COMP6771
Advanced C++ Programming

Week 1
Part 2: Introduction to C++

2017

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The Key Concepts in OO

Objects constructed using constructors from types:

- built-in types, e.g., int and float
- user-defined types
  - string, vector, . . . in the library
  - your types!

Sometimes, we want to use a type where another is expected:

- type conversions
- polymorphic types

We perform computations on an object by calling its member functions, written in terms of variables, statements and expressions.

To become a good C++ programmer, we need to have a solid understanding about the basics of C++ . . .

The C++ Basics

- Types
- Declarations and Definitions
- Scopes and Namespaces
- Expressions and Statements
- Strings
- Arrays
- I/O
- Pointers, References, and `const`
- Lvalues and Rvalues (recurring)
- Functions and Parameter Passing

What is a Type?

- A set of values, and
- A set of operations

e.g. bool:

- values: {true, false}
- operations: &&, ==, !=, ...

Basic C++ Types

1. Primitive types:
   - Built-in types:
     - bool
     - Character types
     - Integer types
     - Floating-point types
     - void
   - Modifiers:
     - Signedness: signed (the default if omitted), unsigned
     - Size: short, long, long long

Basic C++ Types

2. Constructing new types using declarator operators
   - Pointer types: int*
   - References: double&
   - Array types: char[]
3. User-defined types:
   - The containers such as vector defined in the C++ library
   - All the rest defined by you!

Booleans

- Two constants: true and false
- non-zero values converted to true
- zero values converted to false

```
1            bool b1 = 10;     // b1 becomes true
2            bool b2 = 0.0;    // b2 becomes false
3
4            int i1 = true     // i1 becomes 1
5            int i2 = false    // i2 becomes 0
```

Character Types

- signed char: type for signed character representation.
- unsigned char: type for unsigned character representation.
- char: type for character representation which can be most efficiently processed on the target system (equivalent to either signed char or unsigned char).
- wchar_t: type for wide character representation
- char16_t: type for UTF-16 character representation (since C++11)
- char32_t: type for UTF-32 character representation (since C++11)

Integer Types

The C++ Standard guarantees:

```
1 = sizeof(char) <= sizeof(short) <= sizeof(int)
  <= sizeof(long) <= sizeof(long long)
```

The sizes (i.e., ranges) of many types are implementation-defined.

The four widely accepted data models:

- 32 bit systems:
  - LP32 or 2/4/4 (int is 16-bit, long and pointer are 32-bit)
    - Win16 API
  - ILP32 or 4/4/4 (int, long, and pointer are 32-bit)
    - Win32 API
    - Unix and Unix-like systems (Linux, Mac OS X)
- 64 bit systems:
  - LLP64 or 4/4/8 (int and long are 32-bit, pointer is 64-bit)
    - Win64 API
  - LP64 or 4/8/8 (int is 32-bit, long and pointer are 64-bit)
    - Unix and Unix-like systems (Linux, Mac OS X)

Many Integer Types!

Type specifier	Equivalent type	Width in bits by data model				
		C++ standard	LP32	ILP32	LLP64	LP64
`short`	`short int`	at least **16**	**16**	**16**	**16**	**16**
`short int`						
`signed short`						
`signed short int`						
`unsigned short`	`unsigned short int`					
`unsigned short int`						
`int`	`int`	at least **16**	**16**	**32**	**32**	**32**
`signed`						
`signed int`						
`unsigned`	`unsigned int`					
`unsigned int`						
`long`	`long int`	at least **32**	**32**	**32**	**32**	**64**
`long int`						
`signed long`						
`signed long int`						
`unsigned long`	`unsigned long int`					
`unsigned long int`						
`long long`	`long long int` (C++11)	at least **64**	**64**	**64**	**64**	**64**
`long long int`						
`signed long long`						
`signed long long int`						
`unsigned long long`	`unsigned long long int` (C++11)					
`unsigned long long int`						

Floating-Point Types

- float: single precision floating point type. Usually IEEE-754 32 bit floating point type
- double: double precision floating point type. Usually IEEE-754 64 bit floating point type
- long double: extended precision floating point type. Does not necessarily map to types mandated by IEEE-754. Usually 80-bit x87 floating point type on x86 and x86-64 architectures

Generally, `double` should be used instead of `float`, due to its higher precision and negligible overhead.

