Deconstructing Inheritance
Inheritance can be overused.
We consider how it can be abused,
and what alternatives exist.

Pass the Parcel
A look at the advanced features of
Python’s module and package system

Quick Modular Calculations
We conclude this series with a new algorithm
that works for 64-bit operands

It's About Time
How easy is it to make code wait for a
time period before doing something?

Profiting from the Folly of Others
We learn about private access in C++

Using Compile Time Maps for Sorting
How to achieve compile time sorting
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Respect can mean many different things. Frances Buontempo muses on its myriad meanings.

Respect to our writers. We’ve had so many submissions for this issue, I have spent all my time reading through them instead of planning an editorial. Good work people! I also had to stay in the office late for two nights running in order to help with a release, which obviously used even more of my time. I bet several of you manage to release your code during office hours. Perhaps you should write in and tell us how. Anyway, this adds to my excuse for not writing an editorial. On the plus note, one of the business people said thank you on a slack channel when we were finally done. Never under estimate the power of saying thanks. Years ago, in another company, one of the senior devs always said thank you at the end of the day, which seemed a bit odd on the face of it. I’d turned up to work, and mostly done what I was told. Why a word of thanks after that? It turns out, it made me seem a bit odd on the face of it. I’d turned up to work, and mostly done what I was told. Why a word of thanks after that? It turns out, it made me feel appreciated and keener to work harder. Or talk to him when I had ideas of how to make things better, quicker, leaner, meaner. You know. Saying thank you is a small act of kindness that can make a big difference. Respect

Who do you respect? Do you have a favourite writer or speaker? Or band or composer? I’ll bet there’s someone. What makes you respect them? Consistent quality performance? Ability to adapt and react to an audience or situation? Who would you choose to partner with you on a late night release? Why? We recently got a new team member. He’s a rubber duck, called Quackson. He’s the best listener ever. I don’t know how he manages to sit still and say nothing while others rant and rail at him. I find it very hard to do that. I tend to say, “Hang on, that can’t be right.” Or, “I don’t understand.” That sort of thing. I have much to learn from the duck. The colleague who brought in Quackson had never heard of rubber duck debugging [RubberDuck] before, but spontaneously started telling the duck what he was up to. It’s a bit like an imaginary friend you tell your woes to, explaining what you are up to and why, and what you need help with. Then,

At some point you will tell the duck what you are doing next and then realise that that is not, in fact, what you are actually doing. The duck will sit there serenely, happy in the knowledge that it has helped you on your way. Sometimes you give people grudging respect. My editor of choice is Vim. At the expense of fuelling an editor war, a colleague some years ago used Emacs. Watching him find entries in logs and reformat text was a wonder to behold. I know how to exit Emacs, which is good enough for me; however, seeing a man who could drive his tool of choice so well commanded immediate respect. Good work, Moshe.

Respect usually revolves around interactions between people. Respect can take the form of being mindful of other’s needs. Don’t stand in front of the white board and talk to it, if you expect a room of people to hear you. If someone in the meeting is deaf or partially sighted, you need to be even more thoughtful about the layout of the physical space and the format taken. Bigger font sizes. Making sure the person speaking can be seen, if someone needs to lip read. If people are dialled-in to a meeting, make sure they get a chance to speak as well. Don’t speak over people. I’m sure you can draw up your own list. Alternatively, avoid the problem completely and never have a meeting. Many organisations have a hierarchy, no matter how flat they claim it to be. This often carries an implicit assumption that more important people will automatically be obeyed no matter what. Respect the badge. Respect your elders and betters. This sometimes means blind obedience. In some situations, there isn’t time to argue and no harm will come from doing something now and dealing with any fallout later. In other situations, much harm can happen. A classic, often quoted, example is the so-called ‘Charge of the Light Brigade’. During the Crimean War, in 1854, Lord Cardigan led the light cavalry, armed with swords, against Russian forces, armed with guns. Due to a miscommunication, they were sent straight against the artillery and most ended up dead or injured. [Wikipedia-1].

Respecting those in authority, your elders, or even your parents is not the same as doing exactly what they ask. On another late night release, many years ago, a senior manager said he thought you shouldn’t call fabs directly as it could be slow. A team mate thereby halted proceedings and tried to make us go through the code and swap out the calls for a hand-crafted piece of code. I eye-balled the disassembler with another co-worker and could see it was one floating point instruction. Now, I believe the absolute floating point function may have been slower than hand crafted versions once upon a time, but things change. While respecting what the manager said, we showed him the compilation to a single instruction. He was horrified that we’d even considered holding up the release to hack around the code at midnight. Not the charge of the light brigade, but… Try talking to senior people once in a while, and checking what they say. You might get home earlier. Respect is not the same as mindless obedience.

Respect and obedience, though often conflated, are not the same thing. The root of ‘respect’ is ‘re’ for ‘back’, and ‘specere’ for ‘to look at’, giving a similar word ‘regard’, re+gard, or ‘back’ plus ‘guard’ or ‘watch’. You should have watched Moshe driving Emacs, though! Perhaps respect has something to do with looking and seeing. Not just glancing and vaguely guessing what’s going on, but actually looking and paying attention. James 1:23-24 says:

Anyone who listens to the word but does not do what it says is like someone who looks at his face in a mirror and, after looking at himself, goes away and immediately forgets what he looks like.

Do you remember what you look like? Perhaps. Look, carefully; watch, in detail; act, respecting the people and situation you observe.

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Respect isn’t always about people. Given coding guidelines, you can either respect them, perhaps automatically enforcing them, or you can subvert or blatantly disobey from time to time. If you code in C++ and request a function to be inlined, does the compiler respect your wishes? Inline is a request, and therefore might not be respected.

No matter how you designate a function as inline, it is a request that the compiler is allowed to ignore: the compiler might inline-expand some, all, or none of the places where you call a function designated as inline. (Don’t get discouraged if that seems hopelessly vague. The flexibility of the above is actually a huge advantage: it lets the compiler treat large functions differently from small ones, plus it lets the compiler generate code that is easy to debug if you select the right compiler options.) [CPP]

I wonder what the ‘right’ compiler options are? Have an experiment and report back. It’s not just inline. Introduced in C++11, _Alignas is also a keyword in C11, where alignas is a preprocessor macro. [CPPRef]. Aside from this potential clash, the request for alignment may not be respected. Over-alignment (asking for a bigger number) may not be respected [Stackoverflow]. Some may say alignas is always respected for a reasonable use, i.e. no more than max_align_t. If surprising things happen in your code, it might be down to your misunderstanding. Optimisations can uncover data races and similar undefined behaviour (UB). Nasal demons may result [Maudel13].

One of the responsibilities is to learn and understand the contract between yourself and the compiler. If you break the contract, then anything can, and will, happen.

I’ve never witnessed demons flying from someone’s face, but have been confused by UB once in a while. You should respect the tools you are using, and take time to learn them. There will always be more to learn, but that’s what makes programming fun. If you get stuck, ask for help. The accu-general mailing list is a good place to turn to.

Enough of your compiler not respecting your requests, or you not respecting stated boundaries or requirements. Sometimes, respect is meant to be kind. Let’s help each other. And keep writing articles. [Maudel13] Olve Maudel ‘Demons may fly out of your nose’, Overload 115, https://accu.org/index.php/journals/1857

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Pass the Parcel

Python’s module and package system has many features. Steve Love explores some more advanced ones.

This is the second instalment, following on from the introduction to Python modules [Love20]. In that article, we looked at how to create your own modules, a little on how to split your program into modules to make sharing of the code easier, and how to structure packages to make testing them easier. In this article, we will take a more detailed look at making the packages you create easier to import and use. We will explore more ways to share your packages with others, and some ways of ensuring you can always have a dependable environment in which your code runs.

A little more on the import statement

In the previous article, we described a simple package with code to take input in one structured format, e.g. JSON or CSV, and turn it into another format, perhaps performing simple transformations on the way.

Listing 1 shows the basic usage of the code in our own package textfilters. For the sake of keeping the package contents tidy, we created some sub-packages so that the code to perform transformations was separate from the main package, and the tests for the package were all in one place, also separate. The package structure we ended up with is shown below.

```python
<project root/>
|__ main.py
|__ textfilters/
|  |__ __init__.py
|  |__ csv.py
|  |__ json.py
|  |__ transformers/
|  |  |__ __init__.py
|  |  |__ change.py
|  |  |__ choose.py
|  |__ tests/
|  |  |__ __init__.py
|  |  |__ test_filters.py
|  |  |__ test_change.py
|  |  |__ test_choose.py
```

This structure explains the two import statements in Listing 1: the first such import brings in the main filters for taking (in this case) CSV input and turning it into JSON output. The second import is pulling a single function – change_keys – from a module called change. This module is in a package named transformers, which is a sub-package of the textfilters package.

As we mentioned in the previous article [Love20], there are a few ways we could arrange the import statements, with alterations to the usage. The portion of the import line after the `import` statement effectively defines the namespace, so that first import line could be:

```python
import textfilters.csv
```

This demonstrates why namespaces are so important. Python already has a built-in module named `csv` (which our package’s `csv` module uses), and it’s not unimaginable that you would want to import both of those. Explicitly fully naming the `textfilters.csv` module allows Python’s `csv` module to also be used alongside it.

Python provides a shortcut to import all the names from a module. Consider the following:

```python
from textfilters.csv import *
```

By using this statement, all the names from the `textfilters.csv` module are imported into the current namespace. On the face of it, this seems great – we get to use the `input` function unadorned! However, there are pitfalls to this approach. Programming is more than a typing exercise, and names matter.

Whilst that `import *` directive did indeed bring the name of the function we wanted into the current scope, it also brought in every other name exported by the `csv` module (we will return to what ‘exported’ means later). This may, or may not be what you intended. To see why it’s important, create a file called `namespace.py` with the code below (a cut-down version of the `textfilters.csv` contents).

```python
import csv
def input( data ):
    return list( csv.DictReader( data ) )
```

Now run a Python interpreter session in the same directory, and try the following:

```python
>>> csv = '1,2,3'
>>> csv
'1,2,3'
```

Now run a Python interpreter session in the same directory, and try the following:

```python
from namespace import *
```

The import statement here requests that all the names from the `textfilters.csv` module are imported into the current namespace. On the face of it, this seems great – we get to use the `input` function unadorned! However, there are pitfalls to this approach. Programming is more than a typing exercise, and names matter.

Importing `*` from the `namespace` module then `over-writes` that value. I’m

Steve Love is an independent developer constantly searching for new ways to be more productive without endangering his inherent laziness. He can be contacted at steve@arventech.com
while you can be disciplined and always avoid the use of `import *`, you can’t very well impose that on everyone who might use your package.

### Explicit is better than implicit

When you import code from a module, take advantage of the namespace mechanism to ensure your own names don’t get hijacked by imported ones, and to minimize the risk of hiding other names, such as built-in modules. Prefer explicitly qualified names.

sure you can guess why, but to make this completely clear, when the `namespace` module invokes `import csv`, it’s bringing the name `csv` into its scope as an exported name along with the name `input`. When you import the `namespace` module, any exported names are brought into your scope, over-writing your own variable names where they clash.

Of course, while you can be disciplined and always avoid the use of `import *`, you can’t very well impose that on `everyone` who might use your package. There are ways of helping to prevent your users from shooting themselves in their own feet.

### Private names

Not all names are imported when you use the `from module import` form. Python has a convention for making names private to a module (or indeed, a class – the mechanism is the same) by prefixing it with an underscore. Consider the code in Listing 2.

If a user of this module now invokes `from textfilters.csv import *`, those names are not brought into scope. Note how this affects the usage within the module’s code. You can still explicitly request private names when you import from a module, because in Python, private doesn’t mean really private, it just means you have to try a little harder to get access to it.

### Define a public API

You can also limit the set of names brought into local scope when using `from module import *` by defining a module-level list of strings called `__all__`. If this value exists when `from module import *` is encountered, it is taken to mean ‘this is the list of all public names in the module’. It’s just a list of the names from the module you wish to be public. In the instance of the code in Listing 2, this would be defined as:

```
__all__ = [‘input’, ‘output’]
```

Adding this line to `textfilters/csv.py` will change the behaviour of `import *` for everyone so that only the names you defined will get imported.

```python
import csv as _stdcsv
from io import StringIO as _StringIO

def input( data ):
    parser = _stdcsv.DictReader( data )
    return list( parser )
...
```

Listing 2

What have we learned?
- Using `import *` imports all the public names from a module.
- You can rename imported things in the import statement.
- Prefixing names with an underscore makes them ‘private’, so `import *` does not import them.
- As the author of a module, you can also limit the names that `*` imports by defining a value for the special `__all__` list.
- As the user of a module, avoid using `import *`, as it can bring in unexpected names that may hide names in your code.

### Package initialization

In the previous instalment [Love20], we explored how packages are a special kind of Python module which can have sub-modules – some of which may also be packages. Python identifies a package by the existence of a file named `_init_.py`. What we didn’t mention was that this file gets ‘run’ by the Python interpreter when the package is imported, in much the same way that the top-level code of a simple module is run when imported.

