Program Verification using the Spec# Programming System

ECOOP Tutorial

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Introducing Spec#

Spec#: An Overview

Installing Spec#

Using Spec#

Spec#: An Overview

The Spec# Programming System provides language and tool support for assertion checking in object oriented programs.

- The Spec# programming language: an extension of C# with non-null types, checked exceptions and throws clauses, method contracts and object invariants.
- The Spec# compiler: a compiler that statically enforces non-null types, emits run-time checks for method contracts and invariants, and records the contracts as metadata for consumption by downstream tools.
- The Spec# static program verifier: a component (named Boogie) that generates logical verification conditions from a Spec# program. Internally, it uses an automatic theorem prover that analyzes the verification conditions to prove the correctness of the program or find errors in it.

How do we use Spec#?

- The programmer writes each class containing methods and their specification together in a Spec# source file (similar to Eiffel, similar to Java + JML)
- Invariants that constrain the data fields of objects may also be included
- We then run the verifier.
- The verifier is run like the compiler—either from the IDE or the command line.
  - In either case, this involves just pushing a button, waiting, and then getting a list of compilation/verification error messages, if they exist.
  - Interaction with the verifier is done by modifying the source file.

Overview of Lectures

- Goal: Learn to use Spec# to verify programs
- Structure:
  - Getting started with Spec#
    - Overview and Installation
  - Programming in the small.
    - Preconditions, Postconditions, Loop invariants
  - Programming in the large:
    - Object invariants, Ownership

Installing Spec#

- Download the latest version of Spec# from http://research.microsoft.com/specsharp/.
  - Visual Studio 2008 version: the current version (which does not require Visual Studio 2008) or
  - Visual Studio 2005 version: an older version that is longer supported.

- Installation includes the compiler, VS plug-in, Boogie 2, Z3
- Optional: Simplify
- Programs may also be written in any editor and saved as Spec# files (i.e. with a .ssc extension).
- Visual Studio projects provide immediate feedback when an error is detected

Structure of .NET programs

- Programs are split into source files (.ssc).
- Source files are collected into projects (.sscproj).
- Each project is compiled into one assembly (.dll .exe) and each project can use its own language and compiler.
- Projects are collected into solutions (.sln).
- Typical situation: 1 solution with 1 project and many source files.
- Note that the compiler does not compile individual source files, but compiles projects. This means that there need not be a 1:1 correspondence between classes and files.

Using the Visual Studio IDE

- Open Visual Studio
- Set up a new Project (File -> new -> project)
- Open a Spec# project console application.(Spec# projects -> Console application)

```
using System;
using Microsoft.Contracts;
public class Program
{
  public static void Main(string![]! args)
  {
    Console.WriteLine("Spec# says hello!");
  }
}
```

- Build the solution (Build -> Build Solution) F6
- Execute the program (Debug -> Start) F5
- Tip: adding Console.Read(); to the end of your program requires that the user presses a key before the screen disappears.

Interactive mode (in VS 2008)

- To run the program verifier as you program, set the RunProgramVerifierWhileEditing to True
  - Find this in the project properties option of the project menu. Click on Configuration Properties, then Build and under Misc.
  - This means that you get verification errors underlined in green as you type. Anything underlined in red is a compilation error.
- To run the verifier when debugging (F6), set RunProgramVerifier to True
  - Under the Misc heading as above.

<MinFct demo>

Using your favourite Editor

- Type up your Spec# program e.g.

```
using System;
using Microsoft.Contracts;
public class Program
{
    public static void Main(string![]! args)
    {
        Console.WriteLine("Spec# says hello!");
        Console.Read();
    }
}
```

- Save it with a .ssc extension e.g. Program.ssc

Using Boogie at the Command line

- Open the Spec# command prompt

  Start->Programs->Microsoft Spec# Language->Tools->Spec# Cmd Prompt.
- Compile Program.ssc stored in C:\temp.

  C:\temp> ssc /t:library /debug Program.ssc
- This generates a file called Program.dll which is stored in C:\temp.
- C:\temp> ssc /t:library /debug Program.ssc compiles Program.ssc into a .exe executable.
- C:\temp> sscboogie Program.dll (or Program.exe) verifies the compiled file using the SMT solver Z3.
- (In the Spec# version for VS 2005 use C:\temp> boogie Program.dll)

- To create Boogie PL programs use
  sscboogie Program.dll /print:Program.bpl
- You can edit the bpl file by hand and feed it to boogie using
  boogie Program.bpl

- To get more feedback on the verification process use
  sscboogie Program.dll /trace
- Further switches for boogie can be seen by typing
  sscboogie /help

- To create Boogie PL programs use
  sscboogie Program.dll /print:Program.bpl
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- To get more feedback on the verification process use
  sscboogie Program.dll /trace
- Further switches for boogie can be seen by typing
  sscboogie /help
- To execute the program type
  Program.exe

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The Language

- The Spec# language is a superset of C#, an object-oriented language targeted for the .NET Platform.
  - C# features include single inheritance whose classes can implement multiple interfaces, object references, dynamically dispatched methods, and exceptions
  - Spec# adds non-null types, checked exceptions and throws clauses, method contracts and object invariants.

Non-Null Types

!

Non-Null Types

- Many errors in modern programs manifest themselves as null-dereference errors
- Spec# tries to eradicate all null dereference errors
- In C#, each reference type T includes the value null
- In Spec#, type T! contains only references to objects of type T (not null).

```
int []! xs;
```

declares an array called xs which cannot be null

Non-Null Example

```
public class Program
{
  public static void Main(string[] args)
  {
     foreach (string arg in args) // Possible null dereference
     {
        Console.WriteLine(arg); // Possible null dereference
     }
     Console.ReadLine();
  }
}
```

Non-Null Types

- If you decide that it's the caller's responsibility to make sure the argument is not null, Spec# allows you to record this decision concisely using an exclamation point.

- Spec# will also enforce the decision at call sites returning **Error: null is not a valid argument** if a null value is passed to a method that requires a non null parameter.

Non-Null Example

```
public class Program
{
  public static void Main(string![]! args)
  {
        foreach (string arg in args)
        {
              Console.WriteLine(arg);
        }
        Console.ReadLine();
  }
}
```

args != null

args[i] != null

Another Non-Null Example

```
using System;
using Microsoft.Contracts;
class MyLibrary
{
 public static void Clear(int[] xs)
 {
    for (int i = 0; i < xs.Length; i++)
    {
          xs[i] = 0;
    }

 }

}
```

Where is the *possible null dereference*?

Another Non-Null Example

```
using System;
using Microsoft.Contracts;
class MyLibrary
{
 public static void Clear(int[] xs)
 {
    for (int i= 0; i < xs.Length; i++) // Warning: Possible null dereference
    {
          xs[i] = 0;   // Warning: Possible null dereference
    }

 }

}
```

Another Non-Null Example

```
using System;
using Microsoft.Contracts;
class MyLibrary
{
 public static void Clear(int[] ! xs)
 {
    for (int i = 0; i < xs.Length; i++)  // No Warning due to !
    {
          xs[i] = 0;   // No Warning due to !

    }

 }

}
```

Another Non-Null Example

```
using System;
using Microsoft.Contracts;
class MyLibrary
{
 public static void Clear(int[] ! xs)
 {
    for (int i = 0; i < xs.Length; i++)
    {
          xs[i] = 0;
    }

 }

}
```

```
class ClientCode
{
    static void Main()
    {
          int[] xs = null;
          MyLibrary.Clear(xs);
    }
}
```


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Another Non-Null Example

```
using System;
using Microsoft.Contracts;
class MyLibrary
{
 public static void Clear(int[] ! xs)
 {
   for (int i = 0; i < xs.Length; i++)
   {
         xs[i] = 0;
   }

 }

}
```

"Null cannot be used where a non-null value is expected"

```
class ClientCode
{
   static void Main()
   {
        int[] xs = null;
        MyLibrary.Clear(xs);
   }
}
```

Non-Null by Default

	Without /nn	/nn
Possibly-null T	T	T?
Non-null T	T!	T

From Visual Studio, select right-click Properties on the project, then Configuration Properties, and set ReferenceTypesAreNonNullByDefault to true

