References, Arrays, and Pointers
Overview

So far, we have mostly worked with fundamental types

- `void`
- Arithmetic types such as `int`, `float`, etc.

Much of the power of C++ comes from the ability to define compound types

- Functions
- Classes (covered in the next lecture)
- References
- Arrays
- Pointers
Reference Declaration (1)

A reference declaration declares an alias to an already-existing object or function

- **Lvalue reference**: `type& declarator`
- **Rvalue reference**: `type&& declarator`
- Most of the time, `declarator` will simply be a name

References have some peculiarities

- There are no references to `void`
- References are immutable (although the referenced object may be mutable)
- References are not objects, i.e. they do not necessarily occupy storage

Since references are not objects

- There are no references or pointers to references
- There are no arrays of references
Reference Declaration (2)

The & or && tokens are part of the *declarator*, not the type

```c
int i = 10;
int& j = i, k = i; // j is reference to int, k is int
```

However, we may omit or insert whitespaces before and after the & or && tokens

- Both `int& j = i;` and `int &j = i;` are valid C++
- By convention, we use the former notation (`int& j = i;`)
- To avoid confusion, statements should declare only one identifier at a time
- Very rarely, exceptions to this rule are necessary in the *init-statements* of *if* and *switch* statements as well as *for* loops
Reference Initialization

Definitions of references to a type $T$ must be initialized to refer to a valid object or function:

- An object of type $T$
- A function of type $T$
- An object implicitly convertible to $T$

Declarations of references do not need initializers:

- Function parameter declarations
- Function return type declarations
- Class member declarations
- With the `extern` specifier
As an alias for existing objects

```c
unsigned i = 10;
unsigned j = 42;
unsigned& r = i;  // r is an alias for i

r = 21;           // modifies i to be 21
r = j;            // modifies i to be 42

i = 123;
j = r;            // modifies j to be 123
```
Lvalue References (2)

To implement pass-by-reference semantics for function calls

```c
void foo(int& value) {
    value += 42;
}

int main() {
    int i = 10;
    foo(i); // i == 52
    foo(i); // i == 94
}
```
To turn a function call into an lvalue expression

```c
int global0 = 0;
int global1 = 0;

int& foo(unsigned which) {
    if (!which)
        return global0;
    else
        return global1;
}

int main() {
    foo(0) = 42;  // global0 == 42
    foo(1) = 14;  // global1 == 14
}
```
Rvalue References (1)

Can not (directly) bind to lvalues

```
int i = 10;
int&& j = i;  // ERROR: Cannot bind rvalue reference to lvalue
int&& k = 42;  // OK
```

Extend the lifetimes of temporary objects

```
int i = 10;
int j = 32;

int&& k = i + j;  // k == 42
k += 42;  // k == 84;
```
Rvalue References (2)

Allow overload resolution to distinguish between lvalues and rvalues

```c++
void foo(int& x);
void foo(const int& x);
void foo(int&& x);

int& bar();
int baz();

int main() {
    int i = 42;
    const int j = 84;

    foo(i); // calls foo(int&)
    foo(j); // calls foo(const int&)
    foo(123); // calls foo(int&&)
    foo(bar()); // calls foo(int&)
    foo(baz()); // calls foo(int&&)
}
```
 References and CV-Qualifiers

References themselves cannot be cv-qualified

- However, the referenced type may be cv-qualified
- A reference to T can be initialized from a type that is less cv-qualified than T (e.g. \texttt{const int\&} can be initialized from \texttt{int\&})

```
int i = 10;
const int\& j = i;
int\& k = j;  // ERROR: binding reference of type int\& to
             // const int discards cv-qualifiers
j = 42;      // ERROR: assignment of read-only reference
```

Lvalue references to \texttt{const} also extend the lifetime of temporary objects

```
int i = 10;
int j = 32;
const int\& k = i + j;  // OK, but k is immutable
```
Dangling references

It is possible to write programs where the lifetime of a referenced object ends while references to it still exist.

