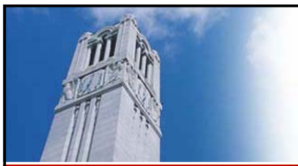

Automated Software Engineering Research Group @NCSU

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Fitness-Guided Path Exploration in Automated Test Generation

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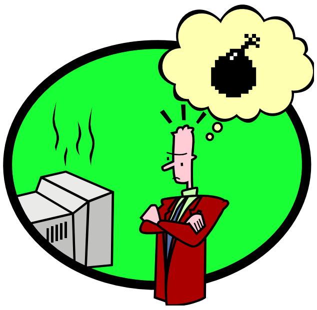
North Carolina State University
http://ase.csc.ncsu.edu/

Joint work with Nikolai Tillmann, Peli de Halleux, Wolfram Schulte from Microsoft Research

Motivation

- Testing is tedious
- Too easy to miss cases
- Old tests get stale
- Too much legacy code – what does it do?



Automated Software Testing to help

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Outline

- Parameterized Unit Tests and Pex
- Dynamic Symbolic Execution
- Fitness-Guided Path Exploration
- Evaluation
- Conclusion

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Unit Testing Today

A unit test is a small program with assertions.

```
void AddTest()
{
    HashSet set = new HashSet();
    set.Add(7);
    set.Add(3);

    Assert.IsTrue(set.Count == 2);
}
```

Many developers write such unit tests by hand.

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Parameterized Unit Testing

```
void AddSpec(int x, int y)
{
    HashSet set = new HashSet();
    set.Add(x);
    set.Add(y);

    Assert.AreEqual(x == y, set.Count == 1);
    Assert.AreEqual(x != y, set.Count == 2);
}
```

Parameterized Unit Tests separate two concerns:
(1) The specification of externally visible behavior (assertions)
(2) The selection of internally relevant test inputs (coverage)

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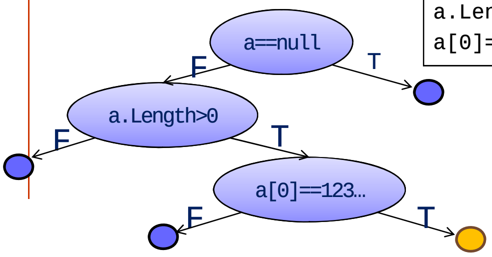
Dynamic Symbolic Execution

Code to generate inputs for:

```
void CoverMe(int[] a)
{
  if (a == null) return;
  if (a.Length > 0)
    if (a[0] == 1234567890)
      throw new Exception("bug");
}
```

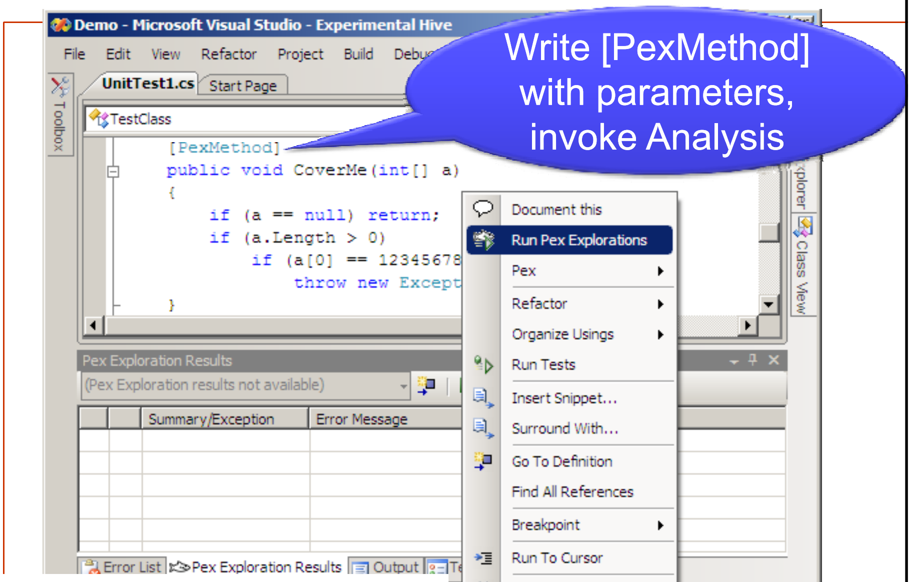
Constraints to solve	Input	Observed constraints
	null	a==null
a!=null	{}	a!=null &&
a!=null a.Length>0		a.Length>0 && a[0]!=1234567890
a!=null && a.Length>0 && a[0]==123456890	{123..}	a==null && a.Length>0 && a[0]==1234567890

