accu
2023

TRIVIAL RELOCATION THROUGH TIME

MUNGO GILL

Trivial Relocation Through Time

A historical perspective on *trivial relocation* and `memcpy`

ACCU 2023
April 21, 2023

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TechAtBloomberg.com

Bloomberg Engineering

Introduction: Who am I?

- Senior Software Engineer at Bloomberg
- Over 20 years of C++ experience
- Various technology and finance companies

Contents

- What problem are we trying to solve?
- How are libraries working around the issue now?
- What proposals are there to solve this?
    - In the past
    - In the present
- Where do we go from here?
- Questions?

Why do we care about trivial relocation?

- What problem are we trying to solve?
- Some background: a short history lesson
    - The C++03 way
    - The C++11 way
    - Going further

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Growing a vector the C++03 way

```
class MyClass {
  public:
    MyClass();
    MyClass(const MyClass &);
};

int main()
{
    std::vector<MyClass> data;

    data.push_back(MyClass());
    // … 3 more times

    data.push_back(MyClass());
}
```

What happens here?

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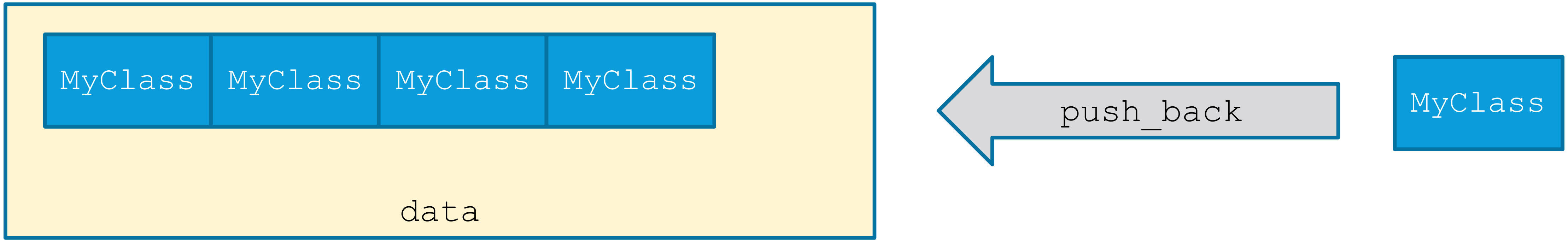
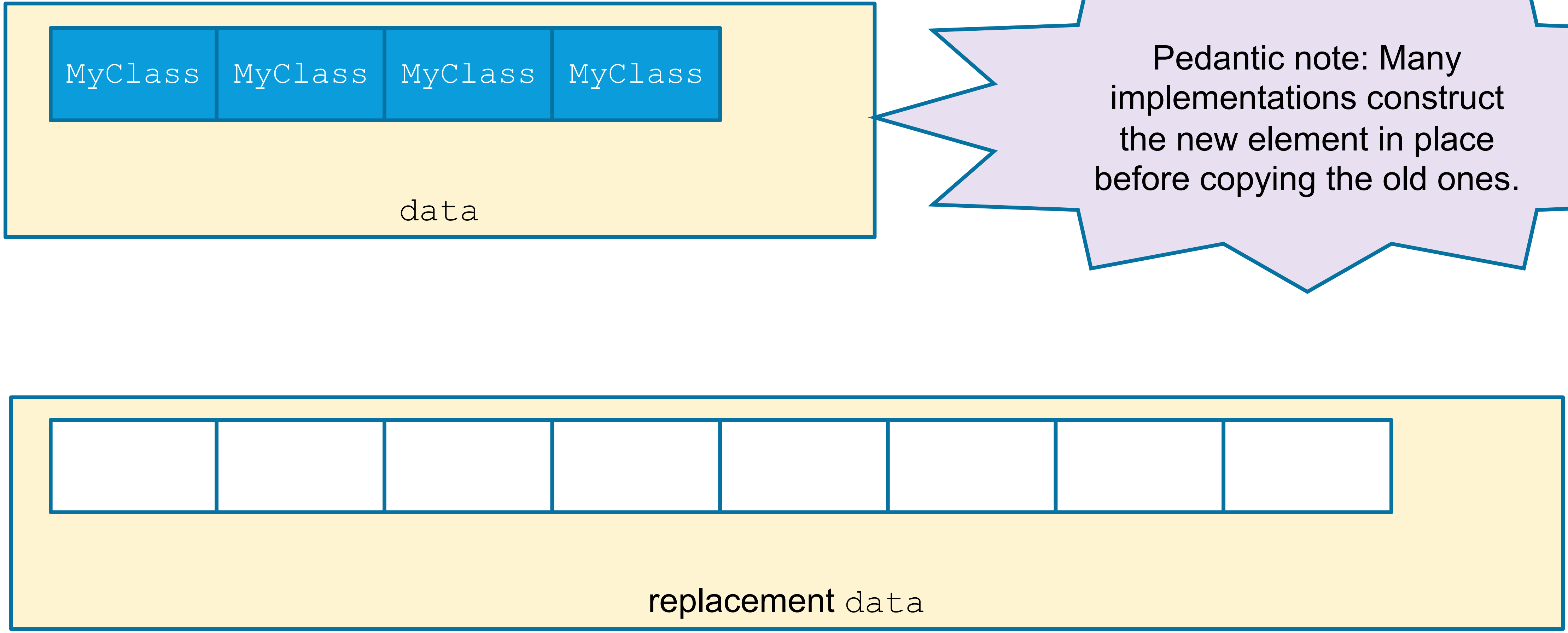
Growing a vector the C++03 way



`data` **is not big enough!**

It needs to grow!

Growing a vector the C++03 way



Pedantic note: Many implementations construct the new element in place before copying the old ones.

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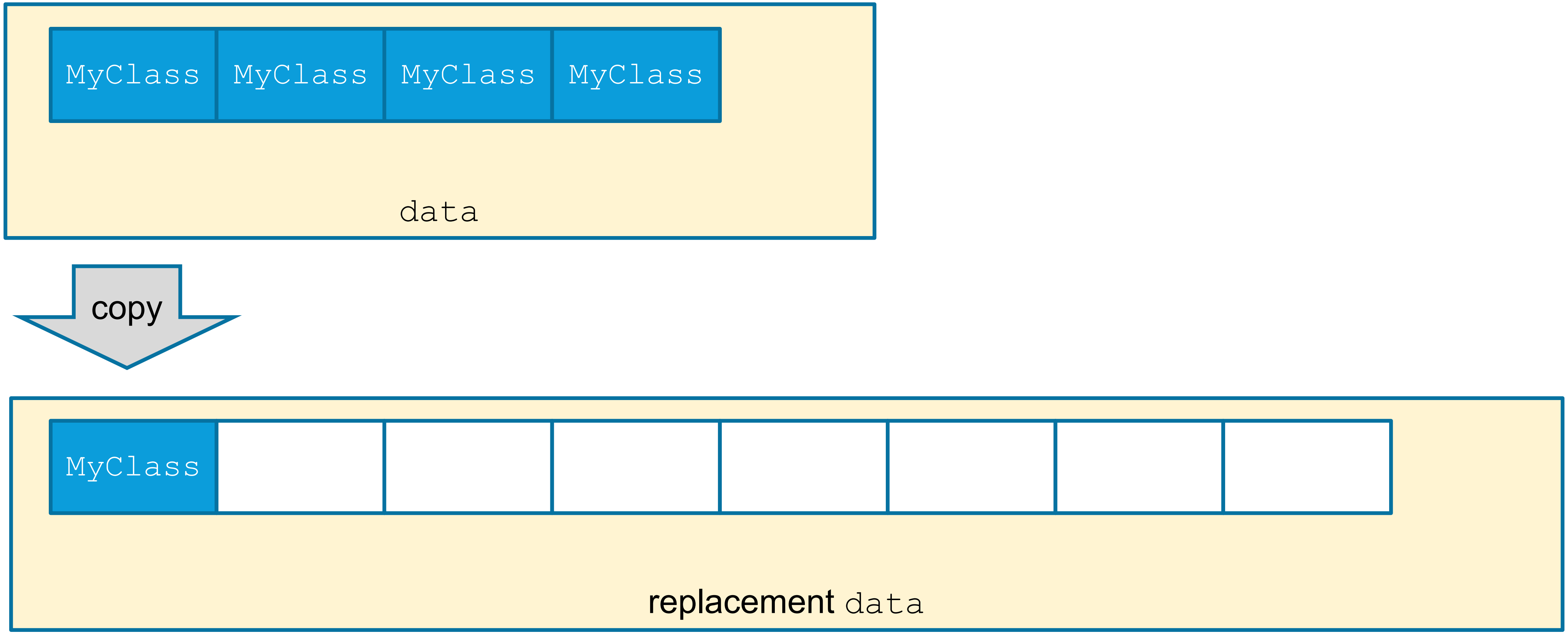
Growing a vector the C++03 way