- This can already happen when referencing objects with automatic storage duration
- Results in *dangling reference* and undefined behavior

Example

```cpp
int& foo() {
    int i = 42;
    return i;  // ERROR: Returns dangling reference
}
```
Array Declaration (1)

An array declaration declares an object of array type (also: C-style array)

- type declarator[expression]
- expression must be an expression which evaluates to an integral constant at compile time
- Again, due to weird parsing rules [expression] is part of the declarator
- type[expression] can be used as a type outside of declarators

For example: T a[N]; for some type T and compile-time constant N

- a consists of N contiguously allocated elements of type T
- Elements are numbered 0, ..., N - 1
- Elements can be accessed with the subscript operator [], e.g. a[0], ..., a[N - 1]
- Without an initializer, every element of a is uninitialized
Array Declaration (2)

Example

```c
unsigned short a[10];

for (unsigned i = 0; i < 10; ++i)
    a[i] = i + 1;
```

Array objects are lvalues, but they cannot be assigned to

```c
unsigned short a[10];
unsigned short b[10];

a = b;  // ERROR: a is an array
```

Arrays cannot be returned from functions

```c
int[] foo();  // ERROR
```
Array Declaration (3)

Elements of an array are allocated **contiguously** in memory

- Given `unsigned short a[10];` containing the integers 1 through 10
- Assuming a 2-byte `unsigned short` type
- Assuming little-endian byte ordering

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
<td>0200</td>
<td>0300</td>
<td>0400</td>
<td>0500</td>
<td>0600</td>
<td>0700</td>
<td>0800</td>
<td>0900</td>
<td>0a00</td>
</tr>
</tbody>
</table>

**Arrays are just dumb chunks of memory**

- Out-of-bounds accesses are not automatically detected, and do not necessarily lead to a crash
- May lead to rather weird bugs
- Exist mainly due to compatibility requirements with C
The elements of an array can be arrays themselves

\begin{verbatim}
unsigned short b[3][2];

for (unsigned i = 0; i < 3; ++i)
    for (unsigned j = 0; j < 2; ++j)
        b[i][j] = 3 * i + j;
\end{verbatim}

Elements are still allocated contiguously in memory

- \(b\) can be thought of as a \(3 \times 2\) matrix in row-major format
- The subscript operator simply returns an array object on the first level, to which the subscript operator can be applied again \(((b[i])[j])\)
Array Initialization

Arrays can be default-initialized, in which case every element is default-initialized

```c
unsigned short a[10] = {}; // a contains 10 zeros
```

Arrays can be list-initialized, in which case the size may be omitted

```c
unsigned short a[] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
```

Multi-dimensional arrays may also be list-initialized, but only the first dimension may have unknown bound

```c
unsigned short b[][2] = {
    {0, 1},
    {2, 3},
    {4, 5}
};
```
C++ has a designated type for indexes and sizes: `std::size_t` from `<cstddef>`

- `size_t` is an unsigned integer type that is large enough to represent sizes and all possible array indexes on the target architecture.
- The C++ language and standard library use `size_t` when handling indexes or sizes.
- Generally, use `size_t` for array indexes and sizes.
- Sometimes you can also use smaller integer types (e.g. `unsigned`) when working with small arrays.
std::array

C-style arrays should be avoided whenever possible
• Use the std::array type defined in the <array> standard header instead
• Same semantics as a C-style array
• Optional bounds-checking and other useful features
• std::array is a template type with two template parameters (the element type and count)

Example

```cpp
#include <array>

int main() {
    std::array<unsigned short, 10> a;
    for (size_t i = 0; i < a.size(); ++i)
        a[i] = i + 1; // no bounds checking
}
```
std::vector (1)

std::array is inflexible due to compile-time fixed size

- The std::vector type defined in the <vector> standard header provides dynamically-sized arrays
- Storage is automatically expanded and contracted as needed
- Elements are still stored contiguously in memory

Useful functions

- push_back – inserts an element at the end of the vector
- size – queries the current size
- clear – clears the contents
- resize – change the number of stored elements
- The subscript operator can be used with similar semantics as for C-style arrays

Familiarize yourself with the reference documentation on std::vector
std::vector (2)

Example

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

int main() {
    std::vector<unsigned short> a;
    for (size_t i = 0; i < 10; ++i)
        a.push_back(i + 1);

    std::cout << a.size() << std::endl; // prints 10
    a.clear();
    std::cout << a.size() << std::endl; // prints 0

    a.resize(10); // a now contains 10 zeros
    std::cout << a.size() << std::endl; // prints 10

    for (unsigned i = 0; i < 10; ++i)
        a[i] = i + 1;
}
```
Range-For (1)

Execute a for-loop over a range