Negated condition



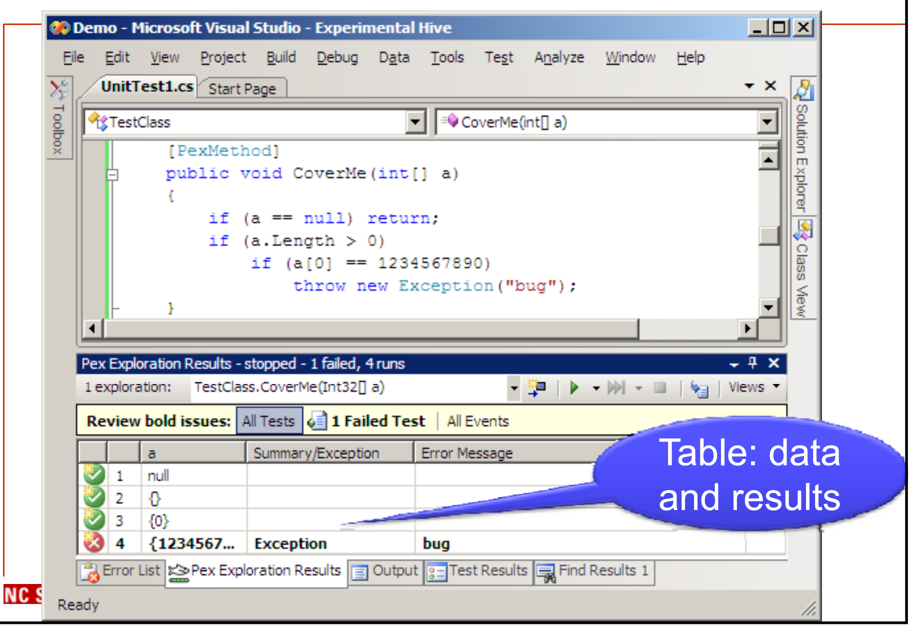
Done: There is no path left.

