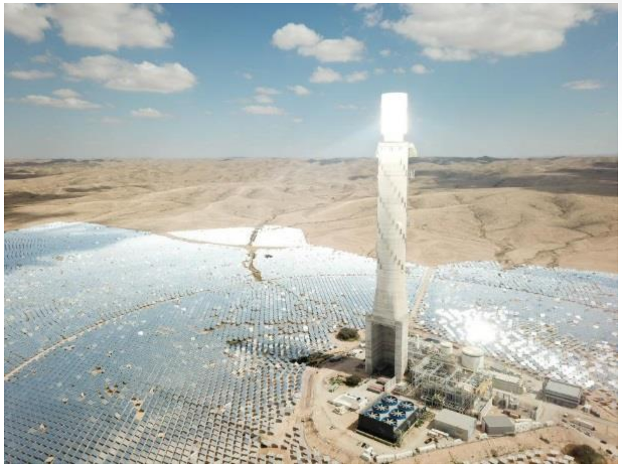

# C++ Programming for the Heap-Deprived

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# Agenda

- Why do we use heap allocations?
- Why not to use heap allocations?
- Use cases and no-heap replacements

# !Agenda

- Containers of unknown sizes
  - Memory pools
  - Allocators

# Storage Duration

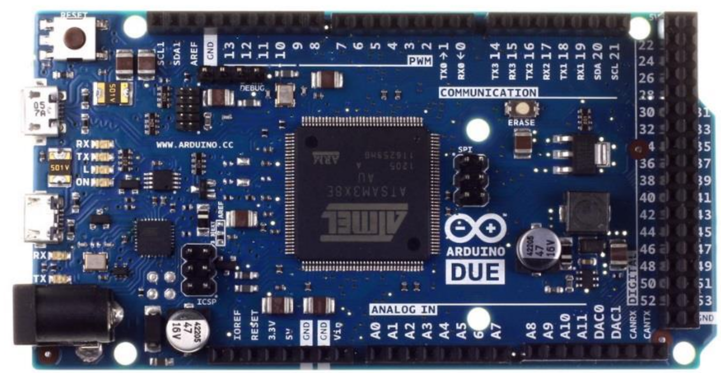
- **Static**:
  - Duration is entire program lifetime. Address is set at link time.
- **Automatic**:
  - aka stack. Automatic variables. Address depends on flow.
- **Dynamic**:
  - aka heap. Manually managed. Address depends on flow.
- (**Thread** – not relevant for this talk)

# Why Use Dynamic Allocations?

- Decide on required memory size at runtime
- Separate allocation and initialization context from object lifetime

# Memory Usage in Micro Controllers

- Direct access to memory – a single memory space
- Define memory sections manually
- Define your own stack(s) memory area
- Define exact memory locations of some data items
- RAM is usually very limited



# Problems with using the Heap

Why not to allocate?

- No determinism
  - We want data addresses to be known in advance
- Memory fragmentation
- Runtime failures
  - We don't want memory-related runtime failures
- Runtime performance

# Memory Pools

- A good solution, but not for this problem
- Might solve fragmentation if designed correctly
- Does not help with determinism and runtime failures

# C++ Standard

- Classes which are guaranteed not to use dynamic memory allocation:
  - Optional

When an instance of optional<T> *contains a value*, it means that an object of type T, referred to as the optional object's *contained value*, is allocated **within the storage** of the optional object. **Implementations are not permitted to use additional storage, such as dynamic memory**, to allocate its contained value.

**23.6.3 Class template optional**

  - Variant

When an instance of variant holds a value of alternative type T, it means that a value of type T, referred to as the variant object's *contained value*, is allocated **within the storage** of the variant object**. Implementations are not permitted to use additional storage, such as dynamic memory**, to allocate the contained value.

**23.7.3 Class template variant**

# Use case 1: A global application object

Ideal – value semantics, app is on stack

```
int main()
{
    MyBigApplication app;
    app.run();
}
```

# Use case 1: A global application object

Heap-Based - Next best thing: Wrap memory allocation with value semantics, app is on heap

```
int main()
{
    auto app = std::make_unique<MyBigApplication>();
    app->run();
}
```

# Use case 1: A global application object

With no heap allocation

```
int main()
{
    auto app = ???;
    app->run();
}
```

Where should we store app?