```
for (init-statement; range-declaration : range-expression)
  loop-statement
```

Explanation

- Executes `init-statement` once, then executes `loop-statement` once for each element in the range defined by `range-expression`
- `range-expression` may be an expression that represents a sequence (e.g. an array or an object for which `begin` and `end` functions are defined, such as `std::vector`)
- `range-declaration` should declare a named variable of the element type of the sequence, or a reference to that type
- `init-statement` may be omitted
Range-For (2)

Example

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

int main() {
    std::vector<unsigned short> a;

    // no range-for, we need the index
    for (size_t i = 0; i < 10; ++i)
        a.push_back(i + 1);

    // range-for
    for (const unsigned short& e : a)
        std::cout << e << std::endl;
}
```
Storage of Objects

A “region of storage” has a physical equivalent

- Typically, objects reside in main memory, either on the stack or on the heap
- Up to now (and for some lectures to come), we have almost exclusively dealt with objects residing on the stack

Objects reside at some specific location in main memory

- As we have seen in the first lecture, this location can be identified by an address in main memory
- It is convenient to think of addresses as simple offsets from the beginning of the address space
- Pointers are a feature of C++ to obtain and interact with these addresses
A pointer declaration declares a variable of pointer type

- \textit{type} \* \textit{cv declarator}
- \textit{declarator} may be any other declarator, except for a reference declarator
- \textit{cv} specifies the \textit{cv}-qualifiers of the pointer (not the pointed-to type), and may be omitted
- Analogous to reference declarations, the \* token is part of the declarator, not the type

Notes

- A pointer to an object represents the address of the \textit{first} byte in memory that is occupied by that object
- As opposed to references, pointers are themselves objects
- Consequently, pointers to pointers are allowed
Examples of valid pointer declarations

```c
int* a;            // pointer to int
const int* b;      // pointer to const int
int* const c;      // const pointer to int
const int* const d;  // const pointer to const int
```

Pointer-to-pointer declarations

```c
int** e;              // pointer to pointer to int
const int* const* const f;  // const pointer to const pointer  
                            // to const int
```

Contraptions like the declaration of f are very rarely (if at all) necessary
The Address-Of Operator

In general, there exists no implicit conversion from a pointed-to type (e.g. \texttt{int}) to its pointer type (e.g. \texttt{int*})

- In order to obtain a pointer to an object, the built-in unary address-of operator \& has to be used
- Given an lvalue expression \texttt{a}, \&\texttt{a} returns a pointer to the value of the expression
- The cv-qualification of \texttt{a} is retained

Example

\begin{verbatim}
int a = 10;
const int b = 42;
int* c = &a; \hfill \textcolor{purple}{// OK: c points to a}
const int* d = &b; \hfill \textcolor{purple}{// OK: d points to b}
int* e = &b; \hfill \textcolor{red}{// ERROR: invalid conversion from}
\hfill \textcolor{red}{// const int* to int*}
\end{verbatim}
The Indirection Operator

In general, there exists no implicit conversion from a pointer type (e.g. `int*`) to its pointed-to type (e.g. `int`)

- In order to access the pointed-to object, the built-in unary indirection operator `*` has to be used
- Given an expression `expr` of pointer type, `*expr` returns an lvalue reference to the pointed-to object
- The cv-qualifiers of the pointed-to type are retained
- Applying the indirection operator is also called dereferencing a pointer

Example

```c
int a = 10;
int* c = &a;
int& d = *c; // reference to a
d = 123; // a == 123
*c = 42; // a == 42
```
What is Happening? (1)

```c
int main() {
    // Stack Memory
    0x00001234
    0x00001230
    00 01 02 03
    unknown
    return address
}
```
What is Happening? (2)

```c
int main() {
    int a = 10;
}
```

Stack Memory:

- `0x00001230` return address
- `0x00001234` unknown
- `0x0000122c` `a = 10`
- `0x00001230` return address
- `0x00001234` unknown
- `0x0000122c` `a = 10`
What is Happening? (3)

```c
int main() {
    int a = 10;
    int b = 123;
}
```

Stack Memory:

```
0x00001234  7b 00 00 00  \ b = 123
0x00001230  0a 00 00 00  \ a = 10
0x0000122c  return address
0x00001228  unknown
0x00001224  00 01 02 03
```
What is Happening? (4)

```c
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
}
```