Range of Values

Type	Size in bits	Format	Value range	
			Approximate	Exact
character	8	signed (one's complement)		-127 to 127
		signed (two's complement)		-128 to 127
		unsigned		0 to 255
integral	16	signed (one's complement)	$\pm 3.27 \cdot 10^4$	-32767 to 32767
		signed (two's complement)		-32768 to 32767
		unsigned	0 to $6.55 \cdot 10^4$	0 to 65535
	32	signed (one's complement)	$\pm 2.14 \cdot 10^9$	-2,147,483,647 to 2,147,483,647
		signed (two's complement)		-2,147,483,648 to 2,147,483,647
		unsigned	0 to $4.29 \cdot 10^9$	0 to 4,294,967,295
	64	signed (one's complement)	$\pm 9.22 \cdot 10^{18}$	-9,223,372,036,854,775,807 to 9,223,372,036,854,775,807
		signed (two's complement)		-9,223,372,036,854,775,808 to 9,223,372,036,854,775,807
		unsigned	0 to $1.84 \cdot 10^{19}$	0 to 18,446,744,073,709,551,615
floating point	32	IEEE-754	$\pm 3.4 \cdot 10^{\pm 38}$ (~7 digits)	• min subnormal: $\pm 1.401,298,4 \cdot 10^{-47}$ • min normal: $\pm 1.175,494,3 \cdot 10^{-38}$ • max: $\pm 3.402,823,4 \cdot 10^{38}$
	64	IEEE-754	$\pm 1.7 \cdot 10^{\pm 308}$ (~15 digits)	• min subnormal: $\pm 4.940,656,458,412 \cdot 10^{-324}$ • min normal: $\pm 2.225,073,858,507,201,4 \cdot 10^{-308}$ • max: $\pm 1.797,693,134,862,315,7 \cdot 10^{308}$

Implementation-defined <limits>

```
1  #include<iostream>
2  #include<limits>
3
4  int main() {
5    std::cout << std::numeric_limits<double>::max() << std::endl;
6    std::cout << std::numeric_limits<double>::min() << std::endl;
7    std::cout << std::numeric_limits<int>::max() << std::endl;
8    std::cout << std::numeric_limits<int>::min() << std::endl;
9    // ...
10 }
```

- Performance sometimes comes at the risk of portability
- Must limit the impact of machine-specific language features

C++ Literal/Constants

- Boolean literals: `true, false`
- Character literals: `'a', '\n', '\r', '\t', L'a'`
  - L'a'stored in wchar_t
- Integer literals: `20, 024, 0x14, 20U, 20L, 20UL`
- Floating-point literals: `12.3, 123E-1F, 1.23E1L`
  - Floating-point literals default to type double

Advice on Deciding Which Types to Use

For most programs,

- Use an unsigned for non-negative values
- Use int for integer arithmetic
- Use double for floating-point computations
- Use char or bool only to hold characters or truth values.

One more basic type?

`void`

A special type with no associated values or operations. It is most often used to specify empty return values for functions.

Caution: Don't mix signed and unsigned types

```
1 #include <iostream>
2
3 int main() {
4   signed int a = -1;
5   unsigned int b = 1;
6   std::cout << a * b << std::endl;
7 }
```

What's the output?

Caution: Don't mix signed and unsigned types

```
1 #include <iostream>
2
3 int main() {
4   signed int a = -1;
5   unsigned int b = 1;
6   std::cout << a * b << std::endl;
7 }
```

4294967295

-1 is promoted to unsigned int, but the binary representation stays the same: 11111111111111111111111111111111 (32 bits)
The unsigned value is: 4294967295, therefore
4294967295 * 1 = 4294967295

Read carefully §2.1.1 – 2.1.2.

