P1031R1: Low level file i/o library

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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. On Freestanding C++, `embedded_file_source` can be used to mark up statically bound file data into an emulated read-only filesystem. 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.

Some early thought on how the C++ contracts syntax could be extended to specify side effects can also be found here, as the specification of (lack of) side effects is highly important for implementing any efficient iostreams v2. The section proposing changes to the C++ memory model to support memory mapped files and virtual memory has been removed in favour of a future standalone paper addressed to SG12 Undefined Behaviour.

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

Changes since R0:

- Wrote partial draft TS wording for `deadline`, `handle`, `io_handle`, `mapped`, `mapped_view`, `native_handle_type` and `file_io_error`.
- Added impact on the standard regarding the proposed `[[no_side_effects]]` et al contracts attributes.
- Added `embedded_file_handle`, `embedded_file_source`, `random_file_handle`.
- Deprecated, pending removal, `async_file_handle` and `io_handle`.
- Added detail on proposed large, huge, massive and super page support.

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 PMR[1] 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[2].

The rise of SSD storage has changed things. Now a SATA connected flash drive takes maybe 800 microseconds for that 4Kb i/o @ 99%[3], 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 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[4].

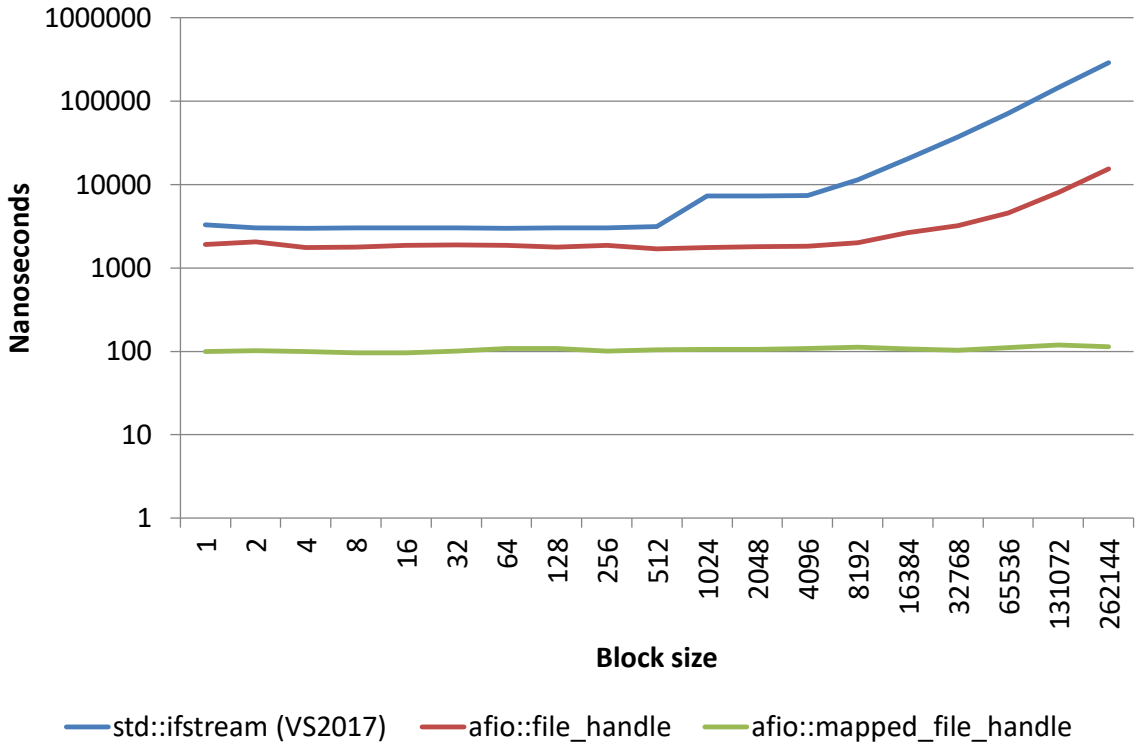
[1] Perpendicular magnetic recording. Some of the recent budget large capacity hard drives use Shingled magnetic recording (SMR), these are approximately 15x slower at writes than PMR drives, though they use a 20Gb PMR write cache to hide the drive's true write speed.

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

[3] 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.

[4] 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

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
`llfio::file_handle`	1915	1766	1869	1873	1855	1750	1812	2633	4576
`llfio::mapped_file_handle`	99	99	96	108	101	105	108	107	111

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 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%

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.

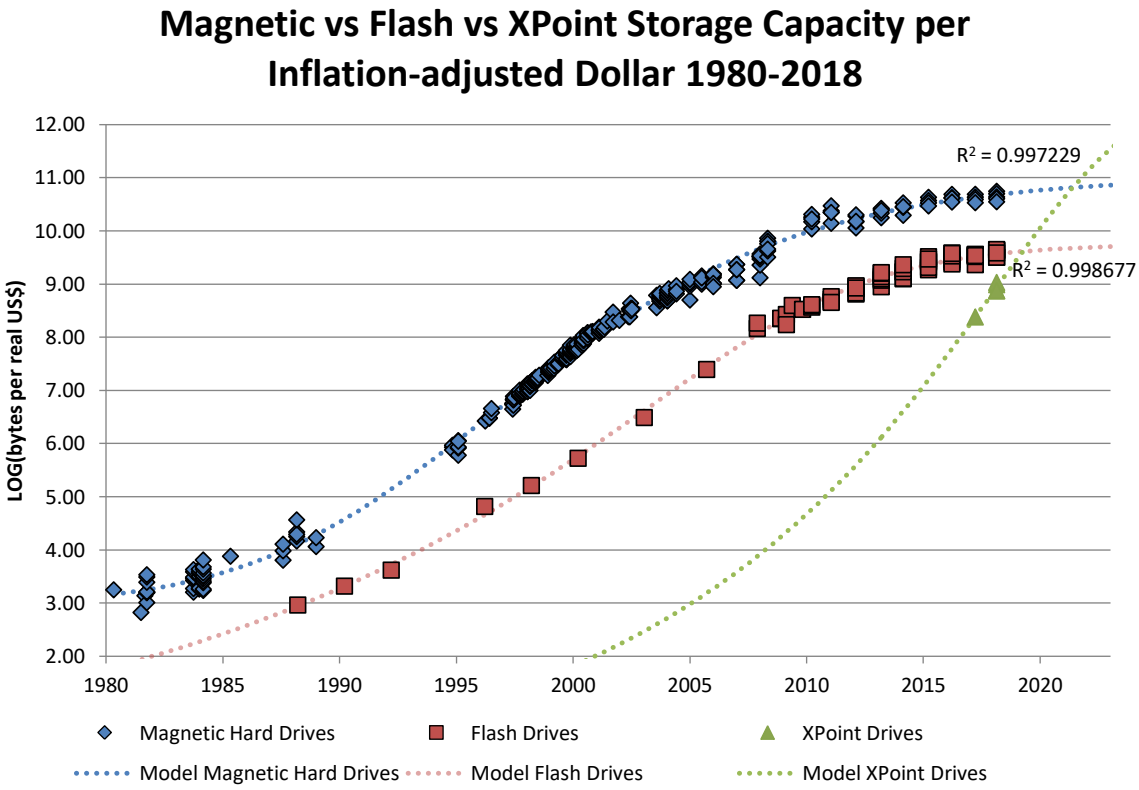


Figure 2: Magnetic vs Flash vs XPoint storage capacity per inflation-adjusted dollar 1980-2018.

and 13 microseconds @ 50%, **and at QD1**. Every unnecessary memory copy in the whole system increases i/o cost by 14-38%.

DDR4 NV-DIMMs have now been standardised, in which your non-volatile storage will do a 4Kb i/o in **8 microseconds**, and indeed a whole 2Mb i/o in just 80 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 in C++ – even ignoring the fact that memory mapped files are pure undefined behaviour in

the current C++ standard – 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, as it happens, 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[5].

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 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.

1.3 The C++ memory and object model needs reform

Nobody likes messing with the C++ memory model. It leads to long protracted arguments about very arcane subject matter on which only a few people on the planet, let alone most of WG21, can argue a point with strong authority. Even those who work all day long in compiler internals can become quite non-commital when it comes to what reform the C++ memory and object model ought to have, though everybody seems to agree that reform is needed.

Much of the workload for SG12 *Undefined behaviour* is related to the C++ memory and object model, specifically because the oodles of undefined behaviour in there which makes much formal reasoning about a C++ program currently impossible, with obvious consequences on inability to optimise or statically analyse code. If you are masochist, you may wish to try rewriting the sections of the current C++ standard relating to memory and objects to support memory mapped files, and then try to wrap your head around what kinds of backwards compatibility issues may now arise with existing C++ programs.

I have made one attempt at this, and mainly came away feeling very stupid and profoundly ignorant. I have come to realise that my twenty years working in C++ is insufficient to really understand it well. Nevertheless, I *strongly* believe that this is worth doing, so I will make a second attempt some

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

time in 2019, this time using the CompCERT memory model v2 as inspiration, and we shall see where we get to.

The reason why the C++ standard needs a low level file i/o library, and not something higher level, is because only at the low level can we properly think through how the C++ memory and object model needs to be reformed to handle things like C++ objects living in persistent memory. For example, we need to devise proper write reordering constraints – which are separate to those in `<atomic>` – to ensure that a sequence of modifications to C++ objects are issued in a sudden-power-loss safe way to persistent memory.

All this is valuable work worth doing, even if WG21 rejects this proposed approach to file i/o.

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:

- 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 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 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 it is 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.

```
namespace llfio = std::experimental::io;

// Open the file for read
llfio::file_handle fh = llfio::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
);

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

// Synchronous scatter read from file
auto bytesread = read(               // read() found using ADL
  fh,                                // handle to read from
  0,                                 // offset
  {{ buffer.data(), buffer.size() }}  // Single scatter buffer of the vector
                                     // default deadline is infinite
);

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

2.2 Write multiple gather buffers to a file:

```
namespace llfio = std::experimental::io;

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

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

```

// 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
    { a, sizeof(a) - 1 },
    { b, sizeof(b) - 1 },
    { c, sizeof(c) - 1 },
    { d, sizeof(d) - 1 },
  }
                           // default deadline is infinite
);

// Explicitly close the file rather than letting the destructor do it
// (this throws if it fails, a failure during destruction terminates the process)
fh.close();
```

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

```
namespace llfio = std::experimental::io;

// Open the mapped file for read
llfio::mapped_file_handle mh = llfio::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
);

auto length = mh.maximum_extent();

// Bless the mapped memory so we can use it directly
std::bless(mh.address(), length);

// 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 llfio = std::experimental::io;

// Open the file for read
llfio::file_handle rfh = llfio::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
);

// Open the same file for atomic append
llfio::file_handle afh = llfio::file(  //
  {},                               // path_handle to base directory
  "foo",                            // path_view to path fragment relative to base directory
  llfio::file_handle::mode::append   // open for atomic append
                                    // default creation is open existing
                                    // default caching is all
                                    // default flags is none
);

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

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

// Append stuff to append only handle
llfio::write(afh,
  0,                // offset is ignored for atomic append only handles
  {{ "hello", 6 }}  // single gather buffer
                    // default deadline is infinite
);

// 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();

// Bless the mapped memory so we can use it directly
std::bless(mh.address(), length);

// 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.

```
namespace llfio = std::experimental::io;

// Get a kernel page of memory. This may call whatever the equivalent
// to mmap() is on this platform to fetch new private memory backed by
// the swap file, or it may reuse a page released earlier. The contents
// of the returned page is unspecified (a parameter exists to request
// that it be all bits zero i.e. always fetch fresh pages from kernel).
// Only on first write will a page fault pin a real page for the returned
// page.
llfio::map_handle mh = llfio::map(4096);

// 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.
std::byte *p = mh.address();
size_t len = mh.length();
memset(p, 'a', len);            // blesses the memory into existence

// 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() });  // unblesses

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

// Fill the memory with 'b' C++ style, probably faulting new pages into existence
llfio::map_view<char> p2(mh);                   // blesses
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()});       // unblesses

// 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() });       // blesses

// 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.
llfio::map_handle::buffer_type pf[] = { mh.address(), mh.length() };
mh.prefetch(pf);
```

```
43
44
45 // You can actually save yourself some time and skip manually creating map handles.
46 // Just construct a mapped directly, this creates an internal map_handle instance,
47 // so memory is released when the span is destroyed
48 llfio::mapped<float> f(1000);  // 1000 floats, allocated used mmap()
49 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.

```
1  namespace llfio = std::experimental::io;
2
3  // Create 4Kb of anonymous shared memory. This will persist
4  // until the last handle to it in the system is destructed.
5  // You can fetch a path to it to give to other processes using
6  // sh.current_path()
7  llfio::section_handle sh = llfio::section(4096);
8
9  {
10   // Map it into memory, and fill it with 'a'
11   llfio::mapped<char> ms1(sh);
12   std::fill(ms1.begin(), ms1.end(), 'a');
13
14   // Destructor unmaps it from memory
15 }
16
17 // Map it into memory again, verify it contains 'a'
18 llfio::mapped<char> ms1(sh);
19 assert(ms1[0] == 'a');
20
21 // Map a *second view* of the same memory
22 llfio::mapped<char> ms2(sh);
23 // Probably ought to be UB to access without deactivating other view first
24 // I'll deal with this in a forthcoming paper in 2019
25 // std::unbless(ms1.data(), ms1.size());
26 assert(ms2[0] == 'a');
27
28 // The addresses of the two maps are unique
29 assert(ms1.data() != ms2.data());
30
31 // Yet writes to one map appear in the other map
32 ms2[0] = 'b';
33 // std::unbless(ms2.data(), ms2.size());      // Select new active view
34 // std::bless(ms1.data(), ms1.size());
35 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.

