Document Number: P1160R1

Date: 2019-10-07

Project: Programming Language C++, Library Evolution Working Group

Reply-to: Attila Fehér afeher@bloomberg.net
Alisdair Meredith ameredith1@bloomberg.net

ADD TEST POLYMORPHIC MEMORY RESOURCE TO THE STANDARD LIBRARY

CONTENTS

VERSION HISTORY

R0: Initial draft

R1: Added new sections addressing LEWGI feedback on relevance of the subject matter
Removed special handling of 0 sized allocations

INTRODUCTION

This document proposes adding to the C++ Standard Library an instrumented polymorphic memory resource (and its accompanying types) and an algorithm to support testing exception safety. The proposed **`test_resource`** implements the **`std::pmr::memory_resource`** abstract interface and can be used to track various details of memory allocated from it. Those available statistics include the number of outstanding allocated memory blocks (and bytes) that are currently in use, the cumulative number of blocks (and bytes) that have been allocated, and the maximum number of blocks (and bytes) that have been in use at any one time. The **`test_resource`** can also be configured to throw an exception after the number of allocation requests exceeds some specified limit, thus enabling testing of exception safety in face of allocation failures using the `exception_test_loop` algorithm.

MOTIVATION

Testing is hard. Testing code that manages memory is harder. The polymorphic memory resource (together with the idea of the replaceable default resource) gives us the ability to replace (or extend) the memory resource with capabilities that allow testing and monitoring of memory management as well as testing robustness in face of memory allocation failure.

When testing a type (or template) that manages memory resources one would like to be assisted in finding hard bugs, such as memory leaks, double releases, use of already released memory, and exception safety issues when an allocation fails. It is also helpful to be able to monitor memory resource usage (or a change in it), such as if a type allocates memory using the default resources when it should not have.

Having a polymorphic memory resource that supports such testing needs allows the programmer to test (polymorphic) allocator enabled code without requiring external tools, or analyzing log files. Testing proper memory management (and robustness in face of memory allocation failure) can be made a normal part of test code. That, in turn, enables targeted testing of individual objects that use polymorphic memory resources, such as using separate `test_resource`s for different objects. What we propose also allows precise testing of local behavior in face of allocation failure. Such validation is hard (if not impossible) to achieve with external tools.

WHY IS THIS APPROPRIATE FOR LEWG ATTENTION?

This paper was presented to LEWGI at San Diego 2018, and given several important questions to answer before the group would consider this proposal on-topic.

TESTING FEATURES DO NOT BELONG IN THE STANDARD

First, the topic material is to support testing. There is a concern that test frameworks have no place in the standard, as there are a variety of successful frameworks already competing in the marketplace, and wg21 has no business approving only one.

However, the proposal under discussion is not a test framework, but rather a tool to support testing that can be applied within any testing framework. There is not even a prototype frame as part of the proposal. Wg21 has already clearly signaled that it does intend to support facilities that help with the full software lifecycle, by adopting `source_location` in C++20, approving a stack trace library for C++23 (once it passes LWG wording review), and instituting SG21 to finalize the work on a contracts facility, also targeting C++23.

However, this proposal is deliberately targeting Library Fundamentals 3 as the variety of information the proposed facility could choose to track is large, and finding the optimal feature set would require feedback from a wider user base with competing demands. See the Experience section below if still concerned that the lower bar for experience has not been achieved.

One additional concern raised was that if we have the facility already, why do we need to add it to the standard? Strictly speaking, we do not. We can happily use our own implementation, and make an open source version available. However, the ability to test correct usage of memory resources turns out to be a significant enough concern that the ability to test such usage has always been considered an integral part of the design. Standardizing some kind of testing resource facility would greatly help in the adoption of the existing memory resource library. Running that exercise through a Library TS seems the best way to get the necessary feedback on whether full adoption by the standard itself is the right answer.

THIS PROBLEM IS BETTER ADDRESSED WITH EXTERNAL TOOLS

There was a suggestion that the market already demonstrated the benefit of external tools to instrument memory allocation, and any work in this space would better belong in SG15. It is true that global memory allocators can be well tracked by such external tooling. However, such tools do not address the needs of stateful allocators so easily. The concerns go beyond the global head, and into whether each object is allocating memory from the correct resource. Testing at this level is handled much more easily within a regular testing framework than with an external tool. Also, the proposed facility goes beyond simple testing of memory allocation, and into telemetry and a tool to test exception safety. While it may be possible to address these concerns with a high level of customization on external tools, it is nowhere near as simple as just plugging in an adapted memory resource that is fit for purpose

WE SPEND TOO MUCH TIME TALKING ABOUT ALLOCATORS

There is a concern that every time we talk about allocators, we are further complicating an already complex part of the language, and we will lose too much time educating folks about the topic under discussion. This proposal is a pure extension, using only the simplest of extension hooks already provided by the library – we implement a class overriding the pure virtual functions in its base class. The intent when standardizing memory resources is that further resources could be easily added in the future, as they demonstrated their benefit. This proposal plugs directly into that features touching nothing else. Historically, it has also been the main application of the `default_resource` function that was adopted in C++17. This library was not proposed earlier as we provided the strictly minimal useful set of resources to bootstrap the library for C++, but is possibly the most widely used resource within our own code base.

EXPERIENCE

The proposed types are not experimental. Their roots can be traces back to the one originally conceived and developed by John Lakos at Bear Sterns (c. 1997) as part of his polymorphic memory allocator model, which itself evolved into the PRM facility now part of C++17. They have also been in use by Bloomberg LP for nearly two decades in testing various software components, including (but not limited to) our own Standard Library implementation. We propose adding those types into standard C++ with just changes in the naming convention as well as removing the use of macros in the automated allocation-failure testing.

The notable differences between the proposed facilities and Bloomberg LP's solution are:

- The Bloomberg implementation uses macros (and not algorithms) to implement the test loop.
- Bloomberg's polymorphic memory resource implementation (the **`BloombergLP::bslma::Allocator`** protocol), unlike the standard **`pmr`**, does not support alignment, and does not support a **`size`** parameter for the deallocate method.

Also note that while Bloomberg LP has other allocators used in testing (such as an allocator that supports functionality similar to Electric Fence https://en.wikipedia.org/wiki/Electric_Fence) that compose with the test memory resource; we are not proposing them for standardization at this time.

FEATURES

The proposed **`test_resource`** type (and its accompanying types and algorithm) provide the following features:

- a thread-safe implementation of the polymorphic memory resource interface
- the detection of memory leaks
- the detection of double releasing of memory
- detection of writing before or beyond the allocated memory area (boundary violation)
- overwriting memory just before deallocating it to help detect use of deleted memory
- tracking of memory use statistics (number of outstanding blocks and bytes) that are currently in use, the cumulative number of blocks (and bytes) that have been allocated, and the maximum number of blocks (and bytes) that have been in use at any one time)
- monitoring of memory use changes (via the **`test_resource_monitor`** type)
- temporary replacement of the default memory resource using the **`default_resource_guard`**
- testing (exception safety) behavior in case of memory allocation failure (when the resource throws) using the **`test_allocation_failure`** algorithm

EXAMPLES OF USE

This section uses a primitive little string implementation as demonstration. The string is called **`pstring`** and is provided only for demonstration purposes. The examples of the code go in stages. As the **`pstring`** class is being built up, and its errors removed, we demonstrate different capabilities of the **`test_resource`**, starting with the detection of memory leaks. The exception test example uses standard **`pmr`** types. Note that in the listings that follow, the **`pstring`** class is being tested, implemented and enhanced in stages.

