



COMP 2012H Honors Object-Oriented Programming and Data Structures

Topic 8: C++ Pointers & Dynamic Data

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Part I

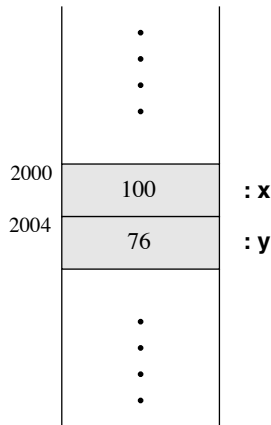
lvalue (Address) and rvalue (Content)



Variables

A **variable** is a symbolic name assigned to some memory storage.

- The size of this storage depends on the **type** of the variable. e.g. char is 1-byte long and int is 4-byte long.
- The difference between a **variable** and a **literal constant** is that a variable is **addressable**.
- e.g. `x = 100;` `x` is a variable and 100 is a literal constant.



lvalue & rvalue

Example: lvalue and rvalue

$x = x + 1;$

- A variable has **dual** roles. Depending on where it appears in the program, it can represent an
 - ▶ **lvalue**: **location** of the memory storage (**read-write**)
 - ▶ **rvalue**: **value** in the storage (**read-only**)
- They are so called because a variable represents an **lvalue** (**rvalue**) if it is written to the **left** (**right**) of an assignment statement.
- Which of the following C++ statements are valid? Why?

```
int x;  
4 = 1;  
(x + 10) = 6;  
cout << ++x << endl; // ANSI C++ Ref. Section 5.3.2  
cout << x++++ << endl; // ANSI C++ Ref. Section 5.2.6
```

lvalue & rvalue: Return-by-Reference vs. Return-by-Value

`++x`: the pre-increment operator

1. requires x to be **passed-by-reference**
2. modify x by incrementing it by 1
3. returns x (with its new value) by **reference**
4. the returned x is an **lvalue**

`x++`: the post-increment operator

1. requires x to be **passed-by-reference**
2. saves the current value of x in some **temporary local variable**
3. modify x by incrementing it by 1
4. returns the old value of x in the local variable by **value**
5. the returned x is an **rvalue**

Get the Address by the Reference Operator &

Syntax: Get the Address of a Variable

& <variable>

```
#include <iostream>    /* File: var-addr.cpp */
using namespace std;

int main()
{
    int x = 10, y = 20;
    short a = 9, b = 99;

    cout << "x = " << x << '\t' << "address of x = " << &x << endl;
    cout << "y = " << y << '\t' << "address of y = " << &y << endl;
    cout << "a = " << a << '\t' << "address of a = " << &a << endl;
    cout << "b = " << b << '\t' << "address of b = " << &b << endl;
    return 0;
}
```

Example: Address of Formal Parameters

```
#include <iostream>      /* File: fcn-var-addr.cpp */
using namespace std;

void f(int x2, int& y2)
{
    short a = 9, b = 99;
    cout << endl << "Inside f(int, int&)" << endl;
    cout << "x2 = " << x2 << '\t' << "address of x2 = " << &x2 << endl;
    cout << "y2 = " << y2 << '\t' << "address of y2 = " << &y2 << endl;
    cout << "a = " << a << '\t' << "address of a = " << &a << endl;
    cout << "b = " << b << '\t' << "address of b = " << &b << endl;
}

int main()
{
    int x = 10, y = 20;
    cout << endl << "Inside main()" << endl;
    cout << "x = " << x << '\t' << "address of x = " << &x << endl;
    cout << "y = " << y << '\t' << "address of y = " << &y << endl;
    f(x, y);
    return 0;
}
```

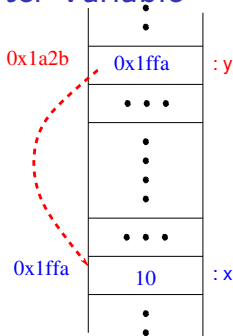
Question: Can you see the difference between PBV and PBR?

Part II

What is a Pointer?



Pointer Variable



Syntax: **Pointer** Variable Definition

`<type>* <variable>;`

- A **pointer variable** stores the **address** of another variable.
- If variable `y` stores the address of variable `x`, we say “`y` points to `x`.”
- Notice that a **pointer variable** is just a variable which has its **own** address in memory.

```
#include <iostream>      /* File: pointer-var.cpp */
using namespace std;

int main() {
    int x = 10; int* y = &x; // y now contains the address of x
    cout << "x = " << x << '\t' << "address of x = " << &x << endl;
    cout << "y = " << y << '\t' << "address of y = " << &y << endl;
    return 0;
}
```

Get the Content by the Dereference Operator *

Syntax: Get the **Content** Through a Pointer Variable

*<pointer variable>

```
#include <iostream>      /* File: pointer-deref.cpp */
using namespace std;

int main()
{
    int x = 10, z = 20;
    int* y = &x; // y now contains the address of x
    cout << "x = " << x << '\t' << "address of x = " << &x << endl;
    cout << "z = " << z << '\t' << "address of z = " << &z << endl;
    cout << "y = " << y << '\t' << "address of y = " << &y << endl;

    z = *y; // Get content from the address stored in y, put it into z
    cout << endl;
    cout << "z = " << z << '\t' << "address of z = " << &z << endl;
    cout << "y = " << y << '\t' << "*y = " << *y << endl;
    return 0;
}
```

Example: Pointer Manipulation

```
#include <iostream>      /* File: pointer.cpp */
using namespace std;

int main()
{
    int x1 = 10, x2 = 20;
    int *p1 = &x1;        // p1 now points to x1
    int *p2 = &x2;        // p2 now points to x2

    *p1 = 5;              // now x1 = 5
    *p2 += 1000;          // now x2 = 1020
    *p1 = *p2;            // now *p1 = *p2 = x1 = x2 = 1020, but p1 != p2
    p1 = p2;              // now p1 and p2 both point to x2

    cout << "x1 = " << x1 << '\t' << "&x1 = " << &x1 << endl;
    cout << "x2 = " << x2 << '\t' << "&x2 = " << &x2 << endl;
    cout << "p1 = " << p1 << '\t' << "*p1 = " << *p1 << endl;
    cout << "p2 = " << p2 << '\t' << "*p2 = " << *p2 << endl;

    return 0;
}
```

