CodeContracts: Specification & Verification for the working programmer

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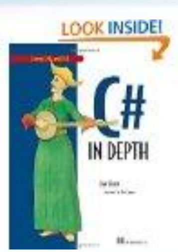
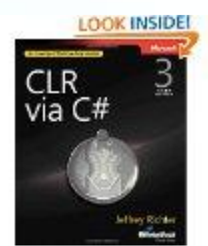
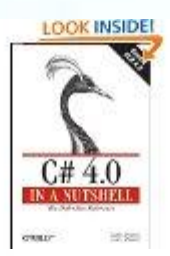
Demo!!!

CodeContracts Impact

- API in .NET 4.0
- Externally available ~20 months
  - >50,000 downloads, very active forum
  - 3 book chapters on CodeContracts
  - Many dozens of blog articles
  - Active forum
- Internal and external adoption
- Publications, talks, lectures
  - POPL, ECOOP, OOPSLA, VMCAI, APLAS, SAS, SAC, FoVeOOS, VSTTE …



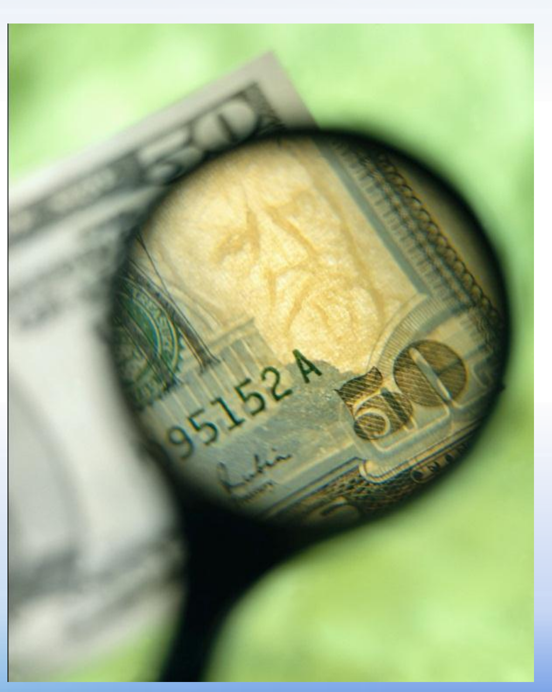




Program verification

- *"The program does not go wrong"*
  - What does it means?
- It does not crash
  - Division by zero
  - Dereference of null (or 0 or nil)
  - No exception is thrown
  - …
- It meets its specification
  - Specification???
  - What's that?

Verification 101



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Specification

- Informally: “What the program should do”
  - “It should sort all the elements of the array”
- Computers do not like English
    - (or Italian for what it matters ;-)
- Which *formal* language?
  - How close to the computer?
  - How close to the human?
  - How close to the programmer?
  - How close to the verification tool?

A plethora of specification lang.

- Implementation
  - Temporal Logic?
  - Z (B) notation?
  - UML?
  - TLA+ ?
  - Abstract state machines (ASM)?
  - JML? Code Contracts?
  - SAL?
  - …
  - Many many
  - …

Potato

The program behavior is included in the behaviors admissible from the specification:

Program is correct ☺

Potato

Specification

Program

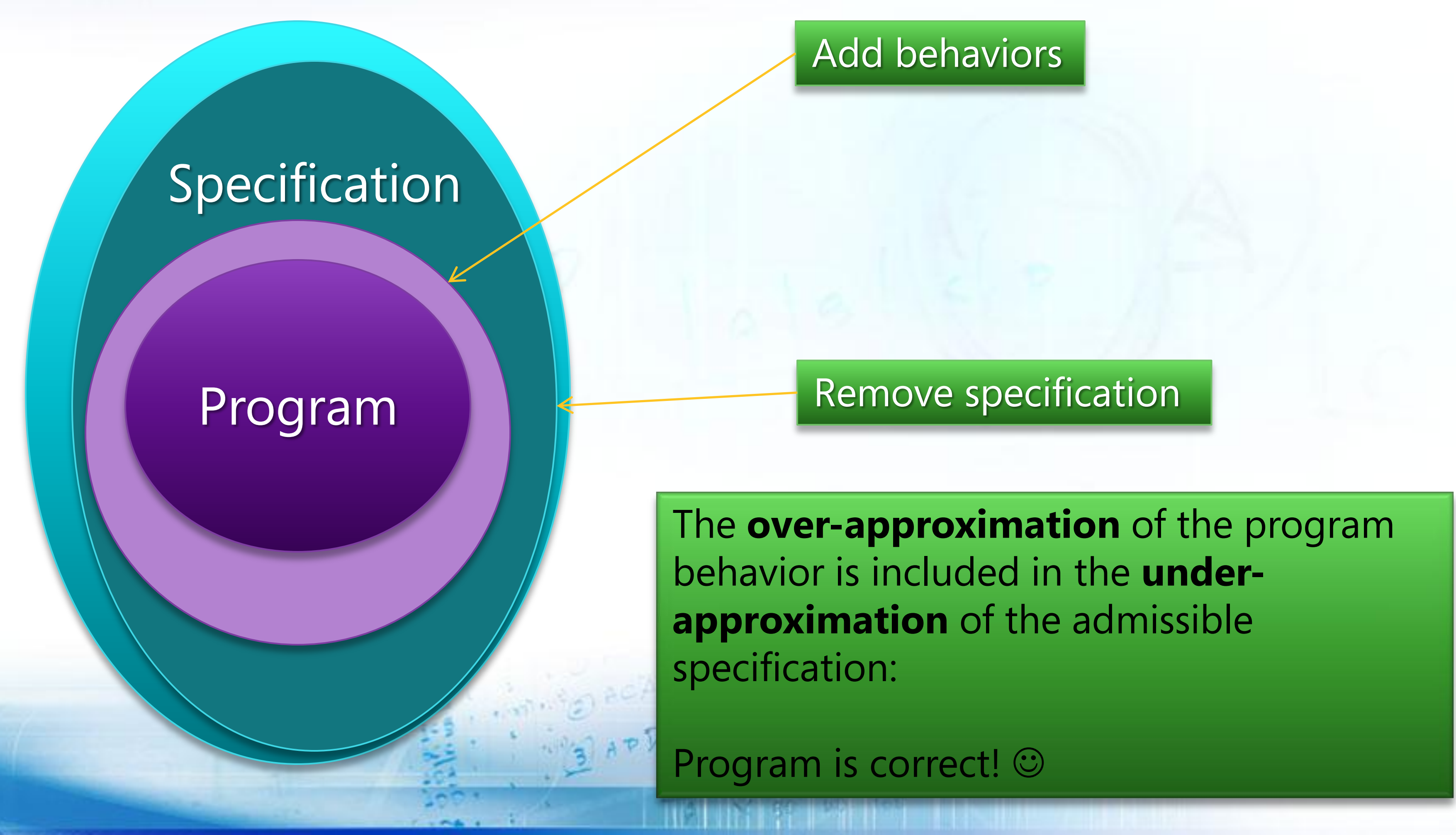
The program behavior is **not** included in the behaviors admissible from the specification:

Program is incorrect ☹
(Some behavior may not meet the specification)