The complete source code of all the examples and a reference implementation of the proposed entities can be found in Bloomberg's GitHub pages at https://github.com/bloomberg/p1160.

MEMORY LEAK DETECTION (STAGE1)

As you may see in Listing 1, the first "implementation" of **`pstring`** has several shortcomings. The most obvious is that it has no destructor so it leaks memory.

Listing 1

```
class pstring {
    // This class is for demonstration purposes *only*.

public:
    using allocator_type = std::pmr::polymorphic_allocator<>;

    pstring(const char *cstr, allocator_type allocator = {});

    allocator_type get_allocator() const {
        return m_allocator_;
    }

    std::string str() const {  // For sanity checks only.
        return { m_buffer_, m_length_ };
    }

private:
    allocator_type  m_allocator_;
    size_t          m_length_;
    char           *m_buffer_;
};

inline
pstring::pstring(const char *cstr, allocator_type allocator)
: m_allocator_(allocator)
, m_length_(std::strlen(cstr))
, m_buffer_(static_cast<char *>(m_allocator_.allocate_bytes(m_length_, 1)))
{
    std::strcpy(m_buffer_, cstr);
}
```

Listing 2 shows the test code. Listing 3 shows the output of the **`test_resource`** reporting the memory leak. We identify the **`test_resource`** using the name stage1. While in this simple example the name does not matter, we may use several **`test_resources`**, for example an additional one for the default resource (to detect that it is not used). Listing 4 shows the **`test_resource`** output with the verbosity on. The verbose output may be used to debug memory management issues; although in this simple case it is not really necessary.

Listing 2

```
    std::pmr::test_resource tpmr{ "stage1", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };

    ASSERT_EQ(astring.str(), "foobar");
```

Listing 3

```
MEMORY_LEAK from stage1:
  Number of blocks in use = 1
   Number of bytes in use = 6
```

Listing 4

```
test_resource stage1 [0]: Allocated 6 bytes (aligned 1) at 00543F48.
==================================================
                TEST RESOURCE stage1 STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        1       6
             MAX        1       6
           TOTAL        1       6
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
 Indices of Outstanding Memory Allocations:
 0
 MEMORY_LEAK from stage1:
  Number of blocks in use = 1
   Number of bytes in use = 6
```

Note that the actual format of the output is not specified by this proposal. The example output is what happens to be produced by the Bloomberg LP example implementation of the proposed features.

WRONG ALIGNMENT AND BUFFER OVERRUN DETECTION (STAGE2)

In Listing 5 we are adding a destructor to get rid of the memory leak and trigger the checks that are done during deallocation. As we are deallocating with the wrong alignment (alignment 2 instead of 1) we are getting an error message (from the **`test_resource`**) telling so. We have also allocated one-too-few bytes for the string (no space for the closing **`NUL`** character), so we are getting a buffer overrun error as well. See Listing 6. The memory leak is still reported because due to the errors (mismatch in the alignment on deallocate and the buffer overrun) the **`test_resource`** did not attempt to free the memory.

Listing 5

```
inline
pstring::~pstring()
{
    m_allocator_.deallocate_bytes(m_buffer_, m_length_, 2);
}
```

Listing 6

```
*** Freeing segment at 00332CC8 using wrong alignment (2 vs. 1). ***
*** Memory corrupted at 1 bytes after 6 byte segment at 00332CC8. ***
Pad area after user segment:
00332CCE:       00 b1 b1 b1   b1 b1 b1 b1
Header:
00332CA0:       ef be ad de   06 00 00 00   01 00 00 00   cd cd cd cd
00332CB0:       00 00 00 00   00 00 00 00   48 b6 32 00   d8 fc 23 00
00332CC0:       b1 b1 b1 b1   b1 b1 b1 b1
User segment:
00332CC8:       66 6f 6f 62   61 72
MEMORY_LEAK from stage2:
  Number of blocks in use = 1
   Number of bytes in use = 1
```

WRONG NUMBER OF BYTES IN DEALLOCATE (STAGE 3)

We fix the allocation (to allocate enough space) and the alignment in the deallocation, but we "forget" to update the size (number of bytes) in the deallocation to match the allocation. See the changes to the code in Listing 7 and the resulting report from the `test_resource` in Listing 8.

Listing 7

```
inline pstring::pstring(const char *cstr, allocator_type allocator)
: m_allocator_(allocator)
, m_length_(std::strlen(cstr))
, m_buffer_(m_allocator_.allocate_object<char>(m_length_ + 1)) {
    std::strcpy(m_buffer_, cstr);
}

inline
pstring::~pstring()
{
    m_allocator_.deallocate_object(m_buffer_, m_length_);
}
```

Listing 8

```
*** Freeing segment at 003C2D48 using wrong size (6 vs. 7). ***
Header:
003C2D20:       ef be ad de   07 00 00 00   01 00 00 00   cd cd cd cd
003C2D30:       00 00 00 00   00 00 00 00   f8 b5 3b 00   a8 fc 22 00
003C2D40:       b1 b1 b1 b1   b1 b1 b1 b1
User segment:
003C2D48:       66 6f 6f 62   61 72
MEMORY_LEAK from stage3:
  Number of blocks in use = 1
   Number of bytes in use = 1
```

SUCCESS OF CREATE/DESTROY (STAGE4)

In Stage 4 we fix the deallocate call to use the proper byte size and the test code runs without any errors being reported.

Listing 9

```
    m_allocator_.deallocate_object(m_buffer_, m_length_ + 1);
```

Listing 10

```
    std::pmr::test_resource tpmr{ "stage4", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };

    ASSERT_EQ(astring.str(), "foobar");
```

DEALLOCATION OF ALREADY DEALLOCATED POINTER (STAGE4A)

In Stage 4a only the test code changes. We test the copy constructor of **`pstring`**. Since we have not declared a copy constructor, we have an implicitly defined one that leads to undefined behavior in the destructor because it does not deep copy the string. Listing 11 shows the new test code; Listing 12 shows the verbose output that indicates the error.

Listing 11

```
    std::pmr::test_resource tpmr{ "stage4a", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };
    pstring string2{ astring };

    ASSERT_EQ(astring.str(), "foobar");
    ASSERT_EQ(string2.str(), "foobar");
```

Listing 12

```
test_resource stage4a [0]: Allocated 7 bytes (aligned 1) at 00815858.
test_resource stage4a [0]: Deallocated 7 bytes (aligned 1) at 00815858.
*** Invalid magic number 0xdead0022 at address 00815858. ***
Header:
00815830:       22 00 ad de   07 00 00 00   01 00 00 00   00 00 00 00
00815840:       00 00 00 00   00 00 00 00   b0 d8 80 00   f8 f8 3b 00
00815850:       b1 b1 b1 b1   b1 b1 b1 b1
User segment:
00815858:       a5 a5 a5 a5   a5 a5 a5

==================================================
                TEST RESOURCE stage4a STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        1       7
           TOTAL        1       7
      MISMATCHES        1
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

IMPLEMENTED A COPY CONSTRUCTOR (STAGE5)

In the Stage 5 version of **`pstring`** we have implemented a copy constructor, as seen in Listing 13. The revised test code is in Listing 14. The verbose output of running the test is in Listing 15.

Listing 13

