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Frictionless Allocators

Alisdair Meredith

Frictionless Allocators

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Alisdair Meredith
Senior Developer
Twitter @AlisdairMered

TechAtBloomberg.com

Outline of Talk

- Why Allocators?
- What do allocators look like in C++20?
- What causes friction?
- What should we do about it?
- What is our experience?
- What next?

What is an allocator?

What is an allocator?

A service that grants exclusive use of a region of memory to clients

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A service that grants exclusive use of a region of memory to clients

Nice clients will return that region to the service when no longer needed

Why Do We Want Allocators?

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Is the `new` operator not good enough?

Why Do We Want Allocators?

- Performance
- Performance
- Performance
- Instrumentation
- Special memory

Performance

- Well chosen allocators can greatly improve memory locality
  - See John Lakos talk:
    Value Proposition: Allocator Aware Software
    https://www.youtube.com/watch?v=ebn1C-mTFVk
  - Papers we wrote on measuring allocator performance:
    https:/wg21.link/p0089 and https:/wg21.link/p0213
  - Factor of 3-5 speedup common for allocation behavior, compared to `new` operator
  - Order of magnitude or more for extreme cases

Performance

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A Faster Allocator

- General purpose allocator tries to minimize contention
  - A better/replacement `operator new`
- Avoid synchronization if we can guarantee all access from a single thread
- Simplified bookkeeping if we never reclaim memory
  - monotonic allocator simply advances a pointer through a buffer on each allocation

Performance

- Better memory locality improves runtime *after* allocation
  - Keeping memory in L1/L2 cache has an enormous impact on runtime performance
    - although CPU is trying to manage cache to make this happen anyway, a local memory pool goes a long way to help
  - Memory pools minimize the effect of *diffusion* on a single task
  - Memory pools on the stack reduce fragmentation of long running processes
  - No synchronization if allocation confined to a single thread

Performance

- Two common strategies to improve locality
  - Try to allocate on the thread stack
    - Typically from a pre-sized memory buffer
  - Manage a pool of memory to avoid needless trips back to the memory manager
    - This is commonly the implementation strategy of `operator new`, but specific pool for each data structure

Utility

- Custom allocators can add extra functionality in addition to supplying memory, such as instrumentation for:
    - Debugging
    - Logging
    - Profiling
    - Test drivers

Special Memory

- Special memory may be hardware specific, or has some other property, e.g., shared memory
  - Often requires a handle with more info than a native C++ pointer
    - e.g., boost::interprocess for shared memory containers
  - Some architectures provide different access to different regions of memory
    - VRAM on video cards?

Emery Berger

- Professor at University of Massachusetts Amherst
  - ACM Fellow: *For contributions in memory management and programming language implementation*
- Developed **Hoard**, first scalable general-purpose memory allocator
  - Algorithm incorporated into IBM & Mac OS X allocators
- Developed **DieHard** & **DieHarder** - reliable & secure memory allocators
  - Directly influenced Windows 7-8 allocator design
- Wrote technical paper evaluating custom allocators
  - *Reconsidering Custom Memory Allocation*, cited over 200 times, Most Influential Paper