Parameterized Unit Test in Pex

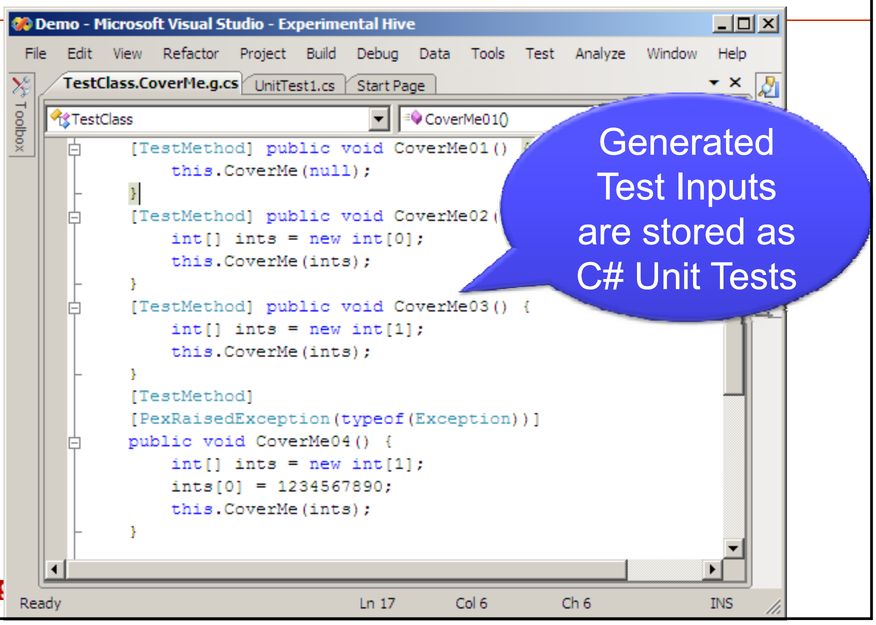


http://research.microsoft.com/Pex

Pex Exploration Results



Generated Unit Tests



Real World Example: ResourceReader

Actual code from .NET base class libraries

Takes stream of bytes, extracts 'resource' chunks

```
[SecurityPermissionAttribute(SecurityAction.LinkDemand, Flags=SecurityPermissionFlag.SerializationFormatter)]
public ResourceReader(Stream stream)
{
    if (stream==null)
        throw new ArgumentNullException("stream");
    if (!stream.CanRead)
        throw new ArgumentException(Environment.GetResourceString("Argument_StreamNotReadable"));

    _resCache = new Dictionary<String, ResourceLocator>(FastResourceComparer.Default);
    _store = new BinaryReader(stream, Encoding.UTF8);
    // We have a faster code path for reading resource files from an assembly.
    _ums = stream as UnmanagedMemoryStream;

    BCLDebug.Log("RESMGRFILEFORMAT", "ResourceReader .ctor(Stream).  UnmanagedMemoryStream: "+(_ums!=null));
    ReadResources();
}
```

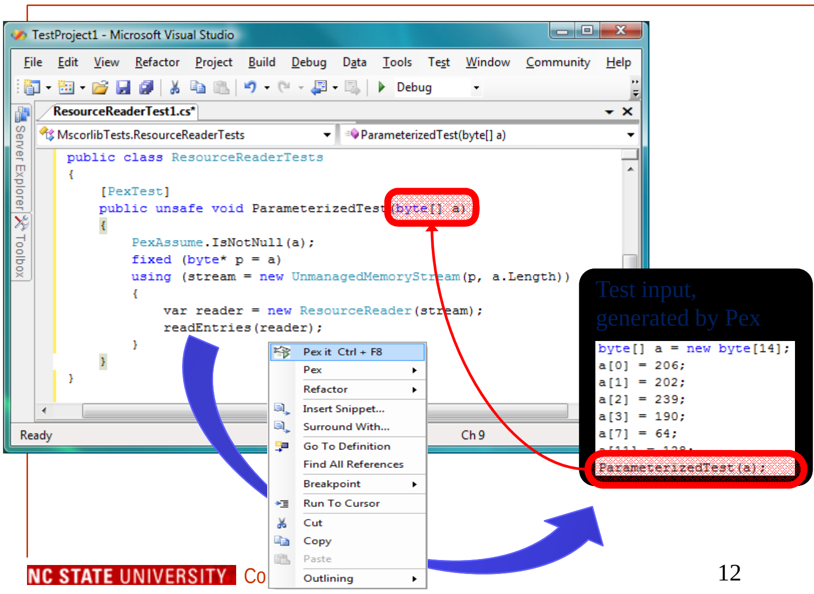
ResourceReader

```
        // Reads in the header information for a .resources file.  Verifies some
        // of the assumptions about this resource set, and builds the class table
        // for the default resource file format.
        private void ReadResources() {
            BCLDebug.Assert(_store != null, "ResourceReader is closed!");
            BinaryFormatter bf = new BinaryFormatter(null, new StreamingContext(StreamingContextStates.File |
#if !FEATURE_PAL
            _typeLimitingBinder = new TypeLimitingDeserializationBinder();
            bf.Binder = _typeLimitingBinder;
#endif
            _objFormatter = bf;
            try {
                // Read ResourceManager header
                // Check for magic number
                int magicNum = _store.ReadInt32();
                if
```

```
public virtual int ReadInt32() {
    if (m_isMemoryStream) {
        // read directly from MemoryStream buffer
        MemoryStream mStream = m_stream as MemoryStream;
        BCLDebug.Assert(mStream != null, "m_stream as MemoryStream != null");

        return mStream.InternalReadInt32();
    }
    else
    {
        FillBuffer(4);
        return (int)(m_buffer[0] | m_buffer[1] << 8 | m_buffer[2] << 16 | m_buffer[3] << 24);
    }
}
```


