

# Apples and Oranges: The Lightweight UnitsC++ Library

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## Introduction

In doing numerical calculations, we all learn the importance of checking our equations for dimensional consistency. However, in using computers for numerical computations, vast numbers of bugs have been created by equating apples to oranges. The problem is not helped by programming languages that constrain all numerical quantities to a few numerical types (typically one floating point type).

In this article I discuss a C++ library called **UnitsC++** that elevates numerical quantities with different units to different types, which keeps apples in their baskets and oranges in their crates. The goal is to show you a way to reduce numerical errors in your programs by preventing you from treating apples and oranges as the same objects.

## Why you might want to use UnitsC++

1. If you write programs that calculate with numbers that represent quantities of objects or physical units, you should consider using this library.
2. It helps you make numerical code easy to read and more likely to be written correctly.
3. It's lightweight: small, little runtime cost in space or time, and you don't need to be a computer scientist to understand it. It was written by a scientist/engineer for scientists and engineers. Most functions (member and otherwise) are one line long; the longest is three.
4. It's simple. Create and use only what you need.
5. The library adapts to your problem domain, not the other way around.

6. It's implemented in one include file generated by a python script from a configuration file. Units, derived units, and constants are easily added or removed in the configuration file. You should never need to edit the include file.
7. The configuration file has a simple syntax. You can define derived units in a natural way by expressions using other fundamental and derived units. Multiplication, division, and integer exponentiation are supported.
8. It should be portable and usable with many C++ compilers. The compiler primarily just needs to support templates and the addition of integer template parameters.
9. It is issued under the Perl Artistic License [PerIAL], which lets you use it in both open source code and closed source code projects.

### **Some things UnitsC++ does not do**

1. Support fractional exponents.
2. Define any of the commonly-used units and constants.

If you desire these features, see some of the "heavyweight" units library implementations listed in the references.

If you like the UnitsC++ library, yet still want fractional exponents, it might not be too hard to change the `gen.py` script to define unit dimensions in units of some fraction. For example, the integer values for Length could be in "units" of 1/360, allowing numerous square and cube roots to be taken. You'd have to write the extra template code for the root functions. This technique will be considered for future releases of the UnitsC++ library.

For help in converting amongst a variety of units, I heartily recommend the GNU units program [GNUunits].

## **Background**

Barton and Nackman's insight [BN1994] into using C++ templates to provide types for units is a useful technique and is the basis for what I discuss here. Brown [Brown2001] implemented the Slunits library using similar ideas, as did Kenniston [Kenn2002]. The `mcs::units` project [SFmcs::units] was apparently once part of Boost, but doesn't currently appear on Boost's pages anymore. These are examples of "heavyweight" implementations.

After examining the heavyweights, it struck me that they might have worked too hard to solve the problem. In particular, they use template metaprogramming techniques, which can burden older compilers. The authors of the heavyweights apparently spent substantial effort on overcoming limitations in various compilers, a familiar and frustrating task when trying to write platform-independent code. `mcs::units` comments that their library does tend to stress compilers and that you'll likely need a current compiler. I felt there was a place to keep the solution simple and not try to solve the general case.

I came across Abhishek Padmanabh's elegantly simple and clean implementation [Pad2007] that was intended to illustrate the principle of templates providing different types for various units. I felt his implementation provided most of what's needed for bread-and-butter numerical calculations, so I decided to base my implementation on it.

## **Important numbers = types**

While pondering the above, I remembered a lesson I learned many years ago. I wrote a computer model of a manufacturing process to help make financial decisions. I spent a good fraction of my time in solving the problem on writing down the equations and making sure they were correct (both

dimensionally and numerically). These equations involved "units" like dollars, hours, widgets, sputter targets, people, polishing compound, etc. This led to the insight

**"Units" are numerical concepts that are important to the problem domain.**

This insight is more general than e.g. using the usual seven fundamental SI units. By "elevating" a concept to a unit, the programmer is stating that this concept is important in the solution of his problem and he wants to make sure he gets it right. A unit is "orthogonal" to all other units.

Here's an example. Angle measure is not a fundamental SI unit. Mathematically, this is fine, as the radian is defined as the ratio of the length of an arc to a radius and is thus a dimensionless number. **Practically, it's a disaster.** We assign the `double` type to an angle variable in our code and then blithely think we can keep our work in radians and degrees straight. Our code gets littered with conversion factors, as we frequently like to work in degrees but the `cmath` library functions want arguments in radians. I don't have enough integers at hand to enumerate the times I've made trig argument mistakes. Ah, I see that gentleman in the back row nodding his head in agreement.

