CSCI 104
Memory Allocation

Sandra Batista & Mark Redekopp
POINTERS, REFERENCES, AND SCOPING REVIEW
A Program View of RAM/Memory

- Code usually sits at low addresses
- Global variables somewhere after code
- System stack (memory for each function instance that is alive)
  - Local variables
  - Return link (where to return)
  - etc.
- Heap: Area of memory that can be allocated and de-allocated during program execution (i.e. dynamically at run-time) based on the needs of the program
- Heap grows downward, stack grows upward...
  - In rare cases of large memory usage, they could collide and cause your program to fail or generate an exception/error
Variables and Static Allocation

- Every variable/object in a computer has a:
  - Name (by which *programmer* references it)
  - Address (by which *computer* references it)
  - Value

- Let's draw these as boxes

- Every variable/object has **scope** (its lifetime and visibility to other code)

- Automatic/Local Scope
  - {...} of a function, loop, or if
  - Lives on the stack
  - Dies/Dealocated when the '{ }' is reached

- Logically, let's draw these as nested container boxes
Automatic/Local Variables

- Physically, local variables (i.e. those declared inside {...}) are allocated on the stack
- Each function has an area of memory on the stack

```
// Computes rectangle area, // prints it, & returns it
int area(int, int);
void print(int);
int main()
{
    int wid = 8, len = 5, a;
    a = area(wid, len);
}

int area(int w, int l)
{
    int ans = w * l;
    print(ans);
    return ans;
}

void print(int area)
{
    cout << "Area is " << area;
    cout << endl;
}
```
Kinds of References

**Pointers**

- A variable (like any other) which occupies memory and stores an address of another variable and can be updated (like any other variable) to store a new address to some other variable
- Declared with the `type*` syntax (e.g. `int*`, `char*`, `Item*`)

**C++ Reference Variable**

- A special variable that simply gives a second (or third, or fourth) name to an already-declared variable
- Declared with the `type&` syntax (e.g. `int&`, `string&`, `Item&`)
- Does not occupy any memory (just tells the compiler to allow another name to reference some other variable)

**Important Note:** When we use the general term "reference" as in "pass-by-reference" we can use EITHER **pointers** **OR** C++ Reference Variables.

Lets' take a look at each...
Review of Pointers in C/C++

• Pointer (type *)
  – Really just the memory address of a variable
  – Pointer to a data-type is specified as type *(e.g. int *)
  – Operators: & and *
    • &object => address-of object (Create a link to an object)
    • *ptr => object located at address given by ptr (Follow a link to an object)
    • *(&object) => object [i.e. * and & are inverse operators of each other]

• Example: Indicate what each line prints or what variable is modified. Use NA for any invalid operation.

```c
int* p, *q;
int i, j;
i = 5; j = 10;
p = &i;
cout << p << endl;
cout << *p << endl;
*p = j;
*q = *p;
q = p;
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbe0</td>
<td></td>
</tr>
<tr>
<td>0xbe4</td>
<td></td>
</tr>
<tr>
<td>0xbe8</td>
<td>5</td>
</tr>
<tr>
<td>0xbec</td>
<td>10</td>
</tr>
</tbody>
</table>

p
q
i
j

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Pointer Notes

- **NULL** (defined in `<cstdlib>`) or now **nullptr** (in C++11) are keywords for values you can assign to a pointer when it doesn't point to anything
  - NULL is effectively the value 0 so you can write:
    ```c
    int* p = nullptr;
    if( p )
    // will never get to this code */}
    ```
  - To use **nullptr** compile with the C++11 version:
    ```bash
    $ g++ -std=c++11 -g -o test test.cpp
    ```

- An uninitialized pointer is a pointer waiting to cause a SEGFAULT

- Beware of SEGFAULTS! What are they and what causes them?

- What tool can help find what is causing SEGFAULTS?
Check Yourself

• Consider these declarations:
  – int k, x[3] = {5, 7, 9};
  – int *myptr = x;
  – int **ourptr = &myptr;

• Indicate the formal type that each expression evaluates to (i.e. int, int *, int **)

To figure out the type of data a pointer expression will yield...
• Each * in the expression cancels a * from the variable type.
• Each & in the expression adds a * to the variable type.

<table>
<thead>
<tr>
<th>Orig. Type</th>
<th>Expr</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>myptr = int*</td>
<td>*myptr</td>
<td>int</td>
</tr>
<tr>
<td>ourptr = int**</td>
<td>**ourptr</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>*ourptr</td>
<td>int*</td>
</tr>
<tr>
<td>k = int</td>
<td>&amp;k</td>
<td>int*</td>
</tr>
<tr>
<td></td>
<td>&amp;myptr</td>
<td>int**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;x[0]</td>
<td></td>
</tr>
<tr>
<td>x</td>
<td></td>
</tr>
<tr>
<td>myptr</td>
<td></td>
</tr>
<tr>
<td>*myptr</td>
<td></td>
</tr>
<tr>
<td>(*ourptr) + 1</td>
<td></td>
</tr>
<tr>
<td>myptr + 2</td>
<td></td>
</tr>
<tr>
<td>&amp;ourptr</td>
<td></td>
</tr>
</tbody>
</table>
Using C++ References

• Reference type (type &) creates an alias (another name) the programmer/compiler can use for some other variable
  – Is NOT another variable; does NOT require memory
• "Syntactic sugar" (i.e. make programmer's life easy) to avoid using pointers
• A variable declared with an ‘int &' doesn’t store an int, but is an alias for an actual variable
• MUST assign to the reference variable when you declare it.

