Construction and Verification of Software

2017 - 2018

MIEI - Integrated Master in Computer Science and Informatics
Consolidation block

Lecture 6 - Arrays in Separation Logic

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based on previous editions by **Luís Caires** (lcaires@fct.unl.pt)

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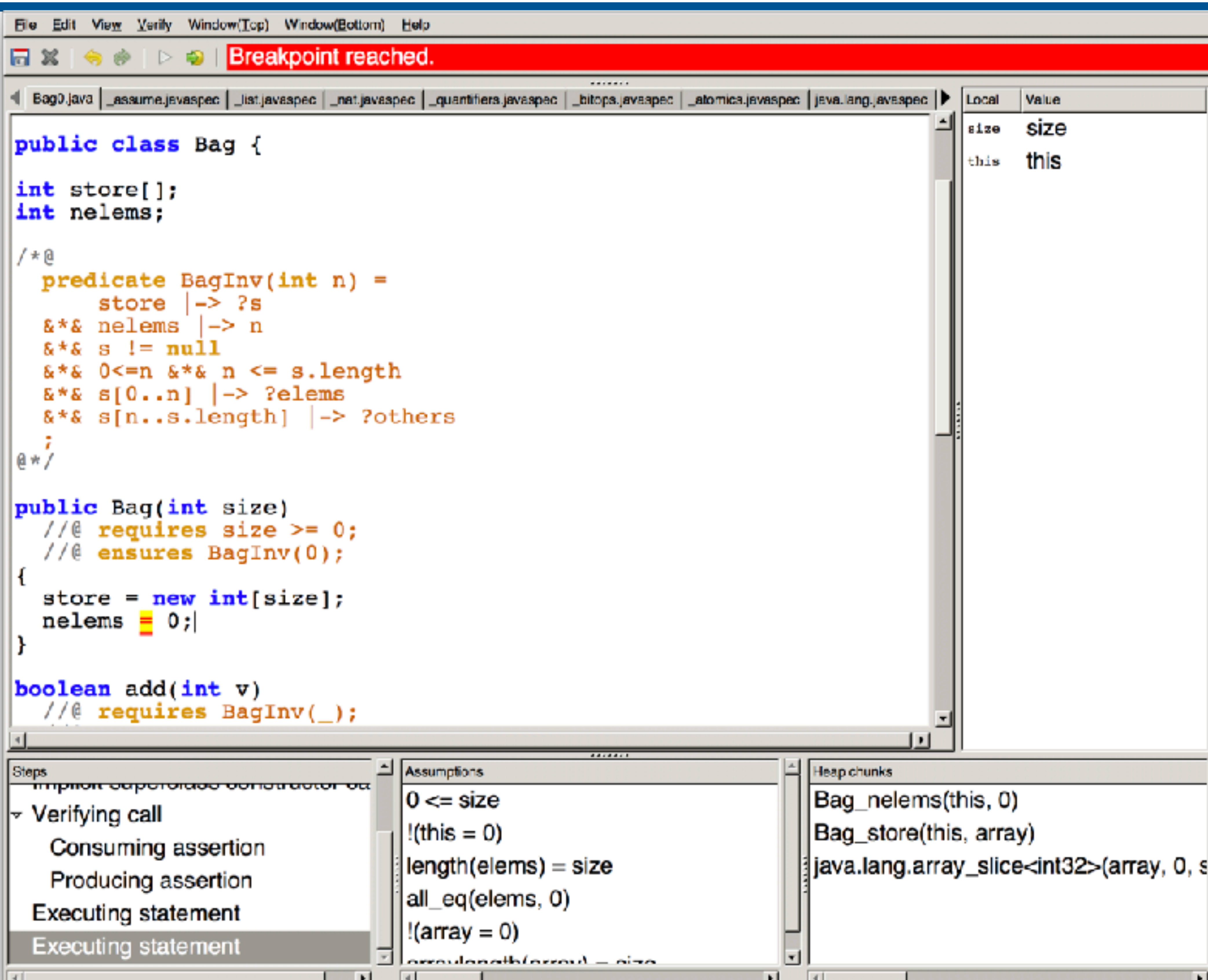
Verifast Example - Bag



