Cache-Line Aware Data Structures
Structuring your program to consider memory can improve performance. We demonstrate this using a producer–consumer queue.

Compile-Time Data Structures in C++17
Using compile-time data structures to speed up runtime

How to Write a Programming Language
We continue writing a simple programming language, this time looking at the parser

(Re)Actor Allocation At 15 CPU Cycles
A lightweight allocator for (Re)Actors

Afterwood
Much ado about nothing
CARE about code? passionate about programming?

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The ACCU
The ACCU is an organisation of programmers who care about professionalism in programming. That is, we care about writing good code, and about writing it in a good way. We are dedicated to raising the standard of programming.

The articles in this magazine have all been written by ACCU members – by programmers, for programmers – and have been contributed free of charge.

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Should I Lead by Example?

Stuck on a problem? Frances Buontempo considers where to turn to for inspiration.

I started to clear my desk and found a cue card with the words “Lead by example” written on it, which distracted me from writing an editorial. This card is from Seb Rose’s closing keynote ‘Learning to Walk again’ at this year’s ACCU conference [Rose18]. The idea was to write down something you had learnt from the conference on a card and give the card, along with contact details, to someone so they could later remind you what you wrote. I failed to comply with the instructions precisely, since I still have my own card, but it did jog my memory, though not enough to recall what had taught me this. It could have been Arne Mertz’s ‘Code review’ session [Mertz18]. You cannot expect to get away with telling others how they can improve their code if you don’t follow your own suggestions. As a mentor, I encouraged new programmers to add unit tests to their code and put it all in version control, but frequently noticed I had strategic scripts with no tests at all and some not even in version control. For shame! Lead by example. Of course, it’s not just unit tests. I complain when others don’t keep a diary, or worse. I can recall many times when I’ve categorically told someone they were stupid and didn’t know what they were doing. I believe I have always need to make everyone go along with one idea. Sometimes it doesn’t. Tempers can get frayed if people don’t see things your way, and I value working software over proving my idea is the best. A recent blog post [DestroyAllSoftware] broke down a response from Linux Tovarlds on union aliasing. Tovarlds’ language was inflammatory and unkind. The blog post showed an alternative way of making the same points without being so hateful. You can disagree with people without resorting to bullying by telling them they are brain-dead or worse. I can recall many times when I’ve categorically told someone they were stupid and didn’t know what they were doing. I believe I have stopped doing this now. Pull me up if you notice me being a bully. Taking the lead by bullying others into submission is not a good idea. What are the alternatives?

To encourage the adoption of a new approach to a problem, instead of arguing or laying down the law, you may be able to knock together a prototype showing the alternative works. Sometimes the better tech wins, so giving people alternatives allowing them to try out your new ideas can be more persuasive than banning older tool-chains or similar. If you want to change an API, try adding new functions and gradually deprecating the older ones as people stop using them. The strangle vine pattern or strangle applicator [Fowler04] describes ways to ensure a new approach strangles or kills off the old way, drawing an analogy with strangle vines, which grow over other plants. It contrasts with a complete re-write allowing new approaches to live side by side with old approaches, at least for a while. This probably doesn’t count as leadership per se, but does give alternative paths. More suggest by alternatives than lead by example, though it incorporates the nub of the idea: have a demonstration or example to make your point.

Any prototype is certainly an example, though whether this counts as leading is another matter. In the sense of pioneering, or going out in front, it surely does? Sometimes attempting to trail-blaze leaves you more a lone lunatic in no-mans’ land than a leader. You need a level of self-confidence to be able to demonstrate an idea or working example without wanting to hide under a blanket or behind a sofa. I hope we manage to encourage Overload writers, even if we don’t always agree with everything that gets written. That’s ok. Thank you for sharing your ideas with us. An article is often an example, sometimes a novel idea even, which can lead readers to try new things, learn or even write in to disagree. That’s ok too. However, an article as a way of leading by example is probably not what my cue card meant.

What did I mean? I am not sure. It sounds like sensible advice, but I am unclear what it really means, as is often the case with slightly trite phrases. Furthermore, it begs the question: should I lead by example? Perhaps this is straying near Betteridge’s law of headlines: ‘Any headline that ends in a question mark can be answered by the word no’. [Wikipedia-1]. When used in a headline, a question is often sensationalist, in order to drum up an audience, something I suspect my title is unlikely to achieve. One website [BetteridgeLaw] has examples filling over two thousand pages. I can’t vouch for the veracity of any of those, though many are hilarious. ‘Does Bill Gates still know what computer users want?’ and so on. I’ll leave you to explore.

You may not aspire to be a leader, but can find yourself out in front from time to time. I sometimes walk quicker than others, finding myself ahead when walking with friends or family to an unfamiliar location, having just said, ‘I’ll follow you.’ It is difficult to follow if you are in front. Perhaps you find yourself reluctantly in front, being the first person to try to make a new technology work, or resurrect some old code no one knows how to build. Bad luck. In that situation, you are unlikely to have examples to follow. You can make sure you put the code in version control, add some kind of tests or at least ways of spotting regressions. You can add a make file, or other build script, once you have figured out how to build the code. A short readme file is a good idea too. Even if it says little more than ‘type

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make then run_tests’. In a sense, this is leading by example because you have improved the situation, just quietly in the background, without needing long meetings to decide what approaches to take. You might need these too, but at least the fundamental parts are in place and you have recorded what you spent time discovering in a simple and clear format. Perhaps that’s all I meant. Instead of moaning about the state of the world, or the project, or codebase, step up and make the changes needed. This might need to be in a non-invasive way, so people can still email themselves files, write word documents and have meetings if they want to. Meanwhile the code builds and runs. And crashes. But that’s another story. This nuance is leading in the sense of forging ahead and getting stuff done. It’s not leadership in the sense of an authoritarian head of state or someone guiding or conducting a process, team or project. A leader can also be a front page news splash or similar. Something at the front, in your face, trying to stir up discussion. An editorial of sorts. The etymology of the ending -ship might trace to the Dutch for cut or hack [Etymology], I presume along the lines of essence of something rather than thrown together or a newspaper hack. Such a pen for hire is not to be confused with relatively recent phone hacking scandals by News International [Wikipedia-2]. In a sense, the hack makes a path through something or in a direction. Any example gives a hint of how to do something or the direction to take. An entrepreneur or pioneer may take a lead, one dealing with the enterprisey requirements to form a business, the other possible being more like a lone ranger going off in front, perhaps a alone. Do such people lead by example? They lead. The best team leads I have ever worked with lead from behind. They were happy to take a back seat and enable the developers. The Harvard Business Review attributes this to Nelson Mandela [Hill04], equating a leader with a shepherd who “stays behind the flock, letting the most nimble go out ahead, whereupon the others follow, not realizing that all along they are being directed from behind.”

Are there leaders, whether team leads at work or from other realms, you admire? I suspect each of us can think of at least one person who seems to have a knack of getting things done in an effective manner. I have a few people I bring to mind when I get stuck on various problems. For coding problems, I wonder what specific coders I know would do. I won’t name and embarrass anyone, but I’ve met many such people through the ACCU. The meme, ‘What would [insert name here] do?’ has run for a long time. As with many memes or inspirational sayings, the question is a cliché. Commonplace sayings become clichés because they capture a heart of a common idea or experience, which rings true for many people. They can give an accurate encapsulation of an idea, or an example to put out in front. I have caught myself a few times thinking a project is going badly wrong and rather than asking ‘What would XXX do?’ I start asking myself what do I want to do. What would I do, if I were leading this project? What would I do if this were a personal project? That’s why I have managed to sneak in a make file and a way to run some regression tests on my current project. I’m not suggesting you use me as a fine example of how to solve any problems. I am asking if you have some self-belief. If you’re suffering from a confidence nose-dive, be kind to yourself. Remind yourself what you are good at, or at least enjoy. Spending time listening to people you admire, reading what they’ve written; articles, code or blogs. Or stories. At least get to a point where you can reflect on the bigger picture and get what you think clear. That might be no more than deciding you are stuck and haven’t got a clue what to do.

If you’re not sure how to tackle a problem, do consider asking yourself what XXX would do. Not necessarily Vin Diesel.¹ Find an example to lead you through your problem. I think I have now devolved into giving myself advice or suggestions using a few suspiciously platitudinous phrases. Thanks for listening. I may have intended to lead by example, but now wonder if perhaps I should re-word my cue card to say “Hack by cliché.” Whichever you think is most appropriate, take a moment to ask yourself, what would Linux do? What would Bjarne do? What should I do? Be the person you want to be. Don’t be mean. Lead by example, or hack by cliché.

References

¹. The film xXx starring Vin Diesel was released in 2002 (https://www.imdb.com/title/tt0295701/)
Cache-Line Aware Data Structures

Structuring your program to consider memory can improve performance. Wesley Maness and Richard Reich demonstrate this with a producer–consumer queue.

In this paper, we explore cache-line friendly data structures, in particular queues built with atomics that will be used in multi-threaded environments. We will illustrate our topic with a real-world use case that is not cache-line aware, measure, incorporate our suggestions, measure again, and finally review our results. Before we get into the nuts and bolts of our data structures, we need to define a few terms followed with some examples. For those readers who are not familiar with the topics of NUMA and CPU cache, we highly recommend reviewing them (at [Wikipedia-1] and [Wikipedia-2]).

Jitter

Jitter can be defined as the variance of time around operations that can arguably have constant time expectations.

A few examples to better illustrate are:

- The wall clock on a system in which each ‘tick’ of the highest-precision unit has some variance. Back in 2012, we measured the wall clock on the best server we had at the time. It was accurate down to 1 microsecond. However, we had jitter of ±1.5 microseconds. Consider that the clock’s accuracy increases over longer time periods, but each tick jittered.
- When we are linearly accessing memory in a system, each access may take a constant time until you hit a page fault. That page fault can introduce delay. In this case, we have a constant time operation that ends up having predictable jitter.
- Sparsely accessing an array can have many cache misses as well as cache hits. Depending on the location and layout of the memory, what should be constant will be different depending on:
  - Is the memory in the same NUMA node? [Tsang17]
  - Is the memory located in the cache?
  - Which cache is the memory located in? (L3, L2, L1)
  - Is the memory in the current cache line?
  - Is the memory contended with another CPU socket/core?

Many of the above are just examples which are not investigated in the scope of the paper and many can also be mitigated by using prefetching.

