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ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ

Εισαγωγή στον Προγραμματισμό
Introduction to Programming

Διάλεξη 15: Διανύσματα και Ελεύθερη Αποθήκευση

Γ. Παπαγιαννάκης

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επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο
ΕΣΠΑ 2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

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HY-150 Προγραμματισμός
CS-150 Programming

Lecture 15:
Vector and Free store

G. Papagiannakis

Abstract

- Vector is not just the most useful standard container,
  - it is also provides examples of some of the most important/powerful/ interesting implementation techniques.
  - In this and the following lectures, we go through a series of increasingly sophisticated vector implementations,
  - seeing classical problems related to use of memory and providing solutions.
  - Here, we discuss free store (heap storage) management, and pointers.

Overview

- Vector revisited
  - How are they implemented?
- Pointers and free store
  - Allocation (new)
  - Access
    - Arrays and subscripting: []
    - Dereferencing: *
  - Deallocation (delete)
- Destructors
- Copy constructor and copy assignment
- Arrays
- Array and pointer problems
- Changing size
- Templates
- Range checking and exceptions

Vector

- Vector is the most useful container
  - Simple
  - Compactly stores elements of a given type
  - Efficient access
  - Expands to hold any number of elements
  - Optionally range-checked access
- How is that done?
  - That is, how is vector implemented?
    - We'll answer that gradually, feature after feature
- Vector is the default container
  - prefer vector for storing elements unless there's a good reason not to

Building from the ground up

- The hardware provides memory and addresses
  - Low level
  - Untyped
  - Fixed-sized
  - No checking
  - As fast as the hardware architects can make it
- The application builder needs something like a vector
  - Higher-level operations
  - Type checked
  - Size varies (as we get more data)
  - Run-time checking
  - Close-to optimally fast

Building from the ground up

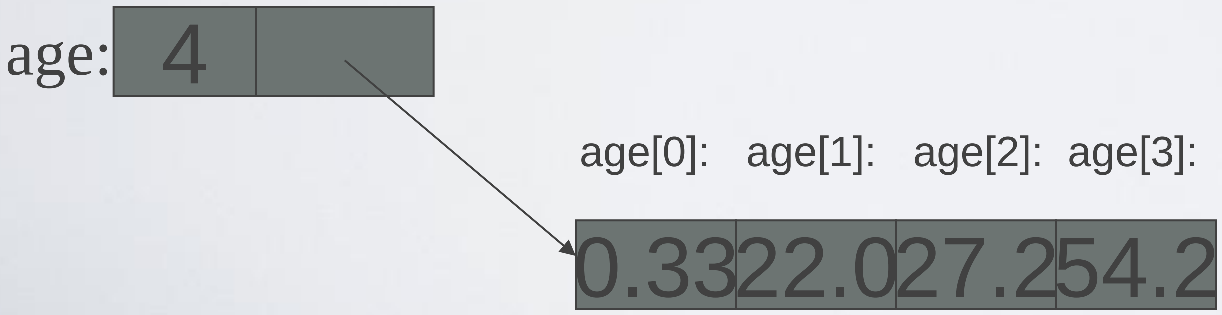
- At the lowest level, close to the hardware, life's simple and brutal
  - You have to program everything yourself
  - You have no type checking to help you
  - Run-time errors are found when data is corrupted or the program crashes
- We want to get to a higher level as quickly as we can
  - To become productive and reliable
  - To use a language "fit for humans"
- Chapter 17-19 basically shows all the steps needed
  - The alternative to understanding is to believe in "magic"
  - The techniques for building vector are the ones underlying all higher-level work with data structures

Vector

- A **vector**
  - Can hold an arbitrary number of elements
    - Up to whatever physical memory and the operating system can handle
  - That number can vary over time
    - E.g. by using **push_back()**
  - Example

vector<double> age(4);

age[0]=.33; age[1]=22.0; age[2]=27.2; age[3]=54.2;