# Use case 1: A global application object

- We want to separate storage duration from object lifetime
- Storage will:
  - Have static duration
  - Be initialized dynamically

```
int main()
{
    static MyBigApplication app;
    app->run();
}
```

# Use case 1: A global application object

- A little too static?

```
int main()
{
    if (isNewerHardware())
    {
        static MyBigApplication app(port1, port2, port3);
        app.run();
    }
    else
    {
        static MyBigApplication app(port1);
        app.run();
    }
}
```

Memory will be allocated for both instances

# Use case 1: A global application object

- Use a static/global variable of type Lazy

```
static Lazy<MyBigApplication> s_app;

int main()
{
    MyBigApplication* app;
    if (isNewerHardware())
    {
        app = &s_app.construct(port1, port2, port3);
    }
    else
    {
        app = &s_app.construct(port1);
    }
    app->run();
}
```

# C++11: std::aligned_storage

```
template< std::size_t Len, std::size_t Align = /*default-alignment*/ >
struct aligned_storage;
```

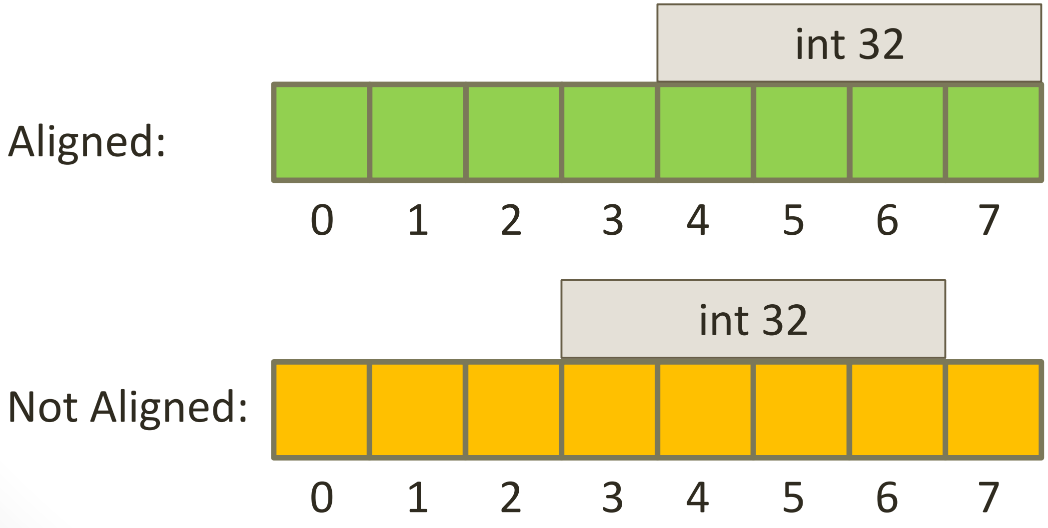
- Usage:

```
std::aligned_storage<8, 4>::type buffer;
```

- Provides an uninitialized storage
- Actual size and alignment are implementation defined
- C++14: std::aligned_storage_t = std::aligned_storage::type

# Memory Alignment in C++

- Each type has its own requirement for alignment, depending on hardware
- Alignment is always a power of 2
- Compilers will take care of that for you. If you let them.
  - #pragma pack doesn't let them
- C++11 added two keywords: alignof, alignas



# Uninitialized Storage for the Unlucky

- Pre-C++11

```
template <class T>
struct Storage
{
    uint64_t buffer[sizeof(T) / 8 + 1];
};
```

# Placement New

- Can be used to construct an object in a pre-allocated memory block
- For example:

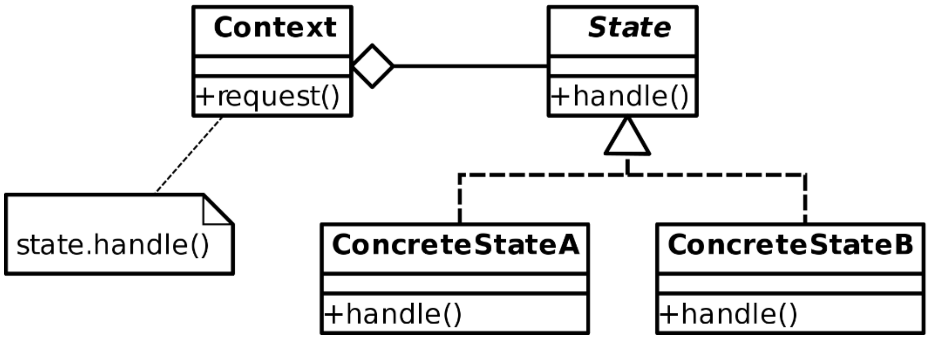
```
struct A { ... };

alignas(A) char buffer[sizeof(A)];

// No allocation, only in-place construction
A* a = new (buffer) A();

// Explicit destruction
a->~A();
```