Cache line

The cache line is the smallest unit of RAM the CPU can load to perform operations. On the Intel CPU, this is 64 bytes, or 8 pointers in a 64-bit operating system. If at least one of the cores is writing, then cache coherency causes the cache line to be synchronized between the cores as each write forces a synchronization between the cores. Many cores reading from the same cache line causes no performance issues if there is no writing to that same cache line.

Cache awareness

Cache awareness really comes down to structuring your memory layout (memory model) of your program and its data structures. Careful consideration of what memory goes where can significantly improve the performance of the resulting machine code that must be verified by measuring.

For example, if we look at the Intel core i7 [Levinthal09] we can see its specifications are: L1 is 4 CPU cycles, L2 is 11 CPU cycles and L3 is 30-40 CPU cycles. Main memory can range from 200-350 CPU cycles on a 3GHz system. Crossing NUMA nodes incurs even more penalties. Code that sparsely accesses memory incurring many cache misses can spend 95% of the time doing nothing!

Motivation

In previous sections, we hinted as to why we would want to be cache aware, but here we will explain in a bit more detail, and then consider the benefits of potential future hardware progression and its impact.

From a multi-threading perspective, we need to be sure that data that are independently accessed by different threads are not shared over a cache line. Doing so will cause all reading threads to stall while the dirty cache line is synchronized across all cores. This is compounded if one or more of the threads exists on a different NUMA node.

The most direct benefit of fully independent data between threads not sharing cache lines is linear scalability. Some of the most obvious costs are:

- Increased code complexity due to increased complexity of the memory model.
- If each thread is accessing small amounts of data, some of the space in each cache line may not be utilized.
- Because of the above, we may need more memory to force alignment. If memory is limited, this could require special consideration.
- Perhaps there are multiple copies of the same data in various locations resulting in less efficient usage of memory.

Each socket is being packed with more and more cores, and FPGA integration into Intel CPUs is on the horizon (as this is written) [Intel] [Patrizio17]. This will effectively model memory to separate memory access at the cache-line level (to avoid false sharing [Bolosky93]). Furthermore, it will have a greater impact as cores and specialized hardware compete for resources.
Next, we will demonstrate the necessity of cache-line awareness with a modern-day use case that would benefit nicely from such consideration.

### Common use case

There exist situations in technology where we find ourselves having to set up and use a shared environment with many agents performing various coordinating tasks. In this use case, we will be given a machine in which we have a single multi-producer multi-consumer queue (MPMC) instance shared amongst a set of producers and consumers. The producers, we can assume, are clients which are running some computations and generating work, or some partial work. Hence each client would be running a different set of computations and each of those publishing their resulting work items to the MPMC for later consumption. Each consumer would be responsible for taking the work off the queue, perhaps performing some post-checks or validation of the work on an item in the queue then dispatching that work out to some client who will need to process or make some determination. Each consumer and producer would run in their own thread and potentially could be pinned to any CPU. Depending on what is required, it’s quite reasonable that the number of producers and consumers would need to scale up or down as clients and or workloads are running (some can go on and off line driven by various external events). The most critical measurement we would want to consider here would be the time it takes to produce or push a work item on the queue and for the work item to be removed from the queue. We consider other types of measurements as well.

### Running the benchmark

To enforce that we are not aligning the data, we use the `alignas` specifier for our data. The `struct` that we will be using is shown in Listing 1. We will store the number of cycles in the `struct` along with some other data fields. How we store these is shown in Listing 2 (not shown is the `GetTravelStore` method which is the same as `GetStore`). We used the `boost::lockfree::queue` for our testing the aligned section and we modify their implementation to disable alignment (not shown) for our baseline numbers.

```cpp
struct Benchmark
{
    uint64_t cycles{0};
    uint32_t serial{0};
};

template <typename Bench, int X>
struct Alignment
{
    alignas(X) Bench cb;
    Bench& get() { return cb; }
};
```

```cpp
std::unique_ptr<uint64_t> GetStore ( uint64_t iter )
{
    thread_local uint64_t* store{nullptr};
    if (store == nullptr)
        store = new uint64_t[iter];
    return std::unique_ptr<uint64_t>(store);
}
```

```cpp
void producer(Q* q, uint32_t iterations)
{
    auto store = Thread::GetStore(iterations);
    while (!Thread::g_pstart.load() == false) {}
    T d;
    d.get().serial = 0;
    int result = 0;
    for ( uint32_t j = 0; j < 2; ++j)
        // warm up
    for ( uint32_t i = 0; i < iterations; ++i)
    {
        ++result;
        d.get().cycles = getcc_b();
        while (!q->push(d));
        store.get()[i] = getcc_e() - d.get().cycles;
        // busy work to throttle production
        // to eliminate "stuffed" queue
        // No noticeable effect
        for (uint32_t k = 0; k<1000; ++k)
            // */
        
        // */
    }
    std::stringstream push;
    genStats(iterations, store, "1 Push", push);
    std::lock_guard<std::mutex>
        lock(Thread::g_cout_lock);
    std::cout << result << std::endl;
    Thread::g_output.emplace(push.str());
}
```

In establishing our baseline number, we will consider various scenarios or ratios of numbers of producers to consumers. Currently we only display results for the ratio 2:2. Each consumer and each producer will spin in a busy loop to minimize overall cycles required to publish and or consume data. The code for producer and consumer is shown in Listing 3. The total we need to be sure that data that are independently accessed by different threads are not shared over a cache line.
number of items produced in each scenario will be scaled to the number of consumers. In these examples, we will use the standard atomics (as part of the MPMC queue) in C++ and spin on their values to identify when data is available. The producers and consumers are constructed in the run method shown in Listing 4.

Finally, for our benchmark without cache-line awareness, we put all of this together:

```
Template<typename T, template<class...>Q>
void run ( int producers, int consumers )
{
    std::cout << "Alignment of T 
    " << alignof(T)
    "std::endl;
    std::vector<std::unique_ptr<std::thread>> threads;
    threads.reserve(producers+consumers);
    Q<T> q(128);
    // need to make this a command line option
    // and do proper balancing between
    // consumers and producers
    uint32_t iterations = 1000000;
    for (int i = 0; i < producers; ++i)
    {
        threads.push_back(
            std::make_unique<std::thread>
            (producer<T,Q<T>>, q,
             iterations));
        // adjust for physical cpu/core layout
        setAffinity("threads.rbegin(), i*2");
    }
    for (int i = 0; i < consumers; ++i)
    {
        threads.push_back(
            std::make_unique<std::thread>
            (consumer<T,Q<T>>, q,
             iterations));
        // adjust for physical cpu/core layout
        setAffinity("threads.rbegin(), 4+i*2");
    }
    Thread::g_cstart.store(true);
    usleep(500000);
    Thread::g_pstart.store(true);
    for (auto& i : threads)
    {
        i->join();
    }
    for (auto& i : Thread::g_output)
    {
        std::cout << i << std::endl;
    }
}
```

We will pin each thread created to its very own CPU to reduce overall variance on measurements. This is done in the method `setAffinity` mentioned in the code examples but not shown. You can find more information about thread affinity on the Linux man pages [Kerrisk]. We will measure push, pop, and total queue traversal time (pop end time – push start time) along with various other metrics. These results are shown in Figure 1. All measurements are in cycles (using RDTSCP and CPUID instructions) using the recommended guidelines from Intel.
These measurements are computed inside the functions \texttt{getcc\_b} and \texttt{getcc\_e} (not shown).

**Applying cache-line awareness to our example**

Now that we have identified how we are going to take advantage of cache-line awareness in our queue, we will re-run our previous tests with the changes we just applied. We will now enable cache-line awareness by using the alignas specifier for our data. The code used here is:

```c++
runc<Alignment<
    Benchmark, 64>
, boost::lockfree::queue>
(producers, consumers);
```

We will run through the same scenarios as we saw in Figure 1. These results are shown in Figure 2.

Note: If the measurements are not clear in Figure 2, the max measurements for Push, Pop, and Traversal are observed as 22977, 20221, and 18102 respectively.

**Analysis**

Comparing where we started and where we ended up, there are several items of considerable mention. The first is that the distribution of the percentiles for Figure 1 clearly show fat tail properties mostly noticeably in the traversal measurements. Another quite fascinating point is that the 90th and 99th percentiles of all measurements dropped considerably in all operations. Push went from 518 cycles to 431 and 715 cycles to 575 for 90th and 99th percentiles. Pop, not necessarily as impressive as Push, went from 414 cycles to 370 and 623 cycles to 500 cycles respectfully. Traversal was even more impressive going from 810236 cycles to 12307 and 8497191 cycles to 15571 for 90th and 99th percentiles respectively.

**Conclusion and future direction**

There are many items we didn’t address in this paper. For example, we did not discuss the data throughput through the queue as a function of cache-line awareness changes. We could have also considered measuring different scenarios and the ratios of producers to consumers. It is important to note that the problem addressed in this paper is just one instance of a group of problems collectively known as flow control problems. These problems exist in many domains, and are quite common in some aspects of financial technology, but have relevancy in many others. We mention the points above to illustrate different ways in which this problem can be expanded upon and perhaps further analysis may be continued.

Finally, as we were writing this paper, running measurements of various scenarios, the results were in many ways quite interesting and often initially appeared to be counter-intuitive, but after carefully examining the assembly and measuring the performance more closely the results made more sense. We can’t stress enough how important it is to measure your applications and the tools used to measure those applications.

**Notes**

Boost 1.63.0 and GCC 5.4.0 were used. For a complete package of the code used in this article and that which is referenced and not shown, please contact the authors directly. All measurements were the average of 1000 runs of 1e6 iterations for 2 consumers and 2 producer threads. Intel i7-3610QM CPU 2.30GHz 4 cores per socket for 8 cores total was used to produce all measurements discussed in the paper. Operating system used was Linux ll 4.12.5-gen too.

**References**


![Figure 2](image-url)
miso: Micro Signal/Slot Implementation

The Observer pattern has many existing implementations. Deák Ferenc presents a new implementation using modern C++ techniques.

miso is short for micro signals and slots and, as the name suggests, it is an implementation of the well-known language construct largely popularized by Qt: The signals and slots mechanism [Wikipedia]. As the Wikipedia article suggests, the signal-slot construct is a short, concise and pain-free implementation of the Observer pattern, i.e. it provides the possibility for objects (called observers) to be recipients of automatic notifications from objects (called subjects) upon a change of state, or any other event worthy of notification.

