Modern C++, From the Beginning to the Middle

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Introduction

- Where is the Beginning
- Data Types
- References
- Const Const Const
- Semantics
- Templates
- Full Example

Where is the Beginning

- Where are you starting from?
  - if your background is from C
    - your definition of a reference may be inaccurate
    - you might think pointer and reference mean the same thing or they are the inverse of each other
  - if you started with C++98
    - your definition of a reference may be incomplete
    - you might think references are implemented as pointers
  - if your background was not C++
    - do you consider how data is passed
    - do you think about when resources are released

Where is the Beginning

- If you think C++11 was just C++98 with a bit more stuff...
  - it should be considered a new language
  - defined new data types
  - added semantics, new value categories
  - constexpr, lambdas, smart pointers
  - added a memory model and threading library
  - sparked new interest in compiled languages

- C++ standard
  - C++98 standard is 832 pages
  - C++11 standard is 1222 pages
  - C++14 standard is 1261 pages
  - C++17 standard is 1485 pages

Where is the Beginning

- We need to start with data types
  - can you define what a data type is?
  - what are the data types in C++?
  - what is a reference and is it a data type?
  - is a reference an idea, hype, or really important to know?
  - what are semantics?
  - is a reference the same as an lvalue reference?
  - is a forwarding reference the same thing as perfect forwarding?

Where is the Beginning

- If you are unable to work through the following, you may not know the fundamentals of C++

  A partially specialized templated class with an enable_if for SFINAE, containing a variadic templated method which takes a parameter pack, with a trailing return type which is deduced based on an expression decltype, then using perfect forwarding to call a policy method.

Data Types 101

- Definition of a data type

A data type is a classification identifying the possible values for that type and the operations which can be done on values of that type.

Data Types 101

- Primitive or Simple Data Types
  - data types provided by the programming language
  - only one value can be associated with a variable of a primitive data type
  - very few languages allow the behavior or capabilities of primitive data types to be modified

- Examples: char, int, bool, double, float
  - the void type has an empty set of values, it is mainly used as a return type for functions

Data Types 101

- Built In Data Types
  - programming language provides built in support

- Examples: lists, hash tables, complex numbers
  - `std::complex<double> z = 1.0 + 2i;`

Data Types 101

- Composite or Compound Data Types
  - data type which is derived from more than one primitive and/or built in data type
  - creating a composite data type generally results in a new data type

- Examples: array, structure, class

Data Types 101

- User Defined Data Types
  - adding classes to your program is the methodology for creating new composite data types in C++
  - another way to create a user defined data type is by declaring an enumeration type

- Examples:
  - `enum class Spices { mint, basil, salt, pepper };`

Data Types 101

- Abstract Data Type
  - any type which does not specify an implementation
  - not necessarily an OOP concept
  - for example, a Stack has push() and pop() which have well defined behavior, however their implementation can be done in a variety of ways

  - An abstract class may not have definitions for all the methods it declares. You can not directly instantiate an abstract class. Instead, create a subclass and instantiate the child class.

Data Types 102

- Atomic Data Types
  - no component parts which can be accessed individually
  - a type which encapsulates a value whose access is guaranteed to not cause data races and can be used to synchronize memory accesses among different threads

- Example 1:
  - a single character such as "x" is atomic

- Example 2:
  - the string "Chocolate Cake" is not atomic as it is composed of multiple individual character values

Data Types 102

- Pointer Data Type
  - the data type of a pointer is derived from the data type or abstract data type it is pointing to
  - the data type of the pointer is a different data type from the data it points to

- `int *foo1;`
  - foo1 is a pointer to something of type int

- `Widget *var2;`
  - var2 is a pointer to something of type Widget

Data Types 102

- Pointer Data Type
  - a pointer refers directly to another value stored elsewhere in computer memory
  - an abstract way of thinking about pointers is like a scavenger hunt
  - you proceed to the first address where you pick up the address of the real treasure is located.
  - the address of the first clue is at 1020 Palm Drive, when you arrive there is information saying the treasure is located at 1619 Pine Street

Data Types 102

- Pointer visibility

```
class Ginger {
  ...

  private:
    std::string *m_string;
};
```

- Quiz 1
  - is the pointer private?
  - is the string m_string points to private?

