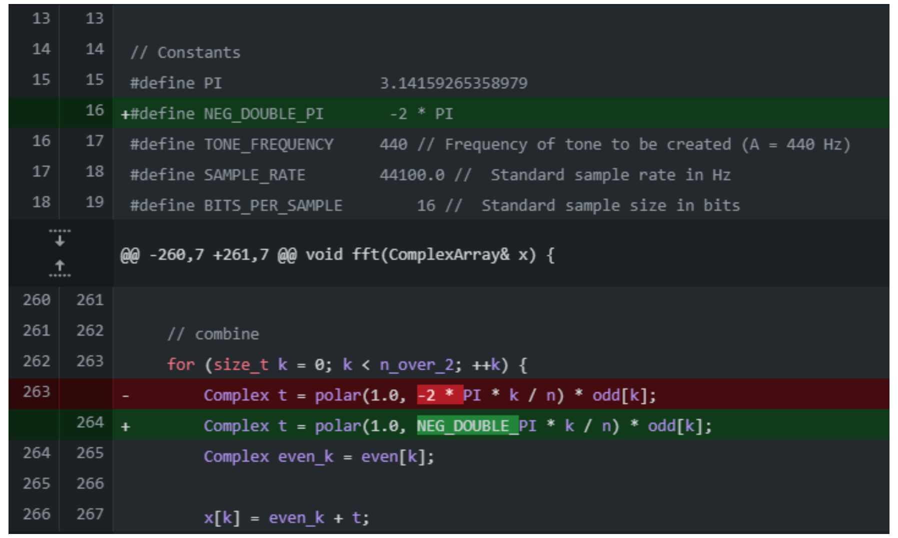
```
cloud@CloudyYoungOmen15 MINGW64 ~/OneDrive/Desktop/cpsc-501-assignment-2 (main)
$ cmp output_dry.wav output_dry_base.wav

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.



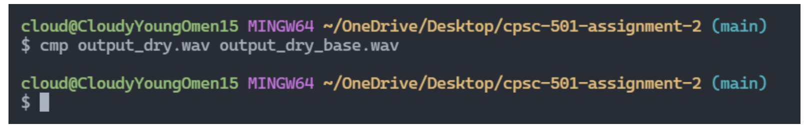
```
// Constants
#define PI                  3.14159265358979
+#define NEG_DOUBLE_PI        -2 * PI
#define TONE_FREQUENCY      440 // Frequency of tone to be created (A = 440 Hz)
#define SAMPLE_RATE         44100.0 //  Standard sample rate in Hz
#define BITS_PER_SAMPLE         16 //  Standard sample size in bits

@@ -260,7 +261,7 @@ void fft(ComplexArray& x) {

    // combine
    for (size_t k = 0; k < n_over_2; ++k) {
-       Complex t = polar(1.0, -2 * PI * k / n) * odd[k];
+       Complex t = polar(1.0, NEG_DOUBLE_PI * k / n) * odd[k];
        Complex even_k = even[k];

        x[k] = even_k + t;
```

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



```
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.

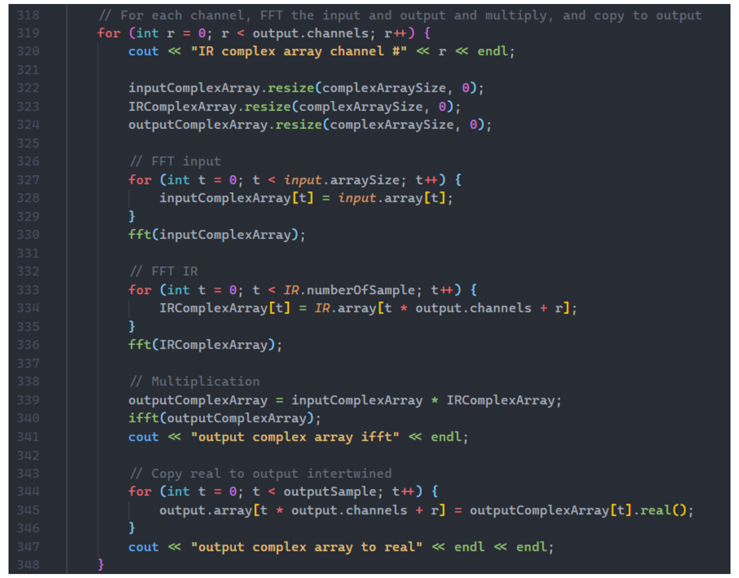
Bonus: Handle Stereo

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;
    }
```

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

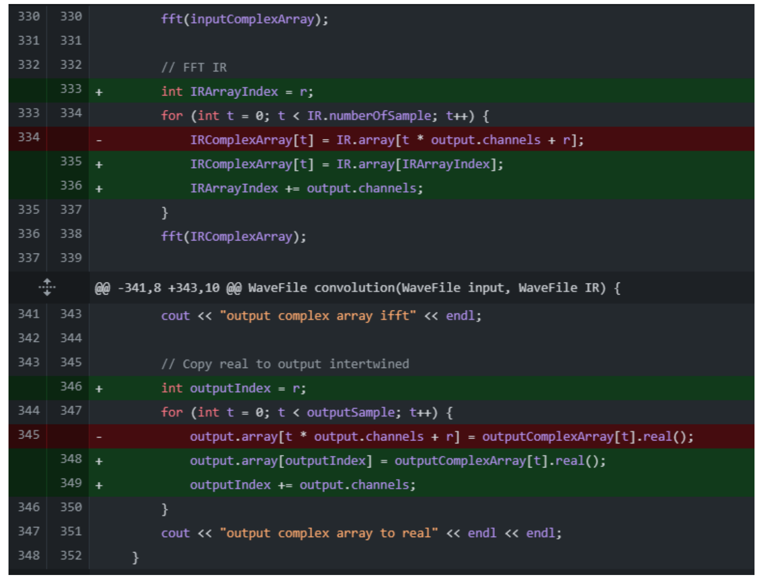
```
  %   cumulative   self              self     total           
 time   seconds   seconds    calls  ms/call  ms/call  name    
 88.89      1.12     1.12        6   186.67   186.67  fft(std::valarray<std::complex<double> >&)
  3.17      1.16     0.04                             __muldc3
  1.59      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: `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.



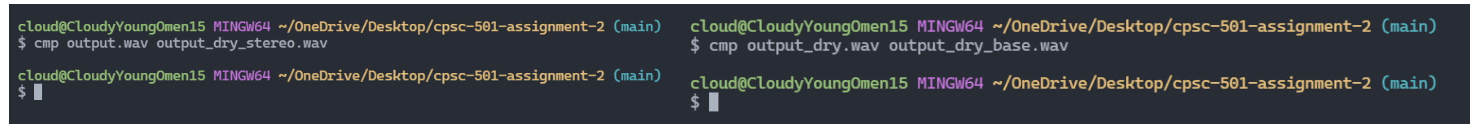
```
        fft(inputComplexArray);

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

@@ -341,8 +343,10 @@ WaveFile convolution(WaveFile input, WaveFile IR) {
        cout << "output complex array ifft" << endl;

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

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



```
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.