Ve 280

Programming and Introductory Data Structures

Dynamic Memory Allocation; Overloading, Default Arguments; Destructor

Learning Objectives:

Understand how dynamic memory allocation works

Know how to define arrays whose sizes are determined at runtime

Know what overloading is and how to have default arguments in functions

Know what a destructor is, how to write one, and when it is needed

Outline

- Dynamic Memory Allocation
- Dynamic Arrays
- Overloaded Constructor and Default Argument
- Destructor

Memory

Dynamic Allocation

- So far, the data structures we've **built** have all had room for "at most N" elements.
  - E.g., the two `IntSet` implementations could have at most `MAXELTS` distinct integers.
- Sometimes, a **fixed-sized** structure is reasonable.
  - E.g., a deck of cards has 52 individual cards in it
- However, there is no meaningful sense in which "a set of integers" is limited to some particular size.
  - No matter how big you make the set's capacity, an application that needs more will eventually come along.

Memory

Dynamic Allocation

- We have seen two types of variables so far:
  1. Global Variables
  2. Local Variables

1. Global Variables
   - These are defined anywhere outside of a function definition.
   - Space is set aside for these variables **before** the program begins its execution, and is reserved for them **until** the program completes.
   - This space is reserved at **compile time**.

Memory

Dynamic Allocation

2. Local Variables
   - Local variables are defined **within a block**.
     - These include function arguments.
   - Space is set aside for these variables when the relevant block is entered, and is reserved for them until the block is exited.
   - This space is reserved at **run time**, but the size is known to the compiler.

- Since the compiler must know how big all of these variables will be, it is **static** information, and must be declared by the programmer.

Memory

Dynamic Allocation

- It turns out that there is a **third** type of object you can create, a "**dynamic**" one.
- They are dynamic in the sense that the compiler:
  - Doesn't need to know **how big it is.**
  - Doesn't need to know **how long it lives.**

- For example:
  - Our implementation of `IntSet` should be able to grow as big as any client needs it to grow, subject to the limits of the physical machine.
  - The `IntSet` should last as long as the client needs to use it, after which the **client** should be the one responsible for **destroying** it.

Memory

Dynamic Allocation

- Dynamic object creation is accomplished through the **dynamic storage management** facilities in the language.

- These facilities consist of two operations:
  - **`new`**: Reserve space for an object of some type, initialize the object, and return a pointer to it.
  - **`delete`**: Given a pointer to an object **created by new**, destroy the object and release the space previously occupied by that object.

Memory

Dynamic Allocation – new

```
int *ip = new int;
```

- This creates a new space for an integer, and returns a pointer to that space, assigning it to `ip`.
- Note that we didn't do anything to initialize the integer – it could be any random integer value.
- We can initialize it to a specific value with an "initializer":

```
int *ip = new int(5);
```

- We can also `new` a class type. E.g.,

```
IntSet *isp = new IntSet;
```

- The **constructor** is called. `isp` points to an empty `IntSet` object with zero elements.

Memory

Dynamic Allocation – delete

- If objects were created by `new`, they can be destroyed by `delete`:

```
delete ip;
```

- This **releases the space**.

- Note: you cannot **`delete`** an object not created by **`new`**!

```
int a = 5;
int *ip = &a;
delete ip; // Error
```

Memory

Dynamic Allocation – delete

- We can also destroy instances of class that were created by new:

```
delete isp;
```

- In this specific case (deleting an `IntSet`), the `IntSet` consists of only "ordinary" types (`int`s, arrays-of-`int`s), so we don't need to do anything to destroy it.
- That won't be true of all class-destruction events!
- Just as we have **constructors** to create objects, sometimes we will need **destructors** to properly destroy them.
  - We will see this later …

Memory

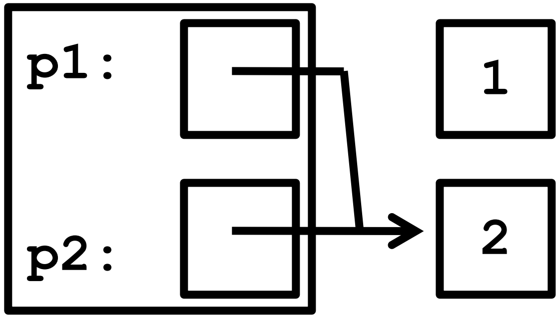
Dynamic Allocation – delete

- Note that a dynamic object's lifetime is completely under the control of the program – it lives until it is **explicitly** destroyed.
- This is true even if you "forget" the pointer to the object.

```
int *p1 = new int(1);
int *p2 = new int(2);
p1 = p2;
```

Any problem?