Stack Memory

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00001224</td>
<td>2c 12 00 00</td>
</tr>
<tr>
<td>0x00001228</td>
<td>7b 00 00 00</td>
</tr>
<tr>
<td>0x0000122c</td>
<td>0a 00 00 00</td>
</tr>
<tr>
<td>0x00001230</td>
<td>return address</td>
</tr>
<tr>
<td>0x00001234</td>
<td>unknown</td>
</tr>
</tbody>
</table>

- `c = 0x122c`
- `b = 123`
- `a = 10`
What is Happening? (5)

```c
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
}
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0001224</td>
<td>2c 12 00 00</td>
<td>c = 0x122c</td>
</tr>
<tr>
<td>0x0001228</td>
<td>7b 00 00 00</td>
<td>b = 123</td>
</tr>
<tr>
<td>0x000122c</td>
<td>2a 00 00 00</td>
<td>a = 42</td>
</tr>
<tr>
<td>0x0001230</td>
<td></td>
<td>return address</td>
</tr>
<tr>
<td>0x0001234</td>
<td>00 01 02 03</td>
<td>unknown</td>
</tr>
</tbody>
</table>
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
    int** d = &c;
}

Stack Memory

<table>
<thead>
<tr>
<th>Address</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00001220</td>
<td>24</td>
<td>12</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>0x00001224</td>
<td>2c</td>
<td>12</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>0x00001228</td>
<td>7b</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>0x0000122c</td>
<td>2a</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>0x00001230</td>
<td></td>
<td></td>
<td></td>
<td>return address</td>
</tr>
<tr>
<td>0x00001234</td>
<td></td>
<td></td>
<td></td>
<td>unknown</td>
</tr>
</tbody>
</table>

- d = 0x1224
- c = 0x122c
- b = 123
- a = 42

Stack Memory:
- 0x00001230: return address
- 0x00001234: unknown
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
    int** d = &c;
    **d = 321;
}

Stack Memory

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00001220</td>
<td>24 12 00 00</td>
</tr>
<tr>
<td>0x00001224</td>
<td>2c 12 00 00</td>
</tr>
<tr>
<td>0x00001228</td>
<td>7b 00 00 00</td>
</tr>
<tr>
<td>0x0000122c</td>
<td>41 01 00 00</td>
</tr>
<tr>
<td>0x00001230</td>
<td>return address</td>
</tr>
<tr>
<td>0x00001234</td>
<td>unknown</td>
</tr>
</tbody>
</table>

- a = 0x122c
- b = 123
- c = 0x122c
- d = 0x1224
- a = 321
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
    int** d = &c;
    **d = 321;
    *d = &b;
}

Stack Memory

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00001220</td>
<td>24 12 00 00</td>
</tr>
<tr>
<td>0x00001224</td>
<td>28 12 00 00</td>
</tr>
<tr>
<td>0x00001228</td>
<td>7b 00 00 00</td>
</tr>
<tr>
<td>0x0000122c</td>
<td>41 01 00 00</td>
</tr>
<tr>
<td>0x00001230</td>
<td>return address</td>
</tr>
<tr>
<td>0x00001234</td>
<td>unknown</td>
</tr>
</tbody>
</table>

- d = 0x1224
- c = 0x1228
- b = 123
- a = 321

Unknown return address.
What is Happening? (9)

```c
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
    int** d = &c;
    **d = 321;
    *d = &b;
    **d = 24;
}
```

Stack Memory:

- `0x00001220` : `24 12 00 00` - `d = 0x1224`
- `0x00001224` : `28 12 00 00` - `c = 0x1228`
- `0x00001228` : `18 00 00 00` - `b = 24`
- `0x0000122c` : `41 01 00 00` - `a = 321`
- `0x00001230` : return address
- `0x00001234` : unknown
What is Happening? (10)

```c
int main() {
    int a = 10;
    int b = 123;
    int* c = &a;
    *c = 42;
    int** d = &c;
    **d = 321;
    *d = &b;
    **d = 24;
    return 0;
}
```

Stack Memory:

```
0x00001234
00 01 02 03
unknown
```

222
Null Pointers

A pointer may not point to any object at all
- Indicated by the special value and corresponding literal `nullptr`
- Pointers of the same type which are both null pointers are considered equal
- It is undefined behavior to dereference a null pointer

Undefined behavior can lead to surprising results