C++: Expression Evaluation Order

- Syntactically similar among C, C++ and Java (but beware of some semantic differences!)
- Should familiarise yourself with the C++ Operator Table
- The order for evaluating the two operands of a binary operator is undefined in the C/C++ language

```
1 int i = 2;
2 int j = (i = 3) * i;
3 std::cout << j << std::endl; // 6 or 9
4 a[i] + i++; // undefined
5 foo(a[i], i++); // undefined
6 f() + g();      // undefined
```

- The exceptions are "&&", "||", the comma operator ","

C++ Operators

A list of common operators in order of precedence:

- `x.y, x->y, x[y], x++, x--`
- `*x, &x, ++x, --x, !x, ~x, sizeof`
- `x * y, x / y, x % y`
- `x + y, x - y`
- `x >> y, x << y`
- `x < y, x <= y, x > y, x >= t`
- `x == y, x != y`
- `x && y` (short-circuit left to right)
- `x || y` (short-circuit left to right)
- `x = y, x += y, x -= y`
- `x ? y1 : y2` (only one of y1 and y2 evaluated)

Declarations vs Definitions

C++ programs typically are composed of many files.

declaration makes known the type and the name of a variable

definition is a declaration, but also allocates storage for, and possibly initialises, a variable

In C++ a variable must be defined exactly once and must be defined or declared before it is used.

The `extern` keyword

It declares a variable without defining it (i.e., does not allocate storage), except when it is initialised.

```
extern int i;      // declaration
extern int i = 1; // declaration & definition
int j;            // declaration & definition
```

Declarations

- A declaration:
  - introduces a name and its type into the program
  - tells the compiler the kind of entity the name refers to
- A variety of declarations are possible:

```
1. extern int error_no;// object declaration
2. typedef int myint;  // typedef declaration
3. int getX(Point *p); // function declaration
   or extern int getX(Point *p)  ;
4. class stack;        // class declaration
5. template <typename T> class Node;
                       // template declaration
```

Definitions

- A definition defines the kind of entity a name refers to

1. `int error_no = 20;`
   entity: the memory allocated for object error_no
   define: allocate memory
2. `typedef int myint;`
   entity: int
   define: myint is a synonym for int
3. `int getX(Point *p) { return p->x; }`
   entity: the specified function
   define: specifies the function body
4. `class Book {...}`
   entity: a data type
   define: a list of its data/member functions

- Every name must be defined before it is used
- The same entity can only be defined once

C++ Must Distinguish Definitions from Declarations

What if in a file you want to refer to an entity defined in another?

In C++, to allow users to refer to some definitions in a 3rd-party (implementation) library, its developer will provide #include files, i.e., an interface containing their declarations.

Definitions vs. Declarations in C++

- Every definition is also a declaration
- There can be multiple declarations for an entity;

Declarations and Definitions using Third-Party Libraries

- third-party.h

```
1 extern int count;
2 extern int doit(int); // extern here is optional
```

- user.cpp

```
1 #include <iostream>
2 #include "third-party.h"
3 int main() {
4   std::cout << doit(++count) << std::endl;
5 }
```

- third-party.cpp (only binaries available)

```
1 int count = 1;
2 int doit(int i) {
3   i++;
4   return i;
5 }
```

Header Files

Header files are used to store related declarations and help us structure source code into multiple files. Header files allow us to make full use of C++'s support for separate compilation.

Header files:

- should contain only logically related declarations
- should generally not include definitions
- may include class definitions, some `const` objects and inline functions
- should always be enclosed by header guards

Section §2.9 deals with header files in more detail.

C++ Preprocessor

The C++ preprocessor inherits the complex features of the C preprocessor, but most of those are not used. We commonly use three features:

The file inclusion directive:

- `#include <standard_header>`
- `#include "my_file.h"`

And the definition and conditional directives:

```
#ifndef MYHEADER_H
#define MYHEADER_H
...
#endif
```

Preprocessor variables are used for avoiding multiple inclusions.

What Are Found Typically in a Header File

```
class Stack;          // class declaration
class Stack { ... }; // class definition
template <typename T> class stack;
template <typename T> class stack { ... }
inline void f() { ... }
int* g(int);
extern int i;
const double pi = 3.1415926;
enumeration Color { RED, GREEN, BLUE };
typedef void* (*f)(*int) FP;
#include <string>
```

What Cannot be Placed in a Header File

- No variable definitions – i multiply defined

```
header.h:
        int i = 1;
file1.cpp:
        #include "header.h"
file2.cpp:
        #include "header.h"
```

- No function definitions – f multiply defined

```
header.h:
        void f() { ... }
file1.cpp:
        #include "header.h"
file2.cpp:
        #include "header.h"
```