With the above insight, the solution is trivial: make angle measure a fundamental unit. Deep down, this means you think it's important enough to ask the compiler to help you keep track of angles and their manipulations. It's that simple and easy. Then it's a short trudge over to the realization that you can ask for this help for **all** the numbers in your program should you wish to.

Static type checking is the technique the compiler uses to help us. See [Strous1997] section 24.2.3 for some thoughts on this. For mission-critical code, I want all the static type checking I can get. If you don't agree with this, I can point to some \$125 million chump change might persuade you to rethink this [NASA1999]. I can translate the above insight into programmer-speak:

**If it's important, make it a type.**

While thinking about the above and iteratively implementing this units library, I decided on the following requirements for the library in roughly decreasing priority:

Characteristic	Comments
Keep it simple	Users will be scientists and engineers, not computer scientists. The library should be easy to understand and use.
Easy to add or remove a dimension	Problems always change, so the library must easily support change without changing lots of code.
Portability	A possible side effect of simplicity. Don't put too many demands on the compiler. And don't compromise the design to cater to a broken compiler.
Features	Arithmetic, ordering, and equality testing. Talk to streams too.
Be independent	Do not use other libraries or tools unless they're part of the package. [ <i>Technically, I failed this requirement because of the need for python.</i> ]
No kitchen sink syndrome	Don't try to handle all cases or make the library bulletproof against all misuses.
Testability	Make it easy to test.

Characteristic	Comments
Documentation	Show the common use cases and the library's limitations.
Easy to understand	Try to write it so users can understand the implementation and adapt it to their needs.

## Implementation

The implementation went through numerous iterations. My first iteration was based on defining the template parameters as macros, which lead to a clean and easy to read include file implementation. The textual "noise" of the template parameters was hidden and it was easy to see how simple the implementation was. But C++ programmers shouldn't use macros.

I switched to an implementation that used a python script `gen.py` to generate the include file. This had the advantage of automatically generating and numbering the template parameters, reducing errors caused by manually editing the macros. The code is still easy to read in the python script, as it uses the handy python feature of named string interpolation from a dictionary:

```
print "The value is %(my_integer)d." % my_dictionary
```

The template parameters are constructed and put into a dictionary, which is then used to "fill out" the templated code in a multi-line string. This is similar to how the macro processor did the job.

The python script uses a user-written configuration file to define the fundamental units, derived units, and constants that the user feels are important to the problem at hand. This lets the library adapt to the problem domain, not the other way around. **This is important**, as it lets the user think about the problem in terms familiar to him.

An advantage of the configuration file is that changes to it can be made at any time and a new include file implementing the library can be quickly generated. No important existing work is lost or needs to be redone. For example, you can easily add a new fundamental unit. Behind the scenes, all the templated types change, but everything else you've already defined continues to work. This is maintenance Nirvana.

The configuration file lets you choose the numerical type you want to use for your calculations. It defaults to `double`, but you can use integers, floating point types, or any object type that has the proper numerical semantics. It should conceivably work with e.g. a multiple-precision numerical type that supports interval arithmetic, leading to sophisticated numerical calculations that still have simple semantics.

The python script `gen.py` uses the `-e` option to send an empty configuration file to stdout. The resulting file has numerous comments to show how to construct a configuration file.

## On the correct path

While implementing this library, I came to a point in writing examples and tests where the library was finding my mistakes much more frequently than I was finding implementation mistakes in the library. From my past experience in writing software, this is a strong indication that I was on track for developing a useful tool. I suspect if you give the library a try, you'll have similar experiences.

Another indicator of a useful tool is that I found it quite pleasurable to write and read code that used the library. It was pleasing to find that code that looked correct was correct. With care, it makes it much easier to write numerical code that works the first time.

The master's description of the development process (section 23.4 of [Strous1997]) describes exactly how this project evolved. The desired characteristics I gave in the table above didn't magically appear all at once -- they evolved iteratively from early versions and introspection.

## Overview of the library

The `gen.py` script is used to generate a problem-specific include file used to provide the desired unit types to a particular program. The contents of the include file are simple, once you filter out the "textual noise" of numerous template parameter lists. The class used for the units contains the following member functions (`NT` refers to the number type used with the class, typically `double`):

<code>operator()</code>	Returns the <code>NT</code> value of the number represented by the class.
<code>dim</code>	Returns a string representing the dimensions of the unit. For example, if the units class consisted of the three dimensions mass, length, and time, a velocity's dimensions would be returned as <code>&lt;0, 1, -1&gt;</code> which represents $M^0 L^1 T^{-1}$ .
<code>to</code>	Convert to a specified (and compatible) unit and return the value as an <code>NT</code> value. Typical use might be (where <code>x</code> is in meters as the fundamental unit):  <pre>cout &lt;&lt; "x is " &lt;&lt; x.to(mm) &lt;&lt; " mm." &lt;&lt; endl;</pre>
<code>operator==, +=</code>	Addition and subtraction with other unit objects.
<code>operator*=/</code>	Multiplication and division with <code>NT</code> types.