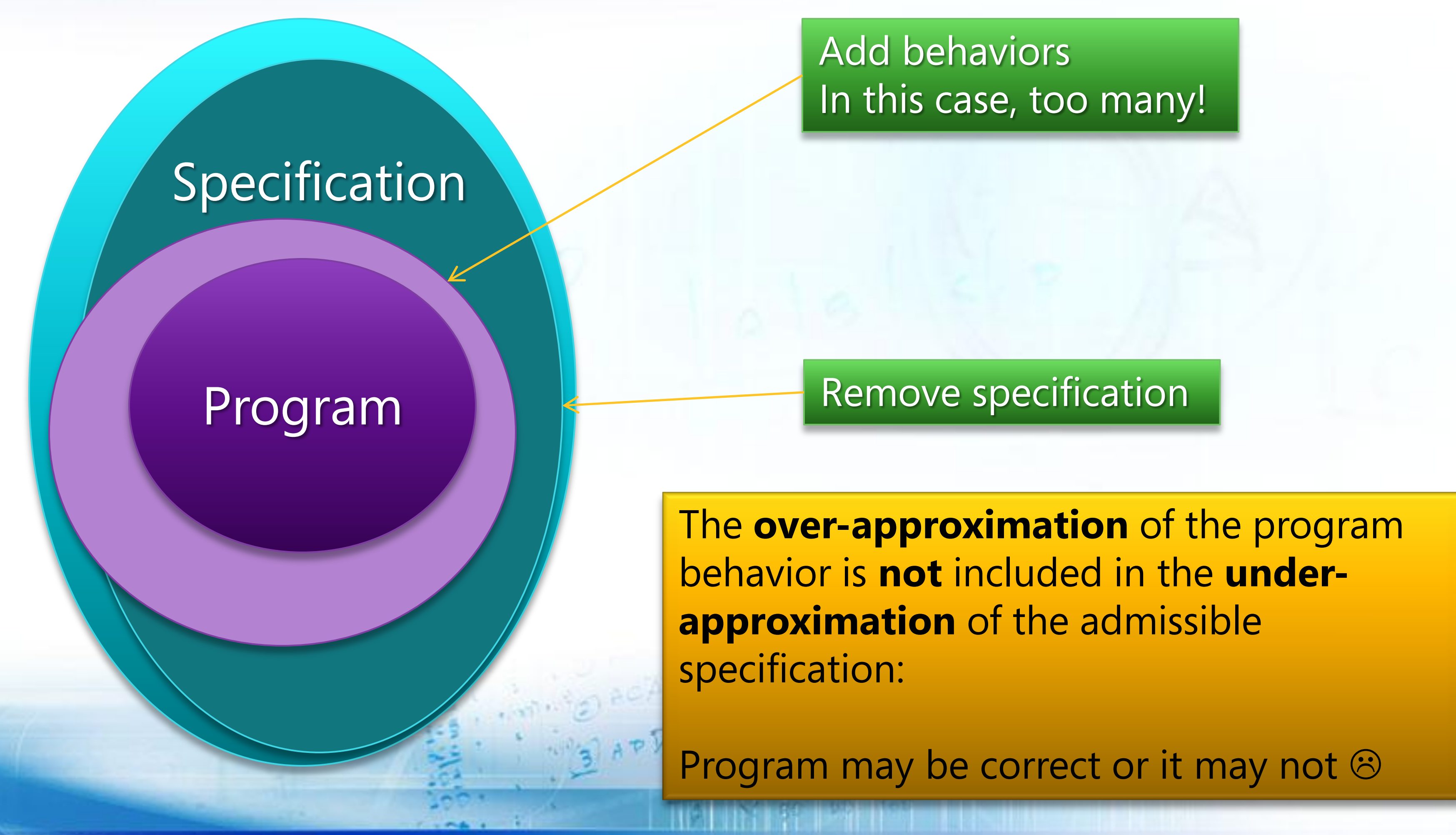
How do we check potatos?

- The problem is undecidable
- Need to perform abstraction
- In the concrete:
  - Is the program correct? Yes/No
- In the abstract:
  - Is the program correct? Yes/No/I do not know
- Which abstraction?
  - Upper-approximate the program semantics
  - Under-approximate the specification semantics

Potato (when lucky)



Potato (when unlucky)



To sum up…

- Specification
  - How do we specify the intent?
    - We should not over-specify
- Verification
  - How do we check the program is doing the right thing?
    - Runtime (testing)
    - Static time (verification)

Microsoft Research

Specification with Contracts

Microsoft

Contracts?

- Each program module specifies
- What it expects from its users
  - Precondition
- What it ensures to its users
  - Postcondition
- What holds in a stable state
  - Object invariants

Contracts: What for?

- Document design decisions

C#

```
public virtual int Next(
    int minValue,
    int maxValue
)
```

Precondition

Parameters

minValue

Type: System.Int32

The inclusive lower bound of the random number returned.

maxValue

Type: System.Int32

The exclusive upper bound of the random number returned. *maxValue* must be greater than or equal to *minValue*.

Return Value

Type: System.Int32

A 32-bit signed integer greater than or equal to *minValue* and less than *maxValue*; that is, the range of return values includes *minValue* but not *maxValue*. If *minValue* equals *maxValue*, *minValue* is returned.

Exceptions

Exception	Condition
ArgumentOutOfRangeException	*minValue* is greater than *maxValue*.

Postcondition

Remarks

Unlike the other overloads of the Next method, which return only non-negative values, this method can return a negative random integer.

Notes to Inheritors:

Starting with the .NET Framework version 2.0, if you derive a class from Random and override the Sample method, the distribution provided by the derived class implementation of the Sample method is not used in calls to the base class implementation of the **Random.Next(Int32, Int32)** method overload if the difference between the *minValue* and *maxValue* parameters is greater than Int32.MaxValue. Instead, the uniform distribution returned by the base Random class is used. This behavior improves the overall performance of the Random class. To modify this behavior to call the Sample method in the derived class, you must also override the **Random.Next(Int32, Int32)** method overload.

Contracts: What for?

- Amplify runtime checking (debugging)
  - More assertions in the code
  - More stable the code
  - Assertions can be disabled in release builds
- Enable modular static analysis
  - Improved precision
    - Analysis should not assume worst case
  - More scalability
  - A little bit as a type-checker (but more refined!)

But we already have assertions!

- All languages have an assert
  - assert(exp) macro in C/C++
  - assert exp keyword in Java
  - Debug.Assert(exp) static method in .NET
- Assert is not visible from the caller!

```
static public int GCD(int x, int y)
{
  Debug.Assert(x > 0);
  Debug.Assert(y > 0);
}
```

Exceptions

- Use exceptions for parameter validation:

```
static public int GCD(int x, int y)
   {
     if (x < 0)
       throw new ArgumentException("Error");
   … }
```

- At library surface
- To protect from unwanted values
- To early detect API misuses
- Again, not visible to callers

But we have Debug.Assert!

- Cannot (easily) specify a postcondition

```
static public int GCD(int x, int y)
   {
     Debug.Assert(x > 0);
     Debug.Assert(y > 0);

     while (true)
       if (x < y) { y %= x; if (y == 0) return x; }
       else { x %= y; if (x == 0) return y; }
   }
```

Debug.Assert(Result > 0) ?

Assert & OOP : ☹

- Inheritance
  - Precondition: Should be weaker
  - Postcondition: Should be stronger
  - How do I enforce it?
- Object invariants
  - Valid in steady states
    - Ex: `this.x != null`
  - Should I add it at every method?
- Interfaces, abstract methods
  - Where I put my assert?

Contracts yesterday

- First class citizens in the language
- Provide syntax to express contracts
  - Examples: Eiffel, D, Spec# …

```
decrement is
        -- Decrease counter by one.
    require
        item > 0
    do
        item := item - 1
    ensure
        item = old item - 1
    end
```

- Why not everyone was using it?
  - New language (start from scratch, or almost)
  - New compiler (do you trust it?)

Contracts yesterday

- Inside comments or as code annotation
  - Ex. JML, Eclipse for non-null …

```
//@ public invariant balance >= 0 && balance <= MAX_BALANCE;

//@ assignable balance;
//@ ensures balance == 0;
public BankingExample() { balance = 0; }

//@ requires 0 < amount && amount + balance < MAX_BALANCE;
//@ assignable balance;
//@ ensures balance == \old(balance + amount);
public void credit(int amount) { balance += amount; }

//@ requires 0 < amount && amount <= balance;
//@ assignable balance;
//@ ensures balance == \old(balance) - amount;
public void debit(int amount) { balance -= amount; }
```

- Why not everyone is using it?
  - Persistence?
  - Need for serialization, parsing…
  - Separate type checking, name resolution…

Code contracts

Code Contracts

- Idea: Use the IL as contract representation
- Use static methods to a contract library
  - Language agnostic: same for C#, VB, F# …

```
Contract.Requires(source != null);
Contract.Requires(!String.IsNullOrEmpty(suffix));

Contract.Ensures(Contract.Result<string>() != null);
Contract.Ensures(!Contract.Result<string>().EndsWith(suffix));
```

```
Contract.Assert(trimmed IsNot Nothing)
Contract.Assert(Not trimmed.EndsWith(".dll"))
```

What are they?

- Plain code for contracts
- Static methods to a contract library
  - Language agnostic: same for C#, VB, F# …
  - Standard from .NET 4.0
- No need for a new compiler/language
  - Precondition: Contract.Requires(…)
  - Postcondition: Contract.Ensures(…)
  - Invariant: Contract.Invariant(…)

Preconditions

- Contract.Requires(exp)

```
int foo(String s, int y)
{
  Contract.Requires(s != null);
  Contract.Requires(y > 0);
  // ...
}
```

C# expressions

Preconditions

- Which is the underlying language specification?

Your programming language!!!

```
Public Function foo(ByVal s As String, ByVal y As Integer)
  As Integer
      Contract.Requires(s IsNot Nothing)
      Contract.Requires(y > 0)
      ‘ …
End Function
```

VB expressions

```
Int32 __gc* foo(String __gc* s, Int32 __gc* y)

     Contract::Requires(s != 0);
     Contract::Requires(y > 0);
```

C++ expressions

Postconditions

- Contract.Ensures(exp)

```
Class Field
{
  int x;

  int Set(int y)
  {
    Contract.Ensures(this.x == y);
    this.x = y;
  }
}
```

Result value?