```
    pstring(const pstring& other, allocator_type allocator = {});

    // Additional members omitted for brevity

inline
pstring::pstring(const pstring& other, allocator_type allocator)
: m_allocator_(allocator)
, m_length_(other.m_length_)
, m_buffer_(m_allocator_.allocate_object<char>(m_length_ + 1))
{
    std::strcpy(m_buffer_, other.m_buffer_);
}
```

Listing 14

```
    std::pmr::test_resource dpmr{ "default", verbose };
    std::pmr::default_resource_guard dg(&dpmr);

    std::pmr::test_resource tpmr{ "stage5", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };
    pstring string2{ astring };

    ASSERT_EQ(astring.str(), "foobar");
    ASSERT_EQ(string2.str(), "foobar");
```

As **`string2`** uses the default resource we use a **`default_resource_guard`** (also introduced in this proposal) to test its memory management activities.

Listing 15

```
test_resource stage5 [0]: Allocated 7 bytes (aligned 1) at 00715858.
test_resource default [0]: Allocated 7 bytes (aligned 1) at 00715898.
test_resource default [0]: Deallocated 7 bytes (aligned 1) at 00715898.
test_resource stage5 [0]: Deallocated 7 bytes (aligned 1) at 00715858.

==================================================
                TEST RESOURCE stage5 STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        1       7
           TOTAL        1       7
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------

==================================================
                TEST RESOURCE default STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        1       7
           TOTAL        1       7
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

WRONG ASSIGNMENT OPERATOR (STAGE6)

In this stage we are testing a wrong copy assignment operator. Note that due to the use of **`polymorphic_allocator<>`** (as a member) the compiler does not generate a default copy assignment operator, so we have to implement a wrong one by hand. See Listing 17. Listing 18 is the verbose output showing double release of the memory that is a result of memberwise copy assignment.

Listing 16

```
    std::pmr::test_resource tpmr{ "stage5a", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };
    pstring string2{ "string", &tpmr };

    string2 = astring;

    ASSERT_EQ(astring.str(), "foobar");
    ASSERT_EQ(string2.str(), "foobar");
```

Listing 17

```
inline
pstring& pstring::operator=(const pstring& rhs)
{
    m_length_ = rhs.m_length_;
    m_buffer_ = rhs.m_buffer_;

    return *this;
}
```

Listing 18

```
test_resource stage5a [0]: Allocated 7 bytes (aligned 1) at 00455858.
test_resource stage5a [1]: Allocated 7 bytes (aligned 1) at 004558D8.
test_resource stage5a [0]: Deallocated 7 bytes (aligned 1) at 00455858.
*** Invalid magic number 0xdead0032 at address 00455858. ***
Header:
00455830:       32 00 ad de   07 00 00 00   01 00 00 00   00 00 00 00
00455840:       00 00 00 00   00 00 00 00   c8 d8 44 00   58 f8 3c 00
00455850:       b1 b1 b1 b1   b1 b1 b1 b1
User segment:
00455858:       a5 a5 a5 a5   a5 a5 a5

==================================================
                TEST RESOURCE stage5a STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        1       7
             MAX        2       14
           TOTAL        2       14
      MISMATCHES        1
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
 Indices of Outstanding Memory Allocations:
 1
 MEMORY_LEAK from stage5a:
  Number of blocks in use = 1
   Number of bytes in use = 1
```

IMPLEMENTED A COPY ASSIGNMENT OPERATOR (STAGE7)

In this stage we implement a copy assignment operator as seen in Listing 19. The verbose test output is in Listing 20. The test code is the same as Stage 6. Note that this assignment operator will still fail in case of self-assignment, as seen in the next stage.

Listing 19

```
inline
pstring& pstring::operator=(const pstring& rhs)
{
    char *buff = m_allocator_.allocate_object<char>(rhs.m_length_ + 1);
    m_allocator_.deallocate_object(m_buffer_, m_length_ + 1);
    m_buffer_ = buff;
    std::strcpy(m_buffer_, rhs.m_buffer_);
    m_length_ = rhs.m_length_;

    return *this;
}
```

Listing 20

```
test_resource stage7 [0]: Allocated 7 bytes (aligned 1) at 003A5858.
test_resource stage7 [1]: Allocated 7 bytes (aligned 1) at 003A5958.
test_resource stage7 [2]: Allocated 7 bytes (aligned 1) at 003A5918.
test_resource stage7 [1]: Deallocated 7 bytes (aligned 1) at 003A5958.
test_resource stage7 [2]: Deallocated 7 bytes (aligned 1) at 003A5918.
test_resource stage7 [0]: Deallocated 7 bytes (aligned 1) at 003A5858.

==================================================
                TEST RESOURCE stage7 STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        3       21
           TOTAL        3       21
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

SELF-ASSIGNMENT TEST (STAGE7A)

Self-assignment is not handled properly in the copy assignment operator code so this test will use deallocated memory (overwritten by the **`test_resource`** before deallocation) and therefore fail.

Listing 21

```cpp
    std::pmr::test_resource tpmr{ "stage6a", verbose };
    tpmr.set_no_abort(true);

    pstring astring{ "foobar", &tpmr };

    astring = astring;

    ASSERT_EQ(astring.str(), "foobar");
```

Listing 22

```
test_resource stage7a [0]: Allocated 7 bytes (aligned 1) at 00575918.
test_resource stage7a [1]: Allocated 7 bytes (aligned 1) at 00575858.
test_resource stage7a [0]: Deallocated 7 bytes (aligned 1) at 00575918.
astring.str() != "foobar"
ÑÑÑÑÑÑ != foobar
test_resource stage7a [1]: Deallocated 7 bytes (aligned 1) at 00575858.

==================================================
                TEST RESOURCE stage7a STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        2       14
           TOTAL        2       14
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

SELF-ASSIGNMENT FIXED (STAGE8)

In this last stage of **`pstring`** development we avoid self-assignment with an early return. The test code is the same as in Stage 7a. The copy-assignment operator code is changed as seen in Listing 23. The verbose output in Listing 24 shows that the copying did not happen (there is only one allocation/deallocation pair).

Listing 23

```
inline
pstring& pstring::operator=(const pstring& rhs)
{
    if (this == &rhs) {
        return *this;                                                  // RETURN
    }

    char *buff = m_allocator_.allocate_object<char>(rhs.m_length_ + 1);
    m_allocator_.deallocate_object(m_buffer_, m_length_ + 1);
    m_buffer_ = buff;
    std::strcpy(m_buffer_, rhs.m_buffer_);
    m_length_ = rhs.m_length_;

    return *this;
}
```

Listing 24

```
test_resource stage8 [0]: Allocated 7 bytes (aligned 1) at 00425858.
test_resource stage8 [0]: Deallocated 7 bytes (aligned 1) at 00425858.

==================================================
                TEST RESOURCE stage8 STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        1       7
           TOTAL        1       7
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

TESTING ROBUSTNESS AGAINST ALLOCATION FAILURE

Testing classes that manage elements that allocate memory is difficult. We have to verify that if *any* of the allocations fail, there are no memory leaks or other mismanagement of resources. Without stateful allocators that task would be daunting, but with polymorphic memory resources and the **`test_resource`** it is quite easy.

The **<test_resource>** header provides the **`std::pmr::exception_test_loop`** algorithm that uses a **`std::pmr::test_resource`** to make sure that every allocation done by the tested code fails with an exception once. This is done by using the allocation limit of the **`test_resource`** in a loop. We start with a 0 allocation limit and we gradually increase it (in a loop) until we get no more test exceptions thrown by allocations. At that time the test succeeded. See Listing 25 for the example code and Listing 26 for the verbose output.

Listing 25

