7. Pointers and Memory Allocation

7.1. Pointers

Reminder: Variables and objects reside in memory. Through the variable name, you can read and change the variable's value. Its type tells the compiler how.

```
/* reserving variables */
int main() {
   int myInteger = 12;    // store an integer
   char mySymbol;    // store one character
   float myFloat = 12.0f;  // store floating point
   bool myBoolean = true;  // store a boolean
   return 0;
}
```

Memory

myInteger=int

0000 0000	0000 0000	0000 0000	0000 1100

mySymbol=char

0000 0000

myFloat=float

0100 0010	0100 0000	0000 0000	0000 0000

myBoolean=bool

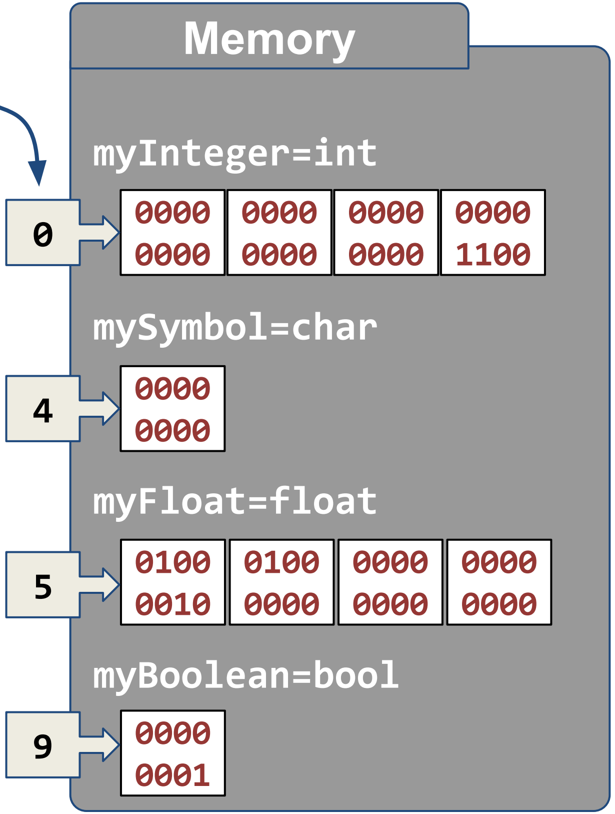
0000 0001

7.1. Pointers

Each memory location has a **memory address**

We assume here that one memory block occupies one byte.

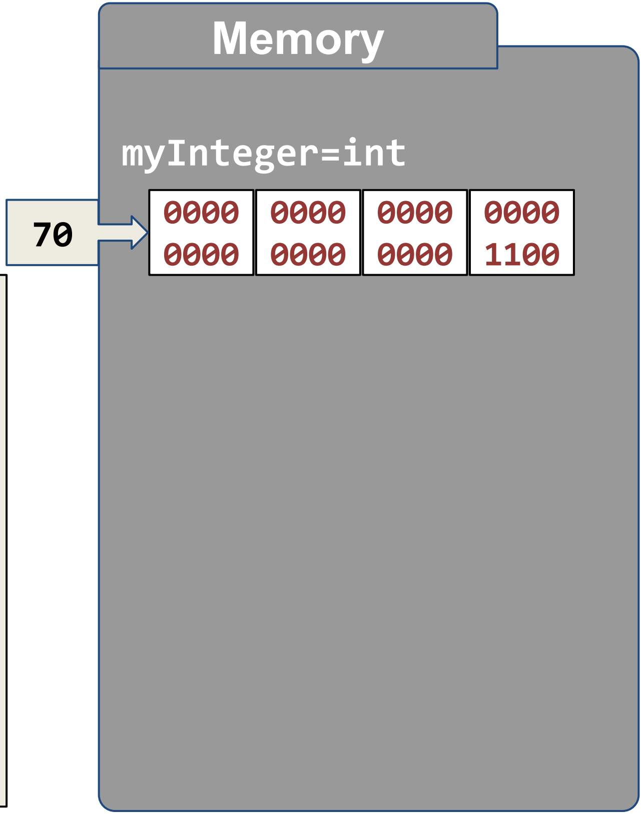
```
/* reserving variables */
int main() {
  int myInteger = 12;   // store an integer
  char mySymbol;   // store one character
  float myFloat = 12.0f;  // store floating point
  bool myBoolean = true;  // store a boolean
  return 0;
}
```



7.1. Pointers

A pointer stores a **memory address and its associated type**

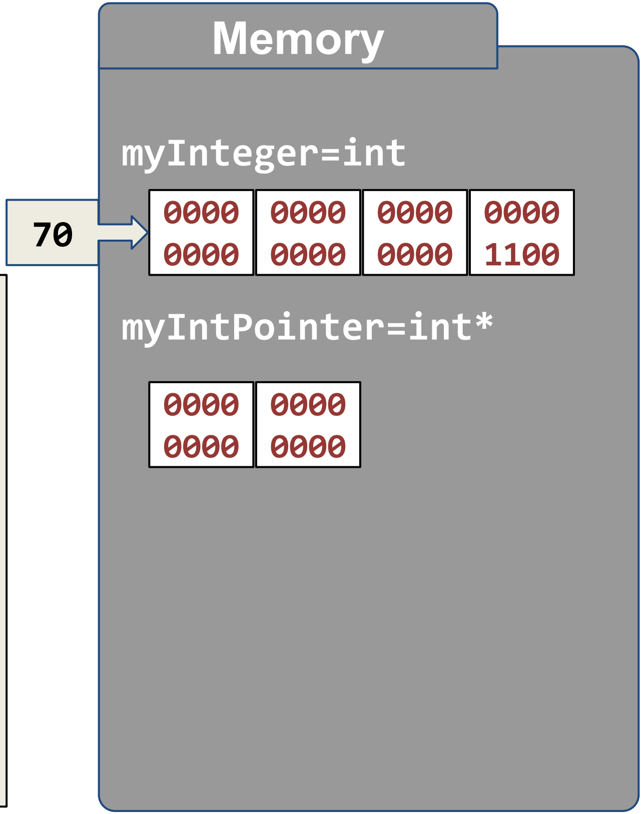
```
/* reserving variables */
int main() {
   int myInteger = 12;    // store an integer
   int * myIntPointer;    // store a pointer to int
   myIntPointer = &myInteger;  // store floating
   *myIntPointer = 17; // myInteger is now also 17
   return 0;
}
```



7.1. Pointers

A pointer stores a **memory address and its associated type.** Pointer variables are declared by using the * operator.

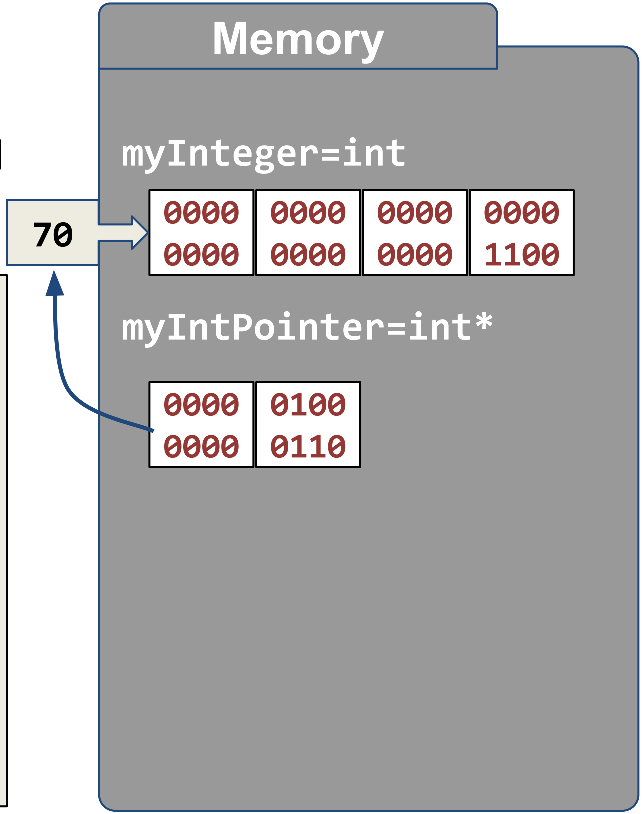
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.1. Pointers

Pointer variables can obtain the address of existing variables of that type using the **&** operator (returning the address of a variable)