Reasoning

So, you may ask, why another signal/slot implementation? Since we already have the granddaddy of them all, the Qt signal/slot implementation which, as presented in [Qt4SigSlot], is a very powerful mechanism already have the granddaddy of them all, the Qt signal/slot implementation.

Or we have the boost signal libraries [BoostSigSlot], which are another excellent implementation of the same mechanism for the users of the boost library.

And we also have other less well-known signal/slot implementations, such as Sarah Thompsons’ signal and slot library [sigslot-1] or the VDK signals and slots written in C++11 [VDK], GNOME’s own libsigc++ [libsigc++], the nano signal slot [nanosigslot], Patrick Hogans’ Signals [Hogan] or several fresher ones from github ([nod] [sigctx] [sigslot-2] [cpp-signal]) or the more hidden ones, which I was not able to discover even with Google’s powerful search algorithm.

All these excellent pieces of software were written specifically for this purpose, and they all serve the needs of software developers wanting to use the signals and slots mechanism without too much hassle.

And on the other side, the Observer pattern is a very widely adopted and successful pattern which has also been widely studied in various articles, including Overload’s own ones, such as Phil Bass’ articles in Overload 52 and 53: ‘Implementing the Observer Pattern’ [Bass02] or Pete Goodliffe’s articles in Overload 37, 38 and 41 (‘Experiences of Implementing the Observer Design Pattern’) [Goodliffe00] – both excellent articles which were not backed up by the power of C++11’s syntax and standard library at the time … due to the fact they were written in the first years of this century – but also Alan Griffiths’ article from 2014 (‘Designing Observers in C++11’) [Griffiths14], which lifted this pattern into the modern age using C++11 constructs.

So with a good reason, you may ask why…

But please bear with me … the implementation of this mechanism seemed to be such an interesting and highly challenging research project that I could not resist it. I wanted to use the elegance of the constructs introduced with C++11 to avoid as much as possible the syntactical annoyances that I found in various signal/slot projects, which were bound to old-style C++ syntax, and I also wanted to keep this implementation short and concise. Hence, this header-only micro library appeared, and in the spirit of keeping it simple, it is under 150 lines, but still tries to offer the full functionality a one would expect from a usable signal/slot library.

This article not only provides a good overview of the usage of and operations permitted by this tiny library, but also presents a few interesting C++11 techniques I have stumbled upon while implementing the library that I considered to be of sufficient calibre to be worth mentioning here.

The library itself

miso, being a single header library, is very easy to use. You just have to include the header file into your project and you’re good to go: #include <miso.h> and from this point on you have access to the namespace miso, which contains all the relevant declarations that you need to use it. Later in this article, we present all the important details of this namespace.

The library was written with portability and standard conformance in mind, and it is compilable for both Linux and Windows; it just needs a C++11 capable compiler.

Signals, slots, here and there

The notion of a slot is sort of uniform between all signal-slot libraries: It must be something that can be called. Regardless whether it’s a function, a functor, a lambda or some anomalous monstrosity returned by std::bind and placed into a std::function… at the end: It must be a callable. With or without parameters. Since this is what happens when you emit a signal: a ‘slot’ is called.

However, there is no real consensus regarding the very nature of signals. Qt adopted the most familiar, clear and easy to understand syntax of all the signatures:

```cpp
signals:
    void signalToBeEmitted(float floatParameter, int intParameter);
```

Simple, and clean, just like a the definition of a member function, with a unique signature, representing the parameters this signal can pass to the slots when it is emitted. And the Qt meta object compiler takes care of it, by implementing the required supporting background operations (ie: the connection from the signal to actually calling the slot function), thus removing the burden from the programmer who can concentrate on implementing the actual functionality of the program.

The other big player in platform independent C++ library solutions, boost, on the other end has chosen a somewhat more complex approach to defining the same signal:

```cpp
boost::signals2::signal<void (float, int)> sig;
```

This way of defining a signal feels very similar to the declaration of a function packed in a templated signal declaration and, because what it means is widely understood, it was adopted not only by [VDK],...
Qt signals and slots

For those who haven’t had the chance to work with Qt’s signals and slots, a small note: Qt has a handy tool, called moc (Meta-Object Compiler) which handles the C++ extensions of the Qt framework, such as signals and slots among other more handy helping features. The moc tool parses a header file containing Qt extensions and generates a C++ source file, which must be included in the compilation in order to get the desired Qt functionality working [QtMoc].

Signals in miso

The signal definition of miso uses the following syntax in order to declare the same signal:

```cpp
signal<float, int> float_int_sig;
```

Achieving the simplicity of Qt’s signal syntax seemed to not to be possible without using an extra step in the compilation phase (I am thinking of moc of Qt) since it is already syntactically correct C++ which the compiler can handle without too much hassle. This declaration also has the side effect that unless like Qt’s signal declaration, we have a tangible C++ variable which possibly is a class with methods and properties we can act upon.

A tiny application

The easiest way to introduce a new library is to present a small and simple example which showcases the basic usage of the library, so Listing 1 is the “Hello world” equivalent of miso.

After skipping the mandatory inclusions, let’s analyze the important pieces:

```cpp
#include "miso.h"
#include <iostream>

struct a_class
{
    miso::signal<const char*> m_s;
    void say_hello()
    {
        emit m_s("Hello from a class");
    }

    void a_function(const char* msg)
    {
        std::cout << msg << std::endl;
    }

    int main()
    {
        a_class a;
        a.m_s.connect(a.m_s, a_function);
        a.say_hello();
    }
```

Firstly, we declare a class (for now with the struct keyword to keep the code short and uncluttered): struct a_class. In the miso framework the signals belong to classes: it is not possible to have a signal living outside of an enclosing entity. This sort of resonates on the same frequency as Qt’s signal and slot mechanism; however, the boost signals are more independent and are not required to be bound to a class.

As mentioned above, the miso signals are to be bound to a class so now is the perfect time to declare the signal object itself: miso::signal<const char*> m_s. All the miso types live in the miso namespace in order to avoid global namespace pollution; however, this does not stop you from using the namespace as per your needs. The signal we have declared is expected to come with a parameter, which is of type const char*.

The next line in the class is a plain method, which has just one role: to emit the signal. This is done with the intriguing line: emit m_s("Hello from a class");. After spending several years with Qt, it just feel so natural to emit a signal and since I wanted to keep the essence of the library close to already existing constructs to ease the transition, the emit was born. emit will be dissected later in the article to understand how it works.

The global method void a_function(const char* msg) is the slot which is connected to this signal. It does not do very much; it only prints the message it receives from the signal to stdout, but for demonstration purposes this is acceptable.

And now we have reached to the main method of the application, which creates an object of type a_class and connect its signal: a.m_s to the global function a_function. And, last but not least, the say_hello
the compiler will take care that slots with matching signatures to the ones the signal requires are actually available.
emitting, and active decides whether this signal is active or not (disconnect calls the same function with active = false).

The parameters to the internal function follow by using forward on the f parameter to the current function, then slot_holders which is a local variable of type:

```cpp
struct common_slot_base {
    virtual ~common_slot_base() = default;
};
```

so, basically it is just an interface to be used by all the different kinds of signals as a means of calling their corresponding slots. An immediate usage of it is in the signal class:

```cpp
struct slot_holder_base {
    using FT = std::function<typename
        std::result_of<T(Args...)>::type(Args...)>;  
    using slot_vec_type = std::vector<internal::func_and_bool<FT>>;  
    slot_vec_type slots;  
    void run_slots(Args... args) override  
    {  
        std::for_each(slots.begin(), slots.end(), 
            [&](internal::func_and_bool<FT>& s)  
            {  
                if (s.active)  
                    (*(s.ft.get()))(args...);  
            });  
    }  
};
```

with further specialization following in Listing 5.

Reading the last method, it is obvious that the main action happens here, i.e. the actual call of a slot as per the corresponding signal takes place in these lines.

A bit more investigation of this structure gives us the declaration of FT being an std::function which at compile time identifies its return type from the template parameter of the slot_holder class (T which is supposed to be a ‘Callable’) which is fed into the std::result_of of the <type_traits> header having the parameters Args... of the signal class that this slot_holder resides in, combined again with the Args... of the signal to obtain a fully understandable expression. Just a clarification, FT stands for Function Type. And last but not least about this construct: Personally, I consider this piece of code to be one of the small wonders of the powers of modern C++... (read: even after writing it, and knowing that it’s syntactically correct and valid code, in my weaker moments I still wonder that it compiles...)

Since in this structure we have introduced a new structure (func_and_bool), here is its definition:

```cpp
template<typename FT>
struct func_and_bool final {
    std::shared_ptr<FT> ft;  
    bool active;  
    void *addr;  
};
```

which roughly holds the lowest level of a slot, i.e.: a function object, whether it is active or not, and its address, thus revealing that at the lowest level all slots are decaying into an std::function (the one which was declared in the type name FT of the struct slot_holder).

Now, that we have covered the necessary structures and functions of a signal, it is time to look at the actual function from the internals, which performs the real connect (see Listing 6).

So, dissecting it into bits we can observe the following:
The type of the static SHT sh; local variable came in via the template parameters, and for our case it will have the structure slot_holder declared in the signal class. Now, this sh (slot holder, for the uninitiated) variable will be common for all the connect_i functions sharing a common prototype (hence, the static). For the perverse among you, SHT stands for Slot Holder Type; don’t you dare start thinking of anything else. There is just one small drawback to using this static variable: miso in its current incarnation is not thread safe (so if someone is feeling tempted to fix this issue … feel free to make a pull request on github or depending on time and resources, the author might fix it).

The next step is to create a func_and_bool object with the type of the FT we discussed in the slot_holder class, and we check whether the newly created object is in the slot holder already (by comparing its physical address to those already in the container). If yes, we set its activeness state to the one required in the parameter, but since we don’t want to add it again, we also flip a boolean flag for later usage.

The next step is updating the incoming parameter holders in order to append the local sh object. This is where the magic happens since this parameter is the same that is declared in the signal class, and since slot_holder<T> is a common_slot_base specialization we successfully managed to gather all the slots regardless of their parameters, this type of signal class is connected to into one common entity we can operate on.

With these covered we have successfully surveyed the mechanisms behind the connection of a slot to a specific signal, so we can jump to the next stage of our library, namely, emitting a signal.