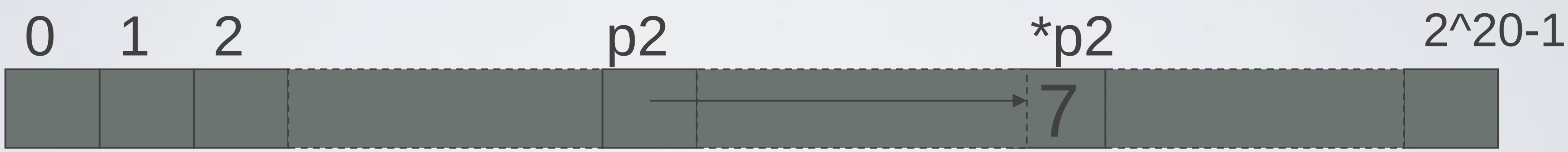
Vector

```
// a very simplified vector of doubles (like vector<double>):
class vector {
   int sz;            // the number of elements ("the size")
   double* elem;      // pointer to the first element
public:
   vector(int s);                 // constructor: allocate s elements,
                                  // let elem point to them
                                  // store s in sz
   int size() const { return sz; }     // the current size
};
```

- ***** means "pointer to" so **double*** is a "pointer to **double**"
  - What is a "pointer"?
  - how do we make a pointer "point to" elements?
  - How do we "allocate" elements?

Pointer values

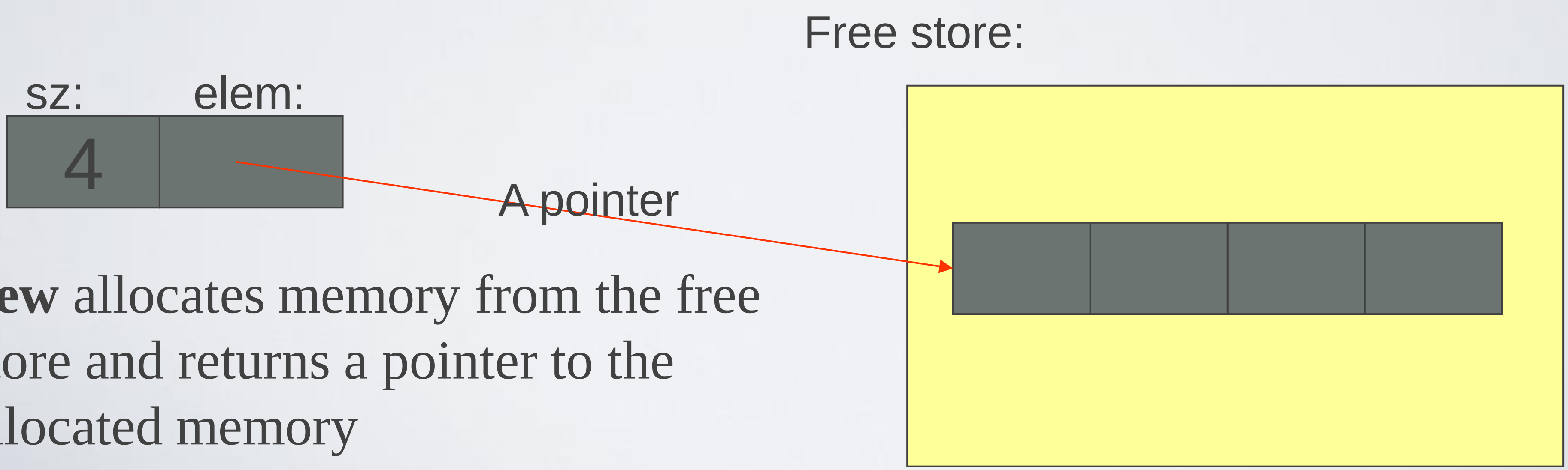
- Pointer values are memory addresses
  - Think of them as a kind of integer values
  - The first byte of memory is 0, the next 1, and so on



- A pointer points to an object of a given type
  - E.g. a double* points to a double, not to a string
- A pointer's type determines how the memory referred to by the pointer's value is used
  - E.g. what a double* points to can be added not, say, concatenated

Vector (constructor)

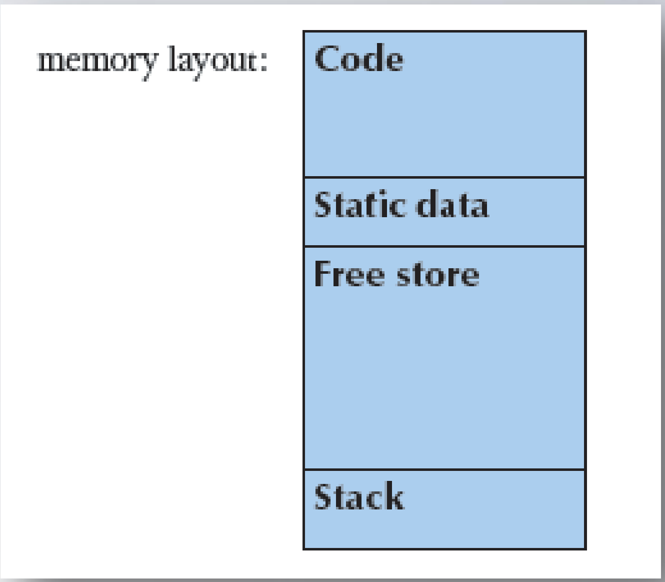
```
vector::vector(int s)        // vector's constructor
    :sz(s),                  // store the size s in sz
     elem(new double[s])     // allocate s doubles on the free store
                             // store a pointer to those doubles in elem
{
}
// Note: new does not initialize elements (but the standard vector does)
```