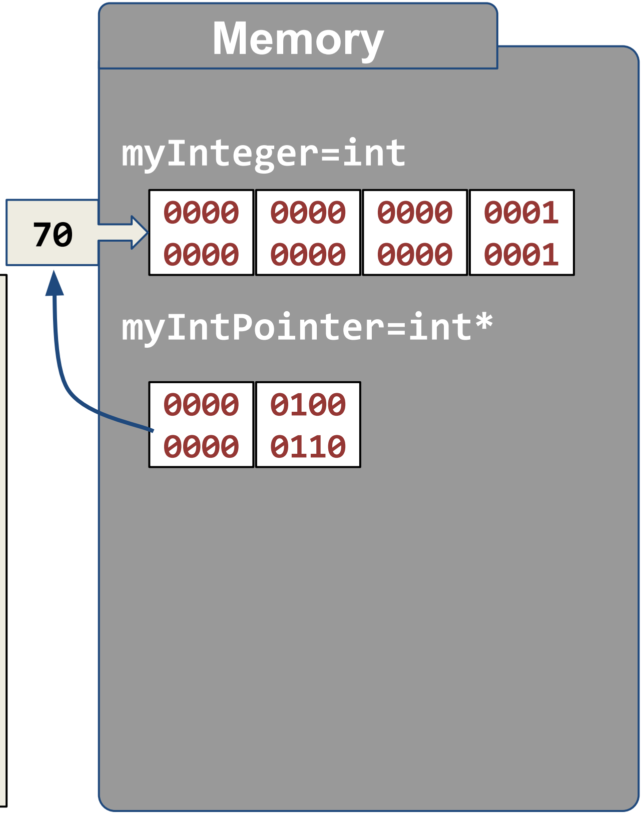
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;   // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.1. Pointers

Dereferencing a pointer means following the pointer's content (memory address) and accessing the variable of that type

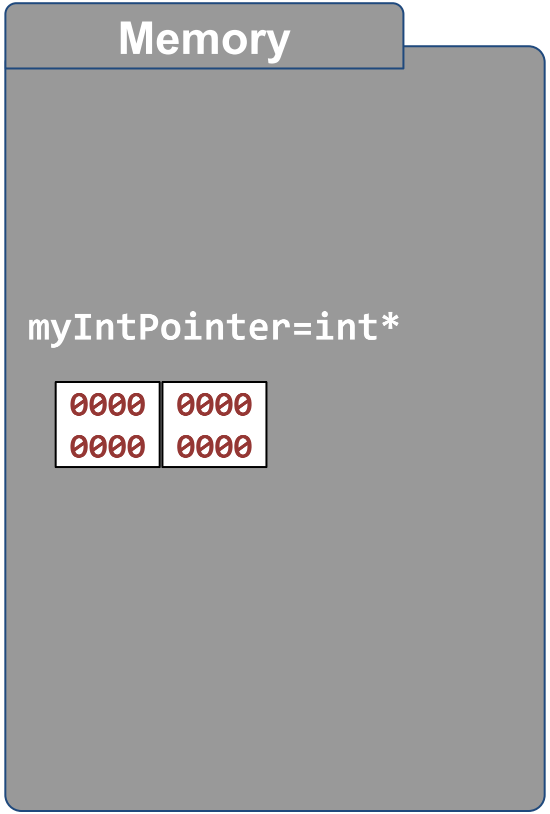
```
/* reserving variables */
int main() {
  int myInteger = 12;    // store an integer
  int * myIntPointer;    // store a pointer to int
  myIntPointer = &myInteger;  // store floating
  *myIntPointer = 17; // myInteger is now also 17
  return 0;
}
```



7.2. **`new`** and **`delete`**

A pointer assumes a memory address is reserved for a variable. Indicate that the pointer isn't pointing to a valid variable with **`NULL`** (or [`nullptr`]() since C++11):

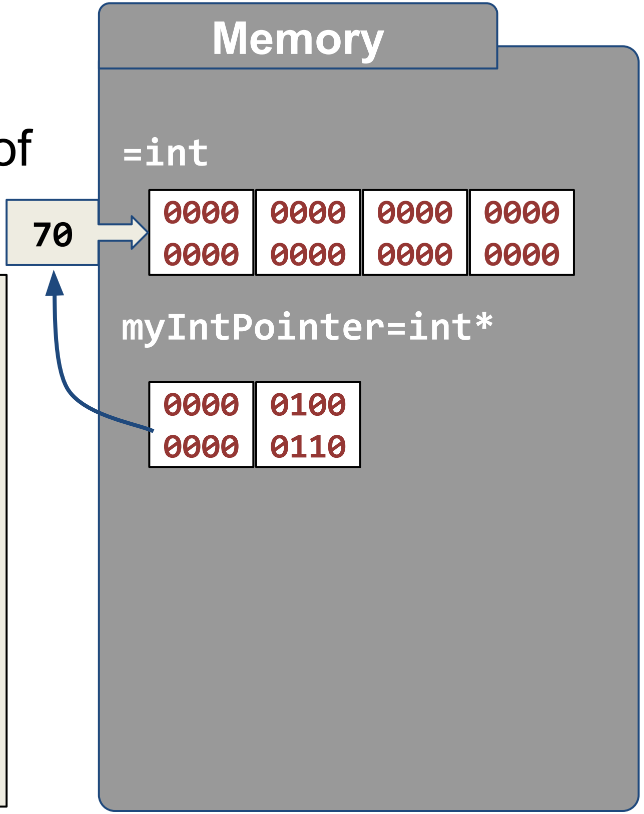
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. **new** and **delete**

A pointer assumes a memory address is already reserved for a variable. We can create the variable of the correct type through the **new** keyword:

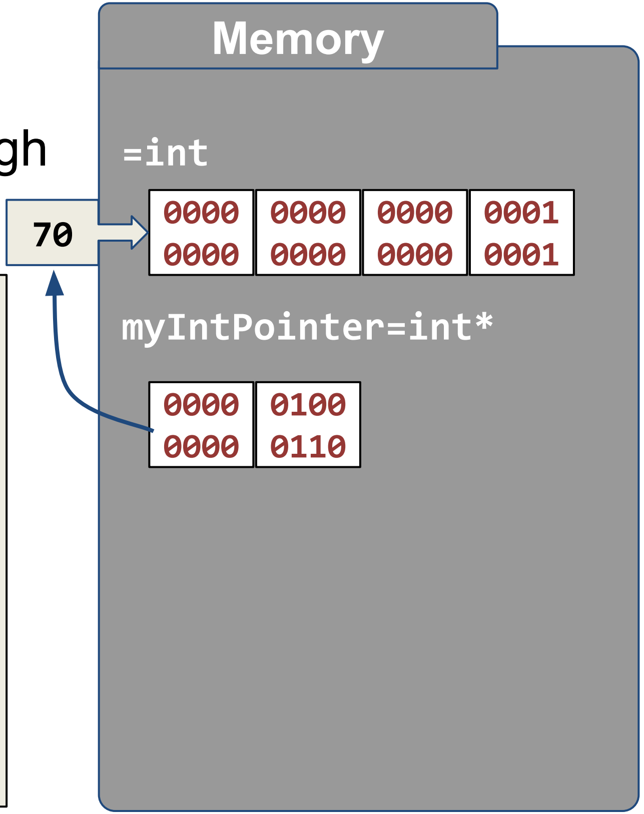
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;   // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. **new** and **delete**

A pointer assumes a memory address is already reserved for a variable. This variable can only through the pointer be read and changed:

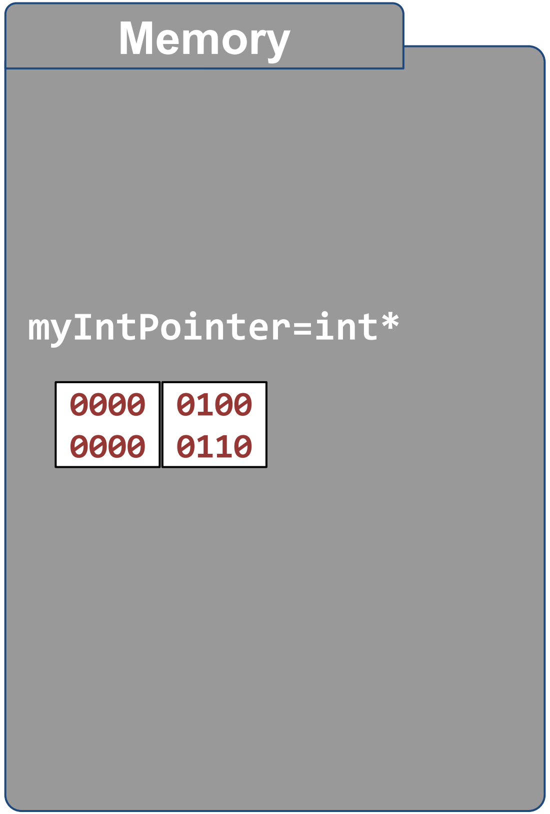
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove the pointer
  return 0;
}
```



7.2. **new** and **delete**

A pointer assumes a memory address is already reserved for a variable. This variable can only through the pointer be read and changed:

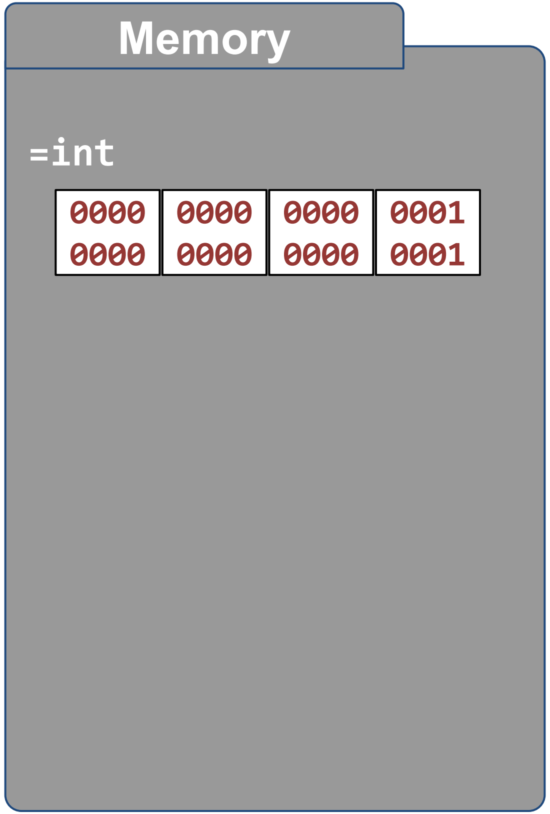
```
/* reserving variables through a pointer */
int main() {
  int * myIntPointer = NULL;  // pointer to int
  myIntPointer = new int;  // create the int
  *myIntPointer = 17;  // the int now holds 17
  delete myIntPointer;  // remove pointer's int
  return 0;
}
```



7.2. **`new`** and **`delete`**

Forgetting to **`delete`** a reserved variable causes a memory leak, since the pointer is removed and the variable cannot be reached anymore (but is reserved).

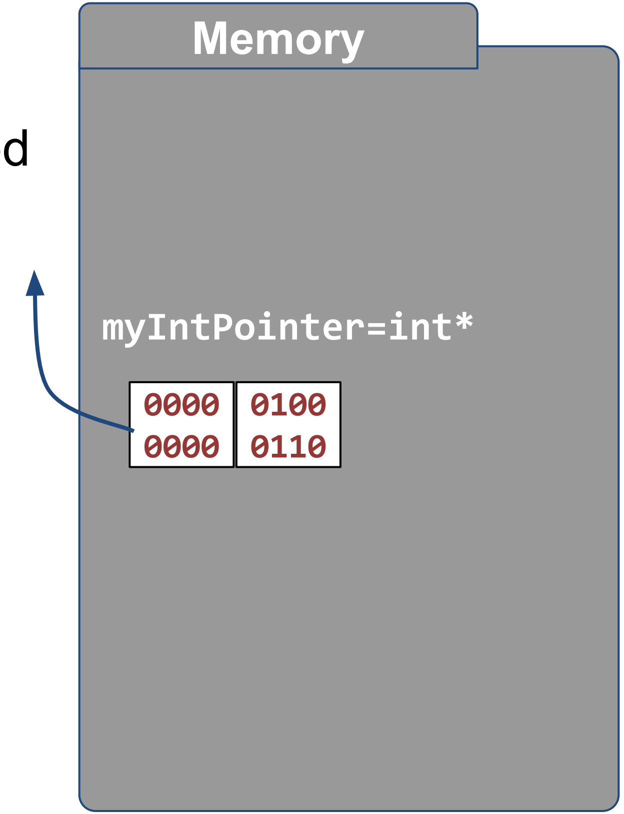
```
void myFunction() {
  int * myIntPointer = new int; // create int
  *myIntPointer = 17;
}
int main() {
  myFunction();
  // after the above function ends, myIntPointer
  // is removed, but not the int variable
  return 0;
}
```



7.2. **new** and **delete**

It is good practice to assign the pointer to **NULL** after **delete** (since the pointer still points to a non-reserved memory location, this is called a *dangling pointer*).

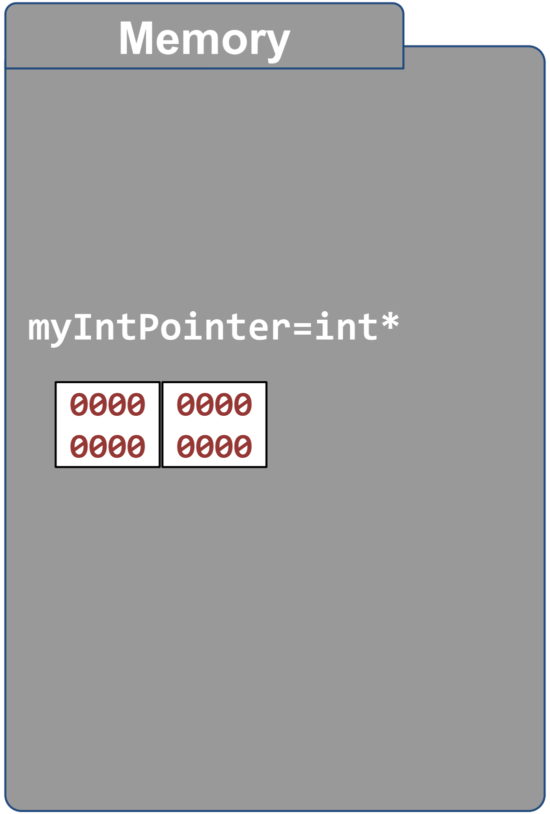
```
void myFunction() {
   int * myIntPointer = new int; // create int
   *myIntPointer = 17;
   delete myIntPointer;  // remove pointer's int
   myIntPointer = NULL;  // point to NULL
}
int main() {
   myFunction();
   return 0;
}
```



7.2. **`new`** and **`delete`**

It is good practice to assign the pointer to **`NULL`** after **`delete`** (since the pointer still points to a non-reserved memory location, this is called a *dangling pointer*).

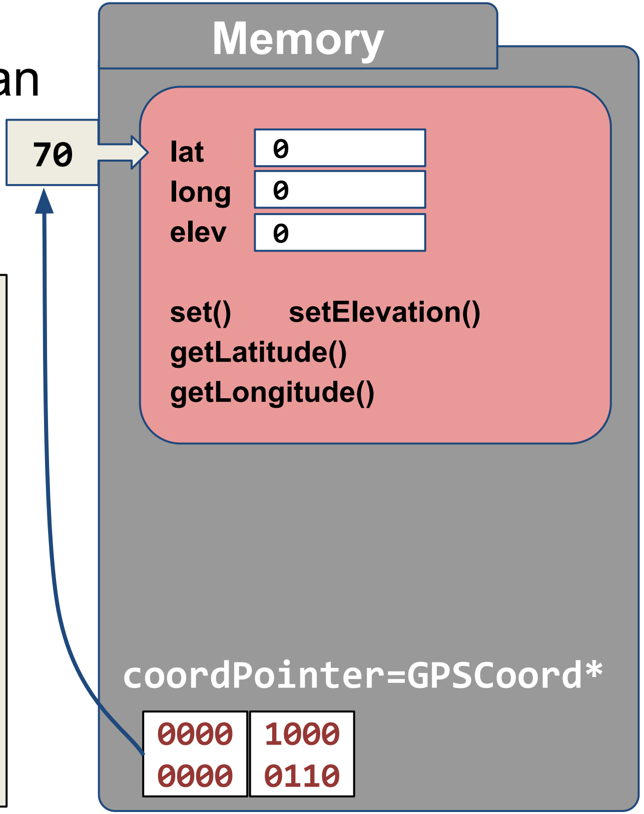
```
void myFunction() {
  int * myIntPointer = new int; // create int
  *myIntPointer = 17;
  delete myIntPointer;  // remove pointer's int
  myIntPointer = NULL;  // point to NULL
}
int main() {
  myFunction();
  return 0;
}
```



7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