# Lazy Initialization

```
template <class T>
class Lazy
{
    std::aligned_storage_t<sizeof(T), alignof(T)> m_storage;
    bool m_isInitialized = false;
public:
    ~Lazy() { destruct(); }

    template <typename... Args> T& construct(Args&&... args)
    {
        auto obj = ::new (&m_storage) T(std::forward<Args>(args)...);
        m_isInitialized = true;
        return *obj;
    }

    void destruct()
    {
        if (m_isInitialized)
        {
            get().~T();
            m_isInitialized = false;
        }
    }

    T& get() { return *reinterpret_cast<T*>(&m_storage); }
};
```

# Use case 2: State Pattern

- Structure:




https://commons.wikimedia.org/wiki/File:State_Design_Pattern_UML_Class_Diagram.png

# Use case 2: State Pattern

- We only need a single state object at a time
- Heap-based implementation:

```
// Given:
struct BaseState {};
struct State1 : public BaseState {};
struct State2 : public BaseState {};
struct State3 : public BaseState {};
struct State4 : public BaseState {};
struct State5 : public BaseState {};

// Use (within a context object):
std::unique_ptr<BaseState> currentState;
currentState = std::make_unique<State1>(*this);

currentState->event();
```

# Use case 2: State Pattern

- No heap – need a storage
- std::variant?
  - C++17…
  - Initial state (monostate)

- Something else:

```
std::aligned_storage_t<sizeof(???), alignof(???)> stateBuffer;
```

- How big?

# Use case 2: State Pattern

- Find maximum size for allowed types – tail recursion:

```
template <typename First, typename... Args>
struct MaxSize
{
    static const std::size_t Size =
         MaxSize<First>::Size > MaxSize<Args...>::Size ?
               MaxSize<First>::Size :
               MaxSize<Args...>::Size;
};
```

```
template <typename First>
struct MaxSize<First>
{
    static const std::size_t Size = sizeof(First);
};
```

```
// C++14
template <typename... Args>
constexpr std::size_t MaxSize_v = MaxSize<Args...>::Size;
```

And similarly for alignment

# Use case 2: State Pattern

- MaxSize for the Unlucky (pre-C++11):

```
template <typename T1, typename T2 = void, typename T3 = void,
          typename T4 = void, typename T5 = void>
class MaxSizeLegacy
{
    static const std::size_t TailSize =
         MaxSizeLegacy<T2, T3, T4, T5>::Size;
public:
    static const std::size_t Size =
           (MaxSizeLegacy<T1>::Size > TailSize) ?
               MaxSizeLegacy<T1>::Size :
               TailSize;
};

template <typename Type>
struct MaxSizeLegacy<Type, void, void, void, void>
{
    static const std::size_t Size = sizeof(Type);
};
```

# Use case 2: State Pattern

- And usage (assuming we know all types):

```
template <class BaseClass, class... DerivedClasses>
class GenericHierarchyFactory
{
    std::aligned_storage_t<
        MaxSize_v<DerivedClasses...>,
        MaxAlign_v<DerivedClasses...>
    > m_buffer;

    ...
};
```

# Use case 2: State Pattern

```
template <class BaseClass, class... DerivedClasses>
class GenericHierarchyFactory
{
    // std::aligned_storage_t<...> m_buffer;
    BaseClass* m_currentObject = nullptr;
public:
    template <class Derived, typename... ConstructionParams>
    BaseClass& construct(ConstructionParams&&... params)
    {
        static_assert(sizeof(Derived) <= sizeof(decltype(m_buffer)),
                "Derived class is too big for buffer");
        static_assert(alignof(Derived) <= alignof(decltype(m_buffer)),
                "Derived class is misaligned for buffer");

        auto createdObject = ::new (&m_buffer)
               Derived(std::forward<ConstructionParams>(params)...);
        m_currentObject = static_cast<BaseClass*>(createdObject);
        return *m_currentObject;
    }
 ...
};
```

# Use case 2: State Pattern

```
template <class BaseClass, class... DerivedClasses>
class GenericHierarchyFactory
{
    ...
    void destruct()
    {
        if (m_currentObject)
        {
            m_currentObject->~BaseClass();
            m_currentObject = nullptr;
        }
    }
};
```

Why do we need to store BaseClass* in addition to buffer?