Verifast Example - Bag

- Fields must be considered in separate heap chunks, pure conditions can be added to assertions and predicates.

```
public class Bag {

    int store[];
    int nelems;

/*@
  predicate BagInv(int n) =
       store |-> ?s
  &*& nelems |-> n
  &*& s != null
  &*& 0<=n &*& n <= s.length
  &*& array_slice(store,0,n,?elems)
  &*& array_slice(store,n,s.length,?others)
  ;
@*/
...
}
```

Verifast Example - Bag

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  &*& s != null
  &*& 0<=n &*& n <= s.length
  &*& s[0..n] |-> ?elems
  &*& s[n..s.length] |-> ?others
  ;
@*/
...
}
```

Verifast Example - Bag

- Fields must be considered in separate heap chunks, pure conditions can be added to assertions and predicates.

```
int get(int i)
  //@ requires BagInv(?n) &*& 0 <= i &*& i < n;
  //@ ensures BagInv(n);
{
  return store[i];
}

int size()
  //@ requires BagInv(?n);
  //@ ensures BagInv(n) &*& result>=0 ;
{
  return nelems;
}
```

Verifast Example - Bag

```
public Bag(int size)
  //@ requires size >= 0;
  //@ ensures BagInv(0);
{
  store = new int[size];
  nelems = 0;
}

boolean add(int v)
  //@ requires BagInv(_);
  //@ ensures BagInv(_);
{
  if(nelems<store.length) {
   store[nelems] = v;
   nelems = nelems+1;
   return true;
  } else {
   return false;
  }
}
```

Verifast Example - Bag

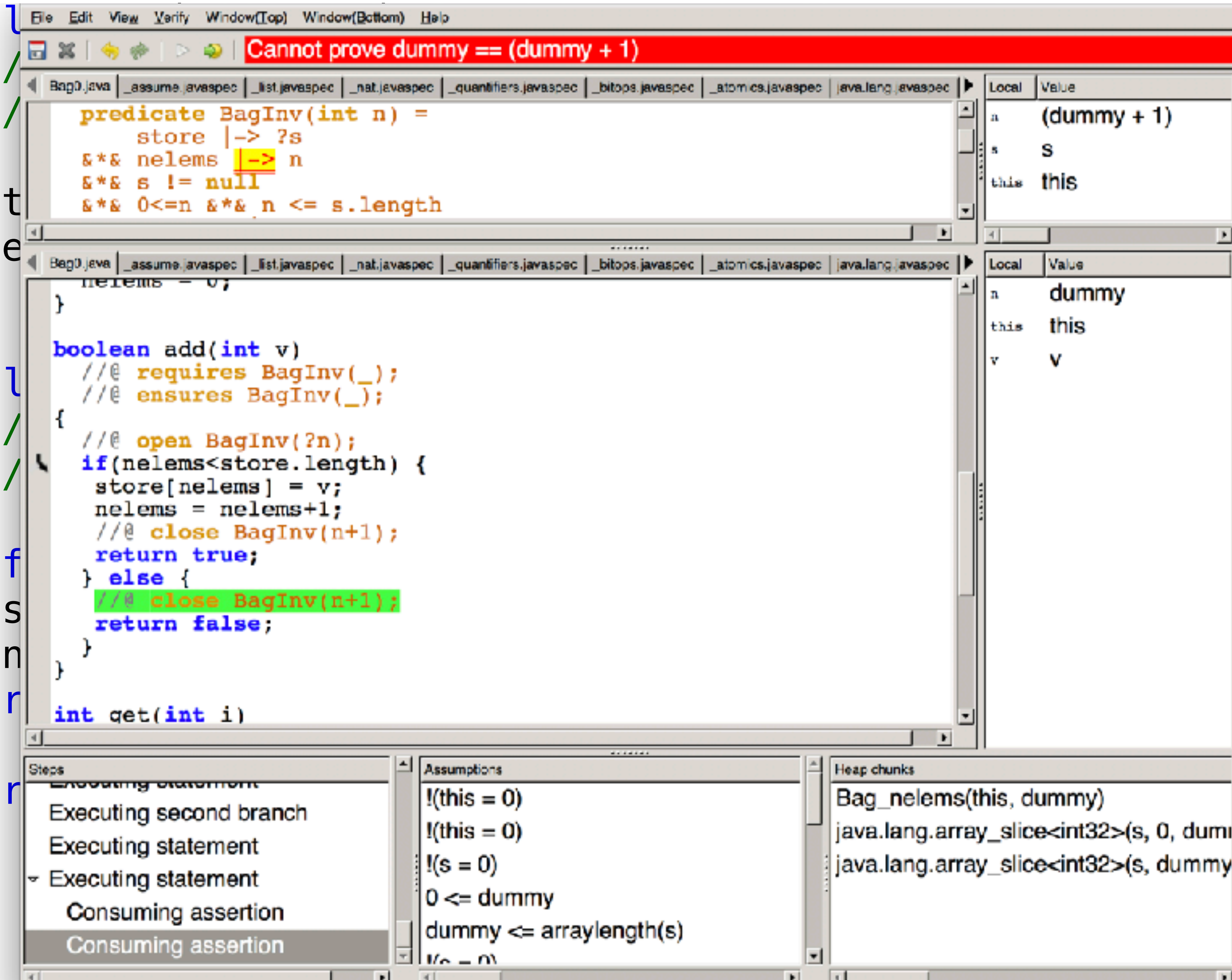
```
public Bag(int size)
  //@ requires size >= 0;
  //@ ensures BagInv(0);
{
  store = new int[size];
  nelems = 0;
}