new allocates memory from the free store and returns a pointer to the allocated memory

The computer's memory

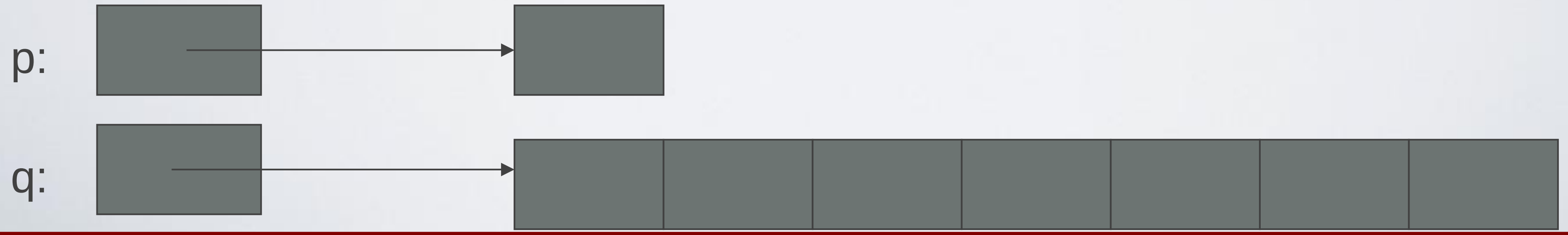
- As a program sees it
  - Local variables "lives on the stack"
  - Global variables are "static data"
  - The executable code are in "the code section"



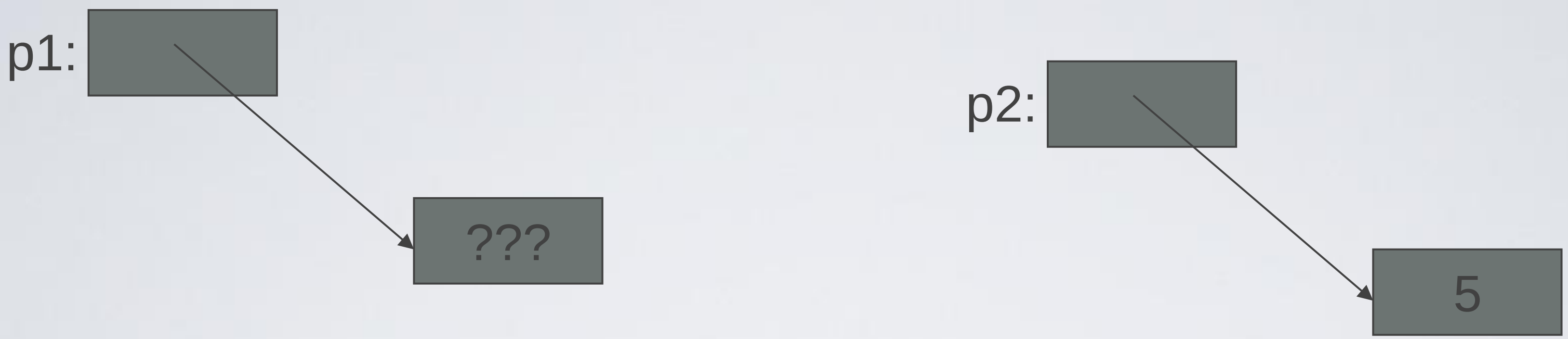
The free store

(sometimes called "the heap")

- You request memory "to be allocated" "on the free store" by the **new** operator
  - The **new** operator returns a pointer to the allocated memory
  - A pointer is the address of the first byte of the memory
  - For example
    - **int* p = new int;** *// allocate one uninitialized **int***
      *// **int*** means "pointer to **int**"*
    - **int* q = new int[7];** *// allocate seven uninitialized **ints***
      *// "an array of 7 **ints**"*
    - **double* pd = new double[n];** *// allocate **n** uninitialized **doubles***
  - A pointer points to an object of its specified type
  - A pointer does ***not*** know how many elements it points to