```
namespace llfio = std::experimental::io;

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

// 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 view of the one trillion integers
// Note that map_view current blesses all 4Tb of data in the view
// I'll need to discuss if this is wise with SG12 in 2019
llfio::map_view<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:

Note that asynchronous file i/o was dropped from this proposal in R1. This use case example remains to remind WG21 members that the reference library can and does implement asynchronous file i/o.

```
namespace llfio = std::experimental::io;

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

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

// 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, { { buffer, sizeof(buffer) } });
```

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

Note that asynchronous file i/o was dropped from this proposal in R1. This use case example remains to remind WG21 members that the reference library can and does implement asynchronous file i/o.

```
namespace llfio = std::experimental::io;

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

// Open the file for read
llfio::async_file_handle fh = llfio::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
);

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

// Schedule asynchronous reads for every valid extent
std::vector<
  std::pair<std::vector<llfio::byte>, llfio::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(;;)
  {
    llfio::async_file_handle::buffer_type scatter_req{
      buffers[n].first.data(), buffers[n].first.size()
    };  // buffer to fill
    // NOTE: Uses proposed catch() operator from P1095 Zero overhead deterministic failure
    std::expected ret = catch(llfio::async_read( //
      fh,                                          // handle to read from
      { { scatter_req }, valid_extents[n].first },  // The scatter request buffers + offset
      [](                                          // The completion handler
        llfio::async_file_handle *,                 // The parent handle
        llfio::async_file_handle::io_result<llfio::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 file_io_error exception under P0709 Deterministic exceptions
    throw ret.error();
  }
}

// Pump i/o completion until no work remains
while (service.run())
{
  // 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
    throw i.second->result.read.error();
  }
}
```

3 Impact on the Standard

Listed at the end of this section are the in-flight WG21 papers this proposal is dependent upon, and which would need to enter the standard before this library can be considered. However a bigger issue involves the potential changes to the C++ memory model, plus new contracts with which to indicate the limited side effects of i/o functions in order to enable improved optimisation.

3.1 Changes to the C++ memory model to support mapped and virtual memory

After lengthy discussion on std-proposals and elsewhere, I have decided to remove this section entirely in favour of a standalone paper addressed to SG12 Undefined Behaviour. You probably noticed

during the use case examples above where there are problems even with the current formulation of [P0593] *Implicit creation of objects for low-level object manipulation.*

This – as yet unwritten – paper is expected to propose merging elements of the CompCERT memory model v2 into the C++ memory model sufficient to be able to express in standardese a specification of how memory mapped files and virtual memory ought to interact with the C++ programming language.

3.2 New attributes `[[no_side_effects]]` and `[[no_visible_side_effects]]`, and new contract syntax for specifying lack of side effects

Our current expected model for any iostreams v2 is that constexpr code will use Reflection to examine types and statically generate sequences of scatter-gather and memory translation buffer operations which will serialise and deserialise objects of that type.

It is highly important for the future efficiency of this that the low level i/o functions do not cause the compiler to dump and reload all state around every i/o, as they must do at present, because a potential kernel syscall could affect program state in unknown-to-the-compiler ways. The compiler must therefore be conservative, and generate highly suboptimal code.

The read i/o functions proposed do not modify their handle on most platforms, and on those platforms we can guarantee to the compiler that there are either no side effects or no visible side effects except for those objects modified by parameters.

Reusing [P0593] `bless()`, I propose the following contracts syntax for the read `io_handle` function so we can tell the compiler what side effects i/o read has:

```
constexpr! void ensure_blessed(buffers_type buffers)
{
  for(auto &buffer : buffers)
  {
    bless(buffer.data(), buffer.size());
  }
}

// This function has no side effects visible to the caller except
// for the objects it creates in the scatter buffer list.
virtual buffers_type io_handle::read(io_request<buffers_type> reqs,
                                     deadline d = deadline()) throws(file_io_error)
    [[no_side_effects]]                          // no side effects at all, so can elide
    [[ensures: ensure_blessed(reqs.buffers)]]    // except the input buffers are modified
    [[ensures: ensure_blessed(return)]];         // except the output buffers are modified
```

The key thing to note here is if the caller never accesses any of the scatter buffers returned by the function, the read can be optimised out entirely due to the `[[no_side_effects]]` attribute. Obviously the compiler also does not dump and reload any state around this scatter read apart from buffers supplied and returned, despite it calling a kernel system call, because we are giving a hard guarantee to the compiler that it is safe to assume no side effects apart from modifying the scatter buffers.

Gather write is a bit more interesting. The maximum extent, or metadata such as last accessed timestamp, of the file may change. Maps of the file's data may also change. Moreover, other open handles to hard links to the same inode may also see changes as a result of a write. This presents a quandry.

One extreme approach is to say that gather writes have no visible side effects to the calling function e.g.

```
virtual const_buffers_type io_handle::write(io_request<const_buffers_type> reqs,
                                            deadline d = deadline())
                            throws(file_io_error)
    [[no_visible_side_effects]];  // cannot elide, but don't dump and reload state
```

Here we are telling the compiler that there are side effects, just not ones visible to the caller. Hence the compiler cannot optimise out calling this function, but it can skip dumping and reloading state despite the kernel system call made by the function.

This is probably too extreme though – iostreams v2 code may make use of fetching the maximum extent property, and the above would mean that the compiler would optimise out a second or third fetch of the maximum extent given that it has been told that there are no visible side effects. So let's try again, saying that the i/o handle instance will be changed:

```
virtual const_buffers_type io_handle::write(io_request<const_buffers_type> reqs,
                                            deadline d = deadline())
                            throws(file_io_error)
    [[no_visible_side_effects]]  // cannot elide, but don't dump and reload state
    [[ensures: *this]];          // except for anything to do with this object instance
```

We might also consider this too extreme. After all, a common use case in low level file i/o is where we have two open handles to the same file: one maps the file into read-only memory, the other performs atomic appends. If the program reads from the read-only map around the current maximum extent, then performs an atomic append, and then reads the same region again, the second read would be optimised out which would wreck the algorithm. So let's try a third time:

```
// Dump and reload state for this function
virtual const_buffers_type io_handle::write(io_request<const_buffers_type> reqs,
                                            deadline d = deadline())
                            throws(file_io_error);

// Example use case
T &value;            // some type being serialised
io_handle &h;        // some i/o handle
extent_type offset;  // some file offset to serialise into

// Any iostreams v2 would statically assemble at constexpr time a sequence
// of serialisation actions for some given type T. The two most basic actions
// would be call some user callable, or write a sequence of gather buffers.
//
// We need to prevent the compiler reloading these every single time we write a buffer.
static constexpr serialisation_actions value_serialisation[] = { ... };

// Perform the serialisation
for(const auto &o : value_serialisation)
```

```
{
  if(o.do_processing)
  {
    o.processing(offset, h, value);  // call some statically instantiated processing function
  }
  else if(o.do_write)
  {
    // Write a sequence of gather buffers
    buffers_type written = h.write({o.write_buffers, offset});
    // Tell the compiler what we have definitely not changed, and so don't reload
    do_not_reload(value, offset, value_serialisation, o, /* NOTE! */ h);
    offset += written.bytes_transferred();
  }
}
// Tell the compiler that h may have changed, so please reload it
bless(h);
```

So here we have a hypothetical `do_not_reload(...)` function which tells the compiler to assume that each of the variables and memory regions passed into it does not require reloading. Note the inclusion of `h` at the end, this means that later code would optimise out any second calls to member functions which could introduce unexpected behaviour. We thus tell the compiler that `h` contains new objects by blessing it, this ought to force the compiler to reload anything relating to `h`.

None of the above is proposed in this paper as that work is to be pushed into the aforementioned paper proposing changes to the C++ memory and object model destined for SG12 some time next year. I left in the detail above so you can see where I intend to head next when proposing those changes.

3.2.1 I/O write reordering barriers

C and C++ allow the programmer to specify constraints on memory read and write operations, specifically to constrain the apparent extent of reordering that the compiler and CPU are permitted to do. One can use atomics with a memory order specified, or one can call a fence function which applies a memory reordering constraint for the current thread of execution either at just the compiler level, or also at the CPU level whereby the CPU is told what ordering its symmetric multiprocessing cores needs to manifest in visible side effects.

File i/o is no different: concurrent users of the same file or directory or file system will experience races unless they take special measures to coordinate amongst themselves.

It might seem self evident that one would also need to propose a standardised mechanism for indicating reordering constraints on i/o, which are separate to those for threads. My current advice is that we should **not** do this – yet.

The first reason why is that persistent memory is just around the corner, and I think it would be unwise to standardise without the industry gaining plenty of empirical experience first. So kick that decision down a few standard releases.

Secondly, the proposed library herein does expose whatever acquire-release semantics is implemented by the host operating system for file i/o, plus the advisory locking infrastructure implemented by the

host, plus the ability to enable write-through caching semantics. It also provides `barrier()`, which is semantically equivalent to `std::atomic_thread_fence(std::memory_order_seq_cst)`, though one should not write code which relies upon it working, as it frequently – and silently – does not work.

Note that if the file is opened in non-volatile RAM storage mode, `barrier()` calls the appropriate architecture-specific assembler instructions to correctly flush CPU writes to main memory, so in this sense there is library, if not language, support for persistent memory. The obvious sticker is that `barrier()` is a virtual function with significant preamble and epilogue, so for flushing a single cache line it is extremely inefficient relative to direct language support for i/o reordering constraints.

Nevertheless, one can write standards conforming code with the proposed library which performs better on persistent memory than on traditional storage, and my advice is that this is good enough for the next few years.

3.3 Non-adopted WG21 proposal dependencies

The proposed low level file i/o library has hard dependencies on the following proposal papers not yet adopted into the C++ standard:

1. P0122 *span: bounds-safe views for sequences of objects* https://wg21.link/P0122.
2. 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]. The draft Technical Specification wording below assumes P0709 is available.
3. P0734 *Concepts* https://wg21.link/P0734.
4. 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. A subset of the proposed low level file i/o library would be available in a freestanding system, specifically `embedded_file_handle` et al which let you create a read-only file system statically linked into the firmware binary.
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]. This low level file i/o library in turn uses custom error code domains extending that `std::error` with relevant path and handle information, into a `file_io_error` object which you will see used frequently throughout this paper.
6. 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 P1028's standard error object to gain the ability to transport `std::exception_ptr` instances directly, a highly desirable feature for improving efficiency of legacy C++ exceptions support under P0709.

Most of the types consumed and returned in the APIs of this *Low level file i/o* proposal have standard layout, are trivially copyable, or are move relocating. Whilst not essential for this proposal, move relocation (or any equivalent alternative) would significantly help quality of codegen.

7. 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. This library uses `path_view` almost universally throughout.

8. P1095/N2289 *Zero overhead deterministic failure – A unified mechanism for C and C++* https://wg21.link/P1095.

   This proposes a specific mechanism for implementing P0709, one based on P1028. Whilst not mandatory for this proposal, our reference implementation library is written around that same specific mechanism.

4 Proposed Design

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

4.1 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 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. This is done for performance, as asking the kernel about handle rights is expensive. 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 `clone()` member function which will duplicate the handle. The reason that the C++ copy constructor is disabled is because duplicating handles with the kernel 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[6]. 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[7].

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 related resources[8] 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.

[6] 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.

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

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

- 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.
- 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_first_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 very recent editions of Microsoft Windows 10, there is a special kernel call to delete a file with POSIX semantics i.e. its entry is removed from the directory immediately.