One-Definition-Rule (ODR)

- An entity has exactly one definition in a program
- But the entity need not to be defined if not used

```
int f(int); // known as ZDR (Zero Definition Rule)
extern int i;
class Stack;
int main () { Stack *sp; }  // compiles ok
```

- Ideally, a definition should reside in exactly one file, but this is difficult to enforce to due separate compilation

Some Violations of ODR

(1)

file1.cpp:
```
class Point { int x; int y;}
```

file2.cpp
```
class Point { int a; int b;}
```

(2)

file1.cpp:
```
class Point { int x; int y;}
```

file2.cpp
```
class Point { int x; char y;}
```

(3)

file1.cpp:
```
class Point { int x; int y;}
```

file2.cpp
```
class Point { int x; }
```

- These programs compile under most implementations – errors not caught by linkers
- Use #include to reduce this kind of violations

One-Definition-Rule

- A head file can contain:

```
class declarations and definitions
template declarations and definitions
inline function definitions
variable (data) declarations
```

- but not

```
variable (data) and function definitions
```

- Why allowing definitions in header file at all?
  - Inline functions
  - Class definitions
  - Class templates

Revision: Pointers

- Pointers are variables that hold the address of an object! They allow indirect access to the objects they point to.
- A pointer has a type, a name, a value (an address!) and an address of its own!
- We obtain the address of an object by using &, the address-of operator on that object.
- We use *, the dereference operator to obtain the object a pointer points to (called pointee).

```
1 int i = 10;
2 int *p = &i;
3 std::cout << *p << std::endl;  // *p is an alias of i
4                                // i, i.e., 10 printed
```

Pointers

To minimise bugs, always initialise pointers when they are defined. If the intended address is not available, then set to nullptr.

```
1 int *p1 = nullptr;
```

Caution

Your code will crash if you defernce a nullptr or uninitialised pointer.

The * modifies a variable not the type, be aware:

```
1 int* p, q; // SAME as int *p, q BUT NOT AS int *p, *q;
```

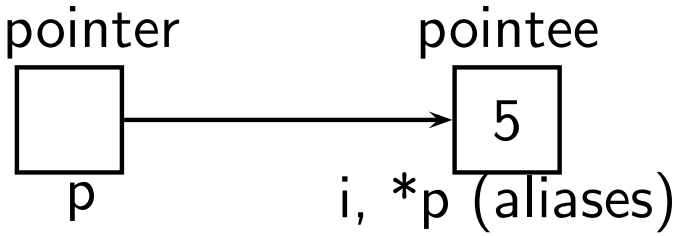
A type mismatch will be detected by the compiler:

```
1 int *i;
2 long *lp = &i;  // error
```

Carefully read §2.3.2

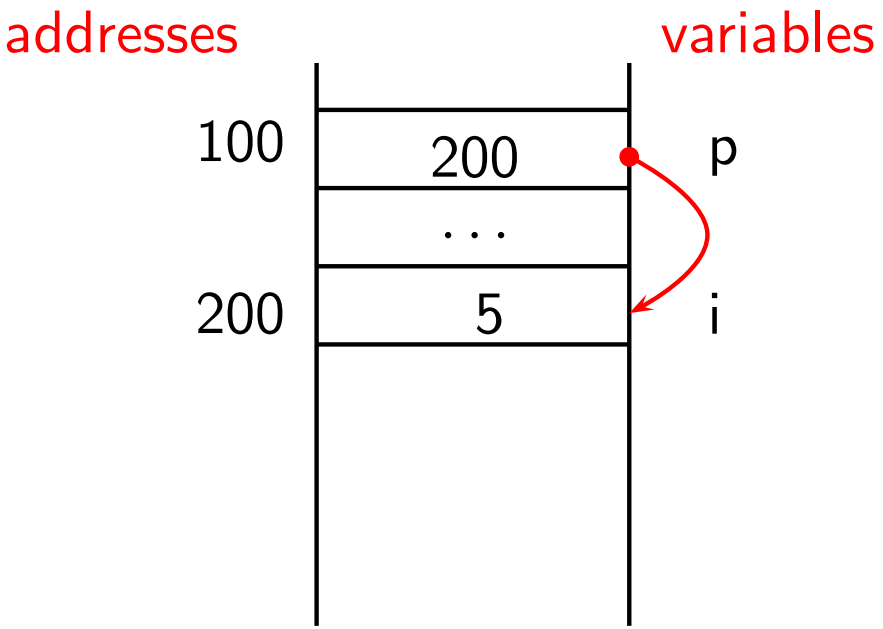
A Pointer and Its Pointee (or Pointed-to Object)