```
void myFunction() {
  GPSCoord * coordPointer = new GPSCoord();
  coordPointer->set(0, 0);  // access method
  delete coordPointer;  // remove object
  coordPointer = NULL; // avoid dangling pointer
}
int main() {
  myFunction();
  return 0;
}
```

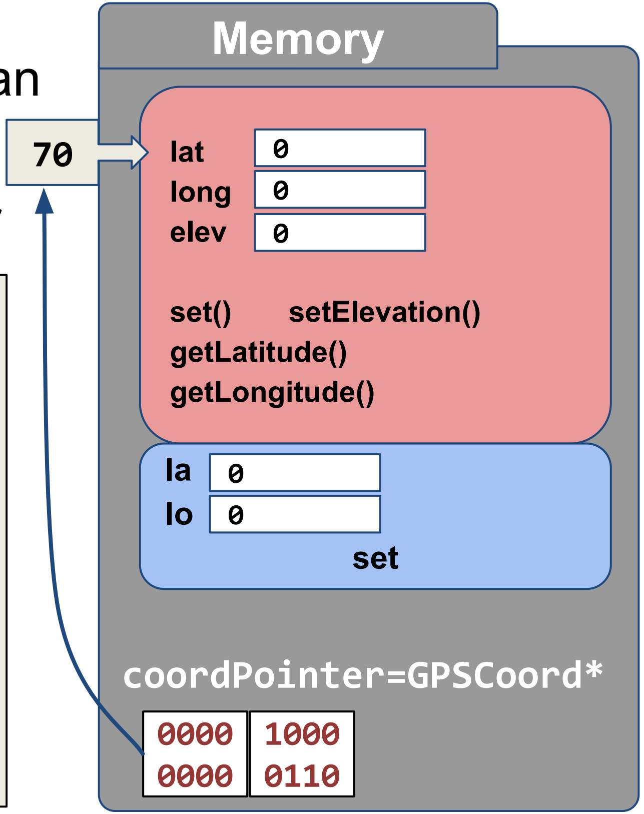


7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

Attributes & methods are accessed with `->` operator

```
void myFunction() {
   GPSCoord * coordPointer = new GPSCoord();
   coordPointer->set(0, 0);   // access method
   delete coordPointer;   // remove object
   coordPointer = NULL; // avoid dangling pointer
}
int main() {
   myFunction();
   return 0;
}
```

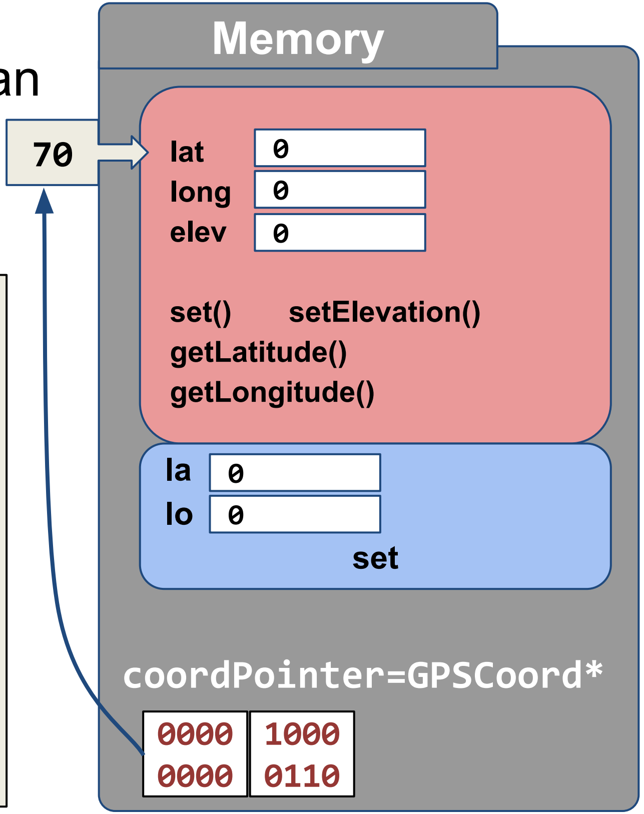


7.3. Creating and deleting objects

Pointers can also point to classes' objects. These can similarly be created and deleted in memory, too.

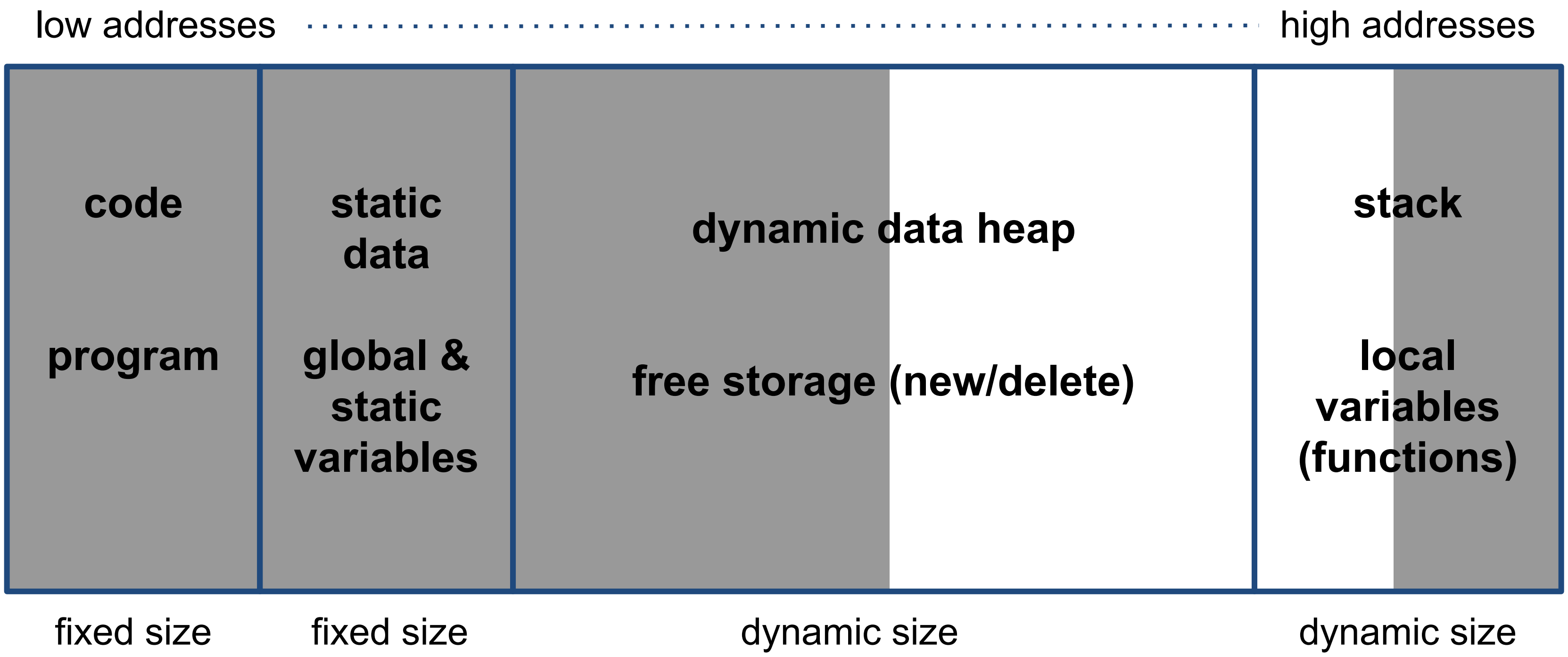
```
void myFunction() {
  GPSCoord * coordPointer = new GPSCoord();
  coordPointer->set(0, 0);  // access method
  delete coordPointer;  // remove object
  coordPointer = NULL; // avoid dangling pointer
}