# Use case 2: State Pattern

- Usage:

```
GenericHierarchyFactory<BaseState, State1, State2,
                        State3, State4, State5> stateFactory;

BaseState* state = &stateFactory.construct<State1>();
stateFactory.destruct();

state = &stateFactory.construct<State2>(1, 2, 3.4f);
stateFactory.destruct();
```

# Use case 3: Type-Erased Function Object

- Type erasure comes at a cost:
  - Indirect call (virtual function) – usually minor
  - Code size (templated called type)
- In some cases not necessary
  - Although will usually still need the virtual call

# Use case 3: Type-Erased Function Object

- Problem definition:
  - Input: Maximum size and alignment
  - Should wrap any callable type
  - If Callable is too big, fail at compile time

# Use case 3: Type-Erased Function Object

- A simplified type-erased function implementation, heap based:

```
template <typename FunctionSignature> class Function;

template <typename ReturnType, typename... Args>
class Function<ReturnType(Args...)>
{
    struct CalleeInterface
    {
         virtual ~CalleeInterface() {}
         virtual ReturnType call(Args&&... args) = 0;
    };

    template <class CalleeType>
    struct Impl : public CalleeInterface
    {
        Impl(CalleeType callee) : m_callee(callee) {}
        virtual ReturnType call(Args&&... args) override
        {
            return m_callee(std::forward<Args>(args)...);
        }
        CalleeType m_callee;
    };

    ...
```

# Use case 3: Type-Erased Function Object

- A simplified type-erased function implementation, heap based:

```
    std::unique_ptr<CalleeInterface> m_impl;

public:
    Function() = default;

    template <typename CalleeType>
    Function(CalleeType callee) :
        m_impl(std::make_unique<Impl<CalleeType>>(callee)) {}

    template <typename CalleeType>
    Function& operator=(CalleeType callee)
    {
        m_impl = std::make_unique<Impl<CalleeType>>(callee);
        return *this;
    }

    ReturnType operator()(Args... args) const
    {
        assert(m_impl);
        return m_impl->call(std::forward<Args>(args)...);
    }
};
```

# Use case 3: Type-Erased Function Object

- That was really super simplified
  - Don’t use in production code
- Now for the storage-based version

# Use case 3: Type-Erased Function Object

- For storage-based, we need a storage for unlimited types:

```
template <std::size_t Size, std::size_t Alignment>
class AnyStorage
{
    std::aligned_storage_t<Size, Alignment> m_storage;
    using DestructorFunction = void(*)(void* objectPtr) noexcept;
    DestructorFunction m_destructorFunction = nullptr;

public:
    template <typename T, typename... Args>
    T& construct(Args&&... args)
    {
        static_assert(sizeof(T) <= sizeof(decltype(m_storage)),
            "Type is too big for buffer");
        static_assert(alignof(T) <= alignof(decltype(m_storage)),
            "Type is misaligned for buffer");
        destruct();
        auto obj = ::new (&m_storage)
                    T(std::forward<Args>(args)...);
        m_destructorFunction = [](void* ptr) noexcept {
                reinterpret_cast<T*>(ptr)->~T(); };
        return *obj;
    }
    ...
```

# Use case 3: Type-Erased Function Object

- For storage-based, we need a storage for unlimited types:

```
template <std::size_t Size, std::size_t Alignment>
class AnyStorage
{
    ...
    void destruct()
    {
        if (m_destructorFunction)
        {
            m_destructorFunction(&m_storage);
            m_destructorFunction = nullptr;
        }
    }

    ~AnyStorage()  { destruct();}

    AnyStorage() = default;

    AnyStorage(const AnyStorage&) = delete;
    AnyStorage(AnyStorage&&) = delete;
    AnyStorage operator=(const AnyStorage&) = delete;
    AnyStorage operator=(AnyStorage&&) = delete;
};
```

# Use case 3: Type-Erased Function Object

- And the InplaceFunction class:

```
template <typename FunctionSignature,
          std::size_t Size, std::size_t Alignment>
class InplaceFunction;

template <typename ReturnType, typename... Args,
          std::size_t Size, std::size_t Alignment>
class InplaceFunction<ReturnType(Args...), Size, Alignment>
{
    AnyStorage<Size, Alignment> m_storage;
    CalleeInterface* m_impl = nullptr;


     ...
```

# Use case 3: Type-Erased Function Object

- And the InplaceFunction class:

```
    ...

public:
    InplaceFunction() = default;

    template <typename CalleeType>
    InplaceFunction(CalleeType callee) :
        m_impl(&m_storage.construct<Impl<CalleeType>>(callee)) {}

    template <typename CalleeType>
    InplaceFunction& operator=(CalleeType callee)
    {
        m_impl = &m_storage.construct<Impl<CalleeType>>(callee);
        return *this;
    }

    ReturnType operator()(Args... args)
    {
        assert(m_impl);
        return m_impl->call(std::forward<Args>(args)...);
    }
};
```