- Each pointer is associated with two objects:



- Runtime stack:

```
void f() {
  int i = 5;
  ...
  int *p = &i;
  // int *p;
  // p = &i;
}
```



Pointers Can Be Complex

```
double **p;          // pointer to pointer to double
char* a[10];         // array of 10 pointers to char
char (*a)[10];       // pointer to array of 10 chars
int* (*fp)(int*); // pointer to function taking
                        a int* and returning a int*
int X::*pm;          // pointer to a member of
                        class X of type int
```

- "`char* a[10]`" is the same as "`char *a[10]`"
- `[]` has the higher precedence than `*`

The misuse of pointers is a major source of bugs!

Revise the pointers if you are rusty

const

- A variable:

```
1 int x = 1;
2 x++;
```

- A const variable:

```
1 const int y = 1;   // equivalent to C's #DEFINE y 1
2           // must be initialised when defined
3 y++;   // error since it is not modifiable
```

const

- Initialises a const variable with a non-const:

```
1 int a = 1;
2 const int b = a;
```

- Initialises a non-const variable with a const:

```
1 const int a = 1;
2 int b = a;
```

Immutability

- The primary role of const is to specify immutability
- Many objects don't have their values changed after initialisation:
  - Many pointers are often read through but never written through
  - Most function parameters are read but not written to:

```
1 char* strcpy(char* dest, const char* src);
2 int strcmp(const char *lhs, const char *rhs );
```

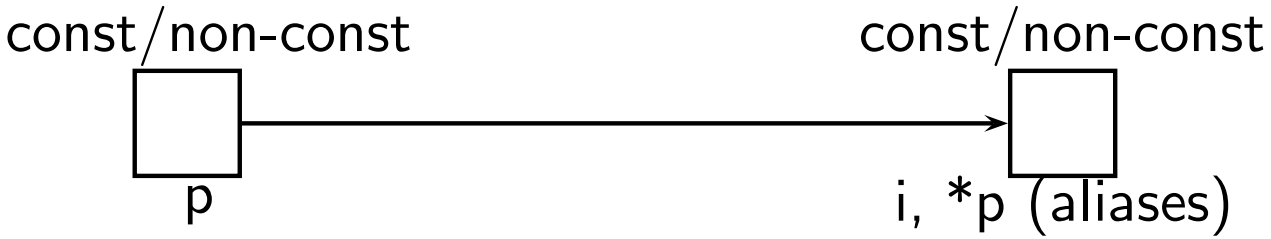
Pointers and `const`

Four combinations:

```
Case 1: int *p = &i;
Case 2: const int* p = &i;
Case 3: int *const p = &i;
Case 4: const int *const p = &i;
```