Data Types 102

- Example:
  - given an object which is a “House”
  - the address of the house is 1600
  - “1600” is stored at memory location 100

```
House *mansion;
```

- What does the receiver want?
  - if the receiver wants the data by reference or by value, then you need to pass the object

  - passing mansion passes a pointer (passing the address 1600)
  - passing *mansion passes the object (passing the entire house)

Data Types 102

- Reference Data Type
  - in C, function arguments are always passed by value
  - passing an object **by value** can be costly since it requires making a copy of the original data and then passing the copy of the data to the function or method
  - to fake pass by reference in C a pointer data type is passed to the function

  - passing **by reference** means only a reference to the data is passed and not the actual data

Data Types 102

- Reference Data Type
  - using a pointer to implement "pass by reference" in C++ works, however it is extremely important to understand this is not a C++ reference
  - if you use a pointer to "pass by reference" you are actually passing the pointer by value
  - the called function must dereference the passed pointer to access the actual data
  - changes to the passed pointer will not affect the pointer value in the caller, but changes to the data the pointer points to, will change the original data

Data Types 102

- Example 1:

```
House *mansion;
thing1(mansion);

void thing1(House *x) {
  print(x);
  print(*x);
}
```

- Example 2:

```
House *mansion;
thing2(*mansion);

void thing2(House &x) {
  print(x);
  print(&x);
}
```

Data Types 102

- Example 1:

```
House *mansion;
thing1(mansion);

void thing1(House *x) {
  print(x);                 // 1600
  print(*x);                // the house
}
```

- Example 2:

```
House *mansion;
thing2(*mansion);

void thing2(House &x) {
  print(x);                 // the house
  print(&x);                // 1600
}
```

Data Types 102

- Reference Data Type
  - the reference data type was added in C++98
  - references were initially introduced to just support operator overloading

  - to support pass by reference efficiently, new reference data types were added to C++11

Data Types 102

- Reference Data Type
  - the & character can represent any of the following:
    - used in reference data types
    - address of operator
    - bitwise AND operator

Data Types 102

- Pointers vs References
  - using a reference to an object is the same as using the original object
  - the "address of operator" will return a pointer referring to the original object
  - the C++ Standard does not force compilers to implement references using pointers

```
Widget button;
Widget & pb = button;
```

Data Types 201

- Expressions
  - a sequence of operators and their operands which specify a computation
  - an operator with its operands, a literal, or a variable name
  - characterized by a (1) data type and a (2) value category
  - expression evaluation may produce a result (x = 2 + 3) or may generate side-effects (printf)

Data Types 201

- Value categories
  - lvalue
  - rvalue

  - every expression is either an lvalue or an rvalue
  - an lvalue is not an rvalue and an rvalue is not an lvalue

  - the sub-categories will be explained

Data Types 201

- Value categories are a property of an expression
  - does it have an identity
    - does the expression have a name
    - does the expression have a memory location
    - can you take the address of the expression
  - can it be moved from

Data Types 201

- lvalue
  - typically an entity which has a name
  - the lifetime persists beyond the current expression
  - must be able to take the address using the & operator
  - has identity and can not be moved from

```
Widget *button = new Widget;
```

  - button is an lvalue of a pointer type
  - *button is an lvalue referring to the object button is pointing to

Data Types 201

- Quiz 2 : values

```
int foo1 = 7;
foo1 = 9;                       // is foo1 an lvalue?


const int foo2 = 7;
foo2 = 9;                       // is foo2 an lvalue?
```

Data Types 201

- rvalue
  - a temporary value which does not persist beyond the expression which uses it
  - may or may not have an identity
  - can be moved from

  - a literal such as 42, true, or nullptr

Data Types 201

- Examples: values

```
int someVarA = 35;
```

  - data type of someVarA is int, it is an lvalue
  - data type of 35 is int, it is an rvalue

```
int 35 = someVarB;
```

  - this is not legal code since 35 is an rvalue and located on the left side of the expression

Data Types 201

- References
  - lvalue reference
  - const reference
  - rvalue reference

- To understand references we ask, what does it mean to pass by value or pass by reference?