Example: Pointer and `sizeof()`

```
#include <iostream>    /* File: pointer-sizeof.cpp */
using namespace std;

int main()
{
    char    c = 'A';    char* pc = &c;
    short   s = 5;      short* ps = &s;
    int     i = 10;     int* pi = &i;
    double  d = 5.6;    double* pd = &d;

    cout << sizeof(pc) << '\t' << sizeof(*pc) << '\t' << sizeof(&pc)
         << endl;
    cout << sizeof(ps) << '\t' << sizeof(*ps) << '\t' << sizeof(&ps)
         << endl;
    cout << sizeof(pi) << '\t' << sizeof(*pi) << '\t' << sizeof(&pi)
         << endl;
    cout << sizeof(pd) << '\t' << sizeof(*pd) << '\t' << sizeof(&pd)
         << endl;

    return 0;
}
```

What can a Pointer Point to?

A pointer can point to

- objects of **basic types**: char, short, int, long, float, double, etc.
- objects of **user-defined types**: struct, class (discussed later)
- another **pointer**!
- even to a **function** \Rightarrow **function pointer**! (discussed later)



Example: Pointer to Pointer to Pointer ...

```
#include <iostream>          /* File: pointer-pointer.cpp */
using namespace std;

int main()
{
    int x = 16;
    int* xp = &x;           // xp --> x
    int** xpp = &xp;        // xpp --> xp --> x
    int*** xppp = &xpp;     // xppp --> xpp --> xp --> x

    cout << "x address    = " << &x    << "    x    = " << x << endl;
    cout << "xp address   = " << &xp    << "    xp    = " << xp
        << "    *xp      = "          << *xp << endl;

    cout << "xpp address  = " << &xpp   << "    xpp   = " << xpp
        << "    *xpp     = "          << *xpp << "    **xpp  = " << **xpp << endl;

    cout << "xppp address = " << &xppp  << "    xppp  = " << xppp
        << "    *xppp    = "          << *xppp << "    **xppp = " << **xppp
        << "    ***xppp = "          << ***xppp << endl;

    return 0;
}
```

Variable, Reference Variable, Pointer Variable

```
#include <iostream>      /* File: confusion.cpp */
using namespace std;

int x = 5;                // An int variable
int& xref = x;            // A reference variable: xref is an alias of x
int* xptr = &x;           // A pointer variable: xptr points to x

void xprint()
{
    cout << hex << endl; // Print numbers in hexadecimal format
    cout << "x = " << x << "\t\tx address = " << &x << endl;
    cout << "xref = " << xref << "\t\txref address = " << &xref << endl;
    cout << "xptr = " << xptr << "\t\txptr address = " << &xptr << endl;
    cout << "*xptr = " << *xptr << endl;
}

int main()
{
    x += 1; xprint();
    xref += 1; xprint();
    xptr = &xref; xprint(); // Now xptr points to xref

    return 0;
}
```

const Pointer

Syntax: const Pointer Definition

`<type>* const <pointer variable> = &<another variable>;`

- A **const pointer** must be **initialized** when it is defined; just like any C++ constant.
- A **const pointer**, once initialized, **cannot** be changed to point to something else.
- However, you are free to **change** the **content** in the address it points to.

Example: const Pointer

```
int x = 10, y = 20;
int* const xcp = &x;
xcp = &y;    // Compile Error: a const pointer!
*xcp = 5;    // Compile Okay: what it points to is not const
```


Pointer to const Objects

Syntax: Definition of Pointer to a **const** Object

```
const <type>* <pointer variable>;
```

Example: Pointer to const Object

```
int x = 10, y = 20;  
const int* pc = &x;
```

```
pc = &y; // Compile Okay: pc is free to point to x, y, z, or any int  
*pc = 5; // Compile Error: its content is const when accessed thru pc!  
y = 8;   // Compile Okay: y is not a const object
```



Pointer to const Objects ..

- It is **not** necessary to initialize a **pointer to const** object when it is defined, though you may.
- You are free to change the **pointer itself** to point to **different** objects during program execution.
- However, the **content of the object** pointed to by such pointer cannot be changed **through the pointer**. But the content of the object can still be changed **by the object directly**!



Quiz: (const) Pointer to (const) Objects

Can you tell the differences among the following?

- `int* p;`
- `const int* p;`
- `int* const p;`
- `const int* const p;`



PBR = PBV + Pointer

- The programming language C only has **one** way to pass arguments to a function, which is **PBV**.
- To simulate the effect of PBR, one may pass the **address** of an object to a function.
- **Inside** the function, the object is represented by a **pointer**.
- Then one may **change** the object's value by **dereferencing** the object's pointer inside the function.



Example: Swap Using PBV + Pointer

```
#include <iostream>      /* File: pbv-pointer.cpp */
using namespace std;

void swap(int* x, int* y)
{
    cout << "x = " << x << "\t*x = " << *x << endl;
    cout << "y = " << y << "\t*y = " << *y << endl << endl;

    int temp = *x; *x = *y; *y = temp;

    cout << "x = " << x << "\t*x = " << *x << endl;
    cout << "y = " << y << "\t*y = " << *y << endl << endl;
}

int main()
{
    int a = 10, b = 20;
    cout << "a = " << a << "\t\t\t&a = " << &a << endl;
    cout << "b = " << b << "\t\t\t&b = " << &b << endl << endl;

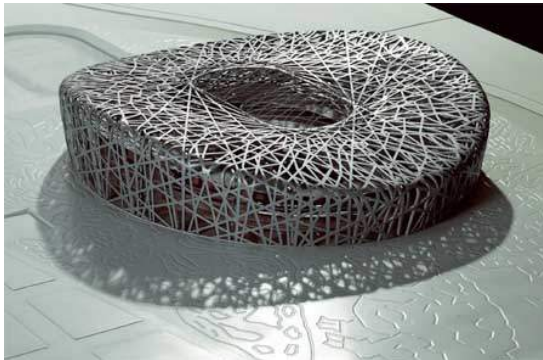
    swap(&a, &b);
    cout << "a = " << a << "\t\t\tb = " << b << endl;
    return 0;
}
```