```cpp
int foo(const int* ptr) {
    int v = *ptr;
    if (ptr == nullptr)
        return 42;
    return v;
}
```

```assembly
 foo(int*):
    movl (%rdi), %eax
    ret
```
Array to Pointer Decay

Arrays and pointers have many similarities

- There is an implicit conversion from values of array type to values of pointer type
- The conversion constructs a pointer to the first element of an array
- The pointer type must be at least as cv-qualified as the array type

Example

```cpp
#include <iostream>

int main() {
    const int* ptr = array;

    std::cout << "The first element of array is ";
    std::cout << *ptr << std::endl;
}
```
The Subscript Operator

The subscript operator is defined on pointer types

- Treats the pointer as a pointer to the first element of an array
- Follows the same semantics as the subscript operator on array types

Example

```cpp
#include <iostream>

int main() {
    const int* ptr = array;
    std::cout << "The elements of array are";
    for (unsigned i = 0; i < 3; ++i)
        std::cout << " " << ptr[i];
    std::cout << std::endl;
}
```
Special Case: String Literals

String literals are another artifact of C compatibility

- String literals are immutable null-terminated character arrays
- That is, the type of a string literal with N characters is `const char[N + 1]`
- Most of the time, programmers take advantage of array-to-pointer decay and write `const char* str = "foo";`
- The character type can be controlled by the prefixes known from character literals (i.e. `u8"string"`, `u"string"`, or `U"string"`)

C-style strings should never be used!

- The C++ standard library provides the much safer `std::string` and `std::string_view` types
- Unfortunately, libraries or syscalls often require C-style string parameters
- If required, the standard library types can expose the C-style string representation
Arithmetic on Pointers (1)

Some arithmetic operators are defined between pointers and integral types

- Treats the pointer as a pointer to some element of an array
- Adding i to a pointer moves the it i elements to the right
- Subtracting i from a pointer moves it i elements to the left
- In general, for a pointer p the expressions p[i] and *(p + i) are equivalent

Example

```cpp
#include <iostream>

int main() {
    const int* ptr = &array[1];

    std::cout << "The previous element is ";
    std::cout << *(ptr - 1) << std::endl;
    std::cout << "The next element is ";
    std::cout << *(ptr + 1) << std::endl;
}
```
Special care has to be taken to only dereference valid pointers

- Especially important since it is valid to take the *past-the-end* pointer of an array or `std::vector`

Example

```c++
int main() {
    std::vector<int> v;
    v.resize(10);

    const int* firstPtr = &v[0]; // OK: valid pointer
    const int* lastPtr = &v[10]; // OK: past-the-end pointer

    int last1 = *lastPtr;       // ERROR, might segfault
    int last2 = v[10];          // ERROR, might segfault
}
```
Arithmetic on Pointers (3)

Subtraction is defined between pointers
- Treats both pointers as pointers to some elements of an array
- Computes the number of elements between these two pointers

Example

```cpp
#include <iostream>

int main() {
    const int* ptr1 = &array[0];
    const int* ptr2 = &array[3]; // past-the-end pointer

    std::cout << "There are " << (ptr2 - ptr1) << " elements ";
    std::cout << "in array" << std::endl;
}
```
Comparisons on Pointers

The comparison operators are defined between pointers

- Interprets the addresses represented by the pointers as integers and compares them
- Only defined if the pointers point to elements of the same array

Example

```cpp
#include <iostream>

int main() {

    std::cout << "The elements of array are"
    for (const int* it = &array[0]; it < &array[3]; ++it)
        std::cout << " " << *it;
    std::cout << std::endl;
}
```
Void Pointers

Pointers to `void` are allowed

- A pointer to an object of any type can implicitly be converted to a pointer to `void`
- The void pointer must be at least as cv-qualified as the original pointer
- The pointer value (i.e. the address) is unchanged

Usage

- Used to pass objects of unknown type
- Extensively used in C interfaces (e.g. `malloc`, `qsort`, ...)
- Only few operations are defined on void pointers (mainly assignment)
- In order to use the pointed-to object, one must cast the void pointer to the required type
The **static_cast** conversion is used to cast between related types

```
static_cast< new_type > ( expression )
```

**Explanation**

- Converts the value of `expression` to a value of `new_type`
- `new_type` must be at least as cv-qualified as the type of `expression`
- Can be used to convert void pointers to pointers of another type
- Many more use cases (see reference documentation)
Void pointers