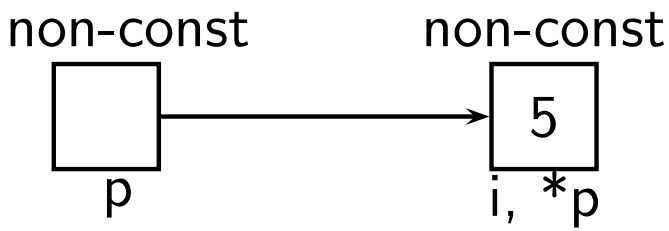
top-level constness

low-level constness

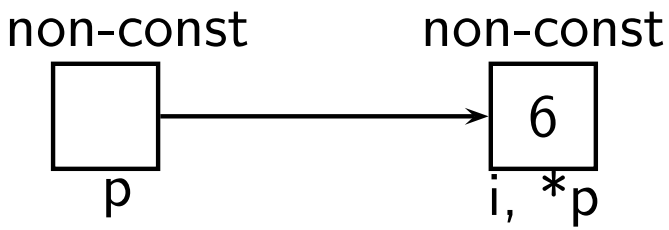


Case 1: no const

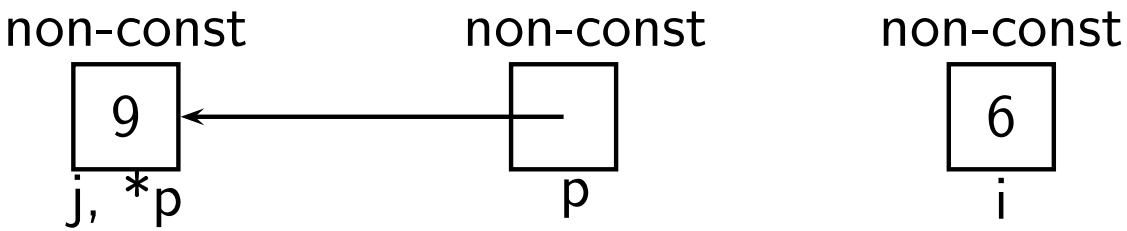
```
int i = 5;
int *p = &i;
```



- After `*p = 6`:

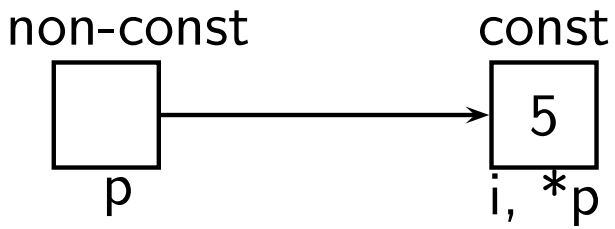


- After `int j = 9; p = &j`:

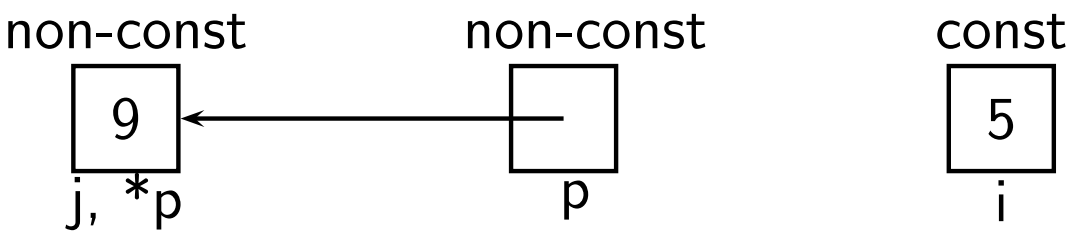


Case 2: read only dereference

```
int i = 5;
const int *p = &i;
```



- `*p = 6` doesn't compile any more
- After `int j = 9; p = &j`:

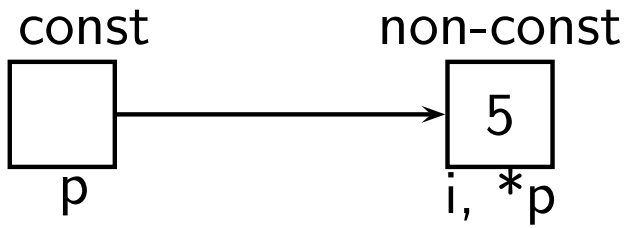


The promise/contract is to not change the pointee

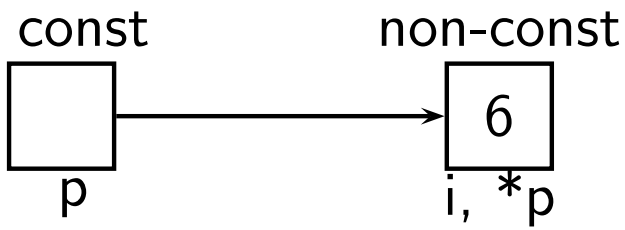
The pointee of p can be either a const or non-const object.