Common Uses of Pointer

- Indirect addressing
- Dynamic object creation/deletion
- Advanced uses that will be covered in this course later:
 - ▶ writing generic functions that can work on any data type (e.g., a sorting function that sorts any data type)
 - ▶ implementation of object-oriented technologies such as
 - ★ inheritance
 - ★ polymorphism (virtual function)

Part III

Pointer to Structure



Pointer to **struct** and the \rightarrow Operator

- You may also define a pointer variable for a **struct** object.
- **Two** ways to access **struct** members through a pointer:
 1. **Dereference** the pointer and use the **.** operator.

```
Point a;                // a contains garbage
Point* ap = &a;         // Now ap points to a

// Dereference ap, then use the . operator
(*ap).x = 3.5;
(*ap).y = 9.7;
```

2. Directly use the \rightarrow operator.

```
Point a;                // a contains garbage
Point* ap = &a;         // Now ap points to a

// No dereferencing when using the -> operator
ap->x = 3.5;
ap->y = 9.7;
```


Example: Euclidean Distance Again — point-test.cpp

```
#include <iostream>      /* File: point-test.cpp */
#include "point.h"
using namespace std;

// To compute and print the Euclidean distance between 2 points
void print_distance(const Point*, const Point*);

int main()    /* To find the length of the sides of a triangle */
{
    Point a, b, c;
    cout << "Enter the co-ordinates of point A: "; cin >> a.x >> a.y;
    cout << "Enter the co-ordinates of point B: "; cin >> b.x >> b.y;
    cout << "Enter the co-ordinates of point C: "; cin >> c.x >> c.y;

    print_distance(&a, &b);
    print_distance(&b, &c);
    print_distance(&c, &a);
    return 0;
}

/* g++ -o point-test point-test.cpp point-distance.cpp */
```

Example: Euclidean Distance Again — point-distance.cpp

```
#include <iostream>      /* File: point-distance.cpp */
#include <cmath>
#include "point.h"
using namespace std;

double euclidean_distance(const Point* p1, const Point* p2)
{
    double x_diff = p1->x - p2->x, y_diff = p1->y - p2->y;
    return sqrt(x_diff*x_diff + y_diff*y_diff);
}

void print_point(const Point* p)
{
    cout << '(' << p->x << ", " << p->y << ')';
}

void print_distance(const Point* p1, const Point* p2)
{
    cout << "Distance between "; print_point(p1);
    cout << " and "; print_point(p2);
    cout << " is " << euclidean_distance(p1, p2) << endl;
}
```

Example: sort-student-record.cpp Again

```
#include "student-record.h" /* File: sort-student-record.cpp */
#include "student-record-extern.h"

int main()
{
    Student_Record sr[] = {
        { "Adam", 12000, 'M', CSE, { 2006 , 1 , 10 } },
        { "Bob", 11000, 'M', MATH, { 2005 , 9 , 1 } },
        { "Cathy", 10000, 'F', ECE, { 2006 , 8 , 20 } } };

    Date d; // Modify the 3rd record
    set_date(&d, 1980, 12, 25);
    set_student_record(&sr[2], "Jane", 18000, 'F', CSE, &d);

    sort_3SR_by_id(sr);
    for (int j = 0; j < sizeof(sr)/sizeof(Student_Record); j++)
        print_student_record(&sr[j]);
    return 0;
}

/* g++ -o sort-sr sort-student-record.cpp student-record-functions.cpp
student-record-swap.cpp */
```

Example: student-record-swap.cpp Again

```
#include "student-record.h" /* File: student-record-swap.cpp */

void swap_SR(Student_Record* x, Student_Record* y)
{
    Student_Record temp = *x;
    *x = *y;
    *y = temp;
}

void sort_3SR_by_id(Student_Record sr[])
{
    if (sr[0].id > sr[1].id) swap_SR(&sr[0], &sr[1]);
    if (sr[0].id > sr[2].id) swap_SR(&sr[0], &sr[2]);
    if (sr[1].id > sr[2].id) swap_SR(&sr[1], &sr[2]);
}
```

Example: student-record-functions.cpp Again I

```
#include <iostream> /* File: student-record-functions.cpp */
#include "student-record.h"
using namespace std;

void print_date(const Date* date)
{
    cout << date->year << '/'
         << date->month << '/'
         << date->day << endl;
}

void print_student_record(const Student_Record* x)
{
    cout << endl;
    cout.width(12); cout << "name: "    << x->name << endl;
    cout.width(12); cout << "id: "      << x->id << endl;
    cout.width(12); cout << "gender: " << x->gender << endl;
    cout.width(12); cout << "dept: "    << dept_name[x->dept] << endl;
    cout.width(12); cout << "entry date: "; print_date(&x->entry);
}
```

Example: student-record-functions.cpp Again II

```
void set_date(Date* x, unsigned int year,
              unsigned int month, unsigned int day)
{
    x->year = year;
    x->month = month;
    x->day = day;
}

void set_student_record(Student_Record* a, const char name[],
                      unsigned int id, char gender, Dept dept,
                      const Date* date)
{
    strcpy(a->name, name);
    a->id = id;
    a->gender = gender;
    a->dept = dept;
    a->entry = *date;    // struct-struct assignment
}
```

Example: student-record-extern.h Again

```
/* File: student-record-extern.h */

void print_date(const Date*);
void print_student_record(const Student_Record*);

void set_date(Date* x, unsigned int, unsigned int, unsigned int);
void set_student_record(Student_Record*, const char[],
                        unsigned int, char, Dept, const Date*);

void swap_SR(Student_Record*, Student_Record*);
void sort_3SR_by_id(Student_Record sr[]);
```

