CS-202

Dynamic Memory (Pt.1)

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Course Week

Course , Projects , Labs:

Monday	Tuesday	Wednesday	Thursday	Friday		Sunday
			Lab (8 Sections)			
	CLASS		CLASS			
PASS Session	PASS Session	**Project DEADLINE**	NEW Project	PASS Session		PASS Session

Your 7th Project will be announced on Thursday 3/28.

- PASS Sessions will resume on Friday, get all the help you need!
- Always check out **WebCampus** CS-202 Samples for some **help** !

Today's Topics

Memory Storage – (Basics)

- Automatic
- Static
- Dynamic

Program Memory

- Stack
- Heap

Program Memory Management

- Expression `new` (`[ ]`)
- Expression `delete` (`[ ]`)

Program Data

Automatic Storage Duration:

Reside in activation frame of the function, destroyed when returning from function. Automatically created at function entry.

- Objects declared at function Block Scope.
- Objects declared in function Parameter Lists.

Note:

- Storage specifier `auto` was sometimes used in older standards to declare such storage duration:
  e.g. `auto int myIntVal;` instead of: `register int myIntVal;`

Attention:

- From C++11 and onwards, these are deprecated and `auto` is used as a type deduction specifier:
  e.g. `auto myVal;`

Program Data

Static Storage Duration:

Memory allocation takes place at compile-time before the associated program is executed.
Static memory storage covers the entire program lifetime.

- All objects declared at namespace scope (including the global namespace).
- Only one instance of the object exists.

Usual examples:

- Global variables.
- `static` local variables (in functions).
- `static` member variables (in Classes).
- Virtual Function Tables (Polymorphism).

Note (Twice-Initialized case of `static` variables):

- Allocated at program start & "early 0-initialized", (i.e. before any other initialization takes place.
- Initialized (actual value-based initialization or constructor call) by program the fist time they are encountered in translation unit.

Program Data

Dynamic Storage Duration:

Explicit programmer-made allocation / deallocation calls in C++.
Allocated and deallocated at run-time per-request.

- Usage of C++ Memory Management Functions.

Usual examples:

- `operator new` (`[]`).
- `operator delete` (`[]`).

Low-level C++ Memory Management

Note: Well-known C-style memory management functions are now part of the `<cstdlib>` header:

- `void * std::malloc(std::size_t)` , `void * std::calloc(std::size_t,std::size_t)`
- `void std::free(void *)` , `void* std::realloc(void *, std::size_t)`

Program Data

Thread–Local Storage Duration (not to our interest at this point):

Allocated when a thread begins and deallocated when that thread ends.

- Each thread has its own instance of the object.

More information and complete reference:

- http://en.cppreference.com/w/cpp/language/storage_duration

Complete reference on:

- Storage Specifiers & Storage Duration.
- Storage Specifiers & Linkage.

Memory Management

Memory Allocation

Static Allocation:

Management of memory (De)-Allocation predescribed at compile-time.

- (*Remember*: "*Static*" binding – means it takes place at compile-time).

Dynamic Allocation:

Management of memory (De)-Allocation performed at run-time.

- (*Remember*: "*Dynamic*" binding – means it takes place at run-time).

Memory Allocation

Static Allocation

Static Allocation is handled automatically (implicitly) at compile-time.

- Global variables or objects:
  Memory allocated (actually loaded) at the start of the program, and `free`'d when program exits; alive throughout program.
  Note: Actually, these live in the Initialized/Uninitialized Data (`.data`) Segments.
  Direct address-based accessing can be guaranteed to succeed from anywhere in the program.
- Local variables (inside a function Block Scope – the `main()` included):
  Memory allocated when function starts and `free`'d when the function `return`s.
  Local variables cannot be accessed from outside the function Block Scope.

Static Allocation

Static Allocation is handled $\boxed{\text{automatically (implicitly)}}$ at compile-time.

- No need to provide explicit handling for memory management.
- Easy to work with, but with certain limitations.

With *Static* Allocation, all variable / object storage must also be known at compile-time.