Functions are provided to allow the following operations

<code>operator+, -, *, /</code>	Multiplication and division with unit and <code>NT</code> types.
<code>operator&lt;, &gt;, &lt;=, &gt;=</code>	Ordering.
<code>operator==</code>	Equality testing.
<code>operator&lt;&lt;</code>	Insertion operator for streams.

That's the extent of the functionality. Most functions are one line of code; a few have two lines and one has three lines. It's a lightweight library.

## Library Usage

Here are the steps to use the library:

1. Write a configuration file.
2. Generate the include file.
3. Write your main code using the units you've defined.

## Configuration files

The `gen.py` script reads the configuration file and generates the include file containing the code that defines the unit types. You can use the `-e` option to `gen.py` to get an empty configuration file with comments explaining how to construct the file.

Lines beginning with `#` (whitespace before the `#` symbol is allowed) are comments and are ignored. Since the comments gotten with the `-e` option explain the details, I'll just cover the key pieces of

information needed.

Each line begins with a token (tokens are separated by whitespace) that defines the line type. There are a few that describe details like defining the (optional) namespace to put things in, the name of the templated class implementing the units types, the name of the include file, and the specification of the numerical type to use.

The main tokens used are:

`Unit` Defines a fundamental unit. All derived units will ultimately be expressed in terms of these fundamental units. Some typical lines might be

```
Unit = Mass
Unit = Length
Unit = Time
```

`DerivedUnit` Defines a unit that is derived ultimately from the fundamental units. You may write expressions with `*`, `/`, `^`, `**`, and parentheses for grouping. `^` and `**` mean exponentiation with an integer exponent. Some example lines are

```
DerivedUnit = Velocity = Length/Time
DerivedUnit = Acceleration = Velocity/Time
DerivedUnit = Force = Mass*Acceleration
DerivedUnit = Pressure = Force/Length^2
DerivedUnit = Stress = Pressure
DerivedUnit = Energy = Force*Length
DerivedUnit = Frequency = 1/Time
```

Such expressions allow you to define units in a natural way.

`Constant` These lines are intended to be used with `const` expressions defining unit values. However, the code after the `=` symbol is copied verbatim to the include file, so any legal C++ code is allowed. Some example lines are

```
Constant = const Length m = 1;
Constant = const Time s = 1;
Constant = const Time hour = 3600*s;
Constant = const Length mm = 1e-3*m;
Constant = const Length um = 1e-6*m;
Constant = const Length nm = 1e-9*m;
Constant = const Length inch = 25.4*mm;
Constant = const Velocity c = 3e8*m/s;
```

You only need to define the constants you want to use in your program. Note that physical constants are defined the same way as "regular" units. This lets an expression like `v.to(c)` convert a velocity to a fraction of the speed of light in an intuitive way. You can also write conversions such as `v.to(nm/hour)` and it's obvious what's going on. Always remember, however, that the `to` method returns an `NT` type, not a units type.

There are also constructs to allow you to include arbitrary code at the beginning and the end of the include file.

## Example: Barlow's Formula

Our first example shows the code for a simple numerical calculation using Barlow's formula for thin-

walled cylinders. It relates the stress, diameter, wall thickness, and fluid pressure inside a pipe. The formula is

$$t = \frac{pD}{2(S+p)}$$

where

t = wall thickness in inches  
p = fluid pressure in pipe in psi  
D = pipe outside diameter  
S = allowable stress in psi

I chose this example in non-SI units to show that you can do the calculations with SI units or define the fundamental units as length and pressure.

Let's solve for the case of a 1 inch diameter 304 stainless steel pipe with a yield strength of 30 kpsi. We want the allowed stress to be one half of this yield strength, so S = 15000 psi. The working pressure will be 500 psi. Plugging the numbers in gives  $t = 500/31000 = 0.016$  inches.

## Calculation using SI units

We'd write the following configuration file:

```
Unit = Length
Unit = Mass
Unit = Time

DerivedUnit = Area = Length*Length
DerivedUnit = Acceleration = Length/Time**2
DerivedUnit = Force = Mass*Acceleration
DerivedUnit = Pressure = Force/Area
DerivedUnit = Stress = Pressure

Constant = const Length m = 1;
Constant = const Time s = 1;

Constant = const Length mm = 1e-3*m;
Constant = const Length inch = 25.4*mm;
Constant = const Force N = 1;
Constant = const Force lbf = 4.4482216*N;
Constant = const Pressure psi = lbf/(inch*inch);

Constant = typedef Length WallThickness;
Constant = typedef Length Diameter;
```

Note the `typedef`s of `WallThickness` and `Diameter`. These aren't strictly needed, but they help to make our code self-documenting.

