C++ now

Designing a Slimmer Vector of Variants

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Overview for this Talk

- This talk details my experience in creating a novel solution to an observed problem with memory usage of `std::vector<std::variant<...>>`
- The talk starts with the motivating use case, considers several candidate designs, refining as we go, and then presents interesting implications of the approach, benchmarks, and lessons learned
- I implemented the data structure mostly for the fun of it, as well as to get more familiar with C++20 features
- The final presented design in this presentation is a simplified version of the actual data structure, but it should illustrate the point

Motivation

- Heterogeneous containers like `std::vector<std::variant<...>>` are an extremely natural way to represent data across many different paradigms
- Naive usage of `std::vector<std::variant<...>>` can result in *comically* bad memory utilization if the types are of disparate sizes
- While fine for trivial examples and slide code, it can lead to significant bloat in real-world code

Trivia: How Much Memory is Used by this Vector?

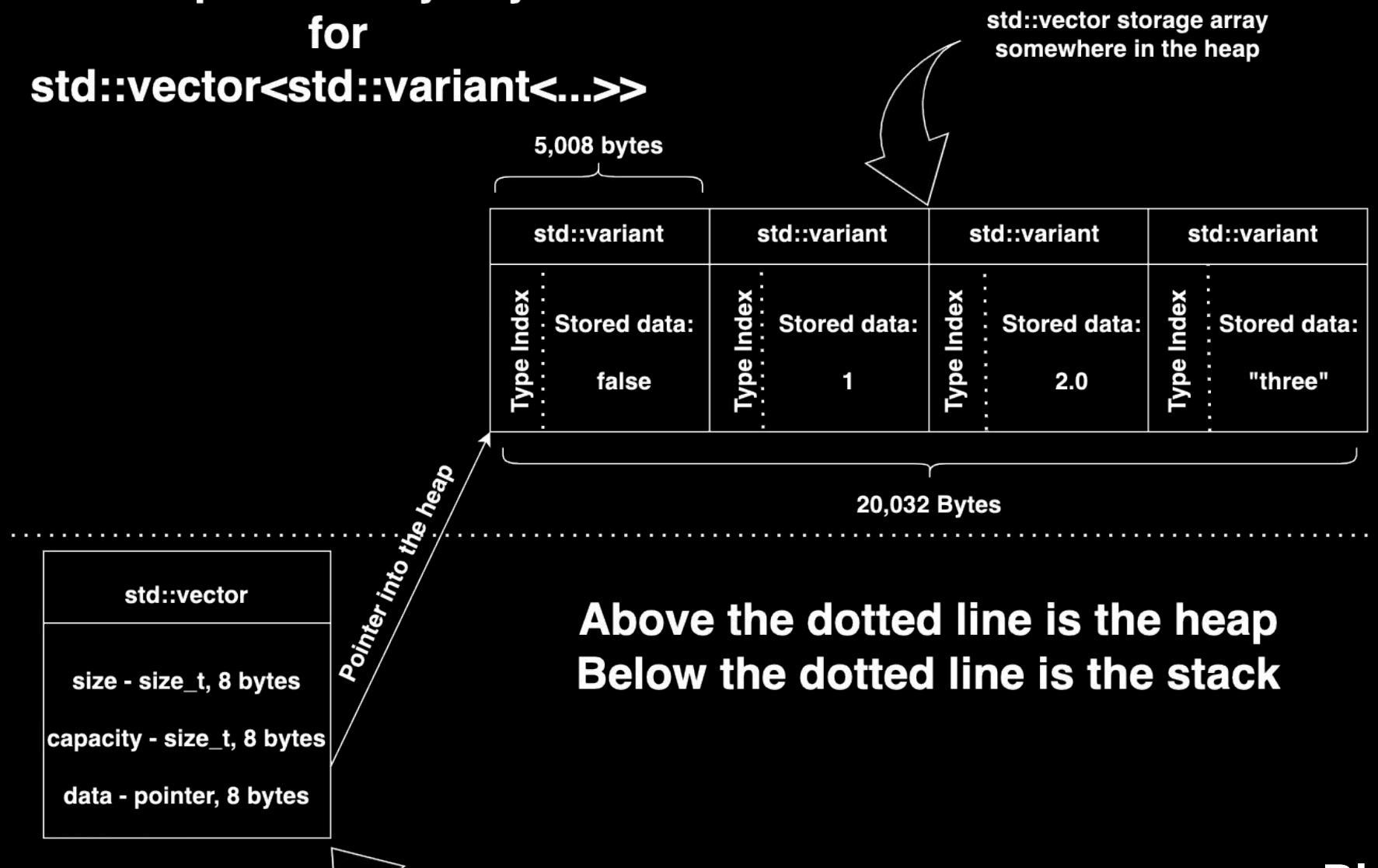
```cpp
#include <vector>
#include <string>
#include <variant>

struct big_data {
    char data[5000];
};

using combo_type = std::variant<bool, int, double, std::string, big_data>;

int main() {
    std::vector<combo_type> vec {false, 1, 2.0, "three"};
}
```

Example Memory Layout for std::vector<std::variant<...>>



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Analysis of Memory Usage

- `std::variant<...>` stores the wrapped types inside of the class
- And so, it must pessimistically be at least as large as the largest T
- `std::vector<T>` assumes all elements are the same size
- Which brings us to our failure state, which requires ~20KB to store a single `bool`, `int`, `double`, and `std::string`
- Assuming a `bool` is 1 byte, an `int` is 4 bytes, a `double` is 8 bytes, and a `std::string` is 24 bytes, the minimum conceivable memory usage is 37 bytes, meaning this represents a bloat factor of 540x!

Why is `std::vector<std::variant<...>>` so wasteful?

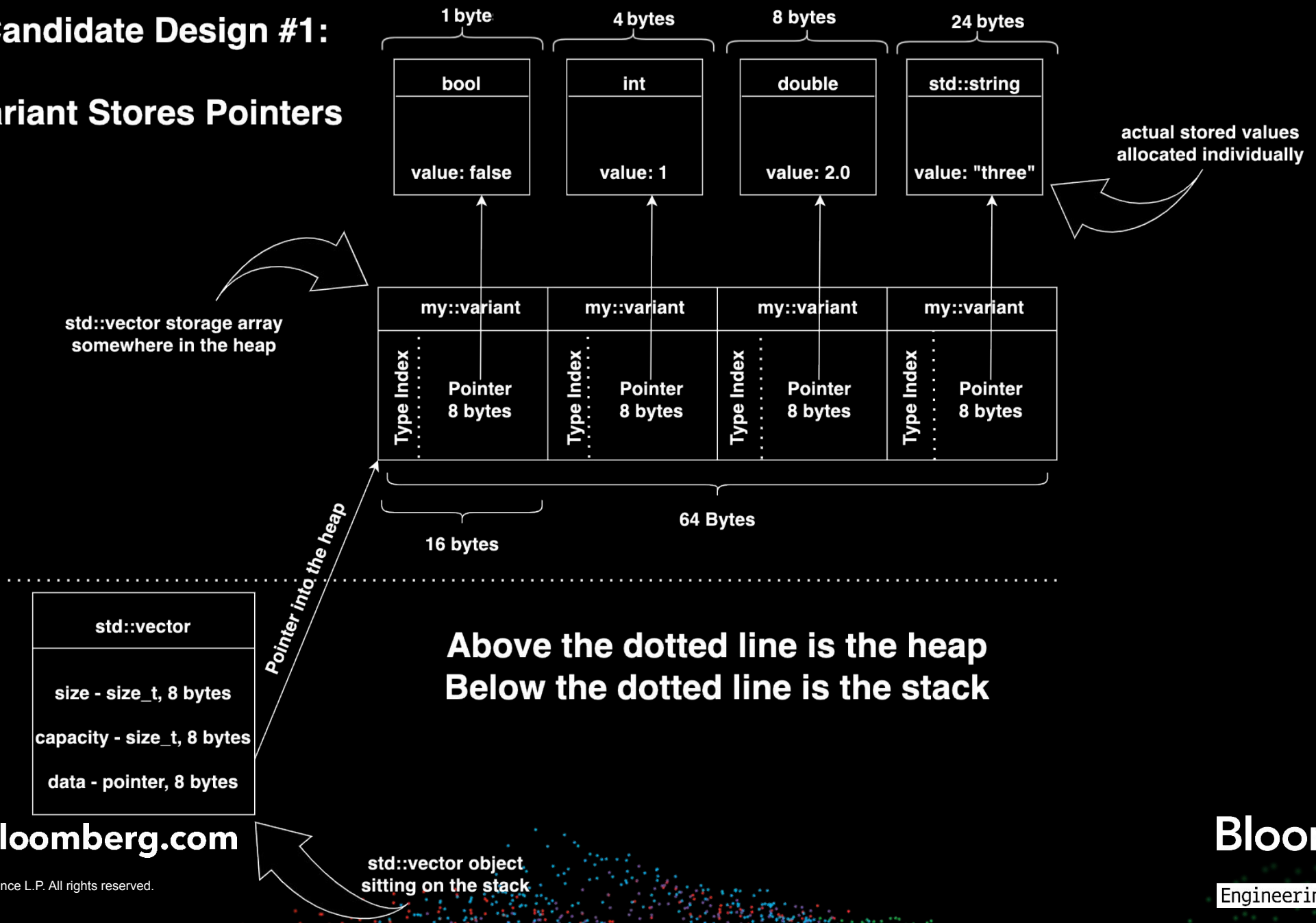
- `std::vector` and `std::variant` are generically composable containers that don't cooperate with each other
- `std::variant` is specified such that it cannot allocate
- If you assume all data is the same size and have to store all types in-situ, this is necessarily the outcome
- Can we do better?

Candidate Design #1

- Say that we relaxed the limitation that `std::variant` can't allocate, where would that get us?