boolean add(int v)
  //@ requires BagInv(?n);
  //@ ensures BagInv(n+1); // Does not hold, why?
{
  if(nelems<store.length) {
   store[nelems] = v;
   nelems = nelems+1;
   return true;
  } else {
   return false;
  }
}
```

Verifast Example - Bag

```
publ
  //
  //
{
  st
  ne
}

bool
  //
  //
{
  if
    s
    n
    r
  }
    r
  }
}
```



Managing arrays in SL

```
/*@
predicate AccountInv(Account a;int b) = a.balance |-> b &*& b >= 0;
@*/

public class Account {

    int balance;

    public Account()
    //@ requires true;
    //@ ensures AccountInv(this,0);
    {
      balance = 0;
    }
    ...
}
```

Managing arrays in SL

- The bank holds an array of accounts…

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    Bank(int max)
    {
        nelems = 0;
        capacity = max;
        store = new Account[max];
    }
    ...
}
```

Managing arrays in SL

- And implements a couple of operations…

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    …
    Account retrieveAccount()
    {
        Account c = store[nelems-1];
        store[nelems-1] = null;
        nelems = nelems-1;
        return c;
    }
    ...
}
```

Managing arrays in SL

- And implements a couple of operations…

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    ...
    void addnewAccount()
    {
        Account c = new Account();
        store[nelems] = c;
        nelems = nelems + 1;
    }
    ...
}
```

Managing arrays in SL

```
/*@
predicate AccountP(unit a,Account c; unit b) = AccountInv(c,?n) &*& b == unit;
@*/

public class Bank {

/*@
predicate BankInv(int n, int m) =
     this.nelems |-> n &*&
     this.capacity |-> m &*&
     m > 0 &*&
     this.store |-> ?accounts &*&
     accounts.length == m &*&
     0 <= n &*& n<=m &*&
     array_slice_deep(accounts, 0, n, AccountP, unit, _, _) &*&
     array_slice(accounts, n, m,?rest) &*& all_eq(rest, null) == true;
@*/

}
```

array slice assertions

```
predicate array_slice<T>(
    T[] array,
    int start,
    int end;
    list<T> elements);
```

- array_slice(a,s,l,v):
  - represents the **footprint** of array a[s..l-1]
- v is a list of the array “values” v_i such that a[i] |-> v_i
- v is an immutable pure value (like a OCaml list)
- array_slice(a,s,l,v) is equivalent to the assertion
  - v = { v_s, ... v_{l-1} }
  - a[s] |-> v_s &*& a[s+1] |-> v_{s+1} &*& ... &*& a[l-1] |-> v_{l-1}

array slice assertions

```
predicate array_slice_deep<T, A, V>(
    T[] array,
    int start,
    int end,
    predicate(A, T; V) p,
    A info;
    list<T> elements,
    list<V> values);
```

- array_slice_deep(a, s, l, P, info, v, s):
  as in the (simple) array_slice
  v is the list of the array “values” v_i such that a[i] |-> v_i,
  the predicate P(info,v_i;o_i) holds for each v_i
  and s is the list of all values o_i