```cpp
int main()
{
    int y = 3, *ptr;
    ptr = &y; // address-of 
              // operator

    int &x = y; // reference 
                // declaration
    // We’ve not copied y into x. 
    // Rather, we’ve created an alias. 
    // What we do to x happens to y. 
    // Now x can never reference 
    // any other int...only y!

    x++;  // y just got incr.
    cout << y << endl;

    int &z;  // NO! must assign

    int w = 5;
    x = w;  // doesn't make x
             // reference w...copies
             // w into y;
    return 0;
}
```

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POINTERS, REFERENCES, AND SCOPING ASSESSMENT
Correct Usage of Pointers

- Commonly functions will take some inputs and produce some outputs
  - We'll use a simple 'multiply' function for now even though we can easily compute this without a function
  - We could use the return value from the function but let's practice with pointers
- Can use a pointer to have a function modify the variable of another

```c
// Computes the product of in1 & in2
int mul1(int in1, int in2);
void mul2(int in1, int in2, int* out);

int main()
{
    int wid = 8, len = 5, a;
    mul2(wid, len, &a);
    cout << "Ans. is " << a << endl;
    return 0;
}

int mul1(int in1, int in2)
{
    return in1 * in2;
}

void mul2(int in1, int in2, int* out)
{
    *out = in1 * in2;
}
```

<table>
<thead>
<tr>
<th>Stack Area of RAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbe0</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>in1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0xbf0</th>
<th>0xbf4</th>
<th>0xbf8</th>
<th>0xbfc</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5</td>
<td>-732</td>
<td>00400120</td>
</tr>
<tr>
<td>wid</td>
<td>len</td>
<td>a</td>
<td>Return link</td>
</tr>
</tbody>
</table>

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Now with C++ References

- We can pass using C++ reference
- The reference 'out' is just an alias for 'a' back in main
  - In memory, it might actually be a pointer, but you don't have to dereference (the kind of stuff you have to do with pointers)

```cpp
void mul(int in1, int in2, int& out);

int main()
{
    int wid = 8, len = 5, a;
    mul(wid, len, a);
    cout << "Ans. is " << a << endl;
    return 0;
}
```

```
// Computes the product of in1 & in2
void mul(int in1, int in2, int& out);

int main()
{
    int wid = 8, len = 5, a;
    mul(wid, len, a);
    cout << "Ans. is " << a << endl;
    return 0;
}
```

Stack Area of RAM

```
<table>
<thead>
<tr>
<th></th>
<th>0xbe0</th>
<th>0xbe4</th>
<th>0xbe8</th>
<th>0xbec</th>
</tr>
</thead>
<tbody>
<tr>
<td>in1</td>
<td>8</td>
<td>5</td>
<td>?0xbf8?</td>
<td>004000ca0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0xbf0</th>
<th>0xbf4</th>
<th>0xbf8</th>
<th>0xbfc</th>
</tr>
</thead>
<tbody>
<tr>
<td>wid</td>
<td>8</td>
<td>5</td>
<td>40</td>
<td>00400120</td>
</tr>
</tbody>
</table>

Return link

-732 = out
`
Misuse of Pointers/References

- Make sure you don't return a pointer or reference to a dead variable
- You might get lucky and find that old value still there, but likely you won't

```
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int& badmul2(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = badmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    return 0;
}

// Bad! Returns a pointer to a var.  // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Bad! Returns a reference to a var.  // that will go out of scope
int& badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return out;
}
```

```
Stack Area of RAM

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbe0</td>
<td>40</td>
<td>out</td>
</tr>
<tr>
<td>0xbe4</td>
<td>8</td>
<td>in1</td>
</tr>
<tr>
<td>0xbe8</td>
<td>5</td>
<td>in2</td>
</tr>
<tr>
<td>0xbec</td>
<td>0x4000ca0</td>
<td>Return link</td>
</tr>
<tr>
<td>0xbf0</td>
<td>8</td>
<td>wid</td>
</tr>
<tr>
<td>0xbf4</td>
<td>5</td>
<td>len</td>
</tr>
<tr>
<td>0xbf8</td>
<td>-732</td>
<td>a</td>
</tr>
<tr>
<td>0xbfc</td>
<td>0x400120</td>
<td>Return link</td>
</tr>
</tbody>
</table>
```
Dynamic Allocation

- Dynamic Allocation
  - Lives on the heap
    - Doesn't have a name, only pointer/address to it
  - Lives until you 'delete' it
    - Doesn't die at end of function (though pointer to it may)
- Let's draw the operation of `goodmul1()`

Stack Area of RAM

<table>
<thead>
<tr>
<th>0xbe4</th>
<th>0x93c</th>
<th>out</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0xbe8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>0xbec</td>
<td>004000ca0</td>
<td>Return link</td>
</tr>
</tbody>
</table>

Heap Area of RAM

<table>
<thead>
<tr>
<th>0x93c</th>
<th>40</th>
</tr>
</thead>
</table>

```cpp
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation

- When `goodmul1()` exits, the out pointer goes out of scope.
- Thus we need to return the pointer or save it somewhere so that there is a record of our allocation, otherwise we will have a leak.