Access

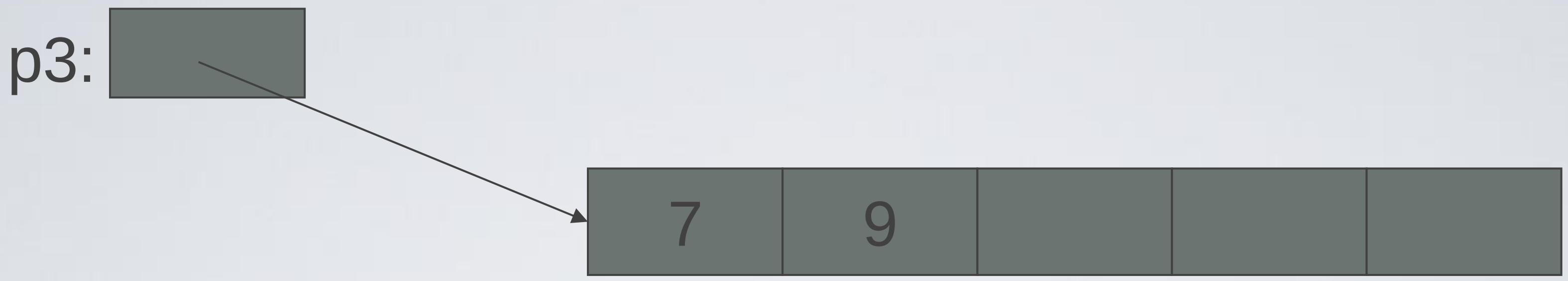


- Individual elements

```
int* p1 = new int;          // get (allocate) a new uninitialized int
int* p2 = new int(5);       // get a new int initialized to 5

int x = *p2;                // get/read the value pointed to by p2
                            // (or "get the contents of what p2 points to")
                            // in this case, the integer 5
int y = *p1;
                            // undefined: y gets an undefined value; don't do that
```

Access



- Arrays (sequences of elements)

```
int* p3 = new int[5];   // get (allocate) 5 ints
                        // array elements are numbered 0, 1, 2, …

p3[0] = 7;              // write to ("set") the 1st element  of p3
p3[1] = 9;

int x2 = p3[1];         // get the value of the 2nd element of p3

int x3 = *p3;           // we can also use the dereference operator * for an array
                        // *p3 means p3[0]  (and vice versa)
```

Why use free store?

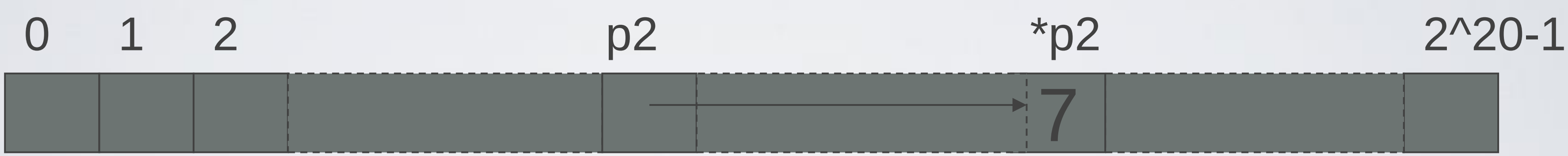
- To allocate objects that have to outlive the function that creates them:
  - For example

```
double* make(int i)
{
    return new double[i];
}
```

  - Another example: vector's constructor

Pointer values

- Pointer values are memory addresses
  - Think of them as a kind of integer values
  - The first byte of memory is 0, the next 1, and so on

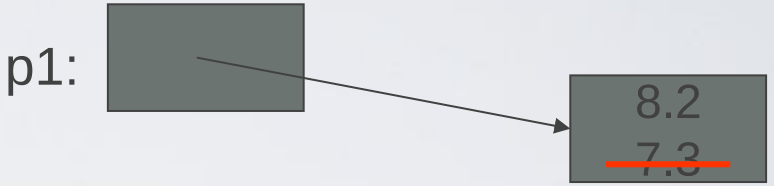



```
// you can see pointer value (but you rarely need/want to):
char* p1 = new char('c');        // allocate a char and initialize it to 'c'
int* p2 = new int(7);            // allocate an int and initialize it to 7
cout << "p1==" << p1 << " *p1==" << *p1 << "\n";  // p1==??? *p1==c
cout << "p2==" << p2 << " *p2==" << *p2 << "\n";  // p2==??? *p2=7
```