Data Types 201

- Pass by Value
  - lvalue and rvalue, pass by value

```
class Widget{ };                    // define a class
void func(Widget pb);               // receives by value

Widget x;                           // lvalue
func(x);                            // lvalue ok

func( Widget{} );                   // rvalue ok
```

Data Types 201

- Pass by Reference
  - lvalue reference, called func() can modify

```
class Widget{ };                    // define a class
void func(Widget & pb);             // receives by lvalue reference

Widget x;                           // lvalue
func(x);                            // lvalue ok

func( Widget{} );                   // rvalue error
```

Data Types 201

- Pass by Reference
  - const reference, called func() can not modify

```
class Widget{ };                    // define a class
void func(const Widget & pb);       // receives by const reference

Widget x;                           // lvalue
func(x);                            // lvalue ok

func( Widget{} );                   // rvalue ok
```

Data Types 201

- Pass by Reference
  - rvalue reference, called func() can modify however the caller can not observe the changes

```
struct Widget{ };                    // define a structure
void func(Widget && pb);             // receives by rvalue reference

Widget x;                            // lvalue
func(x);                             // lvalue error

func( Widget{} );                    // rvalue ok
```

Data Types 201

- lvalue reference
  - caller will observe the modifications made in the called function
- const reference
  - called function can not modify the object
- rvalue reference
  - called function can modify the object
  - caller promises not to observe the changes

Data Types 201

- rvalue reference
  - declared using &&
  - in a declaration && usually means an rvalue reference, however sometimes it means either ‘rvalue reference’ or ‘lvalue reference’
  - can be on the left side of an expression

  - C++11 extended the notion of rvalues by letting you bind an “rvalue reference” to an “rvalue”, this prolongs the lifetime of the rvalue as if it were an lvalue

Data Types 201

- Examples: rvalue reference

```
int && func() {
  return 42;                    // returns an rvalue
}


int main() {
  int && foo = func();          // what is the “value category” of foo?
                                // what is the data type of foo?

  int bar = foo + 3;            // is this valid? if so, what is bar?
  foo = 47;                     // does this compile?
}
```

Data Types 201

- Example: references

```
int & func() {
  return 42;                    // 42 is an rvalue, this does not compile
}
```

  - the return type here is specifying an lvalue reference
  - however, the return expression is an rvalue, this is a compile error to ensure you do not accidentally do this

Data Types 201

- rvalue reference
  - if you think “rvalue reference” whenever you see && in a declaration, you will misread C++
  - && might actually mean &

  - if a variable or parameter is declared to have type T && for some deduced type T, that variable or parameter is a “forwarding reference”

Data Types 201

- Example: references

```
Widget && varA = Widget{};
auto && varB   = varA;                  // && does not mean rvalue reference
```

  - varA is an lvalue (value category) of type (data type) rvalue reference to Widget

  - varB is called a “forwarding reference” which is being initialized with an lvalue
  - this means varB is deduced to be an lvalue reference
  - varB acts as if it were declared using:

```
Widget & varB = varA;
```

Data Types 201

- Example: references

```
const Widget *foo;
someMethod(X);

void someMethod(const Widget &);
```

  - what value category does someMethod want?
  - what data type does someMethod want?
  - foo is a pointer, is it an lvalue or an rvalue?
  - what should be passed for X? (`foo`, `&foo`, `*foo`)

Data Types 201

- Example: references

```
const Widget *foo;
someMethod(X);

void someMethod(const Widget &);
```

  - what value category does someMethod want? either
  - what data type does someMethod want? Widget
  - foo is a pointer, is it an lvalue or an rvalue? lvalue
  - what should be passed for X? *foo