Accelerating Programs via Custom Allocators

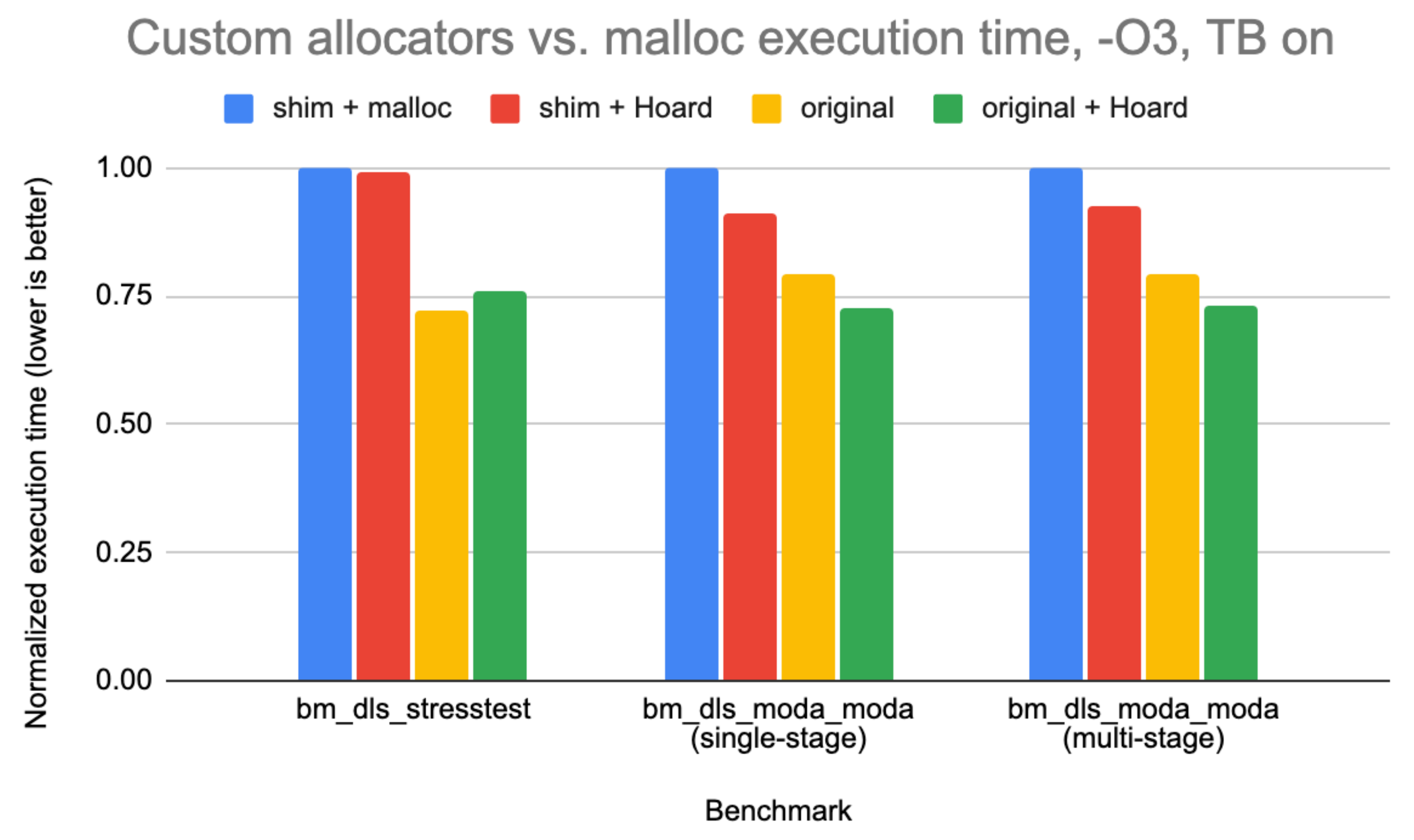
- **Demonstrate value** of custom allocation
  - Empirically measure opportunities (past successes)
    - Performance impact, space impact
- **Help programmers**
  - **Automatically** identify opportunities for custom allocation in legacy code
  - Provide tools to ensure **efficiency** for programs using custom allocation

Initial empirical results

- Replace specific custom allocator: **`BufferedSequentialAllocator`**
- Run with three benchmarks:
  - **`stresstest -`** artificial composition of sorts & filters; changes sort & filter criteria to make the engine rearrange static data based on random numbers
  - **`moda_moda -`** extraction of the DataLayer pipeline of some application that actually drives headline Terminal functions
    - **Single-stage**: benchmarks worksheet computation in a single stage pipeline. Exercises `WorksheetView` (Excel formulas)
    - **Multi-stage**: benchmarks worksheet computation in multiple stages composed by join views. Exercises `WorksheetView`, `UniqueView`, and `JoinView`