    For older editions of Windows, POSIX unlink semantics are emulated by renaming on unlink the file entry to something very random such that it cannot be found[9]. Setting

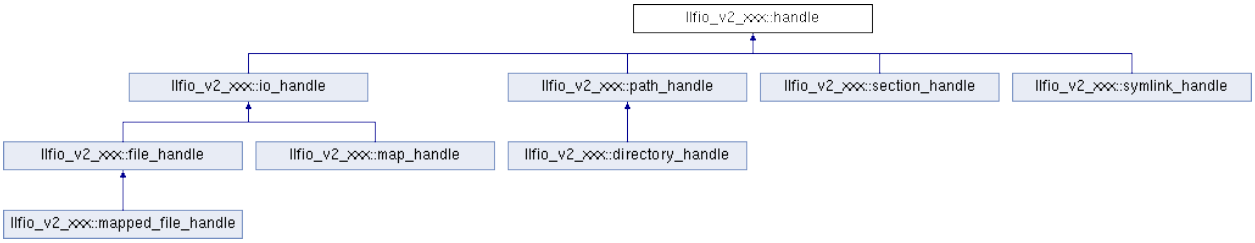
[9] Due to VMS legacy compatibility, NT implements file deletion by marking a file entry as deleted which prevents it being opened for access thenceforth. It does not remove the file entry until some arbitrary time (usually milliseconds)

this flag disables this emulation.

– `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`



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.

  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.

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'.

[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.~~

> [*Note:* Asynchronous file i/o was removed in R1 of this proposal after feedback from the Rapperswil meeting. – end note]

* `embedded_file_handle`

  The embedded file handle refers to data held in static constant duration storage in the program. It is read-only, but provides an option for it to be opened read-write, whereupon it ignores all writes to the handle instead of failing.

* `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.

* `random_file_handle`

  The random file handle synthesises read-only file data by hashing a random or user-supplied nonce with the offset requested in the i/o. This creates the appearance of a file full of random data. It is read-only, but provides an option for it to be opened read-write, whereupon it ignores all writes to the handle instead of failing.

  This handle has a special configuration option whereby scatter reads may randomly return random data buffers instead of data from a supplied source i/o handle. This has a myriad of use cases, including testing the handling of random data corruption, or whether a piece of generic i/o handle using code correctly handles alternation in returned buffers between filled buffers or direct buffers.

- `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.

  Map handle can map small, large, huge, massive and super pages to the same extent as the host operating system kernel.

  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 read 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.
- `nvram`: Assume that this section represents non-volatile memory, and use i/o semantics appropriate for that type of memory. Setting this flag provides much superior performance on persistent memory based hardware, plus it activates various kernel options where appropriate to provide sudden power loss safety on persistent memory.
- `page_sizes_1`: Use `utils::page_sizes()[1]` sized pages, or fail.
- `page_sizes_2`: Use `utils::page_sizes()[2]` sized pages, or fail.
- `page_sizes_3`: Use `utils::page_sizes()[3]` sized pages, or fail.
- `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.

- `directory_entry`

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

- `page_sizes()`

  A function returning const lvalue ref to a `vector<size_t>` representing the page sizes currently available to the calling process on this machine.

- `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.

  One has the ability to stamp an open handle with parts of a `stat_t`, as well as fill parts of a `stat_t` from an open handle.

- `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 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.

- 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.

  It is common on Linux to silently ignore barriers for code running inside virtual machines on publicly shared hypervisors, especially LXC containers as they are a source of denial of service attack. Filing systems on Linux may also be mounted with hardware barriers disabled, in this situation the storage device is not required to observe the ordering of writes issued to it by the kernel.

- Microsoft Windows

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

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.

Filing systems on Windows may be mounted with hardware barriers disabled, in this situation the storage device is not required to observe the ordering of writes issued to it by the kernel.

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 (see standardese for `write()` below).

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

– `shared_fs_mutex::safe_byte_ranges`

[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.

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].

- `map_view<T>`

  A map view is a non-owning `span<T>` of a `map_handle`'s region. It implies a `std::bless<T>` of the `map_handle`'s `byte` mapped memory.

- `mapped<T>`

  A mapped is an owning `span<T>` of a `map_handle`'s region. It implies a `std::bless<T>` of the `map_handle`'s `byte` mapped memory, and when destructed it destroys the internal `map_handle`, thus removing the map.

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).

[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.

- 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.

4.3 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:

[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.

```
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

> [*Note:* Asynchronous file i/o support was removed after feedback from Rapperswil, and thus this section no longer applies. It will be removed in the next revision. – end note]

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

> [*Note:* Asynchronous file i/o support was removed after feedback from Rapperswil, and thus this section no longer applies. It will be removed in the next revision. – end note]

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 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.

[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.

6 Draft Technical Specification

A highly incomplete, work in progress, draft TS wording follows for *Low level file i/o*. The following in-progress WG21 papers – or near equivalents thereof – are assumed to have been standardised in the presented wording:

1. [P0709] *Zero-overhead deterministic exceptions: Throwing values*
2. [P1028] *SG14 status_code and standard error object for P0709 Zero-overhead deterministic exceptions*
3. [P1029] *SG14 [[move_relocates]]*
4. [P1030] *Filesystem path views*
5. [P1095] *Zero overhead deterministic failure – A unified mechanism for C and C++*

We also assume the presence of a new language feature, `bitfield`. This is the combination of an enumeration with individual bits in an unsigned integral value.

6.1 Scope [llfio.scope]

This Technical Specification specifies requirements for implementations of an interface that computer programs written in the C++ programming language may use to perform operations on file systems and their components, such as paths, regular files, and directories. This Technical Specification is applicable to information technology systems that can access hierarchical file systems, such as those with operating systems that conform to the POSIX ([llfio.norm.ref]) interface. This Technical Specification is applicable only to vendors who wish to provide the interface it describes.

6.2 Conformance [llfio.conformance]

Conformance is specified in terms of behavior. Ideal behavior is not always implementable, so the conformance sub-clauses take that into account.

6.2.1 POSIX conformance [llfio.conformance.posix]

Some behavior is specified by reference to POSIX ([llfio.norm.ref]). How such behavior is actually implemented is unspecified.

> [*Note:* This constitutes an 'as if' rule allowing implementations to call native operating system or other API's. – end note]

Implementations are encouraged to provide such behavior as it is defined by POSIX. Implementations shall document any behavior that differs from the behavior defined by POSIX. Implementations that do not support exact POSIX behavior are encouraged to provide behavior as close to POSIX behavior as is reasonable given the limitations of the operating systems and file systems available to the vendor. If an implementation cannot provide any reasonable behavior for more than a small

subset of this specification, an implementation of this library ought to not be provided by the vendor.

6.2.2 Operating system dependent behavior conformance [llfio.conform.os]

Some behavior is specified as being operating system dependent ([llfio.def.osdep]). The operating system an implementation is dependent upon is implementation defined. It is permissible for an implementation to be dependent upon an operating system emulator rather than the actual underlying operating system.

6.3 References [llfio.references]

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

- ISO/IEC 14882, *Programming Language C++*
- ISO/IEC 9945, *Information Technology – Portable Operating System Interface (POSIX)*

  [*Note:* The programming language and library described in ISO/IEC 14882 is herein called the C+ + Standard. The operating system interface described in ISO/IEC 9945 is herein called POSIX. – end note]

This Technical Specification mentions commercially available operating systems for purposes of exposition.[16]

Unless otherwise specified, the whole of the C++ Standard's Library introduction [lib.library] is included into this Technical Specification by reference.

6.4 Terms and definitions [llfio.terms]

For the purposes of this document, the terms and definitions given in the C++ Standard and the following apply.

6.4.1 Cold cache [llfio.terms.cold_cache]

This refers to the situation where any of the contents and/or metadata relating to a filesystem entity have not been cached into kernel memory, and an operation relating to that entity would require the kernel to communicate with the storage device (which may take a non-deterministic period of time).

[16] POSIX® is a registered trademark of the IEEE. Mac OS® is a registered trademark of Apple Inc. Windows® is a registered trademark of Microsoft Corporation. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO or IEC of these products.

6.4.2 File extents [llfio.terms.extents]

A file's ([fs.def.file]) contents are stored as a sequence of zero to many *allocated extents* (some older filing systems can only use zero or one allocated extent). An allocated extent is a region bound in between offset zero and the maximum extent property of the file (often incorrectly called 'file length') which may store non-zero bits. The regions between allocated extents are not stored on the device, and appear to i/o as all bits zero.

6.4.3 Filesystem entity [llfio.terms.entity]

This refers to any single collection of extents on the filesystem which has a POSIX file serial number, and an entity includes any metadata specifically describing it held by other entities. This includes files ([fs.def.file]) and directories ([fs.def.directory]). Note that entities may have zero, or many, canonical paths ([fs.def.link]) on the filesystem.

6.4.4 File serial number [llfio.terms.inode]

The POSIX file serial number is an unsigned integer type identifying an item of storage on a filesystem. It is defined by POSIX to be unique to the specific filesystem it is within (but not unique within the whole system). A colloquial term for it is 'inode'.

6.4.5 Kernel page cache [llfio.terms.page_cache]

Operating system kernels may cache the data read from, and written to, a filesystem entity. This may be a single coherent unified cache, or multiple incoherent caches. Metadata may be cached while extents are not cached. The reference to 'page' is that these caches typically work in granularities of a memory page, so if extents are cached, it is to the nearest memory page alignment and the cached region will be some round multiple of the memory page.

On unified page cache architecture kernels, mapping a file into memory directly maps a portion of the kernel's own page cache for that file's extents into the process. When a C++ program reads or writes a mapped file, it directly works with the kernel's cache of that file.

6.4.6 Mapped files [llfio.terms.mapped_files]

POSIX provides facilities to map the contents of some or all of a file's extents into the address space of a C++ program. Reads from the region read the data in the file; writes to the region modify the data in the file.

6.4.7 Memory page [llfio.terms.memory_page]

Many CPUs will map physical memory to the virtual addresses seen by the C++ program in units of a memory page. A CPU may support zero, or many different sizes of memory page.

[*Note:* For information, the memory page sizes for a x64 processor are 4Kb, 2Mb and 1Gb, with a potential additional future memory page size of 512Gb. For an ARM Cortex A9 CPU, the memory page sizes are 4Kb, 64Kb, 1Mb and 16Mb. Other ARM CPUs vary. For RISC-V, 4Kb + 4Mb or 4Kb + 2Mb + 16Gb memory page sizes are the most common. – end note]

6.4.8 Page fault [llfio.terms.page_fault]

Virtual memory systems implement work-on-demand via *page faulting*. Each memory page in a C++ process can be marked by an operating system kernel to call the kernel upon the first read, or write, inside a memory page. The kernel may then perform a number of actions. A very common action to handle a page fault is allocating memory for that page and making the new allocation available at that address, before resuming execution. Another very common action is that for writable memory maps, to mark a page as dirty and needing later flushing to physical storage.

Page faults significantly complicate the estimation of upper bounds of execution times by introducing a stochastic factor. In some cases, regions of memory can be *prefaulted* in order to eliminate the potential for unexpected page faults later on.

6.4.9 Storage device [llfio.terms.storage]

This is the hardware which retains the state of the filesystem across power loss events. It may, on some systems, be the same as random access memory.

6.4.10 File unique id [llfio.terms.unique_id]

Under POSIX, each file has an unsigned unique identification number which is guaranteed to be unique anywhere on the currently running system. POSIX defines it to be a combination of the device id, and the file serial number.

6.4.11 Virtual memory [llfio.terms.virtual_memory]

This is the simulation of there being far more memory available to a C++ program than there is in reality. It typically works in granularities of a memory page, and POSIX provides quite a few control functions to enable C++ programs to manipulate virtual memory directly. Portable wrappers of many of these control functions are provided by this specification.

6.4.12 Warm cache [llfio.terms.warm_cache]

This refers to the situation where **all** of the contents and metadata relating to a filesystem entity have been cached into kernel memory, and no further read operations relating to that entity would be performed to the storage device. In this situation, any non-modifying operation ought to have bounded execution times, as described in [llfio.principles.latency_preserving].

6.5 General principles [llfio.principles]

This is a low level library intended mainly as a building block for higher level C++ standard library constructs such as Ranges, Containers, and Serialisation. It can be used directly by C++ programs, but at the cost of having to do more work by hand than if the program used the higher level construct instead.

6.5.1 Thinly wrap system calls [llfio.principles.latency_preserving]

This specification is designed to wrap proprietary kernel system calls into a set of *common C++ functions* which are portable across those platforms upon which C++ is implemented. User space overhead between calling the functions in this specification, and calling the kernel system calls directly, shall be statistically unmeasurable in real world use cases, except where documented otherwise.

Specifically:

1. The user space overhead to handle a kernel system call failure shall also be statistically unmeasurable in real world use cases.
2. The functions in this specification shall be *latency preserving*, unless documented to not be so. Latency preservation means that the shape of the sorted distribution of execution latencies for repeated calls of the underlying kernel system call shall be preserved very closely by the functions in this specification. A constant vertical shift upwards to reflect constant time processing etc is, however, permitted.

   Where a function is documented to be latency degrading, the potential causes of this latency degradation shall be documented by this specification.

The most noticeable consequence of this principle is that we do not allocate memory, except where documented. Where memory is required for an operation, we accept buffers supplied by the user instead.

6.5.2 Zero memory copies [llfio.principles.zero_copy]

This specification avoids causing the copying of any form memory wherever possible, even where it is inconvenient to the library user. We do not copy filesystem paths, scatter-gather buffer lists, nor data input/output, except where absolutely unavoidable.

6.5.3 Idealised random access storage [llfio.principles.idealised]

This specification models an idealised random access storage device, one whose curve of sorted distribution of read latencies exactly matches that of the computer's random access memory. The only difference over reads from random access memory is a constant added vertical shift.

> [*Note:* It is important to note that writes are not considered in this idealisation. They have an implicit memory allocation, and thus are not easily predictable. – end note]

Empirically, reads from a warm cached file (i.e. whose contents and metadata are entirely in the kernel page cache) ought to very closely match the curve of those of the idealised random access storage device. This makes this idealisation useful to this specification. In some implementations e.g. those using persistent memory, the storage device *is* your random access memory, and thus by definition the two are quite literally the same thing.

It is therefore important to note in the specification wording below that for reads, it is from the idealised storage device that is specified. If the entity being read is not fully warm cached, the wording (or lack thereof) giving latency guarantees does not apply.

> [*Note:* It is unknowable whether a specific read from a file just immediately read from will be warm cached. For example, in a high memory pressure situation, the data just read and cached may be evicted by the time the second read occurs, or a concurrent update may have invalidated the cached region. – end note]

6.5.4 Genericity in i/o [llfio.principles.io_genericity]

For each of the i/o types, a `buffer_type`, `buffers_type` and `io_request<buffers_type>` is defined as a member type or type alias. Each of the i/o type's `read()` functions will consume an `io_request<buffers_type>`, and return a `buffers_type` (for `write()`, the corollary is `io_request<const_buffers_` and return a `const_buffers_type`).

This design principle is held consistent throughout. Intuitively, a file handle will have a buffer type of `span<byte>`, a buffers type of `span<buffer_type>`, and an `io_request<buffers_type>` type which takes the desired offset to do the i/o at. A directory handle will have a buffer type of `path_view`, a buffers type of `span<buffer_type>` and an `io_request<buffers_type>` type which supplies the directory enumeration options desired e.g. wildcards. A symlink handle will have a buffer type of `path_view`, a buffers type of `path_view` and an `io_request<buffers_type>` type which is nothing more than a `path_view`, as after all a symbolic link can represent exactly one path.

This uniformity of design eases cognitive load on the programmer, and may aid generic code to work with arbitrary i/o capable types, even very different ones.

6.5.5 Race free filesystem [llfio.principles.race_free]

POSIX.1.2008 standardised a suite of kernel system calls which permit use of the filesystem without risk of race conditions caused by concurrent third party modification of paths. At the time of writing, these *race free filesystem* extensions are very widely implemented in the major operating systems, and given their considerable benefit to writing secure code, we standardise these facilities into C++.

This specification discourages the use of absolute filesystem paths, as these are inherently racy. All manipulation operations such as rename or unlink are performed on an open `handle` instance. If this specification is accepted into the standard, is strongly recommended that all functions for accessing the file system in [fs.op] which take an absolute path ought to be deprecated, and their further use discouraged by complete removal in the following standard.

This specification reimplements directory enumeration via `directory_handle::read()` using a mechanism very different to [fs.class.directory_iterator], specifically one without the many correctness and performance problems which have been reported by users on Stack Overflow and other such forums. It is recommended that `filesystem::directory_entry` and `filesystem::directory_iterator` et al be rewritten to use this specification's facilities instead as a backwards compatibility measure, and that new code ought to use this specification instead.

6.6 Header `<io/algorithm/cached_parent_handle_adapter>` [llfio.io.algorithm.cached_parent_handle_adapter]

Todo

6.7 Header `<io/algorithm/shared_fs_mutex>` [llfio.io.algorithm.shared_fs_mutex]

Todo

6.8 Header `<io/deadline>` [llfio.io.deadline]

6.8.1 Synopsis [llfio.io.deadline.synopsis]