```cpp
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Bad! Returns a pointer to a var. that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation – Q1

• What happens if we comment the 'delete a' line?

```
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    // delete a;
    return 0;
}

// Bad! Returns a pointer to a var.
// that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var.
// that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation – A1

- What happens if we comment the 'delete a' line?
  - Memory LEAK!!

```cpp
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    // delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation

- The LinkedList object is allocated as a static/local variable
  - But each element is allocated on the heap
- When y goes out of scope only the data members are deallocated
  - You may have a memory leak

```cpp
struct Item {
  int val;  Item* next;
};
class LinkedList {
  public:
    // create a new item
    // in the list
    void push_back(int v);
  private:
    Item* head;
};

int main()
{
  doTask();
}

void doTask()
{
  LinkedList y;
  y.push_back(3);
  y.push_back(5);
  /* other stuff */
}
```

Stack Area of RAM

- `doTask` at `0xbe8`
- `main` at `0xbfc`
- `Return link`

Heap Area of RAM

- `0x93c` with `y`
- `0x748` with `3` and `0x748` with `5`
- `MEMORY LEAK` when `y` is deallocated we have no pointer to the data

Return link
Dynamic Allocation

- The LinkedList object is allocated as a static/local variable
  - But each element is allocated on the heap
- When y goes out of scope only the data members are deallocated
  - You may have a memory leak

An Appropriate Destructor Will Help Solve This

- Structure of RAM
  - Stack Area of RAM
  - Heap Area of RAM

```cpp
struct Item {
    int val;  Item* next;
};
class LinkedList {
    public:
        // create a new item
        // in the list
        void push_back(int v);
    private:
        Item* head;
};

int main() {
    doTask();
}

void doTask() {
    LinkedList y;
    y.push_back(3);
    y.push_back(5);
    /* other stuff */
}
```

When y is deallocated we have no pointer to the data
If time allows

PRACTICE ACTIVITY 1
Object Assignment

- Assigning one struct or class object to another will cause an element by element copy of the source data destination struct or class

```cpp
#include<iostream>
using namespace std;

enum {CS, CECS};

struct student {
    char name[80];
    int id;
    int major;
};

int main(int argc, char *argv[]) {
    student s1;
    strncpy(s1.name,"Bill",80);
    s1.id = 5; s1.major = CS;
    student s2 = s1;
    return 0;
}
```
Memory Allocation Tips

• Take care when returning a pointer or reference that the object being referenced will persist beyond the end of a function
• Take care when assigning a returned referenced object to another variable...you are making a copy
• Try the examples yourself
  – $ wget http://ee.usc.edu/~redekopp/cs104/memref.cpp
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data?

**ex1**
```cpp
class Item
{ public:
   Item(int w, string y);
};
Item buildItem()
{ Item x(4, "hi");
   return x;
}
int main()
{ Item i = buildItem();
   // access i’s data.
}
```

**ex2**
```cpp
class Item
{ public:
   Item(int w, string y);
};
Item& buildItem()
{ Item x(4, "hi");
   return x;
}
int main()
{ Item& i = buildItem();
   // access i’s data
}
```

**ex3**
```cpp
class Item
{ public:
   Item(int w, string y);
};
Item* buildItem()
{ Item* x = new Item(4, "hi");
   return x;
}
int main()
{ Item* i = buildItem();
   // access i’s data
}
```
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data

ex4

```cpp
class Item
{ public:
    Item(int w, string y);
};
Item* buildItem()
{ Item x(4, “hi”);
    return &x;
}
int main()
{ Item *i = buildItem();
  // access i’s data
}
```

ex5

```cpp
class Item
{ public:
    Item(int w, string y);
};
Item& buildItem()
{ Item* x = new Item(4,”hi”);
    return *x;
}
int main()
{ Item& i = buildItem();
  // access i’s data
}
```
class Item
{
    Item(int w, string y);
};
Item& buildItem()
{
    Item* x = new Item(4, "hi");
    return *x;
}
int main()
{
    Item i = buildItem();
    // access i’s data.
}

Item Item::buildItem()
{
    Item* x = new Item(4, "hi");
    return *x;
}
int main()
{
    Item i = &buildItem();
    // access i’s data.
}

Item* Item::buildItem()
{
    Item* x = new Item(4, "hi");
    return *x;
}
int main()
{
    Item* i = &buildItem();
    // access i’s data.
}
PRE-SUMMER 2021 BACKGROUND
VARIABLES & SCOPE
A Program View of RAM/Memory

- Code usually sits at low addresses
- Global variables somewhere after code
- System stack (memory for each function instance that is alive)
  - Local variables
  - Return link (where to return)
  - etc.
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  – Name (by which programmer references it)
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  – Value

• Let's draw these as boxes

• Every variable/object has **scope** (its lifetime and visibility to other code)

• Automatic/Local Scope
  – {...} of a function, loop, or if
  – Lives on the stack
  – Dies/Deallocated when the '}' is reached

• Let's draw these as nested container boxes
## Automatic/Local Variables

- Variables declared inside `{...}` are allocated on the stack
- This includes functions

```c
// Computes rectangle area, // prints it, & returns it
int area(int w, int l)
{
    int ans = w * l;
    print(ans);
    return ans;
}

void print(int area)
{
    cout << "Area is " << area;
    cout << endl;
}
```