Part IV

Dynamic Memory/Objects Allocation and Deallocation



Static Objects

Example: Static Objects

```
float a = 2.3;           // Global float variable

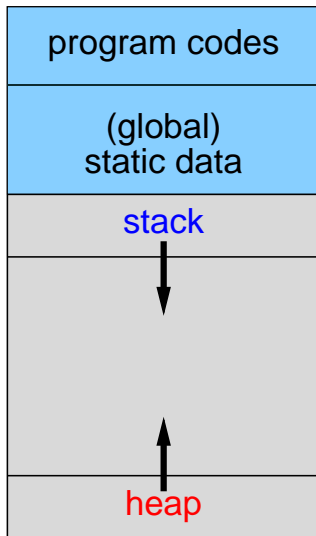
int main()
{
    int x = 5;           // Local int variable
    char s[16] = "hkust"; // Local char array
    return 0;
}
```

- Up to now, all (local and global) variables you use require **static memory allocation**: their memory are allocated by the compiler during compilation.
- When these variables — **static objects** — go **out of** their **scope**, their memory are released **automatically** back to the computer's memory store (RAM).
- **Question**: What if you want to create an object, or an array whose size is unknown until a user specifies at **runtime**?

Dynamic Objects

- C++ allows you to create an object, or an array of objects — **dynamic objects** — **on-the-fly** at **runtime**.
- The memory of **dynamic objects**
 - ▶ has to be **allocated** at runtime **explicitly** by you,
⇒ using the operator **new**.
 - ▶ will **persist** even after the object goes out of **scope**.
 - ▶ has to be **deallocated** at runtime **explicitly** by you,
⇒ using the operator **delete**.
- **Static objects** are managed using a data structure called **stack**.
- **Dynamic objects** are managed using a data structure called **heap**.

Memory Layout of a C++ Program



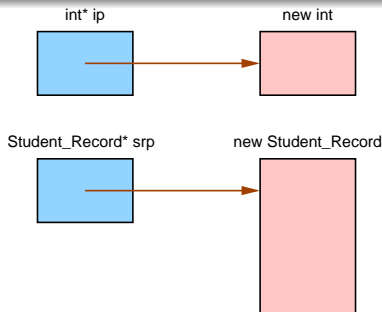
Dynamic Memory Allocation: Operator **new**

Syntax: Dynamic Memory Allocation Using **new**

`<type>* <pointer-variable> = new <type>;`

Examples: Use of the **new** Operator

```
int* ip = new int;  
*ip = 5;  
Date d20010101 = { 2001, 1 , 1 };  
Student_Record* srp = new Student_Record;  
set_student_record(*srp, "Chris", 100, 'M', CSE, d20010101);
```



Dynamic Memory Allocation: Operator `new` ..

For the line: `int* ip = new int;`

- The computer finds from the **heap** an amount of memory equal to `sizeof(int)` and gives it to your program.
- The **new** operator, which is actually a **function**, will return a **value** which is the **address** of the starting location of that piece of memory.
- That piece of memory is **unnamed**, and you need to use an **int pointer variable** (here, `ip`) to point to it — holding its address (that is returned by the **new** operator).
- There is **no** other way to access the **unnamed memory** allocated by the operator **new** except through the **pointers**.

Dynamic Memory Allocation: Operator `new` ...

For the line: `Student_Record* srp = new Student_Record;`

- The computer gives you an amount of **unnamed** memory equal to `sizeof(Student_Record)` from the **heap**.
- You need to hold its address using a **Student_Record pointer variable** (here, `srp`).
- Notice that the variables, `ip` and `srp`, are **static objects**.
- Only the unnamed memories returned by the **new** operator are **dynamic objects**.
- Both **local static objects** and **dynamic objects** come and go.
- However, the **stack** will allocate and deallocate **local static objects** **automatically** for you.
- But you have to manage the allocation and deallocation of **dynamic objects** yourselves.

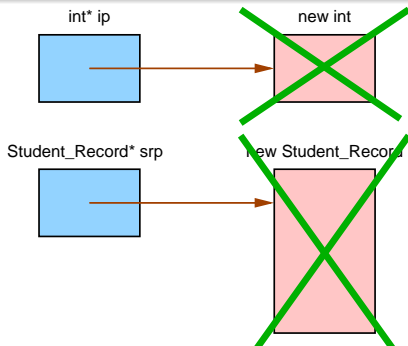
Dynamic Memory Deallocation: Operator `delete`

Syntax: Dynamic Memory Deallocation Using `delete`

`delete` <pointer-variable>;

Examples: Use of the `delete` Operator

```
delete ip;           // ip is now a dangling pointer
ip = nullptr;        // ip is now a null pointer
delete srp;          // srp is now a dangling pointer
srp = nullptr;       // srp is now a null pointer
```



Common Bug I: Dangling Pointer — Case 1

- Operator **delete** releases memory pointed to by a pointer variable (here, ip or srp) back to the **heap** for recycle.
- However, after the **delete** operation, the pointer variable still holds the address of the previously allocated unnamed memory.
- Now the pointer becomes a **dangling pointer**.
- A **dangling pointer** is a pointer that points to a location whose memory is deallocated.
- Runtime error usually occurs when you try to **dereference** a **dangling pointer** either because
 - ▶ the memory is **no long accessible** as it is taken back.
 - ▶ the memory has already been **recycled** and is **re-allocated** to some other functions or even other programs!

Common Bug I: Dangling Pointer — Case 1 ..

- Modifying the object a **dangling pointer** points to leads to **unpredictable** results that usually end up in a program **crash**.
- To play safe, reset a **dangling pointer** to a **null pointer** by setting its value to **nullptr**.
- **nullptr** is a new keyword in C++11 and is used to indicate a pointer that has not been set to point to something useful.
- In the past, a null pointer is represented by **NULL** or **0**.
- Good practices:
 1. Always **initialize** a pointer to **nullptr** when defining a pointer variable.
 2. Always **check** whether a pointer is a **nullptr** before using it.

Common Bug I: Dangling Pointer — Case 2

Example: Dangling Pointer

```
int* create_and_init(int value) /* File: dangling-pointer.cpp */
{
    int x = value;           // x is a local variable
    int* p = &x;             // p is also a local variable
    return p;
}

int main()
{
    int* ip = create_and_init(10);
    cout << *ip << endl;
    return 0;
}
```

- Local pointer variable, `p` is pointing to another local variable, `x`. Both are automatically allocated when the function `create_and_init()` is called, and are automatically deallocated when `create_and_init()` returns.
- **Question:** What does the pointer variable, `ip` point to after the call to `create_and_init()` returns?