int main() {
  myFunction();
}
```



7.3. Creating and deleting objects

Background: Heap and stack in memory

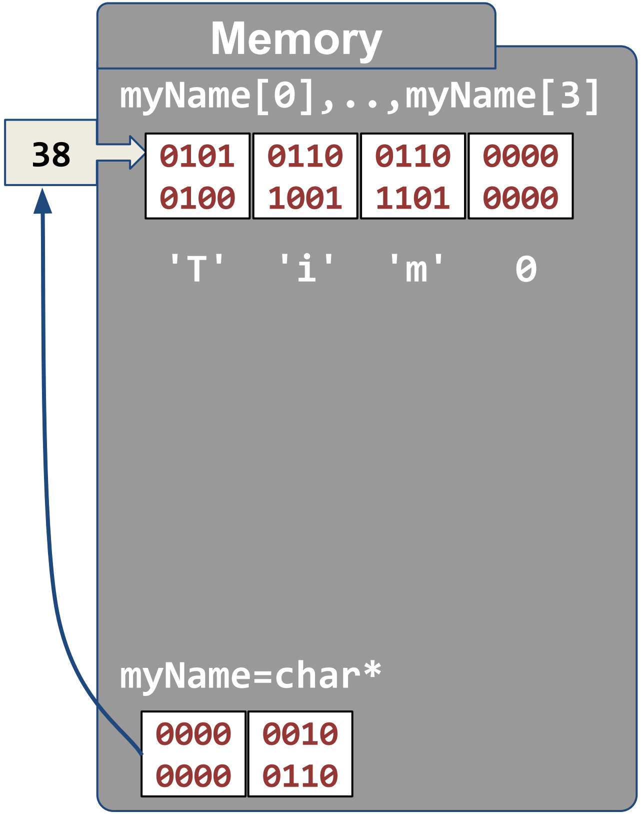


7.4. Pointers and arrays

In C++, an array name is analogue to a pointer to the first element of the array:

```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << '\n';
// → gives out 'T'
std::cout << "2nd: " << myName[1] << '\n';
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << '\n';
// → gives out 'm'
```



7.4. Pointers and arrays

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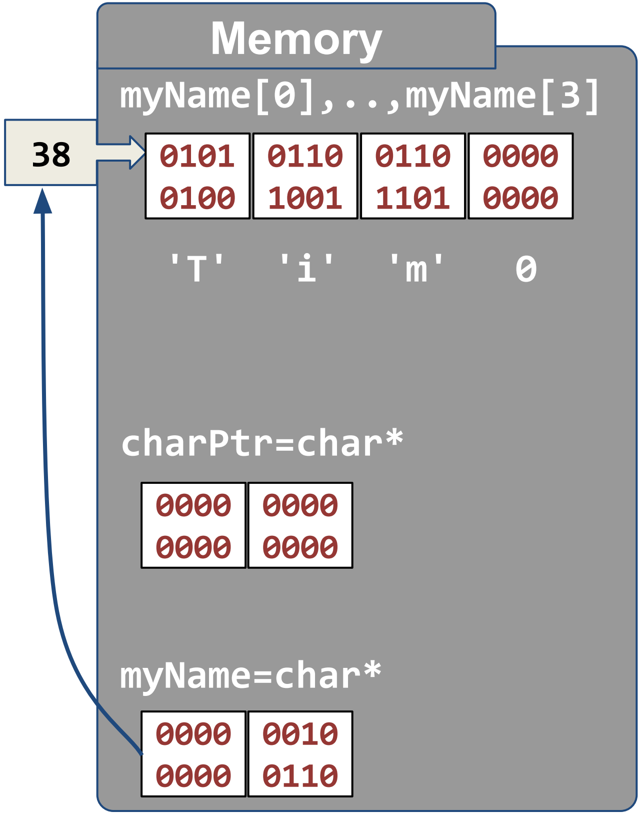
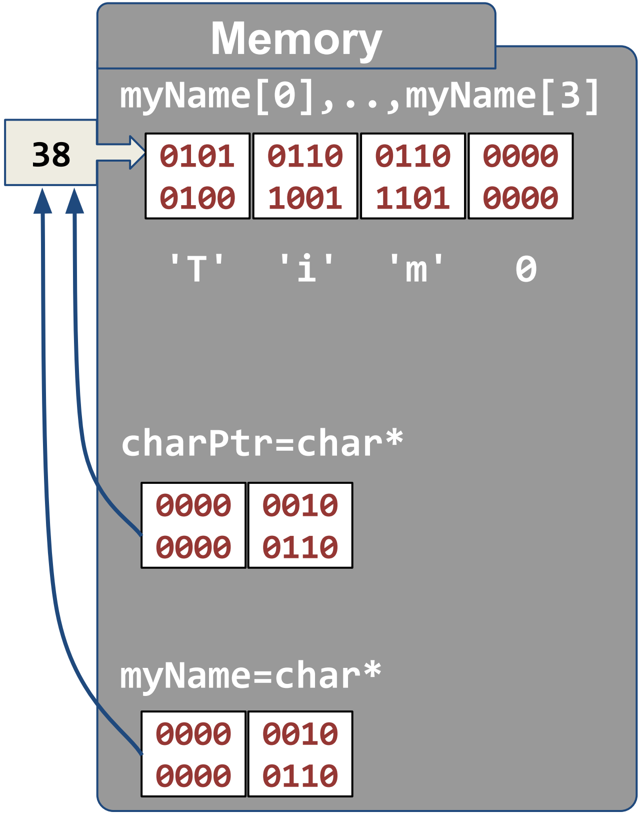
```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << '\n';
// → gives out 'T'
std::cout << "2nd: " << myName[1] << '\n';
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << '\n';
// → gives out 'm'
```



7.4. Pointers and arrays

In C++, an array name is analogue to a pointer to the first element of the array:

```
char myName[4] = "Tim";
char * charPtr = NULL;
charPtr = myName;  // myName == &myName[0]
// note that this is invalid: myName = charPtr;

std::cout << "1st: " << *(charPtr) << '\n';
// → gives out 'T'
std::cout << "2nd: " << myName[1] << '\n';
// → gives out 'i'
std::cout << "3rd: " << *(charPtr+2) << '\n';
// → gives out 'm'
```



7.4. Pointers and arrays

Arrays can be dynamically allocated at run time with pointers:

```
// we receive a size variable here that we need an array around,
// but do not know how large it is at design time:
auto size = fileData.getSize();

// We CAN create an array of the required size:
GPSCoord * myRoute = new GPSCoord[size];  // a route is created as points
for (auto i = 0; i < size; i++) {  // note range-based for loop wouldn't work
  fileData.readNext();  // read data from file, set these as route points:
  myRoute[i].set( fileData[0], fileData[1] );
  myRoute[i].setElevation( fileData[2] );
}

delete[] myRoute;  // for dynamically created arrays, delete needs []
myRoute = NULL;
```

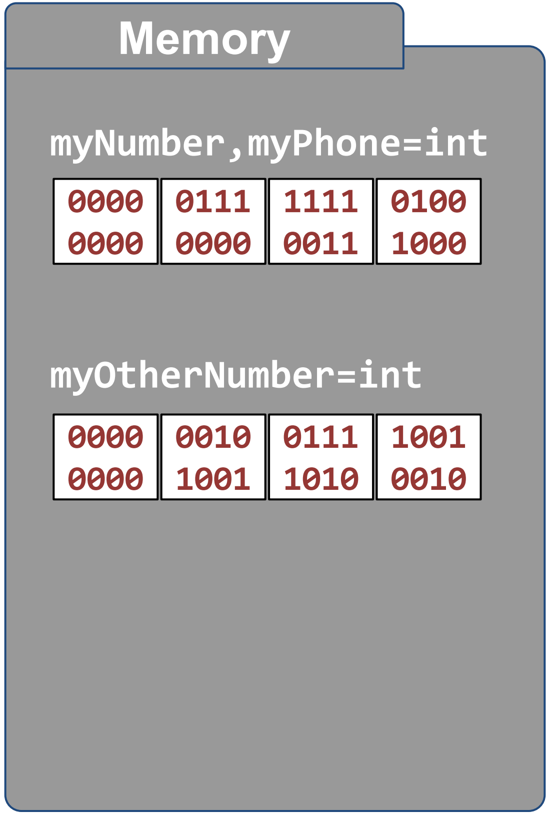
7.4. Pointers and arrays: Example 00 (difficulty level: 🌶️)