Pexing ResourceReader



Division of Testing Labor

Parameterized Unit Tests (PUTs) separate two concerns:

- The specification of external behavior (i.e., assertions)

- The selection of internal test inputs (i.e., coverage)

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PUTs == Algebraic Specifications

- A PUT can be read as a universally quantified, conditional axiom.

  ∀ int name, int data.
      name ≠ null ∧ data ≠ null ⇒
      equals(
          ReadResource(name,
              WriteResource(name, data)),
          data)

- Teaching/training of writing specs is challenging but we do have success with teaching PUT/Pex

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Dynamic Symbolic Execution

Dynamic symbolic execution (DSE) combines static and dynamic analysis:

- Execute a program multiple times with different inputs
  - build ***path condition***: input constraints for the execution path on the side
  - plug in ***concrete results*** of operations which cannot reasoned about symbolically
- Use a constraint solver to obtain new inputs
  - solve a constraint system that represents an execution path not seen before

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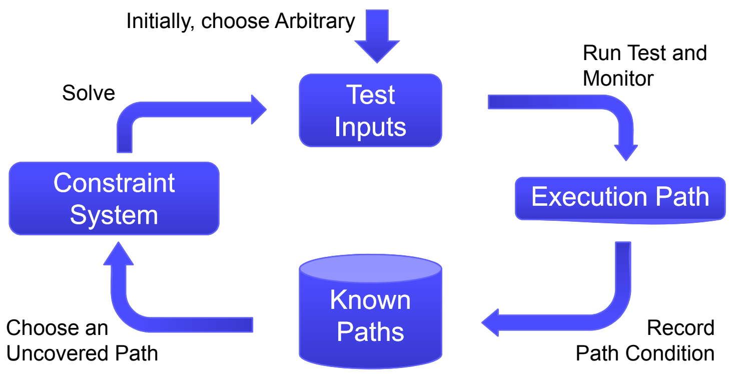
Dynamic Symbolic Execution



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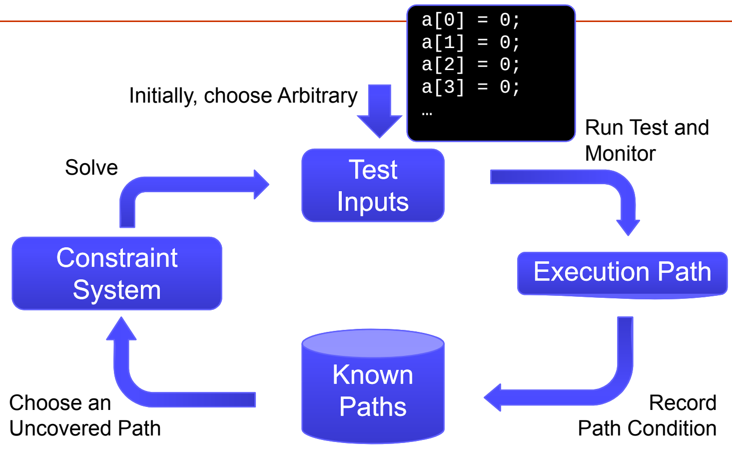
Dynamic Symbolic Execution