### Emitting a signal

The syntax, as seen from the tiny example application provided, is:

```
emit signalname(param1, param2, ...);
```

By digging further in the header file, we find that emit basically is:

```
#define emit \\
  miso::internal::emitter\\
  <std::remove_pointer<decltype(this)>::type>(*this) <<
```

(Yes, that is a << operator at the end of the line)

So, a simple emit will create in its turn a temporary miso::internal::emitter object, which is a helper class like Listing 7, whose role is to keep track of the current object that emitted the signal. I’m confident that the logic for this is covered in the nice self-
struct a_class {
    miso::signal<int> m_s;

    void say_hello() {
        emit m_s(42);
    }
    int x = 45;
};
struct functor {
    void operator() (int aa) {
        std::cout << "functor class’s int slot:"
        << aa << std::endl;
        a_class* ap = miso::sender<a_class>();
        std::cout << "x in emitter class:" << ap->x
        << std::endl;
    }
};
int main() {
    a_class a;
    functor f;
    miso::connect(a.m_s, f);
    a.say_hello();
    return 0;
}

Listing 8

explanatory code above, so let’s just give an example of how can we retrieve the sender of the current signal (see Listing 8). So, in the slot, we just simply call:

```cpp
    a_class* ap = miso::sender<a_class>();
```

and this gives us the type of the class that has emitted the signal resulting in us being in the current slot. Be aware, that if we are not handling the slot class due to an emit from a signal, and we call the miso::sender we will get a std::runtime_error exception.

The internals of calling the signal handler

If you wonder about the << operator in the macro definition of emit, please note the signal class has a very complex friend declaration, in the form of:

```cpp
    template<T, class... Args> friend internal::emitter<T> & & internal::operator
    << (internal::emitter<T> & &e,
        signal<Args...> & &s) {
        s.delayed_dispatch();
        return std::forward<internal::emitter<T>>(e);
    }
```

which looks like:

```cpp
    template<T, class... Args>
    emitter<T> & & operator
    << (internal::emitter<T> & &e,
        signal<Args...> & &s) {
        s.delayed_dispatch();
        return std::forward<internal::emitter<T>>(e);
    }
```

To make the syntax possible, please also note the following in the signal class:

```cpp
    std::tuple<Args...> call_args;
    signal<Args...> & & operator() (Args... args) {
        call_args = std::tuple<Args...>(args...);
        return *this;
    }
```

(so, the signal class in its turn is also a functor :) ) otherwise the required syntax for emit wouldn’t have been possible. The call_args member is nothing more than the calling arguments for emitting the signal populated by this operator(). Now we can see that the temporary emitter object created above will call the overloaded << operator with the signal (which in its turn has already consumed the input parameters via the operator() call), and in there the delayed_dispatch method of the signal is called.

When it comes to delayed dispatch, [Stackoverflow] shows us how to unpack a tuple holding various values of various types to a function with matching parameter types. This is necessary in order to have a perfect match between the values the signal’s call arguments were populated with and the slots that are supposed to get the same values. When the delayed dispatch method runs, it in turn calls run_slots from the slot holder's vector (which, if you remember, were populated in the connect step).

The future

With this lengthy overview, I am confident, that everyone needing to use a lightweight signal-slot library has at least one more choice to select from, making the decision even harder. At the same time, I’m hoping that this article has shed some light into how to use this library. Whether it is a good choice for your team or not that depends entirely on you.

The library

You can find the implementation of the library in miso.h (released under MIT license) at https://github.com/fr00b0/miso Also, please note: For now, this is far from a fully fledged signal-slot library, offering the power and functionality you would expect from Qt or Boost. Depending on time and resources, I would be happy to add features you request (or even approve your pull request in case you consider it worth fixing a few bugs here and there, or adding a new nice to have item to it) but till then kindly treat it lightly.

References


[cpp-signal] https://github.com/Montellese/cpp-signal


[Hogan] https://github.com/pbhogan/Signals


[nanosigslot] https://github.com/NoAvailableAlias/nano-signal-slot

[neosigslot] http://i42.co.uk/stuff/neosigslot.htm

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[sigc++] https://github.com/zhanggyb/sigc++


[sigslot-2] https://github.com/supergroover/sigslot


(Re)Actor Allocation at 15 CPU Cycles

(Re)Actor serialisation requires an allocator. Sergey Ignatchenko, Dmytro Ivanchykhin and Marcos Bracco pare malloc/free down to 15 CPU cycles.

Disclaimer: as usual, the opinions within this article are those of ‘No Bugs’ Hare, and do not necessarily coincide with the opinions of the translators and Overload editors; also, please keep in mind that translation difficulties from Lapine (like those described in [Loganberry04]) might have prevented an exact translation. In addition, the translator and Overload expressly disclaim all responsibility from any action or inaction resulting from reading this article.

Task definition

Some time ago, in our (Re)Actor-based project, we found ourselves with a need to serialize the state of our (Re)Actor. We eventually found that app-level serialization (such as described in [Ignatchenko16]) is cumbersome to implement, so we decided to explore the possibility of serializing a (Re)Actor state at allocator level. In other words, we would like to have all the data of our (Re)Actor residing within a well-known set of CPU/OS pages, and then we’d be able to serialize it page by page (it doesn’t require app-level support, and is Damn Fast™; dealing with ASLR when deserializing at page level is a different story, which we hope to discuss at some point later).

However, to serialize the state of our (Re)Actor at allocator level, we basically had to write our own allocator. The main requirements for such an allocator were that:

- We need a separate allocator for each of (Re)Actors running in the same process
- At the same time, we want our app-level (Re)Actors to be able to use simple new and delete interfaces, without specifying allocators explicitly
- We need each of our allocators to reside in a well-defined set of CPU pages (those pages obtained from the OS via mmap() / VirtualAllocEx())
  This will facilitate serialization (including stuff such as Copy on Write in the future).
- We do NOT need our allocator to be multi-threaded. In the (Re)Actor model, all accesses from within (Re)Actor belong to one single thread (or at least ‘as if’ they are one single thread), which means that we don’t need to spend time on thread sync, not even on atomic accesses.

The only exception is when we need to send a message to another (Re)Actor. In this case, we MAY need thread-safe memory but, in comparison with intra-(Re)Actor allocations, this is a very rare occurrence — so we can either use standard malloc() for this purpose or write our own message-oriented allocator. The latter will have very different requirements and therefore very different optimizations from the intra-(Re)Actor allocator discussed in this article.

Actually, when we realized that we only needed to consider single-threaded code was when we thought, ‘Hey! This can be a good way to improve performance compared to industry-leading generic allocators’. Admittedly, it took more effort than we expected, but finally we have achieved results which we think are interesting enough to share.

What our allocator is NOT

By the very definition of our task, our allocator does not aim to be a drop-in replacement for existing allocators (at least, not for all programs). Use of our allocator is restricted to those environments where all accesses to a certain allocator are guaranteed to be single-threaded; two prominent examples of such scenarios are message-passing architectures (such as Erlang) and (Re)Actors a.k.a. Actors a.k.a. Reactors a.k.a. ad hoc FSMs a.k.a. Event-Driven Programs.

In other words, we did not really manage to outperform the mallocs we refer to below; what we managed to do was to find a (very practical and very important) subset of use cases (specifically message passing and (Re)Actors), and write a highly optimized allocator specifically for them. That being said, while writing it, we did use a few interesting tricks (discussed below), so some of our ‘ideas might’ be usable for regular allocators too.

On the other hand, as soon as you’re within (Re)Actor, our allocator does not require additional programming effort from the app-level; this gives it an advantage over manually managed allocation strategies such as used by Boost::Pool (not forgetting that, if necessary, you can still use Boost::Pool over our allocator).

Major design decisions

When we started development of our allocator (which we named iibmalloc, available at [Github]), we needed to make a few significant decisions.

First, we needed to decide how to achieve multiple allocators per process, preferably without specifying an allocator at app-level explicitly. We decided to handle it via TLS (thread_local in modern C++). Very briefly:

- By task definition, our allocator is single-threaded.
  This allows us to speak in terms of the ‘function which is currently executed within the current thread’.

‘No Bugs’ Bunny Translated from Lapine by Sergey Ignatchenko, Dmytro Ivanchykhin and Marcos Bracco using the classic dictionary collated by Richard Adams.

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Moreover, at any point in time, we can say which allocator is currently used by the app level (it is the allocator which belongs to the currently running (Re)Actor).

Even if there are multiple (Re)Actors per thread, this still stands.

Hence, a **thread_local** allocator will do the job:

- For a *single (Re)Actor per thread*, we can have a per-thread allocator (this is the model we were testing for the purposes of this article).
- For *multiple (Re)Actors per thread*, our Infrastructure Code (which runs threads, instantiates (Re)Actors, and calls `Reactor::react()`) can easily put a pointer to the allocator of the current (Re)Actor right before calling the respective `Reactor::react()`.

In addition, we found that the performance penalties of accessing TLS (usually one indirection from a specially designated CPU register into a highly-likely cached piece of memory) are not too high even for our very time-critical code.

Second, we needed to decide whether we want to spend time keeping track of whole pages becoming empty so we can release them. Based on the logic discussed in NoBugs18, we decided in favor of **not** spending any effort on keeping track of allocation items as long as there is more than one such item per CPU page.

Third, in particular based on NoBugs16, we aimed to use as **few memory accesses as humanly possible**. Indeed, on modern CPUs, register–register operations (which take ~1 CPU cycle) are pretty much free compared to memory accesses (which can go up to 100+ CPU cycles).