```
namespace std { namespace experimental { namespace io { inline namespace v1 {
struct deadline
{
  constexpr deadline() noexcept;
  constexpr explicit operator bool() const noexcept;
  template <class Clock, class Duration>
  constexpr deadline(chrono::time_point<Clock, Duration> tp) noexcept;
  template <class Rep, class Period>
  constexpr deadline(chrono::duration<Rep, Period> d) noexcept;
};
} } } }
```

6.8.2 Class `deadline` [io.deadline.deadline]

A time deadline in either relative-to-now or absolute (system clock) terms. ABI stable, unlike the templated `chrono::duration<>` or `chrono::time_point<>`.

Remarks: The type `deadline` must meet the `TriviallyCopyable` and `StandardLayout` concepts. The internal storage must be of at least nanosecond resolution, but also able to store the full range of dates that `time_t` can store[17].

[17] A union of a `struct timespec` (absolute) and a 64-bit nanosecond count (relative) is suggested, but not required.

6.8.2.1 Class `deadline` constructors [llfio.io.deadline.deadline.constructors]

```
constexpr deadline() noexcept;
```

Effects: Constructs an invalid `deadline`.

Ensures: `!*this`

```
template <class Clock, class Duration>
constexpr deadline(chrono::time_point<Clock, Duration> tp) noexcept;
```

Effects: Implicitly constructs either an absolute (`Clock::is_steady == false`) or duration-from-now (`Clock::is_steady == true`) deadline.

Ensures: `*this`

```
template <class Rep, class Period>
constexpr deadline(chrono::duration<Rep, Period> d);
```

Effects: Implicitly constructs a duration-from-now deadline.

Ensures: `*this`

6.9 Header `<io/directory_handle>` [llfio.io.directory_handle]

Todo

6.10 Header `<io/embedded_file_handle>` [llfio.io.embedded_file_handle]

Todo

6.11 Header `<io/embedded_file_source>` [llfio.io.embedded_file_source]

Todo

6.12 Header `<io/file_handle>` [llfio.io.file_handle]

Todo

6.13 Header `<io/handle>` [llfio.io.handle]

6.13.1 Synopsis [llfio.io.handle.synopsis]

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

class handle
{
public:
  //! The path type used by this handle
  using path_type = filesystem::path;
  //! The file extent type used by this handle
  using extent_type = unsigned long long;
  //! The memory extent type used by this handle
  using size_type = size_t;

  //! The behaviour of the handle: does it read, read and write, or atomic append?
  enum class mode : unsigned char  // bit 0 set means writable
  {
    unchanged = 0,
    none = 2,         //!< No ability to read or write anything, but can synchronise (SYNCHRONIZE or 0)
    attr_read = 4,    //!< Ability to read attributes (FILE_READ_ATTRIBUTES|SYNCHRONIZE or O_RDONLY)
    attr_write = 5,   //!< Ability to read and write attributes
                      //!< (FILE_READ_ATTRIBUTES|FILE_WRITE_ATTRIBUTES|SYNCHRONIZE or O_RDONLY)
    read = 6,         //!< Ability to read
                      //!< (READ_CONTROL|FILE_READ_DATA|FILE_READ_ATTRIBUTES|FILE_READ_EA|SYNCHRONISE
                          or O_RDONLY)
    write = 7,        //!< Ability to read and write
                      //!< (READ_CONTROL|FILE_READ_DATA|FILE_READ_ATTRIBUTES|FILE_READ_EA|
                          FILE_WRITE_DATA|FILE_WRITE_ATTRIBUTES|FILE_WRITE_EA|FILE_APPEND_DATA|
                          SYNCHRONISE or O_RDWR)
    append = 9        //!< All mainstream OSs and CIFS guarantee this is atomic with respect to all
                      //!< other appenders (FILE_APPEND_DATA|SYNCHRONISE or O_APPEND)
  };

  //! On opening, do we also create a new file or truncate an existing one?
  enum class creation : unsigned char
  {
    open_existing = 0,  //!< Open an existing file.
    only_if_not_exist,  //!< Create a new file only if one does not exist.
    if_needed,          //!< Create a new file if one does not exist.
    truncate            //!< Atomically truncate on open, leaving creation date unmodified.
  };

  //! What i/o on the handle will complete immediately due to kernel caching
  enum class caching : unsigned char  // bit 0 set means safety fsyncs enabled
  {
    unchanged = 0,
    none = 1,               //!< No caching whatsoever, all reads and writes come from storage
                            //!< (i.e. 'O_DIRECT|O_SYNC'). Align all i/o to 4Kb boundaries for this
                                to work. 'flag_disable_safety_fsyncs' can be used here.
    only_metadata = 2,      //!< Cache reads and writes of metadata but avoid caching data
                            //!< ('O_DIRECT'), thus i/o here does not affect other cached data for
                                other handles. Align all i/o to 4Kb boundaries for this to work.
    reads = 3,              //!< Cache reads only. Writes of data and metadata do not complete
                            //!< until reaching storage ('O_SYNC'). 'flag_disable_safety_fsyncs' can
                                be used here.
    reads_and_metadata = 5, //!< Cache reads and writes of metadata, but writes of data do not
```

```
                              //!< complete until reaching storage (‘O_DSYNC‘). ‘
                                   flag_disable_safety_fsyncs‘ can be used here.
    all = 4,                  //!< Cache reads and writes of data and metadata so they complete
                              //!< immediately, sending writes to storage at some point when the kernel
                                   decides (this is the default file system caching on a system).
    safety_fsyncs = 7,        //!< Cache reads and writes of data and metadata so they complete
                              //!< immediately, but issue safety fsyncs at certain points. See
                                   documentation for ‘flag_disable_safety_fsyncs‘.
    temporary = 6             //!< Cache reads and writes of data and metadata so they complete
                              //!< immediately, only sending any updates to storage on last handle
                                   close in the system or if memory becomes tight as this file is
                                   expected to be temporary (Windows and FreeBSD only).
  };

  //! Bitwise flags which can be specified
  bitfield flag
  {
    none = 0,  //!< No flags

    /*! Unlinks the file on handle close. On POSIX, this simply unlinks whatever is pointed
    to by ‘path()‘ upon the call of ‘close()‘ if and only if the inode matches. On Windows,
    if you are on Windows 10 1709 or later, exactly the same thing occurs. If on previous
    editions of Windows, the file entry does not disappears but becomes unavailable for
    anyone else to open with an ‘errc::resource_unavailable_try_again‘ error return. Because
    this is confusing, unless the ‘win_disable_unlink_emulation‘ flag is also specified, this
    POSIX behaviour is somewhat emulated on older Windows by renaming the file to a random
    name on ‘close()‘ causing it to appear to have been unlinked immediately.
    */
    unlink_on_first_close = 1U << 0U,

    /*! Some kernel caching modes have unhelpfully inconsistent behaviours
    in getting your data onto storage, so by default unless this flag is
    specified we add extra fsyncs to the following operations for the
    caching modes specified below:
        - truncation of file length either explicitly or during file open.
        - closing of the handle either explicitly or in the destructor.

    Additionally on Linux only to prevent loss of file metadata:
        - On the parent directory whenever a file might have been created.
        - On the parent directory on file close.

    This only occurs for these kernel caching modes:
        - caching::none
        - caching::reads
        - caching::reads_and_metadata
        - caching::safety_fsyncs
    */
    disable_safety_fsyncs = 1U << 2U,

    /*! ‘file_handle::unlink()‘ could accidentally delete the wrong file if someone has
    renamed the open file handle since the time it was opened. To prevent this occuring,
    where the OS doesn’t provide race free unlink-by-open-handle, we compare the inode of
    the path we are about to unlink with that of the open handle before unlinking.
    Setting this flag disables that safety check.
    */
    disable_safety_unlinks = 1U << 3U,
```

```
100
101     /*! Ask the OS to disable prefetching of data. This can improve random
102     i/o performance.
103     */
104     disable_prefetching = 1U << 4U,
105
106     /*! Ask the OS to maximise prefetching of data, possibly prefetching the entire file
107     into kernel cache. This can improve sequential i/o performance.
108     */
109     maximum_prefetching = 1U << 5U,
110
111     win_disable_unlink_emulation = 1U << 24U,  //!< See the documentation for ‘unlink_on_first_close‘
112
113     /*! Microsoft Windows NTFS, having been created in the late 1980s, did not originally
114     implement extents-based storage and thus could only represent sparse files via
115     efficient compression of intermediate zeros. With NTFS v3.0 (Microsoft Windows 2000),
116     a proper extents-based on-storage representation was added, thus allowing only 64Kb
117     extent chunks written to be stored irrespective of whatever the maximum file extent
118     was set to.
119
120     For various historical reasons, extents-based storage is disabled by default in newly
121     created files on NTFS, unlike in almost every other major filing system. You have to
122     explicitly "opt in" to extents-based storage.
123
124     As extents-based storage is nearly cost free on NTFS, llfio by default opts in to
125     extents-based storage for any empty file it creates. If you don’t want this, you
126     can specify this flag to prevent that happening.
127     */
128     win_disable_sparse_file_creation = 1U << 25U,
129
130     overlapped = 1U << 28U,          //!< On Windows, create any new handles with OVERLAPPED semantics
131     byte_lock_insanity = 1U << 29U,  //!< Using insane POSIX byte range locks
132     anonymous_inode = 1U << 30U      //!< This is an inode created with no representation on the
            filing system
133   }
134
135 public:
136   //! Constructs an invalid instance
137   constexpr handle() noexcept;
138
139   //! Adopts a supplied native handle type
140   explicit constexpr handle(native_handle_type h, caching caching = caching::none, flag flags = flag::
          none) noexcept;
141
142   //! Closes the handles if it is valid
143   virtual ~handle() noexcept;
144
145   // Copy construction is expensive, use clone()
146   handle(const handle &) = delete;
147   handle &operator=(const handle &o) = delete;
148
149   // Moves of handle relocate in memory
150   constexpr handle(handle &&o) noexcept [[move_relocates];
151   handle &operator=(handle &&o) noexcept;
152   void swap(handle &o) noexcept;
153
```

```
  //! Retrieve the current path of the open handle
  virtual path_type current_path() const throws(file_io_error) [[no_side_effects]];

  //! Close the handle
  virtual void close() throws(file_io_error);
  //! Clone the handle
  handle clone() const throws(file_io_error);
  //! Release the native handle type from management
  virtual native_handle_type release() noexcept;

  //! True if the handle is valid (and usually open)
  bool is_valid() const noexcept;
  //! True if the handle is readable
  bool is_readable() const noexcept;
  //! True if the handle is writable
  bool is_writable() const noexcept;
  //! True if the handle is append only
  bool is_append_only() const noexcept;
  //! Changes whether this handle is append only or not.
  virtual void set_append_only(bool enable) throws(file_io_error);

  //! True if overlapped
  bool is_overlapped() const noexcept;
  //! True if seekable
  bool is_seekable() const noexcept;
  //! True if requires aligned i/o
  bool requires_aligned_io() const noexcept;

  //! True if a regular file or device
  bool is_regular() const noexcept;
  //! True if a directory
  bool is_directory() const noexcept;
  //! True if a symlink
  bool is_symlink() const noexcept;
  //! True if a memory section
  bool is_section() const noexcept;

  //! Kernel cache strategy used by this handle
  caching kernel_caching() const noexcept;
  //! True if the handle uses the kernel page cache for reads
  bool are_reads_from_cache() const noexcept;
  //! True if writes are safely on storage on completion
  bool are_writes_durable() const noexcept;
  //! True if issuing safety fsyncs is on
  bool are_safety_fsyncs_issued() const noexcept;

  //! The flags this handle was opened with
  flag flags() const noexcept;
  //! The native handle used by this handle
  native_handle_type native_handle() const noexcept;
};
inline std::ostream &operator<<(std::ostream &s, const handle &v);
inline std::ostream &operator<<(std::ostream &s, const handle::mode &v);
inline std::ostream &operator<<(std::ostream &s, const handle::creation &v);
inline std::ostream &operator<<(std::ostream &s, const handle::caching &v);
inline std::ostream &operator<<(std::ostream &s, const handle::flag &v);
```

```
} } } }
```