```
    std::pmr::test_resource tpmr{ "exception_tester", verbose };
    const char *longstr = "A very very long string that allocates memory";

    std::pmr::exception_test_loop(tpmr,
                                  [longstr](std::pmr::memory_resource *pmrp) {
        std::pmr::deque<std::pmr::string> deq{ pmrp };
        deq.emplace_back(longstr);
        deq.emplace_back(longstr);

        ASSERT_EQ(deq.size(), 2);
    });
```

In the verbose output (Listing 26) one can observe the operation of the test loop. First, an immediate allocation failure. Then one allocation succeeds, and because an exception is thrown it is also deallocated. Then we see the **`exception_test_loop`** catching the exception. The process continues until all 4 allocations succeed.

Listing 26

```
        *** exception: alloc limit = 0, last alloc size = 28, align = 4 ***
test_resource tester [1]: Allocated 28 bytes (aligned 4) at 00641018.
test_resource tester [1]: Deallocated 28 bytes (aligned 4) at 00641018.
        *** exception: alloc limit = 1, last alloc size = 48, align = 1 ***
test_resource tester [3]: Allocated 28 bytes (aligned 4) at 00641018.
test_resource tester [4]: Allocated 48 bytes (aligned 1) at 00641090.
test_resource tester [4]: Deallocated 48 bytes (aligned 1) at 00641090.
test_resource tester [3]: Deallocated 28 bytes (aligned 4) at 00641018.
        *** exception: alloc limit = 2, last alloc size = 56, align = 4 ***
test_resource tester [6]: Allocated 28 bytes (aligned 4) at 00641018.
test_resource tester [7]: Allocated 48 bytes (aligned 1) at 00641090.
test_resource tester [8]: Allocated 56 bytes (aligned 4) at 00641120.
test_resource tester [8]: Deallocated 56 bytes (aligned 4) at 00641120.
test_resource tester [7]: Deallocated 48 bytes (aligned 1) at 00641090.
test_resource tester [6]: Deallocated 28 bytes (aligned 4) at 00641018.
        *** exception: alloc limit = 3, last alloc size = 48, align = 1 ***
test_resource tester [10]: Allocated 28 bytes (aligned 4) at 00641018.
test_resource tester [11]: Allocated 48 bytes (aligned 1) at 00641090.
test_resource tester [12]: Allocated 56 bytes (aligned 4) at 00641120.
test_resource tester [13]: Allocated 48 bytes (aligned 1) at 00644030.
test_resource tester [10]: Deallocated 28 bytes (aligned 4) at 00641018.
test_resource tester [11]: Deallocated 48 bytes (aligned 1) at 00641090.
test_resource tester [13]: Deallocated 48 bytes (aligned 1) at 00644030.
test_resource tester [12]: Deallocated 56 bytes (aligned 4) at 00641120.

==================================================
                TEST RESOURCE tester STATE
--------------------------------------------------
        Category        Blocks  Bytes
        --------        ------  -----
          IN USE        0       0
             MAX        4       180
           TOTAL        10      416
      MISMATCHES        0
   BOUNDS ERRORS        0
   PARAM. ERRORS        0
--------------------------------------------------
```

THE PROPOSED ENTITIES IN ALPHABETICAL ORDER

In this section we are introducing the proposed elements in detail.

DEFAULT RESOURCE GUARD

The default resource guard is a simple RAII class that supports installing a new default polymorphic memory resource and then restoring of the original default polymorphic memory resource in its destructor. A possible implementation is in Listing 27. Its typical use is very simple, and in the context of this proposal it usually involves testing the use of the default allocator, like ensuring that an action that should not use the default allocator really does not use it. See

Listing 27

```
namespace std::pmr {

class [[maybe_unused]] default_resource_guard {
    memory_resource * _OldResource;
public:
    explicit default_resource_guard(::std::pmr::memory_resource *_NewDefault) {
        assert(_NewDefault != nullptr);
        _OldResource = ::std::pmr::set_default_resource(_NewDefault);
    }

    default_resource_guard(const default_resource_guard&) = delete;

    default_resource_guard& operator=(const default_resource_guard&) = delete;

    ~default_resource_guard() {
        ::std::pmr:: set_default_resource(_OldResource);
    }
};

}
```

Listing 28

```
void default_resource_use_testing()
{
    std::pmr::test_resource tr{ "object" };
    std::pmr::string astring{
        "A very very long string that will hopefully allocate memory",
        &tr };

    std::pmr::test_resource dr{ "default" };
    std::pmr::test_resource_monitor drm{ &dr };
    {
        std::pmr::default_resource_guard drg{ &dr };

        std::pmr::string string2{ astring, &tr };
    }

    ASSERT(drm.is_total_same());
}
```

EXCEPTION TEST LOOP

Validating the exception safety guarantees of an operation can be tedious without an automated method. Common vocabulary for exception safety guarantees is described by David Abrahams in [Abrahams, D. (2000). Exception-safety in Generic Components], where he also describes an automatic testing method to validate behavior in face of exceptions in section 7 (Automated testing for exception-safety). The exception-testing algorithm used in this proposal was developed independently by John Lakos at Bloomberg LP (c. 2002).

We propose **`exception_test_loop`** as a similar algorithm that takes advantage of the **`test_resource`** having a configurable limit to the number of allocations before it fails by throwing an exception. This algorithm runs a code block (e.g., a lambda, a functor, or a function pointer) in a loop, assuming memory is allocated by a supplied **`test_resource`**. In the first iteration we set the allocation limit of the **`test_resource`** to zero (0), which will cause the very first allocation to immediately fail (by throwing a Test Resource Exception, see Listing 32). If a **`test_resource_exception`** is thrown from the code block, the algorithm increases the allocation limit of the **`test_resource`** by one (1) and then repeats the loop. The loop ends when no **`test_resource_exception`** is thrown.

As long as all relevant allocations inside the code block use the provided **`test_resource`** this simple algorithm ensures that all relevant allocations in that code block will fail at least once (with an exception that inherits from **`std::bad_alloc`**) therefore ensuring that all failure code-paths are tested for leaks and other anomalies.

Listing 29 shows a possible implementation of this algorithm, while Listing 30 shows possible use to test **`deque`**.

Listing 29

```
template <class CODE_BLOCK>
void exception_test_loop(test_resource& pmrp, CODE_BLOCK codeBlock) {
    for (long long exceptionCounter = 0; true; ++exceptionCounter) {
        try {
            pmrp.set_allocation_limit(exceptionCounter);
            codeBlock(pmrp);
            pmrp.set_allocation_limit(-1);
            return;
        } catch (const test_resource_exception& e) {
            if (e.originating_resource() != & pmrp) {
                printf("\t*** test_resource_exception"
                       " from unexpected test_resource %p %.*s ***\n",
                       e.originating_resource(),
                       e.originating_resource()->name().length()
                       e.originating_resource()->name().data());
                throw;
            }
            else if (pmrp.is_verbose()) {
                printf("\t*** test_resource_exception: limit = %lld, "
                       "last size = %zu, align = %zu ***\n",
                       exceptionCounter,
                       e.bytes(),
                       e.alignment());
            }
        }
    }
}
```

Concerns to be aware of include:

- If **`codeBlock`** throws the expected **`test_resource_exception`** *directly* then the loop may repeat infinitely.
- If **`codeBlock`** handles **`bad_alloc`** exceptions and does not rethrow then subsequent failure paths will not be tested.
- The **`codeBlock`** should not manipulate external state that would affect subsequent iterations of the loop.

Listing 30