**Implementation**

We decided to split all our allocations into four groups depending on their size:

- **'small' allocations** – up to about one single CPU page.
  We decided to handle them as ‘bucket allocators’ (a.k.a. ‘memory pools’). Each page contains buckets of the same size; available bucket sizes are some kind of exponent so that we can keep overheads in check.
  Whenever a new page for a specific bucket size is allocated, we ‘format’ it, creating a linked list of available items in the page, and adding these items to the ‘bucket’, which is essentially a single-linked list with all the free items of this size.
- **'medium' allocations** – those taking just a few pages (currently – up to 4 pages IRC).
  These are also handled as ‘bucket allocators’, but they may span several CPU pages (we named these ‘multi-pages’). Note that for 'medium' allocations, all the allocation items are page-aligned.
- **'large' allocations** – those which are already too large for buckets, but which are still too small to request from the OS directly as a single range (doing so would create too many virtual memory areas a.k.a. VMAs, and may result in running out of available VMA space – which is manifested by **ENOMEM** returned by `mmap()` even if there is still lots of both of address space and physical RAM). Currently, ‘large’ allocations go up to about a few hundred kilobytes in size.
  ‘large’ allocations are currently handled as good ol’ Knuth-like first-fit allocators working at page level (i.e. granularity of allocations is one page), and with some further relatively minor optimizations.
  ‘Large’ allocations are not aligned at page boundaries (though, of course, they’re still aligned at 8-byte boundaries).
- **'very large' allocations** – those allocations which are large enough to feed them to the OS directly. Currently, they start at about a few hundred kilobytes.
  Like ‘large’ allocations, ‘very large’ allocations are not aligned on page boundaries.
It was when we faced the problem of **how to do deallocation efficiently that we got into the really interesting stuff**

‘very large’ allocations are the only kind of allocations which can be returned back to the OS.

**Optimizing allocation – calculating logarithms**

Up to now, everything has been fairly obvious. Now, we can get to the interesting part: specifically, what did we do to optimize our allocator? First, let’s note that we spent most of our time optimizing ‘small’ and ‘medium’ allocations (on the basis that they’re by far the most popular allocs in most apps, especially in (Re)Actor apps).

The first problem we faced when trying to optimize small/medium allocations was that – given the allocation size, which comes in a call to our `malloc()` – we need to calculate the bucket number. As our bucket sizes are exponents, this means that effectively we had to calculate an (integer) logarithm of the allocation size.

If we have bucket sizes of 8, 16, 32, 64, ... – then calculating the integer logarithm (more strictly, finding the greatest integer so that two raised to that integer is less or equal to the allocation size) becomes a cinch. For example, on x64 we can/should use a BSR instruction, which is extremely fast. (How to ensure that our code generates a BSR is a different compiler-dependent story but it can be done for all major compilers.) Once we have our BSR, skipping some minor details, we can calculate:

\[
\text{bucket number} = \text{BSR(size-1)} - 2, \text{or, in terms of bitwise arithmetic, the ordinal number of the greatest bit set of (size-1) minus two.}
\]

However, having bucket sizes double at each step leads to significant overheads, so we decided to go for a ‘half-exponent’ sequence of 8, 16, 32, 48, 64, ... In this case, the required logarithm to find our bucket size can still be calculated very quickly along quite similar lines: it is a doubled ordinal number of a greatest bit set of (size-1) plus second greatest bit of (size-1) minus five.

These are still register-only operations, are still branch-free, and are still extremely fast. In fact, when we switched to ‘half-exponent’ buckets, we found that – due to improved locality – the measured speed improved in spite of the extra calculations added.

**Optimizing deallocation – placing information in a dereferenceable pointer?!**

*The key, the whole key, and nothing but the key, so help me Codd* – unknown

Up to now, we have described nothing particularly interesting. It was when we faced the problem of how to do deallocation efficiently that we got into the really interesting stuff.

Whenever we get a `free()` call, all we have is a pointer, and nothing but a pointer (for C++ `delete`). And from this single pointer we need to find:

(a) whether it is to a ‘small’, ‘medium’, ‘large’, or ‘very large’ allocated block, and for small/medium blocks, we have to find (b) which of the buckets it belongs to.

Take 1 – Header for each allocation item

The most obvious (and time-tested) way of handling it is to have an allocated-item header preceding each allocation item, which contains all the necessary information. This works, but requires 2 memory reads (cached ones, but still taking 3 cycles or so each) and, even more importantly, the item header cannot be less than 8 bytes (due to alignment requirements), which means up to twice the overhead for smaller allocation sizes (which also happen to be the most popular ones).

We tried this one, it did work – but we were sure it was possible to do it better.

Take 2 – Dereferenceable pointers and bucket page headers

For our next step, we had two thoughts:

- All large/very-large allocated items have values of `CPU_page_start+16` (this happens naturally as these items in our implementation always start at page beginning, after a 16-byte header). BTW, ‘16’ is not really a magic number, it is just the size of a large/very-large item header.

We can also ensure that all small/medium pointers never start at `CPU_page_start+16`. This is assured by the ‘bucket page formatting’ routine, which, if it runs into such a size, simply skips this one single item (note that it won’t happen for larger item sizes, so the memory overhead due to such skipping is negligible).

This means that (assuming a 64-bit app and a 4K-page, but for other page sizes the logic is very similar) an expression

\[
(\text{pointer_to_be_freed&0xFFFF})==16
\]

will give us an answer to the question of whether we’re freeing a small/medium alloc or a large/very-large alloc.

BTW, this means that we already achieved the supposedly-impossible feat of effectively placing a tiny bit of information into a dereferenceable pointer. In other words, having **nothing but the pointer itself** (not even accessing the memory the pointer refers to), we can reach conclusions about certain properties of the memory it points to.

And for small/medium allocs, we can exploit the fact that all of the buckets within the same page are of the same size. This means that if we place a header into each page (instead of placing it into each allocated item), we’ll be able to reach it using

\[
((\text{page_header}*)(\text{pointer_to_be_freed&0xFFFF}FFF000))
\]

and get information about the bucket number out of our `page_header`.

This approach worked, but while it reduced memory overhead, the cost of the indirectness to the `page_header` (which was less likely to be cached than the allocation item header) was significant, so we observed minor performance degradation.©
Take 3 - Storing the bucket number within a dereferencable pointer

However, (fortunately) we didn’t give up - and came up with the following schema, which effectively allows us to extract the bucket number from each small/medium allocated pointer. It requires a bit of explanation.

Whenever we’re allocating a bunch of pages from the OS (via mmap() / VirtualAllocEx()) – we can do it in the following manner:

- Let’s assume we have 16 buckets (this can be generalized for a different number of buckets, even for non-power-of-2 ones, but let’s be specific here).
- We’re reserving 16 pages, without committing them (yet). Sure, it does waste a bit of address space – but at least for 64-bit programs it is not really significant; and as we’re not committing, we do not waste any RAM (well, except for an additional VMA, but a number of VMAs have to be addressed separately anyway).

As for the wasting of address space, in the worst possible case such a waste is 16x (it won’t happen in the real-world, but let’s assume for the moment it did). And while 16x might look a lot, we can observe that modern OSs running under x64 CPUs have 47-bit address spaces; even with the 16x worst-case overhead, we still can physically allocate $2^{43}$ bytes of RAM, or 8 Terabytes of RAM – which is still well beyond practical capabilities of any x64 box (I’ve ever heard of (as of this writing, even the largest TPC-E boxes which cost $2 million, use ‘only’ 4T of RAM). If you ever have such a beast at your disposal, we’ll still have to see whether it will need all this memory within a single process. In any case, it is clear that this waste won’t matter for the vast majority of currently existing systems.

- Very basic maths guarantees us that among our reserved 16 pages, there is always exactly one page for which the expression page_start&0xFFF000 has the value 0x0000, and exactly one page for which the expression page_start&0xFFF000 has the value 0x1000, and so on all the way up to 0xF000. In other words, while we do not align our reserved page range, we still can rely on having one page with each of 16 possible values of a certain pre-defined expression over a page_start pointer().

- Now, we’re saying, that we need to allocate buckets for bucket_number 7, so let’s pick the page which has the expression page_start&0xFFF000 == 0x7000 (as noted above, such a page always exists in our allocated range). Then commit and ‘format’ this page to have buckets corresponding to bucket index == 7.

- Of course, whenever we need a page for a different bucket size, we can (and should) still re-use those reserved-but-not-yet-committed pages, committing memory for them and formatting them for the sizes which follow from their page_start&0xFFF000.

After we’re done with this, we can say that:

For each and every ‘small’/‘medium’ pointer to be freed, the expression ((pointer_to_be_freed>>12)&0xF) gives us the bucket number.

This information can be extracted purely from the pointer, without any indirections(!). In other words, by doing some magic we did manage to put information about the bucket number into the pointer itself!!.

In practice, it was a bit more complicated than that (to avoid creating too many VMAs, we needed to reserve/commit pages in larger chunks – such as 8M), but the principles stated above still stand in our implementation. This approach happened to be the best one both performance-wise and memory-overhead-wise.

How our deallocation works

To put all the pieces of our deallocation together, let’s see how our deallocation routine works:

- We take the pointer to be freed (which is fed to us as a parameter of a free() call), and use something along the lines of ((pointer_to_be_freed&0xFFF)==16) to find out if it was small/medium alloc, or large/very-large one. NB: there is a branch here, but large/very-large blocks happen rarely, so mispredictions are rare.

- If it is a large/very-large item, we’re using a traditional header-before-allocation-item. As this happens rarely, performance in this branch is not too important (it is fast, but it doesn’t need to be Damn Fast™).

- If it is a small/medium item, we calculate the bucket size using ((pointer_to_be_freed>>12)&0xF) and then simply add the current pointer to the single-linked list of the free items in this bucket.

This is the most time-critical path – and we got it in a very few operations (maybe even close to ‘the-least-possible’). Bingo!

Test results

Of course, all the theorizing about ‘we have very few memory accesses’ is fine and dandy, but to map them into real world, we have to run some benchmarks. So, after all the optimizations (those above and others, such as forcing the most critical path – and only the most critical path – to be inlined), we ran our own ‘simulating real-world loads’ test [Ignatchenko18] and compared our iibmalloc with general-purpose (multithreaded) allocators. We feel that the results we observed for our iibmalloc were well-worth the trouble we took while developing it.

The testing is described in detail in [Ignatchenko18], with just a few pointers here:

- We tried to simulate real-world loads, in particular:
  - The distribution of allocation sizes is based on $p-\frac{1}{sz}$ (where $p$ is the probability of getting allocations of size $sz$).
  - The distribution of life times of allocated items is based on a Pareto distribution.
  - Each allocated item is written once and read once.
  - All 3rd-party allocators are taken from the current Debian ‘stable’ distribution.
  - Unless specified otherwise, we ran our tests with total allocation size of 1.3G.

When running multiple threads, the total allocation size was split among threads, so the total allocation size for the whole process remained more or less the same.

As we can see (Figure 1), CPU-wise, we were able to outperform all the allocators at least by 1.5x.