Candidate Design #1:

Variant Stores Pointers



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Candidate Design #1

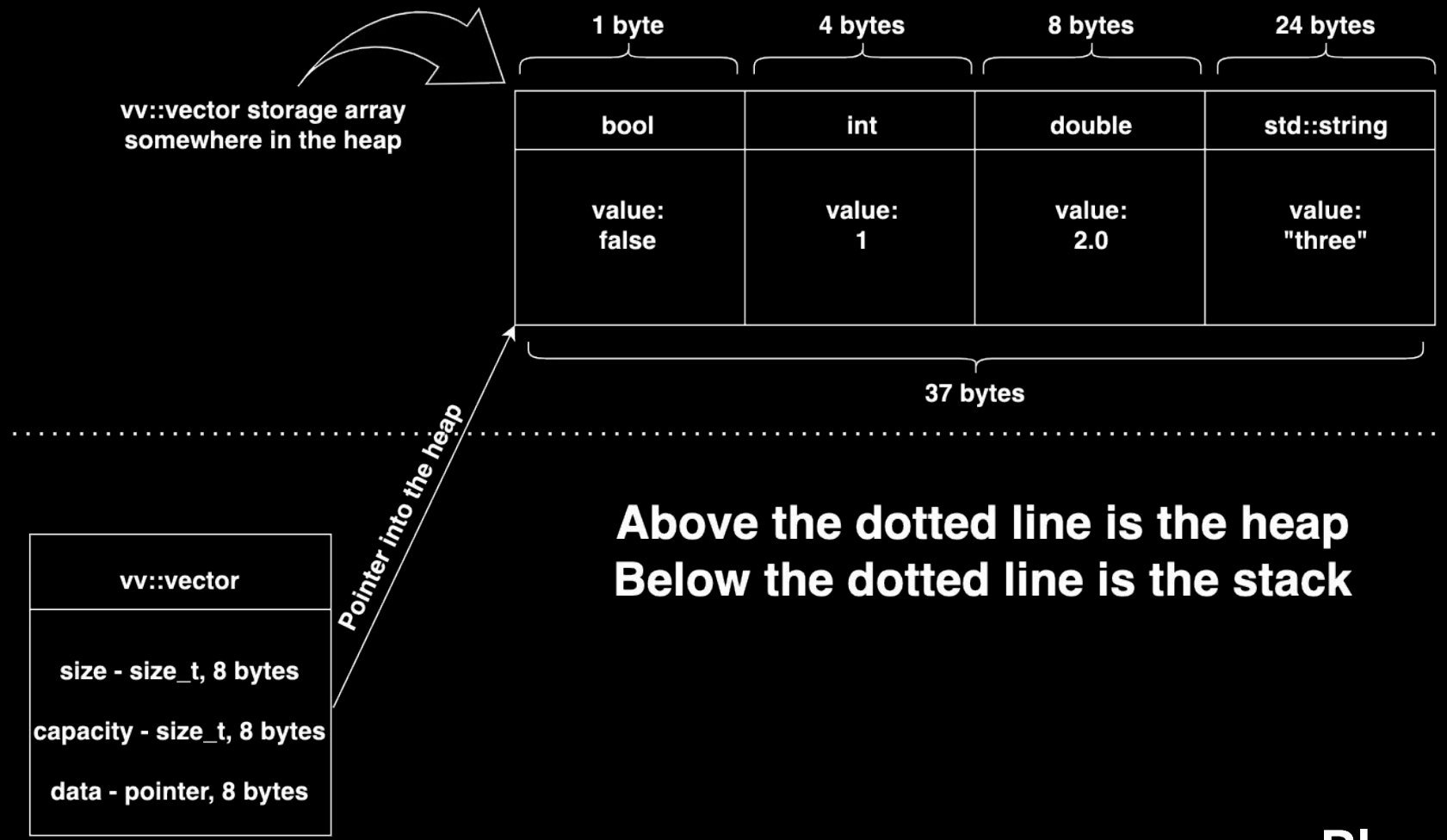
- New design uses only 101 bytes! We're now down to just 2.75x memory bloat
- However, *every* ***single*** `push_back()` now needs to allocate from the heap
- We've saved a lot of memory, and our implementation remains simple, but we've also fragmented the heap and *demolished* the performance characteristics of the original data structure
- Can we do better?

Candidate Design #2

- Performance overhead of allocating for every variant can’t be mitigated
- What if we instead wrote our own vector class that was actually aware of the different types it is storing?

Candidate Design #2:

Vector Stores Multiple Types



Above the dotted line is the heap
Below the dotted line is the stack

Candidate Design #2

- Design uses exactly 37 bytes, which was our theoretical minimum!
- That was easy!
- And people say “C++ is hard!” 🤭

Thank you!

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Not So Fast!

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Some Problems with Candidate Design #2

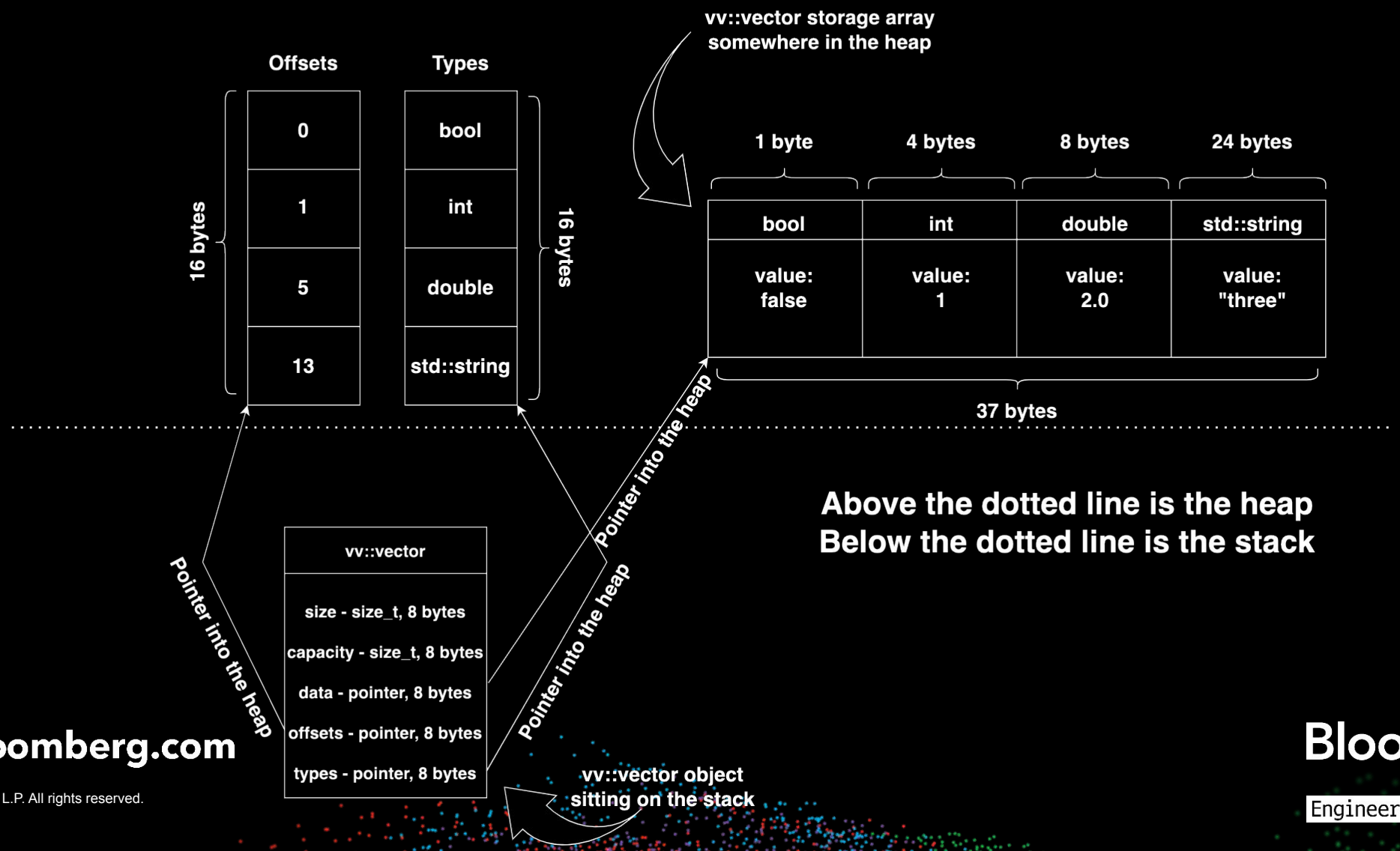
- How do we actually get things back out of this vector?
  - Everything is stored in one array, and each element is potentially a different size. How do we know where element N is?
  - Beyond this, each element is also potentially a different type! How do we know what type element N is?

Candidate Design #3

- Same as Design #2, but let's also add some additional storage to keep track of types and offsets
- We can use `int`s to store both the offsets and the types
  - Offset can be stored as bytes from the base of the storage array
  - Type can be stored as the index in the variant's type list
  - 0 for `bool`, 1 for `int`, and so on

Candidate Design #3:

Vector Stores Multiple Types... but this time, with Metadata!



Above the dotted line is the heap
Below the dotted line is the stack

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Candidate Design #3

- Updated design now uses 69 bytes, so we're now both more memory efficient than Design #1 *and* significantly faster at the same time
- We can now correctly discern between different types, and we also know the offsets where things are located, so we're good to go, right?
- Let's write a quick test program to check… and just to be fun and quirky, let's try running it on Solaris

Design #3 Test Driver

```cpp
#include <varvec.h>
#include <string>

using vector = vv::vector<bool, int, double, std::string>;

int main() {
    vector vec {false, 1, 2.0, "three"};
    for (auto elem : vec) {
        std::visit(elem, [] (auto val) { std::cout << val << std::endl; } );
    }
}
```

Design #3 Test Driver Results

```
sundev9:working $ ./a.out
0
Bus Error (core dumped)
```

The Problem of Memory Alignment 😱

- Welcome to the world of the compiler, or more specifically, the world that the compiler *hides* from you
- Most code never has to think about it, because both the language and compiler work together to abstract it away, but there are strict requirements imposed by the hardware on what kinds of addresses can legally be used by different machine types
- Let’s take a concrete example