Early Results

-O3, TurboBoost on, replacing `BufferManager`



Roughly ~25% improvement using custom allocation

Allocators in C++20

Allocator Traits

(since 2011)

```
template <class Alloc>
struct allocator_traits {
   using allocator_type     = Alloc;
   using value_type = typename Alloc::value_type;
   using pointer            = see below;
   using const_pointer      = see below;
   using void_pointer       = see below;
   using const_void_pointer = see below;
   using difference_type    = see below;
   using size_type          = see below;
   // ...
};
```

Allocator Traits

(since 2011)

```
template <class Alloc>
struct allocator_traits {
   // ...

   template <class T>
   using rebind_alloc = see below;

   template <class T>
   using rebind_traits = allocator_traits<rebind_alloc<T>>;

   // ...
};
```

Allocator Traits

(since 2011)

```
template <class Alloc>
struct allocator_traits {
   // ...
   static pointer allocate(Alloc& a, size_type n);
   static pointer allocate(Alloc& a, size_type n, const_void_pointer hint);
   static void  deallocate(Alloc& a, pointer p, size_type n);

   template <class T, class... Args>
   static void   construct(Alloc& a, T* p,  Args&&... args);

   template <class T>
   static void     destroy(Alloc& a, T* p);

   static size_type max_size(const Alloc& a);

   // ...
};
```

Allocator Traits

(since 2011)

```
template <class Alloc>
struct allocator_traits {
   // ...
   static pointer allocate(Alloc& a, size_type n);
   static pointer allocate(Alloc& a, size_type n, const_void_pointer hint);
   static void  deallocate(Alloc& a, pointer p, size_type n);

   template <class T, class... Args>
   static void   construct(Alloc& a, T* p,  Args&&... args);

   template <class T>
   static void     destroy(Alloc& a, T* p);

   static size_type max_size(const Alloc& a);

   // ...
};
```

Allocator Traits

(since 2011)

```
template <class Alloc>
struct allocator_traits {
   // ...

   using propagate_on_container_copy_assignment = see below;
   using propagate_on_container_move_assignment = see below;
   using propagate_on_container_swap            = see below;

   static Alloc select_on_container_copy_construction(const Alloc& rhs);

};
```

How did we improve support in C++17

- `is_always_equal`
  - Improved exception specifications on containers
- Polymorphic Memory Resources in namespace `std::pmr`
- `std::pmr` containers
- Constraint: fancy pointers must be *contiguous* iterators

std::allocator

C++17

```
template<class T>
struct allocator {
  using value_type                             = T;
  using size_type                              = size_t
  using difference_type                        = ptrdiff_t
  using propagate_on_container_move_assignment = true_type;
  using is_always_equal                        = true_type;

            allocator() noexcept;
            allocator(const allocator&) noexcept;
  template<class U>
            allocator(const allocator<U>&) noexcept;
            ~allocator();
            allocator& operator=(const allocator&) = default;

                           T* allocate(size_t n);
            void deallocate(T* p, size_t n);
};
```

std::allocator

C++17 C++20

```
template<class T>
struct allocator {
  using value_type                             = T;
  using size_type                              = size_t
  using difference_type                        = ptrdiff_t
  using propagate_on_container_move_assignment = true_type;
  using is_always_equal                        = true_type;

  constexpr allocator() noexcept;
  constexpr allocator(const allocator&) noexcept;
  template<class U>
  constexpr allocator(const allocator<U>&) noexcept;
  constexpr ~allocator();
  constexpr allocator& operator=(const allocator&) = default;

  [[nodiscard]] constexpr T* allocate(size_t n);
  constexpr void deallocate(T* p, size_t n);
};
```

How does `pmr` work?