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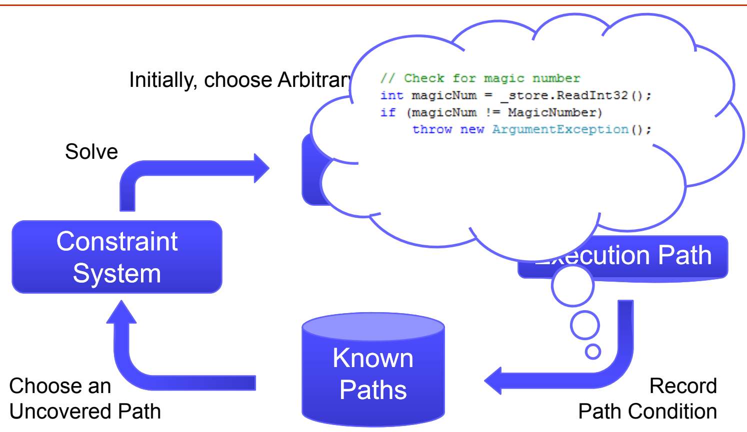
Dynamic Symbolic Execution



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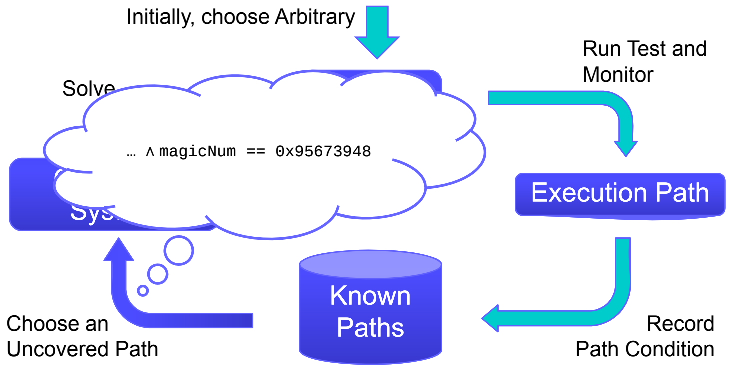
Dynamic Symbolic Execution



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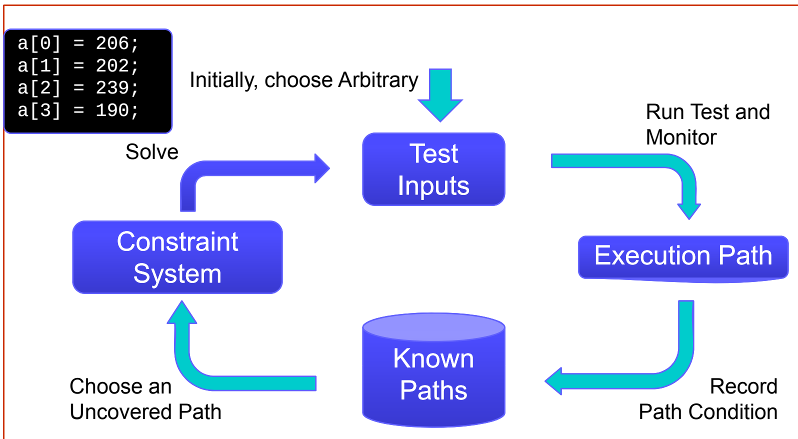
Dynamic Symbolic Execution



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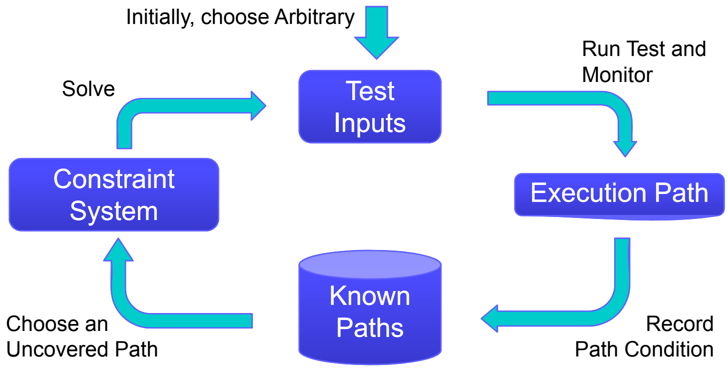
Dynamic Symbolic Execution