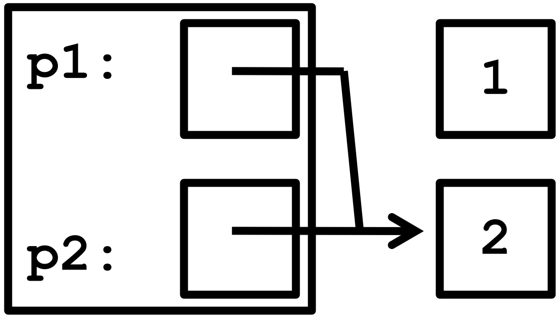
- This leaves us with:



Memory

Dynamic Allocation – delete

```
int *p1 = new int(1);
int *p2 = new int(2);
p1 = p2;
```



- Two pointers point to the object "2", and **none** to the object "1".
- There is no way to release the memory occupied by "1“.
- And worse:

```
delete p1;
delete p2;
```

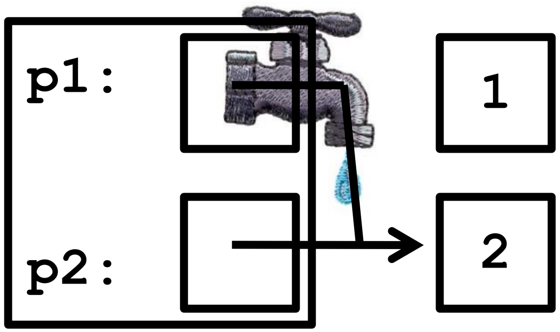
"releases" the memory reserved for "2" **twice**.

- This is surly not good!

Memory

Dynamic Allocation – delete

- Note there is an important difference between the lifetime of a pointer variable and the lifetime of the object it points to!



- In the previous example, exiting the block that defines p1 causes the local object p1 to vanish, but the dynamic object it points to remains!
- This leaves us with an allocated dynamic object that we have no means of recycling. This is called a **memory leak**.
- If memory leaks occur often enough, your program may reach a point where it can no longer allocate new dynamic objects.

Checking Memory Leak

- Tool to use: `valgrind`
- Command:

```
valgrind --leak-check=full ./program <args>
```

  - Function: search for memory leaks and give details of each individual leak.

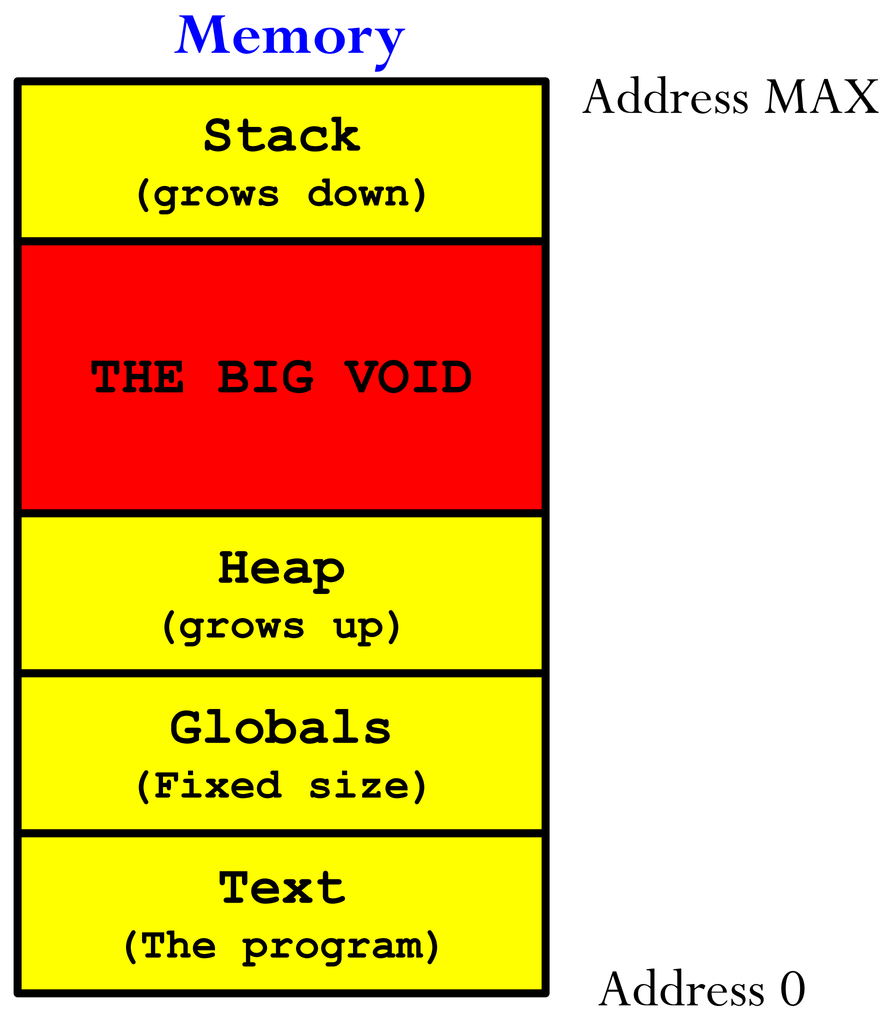
  - To install, type the command:

    ```
    sudo apt-get install valgrind
    ```

Memory

The heap

- The space for objects created via `new` comes from a location in memory called the **heap**.
  - Stack is for function calls.



Outline

- Dynamic Memory Allocation
- Dynamic Arrays
- Overloaded Constructor and Default Argument
- Destructor

Dynamic Arrays

Creating

- So far, the things we create **dynamically** have sizes **known** to the compiler.
  - E.g., `int`, `IntSet`
- However, one can also create objects whose sizes are **unknown** to the compiler, by creating **dynamic arrays**.
- Syntax:

```
int *ia = new int[5];
```

  It creates an array of five integers in the heap, and stores a pointer to the first element of that array in `ia`.

- The size is put inside []. It could even be a variable.

```
int n = 20;
int *ia= new int[n];
```

Dynamic Arrays

Freeing

- Freeing an array works slightly differently than freeing a single object:

```
delete[] ia;
```

- If you allocate an **array-of-T**, you **absolutely must** use the `delete[]` operator, and **not** the "plain" `delete` operator.
- They are completely different:
  - Mixing them leads to undefined behavior.

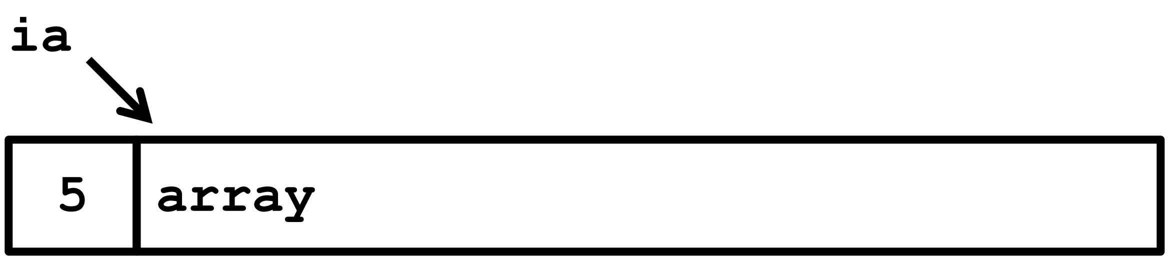
Dynamic Arrays

Freeing

- When the new operator sees it is allocating an array, it stores the **size of the array** along with the array.
- It does this by carving out space for the array, plus a bit extra:

- The space **before** the array records the number of elements in the array, in this case, 5:

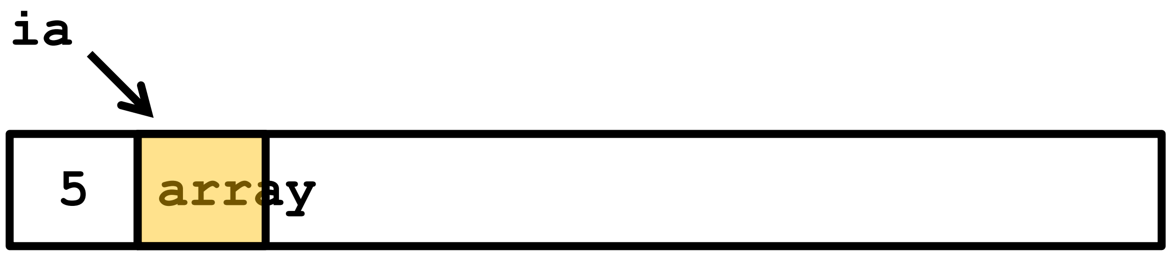
- And a pointer to the beginning of the array is returned:



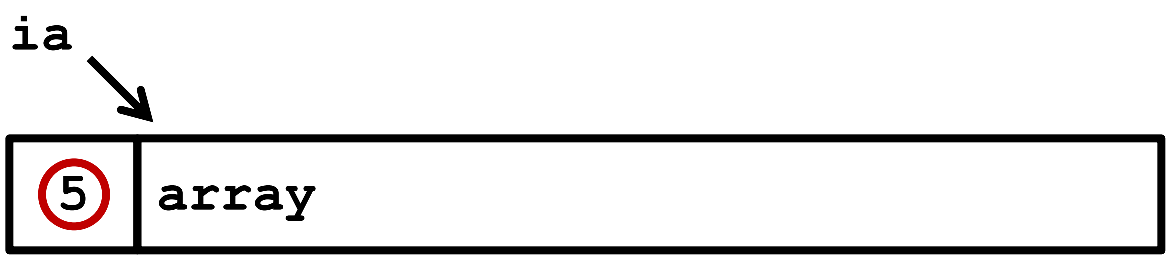
Dynamic Arrays

Freeing

- Now, if you just `delete ia;` the `delete` operator thinks it is only returning enough space for a single integer to the heap.



- The `delete[]` operator knows to look "just before" the pointer, to see **how many** elements to return to the heap.



Dynamic Arrays

Building a new `IntSet`

- We now build a version of `IntSet` that allows the client to specify how large the capacity of the set should be.

- The data elements will change slightly:

Rather than hold an array explicitly, we have a pointer that will (eventually) point to a dynamically-created array.

```
class IntSet {
  int *elts;     // pointer to dynamic array
  int sizeElts;  // capacity of array
  int numElts;   // current occupancy
public:
  ...
};
```

- **`sizeElts` tells us the size of the allocated array (which is not necessarily `MAXELTS`)**
- **`numElts` still tells us how many elements there actually are.**

Dynamic Arrays

Building a new `IntSet`

- We now build a version of `IntSet` that allows the client to specify how large the capacity of the set should be.

- The data elements will change slightly:

```
class IntSet {
   int *elts;     // pointer to dynamic array
   int sizeElts; // capacity of array
   int numElts;  // current occupancy
public:
   ...
};
```

Which member functions should be changed?

Dynamic Arrays

Building a new `IntSet`

- We'll base our changes on the **unsorted** implementation.
- The methods are mostly unchanged. There is a new **default constructor**:

```
IntSet::IntSet() {
  // Allocate the "default-size" array
  elts = new int[MAXELTS];
  sizeElts = MAXELTS;
  numElts = 0;
}
```

Dynamic Arrays

Building a new `IntSet`

- Alternatively, we can write the default constructor using the **initialization syntax**:

```
IntSet::IntSet(): elts(new int[MAXELTS]),
    sizeElts(MAXELTS), numElts(0)
{
}
```

Which Statements Are True?

Select all the correct answers.

- **A.** When using a fixed-sized data structure, it's better to set the capacity as large as possible.
- **B.** A structure whose size is chosen at runtime uses memory more efficiently.
- **C.** Using fixed-sized data structures is simpler than using data structures whose size is determined at runtime.
- **D.** Data structures whose sizes are determined at runtime should be preferred.

Outline

- Dynamic Memory Allocation
- Dynamic Arrays
- Overloaded Constructor and Default Argument
- Destructor

Dynamic Arrays

Building a new `IntSet`

- In addition to the default, we can write an "alternate constructor".
- It has the same name as the default, but a different type signature:

```
class IntSet {
  int *elts;    // pointer to dynamic array
  int sizeElts; // capacity of array
  int numElts;  // current occupancy
 public:
  IntSet();   // default constructor
    // EFFECTS: create a MAXELTS capacity set
  IntSet(int size); // constructor with
                    // explicit capacity
    // REQUIRES: size > 0
    // EFFECTS: create a size capacity set
};
```

Function Overloading

- This is called **function overloading**.
  - Two different functions with exactly the **same name**, but **different argument count** and/or **argument types**.

a) int average(int a, int b);

b) double average(double a, double b);

c) int average(int a, int b, int c);

- Compiler tells which function to call based on the actual argument count and types.

average(2, 3); → int average(int a, int b);

average(2, 3, 5); → int average(int a, int b, int c);

average(2.0, 3.0); → double average(double a, double b);

Dynamic Arrays

Building a new `IntSet`

- The alternate constructor creates an array of the specified size:

```
IntSet::IntSet(int size): elts(new int[size]),
     sizeElts(size), numElts(0)
{
}
```

Dynamic Arrays

Building a new `IntSet`

- Since the compiler knows the argument count and types, it can pick the "right" constructor when a new object is created.

- For example:

```
IntSet is1;  // No arguments
             // Call default constructor
IntSet is2(200); // Integer argument
                 // Call alternate
```

Dynamic Arrays

Building a new `IntSet`

```
IntSet::IntSet(int size):
  elts(new int[size]),
  sizeElts(size),
  numElts(0) {
}
```

```
IntSet::IntSet():
  elts(new int[MAXELTS]),
  sizeElts(MAXELTS),
  numElts(0) {
}
```

- Notice that the two constructors are nearly identical:
  - The only difference is whether we use `size` or `MAXELTS`.
  - Otherwise the code is duplicated.
- This is bad: when we find ourselves writing the same code over and over, we should try to use parametric generalization.

Dynamic Arrays

Building a new constructor

- One way to solve this problem of duplicate definitions is to use **default argument**.
- We can define **just one** constructor, but make its argument **optional**.
- First, we have to re-declare the constructor in IntSet:

```
class IntSet {
  int *elts;     // pointer to dynamic array
  int sizeElts; // capacity of array
  int numElts;  // current occupancy
public:
  IntSet( int size = MAXELTS );
    // EFFECTS: create a set with specified
    //    capacity.  It defaults to MAXELTS if
    //    not supplied.
};
```

Default Argument

- `int add(int a, int b, int c = 1)`
  - The default value of c is 1.

- Using default arguments allows you to call the function with different number of arguments.

```
add(1, 2) // a = 1, b = 2, c = 1 (default value)
add(1, 2, 3) // a = 1, b = 2, c = 3
```

- There could be multiple default arguments in a function, but they must be the last arguments.

```
int add(int a, int b = 0, int c = 1) // OK
int add(in a, int b = 1, int c) // Error
```

Dynamic Arrays

Building a new constructor

- Then, we implement the constructor in a same way as before.

```
IntSet::IntSet(int size):
   elts(new int[size]), sizeElts(size),
   numElts(0)
{
}
```

Don't add "**= MAXELTS**"!

Outline

- Dynamic Memory Allocation
- Dynamic Arrays
- Overloaded Constructor and Default Argument
- Destructor

Problem

- There is a problem with what we've built so far.
- What happens if we have a local `IntSet` inside of a function and the function returns?
- Answer: **Memory leak**! Because link to the `elts` array in `IntSet` is lost.

```
class IntSet {
   int *elts;     // pointer to dynamic array
   int sizeElts; // capacity of array
   int numElts;  // current occupancy
public:
   ...
};
```

Question

- Is this a problem with the "static" version of `IntSet`? Why?

```
void foo() {
   IntSet is2;
   // Do work with is2 in some way
}
```

```
class IntSet {
  int elts[MAXELTS];
  int numElts;  // current occupancy

public:
  ...
};
```

Dynamic Arrays

How to solve the leak

- To solve this memory leak, we have to de-allocate the integer array whenever the "enclosing" `IntSet` is destroyed.
- We do this with a **destructor** and it is the opposite of a constructor.
  - The constructor ensures that the object is a legal instance of its class and the destructor's job is to destroy the object.
- In a class where its methods (including the constructor) allocate **dynamic storage**, the destructor is responsible for **de-allocating** it.

The Destructor

```
class IntSet {
  int *elts;     // pointer to dynamic array
  int sizeElts; // capacity of array
  int numElts;  // current occupancy
public:
  IntSet(int size = MAXELTS);
    // EFFECTS: create a set with size capacity;
    //          capacity is MAXELTS by default.
  ~IntSet(); // Destroy this IntSet
  ...
};

IntSet::~IntSet() {
  delete[] elts;
}
```

Note that we have to use the array-based `delete` operator, not the "standard" `delete` operator

The Destructor

```
class IntSet {
  int *elts;     // pointer to dynamic array
  int sizeElts; // capacity of array
  int numElts;  // current occupancy
public:
  IntSet(int size = MAXELTS);
    // EFFECTS: create a set with size capacity;
    //          capacity is MAXELTS by default.
  ~IntSet(); // Destroy this IntSet
  ...
};

IntSet::~IntSet() {
  delete[] elts;
}
```

When the `IntSet` is destroyed, the elements in the array will first be deleted.

The Destructor

```
class IntSet {
  int *elts;     // pointer to dynamic array
  int sizeElts; // capacity of array
  int numElts;  // current occupancy
public:
  IntSet(int size = MAXELTS);
    // EFFECTS: create a set with size capacity;
    //          capacity is MAXELTS by default.
  ~IntSet(); // Destroy this IntSet
  ...
};

IntSet::~IntSet() {
  delete[] elts;
}
```

Note: the destructors for any ADTs declared locally within a block of code are called automatically when the block ends.

Dynamic Arrays

Dynamic `IntSet`

- The new definition of IntSet can be created/destroyed dynamically, just like anything else:

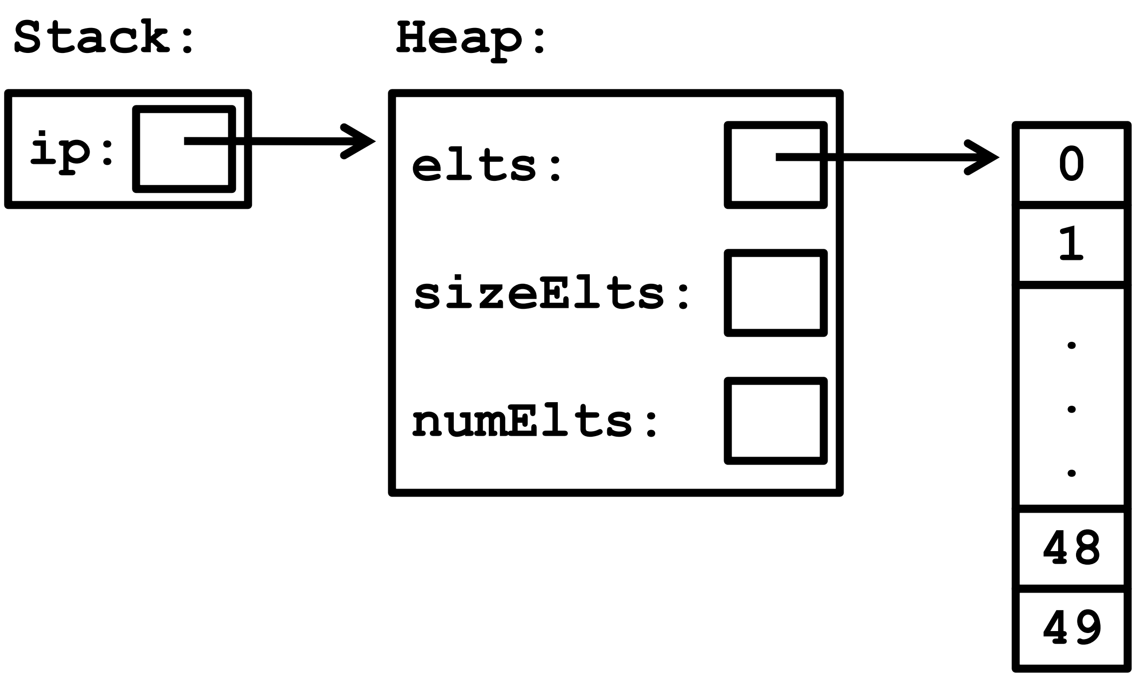
```
// a non-standard size
IntSet *ip = new IntSet(50);

... // do stuff

delete ip; // Destroys the IntSet.
```