6.13.2 Class `handle` [llfio.io.handle.handle]

An `io::native_handle_type` instance, whose lifetime is managed by the lifetime of this object.

Remarks: The type `handle` must meet the `MoveRelocating` concept.

6.13.2.1 Class `handle` constructors and destructor [llfio.io.handle.handle.constructors]

```
constexpr handle() noexcept;
```

Effects: Constructs an invalid `handle`.

Ensures: `!is_valid()`

```
explicit constexpr handle(native_handle_type h, caching caching = caching::none, flag flags = fla
```

Effects: Adopt a `native_handle_type` instance.

Ensures: `is_valid()`

```
constexpr handle(handle &&o) noexcept;
```

Effects: Moves the management of the `native_handle_type` out of `o` and into `*this`.

Ensures: `!o.is_valid()`

```
virtual ~handle() noexcept;
```

Effects: If this handle is valid, call `close()`. If `close()` fails, terminate the process.

Ensures: `!is_valid()`, and that the system resources managed by the handle are released.

6.13.2.2 Class `handle` assignment and swap [llfio.io.handle.handle.assignments]

```
handle &operator=(handle &&o) noexcept;
```

Effects: If this handle is valid, call `close()`. If `close()` fails, terminate the process. Then move the management of the `native_handle_type` out of `o` and into `*this`.

Ensures: `!o.is_valid()`, and that the system resources formerly managed by the handle are released.

```
void swap(handle &o) noexcept;
```

Effects: Exchange the management of the two `native_handle_type` between `o` and `*this`.

6.13.2.3 Class `handle` observers [llfio.io.handle.handle.observers]

```
virtual path_type current_path() const throws(file_io_error) [[no_side_effects]];
```

Effects: Returns the current path of the hard link originally opened by this handle, as is said by the operating system. If the hard link originally opened by this handle has been unlinked, an empty path is returned. If somebody with an open handle to the same hard link which has been unlinked then relinks it, the new path is returned.

Remarks: The path returned may be very different to the path by which the handle was originally opened (e.g. due to a third party renaming it, or due to canonicalisation of a symbolically linked input path), but it must be to the original hard link opened, and not to some arbitrary path which links to the same inode. This implies that either the kernel, or the standard library implementation, must implement *hard link tracking* by keeping with each kernel file descriptor which hard link it was opened with. At the time of writing, the Linux and Microsoft Windows kernels fully implement this; FreeBSD has a partial implementation; Apple MacOS does not implement this. It is permitted on kernels without complete kernel support to implement hard link tracking in the standard library using a shared memory region – in this case, only programs using standard C++ library facilities to work with the filing system would have defined behaviour.

> [*Note:* It is suggested that if your operating system does not fully implement hard link tracking, its kernel ought to be fixed in preference to emulating the support using shared memory. – end note]

Throws: Many possible causes of failure, including failure to allocate memory, any failure returned by the kernel (that the handle does not refer to a resource with a path, that the handle is invalid), etc.

Complexity: This is a latency degrading function, which may make several kernel syscalls, allocate a number of items from memory, perform unbounded loops of checks of properties of filesystem entities, and perform other non-deterministic processing, including waits to hold multiple kernel mutexes.

```
bool is_valid() const noexcept;
```

Returns: True if this handle is managing a valid native handle type.

```
bool is_readable() const noexcept;
```

Returns: True if this handle is managing a native handle type which can be read from.

```
bool is_writable() const noexcept;
```

Returns: True if this handle is managing a native handle type which can be written to.

```
bool is_append_only() const noexcept;
```

Returns: True if this handle is managing a native handle type which can be written to, but only to append to whatever its current maximum extent is.

```
bool is_seekable() const noexcept;
```

Returns: True if this handle observes the offset specified during a read or write, false if the offset is ignored.

```
bool requires_aligned_io() const noexcept;
```

Returns: True if this handle requires reads and writes to be performed on a storage device determined alignment, and in round multiples of that alignment.

```
bool is_regular() const noexcept;
```

Returns: True if this handle represents a regular file or device.

```
bool is_directory() const noexcept;
```

Returns: True if this handle represents a directory.

```
bool is_symlink() const noexcept;
```

Returns: True if this handle represents a symbolic link.

```
bool is_section() const noexcept;
```

Returns: True if this handle represents a mappable section of memory.

```
caching kernel_caching() const noexcept;
```

Returns: The caching value this handle was constructed with.

```
bool are_reads_from_cache() const noexcept;
```

Returns: True if reads from this handle come from kernel page cache memory.

```
bool are_writes_durable() const noexcept;
```

Returns: True if writes to this handle do not complete until all of the data written is wholly upon the storage device.

```
bool are_safety_fsyncs_issued() const noexcept;
```

Returns: True if safety flushes of metadata to storage are automatically issued by the library.

```
flag flags() const noexcept;
```

Returns: The flags value this handle was constructed with.

```
native_handle_type native_handle() const noexcept;
```

Returns: The native handle type managed by this handle instance.

6.13.2.4 Class `handle` modifiers [llfio.io.handle.handle.modifiers]

```
virtual void close() throws(file_io_error);
```

Effects: If this handle is valid, close the managed native handle type with the kernel, releasing any resources.

Ensures: `!is_valid()`, and that the system resources formerly managed by the handle are released.

Throws: Any failure returned by the kernel.

```
handle clone() const throws(file_io_error);
```

Effects: If this handle is valid, duplicates the managed native handle type with the kernel. If this handle is not valid, returns a similarly invalid handle instance.

Throws: Any failure returned by the kernel.

```
virtual native_handle_type release() noexcept;
```

Effects: Release the managed native handle type from management by this handle instance.

Ensures: `!is_valid()`.

```
virtual void set_append_only(bool enable) throws(file_io_error);
```

Effects: Sets whether writes to this handle (atomically) append to whatever its current maximum extent is, or whether the offset specified during the write is used.

Ensures: `is_append_only() == enable`, `is_seekable() == !enable`

6.14 Header `<io/io_handle>` [llfio.io.io_handle]

6.14.1 Synopsis [llfio.io.io_handle.synopsis]

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

class io_handle : public handle
{
public:
  using path_type = handle::path_type;
  using extent_type = handle::extent_type;
  using size_type = handle::size_type;
  using mode = handle::mode;
  using creation = handle::creation;
  using caching = handle::caching;
  using flag = handle::flag;

  //! The scatter buffer type used by this handle.
  //! Guaranteed to be `TrivialType` and `StandardLayoutType` and to match
  //! in layout `struct iovec` on POSIX.
  using buffer_type = span<byte>;
  //! The gather buffer type used by this handle.
  //! Guaranteed to be `TrivialType` and `StandardLayoutType` and to match
  //! in layout `struct iovec` on POSIX.
  using const_buffer_type = span<const byte>;

  //! The scatter buffers type used by this handle.
  //! Guaranteed to be `TrivialType` apart from construction, and `StandardLayoutType`.
  using buffers_type = span<buffer_type>;
  //! The gather buffers type used by this handle.
  //! Guaranteed to be `TrivialType` apart from construction, and `StandardLayoutType`.
  using const_buffers_type = span<const_buffer_type>;

  //! The i/o request type used by this handle.
  //! Guaranteed to be `TrivialType` apart from construction, and `StandardLayoutType`.
  template <class T> struct io_request
  {
    T buffers{};
    extent_type offset{0};

    //! Default constructor
    io_request() = default;
    //! Implicit construction from a set of buffers, and an offset
    constexpr io_request(T _buffers, extent_type _offset);
  };

public:
  //! Default constructor
  io_handle() = default;
  ~io_handle() = default;

  //! Construct a handle from a supplied native handle
  constexpr explicit io_handle(native_handle_type h, caching caching = caching::none, flag flags =
      flag::none) noexcept;
  //! Explicit conversion from handle permitted
  explicit constexpr io_handle(handle &&o) noexcept;
  //! Move construction permitted
  io_handle(io_handle &&) = default;
  //! No copy construction (use `clone()`)
```

```
  io_handle(const io_handle &) = delete;
  //! Move assignment permitted
  io_handle &operator=(io_handle &&) = default;
  //! No copy assignment
  io_handle &operator=(const io_handle &) = delete;

  /*! \brief The *maximum* number of buffers which a single read or write syscall can process
  at a time for this specific open handle.
  */
  virtual size_t max_buffers() const noexcept [[no_side_effects]];

  //! Read data from the open handle.
  virtual buffers_type read(io_request<buffers_type> reqs, deadline d = deadline()) throws(
      file_io_error)
    [[no_side_effects]]
    [[ensures: ensure_blessed(reqs.buffers)]]
    [[ensures: ensure_blessed(return)]];

  //! Write data to the open handle.
  virtual const_buffers_type write(io_request<const_buffers_type> reqs, deadline d = deadline())
      throws(file_io_error);
  //! Convenience overload taking an initialiser list
  size_type write(extent_type offset, initializer_list<const_buffer_type> lst, deadline d = deadline()
      ) throws(file_io_error);

  /*! \brief Issue a write reordering barrier such that writes preceding the barrier will reach
  storage before writes after this barrier.
  */
  virtual const_buffers_type barrier(io_request<const_buffers_type> reqs = {},
                                     bool wait_for_device = false, bool and_metadata = false,
                                     deadline d = deadline()) throws(file_io_error) = 0
                                     [[no_visible_side_effects]];

  /*! \class extent_guard
  \brief RAII holder a locked extent of bytes in a file.
  */
  class extent_guard
  {
  public:
    extent_guard(const extent_guard &) = delete;
    extent_guard &operator=(const extent_guard &) = delete;