### Stack Area of RAM

| Function | Address | Data Type | Data
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>cout</td>
<td>0xb8</td>
<td>0xbdc</td>
<td>004001844</td>
</tr>
<tr>
<td>print</td>
<td>0xb8</td>
<td>0xbc7c</td>
<td>004000ca0</td>
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<tr>
<td>area</td>
<td>0xb0</td>
<td>0xbe4</td>
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<td></td>
<td>0xb0</td>
<td>0xbf4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0xb0</td>
<td>0xbfc</td>
<td>00400120</td>
</tr>
</tbody>
</table>

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POINTERS & REFERENCES
Kinds of References

**Pointers**
- A variable (like any other) which occupies memory and stores an address of another variable and can be updated (like any other variable) to store a new address to some other variable
- Declared with the `type*` syntax (e.g. `int*`, `char*`, `Item*`)

**C++ Reference Variable**
- A special variable that simply gives a second (or third, or fourth) name to an already-declared variable
- Declared with the `type&` syntax (e.g. `int&`, `string&`, `Item&`)
- Does not occupy any memory (just tells the compiler to allow another name to reference some other variable)

**Important Note:** When we use the general term "reference" as in "pass-by-reference" we can use EITHER **pointers OR C++ Reference Variables.**

Let's take a look at each...
Review of Pointers in C/C++

- Pointer (type *)
  - Really just the memory address of a variable
  - Pointer to a data-type is specified as type * (e.g. int *)
  - Operators: & and *
    - &object => address-of object (Create a link to an object)
    - *ptr => object located at address given by ptr (Follow a link to an object)
    - *(&object) => object [i.e. * and & are inverse operators of each other]

- Example: Indicate what each line prints or what variable is modified. Use NA for any invalid operation.

```cpp
int* p, *q;
int i, j;
i = 5; j = 10;
p = &i;
cout << p << endl;
cout << *p << endl;
*p = j;
*q = *p;
q = p;
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbe0</td>
<td></td>
</tr>
<tr>
<td>0xbe4</td>
<td></td>
</tr>
<tr>
<td>0xbe8</td>
<td>5</td>
</tr>
<tr>
<td>0xbec</td>
<td>10</td>
</tr>
</tbody>
</table>
Pointer Notes

- **NULL** (defined in `<cstdlib>`) or now **nullptr** (in C++11) are keywords for values you can assign to a pointer when it doesn't point to anything
  - NULL is effectively the value 0 so you can write:
    ```
    int* p = NULL;
    if( p )
    { /* will never get to this code */ }
    ```
  - To use **nullptr** compile with the C++11 version:
    ```
    $ g++ -std=c++11 -g -o test test.cpp
    ```

- An uninitialized pointer is a pointer waiting to cause a **SEGFAULT**

- Beware of **SEGFAULTS**! What are they and what causes them?

- What tool can help find what is causing **SEGFAULTS**?
Check Yourself

- Consider these declarations:
  - int k, x[3] = {5, 7, 9};
  - int *myptr = x;
  - int **ourptr = &myptr;

- Indicate the formal type that each expression evaluates to (i.e. int, int *, int **)

To figure out the type of data a pointer expression will yield...
- Each * in the expression cancels a * from the variable type.
- Each & in the expression adds a * to the variable type.

<table>
<thead>
<tr>
<th>Orig. Type</th>
<th>Expr</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>myptr = int*</td>
<td>*myptr</td>
<td>int</td>
</tr>
<tr>
<td>ourptr = int**</td>
<td>**ourptr</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>*ourptr</td>
<td>int*</td>
</tr>
<tr>
<td>k = int</td>
<td>&amp;k</td>
<td>int*</td>
</tr>
<tr>
<td></td>
<td>&amp;myptr</td>
<td>int**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;x[0]</td>
<td></td>
</tr>
<tr>
<td>x</td>
<td></td>
</tr>
<tr>
<td>myptr</td>
<td></td>
</tr>
<tr>
<td>*myptr</td>
<td></td>
</tr>
<tr>
<td>(*ourptr) + 1</td>
<td></td>
</tr>
<tr>
<td>myptr + 2</td>
<td></td>
</tr>
<tr>
<td>&amp;ourptr</td>
<td></td>
</tr>
</tbody>
</table>
Using C++ References

- Reference type (type &) creates an alias (another name) the programmer/compiler can use for some other variable
  - Is NOT another variable; does NOT require memory
- "Syntactic sugar" (i.e. make programmer's life easy) to avoid using pointers
- A variable declared with an ‘int &’ doesn’t store an int, but is an alias for an actual variable
- MUST assign to the reference variable when you declare it.

```
int main()
{
    int y = 3, *ptr;
    ptr = &y; // address-of operator

    int &x = y; // reference declaration
    // We’ve not copied y into x.
    // Rather, we’ve created an alias.
    // What we do to x happens to y.
    // Now x can never reference any other int...only y!

    x++;   // y just got incr.
    cout << y << endl;

    int &z; // NO! must assign
    int w = 5;
    x = w; // doesn't make x reference w...copies w into y;
    return 0;
}
```
References in C/C++

• Declare a reference to an object as type& (e.g. int&)
• Must be initialized at declaration time (i.e. can’t declare a reference variable if without indicating what object you want to reference)
  – Logically, C++ reference types DON'T consume memory...they are just an alias (another name) for the variable they reference
  – Physically, it may be implemented as a pointer to the referenced object but that is NOT your concern
• Cannot change what the reference variable refers to once initialized
• Most common usage is for parameter passing (see next slide)
Argument Passing Examples

- **Pass-by-value** => Passes a copy
- **Pass-by-reference** =>
  - **Pass-by-pointer/address** => Passes address of actual variable
  - **Pass-by-reference** => Passes an alias to actual variable (likely its really passing a pointer behind the scenes but now you don't have to dereference everything)