Dynamic Arrays

Dynamic `IntSet` creation

```
IntSet *ip = new IntSet(50);
```

- After the `IntSet` pointer is created, we get:
  - Allocate space to hold the IntSet (a pointer and two integers)
  - Call the constructor on that object (allocates space for the array of 50 integers)

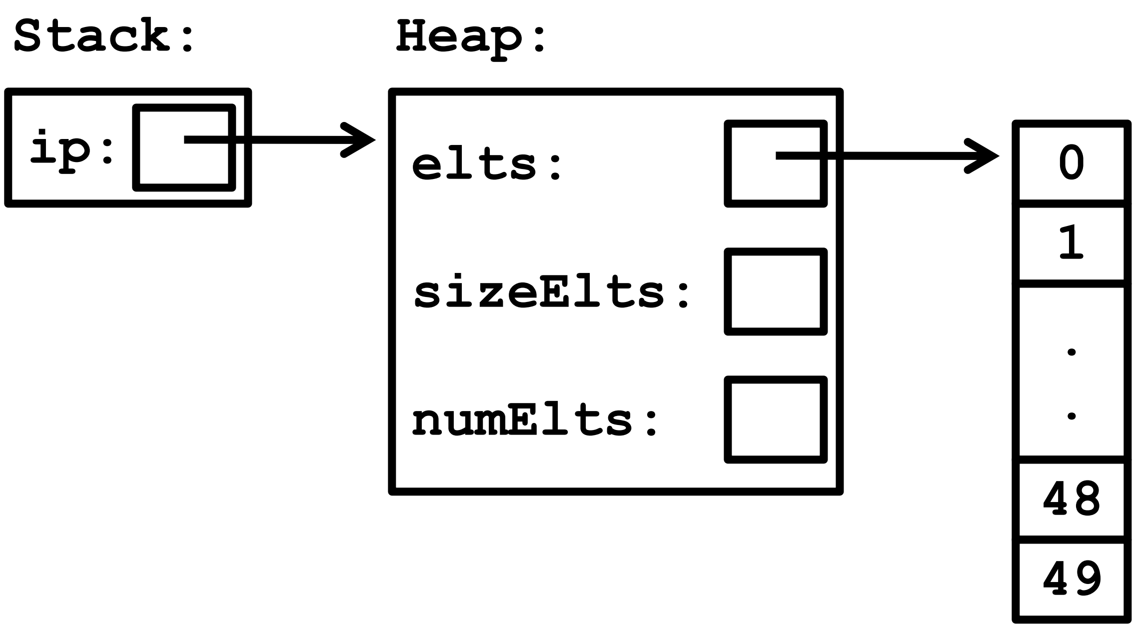


Dynamic Arrays

Dynamic `IntSet` deletion

`delete ip;`

- When you call delete on an instance of a class with a destructor
  - **First** the destructor is called (deallocates the array)
  - **Then** the object itself is deleted



Which Statements Are True?

Select all the correct answers.

- **A.** Any object should be destroyed with delete.
- **B.** Any object created with new should be destroyed with delete.
- **C.** Any object containing a dynamic array should have a destructor.
- **D.** A destructor is only needed when a member variable is a dynamic array.

References

- **Problem Solving with C++ (8th Edition)**, by *Walter Savitch*, Addison Wesley Publishing (2011)
  - Chapter 9.1 Pointers
  - Chapter 9.2 Dynamic Arrays
  - Chapter 11.4 Classes and Dynamic Arrays
  - Chapter 10.2 Constructors for Initialization (pp. 560-570)
  - Chapter 6.3 Default Arguments for Functions (pp. 344-345)