# CS-202

# Dynamic Memory (Pt.1)

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# Course Week

## Course , Projects , Labs:

| Monday | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|
| | | | Lab (9:00-12:50) | |
| | CLASS | | CLASS | |
| PASS Session | PASS Session | **Project DEADLINE** | NEW Project | |

Your 6th Project Deadline is this Wednesday 10/25.

- PASS Sessions held Monday-Tuesday, get all the help you may need!
- 24-hrs delay after Project Deadline incurs 20% grade penalty.
- Past that, NO Project accepted. Better send what you have in time!

# 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;`

Attention:
- From C++11 and onwards, auto is used as 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 now):

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 Allocation

*Static* Allocation:

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

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

*Dynamic* Allocation:

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

- (*Remember*: *Dynamic* binding – 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.

# Memory Allocation

**Static Allocation**

*Static* Allocation is handled 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 (brace 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).

- This includes its Local Variables (as well as parameters, return address, etc.)
- 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.

## 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.

# Memory Allocation

## 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.

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.

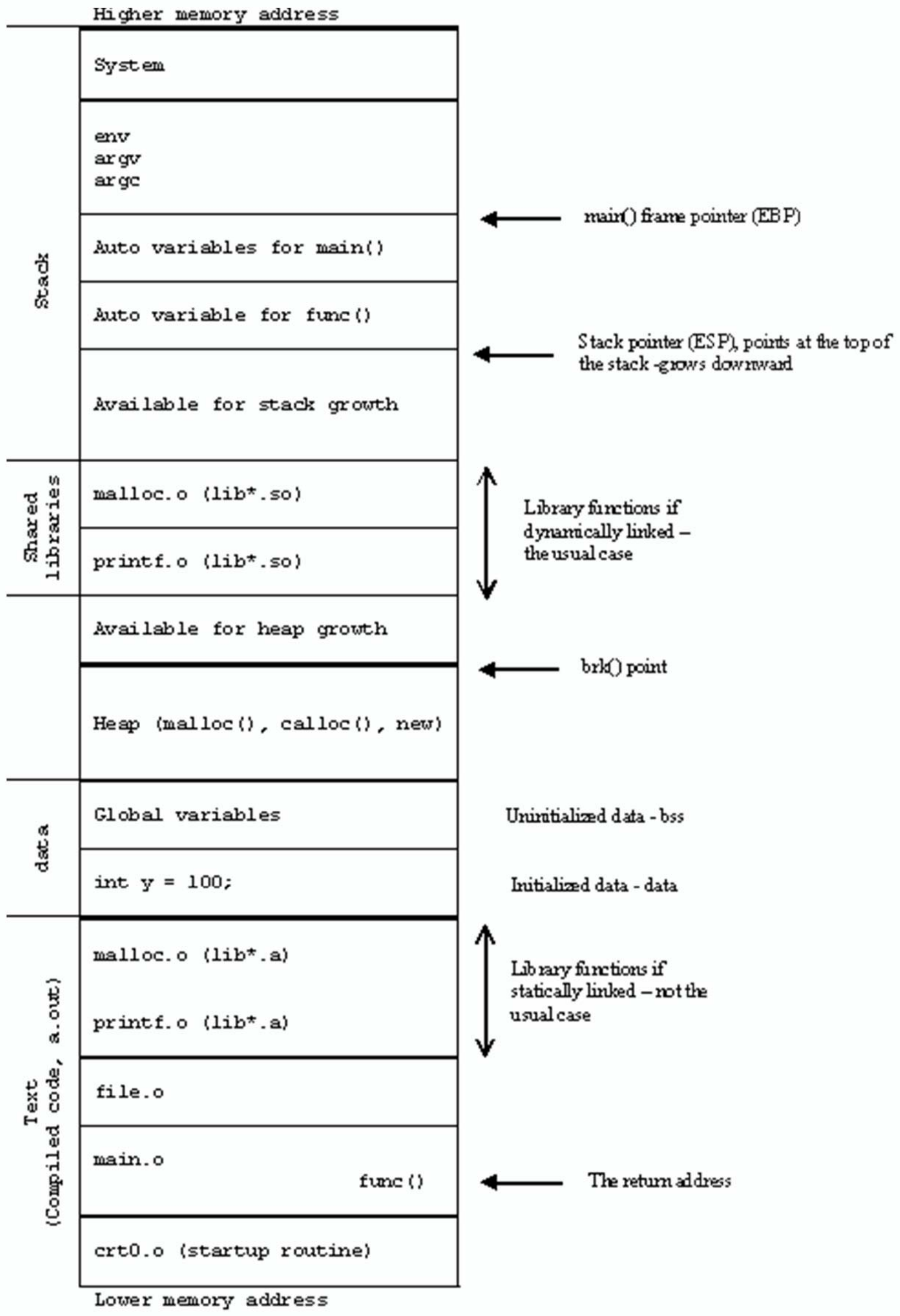
# Memory Allocation

## 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.



# Dynamic Memory Allocation

## 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` (let's say so for 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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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.

## The new ( [ ] ) Expression

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


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

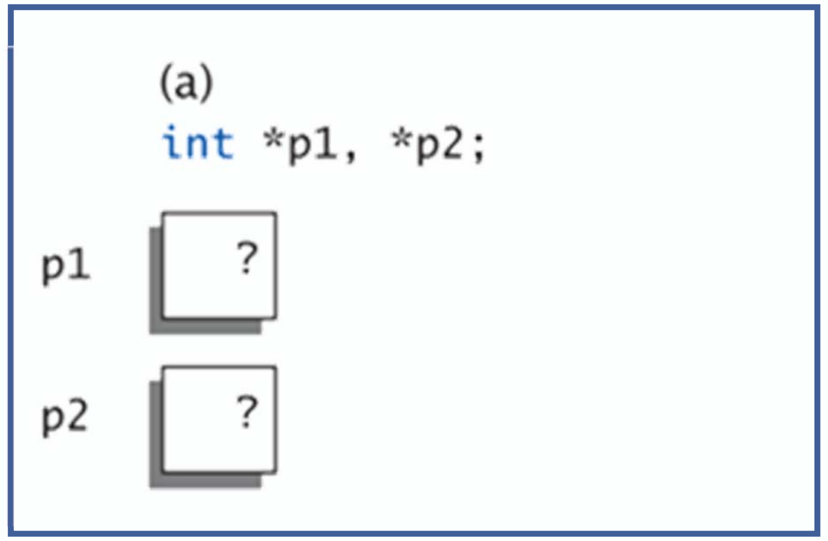
    p1 = new int;
    *p1 = 42;
    p2 = p1;
    cout << "*p1 == " << *p1 << endl;
    cout << "*p2 == " << *p2 << endl;

    *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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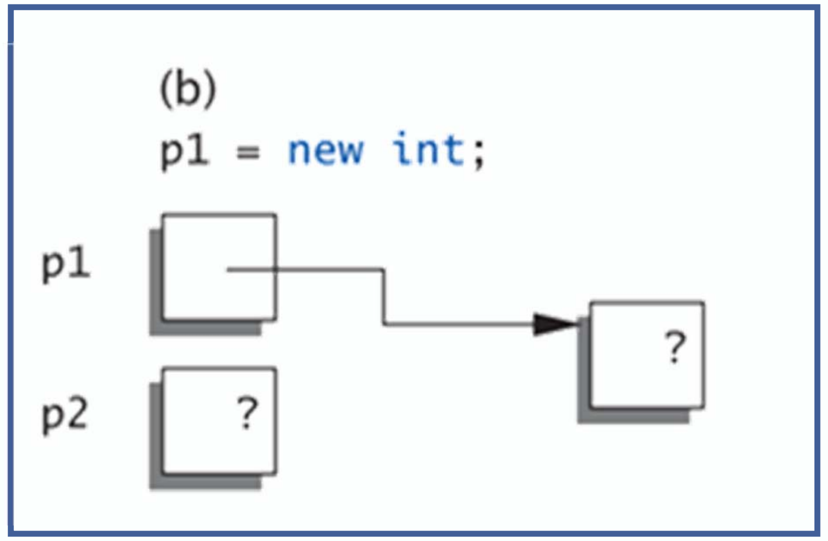

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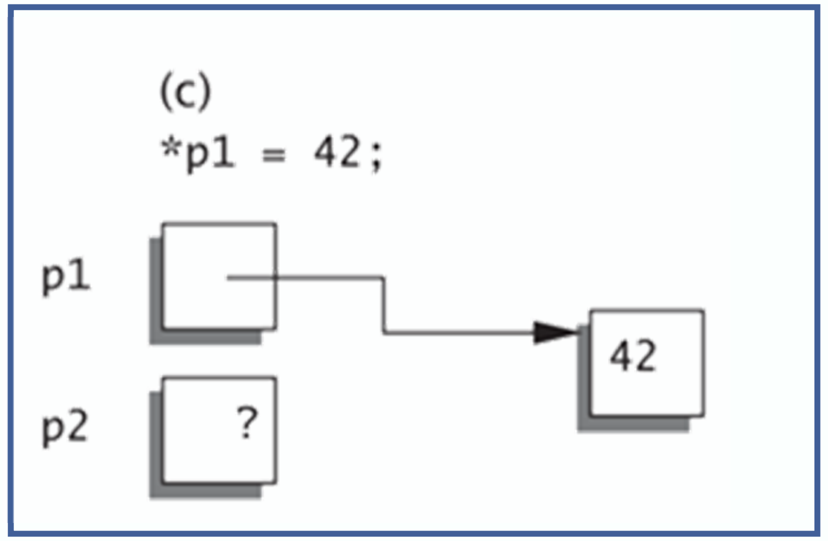

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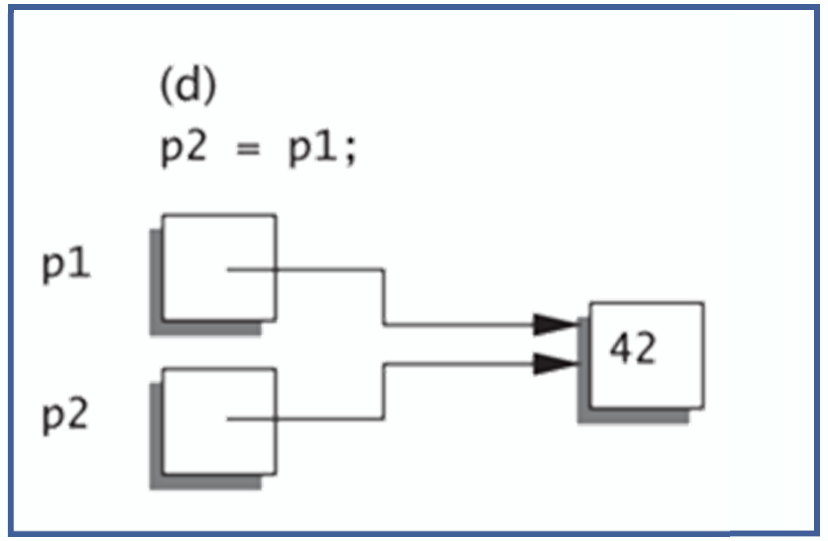

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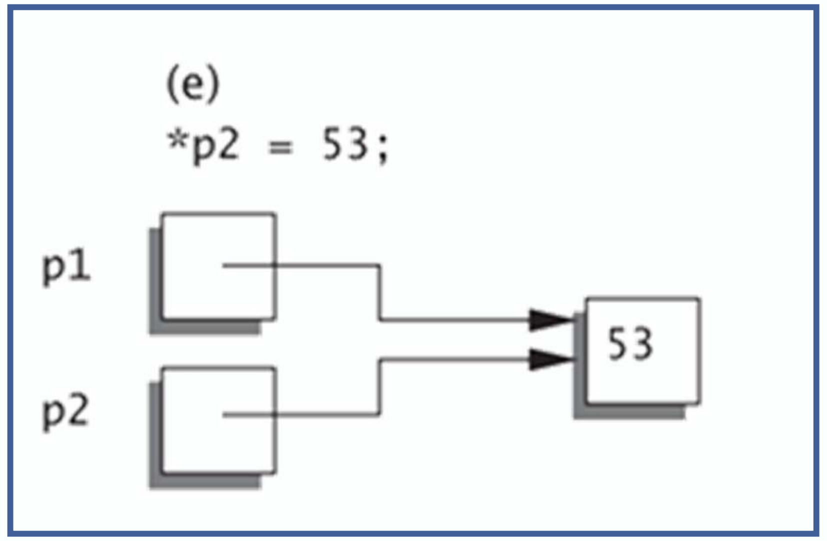