```c
int main()
{
    int x=5, y=7;
    swapit(x, y);
    cout << "x, y=" << x << "," << y;
    cout << endl;
}

void swapit(int x, int y)
{
    int temp;
    temp = x;
    x = y;
    y = temp;
}
```

program output: x=5, y=7

```c
int main()
{
    int x=5, y=7;
    swapit(&x, &y);
    cout << "x, y=" << x << "," << y;
    cout << endl;
}

void swapit(int *x, int *y)
{
    int temp;
    temp = *x;
    *x = *y;
    *y = temp;
}
```

program output: x=7, y=5

```c
int main()
{
    int x=5, y=7;
    swapit(x, y);
    cout << "x, y=" << x << "," << y;
    cout << endl;
}

void swapit(int &x, int &y)
{
    int temp;
    temp = x;
    x = y;
    y = temp;
}
```

program output: x=7, y=5

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Correct Usage of Pointers

• Commonly functions will take some inputs and produce some outputs
  – We'll use a simple 'multiply' function for now even though we can easily compute this without a function
  – We could use the return value from the function but let's practice with pointers
• Can use a pointer to have a function modify the variable of another

```cpp
// Computes the product of in1 & in2
int mul1(int in1, int in2);
void mul2(int in1, int in2, int* out);

int main()
{
    int wid = 8, len = 5, a;
    mul2(wid, len, &a);
    cout << "Ans. is " << a << endl;
    return 0;
}

int mul1(int in1, int in2)
{
    return in1 * in2;
}

void mul2(int in1, int in2, int* out)
{
    *out = in1 * in2;
}
```

Stack Area of RAM

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbe0</td>
<td>8</td>
</tr>
<tr>
<td>0xbe4</td>
<td>5</td>
</tr>
<tr>
<td>0xbe8</td>
<td>0xbf8</td>
</tr>
<tr>
<td>0xbec</td>
<td>0x004000ca0</td>
</tr>
</tbody>
</table>

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</tr>
<tr>
<td>0xbf8</td>
<td>0xbf0</td>
</tr>
<tr>
<td>0xbfc</td>
<td>0x00400120</td>
</tr>
</tbody>
</table>

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Now with C++ References

- We can pass using C++ reference
- The reference 'out' is just an alias for 'a' back in main
  - In memory, it might actually be a pointer, but you don't have to dereference (the kind of stuff you have to do with pointers)

```
#include <iostream>

// Computes the product of in1 & in2
void mul(int in1, int in2, int& out);

int main()
{
    int wid = 8, len = 5, a;
    mul(wid, len, a);
    std::cout << "Ans. is " << a << std::endl;
    return 0;
}

void mul(int in1, int in2, int& out)
{
    out = in1 * in2;
}
```

Stack Area of RAM
Misuse of Pointers/References

- Make sure you don't return a pointer or reference to a dead variable
- You might get lucky and find that old value still there, but likely you won't

```c
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int& badmul2(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = badmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    return 0;
}

// Bad! Returns a pointer to a var.
// that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Bad! Returns a reference to a var.
// that will go out of scope
int& badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return out;
}
```
Pass-by-Value vs. -Reference

• Arguments are said to be:
  – Passed-by-value: A copy is made from one function and given to the other
  – Passed-by-reference (i.e. pointer or C++ reference): A reference (really the address) to the variable is passed to the other function

<table>
<thead>
<tr>
<th>Pass-by-Value Benefits</th>
<th>Pass-by-Reference Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Protects the variable in the caller since a copy is made (any modification doesn’t affect the original)</td>
<td>+ Allows another function to modify the value of variable in the caller + Saves time vs. copying</td>
</tr>
</tbody>
</table>

• Care needs to be taken when choosing between the options
Pass by Reference

- Notice no copy of x need be made since we pass it to sum() by reference
  - Notice that likely the computer passes the address to sum() but you should just think of `dat` as an alias for `x`
  - The `const` keyword tells the compiler to double check that we don't modify the vector (giving the safety of pass-by-value but the performance of pass-by-reference)

```cpp
// Computes the sum of a vector
int sum(const vector<int>&);

int main()
{
    int result;
    vector<int> x = {1,2,3,4};
    result = sum(x);
}

int sum(const vector<int>& dat)
{
    int s = 0;
    for(int i=0; i < dat.size(); i++)
    {
        s += dat[i];
    }
    return s;
}
```

---

Stack Area of RAM