MyClass MyClass MyClass MyClass

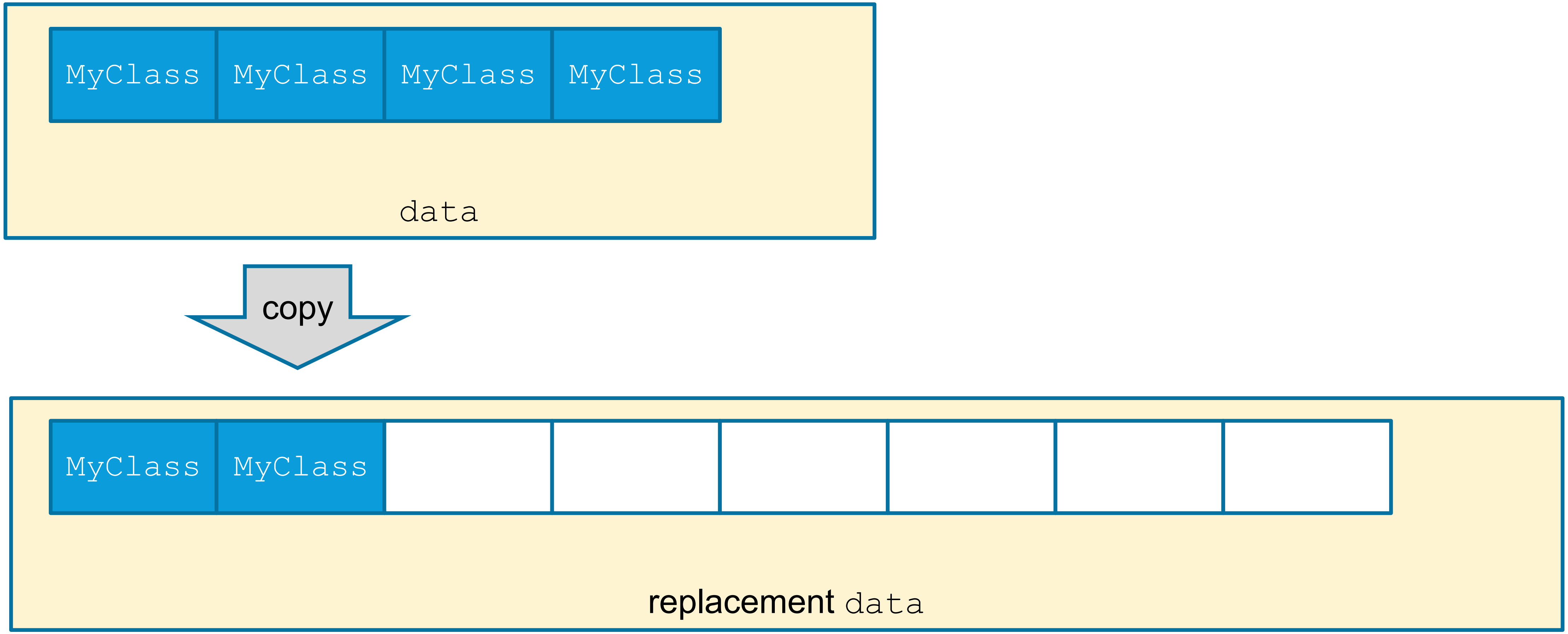
data

copy

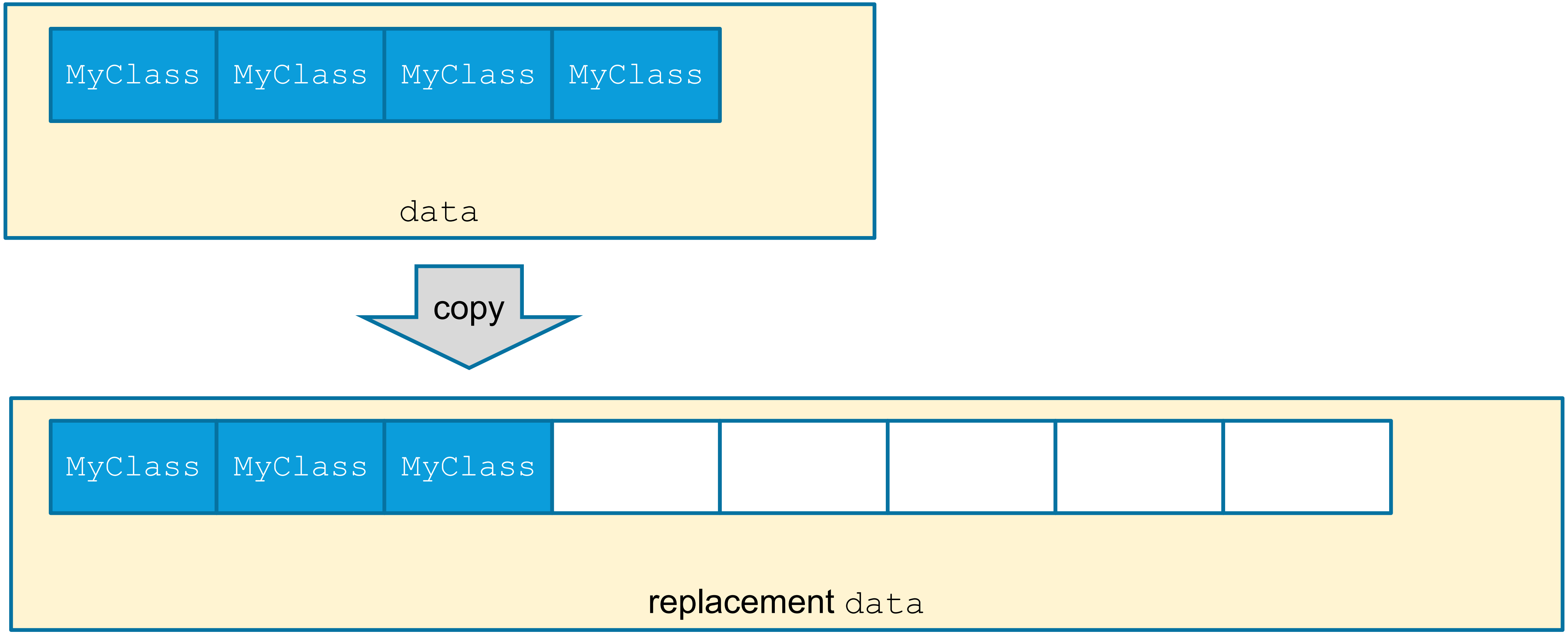
MyClass

replacement data

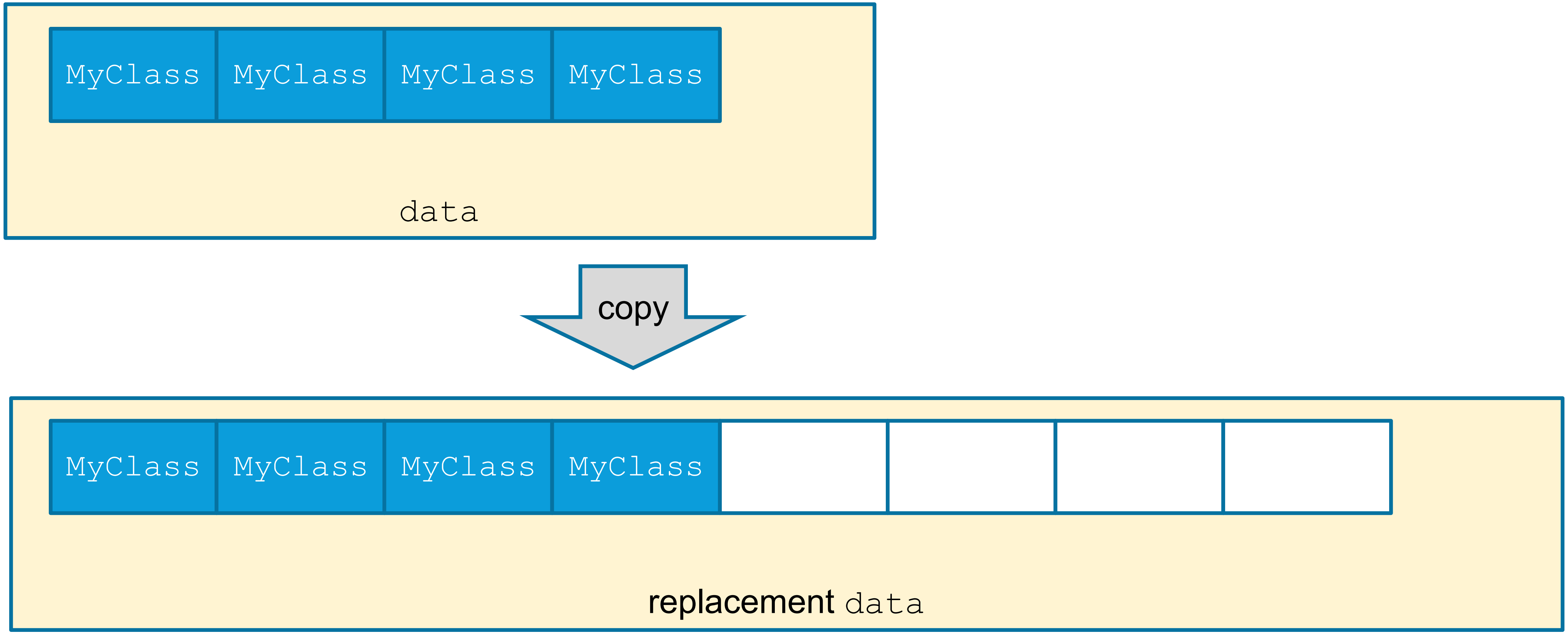
Growing a vector the C++03 way



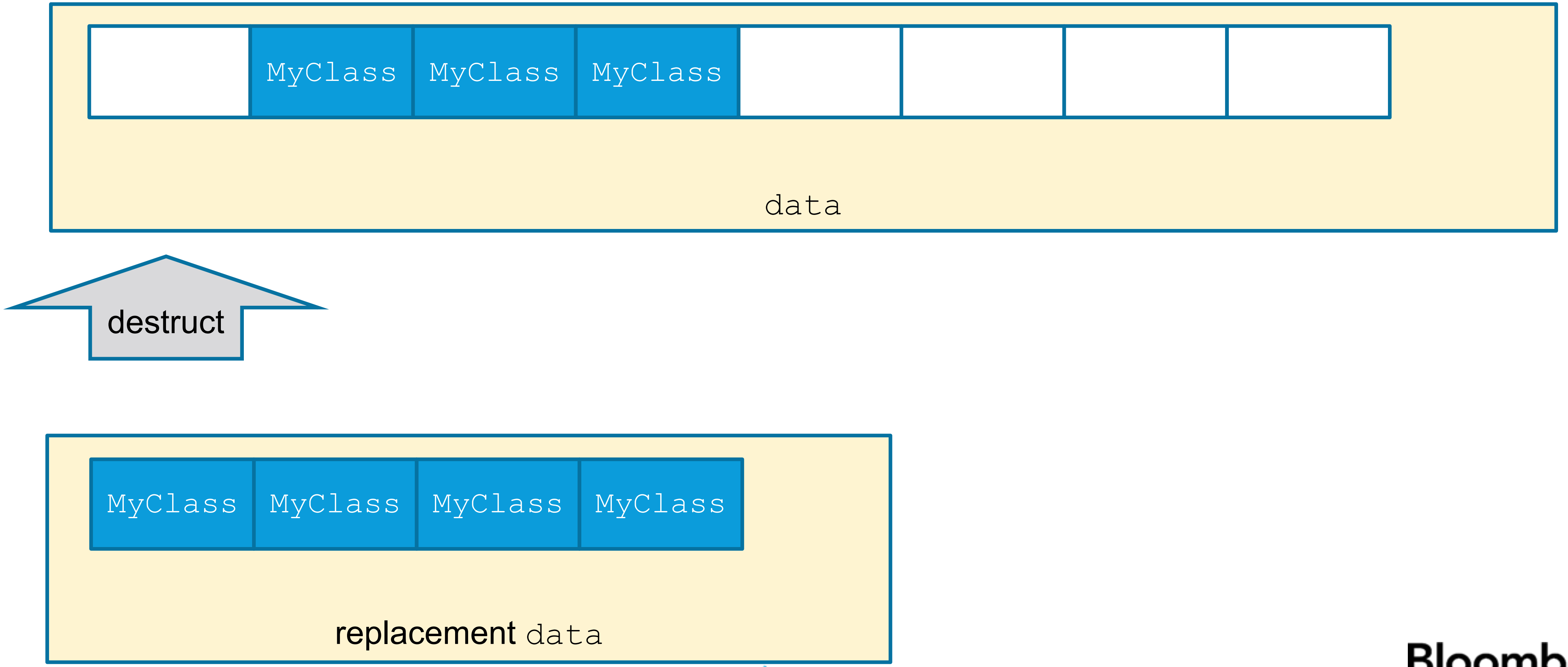
Growing a vector the C++03 way



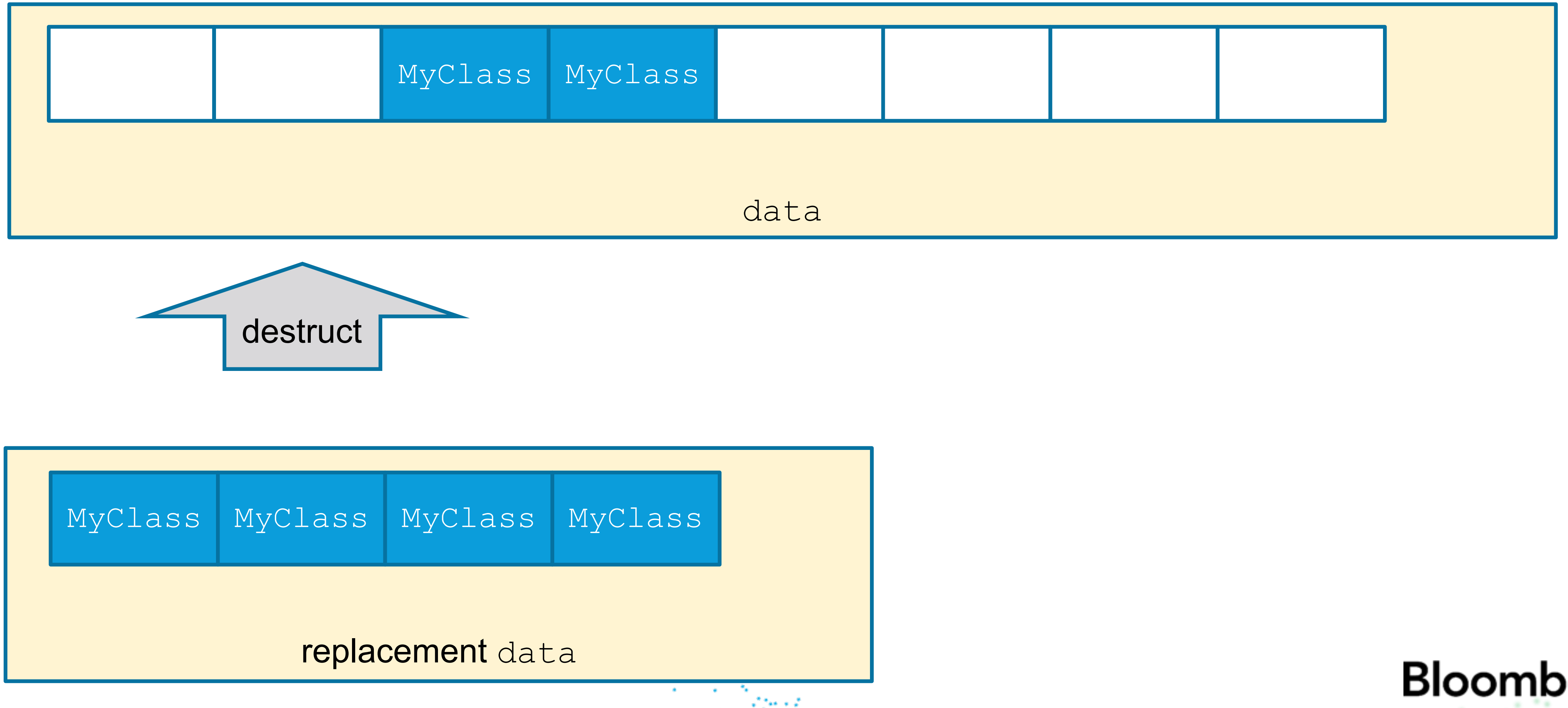
Growing a vector the C++03 way



Growing a vector the C++03 way



Growing a vector the C++03 way



MyClass MyClass

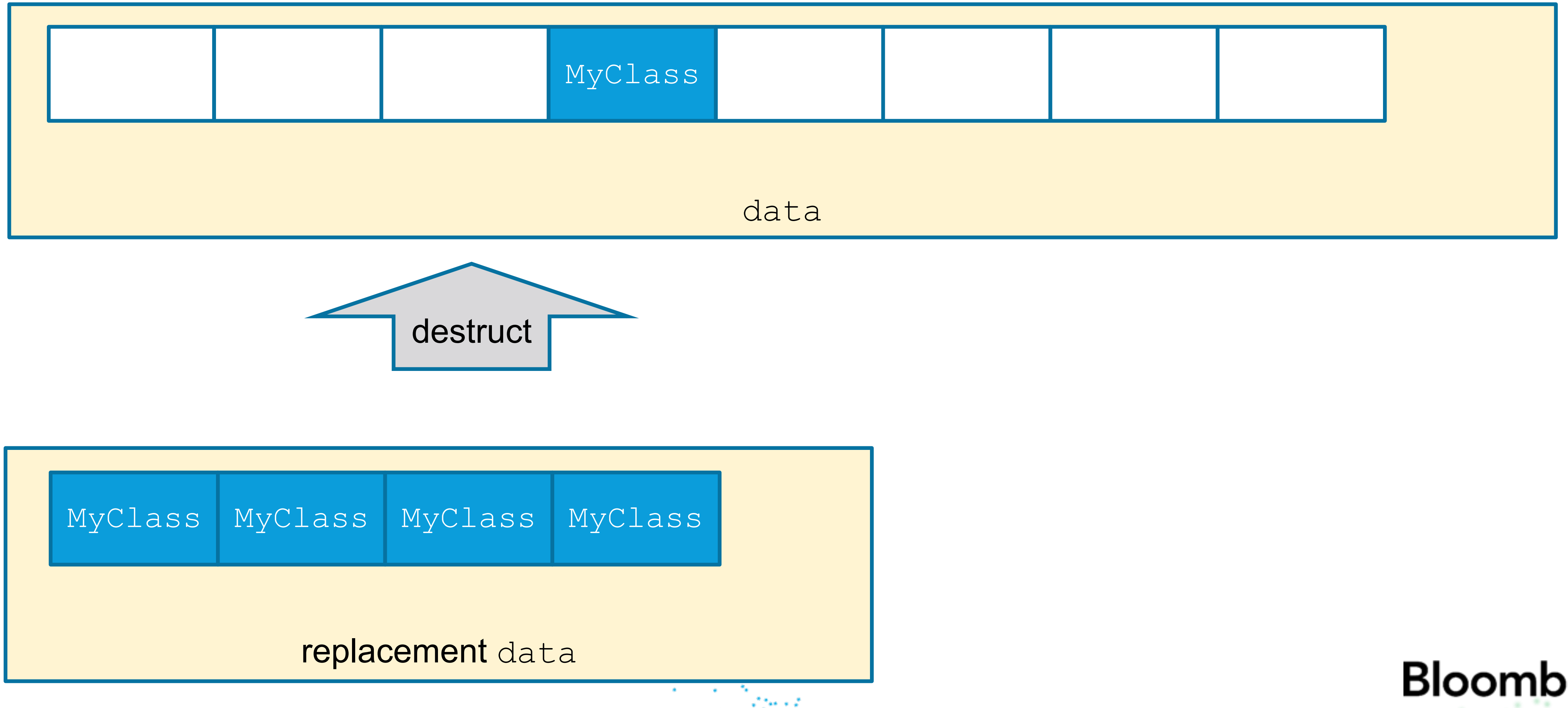
data

destruct

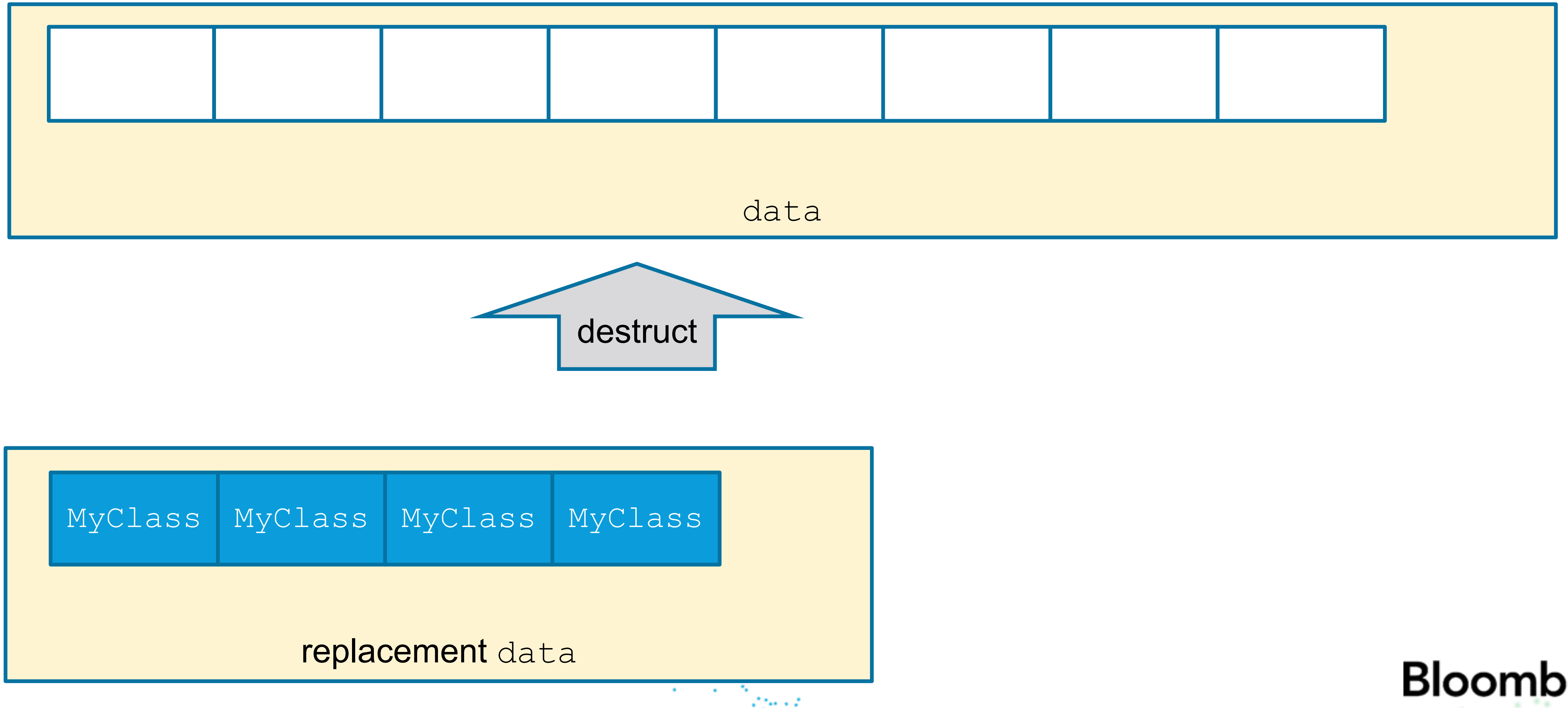
MyClass MyClass MyClass MyClass

replacement data

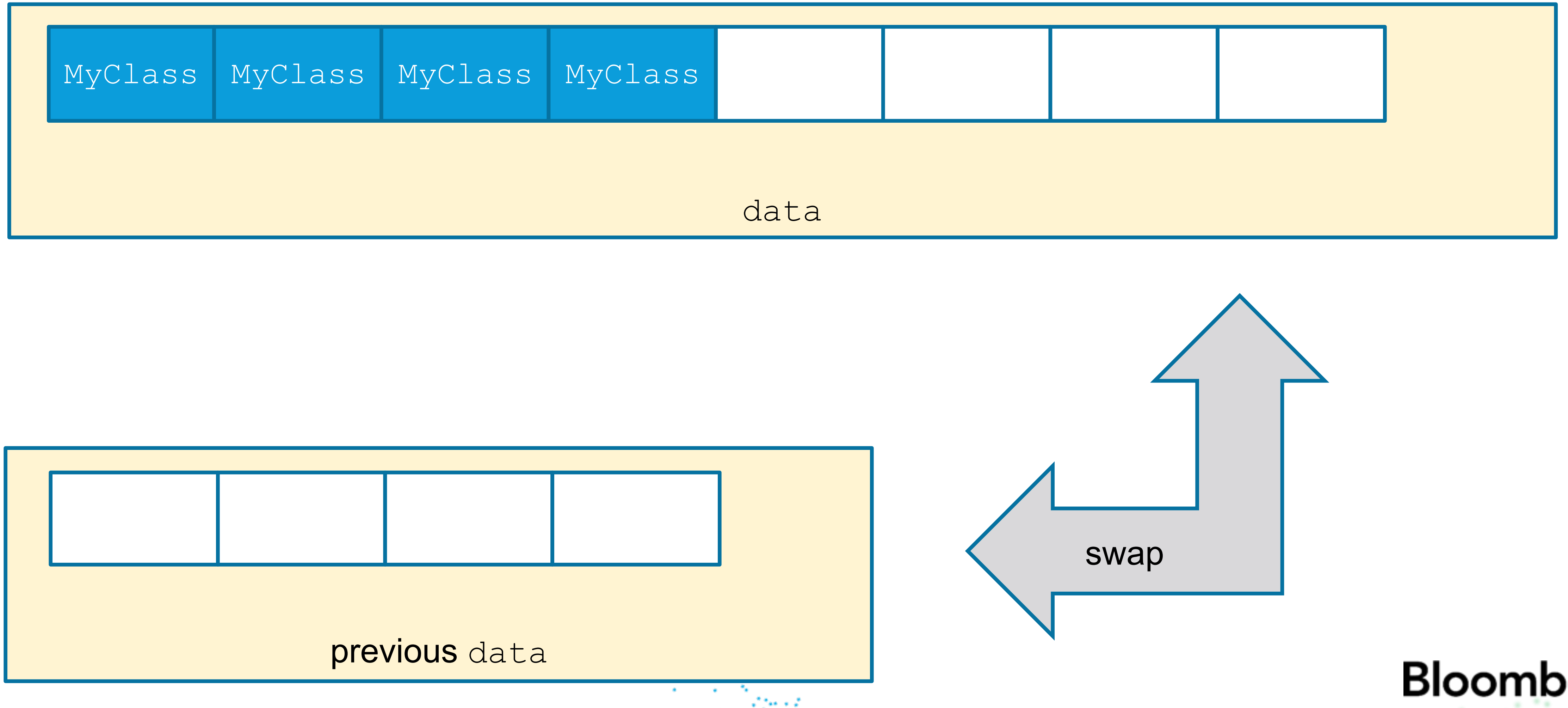
Growing a vector the C++03 way



Growing a vector the C++03 way



Growing a vector the C++03 way



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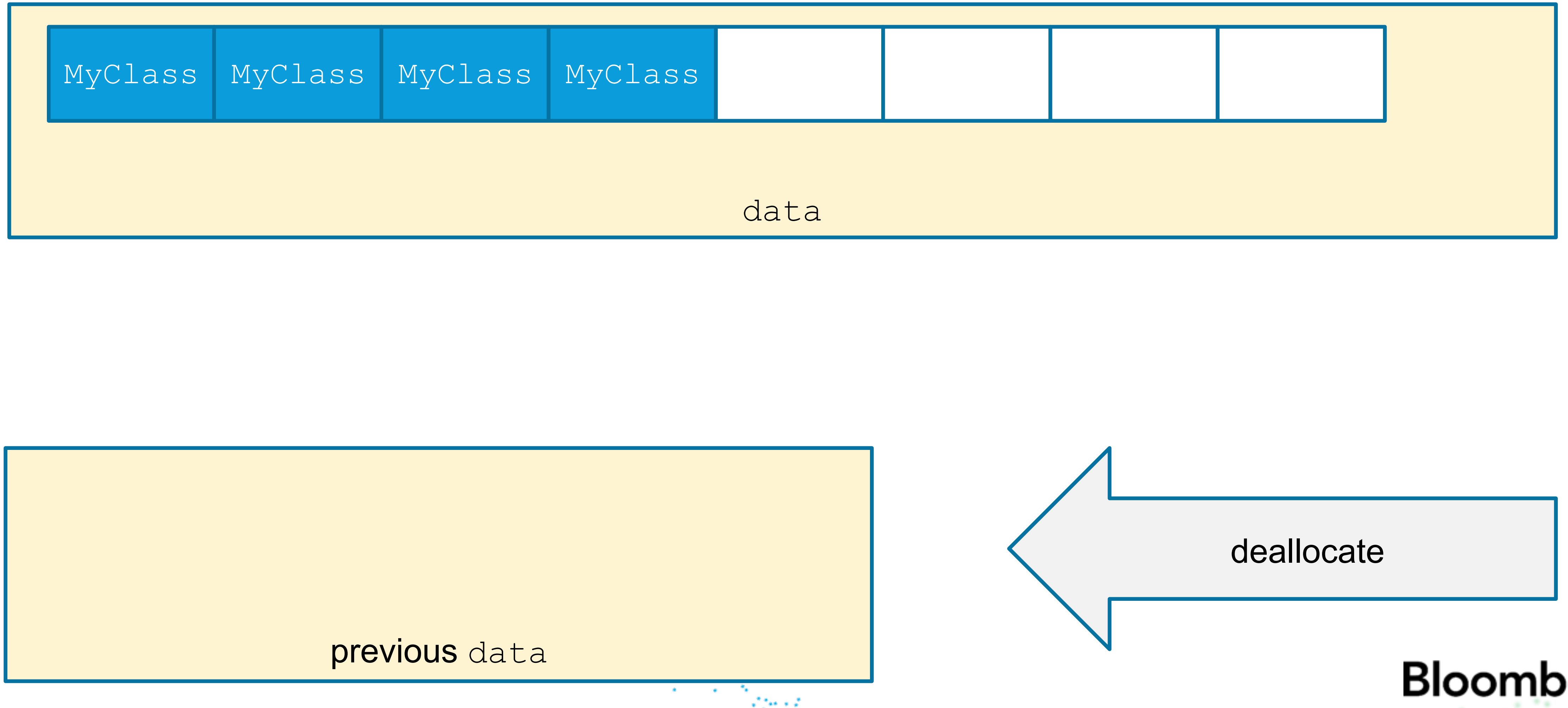
Growing a vector the C++03 way



How can we make this better?

C++11 gave us move constructors!

Growing a vector the C++11 way

```