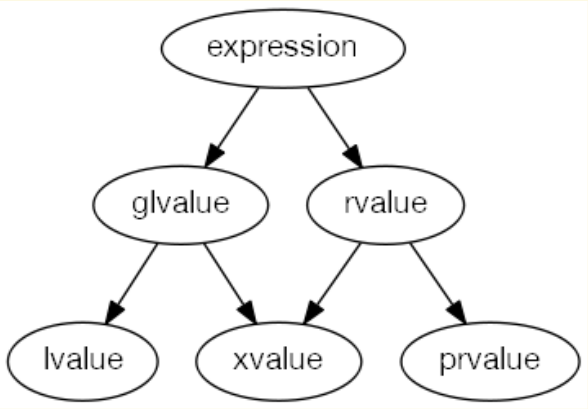
In a Nutshell (Definitions)

- Data Type
  - values
    - 12, true, “cake”
  - operations
    - what can be done with the data (compare, assignment, some manipulation)

- Expression
  - value category
    - lvalue, rvalue
  - data type
    - int, pointer, string, hash, lvalue reference

Data Types - Value Categories

- C++11 additional new value categories
  - every value is either a glvalue or a prvalue, but not both
  - xvalue, an “eXpiring” value



Data Types - Value Categories

- Rules for value categories of an expression
  - prior to C++11 the rules for distinguishing between glvalue/prvalue, the standard referred to lvalue/rvalue
  - these rules were either unintentionally wrong or contained lots of explaining and exceptions
  - the committee decided to clarify the standard and add names and definitions for glvalues and prvalues

Data Types - Const

- Const qualifier
  - const variable
    - const int var
  - const reference
    - const Widget &var
  - const pointer
    - char *const var
  - pointer to const
    - const char *var
  - const methods
    - void someMethod() const

Data Types - Const

- constexpr vs const
  - const means “promise not to change”
    - who promises not to change what
  - constexpr means “known at compile time”

Data Types - Cast

- static_cast
  - always defined behavior, known at compile time
- dynamic_cast
  - always defined behavior, might fail at runtime
- const_cast
  - only used to remove const
- reinterpret_cast
  - should be called shut_up_compiler_cast
- (int)
  - should be called dangerous_cast

Data Types - Semantics

- Semantics
  - relates to the meaning of something
  - “the lawnmower is brave”
    - the grammar or syntax is correct
    - the semantics are meaningless
  - if you misspell a command, it is a syntax error
  - when you type a legal command which does not make any sense, this is a semantic error

  - we should think about semantics when naming classes, structures, methods, functions, variables, enums, etc
  - semantics as related to the behavior of a data type
    - what does it mean when you make a copy
    - what does it mean when you assign

Data Types - Semantics

- Different kinds of Semantics in C++
  - value semantics
  - move semantics
  - reference semantics (pointer semantics)

Data Types - Semantics

- value semantics
  - only the value matters, not the identity or address of the object
  - usually uses the assignment operator to set a new value
    - `int x = 7;`
    - `++x;`
  - implies immutability of the object
    - an immutable object is one whose state can not be modified after it is created
      - the value is immutable, it is 7
      - the identity x, may have a changing value over time

Data Types - Semantics

- move semantics
  - based on rvalue references
  - an rvalue is a temporary object which is going to be destroyed at the end of an expression
  - In older C++, rvalues only bind to const references
  - C++11 allows non-const rvalue references, which are references to an rvalue objects
  - since an rvalue is going to die at the end of an expression, you can steal its data
  - instead of copying it into another object, you move its data into another object

Data Types - Semantics

- reference semantics (pointer semantics)
  - variables refer to a common value when assigned to each other or passed as parameters
  - flexibility, dynamic binding
  - objects can be large and bulky, copying them every time they are passed as parameters is slow
  - if two variables refer to the same object, modifying one of them will also make a change in the other

Data Types - Semantics

- Examples:

```
Widget x;
Widget *y;

foo(std::move(x));          // what got moved? what semantics is this?
foo(std::move(y));          // what got moved? what semantics is this?
```

Data Types - Pointers

- Smart Pointers, brief overview
  - abstract data type which simulates a pointer
  - provides automatic memory management
  - added in C++11
    - unique_ptr
    - shared_ptr
    - weak_ptr
  - auto_ptr
    - deprecated in C++11
    - switch auto_ptr to unique_ptr

Templates

- Templates, defined
  - the purpose of a template is to design an entity without knowing the precise data type
  - used only at compile time to generate a class, method, function, or variable based on one or more data types
  - most of the cost for using templates is paid at compile time