- Resource derives from `std::pmr::memory_resource`
  - Override the pure abstract members
- Clients store pointer to memory resource “like a vtable”
- Resource pointer never propagates
  - Scope resource object with a longer lifetime than consumers
  - Data structures “guarantee” all elements using same resource
- Alias templates for all standard containers to use this new scheme

memory_resource

```
class memory_resource {
  // For exposition only
  static constexpr size_t max_align = alignof(max_align_t);

public:
  virtual ~memory_resource();

  void* allocate(size_t bytes, size_t alignment = max_align);
  void  deallocate(void* p, size_t bytes, size_t alignment = max_align);

  bool is_equal(const memory_resource& other) const noexcept;

protected:
  virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
  virtual void  do_deallocate(void* p, size_t bytes, size_t alignment) = 0;

  virtual bool do_is_equal(const memory_resource& other) const noexcept = 0;
};
```

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};
```

memory_resource

```
class memory_resource {
  // For exposition only
  static constexpr size_t max_align = alignof(max_align_t);

public:
  virtual ~memory_resource();

  void* allocate(size_t bytes, size_t alignment = max_align);
  void  deallocate(void* p, size_t bytes, size_t alignment = max_align);

  bool is_equal(const memory_resource& other) const noexcept;

protected:
  virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
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  virtual bool do_is_equal(const memory_resource& other) const noexcept = 0;
};
```

memory_resource

```
class memory_resource {
  // For exposition only
  static constexpr size_t max_align = alignof(max_align_t);

public:
  virtual ~memory_resource();

  void* allocate(size_t bytes, size_t alignment = max_align);
  void  deallocate(void* p, size_t bytes, size_t alignment = max_align);

  bool is_equal(const memory_resource& other) const noexcept;

protected:
  virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
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```

memory_resource

```
class memory_resource {
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  static constexpr size_t max_align = alignof(max_align_t);

public:
  virtual ~memory_resource();

  void* allocate(size_t bytes, size_t alignment = max_align);
  void  deallocate(void* p, size_t bytes, size_t alignment = max_align);

  bool is_equal(const memory_resource& other) const noexcept;

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memory_resource

```
class memory_resource {
  // For exposition only
  static constexpr size_t max_align = alignof(max_align_t);

public:
  virtual ~memory_resource();

  void* allocate(size_t bytes, size_t alignment = max_align);
  void  deallocate(void* p, size_t bytes, size_t alignment = max_align);

  bool is_equal(const memory_resource& other) const noexcept;

protected:
  virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
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  virtual bool do_is_equal(const memory_resource& other) const noexcept = 0;
};
```

Standard Resources

- `memory_resource* new_delete_resource() noexcept;`
- `memory_resource* null_memory_resource() noexcept;`
- `memory_resource* get_default_resource() noexcept;`

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- `memory_resource* new_delete_resource() noexcept;`
- `memory_resource* null_memory_resource() noexcept;`
- `memory_resource* get_default_resource() noexcept;`

- `class monotonic_buffer_resource;`
- `class synchronized_pool_resource;`
- `class unsynchronized_pool_resource;`

Idiom and usage of `pmr`

- Memory resources are objects, typically scoped to a function, with a lifetime longer than their clients below them
- Default, object, and global “allocators”
  - System-wide default used for all objects unless otherwise specified
  - Use the default for function-scope objects within an allocator-aware class
  - Use object allocator (supplied at construction) only (and always) for data that is part of the object data structure, that persists beyond the function call
  - Use another “global allocator” for any object with static or thread-local storage duration, as may outlive the default resource after `main`

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  - Use another “global allocator” for any object with static or thread-local storage duration, as may outlive the default resource after `main`
- No support for fancy pointers

Quick Example