```
/* Create an array for which the length is given at runtime through an argument
   of the executable. The main function in C++ can also have two parameters:
   argc: integer containing the count of arguments in argv
   argv: array of strings holding command-line arguments.
   argv[0] is the command itself, argv[1] is first argument */
#include <iostream>

int main(int argc, char * argv[]) { // executable's arguments are passed
  // if an argument given, assume it is a number and convert from string:
  if (argc > 1) {
    auto size = std::stoi(argv[1]);

    // add code to create an array of length size, and fill it with increasing
    // numbers from 1 till size, display these, and then delete the array


  }
}
```

7.5. References

In C++, a reference is like an alias, or second name, for a variable. A reference can only be initialized, but never reassigned to another variable.

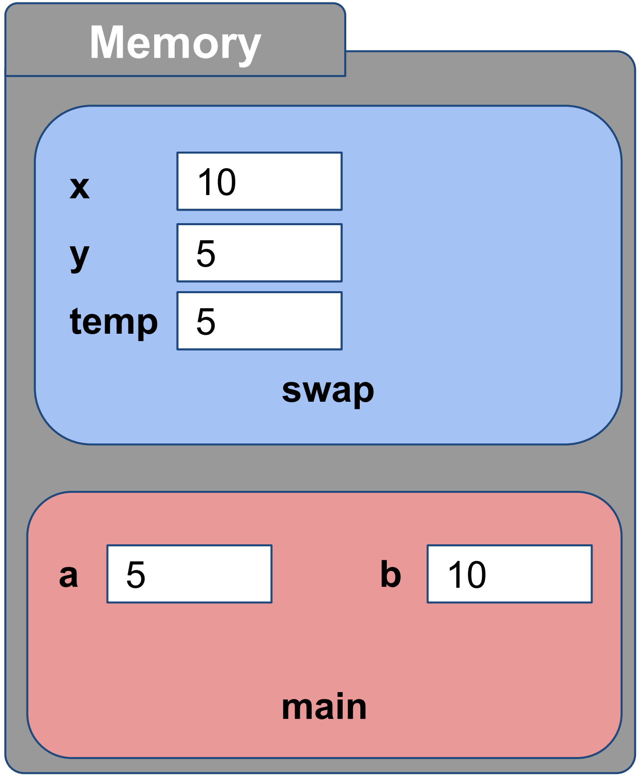
```
int myNumber = 7402312;
int & myPhone = myNumber;  // & in this declaration
// shows that this is a reference. From here on,
// myNumber and myPhone name the same variable.
int myOtherNumber = 2718354;
myPhone = myOtherNumber;
// → Now all three variable names myNumber, myPhone,
// and myOthernumber, have the same value: 2718354
// &myPhone = myOtherNumber; is invalid
```



7.6. Call-by-Reference

Reminder: the swap function below is not going to work, because variables are **passed-by-value**

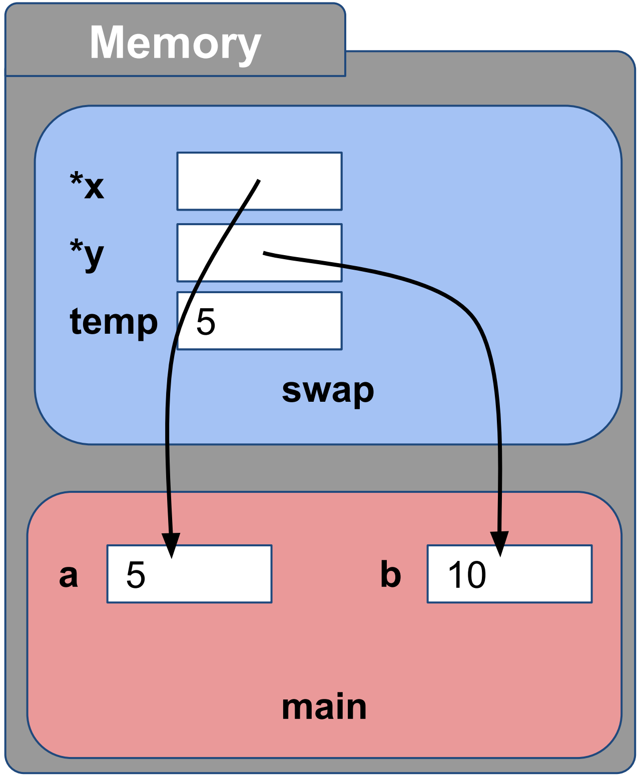
```
#include <iostream>  // output to terminal
void swap(int x, int y){
   auto temp = 0;
   temp = x; x = y; y = temp;
}
int main()  {
   auto a = 5, b = 10;
   swap(a, b);
   std::cout << a << ", " << b << '\n';
}
```



7.6. Call-by-Reference

In C++, parameters can also be pointers. These are passed *by reference*, allowing swap to work:

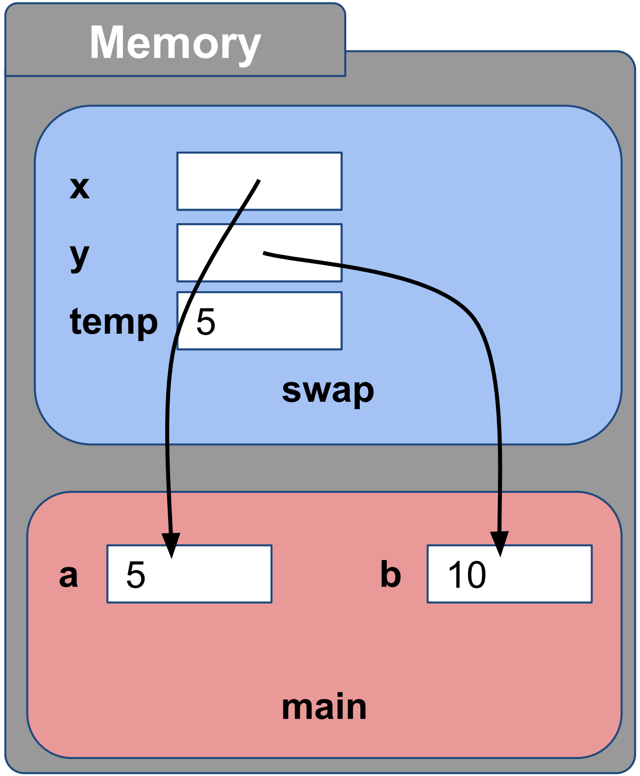
```
#include <iostream>  // output to terminal
void swap(int * x, int * y)    {
   auto temp = 0;
   temp = *x; *x = *y; *y = temp;
}
int main()  {
   auto a = 5, b = 10;
   swap(&a, &b);
   std::cout << a << ", " << b << '\n';
}
```



7.6. Call-by-Reference

References have the same effect: These allow swap to work, too, and are safer and more elegant:

```
#include <iostream>  // output to terminal
void swap(int & x, int & y)    {
   auto temp = 0;
   temp = x; x = y; y = temp;
}
int main()  {
   auto a = 5, b = 10;
   swap(a, b);
   std::cout << a << ", " << b << '\n';
}
```



7.6. Call-by-Reference

Calling by reference avoids copying, which is often preferred. When variables do not change, they can be passed as **`const`** references.

This is generally a clearer signature for developers calling our function/method:

```cpp
#include <iostream>  // output to terminal
[[nodiscard("Please handle this function's return value.")]]
auto printOut(const std::string & x, const std::string & y) {
  return x + ',' + y + '\n';
}

int main() {
  std::string a = "5", b = "10";
  std::cout << printOut(a, b);
}
```

7.6. Call-by-Reference

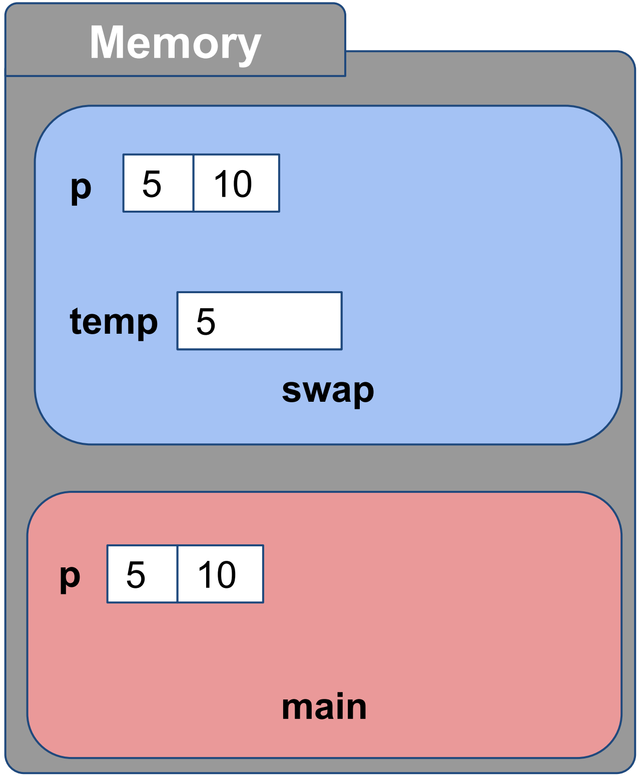
Example 01 (difficulty level: 🌶️)

```
/* Write a class, called Check, below to illustrate in the main function that
   the pointer to an object of class Check b is indeed pointing to the object of
   class Check a. */
#include <iostream>

// write the class Check here

int main() {
  Check a;  // a is an object of class Check
  Check * b = &a;  // assign address of a to pointer b to object of class Check
  if ( b->isThisMe( &a ) ) {
    std::cout << "&a is b \n";
  }
}
```

7.6. Call-by-Reference

Functions / methods create copies of parameters (pass by value). This also is the case for objects.

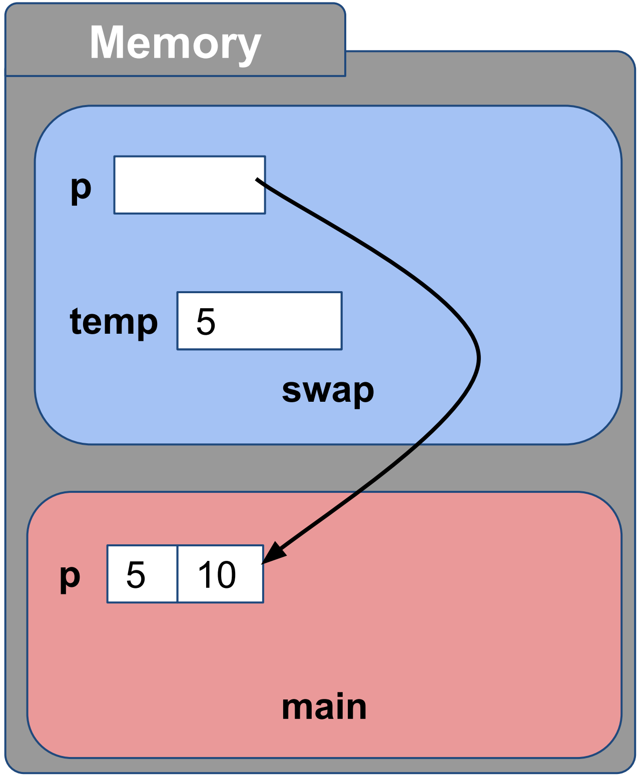
```
#include <iostream>  // output to terminal
struct Pair { int x, y; };
void swap(Pair p)  {
  auto temp = 0;
  temp = p.x; p.x = p.y; p.y = temp;
}
int main()  {
  Pair p; p.x = 5; p.y = 10;
  swap(p);
  std::cout << p.x << ", " << p.y << '\n';
}
```



7.6. Call-by-Reference

Using a reference as function/method parameter allows the function to access the original object:

```
#include <iostream>  // output to terminal
struct Pair { int x, y; };
void swap(Pair & p){
  auto temp = 0;
  temp = p.x; p.x = p.y; p.y = temp;
}
int main()  {
  Pair p; p.x = 5; p.y = 10;
  swap(p);
  std::cout << p.x << ", " << p.y << '\n';
}
```



7.7. Copy Constructors

So when passing an object, it gets automatically copied.

How can we implement this copying of objects?

```
void UTMCoord::from(GPSCoord coord) {
  // transforms from latitude-longitude to UTM coordinates
  // …
}

int main()  {
  GPSCoord place(50.88385, 8.02096);
  UTMCoord place2;
  place2.from( place );  // ← place is here copied into a new object
                         //   and passed
}
```

7.7. Copy Constructors

How can we implement the copying of objects? ⇒ With **copy constructors**

GPSCoord.h

```
class GPSCoord {  // GPS coordinate class
 public:
  GPSCoord() {}  // default constructor
  GPSCoord(GPSCoord const & source);  // copy constructor
  void set(double lat, double lng);  // set latitude, longitude
  void setElevation(double elv);     // set elevation
  void print();  // output coordinates to console
 private:
  double lat, lng, elv;  // latitude, longitude, elevation
};
```

in GPSCoord.cpp

```
GPSCoord::GPSCoord(GPSCoord const & source) {
  lat = source.lat; lng = source.lng; elv = source.elv;
}
```

7.7. Copy Constructors

A copy constructor makes an object from another object of the same class, so in our example, we "clone" our GPSCoord object.

The copy constructor is implicitly called:

- when an object is **passed** to a function or method by value, or
- when a function or method **returns** an object

If a class does not implement a copy constructor, the C++ compiler will provide a default copy constructor, performing a ***member-wise copy*** (also known as ***shallow copy***)

So why do we ever have to implement a copy constructor ourselves?

7.7. Copy Constructors

An example of deep versus shallow copy:

```
class GPSTrace {  // class for a GPS trace

 public:
  GPSTrace(uint16_t numPoints);
  ~GPSTrace();
  // add a new point to trace at position pos:
  void setPoint(GPSCoord newPoint, uint16_t pos);
  [[nodiscard]] int print();  // print trace, forces return handling

 private:
  GPSCoord *points;  // pointer to GPS coordinates
  uint16_t numPoints;
};
```

7.7. Copy Constructors

An example of deep versus shallow copy:

```
GPSTrace::GPSTrace(uint16_t numpoints): numPoints(numpoints) {
  points = new GPSCoord[numPoints];
}

GPSTrace::~GPSTrace() {
  delete[] points; points = NULL; numPoints = 0;
}

void GPSTrace::setPoint(GPSCoord newPoint, uint16_t pos) {
  if (pos < numPoints) points[pos] = newPoint;
}

int GPSTrace::print() {  // output trace to console
  for (auto i = 0; i < numPoints; i++) points[i].print();
  return 0;
}
```

7.7. Copy Constructors

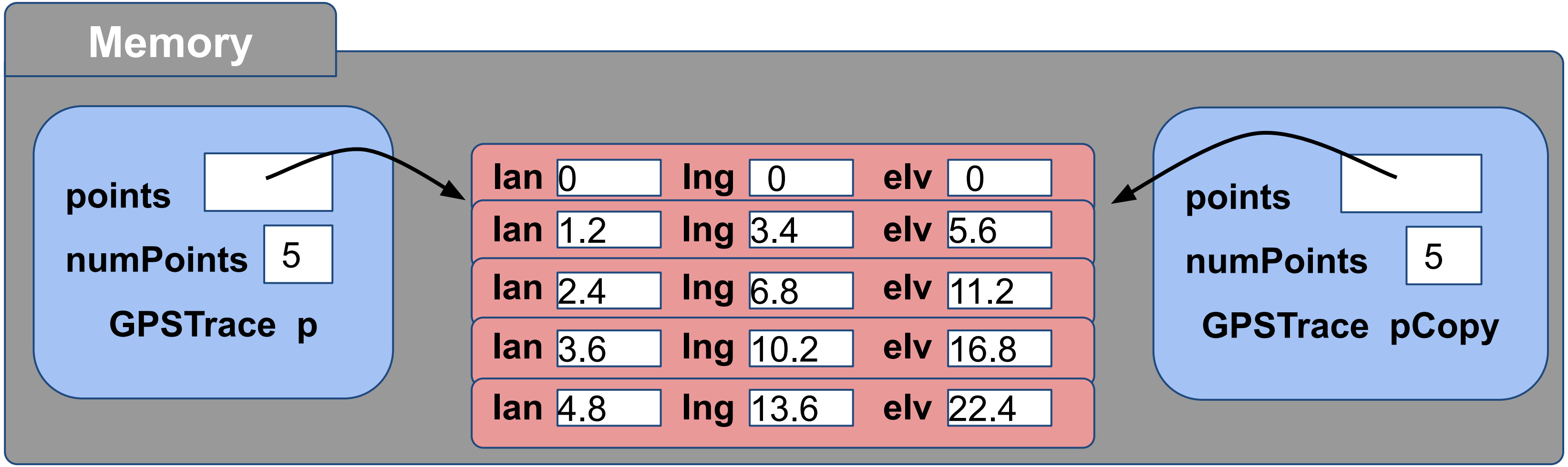
Example 02 (difficulty level: 🌶️🌶️)