- Necessary to have known-Composition data types (Class/Struct members etc.).
- Necessary to have fixed-size arrays (of some `MAX_SIZE` dimensions).
- Simple counter-point against it: What about a container that needs to grow (and potentially shrink) to the program's needs ?

The Stack

The Stack is part of the Program Virtual Memory. It is used to hold all necessary information about the active functions (at run-time).

- This includes its Local Variables (as well as parameters, return address, etc.)
- All Local Variables will take up space from the Stack.

Do(s):

- Very fast memory allocation (but strict size limitations – Thread creation / O.S. limitations / etc.)
- Use for short-lived and "small" data:

```
if (condition){
    double dArr[5];
    /* dArr manipulations */
} /* dArr out of scope, free'd */
```

Auto storage duration (braced Block Scope), allocated on Stack.

The Stack

The Stack is part of the Program Virtual Memory. It is used to hold all necessary information about the active functions (at run-time).

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- All Local Variables will take up space from the Stack.

Don’t(s):

- Stack Memory serves program functionality (also known as “Call Stack”).
- Superseding Stack Memory limitations can cause Stack Overflow:

```
void myFunction(){
    double dArr[100*100*100];
    /* possible stack overflow */
}
```

Auto storage duration (function Block Scope), allocated on Stack.

Memory Allocation

Dynamic Allocation

Dynamic Allocation is handled by the programmer (explicitly) at run-time.

- Programmer explicitly requests Allocation of a specific size memory from the system.
- System `return`s the starting address of the allocated memory chunk. This address can be used to access the allocated memory.

With *Dynamic* Allocation, the data structure/container sizes (e.g. array size) can adjust to the program needs at run-time.

- When memory is no longer required it should be explicitly Deallocated (`free`'d).

The Heap

The Heap is a special Virtual Memory part, “unused” by the Program functions and reserved for dynamically allocated objects / variables.

- All `new` Dynamically Allocated Variables will consume memory in the Heap.
- Future `new` allocations will fail if the memory becomes full.

Do(s):
- Significantly slower memory allocation than Stack.
- But Gbytes to work with – also called “Freestore”.
- Use for “Big” data.
- Use for Dynamic data.

The Heap

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- All `new` Dynamically Allocated Variables will consume memory in the Heap.
- Future `new` allocations will fail if the memory becomes full.

Don't(s):

- Forget to check if the dynamic memory allocation request succeeded.
- Forget to explicitly free any memory explicitly allocated.
- Even with Gbytes available, an HD-resolution camera image capture while loop can clutter the computer memory in less than a minute, if the allocated memory for each image is not properly deallocated at each loop.