```
sum
0xbe0 0
0xbe4 ?0xbf0?
0xbe8 004000ca0

main
0xbec 0
0xbf0 1
0xbf4 2
0xbf8 ...
0xb?? 00400120
```

Return link

```
0xbe0
0xbe4
0xbe8
0xbec
0xbf0
0xbf4
0xbf8
0xb??
```
### Pointers vs. References Summary

- **How to tell references and pointers apart**
  - Check if you see the `&` or `*` in a type declaration or expression

<table>
<thead>
<tr>
<th></th>
<th>With a Type</th>
<th>In an Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&amp;</code></td>
<td>Indicates a C++ Reference Var (int &amp;val, vector&lt;int&gt; &amp;vec)</td>
<td>Address-of yields a pointer to the object</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adds a * to the type of variable</td>
</tr>
<tr>
<td><code>*</code></td>
<td>Declares a pointer type variable (int *valptr = &amp;val, vector&lt;int&gt; *vecptr = &amp;vec)</td>
<td>De-Reference (Value @ address)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cancels a * from the type of variable</td>
</tr>
</tbody>
</table>
DYNAMIC ALLOCATION
Dynamic Memory & the Heap

- Code usually sits at low addresses
- Global variables somewhere after code
- System stack (memory for each function instance that is alive)
  - Local variables
  - Return link (where to return)
  - etc.
- Heap: Area of memory that can be allocated and de-allocated during program execution (i.e. dynamically at run-time) based on the needs of the program
- Heap grows downward, stack grows upward...
  - In rare cases of large memory usage, they could collide and cause your program to fail or generate an exception/error
Motivation

Automatic/Local Variables
• Deallocated (die) when they go out of scope
• As a general rule of thumb, they must be statically sized (size is a constant known at compile time)
  – int data[100];

Dynamic Allocation
• Persist until explicitly deallocated by the program (via ‘delete’)
  – Data lives indefinitely
• Can be sized at run-time
  – int size;
    cin >> size;
    int *data = new int[size];

(These are the 2 primary reasons to use dynamic allocation.)
C Dynamic Memory Allocation

• void* malloc(int num_bytes) function in stdlib.h
  – Allocates the number of bytes requested and returns a pointer to the block of memory
  – Use sizeof(type) macro rather than hardcoding 4 since the size of an int may change in the future or on another system

• free(void * ptr) function
  – Given the pointer to the (starting location of the) block of memory, free returns it to the system for re-use by subsequent malloc calls

```c
#include <iostream>
#include <cstdlib>
using namespace std;

int main(int argc, char *argv[])
{
    int num;
    cout << "How many students?" << endl;
    cin >> num;

    int *scores = (int*) malloc( num*sizeof(int) );
    // can now access scores[0] .. scores[num-1];

    free(scores);
    return 0;
}
```
C++ new & delete operators

• *new* allocates memory from heap
  – followed with the type of the variable you want or an array type declaration
    • double *dptr = new double;
    • int *myarray = new int[100];
  – can obviously use a variable to indicate array size
  – **returns a pointer of the appropriate type**
    • if you ask for a new int, you get an int * in return
    • if you ask for an new array (new int[10]), you get an int * in return

• *delete* returns memory to heap
  – followed by the pointer to the data you want to de-allocate
    • delete dptr;
  – use delete [] for pointers to arrays
    • delete [] myarray;
Dynamic Memory Allocation

```c
int main(int argc, char *argv[]) 
{ 
  int num;
  cout << "How many students?" << endl;
  cin >> num;
  int *scores = new int[num];
  // can now access scores[0] .. scores[num-1];
  return 0;
}
```

```c
int main(int argc, char *argv[]) 
{ 
  int num;
  cout << "How many students?" << endl;
  cin >> num;
  int *scores = new int[num];
  // can now access scores[0] .. scores[num-1];
  delete [] scores
  return 0;
}
```
Fill in the Blanks

• ________ data = new int;

• ________ data = new char;

• ________ data = new char[100];

• ________ data = new char*[20];

• ________ data = new vector<string>;

• ________ data = new Student;
Fill in the Blanks

- ________ data = new int;
  - int*
- ________ data = new char;
  - char*
- ________ data = new char[100];
  - char*
- ________ data = new char*[20];
  - char**
- ________ data = new vector<string>;
  - vector<string>*
- ________ data = new Student;
  - Student*
Dynamic Allocation

- **Dynamic Allocation**
  - Lives on the heap
    - Doesn't have a name, only pointer/address to it
  - Lives until you 'delete' it
    - Doesn't die at end of function (though pointer to it may)
- Let's draw the operation of `goodmul1()`

```c++
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation

- When `goodmul1()` exits, the out pointer goes out of scope
- Thus we need to return the pointer or save it somewhere so that there is a record of our allocation, otherwise we will have a leak

```
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation – Q1

• What happens if we comment the 'delete a' line?

```cpp
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    // delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation – A1

- What happens if we comment the 'delete a' line?
  - Memory LEAK!!

```
// Computes the product of in1 & in2
int* badmul1(int in1, int in2);
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid,len);
    cout << "Ans. is " << *a << endl;
    // delete a;
    return 0;
}

// Bad! Returns a pointer to a var. // that will go out of scope
int* badmul1(int in1, int in2)
{
    int out = in1 * in2;
    return &out;
}

// Good! Returns a pointer to a var. // that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    *out = in1 * in2;
    return out;
}
```

Stack Area of RAM

Heap Area of RAM

0x93c 40

MEMORY LEAK

No one saved a pointer to this data

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xbf0</td>
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</tr>
<tr>
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<td>5</td>
</tr>
<tr>
<td>0xbf8</td>
<td>-73249515</td>
</tr>
<tr>
<td>0xbfc</td>
<td>00400120</td>
</tr>
</tbody>
</table>
Dynamic Allocation – Q2

• What happens if we overwrite the only pointer to a dynamically allocated variable/object?

```cpp
// Computes the product of in1 & in2
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Good! Returns a pointer to a var. that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    out = new int; // another int
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation – A2

- What happens if we overwrite the only pointer to a dynamically allocated variable/object?
  - A memory leak
- Be sure you keep a pointer around somewhere otherwise you'll have a memory leak!