Case 3: const pointer

```
int i = 5;
int *const p = &i; // must be initialised when defined
```



- After `*p = 6;`

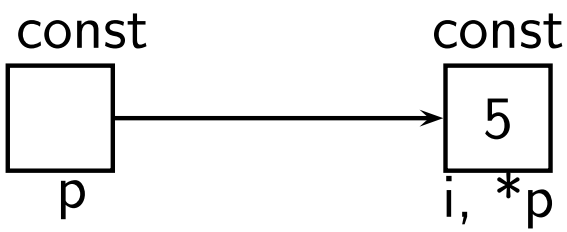


- Any re-assignment for `p` is prohibited:

```
p = &j; // error as p is a const pointer
```

Case 4: const pointer & const dereference

```
int i = 5;
const int *const p = &i;
```



- `*p = 6` doesn't compile
- `p = &j` doesn't compile

const Pointers

A const pointer is *const not const*.

```
1          char *const cp1    // const pointer to char
2          char const* cp2    // pointer to const char
3          const char* cp3    // pointer to const char
```

Read each declaration right-to left

cp1 is a const pointer to char

cp2 is a pointer to const char

cp3 is a pointer to "char const", i.e., const char

References

C++ references are a way of aliasing objects:

```
Case 1: int &r = i;
Case 2: const int &r = i;
```

A reference `r`:

- is just another name for an object called its referent `i`
- must be initialised when defined and may not be rebound to a new object. So a reference is always const.

Terminology

- A reference is always `const` since it must be initialised when defined and cannot be modified later
- A reference is not itself an object unlike a pointer which is an object.
- A reference to a const object is often said to be a const reference
- A reference to a non-const object is often said to be a non-const reference

Use references rather than pointers

They are safer because they can never be null.

Case 5: non-const or lvalue references

```
1 // r is an alias of i
2 int i = 5;
3 int &r = i;
4 r = 6;
5 std::cout << i << std::endl; // 6
6
7 const int j = 5;
8 int &r2 = j;  // error
```

- Must refer to an object of the same type

```
int i;
long &r = i; // error
```

Case 6: const references

```
1 // r is an alias of i
2 int i = 5;
3 const int &r = i;
4 r = 6;       // error
5
6 const int j = 5;
7 const int &r2 = j;
8 r2 = 6; // error
```

- Can refer to an object of a different (but related) type

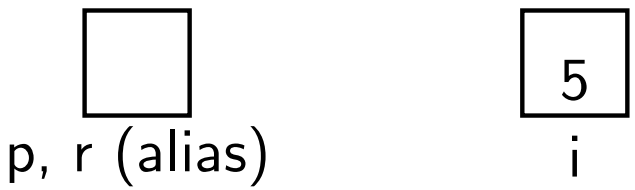
```
int i;
const long &r = i;
const long *p = &i; // error, if i is an int
```

- Can be initialised with a literal

```
const int &r2 = 100;
// REASON: r2 cannot be modified
```

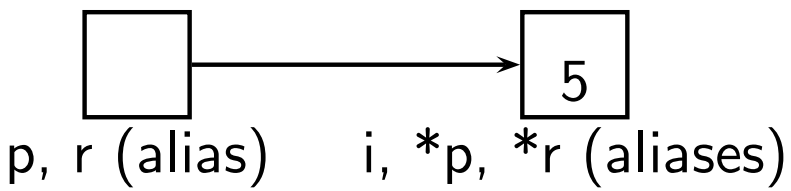
Mixing Pointers and References

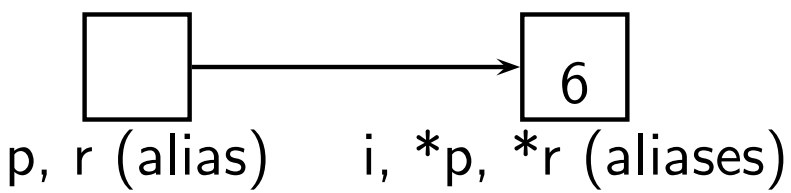
```
int i = 5;
int *p;
int *&r = p;
```




```
r = &i; // SAME AS p = &i;
```

```
*p = 6;
```





The `auto` Type Inference

- Let the compiler infer the type for us:

```
auto i = 0, *p = &i;   // ok: i is int and p is int*
auto sz  = 0, pi = 3.14; // error: inconsistent types
```

The `auto` Deduction

Take exactly the type on the right-hand side but strip off the top-level const and &. But the low-level const must be preserved.

The `auto` Type Inference

- Pointer variables:

```
int i;
const int *const p = i;
auto q = p;                    // const int*
auto const q = p;              // const int* const
```

- References:

```
const int &i = 1; // int
auto j = i;       // int
const auto k = i; // const int
auto &r = i;      // const int& (low-level const kept)
```