```
pmr::string make_string(const char *s) {
   pmr::monotonic_resource res;
   pmr::string x(s, &res);
   return x;
};
```

Quick Example

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pmr::string make_string(const char *s) {
   pmr::monotonic_resource res;
   pmr::string x(s, &res);
   return x;
};
```

String x is declared after resource `res`, so C++ lifetimes should avoid dangling references

Quick Example

```
pmr::string make_string(const char *s) {
   pmr::monotonic_resource res;
   pmr::string x(s, &res);
   return x;   // potential RVO
};
```

Quick Example

```
pmr::string make_string(const char *s) {
   pmr::monotonic_resource res;
   pmr::string x(s, &res);
   return x;    // C++17 guarantees RVO
};
```

Quick Example

```
pmr::string make_string(const char *s) {
   pmr::monotonic_resource res;
   pmr::string x(s, &res);
   return {x};
};
```

Force creation of a temporary, using the default allocator

Scoped Allocator Model

- Simple idea: every element in the data structure uses the same allocator/memory-resource
- Class design: every member of the object graph (all bases and members) use the same allocator
- Key benefit: underpins performance when looking to avoid diffusion and fragmentation
- Important benefit: easy to guarantee allocator/resource has a longer lifetime than its clients
- Implication: allocators can never propagate, or else any swap or assignment could invalidate the whole system

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- Implication: allocators can never propagate, or else any swap or assignment could invalidate the whole system

std::pmr::allocator

C++17 C++20

```
namespace std::pmr {
  template<class Tp = byte>
  class polymorphic_allocator {
    memory_resource* memory_rsrc;    // exposition only
  public:
    using value_type = Tp;

    // 20.12.3.1, constructors
    polymorphic_allocator() noexcept;
    polymorphic_allocator(memory_resource* r);
    polymorphic_allocator(const polymorphic_allocator& other) = default;

    template<class U>
    polymorphic_allocator(const polymorphic_allocator<U>& other) noexcept;

    polymorphic_allocator& operator=(const polymorphic_allocator&) = delete;
```

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  template<class Tp = byte>
  class polymorphic_allocator {
    memory_resource* memory_rsrc;    // exposition only
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    using value_type = Tp;

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    polymorphic_allocator() noexcept;
    polymorphic_allocator(memory_resource* r);
    polymorphic_allocator(const polymorphic_allocator& other) = default;

    template<class U>
    polymorphic_allocator(const polymorphic_allocator<U>& other) noexcept;

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

    // ...
```

std::pmr::allocator

C++17 C++20

```
// ...

// 20.12.3.2, member functions
[[nodiscard]] Tp* allocate(size_t n);
void deallocate(Tp* p, size_t n);

template<class T, class... Args>
  void construct(T* p, Args&&... args);

template<class T>
  void destroy(T* p);

polymorphic_allocator select_on_container_copy_construction() const;

memory_resource* resource() const;

// ...
```

std::pmr::allocator

C++17 C++20

```
    // ...

    [[nodiscard]] void* allocate_bytes(size_t nbytes,
                                       size_t alignment = alignof(max_align_t));
    void deallocate_bytes(void* p, size_t nbytes,
                                       size_t alignment = alignof(max_align_t));