And from the point of view of memory overhead (Figure 2), our iibmalloc has also performed well: its overhead was pretty much on par with the best alloc we have seen overhead-wise (jemalloc) – while significantly outperforming it CPU-wise.

Note that comparison of iibmalloc with other allocs is not a 100% ‘fair’ comparison: to get these performance gains, we had to give up on support for multi-threading. However, whenever you can afford to keep the Shared-Nothing model (= sharing by communicating instead of communicating by sharing memory), this allocator is likely to improve the performance of malloc-heavy apps.

Another interesting observation can be seen in the graph in Figure 3, which shows results of a different bunch of tests, changing the size of allocated memory.

NB: Figure 3 is for a single thread, which as we seen above is the very best case for temalloc; for larger number of threads, temalloc will start to lose ground.

On the graph, we can see that when we’re restricting our allocated data set to single-digit-megabytes (so everything is L2-cached and significant parts are L2-cached), then the combined costs of malloc() / free() pair for our iibmalloc can be as little as 15 CPU clock cycles(!). For malloc() / free() pair, 15 CPU cycles is a pretty good result, which we expect to be quite challenging to beat (though obviously we’ll be happy if somebody
CPU cycles per malloc()/free() pair for different number of threads

Figure 1

CPU cycles per malloc()/free() pair for different allocated RAM

Figure 2
On the other hand, as we have spent only a few man-months on our allocator, there is likely quite a bit of room for further improvements.

**Conclusions**

We presented an allocator which exhibits significant performance gains by giving up multi-threading. We did not really try to compete with other allocators (we’re solving a different task, so it is like comparing apples and oranges); however, we feel that we can confidently say that

> For (Re)Actors and message-passing programs in general, it is possible to have a significantly better-performing allocator than a generic multi-threaded one.

As a potentially nice side-effect, we also demonstrated a few (hopefully novel – at least we haven’t run into them before) techniques, such as storing information in dereferenceable pointers, and these techniques might (or might not) happened to be useful for writers of generic allocators too.

**References**

[GitHub] https://github.com/node-dot-cpp/iibmalloc


How to Write a Programming Language: Part 2, The Parser

We’ve got our tokens: now we need to knit them together into trees. Andy Balaam continues writing a programming language with the parser.

In this series we are writing a programming language, which may sound advanced, but is actually much easier than you might expect. Last time, we wrote a lexer, which takes in a text characters (source code) and spits out tokens, which are the raw chunks a program is made up of such as numbers, strings and symbols.

This time, we will write the parser, which takes the tokens coming out of the lexer and understands how they fit together, building structured objects corresponding to meaningful parts of our program, such as creating a variable or calling a function. These structured objects are called the syntax tree.

Next time, we’ll work on the evaluator, which takes in the syntax tree and does the things it says, executing the program. By the end of this series, you will have seen all the most fundamental parts of an interpreter, and be ready to build your own!

In Cell, if is a function that takes three arguments: a condition, a function to call if the condition is true, and another to call otherwise (the else part). By passing functions as arguments, we avoid the need for a special keyword to define logical structures like if and for. This makes our parser simple, and it also means Cell programmers can write their own functions similar to the if function, and have them be first-class citizens, on a par to built-ins like if and for.

Because of the simplicity this allows, Cell’s parser only needs to recognise a few simple structures.

Cell has four expression types:

- Assignment: x = 3
- Operations: 4 + y
- Function calls: sqrt(-1)
- Function definitions: {:(x, y) x + y;}

The parser’s job is to recognise from the tokens it sees which of these expression types it is seeing, and build up a tree structure of the expressions. For example, this code snippet:

```
x = 3 + 4;
```

should be parsed to a tree structure something like this:

```
Assignment:
Symbol: x
Value:
Operation:
Type: +
Arguments:
3
4
```

In Cell, you can tell what kind of expression you are looking at from the first two tokens. So in the example above, if we look at the first token ("x") we can’t tell whether this is going to be an operation like x + 2, or an assignment. Once we have the second token (=) we know we are dealing with an assignment.

Once the parser has recognised we are dealing with an assignment, it can treat everything on the right-hand side of the = as a new expression. This new expression will be parsed and nested inside the tree structure of the first one. That is how Operation ends up inside the Assignment section above.

Cell is written in Python, and the tree structures built up by the parser are Python tuples like ("operation", "+", 3, 4) or ("assignment", "x", 18).

A bit more about Cell

Last time we saw that the language we are writing, Cell, is designed to be simple to write, rather than being particularly easy to use. It also lacks a lot of the error handling and other important features of a real language, but it does allow us to do the normal things we do when programming: make variables, define functions and perform logic and mathematical operations.

One of the ways Cell is simpler than other languages is that things like if and for that are normally special keywords in other languages are just normal functions in Cell. This program demonstrates this idea for if:

```
if(  
is_even( 2 ),  
{ print "Even!"; },  
{ print "Odd."; }  
);
```

Andy Balaam Andy is happy as long as he has a programming language and a problem. He finds over time he has more and more of each. You can find his open source projects at artificialworlds.net or contact him on andybalaam@artificialworlds.net
They can be nested inside each other like this:

```plaintext
("assignment", "x",
("operation", "+", 3, 4)
)
```

which is the syntax tree representing the code `x = 3 + 4`.

Note: above we wrote "x", 3 and 4 but in the actual syntax tree these will be full lexer tokens like ("symbol", "x") and ("number", "3").

Enough introduction – let’s get into the code.

### The parse() function

Listing 1 shows the `parse()` function. Its job is to create a `Parser` object and call its `next_expression` method repeatedly until we have processed all the tokens coming from the lexer. It uses the `PeekableStream` stream class that we saw in the previous article to create a stream of tokens that we can 'peek' ahead into to see the next token that is coming.

When we create the `Parser` object, we pass two objects in to its constructor: the stream of tokens, and `;`, which tells the parser when to stop. Here we end when we hit a semi-colon because we are parsing whole statements, and all statements in Cell end with a semi-colon. Later we will make other `Parser` objects that stop parsing if we have hit one of the `stop_at` types. Since we were passed the expression so far in the `prev` argument, when we hit a `stop_at` token, we can immediately return it.

```python
def parse(tokens_iterator):
    parser = Parser(PeekableStream(tokens_iterator), ";")
    while parser.tokens.next is not None:
        p = parser.next_expression(None)
        if p is not None:
            yield p
        parser.tokens.move_next()
```

### The Parser class

Listing 2 shows the constructor of `Parser`, which just remembers the stream of tokens we are operating on and `stop_at`, the token type that tells us we have finished.

```python
class Parser:
    def __init__(self, tokens, stop_at):
        self.tokens = tokens
        self.stop_at = stop_at
```

Listing 3 shows the real heart of the parser – the `next_expression` method of the `Parser` object. Similar to the `lex()` function we saw in the previous article, the `next_expression` method is built around a big `if/elif` block.

`next_expression` takes one argument, `prev`, that represents the progress we have made parsing so far. Earlier we found that we only need to see the first two tokens of an expression to know what type it is. By passing the previous expression in to `next_expression`, we can use it, along with the current token, to understand what kind of expression we have. If we’re just starting to parse an expression, we pass in `None` as the value for `prev`.

Several of the branches of `next_expression` call `next_expression` from inside itself – this is because we are building up a nested tree of expressions within expressions. Every time we look for a sub-expression within an expression (for example the "3 + 4" part of "x = 3 + 4") we call `next_expression` again, and use the return value as part of the original expression we are constructing.

Before we enter the big `if/elif` block, `next_expression` has an introductory section in which we get hold of the type and value of the next token we are dealing with, and stop parsing if we have hit one of the `stop_at` types. Since we were passed the expression so far in the `prev` argument, when we hit a `stop_at` token, we can immediately return it.

```python
def next_expression(self, prev):
    if self.tokens.move_next():
        typ, value = self.tokens.next
        if typ in self.stop_at:
            return prev
        self.tokens.move_next()
        if typ in ("number", "string", "symbol") and prev is None:
            return self.next_expression((typ, value))
        elif typ == "operation":
            nxt = self.next_expression(None)
            return self.next_expression(("operation", value, prev, nxt))
        elif typ == "(":
            args = self.multiple_expressions("", ")")
            return self.next_expression(("call", prev, args))
        elif typ == "{":
            params = self.parameters_list()
            body = self.multiple_expressions(";", "}")
            return self.next_expression(("function", params, body))
        elif prev == ";" and not self.tokens.next:
            raise Exception("You can only assign to a symbol.")
            nxt = self.next_expression(("assignment", prev, nxt))
            return self.next_expression(("assignment", prev, nxt))
        else:
            raise Exception("Unexpected token: " + str((typ, value)))
```
If we haven’t finished, we enter the `if` block that checks the type of the token we are processing and returns an expression of the right type. First, we check what to do if we see a normal type (string, number, or symbol) and we have no previous expression (because `prev` is `None`). This means we have only seen one token so far, so we can’t decide what type of expression we are dealing with. To avoid making the decision yet, we call ourselves recursively, using `(typ, value)` – the token we were given – as the value for `prev`. This time we will have a non-`None` value for `prev` (because we just passed it in), and so will be able to make a decision about the expression we are parsing.

Next we check whether `typ` is "operation". If it is, we are nearly ready to return an "operation" syntax tree. We have been given the left-hand side of the operation as `prev`, we’ve just found the operation, so all we need is the right-hand side to complete the expression. We call `next_expression` one more time, passing in `None` as the previous expression, because we want to find a separate expression to use at the right-hand side, and put the answer into a variable called `nxt`. Now we combine `nxt` with the information we already have, then return a tuple representing the whole operation: `("operation", value, prev, nxt)`. This is our syntax tree for this expression.

The next `elif` part checks for " (”, which means we are calling a function. The `prev` variable should already contain the name of the function, so we just need to find the arguments we want to pass in. To find the arguments, we call `self.multiple_expressions()`, which is shown in listing 4. Once we have the arguments, we can build a syntax tree of type "call" and pass it on into another call to `next_expression`.

By calling `next_expression` again, we allow multiple function calls to be stuck together, allowing us to write functions that return other functions and call them immediately. For example, `divide_by(3)(12)`; might return 4, because `divide_by(3)` could return a function that divides whatever you pass in by 3.

The `multiple_expressions` method parses several expressions separated by tokens of the type we provided ("sep") and finishing when we get to another token ("end"). In the example we have seen so far, the separator was "", "=" and the end token was "" because we are looking for the arguments being passed to a function.

