ECE 2400 Computer Systems Programming

Topic 13: Object-Oriented Programming

http://www.csl.cornell.edu/courses/ece2400
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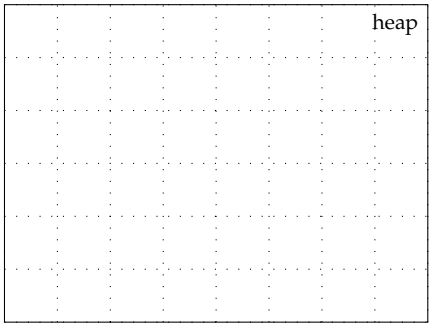
revision: 2021-11-18-20-42

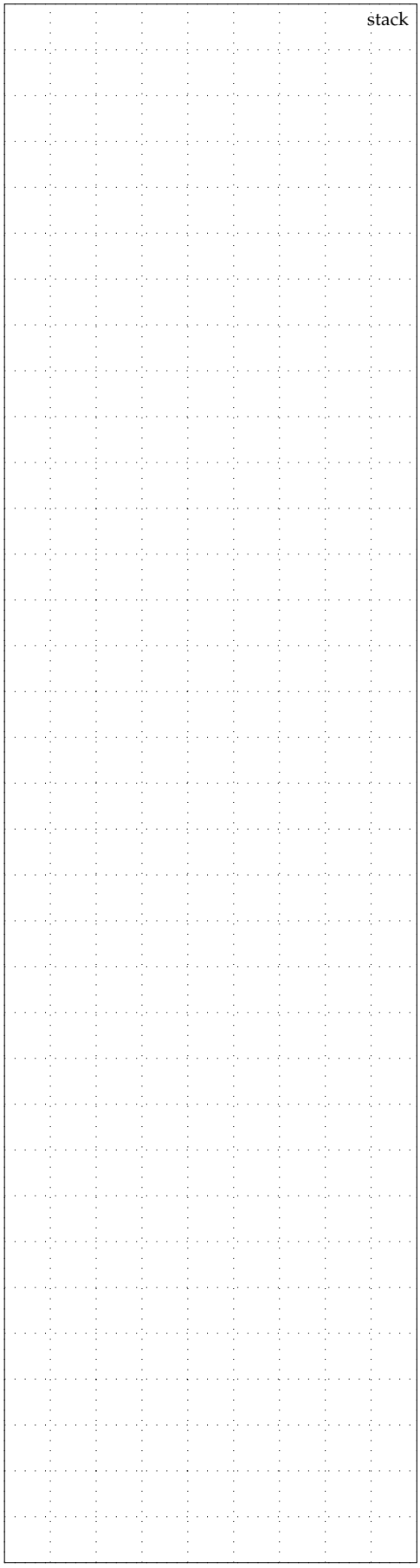
Please do not ask for solutions. Students should compare their solutions to solutions from their fellow students, discuss their solutions with the instructors during lab/office hours, and/or post their solutions on Ed for discussion.

List of Problems

Problem 1. Short Answer

Carefully plan your solution before starting to write your response. Please be brief and to the point; if at all possible, limit your answers to the space provided.





Part 1.A Constructors and Destructors

The following class `Foo` includes a single dynamically allocated integer. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables), explicitly show all constructors and destructors, and fully expand out the stack frames for all function calls.

```
01 class Foo
02 {
03  public:
04
05    Foo() { m_p = nullptr; }
06
07    Foo( int v )
08    {
09      m_p  = new int;
10      *m_p = v;
11    }
12
13    Foo( const Foo& x )
14    {
15      if ( x.m_p != nullptr ) {
16        m_p  = new int;
17        *m_p = *x.m_p;
18      }
19      else
20        m_p = nullptr;
21    }
22
23    ~Foo() { delete m_p; }
24
25  private:
26    int* m_p;
27 };

28 void bar()
29 {
30   Foo a(3);
31   Foo b(a);
32 }

33 int main( void )
34 {
35   bar();
36   return 0;
37 }
```

Part 1.B Accessor Member Function

The following class `Foo` includes a single dynamically allocated integer, and the class `Bar` includes a single dynamically allocated instances of `Foo`. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables), explicitly show all constructors and destructors, and fully expand out the stack frames for all function calls.

```
01 class Foo
02 {
03  public:
04   Foo()  { m_i = new int; }
05   ~Foo() { delete m_i;    }
06
07   void set( int v ) {
08     *m_i = v;
09   }
10
11  private:
12   int* m_i;
13 };
14
15 class Bar
16 {
17  public:
18   Bar()  { m_f = new Foo;  }
19   ~Bar() { delete m_f;     }
20
21   void set( int v ) {
22     m_f->set(v);
23   }
24
25  private:
26   Foo* m_f;
27 };
28
29 int main( void )
30 {
31   Bar bar;
32   bar.set( 12 );
33   return 0;
34 };
```

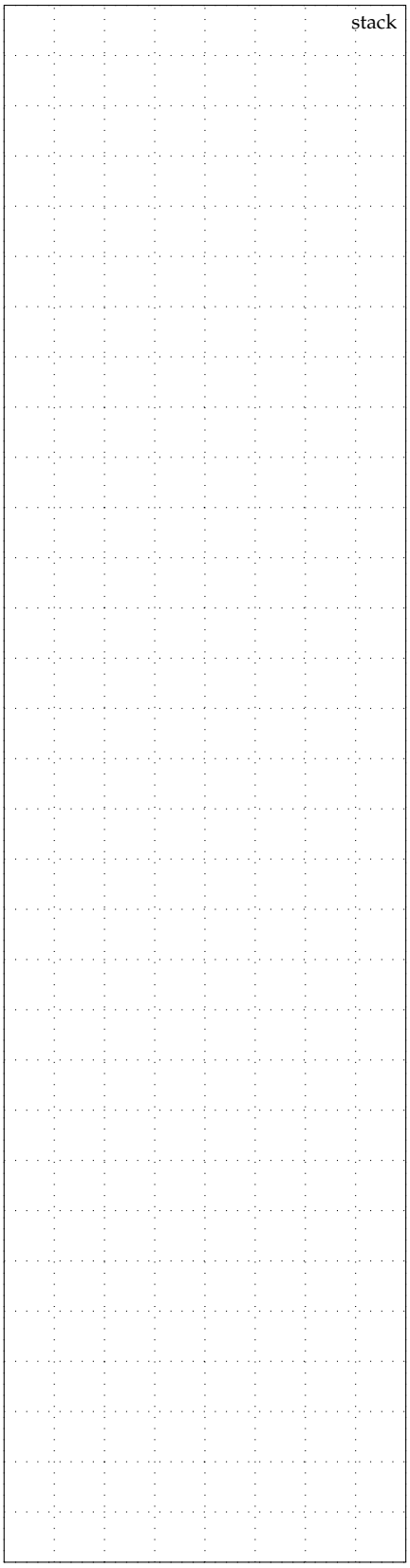
heap

stack

Part 1.C Clock Class (Weight: ×2)

Consider the following C++ program which defines a new class `Clock` to represent a clock with both an hour (`m_hour`) and a minute (`m_min`) field. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables), explicitly show all constructors and destructors, and fully expand out the stack frames for all function calls.

```
1  class Clock
2  {
3   public:
4
5    Clock()
6    {
7      m_hour = 0;
8      m_min  = 0;
9    }
10
11   Clock( int hour, int min ) {
12     if (    (hour < 0) || (hour >  12)
13          || (min  < 0) || (min  >= 60) )
14       throw -1;
15
16     m_hour = hour;
17     m_min  = min;
18   }
19
20   void tick() {
21     m_min++;
22     if ( m_min == 60 ) {
23       m_hour = m_hour + 1;
24       m_min  = 0;
25     }
26     if ( m_hour == 12 )
27       m_hour = 0;
28   }
29
30  private:
31   int m_hour;
32   int m_min;
33 };
34
35 int main( void )
36 {
37   Clock c0;
38   Clock c1( 9, 30 );
39   c0 = c1;
40   c0.tick();
41   return 0;
42 }
```



Part 1.D Integers in Sign Magnitude Form

The following class `Integer` stores integer whole numbers in sign magnitude form (i.e., the `m_pos` field indicates if the number is positive, and the `m_mag` field is the unsigned magnitude). **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables) and fully expand out the stack frames for all function calls. *You do not need to show any constructors or destructors at all in your state diagram! However, you do need to show the execute of constructors and destructors using the execution boxes.*

```
01 class Integer
02 {
03  public:
04
05   Integer()
06   {
07     m_pos = true;
08     m_mag = 0
09   }
10
11   Integer( int v )
12   {
13     m_pos = ( v >= 0 );
14     m_mag = m_pos ? v : -v;
15   }
16
17   int get_value() const
18   {
19     int sign = m_pos ? 1 : -1;
20     return sign * m_mag;
21   }
22
23  private:
24   bool         m_pos;
25   unsigned int m_mag;
26 };
27
28 Integer
29 operator+( const Integer& w, int x )
30 {
31   int y = w.get_value();
32   Integer z( x + y );
33   return z;
34 }
35
36 int main( void )
37 {
38   Integer a(-3);
39   Integer b = a + 2;
40   return 0;
41 }
```

stack

Part 1.E Filling a Sequence with Zeros

Recall the C++ singly linked list data structure from lecture. The interface and implementation are shown below with one addition. We have added a new `size` member function to calculate the number of elements currently stored in the linked list.

```
1  class SListInt
2  {
3   public:
4    SListInt();
5    ~SListInt();
6
7    void push_front( int v );
8    int  size() const;
9
10  private:
11
12   struct Node
13   {
14     int value;
15     Node* next_p;
16   };
17
18   Node* m_head_p;
19 };
```

Consider the following algorithm to fill a `SListInt` with zeros. Note the list may or may not be initially empty. An example is shown below illustrating the use of this algorithm on a list which initially contains two elements.

```
52 void fill_with_zeros( SListInt* lst_p,
53                       int N )
54 {
55   while ( lst_p->size() < N )
56     lst_p->push_front(0);
57 }
58
59 int main( void )
60 {
61   SListInt lst;
62   lst.push_front(42);
63   lst.push_front(13);
64   fill_with_zeros( &lst, 10 );
65   return 0;
66 }
```

```
19 SListInt::SListInt()
20 {
21   m_head_p = nullptr;
22 }
23
24 void SListInt::push_front( int v )
25 {
26   Node* new_node_p   = new Node;
27   new_node_p->value  = v;
28   new_node_p->next_p = m_head_p;
29   m_head_p           = new_node_p;
30 }
31
32 SListInt::~SListInt()
33 {
34   while ( m_head_p != nullptr ) {
35     Node* temp_p
36       = m_head_p->next_p;
37     delete m_head_p;
38     m_head_p = temp_p;
39   }
40 }
41
42 int SListInt::size() const
43 {
44   int num_elm = 0;
45   Node* curr_p = m_head_p;
46   while ( curr_p != nullptr ) {
47     num_elm += 1;
48     curr_p = curr_p->next_p;
49   }
50   return num_elm;
51 }
```

What is the time complexity of the `fill_with_zeros` algorithm when applied to `SListInt` as a function of N? Use asymptotic big-O notation. Use the six-step process described in lecture for complexity analysis to justify your answer. You must explicitly number and identify all six steps to receive full credit.

Part 1.F Nested Virtual Function Calls

Consider the following three classes: `Foo` and `Bar` inherit from `IBase`. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables) and fully expand out the stack frames for all function calls. *You do not need to show any constructors or destructors at all in your state diagram! However, you do need to show the execute of constructors and destructors using the execution boxes. You must explicitly indicate which version of `baz` and `go` is being called.*

```
01 class IBase
02 {
03  public:
04   virtual ~IBase() { }
05   virtual void baz( IBase* x ) = 0;
06   virtual void go() = 0;
07 };
08
09 class Foo : public IBase
10 {
11  public:
12   Foo()                { m_d = 0;  }
13   void baz( IBase* x ) { x->go();  }
14   void go()            { m_d += 1; }
15
16  private:
17   int m_d;
18 };
19
20 class Bar : public IBase
21 {
22  public:
23   Bar()                { m_d = 10; }
24   void baz( IBase* x ) { x->go();  }
25   void go()            { m_d += 2; }
26
27  private:
28   int m_d;
29 };
30
31 int main( void )
32 {
33   Foo a;
34   Bar b;
35   a.baz(&b);
36   Foo c;
37   c.baz(&c);
38   return 0;
39 }
```

stack

Part 1.G Dynamic Polymorphic Array of Objects

The code on the following page illustrates using dynamic polymorphism to create an array of two `IObjects`. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables) and fully expand out the stack frames for all function calls. *However, you do not need to show any constructors or destructors at all on the stack or execution boxes!*

heap

You do not need to show any constructors or destructors at all on the stack or execution boxes!

```
01 class IObject
02 {
03  public:
04   virtual IObject* clone() const = 0;
05   ...
06 };
07
08 class Integer : public IObject
09 {
10  public:
11   Integer( int i ) { m_i = i; }
12   IObject* clone() const {
13     return new Integer( *this );
14   }
15   ...
16  private:
17   int m_i;
18 };
19
20 class Double : public IObject
21 {
22  public:
23   Double( double d ) { m_d = d; }
24   IObject* clone() const {
25     return new Double( *this );
26   }
27   ...
28  private:
29   double m_d;
30 };
31
32 void append( IObject** objs, int idx,
33              const IObject& obj )
34 {
35   objs[idx] = obj.clone();
36 }
37
38 int main( void )
39 {
40   IObject* objs[2];
41   Integer a(5);
42   append( objs, 0, a );
43   Double  b(2.5);
44   append( objs, 1, b );
45   return 0;
46 };
```

stack

Part 1.H Shape Interface Inheritance

Consider the following C++ program which uses an `IShape` class hierarchy similar to lecture. **Draw the state diagram that corresponds to the execution of this C++ program.** You must clearly label all variables in your diagram (including any implicit variables) and fully expand out the stack frames for all function calls. *You do not need to show any constructors or destructors at all in your state diagram!*

```
1  class IShape
2  {
3   public:
4    virtual void scale( int s ) = 0;
5    ...
6  };
7
8  class Point : public IShape
9  {
10  public:
11   Point()               { m_x = 0;     m_y = 0;     }
12   Point( int x, int y ) { m_x = x;     m_y = y;     }
13   void scale( int s )   { m_x = m_x*s; m_y = m_y*s; }
14   ...
15  private:
16   int m_x; int m_y;
17 };
18
19 class Circle : public IShape
20 {
21  public:
22   Circle()                      { m_x=0; m_y=0; m_r=0; }
23   Circle( int x, int y, int r ) { m_x=x; m_y=y; m_r=r; }
24   void scale( int s )           { m_r = m_r*s;         }
25   ...
26  private:
27   int m_x; int m_y; int m_r;
28 };
29
30 void scale_shapes( IShape* s0, IShape* s1, int s )
31 {
32   s0->scale( s );
33   s1->scale( s );
34 }
35
36 int main( void )
37 {
38   Point  a(1,2);
39   Circle b(3,4,2);
40   scale_shapes( &a, &b, 2 );
41   return 0;
42 }
```

stack

Do not show any constructors or destructors at all!

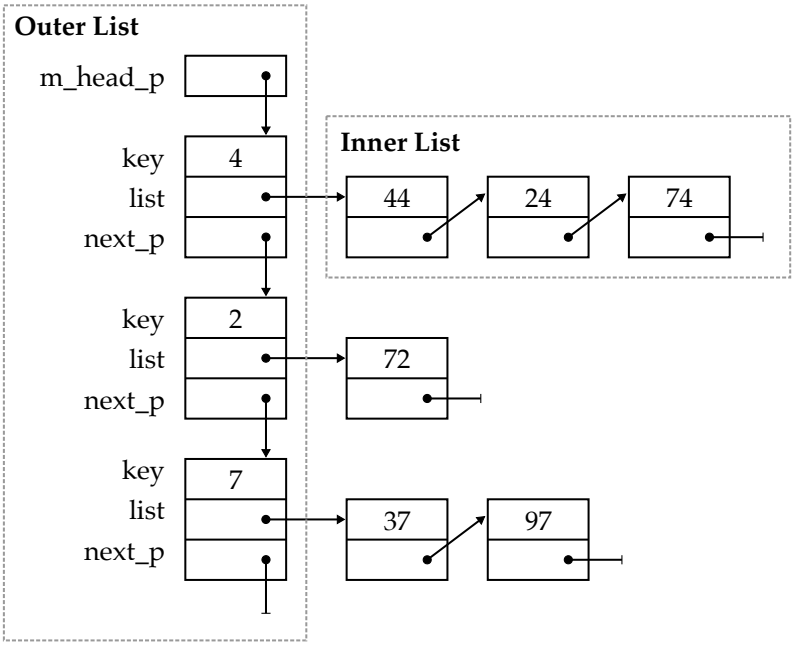
Problem 2. Set Data Structures

In this problem, you will explore two different approaches to implementing a set abstract data type (ADT) for integers. The first approach will use a list of lists, while the second approach will use an array of arrays. Recall that the set ADT should be able to *add* items to the set and to also query if the set *contains* an item.

Part 2.A `SetLL`: Set Implemented with a List of Lists

The first implementation of the set data structure will use a list of lists. An important aspect of this implementation is that it will rely on the notion of a *key* associated with each integer added to the set. The key k of an integer v is defined as $k = v \ \% \ K$ where % is the C/C++ modulus operator and K is an implementation-defined constant. Recall that the modulus operator essentially returns the remainder of v/K. So for example, if $v = 24$ and $K = 10$, then $k = 4$ (i.e., $24/10$ leaves a remainder of 4) and if $v = 30$ and $K = 8$, then $k = 6$ (i.e., $30/8$ leaves a remainder of 6).

The high-level idea for this implementation is shown below. This example uses $K = 10$, and the set contains { 24, 37, 44, 72, 74, 97 }. Each node in the *outer list* contains a *key*, an *inner list* of integers, and a pointer to the next node of the outer list. This implementation should preserve the invariant that all integers with the same key are stored in the same inner list. So we use the following steps when adding integers to the set: (1) check to see if the integer is already in the set; (2) if the integer is not in the set, then we iterate through the outer list to see if the integer's key is already in the set; (3) if the integer's key is in the set, then we simply push the new integer onto the front of the list corresponding to the integer's key; (4) if the integer's key is not in the set, then we add a new node to the outer list and push the new integer onto the front of the list corresponding to this new node.



For the inner list, our implementation will use the standard list data structure for `ints` which we discussed in lecture. The interface for this data structure is shown below for reference. You should assume the implementation of this list data structure is exactly as described in lecture.

```
class ListInt
{
 public:

  ListInt();
  ~ListInt();

  void push_front( int v );

  class Itr
  {
   public:
    Itr( Node* node_p );
    void next();
    int& get();
    bool eq( const Itr& itr ) const;

   private:
    Node* m_node_p;
  };

  Itr begin();
  Itr end();

 private:

  struct Node
  {
    int   value;
    Node* next_p;
  };

  Node* m_head_p;

};

ListInt::Itr  operator++( ListInt::Itr& itr, int ); // postfix (itr++)
ListInt::Itr& operator++( ListInt::Itr& itr );      // prefix  (++itr)
int&          operator*( ListInt::Itr& itr );
bool          operator!=( const ListInt::Itr& itr0, const ListInt::Itr& itr1  );
```

The interface and the private member fields for the set data structure which uses a list of lists is shown below. We have also provided the implementation of the `add` member function. Study this function closely before continuing with this problem.

```
class SetLL
{
 public:

  SetLL();
  ~SetLL();

  void add( int v );
  bool contains( int v ) const;

 private:

  // Compile-time constant
  static const int K = 10;

  struct OuterNode
  {
    int        key;
    ListInt    list;
    OuterNode* next_p;
  };

  OuterNode* m_head_p;
};
```

```
void SetLL::add( int v )
{
  // Key is the remainder of v / K
  int key = v % K;

  // Step 1. See if set already contains v

  if ( contains(v) )
    return;

  // Step 2. See if key is in the set

  bool found = false;
  OuterNode* curr_p = m_head_p;
  while ( !found && (curr_p != nullptr) ) {

    // Step 3. Key is in the set, add v to list
    if ( curr_p->key == key ) {
      curr_p->list.push_front( v );
      found = true;
    }

    curr_p = curr_p->next_p;
  }

  // Step 4. Key is not in set so ...
  // ... create new outer node
  // ... add v to the list in new outer node

  if ( !found ) {
    OuterNode* new_node_p = new OuterNode();
    new_node_p->key    = key;
    new_node_p->list   = ListInt();
    new_node_p->next_p = m_head_p;
    m_head_p           = new_node_p;

    // Insert the value into front of new list
    m_head_p->list.push_front( v );
  }
}
```

Implement the `SetLL::contains` C++ member function. Clearly identify any corner cases and choose a reasonable approach to handle those corner cases. While you are welcome to use pseudocode to plan your approach, your final solution must be written using valid C++ syntax.

```
bool SetLL::contains( int v ) const {
```

Part 2.B `SetLL::contains` **Complexity Analysis**

Assume we have N integers in the set, and that the values of these integers are uniformly distributed across the entire range of integers. Recall that K is a compile-time constant used to calculate the keys. **What is the worst-case execution time and time complexity for the** `SetLL::contains` **member function as a function of N and K? Use asymptotic big-O notation for time complexity. Justify your answer.**

As before, assume we have N integers in the set, and that the values of these integers are uniformly distributed across the entire range of integers. **What is the space usage and space complexity of this data structure as a function of N and K? Use asymptotic big-O notation for space complexity. Justify your answer.** In other words, how much space is requied to store N unique integers in the set as a function of N and K?

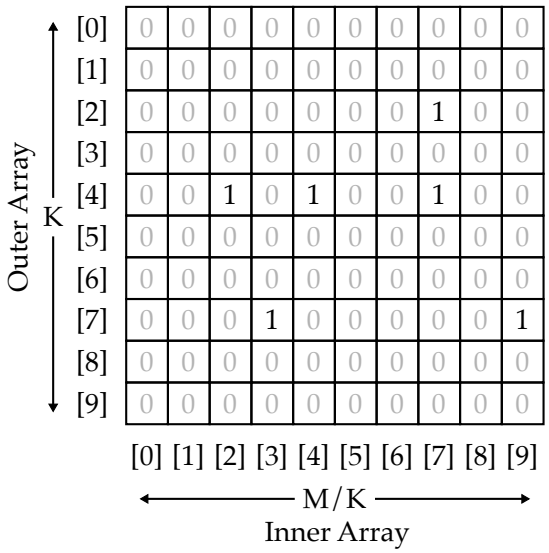
In the previous analysis, we assumed K was fixed at compile time. Consider an adaptive variant of this data structure which attempts to ensure K is always roughly proportional to $\sqrt{N}$. To implement the adaptive variant, we would augment the `SetLL::add` member function to periodically check to see if K is much smaller or larger than $\sqrt{N}$. When K is far from $\sqrt{N}$, the `SetLL::add` member function will create a new list of lists and then copy the contents of the current set into the new list of lists using $K = \sqrt{N}$. The adaptive variant will have the property that K will always be roughly proportional to $\sqrt{N}$. **What is the worst-case execution time and time complexity for the `SetLL::contains` member function for the adaptive variant of this set data structure? Use asymptotic big-O notation for the time complexity. Justify your answer.** Again, you must assume that the N integers currently in the set are uniformly distributed across the entire range of integers. *You can ignore the time it takes to periodically create a new list of lists and copy the integers into this new list of lists.*

Part 2.C `SetAA`: Set Implemented with an Array of Arrays

The second implementation of the set data structure will use an array of arrays. This implementation will also rely on the notion of a *key* associated with each integer added to the set. The key k of an integer v is defined as $k = v \ \% \ K$, exactly as in the previous parts of this problem. This part will also assume that we only wish to add positive integers to the set, and that we know at compile time the maximum integer ($M-1$) we might *ever* want to add to the set. So there are three key parameters or variables we will need to take into consideration: N is the number of integers currently in the set, K is used to calculate the key for any given integer, and $M-1$ is the maximum integer we might ever want to add to the set.

The high-level idea for this implementation is shown below. This example uses $K = 10$ and $M = 100$, and the set contains { 24, 37, 44, 72, 74, 97 }. There is one element in the data structure for every possible integer we might ever want to add to the set. The value of the element is `true` if the corresponding integer is in the set and `false` if the corresponding integer is not in the set. Each element in the *outer array* is essentially an *inner array*. There are K elements in the outer array and each of the K inner arrays have M/K elements. You can assume that M is evenly divisible by K.

The interface and the private member fields for the set data structure which uses an array of arrays is also shown below.




```
1  class SetAA
2  {
3   public:
4
5    SetAA();
6    ~SetAA();
7
8    void add( int v );
9    bool contains( int v ) const;
10
11  private:
12
13   // Compile-time constants
14   static const int M = 100;
15   static const int K = 10;
16
17   bool m_data[K][M/K];
18
19 };
```

Implement the `SetAA::add` and `SetAA::contains` C++ member functions. Clearly identify any corner cases and choose a reasonable approach to handle those corner cases. While you are welcome to use pseudocode to plan your approach, your final solution must be written using valid C++ syntax.

```
void SetAA::add( int v )
{
  assert( (v >= 0) && ( v < M ) );
```

```
bool SetAA::contains( int v )
{
  assert( (v >= 0) && ( v < M ) );
```

Part 2.D `SetAA::contains` **Complexity Analysis**

Assume we have N integers in the set, and that the values of these integers are uniformly distributed across the range from 0 to $M-1$. Recall that K is a compile-time constant used to calculate the keys and that $M-1$ is the largest possible integer we might ever want to add to the set. **What is the worst-case execution time and time complexity for the** `SetAA::contains` **member function? Use asymptotic big-O notation for time complexity. Justify your answer.**

Assume we have N integers in the set, and that the values of these integers are uniformly distributed across the range from 0 to $M-1$. **What is the space usage and space complexity of this data structure? Use asymptotic big-O notation for the space complexity. Justify your answer.** In other words, how much space is required to store N unique integers (in the range 0 to $M-1$) in the set as a function of N, K, and M?

Part 2.E Comparing Set Data Structures

In this problem, you will be qualitatively comparing various search algorithms. **Begin by filling in the following table based on your analysis in this problem.** The time complexity should be the worst-case time complexity for the `contains` member function assume we have N integers in the set, and that the values of these integers are uniformly distributed across the range of 0 to $M-1$. Recall that for the adaptive implementation, you can ignore the time it takes to periodically create a new list of lists and copy the integers into this new list of lists. The space complexity should capture how much heap space is required to store N unique integers in the set. Your answers should be in terms of N, K, and M as appropriate. For the `SetL` row, assume we implement the set using a single linked list as discussed in lecture.

Implementation	**Time Complexity**	**Space Complexity**
`SetL` (one list)		
`SetLL` (list of lists, not adaptive)		
`SetLL` (list of lists, adaptive)		
`SetAA` (array of arrays)		

Use these results along with deeper insights to perform a comparative analysis of these set data structures, with the ultimate goal of **making a compelling argument for which data structure will perform better across a large number of usage scenarios.** While you are free to use whatever approach you like, we recommend you structure your response in several paragraphs. The **first paragraph** might discuss the performance of `contains` for all four data structure using time complexity analysis. Remember that time complexity analysis is not the entire story; it is just the starting point for understanding execution time. The **second paragraph** might discuss the heap space usage of all four data structures using space complexity analysis. Remember that space complexity analysis is not the entire story; it is just the starting point for understanding space usage. The The **third paragraph** might discuss other qualitative metrics such as generality, maintainability, and design complexity. The **final paragraph** can conclude by making a compelling argument for which data structure will perform better in the general case, or if you cannot strongly argue for a single data structure explain why. Your answer will be assessed on how well you argue your position.