    template<class T>
    [[nodiscard]] T* allocate_object(size_t n = 1);
    template<class T>
    void deallocate_object(T* p, size_t n = 1);
    template<class T, class... CtorArgs>
    [[nodiscard]] T* new_object(CtorArgs&&... ctor_args);
    template<class T>
    void delete_object(T* p);
  };
}
```

Limitations of `pmr`

- Solves the vocabulary problem, but only if used consistently (i.e., the vocabulary problem!)
- No support for fancy pointers / special memory regions
- Storing an extra pointer in every object, repeatedly through the whole data structure
- Cost of dynamic dispatch
  - (see Lakos talk for why this may be negligible)

Bloomberg Experience

- Using the progenitor for `pmr` allocators for a decade or more
- `pmr` style allocators can be a big win
  - Performance-critical code benefits significantly
  - Instrumentation helpful, especially in test drivers
- Users still bridle at code complexity

What Causes Friction with `pmr` Allocators?

Unsupported use cases

- Without user-supplied constructors, some types cannot support the scoped allocator model:
  - `pmr::string data[42];`
  - `std::array<pmr::string, 42> more_data;`
  - Lambda objects
  - Structured bindings
  - Default member initializers
  - Problem is recursive, `vector<array<string, 10>>`

Allocator Propagation

- Allocator is bound at construction
- Should allocator be rebound on assignment?
  - Assignment copies data
  - Allocator is orthogonal, specific to each container object
- Traits give control of the propagation strategy
  - Default is to never propagate

Complexity of Propagation

- 3 (or 4?) fine-grained traits is too many dimensions to reasonably support
- What does it mean to propagate on `swap`, but not on move assignment? Or vice-versa?
- Trait for copy construction is actually a function call?!

Syntactic overhead is high

- Mandatory construction through traits looks like expert-level code
- Typically double the number of constructors to allow for optional allocator
  - Cannot have a constructor with multiple defaulted arguments, as need an optional allocator for each subset
  - E.g., for `unordered_map`
    - C++11: 8 constructors
    - C++17: 15 constructors (many delegating to original 8)
- Inconsistent argument order: allocator is final argument, or `MyType(allocator_arg, alloc, …)`

Copy Constructor Issue

- With the trait to select allocator on copies, behavior was unpredictable with optional copy-elision rules
- C++17 nails down mandatory copy elision in the important cases
  - Risk of returning an object with a reference to a memory resource that is about to leave scope
  - Compiler warnings my help in the future

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Reducing Friction

Ideal Model

- No allocator spam in the interface
- A single data structure uses the same allocator throughout
  - e.g., container and its elements
  - e.g., a graph, its nodes, and their contents, etc.
- If a type manages dynamic memory, it *always* supports an allocator
- “allocator aware” types are known to the type system
  - can query if a type is allocator aware
  - can query which allocator an object uses

Allocator Awareness

- A type is *explicitly* allocator aware if:
  - it says so (need a way to mark a class)
- A type is *implicitly* allocator aware if:
  - it derives from an allocator-aware class
  - it has data members that are allocator aware
    - “viral” on members as well as bases

Why Implicit from Members?

- Could just make allocator aware classes derive from a base class with the right behavior
    - Generic code would want conditional bases
    - Arrays, aggregates, etc., need implicit behavior
    - Forces extra vtable pointer in all cases
    - Too much syntax for common/essential usage

Why Implicit from Members?

- Could just make allocator aware classes derive from a base class with the right behavior
  - Generic code would want conditional bases
  - Arrays, aggregates, etc., need implicit behavior
  - Forces extra vtable pointer in all cases
  - Too much syntax for common/essential usage

Allocator Aware Properties

- An allocator-aware class will use its supplied allocator to acquire all memory for the data structure’s persistent needs
- There is a consistent (customizable) API to query which allocator an object is using
- The allocator for an object will not change during its lifetime
  - i.e., allocators do not propagate

Why querying matters

- Some operations require allocators to be the same, e.g., move and swap

- Make a temporary with the same allocator if we expect to move into an existing object

- `swap` should either have a precondition that allocators are the same, or make potentially throwing “copies” with appropriate allocator for swaps

- Users need a means to detect allocator compatibility if they are to avoid violating such preconditions

Simplifying Construction

- Do *not* add allocator overloads to every constructor
- When user wants to supply an allocator, pass it out-of-band from the initializer list with a new syntax

```
multipool_resource res;
set<string>() x{ "hello", “world"} using res;
```

Worked Example

```
class Object {
  std::pmr::string d_name;