Initializing Non-Null Fields

```
class C {
    T! x;
    public C(T! y) {
        x = y;
    }
    public C(int k) {
        x = new T(k);
    }
    ...
```

Delayed

- In C#, if the constructor body does not explicitly call a constructor, a call **base();** is implicitly inserted by the compiler at the beginning of the body, immediately following the field initialisers.
- Before the **base()** constructor has been called, *the object being constructed (**this**) can only be used as the target object in field assignments. We say the reference **this** is delayed.*
- Default in Spec# is that this is delayed throughout the constructor body

Initializing Non-Null Fields

```
class C {
    T! x;
    public C(int k) {
        x = new T(k);
        x.M();
    }
```

Delayed receiver is not compatible with non-delayed method

Initializing Non-Null Fields

```
using Microsoft.Contracts;
class C {
    T! x;
  [NotDelayed]
    public C(int k) {
        x = new T(k);
        base();
        x.M();
    }
```

Allows fields of the receiver to be read

Spec# allows base calls anywhere in a constructor

In non-delayed constructors, all non-null fields (e.g. x) must be initialized before calling base

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Non-Null and Delayed References

- Declaring and checking non-null types in an object-oriented language. Manuel Fähndrich and K. Rustan M. Leino. In *OOPSLA 2003*, ACM.
- Establishing object invariants with delayed types. Manuel Fähndrich and Songtao Xia. In *OOPSLA 2007*, ACM.

Assert

Assert Statements

```
public class Program
{
  public static void Main(string![]! args)
  {
   foreach (string arg in args)
   {    if (arg.StartsWith("Hello"))
        {        assert 5 <= arg.Length; // runtime check
                 char ch = arg[2];
                 Console.WriteLine(ch);
        }
   }
  }
}
```

Assert Statements

```
public class Program
{
  public static void Main(string![]! args)
  {
   foreach (string arg in args)
   {     if (arg.StartsWith("Hello"))
         {        assert 5 < arg.Length; // runtime error
                  char ch = arg[2];
                  Console.WriteLine(ch);
         }
   }
  }
}
```

Assume Statements

- The statement **assume** E; is like **assert** E; at run-time, but the static program verifier checks the assert whereas it blindly assumes the assume.

Design by Contract

Design by Contract

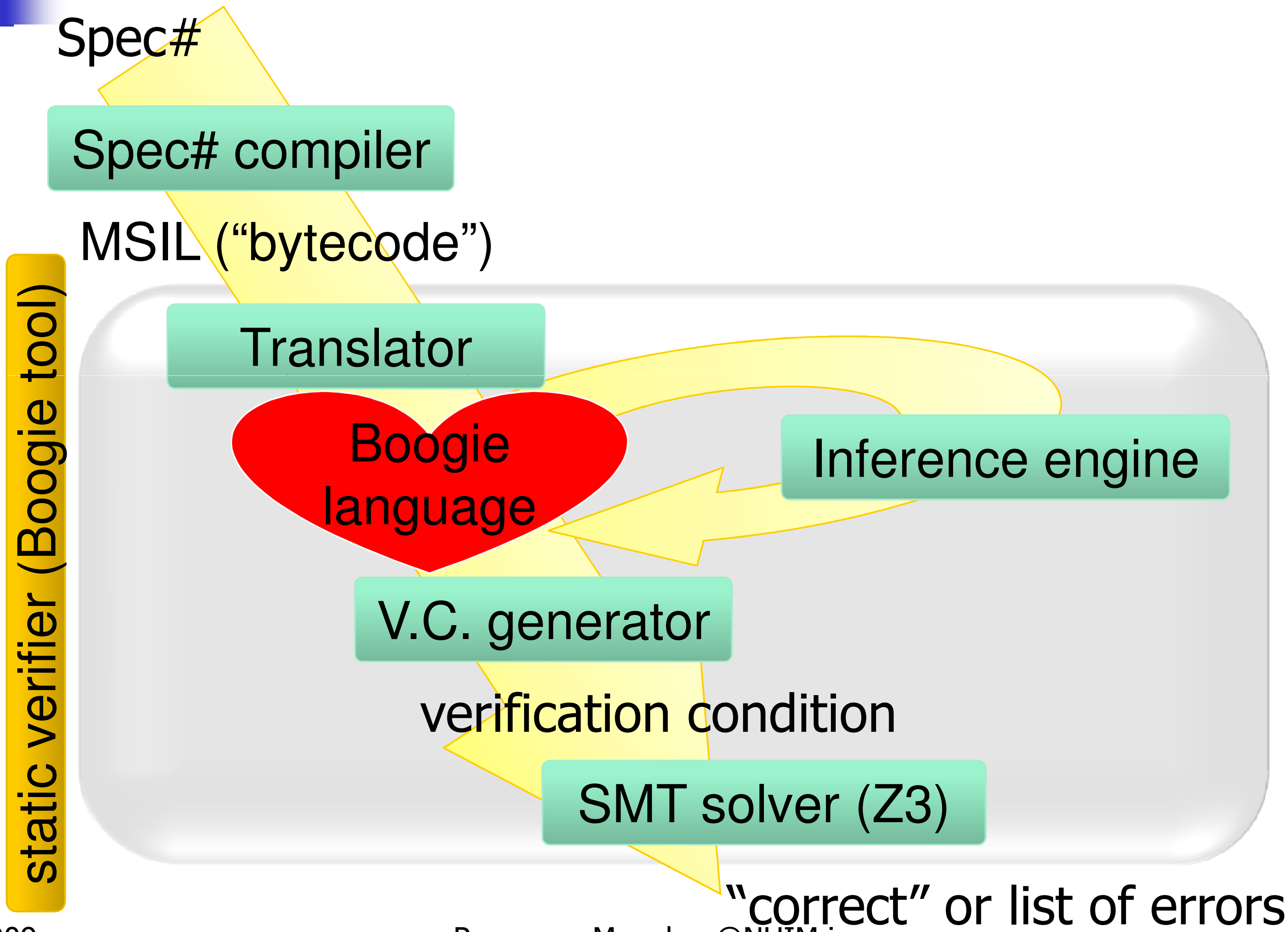
- Every public method has a precondition and a postcondition
- The precondition expresses the constraints under which the method will function properly
- The postcondition expresses what will happen when a method executes properly
- Pre and postconditions are checked
- Preconditions and postconditions are side effect free boolean-valued expressions - i.e. they evaluate to true/false and can't use ++

Static Verification

Static Verification

- Static verification checks all executions
- Spec# characteristics
  - sound modular verification
  - focus on automation of verification rather than full functional correctness of specifications
  - No termination verification
  - No verification of temporal properties
  - No arithmetic overflow checks (yet)

Spec# verifier architecture



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Swap Example:

```
static void Swap(int[] a, int i, int j)
requires 0 <= i && i < a.Length;
requires 0 <= j && j < a.Length;
modifies a[i], a[j];
ensures a[i] == old(a[j]);
ensures a[j] == old(a[i]);
{
    int temp;
    temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

Swap Example:

```
static void Swap(int[] a, int i, int j)
  requires 0 <= i && i < a.Length;
  requires 0 <= j && j < a.Length;
  modifies a[i], a[j];
  ensures a[i] == old(a[j]);
  ensures a[j] == old(a[i]);
{
    int temp;
    temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

requires annotations denote preconditions

Modifies clauses

```
static void Swap(int[] a, int i, int j)
requires 0 <= i && i < a.Length;
requires 0 <= j && j < a.Length;
modifies a[i], a[j];
ensures a[i] == old(a[j]);
ensures a[j] == old(a[i]);
{
    int temp;
    temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

frame conditions limit
the parts of the program state
that the method is allowed to modify.

Swap Example:

```
static void Swap(int[] a, int i, int j)
requires 0 <= i && i < a.Length;
requires 0 <= j && j < a.Length;
modifies a[i], a[j];
ensures a[i] == old(a[j]);
ensures a[j] == old(a[i]);
{
    int temp;
    temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

old(*a[j]*) denotes the value of *a[j]* on entry to the method

Result

```
static int F( int p )
ensures 100 < p ==> result == p - 10;
ensures p <= 100 ==> result == 91;
{
    if ( 100 < p )
        return p - 10;
    else
        return F( F(p+11) );
}
```

`result` denotes the value returned by the method

Spec# Constructs so far

==>	short-circuiting implication
<==>	if and only if
result	denotes method return value
old(E)	denotes E evaluated in method's pre-state
requires E;	declares precondition
ensures E;	declares postcondition
modifies w;	declares what a method is allowed to modify
assert E;	in-line assertion

Modifies Clauses

- **modifies** w where w is a list of:
  - p.x field x of p
  - p.* all fields of p
  - p.** all fields of all peers of p
  - **this**.* default modifies clause, if **this**-dot-something is not mentioned in modifies clause
  - **this**.0 disables the "**this**.*" default
  - a[i] element i of array a
  - a[*] all elements of array a

Loop Invariants

Computing Square by Addition

```
public int Square(int n)
  requires 0 <= n;
  ensures result == n*n;
{
  int r = 0;
  int x = 1;
  for (int i = 0; i < n; i++)
    invariant i <= n;
    invariant r == i*i;
    invariant x == 2*i + 1;
  {
    r = r + x;
    x = x + 2;
  }
  return r;
}
```

Computing Square by Addition

```
public int Square(int n)
  requires 0 <= n;
  ensures result == n*n;
 {
  int r = 0;
  int x = 1;
  for (int i = 0; i < n; i++)
   invariant i <= n;
   invariant r == i*i;
   invariant x == 2*i + 1;
  {
   r = r + x;
   x = x + 2;
  }
  return r;
 }
```

Square(3)

- r = 0 and x = 1 and i = 0
- r = 1 and x = 3 and i = 1
- r = 4 and x = 5 and i = 2
- r = 9 and x = 7 and i = 3

Loop Invariants

```
public static int ISqrt0(int x)
requires 0 <= x;
ensures result*result <= x && x < (result+1)*(result+1);
{
        int r = 0;
        while (!(x < (r+1)*(r+1)))
          invariant r*r <= x;
        {
                r++;
         }
          return r;
}
```

Loop Invariants

```
public static int ISqrt1(int x)
requires 0 <= x;
ensures result*result <= x && x < (result+1)*(result+1);
{
        int r = 0; int s = 1;
        while (s<=x)
          invariant r*r <= x;
          invariant s == (r+1)*(r+1);
        {
                r++;
                s = (r+1)*(r+1);
        }
          return r;
}
```

Quantifiers in Spec#

Examples:

- **forall** {**int** k **in** (0: a.Length); a[k] > 0};
- **exists** {**int** k **in** (0: a.Length); a[k] > 0};
- **exists unique** {**int** k **in** (0: a.Length); a[k] > 0};

Quantifiers in Spec#

Examples:

- **forall** {**int** k **in** (0: a.Length); a[k] > 0};
- **exists** {**int** k **in** (0: a.Length); a[k] > 0};
- **exists unique** {**int** k **in** (0: a.Length); a[k] > 0};

```
void Square(int[]! a)
  modifies a[*];
  ensures forall{int i in (0: a.Length); a[i] == i*i};
```

<Search Demo>

Loop Invariants

```
void Square(int[]! a)
  modifies a[*];
  ensures forall{int i in (0: a.Length); a[i] == i*i};
 {
     int x = 0; int y = 1;
     for (int n = 0; n < a.Length; n++)
      invariant 0 <= n && n <= a.Length;
      invariant forall{int i in (0: n); a[i] == i*i};
     {      a[n] = x;
            x += y;
            y += 2;
     }
  }
```

Error Message from Boogie

Spec# program verifier version 2.00, Copyright (c) 2003-2008, Microsoft.

Error: After loop iteration: Loop invariant might not hold: forall{int i in (0: n); a[i] == i*i}

Spec# program verifier finished with 2 verified, 1 error

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Inferring Loop Invariants

```
void Square(int[]! a)
  modifies a[*];
  ensures forall{int i in (0: a.Length); a[i] == i*i};
{
      int x = 0; int y = 1;
      for (int n = 0; n < a.Length; n++)
       invariant 0 <= n && n <= a.Length;
       invariant forall{int i in (0: n); a[i] == i*i};
       invariant x == n*n && y == 2*n + 1;
      {       a[n] = x;
              x += y;
              y += 2;
      }
}
```

Inferred by /infer:p

Inferred by default

Comprehensions in Spec#

Examples:

- **sum** {**int** k **in** (0: a.Length); a[k]};
- **product** {**int** k **in** (1..n); k};
- **min** {**int** k **in** (0: a.Length); a[k]};
- **max** {**int** k **in** (0: a.Length); a[k]};
- **count** {**int** k **in** (0: n); a[k] % 2 == 0};

Intervals:

- The half-open interval {**int** i **in** (0: n)}
  means i satisfies 0 <= i < n
- The closed (inclusive) interval {**int** k **in** (0..n)}
  means i satisfies 0 <= i <= n

Invariants:Summing Arrays

```
public static int SumValues(int[]! a)
  ensures result == sum{int i in (0: a.Length); a[i]};
{
  int s = 0;
  for (int n = 0; n < a.Length; n++)
    invariant n <= a.Length;
    invariant s == sum{int i in (0: n); a[i]};
  {
        s += a[n];
  }

  return s;
}
```

Quantifiers in Spec#

We may also use **filters**:

- sum {int k in (0: a.Length), **5<=k**; a[k]};
- product {int k in (0..100), **k % 2 == 0;** k};

Note that the following two expressions are equivalent:

- sum {int k in (0: a.Length), **5<=k**; a[k]};
- sum {int k in (5: a.Length); a[k]};

Using Filters

```
public static int SumEvens(int[]! a)
 ensures result == sum{int i in (0: a.Length); a[i] % 2 == 0; a[i]};
 {
  int s = 0;
  for (int n = 0; n < a.Length; n++)
   invariant n <= a.Length;
   invariant s == sum{int i in (0:n), a[i] % 2 == 0; a[i]};
   {
      if (a[n] % 2 == 0)
      {
           s += a[n];
      }
   }
  return s;
 }
```

Filters the even values
From the quantified range

Segment Sum Example:

```
public static int SeqSum(int[] a, int i, int j)
 {
    int s = 0;
    for (int n = i; n < j; n++)
    {
          s += a[n];
    }
    return s;
}
```

<SegSum Demo>

Using Quantifiers in Spec#

A method that sums the elements in a segment of an array `a` i.e. `a[i] + a[i+1] + … + a[j−1]` may have the following contract:

```
public static int SegSum(int[]! a, int i, int j)
requires 0<= i && i <= j && j <= a.Length;
ensures result == sum{int k in (i: j); a[k]};
```

Post condition

Precondition

Non-null type

Loops in Spec#

```
public static int SegSum(int[]! a, i int i, int j)
requires 0 <= i  &&  i <= j  &&  j <= a.Length;
ensures result == sum{int k in (i: j); a[k]};
{
        int s = 0;
        for (int n = i; n < j; n++)
        {
                s += a[n];
        }
        return s;
}
```

Loops in Spec#

```
public static int SegSum(int[]! a, i int i, int j)
requires 0 <= i  &&  i <= j  &&  j <= a.Length;
ensures result == sum{int k in (i: j); a[k]};
{
   int s = 0;
   for (int n = i; n < j; n++)
   {
        s += a[n];
   }
    return s;
}
```

When we try to verify this program using Spec# we get an Error: *Array index possibly below lower bound as the verifier needs more information*

Adding Loop Invariants

Postcondition:

```
ensures result == sum{int k in (i: j); a[k]};
```

Loop Initialisation: n == i

Loop Guard: n < j

Loop invariant:

```
invariant s == sum{int k in (i: n); a[k]};
invariant i <= n && n <= j;
```

Introduce the loop variable & provide its range.

Adding Loop Invariants

```
public static int SegSum(int[]! a, int i, int j)
requires 0 <=i  &&  i <= j  &&  j <= a.Length;
ensures result == sum{int k in (i:j); a[k]};
  {    int s = 0;
       for (int n = i; n < j; n++)
        invariant i <= n && n <= j;
        invariant s == sum{int k in (i:n); a[k]};
       {
            s += a[n];
       }
        return s;
}
```

Verifier Output:
Spec# Program Verifier finished with 3 verified, 0 errors

Variant Functions:Rolling your own!

```
public static int SegSum(int[]! a, int i, int j)
requires 0 <= i  &&  i <= j  &&  j <= a.Length;
ensures result == sum{int k in (i: j); a[k]};
{    int s = 0; int n=i;
     while (n < j)
      invariant i <= n && n <= j;
      invariant s == sum{int k in (i: n); a[k]};
      invariant 0<= j - n;
     {        int vf = j - n; //variant function
              s += a[n]; n++;
              assert j - n < vf;
     }
     return s;
}
```

We can use assert statements to determine information about the variant functions.

Writing Invariants

Some more examples …

Invariant variations: Sum0

```
public static int Sum0(int[]! a)
ensures result == sum{int i in (0 : a.Length); a[i ]};
{   int s = 0;
    for (int n = 0; n < a.Length; n++)
    invariant n <= a.Length && s == sum{int i in (0: n); a[i]};
    {
        s += a[n];
    }
    return s;
}
```

This loop invariant focuses on what has been summed so far.

Invariant variations: Sum1

```
public static int Sum1(int[]! a)
ensures result == sum{int i in (0 : a.Length); a[i ]};
{   int s = 0;
    for (int n = 0; n < a.Length; n++)
    invariant n <= a.Length &&
          s + sum{int i in (n: a.Length); a[i]}
                         == sum{int i in (0: a.Length); a[i]}
    {
          s += a[n];
    }
    return s;
}
```

This loop invariant focuses on what is yet to be summed.

Invariant variations: Sum2

```
public static int Sum2(int[]! a)
ensures result == sum{int i in (0: a.Length); a[i]};
{   int s = 0;
    for (int n = a.Length;0 <= --n; )
    invariant 0 <= n && n <= a.Length &&
                  s == sum{int i in (n: a.Length); a[i]};
    {
          s += a[n];
    }
    return s;
}
```

This loop invariant that focuses on what has been summed so far

Invariant variations:Sum3

```
public static int Sum3(int[]! a)
ensures result == sum{int i in (0 : a.Length); a[i ]};
{   int s = 0;
    for (int n = a.Length; 0<= --n)
    invariant 0 <= n && n<= a.Length &&
          s + sum{int i in (0: n); a[i]}
                         == sum{int i in (0: a.Length); a[i]}
    {
          s += a[n];
    }
    return s;
}
```

This loop invariant focuses on what has been summed so far

The *count* Quantifier

```
public int Counting(int[]! a)
    ensures result == count{int i in (0: a.Length); a[i] == 0};
  {
    int s = 0;
    for (int n = 0; n < a.Length; n++)
      invariant n <= a.Length;
      invariant s == count{int i in (0: n); a[i] == 0};
    {
      if (a[n]== 0) s = s + 1;
    }
    return s;
  }
}
```

Counts the number of 0's in an int []! a;

The *min* Quantifier

```
public int Minimum()
 ensures result == min{int i in (0: a.Length); a[i]};
{
  int m = System.Int32.MaxValue;
  for (int n = 0; n < a.Length; n++)
   invariant n <= a.Length;
   invariant m == min{int i in (0: n); a[i]};
   {
       if (a[n] < m)
           m = a[n];
   }
  }
  return m;
}
```

Calculates the minimum value in an int []! a;

The *max* Quantifier

```
public int MaxEven()
ensures result == max{int i in (0: a.Length), a[i] % 2== 0;a[i]};
 {
  int m = System.Int32.MinValue;
  for (int n = 0; n < a.Length; n++)
   invariant n <= a.Length;
   invariant m == max{int i in (0: n), a[i] % 2== 0; a[i]};
  {
      if (a[n] % 2== 0 && a[n] > m)
           m = a[n];
  }
  return m;
 }
```

Calculates the maximum even value in an int []! a;

How to help the verifier …

Recommendations when using comprehensions:

- Write specifications in a form that is as close to the code as possible.
- When writing loop invariants, write them in a form that is as close as possible to the postcondition

In our *SegSum* example where we summed the array elements a[i] … a[j-1], we could have written the postcondition in either of two forms:

```
ensures result == sum{int k in (i: j); a[k]};
ensures result ==
        sum{int k in (0: a.Length), i <= k && k < j; a[k]};
```

How to help the verifier …

Recommendation: When writing loop invariants, write them in a form that is as close as possible to the postcondition.

```
ensures result == sum{int k in (i: j); a[k]};
invariant i <= n && n <= j;
invariant s == sum{int k in (i: n); a[k]};
OR
ensures result ==
        sum{int k in (0: a.Length), i <= k && k < j; a[k]};
invariant 0 <= n && n <= a.Length;
invariant s == sum{int k in (0: n), i <= k && k < j; a[k]};
```

Some Additional Examples

Insertion Sort

```
public static void sortArray( int[]! a )
modifies a[*];
ensures forall{int j in (1:a.Length);(a[j-1] <= a[j])};
{
    int k;  int t;
    if (a.Length > 0){
       k=1;
       while(k < a.Length)
        invariant 1 <= k && k <= a.Length;
        invariant forall {int j in (1:k), int i in (0:j);(a[i] <= a[j])};
           {
                    //see next slide for nested loop
           }
}
```

Nested loop of Insertion Sort

```
for( t = k;  t>0 && a[t-1]>a[t];  t-- )
      invariant 0<=t && t<=k && k < a.Length;
      invariant forall{int j in (1:k+1),
                       int i in (0:j);  j==t || a[i] <= a[j] };
    {
            int temp;
            temp = a[t];
            a[t] = a[t-1];
            a[t-1] = temp;
    }
    k++;
```

Greatest Common Divisor (slow)

```
static int GCD(int a, int b)
  requires a > 0 && b > 0;
  ensures result > 0 && a % result == 0 && b % result == 0;
  ensures forall{int k in (1..a+b), a % k ==0 && b % k == 0; k <= result};
  {
   int i = 1; int res = 1;
   while (i < a+b)
     invariant i <= a+b;
     invariant res > 0 && a % res == 0 && b % res == 0;
     invariant forall{int k in (1..i), a % k == 0 && b % k == 0; k <= res};
   {
     i++;
     if (a % i == 0 && b % i == 0) {
       res = i;
     }
  }
  return res;
 }
```

BubbleSort

```
public class Bubble {
  static void Sort_Forall(int[]! a)
    modifies a[*];
    ensures forall{int i in (0: a.Length),
                   int j in (0:a.Length), i <= j; a[i] <= a[j]};
  {
        for (int n = a.Length; 0 <= --n; )
        invariant 0 <= n && n <= a.Length;
        invariant forall{int i in (n: a.Length),
                                  int k in (0: i); a[k] <= a[i]};
```

BubbleSort Ctd.

```
{ for (int j = 0; j < n; j++)
    invariant j <= n;
    invariant forall{int i in (n+1: a.Length),
                         int k in (0: i); a[k] <= a[i]};
    invariant forall{int k in (0: j); a[k] <= a[j]};
    {
        if (a[j+1] < a[j]) {
            int tmp = a[j];  a[j] = a[j+1];  a[j+1] = tmp;
        }
    }
  }
}
```

Some more difficult examples…

- Automatic verification of textbook programs that use comprehensions. K. Rustan M. Leino and Rosemary Monahan. In *Formal Techniques for Java-like Programs*, ECOOP Workshop (FTfJP'07: July 2007, Berlin, Germany)

- A method of programming. Edsger W. Dijkstra and W. H. J. Feijen

- Spec# Wiki http://channel9.msdn.com/wiki/default.aspx/SpecSharp.HomePage

Class Contracts

Object Invariants

- Specifying the rules for using methods is achieved through contracts, which spell out what is expected of the caller (preconditions) and what the caller can expect in return from the implementation (postconditions).
- To specify the design of an implementation, we use an assertion involving the data in the class called an *object invariant*.
- Each object's data fields must satisfy the invariant at all stable times
- <RockBand Demo>

Invariants Example:RockBand1

```
public class RockBand
{       int shows;
        int ads;

        invariant shows <= ads;
        public void Play()
        {
                ads++;
                shows++;
        }
}
```

Broken Invariant:RockBand2

```
public class RockBand
{       int shows;
        int ads;

        invariant shows <= ads;
        public void Play()
        {
                shows++;
                ads++;
        }
}
```

Object Invariants:RockBand2

```
public class RockBand
```

RockBand2.ssc(13,5): Error: Assignment to field RockBand.shows of non-exposed target object may break invariant: shows <= ads

Spec# program verifier finished with 4 verified, 1 error

```
        {
            shows++;
            ads++;
        }
}
```

Expose Blocks:RockBand3

```
public class RockBand
{       int shows;
        int ads;
        invariant shows <= ads;
        public void Play()
        {
                expose(this)
                {       shows++;
                        ads++;
                }
        }
}
```

Method Reentrancy:RockBand4

```
public class RockBand
{       int shows;
        int ads;
        invariant shows <= ads;
        public void Play()
        {
                expose(this)
                {       shows++;
                        Play();
                        ads++;
                }
        }
}
```

Method Reentrancy:RockBand4

Verifying RockBand.Play ...
RockBand4.ssc(20,3): Error:

The call to RockBand.Play()
requires target object to be peer consistent

```
    {       expose(this)
            {       shows++;
                    Play();
                    ads++;
            }
    }
}
```

Method Reentrancy:RockBand5

```
public class RockBand
{       int shows;
        int ads;
        invariant shows <= ads;
        public void Play()
        {
                expose(this)
                {       shows++;
                        ads++;
                }
                Play();
        }
}
```

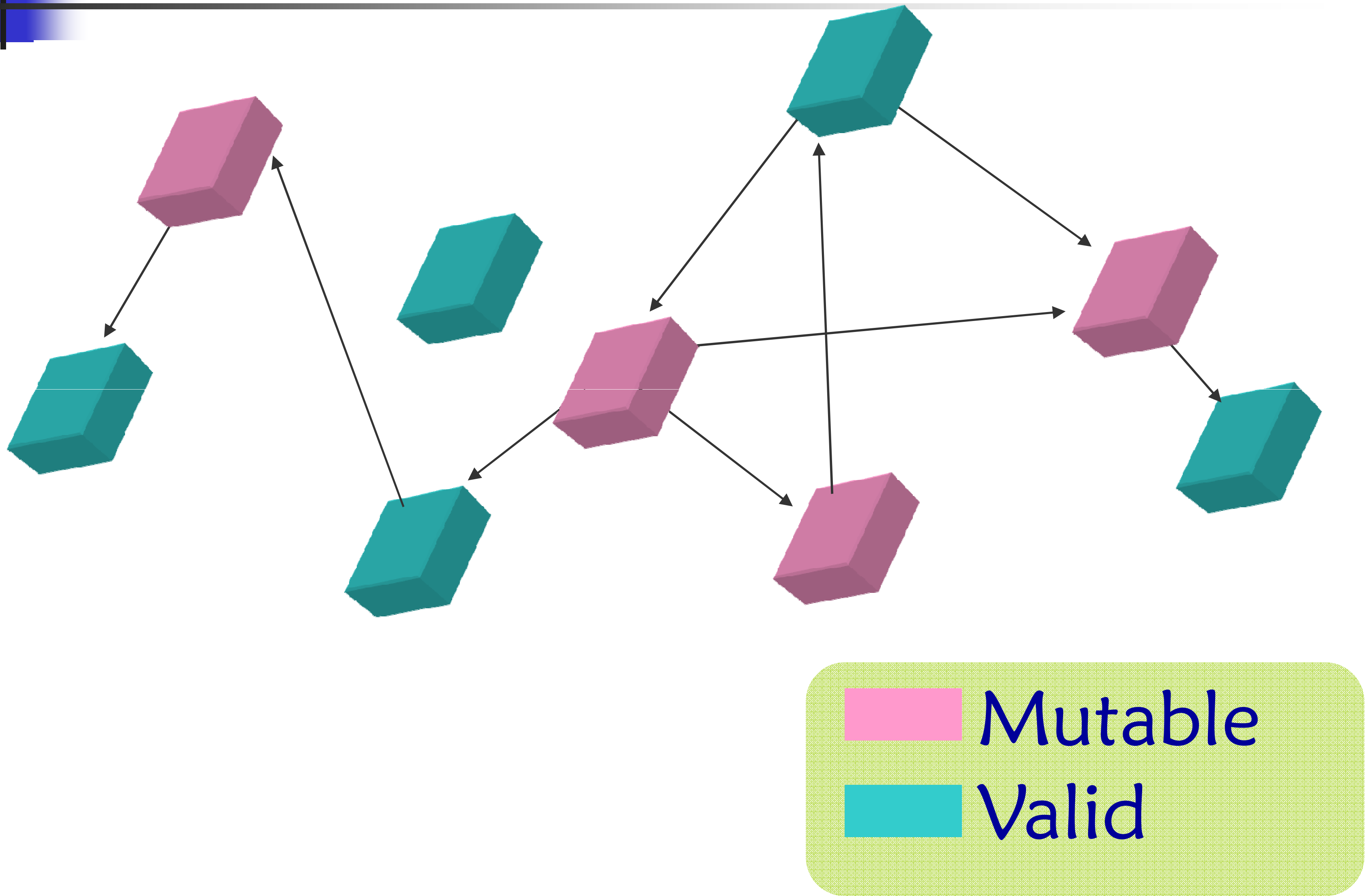
Establishing the Invariant

```
public class RockBand
{       int shows;
        int ads;
        invariant shows <= ads;
        public RockBand()
        {       shows = 0
                ads = shows *100;
        }
        ...
}
```

Object states

- Mutable
  - Object invariant might be violated
  - Field updates are allowed
- Valid
  - Object invariant holds
  - Field updates allowed only if they maintain the invariant

The Heap (the Object Store)



Summary for simple objects

$(\forall o \bullet \; o.\ mutable \vee Inv\ (o))$

- invariant … this.f …;
- x.f = E;

Check:
x.mutable
or
assignment maintains
invariant

o.mutable $\equiv$ $\neg$ o.valid

To Mutable and back: Expose Blocks

```
public class RockBand
{   int shows;
    int ads;
    invariant shows <= ads;
    public void Play()
      modifies shows, ads;
      ensures ads== old(ads)+1 && shows ==old(shows)+1
    {     expose(this) {
                shows++;
                ads ++;
          }
    }
}
```

changes this
from valid to mutable

can update ads and shows
because this.mutable

changes this
from mutable to valid

To Mutable and back: Expose Blocks

```
class Counter{
   int c;
   bool even;
   invariant 0 <= c;
   invariant even <==> c % 2 == 0;
   …
   public void Inc ()
     modifies c;
     ensures c == old(c)+1;
   {     expose(this) {
              c ++;
              even = !even ;
         }
   }
}
```

changes this from valid to mutable

can update c and even, because this.mutable

changes this from mutable to valid

Invariants: Summary

```
class Counter{
    int c;
    bool even;
    invariant 0 <= c;
    invariant even <==> c % 2 == 0;

    public Counter()
    {     c= 0;
          even = true;
    }

    public void Inc ()
      modifies c;
      ensures c == old(c)+1;
    {     expose (this) {
                c++;
                even = !even ;
          }
    }
}
```

The invariant may be broken in the constructor

The invariant must be established & checked after construction

The object invariant may be broken within an expose block

Aggregate Objects and Ownership

Aggregate-Objects

- In Spec#, fields that reference a sub-object of the aggregate object are declared with the [Rep] attribute, where "rep" stands for "representation".
- This makes it possible for the program text to distinguish between component references and other object references that a class may have.
- To keep track of which objects are components of which aggregates, Spec# uses the notion of object ownership.
- An aggregate object owns its component objects.

Sub-Object Example

```
public class Guitar {
        public int solos;

        public Guitar()
         ensures solos == 0;
         {
         }
        public void Strum()
         modifies solos;
         ensures solos == old(solos) + 1;
         {
                solos++;
        }
}
```

Aggregate-Object Example

```
public class RockBand {
  int songs;
  Guitar gt;
  invariant songs == gt.solos;

  public void Play()
{
        gt.Strum();
        songs++;

  }
```

```
public RockBand()
{
    songs = 0;
    gt = new Guitar();
}
```

Aggregate-Object Example

```
public class RockBand {
  int songs;
  Guitar gt;
  invariant songs == gt.solos;

  public void Play()
{
        gt.Strum();
        songs++;
}
```

```
public RockBand()
{
   songs = 0;
   gt = new Guitar();
}
```

RockBand[Rep].ssc(7,22): error CS2696: Expression is not admissible: it is not visibility-based, and first access 'gt' is non-rep thus further field access is not admitted.

Aggregate-Object

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
        gt.Strum();
        songs++;

  }
```

```
public class Client {
public void Main() {
  RockBand b = new
        RockBand();
  b.Play();
  b.Play();
}
```

We annotate Guitar with [Rep] making the the rockBand b the owner of b.gt. We also make it non null.

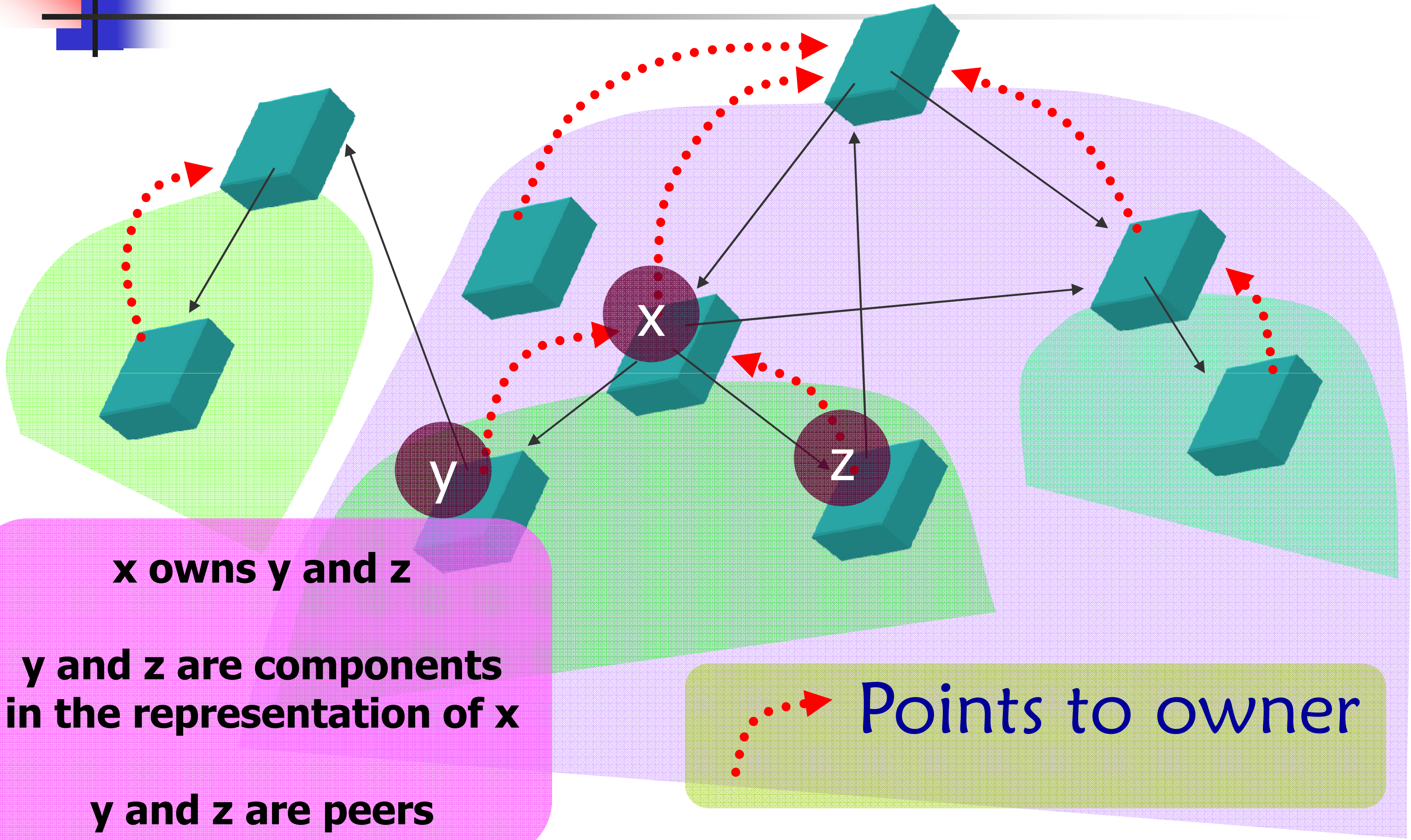
Aggregate-Object

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
        gt.Strum();
        songs++;

 }
```

```
public class Client {
public void Main() {
  RockBand b = new
        RockBand();
  b.Play();
  b.Play();
}
```

Error: The call to Guitar.Strum() requires target object to be peer consistent (owner must not be valid)

Ownership domains



x owns y and z

y and z are components in the representation of x

y and z are peers

Valid objects sub-divided

- If a valid object has no owner object or its owner is mutable, then we say that the object is consistent.
  - This is the typical state in which one would apply methods to the object, for there is no owner that currently places any constraints on the object.
- If the valid object does have an owner and that owner is in the valid state, then we say the object is committed.
  - Intuitively, this means that any operation on the object must first consult with the owner.

Valid objects sub-divided

- A default precondition of a method is that the receiver be consistent (so the receiver is mutable)

- To operate on a component, the method body must first change the receiver into the mutable state (which implies that all of its components change from committed to consistent)

- We can change an object into a mutable state using expose ...

Aggregate-Object

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
        gt.Strum();
         songs++;

 }
```

```
public class Client {
public void Main() {
  RockBand b
        = new RockBand();
  b.Play();
  b.Play();
}
```

Error: The call to Guitar.Strum() requires target object to be peer consistent (owner must not be valid)

Aggregate-Object

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
         expose(this)
         {   gt.Strum();
             songs++;
         }

  }
```

```
public class Client {
public void Main() {
  RockBand b
        = new RockBand();
  b.Play();
  b.Play();
}
```

Ownership Based Invariants

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
        expose(this)
        {   gt.Strum();
            songs++;
        }
}
```

```
public class Client {
public void Main() {
  RockBand b
        = new RockBand();
  b.Play();
  b.Play();
}
```

Note the Ownership based invariant ... This also requires that gt is a [Rep] object as it dereferences gt.

Ownership Based Invariants

```
public class RockBand {
  int songs;
  [Rep] Guitar ! gt;
  invariant songs == gt.solos;

  public void Play()
{
        expose(this)
        {   gt.Strum();
            songs++;
        }
}
```

```
public class Client {
public void Main() {
  RockBand b
       = new RockBand();
  b.Play();
  b.Play();
}
```

Remember: The default precondition of a method is that its receiver is consistent.
This means Guitar.Strum can update solos even if it does not know about the invariant involving solos.

Modifies clauses

- In our example when the Guitar gt is annotated as [Rep], the method Play() does not need to specify modifies gt*
- This is a private implementation detail so the client doesn't need to see it
- Expert level!!! Option on switches – 1,5 and 6

Subtyping and Inheritance

Inheritance
[Additive] and Additive Expose
Overriding methods – inheriting contracts

Base Class

```
public class Car
{
    protected int speed;
    invariant 0 <= speed;

    protected Car()
    {     speed = 0;
    }

    public void SetSpeed(int kmph)
      requires 0 <= kmph;
      ensures speed == kmph;
    {
      expose (this) {
          speed = kmph;
      }
    }

}
```

Inheriting Class: Additive Invariants

```
public class LuxuryCar:Car
{
    int cruiseControlSettings;
    invariant cruiseControlSettings == -1 || speed == cruiseControlSettings;

    LuxuryCar()
    {
        cruiseControlSettings = -1;
    }


}
```

The speed attribute of the superclass
is mentioned in the
the object invariant
of the subclass

Change required in the Base Class

```
public class Car{

    [Additive] protected int speed;
    invariant 0 <= speed;

    protected Car()
    {      speed = 0;
    }

    …
```

The [Additive] annotation is needed as speed is mentioned in the object invariant of LuxuryCar

Additive Expose

```
[Additive] public void SetSpeed(int kmph)
    requires 0<= kmph;
    ensures speed == kmph;
{
        additive expose (this) {
          speed = kmph;
        }
}
```

An additive expose is needed as the SetSpeed method is inherited and so must expose LuxuryCar if called on a LuxuryCar Object

Virtual Methods

```
public class Car{

    [Additive] protected int speed;
    invariant 0 <= speed;

    protected Car()
    {      speed = 0;
    }

    [Additive] virtual public void SetSpeed(int kmph)
      requires 0 <= kmph;
      ensures speed == kmph;
    {
           additive expose (this) {
              speed = kmph;
           }
    }
}
```

Overriding Methods

```
public class LuxuryCar:Car{
protected int cruiseControlSettings;
invariant cruiseControlSettings == -1 || speed == cruiseControlSettings;

    LuxuryCar()
    {
        cruiseControlSettings = -1;
    }
    [Additive] override public void SetSpeed(int kmph)
     //requires 0<= kmph; not allowed in an override
     ensures cruiseControlSettings == 50 && speed == cruiseControlSettings;
    {
         additive expose(this){
              cruiseControlSettings = kmph;
                   additive expose((Car)this){
                   speed =cruiseControlSettings;}
         }         }
}
```

Class Frames

Class Frame: refers to a particular class declaration, not its subclasses or its superclasses. Each frame can declare its own invaraints which constrain the fields declared in that frame.

```
[Additive] override public void SetSpeed(int kmph)
     ensures cruiseControlSettings == 50 && speed == cruiseControlSettings;
   {
         additive expose(this){
                  cruiseControlSettings = kmph;
                           additive expose((Car)this){
                           speed =cruiseControlSettings;}
         }                 }
}
```

Class Frames

- We refine the notions of mutable and valid to apply individually to each class frame of an object.
- We say an object is consistent or committed only when all its class frames are valid.
  - i.e. “consistent” and “committed” apply to the object as a whole, whereas “mutable” and “valid” apply to each class frame individually.
- The **expose** statement changes one class frame of an object from valid to mutable.
- The class frame to be changed is indicated by the static type of the (expression denoting the) given object. E.g. **expose (this)** and **expose ((Car)this)**

Peers

Peer and Rep

- It is appropriate that one object owns another if the other is part of the private implementation of the first as with [Rep] Objects.
- Sometimes, one object holds a reference to another for some other reason ... [Peer]
- E.g. a linked-list node n holds a reference to the next node in the list, n.next. However, n.next is usually not thought of as an implementation detail or component of n. Rather, n and n.next have a more equal relationship, and both nodes may be part of the same enclosing aggregate object.

Peer V Rep

```
class Node {

   public string key;
   public int val;

   [Peer] public Node next;
   public Node(string key, int val) {
           this.key = key;
           this.val = val;
   }
}
```

Back to Aggregates…

```
public class Radio {
  public int soundBoosterSetting;
  invariant 0 <= soundBoosterSetting;

  public bool IsOn()
  {
    int[] a = new int[soundBoosterSetting];
    bool on = true;
    // ... compute something using "a", setting "on" appropriately
    return on;
  }
}
```

Peer

```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Peer] public Radio! r;

  public Car() {
    speed = 0;
    r = new Radio();
  }

public void SetSpeed(int kmph)
    requires 0 <= kmph;
    modifies this.*, r.*;
  {
    speed = kmph;
    if (r.IsOn()) {
      r.soundBoosterSetting =
                              2 * kmph;
    }
  }
```

[Peer] there is only one owner- the owner of the car and radio

Rep

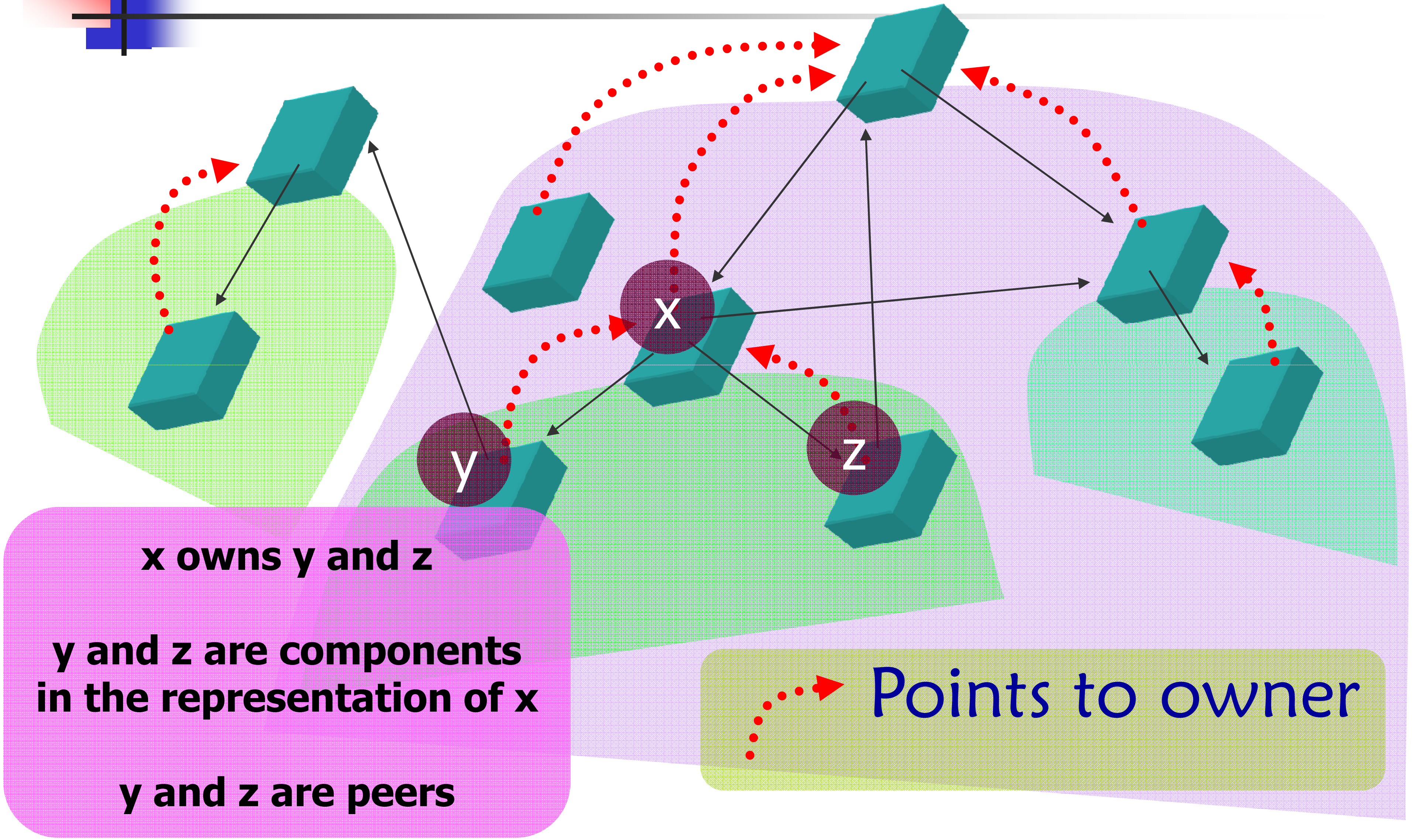
```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Rep] Radio! r;

  public Car() {
    speed = 0;
    r = new Radio();
  }
```

```
public void SetSpeed(int kmph)
    requires 0 <= kmph;
    modifies this.*;
  {
    expose (this) {
      speed = kmph;
      if (r.IsOn()) {
        r.soundBoosterSetting =
                          2 * kmph;
      }
    }
```

[Rep] there is an owner of car and an owner of radio

```
}
```

Ownership domains



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Visibility Based Invariants

```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Peer] Radio! r;

  public Car() {
    speed = 0;
    r = new Radio();
  }
```

```
public void SetSpeed(int kmph)
    requires 0 <= kmph;
    modifies this.*;
  {
    expose (this) {
      speed = kmph;
      if (r.IsOn()) {
        r.soundBoosterSetting =
                            2 * kmph;
      }
    }
}
```

Using [Peer] and expose together would give a visibility based error

Rep

```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Rep] Radio! r;

  public Car() {
    speed = 0;
    r = new Radio();
  }
```

```
public void SetSpeed(int kmph)
    requires 0 <= kmph;
    modifies this.*;
  {
    expose (this) {
      speed = kmph;
      if (r.IsOn()) {
        r.soundBoosterSetting =
                      2 * kmph;
      }
```

Making radio [Rep] makes Radio peer valid

Need the expose block to make it peer consistent.

```
}
```

Rep

Why ever use Rep?

```
                                        kmph)
pu
  invariant 0 <= speed;                {
  [Rep] Radio! r;                        expose (this) {
                                           speed = kmph;
  public Car() {                           if (r.IsOn()) {
    speed = 0;                               r.soundBoosterSetting =
    r = new Radio();                                         2 * kmph;
  }                                        }
                                       }
```

Making radio [Rep] makes Radio peer valid

Need the expose block to make it peer consistent.

Rep

t kmph)

pu

i

invari

[Rep]

Why ever use Rep?

We gain Information Hiding, e.g. if we add an invariant to Car with reference to radio components we get a visibility based error

```
public Car() {
  speed = 0;
  r = new Radio();
}
```

```
if (r.IsOn()) {
  r.soundBoosterSetting =
                    2 * kmph;
}
```

Making radio [Rep] makes Radio peer valid

Need the expose block to make it peer consistent.

}

[Rep] locks

```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Rep] public Radio! r;
  invariant r.soundBoosterSetting == 2 * speed;

  [Rep] bool[]! locks;
  invariant locks.Length == 4;
```

Capture Rep objects

```
public Car([Captured] bool[]! initialLocks)
  requires initialLocks.Length == 4;
{
  speed = 0;
  r = new Radio();
  locks = initialLocks;
}
```

We can't take ownership of initialLocks as someone else might own it so we need to capture it

Modifies clause expanded

```
public void SetSpeed(int kmph)
  requires 0 <= kmph;
  modifies this.*, r.*, locks[*];
 {
  expose (this) {
   if (kmph > 0) {
    locks[0] = true;
   }
   speed = kmph;
   r.soundBoosterSetting = 2 * kmph;
  }
 }
}
```

Peer

```
public class Car {
  int speed;
  invariant 0 <= speed;
  [Rep] public Radio! r;
  invariant r.soundBoosterSetting == 2 * speed;

  [Peer] bool[]! locks;
  invariant locks.Length == 4;
```

[Captured] and [Peer]

[Captured]

```
public Car(bool[]! initialLocks)
  requires initialLocks.Length == 4;
  ensures Owner.Same(this, initialLocks);
{
  speed = 0;
  r = new Radio();
  Owner.AssignSame(this, initialLocks);
  locks = initialLocks;
}
```

Set the owner manually

The constructor has the [Captured] attribute, indicating that the constructor assigns the owner of the object being constructed.

Manual Loop Invariants

```
public void SetSpeed(int kmph)
   requires 0 <= kmph;
   modifies this.*, locks[*];
  {       expose (this) {
              if (kmph > 0)
              {
                     bool[] prevLocks = locks;
                     for (int i = 0; i < 4; i++)
                     invariant locks == prevLocks && locks.Length == 4;
                     {        locks[i] = true;
                     }
              }
              speed = kmph;
             r.soundBoosterSetting = 2 * kmph;
         }
  }
```

Manual Loop invariant to satisfy the modifies clause

Using Collections

```
public class Car {
  [Rep] [ElementsPeer]
  List<Part!>! spares =
    new List<Part!>();

  public void AddPart() {
    expose (this) {
      Part p = new Part();
      Owner.AssignSame(p, Owner.ElementProxy(spares));
      spares.Add(p);
    }
  }

  public void UsePart()
    modifies this.**;
  {
    if (spares.Count != 0) {
      Part p = spares[0];
      p.M();
    }
  }
}
```

Pure Methods

Pure Methods

- If you want to call a method in a specification, then the method called must be *pure*
- This means it has no effect on the state of objects allocated at the time the method is called
- Pure methods must be annotated with [Pure], possibly in conjunction with:
  - [Pure][Reads(ReadsAttribute.Reads.Everything)] methods may read anything
  - [Pure][Reads(ReadsAttribute.Reads.Owned)] (same as just [Pure]) methods can only read the state of the receiver object and its (transitive) representation objects
  - [Pure][Reads(ReadsAttribute.Reads.Nothing)] methods do not read any mutable part of the heap.
- Property getters are [Pure] by default

Using *Pure* Methods

- Declare the pure method within the class definition e.g.

```
[Pure] public bool Even(int x)
  ensures result == (x % 2 == 0);
{
      return x % 2 == 0;
}
```

Using *Pure* Methods

```
public int SumEven()
  ensures result ==
        sum{int i in (0: a.Length), Even(a[i]); a[i]};
 {
  int s = 0;
  for (int n = 0; n < a.Length; n++)
    invariant n <= a.Length;
    invariant s == sum{int i in (0: n) , Even(a[i]); a[i]};
  {     if (Even(a[i]))
        s += a[n];
  }
  return s;
 }
```

Pure method calls

Conclusions

The main contributions of the Spec# programming system are:

- a contract extension to the C# language
- a sound programming methodology that permits specification and reasoning about object invariants even in the presence of callbacks

  (see Verification of object-oriented programs with invariants. Mike Barnett, Rob DeLine, Manuel Fähndrich, K. Rustan M. Leino, and Wolfram Schulte. JOT 3(6), 2004 and Object invariants in dynamic contexts. K. Rustan M. Leino and Peter Müller. In ECOOP 2004, LNCS vol. 3086, Springer, 2004 and Class-local invariants. K. Rustan M. Leino and Angela Wallenburg, ISEC 2008. IEEE.)
- tools that enforce the methodology, ranging from easily usable dynamic checking to high-assurance automatic static verification

References and Resources

- Spec# website http://research.microsoft.com/specsharp/
  - The Spec# programming system: An overview. Mike Barnett, K. Rustan M. Leino, and Wolfram Schulte. In *CASSIS 2004*, LNCS vol. 3362, Springer, 2004.
  - Boogie: A Modular Reusable Verifier for Object-Oriented Programs. Mike Barnett, Bor-Yuh Evan Chang, Robert DeLine, Bart Jacobs, and K. Rustan M. Leino. In *FMCO 2005*, LNCS vol. 4111, Springer, 2006.
  - Automatic verification of textbook programs that use comprehensions. K. Rustan M. Leino and Rosemary Monahan. In *Formal Techniques for Java-like Programs*, ECOOP Workshop (FTfJP'07: July 2007, Berlin, Germany), 2007.
  - The Spec# programming system: An overview. In FM 2005 Tutorial given by Bart Jacobs, K.U.Leuven, Belgium.

Tutorials and Examples

- Spec# wiki http://research.microsoft.com/specsharp/

- Spec# examples and course notes available by emailing Rosemary.Monahan@NUIM.ie and/or on http://www.cs.nuim.ie/~rosemary/

Coming soon at http://research.microsoft.com/specsharp/

- Open source release of Spec#
- Tutorial from Rustan Leino and Peter Müller