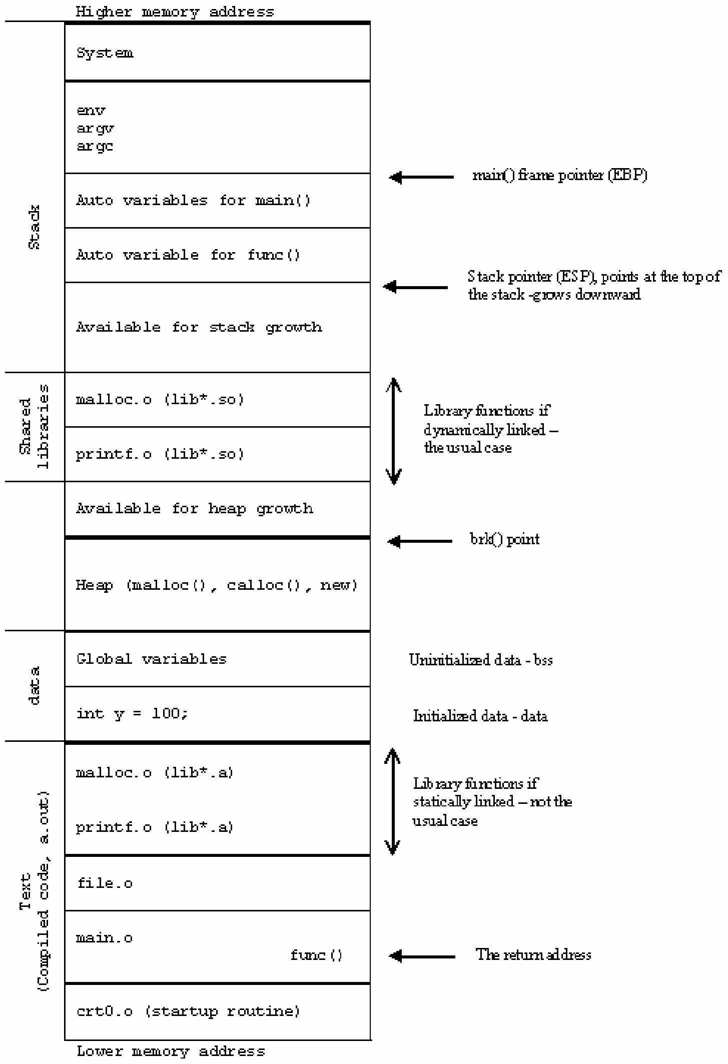
Memory Allocation

Program Memory

Overview of Program Memory Sections
(bottom-up from lower to higher Addresses)

- Compiled Text Section
- Data Section (BSS , Data)
- Dynamic Memory (**Heap**, Linked Libraries)
- **Stack** Memory

Note:
NULL is the `0` Address of the Virtual Memory.



The Basics

There is no named Object / Variable : All work is done on a Pointer-basis.

- Allocation reserves memory space.
- Address of reserved space is returned.
- Marked as "containing a specific data type" (**int**, **double**, **struct**, **class**, arrays, etc.)

Operator **new** dynamically Allocates memory space.

```
void * operator new (std::size_t count);
void * operator new [] (std::size_t count);
```

Operator **delete** can free-up this space (Deallocate memory) later on.

```
void operator delete (void * ptr);
void operator delete [] (void * ptr);
```

Dynamic Memory Allocation

The `new` (`[ ]`) *Expression*

Uses `operator new` (`[ ]`) to allocate memory space for the requested object / array type and size, and `return`s a Pointer-to (Address-of) the memory allocated.

- Pointer type as per requested type, marks what the memory contains.
- If sufficient memory is not available, the new operator returns `NULL` (not quite anymore, but let's say so for right now…)
- The dynamically allocated object/array will persist through the program lifetime (memory will be reserved by it) until explicitly deallocated (i.e. by a `delete` *Expression*).

Dynamic Memory Allocation

The new ([ ]) *Expression*

Allocation of a single variable / object or an array of variables / objects.

Syntax:

`<type_id> * new <type_id_ctor>` (`[SIZE]` : optional)

Examples:

```
char * myChar_Pt = new char;
int * myIntArr_Pt = new int [20];
MyClass * myClass_Pt = new MyClass("mine",1,true);
MyClass * myClassArr_Pt = new MyClass [100];
```

- Simple-type variable.
- Simple-type variable array.
- Class-type instantiation in allocated memory.

Notes:

Before the assignment, the Pointer may or may not point to a “legitimate” memory.
After the assignment, the pointer points to a “legitimate” memory.

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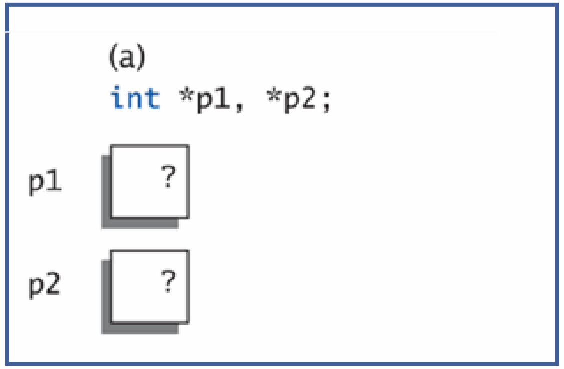
Dynamic Memory Allocation

The new ([ ]) *Expression*

```
//Program to demonstrate pointers and dynamic variables.
#include <iostream>
using std::cout;
using std::endl;

int main( )
{
    int *p1, *p2;

    p1 = new int;
    *p1 = 42;
    p2 = p1;
    cout << "*p1 == " << *p1 << endl;
    cout << "*p2 == " << *p2 << endl;

    *p2 = 53;
    cout << "*p1 == " << *p1 << endl;
    cout << "*p2 == " << *p2 << endl;
    p1 = new int;
    *p1 = 88;
    cout << "*p1 == " << *p1 << endl;
    cout << "*p2 == " << *p2 << endl;

    return 0;
}
```