```
std::pmr::test_resource tpmr{ "tester" };
const char *longstr = "A very very long string that hopefully allocates memory";

std::pmr::exception_test_loop(&tpmr, [longstr](std::pmr::memory_resource& pmrp) {
    std::pmr::deque<std::pmr::string> deq{ &pmrp };
    deq.push_back(longstr);
    deq.push_back(longstr);

    ASSERT_EQ(deq.size(), 2);
    });
}
```

DESIGN CONSIDERATIONS

The algorithm unconditionally changes the allocation limit of the supplied **`test_resource`**. This directly follows Bloomberg's current experience with our macro based implementation. It is consistent with how allocators are used in our test drivers. We have considered restoring the specific allocation limit on successful completion of the loop, but that raises the question of what to do if exiting the loop successfully requires a higher allocation limit than the one set on the supplied **`test_resource`**.

The algorithm loses information about the number of allocations necessary to successfully complete operation of the code block. We have considered returning that number (**`exceptionCounter`**) but we are concerned that such a return value might be interpreted as an error code while both zero and non-zero values are potentially correct.

Another concern is that there is no validation of basic or strong exception safety guarantees after a test exception is caught. We have considered supplying an additional validation block (that could contain the relevant assertions) but have no clear experience with such an API and in particular how to communicate information between the tested code block and the validator. We are looking into this as a future extension with additional overloads.

TEST RESOURCE

The **`test_resource`** is a thread-safe, instrumented memory resource that implements the standard **`std::pmr::memory_resource`** abstract interface and can be used to track various aspects of memory allocated from it, in addition to automatically detecting a number of memory management violations that might otherwise go unnoticed.

The available features are:

- optionally specify a name for the **`test_resource`** that will be printed in reports
- optionally specify a backing memory resource
- detection (or assisting in detection) of memory management violations
    - memory leaks
    - deallocating already deallocated memory
    - buffer underruns
    - buffer overruns
- conditionally aborting on detected memory management violations
- conditionally printing about detected memory management violations
- conditionally printing about allocations/deallocations
- failing allocation after a set allocation limit is reached (if set)
- provide statistics
    - total number of allocations
    - total number of deallocations
    - total number of mismatched allocations (memory is not from this resource)
    - total number of bounds errors (underrun plus overrun)
    - total number of bad deallocate parameters (mismatch on size in bytes or alignment number)
    - current number of memory blocks in use
    - current number of bytes in use
    - maximum allocated number of memory blocks any given time
    - maximum allocated number of bytes any given time
    - total number of blocks allocated
    - total number of bytes allocated
    - last allocated number of bytes
    - last deallocated number of bytes
    - last allocated address
    - last deallocated address

The interface of the **`test_resource`** can be divided into the following sections:

- constructors/destructors
- the implementation of the **`std::pmr::memory_resource`** interface
- the control and access interface for the settings
- access to the instrumentation values
- the **`status`** and the **`print`** function

Listing 31

```
namespace std::pmr {

class test_resource : public memory_resource {
public:
    test_resource(const test_resource&) = delete;
    test_resource& operator=(const test_resource&) = delete;
    test_resource();
    explicit test_resource(memory_resource *pmrp);
    explicit test_resource(const char *name);
    test_resource(const char *name, memory_resource *pmrp);
    explicit test_resource(bool verbose);
    test_resource(bool verbose, memory_resource *pmrp);
    test_resource(const char *name, bool verbose);
    test_resource(const char *name, bool verbose, memory_resource *pmrp);
    ~test_resource();

    [[nodiscard]] void *do_allocate(size_t bytes, size_t alignment) override;
    void do_deallocate(void *p, size_t bytes, size_t alignment) override;
    bool do_is_equal(const memory_resource& that) const noexcept override;

    void set_allocation_limit(long long limit) noexcept;
    void set_no_abort(bool is_no_abort) noexcept;
    void set_quiet(bool is_quiet) noexcept;
    void set_verbose(bool is_verbose) noexcept;
    long long allocation_limit() const noexcept;
    bool is_no_abort() const noexcept;
    bool is_quiet() const noexcept;
    bool is_verbose() const noexcept;
    const char *name() const noexcept;

    void *last_allocated_address() const noexcept;
    size_t last_allocated_bytes() const noexcept;
    void *last_deallocated_address() const noexcept;
    size_t last_deallocated_bytes() const noexcept;

    long long allocations() const noexcept;
    long long blocks_in_use() const noexcept;
    long long max_blocks() const noexcept;
    long long total_blocks() const noexcept;
    long long bounds_errors() const noexcept;
    long long bad_deallocate_params() const noexcept;
    long long bytes_in_use() const noexcept;
    long long max_bytes() const noexcept;
    long long total_bytes() const noexcept;
    long long deallocations() const noexcept;
    long long mismatches() const noexcept;

    void print() const noexcept;
    long long status() const noexcept;
};

} // close namespace
```

TEST RESOURCE EXCEPTION

The **`test_resource_exception`** is thrown by the **`test_resouce`** when its allocation limit is reached and there is an attempt to allocate further memory. It is basically a special form of **`std::bad_alloc`** that allows the exception tester algorithm to differentiate between real out-of-memory situations from the test-induced limits.

The exception inherits from **`std::bad_alloc`** so that when it is thrown, the same code path will be traveled like in case of a real allocation failure. In other words: to ensure that we test the code that would run in production, in case **`std::bad_alloc`** is thrown by a memory resource.

Listing 32

```
class test_resource_exception : public ::std::bad_alloc {
    test_resource *m_originating_;
    size_t         m_size_;
    size_t         m_alignment_;

  public:
    explicit test_resource_exception(test_resource *originating,
                                     size_t         size,
                                     size_t         alignment)
    : m_originating_(originating)
    , m_size_(size)
    , m_alignment_(alignment)
    {
    }

    const char *what() const noexcept override {
        return "std::pmr::test_resource_exception";
    }

    test_resource *originating_resource() const noexcept {
        return m_originating_;
    }

    size_t size() const noexcept {
        return m_size_;
    }

    size_t alignment() const noexcept {
        return m_alignment_;
    }
};
```

TEST RESOURCE MONITOR

The **`test_resource_monitor`** works in tandem with **`test_resource`** to observe changes (or lack of changes) in the statistics collected by a **`test_resource`**. Note that the monitored statistics are based on number of memory blocks and do not depend on the number of bytes in those allocated blocks.

Statistic	Same	up	down
`blocks_in_use`	**`is_in_use_same`**	**`is_in_use_up`**	**`is_in_use_down`**
`max_blocks`	**`is_max_same`**	**`is_max_up`**	*none*
`total_blocks`	**`is_total_same`**	**`is_total_up`**	*none*

Listing 33

```
class test_resource_monitor {
  public:
    explicit test_resource_monitor(const test_resource *monitored) noexcept;
    test_resource_monitor(const test_resource_monitor&) = delete;
    test_resource_monitor& operator=(const test_resource_monitor&) = delete;

    void reset() noexcept;

    bool is_in_use_down() const noexcept;
    bool is_in_use_same() const noexcept;
    bool is_in_use_up() const noexcept;
    bool is_max_same() const noexcept;
    bool is_max_up() const noexcept;
    bool is_total_same() const noexcept;
    bool is_total_up() const noexcept;

    long long delta_blocks_in_use () const noexcept;
    long long delta_max_blocks() const noexcept;
    long long delta_total_blocks () const noexcept;
};
```

PROPOSED WORDING CHANGES

The proposed wording changes are all additions, except for section renumbering, relative to N4762.

EXTEND 19.12.1 HEADER <MEMORY_RESOURCE> SYNOPSIS [MEM.RES.SYN]

Additions are marked with brown background. Changes are underlined (just section renumbering).