- In C#/VB/… no name for the returned value
- Use a dummy method

```
public int Fact(int x)
{
  Contract.Ensures(Contract.Result<int>() >= 0);
  …
}
```

Question

- Why <int> ?
- Why <bool[]> ?

```
public int Fact(int x)
{
  Contract.Ensures(Contract.Result<int>() >= 0);

}
```

```
public bool[] ArrayFactory(int x)
{
  Contract.Ensures(Contract.Result<bool[]>() != null);
  return new bool[x];
}
```

`T Contract.Result<T>()`

Old value?

- No name for the old value

```
Class Account
{
  int balance;

  int Add(int k)
  {
    Contract.Ensures(this.balance ==
      Contract.Old(this.balance) + k);
    this.balance += k;
  }
}
```

```
T Contract.Old<T>(T value)
```

Quantifiers

- Limited form:
  - `Contract.ForAll(0, A.Length, i => A[i] > 0);`
  - `Contract.Exists(0, A.Length, i => A[i] > 0);`
- Exploit higher order functions

Class Invariant

```
Class Account
{
  int balance;

  [ContractInvariantMethod]
  protected void ObjectInvariant()
  {
     Contract.Invariant(balance >= 0);
  }
}
```

Interfaces

```
[ContractClass(typeof(WithdrawContracts))]
interface IWithdraw
{
  long Balance { get; }
  void Withdraw(long money);
}
```

```
[ContractClassFor(typeof(IWithdraw))]
public class WithdrawContracts : IWithdraw {
public long Balance { get {
      Contract.Ensures(Contract.Result<long>() >= 0);
      return -111;  } }
public void Withdraw(long money) {
      Contract.Requires(money < this.Balance);}}
```

Other

- Abstract classes
  - Similar to interfaces
- Out/ref parameters
  - Use dummy method
- Legacy code: *"if !exp throw exception"*
  - Use Contract.EndContract()

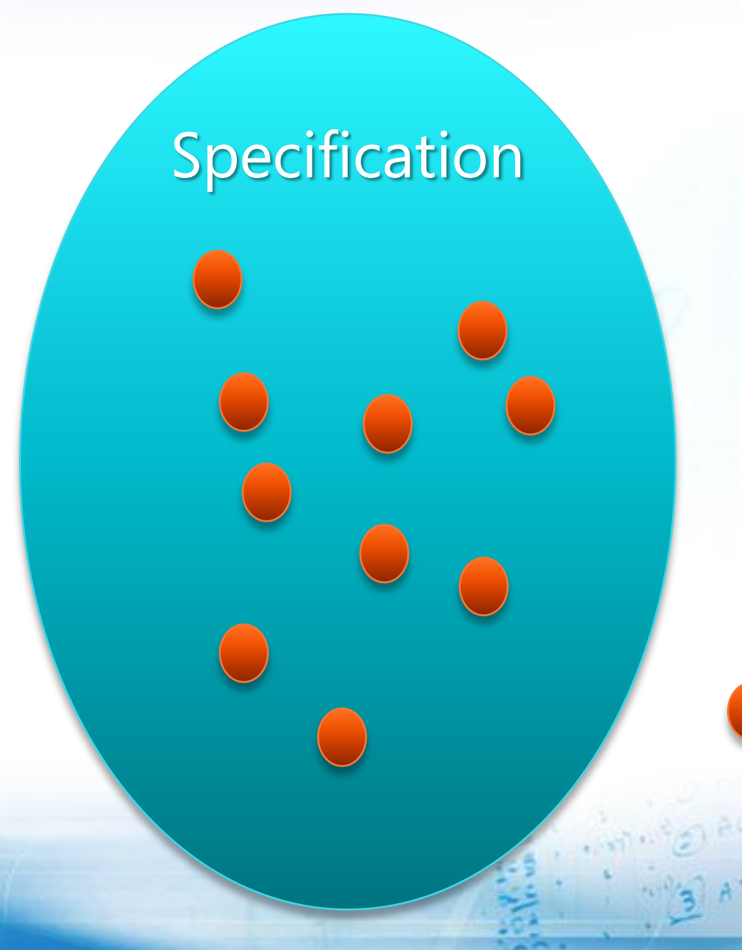
Advantages

- Produced by all the compilers
- Free:
  - Types
  - Intellisense
  - Name resolution…
- Cross language
- Precise semantics
- Uniform format understood by our tools

Runtime checking (aka Testing)

Microsoft

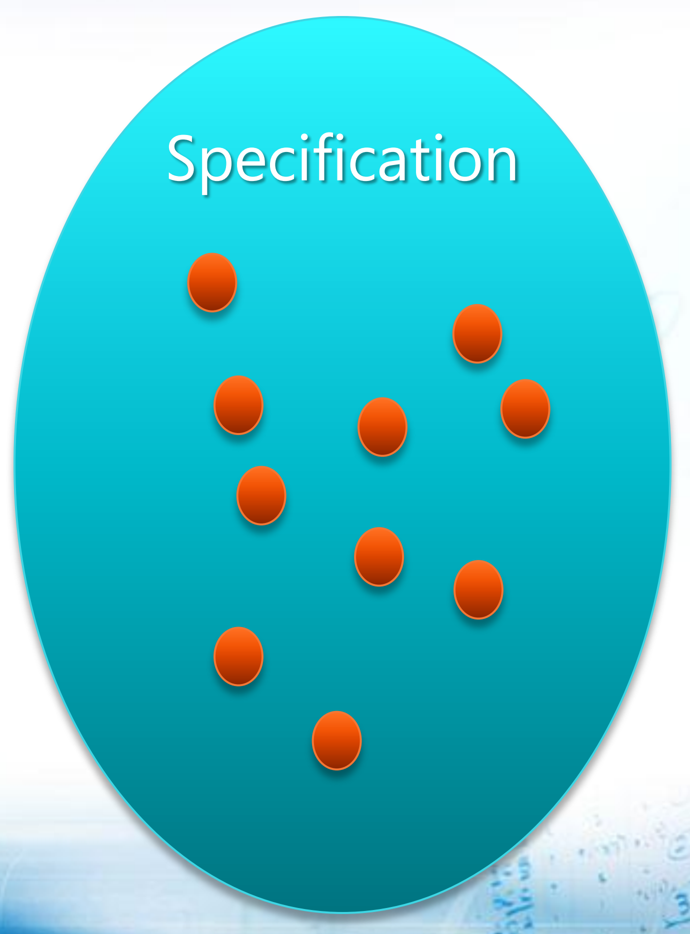
Potato & testing



One execution is outside the specification

The program is incorrect!

Potato & testing



A ***sample*** of the program behavior is included in the behaviors admissible from the specification

Is the program correct?

Testing

- Prove the existence of specification violations
  - i.e. the existence of bugs
  - If a test fails, then there is a bug
- Cannot verify the program
  - i.e. the existence of no bug!
  - Can try only finitely main inputs
    - 100% code coverage do not imply 100% data coverage
- Yet, very useful!!!

Runtime checking of contracts

- C# compiler does not know about contracts
- Achieved via binary rewriting
  - Handle old, result …
  - Inherit contracts
  - Stick contracts to interface implementations

Binary rewriting

```
public virtual int Add(object value){
  Contract.Requires( value != null );

  Contract.Ensures( Count == Contract.OldValue(Count) + 1 );
  Contract.Ensures( Contract.Result<int>() == Contract.OldValue(Count) );

  if (_size == _items.Length) EnsureCapacity(_size+1);
  _items[_size] = value;
  return _size++;
}
```

csc/vbc/…

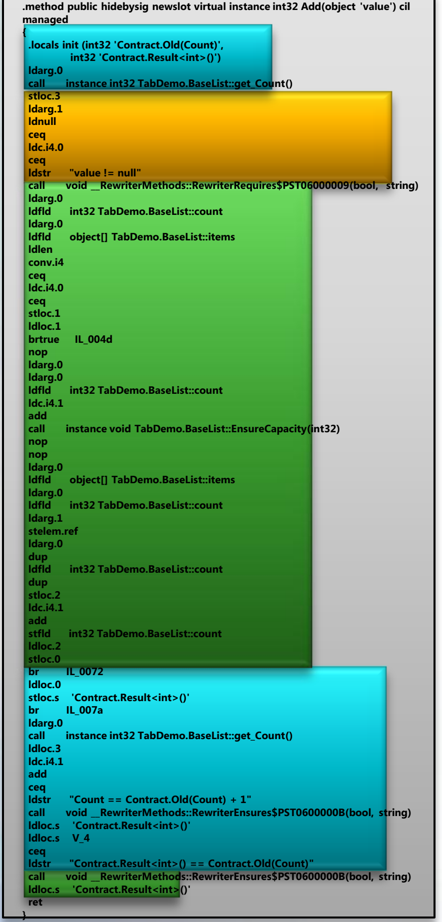
```
.method public hidebysig newslot virtual instance int32 Add(object 'value') cil managed
{
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldarg.0
ldfld      object[] TabDemo.BaseList::items
ldlen
conv.i4
ceq
ldc.i4.0
ceq
stloc.1
ldloc.1
brtrue.s   IL_0029
ldarg.0
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldc.i4.1
add
call       instance void TabDemo.BaseList::EnsureCapacity(int32)
ldarg.0
ldfld      object[] TabDemo.BaseList::items
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldarg.1
stelem.ref
ldarg.0
dup
ldfld      int32 TabDemo.BaseList::count
dup
stloc.2
ldc.i4.1
add
stfld      int32 TabDemo.BaseList::count
ldloc.2
stloc.0
br.s       IL_004b
ldloc.0
ret
}
```

/d:CONTRACTS_FULL

csc/vbc/…

```
.method public hidebysig newslot virtual instance int32 Add(object 'value') cil managed
{
ldarg.1
ldnull
ceq
ldc.i4.0
ceq
call       void [Microsoft.Contracts]Microsoft.Contracts.Contract::Requires(bool)
ldarg.0
call       instance int32 TabDemo.BaseList::get_Count()
ldarg.0
call       instance int32 TabDemo.BaseList::get_Count()
call       !!0 [Microsoft.Contracts]Microsoft.Contracts.Contract::Old<int32>(!!0)
ldc.i4.1
add
ceq
call       void [Microsoft.Contracts]Microsoft.Contracts.Contract::Ensures(bool)
call       !!0 [Microsoft.Contracts]Microsoft.Contracts.Contract::Result<int32>()
ldarg.0
call       instance int32 TabDemo.BaseList::get_Count()
call       !!0 [Microsoft.Contracts]Microsoft.Contracts.Contract::Old<int32>(!!0)
ceq
call       void [Microsoft.Contracts]Microsoft.Contracts.Contract::Ensures(bool)
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldarg.0
ldfld      object[] TabDemo.BaseList::items
ldlen
conv.i4
ceq
ldc.i4.0
ceq
stloc.1
ldloc.1
brtrue.s   IL_0069
ldarg.0
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldc.i4.1
add
call       instance void TabDemo.BaseList::EnsureCapacity(int32)
ldarg.0
ldfld      object[] TabDemo.BaseList::items
ldarg.0
ldfld      int32 TabDemo.BaseList::count
ldarg.1
stelem.ref
ldarg.0
dup
ldfld      int32 TabDemo.BaseList::count
dup
stloc.2
ldc.i4.1
add
stfld      int32 TabDemo.BaseList::count
ldloc.2
stloc.0
br.s       IL_008b
ldloc.0
ret
} // end of method BaseList::Add
```

ccrewrite



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Static verification

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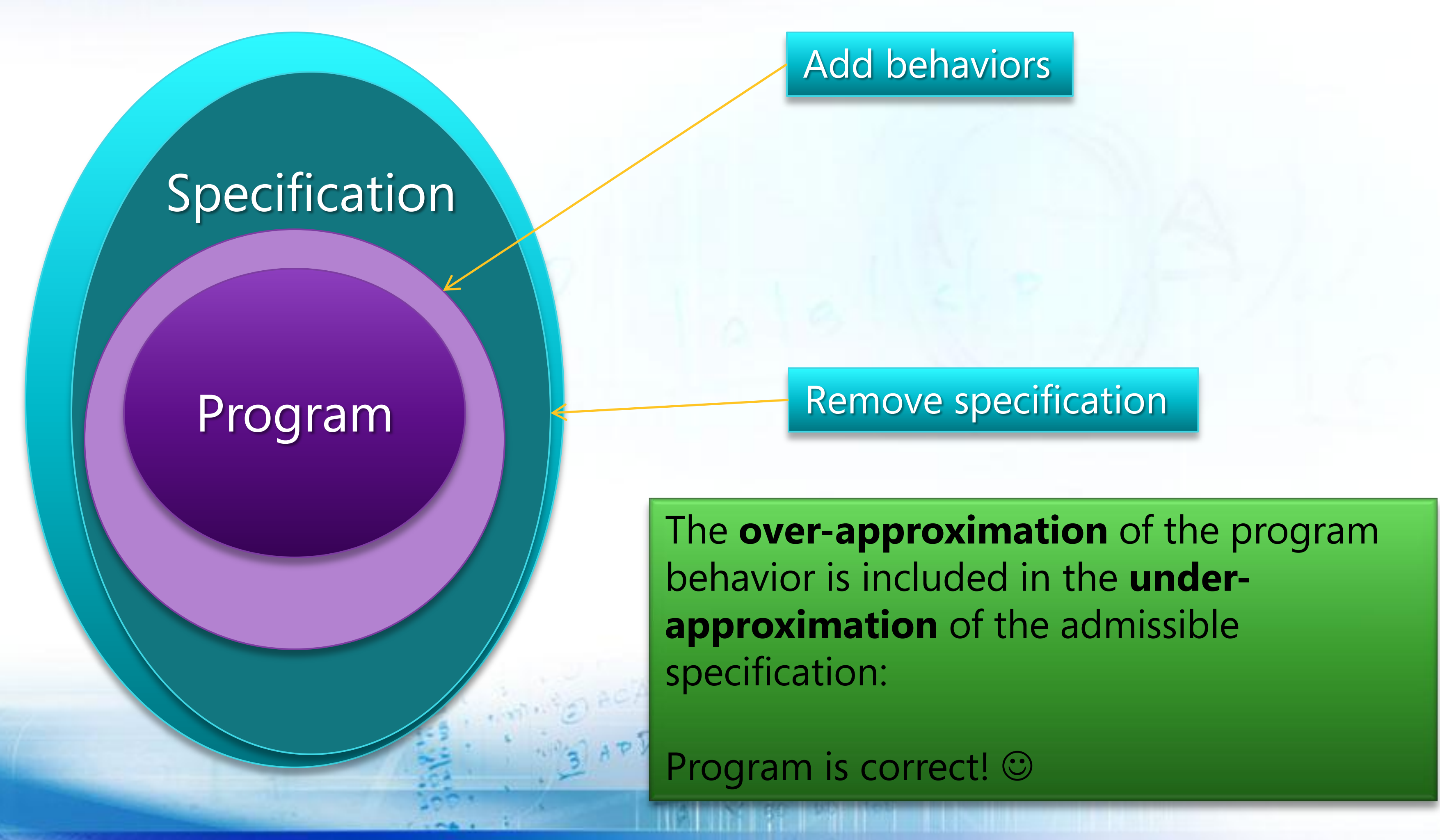
Static verification with potatos



The **over-approximation** of the program behavior is included in the **under-approximation** of the admissible specification:

Program is correct! ☺

Static verification

- Any static verification method is incomplete
  - Verification is not decidable

```
public static bool NotDecidable()
   {
     if (SolvableDiophantineEquation)
       return 1;
     else
       Contract.Assert(false);
   }
```

Not decidable (Hilbert's 10th problem)

Verification techniques

- Many, many out there…
- Model Checking
- Theorem proving
  - Automatic
    - SMT solvers, resolution based, …
  - Semi-automatic
  - 2nd order
- All those instances of Abstract interpretation!

Abstract interpretation

Microsoft

Abstract Interpretation

- Theory of approximations
- Semantics are order according to the precision
- The more the precise the semantics
  The more the properties captured
- A static analysis is a semantics
  - Precise enough to capture the properties of interest
  - Rough enough to be computable

Basic Concepts

- Concrete domain
  - A mathematical structure describing the most precise information on the program
  - Usually the program semantics
    - Traces, operational, denotational …
- Abstract domain
  - A mathematical structure describing the property of interests
  - Ex.: range of a variable

Example: Rule of signs

- Abstract semantics is over signs

$$
\begin{aligned}
a[\![k]\!]\rho &= sign(k) \\
a[\![x]\!]\rho &= \rho(x) \\
a[\![e1 + e2]\!]\rho &= a[\![e1]\!]\rho \,\underline{+}\, a[\![e2]\!]\rho \\
a[\![e1 * e2]\!]\rho &= a[\![e1]\!]\rho \,\underline{*}\, a[\![e2]\!]\rho
\end{aligned}
$$

$\underline{+}$	⊥	neg	zero	pos	T
⊥	⊥	⊥	⊥	⊥	⊥
neg	⊥	neg	neg	T	T
zero	⊥	neg	zero	pos	T
pos	⊥	T	pos	Pos	T
T	⊥	T	T	T	T

Example: Rule of signs

- (12345565 * 13456) + (-9873 * -1344678)
- Sign of the result?
- Do the computation: 179 397 928 534
  - Then take the sign : pos
- Do the abstract computation:

  $(\text{pos} \mathbin{\underline{*}} \text{pos}) \mathbin{\underline{+}} (\text{neg} \mathbin{\underline{*}} \text{neg})$

  $= \text{pos} \mathbin{\underline{+}} \text{pos}$

  $= \text{pos}$

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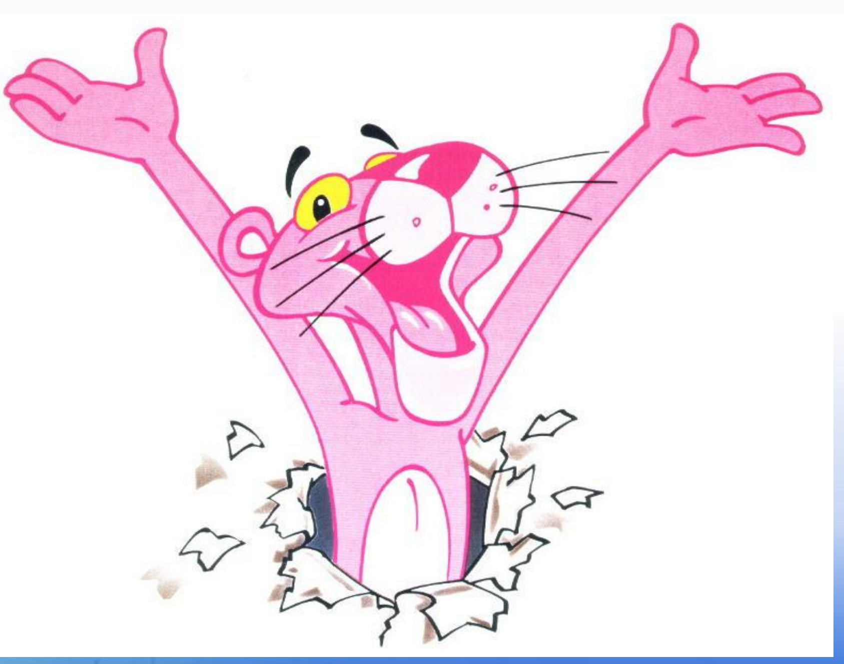
CodeContracts Static checker *aka Clousot*



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Algorithm: High level

- For each assembly A, class C, method M

1. Extract the proof obligations
   - What should I prove?
2. Run the analyses
   - Discover facts on the program
3. Use the facts to prove the proof obligations
   - If not, do something else…

Proof obligations

- Two kinds: Implicit and explicit
- Implicit
  - NonNull checking
  - Bounds checking
  - Arithmetic: Divisions by zero, overflows,
  - …
- Explicit
  - Assertions
  - When calling a method, its precondition
  - When returning from a method, its postcondition

NonNull dereference

```
public bool IsCiao(string s)
   {
      return s.Contains("ciao!");
   }
```

- The string s should not be null
  - Otherwise, exception at run time
- Generate the proof obligation: s `!= null`

Array bounds

```
public int[] RandomArray(int len)
   {
     var random = new Random(len);
     var arr = new int[len];
     for (var i=0; i < len; i++)
     {
       arr[i] = random.Next();
     }
     return arr;
   }
```

len >= 0

i >= 0

i < arr.Length

Overflows

```
public int Div(int x, int y)
   {
     return x / y;
   }
```

```
public int Abs(int x)
{
 if (x < 0)
   return -x;
 return x;
}
```

y != 0

x != MinValue || y != -1

x != MinValue

Explicit obligation: Assertions

```
public string Concat(string p, string q)
  {
    Contract.Requires(p != null);
    Contract.Requires(q != null);

    var concat = p + q;

    Contract.Assert(concat != null);
    Contract.Assert(concat.Length > 0);

    return concat;
  }
```

```
concat != null
```

```
concat.Length > 0
```

Preconditions

```
public string Concat(string p, string q)
  {
    Contract.Requires(p != null);
    Contract.Requires(q != null);
    // …
  }

 public string MyConcat()
  {
    return Concat("Ciao", null);
  }
```

Concat "believes" (assumes) those preconditions

"Ciao" != null

null != null

Postconditions

```
public double Abs(double x)
  {
    Contract.Ensures(
      Contract.Result<double>() >= 0);

    if (x < 0)
      return -x;
    return x;
  }

 public double Sqrt(double z)
 {
   return Math.Sqrt(Abs(z));
 }
```

-x >= 0

x >= 0

Note: the program is wrong, why???

Sqrt "believes" (assumes) Abs(z) >= 0

Algorithm: High level

- For each assembly A, class C, method M

1. Extract the proof obligations
    - What should I prove?
2. Run the analyses
    - Discover facts on the program
3. Use the facts to prove the proof obligations
    - If not, do something else…

Inferred facts

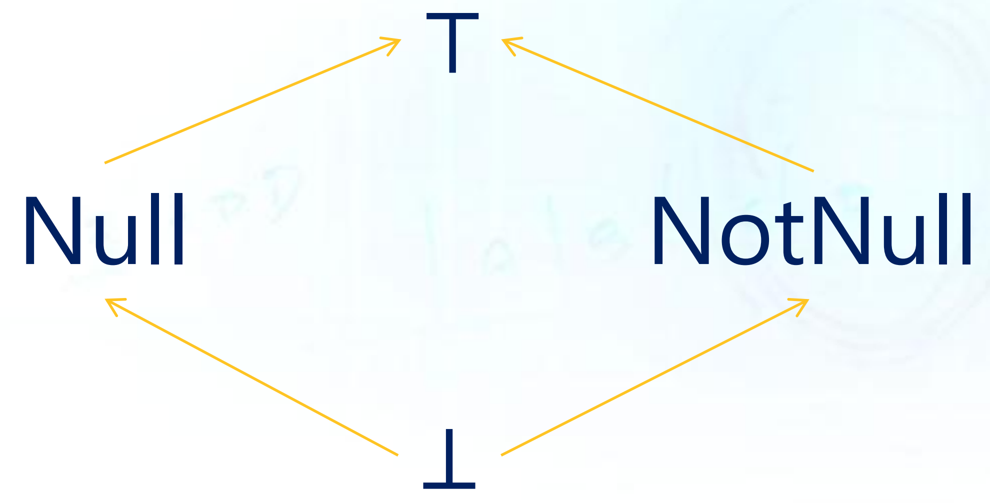
- Heap structure
- Null/Not-Null
- Numerical values
  - Ranges, relations, floating points …
- Enum values
- Array/Collection contents
- …

Example

```
public string TrimSuffix(string s, string suffix)
   {
     Contract.Requires(s != null);
     Contract.Requires(suffix != null);

     string res = s;

     while (res.EndsWith(suffix))
     {
       int len = res.Length - suffix.Length;
       res = res.Substring(0, len);
     }

     Contract.Assert(res != null);

     return res;
   }
```

NonNull analysis

- Associate to each variable an element of



With proof obligations explicit

```
public string TrimSuffixWPO(string s, string suffix)
   {
     Contract.Requires(s != null);
     Contract.Requires(suffix != null);

     string res = s;

     Contract.Assert(res != null);
     while (res.EndsWith(suffix))
     {
       Contract.Assert(res != null);
       Contract.Assert(suffix != null);
       int len = res.Length - suffix.Length;
       Contract.Assert(res != null);
       res = res.Substring(0, len);
       Contract.Assume(res != null);   // Postcondition of res
     }

     Contract.Assert(res != null);

     return res;
   }
```

Checking

```
public string TrimSuffixWPO(string s, string suffix)
   {
     Contract.Requires(s != null);
     Contract.Requires(suffix != null);

     string res = s;

     Contract.Assert(res != null);
     while (res.EndsWith(suffix))
     {
       Contract.Assert(res != null);
       Contract.Asert(suffix != null);
       int len = res.Length - suffix.Length;
       Contract.Assert(res != null);
       res = res.Substring(0, len);
       Contract.Assume(res != null);   // Postcondition of res
     }

     Contract.Assert(res != null);

     return res;
   }
```

s, suffix: NotNull, res : Null

s, suffix, res: NotNull

s, suffix, res: NotNull

s, suffix : NotNull, res: T

s, suffix, res: NotNull

Ok!

What we did?

- We over-approximated the semantics
- We kept the concrete specification

Example: Numerical analysis

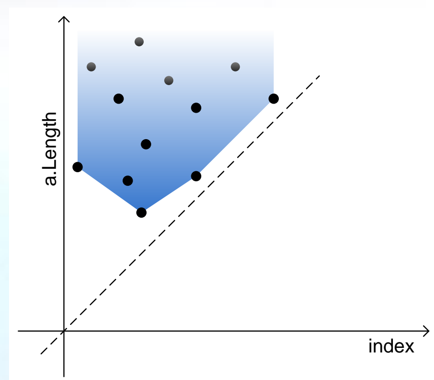
```
static public int GCD(int x, int y)
   {
     Contract.Requires(x > 0);
     Contract.Requires(y > 0);

     Contract.Ensures(Contract.Result<int>() > 0);

     while (true)
     {
       if (x < y)
       {
         y %= x;
         if (y == 0)
           return x;
       }
       else
       {
         x %= y;
         if (x == 0)
           return y;
       }
     }
   }
```

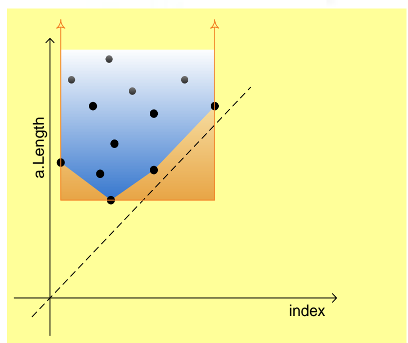
We need numerical reasoning

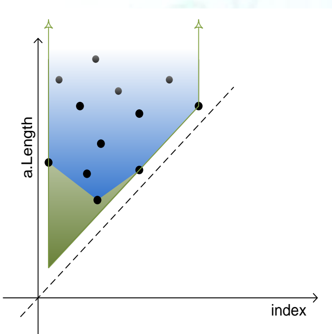
We need to infer loop invariants

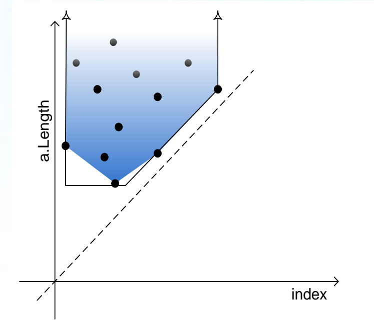
Numerical Analysis

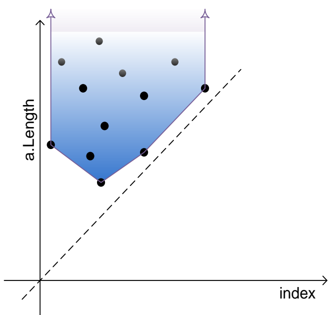
- $0 \leq \text{index} < \text{array.Length}$?











Intervals	Pentagons	Octagons	Polyhedra
$O(n)$	$O(n)$	$O(n^3)$	$O(2^n)$
$a \leq x \leq b$	$a \leq x \leq b$ & $x < y$	$\pm x \pm y \leq a$	$\Sigma a_i x_i \leq b$
No ☹	Yes ☺	Yes ☺	Yes ☺

Intervals

- Approximate each variable with a range

  $[a, b]$ where $a, b \in Z \cup \{ +\infty, -\infty \}$

  - More complex in reality because of
    - Overflows
    - Different Int types (16, 32, 64 bits, signed/unsigned)
- Idea: Replace a value, a set of values with an interval

Example

```
static public int GCD(int x, int y)
   {
     Contract.Requires(x > 0);
     Contract.Requires(y > 0);

     Contract.Ensures(Contract.Result<int>() > 0);

     while (true)
     {
       if (x < y)
       {
         y %= x;
         if (y == 0)
           return x;
       }
       else
       {
         x %= y;
         if (x == 0)
           return y;
       }
     }
   }
```

x :[1,+∞] y :[1,+∞]

x :[1,+∞] y :[1,+∞]

Loop invariant!

x :[1,+∞], y:[2, +∞]

x :[1,+∞], y:[0, +∞]

x :[1,+∞], y:[1, +∞]

x :[1,+∞], y:[1, +∞]

x :[0,+∞], y:[1, +∞]

x :[1,+∞], y:[1, +∞]

Ok!

Bounds checking example

```
public void AllToZero(int[] a)
   {
     for (int i = 0; i < a.Length; i++)
     {
       Contract.Assert(i >= 0);
       Contract.Assert(i < a.Length);

       a[i] = 0;
     }
   }
```

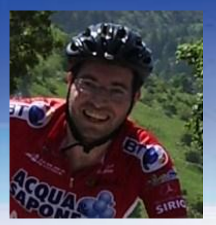
a.Length :[0. +∞] i :[0,+∞]

Not Ok!

What are we missing?

- Intervals keep only numerical information
- No symbolic information
  - Ex. `i < a.Length`
- No relations
- Intervals are an example of a non-relational domain
  - Non-null is non-relational too

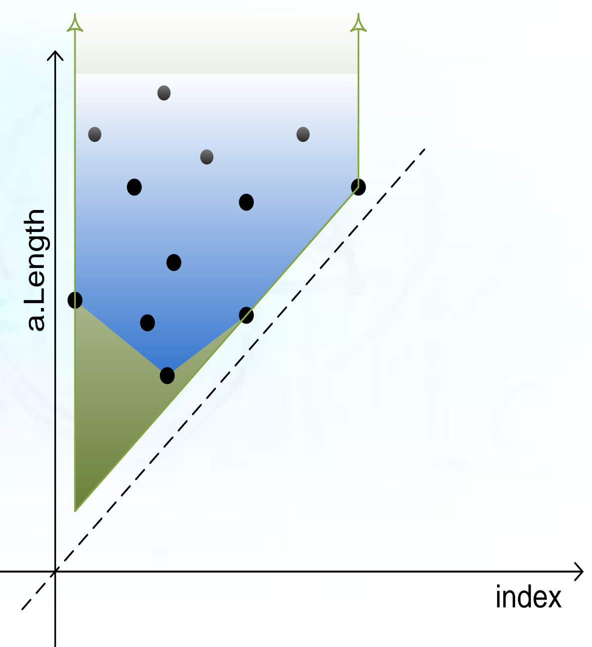
Pentagons



- Capture properties in the form of

$$x \in [a,b] \wedge x < y$$

  - x, y variables
  - a, b constants
- Elements are pairs of maps (Var → Intv) x (Var → ℘(Var))
- Information is propagated
  - "reduction"



Subpolyhedra

- Needed for more complex examples
- $\sum a_i x_i \leq k \Leftrightarrow \sum a_i x_i = \beta \wedge \beta \leq k$
  - Introduce a slack variable β
- Reduced product of
  - Intervals
    - Scalable, fast…
  - Linear Equalities
    - Precise join, fast …
- Challenge: Have a precise Join

Inferring array contents...

```
public void Init(int N)
{
    Contract.Requires(N > 0);

    int[] a = new int[N];
    int i = 0;

    while (i < N)
    {
      a[i] = 222;
      i = i + 1;
    }

    Contract.Assert(∀ k ∈ [0, N). a[k] == 222);
}
```

Challenge 1:
Effective handling of disjunction

If i == 0 then
  a not initialized
else if i > 0
  a[0] == ... a[i] == 222
else
  impossible

Challenge 2:
No overapproximation (can be unsound)
(no hole, *all* the elements are initialized)

Our idea

- Precise and very very fast!
- Basis: Array segments

Example

```
Contract.Requires(N > 0);
int[] a = new int[N];
```

0	0	N

```
int i = 0;
```

0,i	0	N

0	222	1,i	0	N	?

```
assume i ≥ N
```

```
assume i < N
```

0,i	0	N

```
a[i] = 222;
```

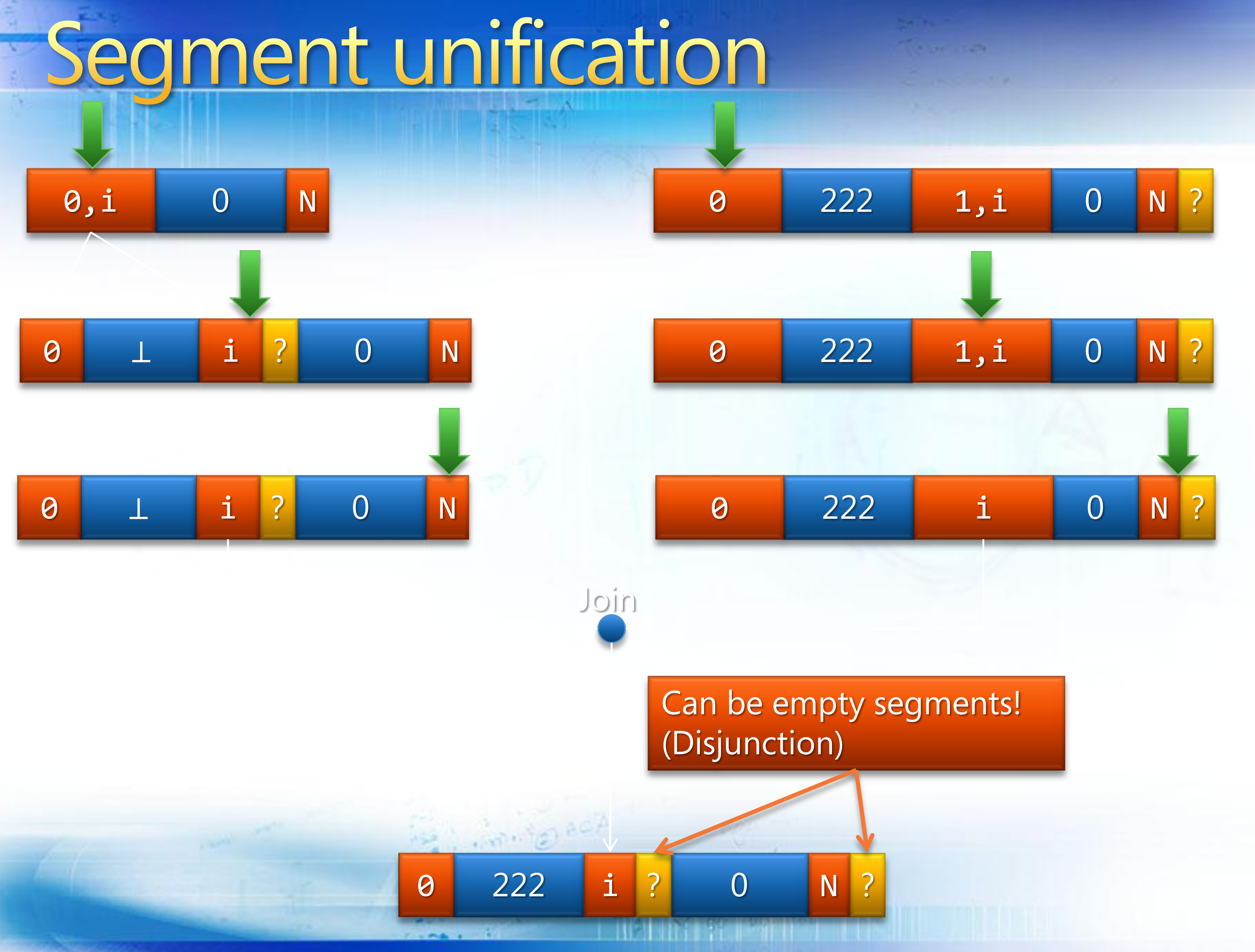
0,i	222	1,i+1	0	N	?

```
j = i+1;
```

0,i	222	1,i+1,j	0	N	?

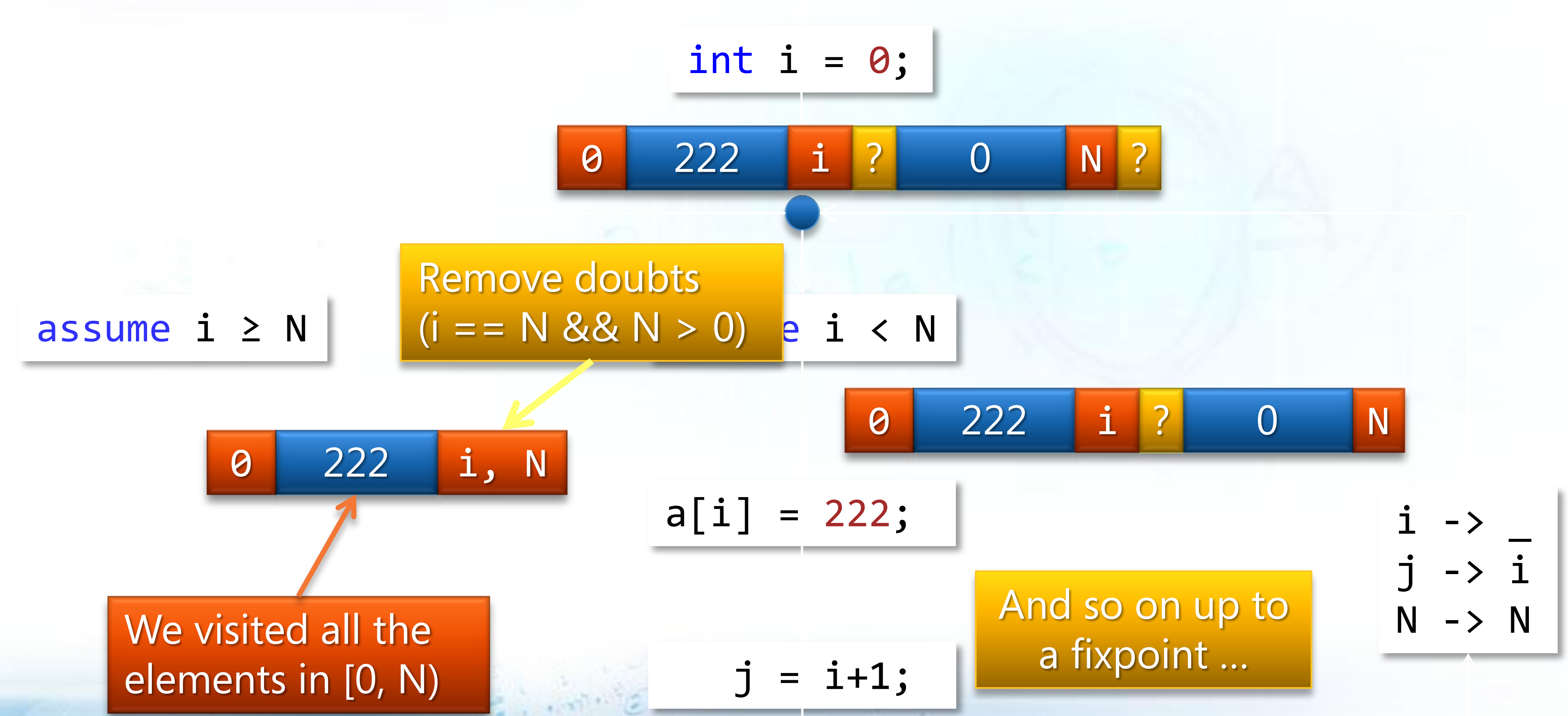
```
i -> _
j -> i
N -> N
```

Segment unification



Example

```
Contract.Requires(N > 0);
int[] a = new int[N];
```



Algorithm: High level

- For each assembly A, class C, method M

1. Extract the proof obligations
   - What should I prove?
2. Run the analyses
   - Discover facts on the program
3. Use the facts to prove the proof obligations
   - If not, do something else…

Proving things

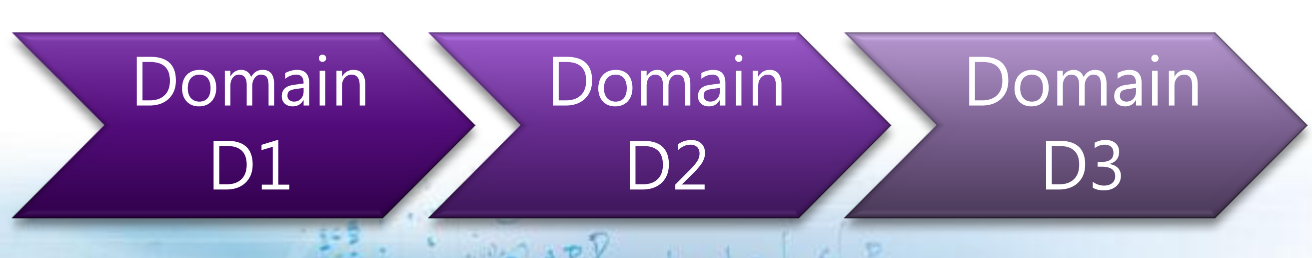
- We inferred many facts on the program
- We use those to prove assertions
- Algorithm:
  - For each assertion *a* at program point *p*
    - For each set of facts F
    - Check if F(*p*) implies *a*:
      - True: It is always ok
      - False: It is always not ok
      - Bottom: The assertion is never reached
      - Top: We do not know

Why do we get Top?

- The analysis is not precise enough
  - Abstract domain not precise
    - Widening loses too many constraints
  - Algorithmic properties
  - Implementation bug
  - Incompleteness
- Some contract is missing
  - Precondition or Postcondition
  - Object-invariant
- The assertion is sometimes wrong

Incremental analysis in Clousot

- First analyze with "cheap" domains
  - If check != Top
    Done!
  - If check == Top
    Try a more precise domain
- On the average great performance gains
  - Persist analysis options in different runs



Disjunctions

- (So far) Join approximates disjunction
  - Compact representation
- Sometimes not enough:

```
public int Simple(bool b)
   {
     int z;
     if (b)
       z = 12;
     else
       z = -12;
     return 1 / z;
   }
```

```
public string Simple2(bool b)
   {
     Contract.Ensures(
       Contract.Result<string>() == null
       || Contract.Result<string>().Length > 0);

     if (b)
       return null;
     else
       return "Ciao!";
   }
```

The solution in Clousot

- Backward analysis
- The failing assertion is pushed back to the program

```
public int Simple(bool b)
   {
      int z;
      if (b)
         z = 12;
      else
         z = -12;

      return 1 / z;
   }
```

z : [12, 12]   z != 0

z : [-12, -12]   z != 0

z :[- ∞,+∞]   z != 0

More complex example

```
public string Simple2(bool b)
    {
      Contract.Ensures(
        Contract.Result<string>() == null
        || Contract.Result<string>().Length > 0);

      if (b)
        return null;
      else
        return "Ciao!";
    }
```

Example with loop

```
public void NonNull()
    {
      string foo = null;

      for (int i = 0; i < 5; i++)
      {
        foo += "foo";

      }


      Contract.Assert(foo != null);
    }
```

foo: Null

foo: T

foo: NotNull

foo: T

foo != null

foo != null

foo != null

Microsoft Research

Contract Inference

Microsoft

Ideal world

- Programmers write all the contracts
  - Even loop invariants?
- Reality
  - Should infer “evident” contracts

Precondition inference

```
public int ZeroValues(int[] a)
  {
    int count = 0;
    for (int i = 0; i < a.Length; i++)
    {
      if (a[i] == 0)
        count++;
    }

    return count;
  }
```

	#	Description
ⓘ	1	CodeContracts: Suggested precondition: Contract.Requires(a != null);
⚠	2	CodeContracts: Possible use of a null array 'a'

The problem

- An inferred precondition should
  - Remove bad runs
  - Keep all the good runs
- Several algorithms in Clousot
  - Precision/cost tradeoff

Static Checking

[x] Perform Static Contract Checking	[x] Check in Background	[x] Show squigglies
[x] Implicit Non-Null Obligations	[ ] Implicit Arithmetic Obligations	[ ] Cache Results
[x] Implicit Array Bounds Obligations	[ ] Redundant Assumptions	[ ] Show Assumptions
[ ] Implicit Enum Writes Obligations	[ ] Implicit Pointer Usage Obligations	
[x] Infer Requires	[x] Suggest Requires	[x] Disjunctive Requires
[ ] Infer Ensures	[x] Suggest Ensures	
[ ] Infer Invariants for readonly	[ ] Suggest Invariants for readonly	

[ ] Baseline   Update   Warning Level: low … hi

The solution

- Propagate a failing assertion the entry
- If it respects the visibility rules,
  - then it is a precondition
- Otherwise
  - Try to suggest as object invariant
    - E.g. assertion on private fields on public method
  - Try to suggest as an assumption
    - The programmer is making some implicit assumption

Postcondition inference: theory

- Have a method m
- For each program point
  - Abstract state a
    - Approximate the concrete states at that point
- Take the abstract state at the exit point of the method

```
public int HalfSum(int x, int y)
   {
     Contract.Requires(x >= 0);
     Contract.Requires(y >= 0);

     return x + (y - x) / 2;
   }
```

CodeContracts: Suggested postcondition: Contract.Ensures(Contract.Result<System.Int32>() >= 0);

In practice

- Filter locals
- Take into account inheritance rules
- Remove redundant information
  - Ex. x >= 0, y == 0, x + y >= 0
- Avoid suggesting existing precondition
- …

Message prioritization

So we have a Top...

- We should report it to the programmer
- It can be:
  - a real bug?
  - a false positive?
- In general impossible to tell
  - Undecidability of the analysis
- Should sort all the messages
  - The one most likely to be bugs at the top

1. Warning partitioning

- Partition warnings in classes
  - Contract violation
  - Non-null
  - Arrays
  - Overflows
  - …
- Assign a *fixed* reward R to each class
  - $R \in [\, C \to \mathbb{N} \,]$
- The highest the reward the more important

2. Scale rewards with outcome

- False = 1.0 * R(c)
  - Important
  - Always wrong…
- Bottom = 0.75 * R(c)
  - Unreached, we wanted it?
- Top = 0.50 * R(c)
  - So many …
- True = 0 * R(c)
  - Don’t care

3. Scale rewards with info

- Proof obligation *p* contains
  - Variables from parameters
  - Variables result of a method call
  - …
  -
- The scale the reward

```
public foo(int z)
{
 // ...
 Contract.Assert(z + x > 0);

 var f = Add();
 Contract.Assert(f != null);
 // ...
}
```

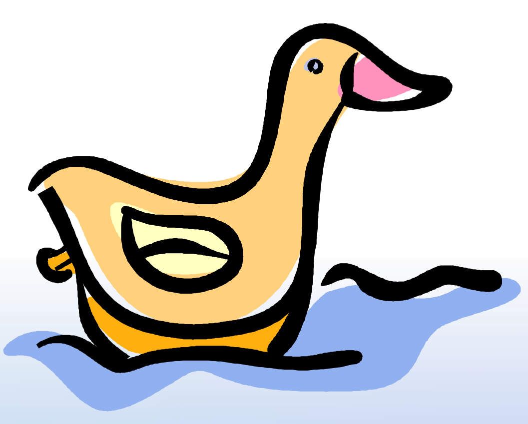
Caching

Microsoft

Caching?

- At design time, few changes between two builds
- Avoid re-analysis by caching
- Algorithm
  - Construct the CFG for the method
    - Includes contracts explicit/inferred
  - Hash the CFG
  - If in the DB, just report the same output
  - Otherwise, re-analyze the method
    - Save it in the cache

Floating points…



Computers & numbers

- Computers crunch numbers
- But computer numbers are not mathematical ones!
- Plethora of Int*
  - Int8, Int16, Int32, Int64, BigInt
  - UInt8, UInt16, UInt32, UInt64
- And even more fun:

  Floating points

$Y > 0 \Rightarrow X + Y > X$?

True: Epsilon > 0

```
Contract.Assert(Double.Epsilon != Double.Epsilon * Double.Epsilon);

Contract.Assert(1.0d == 1.0d + Double.Epsilon);

Contract.Assert(1000000000d == 1000000000d + Double.Epsilon);
```

True!

$(x + k) - (x - k) == 2k$?

```
double x, y, z, r;

x = 1.000000019e+38d;
y = x + 1.0e21d;
z = x - 1.0e21d;
r = y - z;

Contract.Assert(r == 2.0e21d);
```

Assert is false!

X == X ?

Assert is true!

```
Contract.Assert(0.0 == 0.0);

Contract.Assert(Double.NegativeInfinity == Double.NegativeInfinity);

Contract.Assert(Double.NaN == Double.NaN);
```

Assert is false!!!!!!!

1/0 is NaN
Sqrt(-1) is NaN

$K \neq 0 \Rightarrow (x + k) - (x - k) \neq 0$

```
double x, y, z, r;

x = 1.000000019e+38d;
y = x + 1.0e21d;
z = x - 1.0e21d;
r = y - z;

Contract.Assert(r == 0.0d);
```

Assert is true!

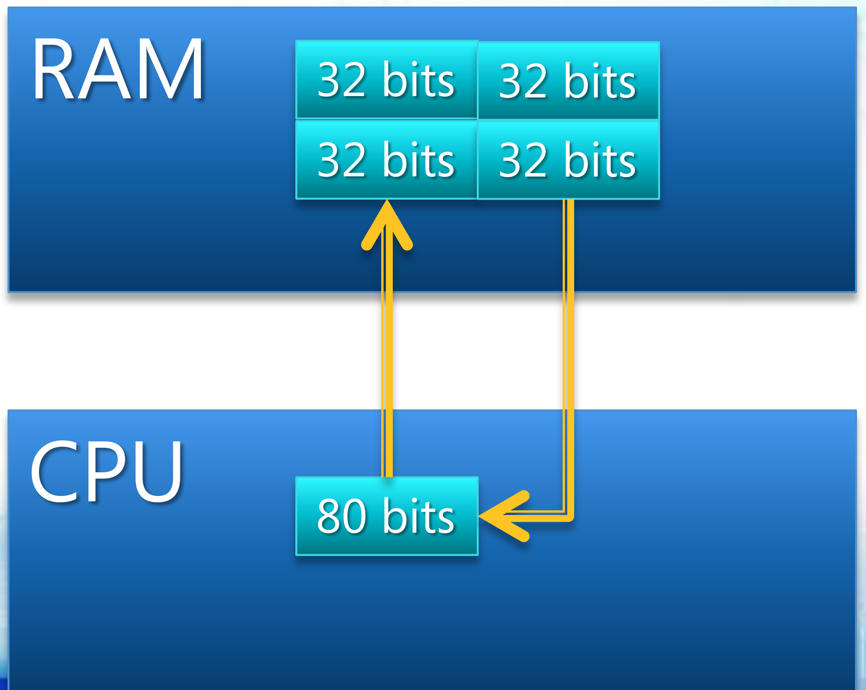
X == X ?

```
public class Point
{
  public double X, Y;

  Point(double x, double y)
  {
    this.X = x;
    this.Y = y;
  }
}

public CreatePoint(double x)
{
  var p = new Point(x, x);

  Contract.Assert(x == p.X);
}
```

Assert is false!!!!!!!

Why?

- A double is a synonym for Float64
- A Float64 is represented
  - in RAM with 64 bits
  - in the CPU with 80 bits!!!



Conclusions…

CodeContracts

- Specify code with code
  - No change to the build environment
  - Part of .NET v4
- Documentation generation
- Runtime checking
- Static checking
  - Based on abstract interpretation
  - Predicatable, tunable, scalable, automatic!!!!
- Try it today!!!!!