SAMPLE DIALOGUE

```
*p1 == 42
*p2 == 42
*p1 == 53
*p2 == 53
*p1 == 88
*p2 == 53
```



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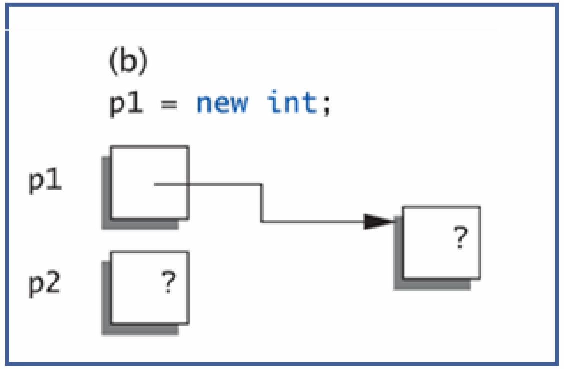

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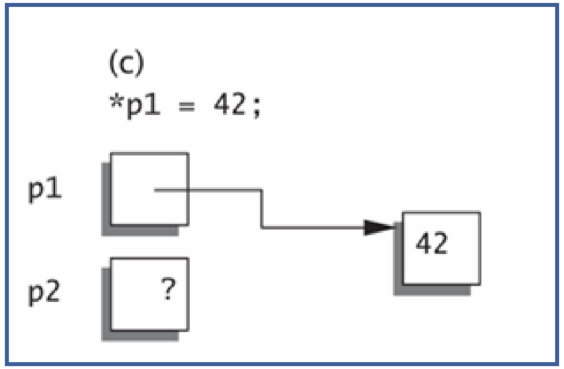

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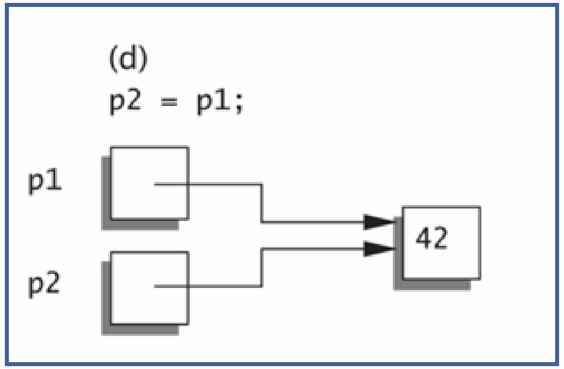

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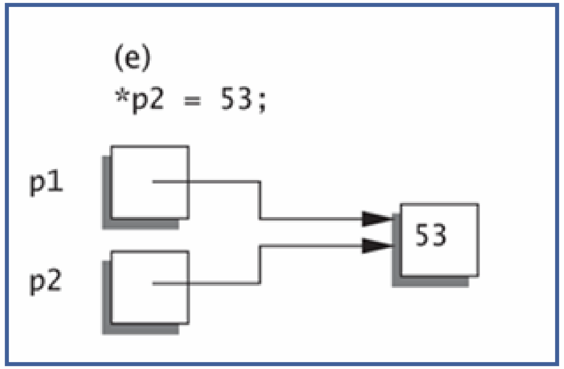

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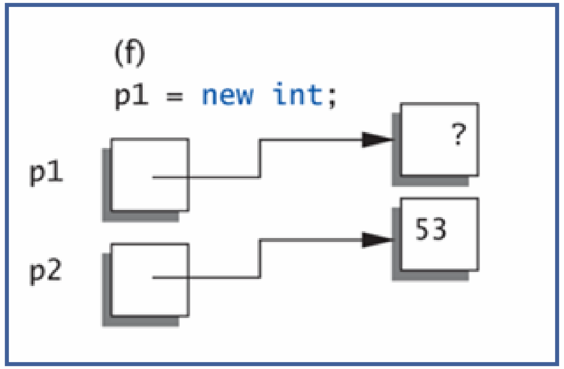