```c++
// Computes the product of in1 & in2
int* goodmul1(int in1, int in2);

int main()
{
    int wid = 8, len = 5;
    int *a = goodmul1(wid, len);
    cout << "Ans. is " << *a << endl;
    delete a;
    return 0;
}

// Good! Returns a pointer to a var.
// that will continue to live
int* goodmul1(int in1, int in2)
{
    int* out = new int;
    out = new int; // another int
    *out = in1 * in2;
    return out;
}
```
Dynamic Allocation

- The LinkedList object is allocated as a static/local variable
  - But each element is allocated on the heap
- When y goes out of scope only the data members are deallocated
  - You may have a memory leak

```cpp
// Computes rectangle area, // prints it, & returns it
struct Item {
    int val;  Item* next;
};
class LinkedList {
public:
    // create a new item
    // in the list
    void push_back(int v);
private:
    Item* head;
};

int main() {
    doTask();
}

void doTask() {
    LinkedList y;
    y.push_back(3);
    y.push_back(5);
    /* other stuff */
}
```
Dynamic Allocation

• The LinkedList object is allocated as a static/local variable
  – But each element is allocated on the heap
• When y goes out of scope only the data members are deallocated
  – You may have a memory leak

An Appropriate Destructor Will Help Solve This

Stack Area of RAM

Heap Area of RAM

```cpp
// Computes rectangle area, // prints it, & returns it
struct Item {
  int val;  Item* next;
};

class LinkedList {
  public:
    // create a new item
    // in the list
    void push_back(int v);
  private:
    Item* head;
};

int main()
{
  doTask();
}

void doTask()
{
  LinkedList y;
  y.push_back(3);
  y.push_back(5);
  /* other stuff */
}
```

MEMORY LEAK
When y is deallocated we have no pointer to the data

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If time allows

PRACTICE ACTIVITY 1
Warm Up Exercise

• Let’s trace this code. What does it do? Draw what is happening in stack and heap memory.

```cpp
#include <iostream>
using namespace std;

int main ()
{
    int stack_array[3][3];

    for (int i = 0; i < 3; i++)
    {
        for (int j = 0; j < 3; j++)
        {
            stack_array[i][j] = (i * 3) + j + 1;
        }
    }
}
```
Warm Up Exercise

• Let’s trace this code. What does it do? Draw what is happening in stack and heap memory.

```c
int **heap_array = new int *[9];

for (int i = 0; i < 9; i++)
{
    if (i / 3 == 1)
    {
        heap_array[i] = &stack_array[i/3][i%3];
    } else {
        heap_array[i] = new int;
    }
    *(heap_array[i]) = i + 11;
}
```
Warm Up Exercise

• Let’s trace this code. What is printed? What would be printed if we wanted to print the heap_array, instead?

```c++
for (int i = 0; i < 3; i++)
{
    for (int j = 0; j < 3; j++)
    {
        cout << stack_array[i][j] << " ";
    }
    cout << endl;
}
```
Warm Up Exercise

• What is wrong? We need to deallocate memory from heap to prevent memory leaks

```c
/* deallocate memory */
for (int i = 0; i < 9; i++)
{
    if (i/3 !=1)
        /* what happens if we do not check this?*/
        {
            delete heap_array[i];
        }
}
delete [] heap_array;
} /* end of main */
```
If time allows

PRACTICE ACTIVITY 2
Object Assignment

- Assigning one struct or class object to another will cause an element by element copy of the source data destination struct or class.

```cpp
#include<iostream>
using namespace std;

enum {CS, CECS};
struct student {
    char name[80];
    int id;
    int major;
};

int main(int argc, char *argv[]) {
    student s1;
    strncpy(s1.name,"Bill",80);
    s1.id = 5; s1.major = CS;
    student s2 = s1;
    return 0;
}
```
Memory Allocation Tips

- Take care when returning a pointer or reference that the object being referenced will persist beyond the end of a function
- Take care when assigning a returned referenced object to another variable...you are making a copy
- Try the examples yourself
  - $ wget http://ee.usc.edu/~redekopp/cs104/memref.cpp
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data?

**ex1**
```cpp
class Item
{
    public:
        Item(int w, string y);
};
Item buildItem()
{
    Item x(4, "hi");
    return x;
}
int main()
{
    Item i = buildItem();
    // access i’s data.
}
```

**ex2**
```cpp
class Item
{
    public:
        Item(int w, string y);
};
Item& buildItem()
{
    Item x(4, "hi");
    return x;
}
int main()
{
    Item& i = buildItem();
    // access i’s data
}
```

**ex3**
```cpp
class Item
{
    public:
        Item(int w, string y);
};
Item* buildItem()
{
    Item* x = new Item(4, "hi");
    return x;
}
int main()
{
    Item* i = buildItem();
    // access i’s data
}
```
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data

ex4

```cpp
class Item
{ public:
    Item(int w, string y);
};
Item* buildItem()
{ Item x(4, "hi");
    return &x;
}
int main()
{ Item *i = buildItem();
    // access i’s data
}
```

ex5

```cpp
class Item
{ public:
    Item(int w, string y);
};
Item& buildItem()
{ Item* x = new Item(4,"hi");
    return *x;
}
int main()
{ Item& i = buildItem();
    // access i’s data
}
```
Understanding Memory Allocation

class Item
{ public:
    Item(int w, string y);
};
Item& buildItem()
{ Item* x = new Item(4, "hi");
    return *x;
}
int main()
{ Item i = buildItem();
    // access i's data.
}
SOLUTIONS
Review of Pointers in C/C++

• Pointer (type *)
  – Really just the memory address of a variable
  – Pointer to a data-type is specified as type * (e.g. int *)
  – Operators: & and *
    • &object => address-of object (Create a link to an object)
    • *ptr => object located at address given by ptr (Follow a link to an object)
    • *(&object) => object [i.e. * and & are inverse operators of each other]

• Example: Indicate what each line prints or what variable is modified. Use NA for any invalid operation.