Common Bug II: Memory Leak

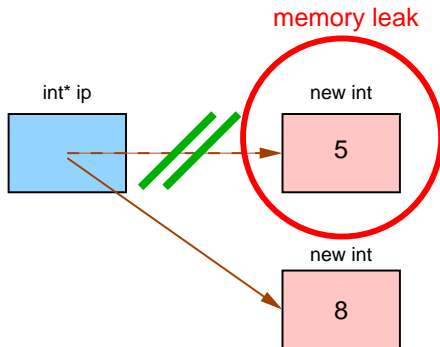
- **Memory leak** occurs when dynamically allocated memory that is **no longer** needed is not released.
- Since the memory allocated by operator **new** is **unnamed**, always keep track of it using a **pointer variable**.
- If you lose track of it, it will become **inaccessible** and there will be **memory leak**.
- When you leak a lot of memory, then the computer does not have enough memory to run your program \Rightarrow **runtime error**.



Common Bug II: Memory Leak ..

Example: Memory Leak

```
int* ip = new int; // First unnamed int
*ip = 5;
ip = new int;      // Last unnamed int is lost
*ip = 8;
```



Example: Memory Leak

Example: Memory Leak Too

```
void swap(Date& x, Date& y)
{
    Date* temp = new Date; *temp = x; x = y; y = *temp;
}

int main()
{
    Date a = { 2006 , 1 , 10 }; Date b = { 2005 , 9 , 1 };
    swap(a, b); return 0;
}
```

- The variable, `Date* temp` is a local variable in the function `swap()`.
- Everytime when `swap()` is called, `temp` is automatically allocated on a **stack**.
- `new Date` returns an unnamed memory of size equal to `sizeof(Date)` from the **heap**.

Example: Memory Leak ..

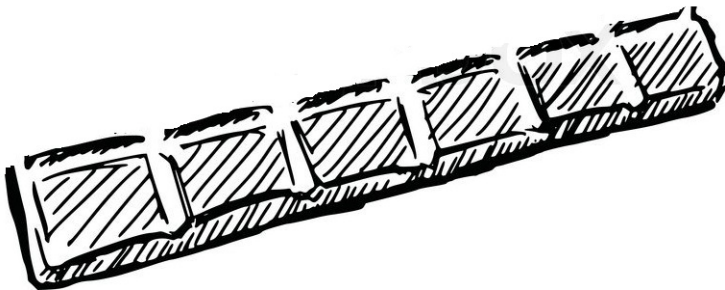
When `swap()` returns,

- the memory for local variables like `temp` will be **deallocated automatically**.
- However, the memory allocated by operator **new** remains until
 - ▶ operator **delete** is used to deallocate it.
 - ▶ the whole program finishes, the operating system will take back all memory dynamically allocated by the program that has not been deleted.

Question: What happens to the unnamed memory returned by `new Date` when `swap()` returns back to `main()`?

Part V

Array as a Pointer



Pointer Arithmetic

- A pointer variable supports 2 arithmetic operations: $+$, $-$.
- If you have `<type> x; <type>* xp = &x;`, then
 - ▶ `xp + N` == `&x + sizeof(<type>) × N`.
 - ▶ `xp - N` == `&x - sizeof(<type>) × N`.
- The result of **pointer arithmetic** should be a **valid** address, otherwise, **dereferencing** it may lead to **segmentation fault**!

Example: Pointer Arithmetic

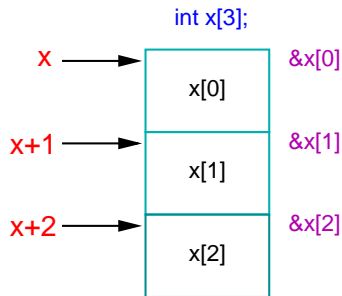
```
#include <iostream>      /* File: pointer-math.cpp */
using namespace std;

int main()
{
    double x = 2.3;      // double is 8-byte
    double* xp = &x;     // xp points to x
    cout << &x << endl << xp + 2 << endl << xp - 2 << endl;

    // Nothing disallows you from assigning an integer value
    // to a pointer variable. Hexadecimal numbers start with 0x.
    int* yp = reinterpret_cast<int*>(0x14);
    cout << yp + 1 << endl << yp - 1 << endl;

    // Since addresses around 0x14 may not be accessible to you
    // Dereferencing them usually leads to runtime error
    cout << *(yp + 1) << endl << *(yp - 1) << endl;
    return 0;
}
```

Array Name Can be Treated as a const Pointer!



- In fact, the **array identifier** can be treated as a **const pointer** to the first **array** element.
- Thus, the variable `x` in `int x[3];` from the pointer perspective, is like `int* const`.

Access Array Items by Another Pointer

- Any **pointer** pointing to an array can be used to access all elements of the array instead of the **original** array identifier.
-

```
#include <iostream>      /* File: array-by-another-pointer.cpp */
using namespace std;

int main()
{
    int x[] = { 11, 22, 33, 44 };
    int* y = x; // Both y and x point to the 1st element of array

    // Modify the array through pointer y
    for (int j = 0; j < sizeof(x)/sizeof(int); ++j)
        y[j] += 100;

    // Print the array through pointer x
    for (int j = 0; j < sizeof(x)/sizeof(int); ++j)
        cout << x[j] << endl;
    return 0;
}
```

Access Array Items by Pointer Arithmetic & Dereferencing

- Using **pointer arithmetic**, you may “**move**” a pointer to point to any array element.
- Dereferencing** a pointer to an array element then obtains the element — and you can use it as either **lvalue** or **rvalue**.
- Again, if `int x[] = {11,22,33}; int* xp = x;`, then we have

ELEMENT ADDRESS	ELEMENT VALUE
$xp == x == \&x[0]$	$*xp == *x == x[0] == 11$
$xp+1 == x+1 == \&x[1]$	$*(xp+1) == *(x+1) == x[1] == 22$
$xp+2 == x+2 == \&x[2]$	$*(xp+2) == *(x+2) == x[2] == 33$

And by definition, numerically, we have $\&x == x == \&x[0]$.