This file can contain any Python code you like, but it’s useful for bringing sub-module names into a narrower scope. Consider again the directory layout of our package:

```
| textfilters/
| | __init__.py
| | _csv.py
| | transformers/
| | | __init__.py
| | | __change.py
| | | __choose.py

| __json.py
| __transformers/
| __choose.py
| __change.py
| __json.py
```

Functions inside the `change.py` sub-module of the sub-package `transformers` need a full-qualification when they’re imported:

```
from textfilters.transformers.change import change_keys
```

This is a bit unwieldy, but arises from the physical separation of the `change` module from the `choose` module. That physical separation helps us as the package author to structure the code for ease of maintenance, but imposes some unnecessary complexity on the users of our package. Listing 3 (overleaf) shows how I’d prefer to present the API to users.

I’ve already mentioned there is more to programming than typing, but there is more to this than reducing key-presses. Your public API needn’t be constrained by the physical structure of the code, and how you choose to lay out your package needn’t be limited by how you wish your users to use it. We can take advantage of the fact that Python, by default, exports all public names from a module – including the modules it imports.

In order to achieve my desired result, a couple of changes are required. The first is to the `transformers/__init__.py` file:

```
from .change import change_keys
```
A common mistake is to presume that importing a package causes Python to go and find all of its sub-modules and import the published names from them all.

```python
from textfilters import csv, json
from textfilters import reshape
import sys
if __name__ == '__main__':
    def key_toupper(k):
        return k.upper()
    data = csv.input( sys.stdin )
    result = [ reshape.change_keys( row, key_toupper ) for row in data ]
    print( json.output( result, sort_keys=True, indent=2 )
```

**Listing 3**

This brings the name `change_keys` into the scope of the `textfilters` namespace, and removes the need for users to explicitly name the intermediate `change` module name.

The second alteration is to the top-level package `__init__.py`.

```python
from . import transformers as reshape
```

This renames the namespace of `transformers` to be `reshape`.

As things stand, however, this will not work. You’ll get an error:

```python
AttributeError: module 'textfilters' has no attribute 'csv'.
```

A common mistake is to presume that importing a package causes Python to go and find all of its sub-modules and import the published names from them all. Such behaviour could be quite expensive! This is why the `__init__.py` file is so important – it is how a package defines all of its published names. In order to achieve what we want in Listing 4, we just need to bring the names `csv` and `json` into the package scope, using the top-level package’s `__init__.py`:

```python
import textfilters as tf
import sys
if __name__ == '__main__':
    def key_toupper(k):
        return k.upper()
    data = tf.csv.input( sys.stdin )
    result = [ tf.reshape.change_keys( row, key_toupper ) for row in data ]
    print( tf.json.output( result, sort_keys=True, indent=2 ) )
```

**Listing 4**

A similar mistake is to presume that `from textfilters import *` would cause Python to automatically load all the sub-modules. For the same reason as above, it does not. Not even the top-level modules (`csv` and `json`). The documented behaviour is that this imports the `textfilters` package, but in our case, `textfilters` is ‘just’ a directory. It does, however, run the `textfilters/__init__.py` and import any published names that result from that.

As with simple modules, packages also recognise the special `__all__` value as a list of strings naming the sub-modules to import. It’s crucial to note, however, that using `__all__` isn’t transitive. Suppose you have the following:

- In `textfilters/__init__.py`: `__all__ = [ 'transformers' ]`
- In `textfilters/transformers/__init__.py`: `__all__ = [ 'change', 'choose' ]`

If you invoke `from textfilters import *`, it will import the `transformers` sub-package, but the sub-packages defined by the `__all__` value in `transformers/__init__.py` will not be loaded. You would also need to invoke `from textfilters.transformers import *` to also bring those names.

You can’t use the top-level `__all__` value to import sub-packages, either. For example, the following will not work:

- `textfilters/__init__.py`
  ```python
  __all__ = [ 'transformers',
             'transformers_change' ]
  ```

The consequence of this is that defining the public API for a package is best done by importing or defining the names you want in `__init__.py`. It’s not necessary to also specify `__all__`, since importing `*` from a package won’t bring any unexpected names into scope, as it might with a simple module.

What have we learned?

- A package’s `__init__.py` file gets run when it’s imported, and this file can contain Python code.
- You can use the `__init__.py` to alter the public API of your package.
- Importing `*` from a package does not automatically bring in any of the public names, only what is defined in the `__init__.py`.

Creating an installable package

Sharing a package directly by copying the package directory, or even better, including it in a shared version control system, is sufficient in most cases. There can be benefits to having a cleaner separation between application and library code, however. One example might be that a package is used across multiple applications. In such a case, it is wasteful and error-prone to have the package sources duplicated in different directories. It’s easier, and supports better reuse, to package them up as a single package.

One way to do this is to use `setup.py`, which supplies a set of custom Python modules that the setuptools library understands. These modules are defined in various files within a directory, and the following `setup.py` file:

```python
from setuptools import setup, find_packages
setup(name='textfilters',
      packages=find_packages(),
      scripts=['scripts/textfilters.py'],
      version='0.1.0',
      description='A text filtering package.'
)```
repositories. It makes more sense to have the shared code separately version-controlled in its own shared repository.

Most modern version control systems have the facility to build a working copy from multiple repositories, so this shouldn’t present a problem. However, you can avoid the need for that by creating your own installable package. If you’ve used Python for anything more sophisticated than simple scripts, you’ll almost certainly have come across pip: the standard Python package installer. In this section we’ll explore how to create a package that can be installed using pip.

The very simplest installable package just needs a file named setup.py, located in the parent directory of the package itself (i.e. in the same directory as main.py in the example). Listing 5 shows the bare minimum contents.

```
from setuptools import setup, find_packages

setup(
    name = 'TextFilters',
    version = '0.0.0.dev1',
    packages = find_packages(),
)
```

Listing 5

The name and version properties are used to create the file name of the package. The version number here follows the recommended practice that is based on Semantic Versioning (see [PEP440] and [SemVer]). The pre-release specifier (.dev1 in this case) departs from the Semantic Version spec, and is the format understood by pip, which – when installing from a shared package repository like PyPI – ignores pre-releases unless they’re explicitly requested.

The last line uses a tool which automatically detects and includes any sub-packages (directories containing __init__.py). The packages property is merely a list of package and module names to be included, so you could explicitly name them:

```
packages = [ 'textfilters',
             'textfilters.transformers' ]
```

This invocation would exclude the tests sub-package, which might be what you intend. Note that sub-packages have to be explicitly named. If you have a large package with several sub-packages, the find_packages() utility is much more convenient. Note also that the file main.py will not be included. In our case, that’s intentional, because it’s not inside a package.

There are many more parameters accepted by the setup() function; we’ll examine a few of the common ones here, but a complete description, along with recommendations on version numbering schemes, and restrictions on things like the name property, can be found in the Python Packaging Guide (PPG). Many of those properties are used by the Python Package Index, PyPi.

For now, we have the bare essentials needed to create an installable package. To build it, run this command within the directory containing setup.py:

```
python setup.py bdist_wheel
```

This invocation creates a ‘binary distribution’, also known in Python circles as a wheel (see [PEP427] for all the gory details). If all went well, you will see a couple of new directories: build and dist, and the dist folder should have your installable package in it, named TextFilters-0.0.0.dev1-py3-none-any.whl. You can create ‘source distributions’, too, if the package is pure Python code, but it doesn’t have any real benefit over a wheel format package.

The components of the file name are partly taken from the name and version parameters given to the setup() function in setup.py (refer back to Listing 5). The last 3 parts identify the targeted Python language version (py3), the ABI (none, in this case) and the required platform (which we didn’t specify, and so is any). You can control these with other parameters to the setup() function, but for our purposes, the code in the package is indeed intended for Python 3, and is pure Python code, with no ABI or platform requirements, so the defaults are appropriate.

The file itself is just a normal Zip file with a .whl extension, so you can examine the contents for yourself (I find 7-zip especially useful). Before we install our shiny new package, however, we should talk about segregation.

Partitioning and separation

Python comes with a rich standard library of tools, some of which our example package is using – csv and json. You can also install 3rd party modules, and our package is using pytest. In [Love20], we looked at how Python locates modules when they’re imported. As a reminder, here is the basic Python algorithm for finding modules:

1. The directory containing the script being invoked, or an empty string to indicate the current working directory in the case where Python is invoked with no script – i.e. interactively.
2. The contents of the environment variable PYTHONPATH. You can alter this to change how modules are located when they’re imported.
3. System defined search paths for built-in modules.
4. The root of the site module.

It’s number 4 we’re interested in now – the site module. When you install a 3rd party package (such as pytest), it is installed into a directory named site-packages, which is a well-known location for the Python interpreter (the location may differ, depending on your platform). Whilst it is obviously convenient to have all the packages you want in one place, easily available for use in your Python programs, it can easily become cluttered. In particular, you might not want (or be able) to install the packages you create to the global site location, especially when they’re in early development.

One way to handle this might be to have multiple installations of Python, but this is wasteful unless you genuinely need multiple versions of Python available. A more light-weight way of handling it is to take advantage of Python’s virtual environments. These are a fully-featured Python environment, but cut back to the bare minimum needed. They don’t contain the 3rd party modules installed in the global Python install location (but you can choose to give a virtual environment access to those libraries) except for a few necessities – including the pip installer module. The important thing is that a virtual environment is entirely independent of all other virtual environments, with its own site-packages location.

The implication of this is that you can create Python virtual environments with different libraries for different needs. This is useful now as a way of quarantining our custom package so that it doesn’t interfere with either the installed Python instance, or anyone else’s virtual environments. You should consider creating your environment somewhere outside of your code folders, maybe by putting the code beneath a new directory (named something like src, for example), and using the parent to hold the new environment.

```
python -m venv localpy
```

On some platforms you may be prompted to install a package for venv to work, for example on my Ubuntu-based Mint distribution, I had to install python3-venv.

This creates a new Python environment in a directory named localpy as a child of the current directory. You can choose wherever you like for it. If all’s gone to plan, you should now have a directory structure like this:

```
<project root>/
  |__src/
  |  |__main.py
  |__setup.py
  |__textfilters/
  |  |__...
  |__localpy/
  |  |__...
```
The structure of the environment will differ, depending on your platform, but will contain Python itself (on Windows, in `\localpy\scripts\pip.exe`, on *nix it’s in `localpy/bin`), along with `pip` to install more libraries, and a script named `activate`.

The `activate` script ensures that the virtual environment’s Python and `pip` are at the front of the current session’s path. It’s not necessary to always activate a virtual environment, however: you can invoke the Python interpreter by fully-qualifying the directory name, and it will ‘just work’. This extends to using `pip` to install packages.

- Windows
  ```cmd
  \localpy\scripts\pip.exe install [package name]
  ```
- Mint (Ubuntu)
  ```cmd
  \localpy/bin/pip install [package name]
  ```

Python internally keeps track of where to find the platform-independent and platform-dependent files it needs in order to run, and where to find installed libraries. These are:

```python
sys.prefix
sys.exec_prefix
```

When a virtual environment is in use (either by activation, or by running the Python program), these values will point to the respective locations within the virtual environment. When no virtual environment is in use, these values point to the locations of the respective Python installation locations. Furthermore, when a virtual environment is in use, two more values can be used to find the location of the Python install from which the virtual environment was created:

```python
sys.base_prefix
sys.base_exec_prefix
```

These values enable the virtual environment to operate independently of the main Python installation(s), as well as any other virtual environments. You can find much more detailed information on how these things work in [venv] and [site], but for our purposes, all that remains is to install our local package into the independent environment. It’s as simple as (on Windows):

```cmd
\localpy\scripts\pip install src\dist\TextFilters-0.0.0.dev1-py3-none-any.whl
```

If you now run a Python session using the virtual environment’s Python, you can import the `textfilters` package, and see from where it was imported:

```python
>>> import textfilters
>>> textfilters
<module 'textfilters' from 'C:\path\to\localpy\lib\site-packages\textfilters\__init__.py'>
```

(This will look slightly different on non-Windows platforms, but the idea is the same).

What have we learned?

- You can create your own installable package to make sharing code even easier.
- Python wheels are zip-files.
- The site module is where Python looks for installed packages for use in code.
- Python virtual environments are a powerful way of segregating requirements with its own, independent site module.

It depends

Sometimes, a package you create will require other packages to be installed. In the case of our package, it can be used without anything other than Python’s standard libraries, but it does have some tests. Whilst they don’t depend exclusively on `pytest`, which is the testing package we used in [Love20] (other frameworks are available, such as Nose2 [Nose2], which would also work just fine), we can use it to explore another feature of package creation.

```python
from setuptools import setup, find_packages
setup(
    name = 'TextFilters',
    version = '0.0.0.dev1',
    packages = find_packages(),
    install_requires = [ 'pytest' ],
)
```

In the `setup.py` file we created for our package, we can indicate that our package requires other libraries. In this case, we can tell the setup tools that the package `pytest` should also be installed when our package is installed.

Listing 6 shows a change to `setup.py` with the addition of a parameter to the `setup()` function named `install_requires`. This is a list of packages, which in this case has only one item, but you can specify as many as you need here.

Now re-create the package, and re-install it with an upgrade:

```cmd
\localpy\scripts\python src\setup.py bdist_wheel
\localpy\scripts\pip install --upgrade dist\TextFilters-0.0.0.dev1-py3-none-any.whl
```

You will see that `pytest`, along with its requirements, is also automatically installed.

Sometimes you need a particular version of a dependent package, or perhaps you’ve tested on a particular stable release, and wish to constrain the versions of your dependencies. This is also specified in `setup.py`:

```python
install_requires = [ 'pytest>=5.0' ],
```

You can also depend on specific versions of Python itself in the `setup.py` parameters. In the case of our package, we may well want to ensure our users are on Python v3 or above. There are many reasons to do this, but chief among them is that the code in a package depends on some feature that was introduced in a specific Python release.