Access

- A pointer does **not** know the number of elements that it's pointing to (only the address of the first element)

```
double* p1 = new double;
*p1 = 7.3;          // ok
p1[0] = 8.2;        // ok
p1[17] = 9.4;       // ouch! Undetected error
p1[-4] = 2.4;       // ouch! Another undetected error
```



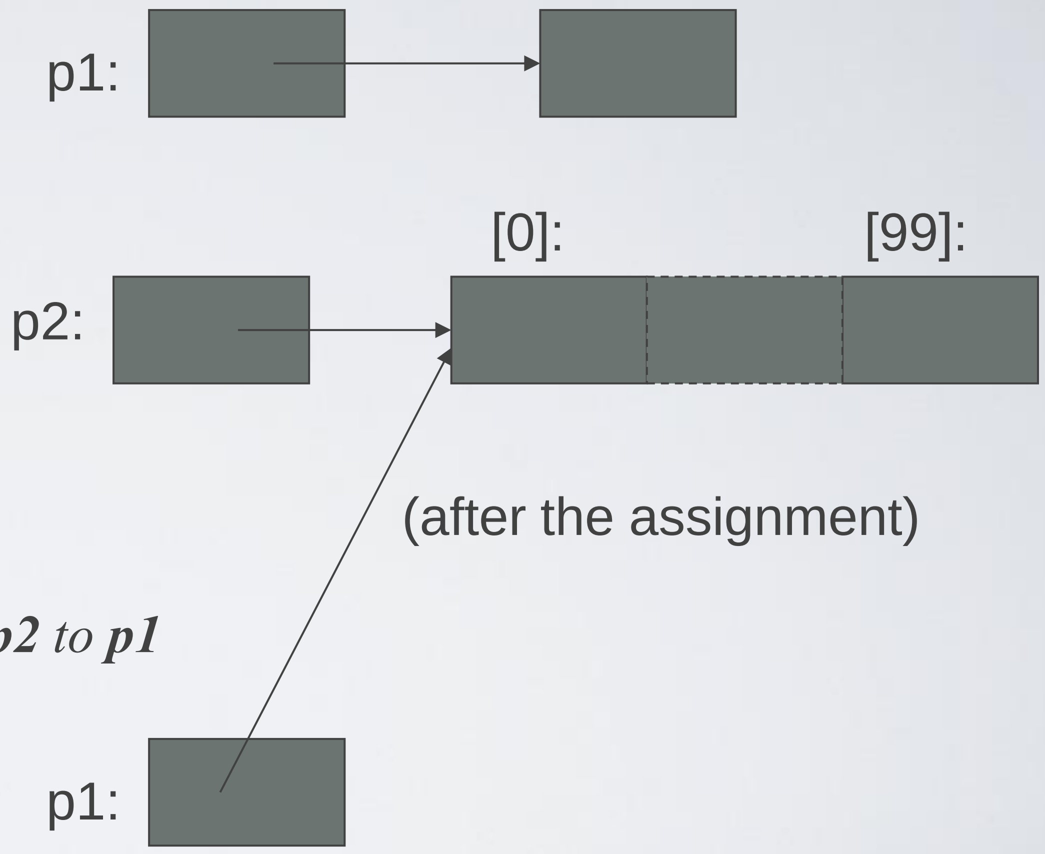

```
double* p2 = new double[100];
*p2 = 7.3;          // ok
p2[17] = 9.4;       // ok
p2[-4] = 2.4;       // ouch! Undetected error
```

Access

- A pointer does ***not*** know the number of elements that it's pointing to

double* p1 = new double;

double* p2 = new double[100];



p1[17] = 9.4; *// error (obviously)*

p1 = p2; *// assign the value of* ***p2*** *to* ***p1***

p1[17] = 9.4; *// now ok:* ***p1*** *now points to the array of 100* ***doubles***

Access

- A pointer ***does*** know the type of the object that it's pointing to

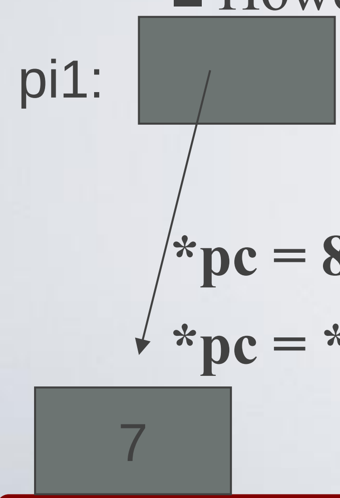
int* pi1 = new int(7);