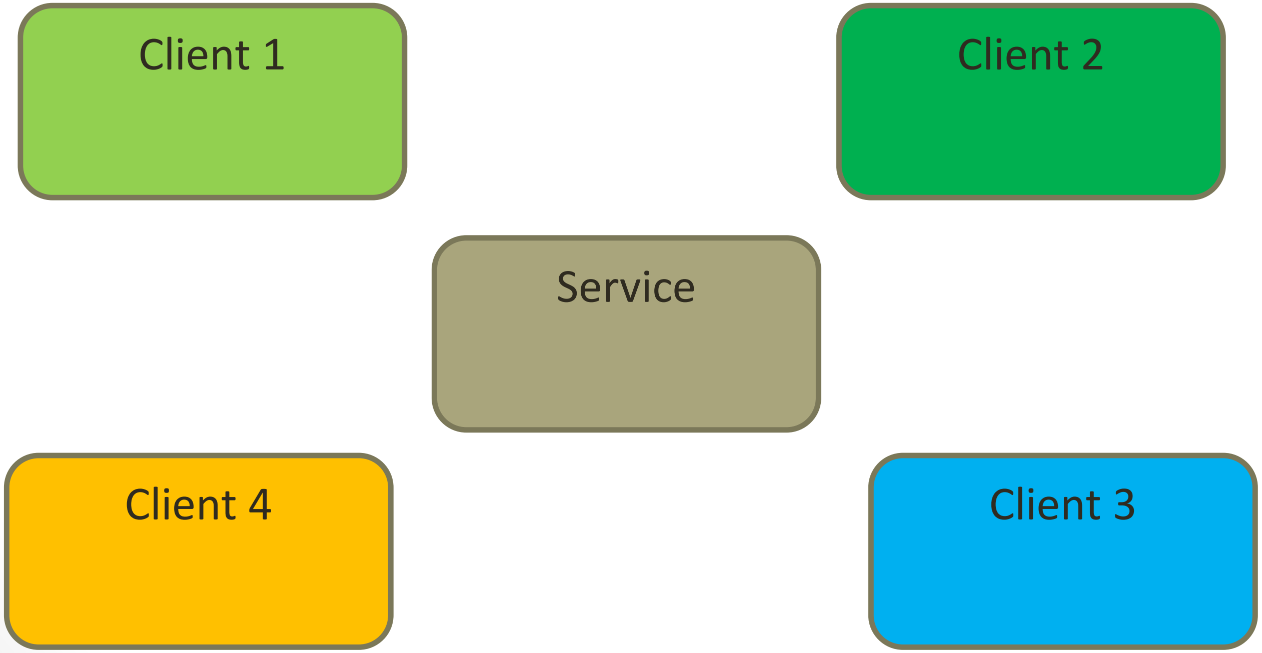
# Use case 3: Type-Erased Function Object

- An already invented wheel:
  - https://github.com/WG21-SG14/SG14
- std::aligned_storage might be bigger than you expect
- Again, super simplified

# Use case 4: Multi-Client Event

**Problem definition:**

- Service class can raise an event
- Multiple Client classes should be able to register to the event
- Service does not know the clients or how many are there



# Use case 4: Multi-Client Event

Two flavors:

- Asynchronous: clients will handle the event in their own flow
- Synchronous: clients will handle the event in the service flow
  - Callbacks

# Use case 4A: Multi-Client Async Event

- “Async” – client will check event on its own cycle.
- No callbacks
- Arbitrary number of ‘observers’
- No multithread synchronization

# Use case 4A: Multi-Client Async Event

What we want to achieve – independent clients:

```
Event e;
e.trigger(); // No observers registered

AsyncObserver o1(e);
AsyncObserver o2(e);

// No triggers since observers construction
assert(o1.wasEventTriggered() == false);
assert(o2.wasEventTriggered() == false);

e.trigger();
e.trigger();

assert(o1.wasEventTriggered() == true);
o1.resetEvent();

// Event was reset for this observer
assert(o1.wasEventTriggered() == false);

// For this observer the event is not reset
assert(o2.wasEventTriggered() == true);
```