Templates

- When is a template used
  - a template is instantiated at compile time
    - for a templated class, the compiler creates a cookie cutter
    - data types in the template list are used to decide which specific instances will be required
  - at run time classes are instantiated
    - cookies are the objects or the instances of a class
    - at runtime the cookies are created and destroyed
    - only objects of the instantiated classes can be constructed

Templates

- Examples: templated class with a specialized method

```
template <class T>                          // “class” or “typename”
class Widget
{
  public:
    void setName();
};

template <>                                 // required, templated class
void Widget<int>::setName()                 // specialization of a member
{
  . . .
}
```

Templates

- Examples: templated class with a templated method

```
template <class T>
class Widget
{
  public:
    template<class M>
    void setName(M data);
};

template <class T>
template <class M>
void  Widget<T>::setName(M data)
{
  . . .
}
```

Templates

- Examples: templated class with a class partial specialization

```
template <class T>
class Widget
{
  . . .
};

template <class X>
class Widget<std::vector<X>>
{
  . . .
};

Widget<int> foo1;                       // T is int
Widget<std::vector<int>> foo2;          // X is int
```

Forwarding

- Perfect Forwarding
  - a template function or method which forwards arguments while preserving the const qualifier and lvalue / rvalue category
  - rvalue reference rules are used to deduce reference types in the template instantiation
  - the called function or method will receive exactly the same arguments, with the same value categories as were passed into the function which is forwarding
  - use std::forward()

Deduction

- Data type deduction in templates

```
template<typename T>
void func(T & someVar);

const int x = 42;
func(x);
```

  - T is deduced to be const int
  - the type of someVar is deduced as const int &

  - func() appears to take an lvalue reference but in fact it can take an “lvalue reference” or a “const reference”
    - const can be added to the T

Deduction

- Example: rvalue reference revisited

```
template<typename T>
void func(std::vector<T> && var3);
```

  - T will be deduced to some data type
  - std::vector<T> is not a deduced data type but rather a dependent data type based on the data type of T
  - the type of var3 can only be an “rvalue reference”

Variadic Templates

- Example:

```
template<typename ...Ts>                // parameter pack Ts
void makeWidget( Ts ...Vs )             // parameter pack Vs
{
  someFunc( Vs...);                     // expansion
}
```

  - the ellipsis (...) operator has two roles
    - to the left of a parameter name, it declares a parameter pack
    - to the right of an expression the ellipsis operator unpacks the parameters into separate arguments

SFINAE

- Definition
  - substitution failure is not an error
  - occurs during template instantiation (compile time)

  - for a given T, if the compiler is unable to evaluate a template parameter then this template specialization is ignored
  - if another template that matches can be instantiated successfully no compile time error is generated

SFINAE

- Example:

```
template <typename T, typename = void>
class Widget

template <typename T>
class Widget< std::vector<T>,
              typename std::enable_if< std::is_enum<T>::value >::type >
```

  - `is_enum<T>::value` // takes a data type, returns a bool value
  - `enable_if<bool>::type` // takes a bool value, returns void or compile error

```
Widget<int>;
Widget<std::vector<Spices>>;
Widget<std::vector<int>>;
```

Full Example

```
template<typename T, typename = void>
class Bento
{
  . . .
};


template<typename T>
class Bento<T, typename std::enable_if<std::is_move_assignable<T>::value>::type>
{
  template<typename ...ArgTypes>
  auto myMethod ( ArgTypes ...&& Vs ) ->
       decltype( T::someMethod( std::forward<ArgTypes>(Vs)... ) )
  {
    return T::someMethod( std::forward<ArgTypes>(Vs)... );
  }
};
```

Libraries

- CopperSpice
  - libraries for developing GUI applications
- CsSignal Library
  - standalone thread aware signal / slot library
- CsString Library
  - standalone unicode aware string library
- libGuarded
  - standalone multithreading library for shared data

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https://www.youtube.com/copperspice

Where to find CopperSpice

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- source, binaries, documentation files
  - download.copperspice.com

- source code repository
  - github.com/copperspice

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