```
/** An exercise illustrating shallow and deep copy: Add to the code of GPSTrace
    the necessary functionality that allows copying a GPSTrace and illustrate this
    in the main function below. */
#include <iostream>     // terminal output

// Classes GPSCoord and GPSTrace come here

int main() {
  GPSTrace t(5);
  for (auto i = 0; i < 5; i++ ) {  // fill in the GPS points
    GPSCoord point;
    point.set( i*1.2, i*3.4 ); point.setElevation( i*5.6 );
    t.setPoint( point, i );
  }
  return t.print();
}
```

7.7. Copy Constructors

Example 02 (difficulty level: 🌶️🌶️)

The standard (shallow) copy of **p** (e.g., **pCopy**) will result in this:



So the (deep) copy needs to be implemented in the copy constructor

7.8. **`const`** and **`const`** Pointers

Reminder: constants are defined with the **`const`** keyword, e.g.:

```
const int gpsTraceLength = 150;  // an integer constant
```

- A constant can only be initialized, a new value can not be assigned to a constant once it is defined.
- Usually this is done to protect the constant from being changed later on when this isn't planned.

7.8. **const** and **const** Pointers

const pointers can come in various forms, what matters is that everything on the left of the **const** keyword is constant. If **const** is on the full left, what is on its right is constant. **const** pointers need to be directly initialized:

```
int myInteger = 71;
const int constInt = 17;
int const *pointToConstInt = &constInt;    // pointer to const int
int * const constPointToInt = &myInteger;  // const pointer to int
int const * const cPointToCInt = &constInt;  // const pointer to const int
const int * pointToConstInt2 = &constInt;  // pointer to const int
```

7.8. `const` and `const` Pointers

`const` pointers protect pointers from being changed later in the code.

This means that changes such as: `*pointToConstInt = myInteger;`, `constPointToInt = &myInteger;`, `*cPointToCInt = myInteger;`, and `cPointToCInt = &myInteger;` will all result in an error.

For example:
The `this` pointer in a class' methods is a `const` pointer to an object of the class, so cannot be changed to point to anywhere else but the current object.

7.8. **`const`** and **`const`** Pointers

`const` member functions or methods (aka *const qualified*):

```
int GPSTrace::print() const;  // output trace to console
```

`const` in the method's declaration *and* definition tells the compiler that the method should not modify the object (i.e., change the attributes)

- The compiler enforces this, and reports an error once the method's code tries to change its attributes
- Using const methods whenever possible will add guarantee that it will be used properly in the future

7.8. **const** and **const** Pointers

Example 03 (difficulty level: 🌶️🌶️🌶️):

```
/** Print a mouse in the console, using a const pointer to avoid changes */
#include <iostream>      // terminal output
[[nodiscard]] auto * getBitmapAddress() {
    static auto bitmap[] = "(^._.^)~\n";  // "bitmap" created in static memory
    return bitmap;  // return pointer to first element
}

int main() {
  // using a pointer to bitmap, and incrementing it, is possible:
  auto * mousePointer = getBitmapAddress();
  while ( *mousePointer != 0 )  std::cout << *(mousePointer++);
  // Here mousePointer has changed, it's hard to get the original pointer.
  // Modify the above by protecting the pointer with const, and looping twice.
}
```

7.9. Passing functions to functions: Passing pointer to function

In C, functions can be passed as a parameter, which will be as a pointer to the function and is just the function's name:

```
#include <iostream>      // terminal output

int addTwo(int x) { return x + 2; }      // functions we can pass in callFunct
int timesFour(int x) { return x * 4; }  // since they match the signature

// callFunct takes a pointer to a function:
int callFunct(int x, int (*funct)(int) ) { return funct(x); /* = (*funct)(x) */ }

int main() {
  std::cout << "addTwo(149) = " << callFunct(149, addTwo) << '\n';
  std::cout << "timesFour(4) = " << callFunct(4, timesFour) << '\n';
}
```

7.9. Passing functions to functions: The **`std::function`**

In C++ 11 and onward, **`std::function`** can be used from **`<functional>`** (using templates, see later):

```
#include <iostream>      // terminal output
#include <functional>     // use std::function to pass functions as parameter

int addTwo(int x) { return x + 2; }      // functions we can pass in callFunct
int timesFour(int x) { return x * 4; }  // since they match the signature

// callFunction takes a pointer to a function:
int callFunct(int x, std::function<int(int)> func ) { return funct(x); }

int main() {
  std::cout << "addTwo(149) = " << callFunct(149, addTwo) << '\n';
  std::cout << "timesFour(4) = " << callFunct(4, timesFour) << '\n';
}
```

7.9. Passing functions to functions: Passing pointer to function

Example04 (difficulty level: 🌶️🌶️🌶️):

```
/** Define the class' methods below so that the main function makes sense */
#include <iostream>       // terminal output
#include <functional>     // use std::function to pass functions as parameter
class NumberSequence {  // class for sequence of whole, positive numbers

 public:
  NumberSequence(uint16_t length = 10);
  // apply the function func() to all numbers:
  void forEach(std::function<uint16_t(uint16_t)> func);
  void print() const;  // print all numbers to console

 private:
  const uint16_t length;  // length of number sequence
  uint16_t *seq;  // the numbers are stored as a dynamic array
};
```

7.9. Passing functions to functions: Passing pointer to function

Example04 (difficulty level: 🌶️🌶️🌶️):

```
// define all NumberSequence methods here
//

uint16_t times2(uint16_t n) { return n*2; }

int main() {
  NumberSequence s;
  s.print();
  s.forEach( &times2 );  // apply the function times2 to all numbers
  s.print();
}
```

7.9. Passing functions to functions: Passing pointer to function

On the pointers behind functions and arrays:

```
#include <iostream>
int fun(int i) { return i+7; }  // a function
int main() {
  int a[3] = {1,2,3};  // an array

  // conversion to function pointers defaults to a bool:
  std::cout << "fun:          " << fun << '\n';  // will result in warning
  std::cout << "&fun:         " << &fun << '\n';
  // Converting to a void pointer works:
  std::cout << "(void*)fun: " << (void*)fun << '\n';
  std::cout << "(void*)&fun:" << (void*)&fun << '\n';
  // The address of an array can be gotten by:
  std::cout << "a:      " <<  a << '\n';
  std::cout << "&a:     " << &a << '\n';
  std::cout << "&a[0]: " << &a[0] << '\n';
}
```

7.10. Smart Pointers in C++

Smart pointers are a wrapper class over pointers, to avoid memory leaks, wild (never initialized), or dangling (pointing to deleted memory) pointers.

They destroy themselves when they go out of scope, and can efficiently manage memory through extra functionality.

They are a part of the **`<memory>`** module (in **`<iostream>`**) and implement:

- ~~**`auto_ptr`**~~**`:`** deprecated after C++11.
- **`unique_ptr:`** an exclusive pointer that cannot be copied (just moved) and cleans up after itself
- **`shared_ptr:`** a pointer that can be shared: Multiple pointers can point to the same object, and this is managed (and counted).
- **`weak_ptr`**: beyond the scope of this course

7.10. Smart Pointers in C++

```
#include <iostream>   // terminal output and smart pointers
struct Coordinate {  // class for an x,y coordinate
  int x = 10, y = 20;
  void print() {
    std::cout << x << ',' << y << '\n';
  }
};

int main() {
  std::unique_ptr<Coordinate> p1(new Coordinate);
  std::unique_ptr<int> p2(new int[15]);
  p1->print();
  std::cout << p2.get() << '\n';  // display pointer p2's address
  // this would give a compiler error:
  //   unique_ptr<Coordinate> p3 = p1;
  // no need to delete p1 or p2 here, that is done for us
}
```