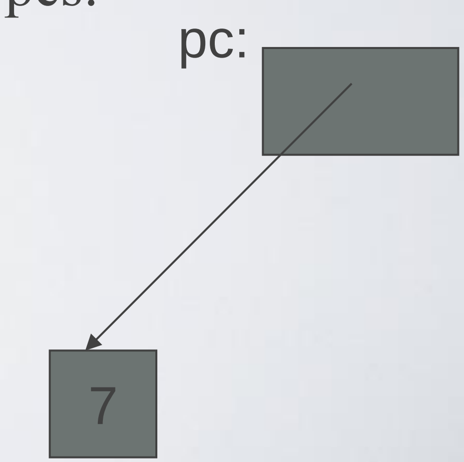
int* pi2 = pi1; *// ok: **pi2** points to the same object as **pi1***

double* pd = pi1; *// error: can't assign an **int*** to a **double****

char* pc = pi1; *// error: can't assign an **int*** to a **char****

  - There are no implicit conversions between a pointer to one value type to a pointer to another value type
  - However, there are implicit conversions between value types:





pc = 8;** *// ok: we can assign an **int** to a **char

pc = *pi1;** *// ok: we can assign an **int** to a **char

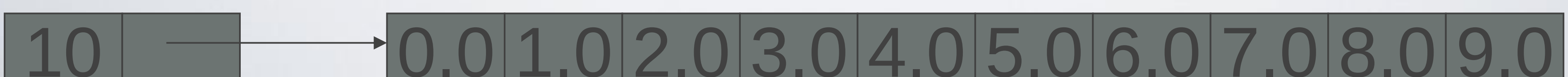
Pointers, arrays, and vector

- Note
  - With pointers and arrays we are "touching" hardware directly with only the most minimal help from the language. Here is where serious programming errors can most easily be made, resulting in malfunctioning programs and obscure bugs
    - Be careful and operate at this level only when you really need to
  - vector is one way of getting almost all of the flexibility and performance of arrays with greater support from the language (read: fewer bugs and less debug time).

Vector (construction and primitive access)

```
// a very simplified vector of doubles:
class vector {
   int sz;               // the size
   double* elem;  // a pointer to the elements
public:
   vector(int s) :sz(s), elem(new double[s]) { }        // constructor
   double get(int n) { return elem[n]; }                 // access: read
   void set(int n, double v) { elem[n]=v; }              // access: write
   int size() const { return sz; }                       // the current size
};

vector v(10);
for (int i=0; i<v.size(); ++i) { v.set(i,i); cout << v.get(i) << ' '; }
```



A problem: memory leak

```
double* calc(int result_size, int max)
{
    double* p = new double[max];  // allocate another max doubles
                                  // i.e., get max doubles from the free store
    double* result = new double[result_size];
    // … use p to calculate results to be put in result …
    return result;
}

double* r = calc(200,100);        // oops! We "forgot" to give the memory
                                  // allocated for p back to the free store
```

- Lack of de-allocation (usually called "memory leaks") can be a serious problem in real-world programs
- A program that must run for a long time can't afford any memory leaks

A problem: memory leak

```
double* calc(int result_size, int max)
{
    int* p = new double[max];          // allocate another max doubles
                                       // i.e., get max doubles from the free store
    double* result = new double[result_size];
    // … use p to calculate results to be put in result …
    delete[ ] p;                       // de-allocate (free) that array
                                       // i.e., give the array back to the free store
    return result;
}

double* r = calc(200,100);
// use r
delete[ ] r;                           // easy to forget
```