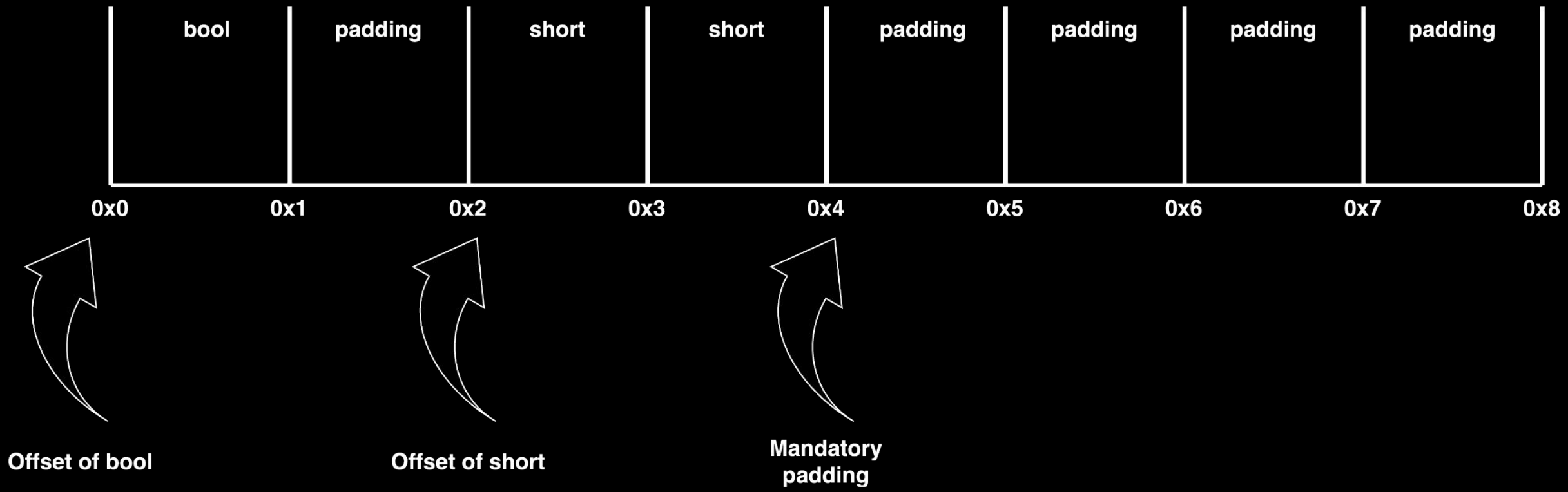
Memory Alignment Example

```
struct example {
    bool flag;
    short state;
    long counter;
};
```

```
static_assert(
    sizeof(example)== 16
);
```

Exercise in Understanding Memory Alignment:

Example struct layout



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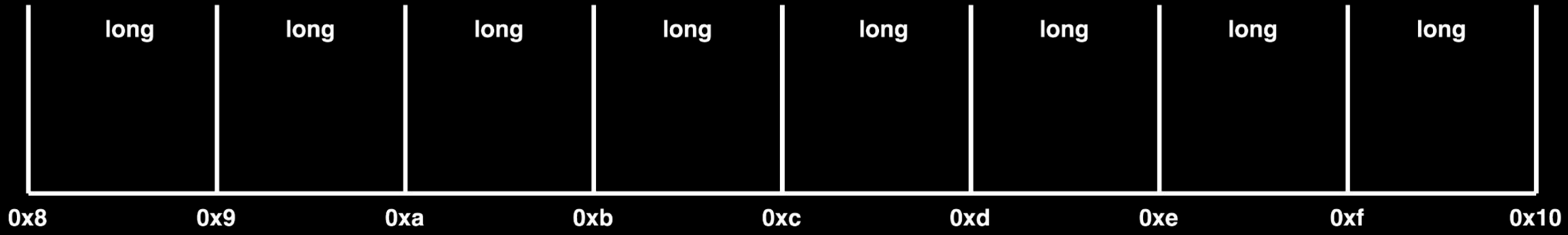
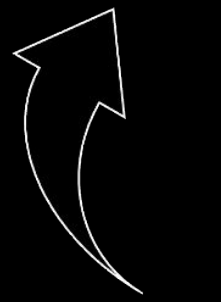
Exercise in Understanding Memory Alignment:

Example struct layout continued





Offset of long

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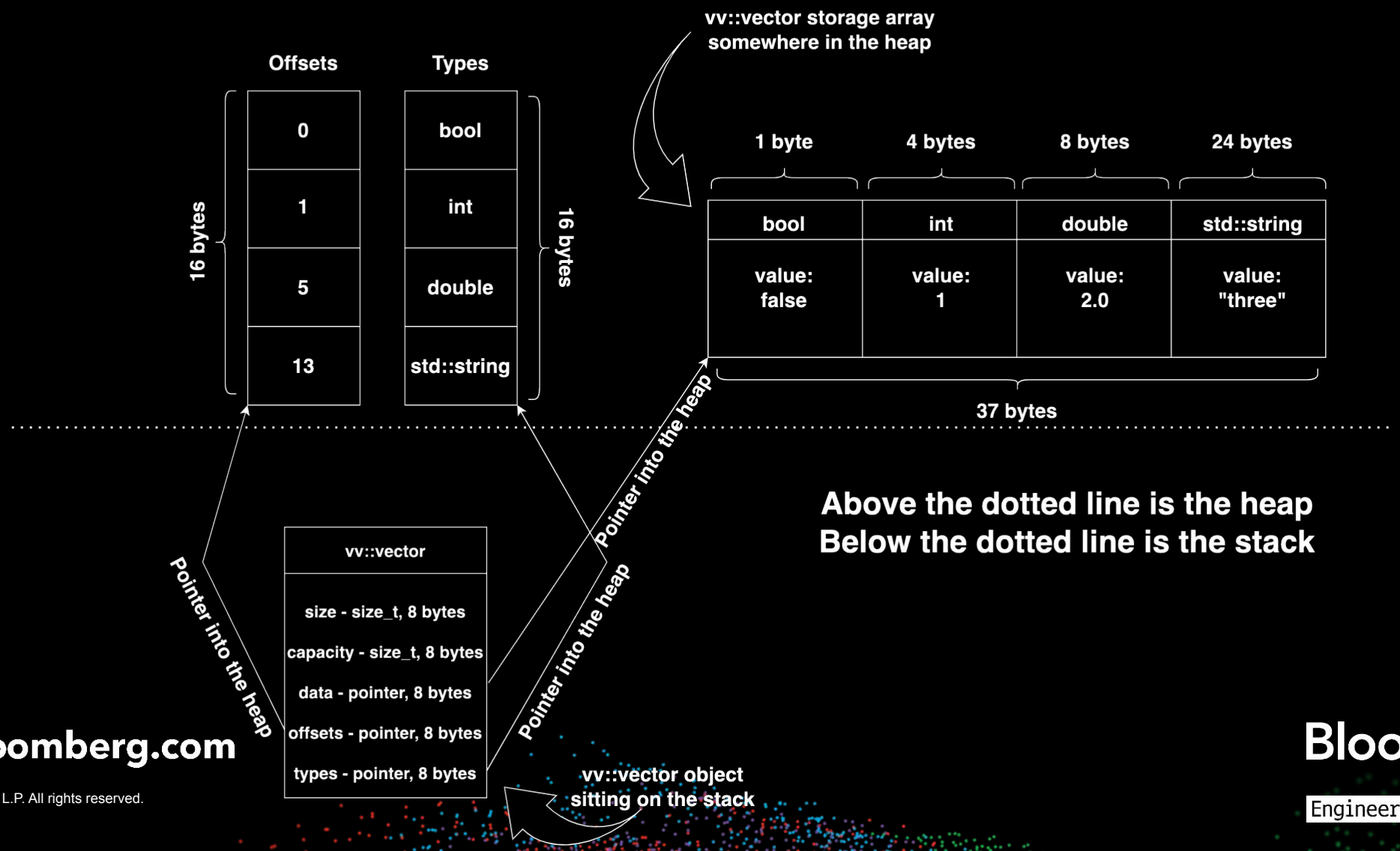
Candidate Design #3:

Vector Stores Multiple Types... but this time, with Metadata!



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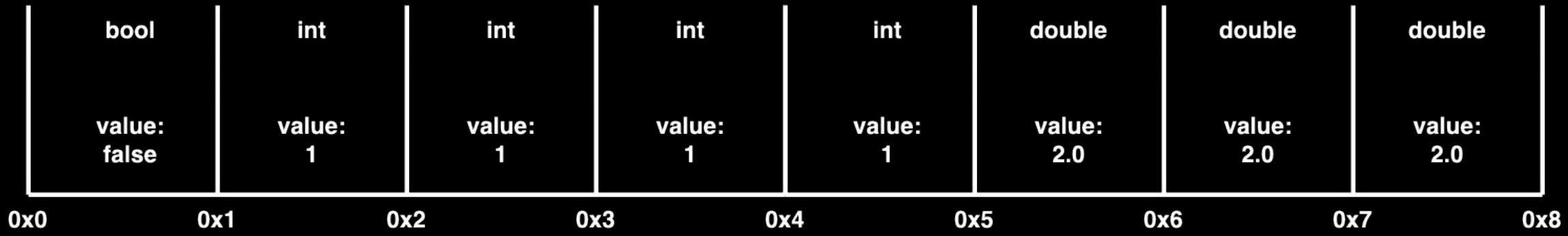
Exercise in Understanding Memory Alignment:

Our current storage layout



Current location of our bool

Current location of our int

Current location of our double

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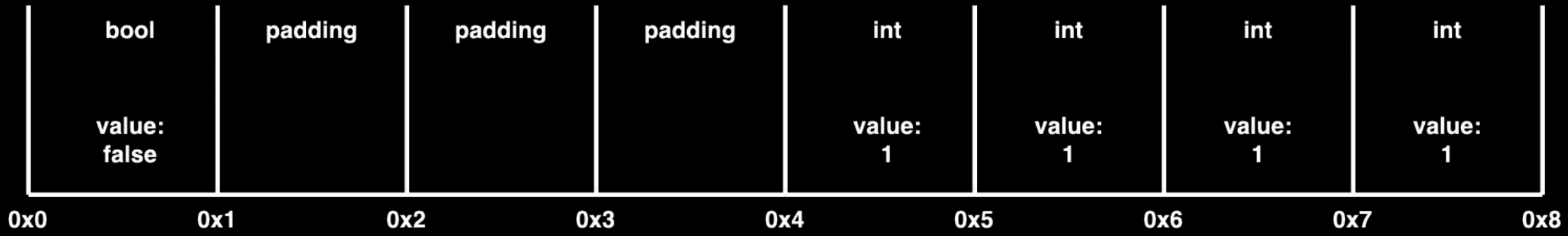
Exercise in Understanding Memory Alignment:

Corrected storage layout



Current location of our bool

Aligned location for our int

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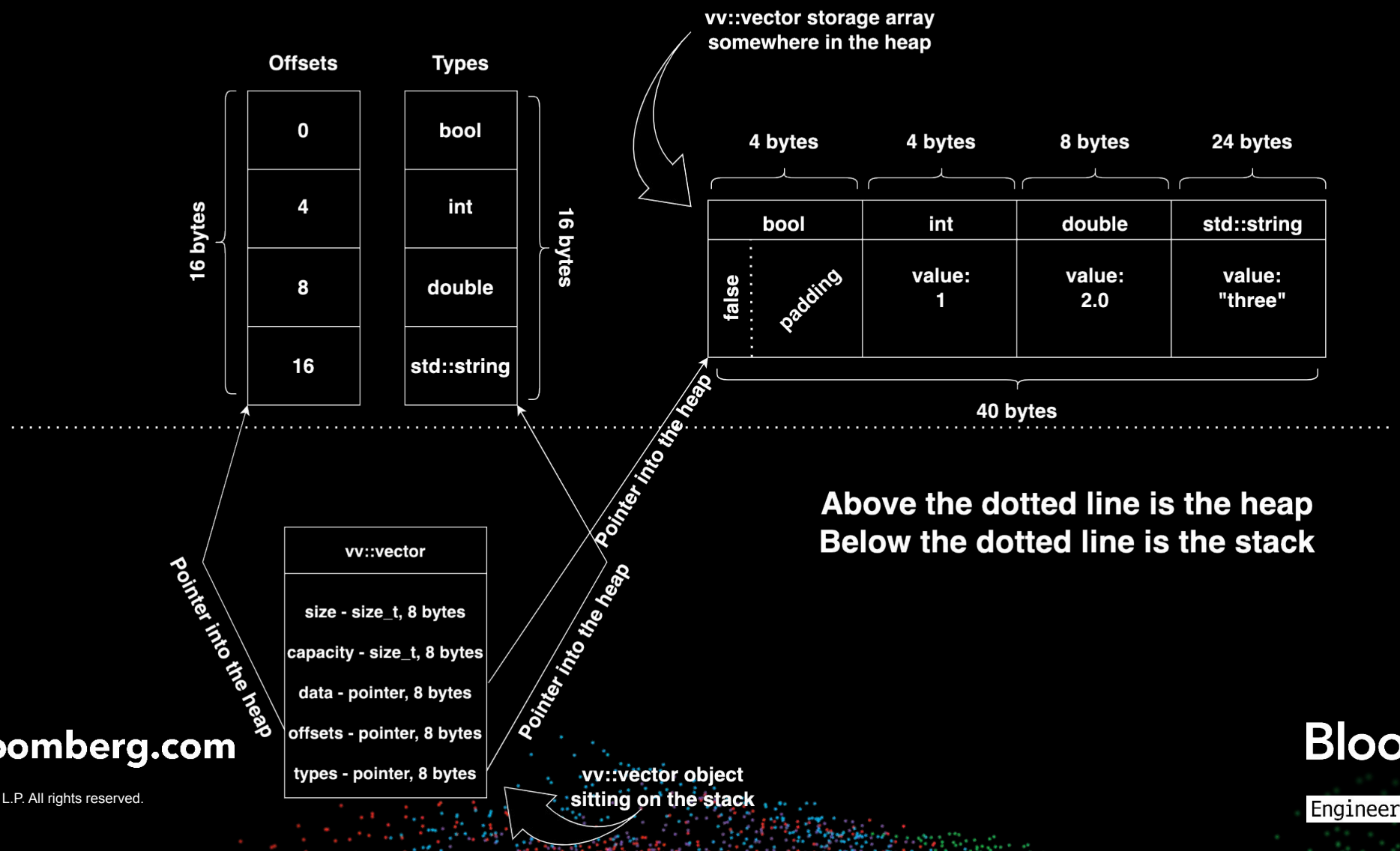
Candidate Design #4

- Same as Design #3, but let's ensure that our data is properly aligned this time around
- C++ has features that can help us:
  - `alignof(T)` can be used to return the alignment required by type T
  - `alignas(T)` can be used to force a specific alignment
  - `new(std::align_val_t(N))` can be used to allocate aligned

Candidate Design #4:

Vector Stores Multiple Types... but this time, with alignment!



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Candidate Design #4

- Finally, we have something that actually works! 🎉🎉
- At this point, our design requires 72 bytes, which is slightly worse than Design #3, but it actually works – and it's also a far cry from the 20KB in the original example
- Can we do better?

Candidate Design #5

- Currently, nearly half of our memory usage (32 bytes) goes into the offset and type storage; it has to be possible to do better than this
- First observation: there will always be a static number of types that our vector is parameterized by
  - It’s unlikely the vector will ever use more than a handful of types
  - If we know how many types we’ll have to store, we can compute the minimum number of bits to uniquely distinguish types, and store the type info in a bitmap, radically decreasing storage requirements

Candidate Design #5

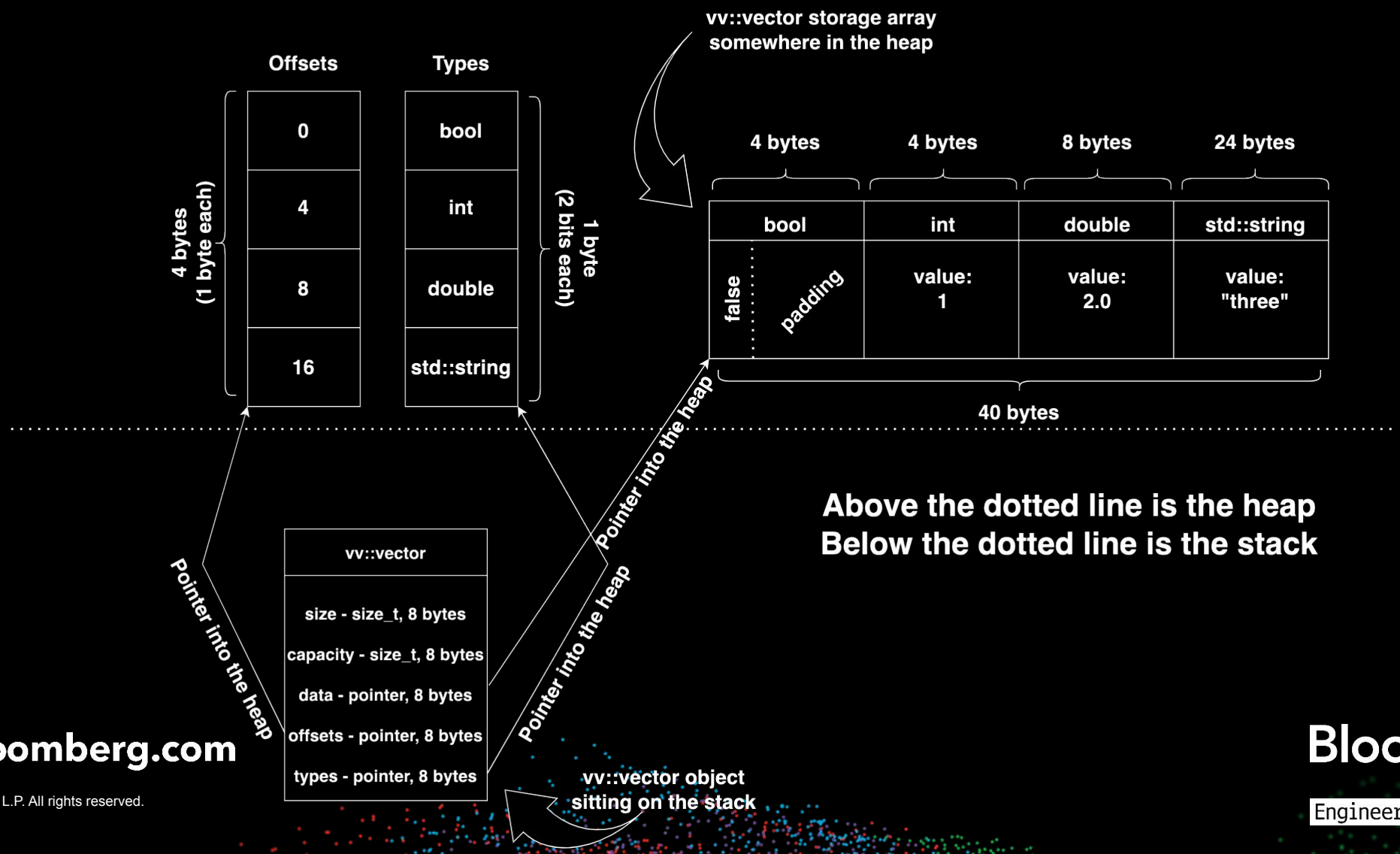
- Second observation: if we can put an upper bound on the size of the vector, we can compute the smallest integer type that can represent the maximum offset
  - It needn’t actually be a hard limit. If we have the ability to “swap out” or “rebuild” our index storage at runtime, we can dynamically select the smallest representation that will suffice

Candidate Design #5

- Replace the current type storage with a bitmap that stores types using the minimum bits possible
- Replace the current offset storage with a virtual interface that will allow us to transparently “rebuild” and “swap out” the offset storage with the smallest usable version at runtime
- Combining both approaches should get us significantly closer to our theoretical minimum

Candidate Design #5:

Compactifying the metadata storage



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Candidate Design #5

- This optimization brings us to a grand total of 45 bytes for the full representation, an overhead factor of only about 20% versus the theoretical minimum
- Can we still do better? Perhaps…

A Few Additional Ideas

- If we can handle the dynamic case, a static vector implementation should be a trivial extension
  - Static vector can store contents in-situ in the class
  - C++ 20 `requires` clause can conditionally disable copy/move operations
  - Very natural extensions for `constexpr`

A Few Additional Ideas

- For **absolute** minimum memory usage, we *could:*
  - Store `trivially_copyable` types contiguously, without alignment
  - Copy-in/out and realign through the stack on access
- Probably to the point of diminishing returns

Implications of Design

- We now have a candidate design for a data structure that radically reduces the memory footprint from our original example, while retaining the same functionality

- We've been hoping for a drop-in replacement for `std::vector<std::variant<...>>`, but do these changes have any implications for its wider API?

