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Managing Heterogeneous Device Memory using C++17 Memory Resources

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Introduction

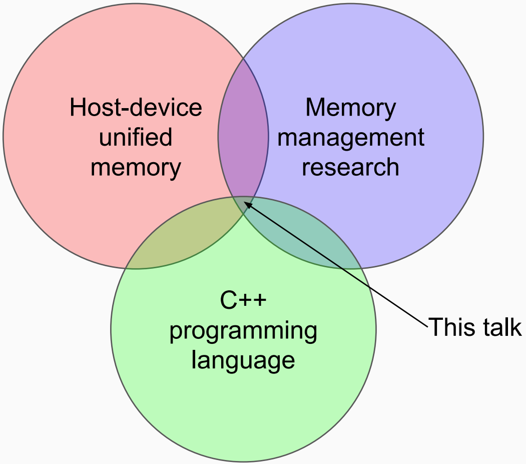
- Writing heterogeneous code is difficult! Traditional CPU programming skills do not always carry over.
  - Often requires fundamentally different algorithm design.
  - Many considerations that are not necessary in “traditional” CPU programming.
- Heterogeneous platforms, by and large, use a memory management paradigm that is not compatible with what we teach domain scientists.
  - Heterogeneous memory management is often *highly explicit*.
  - Heterogeneous memory management is often slow!
- Together with much longer allocation times, this creates a mine field of bugs (functional and non-functional).

vecmem

- In this talk: *vecmem*, a C++ library that brings performance and ergonomics to heterogeneous memory.
- We allow users to use device memory...
  - ...with the same easy-to-use semantics as STL containers;
  - ...with the safety of modern RAII;
  - ...with the performance of host memory.

vecmem

- We exist at the intersection of three areas of development:
  - Recent additions to the C++ standard (specifically *memory resources*);
  - Unified shared memory, accessible transparently from both host and device;
  - Memory management methods, including sub-allocation schemes.



Memory resources

- Polymorphic *memory resources* are a C++17 standard library feature.
  - However, adoption has been slow: ***libstdc++*** added support in 9.1 (2019), ***libc++*** is still lacking full support.
- These resources allow us to make run-time decisions about the allocation schemes used by STL containers.
- *We do not claim novelty* on the design of memory resources – this is part of the library standard.

```
int main(void) {
    std::vector<int> v;

    // Resizing of this vector is
    // handled by the internal logic
    // of the vector class.

    v.push_back(5);
    v.push_back(10);
    v.push_back(2);
}
```

```
int main(void) {
    std::pmr::memory_resource *res = ...;
    std::vector<int,... > v(res);

    // Here, all allocations and
    // deallocations are handled
    // by the memory resource.

    v.push_back(5);
    v.push_back(10);
    v.push_back(2);
}
```

Memory resources

- One of the core ideas: “hijack” the functionality of memory resources to return device(-accessible) memory.
- This allows us to ergonomically put data into device memory without necessarily having to worry about transferring it.

```
int main(void) {
    vecmem::cuda::managed_memory_resource mem;
    vecmem::vector<int> vec(&mem);

    // All data that we insert into
    // this vector is transparently
    // accessible on the device!

    v.push_back(5);
    v.push_back(10);
    v.push_back(2);

    my_kernel<<<...>>>(vecmem::get_data(vec));
}
```

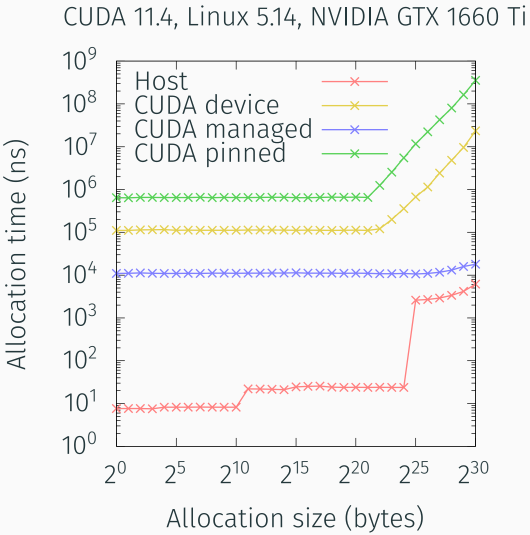
Heterogeneous memory resources

- At this time, vecmem supports nine memory resources across four platforms:
  - Host memory
  - CUDA
    - Device memory[1]
    - Managed memory
    - Pinned host memory
  - HIP / ROCm
    - Device memory
    - Pinned host memory
  - SYCL
    - Device memory[1]
    - Host memory
    - Shared memory

[1] Device-only memory is supported, but with a smaller feature set.