Managing arrays in SL

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    Bank(int max)
    //@ requires max>0;
    //@ ensures BankInv(0,max);
    {
      nelems = 0;
      capacity = max;
      store = new Account[max];
    }
    ...
}
```

Managing arrays in SL

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    Account retrieveLastAccount()
    //@ requires BankInv(?n,?m) &*& n>0;
    //@ ensures  BankInv(n-1,m) &*& AccountInv(result,_);
    {
        Account c = store[nelems-1];
        store[nelems-1] = null;
        // code does not compile without this! Why ?
        nelems = nelems-1;
        return c;
    }

}
```

Managing arrays in SL

```
public class Bank {

    Account store[];
    int nelems;
    int capacity;

    void addnewAccount()
    //@ requires BankInv(?n,?m) &*& n < m;
    //@ ensures  BankInv(n+1,m);
    {
        Account c = new Account();
        store[nelems] = c;
        //@ array_slice_deep_close(store, nelems, AccountP, unit);
        nelems = nelems + 1;
    }
}
```

array slice “lemmas”

```
lemma void array_slice_deep_close<T, A, V>(
   T[] array, int start, predicate(A, T; V) p, A a);
 requires
  array_slice<T>(array,start,start+1,?elems) &*&
  p(a, head(elems), ?v);
 ensures
  array_slice_deep<T,A,V>(array, start, start+1, p, a, elems, cons(v,nil));
```

- incorporates the spec of an array element in a (singleton) slice spec into a (singleton) slice_deep spec
- there are other lemmas, that join together slices
- verifast is usually able to apply lemmas automatically, but not always, in that case the programmer needs to “help”, by calling the needed lemmas.

array slice “lemmas”

```
lemma void array_slice_split<T>(T[] array, int start, int start1);
  requires
    array_slice<T>(array, start, ?end, ?elems) &*&
    start <= start1 &*& start1 <= end;
  ensures
    array_slice<T>(array, start, start1, take(start1 - start, elems)) &*&
    array_slice<T>(array, start1, end, drop(start1 - start, elems)) &*&
    elems == append(take(start1 - start, elems), drop(start1 - start, elems));
```

- this “lemma” splits one array slice assertion into two (sub) array slice assertions.

array slice “lemmas”

Secure https://people.cs.kuleuven.be/~bart.jacobs/verifast/examples/rt/Object.javaspec.html

```
package java.lang;

import java.util.*;

/*@

inductive unit = unit;

inductive pair<a, b> = pair(a, b);

fixpoint a fst<a, b>(pair<a, b> p) {
    switch (p) {
        case pair(x, y): return x;
    }
}

fixpoint b snd<a, b>(pair<a, b> p) {
    switch (p) {
        case pair(x, y): return y;
    }
}

fixpoint t default_value<t>();

inductive boxed_int = boxed_int(int);
fixpoint int unboxed_int(boxed_int i) { switch (i) { case boxed_int(value): return value; } }

inductive boxed_bool = boxed_bool(boolean);
fixpoint boolean unboxed_bool(boxed_bool b) { switch (b) { case boxed_bool(value): return value; } }

predicate array_element<T>(T[] array, int index; T value);
predicate array_slice<T>(T[] array, int start, int end; list<T> elements);
predicate array_slice_deep<T, A, V>(T[] array, int start, int end, predicate(A, T; V) p, A info; list<T> elements

lemma_auto void array_element_inv<T>();
    requires [?f]array_element<T>(?array, ?index, ?value);
    ensures [f]array_element<T>(array, index, value) &*& array != null &*& 0 <= index &*& index < array.length;
```

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Lab Assignment 5 - Introduction to Verifast

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Verifast

- Download the binaries of Verifast from
- https://github.com/verifast/verifast
- Run `vfide` from the `bin` directory and experiment the examples in the slides. Run the verifier in intermediate points in the code and examine the heap chunks available.

Exercise 17

- Verify classes Bank and BankAccount

```
// Download the zip archive from CLIP with an
// implementation of a bank account and a bank
// (store for bank accounts).

// Write and verify the appropriate representation
// invariants, pre-conditions and post-conditions to
// make sure that the BankAccount and Bank abide by the
// expected business rules.

// To verify the whole project Open the file Bank.jarsrc
```