The Challenges of Mixed Type Storage

- Many of the member functions in `std::vector` silently assume that all of its elements are of the same size.
- What does `capacity` mean for this data structure?
- What does `reserve` mean for this data structure?
- What about `resize`?
- All of these functions operate on the number of elements, from which the number of bytes can be directly inferred. We cannot do this

The Challenges of Mixed Type Storage

```cpp
#include <string>
#include <varvec.h>
#include <iostream>

int main() {
    vv::vector<bool, int, double, std::string> vec;
    vec.reserve_bytes(64);
    vec.reserve<std::string>(16);
    vec.resize(16, "a test string");
    std::cout << vec.capacity<std::string>() << std::endl;
    std::cout << vec.capacity_bytes() << std::endl;
}

// => 16
// => 384
```

Implications of Design

- Semantic challenges for “number of elements” functions like `capacity`
- Are there any other implications?

The Challenges of Mixed Alignment

- Beyond the problems coming strictly from types being different sizes, there are also challenges from mixed alignment
- `insert` and `erase`, specifically, are non-trivial to implement for this data structure
- Consider the following code:

The Challenges of Mixed Alignment

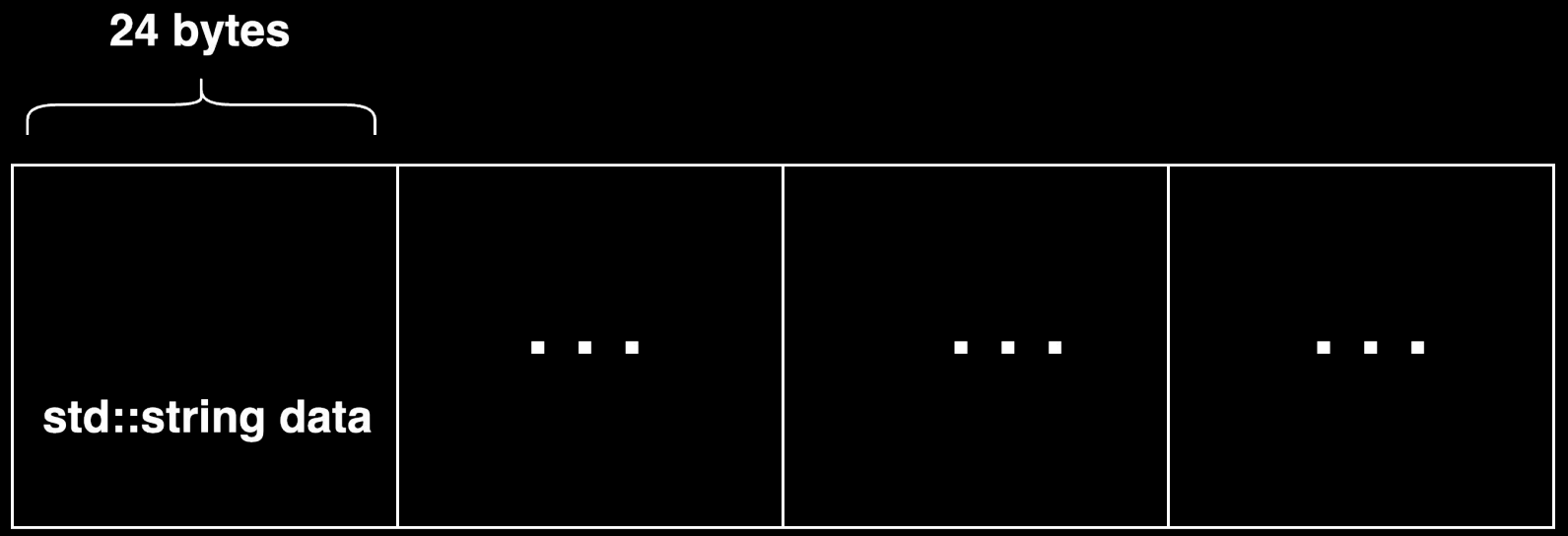
```cpp
#include <string>
#include <varvec.h>
#include <iostream>

int main() {
    vv::vector<bool, std::string> vec {"one", "two", "three"};
    vec.insert(vec.begin(), false);
    std::cout << std::get<std::string>(vec[1]) << std::endl;
}

// => one
```

The Challenges of Mixed Alignment

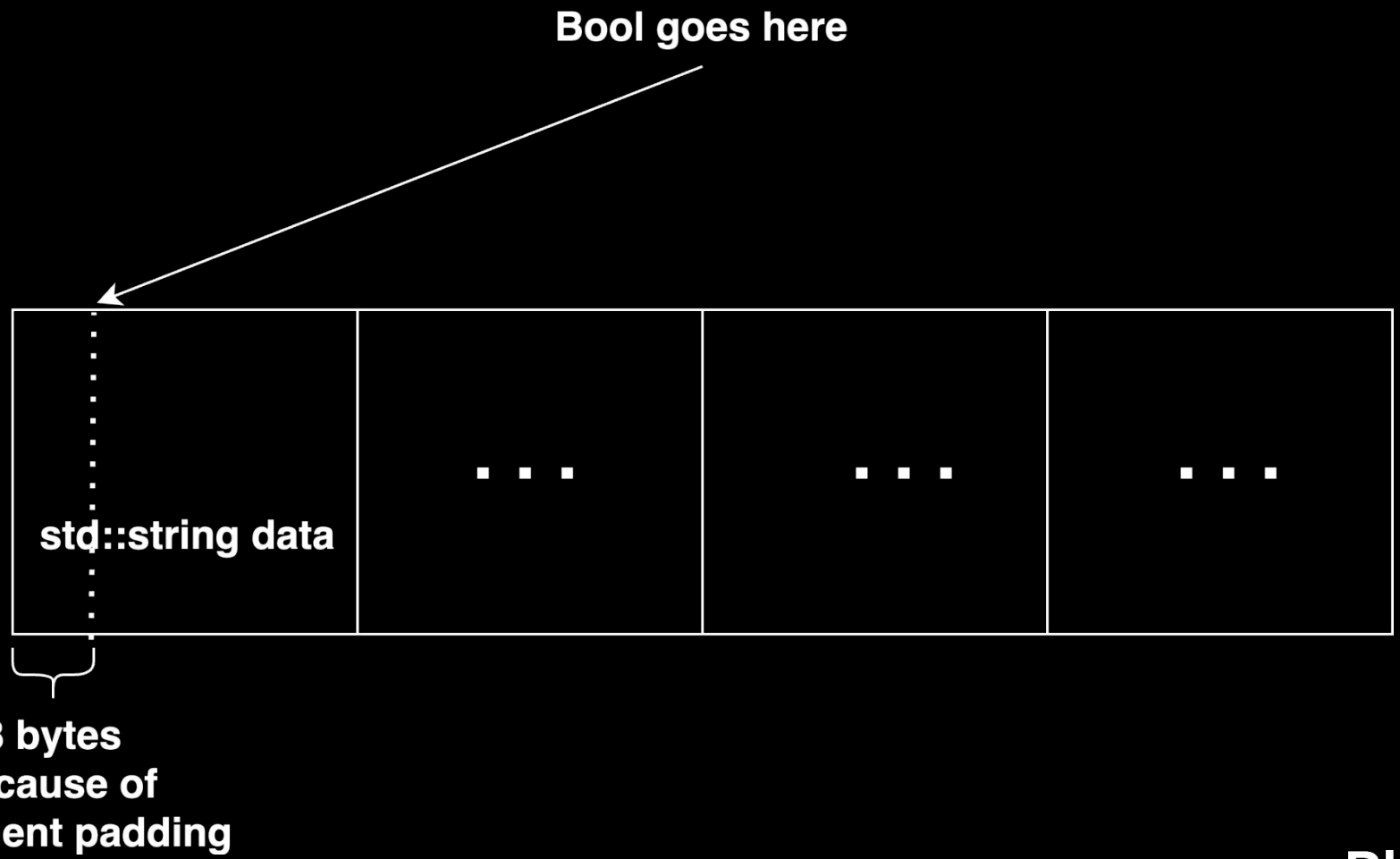
- An insertion into the vector can impact downstream alignment!
- Fix-up can require moving different members by different amounts
- Memory overhead added to maintain alignment can overflow our vector
- Fix-up can require us to shift an object by *less than the size of the object*

Initial State

We want to push a bool onto
the front of this vector



Initial State



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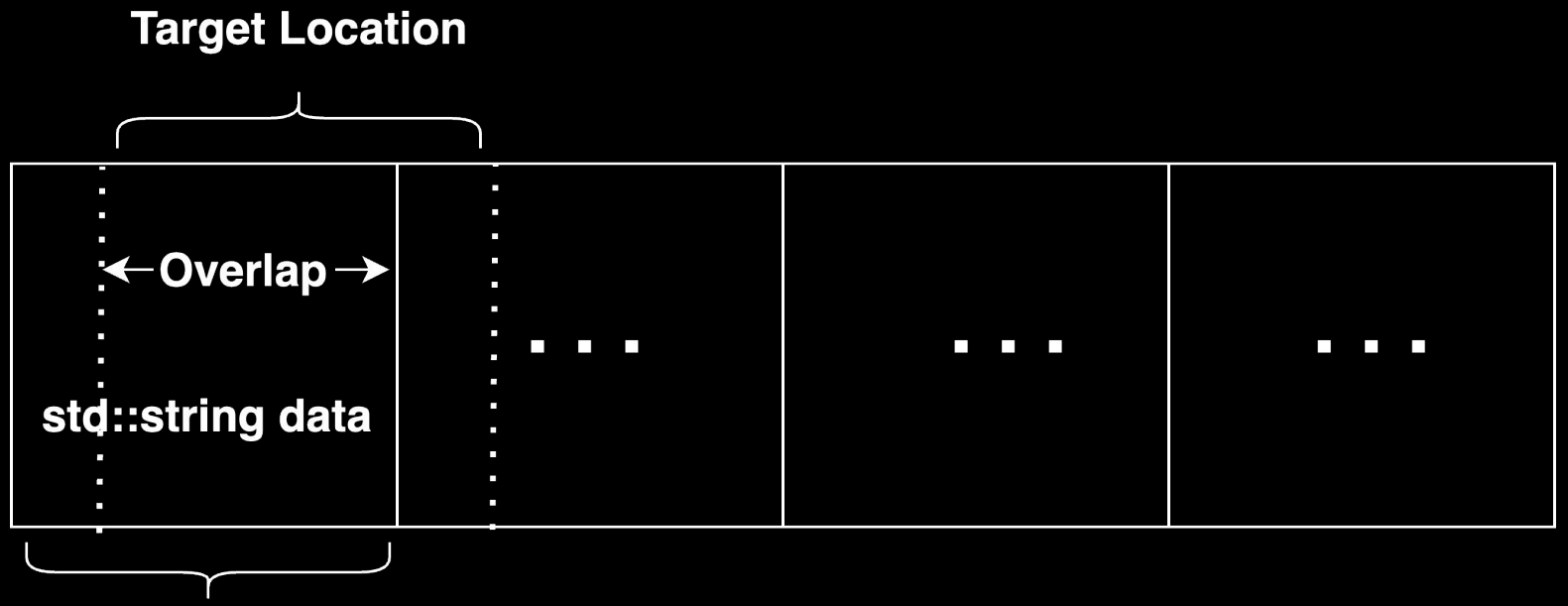
Intermediate State