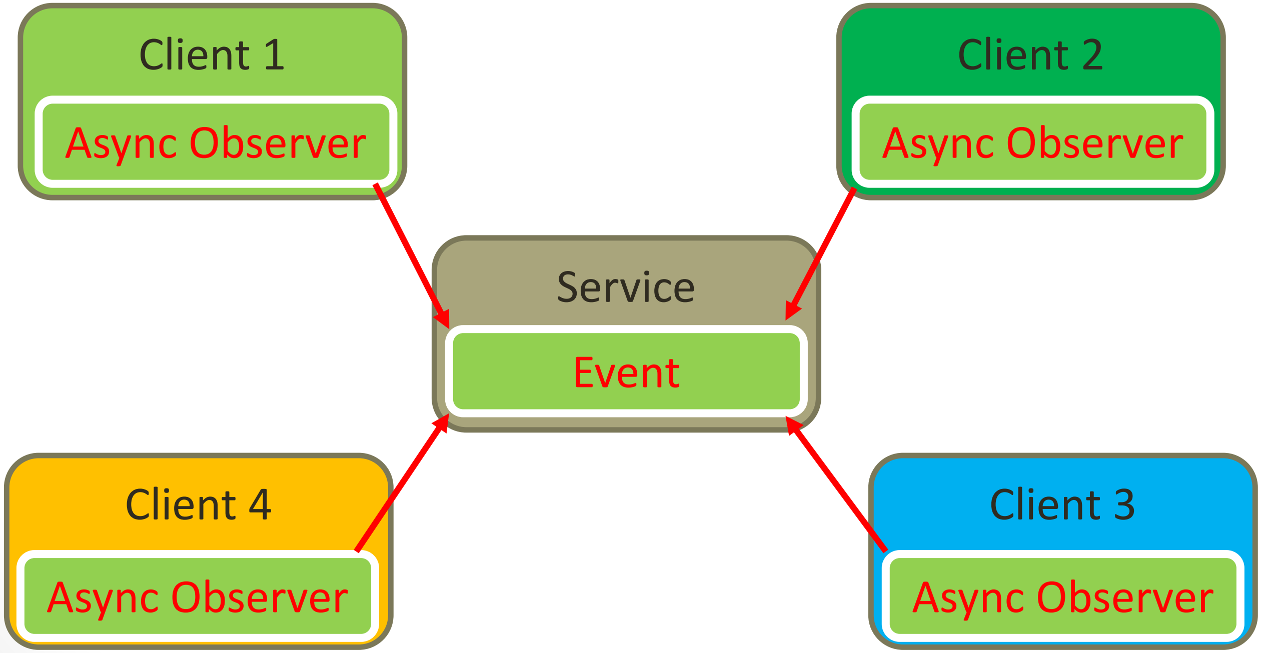
# Use case 4A: Multi-Client Async Event

Can also work with data – application code sample:

```
class Calculator
{
    ConfigurationManager::Observer m_configChanged;

public:
    Calculator(const ConfigurationManager& manager)
    {
        manager.registerForConfigurationChange(m_configChanged);
    }

    void update()
    {
        if (m_configChanged.wasEventTriggered())
        {
            updateParameters(m_configChanged.getLastEventData());
            m_configChanged.resetEvent();
        }
    }
};
```

# Use case 4A: Multi-Client Async Event

- Implementation – no need to hold a list of all clients
- Each observer holds a reference to the event



# Use case 4A: Multi-Client Async Event

- Use an event counter to make the observers independent

```
class BaseEvent
{
public:
    unsigned int getCounter() const { return m_counter; }

protected:
    void countEvent() { ++m_counter; }

private:
    unsigned int m_counter = 0;
};
```

# Use case 4A: Multi-Client Async Event

```
template <typename EventDataType = void>
class Event : public BaseEvent
{
public:
    void trigger(const EventDataType& data)
    {
        countEvent();
        m_lastData = data;
    }
    const EventDataType& getLastData() const { return m_lastData; }

private:
    EventDataType m_lastData;
};
```

```
// No data
template <> class Event<void> : public BaseEvent
{
public:
    void trigger() { countEvent(); }
};
```

# Use case 4A: Multi-Client Async Event

Observer implementation:

```
template <typename EventDataType = void>
class AsyncObserver
{
    const Event<EventDataType>* m_event = nullptr;
    unsigned int m_lastObservedCounter;

public:
    AsyncObserver() = default;
    AsyncObserver(const Event<EventDataType>& event)
    {
        observe(event);
    }

    void observe(const Event<EventDataType>& event)
    {
        m_event = &event;
        resetEvent();
    }

    void resetEvent()
    {
        if (m_event) { m_lastObservedCounter = m_event->getCounter(); }
    }
```