We'd run the `gen.py` script with this configuration file. Let's suppose we saved the output to a file named `units.h`.

Then we'd put the following code into the file `barlow.cpp`:

```
#include <iostream>
#include <iomanip>
using namespace std;
```

```

#include "units.h"

WallThickness Barlow
(
    const Pressure & p,
    const Diameter & OD,
    const Stress & S
)
{
    return p*OD/(2*(S + p));
}

int main(void)
{
    const Pressure p = 500*psi;
    const Diameter OD = 1*inch;
    const Stress S = 15e3*psi;
    const WallThickness t = Barlow(p, OD, S);
    cout << "304 SST pipe wall thickness = " << t.to(inch)
         << " inches" << endl;
}

```

I feel this is quite readable code with the advantage of having the compiler check to make sure you don't make errors in calculations due to variables or constants having the wrong units. Normally, I demand descriptive variable names, but the short names make it easy to see the structure of Barlow's equation (and compare it to the printed form). The variable types add significant information for the reader.

An advantage of defining units above in SI is that the metric equivalents are easily gotten if desired.

## Calculation using direct units

Some engineers might prefer to see the calculations done directly in inches and pressure. This is easily done with the following configuration file:

```

Unit = Length
Unit = Pressure

Constant = const Length inch = 1;
Constant = const Pressure psi = 1;

Constant = typedef Pressure Stress;
Constant = typedef Length WallThickness;
Constant = typedef Length Diameter;

```

These simple definitions will yield the identical answer as the previous example (note `Stress` was changed from a derived unit to a typedef; the results are still the same). This demonstrates a strength of the UnitsC++ library: only define what you need.

## Example: A non-traditional example

xx Need an example showing non-traditional use of units

## Comments on gen.py

The python script `gen.py` is used to generate the include file that implements the units library. The script is commented to help you inspect it, but I want to comment on some of python's features used in the script to perhaps whet the appetite of folks unfamiliar with python -- hopefully, you'll take a look at it as a general purpose programming tool.

### List comprehensions

List comprehensions look much like typical mathematical language for describing sets. See [http://en.wikipedia.org/wiki/List\\_comprehension](http://en.wikipedia.org/wiki/List_comprehension) for details. In python, arrays are lists, which are mutable (as opposed to tuples, which are immutable arrays; both have their place).

Suppose we want the set  $S$  of the squares of even numbers from 0 to 10. We could specify these using the common mathematical language of  $S = \{x^2 \mid x \in \mathbb{N} \text{ and } 0 \leq x \leq 10 \text{ and } x \bmod 2 = 0\}$ . In python, this could be written using a list comprehension. For example, the python code

```
print [x*x for x in range(11) if x % 2 == 0]
```

results in

```
[0, 4, 16, 36, 64, 100]
```

List comprehensions can be used instead of the functional programming tools of `map()`, `filter()`, and `lambda` (anonymous) functions, all of which python also supports. Most folks find list comprehensions more readable.

In the `gen.py` script, take a look at the `MakeTemplateParameters()` function, which uses list comprehensions to concisely construct the needed template parameters for the include file.

### The U class

Python is an object-oriented language and supports the notion of a class, similar to C++. I defined the `U` class to allow the evaluation of expressions of already-defined units. The basic output (from the `__repr__` method) is the set of integers that define the exponents of the basic units. This lets the python expression parser do the work of parsing derived unit expressions so I didn't have to write a parser. The member functions `__mul__` and `__div__` allow the support of the `*` and `/` binary operators. The `__pow__` allows the support of integral powers. List comprehensions give concise but readable expressions. The `join` function is part of the `string` module and is used to create a single string from a sequence of strings.

### Nested functions

It's handy to be able to write a function inside of a function. This controls the scope and avoids pollution of the module's namespace. It also lets a person reading the code immediately see the implementation (assuming functions are kept short), instead of having to search through the file for it.

## Summary

The UnitsC++ units library has been presented that should be easy to use, modify, and understand. Its main advantages are:

1. It makes code easier to read and understand.
2. It helps make C++ numerical code easier to make correct by using the compiler to catch dimension errors in calculations.

3. It's lightweight. Once you're familiar with it, all you need to have on hand is the 30 kilobyte `gen.py` script. There's essentially no runtime penalty in space or time for using the library. The size of a units object is the same as the numerical type you've chosen to use with it. (I said essentially because some compilers might use extra space for the constant definitions in multiple compilation units.)

## References

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