```python
python_requires = '>=3',
```

There is much more you can specify, and describe, about your package in the `setup.py` file, but you can find a wealth of documentation on that in the Python packaging guide ([dist]). We do need to revisit one aspect we’ve already looked at briefly – the version number.

As we’ve already seen, the version number specified in `setup.py` gets used to generate the file name of the resulting package wheel. In our example, we marked the version with a trailing `.dev1`, which marks the package as a pre-release – specifically, still in development – which is used by `pip` when performing upgrades.

Given a package with a version number indicating it’s stable (e.g. 0.0.1), and a later version that’s marked as a pre-release (e.g. 0.1.0a1), when performing an upgrade, `pip` will by default give you the latest applicable stable release, which in this case is 0.0.1. You can explicitly request that pre-releases are considered by passing the `--pre` argument to `pip` on the command line, or by specifically requesting a pre-release version.

Whilst we’re in development mode, and installing specific locally-created wheels, this isn’t an issue for our package, of course, but it does make a difference for the dependent packages in the `install_requires` list. It also makes a difference in a file that’s normally named `requirements.txt` (but needn’t be, necessarily), which is a file you

<table>
<thead>
<tr>
<th>Know your dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowling the full set of dependent packages, right down to individual versions, makes sharing an application code base easier. Allowing different versions of libraries within a team can lead to very difficult-to-track errors.</td>
</tr>
</tbody>
</table>

3. Setting an upper limit on the version is possible too, but be careful of that. If you tie down your requirements too tightly, it might make your package unusable.
can use alongside a virtual environment to have `pip` install a whole collection of packages. This is a useful technique for specifying the library contents of a virtual environment, with needed packages at specific versions. It’s common to want this to ensure, for example, that different developers on a team have *identical* environments; if one person is developing against version 1 of some package, and someone else is using version 2, chaos is bound to ensue! The `requirements` file provides a way of creating a coherent environment that the whole team can use.

The simplest way to create the requirements file is to have `pip` itself create one:

```
localpy\scripts\pip freeze > requirements.txt
```

The requirements file should contain something similar to this (truncated here for brevity):

```
...  
pytest==5.4.1  
six==1.14.0  
TextFilters==0.0.0.dev1  
...  
```

Here, the file requires a specific version of each installed package. You can modify the version numbers if you need versions after a particular one, or within a range of versions, for example. Note that our own package, `TextFilters`, is explicitly naming the pre-release version. Suppose we had been working on the package for a while, and had a few releases available in our directory:

```
TextFilters-0.0.0.dev1-py3-none-any.whl  
TextFilters-0.0.1-py3-none-any.whl  
TextFilters-0.0.2.dev1-py3-none-any.whl  
TextFilters-0.0.2.dev1-py3-none-any.whl  
TextFilters-0.0.2.dev1-py3-none-any.whl  
```

We have stable 0.0.1 and 0.0.2 versions, but only a pre-release for 0.0.3. Our `requirements.txt` file might have this line:

```
TextFilters==0.0.1  
```

We might create our virtual environment from scratch as follows:

```
python -m venv localpy  
localpy\scripts\pip install -r requirements.txt  
```

Here, the `-r` parameter to `pip` instructs it to read the list of packages to install from the indicated file. By default, pip looks on PyPI [PyPI] for packages, but we haven’t published our package there yet, so the `-f` parameter tells `pip` to find packages in the specified location (which might, for example, be a file share available to the team), and look in PyPI for packages not found there.

This would result in our new environment having version 0.0.2 of our `TextFilters` package, because it’s the latest stable version available. If we had also added the parameter `--pre` to the pip command line, the latest pre-release version – 0.0.3a1 – would have been installed.

What have we learned?

- An installable package can explicitly define other packages upon which it depends.
- The `pip` installer makes sophisticated use of the version numbers exposed by a package to determine how to install requirements.
- You can easily create a canned fully-working virtual environment by using a library requirements file.

### A wider audience

In this article we’ve explored in more detail the idea of Python ‘namespaces’, and how you can take advantage of package initialization to make using your package easier for your users. We’ve looked at some of the pitfalls of wild-card imports, and highlighted the benefits of creating a public API for your modules that might not match its physical structure. We also explored virtual environments, and how to create and install your own package ‘wheels’, and looked at why this segregation is important. Finally we looked at package dependencies, and how to manage them in concert with virtual environments and the `pip` installer.

Taken all together, these things will help you structure your packages so they can be shared easily, and your users will find your packages easier to install and use as a result.

There is more you can do with your own packages. For example, in the previous article we looked at the `pytest` unit-testing framework, and in this article we’ve looked at Python’s `venv`. Both of these are installable modules that can be run, e.g.:

```
python -m venv
```

This is achieved by adding another special file to the package: `__main__.py`, which is executed when the package is run in this way.

The ultimate sharing of packages with the wider community means publishing it to the Python Package Index ([PyPI]). There is excellent documentation on this in the Python packaging guide ([PPG]). Taking this extra step involves some extra responsibility, of course, in maintaining and documenting your package.

These things – and more! – I leave for you to discover.

### References


### Other resources

‘Packaging a Python library’, https://blog.ionelmc.ro/2014/05/25/python-packaging/#the-structure

4. I wanted to explore this a bit more in the example package, but was defeated by the fact I’d (deliberately) used names that clashed with built-in Python modules. Another example of why not to do that!
Quick Modular Calculations (Part 3)

This article concludes the 3-part series. Cassio Neri presents a new algorithm that also works for 64-bit operands.

Recall and warm up

Figure 1 graphs the time taken by different algorithms to check whether each element of an array of 65,536 uniformly distributed unsigned 64-bit dividends in the interval $[0, 10^6]$ leaves a remainder less than 5 when each element of an array of 65,536 uniformly distributed unsigned 64-bit dividends is used as unit of time. All algorithms, including new_algo, are implemented in qmodular. Recall once again that the intention is not to ‘beat’ the compiler but, on the contrary, to help it. The hope is that compiler writers will consider incorporating these algorithms into their products for the benefit of all programmers. As I reported in [Neri19], minverse has been implemented by GCC since version 9.1 but the implementation falls back to a less efficient algorithm for certain inputs. Indeed, Euclidean division states that any integer $n$ can be uniquely written as $n = q \cdot d + r$, where $q$ and $r$ are integers with $0 \leq r < d$. Dividing this equality by $d$ gives that $q$ and $r/d$ are, respectively, the integer and fractional parts of $n/d$. Hence, knowing the fractional part of $n/d$, or an approximation of it, is enough to identify $r$. Since $d$ is known by the compiler, an approximation $M$ of $1/d$ is precomputed at compile time and only the cheaper multiplication $n \cdot M$ is performed at runtime. The multiplication has the effect of increasing the error and when $n$ is large enough the result is unreliable to allow the identification of $r$.

The last paragraph’s arguments supported the works of mshift and mcomp [Neri20] and they equally support new_algo’s main ideas by means of examples. (Deeper previous work on the same algorithm.

Finally, recall that we are interested in modular expressions where the divisor is a compile time constant and the dividend is a runtime variable. The value compared to the remainder can be either. They all have the same unsigned integer type which implements modulus $2^w$ arithmetic. (Typically, $w = 32$ or $w = 64$.) We focus on GCC 8.2.1 for the x86_64 target but some ideas might also apply to other platforms.

The new_algo

The fractional part of $n/d$ corresponds to the remainder of the division. Indeed, Euclidean division states that any integer $n$ can be uniquely written as $n = q \cdot d + r$, where $q$ and $r$ are integers with $0 \leq r < d$. Dividing this equality by $d$ gives that $q$ and $r/d$ are, respectively, the integer and fractional parts of $n/d$. Hence, knowing the fractional part of $n/d$, or an approximation of it, is enough to identify $r$. Since $d$ is known by the compiler, an approximation $M$ of $1/d$ is precomputed at compile time and only the cheaper multiplication $n \cdot M$ is performed at runtime. The multiplication has the effect of increasing the error and when $n$ is large enough the result is unreliable to allow the identification of $r$. The last paragraph’s arguments supported the works of mshift and mcomp [Neri20] and they equally support new_algo. The novelty is that this algorithm, rather than accepting the approximation error until the result becomes unreliable, takes steps to reduce the error. As a consequence, the algorithm’s applicability is extended. As usual in this series, we shall present new_algo’s main ideas by means of examples. (Deeper previous work on the same algorithm.

1. I would be grateful if a well-informed reader could point me towards a previous work on the same algorithm.
2. Powered by quick-bench.com. For readers who are C++ programmers and do not know this site, I strongly recommend checking it out. In addition, I politely ask all readers to consider contributing to the site to keep it running. (Disclaimer: apart from being a regular user and donor, I have no other affiliation with this site.)
3. YMMV. Reported numbers were obtained by a single run in quick-bench.com using GCC 8.2 with -O3 and -std=c++17 [QuickBench]. I do not know details about the platform it runs on, especially, the processor.

Cassio Neri

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The hope is that compiler writers will consider incorporating these algorithms into their products for the benefit of all programmers.

Table 1

<table>
<thead>
<tr>
<th>n</th>
<th>(n/7)₂</th>
<th>(n \cdot M)₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>3</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>4</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>5</td>
<td>0.101</td>
<td>0.101</td>
</tr>
<tr>
<td>6</td>
<td>0.110</td>
<td>0.110</td>
</tr>
<tr>
<td>7</td>
<td>0.111</td>
<td>0.111</td>
</tr>
<tr>
<td>8</td>
<td>1.001</td>
<td>1.001</td>
</tr>
</tbody>
</table>

Table 1 contrasts, for all \(n \in \{0, \ldots, 8\}\), the binary expansions of \(n/7\) and \(n \cdot M\). Bits are grouped in triples to highlight the period. Observe that for \(n \leq 7\), multiplication by \(1/7\) and by \(M\) can be done separately on each triple, since the result of one group does not spill to its left. (Take notice that the 2nd column shows \(n/7 = (0.1111111...)₂\) which is the binary analog of \(1 = 0.999\ldots\). This exemplifies the relevance for new_algo of the periodic representation of terminating expansions.)

The row for \(n = 8\) is the first where the fractional parts of \(n/7\) and \(n \cdot M\), up to the 9th bit, differ. (The relevant triple of bits is emphasised.) To understand the origin of this difference, we observe that this row can be obtained from the one for \(n = 1\) by multiplication by 8 or, equivalently, by left shift by 3. The 2nd column illustrates infinite precision and the periodicity ensures that any triple of bits after the binary point has a replica on its right which is also left-shifted. This contrasts to the 3rd column, where the bits feeding the left shift at the rightmost position are 0s. Having realised that there is an error coming from the right, we shall see how new_algo reduces it.

The previous paragraph pointed out a discrepancy between the fractional parts of \(n/7\) and \(n \cdot M\) for \(n = 8\). Observe now the disparity between the integral parts. It turns out the two divergences compensate each other and by uniting the two parts we can correct the error of division.

Figure 2 illustrates the steps of the process (grey 0-bits are included for clarity) as applied to \(n = 8\): right shift the integer part of \(n \cdot M\) by 9 bits and add the result to \(n/7\). Comparing the outcome with \(8/7\) (shown in Table 1) we realise it is much closer than the original value \(8 \cdot M\) is.

The procedure is very effective in making the fractional parts of the result for \(n = 8\) identical to that for \(n = 1\), that is, \((0.001\ 001\ 001)₂\).

The fact that multiplication by \(n = 8\) is equivalent to left shift by 3 bits makes clear that the quantity on the left of the binary point is the exact amount required to correct the error on the right. For other values of \(n\), this property might be more difficult to see but it still holds. For instance, consider \(n = 15\), which is the next dividend with remainder 1. Then \(n \cdot M\)

Listing 1