The code of `multiple_expressions` itself creates a new instance of the `Parser` class for every expression it looks at, and then calls `self.parameters_list` to find the statements inside the function, and to find the names of the arguments, it uses the `parameters_list` function, which is like a simplified version of `multiple_expressions` that just looks for the names of the arguments to the function (we skip it here for brevity).

If you were watching closely, you might have noticed one of the quirks of Cell’s parser that makes it different from most similar-looking languages: the order in which expressions are grouped when they contain multiple terms.

Most languages follow rules inspired by mathematical expressions, so that e.g. multiplications are grouped together before additions, meaning "3*4+1" evaluates to 12.

Cell is different. Because we parse ‘everything else’ and use it as the right-hand side in the operation, we group things on the right before things on the left, and we treat all operators the same, so 3*4+1 evaluates to 15.

Cell works this way because it means have to write less code, but doing things the more normal way would be perfectly possible – we simply need to collect the full list of chained expressions before we start grouping them according to some precedence rules.

A note on operator precedence

If you’re managing to follow so far, you have seen all the interesting parts of Cell’s parser – why not try adapting it or writing your own language that works the way you want it to?

References

[Balaam] https://github.com/andybalaam/cell
Compile-time Data Structures in C++17: Part 1, Set of Types

Compile time data structures can speed things up at runtime. Bronek Kozicki details an implementation of a compile time set.

The standard collection `std::set` is known to every C++ programmer. The runtime complexity of its `find` and `insert` operations `O(N ln N)` is one of the reasons why it is often replaced with `std::unordered_set`, which has amortised complexity of `O(1)`. But what if we had access to a similar data structure with a guaranteed complexity of `O(0)`, that is one where no computation is performed during runtime at all, and calls to member functions (such as `insert` or `find`) are directly replaced, during the compilation, by the results of the call? That also means that such data structure could be used inside compile-time expressions, such as `std::conditional` or `std::enable_if`, whose sample implementations are shown in Listing 1.

```
template <bool S, typename T, typename F> struct conditional;
template <typename T, typename F> struct conditional<true, T, F> { using type = T; };
template <typename T, typename F> struct conditional<false, T, F> { using type = F; };

template <bool S, typename T> struct enable_if {};
template <typename T> struct enable_if<true, T> { using type = T; };
```

Listing 1

Of course, there must be a drawback to such a data structure: since we expect the lookup operation to work during compilation, it follows that such a set must also be fully populated during compilation. That might not seem very useful in a small program; however, design concerns in large programs often drive to more decoupling, where such ability might be useful. For a trivial example, see the `if constexpr` expression in the body of the `Foo` constructor in Listing 2.

The sample code in Listing 2 demonstrates another important point about compile-time data structures: the ‘value’ looked for is a tag type (named `Bar` in this example). Such types provide us with symbolic, unique names without the need for a central repository (e.g. an `enum` type), hence avoiding accidental coupling inside such a repository, while at the same time minimising the risk of clashes if there is no such central location (e.g. from `extern const int` or C-style `#define`). Examples of tag types in the C++ standard include `std::nothrow_t` or types defined for various overloads of `std::unique_lock` constructor.

```
struct Bar {};
struct Foo { int i = 0;
template <typename Set> constexpr explicit Foo(Set) { if constexpr ((bool)Set::template test<Bar>()) i += 1; }
};
```

Listing 2

About O(0)

There is no such thing as ‘O(0)’, hence quotes. That is because in big-O notation, we disregard the constant component, and the difference between `O(1)` and `O(0)` is only the constant component (equal to `C`, for some unspecified fixed value `C`). In practice, the notion of big-O applies only to runtime complexity, and, as explained on the left, we are seeking to remove the runtime cost entirely. Hence our choice is to either disregard the big-O notation as not applicable or use a dummy ‘O(0)’. What would be the interface of such a ‘set of types’ utility? One member function has already been presented above; it is the `test` template variable (NB, `bool`) cast is a workaround for a bug in MSVC 15.7, to be fixed in version 15.8 and superfluous for other modern compilers). We also want the ability to populate the set and compare it to other sets. But how can we populate a compile-time construct? It is immutable, after all. The solution is to apply the principles of functional programming – in the compile time.

That is, we can create a new container instance (or, in our case, a new container type) as a copy of the existing container with the addition of a new element. That sounds expensive, but let’s not forget that the set must be filled during the compilation, which means that the runtime complexity of such an operation is still going to be ‘O(0)’, at the cost of compilation time. In other words, to populate our set we are going to use a pure function, to be entirely evaluated during the compilation, which returns either a value or an imutable value: a meta-function. As we will see, quite often meta-functions are not functions at all – they can be immutable template values or template types. A simplistic example is presented in Listing 3.

The implementation of `test` presented in Listing 3 is indeed simplistic (we are going to improve it later). It is encapsulated as an implementation detail `struct contains` (in the `set_impl` namespace), which is a variadic template just like `set`, but dedicated to the calculation of the value `contains`, with the help of standard type trait `std::is_same_v` and two template specialisations, acting the role of a recursive meta-function. Specialisation `contains<T, L...>` performs equality check between `U` and `T`, while `contains<>` returns the terminating condition ‘not found’. Note how we used immutable template value `template <typename U> constexpr static bool value = ...` to pass the result of the nested meta-function to its caller. Such recursive calls are a common pattern in functional programming because they work well with immutable data. For the same reason, they work well with meta-functions, and we will employ recursion often. However, in meta-programming, we...
have always to remember to provide a terminating specialisation – which
is an equivalent of a recursion terminating execution branch in functional
programming.

The implementation of the `insert` meta-function is trivial, but sadly also
incorrect, as we will see below. That is because of two outstanding, and
so far ignored, properties of most sets, which are:

- Uniqueness of the elements.
- Constraints on the type of elements.

It is the presence of both which gives as a ‘set of something’. In
`std::set`, the first guarantee is provided by quietly ignoring duplicate
inserts, while the template parameter captures the later one. For our ‘set
of types’, we are going to follow the lead of
`std::set` to remove qualifiers or reference. The constraint to disallow p

The proposed constraints do not impact the uses of our set where tag types
are passed directly, for example, hardcoded. If they are deduced, or coded
in a remote location, they only require additional use of `std::decay_t` to
remove qualifiers or reference. The constraint to disallow pointers is
meant to protect against user errors – either a typo or deduced type which
unexpectedly turns out to be a pointer. Additionally, since our elements are
types, we need to consider how to handle `void`. One useful solution is
to handle it as an element of an empty set – that is, a non-element. In
other words, we are going to use `void` as a placeholder for an element,
where no element is available (the similarity to the role of `void` in C and
C++ becomes obvious when ‘element’ is replaced by ‘type’).

Back to our code example, one can easily spot that the `insert` meta-
function is not doing anything to enforce uniqueness of added types.
Similarly, nothing is preventing the user from instantiating, e.g.

```cpp
set<int, int>
```

These two problems aside, yet another limitation of our set is that
`set<int, long>` and `set<long, int>` are both distinct types but they are one set (because the order of elements does not matter
to mathematical sets). There is probably no robust solution for the last
problem, but a workable compromise would be a `unique` member type
inside `set` to hold unique types, and creation of an `is_same` member
meta-function to test set equality with no regard to order. That might look
like Listing 4.

```cpp
namespace set_impl { 
  template <typename ... L> struct contains;
  template <> struct contains<> { 
    constexpr explicit set() = default;
    template <typename T> 
    constexpr static bool test = 
      set_impl::contains<L...>::template value<T>;
    template <typename T> 
    using insert = set<T, L...>;
  }

  template <typename ... L> struct set { 
    constexpr explicit set() = default;
    template <typename T> 
    constexpr static bool test = 
      set_impl::contains<L...>::template value<T>;
    template <typename T> 
    using insert = set<T, L...>;
  }

  template <typename T, typename ... L> struct contains<L...> { 
    static_assert(std::is_same_v<T, 
      std::decay_t<T>>);
    static_assert(not std::is_pointer_v<T>);
    static_assert(std::is_void_v<T>);
  }

  template <typename T> struct check { 
    static_assert(std::is_same_v<T, 
      std::decay_t<T>>);
    static_assert(not std::is_pointer_v<T>);
    static_assert(std::is_void_v<T>);
  }

  template <typename T> struct cracker; 
  template <typename ... L> struct cracker_list; 
  template <typename ... L> struct insert_detail; 
  template <typename T, typename ... L> struct contains_detail; 
  template <typename T, typename ... L> struct set; 
  template <typename T> struct check; 
}
```

test:
```cpp
int main() { 
  struct Fuz; struct Baz; 
  constexpr static auto s2 = 
    decltype(s1)::insert<Bar>{}; 
  constexpr static auto s1 = 
    set<>::insert<Baz>::insert<Fuz>{}; 
  using insert = set<int, long>;
  cout << foo2.i << std::endl;
}
```
template <typename ... L> struct
intersect_detail;
template <typename ... T> struct
intersect_detail<unchecked_list<T>>,
unchecked_list<T...>>
{
    constexpr static size_t size = 0;
};
template <typename V, typename ... L,
type name ... > T struct
intersect_detail<unchecked_list<V,L...>,
unchecked_list<T...>>
{
    constexpr static size_t size =
    intersect_detail<unchecked_list<L...>,
    unchecked_list<T...>>::size +
    (not std::is_void_v<V>
            && contains_detail<V,T...>::value);
};
template <typename ... L> struct unique;
template <> struct unique
{ using type = set<>;
    constexpr explicit set() = default;
    public:
    using impl = set_impl::unique<L...>;
    template <typename T>
    struct set
    {
        using insert =
        typename set_impl::unique<T, L...>::type;
    };
};

namespace set_impl {
    template <typename V, typename ... L,
type name ... > struct
intersect_details
{ using unique = typename set_impl::unique<T, L...>::type;
    template <typename T>
    class set
    {
        using impl = set_impl::type;
        using insert =
        typename set_impl::unique<T, L...>::type;
    };
}

The code may appear complex, but that is only because of the amount of typing necessary in C++ to code each simple meta-function. In fact, it is quite simple, although there are few things to note. Again we are delegating the work required to individual meta-functions, and we also have a unique type to build the unique set of types (this ensures that e.g. set<int, int> will be recognised as having only one element since repeated elements do not count). Inside this unique type we delegate tasks to individual meta-functions insert_details, contains_details and intersect_details. The last one calculates the size of the intersection of sets, which is required to test set equality using a simple formula: sets are equal if they have equal size and their intersection is equal to that size as well. We could reuse intersect_details to implement two more useful checks is_cross to check whether two sets share a non-empty intersection and is_super to check whether one set is a subset of another (in reverse, since our 'superset' will be on the left side and 'subset' on the right). In the first case, we only need to know that the size of the set intersection is greater than 0. In the latter, the size of the intersection will be equal to the size of a subset. The opportunity for reuse of intersect_details is obvious, and to do so we are going to introduce a higher order meta-function compare, to replace unique::is_same. In functional programming, a higher order function is a function which consumes (or produces, or both) a function. In our case, a meta-function is a template (whereas types take the role of values) which means that higher-order meta-function compare is going to consume a template template parameter (yes, that is the word ‘template’ twice in a row) which encapsulates the meta-function to perform the size comparison required. See Listing 5.

Listing 5

```cpp
namespace set_impl {
    template <size_t Mine, size_t Cross,
    size_t Theirs> struct is_cross {
        constexpr static bool compare =
        Cross > 0;
    };
    template <size_t Mine, size_t Cross,
    size_t Theirs> struct is_super {
        constexpr static bool compare =
        Cross == Theirs;
    };
    template <size_t Mine, size_t Cross,
    size_t Theirs> struct is_same {
        constexpr static bool compare =
        Mine == Cross && Cross == Theirs;
    };
}
```
Right at the end, it is time to revisit the set of constraints imposed on types stored in our set of types. As we have just seen, a template parameter can be used to implement a higher order (meta-) function, which is an ideal way for the user to select their own set of constraints, and perhaps even type transformations. The final program (Listing 6) makes use of this ability.

Listing 6

```cpp
#include <cstdio>
#include <utility>
#include <type_traits>

template <typename T> struct cracker_list;

namespace set_impl {
  template <typename T> struct cracker_list<set<T>> {
    using type = unchecked_list<T>;
  };
}

namespace set_impl {
  template <typename T, typename ... L> struct cracker_list<set<T, L...>> {
    using type = unchecked_list<T, L...>;
  };
}

namespace set_impl {
  template <typename T, typename ... L> struct unchecked_list {
    using type = cracker_list<T, L...>;
  };
}

namespace set_impl {
  template <typename T, typename ... L> struct intersect_detail {
    constexpr static size_t size = 0;
  };
}

namespace set_impl {
  template <typename V, typename ... L, typename ... T> struct intersect_detail<unchecked_list<V, L...>, unchecked_list<T...>> {
    constexpr static size_t size = intersect_detail<unchecked_list<L...>, unchecked_list<T...>>::size +
      (not std::is_void_v<V>
       && contains_detail<dummy_check, V, T...>::value);
  };
}

namespace set_impl {
  template <typename T> struct dummy_check {
    using type = T;
  };
}

namespace set_impl {
  template <typename ... L> struct unchecked_list;
  template <typename T, typename ... L> struct cracker_list<set<T, L...>> {
    using type = unchecked_list<T, L...>;
  };
  template <typename T, typename ... L> struct cracker_list<set<T, L...>> {
    using type = unchecked_list<T, L...>;
  };
}

namespace set_impl {
  template <typename T> struct dummy_check {
    using type = T;
  };
}

namespace set_impl {
  template <typename T, typename ... L> struct unchecked_list {
    using type = cracker_list<T, L...>;
  };
}

namespace set_impl {
  template <typename T, typename ... L> struct cracker_list<set<T, L...>> {
    using type = unchecked_list<T, L...>;
  };
}
```

Listing 6 (cont’d)
template <template <typename> typename Check, 
typename T, typename ... L>
struct unique<Check, T, L...> {  
    using type = typename std::conditional<
        contains_detail<Check, T, L...>::value,
        typename unique<Check, L...>::type,
        typename insert_detail<Check, T,
        typename unique<Check, L...>::type>::type>::type;
    constexpr static size_t size =
        contains_detail<Check, T, L...>::value
            ? unique<Check, L...>::size
            : unique<Check, L...>::size + 1;
};

template <typename T, size_t size_t>
struct Baz { Baz() = delete; };  
struct Bar { Bar() = delete; };  
struct Fuz { Fuz() = delete; };  
struct Foo {
    int i = 0;
    template <typename Set> constexpr explicit set() = default;
    using unique = typename impl::type;
    constexpr static size_t size = impl::size;
    constexpr static bool empty = size == 0;
    template <typename T>
    constexpr static bool is_same =
        impl::template compare<impl::is_same,
        typename impl::cracker<T>::list,
        impl::cracker<T>::size>;
    template <typename T>
    constexpr static bool is_cross =
        impl::template compare<impl::is_cross,
        typename impl::cracker<T>::list,
        impl::cracker<T>::size>;
    template <typename T>
    constexpr static bool is_super =
        impl::template compare<impl::is_super,
        typename impl::cracker<T>::list,
        impl::cracker<T>::size>;
    template <typename T>
    constexpr static bool test =
        impl::template test<T>;
    template <typename T>
    using type =
        typename std::enable_if<!std::is_void_v<T>
        && test<T> , impl::type>::type;
    template <typename T>
    using insert = typename
        impl::unique<Check, T, L...>::type;
};

int main() {
    constexpr static set<PlainTypes> s0{};
    constexpr static auto s1 =
        decltype(s0)::insert<Baz>::insert<Fuz>{};
    constexpr static Foo foo1{s1};
    std::printf("foo1.i=%d\n", foo1.i);
    constexpr static auto s2 =
        decltype(s1)::insert<Bar>{};
    constexpr static Foo foo2{s2};
    std::printf("foo2.i=%d\n", foo2.i);
}
Afterwood

Much ado about nothing. Chris Oldwood considers what we have when we have nothing.

There is a classic puzzle that goes:

The poor have it, the rich need it, and if you eat it you’ll die.
What is it?

If you haven’t come across this before and Google is out of reach because you’re reading the printed edition going through a tunnel or an internet blackspot, the answer is ‘nothing’. I think it would be fairly easy to come up with a programming specific version of this particular puzzle as there appears to be quite a few variants of ‘nothing’ in our world, many of which seem to occupy a significant amount of our time due to their cunning camouflaged outfits.

It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one. It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one.

It probably seems strange to us now but once upon a time there was no zero. Essentially you had something which was countable or you had nothing. There were no negative numbers either and nothing preceded one.

History of Zero

Zero is almost certainly our ‘go to choice’ for representing a lack of something as it’s been with us since our early days of schooling and support for integer values has also been around in programming pretty much since the beginning too whether you’re using assembly or a high-level language. Even most children could tell you numApples = 0 means you don’t have any apples.

Where it starts to go astray is when we have to squeeze the concept of ‘none’ into a domain that doesn’t really support it because you are no longer representing countable things. A classic example here is representing dates where day zero represents some epoch like 1st January 1970 or 1st January 1900 and negative values stretch backwards in time. Here every value in the domain represents a valid value and so if we want something to accommodate the notion of ‘no value’ we probably have to re-purpose one or other end of the spectrum, e.g. INT_MIN or INT_MAX.

What about if we’re searching an array for some value or object and there is nothing to be found? If our array starts at index 1 (e.g. Visual Basic) we could use the value 0, but many languages have adopted the 0-based approach and Stan Kelly-Bootle’s suggestion of using 0.5 has never really received any uptake. For languages like Java and C# that are inherently based on signed integers they can return any negative value for the ‘none found’ answer. In C++ where unsigned integers are the preferred choice we have no such luck and instead have concocted a magical value by the name of npos for strings which (implementation-wise) sits within the valid range of values but on the precipice such that you’d probably run out of memory long before it could ever be a valid result.

Sadly the use of -1 (in either of its signed or unsigned guises) as both a perfectly good response to a question and as a way of signalling an error has only succeeded in muddying the waters further. The Windows API for example uses the constants LB_ERR (and CB_ERR) in this way which means you often stumble across code that initialises variables with it, e.g. index = LB_ERR, because it allows us to exploit a duality of semantics (‘no value, yet’ and ‘not found’) and write less code, irrespective of whether it makes comprehending it any easier. (You might argue not finding it is an error; either way you still have the same type representing two different domains – index and error.)

With enumerated types we often walk right into the same trap with our eyes wide open thinking we’re being clever by adding an explicit value called None or Default (usually with a value of 0 in languages that zero-initialise values and references for ‘safety’s sake’).

Of course when you’re forced to abuse the type system it will get its own back. By masquerading two different result values within the normal course of events you will trick the caller into believing it’s safe to simply compose functions when in reality they’re just storing up a world of pain in the form of an IndexOutOfBoundsException exception, access violation or, if really unlucky, undefined behaviour and subsequent data corruption.

The NullPointerException, or ‘NPE’ as it is commonly referred to in the Java world, is a blight on modern programming caused in part by our use of programming languages which embrace the use of reference types over value types meaning that all of our objects can potentially exist or not exist. Unless the use is entirely local it can be difficult to reason about any object’s existence and therefore null checks can easily dominate a codebase in an act of overly defensive programming. The introduction of the . operator in some languages might reduce the noise but it’s just a case of treating the symptoms, not the disease.

This particular foe likes to disguise themselves by changing their name too, but whether they be null, NULL, nullptr, nil, 0, end, -1, npos, "", NaN, None, etc. we should be on our guard and be ready to banish them to computing history or at the very least quarantine them.

But what can be done, surely we can’t undo the past? Well, maybe we can. Over the years the awareness of the Optional (Option, Maybe, etc.) type has grown so that it’s no longer just a niche technique used by Comp Sci purists. The desire to right this wrong is so strong in some circles that there is currently a preview of C# [GitHub] where reference types have been given the Nullable make over thereby allowing us to finally consider deleting our own homebrew variants and deprecating our static analysis annotations in favour of a kosher type annotation. Surprised?

One of Shakespeare’s most famous comedies is titled Much Ado About Nothing. Given the amount of time we’ve lost over the years debugging issues caused by our inability to express ‘nothing’ in a way that is obvious to our fellow programmers I’d say it was no laughing matter. We need to realise that failure can indeed be an option and that the type system should be there to help us, nothing more nothing less.

Reference

[GitHub] https://github.com/dotnet/csharplang/wiki/Nullable-Reference-Types-Preview
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