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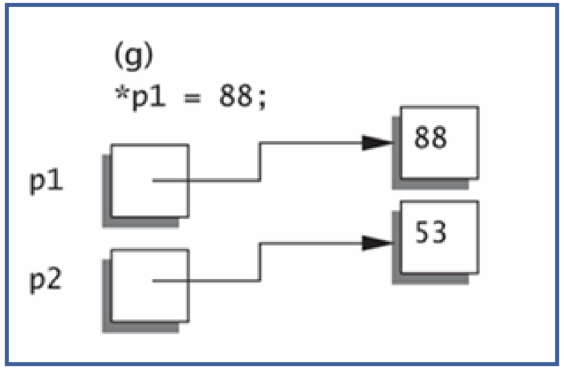

The `delete` (`[ ]`) *Expression*

Uses `operator delete` (`[ ]`) to Deallocate the object / array pointed-to by a pointer, which was the run-time result of a previous `new` *Expression*.

- Memory is `free`'d and returned to the Heap.
- Pointer is to be considered *invalid*:
  (According to C++ Standard, 3.7.3.2/4 - the deallocation function will render invalid all pointers referring to all parts of deallocated storage)
- If the value of the pointer is `NULL`, then `delete` has no effect
  (and it is safe to call).

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- After `delete` is called on a memory region, it should no longer be accessed by the program.
  Note: Otherwise, the result is Undefined Behavior (best hope is Segmentation Fault !).
- Convention is to set (/"mark") pointer to `delete`'d memory to `NULL`.
- Every `new` must have a corresponding `delete`.
  Note: Otherwise, the program has memory leak.
- `new` and `delete` may not be in the same routine.
  Note: But have to be properly sequenced during program execution.

The delete ([ ]) *Expression*

Uses **operator delete** ([ ]) to deallocate the object / array pointed-to by a pointer, which was the run-time result of a previous **new** *Expression*.

- Called on a Pointer to dynamically allocated memory when it is no longer needed (only **new**'ed objects / variables can be **delete**'d).

```
int globInt, globIntArr[5];
int main(){
  int locInt, locIntArr[5];
  int * int_Pt;
  int_Pt = &locInt;          delete intPt;
  int_Pt = &locIntArr;       delete [] intPt;
  int_Pt = &globInt;         delete intPt;
  int_Pt = &globIntArr;      delete [] intPt;
  return 0;
}
```

- Segmentation Fault

Trying to free non-dynamic (local variable, auto storage).

- Invalid Pointer Free

Memory address of global.

The delete ([ ]) *Expression*

Can delete a single object/variable or an array of objects/variables.

Syntax:

```
delete <ptr_name> ([ ] : optional)
```

Examples:

```
int * myInt_Pt = new int;
delete myInt_Pt;
char * myChar_Pt = new char [255];
delete [] myChar_Pt;

MyClass * myClass_Pt = new MyClass("mine", 1, true);
delete myClass_Pt;
MyClass * myClassArr_Pt = new MyClass [100];
delete [] myClassArr_Pt;
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```

The delete ([ ]) Expression

Deleting an object/variable.

By-example:

```
int * ptr;
ptr = new int;
*ptr = 22;
cout << *ptr << endl;
delete ptr;
ptr = NULL;
```

ptr

Address	Value
FDE0	???
FDE1	
FDE2	
FDE3	
⋮	⋮
0EC4	
0EC5	
0EC6	
0EC7	

The `delete` (`[ ]`) Expression

Deleting an object/variable.

By-example:

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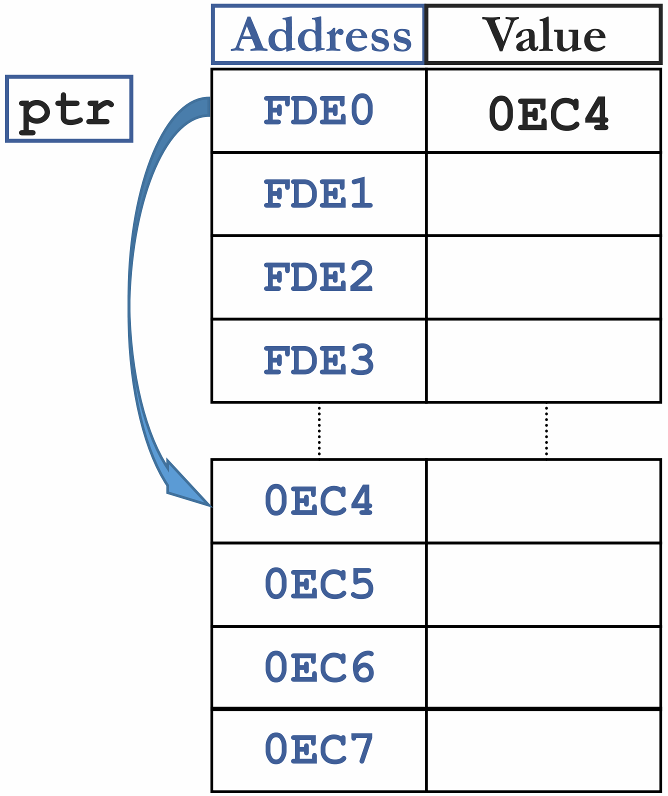

Dynamic Memory Allocation

The delete ([ ]) Expression

Deleting an object/variable.

By-example:

```
int * ptr;
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*ptr = 22;
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```

ptr

Address	Value
FDE0	0EC4
FDE1	
FDE2	
FDE3	
0EC4	22
0EC5	
0EC6	
0EC7	

The delete ([ ]) Expression

Deleting an object/variable.

By-example:

```
int * ptr;
ptr = new int;
*ptr = 22;
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delete ptr;
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```
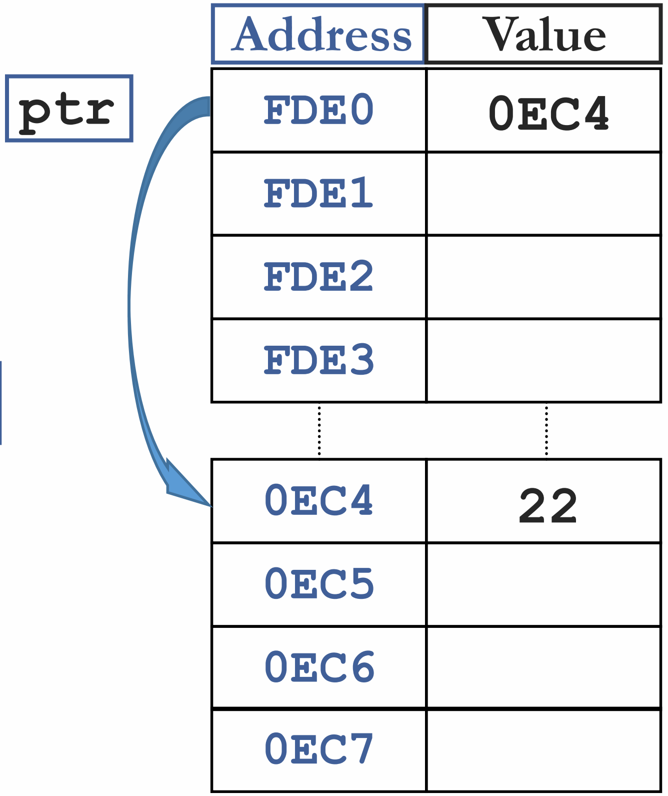

Output: 22



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By-example:

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ptr = NULL;
```

Note:
Value after **delete** depends on implementation
(not specified by the C++ Standard)

ptr

Address	Value
FDE0	?
FDE1	
FDE2	
FDE3	
⋮	⋮
0EC4	
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Dynamic Memory Allocation

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Deleting an object/variable.

By-example:

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```

Note:
We will be (re)setting pointer value to **NULL**
(by-Convention after **delete** *Expression*)

ptr

Address	Value
FDE0	0
FDE1	
FDE2	
FDE3	
⋮	⋮
0EC4	
0EC5	
0EC6	
0EC7	

Dynamic Arrays

Remember: **Variable-Length Arrays (VLAs) are only an *Extension***

- A C++ (non-Standard) extension by GCC

```
const int start, end;
… // possible manipulation of start, end, etc.
double dNumbers[(start + end) / 2];
```

Hint: Try compiling with **`-pedantic`**

Note:
Non-constant expression used for size

By the GNU Compiler Collection – Online Docs
(http://gcc.gnu.org/onlinedocs/gcc/Variable-Length.html)

- Variable-length automatic arrays are allowed in ISO C99, and as an extension GCC accepts them in C90 mode and in C++. These arrays are declared like any other automatic arrays, but with a length that is not a constant expression. The storage is allocated at the point of declaration and deallocated when the block scope containing the declaration exits.

Dynamically Allocated Array

The **[IntExp]** Array-variant of the **new** *Expression* can be used to allocate arrays of objects/variables in Dynamic Memory.

```
char * myString = new char [255];
Car * myInventory = new Car [100];
```

Then **[IntExp]** Array-variant of the **delete** *Expression* can be used to indicate that an array of objects is to be Deallocated.

```
delete [] myString;
delete [] myInventory;
```

Note: Use Simple-variant or Array-variant properly (on an array).
Otherwise the C++ Standard gives Undefined Behavior.

Dynamically Allocated Array

By-Example:

```
int * grades = NULL;
int numberOfGrades;

cout << "Enter the number of grades: ";
cin >> numberOfGrades;

grades = new int[ numberOfGrades ];

for (size_t i = 0; i < numberOfGrades; ++i)
{   cin >> grades[i];   }

for (size_t j = 0; j < numberOfGrades; ++j)
{   cout << grades[j] << " ";   }

delete [] grades;
grades = NULL;
```

Dynamically Allocated Array

By-Example:

```
int * grades = NULL;
int numberOfGrades;

cout << "Enter the number of grades: ";
cin >> numberOfGrades;
grades = new int[ numberOfGrades ];
for (size_t i = 0; i < numberOfGrades; ++i)
{  cin >> grades[i];  }
for (size_t i = 0; i < numberOfGrades; ++i)
{  cout << grades[i] << " ";  }
delete [] grades;
grades = NULL;
```

Array size is determined during run-time!

Dynamically Allocated 2D Array

A two-dimensional array is an array of arrays (e.g. rows).

To dynamically allocate a 2D array, a double pointer is used.

- A pointer to a pointer.

```
<type_id> ** myMatrix;
```

Example: For a 2D integer array:

```
int ** intMatrix;
```

Dynamically Allocated 2D Array

Memory allocation the 2D array with **rows** rows and **cols** columns:

- Allocate an array of pointers:
  (these will be used to point to the sub-arrays – i.e. the rows)

```
int ** intMatrix = new int * [rows];
```

  This creates space for **rows** number of Addresses (each element is an **int ***).

- Then allocate the space for the 1D arrays (i.e. the rows) themselves, each with a size of **cols**.

```
for (size_t i=0; i<rows; ++i)
  intMatrix[i] = new int [cols];
```

Dynamically Allocated 2D Array

The elements of the 2D array can still be accessed by the notation:

```
intMatrix[i][j];
```

Note: The entire array is *NOT* (guaranteed to be) in contiguous space.
Unlike a statically allocated 2D array!

- Each row sub-array is contiguous in memory.
- But the sequence of rows is not.

`intMatrix[i][j+1]` is after `intMatrix[i][j]` in memory.

`intMatrix[i+1][0]` may be before or after `intMatrix[i][0]` in memory.

Dynamically Allocated 2D Array

By-Example:

```
int rows, cols;
int ** intMatrix;

cin >> rows >> cols;
```

```
a) intMatrix = new int * [rows];
b) for (size_t i=0; i<rows; ++i)
     intMatrix[i] = new int [cols];
```

Allocation:

a) Rows array of pointers first.

b) Each row sub-array then.

```
c) for (size_t i=0; i<rows; ++i)
     delete [] intMatrix[i];
d) delete [] intMatrix;
```

Deallocation:

c) Each row sub-array first.

d) Rows array of pointers last.

CS-202

Time for Questions !