```
namespace std::pmr {
 // 19.12.2, class memory_resource
 class memory_resource;

 bool operator==(const memory_resource& a, const memory_resource& b) noexcept;
 bool operator!=(const memory_resource& a, const memory_resource& b) noexcept;

 // 19.12.3, class template polymorphic_allocator
 template<class Tp> class polymorphic_allocator;

 template<class T1, class T2>
   bool operator==(const polymorphic_allocator& a, const polymorphic_allocator& b) noexcept;
 template<class T1, class T2>
   bool operator!=(const polymorphic_allocator& a, const polymorphic_allocator& b) noexcept;

 // 19.12.4, global memory resources
 memory_resource* new_delete_resource() noexcept;
 memory_resource* null_memory_resource() noexcept;
 memory_resource* set_default_resource(memory_resource* r) noexcept;
 memory_resource* get_default_resource() noexcept;

 // 19.12.5, class default_resource_guard
 class default_resource_guard;

 // 19.12.6, pool resource classes
 struct pool_options;
 class synchronized_pool_resource;
 class unsynchronized_pool_resource;

 // 19.12.7 class monotonic_buffer_resource
 class monotonic_buffer_resource;

 // 19.12.8 testing support
 class test_resource;
 class test_resource_exception;
 class test_resource_monitor;

 template <class Tp>
   void exception_test_loop(test_resource& tr, Tp code);
}
```

ADD 19.12.5 DEFAULT RESOURCE GUARD [MEM.RES.DEFGUARD]

19.12.5 Class `default_resource_guard` [mem.res.defguard]

```
namespace std::pmr {
  class default_resource_guard {
  public:
    explicit default_resource_guard(memory_resource* r);
    ~default_resource_guard();

    default_resource_guard(const default_resource_guard&) = delete;
    default_resource_guard& operator=(const default_resource_guard&) = delete;
  private:
    memory_resource *old_default;              // exposition only
  };
}
```

1 An object of type **`default_resource_guard`** controls the setting of the default memory resource within a block ([stmt.block]). A **`memory_resource`** is given to the guard at construction, which the guard sets as the default resource (as if by calling **`set_default_resource`**) and saves the previously set default resource. The guard object restores the previous default resource (using **`set_default_resource`**) when destroyed. The behavior of the program is undefined if the supplied **`memory_resource`** is destroyed before the **`default_resource_guard`** object.

`explicit default_resource_guard(memory_resource* r);`

2 *Requires:* **`r`** is not **`nullptr`**.

3 *Effects:* As if by **`old_default = set_default_resource(r);`**

4 *Postconditions:* **`get_default_resource() == r`**

5 *Throws:* Nothing.

`~default_resource_guard();`

6 *Effects:* As if by **`set_default_resource(old_default);`**

7 *Postconditions:* **`get_default_resource() == old_default`**

RENUMBER 19.12.5, 19.12.6

Renumber 19.12.5 and 19.12.6 and their subsections to 19.12.6 and 19.12.7 respectively ([mem.res.pool] and subsections, [mem.res.monotonic.buffer] and subsections).

INSERT SECTION 19.12.8 TESTING SUPPORT [MEM.RES.TEST]

19.12.8 Testing support [mem.res.test]

1 Testing support provides several types and an algorithm to aid in testing memory handling of types using polymorphic memory resources.

2 All attempts to catch allocator misuse are necessarily imprecise as any such issue is undefined behavior or an out-of-contract call. [Note: The program may abort or fail catastrophically in other ways, too. – End Note] False negatives (missed detections) are permitted for any specification below that mandates detecting an error. False positives are never allowed.

19.12.8.1 Class `test_resource` [mem.res.test.res]

```
namespace std::pmr {
  class test_resource : public memory_resource {
    [[nodiscard]] void* do_allocate(size_t bytes, size_t alignment) override;
    void do_deallocate(void* ptr, size_t bytes, size_t alignment) override;
    bool do_is_equal(const memory_resource& that) const noexcept override;

  public:
    test_resource() : test_resource(false, "", new_delete_resource()) {}
    explicit test_resource(memory_resource* upstream) : test_resource(false, "", upstream) {}
    explicit test_resource(string_view name)
        : test_resource(false, name, new_delete_resource()) {}
    explicit test_resource(bool verbose)
        : test_resource(verbose, "", new_delete_resource()) {}
    test_resource(string_view name, memory_resource* upstream)
        : test_resource(false, name, upstream) {}
    test_resource(bool verbose, memory_resource* upstream)
        : test_resource(verbose, "", upstream) {}
    test_resource(bool verbose, string_view name)
        : test_resource(verbose, name, new_delete_resource()) {}
    test_resource(bool verbose, string_view name, memory_resource* upstream);
    ~test_resource();
    test_resource(const test_resource&) = delete;
    test_resource& operator=(const test_resource&) = delete;

    void set_allocation_limit(long long limit) noexcept;
    void set_no_abort(bool flag) noexcept;
    void set_quiet(bool flag) noexcept;
    void set_verbose(bool flag) noexcept;

    long long allocation_limit() const noexcept;
    bool is_no_abort() const noexcept;
    bool is_quiet() const noexcept;
    bool is_verbose() const noexcept;
    string_view name() const noexcept;
    memory_resource* upstream_resource() const noexcept;

    void *last_allocated_address() const noexcept;
    size_t last_allocated_bytes() const noexcept;
    size_t last_allocated_alignment() const noexcept;
    void *last_deallocated_address() const noexcept;
    size_t last_deallocated_bytes() const noexcept;
    size_t last_deallocated_alignment() const noexcept;

    long long allocations() const noexcept;
    long long deallocations() const noexcept;

    long long blocks_in_use() const noexcept;
    long long max_blocks() const noexcept;
    long long total_blocks() const noexcept;
```

```
    long long bounds_errors() const noexcept;
    long long bad_deallocate_params() const noexcept;
    long long mismatches() const noexcept;

    long long bytes_in_use() const noexcept;
    long long bytes_max() const noexcept;
    long long bytes_total() const noexcept;

    void print() const noexcept;
    bool has_errors() const noexcept;
    bool has_allocations() const noexcept;
    long long status() const noexcept;

  private:
    unspecified-integer allocations_;                 // exposition only

    unspecified-integer allocation_limit_;            // exposition only
    unspecified-integer deallocations_;               // exposition only

    unspecified-integer blocks_in_use_;               // exposition only
    unspecified-integer total_blocks_;                // exposition only
    unspecified-integer max_blocks_;                  // exposition only

    unspecified-integer bytes_in_use_;                // exposition only
    unspecified-integer total_bytes_;                 // exposition only
    unspecified-integer max_bytes_;                   // exposition only

    unspecified-integer last_deallocated_bytes_;      // exposition only
    unspecified-integer last_deallocated_alignment_;  // exposition only
    void *last_allocated_address_;                    // exposition only
  };
}
```

`test_resource(bool verbose, string_view name, memory_resource* upstream);`

1 *Requires:* **`upstream != nullptr`**

2 *Effects:* Create a **`test_resource`** object that uses the specified upstream **`memory_resource`**. Optionally specify verbosity setting and a name. Initialize the remaining settings and instrumentation (as described in *Postconditions*). [Note: To avoid memory allocation the name is stored as a **`string_view`**, not deep copied. – End note] The behavior of the program is undefined if the supplied **`upstream`** objects is destroyed before the **`test_resource`** object.

3 *Postconditions:*