class MyClass {
  public:
    MyClass();
    MyClass(const MyClass &);
    MyClass(MyClass &&) noexcept;
};

int main()
{
    std::vector<MyClass> data;

    data.push_back(MyClass());
    // … 3 more times

    data.push_back(MyClass());
}
```

What happens now?

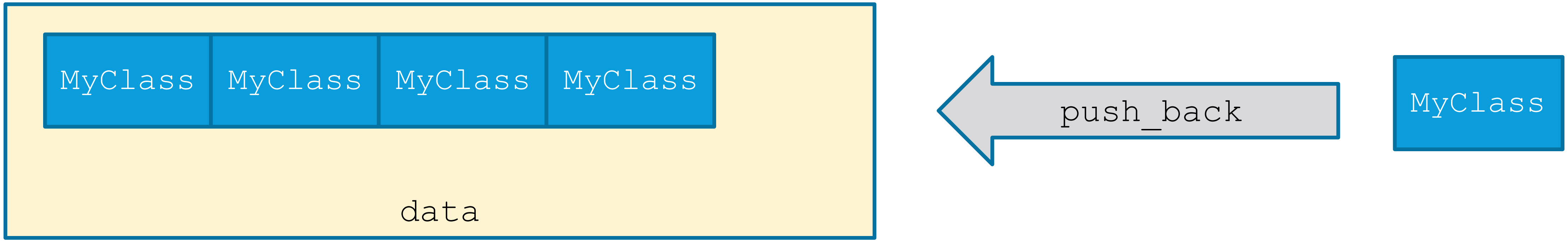
Growing a vector the C++11 way

There are now two possible paths.

1. If MyClass **does not** have a `noexcept` move constructor and is copy constructible, then we do what we did in C++03.

2. If MyClass **does** have a `noexcept` move constructor, then we have a new, more efficient approach.

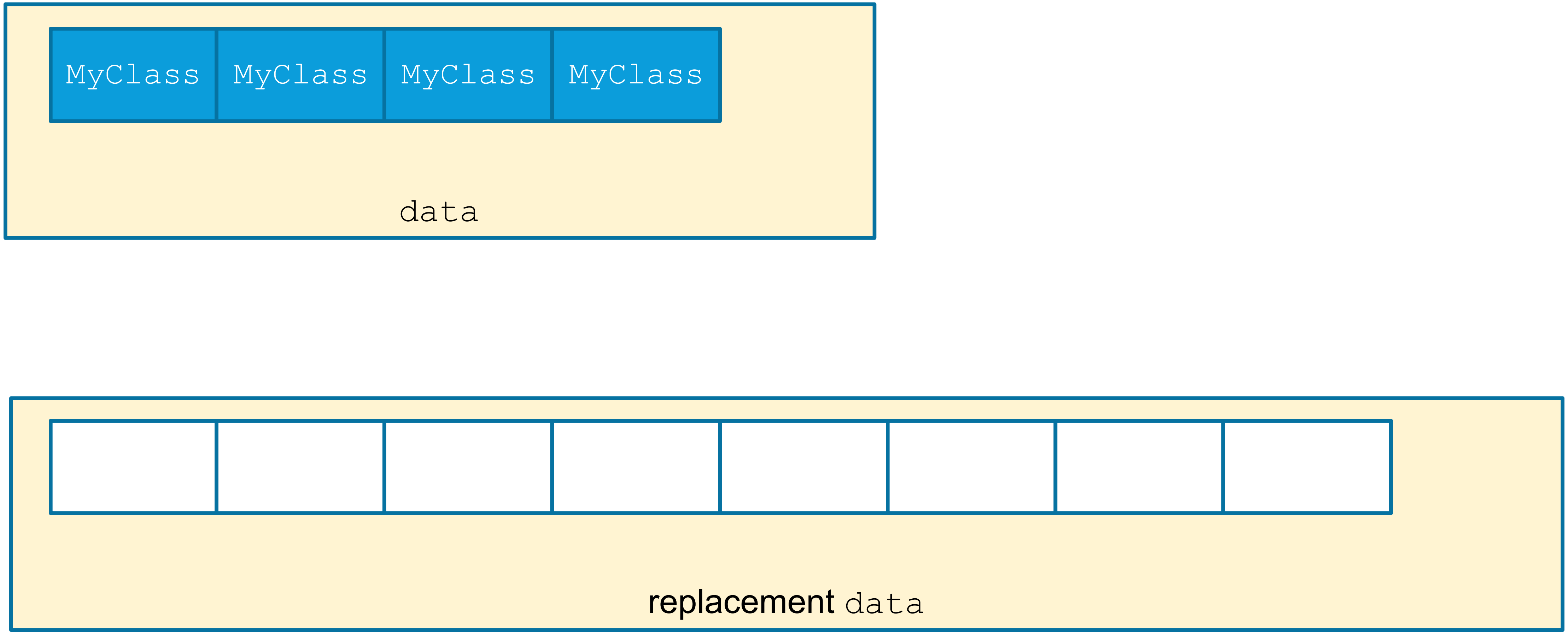
Growing a vector the C++11 way



`data` is not big enough!

It needs to grow!

Growing a vector the C++11 way



MyClass MyClass MyClass MyClass

data

replacement data

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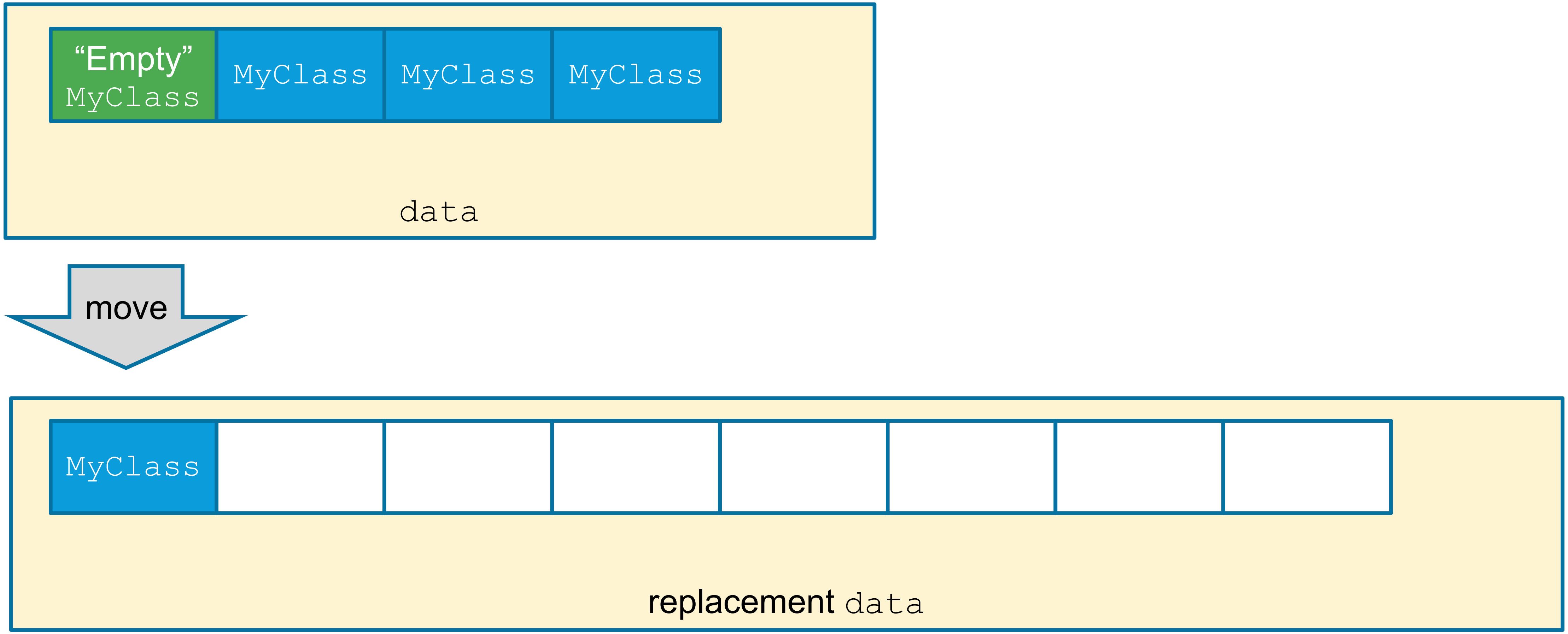
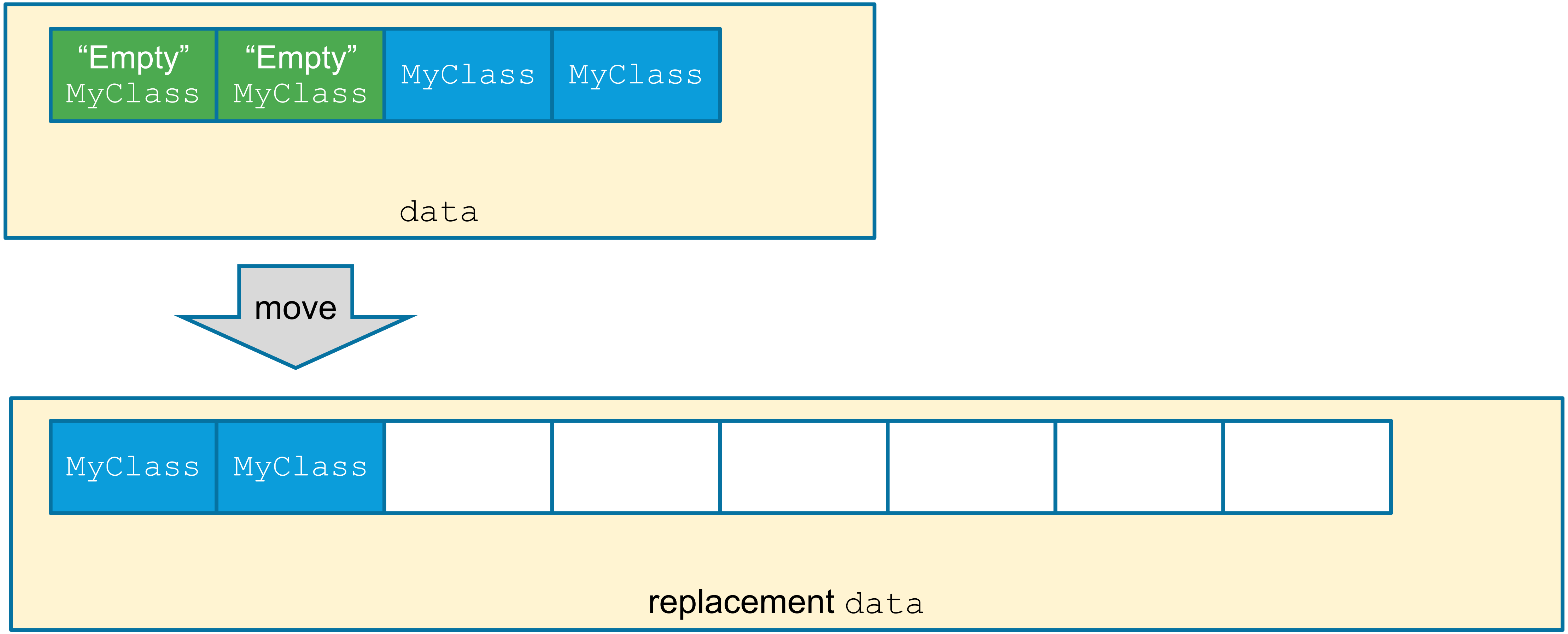
Growing a vector the C++11 way



Growing a vector the C++11 way



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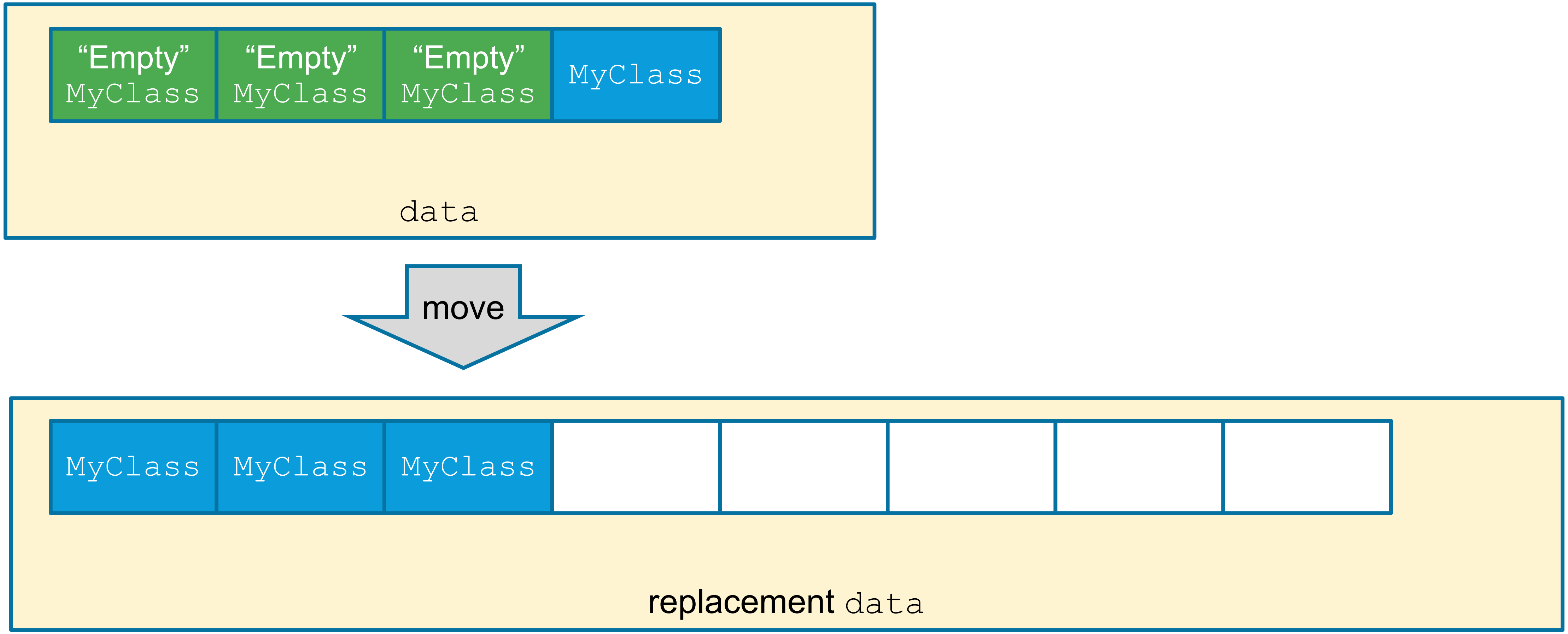
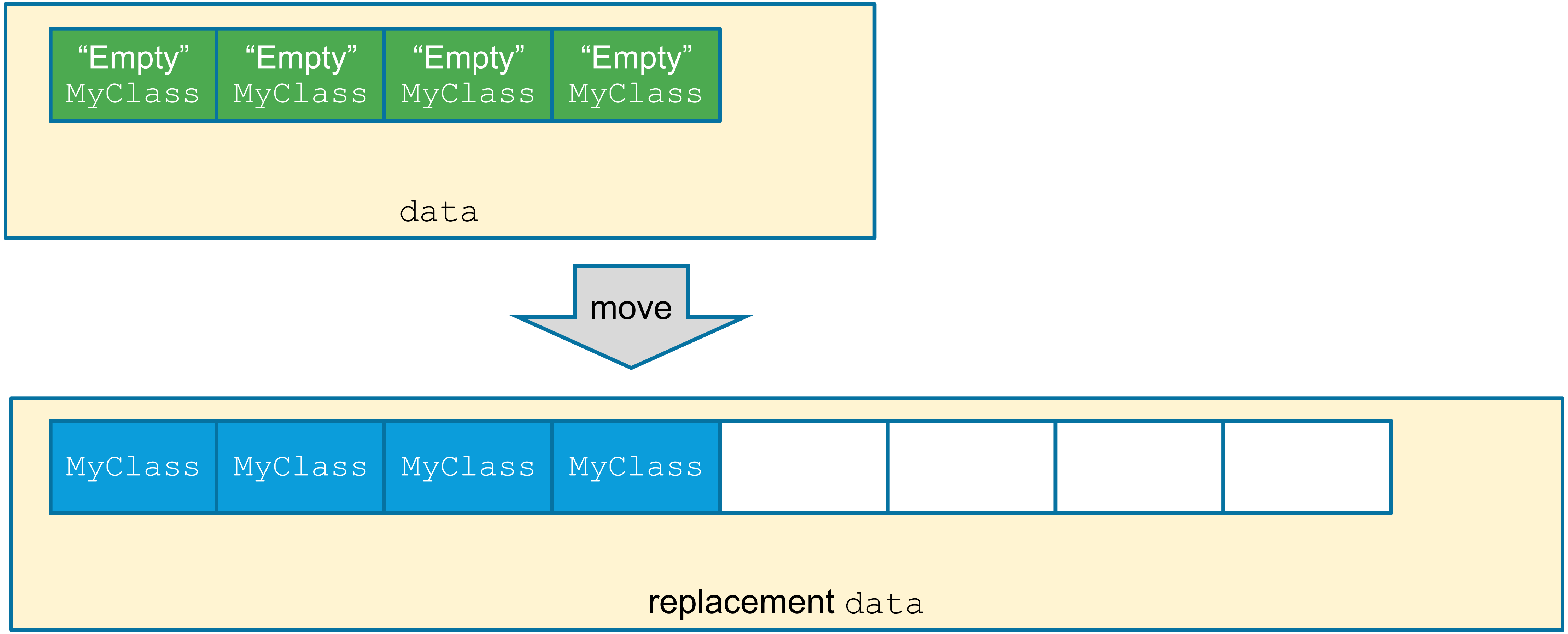
Growing a vector the C++11 way



Growing a vector the C++11 way



“Empty” `MyClass` | “Empty” `MyClass` | “Empty” `MyClass` | “Empty” `MyClass`

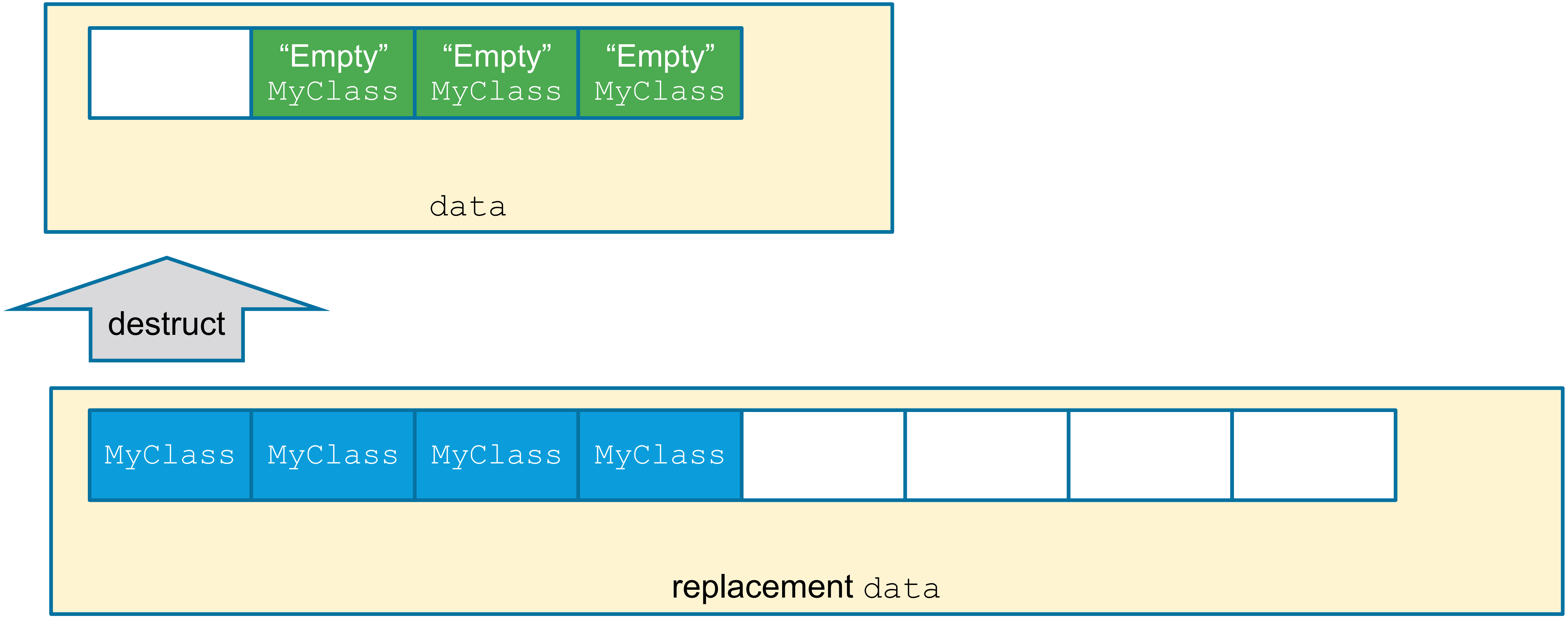
`data`

move

`MyClass` | `MyClass` | `MyClass` | `MyClass`

replacement `data`

Growing a vector the C++11 way



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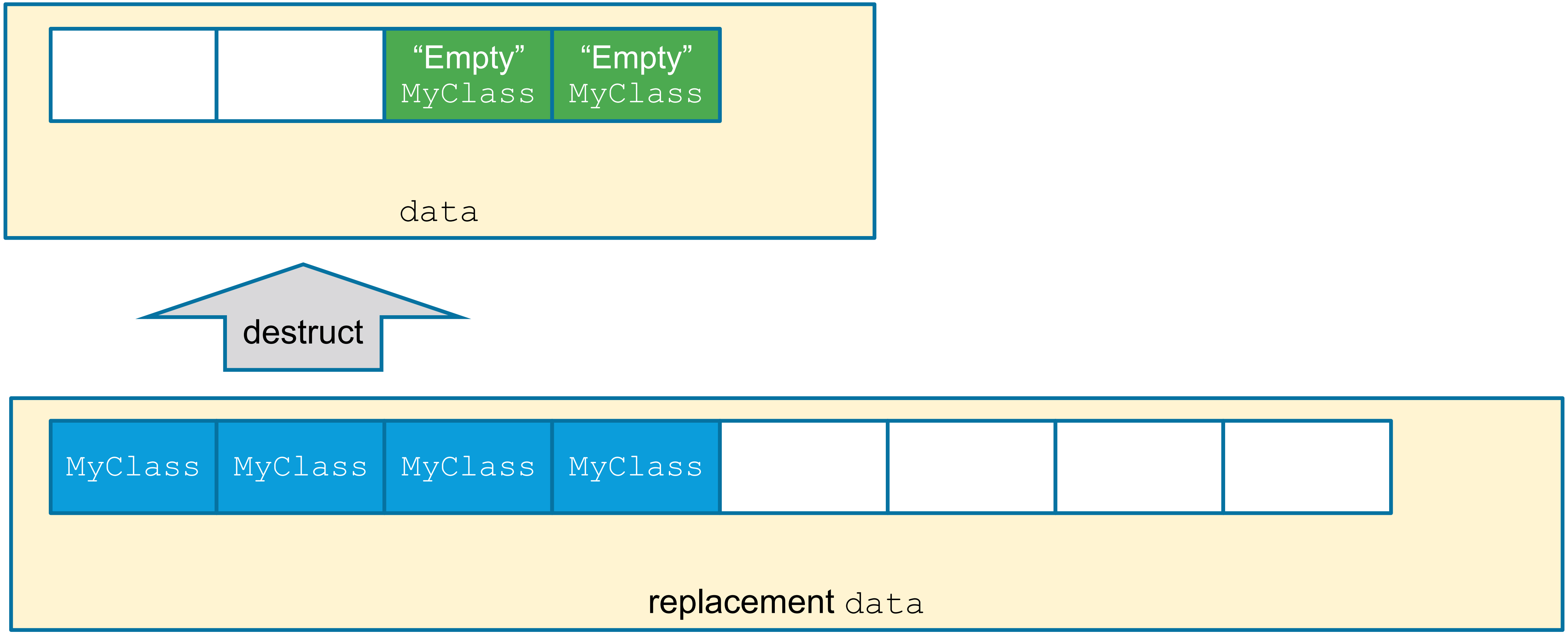
Growing a vector the C++11 way



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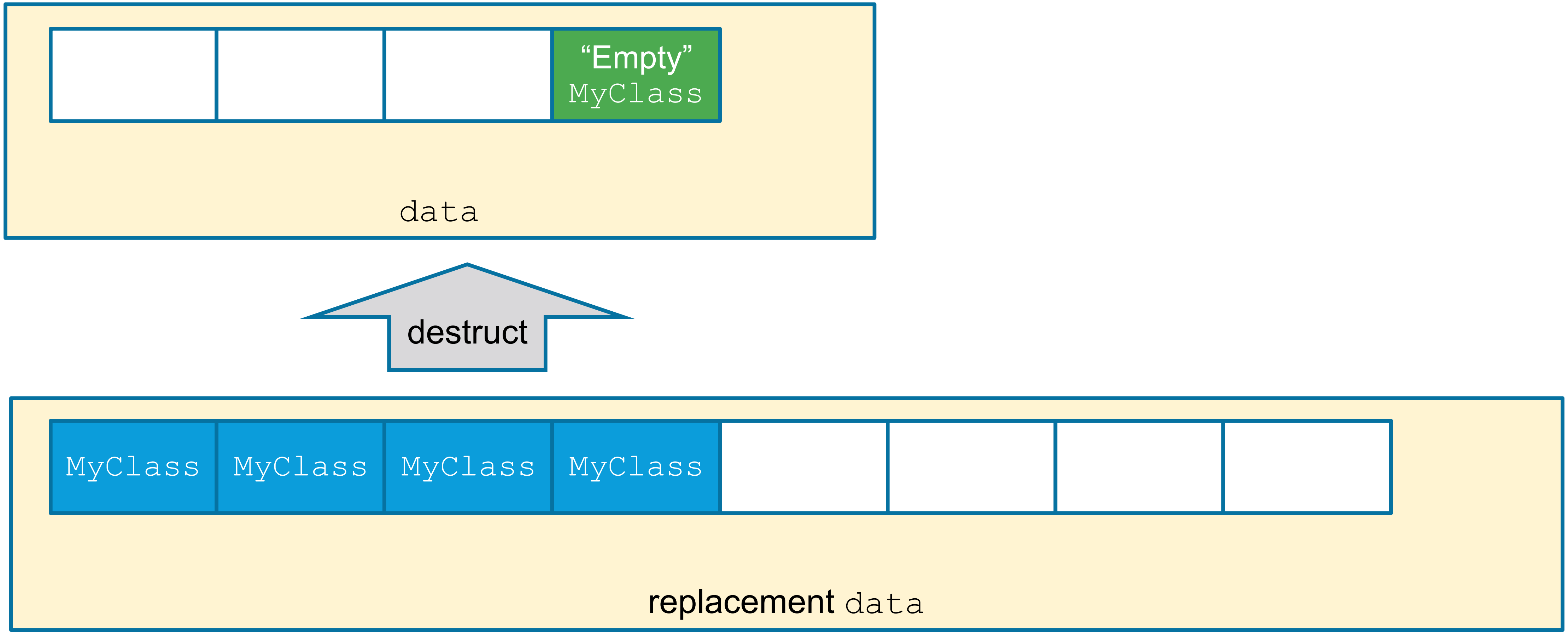
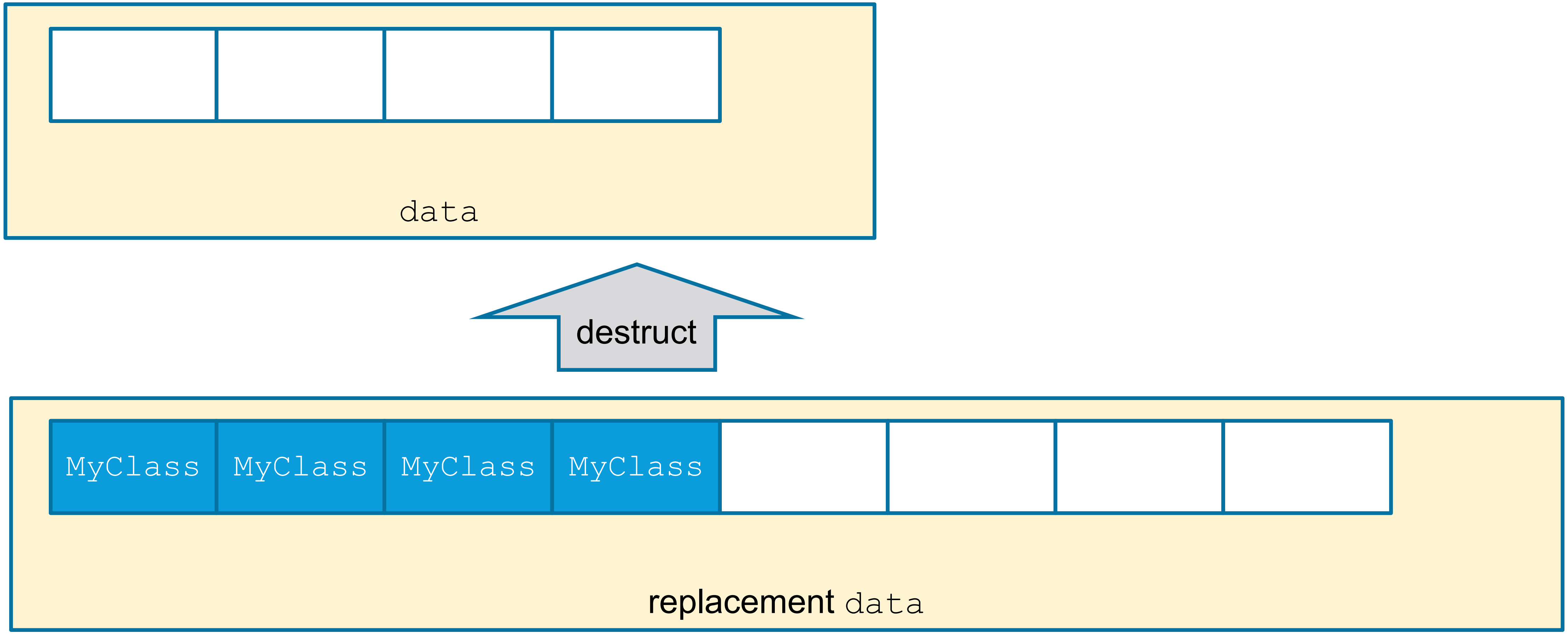
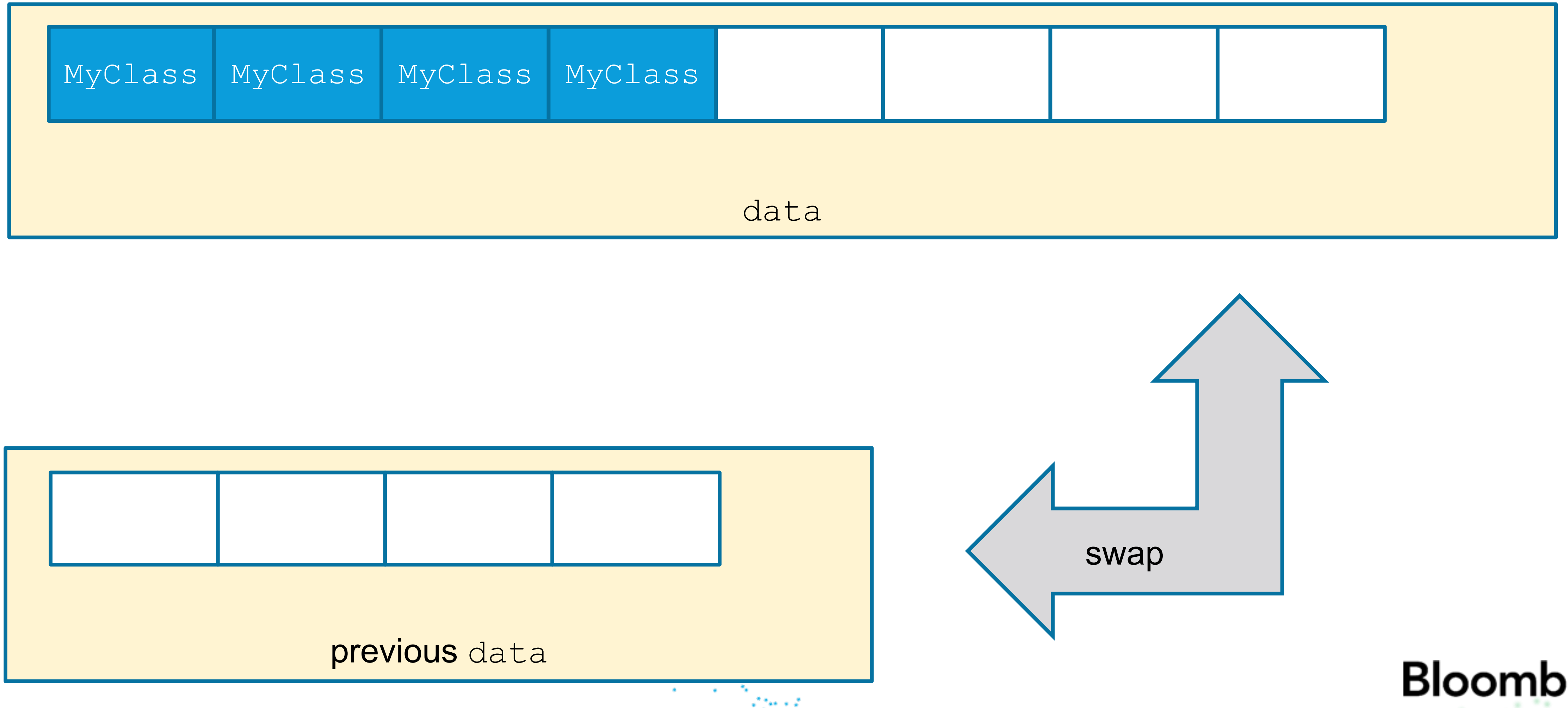
Growing a vector the C++11 way



Growing a vector the C++11 way



Growing a vector the C++11 way



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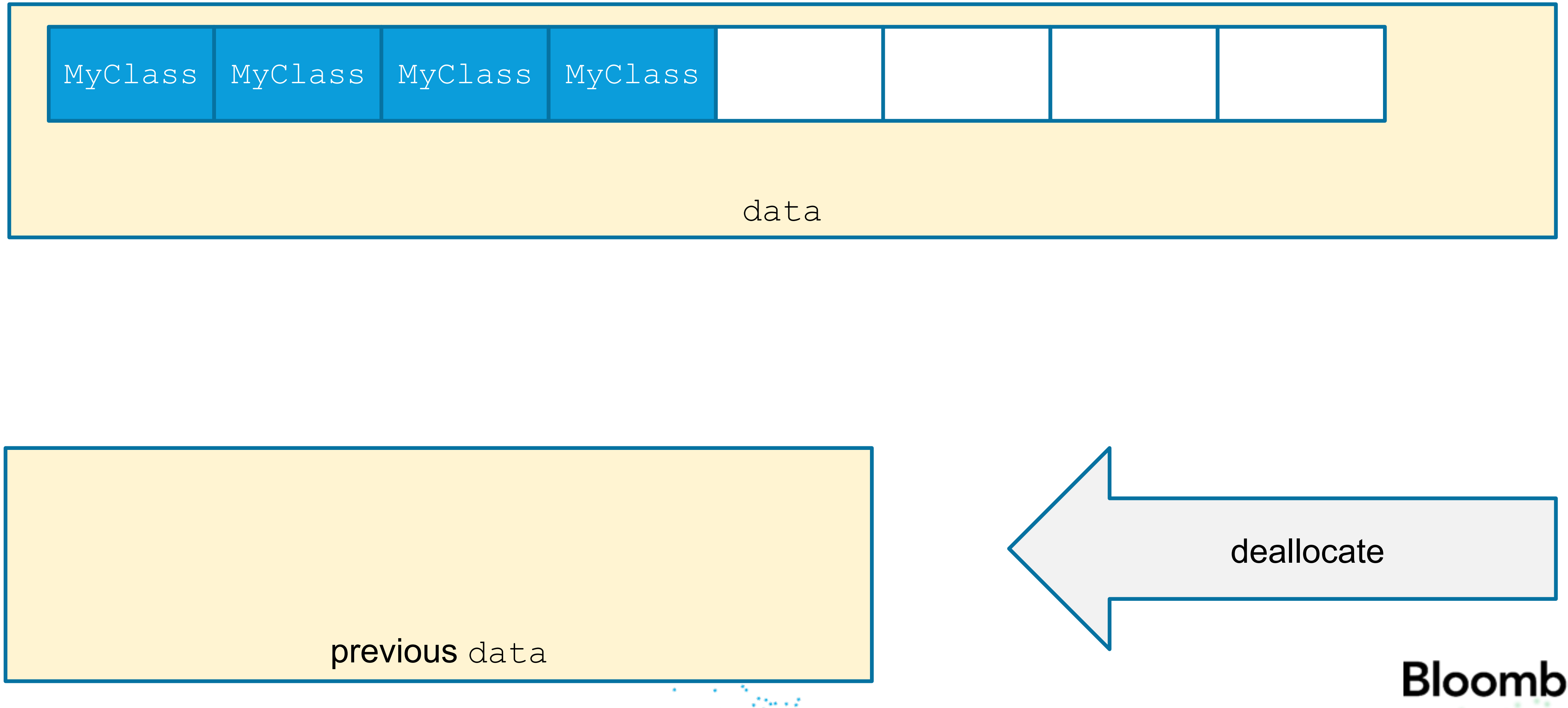
Growing a vector the C++11 way



Growing a vector the C++11 way

- For every entry in an array, we would have to call the move constructor on the destination and the destructor on the source.

- Let us consider `vector<unique_ptr>`.

Constructor (once per element)	Destructor (once per element)

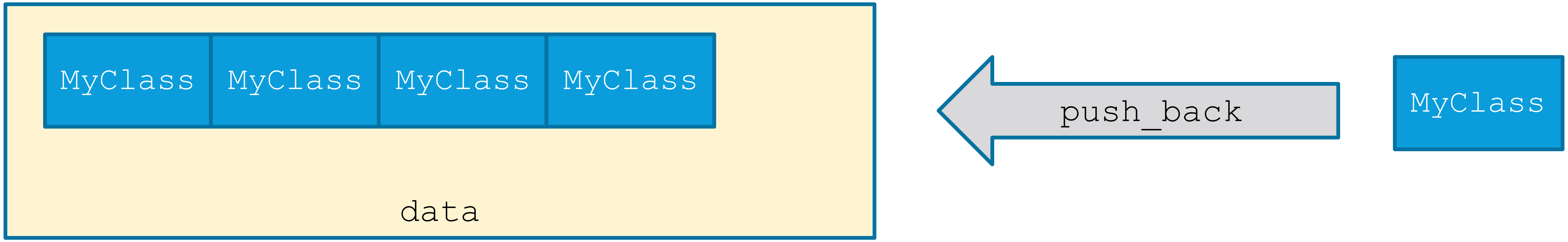
`unique_ptr::unique_ptr(`
`        unique_ptr&& other)`
`{`
`    pointer = other.pointer;`
`    deleter = other.deleter;`
`    other.pointer = nullptr;`
`}`
	`unique_ptr::~unique_ptr()`
	`{`
	`    // In our case, pointer is`
	`    // always null.`
	`    if (pointer)`
	`        deleter(pointer);`
	`}`

Growing a vector with byte copies

- How can we make this even faster?

- Would it be faster if we were allowed to just copy the bytes?

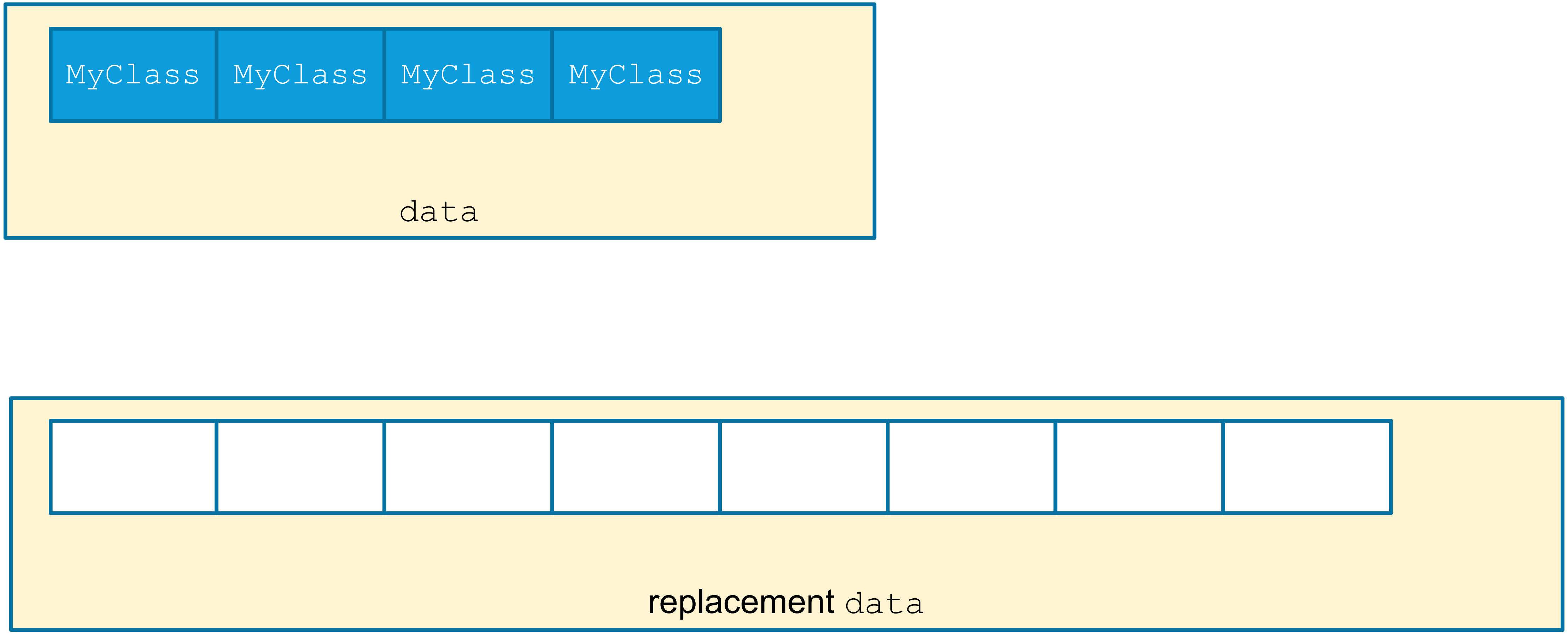
Growing a vector with byte copies



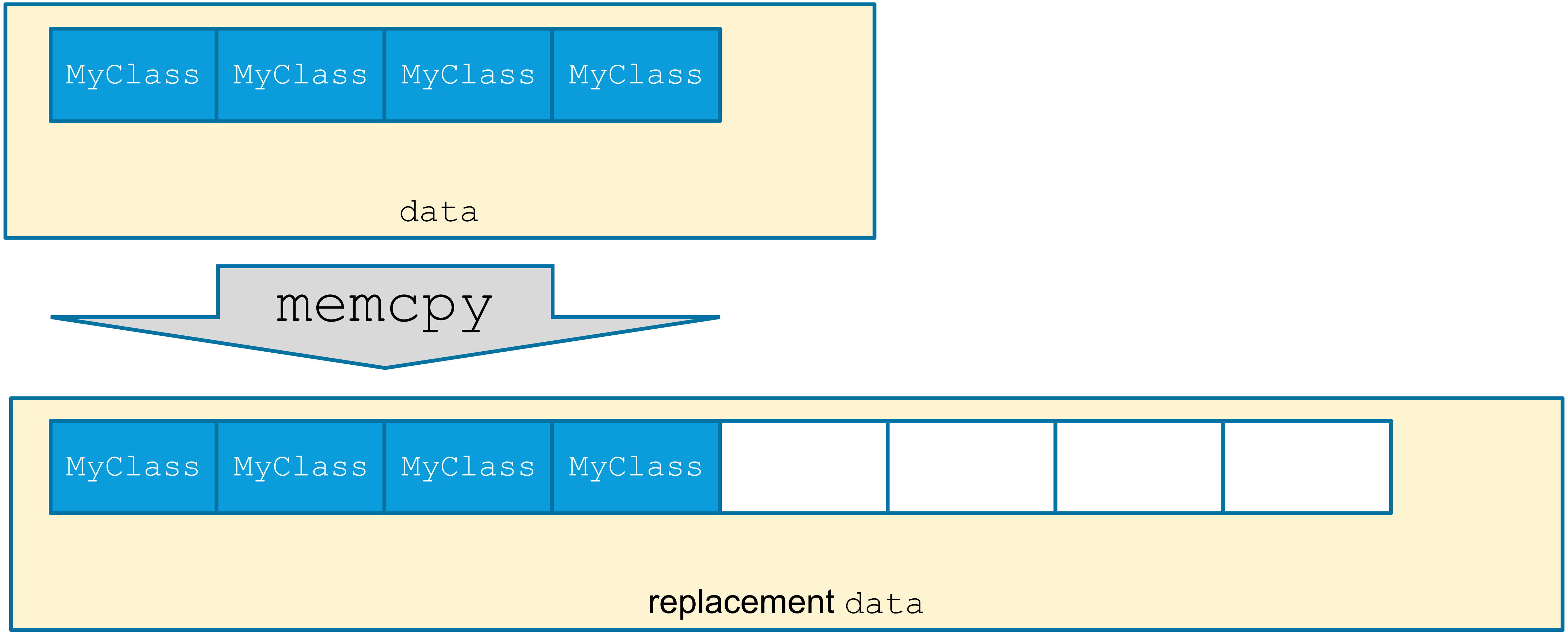
`data` is not big enough!

It needs to grow!

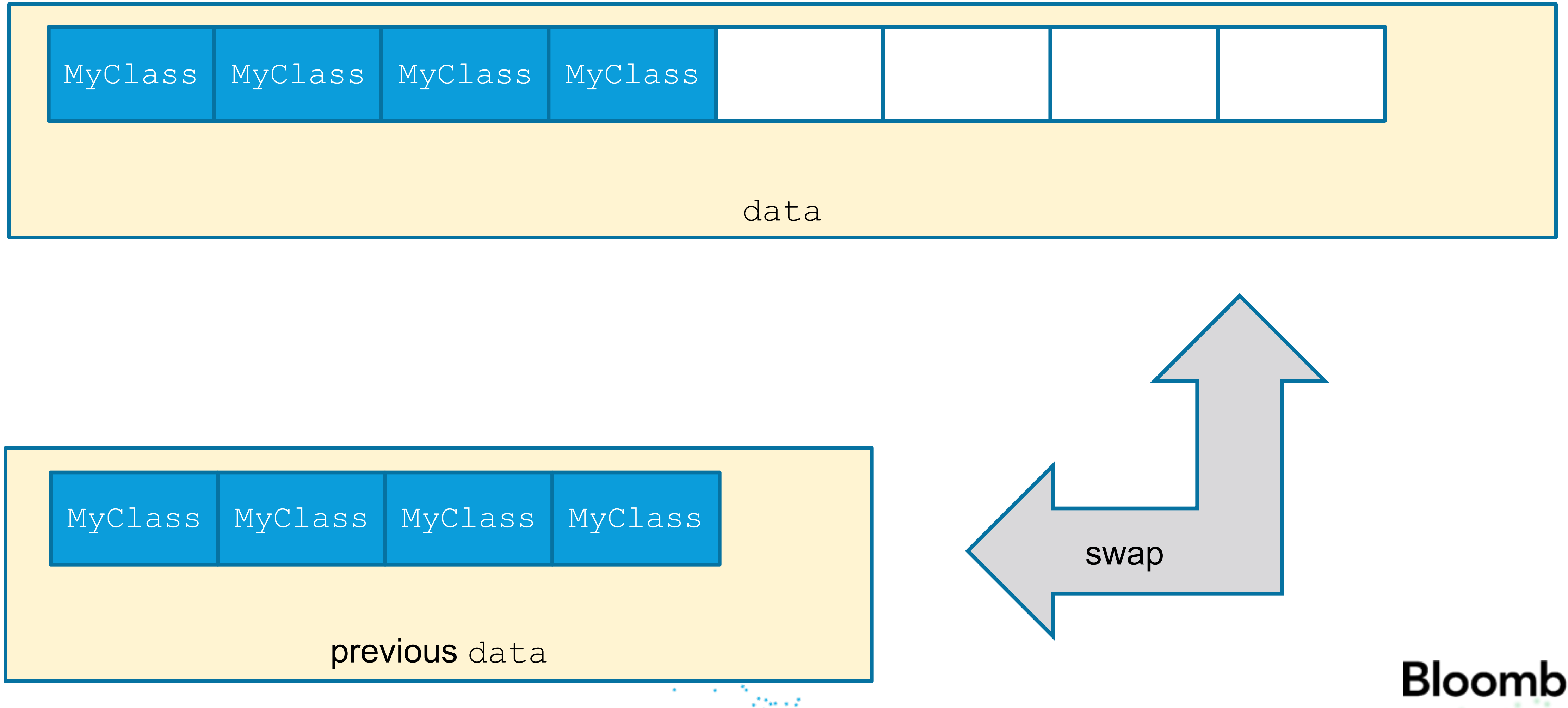
Growing a vector with byte copies



Growing a vector with byte copies



Growing a vector with byte copies



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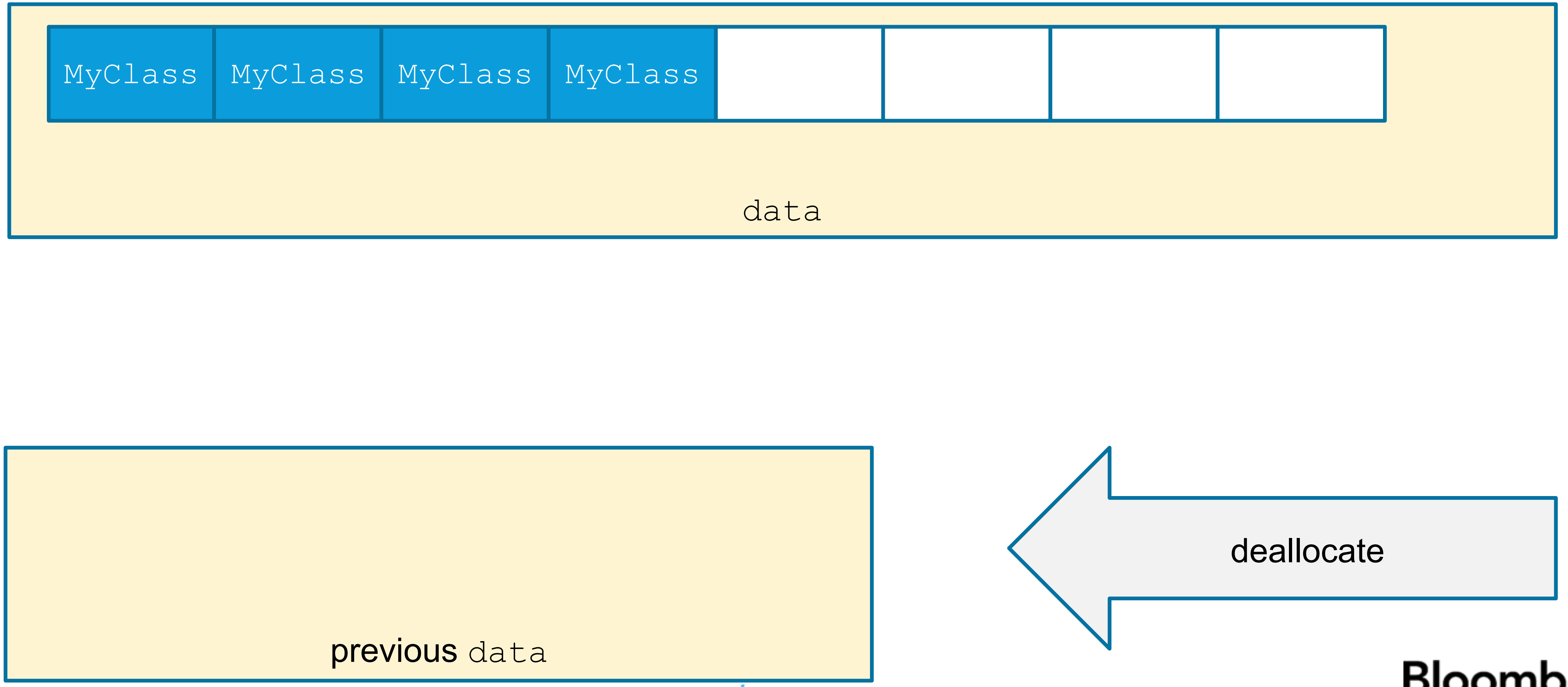
Growing a vector with byte copies



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Growing a vector with byte copies

- Consider growing a 4-element `vector<unique_ptr>`.

Using move construction	Using byte copying

tmp=::operator new(8*sizeof(unique_ptr));
tmp[0].pointer = src[0].pointer;
tmp[0].deleter = src[0].deleter;
src[0].pointer = 0;
tmp[1].pointer = src[1].pointer;
tmp[1].deleter = src[1].deleter;
src[1].pointer = 0;
tmp[2].pointer = src[2].pointer;
tmp[2].deleter = src[2].deleter;
src[2].pointer = 0;
tmp[3].pointer = src[3].pointer;
tmp[3].deleter = src[3].deleter;
src[3].pointer = 0;
if(src[0].pointer) …
if(src[1].pointer) …
if(src[2].pointer) …
if(src[3].pointer) …
::operator delete(src);
src=tmp
	tmp=
	 ::operator new(8*sizeof(unique_ptr));
	memcpy(tmp,
	       src,
	       4*sizeof(unique_ptr));
	::operator delete(src);
	src=tmp

Growing a vector with byte copies

- We can compare the optimised assembly to grow `vector<unique_ptr>`.

Using move construction

```
movsxd  r15, esi
lea     rdi, [8*r15]
call    operator new(unsigned long)@PLT
mov     rbx, rax
test    r15d, r15d
jle     .LBB0_1
mov     r15d, ebp
cmp     ebp, 4
jae     .LBB0_6
xor     eax, eax
jmp     .LBB0_5
.LBB0_1:
mov     rdi, r14
call    operator delete(void*)@PLT
jmp     .LBB0_2
.LBB0_6:
mov     eax, r15d
and     eax, -4
lea     rcx, [8*r15]
and     rcx, -32
xor     edx, edx
xorps   xmm0, xmm0
.LBB0_7: # =>This Inner Loop Header:
             Depth=1
movups  xmm1, xmmword ptr [r14 + rdx]
movups  xmm2, xmmword ptr [r14 + rdx +
16]
movups  xmmword ptr [rbx + rdx], xmm1
movups  xmmword ptr [rbx + rdx + 16],
xmm2
movups  xmmword ptr [r14 + rdx], xmm0
movups  xmmword ptr [r14 + rdx + 16],
xmm0
add     rdx, 32
cmp     rcx, rdx
jne     .LBB0_7
cmp     rax, r15
je      .LBB0_9
```

```
.LBB0_5: # =>This Inner Loop Header:
             Depth=1
mov     rcx, qword ptr [r14 + 8*rax]
mov     qword ptr [rbx + 8*rax], rcx
mov     qword ptr [r14 + 8*rax], 0
inc     rax
cmp     r15, rax
jne     .LBB0_5
.LBB0_9:
mov     rdi, r14
call    operator delete(void*)@PLT
test    ebp, ebp
jle     .LBB0_2
xor     r14d, r14d
jmp     .LBB0_11
.LBB0_13: #   in Loop: Header=BB0_11
              Depth=1
inc     r14
cmp     r15, r14
je      .LBB0_2
.LBB0_11: # =>This Inner Loop Header:
              Depth=1
mov     rdi, qword ptr [rbx + 8*r14]
mov     qword ptr [rbx + 8*r14], 0
test    rdi, rdi
je      .LBB0_13
call    operator delete(void*)@PLT
jmp     .LBB0_13
```

Using byte copying

```
movsxd  r14, esi
shl     r14, 3
mov     rdi, r14
call    operator new(unsigned long)@PLT
mov     r15, rax
mov     rdi, rax
mov     rsi, rbx
mov     rdx, r14
call    memcpy@PLT
mov     rdi, rbx
call    operator delete(void*)@PLT
```

Growing a vector with byte copies

- We can compare the optimised assembly to grow `vector<string>`.

Using move construction

```
movsxd  r15, esi
lea     rax, [8*r15]
lea     rdi, [rax + 2*rax]
call    operator new(unsigned long)@PLT
mov     rbx, rax
test    r15d, r15d
jle     .LBB0_1
mov     r15d, ebp
cmp     ebp, 1
jne     .LBB0_12
xor     eax, eax
jmp     .LBB0_5
.LBB0_1:
mov     rdi, r14
call    operator delete(void*)@PLT
jmp     .LBB0_2
.LBB0_12:
mov     ecx, r15d
and     ecx, -2
xor     edx, edx
xorps   xmm0, xmm0
xor     eax, eax
.LBB0_13: # =>This Inner Loop Header:
               Depth=1
mov     rsi, qword ptr [r14 + rdx + 16]
mov     qword ptr [rbx + rdx + 16], rsi
movups  xmm1, xmmword ptr [r14 + rdx]
movups  xmmword ptr [rbx + rdx], xmm1
movups  xmmword ptr [r14 + rdx], xmm0
mov     qword ptr [r14 + rdx + 16], 0
mov     rsi, qword ptr [r14 + rdx + 40]
mov     qword ptr [rbx + rdx + 40], rsi
movups  xmm1, xmmword ptr [r14 + rdx + 24]
movups  xmmword ptr [rbx + rdx + 24], xmm1
movups  xmmword ptr [r14 + rdx + 24], xmm0
mov     qword ptr [r14 + rdx + 40], 0
add     rax, 2
add     rdx, 48
cmp     rcx, rax
jne     .LBB0_13
```

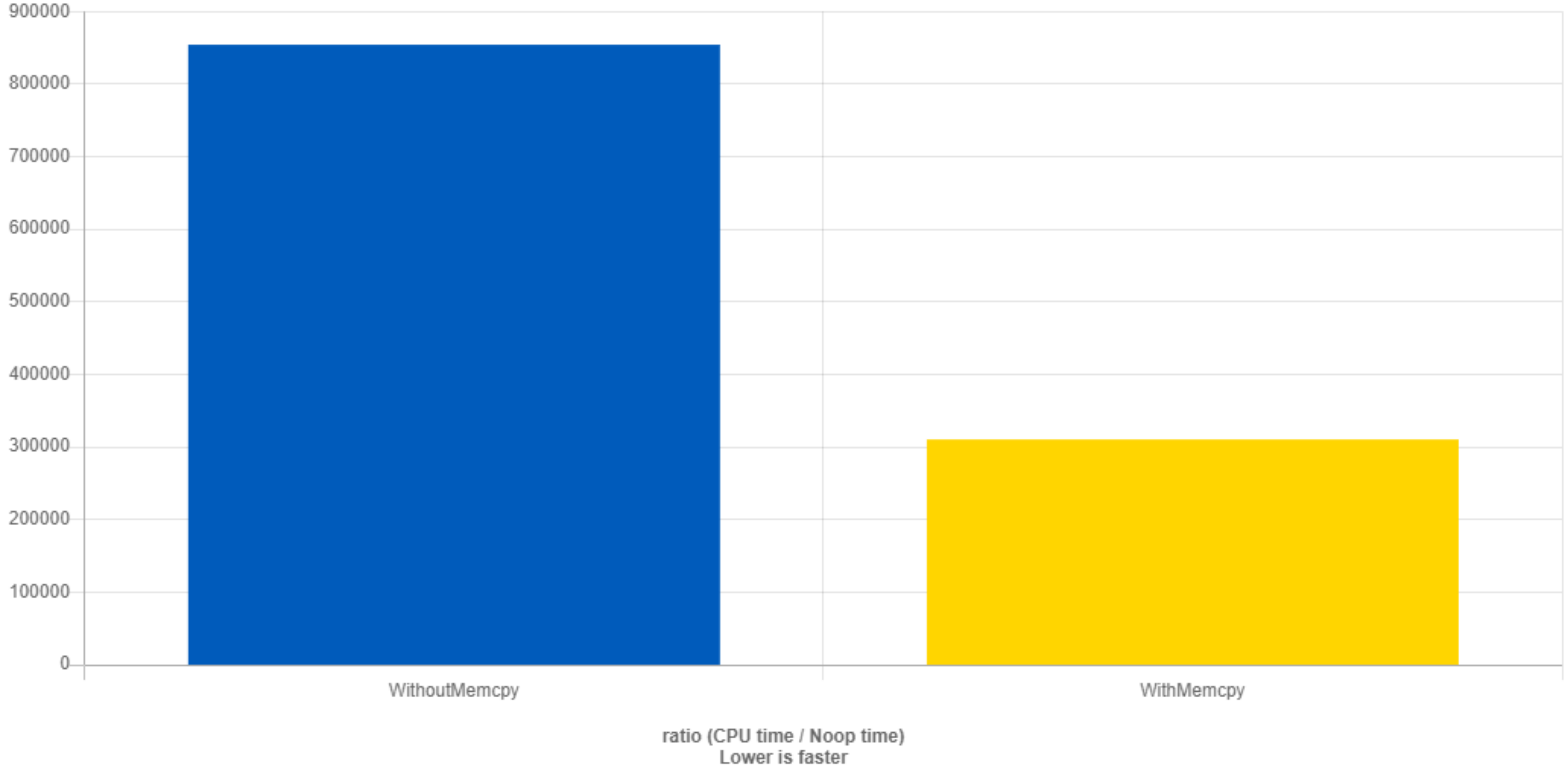
```
.LBB0_5:
test    r15b, 1
je      .LBB0_7
shl     rax, 3
lea     rax, [rax + 2*rax]
mov     rcx, qword ptr [r14 + rax + 16]
mov     qword ptr [rbx + rax + 16], rcx
movups  xmm0, xmmword ptr [r14 + rax]
movups  xmmword ptr [rbx + rax], xmm0
xorps   xmm0, xmm0
movups  xmmword ptr [r14 + rax], xmm0
mov     qword ptr [r14 + rax + 16], 0
.LBB0_7:
mov     rdi, r14
call    operator delete(void*)@PLT
test    ebp, ebp
jle     .LBB0_2
shl     r15, 3
lea     r14, [r15 + 2*r15]
xor     r15d, r15d
jmp     .LBB0_9
.LBB0_11: #   in Loop: Header=BB0_9
                       Depth=1
add     r15, 24
cmp     r14, r15
je      .LBB0_2
.LBB0_9: # =>This Inner Loop Header:
               Depth=1
test    byte ptr [rbx + r15], 1
je      .LBB0_11
mov     rdi, qword ptr [rbx + r15 + 16]
call    operator delete(void*)@PLT
jmp     .LBB0_11
```

Using byte copying

```
movsxd  rax, esi
shl     rax, 3
lea     r14, [rax + 2*rax]
mov     rdi, r14
call    operator new(unsigned long)@PLT
mov     r15, rax
mov     rdi, rax
mov     rsi, rbx
mov     rdx, r14
call    memcpy@PLT
mov     rdi, rbx
call    operator delete(void*)@PLT
```

Growing a vector with byte copies

- Applying trivial relocation optimisations to `vector<string>` gives a factor-2.8 speed-up versus the C++20 Standard Library version, according to a test on quick-bench.com (with optimisation).



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Can we really just copy the bytes?

Introducing ***trivially copyable***

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Trivially copyable

The C++ Standard defines the term ***trivially copyable type*** as follows:

6.8.1 General [basic.types.general]

- Arithmetic types ([basic.fundamental]), enumeration types, pointer types, pointer-to-member types ([basic.compound]), `std::nullptr_t`, and cv-qualified versions of these types are collectively called *scalar types.* Scalar types, trivially copyable class types ([class.prop]), arrays of such types, and cv-qualified versions of these types are collectively called ***trivially copyable types***.

11.2 Properties of classes [class.prop]

A ***trivially copyable class*** is a class:

- (1.1) that has at least one eligible copy constructor, move constructor, copy assignment operator, or move assignment operator ([special], [class.copy.ctor], [class.copy.assign]),
- (1.2) where each eligible copy constructor, move constructor, copy assignment operator, and move assignment operator is trivial, and
- (1.3) that has a trivial, non-deleted destructor ([class.dtor]).

[*Note 1*: In particular, a trivially copyable or trivial class does not have virtual functions or virtual base classes. — *end note*]

Trivially copyable

The C++ Standard defines the term ***trivial*** for such functions as follows (slide 1/2):

11.4.5.2 Default constructors [class.default.ctor]

- A default constructor is *trivial* if it is not user-provided and if:
- (3.1) its class has no virtual functions ([class.virtual]) and no virtual base classes ([class.mi]), and
- (3.2) no non-static data member of its class has a default member initializer ([class.mem]), and
- (3.3) all the direct base classes of its class have trivial default constructors, and
- (3.4) for all the non-static data members of its class that are of class type (or array thereof), each such class has a trivial default constructor.

11.4.5.3 Copy/move constructors [class.copy.ctor]

- A copy/move constructor for class `X` is trivial if it is not user-provided and if:
- (11.1) class `X` has no virtual functions ([class.virtual]) and no virtual base classes ([class.mi]), and
- (11.2) the constructor selected to copy/move each direct base class subobject is trivial, and
- (11.3) for each non-static data member of `X` that is of class type (or array thereof), the constructor selected to copy/move that member is trivial;

Trivially copyable

The C++ Standard defines the term ***trivial*** for such functions as follows (slide 2/2):

11.4.6 Copy/move assignment operator [class.copy.assign]

- A copy/move assignment operator for class `X` is trivial if it is not user-provided and if:
- (9.1) class `X` has no virtual functions ([class.virtual]) and no virtual base classes ([class.mi]), and
- (9.2) the assignment operator selected to copy/move each direct base class subobject is trivial, and
- (9.3) for each non-static data member of `X` that is of class type (or array thereof), the assignment operator selected to copy/move that member is trivial;

11.4.7 Destructors [class.dtor]

- A destructor is trivial if it is not user-provided and if:
- (8.1) the destructor is not virtual,
- (8.2) all of the direct base classes of its class have trivial destructors, and
- (8.3) for all of the non-static data members of its class that are of class type (or array thereof), each such class has a trivial destructor.

Trivially copyable

In high-level terms, a good way to think about this is that, if you have any of the following, then your class is unlikely to be *trivially copyable:*

- Your own constructor(s)
- Your own destructor
- Your own assignment operator(s)
- Any `virtual` function(s) or base class(es)
- Any members or bases that are not *trivially copyable*

So, generally speaking, only the most simple types tend to be trivially copyable.

Trivially copyable

Example of a type that is *trivially copyable* and, therefore, a `vector` would use an optimised implementation:

```
struct MyClass {
        int data1;
        int data2;
        double calculate();
    };
```

Trivially copyable

Examples of types that are not *trivially copyable*:

```
std::unique_ptr
std::shared_ptr
std::string
std::pair<int, int>
```

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Trivially copyable

Most current implementations of vector will use `memcpy` as an optimization for *trivially copyable* types.

What do current libraries do?

Introducing ***trivially relocatable***

Facebook Folly (open source)

Bloomberg BDE (open source)

Others (such as Qt)

Common themes

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Trivially relocatable

- The term *trivially relocatable* is not defined in the Standard.

- For the purposes of this presentation, we will use the term *trivially relocatable* to describe a type that we can relocate using `memcpy` (given the proviso that we do not subsequently call the destructor on the relocated-from object).

  - A good mental model is to consider, after a relocation operation, that the source object is no more. It has ceased to be. Bereft of life, it rests in peace. It is an ex-object.

Trivially relocatable

Trivial relocation	Relocation using move constructor

// allocate destination memory
dest =
  ::operator new(sizeof(Type));
 	
// copy bytes
memcpy(dest, source,
       sizeof(Type));
 	
// deallocate source
::operator delete(source);
	// allocate destination memory
	dest =
	  ::operator new(sizeof(Type));
	
	// move construct
	::new(dest)
	      Type(std::move(*source));
	
	// destruct source
	source->~Type();
	
	// deallocate source
	::operator delete(source);

Facebook Folly (open source)

- Folly’s `fbvector` class supports `memcpy` for relocations.
- If your type can be relocated using `memcpy`, you need to indicate this fact by partially specialising `IsRelocatable<>`.

```
// at global namespace level
namespace folly {
    struct IsRelocatable<Widget> : boost::true_type {};
}
```

- This must be done after your definition of `Widget` but before you make use of `fbvector<Widget>`.

Bloomberg BDE (open source)

- Bloomberg BDE’s `vector` implementation also supports `memcpy` for relocations.

- If your type can be relocated using `memcpy`, you need to indicate this, which can be done with either a nested trait syntax or a standard trait-like partial specialization.

Bloomberg BDE (open source)

```
class Widget {
    // ...
    // TRAITS
    BSLMF_NESTED_TRAIT_DECLARATION(Widget,
                                   BloombergLP::bslmf::IsBitwiseMoveable);
        // 'Widget' is trivially relocatable.
    // ...
};
```

```
// TYPE TRAITS
namespace bslmf {

template <>
struct IsBitwiseMoveable<Widget> : bsl::true_type
{
    // 'Widget' is trivially relocatable.
};

}  // close namespace bslmf
```

Others

- Many other libraries, lacking language support, adopt similar approaches.

- In Qt, for example, the syntax uses a macro.

```
Q_DECLARE_TYPEINFO( Widget, Q_RELOCATABLE_TYPE );
```

Common themes

- Every single non-*trivially copyable* type that we wish to optimise using `memcpy` must be individually flagged.
- Flagging Standard Library types results in code portability issues (e.g., std::string in libc++ vs. libstdc++).
- The elephant in the room: Both libraries rely on compilers allowing what is, technically, undefined behaviour.

Note: `std::string` can be trivially relocated in libc++ but not in libstdc++,
which uses self-references in its short string optimization.

Relying on undefined behaviour

The caveat with using `memcpy`:

> If the type is not an ***implicit-lifetime*** type, then it is, technically, undefined behaviour to access any non-static members or call any non-static functions on the copied object.
> (C++ Standard, section [basic.life])

The good news:

> No current compilers track this, so libraries can “get away with it”, but there is no guarantee that a future compiler will not decide to optimise away that access and break our code.

Note: All *trivially copyable* types are, by definition, *implicit-lifetime* types.

Is trivial relocation worth doing?

- The vast majority of types are not *trivially copyable*, and those that are tend to be very small and very simple.

- The vast majority of types can be trivially relocated.

- The only non-trivially relocatable types tend to be complex structures that store (directly or indirectly) pointers to themselves or to their own members.

- Thus, adding trivial relocatability to the language would allow std::vector to use `memcpy` in almost all cases.

Is trivial relocation worth doing?

All of the following Standard Library types, though not *trivially copyable,* may be, depending on the library implementation, trivially relocatable:

```
std::unique_ptr
std::shared_ptr
std::string
std::pair<int, int>
```

Note: `std::string` can be trivially relocated in libc++ but not in libstdc++, which uses self-references in its short string optimization.

Adding trivial relocation to the C++ Standard

First attempt: 2014, N4034, Pablo Halpern

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First attempt, 2014, Pablo Halpern

N4158: Destructive Move

https://wg21.link/n4158

First attempt, 2014, Pablo Halpern

- This originally started out as paper N4034 https://wg21.link/n4034.

- It was based on (or at least inspired by) the BDE library approach.

- Note that this proposal also considers the case of non-trivial relocations, but that is out of scope for this presentation.

First attempt, 2014, Pablo Halpern

- New Standard Library type traits were proposed.

```
is_trivially_destructive_movable
is_nothrow_destructive_movable
```

- `is_trivially_destructive_movable` defaults to true for types that are both
  - *trivially move constructible.*
  - *trivially destructible.*

- `is_nothrow_destructive_movable` defaults to true if calling `uninitialized_destructive_move` on a type is `noexcept`.

First attempt, 2014, Pablo Halpern

- A new low-level Standard Library function was proposed.

```
template<class T>
uninitialized_trivial_destructive_move(T* from, T* to);
```

- This function is equivalent to
  - — running `memcpy(to, from, sizeof(T))`.
  - — starting the lifetime of `*to`.
  - — ending the lifetime of `*from`.

- This function requires the trait `is_trivially_destructive_movable<T>` to be true.

First attempt, 2014, Pablo Halpern

- New Standard Library functions were proposed.

```
uninitialized_destructive_move
uninitialized_destructive_move_n
```

- These functions default to calling the move constructor and destructor if `is_trivially_destructive_movable` is false, otherwise they call `uninitialized_trivial_destructive_move`.

- Standard Library container implementations can profit by using these methods.

First attempt, 2014, Pablo Halpern

- So what happens if a type, say, `Widget`, can be relocated using `memcpy`?

- You would specialise the `is_trivially_destructive_movable` trait as follows:

```
template <> struct
is_trivially_destructive_movable<Widget> : std::true_type
```

- As a result of this, the function `uninitialized_destructive_move` uses `uninitialized_trivial_destructive_move` rather than construction and destruction
(as does `uninitialized_destructive_move_n`).

First attempt, 2014, Pablo Halpern

- This paper did not progress as it would have required a core language proposal to change the lifetime model and allow something other than a constructor to start the lifetime of an object.

- The WG21 discussion of the lifetime issues raised by this paper did inspire another subsequent paper N4393, “Noop Constructors and Destructors” https://wg21.link/n4393.

- N4393 proposed special constructor and destructor syntax to begin and end the lifetime of an object.

Adding trivial relocation to the C++ Standard

First attempt:	2014, N4034, Pablo Halpern
Second attempt:	2016, P0023, Denis Bider

Second attempt, 2016, Denis Bider

P0023: Relocator: Efficiently moving objects

https://wg21.link/p0023

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Second attempt, 2016, Denis Bider

- A relocation constructor, somewhat akin to move constructors, was proposed.

```
class A {
   >>A(A&);    // relocator
};
```

Second attempt, 2016, Denis Bider

- This was the very first proposal to include rules whereby the compiler can deduce a type’s trivial relocatability.

> If the definition of a class X does not explicitly declare a relocator, a non-explicit one is implicitly declared as defaulted, if and only if class X satisfies the following criterion for each other special member:
>
> - X does not have a user-declared (*special member*), or the user-declared (*special member*) is defaulted at first declaration.

Second attempt, 2016, Denis Bider

- Two new type traits were proposed.

```
template struct is_relocatable;
template struct is_trivially_relocatable;
```

- These were defined as follows:

> The value of `is_relocatable::value` is true if T has either a user-defined relocator, or a defaulted relocator that is not defined as deleted.
>
> The value of `is_trivially_relocatable::value` is true if T has a trivial relocator. A trivial relocator is one that is defaulted, not deleted, and calls only other trivial relocators. It is equivalent to `memcpy`.

Second attempt, 2016, Denis Bider

- So what happens if a type, say, `Widget`, can be relocated using `memcpy`?

- You would default the relocator using the following syntax:

```
class A {
   >>A(A&) = default;    // relocator
};
```

- Library functions can then, if they wish, test this using `is_trivially_relocatable` and optimise accordingly.

Second attempt, 2016, Denis Bider

- Note that this proposal also looks at the case of non-trivial relocations, but that is out of scope for this presentation.

- For unrelated reasons, this proposal did not progress beyond the initial (revision 0) version.

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Adding trivial relocation to the C++ Standard

First attempt:	2014, N4034, Pablo Halpern
Second attempt:	2016, P0023, Denis Bider
Third attempt:	2020, P1029, Niall Douglas

Third attempt, 2020, Niall Douglas

P1029: move = bitcopies

https://wg21.link/p1029

Third attempt, 2020, Niall Douglas

- This proposal was partly motivated by a desire to optimise lightweight exceptions.

- For more details, see the paper “Zero-overhead deterministic exceptions: Throwing values” by Herb Sutter https://wg21.link/p0709

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Third attempt, 2020, Niall Douglas

- This proposal suggests a mechanism to specify that the move constructor can be performed by means of a `memcpy`.

```
class A {
    A(A &&) = bitcopies;
};
```

- This causes the compiler to perform all move constructions using as-if `memcpy` (i.e., the compiler is permitted to elide the copy if it is able to do so).

Third attempt, 2020, Niall Douglas

A type trait was proposed

```
template is_move_constructor_bitcopying;
```

> If a type `T`’s move constructor has `= bitcopies` compatible semantics (which includes trivial copyability), the trait `std::is_move_constructor_bitcopying<T>` shall be true.

which enables libraries to optimise based on trivial relocatability.

Third attempt, 2020, Niall Douglas

- This proposal also includes a mechanism to delegate the decision-making to the compiler.

```
class A {
   A(A &&) = bitcopies(auto);
};
```

Third attempt, 2020, Niall Douglas

- An `= bitcopies` move requires two `memcpy` operations (although the compiler may choose to elide one or both of these).
- Such a move is defined to be equivalent to the following:

```
// Copy bytes of src to dest
memcpy(dest, src, sizeof(Type));

// Copy bytes of constexpr default constructed
// instance to src
static constexpr Type default_constructed{};
memcpy(src, &default_constructed, sizeof(Type));
```

Third attempt, 2020, Niall Douglas

- There are a number of limitations on using move = bitcopies.
  - All bases and members must be either *trivially copyable* or have an `= bitcopies` move constructor.
  - There must be no virtual inheritance.
  - The type itself, as well as all bases and members, must have a `constexpr` default constructor.

Third attempt, 2020, Niall Douglas

- So, not all trivially relocatable types can be given an `= bitcopies` move constructor!
  - This excludes, for example, `std::list,` which is permitted to allocate on construction.
  - This also excludes, for example, anything that writes debug output to a log file on construction.

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Third attempt, 2020, Niall Douglas

- For various unrelated reasons, this proposal didn’t progress beyond the initial paper.

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Adding trivial relocation to the C++ Standard

First attempt:	2014, N4034, Pablo Halpern
Second attempt:	2016, P0023, Denis Bider
Third attempt:	2020, P1029, Niall Douglas
Fourth attempt:	2018-present, P1144, Arthur O’Dwyer
Fifth attempt:	2023-present, P2786, Alisdair Meredith & Mungo Gill

Fourth and fifth attempts, 2018-present

P1144: Object relocation in terms of move plus destroy

Arthur O’Dwyer

https://wg21.link/p1144r6

P2786: Trivial relocatability options

Alisdair Meredith & Mungo Gill

https://wg21.link/p2786

Note: As of revision 7, the title of P1144 has been changed to std::is_trivially_relocatable.

Fourth and fifth attempts, 2018-present

- P1144 has been under development since 2018.

- P2786 was first introduced during the WG21 2023 Issaquah meeting.

- Unlike the previous papers, these are still under consideration for possible inclusion in the C++ Standard.

- As both proposals are very similar, we will discuss them together and then talk about the differences.

Fourth and fifth attempts, 2018-present

- Both proposals focus almost entirely on the trivially relocatable case.
  - Trivial relocation is less complicated than non-trivial relocation.
  - Trivial relocation provides the greatest opportunities for optimisation compared to non-trivial relocations.
- Both proposals agree that the object lifetime model will need to be addressed to avoid reliance on technically undefined behaviour, involving changes to the abstract machine.

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Fourth and fifth attempts, 2018-present

- Neither proposal requires or relies upon any changes to the existing Standard Library containers and algorithms.

- Both proposals have reference implementations (compiler and Standard Library) either completed or in progress.
  - The P1144 reference implementation is publicly available on https://godbolt.org, e.g., see https://godbolt.org/z/1MzfsPGxd.

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Fourth and fifth attempts, 2018-present

- Both proposals agree that trivially copyable types are implicitly trivially relocatable.

- Both proposals agree that, after relocating from an object, the destructor must not be called for that object (now bereft of life); to do so leads to undefined behaviour.

  - Relocating to or from an automatic variable is generally a bad idea, unless you really know what you are doing.

- If a type is explicitly marked as trivially relocatable, but for that type move+destroy is not equivalent to `memcpy`, then greater care is required as resulting behaviour may not be what you intended.

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Fourth and fifth attempts, 2018-present

- Both proposals provide type traits to enable library implementors to determine trivial relocatability.

P1144	P2786

template< class T > struct is_relocatable;
template< class T > struct is_nothrow_relocatable;
template< class T > struct is_trivially_relocatable;
	template< class T > struct is_trivially_relocatable;

Fourth and fifth attempts, 2018-present

- Both proposals provide a syntax to flag classes as trivially relocatable.

P1144	P2786
`struct`	`struct C`
`[[trivially_relocatable(true)]]`	`trivially_relocatable(true)`
`C {`	`{`
`    C(C&&);`	`    C(C&&);`
`    ~C();`	`    ~C();`
`};`	`};`
`static_assert(`	`static_assert(`
`is_trivially_relocatable_v<C>);`	`is_trivially_relocatable_v<C>);`

Fourth and fifth attempts, 2018-present

- Both proposals provide relocation functions although, as we will show in a subsequent slide, they behave very differently.

P1144

```cpp
template<class T>
T *relocate_at(T* source, T* dest);

template<class T>
T relocate(
    T* source);
```

P2786

```cpp
template<class T>
requires
(is_trivially_relocatable_v<T> &&
                 !is_const_v<T>)
void trivially_relocate(
    T* begin,
    T* end,
    T* new_location) noexcept;
```

Fourth and fifth attempts, 2018-present

- Both also provide convenience functions.

P1144

```
template<class InputIterator,
         class NoThrowFwdIterator>
NoThrowFwdIterator
uninitialized_relocate(
    InputIterator first,
    InputIterator last,
    NoThrowFwdIterator result);

template<class InputIt, class Size,
         class NoThrowFwdIt>
pair<InputIt, NoThrowFwdIt>
uninitialized_relocate_n(
    InputIt first, Size n,
    NoThrowFwdIt result);
```

P2786

```
template<class T>
requires
((is_trivially_relocatable_v<T> &&
 !is_const_v<T>) ||
is_nothrow_move_constructible_v<T>)
T* relocate(
    T* begin, T* end,
    T* new_location)
```

NOTE: P1144’s `relocate` and P2786’s `relocate` are very different functions. They just happen to have the same name in both proposals.

Fourth and fifth attempts, 2018-present

- Both proposals provide automatic compiler detection of trivially relocatable types.

P1144

A object type T is a ***trivially relocatable*** type if it is:
— a trivially copyable type, or
— an array of trivially relocatable type, or
— a (possibly cv-qualified) class type declared with a [[trivially_relocatable]] attribute with value true, or
— a (possibly cv-qualified) class type which:
  — has no user-provided move constructors or move assignment operators,
  — has no user-provided copy constructors or copy assignment operators,
  — has no user-provided destructors,
  — has no virtual member functions,
  — has no virtual base classes,
  — all of whose members are either of reference type or of trivially relocatable type, and
  — all of whose base classes are trivially relocatable.

Fourth and fifth attempts, 2018-present

- Both proposals provide automatic compiler detection of trivially relocatable types.

P2786 (This definition is currently being revised.)

A trivially relocatable class is a class that:
— has no base classes that are not of trivially relocatable type,
— has no non-static non-reference data members whose type is not a trivially relocatable type,
— has no virtual base classes,
— has no user-provided or deleted destructors,
— either has no trivially_relocatable predicate, or has a trivially_relocatable predicate that evaluates to true,
— and either
    — has a move constructor that is neither user-provided nor deleted, or
    — has no move constructor and has a copy constructor that is neither user provided nor deleted.

Fourth and fifth attempts, 2018-2023

- So, if they have so much in common, why are there two proposals under consideration?

- Why are they different?

- (We will ignore any cosmetic stuff like function names and the keyword vs. attribute question.)

Key differences: A difference in tone

- P1144 is more focused on providing methods for higher-level language users.
  - There are more utility functions.
  - Iterator-based interfaces are provided.
  - There is less implementation detail.
- P2768 is more focused on providing a low-level interface for library implementors.
  - A key focus is on the implications for the *abstract machine.*
  - Only one low-level interface and one optional utility function are provided.

Key differences: Utility functions vs. a low-level interface

- In P1144, the functions `relocate_at` (and `relocate`) will use `memcpy` for trivially relocatable types but will fall back to using move construction and destruction otherwise.

- In P2768, `trivially_relocate` will use `memcpy` for trivially relocatable types and will fail to compile otherwise.

Key differences: Interface vs. semantics

- P1144 supports relocation based on the public interface of a type.
  - It is explicitly stated that relocation is equivalent to move+destroy.
  - A type must have a public constructor and destructor.
- P2768 is instead based on the semantics of a type.
  - Relocation is a primitive operation in the memory/object model.
  - Constructors and destructors are not required to be public.
  - Assignment operators have no bearing on the matter.

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Key differences: Examples

- Types considered trivially relocatable under P2768 but not P1144 include
  - polymorphic types.
  - everything in `pmr` (i.e., types following scoped allocator model).
  - `const` objects.
  - (some) types with `const` data members.
- Types considered trivially relocatable under P1144 but not P2786 include
  - objects with data members from third-party libraries where those types are not marked as trivially relocatable.

Key differences: Ill-formed code

- P1144 is more dangerous but gives developers greater freedom.
  - Marking a type trivially relocatable where that doesn't make sense is ill formed but is not required to generate any diagnostics and will result in undefined behaviour.
- P2768 is safer but more restrictive for developers.
  - Marking a type trivially relocatable will result in a compile-time error where any members or base classes are not trivially relocatable or where there is virtual inheritance.

Note: In the interests of openness I should point out that the author of P1144 disagrees with this opinion of the relative safety of these proposals.

Key differences: What about assignment and `std::swap`?

- P1144 includes an assumption that, for a trivially relocatable type
  - `memcpy` can be used in place of move-constructor relocation.
  - `memcpy` can be used in place of assignment-operator relocation.
  - `memcpy` can be used for swapping.
- P2768 assumes only the first of these.
- Note: The author of P1144 subsequently discussed the generic swap question in blog posts at https://quuxplusone.github.io/blog/2023/02/24/trivial-swap-x-prize/.

Key differences: What about assignment and `std::swap`?

Is relocation using the move constructor equivalent to relocation using the assignment operator?

Move constructor	Assignment operator

`// Destruct the destination.`
`destination->~Type();`
`// move construct`
`new(destination)`
`      Type(std::move(*source));`
	`// assign`
	`*destination = *source;`

Key differences: What about assignment and `std::swap`?

Is relocation using the move constructor equivalent to relocation using the assignment operator?

- For some types, this is generally NOT the case, such as
  - types with `const` and/or reference members (such types are not assignable).
  - types with non-propagating allocators, such as `std::pmr::string`, unless it can be guaranteed that the source and target objects have the same allocator.

Key differences: What about assignment and `std::swap`?

Is relocation using the move constructor equivalent to relocation using the assignment operator?

- For `std::pmr::vector`, we can safely assume that all members of that vector have been constructed using the same allocator.

- Therefore, for P2786-style trivially relocatable types,
  - it is perfectly safe to use `memcpy` to move elements around within a `std::pmr::vector` or similarly allocator-aware container.
  - we cannot assume this is safe in any other situation.

Fourth and fifth attempts – Next steps

- The papers' authors will work together to reconcile their papers, where possible.

- Commonalities and irreconcilable differences will be re-presented to the WG21 committee for further guidance.

- This process will not be quick, but we need to be confident we are doing the right thing before changing the language Standard.

Conclusion

- Enabling containers to use `memcpy` would be a valuable optimisation.

- Current libraries have workarounds, but they are not perfect and cannot be perfect without language support.

- Over the last 9 years, three previous proposals and two current, ongoing proposals indicate the need for adding support for trivial relocatability into the language.

- Perhaps some combination of the two current attempts will make it into C++26.

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Thank you! Questions?

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We are hiring: bloomberg.com/engineering

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