```assembly
built_in
0: movabs $0x2492492492492492,%rdx
 a: mov %rdi, %rax
 d: mul %rdx
10: mov %rdi, %rax
13: sub %rdx, %rax
16: shr %rax
19: add %rax, %rdx
1c: shr %0x2,%rdx
20: lea 0x0(%rdx,8),%rax
28: sub %rdx, %rax
2b: sub %rdx, %rax
2c: cmp %rdi, %rax
30: mov %rdi,%rax
32: setbe %al
35: retq

new_algo
0: movabs $0x2492492492492492,%rcx
 a: mov %rdi, %rax
 d: mul %rcx
10: add %rcx, %rax
13: lea (%rax,%rdx,2),%rdx
17: movabs $0xb6b6b6b6b6b6b6b6,%rax
21: cmp %rax, %rdx
24: setbe %al
27: retq
```

mathematical proofs of correctness can be seen in [qmodular] and references therein.)

Although a rigorous proof is out of scope, the fundamental idea behind new algo’s error reduction has elementary school level: the periodicity of decimal expansions of rational numbers. For example, \(1/3 = 0.333\ldots\) and the sequence of 3s goes on indefinitely. Also, \(1/7 = 0.142857\ldots\) and 142857 repeats over and over. Some readers might object and point to terminating expansions like \(1/2 = 0.5\) or, even more obvious, \(1/1 = 1\).

Nevertheless, a terminating expansion can be identified with a periodic one by appending an infinity of trailing 0s. For instance, \(0.5 = 0.5000\ldots\) and \(1 = 1.000\ldots\). Furthermore, a terminating expansion is also identified with yet another periodic representation ending in 9s. Indeed, recall (or try to convince yourself) that \(0.5 = 0.4999\ldots\) and \(1 = 0.999\ldots\). More generally, periodicity occurs for any base and, in particular, in binary expansions. For instance, \(1/7 = (0.001001\ldots)₂\), with repeating 011 built_in.

Reality kicks in again to remind us that CPUs have finite precision. In practice, \(n, d\) and \(r\) are 32 or 64 bits long but, for ease of exposition, we assume the number of bits is \(w = 10\). Hence, truncation at the 10th bit after the binary point yields \(1/7 \approx (0.001001001)₂\). Keeping the example of the previous section in mind, we set \(d = 7\) and the approximation \(M = (0.001001001)₂\) of \(1/7\).

4. I cannot help myself from highlighting the beauty of this simplicity.
Table 1 shows that the integer part of the outcome is off by deficiency when compared to the expected result. Therefore, for \( n \cdot M \) has up to 20 bits. How can a 10-bit CPU calculate such a number? In the real world, the question is how can a x86_64 CPU compute the 128-bit product of two 64-bit operands? The mul instruction (see Listing 1) does exactly that, by splitting the 128-bit product into its 64-bit higher and lower parts and storing them in registers edx and eax, respectively. Coming back to our exposition, we assume that our imaginary 10-bit CPU provides a similar mul instruction.

Notwithstanding the change in the definition of \( M \), figures 2, 3 and 4, still illustrate the correction with little differences. Previously, the small dot symbolised the binary point but now it separates the higher and lower parts.

To correctly align the bits of the higher part to those of the lower one, the higher part, it can be performed in modulus 2^{10} arithmetic.

Putting all pieces together, a C++ implementation of new algo to evaluate \( n \% d < r \) looks like this:

```c++
bool has_remainder(uint_t n, uint_t r) {
    auto [high, low] = mul(M, n);
    uint_t f = low + (high << k);
    return f + M <= r * M;
}
```

where mul(M, n) returns a pair of uint_t with the higher and lower parts of \( M \times n \). The last line is the condition \( 0 < f(n) + M \leq r \cdot M \) in simplified form since it can be shown that \( 0 < f(n) \) always holds.

For readers accustomed to x86_64 assembly, it should not be difficult to recognise the C++ code above in Listing 1. (With compile time constants \( M = 02x0010010010010010 \), \( k = 1 \) and \( r * M = 5 * M = 0xb6db6db6db6db6da \)).

A naive implementation of new algo for \( n \% d == r \) follows:

```c++
bool has_remainder(uint_t n, uint_t r) {
    auto [high, low] = mul(M, n);
    uint_t f = low + (high << k);
    return f + M <= r * M;
}
```

The last line comes from \( r \cdot M < f(n) + M \leq (r + 1) \cdot M \). This code contains many inefficiencies (e.g., the branch implied by \( \&\& \) and is shown for exhibition only. A faster implementation is provided in [qmodular]. Depending on a number of factors, many optimisations are possible. For instance, for small values of \( k \), the addition and left shift in the second line can be combined in a single lea instruction. (See Listing 1.) Also, as we have seen, for larger values of \( k \) the only condition to be tested is \( f(n) > r \cdot M \). The important point here is that new algo’s final form depends on several aspects that have a visible impact on the performance, as we shall see in the next section.

**Performance analysis**

As in the warm up, all measurements shown in this section concern the evaluation of modular expressions for 65,536 uniformly distributed unsigned 64-bit dividends in the interval \([0, 10^6]\). Charts show divisors on the x-axis and time measurements, in nanoseconds, on the y-axis. Timings are adjusted to account for the time of array scanning.
For clarity, we restrict divisors to \([1, 50]\) which suffices to spot trends. (Results for divisors up to 1,000 are available in [qmodular].) In addition, we filter out divisors that are powers of two since the bitwise trick (see [Warren13]) is undoubtedly the best algorithm for them.

The timings were obtained with the help of Google Benchmark [Google] running on an AMD Ryzen 7 1800X Eight-Core Processor @ 3600Mhz; caches: L1 Data 32K (x8), L1 Instruction 64K (x8), L2 Unified 512K (x8), L3 Unified 8192K (x2).

Figure 5 concerns the evaluation of \(n \mod d = 0\). Readers might already be familiar with minverse’s zigzag and its great performance. Although mcomp and mshift are even faster and have a pretty regular performance across divisors (a good feature on its own), recall they are not available for all values of \(n\). They are shown here for the sake of completeness but in practice a compiler cannot use them.

Looking at new_algo, we observe that its performance changes considerably across divisors depending on the availability of different micro-optimisations. Actually, new_algo is not very performant here and given the limitations of mcomp and mshift, we conclude that minverse is the best option.

Figure 6 shows the evaluation of \(n \mod d = 1\). Due to mshift’s and mcomp’s limitation, they have now been excluded from this picture. The situation changed considerably with respect to the previous case. Indeed, new_algo beats the built_in algorithm for all divisors shown and for a handful of them (e.g., \(d = 14\)) it even beats minverse.

Finally, Figure 7 considers the expression \(n \mod d > 1\). Recall that minverse cannot evaluate this expression. It is fair to say that new_algo beats the built_in algorithm for most of the divisors shown in the picture.

Conclusion

We presented a new algorithm, designated here as new_algo, for the evaluation of certain modular expressions. It overcomes limitations of other algorithms previously seen in this series [Neri19] and [Neri20]. Specifically, minverse cannot be used for expressions like \(n \mod d < r\) and mshift and mcomp cannot be efficiently implemented in 64-bit CPUs. Alas, the new_algo has its own limitation: it is not available for all divisors.

Like mshift and mcomp, new_algo operates on an approximation of \(n / d\) which contains an error that increases with the numerator. Contrarily to the others, new_algo performs steps to delay the error growth by using the periodicity of binary expansions of rational numbers. In essence, errors on the right side of the truncated expansion can be corrected using bits appearing on the left.

Performance analysis shows that, in some cases, new_algo can be faster than others. However, it is worth mentioning that no algorithm seen in this series beats all others in all circumstances. Therefore, a compiler aiming to emit the most efficient code for modular expressions needs to implement all these algorithms and carefully pick the one that is best for the particular case in hand. Amongst other aspects, this decision must consider the value of the divisor, the type of the expression (e.g., \(n \mod d = r\) as opposed to \(n \mod d > r\)), the size of operands (32 versus 64 bits). A particularly interesting point about new_algo is that to emit efficient code just for this one algorithm, the compiler (writer) has already to deal with many choices of micro-optimisations.

This article brings this series to an end but more research is needed. To compiler writers: “I don’t know why you say goodbye, I say hello.”

Acknowledgements

I am deeply thankful to Fabio Fernandes for the incredible advice he provided during the research phase of this project. I am equally grateful to Lorenz Schneider and the Overload team for helping improve the manuscript.

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[Godbolt] https://godbolt.org/z/xxMLeP
[Google] https://github.com/google/benchmark
[QuickBench] http://quick-bench.com/"of3Bm1mHz3_pb8SuLHV4NdqY1edw
[qmodular] https://github.com/cassioneri/qmodular
Deconstructing Inheritance

Inheritance can be overused. Lucian Radu Teodorescu considers how it can go wrong and the alternatives.

After glancing at the title, the reader might accuse me of trying to destroy inheritance; probably by arguing that it should be replaced by some other mechanism. But that is not the case; that is not my intent. According to Merriam-Webster [MW], deconstruction is defined as:

> a philosophical or critical method which asserts that meanings, metaphysical constructs, and hierarchical oppositions (as between key terms in a philosophical or literary work) are always rendered unstable by their dependence on ultimately arbitrary signifiers

> the analytic examination of something (such as a theory) often in order to reveal its inadequacy

My intent here is to reveal inheritance’s actual meanings versus the meanings that most Object-Oriented programmers will infuse it with; to show hidden oppositions in its structure, to show that some signifiers are somehow arbitrary, and finally to reveal inner inadequacies. The main point is to test the limits of inheritance, and how far we can go until our beliefs about inheritance break.

One of the main topics of the article will be the relation between inheritance and the is-a relationship, and how this connects to the principle of correspondence (the common design belief that modelling OOP software should maintain a correspondence to the real-world that the software somehow models). Another important topic that is frequently referred to in this article is the Liskov Substitution Principle (LSP) [Liskov94] [Liskov88].

These two topics are a crucial point in analysing inheritance. They both define what inheritance is, but also subversively work against it, creating this amorphous concept that encompasses both good and bad.

Some simple problems are hard

Let’s look at a very simple OOP modelling problem: we want to model the Rectangle and the Square concepts in software. For our problem, we are only interested in dimensions. As the two concepts are closely related in the real-world, we want to relate them with an inheritance in our software. There are 2 main options:

- make Rectangle inherit from Square
- make Square inherit from Rectangle

Let us analyse both options.

**Rectangle is-a Square**

First thing: this is mathematically incorrect. In the real-world, the is-a relationship is revered. But, let’s ignore this for a moment. Let’s look at the code in Listing 1, which is modelling Rectangle is-a Square.

```cpp
class Square {
    int size;
    public:
        virtual int getSize() const { return size; }
        virtual void setSize(int x) { size = x; }
        virtual int getArea() const {
            return size*size; }
    }

class Rectangle: public Square {
    int width;
    public:
        virtual int getWidth() const { return width; }
        virtual int getHeight() const {
            return Square::getSize(); }
        virtual void setSize(int x) {
            Square::setSize(x); width = x; }
        virtual void setWidth(int x) { width = x; }
        virtual void setHeight(int x) {
            Square::setSize(x); }
        virtual int getArea() const {
            return width*getSize(); }
    }
```

Not only is the mathematical relation broken, but the interface of the Rectangle class is polluted by concerns that it doesn’t have (size is confusing for Rectangle). Moreover, we can easily find an example (see Listing 2) in which this breaks the LSP test (if you change the type, does the code still functions well?).

Passing a Rectangle object to the increaseArea function will make the code break. This variant is definitely not right. Let’s try the other one.

**Square is-a Rectangle**

Let’s look at the code in Listing 3 (overleaf).

Mathematically, this seems to be correct. And the interface of Square is not necessarily polluted with the unneeded stuff (the inherited methods can be hidden). Let’s now try to see if it passes the LSP test (see Listing 4).

Similarly to the previous test, if we assume that \( r \) is a veritable rectangle, doubling the width will double the area. But, if \( r \) is a square, then the area will increase by 4 times.