Example: Print an Array using Pointer

```
#include <iostream> /* File: print-array-by-pointer.cpp */
using namespace std;
int main()
{
    int x[] = { 11, 22, 33, 44 };
    for (int* xp = x, j = 0; j < sizeof(x)/sizeof(int); ++j, ++xp)
        cout << *xp << endl;
    return 0;
}
```

```
#include <iostream> /* File: print-char-array-by-pointer.cpp */
using namespace std;
int main()
{
    char s[] = "hkust";
    for (const char* sp = s; *sp != '\0'; ++sp)
        cout << *sp << endl;
    return 0;
}
```

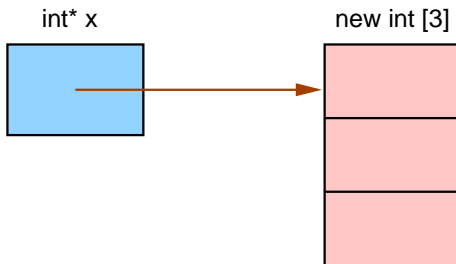
Creation of Dynamic Array: Operator **new** Again

Syntax: **new** a Dynamic Array

```
<type>* <pointer-variable> =  
    new <type> [ <integer-expression> ] ;
```

Examples: Use of the **new** Operator

```
int array_size; cin >> array_size; // Unknown till runtime  
int* x = new int [array_size];  
for (int j = 0; j < array_size; ++j)  
    x[j] = j; // Actually a pointer but treated like an array
```



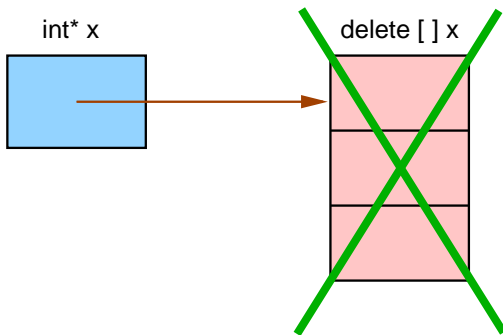
Destruction of Dynamic Array: Operator `delete` Again

Syntax: `delete` a Dynamic Array

`delete []` <pointer-variable> ;

Examples: Use of the `new` Operator

```
delete [ ] x;    // x is now a dangling pointer  
x = nullptr;    // x is now a nullptr pointer
```



Example: Dynamic 1D Array

```
#include <iostream>      /* File: dynamic-point-array.cpp */
#include "point.h"
using namespace std;

int main()
{
    void print_distance(const Point*, const Point*);
    int num_points;
    cout << "Enter the number of points : "; cin >> num_points;
    Point* point = new Point [num_points]; // Dynamic array of points

    for (int j = 0; j < num_points; ++j)    // Input the points
    {
        cout << "Enter the x & y coordinates of point #" << j << " : ";
        cin >> point[j].x >> point[j].y;
    }

    for (int i = 0; i < num_points; ++i) // Compute distance between 2 points
        for (int j = i+1; j < num_points; ++j)
            print_distance(point+i, point+j);

    delete [] point; // Deallocate the dynamic array of points
    return 0;
} /* g++ dynamic-point-array.cpp point-distance.cpp */
```


Example: Dynamic 1D Array ..

```
#include <iostream>      /* File: point-distance.cpp */
#include <cmath>
#include "point.h"
using namespace std;

double euclidean_distance(const Point* p1, const Point* p2)
{
    double x_diff = p1->x - p2->x, y_diff = p1->y - p2->y;
    return sqrt(x_diff*x_diff + y_diff*y_diff);
}

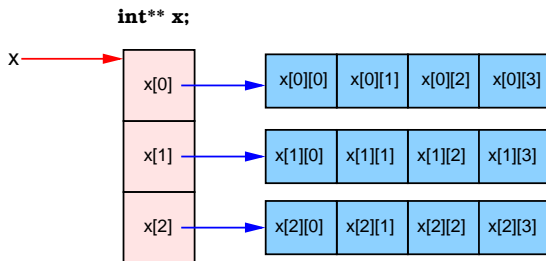
void print_point(const Point* p)
{
    cout << '(' << p->x << ", " << p->y << ')';
}

void print_distance(const Point* p1, const Point* p2)
{
    cout << "Distance between "; print_point(p1);
    cout << " and "; print_point(p2);
    cout << " is " << euclidean_distance(p1, p2) << endl;
}
```

Part VI

Multi-dimensional Array and Pointer

Dynamic Allocation of a 2D Array



- To create a 2D int array with **M** rows and **N** columns at runtime:
 1. Allocate a **1D array** of **M int*** (int pointers).
 2. For each of the **M** elements, create another **1D array** of **N int** (integers), and set the former to point to the latter.

Question: Can you generalize this to 3D, 4D, ..., arrays?

Example: Operations of a Dynamic 2D Array

```
#include <iostream>      /* File: 2d-dynamic-array-main.cpp */
using namespace std;

int** create_matrix(int, int);
void print_matrix(const int* const*, int, int);
void delete_matrix(int**, int, int);

int main()
{
    int num_rows, num_columns;
    cout << "Enter #rows followed by #columns: ";
    cin >> num_rows >> num_columns;
    int** matrix = create_matrix(num_rows, num_columns);

    // Dynamic array elements can be accessed like static array elements
    for (int j = 0; j < num_rows; ++j)
        for (int k = 0; k < num_columns; ++k)
            matrix[j][k] = 10*(j+1) + (k+1);

    print_matrix(matrix, num_rows, num_columns);
    delete_matrix(matrix, num_rows, num_columns);
    matrix = nullptr;    // Avoid dangling pointer
    return 0;
} /* g++ 2d-dynamic-array-main.cpp 2d-dynamic-array-functions.cpp */
```