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

  explicit Object(allocator_type a = {}) : d_name("<UNKNOWN>", a) {}

  Object(const Object& rhs, allocator_type a = {}) : d_name(rhs.d_name, a) {}

  Object(Object&&) = default;
  Object(Object&& rhs, allocator_type a) : d_name(std::move(rhs.d_name), a) {}

  // Apply rule of 6
  ~Object() = default;
  Object& operator=(const Object& rhs) = default;
  Object& operator=(Object&& rhs) = default;
};
```

Worked Example

```
class Object {
  std::pmr2::string d_name;

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

  Object() : d_name("<UNKNOWN>") {}      // no longer explicit

  Object(const Object& rhs) = default;

  Object(Object&&) = default;
  // Object(Object&& rhs, allocator_type a);

  // Apply rule of 6
  ~Object() = default;
  Object& operator=(const Object& rhs) = default;
  Object& operator=(Object&& rhs) = default;
};
```

Worked Example

```
class Object {
  std::pmr2::string d_name = "<UNKNOWN>";

public:


  Object() = default;

  Object(const Object& rhs) = default;

  Object(Object&&) = default;


  // Apply rule of 6
  ~Object() = default;
  Object& operator=(const Object& rhs) = default;
  Object& operator=(Object&& rhs) = default;
};
```

Worked Example

```
class Object {
  std::pmr2::string d_name = "<UNKNOWN>";

public:

  // Rule of zero !!









};
```

Worked Example

```
class Object {
  std::pmr2::string d_name = "<UNKNOWN>";

public:

  // Rule of zero !!

};

pmr::multipool_resource res;
Object x{"Hello world”} using res;
```

Implementing Awareness

- Stash an allocator pointer at construction, much like a vtable pointer
  - does not vary through constructing a hierarchy though
- Customization API to give precise control of storage if needed
  - e.g., optional object needs to stash allocator when empty, but can re-use the storage for the missing object
- If awareness is *implicit*, access the allocator through the entity granting awareness
  - do not pay to store excess copies of the pointer
  - Leaf nodes of data structures will always need a pointer though

Implicit Awareness

- In most cases, allocator awareness will be implicit, greatly reducing the implementation cost for user code

- Implicit awareness clearly implies a new language feature

- Implicit awareness can be supported by C++11 containers, using an allocator-aware allocator object (i.e., the allocator template parameter)

Allocator Injection

- Inject an allocator at object creation time, in addition to constructor arguments
    - needs language support with an extension syntax (such as `using`)
    - `new` operator one obvious customization, but need local object support too
- An implicit extra argument for every constructor
    - no constructor spam with allocator overloads
    - process-wide default is provided if not supplied by the caller
        - note: the move constructor is special
- Implicitly propagate that injection through member initializers for all bases and members
    - but **not** into constructor body

Early Experience

Sean Baxter and Circle

- Sean Baxter has written his own C++20 compiler with an LLVM back-end over the last 3 1/2 years
- Designed for rapid prototyping and language evolution, ultimately to advance his own post-C++ language, Circle

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- After seeing previous talks online, implemented allocator injection through `using` in around a week…

Injecting Allocators with `using`

- Works well on existing standard library
- Relies on existing allocator_type mark-up, and existing allocator-aware constructors
  - No implicit generation (yet)
- CTAD support fell out for free
  (Constructor Template Argument Deduction)
- Supports full C++20 allocator model, *not* limited to `pmr`

```
// allocator-specifier in initializers and postfix-expressions

#include <list>
#include "logger.hxx"

int main() {
  logging_resource_t logger("logger");

  // using-allocator in a braced initializer for a declaration.
  // creates a PMR list when the allocator expression derives
  // memory_resource.
  pmr::list<int> my_list { 1, 2, 3 } using logger;

  // using-allocator in a braced initializer on an expression.
  auto my_list2 = pmr::list<int> { 4.4, 5.5, 6.6 } using logger;
}
```

Factory Functions

- Functions that return a new object by value
  - e.g., `std::make_shared`, `std::to_string`
- How should we provide an allocator for the return value?
  - Pass an extra function argument?
  - Add `using` support?

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  - Add `using` support (explicit for overloading, or implicit)

Factory Functions

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- How should we provide an allocator for the return value?
  - Add `using` support
- How do we avoid redundant allocations with default allocator inside the factory?

The Conundrum

What should we do with an extended move constructor?