Memory leaks

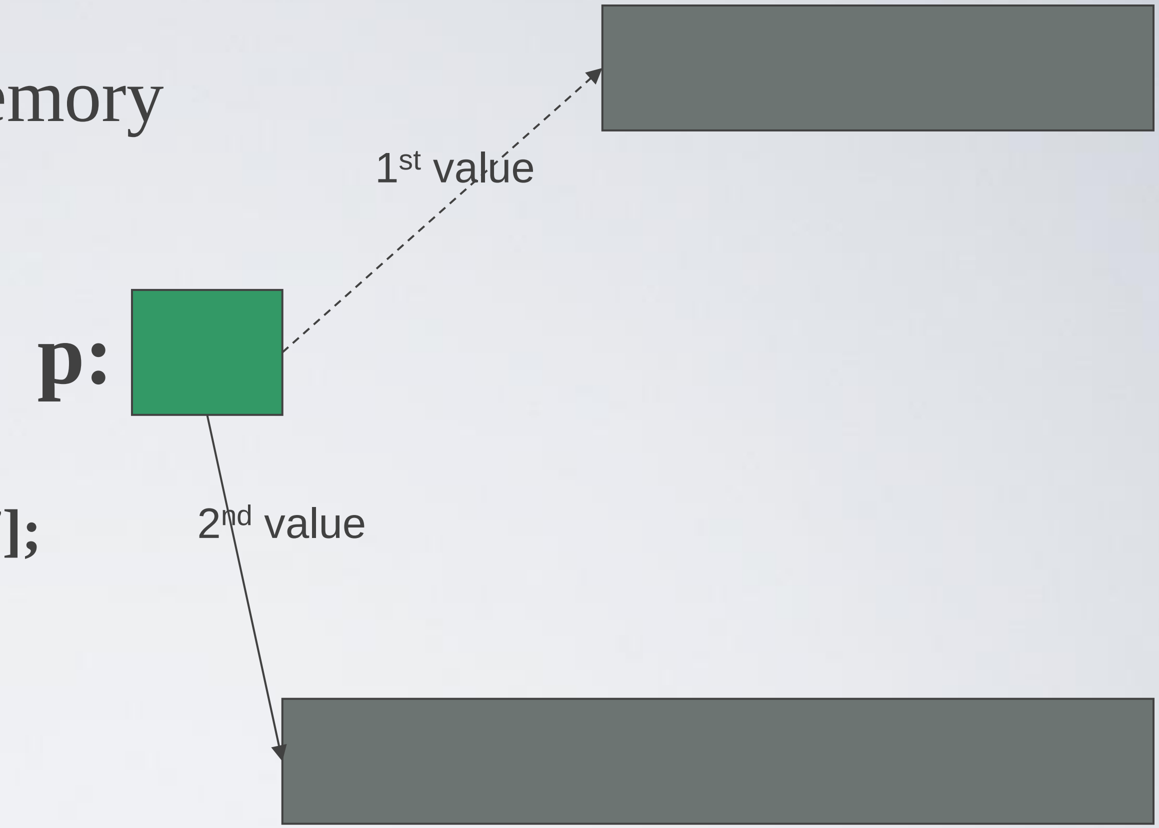
- A program that needs to run "forever" can't afford any memory leaks
  - An operating system is an example of a program that "runs forever"
- If a function leaks 8 bytes every time it is called, how many days can it run before it has leaked/lost a megabyte?
  - Trick question: not enough data to answer, but about 130,000 calls
- All memory is returned to the system at the end of the program
  - If you run using an operating system (Windows, Unix, whatever)
- Program that runs to completion with predictable memory usage may leak without causing problems
  - *i.e.*, memory leaks aren't "good/bad" but they can be a problem in specific circumstances

Memory leaks

- Another way to get a memory leak

```
void f()
{
   double* p = new double[27];
   // …
   p = new double[42];
   // …
   delete[] p;
}

// 1st array (of 27 doubles) leaked
```



Memory leaks

- How do we systematically and simply avoid memory leaks?
  - don't mess directly with **new** and **delete**
    - Use **vector**, etc.
  - Or use a garbage collector
    - A garbage collector is a program the keeps track of all of your allocations and returns unused free-store allocated memory to the free store (not covered in this course; see http://www.research.att.com/~bs/C++.html)
    - Unfortunately, even a garbage collector doesn’t prevent all leaks

A problem: memory leak

```
void f(int x)
{
    vector v(x);        // define a vector
                        // (which allocates x doubles on the free store)
    // ... use v ...

    // give the memory allocated by v back to the free store
    // but how? (vector's elem data member is private)
}
```

Vector (destructor)

```
// a very simplified vector of doubles:
class vector {
    int sz;              // the size
    double* elem;        // a pointer to the elements
public:
    vector(int s)                    // constructor: allocates/acquires memory
            :sz(s), elem(new double[s]) { }
    ~vector()                        // destructor: de-allocates/releases memory
            { delete[ ] elem; }
    // ...
};
```