    //! Default constructor
    constexpr extent_guard();
    //! Move constructor
    extent_guard(extent_guard &&o) noexcept;
    //! Move assign
    extent_guard &operator=(extent_guard &&o) noexcept;
    ~extent_guard();
    //! True if extent guard is valid
    explicit operator bool() const noexcept;
    //! True if extent guard is invalid
    bool operator!() const noexcept;

    //! The io_handle to be unlocked
    io_handle *handle() const noexcept;
```

```
    //! Sets the io_handle to be unlocked
    void set_handle(io_handle *h) noexcept;
    //! The extent to be unlocked
    std::tuple<extent_type, extent_type, bool> extent() const noexcept;

    //! Unlocks the locked extent immediately
    void unlock() noexcept;

    //! Detach this RAII unlocker from the locked state
    void release() noexcept;
  };

  /*! \brief Tries to lock the range of bytes specified for shared or exclusive access. Be aware this
  passes through the same semantics as the underlying OS call, including any POSIX insanity present on
  your platform:
  - Any fd closed on an inode must release all byte range locks on that inode for all
  other fds. If your OS isn't new enough to support the non-insane lock API,
  'flag::byte_lock_insanity' will be set in flags() after the first call to this function.
  - Threads replace each other's locks, indeed locks replace each other's locks.
  You almost cetainly should use your choice of an 'algorithm::shared_fs_mutex::*' instead of this
  as those are more portable and performant.
  \warning This is a low-level API which you should not use directly in portable code. Another issue
  is that atomic lock upgrade/downgrade, if your platform implements that (you should assume
  it does not in portable code), means that on POSIX you need to *release* the old 'extent_guard'
  after creating a new one over the same byte range, otherwise the old 'extent_guard''s
  destructor will simply unlock the range entirely. On Windows however upgrade/downgrade
  locks overlay, so on that platform you must *not* release the old
  'extent_guard'. Look into 'algorithm::shared_fs_mutex::safe_byte_ranges' for a portable solution.
  \return An extent guard, the destruction of which will call unlock().
  \param offset The offset to lock. Note that on POSIX the top bit is always cleared before use
  as POSIX uses signed transport for offsets. If you want an advisory rather than mandatory lock
  on Windows, one technique is to force top bit set so the region you lock is not the one you will
  i/o - obviously this reduces maximum file size to (2^63)-1.
  \param bytes The number of bytes to lock. Zero means lock the entire file using any more
  efficient alternative algorithm where available on your platform (specifically, on BSD and OS X use
  flock() for non-insane semantics).
  \param exclusive Whether the lock is to be exclusive.
  \param d An optional deadline by which the lock must complete, else it is cancelled.
  \errors Any of the values POSIX fcntl() can return, 'errc::timed_out', 'errc::not_supported' may be
  returned if deadline i/o is not possible with this particular handle configuration (e.g.
  non-overlapped HANDLE on Windows).
  \mallocs The default synchronous implementation in file_handle performs no memory allocation.
  The asynchronous implementation in async_file_handle performs one calloc and one free.
  */
  virtual extent_guard lock(extent_type offset, extent_type bytes, bool exclusive = true, deadline d =
       deadline()) throws(file_io_error) [[no_visible_side_effects]];

  extent_guard try_lock(extent_type offset, extent_type bytes, bool exclusive = true) throws(
      file_io_error) [[no_visible_side_effects]];

  //! \overload Locks for shared access
  extent_guard lock(io_request<buffers_type> reqs, deadline d = deadline()) throws(file_io_error) [[
      no_visible_side_effects]];
  //! \overload Locks for exclusive access
  extent_guard lock(io_request<const_buffers_type> reqs, deadline d = deadline()) throws(file_io_error
      ) [[no_visible_side_effects]];
```

```
160
161   /*! \brief Unlocks a byte range previously locked.
162   \param offset The offset to unlock. This should be an offset previously locked.
163   \param bytes The number of bytes to unlock. This should be a byte extent previously locked.
164   \errors Any of the values POSIX fcntl() can return.
165   \mallocs None.
166   */
167   virtual void unlock(extent_type offset, extent_type bytes) noexcept  [[no_visible_side_effects]];
168 };
169
170 } } } }
```

6.14.2 Class `io_handle` [llfio.io.io_handle.io_handle]

A refinement of `handle` capable of scatter-gather reading and writing data, as well as locking regions of data for shared or exclusive access. As the base handle type for all specific implementations of i/o handle, using this abstracted base class is considerably more complex to get correct that using a specific implementation type, where usage behaviour guarantees are known. Normative guidance notes for correct use is therefore given in some cases.

Remarks: The type `io_handle` must meet the `MoveRelocating` concept.

6.14.2.1 Class `io_handle` constructors [llfio.io.io_handle.io_handle.constructors]

```
constexpr explicit io_handle(native_handle_type h, caching caching = caching::none,
                             flag flags = flag::none) noexcept;
```

Effects: Adopt a `native_handle_type` instance.

Ensures: `is_valid()`

6.14.2.2 Class `io_handle` observers [llfio.io.handle.handle.observers]

```
virtual size_t max_buffers() const noexcept [[no_side_effects]];
```

Returns: The *maximum* number of i/o buffers which a single read or write function can *atomically* process at a time for this specific open handle. This enables programs to not prepare longer scatter-gather buffers than the system is capable of.

> [*Note:* The *actual* maximum number of i/o buffers which a single read or write function can process at a time is dependent upon available system resources at the time of the call. As an example of how low they can be, MAC OS permits a maximum of sixteen asynchronous i/o operations to be in flight per process. – end note]
>
> [*Note:* If this function returns `1`, scatter-gather i/o is implemented as a loop over the supplied buffer list. In this situation, there is no particular benefit to supply more than one buffer per operation, apart from programmer convenience. – end note]

6.14.2.3 Class `io_handle` modifiers [llfio.io.handle.handle.modifiers]

```
virtual buffers_type read(io_request<buffers_type> reqs,
                          deadline d = deadline()) throws(file_io_error)
    [[no_side_effects]]
    [[ensures: ensure_blessed(reqs.buffers)]]
    [[ensures: ensure_blessed(return)]];
```

Effects: For each buffer, if the address of the buffer returned is that of the buffer supplied:

- Input buffers are filled to no further than their size on input, with data read from the open handle at the offset supplied by the caller (if the open handle supports offset seeks), proceeding byte by byte from that offset onwards.
- If the handle was opened with `mode::append` i.e. `is_append_only()` is true, behaviour is implementation defined.
- At least one byte of the first of the non-zero sized input buffers will be filled.
- Each buffer is wholly filled before the next buffer is filled.
- If a buffer is not completely filled, its size in the returned buffers will be set to the bytes filled into that buffer (which includes zero bytes filled). As the individual buffers returned are the individual buffers input (i.e. the array of `buffer_type` pointed to by `buffers_type`), you must ensure that the individual buffers input you supply are safe to write to.
- If the deadline is default constructed, the function may block, possibly forever, until at least one byte is read, or possibly until all requested bytes are read, or anywhere in between depending on implementation.

  If the deadline specifies an absolute deadline, and the system clock passes that deadline, any pending i/o will be cancelled and a failure comparing equal to `errc::timed_out` shall be returned.

  If the deadline specifies an elapsed period and the i/o has not completed after that period, any pending i/o will be cancelled and a failure comparing equal to `errc::timed_out` shall be returned.

  If the deadline specifies a zeroed deadline, the implementation will fill as many buffers as it can without blocking, and return immediately.

  > [*Note:* Cancelling pending i/o may be a blocking operation of indeterminite length for some implementations i.e. there is no guarantee that the function will return at a time anywhere close to what you requested. – end note]

If the address of the buffer returned is not that of the buffer supplied:

- The address and size returned points to data which would have been filled had the buffers input been filled, same as above.
- You may not write into the buffer in this situation as the memory does not belong to you.

- You are guaranteed that the memory region returned to you will exist as long as this handle instance remains valid.

  [*Note:* It is possible for implementations to return a mixture of filled buffers and buffers pointing elsewhere. If you need to test that your code using `io_handle` works correctly, `random_file_handle` can be configured to return random mixes of filled buffers input and buffers pointing elsewhere. – end note]

Other things to consider:

- Not all buffers supplied may be filled during the call, even if the data is available, and may require unlimited subsequent calls to complete the original scatter fill request. In this situation, you should adjust the buffers input based on the buffers returned, and perform the operation again, looping this procedure until all original input buffers are filled. See below for an illustrative example.
- It is implementation defined whether concurrent reads of one or more buffers may see partial completion of any concurrent writes to the same offset and extent. In particular, a concurrent write may not update in a linear lower to upper offset fashion – it may appear to update a later offset first, then an earlier one, then a middle one, in any arbitrary (i.e. unpredictable) order.
- It is implementation defined if a read exceeds any current maximum extent of the storage referenced by the handle. It may clamp buffers returned to that maximum extent (i.e. by partially filling the last fillable buffer, and marking all remaining buffers as being unfilled), or fill with garbage instead, or clamp to a different maximum extent, or any other behaviour.
- It is implementation defined whether any system current file pointer for the open handle is affected by this operation.
- If you perform a read after a write, only fully completed writes to the same handle instance you read from are guaranteed to be wholly observable to the read. It is implementation defined whether, or when, writes to other handles to the same resource will become visible to reads from a separate handle instance.

Throws: There are multiple causes of failure: (i) any failure returned by the kernel (that the handle is invalid, that the handle is not open for reading, that insufficient system resources are available to perform the read, that the operation was cancelled by another thread etc) (ii) if a non-infinite deadline is supplied and this handle does not support deadline i/o, may fail with an error comparing equal to `errc::function_not_supported` (iii) if a non-infinite deadline is supplied and that deadline expired, an error comparing equal to `errc::timed_out` will be thrown.

Complexity: Depending on implementation, this may be a latency preserving function in the warm cache use case, where the curve of the sorted latency distribution will closely match that of the curve of copying memory at the same offsets over the same extent of storage. However it may also be a latency degrading function which allocates memory, or performs network access of indeterminate duration. At this abstract level in the type hierarchy, you cannot know which. You should use a refinement of this type directly if you want stronger guarantees.

[*Example:* Given the conditions of use just described, it will be non-trivial to use this

function correctly via `io_handle`. It is recommended that the first course of action is to use a derived type with much stronger guarantees – such as `file_handle` – where most of the complexity below can be dispensed with. If however you can have no idea what the implementation type actually is, one ends up with code like the below function which will retry individual read operations until a scatter buffer list is filled. Note that the below code may hang forever depending on the `io_handle` implementation, which is why it is not supplied as part of the proposed standard library. It also does not handle large gather buffer lists, which would overflow the stack.

```
inline io_handle::buffers_type read_all(io_handle &h, io_handle::io_request<io_handle::buffers_type> reqs, deadline d = deadline()) throws(file_io_error)
{
  // Record beginning if deadline is specified
  chrono::steady_clock::time_point began_steady;
  if(d && d.steady)
    began_steady = chrono::steady_clock::now();

  // Take copy of input buffers onto stack, and set output buffers to buffers supplied
  auto *input_buffers_mem = reinterpret_cast<io_handle::buffer_type *>(alloca(reqs.buffers.size() * sizeof(io_handle::buffer_type)));
  auto *input_buffers_sizes = reinterpret_cast<io_handle::extent_type *>(alloca(reqs.buffers.size() * sizeof(io_handle::extent_type)));
  io_handle::buffers_type output_buffers(reqs.buffers);
  io_handle::io_request<io_handle::buffers_type> creq({input_buffers_mem, reqs.buffers.size()}, 0);
  for(size_t n = 0; n < reqs.buffers.size(); n++)
  {
    // Copy input buffer to stack and retain original size
    creq.buffers[n] = reqs.buffers[n];
    input_buffers_sizes[n] = reqs.buffers[n].size();
    // Set output buffer length to zero
    output_buffers[n] = io_handle::buffer_type{output_buffers[n].data(), 0};
  }

  // Track which output buffer we are currently filling
  size_t idx = 0;
  do
  {
    // New deadline for this loop
    deadline nd;
    if(d)
    {
      if(d.steady)
      {
        auto ns = chrono::duration_cast<chrono::nanoseconds>((began_steady + chrono::nanoseconds(d.nsecs)) - chrono::steady_clock::now());
        if(ns.count() < 0)
          nd.nsecs = 0;
        else
          nd.nsecs = ns.count();
      }
      else
        nd = d;
    }
    // Partial fill buffers with current request
```

```
    io_handle::buffers_type filled = h.read(creq, nd);

    // Adjust output buffers by what was filled, and prepare input
    // buffers for next round of partial fill
    for(size_t n = 0; n < creq.buffers.size(); n++)
    {
      // Add the amount of this buffer filled to next offset read and to output buffer
      auto &input_buffer = creq.buffers[n];
      auto &output_buffer = output_buffers[idx + n];
      creq.offset += input_buffer.size();
      output_buffer = io_handle::buffer_type{output_buffer.data(), output_buffer.size() +
          input_buffer.size()};
      // Adjust input buffer to amount remaining
      input_buffer = io_handle::buffer_type{input_buffer.data() + input_buffer.size(),
          input_buffers_sizes[idx + n] - output_buffer.size()};
    }