DSE Example - Loop

```
public bool TestLoop(int x, int[] y) {
   if (x == 90) {
         for (int i = 0; i < y.Length; i++)
                if (y[i] == 15)
                     x++;
         if (x == 110)
                return true;
   }
   return false;
}
```

TestLoop(0, {0})

Path condition:
!(x == 90)
↓
New path condition:
(x == 90)
↓
New test input:
TestLoop(90, {0})

DSE Example - Loop

```
public bool TestLoop(int x, int[] y) {
   if (x == 90) {
        for (int i = 0; i < y.Length; i++)
             if (y[i] == 15)
                  x++;
        if (x == 110)
             return true;
   }
   return false;
}
```

TestLoop(90, {0})

Path condition:
(x == 90) && !(y[0] ==15)
↓
New path condition:
(x == 90) && (y[0] ==15)
↓
New test input:
TestLoop(90, {15})

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Challenge in DSE - Loop

```
public bool TestLoop(int x, int[] y) {
   if (x == 90) {
        for (int i = 0; i < y.Length; i++)
             if (y[i] == 15)
                  x++;
        if (x == 110)
             return true;
   }
   return false;
}
```

TestLoop(90, {15})

Path condition:
(x == 90) && (y[0] ==15)
&& !(x+1 == 110)
↓
New path condition:
(x == 90) && (y[0] ==15)
&& (x+1 == 110)
↓
New test input:
No solution!?

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A Closer Look

```
public bool TestLoop(int x, int[] y) {
   if (x == 90) {
         for (int i = 0; i < y.Length; i++)
               if (y[i] == 15)
                  x++;
         if (x == 110)
               return true;
   }
   return false;
}
```

TestLoop(90, {15})

Path condition:
(x == 90) && (y[0] ==15)
&& (0 < y.Length)
&& !(1 < y.Length)
&& !(x+1 == 110)
↓
New path condition:
(x == 90) && (y[0] ==15)
&& (0 < y.Length)
&& (1 < y.Length)
→ **Expand array size**

A Closer Look

```
public bool TestLoop(int x, int[] y) {
   if (x == 90) {
         for (int i = 0; i < y.Length; i++)
               if (y[i] == 15)
                  x++;
         if (x == 110)
               return true;
   }
   return false;
}
```

TestLoop(90, {15})

We can have infinite paths!

Manual analysis → need at least 20 loop iterations to cover the target branch

Exploring all paths up to 20 loop iterations is infeasible: 2^{20} paths

Fitnex: Fitness-Guided Exploration

```
public bool TestLoop(int x, int[] y) {
 if (x == 90) {
   for (int i = 0; i < y.Length; i++)
      if (y[i] == 15)
        x++;
   if (x == 110)
      return true;
 }
 return false;
}
```

TestLoop(90, {15, 0})
TestLoop(90, {15, 15})

Key observations: with respect to the coverage target
- not all paths are equally promising for branch-node flipping
- not all branch nodes are equally promising to flip

- Our solution:
  - Prefer to flip branch nodes on the most ***promising*** paths
  - Prefer to flip the most ***promising*** branch nodes on paths
  - Fitness function to measure "promising" extents

Fitness Function

- Compute fitness value (distance between the current state and the goal state)
- Search tries to minimize fitness value

Predicate	Fitness function	
	True	False
$F(a == b)$	0	$\|a - b\|$
$F(a > b)$	0	$(b - a) + K$
$F(a >= b)$	0	$(b - a)$
$F(a < b)$	0	$(a - b) + K$
$F(a <= b)$	0	$(a - b)$
$F(P_1 \&\& P_2)$	0	$F(P_1) + F(P_2)$
$F(P_1 \|\| P_2)$	0	$(F(P_1) * F(P_2))/(F(P_1) + F(P_2))$