Example: Operations of a Dynamic 2D Array ..

```
#include <iostream>      /* File: 2d-dynamic-array-functions.cpp */
using namespace std;

int** create_matrix(int num_rows, int num_columns) {
    int** x = new int* [num_rows];    // STEP 1
    for (int j = 0; j < num_rows; ++j) // STEP 2
        x[j] = new int [num_columns];
    return x;
}

void print_matrix(const int* const* x, int num_rows, int num_columns) {
    for (int j = 0; j < num_rows; ++j)
    {
        for (int k = 0; k < num_columns; ++k)
            cout << x[j][k] << '\t';
        cout << endl;
    }
}

void delete_matrix(int** x, int num_rows, int num_columns) {
    for (int j = 0; j < num_rows; ++j) // Delete is done in reverse order
        delete [] x[j];                // (compared with its creation)
    delete [] x;
}
```

Example: Relation between Dynamic 2D Array & Pointer

```
#include <iostream>          /* File: 2d-dynamic-array-and-pointer.cpp */
using namespace std;

int main()
{
    // Dynamically create an array with 3 rows, 4 columns
    int** x = new int* [3];    // STEP 1
    for (int j = 0; j < 3; j++) // STEP 2
        x[j] = new int [4];

    cout << endl << "Info about x:" << endl;
    cout << "sizeof(x) :\t" << sizeof(x) << endl << endl;
    cout << "x\t\t" << "&x[0]\t\t" << "&x[0][0]" << endl;
    cout << x << '\t' << &x[0] << '\t' << &x[0][0] << endl << endl;
    cout << "&x[j]\t\t" << "x[j]\t\t"
        << "&x[j][0]" << '\t' << "x+j" << endl;

    for (int j = 0; j < 3; j++)
        cout << &x[j] << '\t' << x[j] << '\t'
            << &x[j][0] << '\t' << x+j << endl;

    return 0;
}
```

Example: Relation between Dynamic 2D Array & Pointer ..

Info about x:

sizeof(x) : 8

x	&x[0]	&x[0][0]	
0x14ea5010	0x14ea5010	0x14ea5030	
&x[j]	x[j]	&x[j][0]	x+j
0x14ea5010	0x14ea5030	0x14ea5030	0x14ea5010
0x14ea5018	0x14ea5050	0x14ea5050	0x14ea5018
0x14ea5020	0x14ea5070	0x14ea5070	0x14ea5020

Notice that, numerically, we have

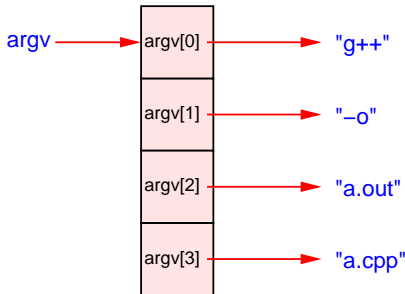
- $x == \&x[0] \neq \&x[0][0]$
 $\Rightarrow x$ points to $x[0]$ (and not $x[0][0]$ as in static 2D array)
- $\&x[j] == x+j$
 \Rightarrow a proof of the pointer arithmetic.
- $x[j] == \&x[j][0]$
 $\Rightarrow x[j]$ points to the first element of the j th row.

main() Function Arguments

- Up to now, you write the `main` function header as `int main()` or `int main(void)`.
- In fact, the general form of the `main` function allows **variable number** of arguments (**overloaded function**).

```
int main(int argc, char** argv)
int main(int argc, char* argv[ ])
```

- `argc` gives the actual number of arguments.
- `argv` is an array of `char*`, each pointing to a character string.
- e.g. `g++ -o a.out a.cpp` calls the `main` function of the `g++` program with 3 additional **commandline arguments**. Thus, `argc = 4`, and



Example: Operations of a Dynamic 2D Array using `argv`

```
#include <iostream> /* File: 2d-dynamic-array-main-with-argv.cpp */
using namespace std;
int** create_matrix(int, int);
void print_matrix(const int* const*, int, int);
void delete_matrix(int**, int, int);

int main(int argc, char** argv)
{
    if (argc != 3)
    { cerr << "Usage: " << argv[0] << " #rows #columns" << endl; return -1; }

    int num_rows = atoi(argv[1]);
    int num_columns = atoi(argv[2]);
    int** matrix = create_matrix(num_rows, num_columns);

    // Dynamic array elements can be accessed like static array elements
    for (int j = 0; j < num_rows; ++j)
        for (int k = 0; k < num_columns; ++k)
            matrix[j][k] = 10*(j+1) + (k+1);

    print_matrix(matrix, num_rows, num_columns);
    delete_matrix(matrix, num_rows, num_columns);
    matrix = nullptr; // Avoid dangling pointer
    return 0;
} /* g++ 2d-dynamic-array-main-with-argv.cpp 2d-dynamic-array-functions.cpp */
```

That's all!

Any questions?

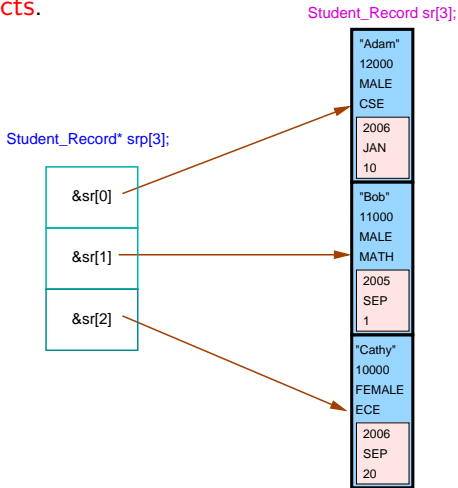


Further Reading



Array of Pointers to Structures

- You may create an **array** of basic data types as well as user-defined data types, or **pointers** to them.
- Thus, you may have an **array** of **struct objects**, or an **array** of **pointers to struct objects**.