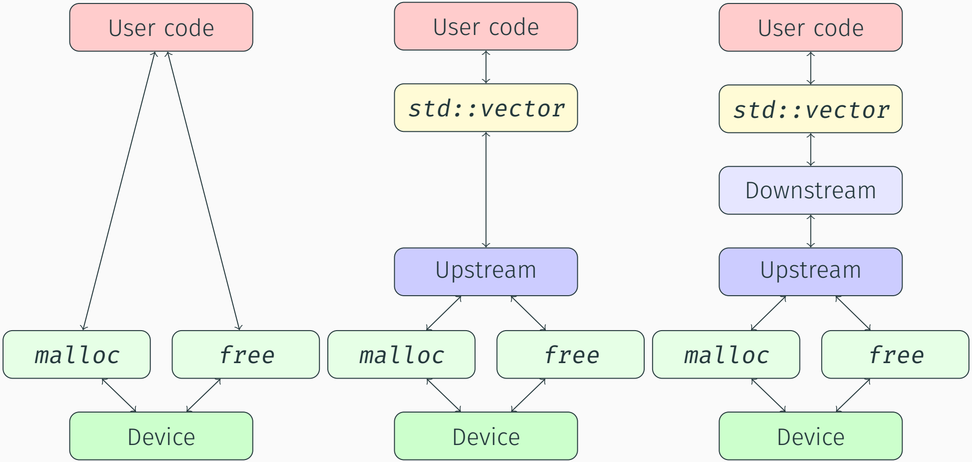
Performance considerations

- This gives us the tools to ergonomically manage memory on a bunch of platforms!
- But doing this naively is a performance death trap...
- C++ allocation and deallocation patterns assume very low overhead.
- We need a *translation layer* to platform-friendly allocation patterns.
- For example, the CUB caching allocator, but this has some issues:
    - Only works for CUDA device memory.
    - Only supports one caching scheme.



Composition

- *vecmem* solves the same problem by taking a compositional approach.
  - Compositionality is *the* way to control complexity in computation, so why not in memory?



Downstream resources

- With *vecmem*, we can construct a caching allocator for CUDA from its components:
  - An upstream CUDA resource;
  - A downstream caching allocator.
- In this example, we use a buddy allocator.
- More caching resources available, such as an arena allocator.

```
int main(void) {
    vecmem::cuda::device_mr up;
    vecmem::buddy_mr dn(up);
    vecmem::vector<int> v(&dn);

    // The first allocation hits the
    // device.

    v.reserve(1024);

    // The following allocations
    // use the cached memory!
    v.shrink_to_fit();
    v.reserve(1024);
    v.shrink_to_fit();
    v.reserve(512);
}
```

Downstream resources

- Downstream resources form a monoid $\langle \mathcal{M}^{\downarrow}, \circ \rangle$ under composition[1].
- This means that we can create arbitrarily complex allocation schemes out of simple components.
    - Caching memory resources
    - Conditional memory resources
    - Side-effecting memory resources
- Also, we can do this *at runtime*, allowing us to treat memory management as a tunable hyperparameter.
- This compositional design delivers high potential for code re-use.
    - New upstream resources can immediately be used with all of our downstream resources.
    - New downstream resources can immediately be used with all of our upstream resources.

[1] This follows from the definition of $\mathcal{M}^{\downarrow}$ as an endomorphism: $\mathcal{M} \to \mathcal{M}$.

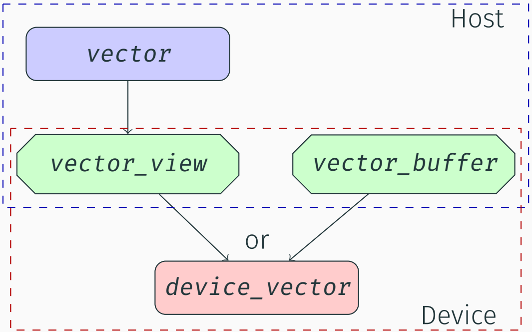
Device code

- *vecmem* makes managing memory on the *host* easier.
- We also provide STL-like containers on the *device*!
    - “Real” STL containers are not supported in device code, regardless of where they are allocated.
- This provides *source-level* portability between device code and host code (often without templating).
- Many modern C++ concepts and semantics are supported on the device.

```
__global__
void kernel(vecmem::vector_view<float> a_data) {
    vecmem::device_vector<float> a_device(a_data);

    float a1 = a_device.at(1);

    ...
}

int main() {
    vecmem::cuda::managed_memory_resource mr;
    vecmem::vector<float> a_host(&mr);

    ...

    kernel<<<...>>>(vecmem::get_data(a_host));
}
```

Device code

- Device containers are created from convenient data-management objects.
- Container data can be elegantly moved to and from the device using:
  - Owning *buffer* types;
  - Non-owning *view* types.
- Light-weight types that can be passed by value to device kernels.
- Provide the tools necessary to work with host-inaccessible memory.



Device code

- *vecmem* vectors provide support for limited insertion on the device.
    - Requires sufficient capacity allocated before kernel launch.
- We also support a variety of other datatypes on the device side:
    - Jagged vectors, vectors-of-vectors of different sizes.
    - Static vectors, with compile-time fixed capacity.
    - Arrays of compile-time static size, for environments where ***`constexpr`*** relaxation is not available.

Conclusions

- Memory management in C++ and heterogeneous platforms has diverged significantly.
- Clever use of *memory resources* allow us to use them for heterogeneous allocation.
- *vecmem* delivers the tools necessary to do this, as well as device-side containers.
- Available under the MPL 2.0 license at `https://github.com/acts-project/vecmem`.