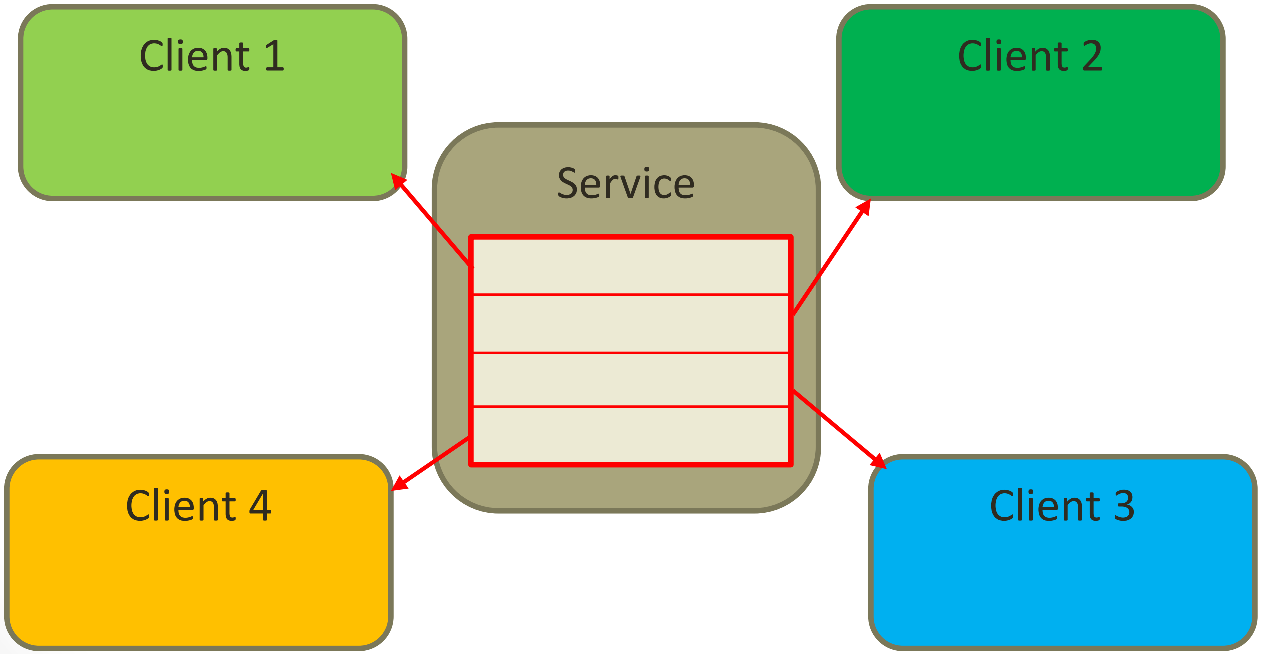
# Use case 4A: Multi-Client Async Event

Observer implementation (cont.):

```
    bool wasEventTriggered() const
    {
        if (!m_event) return false;
        return m_event->getCounter() != m_lastObservedCounter;
    }

    template <class ReturnType = const EventDataType&>
    typename std::enable_if_t<
             !std::is_same_v<EventDataType, void>, ReturnType>
    getLastEventData() const
    {
        assert(m_event);
        return m_event->getLastData();
    }
};
```