```
allocation_limit() == -1
is_no_abort() == false
is_quiet() == false
is_verbose() == verbose
name() == name
upstream_resource() == upstream
last_allocated_address() == nullptr
last_allocated_bytes() == 0
last_allocated_alignment() == 0
last_deallocated_address() == nullptr
last_deallocated_bytes() == 0
last_deallocated_alignment() == 0
allocations() == 0
deallocations() == 0
blocks_in_use() == 0
blocks_max() == 0
blocks_total() == 0
bounds_errors() == 0
bad_deallocate_params() == 0
bytes_in_use() == 0
bytes_max() == 0
bytes_total() == 0
status() == 0
```

4 *Throws:* Nothing

`~test_resource();`

5 *Effects:* If **`is_verbose() == true`**, call **`print`**. If **`is_quiet() == false`** check for and report allocations through this test memory resource that have not been deallocated by printing to the standard output. If such leaks are found and if **`is_no_abort() == true`** call **`abort()`**.

`void* do_allocate(size_t bytes, size_t alignment) override;`

6 *Requires:* **`alignment != 0`**

7 *Effects:* Increment **`allocations_`**. If **`allocation_limit_`** is non-negative, decrement **`allocation_limit_`** and if the limit becomes negative, throw a **`test_resource_exception`** with the supplied **`bytes`** and **`alignment`**. Otherwise allocate at least **`bytes`** using the upstream memory resource. [Note: Additional memory (larger than **`bytes`**) may be allocated to accommodate for buffer overrun/underrun verification and a memory-block descriptor that aids in identifying blocks allocated by a **`test_resource`**. – End note] Increment **`blocks_in_use_`** and **`total_blocks_`**. **`max_blocks_ = max(max_blocks_, blocks_in_use_)`**. Increase **`bytes_in_use_`** and **`total_bytes_`** by **`bytes`**. **`max_bytes_ = max(max_bytes_, bytes_in_use_)`**. Store the returned address into **`last_allocated_address_`**. If **`is_verbose() == true`** print out, to the standard output, information about the allocation.

8 *Postconditions:*

- **`last_allocated_bytes() == bytes`**
- **`last_allocated_alignment() == alignment`**

9 *Returns:* a pointer well-aligned for `alignment` and pointing to at least `bytes` bytes of memory provided by the upstream memory resource

10 *Throws:* `test_resource_exception` or any exception thrown by the upstream memory resource

```
void do_deallocate(void* ptr, size_t bytes, size_t alignment) override;
```

11 *Effects:* Increment `deallocations_`. A parameter error is detected if `ptr != nullptr` and the parameters do not match the `bytes` and `alignment` parameters provided to `do_allocate()`. A mismatched deallocation is detected if `ptr != nullptr` and this memory resource did not allocate that pointer. Underrun and overrun errors may be detected if guard bytes in either side of the allocated block do not have their expected values.

12 If any error is detected, increment its corresponding counter; if `is_quiet() == true` immediately return to the caller, otherwise report the errors found and `is_no_abort() == false` return immediately to the caller, otherwise call `abort`.

13 If no errors were detected update `last_deallocated_bytes_` to `bytes`, `last_deallocated_alignment_` to `alignment`, `last_deallocated_address_` to `ptr`, decrement `blocks_in_use_`, and decrease `bytes_in_use_` by `bytes`. Finally deallocate the memory block using the upstream memory resource. [Note: Implementations may overwrite the memory block before deallocation with a pattern that indicates deleted memory or use other tactics to detect use of deleted memory. – End note] If `is_verbose() == true` print out the details of the deallocation to the standard output.

```
bool do_is_equal(const memory_resource& that) const noexcept override;
```

14 *Returns:* `this == &that;`

```
void set_allocation_limit(long long limit) noexcept;
```

15 *Effects:* Sets the allocation limit to the supplied `limit`. [Note: Any negative value for `limit` means there is no allocation limit imposed by this test memory resource. – End Note]

16 *Postconditions:* `allocation_limit() == limit`

```
void set_no_abort(bool flag) noexcept;
```

17 *Effects:* Set the no-abort behavior. [Note: If `flag` is `true`, do not abort the program upon detecting errors. The default value of the setting is `false`. – End Note]

18 *Postconditions:* `is_no_abort() == flag`

```
void set_quiet(bool flag) noexcept;
```

19 *Effects:* Set the quiet behavior. [Note: If `flag` is `true`, do not report detected errors and imply `is_no_abort() == true`. The default value of the setting is `false`. – End Note]

20 *Postconditions:* `is_quiet() == flag`

`void set_verbose(bool flag) noexcept;`

21 *Effects:* Set the verbose behavior. [Note: If **`flag`** is **`true`**, report all allocations and deallocations to the standard output. The default value of the setting is **`false`** or what is specified in the constructor. – End Note]

22 *Postconditions:* **`is_verbose() == flag`**

`long long allocation_limit() const noexcept;`

23 *Returns:* the number of allocation requests permitted before throwing **`test_resource_exception`** or a negative value if this test memory resource does not impose a limit on the number of allocations [Note: This value will decrement with every call to **`do_allocate`**. – End Note]

`bool is_no_abort() const noexcept;`

24 *Returns:* the current no-abort flag

`bool is_quiet() const noexcept;`

25 *Returns:* the current quiet flag

`bool is_verbose() const noexcept;`

26 *Returns:* the current verbosity flag

`string_view name() const noexcept;`

27 *Returns:* the name supplied to this **`test_resource`** at construction

`memory_resource* upstream_resource() const noexcept;`

28 *Returns:* the pointer to the upstream **`memory_resource`** supplied to this **`test_resource`** at construction

`void *last_allocated_address() const noexcept;`

29 *Returns:* the pointer to the last memory block successfully allocated by this **`test_resource`**

`size_t last_allocated_bytes() const noexcept;`

30 *Returns:* the requested number of bytes of the last memory block successfully allocated by this **`test_resource`**

`size_t last_allocated_alignment() const noexcept;`

31 *Returns:* the requested alignment of the last memory block successfully allocated by this **`test_resource`**

`void *last_deallocated_address() const noexcept;`

32 *Returns:* the pointer to the last memory block successfully deallocated by this **`test_resource`**

`size_t last_deallocated_bytes() const noexcept;`

33 *Returns:* the requested number of bytes of the last memory block successfully deallocated by this **`test_resource`**

`size_t last_deallocated_alignment() const noexcept;`

34 *Returns:* the requested alignment of the last memory block successfully deallocated by this **`test_resource`**

`long long allocations() const noexcept;`

35 *Returns:* the total number of allocations requested from this **`test_resource`** [Note: This number includes failed allocations. – End note]

`long long deallocations() const noexcept;`

36 *Returns:* the number of total deallocations requested from this **`test_resource`** [Note: This number includes failed deallocations. – End Note]

`long long blocks_in_use() const noexcept;`

37 *Returns:* the number of memory blocks still allocated by this **`test_resource`**

`long long max_blocks() const noexcept;`

38 *Returns:* the largest number of memory blocks allocated at any given time by this **`test_resource`**

`long long total_blocks() const noexcept;`

39 *Returns:* the total number of memory blocks ever successfully allocated by this **`test_resource`**

`long long bounds_errors() const noexcept;`

40 *Returns:* the number of buffer overruns and underruns detected by this **`test_resource`**.

`long long bad_deallocate_params() const noexcept;`

41 *Returns:* the number of mismatched deallocation size and alignment parameters detected by this **`test_resource`**

`long long mismatches() const noexcept;`

42 *Returns:* the number of mismatched deallocations detected by this **`test_resource`** [Note: Mismatched deallocations are deallocation attempts of memory blocks not obtained from this **`test_resource`**. – End Note]

`long long bytes_in_use() const noexcept;`

43 *Returns:* the number of bytes currently allocated by this **`test_resource`**

`long long max_bytes() const noexcept;`

44 *Returns:* the largest number of bytes allocated at any given time by this **`test_resource`**

`long long total_bytes() const noexcept;`

45 *Returns:* the total number of bytes ever successfully allocated by this **`test_resource`**

`void print() const noexcept;`

46 *Effects:* Print a report to the standard output that contains the **`name`** of this test allocator (if not empty) and describes the current state of this **`test_resource`**. [Note: The printout is intended for human consumption by someone debugging a program. – End Note]

`bool has_errors() const noexcept;`

47 *Returns:* **`false`** if **`mismatches()`** and **`bounds_errors()and bad_deallocate_params()`** all return zero and **`true`** otherwise