- Note: this is an example of a general and important technique:
  - acquire resources in a constructor
  - release them in the destructor
- Examples of resources: memory, files, locks, threads, sockets

A problem: memory leak

```
void f(int x)
{
   int* p = new int[x];   // allocate x ints
   vector v(x);           // define a vector (which allocates another x ints)
   // ... use p and v ...
   delete[ ] p;     // deallocate the array pointed to by p
   // the memory allocated by v is implicitly deleted here by vector's destructor
}
```

- The **delete** now looks verbose and ugly
  - How do we avoid forgetting to **delete[ ] p**?
  - Experience shows that we often forget
- Prefer **delete**s in destructors

Free store summary

- Allocate using **new**
  - New allocates an object on the free store, sometimes initializes it, and returns a pointer to it
    - **int* pi = new int;** *// default initialization (none for **int**)*
    - **char* pc = new char('a');** *// explicit initialization*
    - **double* pd = new double[10];** *// allocation of (uninitialized) array*
  - New throws a **bad_alloc** exception if it can't allocate
- Deallocate using **delete** and **delete[ ]**
  - **delete** and **delete[ ]** return the memory of an object allocated by **new** to the free store so that the free store can use it for new allocations
    - **delete pi;** *// deallocate an individual object*
    - **delete pc;** *// deallocate an individual object*
    - **delete[ ] pd;** *// deallocate an array*
  - Delete of a zero-valued pointer ("the null pointer") does nothing
    - **char* p = 0;**
    - **delete p;** *// harmless*

void*

- **void*** means "pointer to some memory that the compiler doesn't know the type of"
- We use **void*** when we want to transmit an address between pieces of code that really don't know each other's types – so the programmer has to know
  - Example: the arguments of a callback function
- There are no objects of type **void**
  - **void v;** *// error*
  - **void f();** *// f() returns nothing – f() does **not** return an object of type **void***
- Any pointer to object can be assigned to a **void***
  - **int* pi = new int;**
  - **double* pd = new double[10];**
  - **void* pv1 = pi;**
  - **void* pv2 = pd;**

void*

- To use a **void*** we must tell the compiler what it points to

```
void f(void* pv)
{
    void* pv2 = pv;         // copying is ok (copying is what void*s are for)
    double* pd = pv;        // error: cannot convert void* to double*
    *pv = 7;                // error: you can't dereference a void*
                            // good! The int 7 is not represented  like the double 7.0)
    pv[2] = 9;              // error: you can's subscript a void*
    pv++;                   // error: you can't increment a void*
    int* pi = static_cast<int*>(pv);        // ok: explicit conversion
    // …
}
```

- A **static_cast** can be used to explicitly convert to a pointer to object type
  - "**static_cast**" is a deliberately ugly name for an ugly (and dangerous) operation – use it only when absolutely necessary

void*

- **void*** is the closest C++ has to a plain machine address
  - Some system facilities require a **void***
  - Remember FLTK callbacks?
    - **Address** is a **void***:

```
typedef void* Address;

void Lines_window::cb_next(Address,Address)
```

Pointers and references I

- Think of a reference as an automatically dereferenced pointer
  - Or as “an alternative name for an object”
  - A reference must be initialized
  - The value of a reference cannot be changed after initialization

```
int x = 7;
int y = 8;
int* p = &x;
*p = 9;        ///Iuse * to assign to x through p
p = &y;        // ok
int& r = x; x = 10;
r = &y;        // error (and so is all other attempts to change what r refers to)
```

Pointers and references II

- Pointers example

```
int x = 10;
int* p = &x;          // you need & to get a pointer
*p = 7;               // use * to assign to x through p
int x2 = *p;          // read x through p
int* p2 = &x2;        // get a pointer to another int
p2 = p;               // p2 and p both point to x
p = &x2;              // make p point to another object
```

- Equivalent references example

```
int y = 10;
int& r = y;       // the & is in the type, not in the initializer
r = 7;            // assign to y through r (no * needed)
int y2 = r;       // read y through r (no * needed)
int& r2 = y2;     // get a reference to another int
r2 = r;           // the value of y is assigned to y2
r = &y2;          // error: you can't change the value of a reference
                  // (no assignment of an int* to an int&)
```

Next lecture

- The next lecture discusses copying and arrays

Acknowledgements

Bjarne Stroustrup

Programming -- Principles and Practice Using C++

http://www.stroustrup.com/Programming/

Thank you!

Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο
ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ
ΕΣΠΑ 2007-2013
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ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης