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Dynamic Variables

Static Variables
- Size is fixed throughout execution
- Size is known at compile time
- Space/memory is allocated at execution

Dynamic Variables
- Created during execution
  † "dynamic allocation"
- No space allocated at compilation time
- Size may vary
  † Structures are created and destroyed during execution.
- Knowledge of structure size not needed
- Memory is not wasted by non-used allocated space.
- Storage is required for addresses.

Example of Pointers
- Assume:
  Houses represent data
  Addresses represent the locations of the houses.
- Notice:
  To get to a house you must have an address.
  No houses can exist without addresses.
  An address can exist without a house (vacant lot / NULL pointer)
On modern computers, memory is organized in a manner similar to a one-dimensional array:

- memory is a sequence of bytes (8 bits)
- each byte is assigned a numerical address, similar to array indexing
- addresses are nonnegative integers; valid range is determined by physical system and OS memory management scheme
- OS (should) keep track of which addresses each process (executing program) is allowed to access, and attempts to access addresses that are not allocated to a process should result in intervention by the OS
- OS usually reserves a block of memory starting at address 0 for its own use
- addresses are usually expressed in hexadecimal (base 16), typically indicated by use of a prefix: 0xF4240

Memory Organization

- **run-time stack** used for statically allocated storage
- **heap** used for dynamically allocated storage
Pointer Type

- Simple type of variables for storing the memory addresses of other memory locations

Pointer Variables Declarations

- The asterisk ‘*’ character is used for pointer variable declarations:

  ```
  int* iptr;
  float* fptr,
  fptr2;
  ```

- `iptr` is a pointer to an integer
- `fptr` is a pointer to a real

- Given the equivalent declaration:

  ```
  int* iptr1, iptr2;
  ```

† Declares `iptr1` to be a pointer variable, but `iptr2` is a simple integer variable.

- Typedef declaration:

  ```
  typedef int* intPtr;
  intPtr iptr1;
  ```

† Declare all pointer variables in separate declaration statements.

- Pointer Type Definitions:

  ```
  strong type declaration (preferred)
  ```
Address Operator: & (ampersand)
- Unary operator that returns the hardware memory location address of it’s operand.

Given:

```
int* iptr1;
int* iptr2;
int numa, numb;
numa = 1;
numb = 2;
```

- Address Assignment:

```
iptr1 = &numa;
iptr2 = &numb;
```

Dereference / Indirection Operator: * (asterisk)
- unary ‘pointer’ operator that returns the memory contents at the address contained in the pointer variable.

- Pointer Output:

```
cout << iptr1 << *iptr1 << endl;
cout << iptr2 << *iptr2 << endl;
```

- (Possible) results:

```
0xF4240 1
0x3B9ACA00 2
```
NULL Pointer

- Pointer constant, address 0

- Named constant in the `<cstddef>` include header
  `<stddef.h>` old style header.

- Represents the empty pointer
  † points nowhere, unique pointer/address value

- Symbolic/graphic representations:

- Illegal: NEVER dereference a pointer that equals NULL

*NULL

![Error Message]

The instruction at "0x0040f61a" referenced memory at "0x00000000". The memory could not be "read".

Click on OK to terminate the program
Click on CANCEL to debug the program

OK  Cancel
Pointer Manipulation

Pointer Diagrams
- Given (text/code representation)
  representation

```c
#include <cstddef>
void main() {
    int* iptr1 = NULL;
    int* iptr2 = NULL;
    int numa, numb;

    numa = 1;
    numb = 2;
}
```

Graphic

<table>
<thead>
<tr>
<th>iptr1</th>
<th>numa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>iptr2</td>
<td>numb</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

Pointer Assignments

- #1
  ```c
  iptr1 = &numa;
iptr2 = &numb;
  ```

- #2
  ```c
  *iptr2 = *iptr1 - 1;
iptr2 = iptr1;
  *iptr2 = 3;
  ```

No pointer access to numb remains.
Pointers have type:

- The type of a pointer is determined by the type of target that is specified in the pointer declaration.

```
int* iptr1 = NULL;
int* iptr2 = NULL;
```

- Here, `iptr1` and `iptr2` are pointers to `int` (type `int*`).

- It is a compile-time error to assign a non-pointer value to a pointer:

```
iptr2 = *iptr1; // error: assign int to int*
```

or vice versa:

```
*iptr1 = iptr2; // error: assign int* to int
```

Typecasts and pointers:

- The assignments above would be legal if an explicit typecast were used:

```
int* iptr2 = (int*) *iptr1; // legal
```

```
typedef int* iPtr;
iptr2 = iPtr(*iptr1); // legal
```

```
*iptr1 = int(iptr2); // legal
```

However, be very cautious with this sort of code. It rarely, if ever, makes much sense to assign a pointer a value that's not either another pointer, or obtained by using the dereference operator.
Direct Addressing
- normal variable access
- non-pointer variables represent one-level of addressing
- non-pointer variables are addresses to memory locations containing data values.
- compilers store variable information in a “symbol table”:

<table>
<thead>
<tr>
<th>symbol</th>
<th>type</th>
<th>address</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>int</td>
<td>0xF4240</td>
</tr>
<tr>
<td>iptr</td>
<td>int*</td>
<td>0xF4244</td>
</tr>
</tbody>
</table>

- compilers replace non-pointer variables with their addresses & fetch/store operations during code generation.

Indirect Addressing
- accessing a memory location’s contents thru a pointer
- pointer variables represent two-levels of addressing
- pointer variables are addresses to memory locations containing addresses.
- compilers replace pointer variables with their addresses & double fetch/store operations during code generation.

<table>
<thead>
<tr>
<th>MEMORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>address</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>0xF423C</td>
</tr>
<tr>
<td>0xF4240</td>
</tr>
<tr>
<td>0xF4244</td>
</tr>
<tr>
<td>0xF4248</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Note: indirect addressing required to dereference pointer variable.

x = 28;
iptr = &x;
Record Pointers

Pointers to structures:

- Given:

```cpp
const int f3size = 20;

struct rectype {
    int field1;
    float field2;
    char field3[f3size];
};

typedef rectype *recPtr;

rectype rec1 = {1, 3.1415f, "pi"};
recPtr r1ptr;

r1ptr = &rec1;
```

Member Access

- Field Access Examples:

```cpp
cout << (*r1ptr).field1
<< (*r1ptr).field2
<< (*r1ptr).field3;
```

- Errors:

```cpp
cout << *r1ptr.field1
<< *r1ptr.field2
<< *r1ptr.field3;
```

Arrow Operator

- Short-hand notation:

```cpp
cout << r1ptr->field1
<< r1ptr->field2
<< r1ptr->field3;
```

Note: parentheses are required due to operator precedence; without () compiler attempts to dereference fields.

Note: -> is an ANSI “C” pointer member selection operator. Equivalent to: (*pointer).member
Arrays == Pointers

- Non-indexed Array variables are considered pointers in C
- Array names as pointers contain the address of the zero element (termed the base address of the array).

Given:

```cpp
const int size = 20;
char name[size];
char *person;
person = name;
person = &name[0];
```

Pointer Indexing

- All pointers can be indexed,
  (logically meaningful only if the pointer references an array).
- Example:

  ```cpp
  person[0] = ' ';  
  person[size-2] = '.';
  ```

Logical Expressions

- NULL tests:

  ```cpp
  if (!person)  //true if (person == NULL)
  ```

- Equivalence Tests:

  ```cpp
  if (person == name)  //true if pointers reference the same memory address
  ```
# Dynamic Storage

## Heap (Free Store, Free Memory)
- Area of memory reserved by the compiler for allocating & deallocating to a program during execution.

### Operations:

<table>
<thead>
<tr>
<th>C++</th>
<th>function</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>new type</strong></td>
<td><strong>allocation</strong></td>
<td><strong>malloc(# bytes)</strong></td>
</tr>
<tr>
<td><strong>delete pointer</strong></td>
<td><strong>deallocation</strong></td>
<td><strong>free pointer</strong></td>
</tr>
</tbody>
</table>

With most compilers, **NULL** is returned if the heap is empty. However, see slide 3.16 for a caveat ...

### Allocation

```c

char* name;
int* iptr;

// C++
name = new(nothrow)char;

iptr =
    new(nothrow) int [20];

//initialization
name = new char ('A');
```

### Deallocation

```c

// C++
delete name;
nname = NULL;
delete [] iptr;
//delete [20] iptr;
iptr = NULL;
```

// C
free(name);
free(iptr);

Pointers are undefined after deallocation and should be set to NULL.
### Declaration Syntax

```c++
int Size;
cin >> Size;           // dynamic value
                     // use as array dim
char* Name = new (nothrow) char[Size];
int*  Scores;
Scores = new (nothrow) int[Size];
Size = 4 * Size + 1;   // does NOT change array
```

### Effect of array allocation via `new`

The `new` operator allocates contiguous storage space in memory for the array `Scores`. The address returned by `new` is `0x3F42740`. The values at each index are shown below:

- **Index 0**: `3F42740`
- **Index 1**: `3F42744`
- **Index 2**: `3F42748`
- **Index 3**: `3F4274C`
- **Index 4**: `3F42750`

The storage space is allocated contiguously in memory.
Allocating Arrays Cont’d

Use like any statically-allocated array

```cpp
strcpy(Name, "Fred G Flintstone");  // static size

for (int Idx = 0; Idx < Size; Size++)
    Scores[Idx] = 0;
SortScores(Scores, Size);
```

Deallocation

```cpp
delete [] Name;
delete [] Scores;
delete [20] Scores; // including dim is optional
    // and has no effect
```

Failure to explicitly `delete` a dynamic variable will result in that memory **NOT** being returned to the system, even if the pointer to it goes out of scope.

This is called a “**memory leak**” and is evidence of poor program implementation.

If large dynamic structures are used (or lots of little ones), a memory leak can result in depletion of available memory.

```cpp
    // WARNING
    delete Name;

    //May not release array memory, undefined results
```
Growing a dynamically-allocated array

```cpp
int* newArray = new int[newSize];

// copy contents of old array into new one
for (int Idx = 0; Idx < oldCapacity; Idx++)
    newArray[Idx] = Scores[Idx];

// delete old array
delete [] Scores;

// retarget old array pointer to new array
Scores = newArray;

// clean up alias
newArray = NULL;
```
An invocation of operator `new` will fail if the heap does not contain enough free memory to grant the request.

Traditionally, the value `NULL` has been returned in that situation. However, the C++ Standard changes the required behavior. By the Standard, when an invocation of `new` fails, the value returned may or may not be `NULL`; what is required is that an *exception* be thrown. We do not cover catching and responding to exceptions in this course.

Fortunately, for the present, most C++ language implementations will continue to guarantee that `NULL` is returned in this case.

Better still, the Standard provides a way to force a `NULL` return *instead* of an exception throw:

```cpp
const int Size = 20;
int* myList = new(nothrow) int[Size];
```

Use of this syntax will guarantee that `myList` will be assigned `NULL` if the allocation fails.

// to turn off nothrow warning
#pragma warning (disable:4291)
The following program attempts to allocate an array, initialize it, and then display its contents. However, the allocation will almost certainly fail.

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

int main() {
    int Count;
    int* t;
    const int Size = 900000000;
    int* myList = new(nothrow) int[Size];

    if (myList == NULL) {
        cout << "Allocation failed!!" << endl;
        return( EXIT_FAILURE );
    }

    for (t = myList, Count = 0; Count < Size; Count++, t++)
    {  
        *t = Count;
    }

    for (t = myList, Count = 0; Count < Size; Count++, t++)
    {  
        cout << t << setw(5) << *t << endl;
    }

    return( EXIT_SUCCESS );
}
```

What if `t` was replaced with `myList`?
In C++, all function parameters are, by default, passed by value. When passing a pointer as a parameter to a function, you must decide how to pass the pointer.

If the called function needs to modify the value of the pointer, you must pass the pointer by reference:

```cpp
// Pre: newSize > oldSize
void growArray(int*& Array, const int oldSize,
                  const int newSize) {
    assert(newSize > oldSize);
    int* tempArray = new int[newSize];
    Copy(tempArray, Array, oldSize);
    delete [] Array;
    Array = tempArray;                   // modifies VALUE of Array
    tempArray = NULL;                    // is this statement necessary?
}
```

This pointer is being passed by reference.

```
42 31 72 87 17
```

```
42 31 72 87 ?? ?? ?? ?? ??
```

```
Array
```

```
tempArray
```
Value Pointer Parameters

If the called function only needs to modify the value of the target of the pointer, you may pass the pointer by value:

```c
void Copy(int* Target, int* Source, const int Dim) {
    for (int Idx = 0; Idx < Dim; Idx++)
        Target[Idx] = Source[Idx];
}
```

Copy() copies the target of one pointer to the target of another pointer. Neither pointer is altered.

This is termed a side-effect. Considered poor practice. Better to pass pointers by reference to indicate the change of target, (or better still to explicitly pass the pointer by const but not the target).

```c
void Copy( int* const Target,
           const int* const Source,
           const int Dim) ;
```
Passing a pointer by value is somewhat dangerous. As shown in the implementation of Copy( ) on the previous slide, if you pass a pointer to a function by value, the function does have the ability to modify the value of the target of the pointer. (The called function receives a local copy of the pointer’s value.)

This is objectionable if the function has no need to modify the target. The question is: how can we pass a pointer to a function and restrict the function from modifying the target of that pointer?

```c++
void Print(const int* Array, const int Size) {
    for (int Idx = 0; Idx < Size; Idx++) {
        cout << setw(5) << Idx << setw(8) << Array[Idx] << endl;
    }
}
```

The use of “const” preceding a pointer parameter specifies that the value of the target of the pointer cannot be modified by the called function. So, in the code above, Print( ) is forbidden to modify the value of the target of the pointer Array.

Print( ) also cannot modify the value of the actual pointer parameter since that parameter is passed by value.
If “const int* iPtr” means that the TARGET of iPtr is to be treated as a const object, how would we specify that a pointer is itself to be a const?

```cpp
// constant pointer to int
int* const iPtr = new int(42);
```

Here, the value stored in the target of iPtr can be changed, but the address stored in iPtr cannot be changed. So, iPtr will always point to the same location in memory, but the contents of that location may change. (Array variables are essentially const pointers.)

Given the declaration of iPtr above:

```cpp
*iPtr = 17; // legal
int anInt = 55;
iPtr = &anInt; // illegal
```

Finally we can have a constant pointer to a constant target:

```cpp
const int* const cPtr = new int(42);
```
void f1(char* p) {
    char s[] = "Gorm";    // pointer to char
    const char* pc = s;  // pointer to constant char
    pc[3] = 'g';         // error: target is constant
    pc = p;              // legal: pointer is malleable

    char* const cp = s;  // constant pointer
    cp[3] = 'g';         // legal: target is malleable
    cp = p;              // error: pointer is constant

    const char* const cpc = s;    // constant pointer to
                                 // constant target
                                // cpc[3] = 'g';        // error: target is constant
                                // cpc = p;          // error: pointer is constant
}

How to keep it straight? Stroustrup suggests reading the declarations backwards (right to left):
char* const cp = s;

\textbf{cp} \textbf{is a constant pointer to a char}
If a pointer targets an array, it is possible to navigate the array by performing arithmetic operations on the pointer:

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

void main() {
    char s[] = "Gorm";
    char* p = s;

    for (int Idx = 0; Idx < strlen(s); Idx++, p++) {
        cout << setw(3) << Idx << "    " << *p << endl;
    }
}
```

produces the output:

```
0    G
1    o
2    r
3    m
```

Consider the update section of the for loop. At the end of each pass through the loop, we increment the value of the pointer \(p\):

```
p++;    // increments the value of p
(*p)++; // increments the value of the target of p
```

The mystery here is: why does incrementing the value of \(p\) cause \(p\) to step through the array of characters, one-by-one?
From B. Stroustrup, “The C++ Programming Language”:
The result of applying the arithmetic operators +, −, ++, or −− to pointers depends on the type of the pointed to target object. When an arithmetic operator is applied to a pointer \( p \) of type \( T* \), \( p \) is assumed to point to an element of an array of objects of type \( T \); \( p+1 \) points to the next element of that array, and \( p-1 \) points to the previous element. This implies that the integer value of \( p+1 \) will be \( \text{sizeof}(T) \) larger than the integer value of \( p \).

In other words, the result of incrementing a pointer depends on the type of thing to which it points.

```cpp
const int SIZE = 5;
int iArray[SIZE] = {32, 17, 89, 43, 91};
int* iPtr = iArray;

for (int k = 0; k < SIZE; k++, iPtr++)
    cout << setw( 3) << k << setw(10) << iPtr << setw(10) << *iPtr;
```

produces:

```
0  006AFD00  32
1  006AFD44  17
2  006AFD88  89
3  006AFDC0  43
4  006AFDE0  91
```

Why does this output make sense?
#include <iostream>
#include <iomanip>
using namespace std;

struct Complex {
    double Real;
    double Imaginary;
};

void main() {
    const int SIZE = 5;
    Complex cArray[SIZE];
    Complex* cPtr = cArray;

    cout << "cPtr: " << cPtr << endl;
    cPtr++;
    cout << "cPtr: " << cPtr << endl;
}

produces:

    cPtr: 006AFD78
    cPtr: 006AFD88

Be very careful with code such as this….