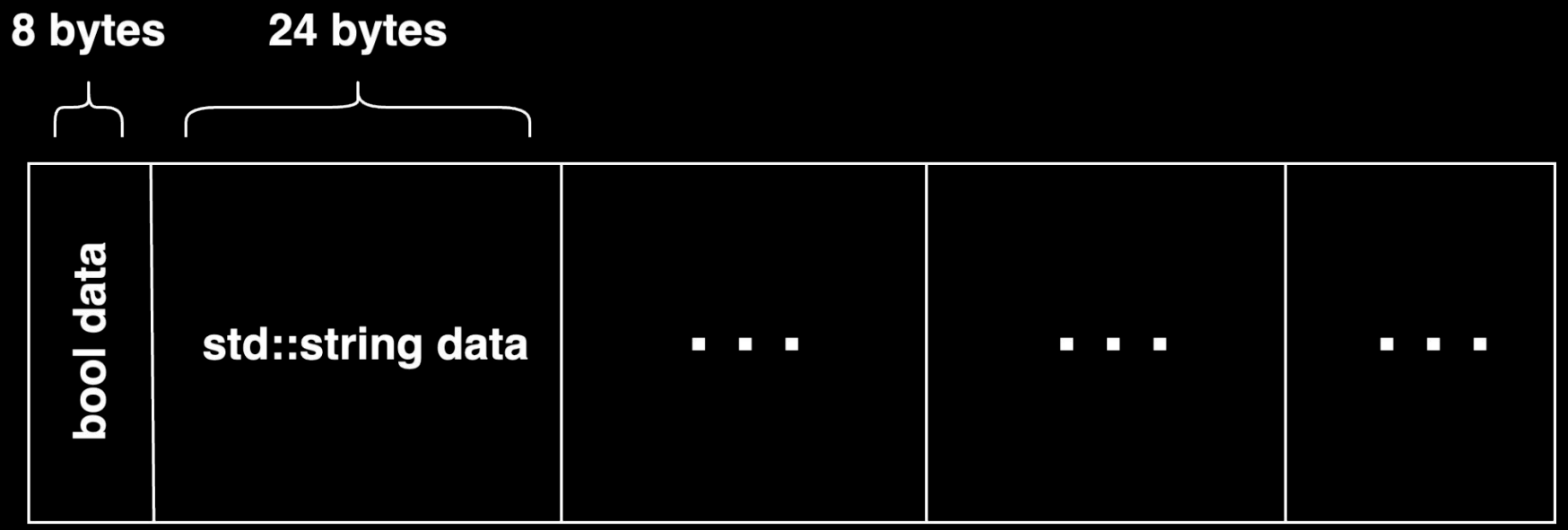
std::string must be shifted in memory by 8 bytes, and yet the class is 24 bytes wide



If done naively, this will lead to overlapping src and dst pointers during the std::move

End State

Entire vector shifted down 8 bytes, requires recomputing alignment



To avoid overlapping pointers, move through a temporary

The Challenges of Mixed Alignment

- During an insert, we must walk the vector and recompute alignment boundaries as we go, reallocating at the end if necessary
- We can then walk backwards and move the objects forwards to make space for the insertion
- If a move would result in overlapping pointers, we move *through* a temporary instance on the stack to avoid corruption
- `erase` has similar challenges, but operates in reverse

Implications of Design

- Semantic challenges for “number of elements” functions like `capacity`
- Member functions like `insert` and `erase` come with unique challenges
- Mixed alignment can lead to complex interactions
- Are there any other implications?

The Woes of `operator []`

- In addition to the subtleties around insertion, there are also complications for access APIs
- While the design presented thus far minimizes memory usage quite nicely, it has necessary implications for the subscript operator
- Consider the following code:

The Woes of `operator []`

```cpp
#include <vector>
#include <string>
#include <variant>
#include <iostream>

using combo_type = std::variant<bool, int, double, std::string>;

int main() {
    std::vector<combo_type> vec {false, 1, 2.0, "three"};
    vec[3] = "one plus two";
    std::cout << std::get<std::string>(vec[3]) << std::endl;
}

// => one plus two
```

The Woes of `operator []`

- How does the assignment inside of `main` actually work?
  - The subscript operator of `std::vector` returns an lvalue reference to the requested index, of type `std::variant<...>&`
  - The assignment operator of `std::variant` is called, and it does some template magic to ultimately select and call the assignment operator of `std::string`
    - The assignment operator of `std::string` receives the string literal and changes its value, causing the print statement to see the new value

The Woes of `operator []`

- What happens if we try the same with our vector?

The Woes of `operator []`

```cpp
#include <string>
#include <variant>
#include <iostream>
#include <varvec.h>

using vector = vv::vector<bool, int, double, std::string>;

int main() {
    vector vec {false, 1, 2.0, "three"};
    vec[3] = "one plus two";
    std::cout << std::get<std::string>(vec[3]) << std::endl;
}

// => three
```

The Woes of `operator []`

- The assignment runs fine, and yet the value doesn't update. What gives?
- The issue lies in the first bullet-point of our assignment explanation:

  — "The subscript operator of `std::vector` returns an lvalue reference…"

- `std::vector` is storing a variant, and so it can return a reference to that variant upon access. Our vector, however, is *not* storing an actual variant
- Upon access, our vector creates a temporary variant to return, which *does* get assigned to, but it then evaporates at the end of the line

The Woes of `operator []`

- This is extremely unfortunate, but is an inevitable outcome of not actually storing variants inside the vector
- Could theoretically work around this by returning a proxy class, but this seems like an anti-pattern
- To work around this, we need some new APIs:

The Woes of `operator []`

```cpp
#include <string>
#include <variant>
#include <iostream>
#include <varvec.h>

using vector = vv::vector<bool, int, double, std::string>;

int main() {
    vector vec {false, 1, 2.0, "three"};
    vec.get<int>(1) = -1;
    vec.get<std::string>(3) = "one plus two";
    vec.visit(1, [] (auto& val) { std::cout << val << std::endl; });
    std::cout << std::get<std::string>(vec[3]) << std::endl;
}
// => -1
// => one plus two
```

The Woes of `operator []`

- The `.get<T>(idx)` and `.visit(idx, [] (auto&) {})` APIs both model their STL equivalents and allow for in-place mutation
- Can also add `.replace(idx, val)` to handle changing types
- Note that the subscript operator still works as expected for read-only interaction, like so:

The Woes of `operator []`

```cpp
#include <string>
#include <variant>
#include <iostream>
#include <varvec.h>

using vector = vv::vector<bool, int, double, std::string>;

int main() {
    vector vec {false, 1, 2.0, "three"};
    std::visit(
        [] (auto&& val) { std::cout << val << std::endl; },
        vec[2]
    );
}

// => 2.0
```

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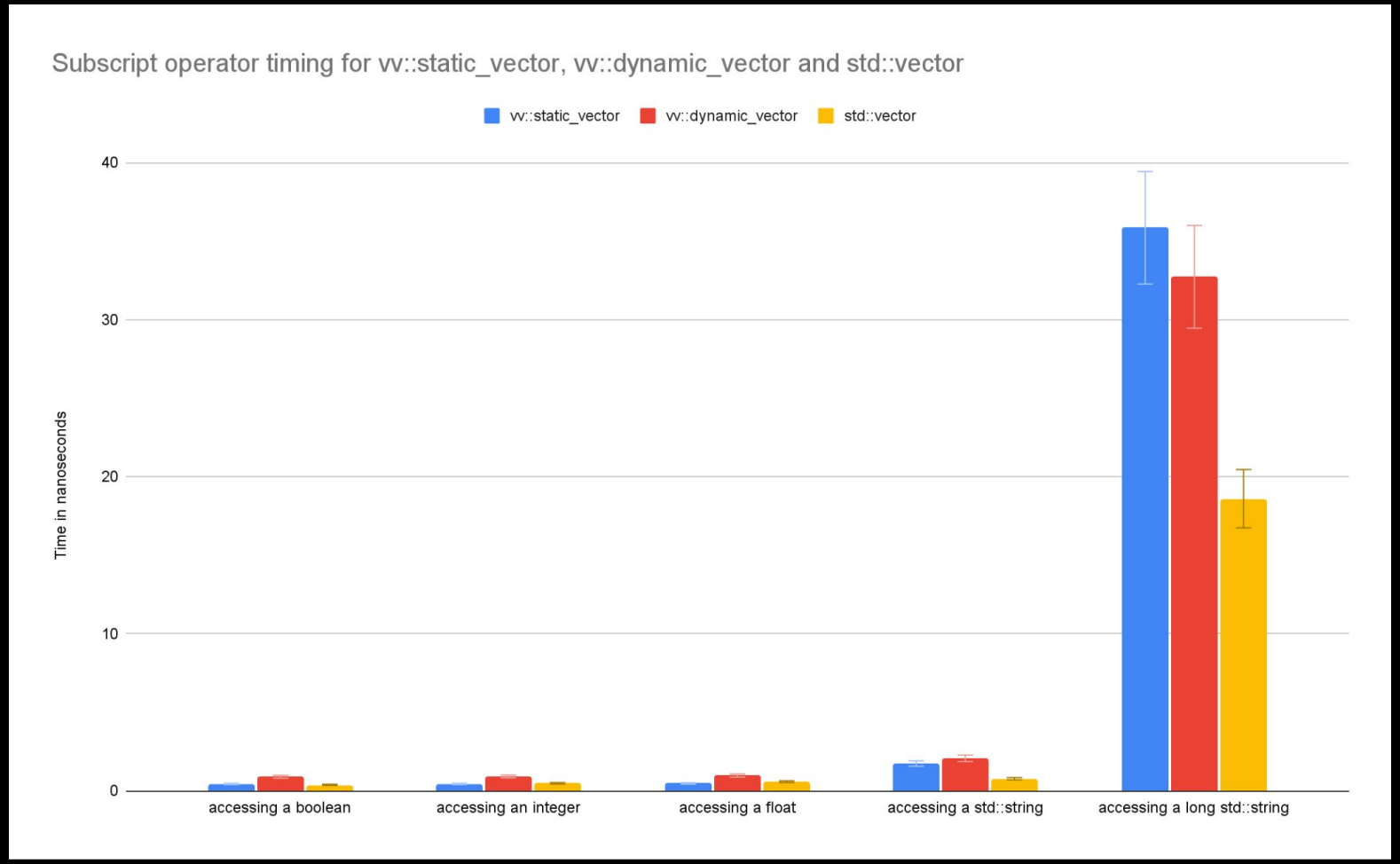
Implications of Design