```
template <class T>
struct NamedValue {
   std::string name;
   T           value;

   NamedValue(NamedValue&&)             = default;
   NamedValue(NamedValue&&) using Alloc = default;
};
```

Option 1

- Member initializers call extended-move-with-allocator for each base and member

- The classes that handle memory allocation directly (i.e., vector, rather than class with a vector member) will implement the custom logic to test the allocator, and move or make copies as needed

- Supports move-only types as members, as long as they manage any extended-move logic themselves, which is trivial by default for *non*-allocator aware types

Option 2

- Test whether the allocators are compatible
- If compatible, delegate directly to the regular move constructor
- If incompatible, delegate to the extended copy constructor
- Ill-formed if the extended copy constructor is not available
- (ideally) provide custom overload to handle non-default cases.

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Internal Pointers

```
struct highlight {
   std2::vector<int> d_values;
   int * d_focus;  // invariant: points to an element in d_values

   highlight(highlight const &) = delete;
   highlight(highlight&&)       = default;
};
```

Internal Pointers

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Copying `d_focus` would violate invariant so `delete` the copy constructor. Alternatively, implement with a look-up to fix up pointer to the corresponding element.

Internal Pointers

```
struct highlight {
   std2::vector<int> d_values;
   int * d_focus;  // invariant: points to an element in d_values

   highlight(highlight const &);   // user provided
   highlight(highlight&&)         = default;
};
```

Copying `d_focus` would violate invariant unless allocators match.
Option 2 is the only safe default: delegate to copy if allocators do not match, and `using` construction (but not regular move) is deleted if copy constructor is deleted.

Dispatching Extended Move

```
struct highlight {
   std2::vector<int> d_values;
   int * d_focus;  // invariant: points to an element in d_values

   highlight(highlight const &other)
   : d_values(other.d_values)
   , d_focus(nullptr)
   {
      // maybe find new address for d_focus in d_values
   }

   highlight(highlight&& other) = default;

   highlight(highlight&& other) [[?]]  // magical using overload
   : highlight(copy_or_move(other)) {} // delegating constructor

private:
   // factory function
   static highlight copy_or_move(highlight& other) {
      if (allocator_of(other) == allocator_of(copy_or_move)) {
         return std::move(other);
      }
      else {
         return other;
      }
   }
};
```

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Next Step

Basic Feature Set

- Pass allocators to *factory* functions and initializers through extra `using` argument
- A special allocator type that imbues enclosing classes as allocator aware
  - Fundamental type to avoid specifying customization interface
  - Acts like a reference to a `pmr::memory_resource`
- *All* constructors of allocator aware type are implicitly allocator aware
  - Move constructor is special and split in two
- allocator_of implicit hidden friend function
- *Implicit* factory functions (only)

Implicit Factory Functions

- Support a using when return type is allocator aware
    - Will explore what it means when calling from templates
- Implicitly supply allocator to return value
- Where guaranteed (N)RVO applies, supply allocator to variable declarations
    - P2025 Guaranteed Copy Elision for Named Return Objects

Validation Tests

- std2::string
- std2::vector<T>
- std2::vector<std2::string>
- aggregate classes
- local arrays
- std::array
- std::tuple
- std::pair
- lambda expressions

Open Questions

- Argument passing in factory functions
- Explicit factory functions
- Overloading constructors on allocator
- More customization points
    - e.g. overloading `allocator_of` to avoid redundant copy in optional
- `using` in more places, such as function arguments?
- Unions and `variant`

Fin