…. the logic makes sense only if the target of the pointer is an array….

…. but, the syntax is legal no matter what the target of the pointer happens to be….
#include <iostream>
#include <iomanip>
using namespace std;

void main() {
    double x = 3.14159;
    double* dPtr = &x;

    cout << " dPtr: " << dPtr << endl
         << " *dPtr: " << *dPtr << endl;

dPtr++;

    cout << " dPtr: " << dPtr << endl
         << " *dPtr: " << *dPtr << endl;
}

produces:

    dPtr: 006AFDC0
    *dPtr: 3.14159
    dPtr: 006AFDC8
    *dPtr: 1.20117e-306

Incrementing dPtr makes no sense (logically) since that will simply make the target of dPtr the 8 bytes of memory that follow x.
Arrays of Pointers

Declarations:
- Given:

```c
const int size = 20;

struct rectype {
    int field1;
    float field2;
    char field3[size];
};
typedef rectype *recPtr;
rectype recl = {1, 3.1415f, "pi"};
recPtr rayPtrs[size];
rayPtrs[size-1] = &recl;
```

Member Access
- Field Access Examples:

```c
cout << (*rayPtrs[size-1]).field1
    << (*rayPtrs[size-1]).field2
    << (*rayPtrs[size-1]).field3;
```

Arrow Operator
- Short-hand notation:

```c
cout << rayPtrs[size-1]->field1
    << rayPtrs[size-1]->field2
    << rayPtrs[size-1]->field3;
```

Using the same sorting algorithm, why is sorting an array of pointers to records faster than sorting an array of records?
Dynamic Memory Problems

Given:

```cpp
typedef int *intPtr;
intPtr intptr1, intptr2;
```

Garbage
- Previously allocated memory that is inaccessible thru any program pointers or structures.
- Example:

```cpp
intptr1 = new int (6);
intptr1 = NULL;
```

Aliases
- Two or more pointers referencing the same memory location.
- Example:

```cpp
intptr1 = new int (6);
intptr2 = intptr1;
```

Dangling Pointers
- Pointers that reference memory locations previously deallocated.
- Example:

```cpp
intptr1 = new int (6);
intptr2 = intptr1;
delete intptr1;
```
Reference Variables

Reference Variable Declarations

- The ampersand ‘&’ character is used for reference variable declarations:

  ```
  int&  iptr;
  float &fptr1, &fptr2;
  ```

Reference variables are aliases for variables.

Pointer Differences

- Reference variables do NOT use the address and dereference operators (& *).
- Compiler dereferences reference variables transparently.
- Reference variables are constant addresses, assignment can only occur as initialization or as parameter passing, reassignment is NOT allowed.
- Examples:

  ```
  char   achar = ‘A’;
  char&  chref = achar;
  //char* chptr = &achar;

  chref   = ‘B’;
  //achar = ‘B’;
  //*chptr = ‘B’;
  ```

Purpose

- Frees programmers from explicitly dereferencing accessing, (in the same way nonpointer variables do).
- ‘Cleans up the syntax’ for standard C arguments and parameters.
Reference Returns

Return by Value

Normally most function returns are by value:

```cpp
int f(int& a) {
    int b = a;
    // . . .
    return( b );
}//f
```

The function does not actually return b, it returns a copy of b.

Return by Reference

Functions can return references:

```cpp
int& f(int& a) {
    int b = a;
    // . . .
    return( b );
}//f *** bad ***
```

Good compilers will issue a warning for returning a reference to a local variable.

The code above contains a subtle trap. The function returns a reference to a variable b which will no longer exist when the function exits and goes out of scope. Returning a reference to an already referenced variable is acceptable, (although most likely unnecessary and confusing).

```cpp
int& f(int& a) {
    int b = a;
    // . . .
    return( a );
}//f *** alias ***
```

Do NOT return references to private data members of a class. This violates the encapsulation of the class.