    // Remove completely filled input buffers
    while(!creq.buffers.empty() && creq.buffers[0].size() == 0)
    {
      creq.buffers = io_handle::buffers_type(creq.buffers.data() + 1, creq.buffers.size()
          - 1);
      ++idx;
    }
  } while(!creq.buffers.empty());
  return output_buffers;
}
```

– end example]

```
virtual const_buffers_type write(io_request<const_buffers_type> reqs,
                                 deadline d = deadline()) throws(file_io_error);
```

Effects: For each buffer supplied, write the specified data and amount of data to the specified offset into the open handle (if the open handle supports offset seeks), incrementing the offset by each buffer written in turn.

If the handle was opened with `mode::append` i.e `is_append_only()` is true, the specified offset shall be ignored, and instead the maximum extent of the file will be atomically incremented by the sum of the lengths of the buffers up as far as `max_buffers()` at a time, and then the data shall be written into the newly appended extent.

At least one byte of the first of the non-zero sized input buffers will be written. Each buffer is wholly written before the next buffer is written. If a buffer is not completely written, its size in the returned buffers will be set to the bytes written out of that buffer (which includes zero bytes written). As the invididual buffers returned are the individual buffers input (i.e. the array of `buffer_type` pointed to by `buffers_type`), you must ensure that the individual buffers input you supply are safe to write to.

If the deadline is default constructed, the function may block, possibly forever, until at least one byte is written, or possibly until all requested bytes are written, or anywhere in between depending on implementation.

If the deadline specifies an absolute deadline, and the system clock passes that deadline, any pending i/o will be cancelled and a failure comparing equal to `errc::timed_out` shall be returned.

If the deadline specifies an elapsed period and the i/o has not completed after that period, any pending i/o will be cancelled and a failure comparing equal to `errc::timed_out` shall be returned.

If the deadline specifies a zeroed deadline, the implementation will write as many buffers as it can without blocking, and return immediately.

> [*Note:* Cancelling pending i/o may be a blocking operation of indeterminite length for some implementations i.e. there is no guarantee that the function will return at a time anywhere close to what you requested. – end note]

Other things to consider:

- Not all buffers supplied may be written during the call, and may require unlimited subsequent calls to complete the original gather write request. In this situation, you should adjust the buffers input based on the buffers returned, and perform the operation again, looping this procedure until all original input buffers are written. See above for an illustrative example.
- It is implementation defined whether concurrent reads of one or more buffers may see partial completion of any concurrent writes to the same offset and extent. In particular, a concurrent write may not update in a linear lower to upper offset fashion – it may appear to update a later offset first, then an earlier one, then a middle one, in any arbitrary (i.e. unpredictable) order.
- It is implementation defined if a write exceeds any current maximum extent of the storage referenced by the handle. It may clamp buffers returned to that maximum extent (i.e. by partially writing the overlapping buffer, and marking all remaining buffers as being unwritten), or appear to succeed but in fact the data written past the maximum extent is lost, or clamp to a different maximum extent, or any other behaviour. If you wish to guarantee that writes past the maximum extent are safe, open the handle with `mode::append`, or use `set_append_only()` on the handle before the write.
- It is implementation defined whether the order of writes issued by the C++ program to a cached writes configured handle are retained in an order on any underlying storage device i.e. if sudden power loss occurs after a sequence of writes to a handle with cached writes, it is permitted for an implementation to have completely reordered, or partially torn, any of those writes. For handles where write caching was disabled, you are guaranteed that the order of writes is preserved to the storage device, but the metadata to retrieve them may not be. For handles where write and metadata caching was disabled, you are guaranteed that writes form a sequentially consistent ordering fully retrievable in the order they were issued before any unexpected interruption.
- It is implementation defined whether any system current file pointer for the open handle is affected by this operation.

Throws: There are multiple causes of failure: (i) any failure returned by the kernel (that the handle is invalid, that the handle is not open for writing, that insufficient system resources are available to perform the write, that the operation was cancelled by another thread etc) (ii) if a non-infinite

deadline is supplied and this handle does not support deadline i/o, may fail with an error comparing equal to `errc::function_not_supported` (iii) if a non-infinite deadline is supplied and that deadline expired, an error comparing equal to `errc::timed_out` will be thrown.

Complexity: Depending on implementation, this may be a latency preserving function in the warm cache use case, where the curve of the sorted latency distribution will closely match that of the curve of copying memory at the same offsets over the same extent of storage. However it may also be a latency degrading function which allocates memory, or performs network access of indeterminate duration. At this abstract level in the type hierarchy, you cannot know which. You should use a refinement of this type directly if you want stronger guarantees.

```
size_type write(extent_type offset, initializer_list<const_buffer_type> lst,
                deadline d = deadline()) throws(file_io_error);
```

Effects: Convenience overload for the preceding `write()` function, this instantiates a stack allocated `io_request<const_buffers_type>` out of the initialiser list supplied, calls the preceding `write()` function, sums the total bytes filled into the buffers returned, and returns that value.

Throws: All the ways in which the preceding `write()` function can fail; also `errc::no_buffer_space` if the size of the input initialiser list exceeds an implementation defined limit (prevents stack overflow).

```
virtual const_buffers_type barrier(io_request<const_buffers_type> reqs = {},
                                   bool wait_for_device = false,
                                   bool and_metadata = false,
                                   deadline d = deadline()) throws(file_io_error)
                                   [[no_visible_side_effects]] = 0;
```

Effects: For each buffer supplied, do not reorder writes of bytes within those regions across this write barrier. For an empty buffer list, the whole file is assumed.

If `wait_for_device` is true, block the calling thread until all writes to the regions specified have reached the device before returning. This may take some time, but may be relatively fast for some implementations as one need not necessarily wait for acknowledgement that the writes have been persisted, just that they have been received by the device.

If `and_metadata` is true, also block the calling thread until the metadata necessary for retrieving, after sudden power loss, the writes preceding the write barrier to the regions specified have also reached the device before returning. This almost invariably causes a significant blocking wait as one must await acknowledgement that writes, plus metadata, plus any allocations to store them, have been completely persisted.

A non-default deadline permits the call to return with a failure comparing equal to `errc::timed_out` if the writes to the regions specified have not reached the device by the time of the deadline.

> [*Note:* In POSIX terms, `wait_for_device` corresponds in terms of semantics to `fdatasync()`, and when combined with `and_metadata`, to `fsync()`, though note that implementations may not actually use these POSIX functions where proprietary functions offer more

control. – end note]

Implementations are *completely free* to implement this function as a null operation i.e. to do nothing, yet to report success.

> [*Note:* This is required by POSIX, but is also common practice in virtual machine hosts to prevent a single virtual machine causing a denial of service attack to the other virtual machines. End users should very strongly consider opening the handle with `caching::reads` instead, this causes all writes to such a handle to have a sequentially consistent order, and unlike write barriers, if you obtain an open handle with that caching, you are guaranteed that it is working. Note that filing systems use alternative algorithms for files opened with `caching::reads` which often yield *far* superior performance than using this function. – end note]

Implementations may also choose to always flush metadata when blocking on preceding writes i.e. `and_metadata` is assumed to be always true.

Implementations may ignore the regions supplied for barrier, and may always barrier the whole file instead. In this situation, the buffers returned would be empty to indicate the actual operation carried out.

Implementations may implement non-blocking barriers as blocking barriers (i.e. `wait_for_device` is always true) if the platform does not support non-blocking write barriers[18].

> [*Alternative to the above yet to be discussed:* Where an implementation knows for a fact that it cannot implement a requested function because of lacking support on the host platform e.g. to barrier writes without blocking until they reach the device, a failure comparing equal to `errc::function_not_supported` should be returned. – end alternative]

Implementations may be racy with respect to concurrent barriers on overlapping regions by different threads or processes. In this situation, there may be no sequentially consistent ordering, rather an interleaving of regions updated.

Throws: (i) Any failure returned by the kernel (ii) if a non-infinite deadline is supplied and this handle does not support deadline i/o, may fail with an error comparing equal to `errc::function_not_supported` (iii) if a non-infinite deadline is supplied and that deadline expired, an error comparing equal to `errc::timed_out` will be thrown.

Complexity: Depending on implementation, this may be a latency preserving function with a fixed cost of execution. It may also be a latency degrading function of indeterminate execution time.

```
virtual extent_guard lock(extent_type offset,
                          extent_type bytes,
                          bool exclusive = true,
                          deadline d = deadline()) throws(file_io_error)
```

[18] Note to implementers: On impoverished POSIX implementations without better proprietary system calls, a non-blocking barrier can be implemented by launching a `fsync()` task in a separate worker thread, and blocking any further writes on that handle until the worker thread task completes.

```
[[no_visible_side_effects]];
```

Effects: Tries to place an advisory lock on the range of bytes between `offset` and `bytes` for shared or exclusive access, returning an object of type `extent_guard` whose destruction releases the lock via calling `unlock()` upon the same region. If `bytes` is zero, the whole file is locked[19] i.e. zero up to the maximum possible extent inclusive. Locked regions and allocated extents have nothing to do with one another, so one can lock regions not within any maximum extent.

The effects of this call are permitted to vary widely between implementations. Some known variations:

- All advisory locks may be silently released if any handle to the same inode is closed in the process. If the implementation detects this to be the case for a given handle instance, it will set `flags::byte_lock_insanity` so code can detect such unhelpful semantics.

  [*Note:* This is the infamous 'byte lock insanity' mandated by POSIX. The sooner POSIX fixes such daft semantics, the better. – end note]

- Advisory locks on an inode may silently replace existing locks which overlap any of the same region, including those issued by other threads in the same process to other handles to the same inode.

  [*Note:* This unfortunate semantic is also required by POSIX. – end note]

- Some of the top bits of `offset` may be ignored in some implementations, thus making it impossible to take locks on later extents in a file.

- Some of the top bits of `bytes` may be ignored in some implementations, thus limiting the size of the region locked.

  [*Note:* The above two are caused by POSIX requiring offset and length to be signed values, and possibility of 31 bit quantities even when files have 64 bit maximum extents. Given that the top bit is always ignored on POSIX, it is suggested that non-POSIX implementations may choose to emulate advisory locks on systems with only mandatory locks by silently forcing the top bit to set. – end note]

- The effects of placing an exclusive lock on top of a shared lock (lock upgrade) is implementation defined. It may be atomic or not. It may replace the shared lock, or not. It may silently not work as well.

- The effects of downgrading an exclusive lock to a shared lock of the same region is implementation defined. It may atomic, or not. It may release the exclusive lock, or not. It may silently not work as well.

  [*Note:* Portable code should never perform lock upgrades or downgrades. Completely release the region, and take a fresh lock with the setting you want. Make sure to reexamine the region for changes by other code. – end note]

[19] Some implementations use a completely different mechanism in this situation, though you are guaranteed that whole file and byte region locks see one another.

- Whether it is possible to unlock part of a region previously locked is implementation defined (some implementations may insist that what is unlocked is precisely what was previously locked i.e. they 'stack' region locks).
- Whether it is possible to unlock overlapping regions in a different order to the order of their locking is implementation defined.

  [*Note:* Portable code should always unlock exact regions locked, never taking locks on overlapping regions on the same inode, even if multiple handles are in use anywhere in the process including in third party code. – end note]

Throws: (i) Any failure returned by the kernel (ii) if a non-zero and non-infinite deadline is supplied and this handle does not support timed deadline i/o, may fail with an error comparing equal to `errc::function_not_supported` (iii) if a non-infinite deadline is supplied and that deadline expired, an error comparing equal to `errc::timed_out` will be thrown.

Complexity: Depending on implementation, this may be a latency preserving function with a fixed cost of execution. It may also be a latency degrading function of indeterminate execution time.