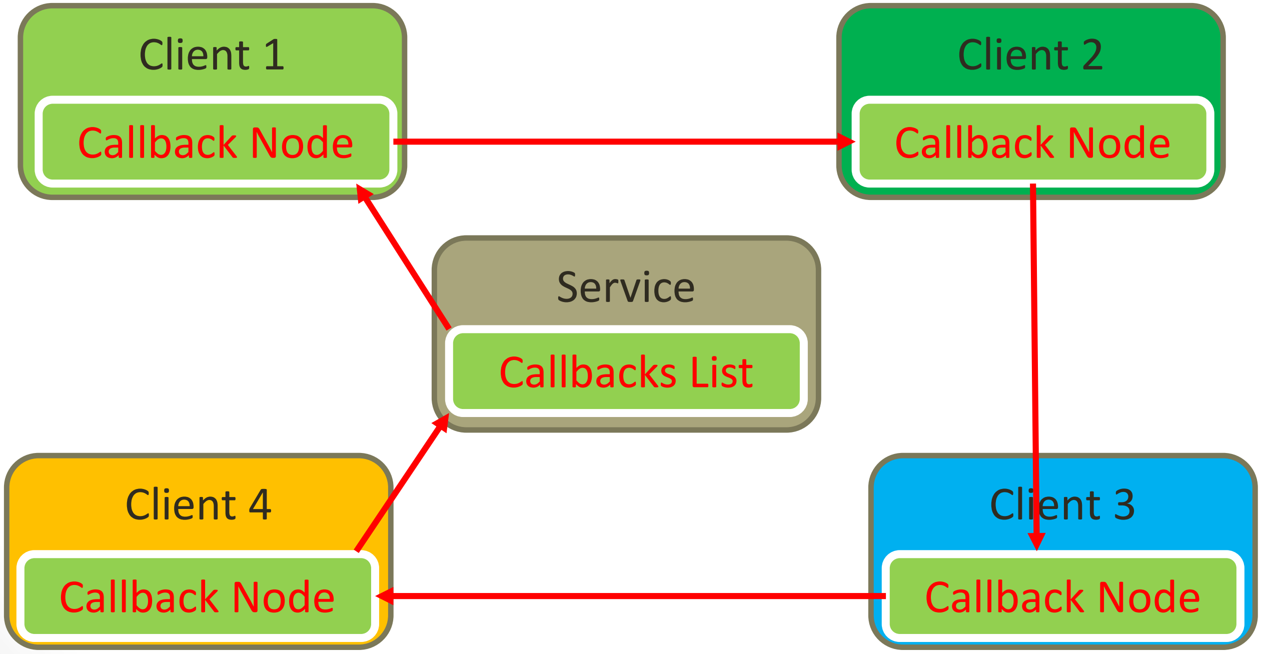
# Use case 4B: Multi-Callback Event

- Heap-based solution:
  - Service class holds a vector<callback>



# Use case 4B: Multi-Callback Event

- Non-heap based solution: Again, a storage issue
- A special case of ‘container of unknown size’:
  - At compile time size is unknown locally, but known globally
- Solution: A ‘distributed’ list, where each node is allocated in the storage of a client



# Use case 4B: Multi-Callback Event

We want to have something like this

(Service interface):

```
class Service
{
public:
    using EventCallbackType = ...;
    void registerCallback(EventCallbackType& item);
    void sendData(const DataItem& data);
};
```

# Use case 4B: Multi-Callback Event

We want to have something like this

(Client implementation):

```
class Client
{
    Service::EventCallbackType myCallbackNode;
    DataItem m_lastData;
    int m_receiveCounter = 0;

public:
    Client(Service& service)
    {
        myCallbackNode.m_callback = [this](const DataItem& data)
        {
            ++m_receiveCounter;
            m_lastData = data;
        };
        service.registerCallback(myCallbackNode);
    }
};
```

# Use case 4B: Multi-Callback Event

Node implementation:

```
template <typename CallbackType>
class CallbacksList;

template <typename CallbackType>
class CallbackNode
{
private:
    using List = CallbacksList<CallbackType>;
    using Node = CallbackNode <CallbackType>;
    friend List;

    List* m_list = nullptr;
    Node* m_next = nullptr;
    Node* m_prev = nullptr;

    ...
```

# Use case 4B: Multi-Callback Event

Node implementation:

```
public:
    CallbackType m_callback;

    ~CallbackNode() { unlink(); }
    bool isLinked() { return m_list != nullptr; }

    void link(List& list)
    {
        unlink();
        m_list = &list;
        m_list->addToEnd(*this);
    }
    void unlink()
    {
        if (!isLinked()) { return; }
        m_list->remove(*this);
        m_list = m_next = m_prev = nullptr;
    }
    template <typename DataType>
    void onEventRaised(const DataType& data)
    {
        m_callback(data);
    }
};
```

# Use case 4B: Multi-Callback Event

List implementation:

```
template <typename CallbackType>
class CallbacksList
{
public:
    using Node = CallbackNode <CallbackType>;

    template <typename DataType>
    void trigger(const DataType& data)
    {
        auto node = m_head;
        while (node)
        {
            node->onEventRaised(data);
            node = node->m_next;
        }
    }
    ...
```

# Use case 4B: Multi-Callback Event

List implementation:

```
template <typename CallbackType>
class CallbacksList
{
    ...
private:
    Node* m_head = nullptr;
    Node* m_tail = nullptr;

    // Called within Node::link()
    void addToEnd(Node& node) { ... }

    // Called within Node::unlink()
    void remove(Node& node) { ... }
    friend Node;
};
```

# Use case 4B: Multi-Callback Event

Service implementation:

```
class Service
{
public:
    using CallbackType = InplaceFunction<void(const DataItem&), 8, 8>;
    using EventCallbackList = CallbacksList<CallbackType>;
    using EventCallbackType = EventCallbackList::Node;

private:
    EventCallbackList m_dataList;

public:
    void registerCallback(EventCallbackType& item)
    {
        item.link(m_dataList);
    }

    void sendData(const DataItem& data)
    {
        m_dataList.trigger(data);
    }
};
```

# Summary

**To avoid dynamic memory allocations:**

- Use static instead of automatic storage
- Use std::aligned_storage, except where actual size is important
- Use compile time size calculations if possible types are known at compile time
- To get type erasure, specify maximum size and alignment and check at compile time
  - For a function wrapper, use an existing solution
- Even if container size is unknown at compile time locally, it might be known globally, so can use other code for storage
  - Distributed list of callbacks