- Semantic challenges for “number of elements” functions like `capacity`
- Member functions like `insert` and `erase` come with unique challenges
- Mixed alignment can lead to complex interactions
- Not storing actual variants leads to difficulties for the subscript operator

Benchmarks!

Benchmarks!



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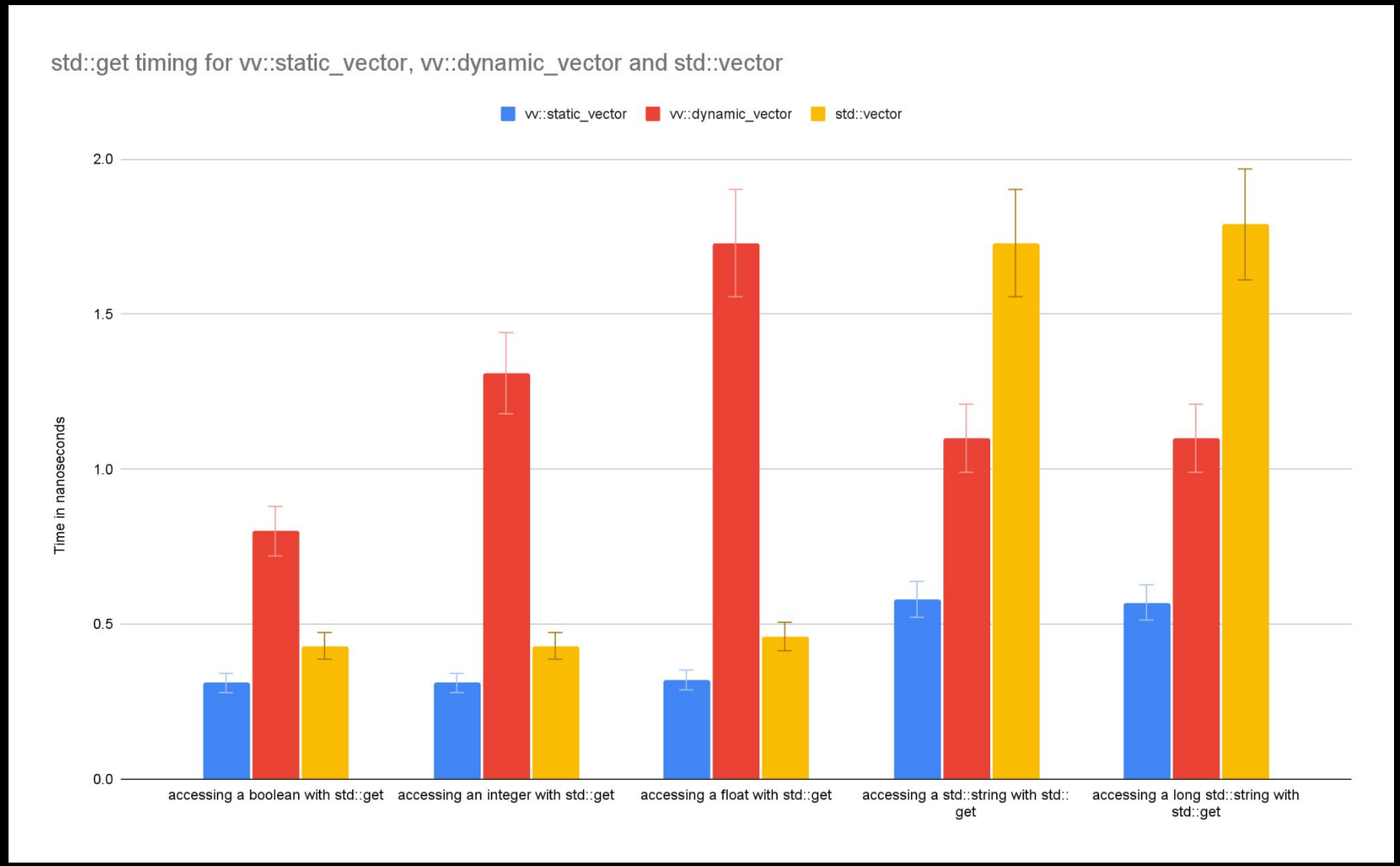
Benchmarks!



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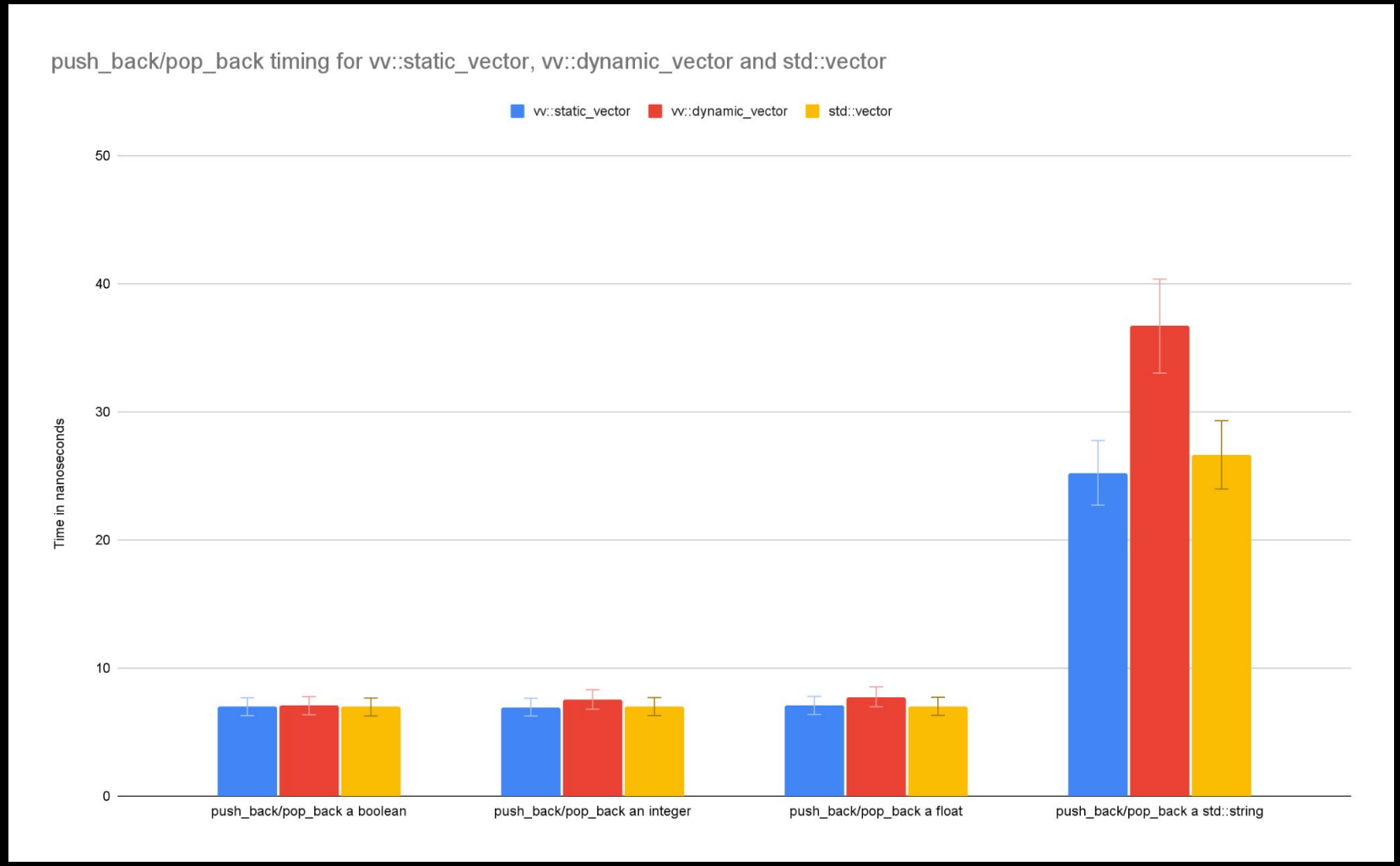