```
extent_guard try_lock(extent_type offset,
                      extent_type bytes,
                      bool exclusive = true) throws(file_io_error)
                      [[no_visible_side_effects]];
```

Effects: Identical in effects to writing:

```
lock(offset, bytes, exclusive, chrono::seconds(0));
```

6.15 Header `<io/map_handle>` [llfio.io.map_handle]

Todo

6.16 Header `<io/mapped_file_handle>` [llfio.io.mapped_file_handle]

Todo

6.17 Header `<io/mapped>` [llfio.io.mapped]

6.17.1 Synopsis [llfio.io.mapped.synopsis]

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

template <class T> class mapped : public map_view<T>
{
public:
  //! The extent type.
  using extent_type = typename section_handle::extent_type;
```

```
  //! The size type.
  using size_type = typename section_handle::size_type;

public:
  //! Default constructor
  constexpr mapped() noexcept;

  //! Returns a reference to the internal section handle
  const section_handle &section() const noexcept;
  //! Returns a reference to the internal map handle
  const map_handle &map() const noexcept;

  //! Create a view of newly allocated unused memory, creating new memory if insufficient unused
      memory is available.
  explicit mapped(size_type length, bool zeroed = false, section_handle::flag _flag = section_handle::
      flag::readwrite) throws(file_io_error);

  //! Construct a mapped view of the given section handle.
  explicit mapped(section_handle &sh, size_type length = (size_type) -1, extent_type byteoffset = 0,
      section_handle::flag _flag = section_handle::flag::readwrite) throws(file_io_error);

  //! Construct a mapped view of the given file.
  explicit mapped(file_handle &backing, size_type length = (size_type) -1, extent_type maximum_size =
      0, extent_type byteoffset = 0, section_handle::flag _flag = section_handle::flag::readwrite)
      throws(file_io_error);
};

} } } }
```

6.17.2 Class `mapped` [llfio.io.mapped.mapped]

A convenience wrapper of `map_handle` and `map_view<T>` with owning semantics.

Remarks: The type `mapped` must meet the `MoveRelocating` concept.

6.17.2.1 Class `mapped` constructors [llfio.io.mapped.mapped.constructors]

```
constexpr mapped() noexcept;
```

Effects: Constructs an invalid `mapped`.

```
explicit mapped(size_type length,
                bool zeroed = false,
                section_handle::flag _flag = section_handle::flag::readwrite)
         throws(file_io_error);
```

Effects: Creates an owning, reachable view of new memory via constructing an unbacked internal `map_handle` with the given parameters.

Ensures: `bless<T>(data(), size())`

Throws: Any failures of the construction of the internal `map_handle`.

```
explicit mapped(section_handle &sh,
                size_type length = (size_type) -1,
                extent_type byteoffset = 0,
                section_handle::flag _flag = section_handle::flag::readwrite)
        throws(file_io_error);
```

Effects: Creates an owning, reachable view of the memory represented by the section handle via constructing an internal `map_handle` of length `length` with a byte offset into the section handle's memory of `byteoffset`. If `length` is all bits one, use the current length of the section handle divided by the size of `T`.

Ensures: `bless<T>(data(), size())`

Throws: Any failures of the construction of the internal `map_handle`.

```
explicit mapped(file_handle &backing,
                size_type length = (size_type) -1,
                extent_type maximum_size = 0,
                extent_type byteoffset = 0,
                section_handle::flag _flag = section_handle::flag::readwrite)
        throws(file_io_error);
```

Effects: Creates an owning, reachable view of the storage represented by the file handle via constructing an internal `section_handle` to the file of length `maximum_size`, and an internal `map_handle` of length `length` with a byte offset into the section handle's memory of `byteoffset`. If `maximum_size` is zero, use the current maximum extent of the file for creating the section handle. If `length` is all bits one, use the current length of the section handle divided by the size of `T`.

Ensures: `bless<T>(data(), size())`

Throws: Any failures of the construction of the internal `section_handle` and `map_handle`.

6.17.2.2 Class `mapped` destructors [llfio.io.mapped.mapped.destructors]

```
~mapped();
```

Effects: Unmaps any region mapped by a constructor.

Ensures: `unbless<T>(data(), size())`

6.18 Header `<io/map_view>` [llfio.io.map_view]

6.18.1 Synopsis [llfio.io.map_view.synopsis]

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

template <class T> class map_view : public span<T>
{
public:
  //! The extent type.
  using extent_type = typename section_handle::extent_type;
  //! The size type.
  using size_type = typename section_handle::size_type;

public:
  //! Default constructor
  constexpr map_view() noexcept;

  //! Implicitly construct a mapped view of the given mapped data.
  map_view(mapped<T> &map, size_type length = (size_type) -1, size_type offset = 0) noexcept;

  //! Construct a mapped view of the given map handle.
  explicit map_view(map_handle &mh, size_type length = (size_type) -1, extent_type byteoffset = 0)
      noexcept;

  //! Construct a mapped view of the given mapped file handle.
  explicit map_view(mapped_file_handle &mfh, size_type length = (size_type) -1, extent_type byteoffset
       = 0) noexcept;
};
} } } }
```

6.18.2 Class `map_view` [llfio.io.map_view.map_view]

A non-owning reference to a region of mapped data, refining `span<T>`.

Remarks: The type `map_view` must meet the `TriviallyCopyable` concept.

6.18.2.1 Class `map_view` constructors [llfio.io.map_view.map_view.constructors]

`constexpr map_view() noexcept;`

Effects: Constructs an invalid `map_view`.

```
map_view(mapped<T> &map,
         size_type length = (size_type) -1,
         size_type offset = 0) noexcept;
```

Effects: Implicitly constructs a non-owning, reachable view of a mapped range of contiguous `T` from the specified item offset and of the specified number of items. If `length` is all bits one, the number of items used is that of the source map minus the item offset.

Ensures: `bless<T>(data(), size())`

```
explicit map_view(map_handle &mh,
                  size_type length = (size_type) -1,
                  extent_type byteoffset = 0) noexcept;
```

Effects: Constructs a non-owning, reachable view of memory mapped from the specified map handle from the specified byte offset and of the specified number of items. If `length` is all bits one, the number of items used is the length of the map handle minus the byte offset divided by the size of `T`.

Ensures: `bless<T>(data(), size())`

```
explicit map_view(mapped_file_handle &mfh,
                  size_type length = (size_type) -1,
                  extent_type byteoffset = 0) noexcept;
```

Effects: Constructs a non-owning, reachable view of memory mapped from the specified mapped file handle from the specified byte offset and of the specified number of items. If `length` is all bits one, the number of items used is the maximum extent of the mapped file handle minus the byte offset divided by the size of `T`.

Ensures: `bless<T>(data(), size())`

6.19 Header `<io/native_handle>` [llfio.io.native_handle]

6.19.1 Synopsis [llfio.io.native_handle.synopsis]

`native_handle_type` is already in the C++ 17 library as an implementation defined type, and appears in the Networking TS amongst other places.

The below does not propose replacing that implementation defined type, but it does suggest that a *disposition* be added to any implementation defined type if one is not already present. The disposition specifies metadata about the native handle, which greatly eases a number of interoperation issues such as trying to supply a process native handle type to a thread function, and so on.

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

struct native_handle_type
{
  //! The type of handle.
  bitfield disposition
  {
    invalid = 0U,  //!< Invalid handle

    readable = 1U << 0U,     //!< Is readable
    writable = 1U << 1U,     //!< Is writable
    append_only = 1U << 2U,  //!< Is append only

    overlapped = 1U << 4U,  //!< Requires additional synchronisation
    seekable = 1U << 5U,    //!< Is seekable
    aligned_io = 1U << 6U,  //!< Requires sector aligned i/o (typically 512 or 4096)
```

```
    file = 1U << 8U,          //!< Is a regular file
    directory = 1U << 9U,     //!< Is a directory
    symlink = 1U << 10U,      //!< Is a symlink
    multiplexer = 1U << 11U,  //!< Is a kqueue/epoll/iocp
    process = 1U << 12U,      //!< Is a child process
    section = 1U << 13U       //!< Is a memory section
  }
  disposition behaviour;  //! The behaviour of the handle
  union {
    intptr_t _init{-1};
    //! A POSIX file descriptor
    int fd;  // NOLINT
    //! A POSIX process identifier
    int pid;  // NOLINT
    //! A Windows HANDLE
    win::handle h;  // NOLINT
  };
  //! Constructs a default instance
  constexpr native_handle_type();
  ~native_handle_type() = default;
  //! Construct from a POSIX file descriptor
  constexpr native_handle_type(disposition _behaviour, int _fd) noexcept;
  //! Construct from a Windows HANDLE
  constexpr native_handle_type(disposition _behaviour, win::handle _h) noexcept;

  //! Copy construct
  native_handle_type(const native_handle_type &) = default;
  //! Move construct
  constexpr native_handle_type(native_handle_type &&o) noexcept;
  //! Copy assign
  native_handle_type &operator=(const native_handle_type &) = default;
  //! Move assign
  constexpr native_handle_type &operator=(native_handle_type &&o) noexcept;
  //! Swaps with another instance
  void swap(native_handle_type &o) noexcept;

  //! True if valid
  explicit constexpr operator bool() const noexcept;
  //! True if invalid
  constexpr bool operator!() const noexcept;

  //! True if the handle is valid
  constexpr bool is_valid() const noexcept;

  //! True if the handle is readable
  constexpr bool is_readable() const noexcept;
  //! True if the handle is writable
  constexpr bool is_writable() const noexcept;
  //! True if the handle is append only
  constexpr bool is_append_only() const noexcept;

  //! True if overlapped
  constexpr bool is_overlapped() const noexcept;
  //! True if seekable
  constexpr bool is_seekable() const noexcept;
```

```
  //! True if requires aligned i/o
  constexpr bool requires_aligned_io() const noexcept;

  //! True if a regular file or device
  constexpr bool is_regular() const noexcept;
  //! True if a directory
  constexpr bool is_directory() const noexcept;
  //! True if a symlink
  constexpr bool is_symlink() const noexcept;
  //! True if a multiplexer like BSD kqueues, Linux epoll or Windows IOCP
  constexpr bool is_multiplexer() const noexcept;
  //! True if a process
  constexpr bool is_process() const noexcept;
  //! True if a memory section
  constexpr bool is_section() const noexcept;
};

} } } }
```

6.19.2 Class `native_handle_type` [llfio.io.native_handle.native_handle_type]

As `native_handle_type` is merely here for exposition and to remind readers of the same implementation defined type already in the C++ standard, it will not be explained further.

Remarks: The type `native_handle_type` must be constexpr constructible, and meet the `TriviallyCopyable` and `StandardLayout` concepts.

6.20 Header `<io/status_code>` [llfio.io.status_code]

6.20.1 Synopsis [llfio.io.status_code.synopsis]

Note that `status_code<>` is from [P1028] *SG14 status_code and standard error object for P0709 Zero overhead deterministic exceptions.*

```
namespace std { namespace experimental { namespace io { inline namespace v1 {

using file_io_error = errored_status_code<file_io_status_code_domain>;
// as-if:
{
public:
  using errored_status_code<file_io_status_code_domain>::errored_status_code;

  //! Returns any first path associated with the errored status
  filesystem::path path1() const;

  //! Returns any second path associated with the errored status
  filesystem::path path2() const;
};

} } } }
```

6.20.2 Class `file_io_error` [llfio.io.status_code.file_io_error]

A status code capable of transporting a system code with information on how to fetch on demand up to two filesystem paths.

Remarks: The type `file_io_error` must be constexpr constructible, and meet the `TriviallyCopyable` and `StandardLayout` concepts. It is not permitted to allocate nor free memory during construction and destruction.

6.20.2.1 Class `file_io_error` constructors [llfio.io.status_code.file_io_error.constructors] Todo

6.21 Header `<io/path_discovery>` [llfio.io.path_discovery]

Todo

6.22 Header `<io/path_handle>` [llfio.io.path_handle]

Todo

6.23 Header `<io/random_file_handle>` [llfio.io.random_file_handle]

Todo

6.24 Header `<io/section_handle>` [llfio.io.section_handle]

Todo

6.25 Header `<io/stat>` [llfio.io.stat]

Todo

6.26 Header `<io/statfs>` [llfio.io.statfs]

Todo

6.27 Header `<io/symlink_handle>` [llfio.io.symlink_handle]

Todo

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. For example, 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, POSIX `read()` and `write()` implement the POSIX file i/o atomicity guarantees for file i/o as they are supposed to do, 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[20].

[20] 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!

These are very useful guarantees for implementing lock free filesystem algorithms, and are a major reason to use POSIX `read()` and `write()` (i.e. our proposed `file_handle`) instead memory maps (i.e. our proposed `map_handle`) because one can forego using any additional locking in the former. Major platform support for the POSIX read/write atomicity guarantees is pretty good in recent years[21]:

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

Such domain specific knowledge requirements as this may seem to strongly recommend against standardisation into C++. However, I would counter with the point that lock free programming requires extensive domain specific knowledge. As does SIMD programming. And as does the standard library's generic algorithms and containers themselves.

We in C++ have historically not shied away from requiring significant domain specific knowledge to fully realise the potential of the low level parts of the ecosystem. I don't think we should exclude low level file i/o just because parts of it vary in semantics between operating systems. After all, even simple RAM varies in semantics between systems, yet we still manage to write C++ programs which are reasonably performant and portable across a wide range of systems, by avoiding doing things which are not portable. Same applies to the filesystem, in my opinion.

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[22] to implement the missing support. If WG21 forms the proposed Memory 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.

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[23]. 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

[21] 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.

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

[23] Feel fear after reading http://danluu.com/file-consistency/.

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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