```
bool has_allocations() const noexcept;
```

48 *Returns:* **`true`** if **`blocks_in_use()`** or **`bytes_in_use()`** are non-zero and **`false`** otherwise [Note: if either is non-zero both are non-zero. – End Note]

```
long long status() const noexcept;
```

49 *Returns:* 0 if this **`test_resource`** has detected no errors and it does not currently have any active allocations (no memory leaks). The number of detected errors if there are any. -1 if there are active allocations (but no errors).

19.12.8.2 Class `test_resource_exception` [mem.res.test.exc]

```
namespace std::pmr {
  class test_resource_exception : public bad_alloc {
  public:
    test_resource_exception(test_resource *originating, size_t bytes, size_t align) noexcept;

    const char *what() const noexcept override;

    test_resource *originating_resource()const noexcept;
    size_t bytes() const noexcept;
    size_t alignment() const noexcept;
  };
}
```

```
test_resource_exception(size_t bytes, size_t align) noexcept;
```

1 *Postconditions:* **`bytes() == bytes && alignment() == align`**

```
const char *what() const noexcept override;
```

2 *Returns:* an implementation-defined NTBS.

```
test_resource *originating_resource()const noexcept;
```

3 *Returns:* the **`originating`** resource pointer supplied at construction

```
size_t bytes() const noexcept;
```

4 *Returns:* the **`bytes`** supplied at construction

```
size_t alignment() const noexcept;
```

5 *Returns:* the **`alignment`** supplied at construction

19.12.8.3 Class `test_resource_monitor` [mem.res.test.mon]

```
namespace std::pmr {
  class test_resource_monitor {
  public:
    explicit test_resource_monitor(const test_resource& monitored) noexcept;
    explicit test_resource_monitor(test_resource&&) = delete;

    test_resource_monitor(const test_resource_monitor&) = delete;
    test_resource_monitor& operator=(const test_resource_monitor&) = delete;

    void reset() noexcept;

    bool is_in_use_down() const noexcept;
    bool is_in_use_same() const noexcept;
    bool is_in_use_up() const noexcept;

    bool is_ max_same() const noexcept;
    bool is_ max_up() const noexcept;

    bool is_total_same() const noexcept;
    bool is_total_up() const noexcept;

    long long in_use_change() const noexcept;
    long long max_change() const noexcept;
    long long total_change() const noexcept;
  private:
    long long            initial_in_use;         // exposition only
    long long            initial_max;            // exposition only
    long long            initial_total;          // exposition only
    const test_resource& monitored_resource;     // exposition only
  };
}
```

`explicit test_resource_monitor(const test_resource& monitored) noexcept;`

1 *Postconditions:*

- `&monitored_resource == &monitored`
- `initial_in_use == monitored.blocks_in_use()`
- `initial_max == monitored.max_blocks()`
- `initial_total == monitored.total_blocks()`

`void reset() noexcept;`

2 *Postconditions:*

- `initial_in_use == monitored_resource.blocks_in_use()`
- `initial_max == monitored_resource.max_blocks()`
- `initial_total == monitored_resource.total_blocks()`

`bool is_in_use_down() const noexcept;`

3 *Returns:* `monitored_resource->blocks_in_use() < initial_in_use`

`bool is_in_use_same() const noexcept;`

4 *Returns:* `monitored_resource->blocks_in_use() == initial_in_use`

`bool is_in_use_up() const noexcept;`

5 *Returns:* `monitored_resource->blocks_in_use() > initial_in_use`

`bool is_ max_same() const noexcept;`

6 *Returns:* **`monitored_resource->blocks_max() < initial_max`**

`bool is_ max_up() const noexcept;`

7 *Returns:* **`monitored_resource->blocks_max() > initial_max`**

`bool is_total_same() const noexcept;`

8 *Returns:* **`monitored_resource->blocks_total() < initial_total`**

`bool is_total_up() const noexcept;`

9 *Returns:* **`monitored_resource->blocks_total() > initial_total`**

`long long in_use_change() const noexcept;`

10 *Returns:* **`monitored_resource->blocks_in_use() - initial_in_use`**

`long long max_change() const noexcept;`

11 *Returns:* **`monitored_resource->blocks_max() - initial_max`**

`long long total_change() const noexcept;`

12 *Returns:* **`monitored_resource->blocks_total() - initial_total`**

19.12.8.4 Function template `test_resource_loop` [mem.res.test.loop]

```
namespace std::pmr {
  template <class Block >
    void exception_test_loop(test_resource& tr, Block code);
}
```

1 *Requires:* The **`code`** argument must be a function object callable with a single **`test_resource&`** parameter.

2 *Effects:* As if by

```
for (long long counter = 0; true; ++counter) {
    try {
        tr.set_allocation_limit(counter);
        code(tr);
        tr.set_allocation_limit(-1);
        return;
    } catch (const test_resource_exception& e) {
        if (e.originating_resource() != &tr) {
            reportUnexpectedException(e);
            throw;
        }
        else if (tr.is_verbose()) {
            reportProgress(counter, tr, e);
        }
    }
}
```

3 [Note: The function might never return if code throws a **`test_resource_exception`** with the originating resource set to **`tr`** other than by calling **`tr.allocate`** . — End Note]

ACKNOWLDGEMENTS

Thanks to John Lakos who has provided the original inspiration, implementation, and much encouragement for this proposal.

Thanks to the colleagues at Bloomberg LP who reviewed the many drafts of this proposal!

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Note that the exception-testing algorithm used in this proposal was developed independently by John Lakos at Bloomberg LP (c. 2002).

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