```cpp
void increaseArea(Square& square) {
    auto oldArea = square.getArea();
    square.setSize(square.getSize() * 2);
    auto newArea = square.getArea();
    assert(newArea == 4 * oldArea);
}
```

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Another problem is with the existence of the `setWidth` and `setHeight` functions of the base class. No matter how we override them in the derived class, the existence of these setters will make possible clients of `Rectangle` break. If we ignore to override them, it’s easy to see that a call to any of these will break the invariants of `Square`. If we throw exceptions, we may break `Rectangle` clients that used to work ok. If we change both the width and the height when one setter is called, then we can find examples similar to Listing 4. There is no reasonable override to these methods that cannot be proven to be wrong with the help of LSP.

More discussion

The previous examples showed us that, if we want to force the mathematical relationship between area and the sizes of the square/rectangle, no matter how we do the inheritance, we cannot do it right. One good observation that will allow us to fix things is to remove the setters; make objects of those two classes immutable. Something similar to the code in Listing 5. This code doesn’t break LSP as, once created, the objects cannot be made to break their invariants. However, then the main question that arises is what are actually gaining from the inheritance anyway? We occupy more memory for the `Square` objects, and we make a few functions virtual, that most probably are not used. The only thing that is reused is the `area()` method, which, mostly by coincidence, did not need rewritten. Adding inheritance here does not help us.

Let’s look at what others are saying about this problem:

The truth is that Squares and Rectangles, even immutable Squares and Rectangles, ought not be associated by inheritance – Robert C. Martin

The class Square is not a square, it is a program that represents a square. The class Rectangle is not a rectangle, it is a program that represents a rectangle. […] The fact that a square is a rectangle does not mean that their representatives share the ISA relationship. – Robert C. Martin

ISA is useful when trying to model real world relations to make class hierarchies intuitive, but classes are metaphors, and metaphors, if extended too far will break – Bjørn Konestabo

One cannot use inheritance to model a very simple mathematical problem. Even though we have a good insight into what the real-word concepts mean when we place them into code, the metaphor breaks. Inheritance doesn’t work the way the is-a relationship works in mathematics.

Concepts, is-a and inheritance

The previous sections showed us that inheritance cannot always properly model the is-a relationships from the real-world. Let’s look at some more cases in which the analogy with the real-world breaks.

Let’s think of modelling an elevator system. Besides the elevator car, motor or doors, we have a lot of buttons. We have buttons on each floor (up/down), we have buttons inside the elevator, both for floors and for cancelling or alerting. We can model the system as shown in Figure 1 (overleaf). But we can also model it with Figure 2.

Or, we can simply model everything with just one `Button` class (Figure 3).

To be honest, I would probably go for the last option, but that doesn’t matter too much for this discussion.
each time we look at inheritance, instead of thinking about is-a relationships, we should think of behaves-like-a relationships

If we carefully look at the various methods (and others can easily be found), we realise that the Button concept is probably the only real-world concept. Things like TravelButton, InsideButton, and FloorButton are concepts invented in software modelling, and then somehow look real. Nobody thinks of an inside-button concept in the real world. Yes, we sometimes distinguish between buttons that are inside the lift car and the ones that are fixed to the floors, but that’s a property of the objects themselves; inside-button and outside-button are not strong enough to be concepts by themselves.

Without dwelling too much on the semantics of the concept concept, we observe a discrepancy between concepts inspired between real-life (concepts as building blocks of thoughts) and concepts that are generated through our design process (concepts as sets, that can always be divided into smaller sets). If we want to stick to the classes that should be inspired by real-world concepts, we should probably abandon the second type of concepts.

And now we’ve reached the fun part: what does ‘is-a’ mean? What does it take for a concept to be another concept? Too bad for us that metaphysics has not been able to figure out the answer to this issue in the last 2000+ years. While we wait for the philosophers to figure this out, we can safely assume at least that we cannot say A is-a B if A and B belong to different species. And, in our case, we just argued that InsideButton and Button belong to different species: one in an artificially constructed concept and one is a real-world inspired concept. That means that is improper to say that InsideButton is-a Button (at least, not while considering Button as a real-world concept).

A far more useful relation would be the behaves-like-a relationship. We can safely say that InsideButton behaves-like-a Button, even if the two concepts come from different worlds (e.g., a dolphin can behave like a fish even if it’s not a fish). Moreover, from a software perspective, we are only interested in the behaves-like-a relationship, and we can leave the is-a to metaphysics. When I say D behaves-like-a B, what I mean is that D inherits all the properties of B, that I can use D in all the places that I would use B. But this is exactly what the Liskov Substitution Principle says.

So, in other words, each time we look at inheritance, instead of thinking about is-a relationships, we should think of behaves-like-a relationships, and then immediately think of LSP.

If my digression into semiotics and metaphysics left the users too confused, maybe a quote would do better [Sutter04]:

> The “is-a” description of public inheritance is misunderstood when people use it to draw irrelevant real-world analogies: A square “is-a” rectangle (mathematically) but a Square is not a Rectangle (behaviorally). Consequently, instead of “is-a,” we prefer to say “works-like-a” (or, if you prefer, “usable-as-a”) to make the description less prone to misunderstanding.

To prove my point, this quote was taken from the chapter named ‘Public inheritance is substitutability. Inherit, not to reuse, but to be reused’. Public inheritance is substitutability. q.e.d.

**On the fine details of LSP**

Formally, LSP states the following [Liskov94]:

Subtype requirement: Let ?(x) be a property provable about objects x of type T. Then ?(y) should be true for objects y of type S where S is a subtype of T.

The informal principle goes the following way [Liskov88] (see also [ObjectMentor03]):

If for each object o1 of type S there is an object o2 of type T such that for all programs P defined in terms of T, the behavior of P is unchanged when o1 is substituted for o2 then S is a subtype of T.

It basically defines what a subtyping relation should be, and by extension, it describes what successful inheritance should be.
Inheritance was supposed to be an abstraction feature, one that reduces the complexity of the software.

LSP and invariants

Let’s now analyse how LSP applies from a different point of view: that of maintaining invariants. The base class has some invariants. The main question would be for a derived class on how it can change the behaviour of the objects while maintaining the same invariants – after all, invariants are visible properties, and LSP dictates that they should not change.

One can think of invariants as predicates that can be applied to objects. Whenever the predicate returns false for an object, the invariant doesn’t hold. Moreover, it can be chained as a conjunctive form giving a series of conditions \( C_1, C_2, \ldots, C_n \). The predicate holds if all the conditions are true. Can we add or remove conditions in the derived classes? Let’s look at both cases.

Let’s assume that the invariant of the base class is \( I_B = C_1 \land C_2 \land \ldots \land C_3 \). First, let’s consider that case in which the derived class removes a constraint, let’s say \( C_3 \). The invariant for the derived class will be \( I_D = C_1 \land C_2 \). Now, all the \( D \) objects that properly satisfy \( I_D \), but do not satisfy \( C_3 \), will not satisfy \( I_B \). LSP will not apply to those objects. Thus, removing constraints in derived classes will break LSP.

In the other case, when we add constraints, things appear to work well. Mathematically we can easily prove that the invariants of the base class are met for the derived objects: \( I_D \Rightarrow I_B \).

But this works well only when all the invariants are known upfront. And, most of the time, as software is in its essence just complexity [Brooks93], not all invariants are known upfront – there are a lot of implicit assumptions. Let’s say that \( I_B = C_1 \land C_2 \land C_3 \) and \( I_D = C_1 \land C_2 \land C_3 \land \neg C_4 \), and that \( C_4 \) never applies to any object of \( B \). In such cases, a user can accidentally assume that \( C_4 \) never happens. This becomes an accidental assumption in \( B \)’s invariant: \( I_B = C_1 \land C_2 \land C_3 \land \neg C_4 \). If this happens, then again LSP is broken.

So, to make LSP work, we have to survey all user code to check for hidden assumptions, before we can derive from \( B \); both when trying to keep the same or when adding new constraints to the invariant of the derived class.

Inheritance and composition

We can start with Robert C. Martin’s quote to set the basis for the discussion in this section:

> A pox on the ISA relationship. It’s been misleading and damaging for decades. Inheritance is not ISA. Inheritance is the redeclaration of functions and variables in a sub-scope. No more. No less.

Well, the content misses one big point: inheritance also adds subtyping (allowing us to implicitly convert derived-class objects into base-class objects); which in turn can be used to implement polymorphism. But the rest is true.

If inheritance is just a redeclaration of functions and variables, then we can easily transform it into composition. Instead of making \( D \) derive from \( B \), we can make \( D \) contain a \( B \).

Therefore, if subtyping is not needed, it’s better to just use composition instead of inheritance as we don’t have to deal with the complications introduced by subtyping.

Now, if we assume a strict interpretation of the formal principle, we can argue that polymorphism cannot happen under subtyping, rendering inheritance useless.

Let us quickly sketch a proof. Let’s say that we have classes \( D \) and \( B \), \( D \) being a subtype of \( B \). Then we have a method \( m \), implemented as \( m_1 \) in \( B \) and as \( m_2 \) in \( D \), using a different implementation. In this case we can define the provable property \( \phi(x) \) as being \( \phi(x) = x.m() \) has-exactly-the-same-behaviour-as \( m_1 \). It is clear that this property holds for any object of type \( B \), but it does not hold for objects of type \( D \). The only way to make LSP work for such properties is to make the methods have identical behaviour, so, therefore, to eliminate polymorphism. q.e.d.

The reader might accuse us of exaggerating the matter by artificially constructing counterexamples; something that cannot happen in practice. But if we consider our statement in the context of the Open/Closed Principle, then we can easily imagine how this is not exaggerating. After all, with the types under the incidence of inheritance can be a closed system, and we should be able to extend this system with functionality that contains our counterexample. And this is not just a theoretical problem. Myself, I’ve encountered violations of LSP built on the same pattern as our proof above multiple times (of course, unintentional).

At this point, some readers might still argue that we should probably not be applying the LSP principle so strictly. We should only consider the properties relevant to the program in question. That is, if we want to make \( D \) derive from \( B \), we should consider all the ‘practical’ properties associated with \( D \) and \( B \). This idea is similar to the one that Sutter and Alexandrescu argue in their ‘Public inheritance is substitutability. Inherit, utilises it. We can easily document it and explain it to other engineers. But, not to reuse, but to be reused’ recommendation; they argue that creating associations with \( D \) are visible properties, and LSP dictates that they should not change.

Therefore, if subtyping is not needed, it’s better to just use composition instead of inheritance as we don’t have to deal with the complications introduced by subtyping.
The same conclusion reaches Sutter and Alexandrescu in their *C++ coding standards: 101 rules, guidelines, and best practices* book [Sutter]; see the section called ‘Prefer composition to inheritance’. I won’t repeat the arguments, as the idea is relatively straightforward.

**Inheritance is stronger than friendship**

Sutter and Alexandrescu argue that inheritance is almost as strong as friendship (same section of [Sutter]). My opinion is that we should move forward and argue that inheritance is even stronger than friendship. Making an analogy with real-life, one’s children are closer than one’s friends. The children can be friends, but in general, are more than that. Yes, children, especially young ones, may not have access to all the information their parent shares with friends but may dramatically alter the life of the parent.

The analogy works with classes. Yes, derived classes may not access all the fields of the base class, but they can seriously affect the space of the invariants. Future development in the derived classes may involve changing the invariants in the base class, and therefore affecting all the other derived classes, and all their users.

Friendship can affect private data, the internals of the class. But, if encapsulation is done right, this will not change the public interface of the class, and therefore the behaviour of the clients. Like any abstraction, class-level encapsulation restrains the impact of a change. In contrast, an inheritance that changes the invariants (directly or indirectly) is a public change, and it affects all the clients of the class.

To exemplify the impact of inheritance, let’s look at Figure 4. Let’s assume that the *AirplaneUser* needs a change to the flying behaviour. This affects the *Airplane* class, which changes the invariants of *FlyingThing*, which, in turn, affects *Duck* and finally *DuckUser*. In effect, the *AirplaneUser* and *DuckUser* classes are indirectly coupled.

This is stronger than friendship. Friendship may change your internal state, but if it’s not done particularly badly, it tends not to break your invariants, and your users are isolated from the change.

Looking only at the difference between protected and private access is missing the larger impact of inheritance. However, if we look at the bigger picture, if we consider LSP and the example above, we can conclude that inheritance implies more coupling than friendship.

**Conclusions**

In this article, we have tried to cast a critical perspective on inheritance, as one of the most used (or abused) features of OOP. The intent of this critical perspective was not to prove that inheritance should not be used at all, but rather to test its limits. What becomes apparent is that this is not a feature that should be abused, and great care needs to be taken when adding new inheritance to a software system, not to break existing code. In other words, we don’t have local guarantees when adding inheritance.

We started with a classic problem of *Rectangle* and *Square*, and have shown that inheritance doesn’t quite make sense in code, even though a square is a rectangle in mathematics. We explored the meaning of the is-a relationship and its relation to the real-world; after all, a common strategy in OOP modelling is to use real-world analogies. We concluded that this analogy works only to a point. Inheritance is not is-a. Furthermore, the term is-a can be confusing (unless we solve a large part of metaphysics). A slightly more appropriate way to think of inheritance is to think of it as a behaves-like-a relationship; i.e., what LSP preaches.

Moving forward, we showed that LSP is hard to apply. If we want to be strictly formal, we cannot apply it. In practice, we can, however, apply it, but not as easily as we may think. We cannot have local reasoning (looking just at the base class and the derived code). We need to look at all the user code and all the implicit assumptions that this code makes. Depending on the software, there may be semantic leaks towards all parts of the code; yes, that may be a badly structured code, but there is no clear algorithm that indicates whether we have such semantic leaks. As much as we would like to put boundaries to the implications of inheritance and LSP, it seems that we can’t.

We also briefly argued that whenever possible composition should be preferred to inheritance. And, to add one more negative aspect to inheritance, we’ve argued that inheritance is a stronger relationship than friendship, relation widely considered harmful.

And, as we are enumerating some negative aspects of inheritance, we should mention the presentation called *Inheritance Is The Base Class of Evil*, by Sean Parent [Parent13] – the name is too good not to be mentioned.

But again, the purpose of our deconstruction is not to show that inheritance should not be used. The main idea is to better know its limits, to find its weak points, and to find its internal inadequacies; when it can be applied, and where it can generate problems. There are cases in which inheritance is, at least useful, if not more. But this can be the topic of another article.

**References**


[Liskov94] Barbara H. Liskov, Jeannette M. Wing (1994), *A behavioral notion of subtyping. ACM Transactions on Programming Languages and Systems*


Using Compile Time Maps for Sorting

Compile time sorting can be interesting. Norman Wilson shows how to sort a map.

In the previous article I described a way of doing compile time sorting. One of the questions that came out of this was why would anyone want to do that? The first answer is just for fun, it’s just pretty for its own sake, and I think we as programmers ought to be able to appreciate that even if there is no practical use. To put it another way, quoting Albert Einstein, what use is a newborn baby? Secondly, the sorting algorithm illustrates some techniques that can be applied more generally to solve other problems – really it’s just playing with parameter pack expansion. Last but not least, there are real reasons why you’d want to sort at compile time and in this article I’m going to show you one.

Firstly though I’m going to show another little trick, apply it to create yet another compile time sorting algorithm and then use that to solve a practical problem.

A simple compile time map

Look at the following bit of code.

```cpp
template<typename... Members>
struct Map: Members... {};
```

If we instantiate `Map` with a pack of types, (assuming we can derive from all of the types) we end up with a type that is a composition of these. Furthermore we also know we can implicitly cast from the composed type to any of its bases. So given:

```cpp
struct A {}; struct B {}; struct C {};
auto abc = Map<A, B, C>{};
```

Then I can select the `A` base of `abc` like this:

```cpp
inline decltype(auto) getA(const A& a) { return a; }
const A& a = getA(abc);
```

And similarly for the other bases. Nothing particularly radical about that, but what if our bases look like this?

```
#include <cstddef>
template<std::size_t key, typename Value>
struct Pair { using type = Value; }
```

Now we can write a generalised `get`.

```cpp
template<std::size_t key, typename Value>
inline constexpr decltype(auto) get(const Pair<key, Value>& result) { return result; }
```

The crucial thing is that type deduction now comes into play. So given:

```cpp
using ABCMap = Map<Pair<0, A>, Pair<1, B>, Pair<2, C>>;
```

We have constrained key and, since our keys are unique, when the compiler tries to deduce `Value` there is only one possible solution, `abcMap` must be cast to `const Pair<1, B>&`. The expression is unambiguous and `x` ends up referencing the appropriate base of `abcMap`.

```cpp
static_assert(std::is_same_v<std::decay_t<
  decltype(x)>, Pair<1, B>>,
  "get() pulls out the corresponding base.");
```

We can translate this back to the world of types with this slightly ugly incantation:

```cpp
using typename M, std::size_t key>
using Get = typename std::decay_t<
  decltype(get<key>(std::declval<M>()))>::type;
static_assert(std::is_same_v<Get<ABCMap, 2>, C>,
  "Get works too.");
```

So we have a very simple way of mapping from integers to types. The `key` doesn’t have to be a non-type and it doesn’t have to be an `int`, but it does have to be a compile time construct. There are other ways of making compile time maps but I quite like this one as it’s simple, and uses the basic rules of C++ that we all (should) understand. This map type is obviously very similar to `std::tuple` – but we’ll come back to that later. The order we declare the pairs in the mapping is not important. We could have said:

```cpp
using ABCMap2 = Map<Pair<2, C>, Pair<1, B>,
  Pair<0, A>>;
```

Type deduction will still produce the same result – another MacGuffin.

Another way to sort

If we can rank each element of a set, then sorting is just forming a mapping from rank to element. In other words a sorted sequence allows us to access the elements by rank. Let’s express that in code.

Let’s start with a simple type:

```cpp
template<typename... Ts> struct TypeList {};
```

Primary definition. We require an `index_sequence`, some traits to generalize how we do the sort and some types to sort.

```cpp
namespace std {
  template<typename Index, typename Traits,
    typename... Ts> struct MapSortImpl;
}
```

Partially specialize to break out the `index_sequence`. The index pack gives us `0..sizeof...(Ts) - 1`. This corresponds to the position of each `T` in `Ts`. We’ll need this throughout the following code and a shorthand to use traits.

```cpp
using ABCMap = Map<P\(Pair<0, A>, Pair<1, B>, Pair<2, C>>;
```

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To get a space-efficient layout, we should sort our members by size, biggest to smallest. Efficient layouts make better use of cache and that makes code go faster.

```cpp
#include <functional>

template<int i>
using Int = std::integral_constant<int, i>;

struct Traits {
    template<typename T>
    static constexpr auto auto value() { return T::value; }
    static constexpr std::less<> compare;
};

using In = TypeList<Int<42>, Int<7>, Int<13>, Int<7>>, Int<13>, Int<42>>;
using Out = decltype(mapSort<Traits>(In{}));
static_assert(std::is_same_v<Out, TypeList<Int<7>, Int<7>, Int<13>, Int<42>>>, "mapSort works!");
```

**What’s the point?**

Consider:

```cpp
using T1 = std::tuple<bool, std::int16_t, char, std::int32_t, std::int64_t>;
static_assert(sizeof(T1) == 24, "pathological case std::tuple pads");

using T2 = std::tuple<std::int64_t, std::int32_t, std::int16_t, bool, char>;
static_assert(sizeof(T2) == 16, "efficient layout sorts by size");
```

We all know that on most architectures types have an alignment. And we ought to know that to get a space-efficient layout, we should sort our members by size, biggest to smallest. Efficient layouts make better use of cache and that makes code go faster.

In many cases where we define a `std::tuple` we can rearrange the members by hand for efficiency, but sometimes we might not be able to – maybe the type is generated by TMP, or maybe we want future proof our code against changes which affect the alignments. So can we come up with something like a `std::tuple` but which automatically lays itself out efficiently? Let’s try.

Firstly we’ll revisit the compile time map we started with, but with a little tweak. Field now holds a value.

```cpp
template<std::size_t key, typename T>
struct Field { T value; }

decltype(auto) get(const Field<key, T>& f) { return (f.value); }
```

Does it work? See Listing 1.
We can actually reuse the `Map` template but the name no longer makes sense so I’ll rename it.

```cpp
template<typename... Ts>
using Tuple = Map<Ts...>;
```

To prove this works I define the contents of Listing 2.

So we’ve defined the very barest bones of a tuple template. I leave it to the reader to flesh out the missing parts. The important difference from `std::tuple` is that we explicitly associate a key with an element. The keys could be given out of order and could be non-contiguous, but the association between key and type is still maintained. So we can define a tuple where the elements can be reordered to form a space efficient layout? All we need to do now is sort the types by size. Listing 3 shows we do that.

### Footnote: is it any good?

The sort I presented in the previous article – no. It’s actually astonishingly bad. Never in all my time as a programmer have I burned so many clock cycles on so simple a problem. So let’s add another reason to why you’d want to do a compile time sort – you can go and make a coffee while your code is compiling.

What about `mapSort`? That’s actually much better but is still at least \(n^2\). I’ve pulled down the code for `skew_sort` that comes from the Stack Overflow thread [Stackoverflow] that started all this off to compare. The graphs show this is radically faster than both, but blows the compiler’s maximum template recursion depth for data sets larger that 1024. Clearly the story is not over. Can we write a non-recursive sort in \(n \log(n)\)? Will it be any good? Find out next time.

### Reference

Profiting from the Folly of Others

Code referred to as a hack can raise an eyebrow. Alastair Harrison learns about accessing private members of C++ classes by investigating a header called UninitializedMemoryHacks.h

always enjoy browsing through the source code of libraries written by other people. With so many dark corners in C++ I often come across new and interesting ideas. I’d like to share one such example from the ‘Folly’ library. Not because I think it illustrates best practice (it doesn’t!), but because I learned something about C++ in the process of deciphering it.

Folly [GitHub] is a C++ library developed at Facebook and released under the open-source Apache 2.0 licence. It contains useful algorithms, overloaded functions in the `std::vector` namespace, named `folly::resizeWithoutInitialization` and whose purpose is to ‘resize std::string or std::vector without constructing or initializing new elements’.

It does what?

Normally when we call `resize` to increase the size of a `std::vector`, the container first checks to see if the existing capacity is sufficient to hold the requested number of elements. Even when the existing capacity is sufficient, the implementation needs to do something with the newly added elements. They each need to be constructed or initialized to ensure that they are in a valid state. For trivial types such as `int` it’s actually OK to leave the values uninitialized, as long as we don’t try to read them before we’ve first written something to them. But `std::vector` always forces us to pay the cost of initialization, even if we were intending to overwrite all of the newly initialized elements straight after calling `resize`.

In contrast, when we call `folly::resizeWithoutInitialization` on a `std::vector` with sufficient capacity, it simply reaches in to the private implementation and moves the pointer representing the end of the sequence. The memory for the new elements is left uninitialized, leaving the caller responsible for that task.

The first time I looked at the implementation of this function, I was amazed and alarmed to see how it manages to bypass the normal C++ access restrictions to modify a private member variable of a standard library component. I say ‘somehow’ because the precise mechanism was so thoroughly obfuscated behind layers of macros, template trickery and arcane member function pointer syntax that it might as well have been magic. The baffling part was that it claimed to pull off this magic trick without invoking any undefined behaviour. I had to know how this worked!

I won’t dwell further on the specifics of how Folly meddles with the internals of the standard containers. The interesting part is how it bypasses the access control mechanisms of C++, Herb Sutter has a Guru of the Week article [GotW] discussing three nefarious techniques for accessing private members of a class, though none of them quite matches the applicability of the method in the Folly library. The first two are illegal and the third involves writing a sneaky member function specialization, which makes it relevant only to classes that contain member function templates.

What’s interesting about the technique used in Folly is that it’s able to freely access private members of any class, without any particular structural requirements. It does this with a clever combination of infrequently-used language features and a small loophole allowed by the C++ standard.

The effect

Let’s take a simple class with a private member function:

```cpp
class Widget {
  private:
    void forbidden();
};
```

Our aim is to write a free function called `hijack` which takes a reference to a `Widget` as input and calls the `Widget::forbidden()` member function on it. Assume that the `Widget` class is closed for modification by us, so we can’t just change the `private` to `public`, or make `hijack` a friend of `Widget`.

Obviously we can’t call the private member function directly:

```cpp
void hijack(Widget& w) {
    w.forbidden();  // ERROR!
}
```

because the compiler will stop us:

```cpp
In function 'void hijack(Widget&)':
error: 'void Widget::forbidden()' is private within this context
 |  w.forbidden();
 | ^
```

Using techniques from the Folly library, we’ll build up a solution piece-by-piece. This article covers the specific case of calling private member functions, but the approach is equally applicable to accessing and mutating private member variables in a class. The underlying techniques all work in C++98, but some more modern features will be used to ease exposition.

A syntax refresher for pointers to member functions

We’ll be using pointers to member functions (PMFs) extensively, so it’s worth revisiting their syntax before we dive in further. PMFs enable a
primitive form of polymorphism over methods in a class. For the sake of exposition, let’s start with a hypothetical calculator class (Listing 1)

Arguably the easiest way to work with pointers to member functions is through type aliases. The type alias is specific to a given class, but the pointer can be bound to any member function in the class that matches the signature. In the case of Calculator, both multiply and add take a single float argument and return void, so we can use the same type alias for both. It looks like this:

```
using Operation = void (Calculator::*)(float);
```

We can then store the address of either multiply or add. But value doesn’t match the signature, so its address cannot be assigned to an Operation pointer.

```
// OK
Operation op1 = &Calculator::add;
Operation op2 = &Calculator::multiply;
```

We’ll need to make a new alias to match the signature of value:

```
using Getter = float (Calculator::*)() const;
```

We can then store the address of either value. But value doesn’t match the signature, so its address cannot be assigned to a Getter pointer.

```
// OK - signature now matches
Getter get = &Calculator::value;
```

A pointer to a member function isn’t very useful unless we know which object instance we want to call it on. Here’s the syntax for calling members of Calculator through their pointers:

```
Calculator calc{};
(calc::*op1)(123.0f); // Calls add
(calc::*op2)(10.0f); // Calls multiply
```

One of the interesting things about pointers to member functions is that they can be bound to private member functions. That’s the first piece of the Folly puzzle.

### Puzzle piece 1: Pointers to private member functions can be called from any scope

Suppose the author of the Widget class had helpfully provided a means to obtain a pointer to the Widget::forbidden() member function. Once we have that pointer, we are able to call it from any scope where we have a Widget available (Listing 2).

```
void hijack(Widget& w) {
using ForbiddenFun = void (Widget::*)();
ForbiddenFun const forbidden_fun = Widget::forbidden_fun();
// Calls a private member function on the Widget
// instance passed in to the function.
(w.*forbidden_fun)();
}
```

That’s useful to know, but most classes don’t offer to hand out pointers to their private member functions. We need to find a sneakerier way to get hold of one from outside of the class scope.

There’s a curious loophole in the C++ standard around the use of explicit template instantiation which allows us to refer to private class members. That gives us the second piece of the Folly puzzle.

### Puzzle piece 2: The explicit template instantiation loophole

The C++17 standard contains the following paragraph (with the parts of interest to us marked in bold):

```
17.7.2 (item 12)
The usual access checking rules do not apply to names used to specify explicit instantiations. [Note: In particular, the template arguments and names used in the function declarator (including parameter types, return types and exception specifications) may be private types or objects which would normally not be accessible and the template may be a member template or member function which would not normally be accessible.]
```

---

1. C++17 introduced the std::invoke template, which gives a unified syntax for working with callables.
To understand the reason behind this curiosity, we need to discuss the explicit template instantiation mechanism for a moment.

Suppose we’ve got a `Company` class with an internal private member function template, `update_employee`. Perhaps there is one particular template argument, `OnSiteEmployeePolicy` which is expensive to compile, but used regularly. We’d like to avoid the cost of instantiating that version of the template in lots of translation units. We can achieve this by explicitly instantiating the member template in just one translation unit and marking it as `extern` everywhere else. See Listing 3 (`company.h`) and Listing 4 (`company.cpp`).

Brushing aside the question of how someone ever snuck such an awkward API design through code review, notice how the template instantiation mechanism needs to allow a reference to an API design through code review, not how the template instantiation fibre have probably already worked out how to use a macro to remove the duplication in the template arguments.

Puzzle piece 3: Passing a member-function pointer as a non-type template parameter

In C++, template arguments are usually types, but there is some support for non-type template parameters if they are of integral or pointer type. Conveniently enough, it’s perfectly legal to pass a pointer-to-member-function as a template argument. Listing 5 is an example of what looks like the intermediate `SpaceShipFun` alias hampers the genericity of the `SpaceStation` template, so we can move the type of the pointer-to-member-function into the template arguments too (Listing 6).

We can take that a step further and have the compiler deduce the type of the member function for us:

That relieves us of some of the burden of passing the member function signature to the template. We’ll stick with this approach for the rest of the article as it’s what’s used in the Folly library, but it’s worth mentioning that C++17’s `template <auto>` feature removes the need for the first template parameter entirely.4

Passing a private pointer-to-member-function as a template parameter

Let’s combine the explicit template instantiation loophole with the ability to pass member function pointers as template parameters. The HijackImpl struct receives a pointer to `Widget::forbidden` as a template parameter (see Listing 7).

Brilliant! We’ve instantiated a template that is able to reach in and call the `forbidden()` member function on any `Widget` that we care to pass in. So we just have to write the free function, hijack and we can go back to watching cat videos on YouTube, right?

2. C++20 will significantly relax the restrictions on non-type template parameters.
3. I imagine it’s staggeringly useful to someone.
4. Readers lacking both a C++17 compiler and a certain amount of moral fibre have probably already worked out how to use a macro to remove the duplication in the template arguments.
The only problem is that it doesn’t work. The compiler sees through our ruse and raps us smartly on the knuckles:

```cpp
error: 'forbidden' is a private member of 'Widget'
HijackImpl<decetype(&Widget::forbidden),
      &Widget::forbidden>::hijack(w);
```

The use of the HijackImpl template inside the hijack function is not an explicit template instantiation. It’s just a ‘normal’ implicit instantiation. So the loophole doesn’t apply. It’s time to phone a friend for help with solving the next piece of the puzzle.

### Puzzle piece 4: A friend comes to our aid

Because we’re not allowed to refer to Widget::forbidden inside our hijack function, we must solve the conundrum of accessing the value of the ForbiddenFun template parameter without making any direct reference to the HijackImpl<...> template. This apparently unreasonable requirement is easily solved with a shrewd application of the friend keyword.

Let’s take another step back from the task in hand and look at some of the different effects one can achieve when marking a free function as a friend of a class. The behaviour depends on whether the class contains only a declaration of the function (i.e. function signature only), or whether the complete definition (including the function body) appears inside the class.

### ‘Friend’ function declarations

Most C++ developers will be familiar with the pattern of placing a free function declaration inside of a class definition and marking it as a friend. The definition of the free-function still lives outside of the class, but is now allowed to access private members of the class. (See Listing 8.)

If we could make hijack be a friend of Widget then the compiler would allow us to refer to Widget::forbidden inside the hijack function. Alas, this option is unavailable because the rules of our game don’t allow us to modify Widget. Let’s try something else.

### Inline ‘Friend’ function definitions

It’s also possible to define a friend function inside a class (as opposed to just declaring it there). This isn’t something seen as often in C++ code. Probably because when we try to call the free function, the compiler is unable to find it! (See Listing 9.) Here’s the compile error:

```cpp
error: 'frobnicate' was not declared in this scope
|    ^
```

As before, frobnicate() is still a free function that lives in the global namespace, but it behaves quite differently under name lookup now that it is defined inside the Gadget class. A friend function defined inside a class is sometimes known as a ‘hidden friend’ [JSS19] [Saks18]. Hidden friends can only be found through Argument Dependent Lookup (ADL) and ADL only works if one of the arguments to the function is of the enclosing class type. In the above example frobnicate() takes no arguments, so argument dependent lookup won’t happen. The result is that frobnicate() can’t be called from anywhere. Not even from within frobnicate() itself!

If we add a parameter of the enclosing class type to frobnicate() then we’re able to call it via ADL (Listing 10, overleaf).

### Making hidden friends visible

The hidden-friend ADL trick can be very useful; it’s an ideal tool when writing operator overloads for user-defined types. But we’ll use a slightly bigger hammer for our hijack function. There’s another way of allowing the compiler to find hidden friends, and that is to put a declaration of the function in the enclosing namespace (Listing 11).

This is exactly the opposite of the usual pattern of defining a free function and then placing a friend declaration for it inside of a class. The new behaviour is almost identical except for one critical difference: when the enclosing class is a template, the free function has access to the template parameters!

```cpp
class Gadget {
  // Friend declaration gives 'frobnicate' access
  // to Gadget's private members.
  friend void frobnicate();

  private:
    void internal() {
      // ...
    }

  // Definition as a normal free function
  void frobnicate() {
    Gadget g;
    // OK because 'frobnicate' is a friend of
    // 'Gadget'.
    g.internal();
  }
}
```

```cpp
// The first template parameter is the type
// signature of the pointer-to-member-function.
// The second template parameter is the pointer // itself.
template <
  typename ForbiddenFun,
  ForbiddenFun forbidden_fun
>
struct HijackImpl {
  static void apply(Widget& w) {
    // Calls a private method of Widget
    (w.*forbidden_fun)();
  }
};
```

```cpp
Listing 9

```cpp
// Explicit instantiation is allowed to refer to
// 'Widget::forbidden' in a scope where it's not
// normally permissible.
template struct HijackImpl<
  decetype(&Widget::forbidden),
  &Widget::forbidden
>;
```

```cpp
Listing 7

```cpp
class Gadget {
  // Free function declared as a friend of Gadget
  friend void frobnicate() {
    Gadget g;
    g.internal(); // Still OK
  }

  private:
    void internal() {
    // NOT OK: Compiler can't find frobnicate()
    // during name lookup
    frobnicate();
  }
};
```

```cpp
Listing 10

```cpp
void do_something() {
  // NOT OK: Compiler can't find frobnicate()
  // during name lookup
  frobnicate();
}
```

```cpp
Listing 8

```cpp
void frobnicate() {
  Widget g;
  // OK because 'frobnicate' is a friend of
  // 'Widget'.
  g.internal();
}
```

```cpp
Listing 11

```cpp
friend void frobnicate() {
  Widget g;
  // Free function declared as a friend of Widget
  g.internal();
}
```

```cpp
Listing 10

```cpp
friend void frobnicate();
```
Using friends to pilfer template parameters

I trust you will be at least a little unsettled to discover that the program in Listing 12 is valid.

What’s happening is that the `observe()` function is not defined until the point at which the SpookyAction template is instantiated (by its use in the main function). There is a single definition of the `observe()` function, because there is a single instantiation of the SpookyAction template. The really useful part is that the `observe()` function gains access to the template parameter of the SpookyAction template that caused it to be defined.

Of course things go wrong very quickly if we try to instantiate any more versions of the SpookyAction template, as each one results in a redefinition of the `observe()` function and an angry compiler.

Provided we use it carefully, we now have the last piece of our puzzle—a way to access the template parameters of a class from a scope external to that class.

Putting the puzzle pieces together

Let’s go back to our original Widget example, now that we’ve got all of the pieces that we need to be able to reach in and call its private member function, `Widget::forbidden()`. In summary:

1. We use the loophole in the explicit template instantiation rules to allow us to refer to `Widget::forbidden()` from outside of the Widget class.
2. We inject the address of `Widget::forbidden()` into our HijackImpl class as a template parameter.
3. We define the `hijack()` function directly inside of HijackImpl so that it can access the template parameter containing the address of `Widget::forbidden()`.
4. We mark `hijack` as a friend so that it becomes a free function and we provide a declaration of `hijack` at namespace scope so that it participates in name-lookup.
5. We can now invoke `Widget::forbidden()` on any Widget instance through the member-function address that is exposed to the `hijack` function.

The key parts of the mechanism are shown in Listing 13.

Dealing with multiple definitions of the friend function

There’s still one more issue to overcome. To avoid violating the One Definition Rule, there must be one—and only one—explicit instantiation of a template (with given template arguments) across all translation units.

```
#include <iostream>

template <int N>
class SpookyAction {
  friend int observe() {
    return N;
  }
};

int observe();

int main() {
  SpookyAction<42>{};
  std::cout <<observe() << '\n';  // Prints 42
}
```

```
// HijackImpl is the mechanism for injecting the
// private member function pointer into the
// hijack function.

template <
  typename ForbiddenFun,
  ForbiddenFun forbidden_fun
>
class HijackImpl {
  // Definition of free function inside the class
  // template to give it access to the
  // forbidden_fun template argument.
  // Marking hijack as a friend prevents it from
  // becoming a member function.
  friend void hijack(Widget& w) {
    (w.*forbidden_fun)();
  }
};

// Declaration in the enclosing namespace to make
// hijack available for name lookup.

void hijack(Widget& w);
```

5. If you choose to ignore the pitchfork-bearing members of the C++ standards committee currently approaching your front door with a polite request that you stop doing this sort of thing at all.
Consider what happens when our HijackImpl class is put in a header and is used in multiple translation units. The explicit instantiation of the class template must live outside of that header, otherwise it will appear in every translation unit that includes the header. We need to ensure that there is just one explicit template instantiation in the whole program. What’s more, the linker is not actually required to report duplicate instantiations across multiple translation units, so it won’t even help us to avoid the problem. That’s a recipe for a big maintenance headache.

The approach employed by the Folly library is to add an extra template parameter to the HijackImpl class and use it to accept an empty ‘tag’ struct which is defined in an anonymous namespace.

The anonymous namespace ensures that the tag parameter is of a different type in every translation unit. Every translation unit will therefore get its own unique explicit instantiation of the HijackImpl class.

The final solution is short, but packs in a surprising amount of nuance. See widget.h (Listing 14), widget_hijack.h (Listing 15) and main.cc (Listing 16.)

Conclusion
Should you use this access-violation hack in production code? Almost certainly not. Well, not unless you enjoy the excitement and explosive unpredictability of maintaining extremely brittle code. The C++ class member access rules are there to help authors of types to enforce invariants. If you fool the compiler into mutating private class members then you’re likely to be violating the class invariants, which risks leaving the program in an invalid state. You’re also relying on intimate knowledge of internal implementation details, for which the library author is under no stability obligations.

Should you experiment with this access-violation technique outside of production code? Absolutely! Learning how to subvert a system in a safe environment is not only fun, but it helps to foster a deeper understanding and fosters the development of new techniques that can be brought to production.

A note on the origins of the technique
The idea of using explicit template instantiation to bypass class access rules pre-dates the Folly library by a few years. The first mention I can find is from a 2010 blog post by Johannes Schaub [Schaub10], which describes a method using initialization of static class members.

A year later, Schaub offered the dubiously tempting promise of ‘Safer Nastiness’ in a follow-up blog post [Schaub11] in which he presented an improved version of the code. This removed the need for static class members and is much closer to what’s used today by the Folly library.

Acknowledgements
The author would like to thank Geoff Hester, Anthony Kirby and Kirsty McNaught for advice on early drafts of this article and Balog Pal for very patiently explaining some finer points of the one-definition rule.

References
[GitHub]: Facebook Folly on GitHub: https://github.com/facebook/folly
[Saks18]: Dan Saks ‘Making New Friends’ recorded at CPPCon 18, available at: https://www.youtube.com/watch?v=POa_V15je8Y

Listings

```cpp
#pragma once
#include <iostream>

class Widget {
   private:
      void forbidden() {
         std::cout << "Whoops...\n";
      }
};
```

List 14

```cpp
#include "widget.h"

namespace {

   struct TranslationUnitTag {};

   friend void hijack(Widget& w) {
      w.*forbidden_fun();
   }

};

void hijack(Widget& w);

template <
   typename Tag,
   typename ForbiddenFun,
   ForbiddenFun forbidden_fun
>
class HijackImpl {
   friend void hijack(Widget& w) {
      (w.*forbidden_fun());
   }
};

// Every translation unit gets its own unique
// explicit instantiation because of the
// guarenteed-unique tag parameter.

template class HijackImpl<
   TranslationUnitTag,
   decltype(&Widget::forbidden),
   &Widget::forbidden
>;
```

List 15

```cpp
#include "widget.h"
#include "widget_hijack.h"

int main() {
   Widget w;
   hijack(w); // Prints "Whoops..."
}
```

List 16
It’s About Time

How easy is it to make code wait for a time period before doing something? Mike Crowe looks at ways to avoid problems when a system clock changes.

Most developers know how to implement a timeout so that an operation can be attempted for a certain period of time before stopping or giving up. Something like Listing 1.

Or, perhaps, in C++, as in Listing 2.

This pattern even works when efficiently blocking for something to happen using a condition variable as in Listing 3.

In these examples, I’m using `std::chrono::system_clock` because it is equivalent to `std::chrono::high_resolution_clock` in libstdcpp. You may want to check your standard library documentation to determine which would be best for you.

But what happens if someone changes the system clock during the loop? Not every device has a real-time clock to keep time when the device is off. Even if a device does, it may not be particularly accurate. This could mean that the system clock jumps by a few seconds or even a few decades after a power cycle when the device does eventually find an accurate time source, perhaps via NTP [Wikipedia-1], when it gains an Internet connection. This can lead to strange hard-to-reproduce bug reports from the field and unhappy users. Note that `std::chrono::system_clock` is required to be Coordinated Universal Time (UTC), which does not change due to daylight saving. Time zones and daylight saving are a completely different subject, one that is not well addressed in standard C++ until C++20 [Hinnant18].

How do we avoid this problem? When possible, just use relative timeouts. Use `std::condition_variable::wait_for` rather than `std::condition_variable::wait_until`. An absolute timeout is like setting an alarm clock – if you change the time shown on the clock then you affect how long it will be until the alarm sounds. A relative timeout is like setting an egg timer, and leaving it alone – the time shown on your clock does not affect how long it will be until the alarm sounds.

Unfortunately a relative timeout doesn’t work well for the examples above because the timeout may cover multiple waits. It’s possible to recalculate a relative timeout but that’s easy to get wrong and it risks the timeout being extended unintentionally as small errors accumulate over many loops.

A better solution is to use a monotonic or steady clock that is immune to the warping of the system clock. Such a clock is defined to keep running at an approximately-consistent rate without warping either forwards or backwards. If the machine has access to an accurate clock source, often via NTP, the monotonic clock can be slewed slightly in order to try to keep it running correctly relative to real time. Clock slewing means slowing down or speeding up the clock by small amounts in order to keep time accurately on average over a longer period of time.

Mike Crowe

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```cpp
bool do_something_for_a_while(void)
{
    const time_t expire = time(NULL) + 5;
    while (time(NULL) < expire)
    {
        if (try_to_do_something())
            return true;
    }
    return false;
}
```

```cpp
do_something_for_a_while()
{
    using namespace std::chrono;
    auto const expire =
        system_clock::now() + seconds(5);
    while (system_clock::now() < expire)
    {
        if (try_to_do_something())
            return;
    }
    throw std::runtime_error("Timed out");
}
```

```cpp
using namespace std;
void do_something_for_a_while(deque<int> &q,
    mutex &protect_q,
    condition_variable &q_changed)
{
    std::unique_lock<mutex> lock(protect_q);
    auto const expire = system_clock::now()
        + seconds(5);
    while (system_clock::now() < expire)
    {
        if (q_changed.wait_until(lock, expire,
            [&q] { return !q.empty(); }))
    }
```

On POSIX systems, this clock is known as `CLOCK_MONOTONIC` and the current time can be retrieved using the `clock_gettime` POSIX function. Unfortunately, the lack of 64-bit types back when this function was invented means that the seconds and nanoseconds are stored separately in a structure. Listing 4 (overleaf) uses a function to tell whether a specified timeout has expired.

This gets more complex if the timeout is not a whole number of seconds because extra housekeeping is required to ensure that the nanoseconds part is kept within permitted bounds. If you find yourself needing to do this then gnulib [GNU] provides helpful functions.
libstdc++ and libc++ use `CLOCK_MONOTONIC` to implement C++ `std::chrono::steady_clock`, which provides a much easier way to work with absolute timeouts. Using it is just a matter of changing `system_clock` to `steady_clock` in Listing 2 to get Listing 5 and in Listing 3 to get Listing 6.

The compiler’s type checking ensures that you can’t accidentally compare time points from different clock sources against each other, making this much safer than the C version, which must rely on the clock passed to `clock_gettime` being consistent.

Both of these examples are now immune to system clock changes.

---

If you’re stuck using C++98 or C++03 then Boost [Boost] provides `boost::chrono`. It also provides a precursor named `boost::posix_time`, but that should probably be avoided for new code.

Time points measured against a monotonic clock will usually not be comparable between machines. On Linux, `CLOCK_MONOTONIC` is actually the system uptime. In a distributed system, such as video playback synchronised across multiple screens, you may have NTP or PTP [Wikipedia-2] working hard to keep the system clock synchronised across multiple devices. In that case it makes more sense to use `std::chrono::system_clock` to agree a specific time to start playback and to control the playback speed. I imagine that a similar situation could occur in other distributed systems.

If we follow the advice above to use relative timeouts where we can and `CLOCK_MONOTONIC` or `std::chrono::steady_clock` where we can’t, then all will be lovely, right? Well, yes and no. Unfortunately, current versions of GNU libstdc++ and Clang libc++ lack full support for using `std::chrono::steady_clock` timeouts for thread-synchronisation primitives and tend to convert silently back to `std::chrono::system_clock`, which makes the timeouts subject to misbehaviour when the system clock warps again (although in some cases the window of opportunity can be very small due to the actual wait being a relative one again.) They need to do this because POSIX doesn’t currently provide suitable equivalents of the thread functions that are capable of accepting `CLOCK_MONOTONIC` timeouts [Crowe18]. There are new functions [AustinGroup] planned to address this. Glibc v2.30 and later contain these new functions and various patches have already been accepted for libstdc++ to use these functions in GCC 10 to fix the methods on `std::condition_variable`, `std::timed_mutex` and `std::shared_timed_mutex` that accept timeouts. Unfortunately some of the patches [Crowe20] to fix `std::future` didn’t make it in before the freeze, but they’ll hopefully be in GCC 11. I believe that similar changes are making their way into Clang libc++ too. If you are stuck using

---

### Listing 4

```c
bool expired(const timespec *expire) {
  struct timespec now;
  clock_gettime(CLOCK_MONOTONIC, &now);
  if (now.tv_sec < expire.tv_sec)
    return false;
  if (now.tv_sec > expire.tv_sec)
    return true;
  return now.tv_nsec > expire.tv_nsec;
}

bool do_something_for_a_while() {
  struct timespec expire;
  clock_gettime(CLOCK_MONOTONIC, &expire);
  expire.tv_sec += 5;
  while (!expired(&expire)) {
    if (try_to_do_something())
      return true;
  }
  return false;
}
```

---

### Listing 5

```c
void do_something_for_a_while()
{
  using namespace std::chrono;
  auto const expire = steady_clock::now() + seconds(5);
  while (steady::now() < expire) {
    if (try_to_do_something())
      return;
  }
  throw std::runtime_error("Timed out");
}
```

---

### Listing 6

```c
using namespace std;
void do_something_for_a_while(deque<int> &q, mutex &protect_q, condition_variable &q_changed)
{
  std::unique_lock<mutex> lock(protect_q);
  auto const expire = steady_clock::now() + seconds(5);
  while (steady_clock::now() < expire) {
    if (q_changed.wait_until(lock, expire, [&q] { return !q.empty(); }))
      do_something(q);
  }
  throw std::runtime_error("Timed out");
}
```
If you follow the advice ... you will automatically get the fixes when your code is compiled with newer standard library versions.

earlier versions then I believe that at least some of these problems are resolved in the Boost equivalents of the standard library functions. If you follow the advice above, then the situation will be slightly better than if you’d used `std::chrono::system_clock` in your code right now and you will automatically get the fixes when your code is compiled with newer standard library versions. Many of the functions involved are inline so the fixes require more than upgrading the shared library.

**Summary**

- Use relative timeouts to standard library functions when performing a single operation.
- Use `CLOCK_REALTIME` or `std::chrono::system_clock` when your times and timeout relate to time in the real world and you want to react to someone warping the system clock. For example, a calendar or public transport tracking application.
- Use `CLOCK_MONOTONIC` or `std::chrono::steady_clock` when your times relate to elapsed time that should not change if someone warps the system clock. For example, network timeouts and refresh intervals.
- Use `CLOCK_REALTIME` and `std::chrono::system_clock` when the devices involved are known to have their clocks synchronised and you wish to share timestamps between those devices.
- Keep your toolchain up to date (and apply patches if you can) to ensure that you have the latest fixes. If you can’t then look at using Boost instead.

**Thanks**

Thanks to members of the Austin Group, glibc and libstdc++ maintainers for helping me to turn the scratching of one small itch (in `std::condition_variable`) into fixing this class of problems more widely across POSIX and the C++ standard library. Thanks to the ACCU Overload reviewers and Jean-Marc Beaufils for providing feedback.

**References**

[AustinGroup] Mike Crowe in Austin Group Defect Tracker: https://www.austingroupbugs.net/view.php?id=1216

[Boost] https://www.boost.org

[Crowe18] Mike Crowe ‘The clock used for waiting on a condition variable is a property of the wait, not the condition variable’, at: http://randombitsofuselessinformation.blogspot.com/2018/10/the-clock-used-for-waiting-on-condition.html


A Day in the Life of a Full-Stack Developer

Many roles claim to be full stack. Teedy Deigh shares a day in the life of a full stack developer.

06:00
Uh... what... Snooze

06:15
Snooze

06:30
Snooze

06:45
Falls out of bed

Why did I set my alarm for this time of night... morning... whatever...?
Oh yes. Full-stack development. Read and watched some stuff on it yesterday. Couldn’t find anything of substance. Sure, a whole load of stuff on web development – JavaScript, HTML, CSS and the occasional database – but nothing on the rest of the stack and how to do it properly.
So, thought I’d better explore it for myself. Full stack, full day, full on!

07:03
OK, dragged a comb across my head, found my way downstairs, drank a cup. Now I’ve looked up, I’ve noticed I’m late.
I said was going to get my head down and online by 06:30. Time for another cup.

07:54
OK, someone on the internet was wrong, but I’ve fixed that now. Where shall we start? Oh yeah, that JavaScript framework I was looking at yesterday – Anglia? Nod? Mithrandir? Whatever. If we’re gonna code the full stack properly, we’re going to need to write our own framework. Can’t just go around reusing other people’s stacks – they don’t call it partial-stack development, amiright?!

12:03
Time for a rewrite – OverReact.JS2! Maybe this time I’ll write some tests. Gonna need a testing framework.

12:29
Well, I must confess, I’m a little surprised that that person on the internet is still wrong, especially after all the suggestions I offered!
Anyway. Onward to OverReact.JS2!

15:11
OK, that took a little longer than expected, but given what I can now see are the glaring deficiencies of the first version, it’s important to account for all possible use cases and make everything more configurable. I think I once heard someone say that it was important to try to please all the people all of the time... or something like that.

15:33
I don’t believe it! A bug. Again.
Hmm... perhaps I should have used my Jitters framework to write some tests with?
Is it time for lunch? Must be time for lunch.

15:57
The plan was to write some tests, but I’ve changed my mind as that will just slow me down, and I’m trying to be Agile™. ‘Responding to change over following a plan’ is the mantra I’m following today.
The OverReact.JS2 code doesn’t look like it has any issues – in fact, it looks quite happy from where I’m sitting: emoji identifiers FTW! I chose an uncompromisingly minimal coding style that shuns the excesses of commenting, indentation, long identifiers and clunky, procedural control flow. So the problem can’t be there, right? Must be somewhere else on the stack.
Perhaps the JavaScript engine is at fault?

18:12
Writing Veg.JooS, my new JavaScript engine, seems to be going well so far, although I suspect that I might be looking at an all-nighter. That, however, is not my main concern: my reliance on an existing C compiler,
regardless of its long-standing open-source pedigree, may be a weak link in my tool chain. Rather than stand on the toes of giants, it may be wiser to write my own compiler.

19:49
Occurs to me that it might be time for lunch... or something.

20:01
Well, this is turning into something of an odyssey, but I can’t believe I overlooked an obvious step: I need to create a compiler compiler to save time and trouble in future!

OK, back to food... and, can you believe it, that person on the internet is still wrong?

20:15
The patterns I’m going to use to create YakShavR are clear in my head, but there’s a couple of things I think I’m missing.

Ah yes, coffee’s what I’m missing!

20:59
It’s clear that what I’ve been missing is the right language. No, I don’t mean “@#$%!” – although there’s been plenty of that today – I mean for implementing YakShavR. I started writing it in C but, you know, chickens and eggs!

I’ve also decided that maybe C is not the right way to go for Veg.JooS. I need a better systems programming language, something with less historical baggage, unsullied by popularity and compromise. Think I might call it ToldUSo, and will post a repo link to the person – now people! – on the internet who is wrong.

Anyway, how to break the chicken-and-egg cycle? Lisp! Pure and simple, and no need for tests as it’s already functional.

21:49
Two pomodoros later (minus the wasteful five-minute breaks) and I’ve got the core Lisp eval function written out on my whiteboard. Or evil, looking at the way I’ve written it – well, scribbled – which does highlight a bit of a problem: I was going to code it up, but I’m not sure I can read it now. Looks like it was written by a caffeinated spider.

Caffeine. Coffee. Yup, that’s the problem. Gonna need more of that if I’m to crack this code.

22:41
OK, I think I’ve almost got it. Must be time for... a meal.

23:45
Perhaps, a little unbelievably, the people on the internet who are wrong might actually be right. They pointed out that I don’t seem to be willing to compromise. Damn straight! Uncompromising is my middle name (albeit one I had to get changed by deed poll, as my parents originally chose Davina).

Andrew Koenig observed that “People who brook no compromise in programming languages should program in lambda calculus or machine language.” I need to bootstrap the Lisp interpreter and the answer has been staring me in the face. Time to get back to the metal.

01:23
More coffee. Things are going well.

02:11
More coffee. Things are not going well. Working at this level is high RISC; I need to go high Church. Alonzo Church, that is. Lambda calculus is the purest of the pure. It’s so pure that it makes Haskell look like JavaScript. So pure, in fact, that it doesn’t even have numbers – there are only lambdas. Using Church numeral encodings, you define your own numbers.

This is perhaps the truest expression of the software craft movement: hand-crafted, artisanal integers. There are no Booleans, so you make your own truth. Mind-blowing. Want a list? You can define a pair, and then nominate roles for each element – first blow your mind out in a car, second cdr be used as the tail – and cons everything up from there.


Definitely jitters – no, not the testing framework. Hallucinations? Hallucinations.

03:14
Progress so far: I’ve got zeroes and ones. Lots of them. Frolicking lambdas ready to be crafted into a full stack.

Instead of FizzBuzz, I’m going to work on some more ambitious and algorithmic: a highly configurable, reusable, general-purpose algorithm that counts anything from sheep in a field, a semiring or a group, to holes in Blackburn, Lancashire (even if they’re rather small).

Feeling a little strange. And I’m out of coffee.

06:00
Uh... what... Snooze
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