```cpp
int i = 42;
void* vp = &i;
int* ip = static_cast<int*>(vp);
```

Other related types

```cpp
int sum(int a, int b);
double sum(double a, double b);

int main() {
    int a = 42;
    double b = 3.14;

    double x = sum(a, b);  // ERROR: ambiguous
    double y = sum(static_cast<double>(a), b);  // OK
    int z = sum(a, static_cast<int>(b));        // OK
}
```
The `reinterpret_cast` conversion is used to convert between unrelated types

```cpp
reinterpret_cast < new_type > ( expression )
```

**Explanation**

- Interprets the underlying bit pattern of the value of `expression` as a value of `new_type`
- `new_type` must be at least as cv-qualified as the type of `expression`
- Usually does not generate any CPU instructions

**Only a very restricted set of conversions is allowed**

- A pointer to an object can be converted to a pointer to `std::byte`, `char` or `unsigned char`
- A pointer can be converted to an integral type (typically `uintptr_t`)
- Invalid conversions usually lead to `undefined behavior`
It is **undefined behavior** to access an object using an expression of different type.

- In particular, we are not allowed to access an object through a pointer to another type (pointer aliasing).
- Consequently, compilers typically assume that pointers to different types cannot have the same value.
- There are very few exceptions to this rule.
Strict Aliasing Rule (2)

```cpp
foo.cpp

static int foo(int* x, double* y) {
    *x = 42;
    *y = 3.0;
    return *x;
}

int main() {
    int a = 0;
    double* y = reinterpret_cast<double*>(a);
    return foo(&a, y);
}
```

Compiling this with `g++ -O1` will result in the following assembly

```assembly
main:
    movl $0, %eax
    ret
```
Strict Aliasing Rule (3)

```cpp
static int foo(int* x, double* y) {
    *x = 42;
    *y = 3.0;
    return *x;
}

int main() {
    int a = 0;
    double* y = reinterpret_cast<double*>(&a);
    return foo(&a, y);
}
```

Compiling this with `g++ -O2` will result in the following assembly:

```asm
main:
    movl   $42, %eax
    ret
```
Examining the Object Representation (1)

Important exception to the strict aliasing rule

- Any pointer may legally be converted to a pointer to char, or unsigned char
- Any pointer may legally be converted to a pointer to std::byte (defined in <cstdint> header, requires C++17),
- Permits the examination of the object representation of any object as an array of bytes

std::byte behaves similarly to unsigned char

- Represents a raw byte without any integer or character semantics
- Only bitwise operators are defined on bytes
Examining the Object Representation (2)

Example (compile with `g++ -std=c++20`)

```cpp
#include <iostream>
#include <iomanip>
#include <cstddef>

int main() {
    double a = 3.14;
    const std::byte* bytes = reinterpret_cast<const std::byte*>(&a);

    std::cout << "The object representation of 3.14 is 0x";
    std::cout << std::hex << std::setfill('0') << std::setw(2);
    for (unsigned i = 0; i < sizeof(double); ++i)
        std::cout << static_cast<unsigned>(bytes[i]);
    std::cout << std::endl;
}
```
Any pointer may legally be converted to an integral type

- The integral type must be large enough to hold all values of the pointer
- Usually, `uintptr_t` should be used (defined in `<cstdint>` header)
- Useful in some cases, especially when building custom data structures

Example

```c++
#include <cstddef>
#include <iostream>

int main() {
    int x = 42;
    uintptr_t addr = reinterpret_cast<uintptr_t>(&x);
    std::cout << "The address of x is " << addr << std::endl;
}
```
The `sizeof` Operator (1)

The `sizeof` operator queries the size of the object representation of a type

```
sizeof( type )
```

Explanation

- The size of a type is given in bytes
- `sizeof(std::byte), sizeof(char), and sizeof(unsigned char)` return 1 by definition
- Depending on the computer architecture, there may be 8 or more bits in one byte (as defined by C++)
The `sizeof` Operator (2)

The size of an object and pointer arithmetics are closely related.