[Tracey et al. 98, Liu at al. 05, …]

Fitness Function for (x == 110)

```
public bool TestLoop(int x, int[] y) {
 if (x == 90) {
   for (int i = 0; i < y.Length; i++)
     if (y[i] == 15)
       x++;
   if (x == 110)
     return true;
 }
 return false;
}
```

Fitness function: |110 - x |

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Compute Fitness Values for Paths

```
public bool TestLoop(int x, int[] y) {
 if (x == 90) {
   for (int i = 0; i < y.Length; i++)
     if (y[i] == 15)
       x++;
   if (x == 110)
     return true;
 }
 return false;
}
```

Fitness function: |110 - x |

(x, y)	Fitness Value
(90, {0})	20
(90, {15})	19
(90, {15, 0})	19
(90, {15, 15})	18
(90, {15, 15, 0})	18
(90, {15, 15, 15})	17
(90, {15, 15, 15, 0})	17
(90, {15, 15, 15, 15})	16
(90, {15, 15, 15, 15, 0})	16
(90, {15, 15, 15, 15, 15})	15
…	

Give preference to flip paths with better fitness values

We still need to address which branch node to flip on paths …

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Compute Fitness Gains for Branches

```
public bool TestLoop(int x, int[] y) {
 if (x == 90) {
   for (int i = 0; i < y.Length; i++)
       if (y[i] == 15)
         x++;
   if (x == 110)
       return true;
 }
 return false;
}
```

Fitness function: |110 - x |

Branch b1: i < y.Length
Branch b2: i >= y.Length
Branch b3: y[i] == 15
Branch b4: y[i] != 15

(x, y)	Fitness Value
(90, {0})	20
(90, {15}) ← flip b4	19
(90, {15, 0}) ← flip b2	19
(90, {15, 15}) ← flip b4	18
(90, {15, 15, 0}) ← flip b2	18
(90, {15, 15, 15}) ← flip b4	17
(90, {15, 15, 15, 0}) ← flip b2	17
(90, {15, 15, 15, 15}) ← flip b4	16
(90, {15, 15, 15, 15, 0}) ← flip b2	16
(90, {15, 15, 15, 15, 15}) ← flip b4	15
…	

•Flipping Branch b4 (b3) gives us average 1 (-1) fitness gain (loss)
•Flipping branch b2 (b1) gives us average 0 fitness gain (loss)

Compute Fitness Gain for Branches cont.

- For a flipped node leading to *Fnew*, find out the old fitness value *Fold* before flipping
  - Assign Fitness Gain (*Fold - Fnew*) for the branch of the flipped node
  - Assign Fitness Gain (*Fnew - Fold*) for the other branch of the branch of the flipped node
- Compute the average fitness gain for each branch over time

Search Frontier

- Each branch node candidate for being flipped is prioritized based on its composite fitness value:
  - (Fitness value of node – Fitness gain of its branch)
- Select first the one with the best composite fitness value
- To avoid local optimal or biases, the fitness-guided strategy is integrated with Pex's previous search strategies

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Evaluation Subjects

- A collection of micro-benchmark programs routinely used by the Pex developers to evaluate Pex's performance, extracted from real, complex C# programs

Ranging from string matching like
if (value.StartsWith("Hello") &&
value.EndsWith("World!") &&
value.Contains(" "))
to a small parser for a Pascal-like language where the target is to create a legal program

subject	#basic blocks	subject	#basic blocks
1	9	16	9
2	16	17	40
3	29	18	18
4	40	19	11
5	20	20	18
6	28	21	25
7	21	22	25
8	34	23	19
9	29	24	16
10	25	25	44
11	27	26	11
12	27	27	9
13	27	28	9
14	39	29	21
15	34	30	62

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Techniques under Comparison

- Pex with the Fitnex strategy
- Pex without the Fitnex strategy
  - Pex's previous default strategy
- Random
  - a strategy where branch nodes to flip are chosen randomly in the already explored execution tree
- Iterative Deepening
  - a strategy where breadth-first search is performed over the execution tree

