Deep Dive into Pex

How Pex works, implications for design of Code Hunt puzzles

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Agenda

- Dynamic Symbolic Execution with Pex
  - Symbolic state representation, constraint solving, the environment
- The Pex Family
- Code Hunt Deep Dive
  - How the game works
  - Pex in the cloud @ api.codehunt.com
  - Inputs and outputs, assumptions, overflows
  - Path explosion
  - Sandbox, and how to peek below
  - Side effects
  - Forcing values by branching
  - Back end: Public REST APIs

Dynamic Symbolic Execution with Pex

Symbolic state representation, constraint solving, the environment

Dynamic Symbolic Execution

- This choice decides search order
- Search order decides how quick we can achieve high code coverage!
- Incomplete constraint-solver leads to under-approximation

05][Tillmann et al. 08]

d program inputs)

Loop

Choose program input $i \notin J$ (stop if no such i can be found)

Output i

Execute P(i); reco

Set J := J ∪ C

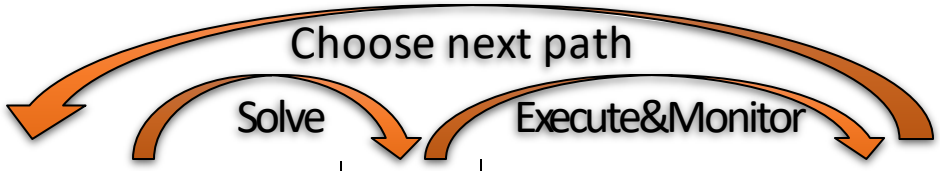
End loop

)

Loop does not terminate if number of execution paths is infinite (in the presence of loops/recursion)

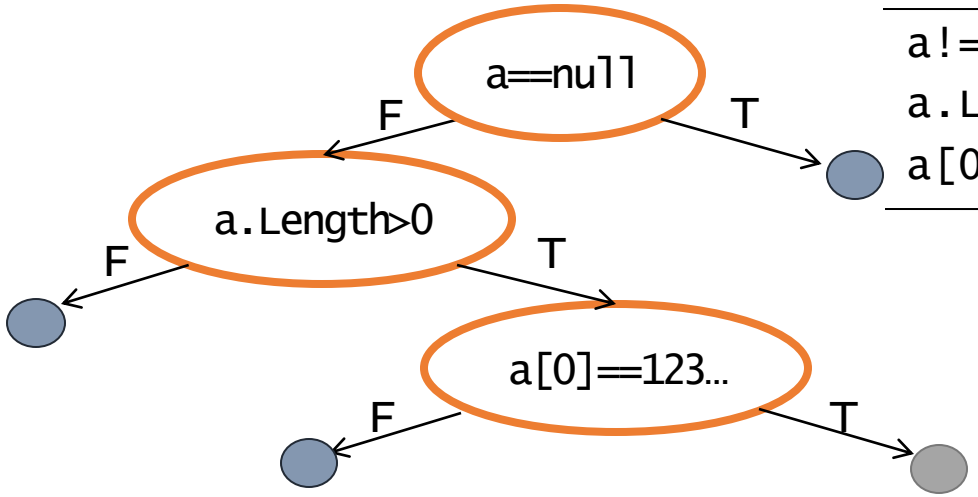
Dynamic Symbolic Execution with Pex

```
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.Length>0)
a!=null && a.Length>0	{0}	a==null && a.Length>0 && a[0]!=1234567890
a!=null && a.Length>0 && a[0]==123456890	{123..}	a==null && a.Length>0 && a[0]==1234567890

Done: There is no path left.



http://pex4fun.com/CoverMe

Symbolic State Representation

Representation of symbolic values and state is **similar to** the ones used to build verification conditions in **ESC/Java, Spec#, …**

Terms for

- Primitive types (integers, floats, …), constants, expressions
- Struct types by tuples
- **Instance fields of classes by mutable ”mapping of references to values"**
- **Elements of arrays, memory accessed through unsafe pointers by mutable “mapping of integers to values"**

Efficiency by

- **Many reduction rules, including reduction of ground terms to constants**
- **Sharing of syntactically equal sub-terms**
- **BDDs over if-then-else terms to represent logical operations**
- **Patricia Trees to represent AC1 operators (including parallel array updates)**

Constraint Solving

- 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
- Limitations
  - We are not using decision procedure for floating point arithmetic and strings
  - Instead, heuristic search-based approaches
- Pex uses Z3: http://research.microsoft.com/z3

Dynamic Symbolic Execution Exercises

CodeMe
All explicit branches.

ArrayIndexLength
Pex knows about all implicit, exception-throwing control-flow branches

ArrayHeap
Pex models the heap

Assert, Assert123
Assertions connect code coverage and correctness

pex4fun.com/DynamicSymbolicExecutionExercises

Note: Pex actually runs your code

- **Dynamic** symbolic execution
- Behavior of environment is unknown
- Pex comes with a built-in way to isolate code from environment dependencies (“Moles”)