Example: (Previously) Sort by Struct Objects Themselves

```
#include "student-record.h" /* File: sort-student-record.cpp */
#include "student-record-extern.h"

int main()
{
    Student_Record sr[] = {
        { "Adam", 12000, 'M', CSE, { 2006 , 1 , 10 } },
        { "Bob", 11000, 'M', MATH, { 2005 , 9 , 1 } },
        { "Cathy", 10000, 'F', ECE, { 2006 , 8 , 20 } } };

    Date d; // Modify the 3rd record
    set_date(&d, 1980, 12, 25);
    set_student_record(&sr[2], "Jane", 18000, 'F', CSE, &d);

    sort_3SR_by_id(sr);
    for (int j = 0; j < sizeof(sr)/sizeof(Student_Record); j++)
        print_student_record(&sr[j]);
    return 0;
}

/* g++ -o sort-sr sort-student-record.cpp student-record-functions.cpp
   student-record-swap.cpp */
```

Advantage of Indirect Addressing

- During a sorting procedure, in general, many array items are **swapped**.
- When 2 items are swapped, 3 copy actions are required.
- When the array items are **big** — say, 1MB — objects, the copying actions may take **substantial** amount of computation and time.
- A common solution is to make use of **indirect addressing** and to sort using the **pointers** to the objects instead.
- The size of pointers is **fixed, independent** of the objects they point to. For a 32-bit CPU, it is 4 bytes; for a 64-bit CPU, it is 8 bytes.
- When 2 items are sorted and swapped by their **pointers**, the 3 copy actions involve only copying 4-byte pointers (for 32-bit CPU and 8-byte pointers for 64-bit CPU) which are **independent** of the size of items they point to.

Example: Sort by Pointers to Struct Objects

```
#include "student-record.h" /* File: sort-student-record-ptr.cpp */
void swap_SR_ptr(Student_Record*&, Student_Record*&);
void print_student_record(const Student_Record*);

void sort_3SR_by_id_by_ptr(Student_Record* srp[])
{
    if (srp[0]->id > srp[1]->id) swap_SR_ptr(srp[0], srp[1]);
    if (srp[0]->id > srp[2]->id) swap_SR_ptr(srp[0], srp[2]);
    if (srp[1]->id > srp[2]->id) swap_SR_ptr(srp[1], srp[2]);
}

int main()
{
    Student_Record sr[] = {
        { "Adam", 12000, 'M', CSE, { 2006 , 1 , 10 } },
        { "Bob", 11000, 'M', MATH, { 2005 , 9 , 1 } },
        { "Cathy", 10000, 'F', ECE, { 2009 , 6 , 20 } } };

    Student_Record* srp[] = { &sr[0], &sr[1], &sr[2] }; // Array of pointers
    sort_3SR_by_id_by_ptr(srp);

    for (int j = 0; j < sizeof(srp)/sizeof(Student_Record*); ++j)
        print_student_record(srp[j]);
    return 0;
} /* g++ sort-student-record-ptr.cpp student-record-ptr-functions.cpp */
```

Example: Sort by Pointers to Struct Objects ..

```
#include <iostream> /* File: student-record-ptr-functions.cpp */
#include "student-record.h"
using namespace std;

// Swap 2 Student_Record's by their pointers
void swap_SR_ptr(Student_Record*& srp1, Student_Record*& srp2)
{
    Student_Record* temp = srp1; srp1 = srp2; srp2 = temp;
}

void print_date(const Date* date)
{
    cout << date->year << '/' << date->month << '/' << date->day << endl;
}

void print_student_record(const Student_Record* x)
{
    cout << endl;
    cout.width(12); cout << "name: " << x->name << endl;
    cout.width(12); cout << "id: " << x->id << endl;
    cout.width(12); cout << "gender: " << x->gender << endl;
    cout.width(12); cout << "dept: " << dept_name[x->dept] << endl;
    cout.width(12); cout << "entry date: "; print_date(&x->entry);
}
```


Another Way of Implementing Pointer by Index

- The principle of “sort-by-pointers” is that the actual objects in an array do **not** move. Instead, their pointers move to indicate their positions during and after sorting.
- Before we have C++ pointers, one may implement the same concept by using a separate array of object indices.
- In a similar fashion, one sort the actual objects by manipulating their indices (which are conceptually equivalent to the pointers).

Example: Sort by Indices to Struct Objects

```
#include "student-record.h" /* File: sort-student-record-by-index.cpp */
void swap_SR_index(int&, int&);
void print_student_record(const Student_Record&);

void sort_3SR_by_id_by_index(Student_Record sr[], int index[])
{
    if (sr[index[0]].id > sr[index[1]].id) swap_SR_index(index[0], index[1]);
    if (sr[index[0]].id > sr[index[2]].id) swap_SR_index(index[0], index[2]);
    if (sr[index[1]].id > sr[index[2]].id) swap_SR_index(index[1], index[2]);
}

int main()
{
    Student_Record sr[] = {
        { "Adam", 12000, 'M', CSE, { 2006 , 1 , 10 } },
        { "Bob", 11000, 'M', MATH, { 2005 , 9 , 1 } },
        { "Cathy", 10000, 'F', ECE, { 2009 , 6 , 20 } } };

    int index[ ] = { 0, 1, 2 }; // Array of indices of student records
    sort_3SR_by_id_by_index(sr, index);

    for (int j = 0; j < sizeof(index)/sizeof(int); ++j)
        print_student_record(sr[index[j]]);
    return 0;
} // g++ sort-student-record-by-index.cpp student-record-by-index-functions.cpp
```

Example: Sort by Indices to Struct Objects ..

```
#include <iostream> /* File: student-record-by-index-functions.cpp */
#include "student-record.h"
using namespace std;

// Swap 2 Student_Record's by their indices
void swap_SR_index(int& index1, int& index2)
{
    int temp = index1; index1 = index2; index2 = temp;
}

void print_date(const Date& date)
{
    cout << date.year << '/' << date.month << '/' << date.day << endl;
}

void print_student_record(const Student_Record& x)
{
    cout << endl;
    cout.width(12); cout << "name: " << x.name << endl;
    cout.width(12); cout << "id: " << x.id << endl;
    cout.width(12); cout << "gender: " << x.gender << endl;
    cout.width(12); cout << "dept: " << dept_name[x.dept] << endl;
    cout.width(12); cout << "entry date: "; print_date(x.entry);
}
```