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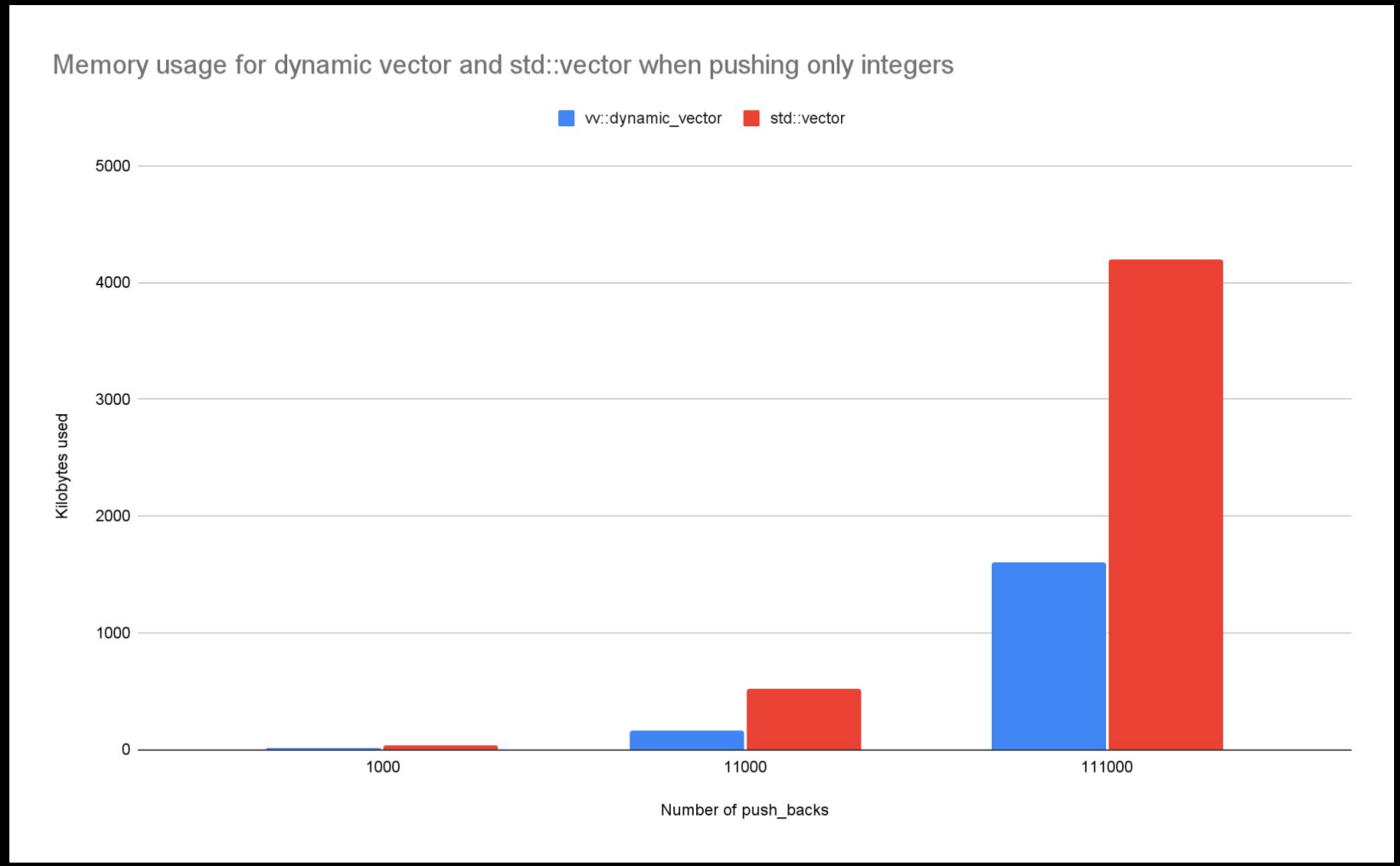
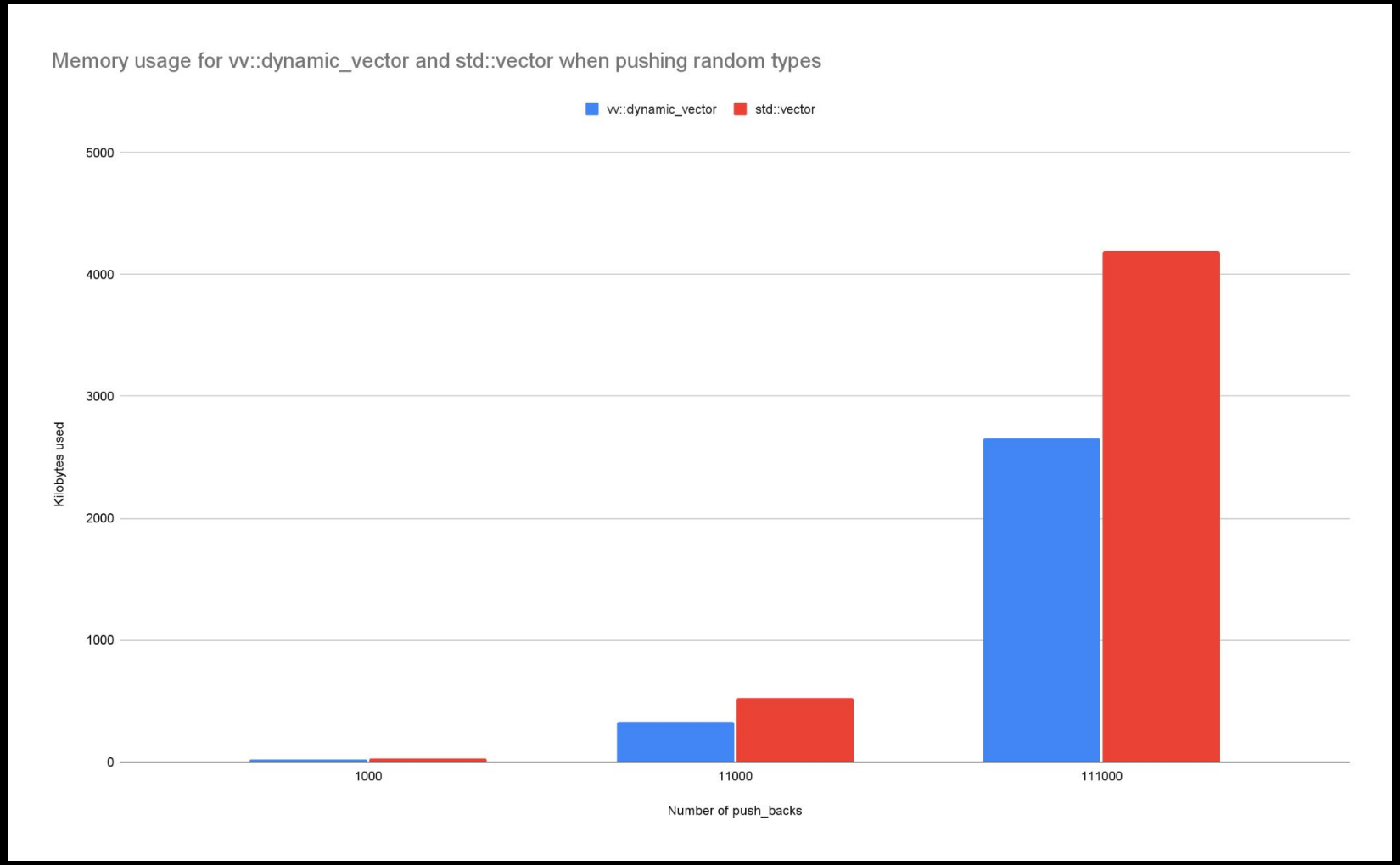
Benchmarks!



Benchmarks!



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Lessons Learned

- Working with C++20 provided many opportunities for learning new things:
  - Implicit lifetime types can make C-style type-punning well defined
  - `std::bit_cast` can discard `const`
  - The presence of exceptions in code can result in less aggressive optimization
  - Seemingly innocuous optimizations can bubble up into interface-impacting changes

`memcpy` is magic

- C++20 defines “implicit lifetime types”
- `memcpy` will now implicitly begin the lifetime of “zero or more objects” as a side-effect of it being called, “if doing so would result in the program having defined behavior”
  - Quoted text comes directly from the standard
  - Types are entirely notional, `memcpy` doesn’t even know what it’s initializing
- Aggregates of implicit lifetype types are also implicit lifetime types

The Hidden Cost of Exceptions

- In C++, exceptions are expected to be zero-cost on the non-throwing path
- “You don’t pay for what you don’t use”
- Yet, although they may not come with a runtime cost, the simple presence of exceptions in code can cause some compilers to optimize less aggressively
- Consider the following code:

The Hidden Cost of Exceptions

```cpp
#include <varvec.h>

int main() {
    vv::static_vector<64, 16, int> vec;
    vec.push_back(rand());
    return vec.get<int>(0);
}
```

The Hidden Cost of Exceptions

```
main:
        jmp     rand
```

The Hidden Cost of Exceptions

```cpp
#include <varvec.h>

int main() {
    vv::static_vector<64, 16, int> vec;
    vec.push_back(rand());
    return vec.get<int>(0);
}
```

The Hidden Cost of Exceptions

```
uint8_t* resize(size_type) noexcept {
  assert(false);
  return nullptr;
}
```

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The Hidden Cost of Exceptions

```
uint8_t* resize(size_type) {
    throw std::bad_alloc();
}
```

The Hidden Cost of Exceptions

```
main:
        sub     rsp, 120
        pxor    xmm0, xmm0
        xor     eax, eax
        movups  XMMWORD PTR [rsp+20], xmm0
        pxor    xmm0, xmm0
        movups  XMMWORD PTR [rsp+36], xmm0
        movups  XMMWORD PTR [rsp+52], xmm0
        movups  XMMWORD PTR [rsp+68], xmm0
        movups  XMMWORD PTR [rsp+84], xmm0
        mov     WORD PTR [rsp+16], 0
        mov     WORD PTR [rsp+18], ax
        call    rand
        lea     rsi, [rsp+12]
        lea     rdi, [rsp+16]
        mov     DWORD PTR [rsp+12], eax
        call    void varvec::basic_variable_vector<varvec::storage::static_storage_context<64ul, 16ul>::static_storage,
std::variant, int>::push_back<int>(int&&)
        movzx   eax, BYTE PTR [rsp+20]
        mov     eax, DWORD PTR [rsp+36+rax]
        add     rsp, 120
        ret
```

The Hidden Cost of Exceptions

- Behavior is present in GCC 10, 11, and 12, fixed in 13 and on
- Issue also presents in MSVC, though to a lesser extent
- All versions of clang seem immune to this particular issue

Wrapping Up

- Final Design
  - Retain contiguous storage array, supported by metadata to track offsets and types
  - Bit-pack all the things
  - Deal with mixed alignment gracefully
  - Provide alternative APIs for the subscript operator to work around fundamental design implications

Wrapping Up

- The data structure presented in this talk is a simplified version of the actual data structure created, and leaves many things unhandled, such as:
  - Handling types with throwing move constructors
  - Iteration
  - Dynamic growth strategy
  - Exception safety guarantees

Thank you!

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