```c
int * p, *q;
int i, j;
i = 5; j = 10;
p = &i;
cout << p << endl;
cout << *p << endl;
*p = j;
*q = *p;
q = p;
```

```
0xbe0 0xbe4 0xbe8 0xbec
 p q i j
```

```
0xbe0 0xbe8
 p
```

```
0xbe8
5
```

```
0xbe8
10
```

```
0xbe8
Undefined
```

```
0xbe4 0xbe8
q
```
Check Yourself

• Consider these declarations:
  – int k, x[3] = {5, 7, 9};
  – int *myptr = x;
  – int **ourptr = &myptr;

• Indicate the formal type that each expression evaluates to (i.e. int, int *, int **)

To figure out the type of data a pointer expression will yield...
• Each * in the expression cancels a * from the variable type.
• Each & in the expression adds a * to the variable type.

<table>
<thead>
<tr>
<th>Orig. Type</th>
<th>Expr</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>myptr = int*</td>
<td>*myptr</td>
<td>int</td>
</tr>
<tr>
<td>ourptr = int**</td>
<td>**ourptr</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>*ourptr</td>
<td>int*</td>
</tr>
<tr>
<td>k = int</td>
<td>&amp;k</td>
<td>int*</td>
</tr>
<tr>
<td></td>
<td>&amp;myptr</td>
<td>int**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;x[0]</td>
<td>int*</td>
</tr>
<tr>
<td>x</td>
<td>int*</td>
</tr>
<tr>
<td>myptr</td>
<td>int*</td>
</tr>
<tr>
<td>*myptr</td>
<td>int</td>
</tr>
<tr>
<td>(*ourptr) + 1</td>
<td>int*</td>
</tr>
<tr>
<td>myptr + 2</td>
<td>int*</td>
</tr>
<tr>
<td>&amp;ourptr</td>
<td>int***</td>
</tr>
</tbody>
</table>
Argument Passing Examples

- Pass-by-value => Passes a copy
- Pass-by-reference =>
  - Pass-by-pointer/address => Passes address of actual variable
  - Pass-by-reference => Passes an alias to actual variable (likely its really passing a pointer behind the scenes but now you don't have to dereference everything)

```cpp
int main()
{
    int x=5, y=7;
    swapit(x, y);
    cout <<"x,y=" << x <<"," << y << endl;
}

void swapit(int x, int y)
{
    int temp;
    temp = x;
    x = y;
    y = temp;
}
```

program output: x=5,y=7

```cpp
int main()
{
    int x=5, y=7;
    swapit(&x, &y);
    cout <<"x,y=" << x <<"," << y << endl;
}

void swapit(int *x, int *y)
{
    int temp;
    temp = *x;
    *x = *y;
    *y = temp;
}
```

program output: x=7,y=5

```cpp
int main()
{
    int x=5, y=7;
    swapit(x, y);
    cout <<"x,y=" << x <<"," << y << endl;
}

void swapit(int &x, int &y)
{
    int temp;
    temp = x;
    x = y;
    y = temp;
}
```

program output: x=7,y=5
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data?

**ex1**
```cpp
class Item
{
public:
    Item(int w, string y);
};
Item buildItem()
{
    Item x(4, "hi");
    return x;
}
int main()
{
    Item i = buildItem();
    // access i's data.
}
```

**ex2**
```cpp
class Item
{
public:
    Item(int w, string y);
};
Item& buildItem()
{
    Item x(4, "hi");
    return x;
}
int main()
{
    Item& i = buildItem();
    // access i's data
}
```

**ex3**
```cpp
class Item
{
public:
    Item(int w, string y);
};
Item* buildItem()
{
    Item* x = new Item(4,"hi");
    return x;
}
int main()
{
    Item* i = buildItem();
    // access i's data
}
```

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data:

- **ex1**
- **ex2**
- **ex3**
Understanding Memory Allocation

There are no syntax errors. Which of these can correctly build an Item and then have main() safely access its data?

**ex4**

class Item
{
    public:
        Item(int w, string y);
};
Item* buildItem()
{
    Item x(4, "hi");
    return &x;
}
int main()
{
    Item *i = buildItem();
    // access i’s data
}

**ex5**

class Item
{
    public:
        Item(int w, string y);
};
Item& buildItem()
{
    Item* x = new Item(4,"hi");
    return *x;
}
int main()
{
    Item& i = buildItem();
    // access i’s data
}
class Item
{
    public:
        Item(int w, string y);
    }
Item& buildItem()
{ Item* x = new Item(4, "hi");
    return *x;
}
int main()
{ Item i = buildItem();
    // access i’s data.
}

ex6

ex7

ex8