Copying Data

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Contents

Copying Data Structures

Copying data is one of the most common operations in C++.

- Every time we write an assignment

```
x = y;
```

  we are copying data.

- As our data gets more complicated, so does copying.

. . . . . .

But, First...

A slight diversion...

. . . . . .

1 Destructors

Destructors

Destructors are used to clean up objects that are no longer in use.

- A destructor for a class *C* is a function named *~C*
  - This function takes no parameters
- The most common action within a destructor is deleting pointers

. . . . . .

Destructors are never Called Explicitly

The compiler generates all calls to destructors implicitly

- when a variable goes out of scope,
- or when we delete a pointer.

. . . . . .

Implicit Destructor Call 1

If we write

```
void foo (int d, int c)
{
  Money m (d,c);
  for (int i = 0; i < 100; ++i)
    {
       Money mon2 = m;
        ⋮
    }
}
```

the compiler generates

```
void foo (int d, int c)
{
  Money m (d,c);
  for (int i = 0; i < 100; ++i)
    {
       Money mon2 = m;
        ⋮
       mon2.~Money();
    }
  m.~Money();
}
```

. . . . . .

Implicit Destructor Call 2

If we write

```
void foo (int d, int c)
{
  Money* m  = new Money (d,c);
        ⋮
  delete m;
}
```

the compiler generates

```
void foo (int d, int c)
{
  Money* m  = new Money (d,c);
        ⋮
  m->~Money();
  free(m);
}
```

.....

A Typical Destructor

We use destructors to clean up data "owned" by our structured types:

```
class BidCollection {

  int MaxSize;
  int size;
  Bid* elements; // array of bids

public:
  BidCollection (int MaxBids = 1000);

  ~BidCollection ();
    ⋮
```


. . . . . .

Implementing the Destructor

The destructor would be implemented as

```
BidCollection::~BidCollection()
{
  delete [] elements;
}
```

. . . . . .

Compiler-Provided Destructors

If you don't provide a destructor for a class, the compiler generates one for you automatically.

- The automatically generated destructor simply invokes the destructors for any data member objects.
- If none of the members have programmer-supplied destructors, does nothing.

. . . . . .

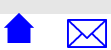
A Compiler-Generated Destructor

- We have not declared or implemented a destructor for our *Time* class,

```
#ifndef TIMES_H
#define TIMES_H

#include <iostream>

/**
 * Times in this program are represented by three integers: H, M, & S, representing
```

```
 * the hours, minutes, and seconds, respecitvely.
 */


class Time {
public:
  // Create time objects
  Time(); // midnight
  Time (int h, int m, int s);

  // Access to attributes
  int getHours() const;
  int getMinutes() const;
  int getSeconds() const;

  // Calculations with time
  void add (Time delta);
  Time difference (Time fromTime);

  /**
   * Read a time (in the format HH:MM:SS) after skipping any
   * prior whitepace.
   */
  void read (std::istream& in);


  /**
   * Print a time in the format HH:MM:SS (two digits each)
   */
  void print (std::ostream& out) const;
```


```
  // Comparison operators
  bool operator== (const Time&) const;
  bool operator< (const Time&) const;

private:
  // From here on is hidden
  int secondsSinceMidnight;
};

inline
std::ostream& operator<< (std::ostream& out, const Time& t)
{
  t.print(out);
  return out;
}


inline
bool operator!= (const Time& t1, const Time& t2)
{
  return !(t1 == t2);
}

inline
bool operator> (const Time& t1, const Time& t2)
{
  return t2 < t1;
```


```
}

inline
bool operator<= (const Time& t1, const Time& t2)
{
  return !(t1 > t2);
}

inline
bool operator>= (const Time& t1, const Time& t2)
{
  return !(t1 < t2);
}

#endif // TIMES_H
```

  - That's OK

- We have not declared a destructor for our *Bid* class

```
#ifndef BIDS_H
#define BIDS_H

#include <iostream>
#include <string>
#include "time.h"
#include "money.h"


//
```



```
//  Bids Received During Auction
//

class Bid {

  std::string bidderName;
  Money amount;
  std::string itemName;
  Time bidPlacedAt;

public:

  Bid (std::string bidder, double amt,
       std::string item, Time placedAt);

  Bid();

  // Access to attribute
  std::string getBidder() const {return bidderName;}
  double getAmount() const {return amount;}
  std::string getItem() const {return itemName;}
  Time  getTimePlacedAt() const {return bidPlacedAt;}

  // Print a bid
  void print (std::ostream& out) const;


  // Comparison operators
  bool operator== (const Bid&) const;
  bool operator< (const Bid&) const;
```


```
};

inline
std::ostream& operator<< (std::ostream& out, const Bid& b)
{
  b.print(out);
  return out;
}



#endif
```

- Again that's OK
  - Despite the fact that the strings may need cleanup.

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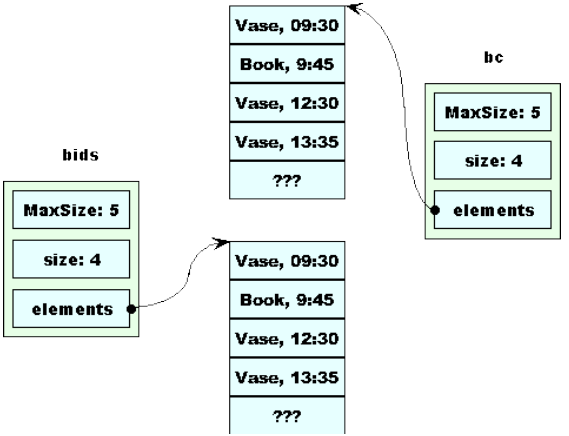
Trusting the Compiler-generated Destructor


What would happen if we trusted the compiler-generated destructor for *BidCollection*?



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Compiler-generated destructors are wrong when...

The compiler-generated destructor will leak memory when

- Your ADT has pointers among its data members, and
- Your ADT objects do not share those pointers with other objects.

. . . . . .

2 Copy Constructors

Copy Constructors

The copy constructor for a class `Foo` is the constructor of the form:

```
Foo (const Foo& oldCopy);
```

. . . . . .

2.1 Where Do We Use a Copy Constructor?

Where Do We Use a Copy Constructor?

The copy constructor gets used in 5 situations:

1. When you declare a new object as a copy of an old one:

```
Time time2 (time1);
```

or

```
Time time2 = time1;
```

2. When a function call passes a parameter "by copy" (i.e., the formal parameter does not have a &):

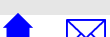
```
void foo (Time b, int k);
  ⋮

Time noon (12, 0, 0);
foo (noon, 0);    // foo actually gets a copy of noon
```

3. When a function returns an object:

```
Time foo (int k);
{
  Time t (k, 0, 0);
  ⋮
  return t;
}
```

4. When explicitly invoked in another constructor's initialization list:

```
  Name (string gName, string sName)
    : givenName(gName), surName(sName) {}
```

5. When an object is a data member of another class for which the compiler has generated its own copy constructor.

. . . . . .

2.2 Compiler-Generated Copy Constructors

Compiler-Generated Copy Constructors

If we do not create a copy constructor for a class, the compiler generates one for us.

- copies each data member via *their* individual copy constructors.
  - For primitive types (int, double, pointers, etc.), just copies the bits.

. . . . . .

2.3 Example: Bid: Compiler-Generated Copy Constructor

Example: Bid: Compiler-Generated Copy Constructor

```
struct Bid {
  std::string bidderName;
  Money amount;
  std::string itemName;
  Time bidPlacedAt;

};
```

`Bid` does not provide a copy constructor, so the compiler generates one for us, just as if we had written:

```
struct Bid {
  std::string bidderName;
  Money amount;
  std::string itemName;
  Time bidPlacedAt;
```


```
  Bid (const Bid&);
};
  ⋮
Bid::Bid (const Bid& b)
  : bidderName(b.bidderName), amount(b.amount),
    itemName(b.itemName), bidPlacedAt(b.bidPlacedAt)
{}
```

and that's probably just fine.

.....

2.4 Example: BidCollection: Compiler-Generated Copy Constructor

Example: BidCollection: Compiler-Generated Copy Constructor

```
struct BidCollection {
  int MaxSize;
  int size;
  Bid* elements; // array of bids

  /**
   * Create a collection capable of holding the indicated number of bids
   */
  BidCollection (int MaxBids = 1000);

  ~BidCollection ();

  /**
   * Read all bids from the indicated file
   */
  void readBids (std::string fileName);
};
```

`BidCollection` does not provide a copy constructor, so the compiler generates one for us, just as if we had written:

```
struct BidCollection {
  int MaxSize;
  int size;
  Bid* elements; // array of bids

  /**
   * Create a collection capable of holding the indicated number of bids
   */
  BidCollection (int MaxBids = 1000);
  BidCollection (const BidCollection&);
};
  :
BidCollection::BidCollection (const BidCollection& bc)
   : MaxSize(bc.MaxSize), size(bc.size),
     elements(bc.elements)
{}
```

which is not good at all!

.....

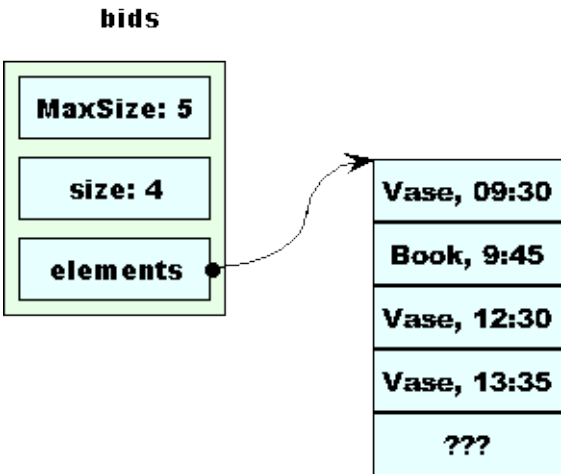
Example: BidCollection is hard to copy

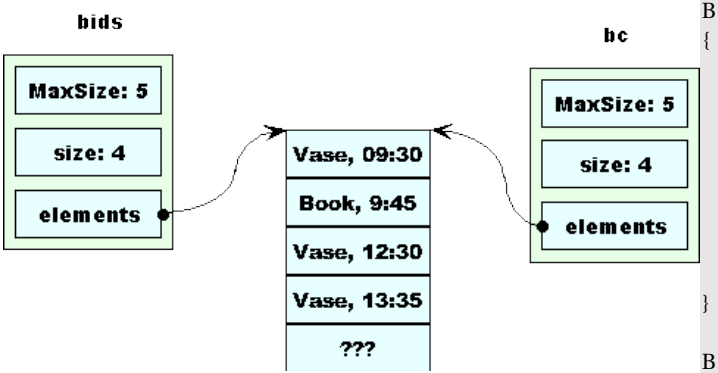
To see why, suppose we had some application code:

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
```


```
    }
  return bc;
}
   ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```

Assume we start with this in `bids`.



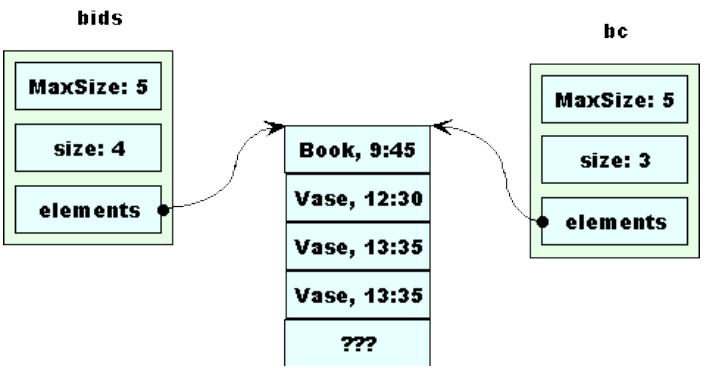


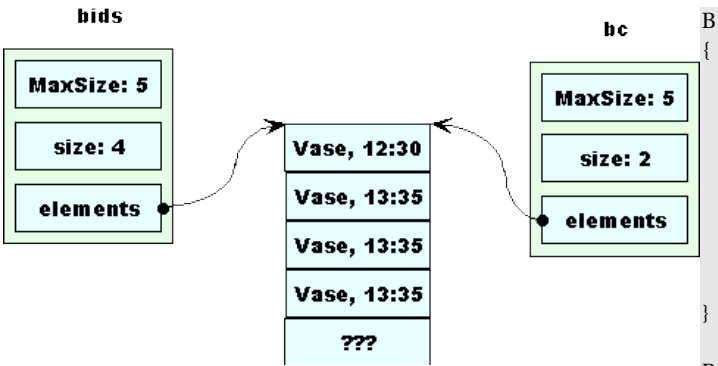
When `removeEarly` is called, we get a copy of `bids` .

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
    ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```

`removeEarly` removes the first morning bid from `bc`.

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
    ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```



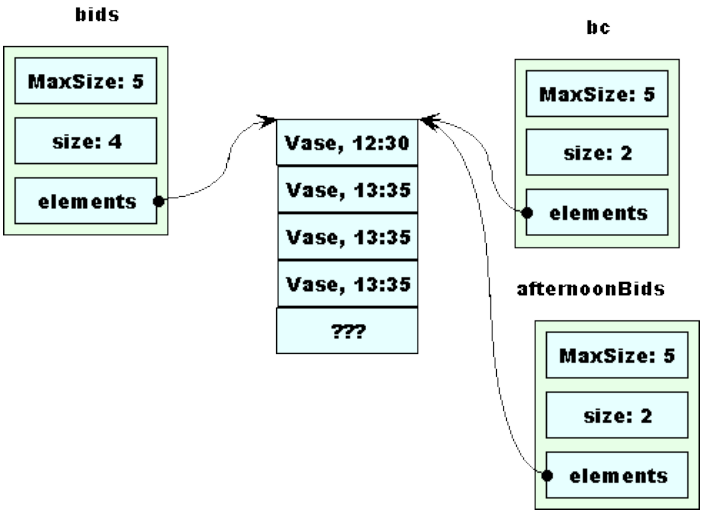


Then `removeEarly` removes the remaining morning bid from `bc`.

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
   ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```


The return statement makes a copy of bc, which is stored in `afterNoonBids`
`removeEarly` removes the remaining morning bid from bc.

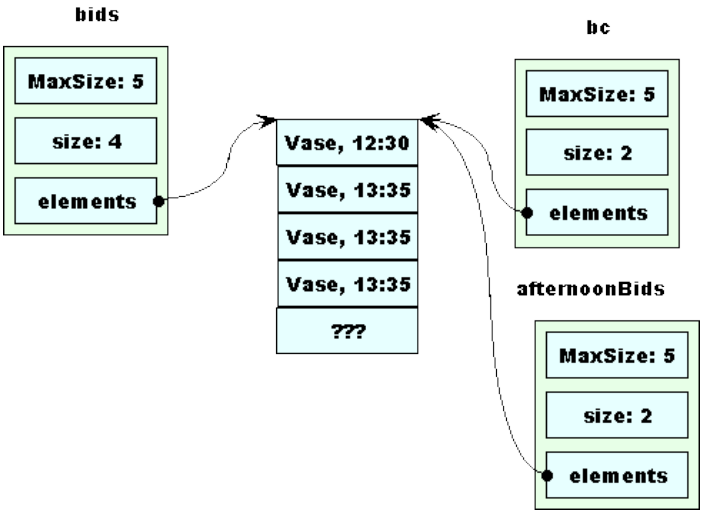
```
BidCollection removeEarly (BidCollection bc, Time t)
{
    ⋮
  return bc;
}
    ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```



Trouble: bids is corrupted

Note that we have corrupted the original collection, `bids`

- It thinks it has more (according to `size`) bids than are left in the array
- The bids that it has are now changed



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That's not the worst of it!

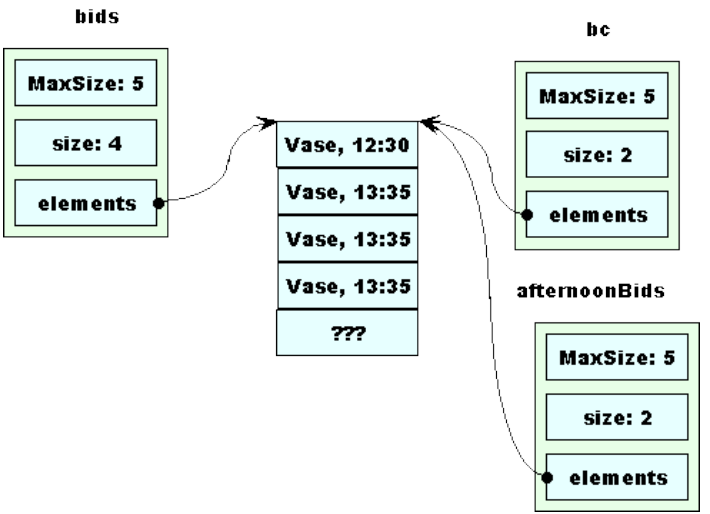
When we exit `removeEarly`,

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
```


the destructor for `BidCollection` is called on `bc`

```
BidCollection::~BidCollection()
{
  delete [] elements;
}
```

Taking us from this...



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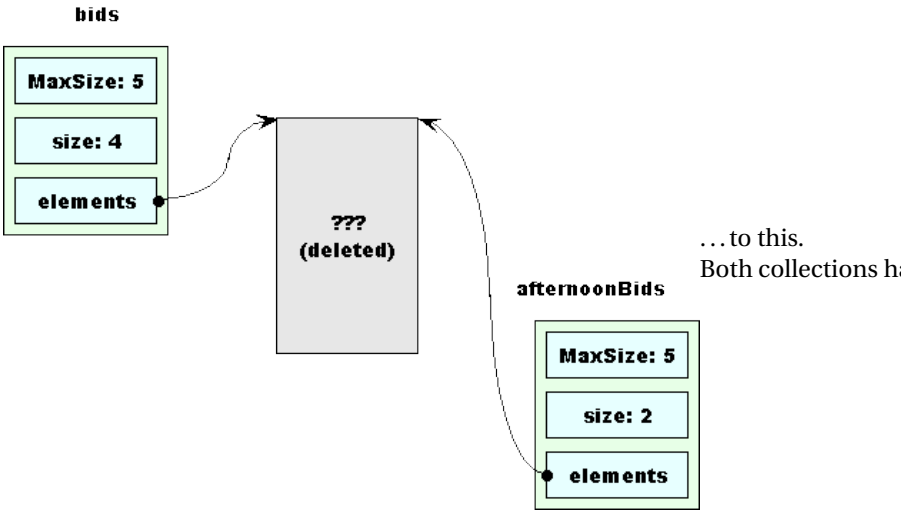
What a Mess!



. . . to this.
Both collections have "dangling pointers"

Avoiding this Problem

We could

- Decide never to pass a `BidCollection` by copy, never return one from a function, never to create a new `BidCollection` as a copy of an old one
  - We would have to remember this in all future applications
- or, write our own copy constructor that actually works
  - Every `BidCollection` should have its own unique array

2.5 Writing a BidCollection Copy Constructor

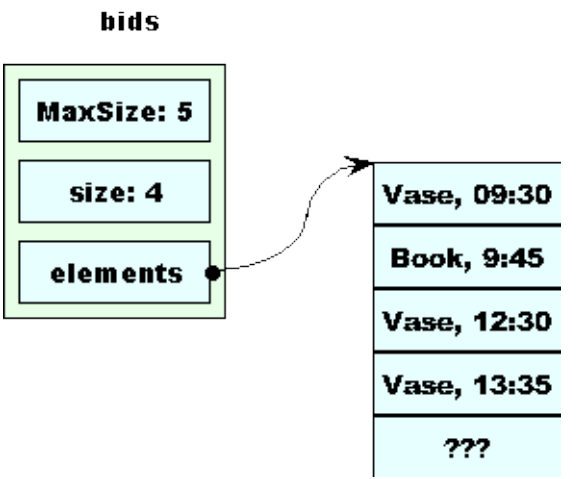
Writing a BidCollection Copy Constructor

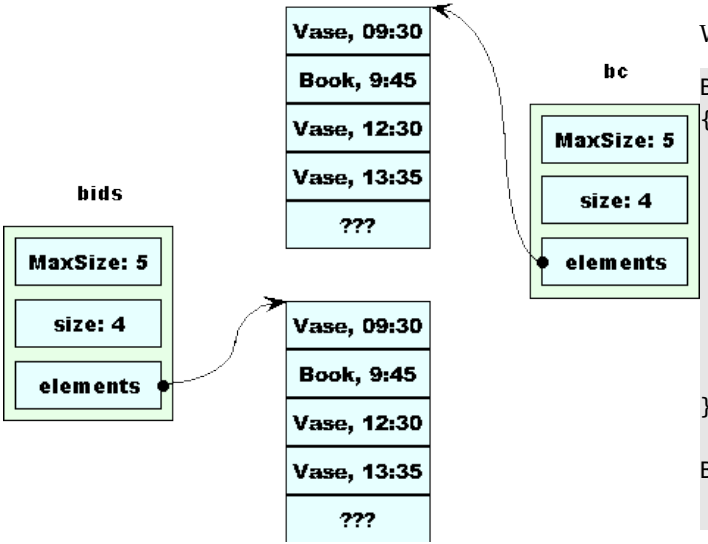
```
BidCollection::BidCollection (const BidCollection& bc)
  : MaxSize (bc.MaxSize), size (bc.size)
{
  elements = new Bid[MaxSize];
  for (int i = 0; i < size; ++i)
    elements[i] = bc.elements[i];
}
```

. . . . . .

Once More, With Feeling!

With this copy constructor in place, things should go much more smoothly.



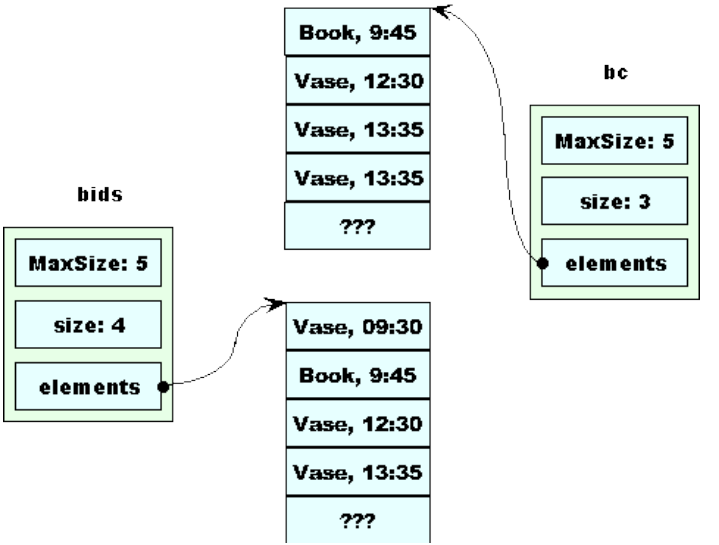


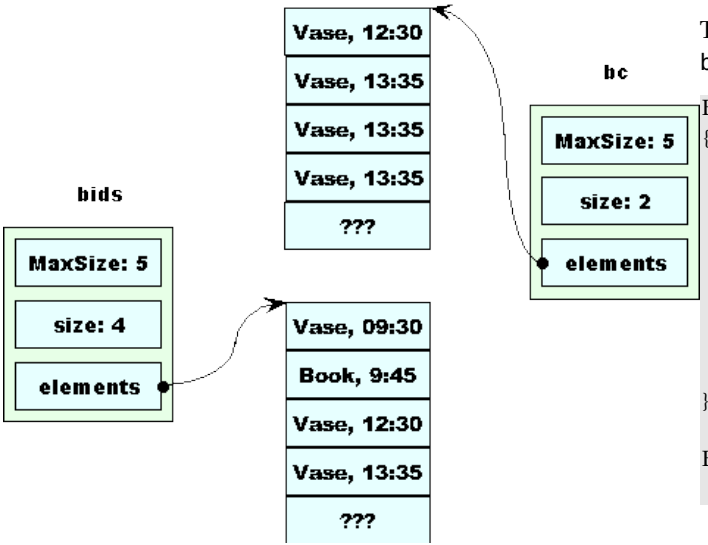
When `removeEarly` is called, we get a copy of `bids`.

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t)
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
   :
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```


`removeEarly` removes the first morning bid from `bc`.

```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t )
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
    ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```



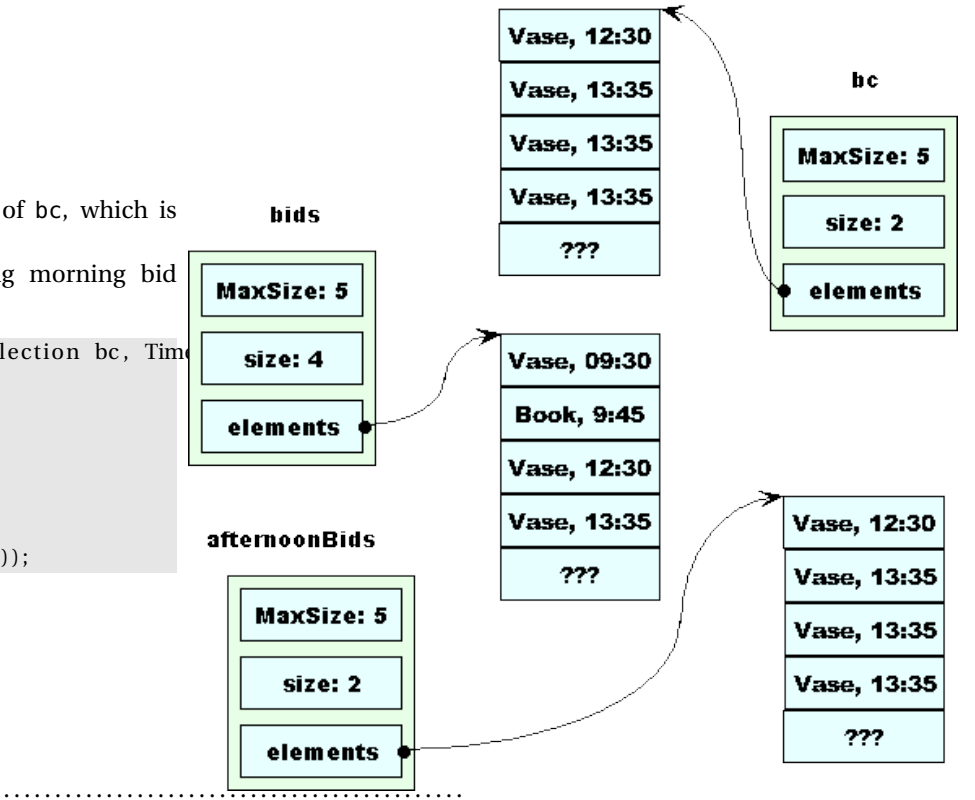


Then `removeEarly` removes the remaining morning bid from `bc`.

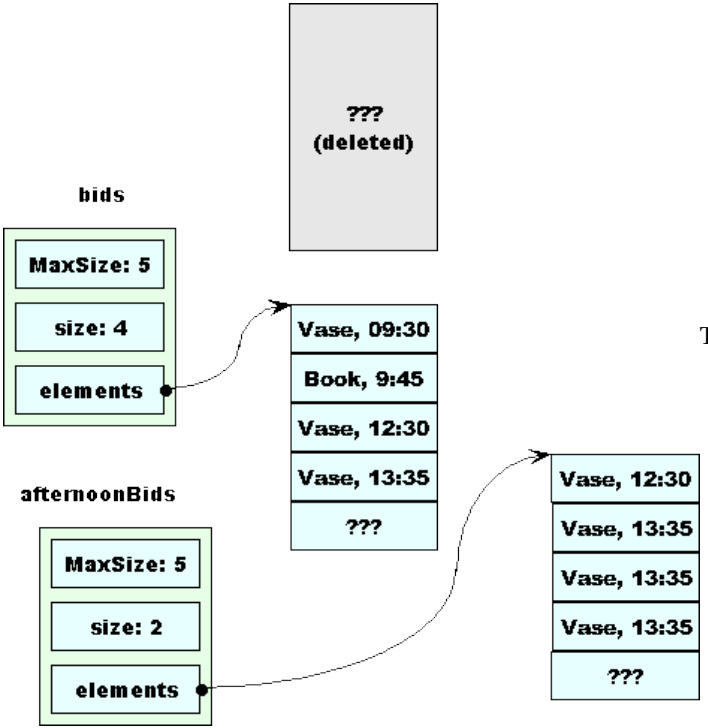
```
BidCollection removeEarly (BidCollection bc, Time t)
{
  for (int i = 0; i < x.size;)
    {
     if (bc.elements[i].bidPlacedAt < t )
        removeElement (elements, size, i);
     else
        ++i;
    }
  return bc;
}
   :
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```

The return statement makes a copy of `bc`, which is stored in `afterNoonBids`.
`removeEarly` removes the remaining morning bid from `bc`.

```
BidCollection removeEarly (BidCollection bc, Tim
{
    ⋮
  return bc;
}
    ⋮
BidCollection afterNoonBids =
   removeEarly (bids, Time(12,0,0));
```



Much Nicer



The destructor for `BidCollection` is called on `bc`

- Both remaining collections are OK.

2.6 Shallow & Deep Copying

If We Never Write Our Own

If our data members do not have explicit copy constructors (and their data members do not have explicit copy constructors, and . . .) then the compiler-provided copy constructor amounts to a bit-by-bit copy.

Shallow vs Deep Copy

Copy operations are distinguished by how they treat pointers:

- In a *shallow copy*, all pointers are copied.
  - Leads to shared data on the heap.
- In a *deep copy*, objects pointed to are copied, then the new pointer set to the address of the copied object.
  - Copied objects keep exclusive access to the things they point to.

. . . . . .

Shallow copy is wrong when...

- Your ADT has pointers among its data members, and
- You don't want to share the objects being pointed to.

. . . . . .

Compiler-generated copy constructors are wrong when...

- Your ADT has pointers among its data members, and
- You don't want to share the objects being pointed to.

. . . . . .

3 Assignment

Assignment

Copy constructors are not the only way we make copies of data.

- Even more common is the use of assignment:

```
time2 = time1;
```

- Assignment is so common that it can be hard to imagine programming without it
  - though in rare conditions we will do so
  - E.g., you cannot assign `istreams` and `ostreams`
    - You cannot copy them by constructor either
- So the compiler will try to be helpful again

. . . . . .

3.1 Compiler-Generated Assignment Ops

Compiler-Generated Assignment Ops

If you don't provide your own assignment operator for a class, the compiler generates one automatically.

- assigns each data member in turn.
- If none of the members have programmer-supplied assignment ops, then this is a *shallow copy*

. . . . . .

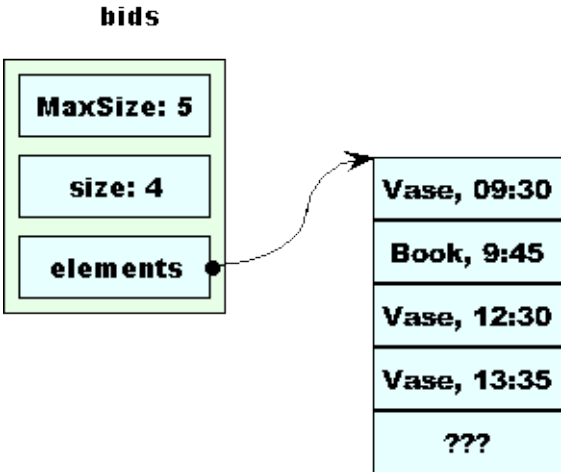
Example: BidCollection: Guess what happens

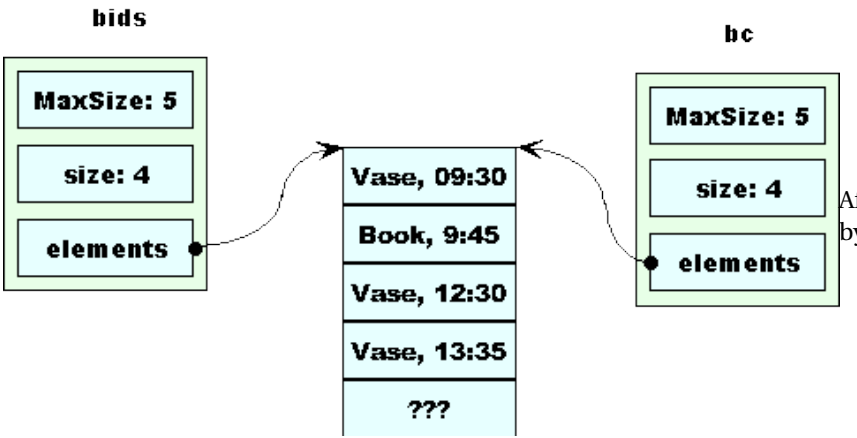
Our `BidCollection` class has no assignment operator, so the code below uses the compiler-generated version. Suppose we had some application code:

```
BidCollection bids;
  ⋮
BidCollection bc;
Time t (12, 0, 0);
bc = bids;
for (int i = 0; i < x.size;)
  {
   if (bc.elements[i].bidPlacedAt < t)
      removeElement (elements, size, i);
   else
      ++i;
  }

BidCollection bc;
Time t (12, 0, 0);
bc = bids;
for (int i = 0; i < x.size;)
  {
   if (bc.elements[i].bidPlacedAt < t)
      removeElement (elements, size, i);
   else
      ++i;
  }
```


Assume we start with this in `bids`.



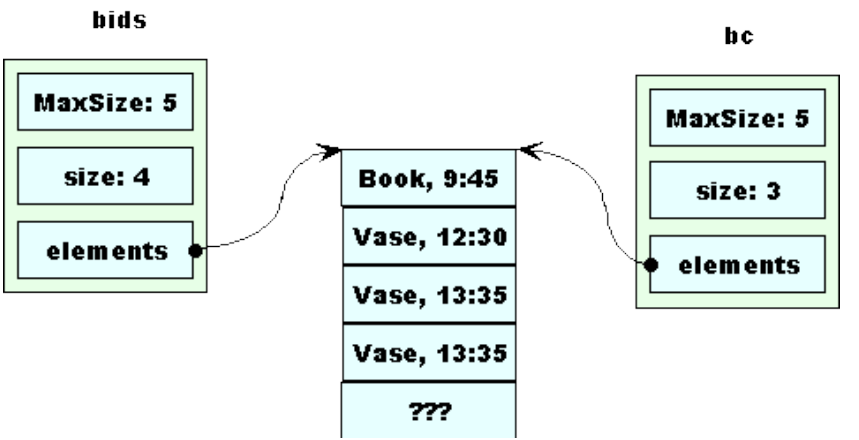


After the assignment, we have copied `bids`, bit-by-bit, into `bc`.

```
BidCollection bc;
Time t (12, 0, 0);
```

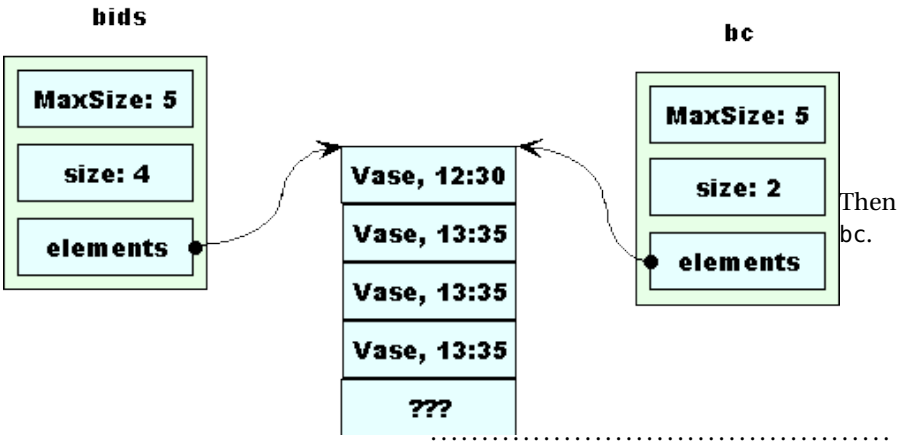

```
bc = bids;
for (int i = 0; i < x.size;)
  {
   if (bc.elements[i].bidPlacedAt < t)
      removeElement (elements, size, i);
   else
      ++i;
  }
```

We remove the first morning bid from bc.




```
BidCollection bc;
Time t (12, 0, 0);
bc = bids;
for (int i = 0; i < x.size;)
  {
   if (bc.elements[i].bidPlacedAt < t)
      removeElement (elements, size, i);
   else
```


```
        ++i;
    }
```

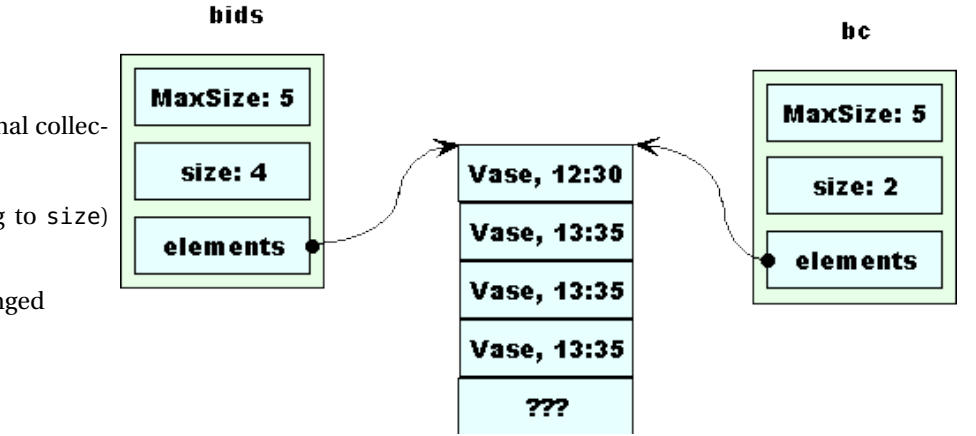


Then remove the remaining morning bid from `bc`.

bids is corrupted

Note that we have corrupted the original collection, `bids`

- It thinks it has more (according to `size`) bids than are left in the array
- The bids that it has are now changed



Avoiding this Problem

We have already seen that, for this class, we need to implement our own copy constructor:

```
BidCollection::BidCollection (const BidCollection& bc)
  : MaxSize (bc.MaxSize), size (bc.size)
{
  elements = new Bid[MaxSize];
  for (int i = 0; i < size; ++i)
    elements[i] = bc.elements[i];
}
```

For all the same reasons, we will want to implement our own assignment operator.

3.2 Implementing Assignment

Implementing Assignment

```
BidCollection& BidCollection::operator=
    (const BidCollection& bc)
{
  MaxSize = bc.MaxSize;
  size = bc.size;
  delete [] elements;

  elements = new Bid[MaxSize];
  for (int i = 0; i < size; ++i)
    elements[i] = bc.elements[i];

  return *this;
}
```

. . . . . .

Why return *this?

- By tradition in C++, assignments can be chained:

  ```
  a = b = c = 0;
  ```

  - Works because compiler interprets this as

    ```
    a = (b = (c = 0));
    ```

  - Not unlike <<

. . . . . .

Self-Assignment

What would happen if we did

```
bids = bids;
```


using this assignment operator:

```
BidCollection& BidCollection::operator=
    (const BidCollection& bc)
{
  MaxSize = bc.MaxSize;
  size = bc.size;
  delete [] elements;

  elements = new Bid[MaxSize];
  for (int i = 0; i < size; ++i)
    elements[i] = bc.elements[i];

  return *this;
}
```

- Would delete all the elements before copying them

. . . . . .

Self-Assignment – Really?

May seem an unlikely occurrence, but can often happen in a disguised form, e.g., during array processing,

```
bidSet[i] = bidSet[j];
```

- What if `i == j`?

. . . . . .

Coping with Self-Assignment

To allow for this possibility, most assignment operator functions check to see if the variable on the left (*this*) is at the same address as the variable on the right:

```
BidCollection& BidCollection::operator= (const BidCollection& bc)
{
  if (this != &bc)
    {
     MaxSize = bc.MaxSize;
     size = bc.size;
     delete [] elements;

     elements = new Bid[MaxSize];
     for (int i = 0; i < size; ++i)
       elements[i] = bc.elements[i];
    }
  return *this;
}
```

. . . . . .

4 The Rule of the Big 3

A Question of Trust

- When do we not trust the compiler-provided copy constructor?
- When do we not trust the compiler-provided assignment operator?
- When do we not trust the compiler-provided destructor?

. . . . . .

A Question of Trust

- When do we not trust the compiler-provided copy constructor?

  - When we have pointers among our data members, and
  - We don't want to share the data we are pointing to

- When do we not trust the compiler-provided assignment operator?
  - When we have pointers among our data members, and
  - We don't want to share the data we are pointing to
- When do we not trust the compiler-provided destructor?
  - When we have pointers among our data members, and
  - We don't want to share the data we are pointing to

Notice a pattern?

. . . . . .

The Rule of the Big 3

- The copy constructor, assignment operator, and destructor are known as the *Big 3*.
- The *Rule of the Big 3* states:

  If you provide your own version of any one of the Big 3, you should provide your own version of all three.

. . . . . .

Providing the Big 3

- The Bid ADT: `auctionBig3/bids.h` and `auctionBig3/bids.cpp`
- The Bidder ADT: `auctionBig3/bidders.h` and `auctionBig3/bidders.cpp`
- The Item ADT: `auctionBig3/items.h` and `auctionBig3/items.cpp`

- The Time ADT: `auctionBig3/time.h` and `auctionBig3/time.cpp`
- The BidCollection ADT: `auctionBig3/bidcollection.h` and `auctionBig3/bidcollection.cpp`
- The BidderCollection ADT: `auctionBig3/biddercollection.h` and `auctionBig3/biddercollection.cpp`
- The ItemCollection ADT: `auctionBig3/itemcollection.h` and `auctionBig3/itemcollection.cpp`

.....