P1031R0: Low level file i/o library

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Library Evolution Working Group
Reply-to: Niall Douglas
<s_sourceforge@nedprod.com>

A proposal for a low level file i/o library very thinly wrapping kernel syscalls into a portable standard library API, preserving all of the time and space complexities of the host platform.

See [P1026] *A call for a Data Persistence (`iostream` v2) study group* for some of the interesting things one can build with this library as a foundation.

A reference implementation of the proposed library with reference API documentation can be found at `https://ned14.github.io/afio/`. It works well on FreeBSD, MacOS, Linux and Microsoft Windows on ARM, AArch64, x64 and x86.

Contents

1 Introduction

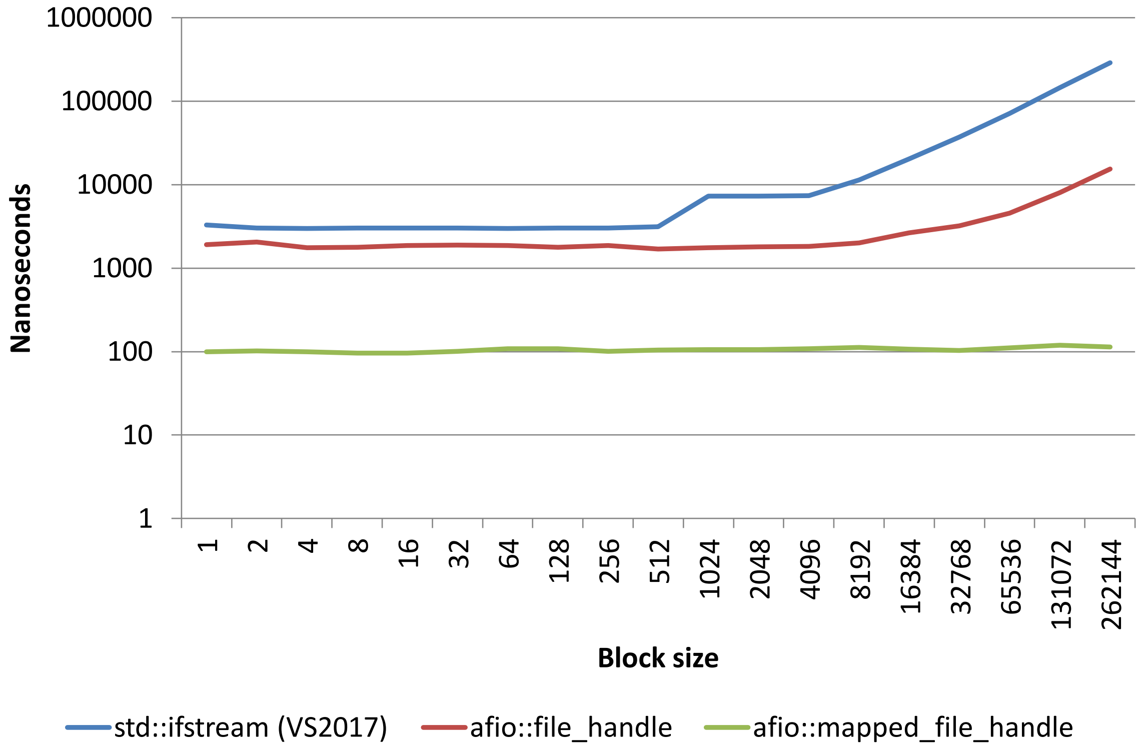
Why does the C++ standard need a low level file i/o library, above and beyond needing one to build out an iostreams v2?

1.1 Latency to storage has become more important than it was

For a long time now, kernels have kept a cache of recently accessed filesystem data in order to improve read latencies, but also to buffer writes in order to reorder those writes into strides suitable for efficiently making use of a spinning hard drive's actuators. A randomly placed 4Kb i/o to main memory takes about 5 microseconds, whereas the same i/o to a hard drive takes up to 26,000 microseconds 99% of the time. One could afford a few extra memory copies of an i/o without noticing a difference. Thus the standard library's `iostreams` does not worry too much about the multiple memory copies (in the whole system between the C++ code and the hard drive) that all the major STL implementations make per i/o[1].

[1]All the major STL implementations implement `std::ofstream::write()` via the C function `fwrite()`. Because of buffering, `fwrite()` often calls `write()` multiple times. Each is an unavoidable memory copy into the kernel page

Figure 1: Latency differential between reads performed using `std::ifstream` and the proposed *Low level file i/o library* as the size of the i/o increases. Test was conducted on a warm cache 100Mb file with random offset i/o, and represents the average of 100,000 iterations. Note the invariance to block size of the low level file i/o library's `file_handle` benchmark up to half the CPU's L1 cache size, demonstrating that no unnecessary memory copies have occurred. Note that the low level file i/o library's `mapped_file_handle` benchmark demonstrates no copying of memory at all.



Block size	1	4	16	64	256	1024	4096	16384	65536
`std::ifstream` (VS2017)	3301	2986	3017	2994	3020	7254	7389	20282	71538
`afio::file_handle`	1915	1766	1869	1873	1855	1750	1812	2633	4576
`afio::mapped_file_handle`	99	99	96	108	101	105	108	107	111

The rise of SSD storage has changed things. Now a SATA connected flash drive takes maybe 800 microseconds for that 4Kb i/o @ 99%[2], and random access is as fast as sequential access, so that is no longer an amortised latency figure hiding large individual i/o latency variance. Furthermore, flash based SSDs are highly concurrent, they can service between 16 and 32 concurrent random 4Kb i/o's (queue depth, QD) in almost the same time as a single random 4Kb i/o. These two differences

cache, plus kernel transition. Eventually the dirty page in the kernel page cache will reach its age deadline, and be flushed to storage.

[2]The 99% means that 99% of i/o latencies will be below the given figure. All latency numbers in this section come from empirical testing by me on hardware devices. They differ significantly from manufacturer figures. Device manufacturers tend to quote the latency of the device without intervening filesystem or user space transition. All latency values quoted in this paper include intervening software systems, and are what a user space process can realistically expect to achieve.

profoundly transform how to write algorithms which work well on a filesystem, but it also has an important consequence for C++:

$$\frac{800\ microseconds}{32} = 25\ microseconds\ per\ 4Kb\ i/o\ amortised\ @\ 99\%.$$

On a SATA connected flash SSD with QD32 i/o, every unnecessary memory copy increases i/o cost by a minimum of 20%!

Achieving sustained QD32 i/o is rare however – one needs to be performing large sequential blocks of i/o of at least 32 x 4Kb = 128Kb to have any chance of sustaining QD32, and for large sequential block i/o, latency is usually unimportant for most users[3].

However, just recently NVMe rather than SATA connected flash drives have become available to the mass market. These perform that random 4Kb i/o in just 300 microseconds @ 99%. At QD4, which is much more common than QD32, every unnecessary memory copy in the whole system increases

[3]But not all. A past consulting client of mine had a problem whereby their application was applying real-time filters to *uncompressed* 8k video at a high frame rate. The CPU demands were not the problem, it was the storage subsystem: to get smooth video added an unacceptable amount of latency to the real-time video stream for their customers. This is exactly the sort of problem domain C++ ought to excel at.

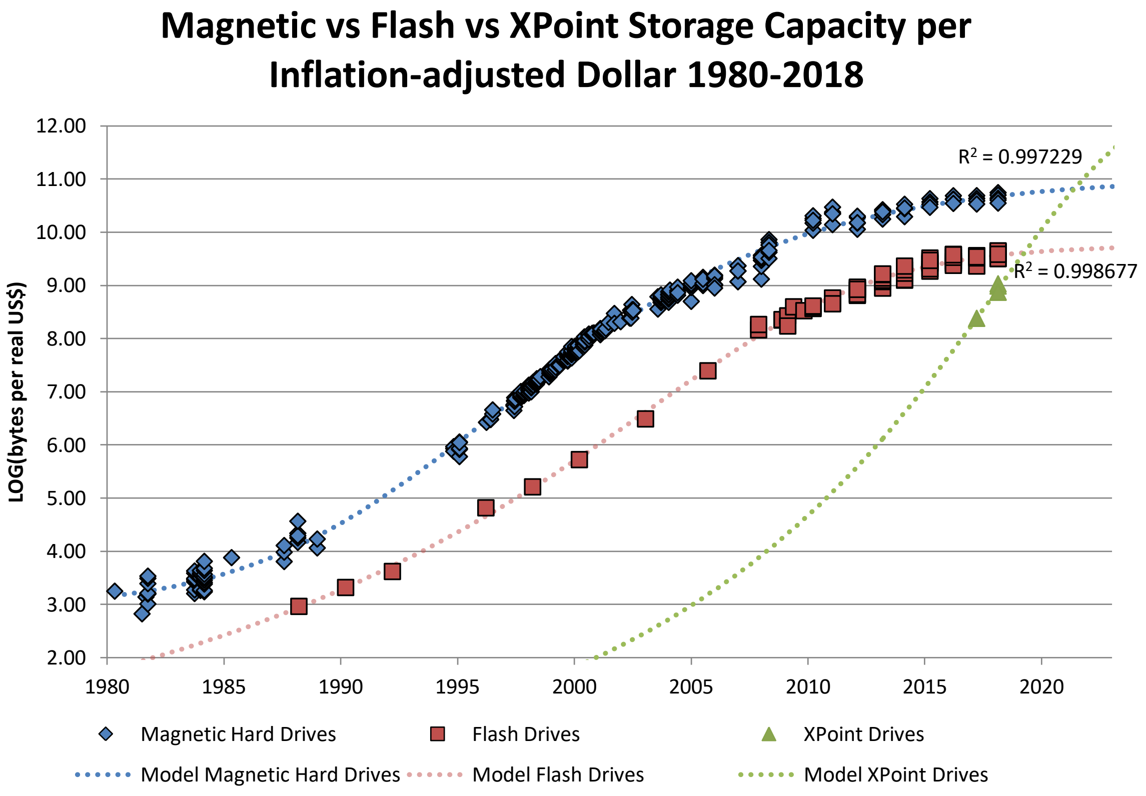


Figure 2: Magnetic vs Flash vs XPoint storage capacity per inflation-adjusted dollar 1980-2018.

i/o cost by 6%. If you are using `<iostream>` on a recent MacBook Pro (which has a high end NVMe flash SSD), perhaps 10% of your i/o cost is due to your choosing `<iostream>`, and especially with larger block sizes it really begins to hurt, as you can see in Figure 1. In my opinion, that is unacceptable in the C++ standard going forward.

And the march of technological progress will make things even worse soon. Intel's NVMe Optane drives using X-Point non-volatile memory will do that 4Kb i/o in just 35 microseconds @ 99% and 13 microseconds @ 50%, **and at QD1**. Every unnecessary memory copy in the whole system increases i/o cost by 14-38%. Next year NV-DIMMs will be standardised, at which point your non-volatile storage will do a 4Kb i/o in **8 microseconds**. Every unnecessary memory copy is now adding **60%** to i/o costs. See Figure 2 for a logistic regression plot of the evolution of storage bytes per inflation adjusted dollar for spinning rust, flash and X-Point technology storage.

If C++ is to achieve the direction laid out in [P0939] *Direction for ISO C++*, in my opinion it needs a data persistence implementation which enables zero memory copies throughout the whole system. One will soon no longer be able to get away with anything less.

1.2 The immature standard library support for file i/o leads to a lot of inefficient and buggy code and/or reinvention of the wheel

Memory mapped files, especially on 64 bit architectures, are usually a good reasonable default choice for most i/o to non-networked drives. They usually have superb sequential and random i/o performance, and usually cause no more than one memory copy in the whole system. Yet using them from standard C++ is not as trivial as one would imagine. Even with the Boost C++ Libraries to hand, there are two main mechanisms for mapping files into memory, and the plethora of questions about various corner case use issues on Stack Overflow would suggest that neither is entirely obvious to people. They are certainly not 'fire and forget', like a `std::ofstream` would be.

One area where a lot of people get stuck is how to efficiently *append* to a memory mapped file. Most developers – probably even most of the WG21 experts reading this paper right now – would suggest making the file much bigger and coordinate between your processes at what offset one 'appends' new data. They would suggest this because there is a widespread, *and completely inaccurate*, belief that memory maps are fixed size, and you must tear them down and recreate bigger ones in order to expand a map.

In fact, all the major platforms let you reserve address space for future expansion of a memory map. Indeed, often they will auto-expand your memory map into that reservation if the maximum extent of the backing file is increased, or they provide a super fast syscall for poking the kernel to expand maps of that file across the system. So, in fact, appending to memory mapped files without costly teardown and recreation of maps is fully supported by kernels, yet judging from Stack Overflow posts, very few realise this[4].

A standard library supplied implementation of a 'fire and forget' memory mapped file primitive object would help address these sorts of problem. The proposed low level file i/o library proposes a suite of polymorphic objects which can perform i/o. Code written to use them need not consider their implementation, thus allowing initiating code to choose whichever implementation is most

[4]https://stackoverflow.com/questions/4460507/appending-to-a-memory-mapped-file

suitable. Virtual function overrides then choose an optimised implementation, and the code need not worry itself about implementation details. Appends, for example, 'just work' with optimal performance for the chosen implementation.

2 Examples of use

A surprising number of people wanted examples of usage before any further discussion of the proposed library design. I therefore supply many such use examples, and my thanks to std-proposals for suggesting which.

I make the following caveats in the following use examples:

- These use examples are for the reference library written in C++ 14, not the proposed approximate C++ 23 library which assumes that something approximating [P0709] *Zero-overhead deterministic exceptions* have been added to the language. Specifically, this means that the `.value()` at the end of each call would not be there any more, and because `std::byte` is now in the language, we wouldn't have to keep reinterpret casting between `byte` and `char`.
- This is a very low level library offering absolute maximum performance, with minimum guarantees of effects, semantics, or behaviours. It is correspondingly less convenient to use. Specifically, no single buffer overloads, no integration with STL containers, no serialisation/deserialisation, no dynamic memory allocation, no (traditional) exception throws, all as per [P1027] *SG14 Design guidelines for future low level libraries*. All these convenience APIs, and stronger behaviour guarantees, would be in later standardised layers built on top of this bottom most layer. Please see [P1026] *A call for a Data Persistence (`iostream` v2) study group* for a broad overview of the vision of which this proposed library is just a foundation.
- There is also no file length. Files do not have length. They have a maximum extent *property*. This property refers to the maximum possible extent offset which you will encounter when reading the valid extents which constitute the file's storage. It is extremely important to understand this difference: files, especially ones built using the planned generic filesystem algorithms template library, may regularly have a maximum extent in the Petabytes range, but store only a few Kb of extents. Algorithms and programs which treat the maximum extent as a length will perform *extremely* poorly in this situation.

  This is why we *truncate* files, we do not resize files, because we are truncating those extents exceeding the new maximum extent. We can also truncate to a later maximum extent. I appreciate that many find the idea of 'truncating to extend' confusing, but remember that increasing the maximum extent of a file doesn't actually *do* anything. It simply adjusts a number in the metadata in the inode of the file, and any related kernel resources. It does nothing to the actual file storage. This is why `.extend()` is a poor choice of name, because nothing is extended.

  I agree that `.truncate()` is not ideal either, but I feel better to focus on the data which could be lost when naming. Better suggestions are, of course, welcome. But do bear in mind that there is a single kernel syscall for changing the maximum extent value, and there is no race free concept of 'set to X if X > Y' etc.

2.1 Read an entire file into a vector assuming a single valid extent:

For brevity, the initial examples are lazy code which will suffer from pathologically poor performance on files with a large maximum extent. Later examples account for allocated extents.

```cpp
namespace afio = AFIO_V2_NAMESPACE;

// Open the file for read
afio::file_handle fh = afio::file(  //
  {},       // path_handle to base directory
  "foo"     // path_view to path fragment relative to base directory
            // default mode is read only
            // default creation is open existing
            // default caching is all
            // default flags is none
).value();  // If failed, throw a filesystem_error exception

// Make a vector sized the current maximum extent of the file
std::vector<afio::byte> buffer(fh.maximum_extent().value());

// Synchronous scatter read from file
afio::file_handle::buffers_type filled = afio::read(
  fh,                              // handle to read from
  0,                               // offset
  {{ buffer.data(), buffer.size() }}  // Single scatter buffer of the vector
                                   // default deadline is infinite
).value();                         // If failed, throw a filesystem_error exception

// In case of racy truncation of file by third party to new length, adjust buffer to
// bytes actually read
buffer.resize(filled[0].len);
```

2.2 Write multiple gather buffers to a file:

```cpp
namespace afio = AFIO_V2_NAMESPACE;

// Open the file for write, creating if needed, don't cache reads nor writes
afio::file_handle fh = afio::file(  //
  {},                                         // path_handle to base directory
  "hello",                                    // path_view to path fragment relative to base directory
  afio::file_handle::mode::write,             // write access please
  afio::file_handle::creation::if_needed,     // create new file if needed
  afio::file_handle::caching::only_metadata   // cache neither reads nor writes of data on this handle
                                              // default flags is none
).value();                                    // If failed, throw a filesystem_error exception

// Empty file. Note this is racy, use creation::truncate to be non-racy.
fh.truncate(0).value();

// Perform gather write
const char a[] = "hel";
const char b[] = "l";
const char c[] = "lo w";
const char d[] = "orld";

fh.write(0,                // offset
  {                        // gather list, buffers use std::byte
    { reinterpret_cast<const afio::byte *>(a), sizeof(a) - 1 },
    { reinterpret_cast<const afio::byte *>(b), sizeof(b) - 1 },
    { reinterpret_cast<const afio::byte *>(c), sizeof(c) - 1 },
    { reinterpret_cast<const afio::byte *>(d), sizeof(d) - 1 },
  }
                          // default deadline is infinite
).value();                // If failed, throw a filesystem_error exception

// Explicitly close the file rather than letting the destructor do it
fh.close().value();
```

2.3 Map a file into memory and search it for a string (1):

```
namespace afio = AFIO_V2_NAMESPACE;

// Open the mapped file for read
afio::mapped_file_handle mh = afio::mapped_file(  //
  {},       // path_handle to base directory
  "foo"     // path_view to path fragment relative to base directory
            // default mode is read only
            // default creation is open existing
            // default caching is all
            // default flags is none
).value();  // If failed, throw a filesystem_error exception

auto length = mh.maximum_extent().value();

// Find my text
for (char *p = reinterpret_cast<char *>(mh.address());
     (p = (char *)memchr(p, 'h', reinterpret_cast<char *>(mh.address()) + length - p));
     p++)
{
  if (strcmp(p, "hello"))
  {
    std::cout << "Happy days!" << std::endl;
  }
}
```

2.4 Map a file into memory and search it for a string (2):

The preceding example used the wrap of other facilities into a convenience type `mapped_file_handle`. For more control and customisation, it can also be done by hand:

```
namespace afio = AFIO_V2_NAMESPACE;

// Open the file for read
afio::file_handle rfh = afio::file(  //
  {},       // path_handle to base directory
  "foo"     // path_view to path fragment relative to base directory
            // default mode is read only
            // default creation is open existing
            // default caching is all
            // default flags is none
).value();  // If failed, throw a filesystem_error exception

// Open the same file for atomic append
afio::file_handle afh = afio::file(  //
  {},                                // path_handle to base directory
  "foo",                             // path_view to path fragment relative to base directory
  afio::file_handle::mode::append    // open for atomic append
                                     // default creation is open existing
                                     // default caching is all
                                     // default flags is none
).value();                           // If failed, throw a filesystem_error exception

// Create a section for the file of exactly the current maximum extent of the file
afio::section_handle sh = afio::section(rfh).value();

// Map the end of the file into memory with a 1Mb address reservation
afio::map_handle mh = afio::map(sh, 1024 * 1024, sh.length().value() & ~4095).value();

// Append stuff to append only handle
afio::write(afh,
  0,                                                      // offset is ignored for atomic append only
      handles
  {{ reinterpret_cast<const afio::byte *>("hello"), 6 }}  // single gather buffer
                                                          // default deadline is infinite
).value();

// Poke map to update itself into its reservation if necessary to match its backing
// file, bringing the just appended text into the map. A no-op on many platforms.
size_t length = mh.update_map().value();

// Find my appended text
for (char *p = reinterpret_cast<char *>(mh.address());
     (p = (char *) memchr(p, 'h', reinterpret_cast<char *>(mh.address()) + length - p));
     p++)
{
  if (strcmp(p, "hello"))
  {
    std::cout << "Happy days!" << std::endl;
  }
}
```

2.5 Kernel memory allocation and control (1):

Something not initially obvious is that this library standardises kernel virtual memory support. This is 'for free' as we implement all of the support and control for memory mapped files, and the exact same kernel APIs work with swap file mapped memory (e.g. `mmap()`).

Standardising this support adds lots of interesting opportunities for how STL containers and algorithms which work on reasonably large datasets are implemented.

```cpp
namespace afio = AFIO_V2_NAMESPACE;

// Call whatever the equivalent to mmap() is on this platform to fetch
// new private memory backed by the swap file. This will be the system
// all bits zero page mapped into each page of the allocation. Only on
// first write will a page fault allocate a real zeroed page for that
// page.
afio::map_handle mh = afio::map(4096).value();

// Fill the newly allocated memory with 'a' C style. For each first write
// to a page, it will be page faulted into a private page by the kernel.
afio::byte *p = mh.address();
size_t len = mh.length();
memset(p, 'a', len);

// Tell the kernel to throw away the contents of any whole pages
// by resetting them to the system all zeros page. These pages
// will be faulted into existence on first write.
mh.zero_memory({ mh.address(), mh.length() }).value();

// Do not write these pages to the swap file (flip dirty bit to false)
mh.do_not_store({mh.address(), mh.length()}).value();

// Fill the memory with 'b' C++ style, probably faulting new pages into existence
afio::algorithm::mapped_span<char> p2(mh);
std::fill(p2.begin(), p2.end(), 'b');

// Kick the contents of the memory out to the swap file so it is no longer cached in RAM
// This also remaps the memory to reserved address space.
mh.decommit({mh.address(), mh.length()}).value();

// Map the swap file stored edition back into memory, it will fault on
// first read to do the load back into the kernel page cache.
mh.commit({ mh.address(), mh.length() }).value();

// And rather than wait until first page fault read, tell the system we are going to
// use this region soon. Most systems will begin an asynchronous population of the
// kernel page cache immediately.
afio::map_handle::buffer_type pf[] = { mh.address(), mh.length() };
mh.prefetch(pf).value();


// You can actually save yourself some time and skip manually creating map handles.
// Just construct a mapped_span directly, this creates an internal map_handle instance,
// so memory is released when the span is destroyed
afio::algorithm::mapped_span<float> f(1000);  // 1000 floats, allocated used mmap()
std::fill(f.begin(), f.end(), 1.23f);
```

2.6 Kernel memory allocation and control (1):

Another thing not initially obvious is that this library standardises shared memory support. This is also 'for free' as memory maps are by default shared memory when multiple processes open the same file.

```cpp
namespace afio = AFIO_V2_NAMESPACE;

// Create 4Kb of anonymous shared memory. This will persist
// until the last handle to it in the system is destructed.
// You can fetch a path to it to give to other processes using
// sh.current_path()
afio::section_handle sh = afio::section(4096).value();

{
  // Map it into memory, and fill it with 'a'
  afio::algorithm::mapped_span<char> ms1(sh);
  std::fill(ms1.begin(), ms1.end(), 'a');

  // Destructor unmaps it from memory
}

// Map it into memory again, verify it contains 'a'
afio::algorithm::mapped_span<char> ms1(sh);
assert(ms1[0] == 'a');

// Map a *second view* of the same memory
afio::algorithm::mapped_span<char> ms2(sh);
assert(ms2[0] == 'a');

// The addresses of the two maps are unique
assert(ms1.data() != ms2.data());

// Yet writes to one map appear in the other map
ms2[0] = 'b';
assert(ms1[0] == 'b');
```

2.7 Sparsely stored arrays:

A neat use case making use of the new kernel memory allocation support is for sparsely allocated huge arrays. One can allocate up to 127Tb of address space on most 64 bit architectures.

```cpp
namespace afio = AFIO_V2_NAMESPACE;

// Make me a 1 trillion element sparsely allocated integer array!
afio::mapped_file_handle mfh = afio::mapped_temp_inode().value();

// On an extents based filing system, doesn't actually allocate any physical
// storage but does map approximately 4Tb of all bits zero data into memory
(void) mfh.truncate(1000000000000ULL * sizeof(int));

// Create a typed view of the one trillion integers
afio::algorithm::mapped_span<int> one_trillion_int_array(mfh);
```

```

// Write and read as you see fit, if you exceed physical RAM it'll be paged out
one_trillion_int_array[0] = 5;
one_trillion_int_array[999999999999ULL] = 6;
```

2.8 Resumable i/o with Coroutines:

```
namespace afio = AFIO_V2_NAMESPACE;

// Create an asynchronous file handle
afio::io_service service;
afio::async_file_handle fh =
  afio::async_file(service, {}, "testfile.txt",
    afio::async_file_handle::mode::write,
    afio::async_file_handle::creation::if_needed).value();

// Resize it to 1024 bytes
truncate(fh, 1024).value();

// Begin to asynchronously write "hello world" into the file at offset 0,
// suspending execution of this coroutine until completion and then resuming
// execution. Requires the Coroutines TS.
alignas(4096) char buffer[] = "hello world";
co_await co_write(fh, 0, { { reinterpret_cast<afio::byte *>(buffer), sizeof(buffer) } }).value();
```

2.9 Read all valid extents of a file using asynchronous file i/o:

```
namespace afio = AFIO_V2_NAMESPACE;

// Create an i/o service to complete the async file i/o
afio::io_service service;

// Open the file for read
afio::async_file_handle fh = afio::async_file(  //
  service,  // The i/o service to complete i/o to
  {},       // path_handle to base directory
  "foo"     // path_view to path fragment relative to base directory
            // default mode is read only
            // default creation is open existing
            // default caching is all
            // default flags is none
).value();  // If failed, throw a filesystem_error exception

// Get the valid extents of the file.
const std::vector<
  std::pair<afio::file_handle::extent_type, afio::file_handle::extent_type>
> valid_extents = fh.extents().value();

// Schedule asynchronous reads for every valid extent
std::vector<
  std::pair<std::vector<afio::byte>, afio::async_file_handle::io_state_ptr>
```

```
> buffers(valid_extents.size());
for (size_t n = 0; n < valid_extents.size(); n++)
{
  // Set up the scatter buffer
  buffers[n].first.resize(valid_extents[n].second);
  for(;;)
  {
    afio::async_file_handle::buffer_type scatter_req{
      buffers[n].first.data(), buffers[n].first.size()
    };  // buffer to fill
    auto ret = afio::async_read( //
      fh,                                           // handle to read from
      { { scatter_req }, valid_extents[n].first },  // The scatter request buffers + offset
      []{                                           // The completion handler
        afio::async_file_handle *,                  // The parent handle
        afio::async_file_handle::io_result<afio::async_file_handle::buffers_type> &  // Result of the
            i/o
        ) { /* do nothing */ }
                                                    // default deadline is infinite
    );
    // Was the operation successful?
    if (ret)
    {
      // Retain the handle to the outstanding i/o
      buffers[n].second = std::move(ret).value();
      break;
    }
    if (ret.error() == std::errc::resource_unavailable_try_again)
    {
      // Many async file i/o implementations have limited total system concurrency
      std::this_thread::yield();
      continue;
    }
    // Otherwise, throw a filesystem_error exception
    ret.value();
  }
}

// Pump i/o completion until no work remains
while (service.run().value())
{
  // run() returns per completion handler dispatched if work remains
  // It blocks until some i/o completes (there is a polling and deadline based overload)
  // If no work remains, it returns false
}

// Gather the completions of all i/o scheduled for success and errors
for (auto &i : buffers)
{
  // Did the read succeed?
  if (i.second->result.read)
  {
    // Then adjust the buffer size to that actually read
    i.first.resize(i.second->result.read.value().size());
  }
  else
  {
    // Throw the cause of failure as an exception
    i.second->result.read.value();
  }
}
```

3 Impact on the Standard

The proposed low level file i/o library is potentially a pure-library solution with dependencies on:

1. `std::filesystem`
2. P0057 *C++ Extensions for Coroutines* `https://wg21.link/P0057`. Status: Approved for C++ 20.
3. P0122 *span: bounds-safe views for sequences of objects* `https://wg21.link/P0122`. Status: Approved for C++ 20.
4. P0734 *Concepts* `https://wg21.link/P0734`. Approved for C++ 20.
5. P1028 *SG14 status_code and standard error object for P0709 Zero-overhead deterministic exceptions* `https://wg21.link/P1028`.

   This proposes a refactored, even lighter weight `<system_error>` v2 which fixes a number of problems which have emerged in the use `<system_error>` as hindsight has emerged. The replacement for `std::error_code`, `status_code`, is rarefied into a proposed `std::error` object for [P0709].
6. P1030 *Filesystem path views* `https://wg21.link/P1030`.

   This proposes a lightweight view of a filesystem path. Path views can help eliminate the often frequent copying of filesystem paths when calling a library such as this one.

There are two design guideline papers which the proposed library mostly meets:

1. P0829 *Freestanding C++* `https://wg21.link/P0829`.

   This paper sets out the parts of the C++ language and standard library which are widely compatible with embedded systems. This low level file i/o library would not work on many embedded systems due to their lack of a filing system, but the discipline of laser focus upon determinism and not using unnecessary memory nor features is retained.
2. P1027 *SG14 Design guidelines for future low level libraries* `https://wg21.link/P1027`.

   This paper refines [P0939] *Direction for ISO C++* with concrete design guidelines for future low level library additions to the standard C++ library. Such low level libraries would historically have been an internal implementation detail of a standard library, P1027 calls for them to become public and standardised.

There is an optional dependency on two core language enhancements:

1. [P0709] *Zero-overhead deterministic exceptions: Throwing values* `https://wg21.link/P0709`.

   This proposes that the C++ language implements the lightweight throwing of error/status codes similar to that implemented by Boost.Outcome [1].

2. P1029 *SG14* *`[[move_relocates]]`* `https://wg21.link/P1029`.

   This proposes a new C++ attribute `[[move_relocates]]` which lets the compiler optimise such attributed moves as aggressively as trivially copyable types. If approved, this would enable a large increase in the variety of types permissible in P1027's guidelines, plus P1028's standard error object would gain the ability to transport `std::exception_ptr` instances directly, a highly desirable feature for improving efficiency of legacy C++ exceptions support under P0709.

   All types consumed and returned in the APIs of this *Low level file i/o* proposal have standard layout, are trivially copyable, or move relocating, as per the low level library design guidelines in P1027.

There *may* be a dependency on [P0443] *A Unified Executors Proposal for C++* depending on design decisions not yet taken (see below).

The low level file i/o library generally works with `span<T>` or `span<span<T>>`, and thus should automatically work well with Ranges.

4 Proposed Design

4.1 Handles to kernel resources

The design is very straightforward and intuitive, if you are familiar with low level i/o. We do not innovate in this proposed design. It is more, or less, a straight thin wrap of a subset of the POSIX file i/o specification, as it was standardised in the POSIX.1-2008 specification (ten years ago was chosen as it has wide implementation conformance), but with significantly weakened behaviour guaramtees than than those in the POSIX specification. This weakening was done to aid portability, specifically to far-from-POSIX filesystems such as those typically used in HPC and heterogeneous compute.

There is a fundamental type called `native_handle_type` which is a simple, *unmanaged* union storage of one of a POSIX file descriptor, or a Windows `HANDLE`. Any other platform-specific resource identifier types would be added here.

`native_handle_type` contains *disposition* about the identifier, specifically what kind it is, what rights it has, is it seekable, does it require aligned i/o, must it be spoken to in overlapped and so on. It can be made invalid i.e. it has a formal invalid state. It is all-constexpr.

At the base of the inheritance hierarchy is the polymorphic `class handle`. It manages a `native_handle_type`, which can be released from its handle if wished. When the handle is destructed, the `native_handle_type` inside the instance is closed.

`class handle` is a move-only type. It does provide a polymorphic clone member function which will duplicate the handle. The reason that the C++ copy constructor is disabled is because duplicating handles is expensive, and unintentionally doing so would be bad.

Apart from releasing, cloning and closing, the only other thing one can do with a handle is to retrieve its current path on the filesystem. It is very important to understand that this is **not** the path it was opened with (if the user wants that, they can cache it themselves). Rather it is what the kernel *says* is the current path for this inode right now[5]. This can be useful to know, as other processes can arbitrarily change the path of large numbers of open files in a single syscall simply by changing the name of a directory further up the hierarchy. In fact, handle has entirely trivial storage as it stores nothing which is allocated from memory, it can thus be constexpr constructed, and moves of it relocate[6].

Handle defines many types and bitfields used by its refinements:

- `mode`

  This selects what kind of i/o we wish to do with a handle. One of none, attribute read, attribute write, read, write, (atomic) append.

- `creation`

  This selects what opening a handle ought to do if the path specified already exists or doesn't exist. One of open existing, only if not exist, if needed, (atomic) truncate.

- `caching`

  This selects what kind of caching (buffering) the kernel ought to perform for this handle:

  - No caching whatsoever, and additionally `fsync()` the file and any other resources[7] at certain key moments to ensure recovery after sudden power loss (immediately after creation, immediately after maximum extent change, immediately before close). On many, but not all, platforms this is direct DMA to the device from user space which comes with a list of special use requirements (see later in paper).
  - Cache only metadata. On many, but not all, platforms this is direct DMA to the device from user space.
  - Cache only reads, and with `fsync()` at key moments described above. Writes block until they and the metadata to retrieve them after power loss fully reach storage.
  - Cache reads and metadata, and `fsync()` at key moments described above. Writes block until they fully reach storage, but the metadata to retrieve them is written out asynchronously.

[5] A standard API for this is not present in POSIX.1-2008, but proprietary APIs are available on all the major platforms and most of the minor ones, including embedded operating systems. For those few systems without kernel support, we provide a templated adapter for all handle types which caches the path for you.

[6] This is a concept which doesn't exist in the language yet, see [P1029] for its proposal paper.

[7] On Linux ext4, one must also sync the parent directory as well as the inode to ensure complete recovery after power loss.

  - Cache reads, writes, and metadata (the default). Writes are enqueued and written to storage at some later point asynchronously.
  - Cache reads, writes, and metadata, and `fsync()` at key moments described above.
  - Avoid writing to storage as much as possible. Useful for temporary files.

  For those not familiar with data synchronisation outside of `fsync()`, explicitly disabling some or all of kernel caching at handle open results in much better performance than following every write with a `fsync()`. Indeed, in some filing systems like ZFS, a special fast non-volatile device is used to complete an uncached write immediately, which is synced later to slow non-volatile storage.

- `flags`

  This selects various bespoke behaviours and semantics:

  - `unlink_on_close`

    Causes the entry in the filesystem to disappear on first close by any process in the system.

    Microsoft Windows partially implements this in its kernel, and significantly changes how it caches data based on the setting of this flag.

  - `disable_safety_fsyncs`

    Disables the safety `fsync()`'s for the modes listed above.

  - `disable_safety_unlinks`

    Do not compare inode and device with that of the open file descriptor before unlinking it.

  - `disable_prefetching`

    Most kernels prefetch data into the kernel cache after an i/o. For truly random i/o workloads, this flag ought to be set.

  - `maximum_prefetching`

    If we are copying a file's contents using caching i/o, this flag ought to be set.

  - `win_disable_unlink_emulation`

    On Microsoft Windows, POSIX unlink semantics are emulated by renaming on unlink the file entry to something very random such that it cannot be found[8,9]. Setting this flag disables this emulation.

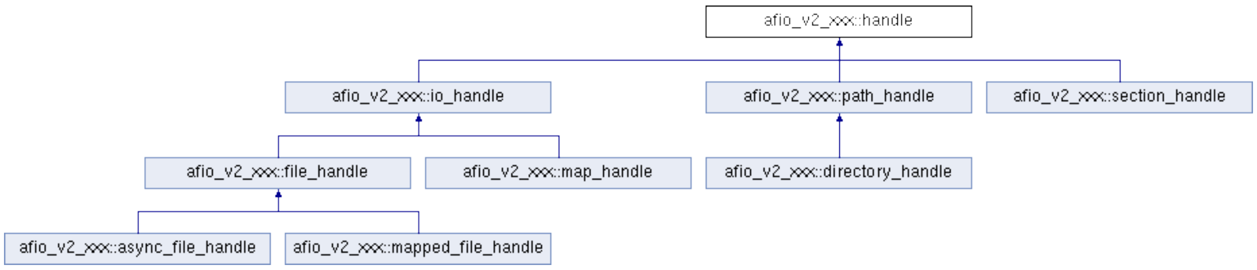
[8]Due to VMS legacy compatibility, NT implements file deletion by marking a file entry as deleted which prevents it being opened for access thenceforth. It does not remove the file entry until some arbitrary time (usually milliseconds) after the last open handle to it in the system has closed. This confounds code written to expect POSIX semantics whereby unlinking a file causes it to immediately disappear from the filesystem. This workaround of renaming the file to something very random simulates, incompletely, POSIX semantics on Microsoft Windows, sufficiently so at least that most filesystem algorithms 'just work'.

[9]I have been told by Microsoft that the next version of Windows 10 implement opt-in POSIX unlink semantics, so on newer Windows we can avoid rename-to-random workarounds.

- `win_disable_sparse_file_creation`

  Microsoft's NTFS file system was designed in the 1980s back when extents-based filing systems were not common. It was later upgraded to an extents-based implementation capable of working with sparse files. Due to backwards compatibility, during file creation one must *opt-in* to using extents-based storage. That setting remains attached to that file for the remainder of its life, which could theoretically break some programs. The proposed library always opts in to extents based storage by default for newly created files to match semantics with almost every modern filing system elsewhere. This flag disables that default opt-in.

4.1.1 Class hierarchy inheriting from `handle`


afio_v2_xxx::handle
afio_v2_xxx::io_handle
afio_v2_xxx::path_handle
afio_v2_xxx::section_handle
afio_v2_xxx::file_handle
afio_v2_xxx::map_handle
afio_v2_xxx::directory_handle
afio_v2_xxx::async_file_handle
afio_v2_xxx::mapped_file_handle

Inheriting from `class handle` are these refinements of handle:

- `io_handle`

  I/O handle adds types and member functions for scatter-gather synchronous i/o to a seekable handle[10].

  All i/o is optionally deadline based, with a choice of interval or absolute timeout. Deadline i/o for files only works if the most derived implementation is `async_file_handle` as these synchronous calls are implemented using an asynchronous implementation which can be cancelled.

  I/O handle also adds member functions for mutually excluding part, or all of, the resource represented by the handle from any other process in the system. These are always *advisory* not mandatory exclusions i.e. they require all processes to cooperate by checking for locks before an i/o.

  Inheriting from `io_handle` are these refinements of i/o handle:

  - `file_handle`

    File handle is the simple, unfussy thin wrap of the platform's file read and write facilities. All i/o is always performed via the appropriate syscall. This passes through any POSIX read-write atomicity and sequential consistency guarantees which may be implemented by the platform.

[10]Non-seekable handles are valid, but that would start to overlap the Networking TS. For various technical reasons, asynchronous socket and pipe i/o cannot portably use the same i/o service implementation as asynchronous file i/o, this is why this proposed library is orthogonal to the Networking TS.

File handles provide the following additional static member functions:

* For creating and opening a named file using a `path_handle` instance as the base (a default constructed `path_handle` instance requires the path view to refer to an absolute path).
* For creating a cryptographically randomly named file at a location specified by a `path_handle` instance. This is useful for creating a temporary file which once fully written to, will be atomically renamed to replace an existing file.
* For creating a temporary file in one of the temporary file locations found during path discovery (see `path_discovery` below), counted against user quota or system RAM quota.
* For securely creating an anonymous temporary inode at a location specified by a `path_handle` instance. These are always unnamed, always inaccessible inodes which do not survive process exit. These are used especially by generic template algorithms to implement novel STL containers like vectors with constant, rather than linear, capacity expansion times.

File handles provide the following additional polymorphic member functions:

* For getting and setting the maximum file extent (not 'the length', though many people get confused on this).
* For issuing a write reordering barrier which can be optionally applied to a subset of extents in the file, optionally with blocking until preceding writes reach storage, and optionally with an additional flush of inode metadata which indicates current maximum extent, timestamps etc.
* For enumerating the valid extents in the file. Modern extents-based filing systems (pretty much all in common use today except for FAT) only store the extents written to, so a 1Tb maximum extent file might only have 4Kb of extents allocated within it. Colloquially known as 'sparse files'.
* For deallocating a valid extent in the file. Colloquially known as 'hole punching'.
* For unlinking the hard link currently referred to by the open handle.
* For relinking the hard link currently referred to by the open handle to another path, optionally atomically replacing any item currently at that path.
* For creating a new hard link to the inode referred to by the open handle at a new path location.

Note that one can instance any refinement of `file_handle` implementation and pass it to functions as if it were a true `file_handle`. Under the bonnet, scatter-gather synchronous i/o is implemented as whatever is the most optimal for that implementation type e.g. for `mapped_file_handle` scatter-gather synchronous i/o is implemented with `memcpy()`.

Inheriting from `file_handle` are these refinements of file handle:

* `async_file_handle`

The async file handle can behave in every way as if a synchronous file handle i.e. the member functions inherited from `io_handle` behave as if synchronous, though unlike in other implementations, they can observe timeouts.

It adds member functions for scatter-gather asynchronous i/o taking a completion callback (`async_read()`, `async_write()`). Instantiating an async file handle requires the user to supply an instance of `io_service` to issue callback completions against, this must be pumped for completion dispatch very similarly to the `io_service` in the Networking TS.

Async file handle also provides member functions for coroutinised i/o (`co_read()`, `co_write()`) whereby the calling coroutine is suspended until the i/o completes, whereupon it is resumed.

    * `mapped_file_handle`

      The mapped file handle is the most highly performing file handle implementation in terms of i/o, but comes with significantly higher cost construction, extension and destruction and with severe usability limits on 32 bit architectures. It also loses any POSIX read-write atomicity and sequential consistency guarantees which may be implemented by the platform on the other types of handle.

      It always maps the whole file into memory, extending the map as needed into an *address reservation*. Unless you are opening and closing files frequently, or the files you are working with are much smaller than the system page size, or you are on a 32 bit architecture, this is an excellent default choice for most users giving maximum zero whole system memory copy performance on all devices apart from network attached storage devices.

  - `map_handle`

    Map handle is a region of shared or private memory mapped from a backing `section_handle`, or unmapped private memory backed by the swap file, or reserved address space. Within the committed (i.e. allocated) part of that region, i/o can be performed, or more usefully, the region can be accessed directly as memory.

    Added member functions include the ability to commit (allocate) sub-regions of reserved address space, or to decommit (deallocate) previously allocated sub-regions.

    It comes with a comprehensive set of static member functions which can be applied to any memory in a process e.g. 'please kick the contents of this memory page out to backing storage', 'please unset the dirty bit of this memory page (i.e. don't flush its contents to storage until the next modification)', or 'please asynchronously ready this range of memory for access (i.e. prefault it)' and so on.

    `mapped_file_handle` and many other classes use this class as an internal implementation primitive for all forms of mapped and unmapped and reserved memory.

- `path_handle`

  Path handles refer to some base location on the filesystem from which path lookup begins.

The inode opened may change its path arbitrarily and at any time without affecting the paths which use an open path handle as their base. This handle is, therefore, the foundation of the race free filesystem which the proposed library implements.

Many platforms implement the creation of these handles as an especially lightweight operation, hence they are standalone from `directory_handle`.

Inheriting from `path_handle` are these refinements of path handle:

  - `directory_handle`

    Directory handles refer to inodes which list other inodes. The main added member function is to enumerate that list of other inodes into a user supplied array (`span`) of `directory_entry`. One can open existing directories, create new directories, create randomly named new directories, and in your choice of path including temporary paths found during path discovery. One can of course also unlink and relink directories.

- `section_handle`

  Section handles refer to a section of shared or private memory. They may be backed by a user supplied `file_handle`, or by an anonymous inode in one of the path categories returned by `path_discovery`, or by some other source of shared memory. They are particularly useful for when you need some temporary storage (counted against either the RAM quota or the current user's quota) which will be thrown away at process end.

  Section handles have a length which can be queried and changed. It may be less than, but cannot exceed, the maximum extent of any backing file.

  Section handles have additional flags in addition to those inherited from `handle`. Section handle flags are reused by `map_handle`:

  - `none`: This memory region is reserved address space.
  - `read`: This memory region can be read.
  - `write`: This memory region can be written.
  - `cow`: This memory region is copy-on-write (i.e. when you first write, the kernel makes you a process-local copy of the page).
  - `execute`: This memory region can contain code which the CPU will execute.
  - `nocommit`: Don't immediately allocate resources for this section/memory region upon construction. Most kernels allocate space for unbacked sections against the system memory + swap files, and will refuse new allocations once some limit is reached. Setting this flag causes unbacked sections to allocate system resources 'as you go' i.e. as you explicitly commit pages using the appropriate member functions of `map_handle`.
  - `prefault`: Prefault, as if by reading every page, any views of memory upon creation. This eliminates first-page-access latencies where on first access, the page is faulted into existence.
  - `executable`: This section represents an executable binary.

  - `singleton`: A single instance of this section is to be shared by all processes using the same backing file. This means that when one process changes the section's length, all other processes are instantly updated (with appropriate updates of maps of the section) at the same time, which can be considerably more efficient.
  - `barrier_on_close`: Maps of this section, if writable, issue a blocking `barrier()` when destructed, blocking until data (not metadata) reaches physical storage.

- `symlink_handle`

  Symlink handles refer to inodes which contain a relative or absolute path. Added member functions can read and write that stored path.

4.1.2 Miscellaneous and utility classes and functions

There are also some utility classes:

- `deadline`

  A deadline is a standard layout and trivially copyable type which specifies either an interval or absolute deadline. Deadlines can construct from any arbitrary `std::chrono::duration<>` or `std::chrono::time_point<>`. The advantage to this object is halving the number of polymorphic function overloads required, and maintaining a stable ABI as per the guidelines in [P1027].

- `directory_entry`

  A `path_view` and `stat_t` combination. Filled by `directory_handle`'s enumeration function. Note that it has standard layout and is trivially copyable.

- `io_service`

  A completion handler dispatcher used by `async_file_handle`. Looks deliberately like a simplified subset of the Networking TS's `io_service`, but must be distinct as asynchronous file i/o cannot be portably implemented using the same i/o service as pipe and socket i/o.

- `path_discovery`

  Path discovery generally runs once per process and it interrogates the platform to discover suitable paths for (i) storage backed temporary files (counted against the current user's quota) and (ii) memory backed temporary files (counted against available RAM). Path discovery does not trust the platform specific APIs, and it tries creating a file in each of the directories reported by the platform to find out which are valid. This is slow, so the results are statically cached.

- `path_view`

  Path views are covered in detail in [P1030], but in essence they are a lightweight reference to a string which is the format of a filesystem path. They are standard layout and trivially copyable. Path views are very considerably more efficient to work with than filesystem path objects, and make a big difference to performance, especially when enumerating large directories.

- `stat_t`

  Almost certainly WG21 will want the name to be changed to avoid conflict with the platform `stat_t`, but I haven't personally found it to be an issue in practice. This is a C++-ified `struct stat_t`, it uses `std::filesystem` constants and data types instead of the platform-specific ones. It is standard layout and trivially copyable.

- `statfs_t`

  Similarly, almost certainly WG21 will want the name to be changed to avoid conflict with the platform `statfs_t`, but I haven't personally found it to be an issue in practice. This is a C++-ified `struct statfs_t`, it uses `std::filesystem` constants and data types instead of the platform-specific ones. Unusually for types in the proposed library, this one is not trivially copyable as it contains two `std::string`'s and a `std::filesystem::path` for the `f_fstypename`, `f_mntfromname` and `f_mntonname` members.

There are some minor utility functions as well which are not described in detail for now. They fetch things like the TLB page size entries for this machine, have the kernel return single TLB entry allocations of varying sizes either via a C malloc type API or via a special STL allocator, ask the kernel to fill a buffer with cryptographically strong random data, fast to-hex and from-hex routines and so on. These minor utility functions are used throughout the internal implementation of the library, but are useful to other code built on top of the library as well.

4.2 Generic filesystem algorithms and template classes

4.2.1 Introduction

A key thing to understand about this low level library is the lack of guaranteed behaviours it provides in its very lowest layers. This is principally because file i/o has surprisingly few guarantees in the POSIX standard, and thus we are gated as to what the thin kernel syscall wraps can guarantee. For example, `file_handle::barrier()` asks the kernel to issue a write reordering barrier on a range of bytes in the open file, with options for blocking until preceding writes reach storage, and whether to also flush the metadata with which to retrieve the region after sudden power loss. This looks great, but you will find wide variation as to how well that is implemented across platforms. These are the current behaviours on the three major platforms[11]:

- FreeBSD/MacOS

  For normal files, range barriers are not available, so the whole file is barriered. Metadata is always synchronised. On MacOS only, non-blocking barriers are available, on FreeBSD all barriers always block until completion of the entire file plus metadata. On FreeBSD a total sequentially consistent ordering is maintained, so concurrent barriers exclude other barriers until completion. I do not know the behaviour on MacOS, but I would assume it is the same.

  For mapped files, range barriers are only available if not synchronising metadata, in which case it is to the nearest 4Kb page level. Blocking until writes reach storage forms a sequentially consistent ordering, otherwise concurrent barriers are racy.

[11]This is from memory, it may be inaccurate.

- Linux

  For normal and mapped files, fully implemented to the nearest 4Kb page level. BUT with the huge caveat that these do not form a total sequential ordering amongst concurrent callers upon overlapping byte ranges, so it is therefore racy in terms of useful recovery after sudden power loss.

- Microsoft Windows

  For normal files, range barriers are not available, so the whole file is barriered. Otherwise full implementation, and a total sequentially consistent ordering is maintained so concurrent barriers exclude other barriers until completion.

  For mapped files, range barriers are only available if not synchronising metadata, in which case it is to the nearest 4Kb page level. Concurrent barriers are always racy.

What this means is that on Linux or if barriering on a mapped file, you must coordinate between multiple processes or threads using your own mechanism to ensure only one thing issues a barrier for some range at a time. On all platforms apart from Linux, currently range barriers with metadata actually barrier the whole file, so there is no point in trying to achieve any concurrency in your write reordering barriers.

In case you think this sort of platform specific variance is limited to just write reordering barriers, you may be in for a surprise. In my own personal opinion (explained in more detail below), I don't think any standards text can claim anything more than 'implementation defined' for all the lowest level functions. Even the humble write data function has a multitude of platform specific surprise.

These variations may seem problematic, but it is exactly what generic filesystem algorithms and template classes are for: to add layers of increasing abstraction plus guarantees on top of the raw low level API. That way, for those who need the raw bare metal performance, they can get that. But for more portable code where we need some consistency, template algorithms can abstract out these platform specific details for us.

As an analogy, in the Networking TS we have lowest level functions such as `async_write_some()` which attempts to write some or all of a gather buffer sequence. But we also have higher level functions – `async_write()` – which guarantees to write a whole gather buffer sequence, not completing until it is all done. That design pattern of API layers of increasing guarantees is present in file i/o as well, just a bit more complex than (and quite different to) socket i/o.

4.2.2 Filesystem template library (so far) – the 'FTL'

These are some generic algorithms and template classes which act as abstraction primitives for more complex filesystem algorithms. It should be stressed that all of the below are 100% header only code, and use **no** platform-specific APIs. They are implemented **exclusively** using the public APIs in the proposed low level file i/o library. This may give an idea of the expressive power to build useful and interesting filesystem algorithms using the proposed design.

- `shared_fs_mutex`

This is an abstract base class for a family of shared filing system mutexs i.e. a suite of algorithms for excluding other processes and threads from execution using the filesystem as the interprocess communication mechanism.

Unlike memory-based mutexes already in the standard library, in the lock operation these mutexes take a sequence of *entities* upon which to take a shared or exclusive lock. An entity is a 63 bit number (the top bit stores whether it is exclusive or not)[12].

The reason that these mutexes are list-of-entities based is because it is very common to lock more than one thing concurrently on the filing system, whereas with memory-based mutexes that is the exception rather than the norm. For example, if you were updating file number 2 and file number 10 in a list of files at the same time, you would concurrently lock entities 2 and 10. If you were implementing a content addressable database like a git store, you'd use the last 63 bits of the git SHA as the entity, and so on.

Each of the implementations has varying benefits and tradeoffs, including the ability to lock many entities in the same time as one entity. The appropriate choice depends on use case, and to an extent, the platform upon which the code is running.

– `shared_fs_mutex::atomic_append`

  This implementation uses an atomically appended shared file as the IPC mechanism. Advantages include invariance to number of entities locked at a time, ability to sleep the CPU and compatibility with all forms of storage except NFS. Disadvantages include an intolerance to one of the using processes experiencing sudden process exit during lock hold, and filling all available free space on filing systems which are not extents based (i.e. incapable of 'hole punching').

– `shared_fs_mutex::byte_ranges`

  This implementation uses the byte range locks feature of your platform as the IPC mechanism. Advantages include ability to sleep the CPU and automatic handling of sudden process using during lock hold. Disadvantages include wildly differing performance and scalability between platforms, lack of thread compatibility with POSIX implementations other than recent Linux, ability to crash NFS in the kernel due to overload.

– `shared_fs_mutex::lock_files`

  This implementation uses exclusively created lock files as the IPC mechanism. Advantages include simplicity and wide compatibility without corner case quirks on some platforms. Disadvantages include an inability to sleep the CPU, and an intolerance to one of the using processes experiencing sudden process exit during lock hold.

– `shared_fs_mutex::memory_map`

  This implementation uses a shared memory region as the IPC mechanism. Advantages include blazing performance to the extent of making your mouse pointer stutter. Disadvantages include inability to use networked storage, inability to sleep the CPU, and an

[12]This design choice works around the problem that on some platforms, byte range locks are *signed* values, and attempting to take a lock on a top bit set extent will thus always fail.

intolerance to one of the using processes experiencing sudden process exit during lock hold.

  - `shared_fs_mutex::safe_byte_ranges`

    This implementation – on POSIX only – wraps the byte range locks on the platform with a thread locking layer such that individual threads do not overwrite the locks of other threads within the same process, as is required by the POSIX standard for byte range locks. On other platforms, this is a typedef to `shared_fs_mutex::byte_ranges`.

- `cached_parent_handle_adapter<T>`

  Ordinarily, handles do not store any reference to their parent inode. They provide a member function which will obtain a such a handle by fetching the current path of the inode and looping the check to see if it has a leaf with the same inode and device number as the handle. This, obviously enough, is expensive to call.

  For use cases where a lot of race free sibling and parent operations occur, one can instantiate any of the handle types using this adapter. It overrides some of the virtual functions to use a cached parent inode implementation instead. These parent inode handles are kept in a global registry, and are reference counted to minimise duplication. This very considerably improves the performance of race free sibling and parent operations, at the cost of increasing the use of file descriptors, plus synchronising all threads on accessing the global registry.

  There is an additional use case, and that is where the platform does not implement file inode path discovery reliably, which can afflict some older editions of some kernels [13].

- `mapped_span<T>`

  A mapped span is a `span<T>` of a `map_handle`'s region. It implies a `reinterpret_cast<T>` of the `map_handle`'s `char` mapped memory.

  Mapped spans allow one to easily adapt sparse storage into a sparsely stored array:

```
namespace afio = AFIO_V2_NAMESPACE;

// Make me a 1 trillion element sparsely allocated integer array!
afio::mapped_file_handle mfh = afio::mapped_temp_inode().value();

// On an extents based filing system, doesn't actually allocate any physical
// storage but does map approximately 4Tb of all bits zero data into memory
mfh.truncate(1000000000000ULL*sizeof(int));

// Create a typed span of the one trillion integers
afio::algorithm::mapped_span<int> one_trillion_int_array(mfh);

// Write and read as you see fit, if you exceed physical RAM it'll be paged out
one_trillion_int_array[0] = 5;
one_trillion_int_array[999999999999ULL] = 6;
```

[13] At the time of writing, OS X's path fetching API returns one of the paths for any hard link to the inode, randomly. This is almost certainly a bug. FreeBSD does not reliably provide path fetching for file inodes, but does for directory inodes. From examination of the kernel source, this ought to be easy to fix. In both cases, fetching the path of a directory inode is reliable, and thus via this adapter works around these platform-specific quirks and bugs.

Virtual memory based kernels have been able to do this sort of stuff for decades, but making use of it, especially portably, was tedious and error prone. The above shows how much easier this sort of programming becomes.

4.2.3 Planned generic filesystem template algorithms yet to be reference implemented

- Persistent page allocator which is interruption safe, concurrency safe, lock free. This is effectively a persistent linked-list implementation of allocated and non-allocated regions within the file.
- The aforementioned B+ tree implementation [2] which is interruption safe, concurrency safe, lock free.
- Persistent vector which is interruption safe, concurrency safe, lock free.
- Coroutine generators for valid, or all, file extents.
- Compare two directory enumerations for differences (Ranges based).
- B+-tree friendly[14] directory hierarchy deletion algorithm.
- B+-tree friendly directory hierarchy copy algorithm.
- B+-tree friendly directory hierarchy update (two and three way) algorithm.

4.2.4 Functionality whose design is blocked on undecided features at WG21

Most of the just listed items are tricky to implement until compilers and standard libraries implement Coroutines and Ranges without quality of implementation problems, hence why they have not been reference implemented yet.

Some, however, are blocked on WG21. In particular, the directory algorithms need to be available to multiple kernel threads as the filesystem tends to scale linearly with CPU cores if poked at right i.e. the algorithm would sometimes choose to execute a list of operations in parallel knowing that this filing system will scale for this operation, but execute another list sequentially knowing that that will scale better, and this would need to be dynamically determined inside the algorithm's execution tree.

In theory, the [P0443] Executors proposal should fit the bill. Perhaps it is my ignorance of the proposed design, but it seems too 'heavy' for the kind of micro-operations that the directory algorithms would do. In particular, it appears to require allocating memory for every task executed, and the future-based completion notification mechanism which implies another memory allocation, plus atomic reference counting, is hardly lightweight. An alternative is something based on the Parallelism TS, but that would suffer from being too much a 'one size fits all' approach.

[14]By 'B+-tree friendly', I mean that the algorithm orders its operations to avoid the filesystem's B+-tree rebalancing frequently, as a naïve algorithm which almost everybody writes without thinking will do. This can improve performance by around 20% on the major filing systems.

My ideal solution would in fact be completely agnostic to the concurrency mechanism employed, so the user decides. But designing such an implementation with so many as yet undecided design choices at WG21 is hard, and it will get easier if I simply kick the can down the road. Which is what I have done until now.

If WG21 agrees to set up a *Data Persistence Study Group* as [P1026] calls for, that would be an excellent place to bounce around some ideas on how best to implement these remaining generic filesystem algorithms.

4.3 Filesystem functionality deliberately omitted from this proposal

The eagle eyed will have spotted entire tracts of the filesystem have been omitted from this initial proposal:

- Permissions

  Standardising this is a ton of extra work best pushed, in my opinion, into a later standardisation effort.

- Extended attributes

  These probably could be standardised without much effort, but I am also unsure of the demand from the user base. Despite almost universal support in file systems nowadays, they are not widely used outside of MacOS, which is a shame.

- Directory change monitoring

  This is surprisingly hard to implement correctly. Imagine writing an implementation which scales up to 10M item directories and never misrepresents a change? The demands on handling race conditions correctly are very detailed and tricky to get right in a performant and portable way. I would like the change delta algorithms decided upon before tackling this one.

5 Design decisions, guidelines and rationale

The design decisions are as follows, in priority:

5.1 Race free filesystem

As anyone familiar with programming the filesystem is aware, it is riddled with race conditions because most code is designed assuming that the filesystem will not be changed by third parties during a sequence of operations. Yet, not only can the filesystem permute at any time, it is also a bountiful source of unintended data loss and security exploits via Time-of-check-Time-of-use (TOCTOU) failures.

As an example, imagine the following sequence of code which creates an anonymous inode to temporarily hold data which will be thrown away on the close of the file descriptor, perhaps to pass to a child process or something:

```
int fd = ::open("/home/ned/db/foo", O_RDWR|O_CREAT|O_EXCL, S_IWUSR);
::unlink("/home/ned/db/foo");
::write(fd, child_data, ...);
```

Imagine that privileged code is executing that code. Now witness this:

```
int fd = ::open("/home/ned/db/foo",
  O_RDWR|O_CREAT|O_EXCL, S_IWUSR);


::unlink("/home/ned/db/foo");  // oh dear!
```

```


::rename("/home/ned/db", "/home/ned/db.prev");
::symlink("/etc", "/home/ned/db");
```

We have just seen unintended data loss where `/etc/foo` is unlinked instead of the programmer intended `/home/ned/db/foo`.

Here is another common race on the filesystem:

```
int storefd = ::open("/home/ned/db/store",
  O_RDWR);


int indexfd = ::open("/home/ned/db/index",
  O_RDWR);
```

```


::rename("/home/ned/db", "/home/ned/db.prev");
::rename("/home/ned/db.other", "/home/ned/db");
```

Now the index opened is not the correct index file for the store file. Misoperation and potential data corruption is likely.

POSIX.1-2008, and every major operating system currently in use, fixes this via a *race free* filesystem API. Here are safe implementations:

```
int dirh = ::open("/home/ned/db", O_RDONLY|O_DIRECTORY);
int fd = ::openat(dirh, "foo", O_RDWR|O_CREAT|O_EXCL, S_IWUSR);
::unlinkat(dirh, "foo", 0);
```

```
int dirh = ::open("/home/ned/db", O_RDONLY|O_DIRECTORY);
int storefd = ::openat(dirh, "store", O_RDWR);
int indexfd = ::openat(dirh, "index", O_RDWR);
```

The proposed low level file i/o library considers race free filesystem to be sufficiently important that it is enabled by default i.e. it is always on unless you explicitly ask for it to be off. The natural question will be 'How expensive is this design choice?'.

These are figures for the reference library implementation running on various operating systems and filing systems. They were performed with a fully warm cache i.e. entirely from kernel memory without accessing the device. They therefore represent a **worst case** overhead.

	FreeBSD ZFS	Linux ext4	Win10 NTFS
Delete File:	6.2%	11.6%	0%

The extra cost on POSIX for deletion is due to opening the inode's parent directory, checking that a leaf item with the same name as the file to be unlinked has the same inode and device as that of the open handle, and if so then unlinking the leaf in that directory. This algorithm makes file deletion impervious to concurrent third party changes in the path, up to the containing directory, during the deletion operation. A similar algorithm is used for renames, and added overhead is typically around 10%.

One will surely note that overhead on Microsoft Windows is zero. The is because the NT kernel provides much more extensive a race free filesystem API than POSIX does. In particular, it provides a by-open-file-handle API for deletion and renaming so one need not implement any additional work to achieve race freedom.

I appreciate that the choice to make race free filesystem opt-out rather than opt-in will be a controversial one on the committee, not least due to implementation concerns on the less major kernels[15]. However it is my belief that correctness trumps performance for the default case, and for those users who want the fastest possible filesystem performance, race free filesystem can be disabled per object in the constructor.

5.2 No (direct) support for kernel threads

For those coming from a Networking TS/ASIO background, the choice to not support kernel threads in the proposed library's `io_service` seems stunning. I know this from the more than one bug report filed against the reference library implementation over the years: there is a widespread belief that asynchronous i/o *ought* to support kernel threads. I therefore need to explain why the proposed library does not.

Kernels implement synchronous i/o by enqueuing a request to the hardware on the same CPU as the thread which initiated the i/o. When the hardware completes the i/o, it raises an interrupt on that CPU, and the kernel resumes the thread. Asynchronous i/o is little different, except that the initiating thread continues immediately and is not suspended until the hardware raises an interrupt, rather usually some form of signal or notification is posted to the initiating thread for collection later when that thread is ready to execute completions.

There is a second variant of asynchronous i/o however, whereby the interrupt is directed to the next currently idle CPU within a pool of threads attached to completing the i/o. It is this second variant which ASIO uses, whereas this proposed library uses the first variant.

Threaded asynchronous i/o was without doubt much faster than alternatives fifteen years ago, back when ASIO was designed. But kernels have improved greatly since then, sufficiently so that *asynchronous i/o is usually slower than synchronous i/o* because the kernel must do more work to schedule an asynchronous i/o (specifically, it must almost always allocate some memory). In addition, kernel threads damage locality of CPU cache utilisation which has become much more important on today's CPUs than those of fifteen years ago. If you're accessing any memory other

[15]See the description of `cached_parent_handle_adapter<T>` above. However I believe that kernel maintainers are highly amenable to adding a syscall to unlink-by-fd or relink-by-fd, they just need to be given a business case for it. It certainly is trivially easy to implement in any of the kernel sources I have investigated.

than the i/o, increasingly you want that hot in the CPU cache of the kernel thread implementing the i/o completion, a good bet for which usually is the kernel thread which initiated that i/o.

Many latency-sensitive users of ASIO therefore end up running an `io_service` instance per CPU pinned kernel thread in order to better control cache locality. However, ASIO still is employing, under the bonnet, all the machinery to support multiple threads, and that may make it run less efficiently than it might otherwise. I will not say more about ASIO on this, but for file i/o this author benchmarked a wide variety of file i/o patterns using blocking i/o, alertable i/o (complete i/o to the initiating thread) and IOCP (complete i/o to the next idle CPU) on Microsoft Windows, and found that alertable i/o bested IOCP in every way for file i/o. Latency variance was an order of magnitude lower. No mutexs were required. Implementation was considerably more simple. This is why the proposed low level file i/o library does not support multiple kernel threads.

Two points are important to understand however. The first is that it is straightforward to build a pool of threads running file i/o services using this proposed library, and to distribute i/o work across them, if that is what you want. The second is that C++ Coroutines work very well with this library, you simply write code such as:

```
namespace afio = AFIO_V2_NAMESPACE;

// Create an asynchronous file handle
afio::io_service service;
auto fh = afio::async_file(service, {}, "testfile.txt",
                           afio::async_file_handle::mode::write,
                           afio::async_file_handle::creation::if_needed).value();

// Resize it to 1024 bytes
truncate(fh, 1024).value();

...

// Begin to asynchronously write "hello world" into the file at offset 0,
// suspending execution of this coroutine until completion and then resuming
// execution. Requires the Coroutines TS.
alignas(4096) char buffer[] = "hello world";
co_await co_write(fh, {{{buffer, sizeof(buffer)}}, 0}).value();
```

This works exactly as one would expect: coroutines initiate i/o which suspends the coroutine until it completes. In the meantime, other coroutines on the same kernel thread execute if they are ready to be resumed.

5.3 Asynchronous file i/o is much less important than synchronous file i/o

A theme running throughout this proposal paper is that asynchronous file i/o is usually not worth the extra CPU cost on recent kernels of the major operating systems, and hence the proposed low level file i/o library mostly speaks of synchronous, not asynchronous, file i/o. I have noticed that some on WG21 are very keen on bringing complex coroutinised asynchronous i/o frameworks similar to WinRT to the C++ standard soon – indeed, these papers from me are being submitted now in order to preempt misguided papers from those others.

Firstly, of the major operating systems, the only one to actually implement asynchronous file i/o on buffered (cached) files is Microsoft Windows. Linux, FreeBSD, and MacOS all use userspace or kernel threadpools to *emulate* asynchronous i/o, if the handle is buffered. And with Microsoft Windows it definitely is an order of magnitude latency variance penalty to use IOCP to complete asynchronous i/o, only alertable i/o has a reasonable variance, and that still is markedly worse than straight synchronous i/o. So let me be clear on this: *empirical testing suggests that you are almost always worse off employing asynchronous i/o on buffered files on all platforms* because asynchronous i/o is always more work for the CPU to complete, and half the time, even with random i/o, intelligent prefetching by the kernel page cache will be able to complete the i/o immediately in any case, making the asynchronous ceremony a waste of CPU time.

All of the major operating systems do implement true asynchronous file i/o if the handle is *unbuffered*, though rarely by the POSIX asynchronous file i/o API as it scales poorly to queue depth. Unbuffered i/o generally requires all i/o to be performed on native device sector alignment boundaries and multiples: 4Kb is a widely portable choice with today's storage devices. It is therefore unsuitable for WinRT-style general purpose coroutinised asynchronous i/o frameworks. It is quite hard for the typical developer to write an unbuffered filesystem algorithm which significantly outperforms buffered i/o[16]. Countless thousands of hours by the best filesystem engineers in the world have been invested on tuning buffered i/o to perform excellently under a very wide range of use cases.

There are important use cases for unbuffered i/o, especially in the bulk copying of files to avoid evicting the current kernel page cache. This proposed library hence has excellent support for unbuffered i/o. There are few cases where asynchronous file i/o makes sense over synchronous i/o. If you really need to multiplex i/o, you are far better off using a userspace pool of threads doing synchronous i/o, ideally to memory maps to get true zero copy. It parallelises much better, scales much better, does both consistently across all the major platforms, and makes great use of the kernel page cache.

All this could be seen as an argument against this proposed library supplying asynchronous i/o at all. I would not oppose that conclusion, it is a rational one based on empirical fact. However I can see that deadline file i/o could be extremely useful for some applications, and that is implemented using asynchronous i/o. There is also a desirable impact on discipline: even if one never standardises the asynchronous file i/o part of this proposal, having it in here forces one to make a better designed, more extensible, more customisable library in my opinion.

5.4 Pass through the raciness at the low level, abstract it away at the high level

Anyone with experience with the file system knows how racy many of the kernel syscalls are. For example, enumerating valid extents on POSIX is utterly racy due to a particularly bad choice of enumeration API design. There are races in anything which involves a filesystem path, by definition, but there are also races in the ordering of reads and writes to a file, the reported maximum extent

[16]This is not to say that one should not *manage* the kernel page cache by proactively evicting and hinting pages where it makes sense to do so. The proposed library has a comprehensive suite of static member functions for doing this.

of a file, and lots more races in what order all changes land on non-volatile storage, which affects recoverability after sudden power loss.

It is not the business of a low level library to hide this stuff. So pass it through, unmodified, and supply higher level layers, templates, and algorithms which abstract away these core problems.

6 Technical specifications

It is proposed that due to its size, complexity and relative independence from other parts of the C++ standard library, that the low level file i/o library be formulated in a Technical Specification under a new Persistent Data and Algorithms study group [P1026].

7 Frequently asked questions

7.1 Why bother with a low level file i/o library when calling the kernel syscalls directly is perfectly fine?

1. This low level file i/o library defines *a common language* of basic operations across platforms. In other words, it chooses a common denominator across 99% of platforms out there. If you append to a memory mapped file, that'll do the platform-specific magic on all supported platforms.

2. This low level file i/o library only consumes and produces trivially copyable, move relocatable and standard layout objects. Empirical testing has found that the optimiser will eliminate this low level library almost always, inlining the platform specific syscall directly. So, it is *no worse* in any way over calling the platform syscalls directly, except that this library API is portable.

3. Where trivial to do so, we encode domain specific knowledge about platform specific quirks. For example, `fsync()` on MacOS does not do a blocking write barrier, so our `barrier()` function calls the appropriate magic `fcntl()` on MacOS only where the `barrier()` is requested to block until completion.

4. This low level file i/o library is a bunch of primitives which can be readily combined together to build filesystem algorithms whose implementation code is much cleaner looking and easier to rationalise about than using syscalls directly.

5. We can provide deep integration with C++ language features in a way which platform specific syscalls cannot. Ranges, Coroutines and Generators are the obvious examples, but we also make a ton of use of `span<T>`, so all code which understands `span<T>` – or more likely the `std::begin()` and `std::end()` overloads it provides – automagically works with no extra boilerplate needed.

7.2 The filesystem has a reputation for being riddled with unpredictable semantics and behaviours. How can it be possible to usefully standardise anything in such a world?

That is a very good question. This proposal *passes through*, for the most part, whatever the platform syscalls do. If, for example, `read()` and `write()` implement the POSIX file i/o atomicity guarantees, then:

1. A write syscall's effects will either be wholly visible to concurrent reads, or not at all (i.e. no 'torn writes').
2. Reads of a file offset *acquire* that offset, writes to a file offset *release* that offset. Acquire and release have the same meaning as for atomic acquire and release, so they enforce a sequential ordering of visibility to concurrent users based on overlapping regions[17].

These are very useful guarantees for implementing lock free filesystem algorithms, and are a major reason to use `read()` and `write()` instead memory maps because one can forego using any additional locking. Major platform support for the POSIX read/write atomicity guarantees is pretty good in recent years[18]:

	FreeBSD ZFS	Linux ext4	Win10 NTFS
Buffered i/o	Scatter-gather	No	Per buffer
Unbuffered i/o	Scatter-gather	Scatter-gather	Scatter-gather

As another example, `fsync()` commonly has no effect on the current configured platform[19], and thus `io_handle::barrier()` may do nothing useful. Moreover, code cannot tell if `fsync()` is working or not. Writing portable code which works correctly would therefore seem impossible, but in truth this is a *configuration* issue. Software cannot be expected to predict things outside its control. All it can do is call the correct syscalls at the correct times to prevent unsafe write reordering, and proceed as if those syscalls are working correctly.

So how would I propose that one writes up the pre and post conditions for the functions in this library? I propose to mandate certain minimum behaviour guarantees, and to explicitly list those behaviours which we allow to float. For example, consider the gather write function:

```
io_result<const_buffers_type> io_handle::write(io_request<const_buffers_type> reqs,
                                               deadline d = deadline()) noexcept;
```

[`io_result<T>` is like an Expected which can return either a `T` or an error code of a form similar to `std::error_code`.]

We can write what is required of a conforming implementation:

[17] Many, if not most, filing systems actually implement a RW mutex per inode so their guarantees are rather stronger than POSIX requirements. One should not rely on this in portable code however!

[18] Scatter-gather atomicity means that the entire of a scatter-gather buffer sequence is treated as an atomic unit. Per buffer atomicity means that atomicity is per scatter-gather buffer only.

[19] `fsync()` having no effect is surprisingly common in the real world. First, POSIX permits it to be a no-op, so that is what it is in many cases. Secondly, 'it makes software go slow', so there is huge incentive to partially or wholly disable it. For example, MacOS makes it into a non-blocking write reordering barrier, which is decidedly out of spec. Most LXC containers make it into a no-op to prevent containers implementing a denial of service attack on the other containers.

1. If the handle is not open, or not open for writing, the function will fail by returning an error code which compares equal to `std::errc::bad_file_descriptor`, `std::errc::permission_denied`, or `std::errc::operation_not_permitted`. [The ambiguity is due to platform-specific differences between the major platforms, we never remap error codes returns by syscalls]
2. If the handle implementation does not implement deadline i/o, the function will fail by returning an error code which compares equal to `std::errc::not_supported`.
3. If not opened for append (`handle::mode::append`), an attempt shall be made to write each of the regions of memory specified by the i/o request, consecutively, to the offset within the open file specified by the i/o request's offset member.
4. If opened for append, the open file's maximum extent shall be atomically increased by the size necessary to write all of the gather buffers list, followed by an attempt to write each of the regions of memory specified by the i/o request into this newly allocated extent.
5. If the time taken to write the regions exceeds the deadline, the remaining write may be cancelled and the function may fail by returning an error code which compares equal to `std::errc::timed_out`.
6. Upon at least partial success (defined by at least one byte written), the buffers returned shall be updated to reflect the memory regions actually written. **These may have different addresses, as well as sizes, to the buffers input**, so correct code must always work with the buffers returned, NOT the buffers input.
7. If the system currently does not have the resources to write even one of the buffers supplied, an error code comparing equal to `std::errc::resource_unavailable_try_again` will be returned. If at least part of one buffer is written, this will be considered a partial success and the buffers returned will have their sizes updated to indicate actual data written.
8. If any failure is returned by any of the syscalls called by the implementation which cannot be obviously handled immediately, these shall be returned unmodified and unmapped in the error code.

We can write what we knowingly leave up to implementations to define:

- It is implementation defined whether cancellation of i/o completes at any point close to the deadline specified, or at all.
- It is implementation defined whether the system has sufficient resources to issue any more than one of the gather buffers in this operation (some implementations have very limited gather buffer limits which depend on system load, these limits can vary from call to call).
- It is implementation defined whether other processes doing a read of offsets overlapping those being updated will see torn writes (i.e. the write in the process of being applied).
- It is implementation defined whether writes are made visible to other processes, or placed onto storage, in the order the program issues them.
- It is implementation defined whether a write which exceeds the file's maximum extent may cause the automatic increase of the file's maximum extent, and whether the change in the

file's maximum extent will be propagated in a timely fashion to other users of the file[20]. It is required that retrieving the file's maximum extent immediately after a write which may have automatically extended it, will return an accurate value for that instance of the handle only.

- It is implementation defined whether gather buffers shall be issued to the system one by one, or as an atomic group/batch.
- It is implementation defined whether the current file pointer for the underlying handle shall be affected by the write.

There are some gotchas in the above though. For example, NFS has no wire format method of indicating atomic appends, so append-only files do not append atomically (Samba gets this right). So saying that the function will do atomic appends is clearly not possible for some platform configurations unless the standard library always takes a byte range lock at the end of all files opened for append only on a NFS mount.

And one might think that wise, until one considers what happens if you have a situation where some processes are atomic appending locally and others are atomic appending via NFS. Now for correctness, *all* atomic append files need to take a byte range lock, which rather defeats the purpose of the proposed library exposing kernel support for atomic appends.

My own personal viewpoint on this is to simply consider NFS to have a bug, and to not consider it further. We mandate the minimum required semantics in the ISO specification per function in the low level file i/o library, and leave the rest to float as implementation defined, naming them specifically where we know of them. We accept that implementations will have a quality of implementation choice which they themselves can make decisions on based on the platforms they support, and their user bases.

7.3 Why do you consider race free filesystem so important as to impact performance for all code by default, when nobody else is making such claims?

Firstly, performance is only impacted if the host platform does not support direct syscall implementations for all the race free operations exposed by the proposed low level file i/o library, and the missing functionality must be emulated from user space. At least one major platform provides a full set (Microsoft Windows), and I have an enhancement ticket open for Linux[21] to implement the missing support. If WG21 forms the proposed study group, you can be assured that I will try to bang the drum with the OS vendors to add the missing support to their syscalls, indeed I may just go submit a kernel patch to Linux myself (or persuade a Study Group member to do it).

I strongly take the opinion that correctness must precede performance, and as the filesystem is free to be concurrently permuted at any time by third parties, a correct implementation **requires** program code to be as impervious as possible to filesystem race conditions.

[20]Some major platforms do not present changes to maximum extent to other processes until the metadata for the change has reached storage, yet reading off the end of the apparent maximum extent will succeed. The time required for the maximum extent value to propagate to all processes can take some milliseconds sometimes, and can confound algorithms.

[21]https://bugzilla.kernel.org/show_bug.cgi?id=93441

I appreciate that many do not share this opinion. A great many ran ext3 as their Linux filing system when it was demonstrably incorrect in a number of important behaviours[22]. Such users preferred maximum performance to losing data occasionally, and I don't mind any individual choosing that for their individual needs.

But international engineering standards must be more conservative. Choices made here affect everybody, including users where data loss must be avoided at all costs. Defaulting to race free filesystem is the safest choice. Without defaulting to race free filesystem, code written using this low level file i/o library would be much less secure, more prone to surprising behaviour, and end users of C++ code exposed to a higher risk of loss of their data.

8 Acknowledgements

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