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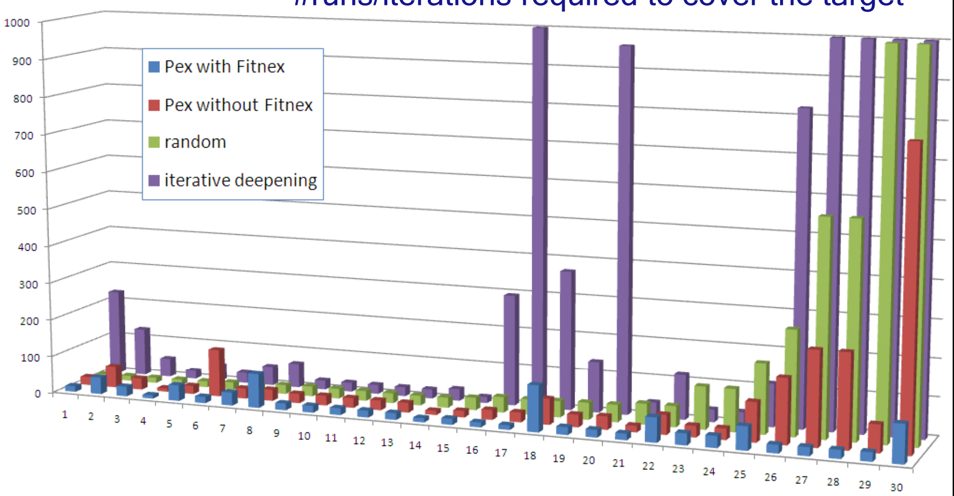
Evaluation Results

#runs/iterations required to cover the target



Pex w/o Fitnex on average by a factor of 1.9 improvement over *Random*
Pex w/ Fitnex on average by a factor of 5.2 improvement over *Random*

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Impact

- Since Sept 17, 2008, Pex releases' default exploration strategy integrates Fitnex
  - http://research.microsoft.com/Pex
- Fitnex is released as open source
  - http://www.codeplex.com/Pex
- Download counts of Pex in early Nov 2008
  - About 4000 after available for about half a year.
  - About 1000 of Pex for Visual Studio 2010 Community Technology Preview (Microsoft Incubation Software) after available for about two weeks

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Case Study on Pex [TAP 2008]

- A previous version of Pex was applied on a core .NET component
  - Already extensively tested for several years
  - Assertions written by developers
  - >10,000 public methods
  - >100,000 basic blocks
- Found a significant number of benign bugs, e.g. NullReferenceException, IndexOutOfRangeException, …
- 17 unique bugs involving
  - violation of developer-written assertions,
  - exhaustion of memory,
  - other serious issues.

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Ongoing/Future Work

- Method sequence generation
- Regression test generation
- String generation (e.g., regular expressions)
- Environment mocking
- Test generalization
- Guidance from tool users
- …

Conclusion

- Parameterized Unit Tests separate
  - Manual specification of external behavior
  - Pex's selection of internal test inputs
- Dynamic Symbolic Execution enables Pex to deal with various complications
- Real-world challenges of path explosion call for guided path exploration
  - Fitness values of explored paths
  - Fitness gains of branches' past flipping
- Evaluation results show the effectiveness of the new Fitnex strategy
- Fitnex has been integrated in Pex' default strategy

Questions?

http://ase.csc.ncsu.edu/
http://research.microsoft.com/Pex
http://www.codeplex.com/Pex

Constraint Solving: Z3

- SMT-Solver ("Satisfiability Modulo Theories")
  - Decides logical first order formulas with respect to theories
  - SAT solver for Boolean structure
  - Decision procedures for relevant theories: uninterpreted functions with equalities, linear integer arithmetic, bitvector arithmetic, arrays, tuples
- Model generation for satisfiable formulas
  - Models used as test inputs
- Incremental solving
  - Enables efficient model minimization