```cpp
#include <iostream>

int main() {

    std::cout << "sizeof(int) = " << sizeof(int) << std::endl;

    int* ptr0 = &array[0];
    int* ptr1 = &array[1];

    uintptr_t uptr0 = reinterpret_cast<uintptr_t>(ptr0);
    uintptr_t uptr1 = reinterpret_cast<uintptr_t>(ptr1);

    std::cout << "(ptr1 - ptr0) = " << (ptr1 - ptr0) << std::endl;
    std::cout << "(uptr1 - uptr0) = " << (uptr1 - uptr0) << std::endl;
}
```
The sizeof Operator (3)

On an x86-64 machine, the program might produce the following output

```
$ ./foo
sizeof(int) = 4
(ptr1 - ptr0) = 1
(uptr1 - uptr0) = 4
```

Interpretation

- One `int` occupies 4 bytes
- There is one `int` between `ptr0` and `ptr1`
- There are 4 bytes (i.e. exactly one `int`) between `ptr0` and `ptr1`
The `alignof` Operator

Queries the alignment requirements of a type

```c
alignof( type )
```

**Explanation**

- Depending on the computer architecture, certain types must have addresses aligned to specific byte boundaries.
- The `alignof` operator returns the number of bytes between successive addresses where an object of `type` can be allocated.
- The alignment requirement of a type is always a power of two.
- Important (e.g.) for SIMD instructions, where the programmer must explicitly ensure correct alignment.
- Memory accesses with incorrect alignment leads to undefined behavior, e.g. SIGSEGV or SIGBUS (depending on architecture).
Usage Guidelines

When to use references

- Pass-by-reference function call semantics
- When it is guaranteed that the referenced object will always be valid
- When object that should be referenced is always the same

When to use pointers

- Only when absolutely necessary!
- When there may not be a pointed-to object (i.e. `nullptr`)
- When the pointer may change to a different object
- When pointer arithmetic is desired

We will revisit this discussion later during the lecture

- Decision is intricately related to *ownership* semantics
- We would actually like to avoid using raw pointers as much as possible
- There are standard library classes which encapsulate pointers
Troubleshooting

Pointers have a reputation of being highly error-prone
- It is very easy to obtain pointers that point to invalid locations
- Once such a pointer is dereferenced, a number of bad things can happen

Bad things that may happen
- The pointer pointed outside of the program’s address space
  - The program will likely segfault immediately
- The pointer pointed outside of the intended memory region, but still inside the program’s address space
  - The program might segfault immediately
  - …or simply corrupt some memory, which might lead to problems later

With the right tools, debugging is not as daunting as it may seem
The Infamous Segfault (1)

Every C++ programmer will encounter a segfault eventually

- Raised by hardware in response to a memory access violation
- In most cases caused by invalid pointers or memory corruption

Obvious example

```cpp
#include <iostream>

int main() {
    int* a;
    return *a;  // ERROR: Dereferencing an uninitialized pointer
}
```

Executing this program might result in the following

```
$ ./foo
[1] 5128 segmentation fault (core dumped) ./foo
```
The Infamous Segfault (2)

Sometimes, the root cause may be (much) more difficult to determine

```cpp
int main() {
    long* ptr;
    ptr = &array[0];
    array[3] = 987; // ERROR: off-by-one access

    return *ptr;
}
```

When compiled with `g++ -fno-stack-protector`, this will also segfault

- The off-by-one access `array[3] = 987` actually changes the value of `ptr`
- Dereferencing this pointer in the return statement will result in a segfault
- The `−fno-stack-protector` option is required, because `g++` will by default emit extra code to prevent such buffer overflows
The Infamous Segfault (3)

Use the address sanitizer!

```bash
$ g++ -g -fno-stack-protector -obar bar.cpp
$ ./bar
[1] 4199 segmentation fault (core dumped) ./bar
$ g++ -g -fno-stack-protector -fsanitize=address -obar bar.cpp
$ ./bar
=================================================================
==4229==ERROR: AddressSanitizer: stack-buffer-overflow on address [...]
WRITE of size 8 at 0x7fff536479d8 thread T0
    #0 0x5617976d529f in main (/tmp/bar+0x129f)
    #1 0x7f6a0fcc3022 in __libc_start_main (/usr/lib/libc.so.6+0x27022)
    #2 0x5617976d50ad in _start (/tmp/bar+0x10ad)

Address 0x7fff536479d8 is located in stack of thread T0 at offset 56 in
  frame
    #0 0x5617976d5188 in main (/tmp/bar+0x1188)

This frame has 1 object(s):
    [32, 56) 'array' (line 3) <= Memory access at offset 56 overflows
  this variable
[...]
==4229==ABORTING
```