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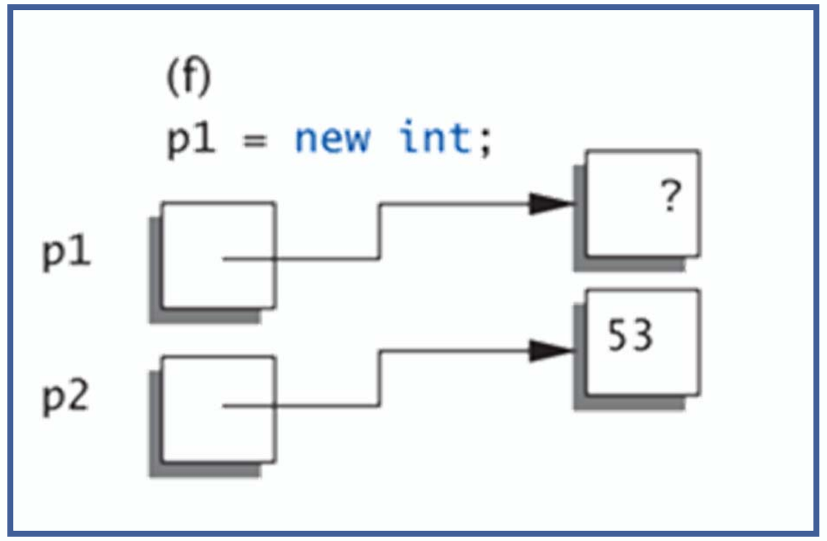

# Dynamic Memory Allocation

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}
```

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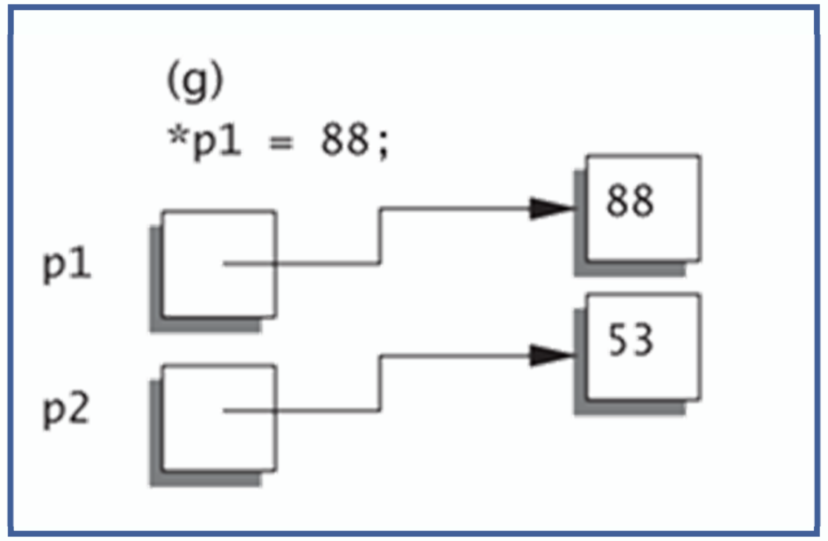

## The `delete` (`[ ]`) Expression

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 considered unassigned.
- If the value of the pointer is `NULL`, then `delete` has no effect (and it is safe to call).

# Dynamic Memory Allocation

## 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.

- After `delete` is called on a memory region, it should no longer be accessed by the program.
  Note: Otherwise, the result will be a 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.

# Dynamic Memory Allocation

## 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;
  int_Pt = &locIntArr;
  int_Pt = &globInt;
  int_Pt = &globIntArr;
  return 0;
}
```

```
delete intPt;
delete [] intPt;
```

- Segmentation Fault

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

```
delete intPt;
delete [] intPt;
```

- 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;
```

## 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 | |

# Dynamic Memory Allocation

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

Deleting an object/variable.

By-example:

```
int *ptr;
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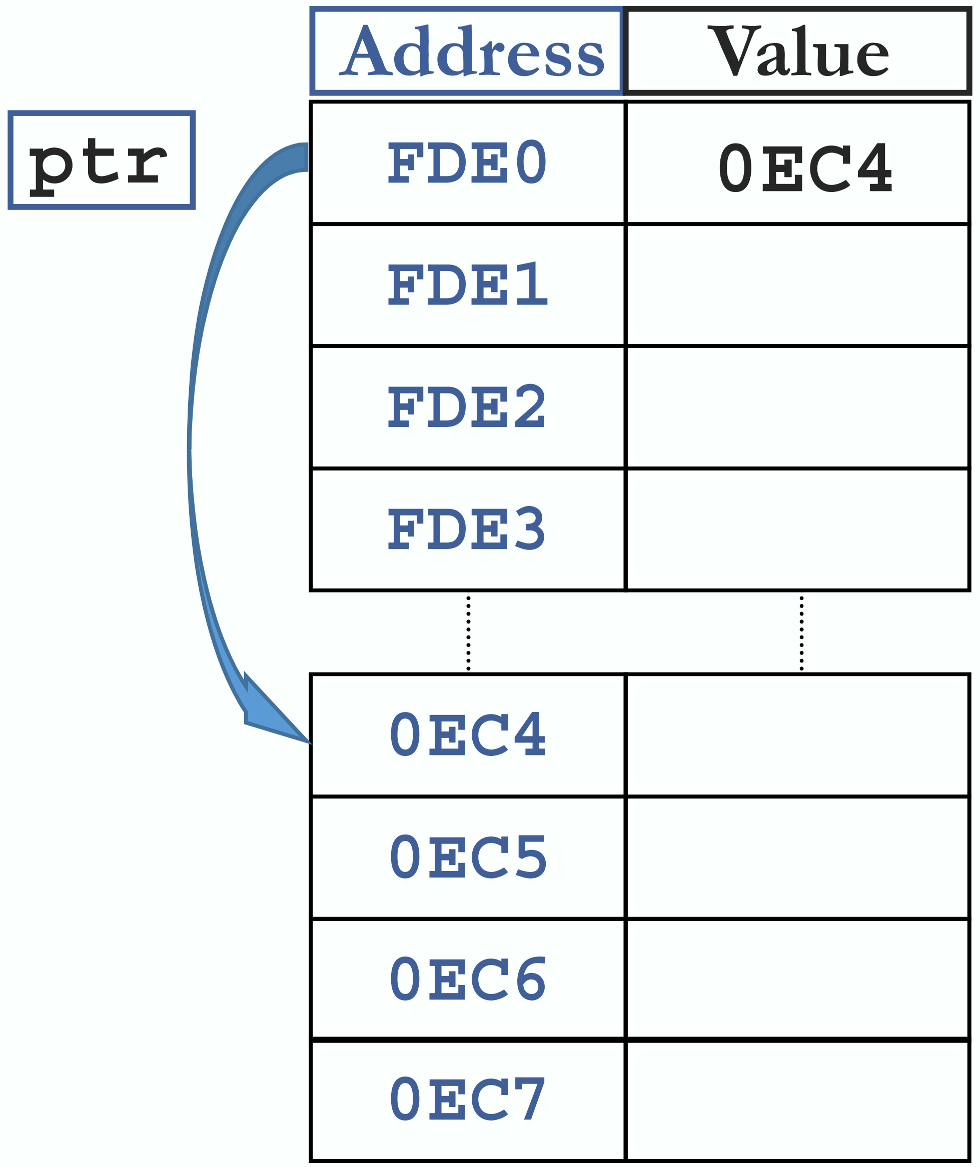
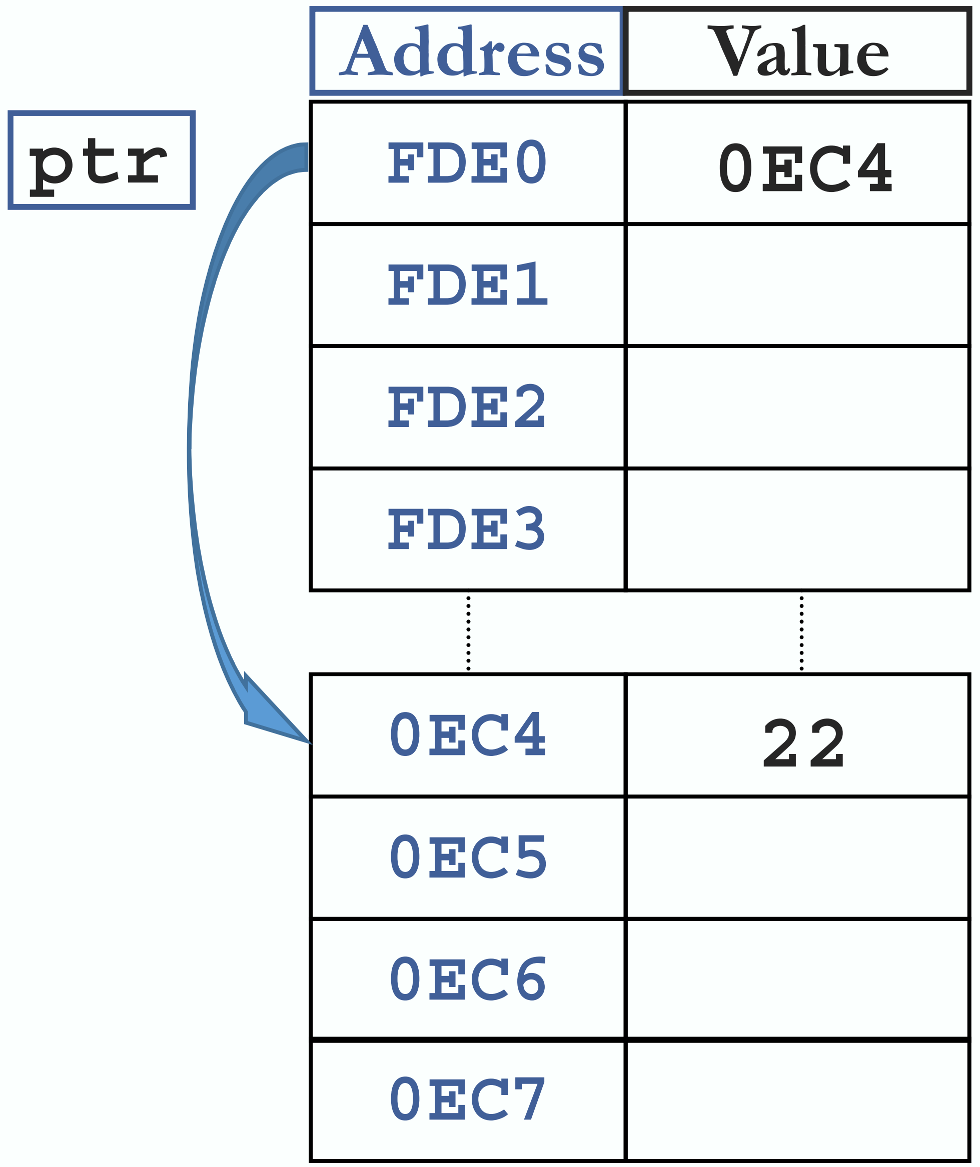


## The delete ([ ]) Expression

Deleting an object/variable.

By-example:

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



# Dynamic Memory Allocation

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

Deleting an object/variable.

By-example:

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

Output: 22

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;
ptr = NULL;
```

ptr

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

## 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 | 0 |
| FDE1 | |
| FDE2 | |
| FDE3 | |
| ... | ... |
| 0EC4 | |
| 0EC5 | |
| 0EC6 | |
| 0EC7 | |

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

for (int 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 (int i = 0; i < numberOfGrades; i++)
{  cin >> grades[i];  }
for (int j = 0; j < numberOfGrades; j++)
{  cout << grades[j] << " ";  }
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 of 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 (int 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 (int 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 (int i=0; i<rows; i++)
  delete [] intMatrix[i];
```
d)
```
delete [] intMatrix;
```

Deallocation:
c) Each row sub-array first.
d) Rows array of pointers last.

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Time for Questions !