```
void CoverMe()
{
  var lines = File.ReadAllLines(“a.txt”);
  if (lines[0] == “[complicated]”)
    throw new Exception(“bug”);
  if (lines[1] == “[clear]”)
    Disk.Format(“c:”);
}
```

The Pex Family

Timeline + Impact

- **Pex** (released May 2008, Microsoft Research download)
  - 30,388 downloads (20 months, Feb 08-Oct 09)
  - **Ships** with Visual Studio 2015 Ultimate "in the box" as **Smart Unit Tests**
- **Moles** (released September 2009 , Microsoft Research download)
  - **Shipped** with Visual Studio 2012 Ultimate "in the box" as **Fakes**
- **Pex4Fun** website (released June 2010)
  - 1.6 million user interactions (clicks on "Ask Pex")
- **Code Digger** (simplified Pex, released on April 2013 as VS Gallery download)
  - 22,466 downloads (10 months, Apr 13-Jan 14)
- **Code Hunt** website (released May 2014)

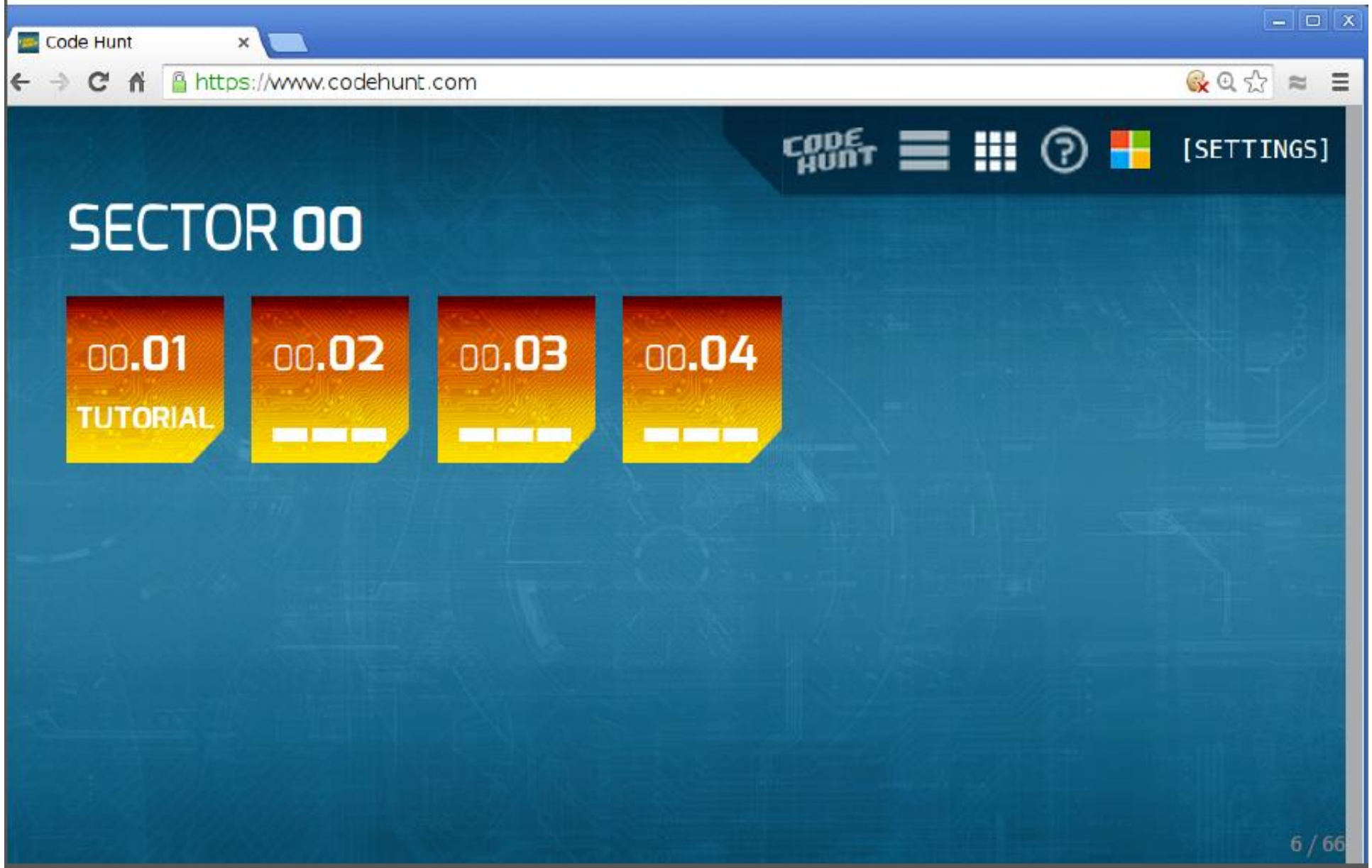
Code Hunt Deep Dive

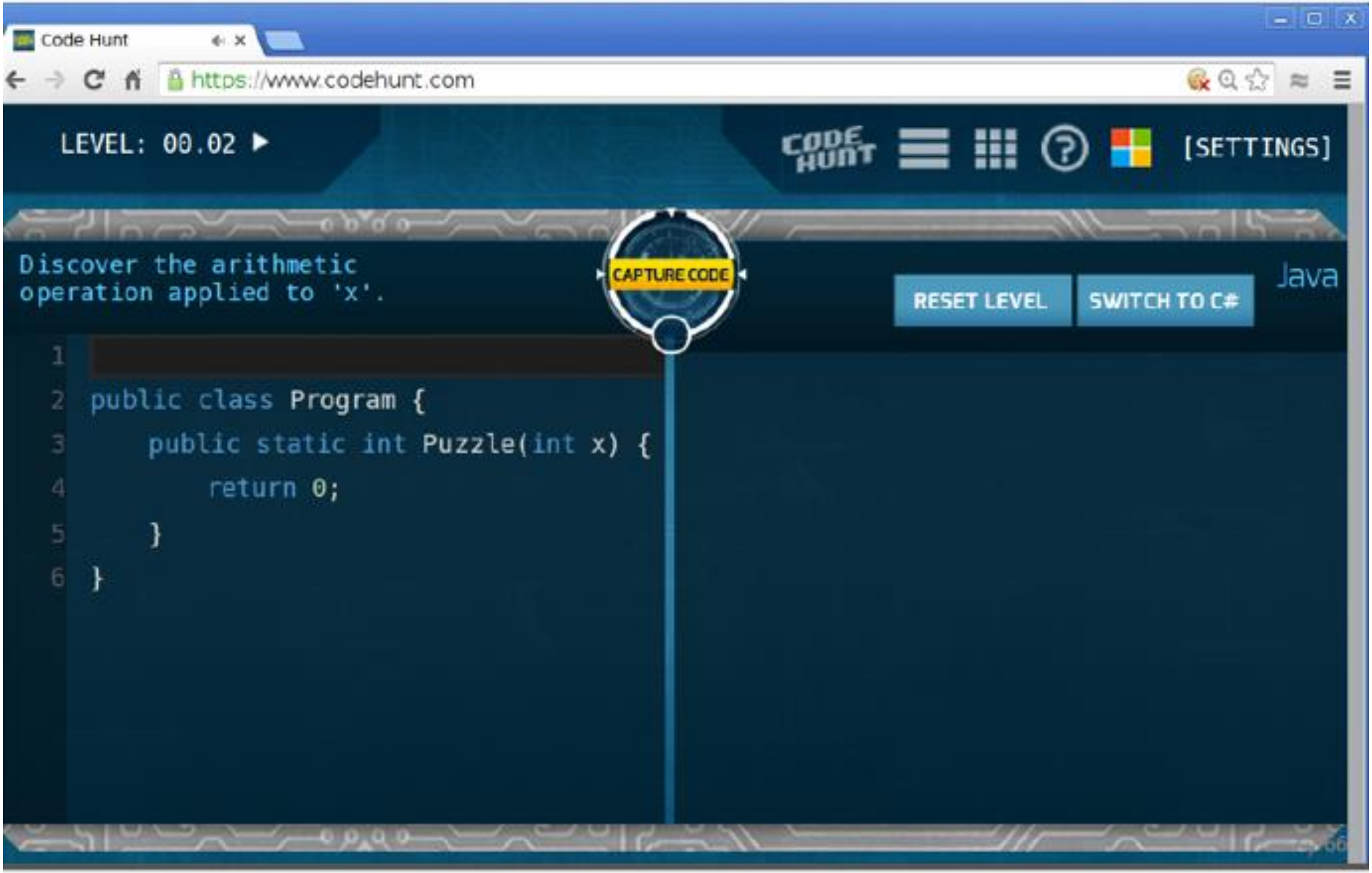
How the game works, Pex in the cloud @ api.codehunt.com, Inputs and outputs, assumptions, overflows, Path explosion, Sandbox, and how to peek below, Side effects, Forcing values by branching, Back end: Public REST APIs

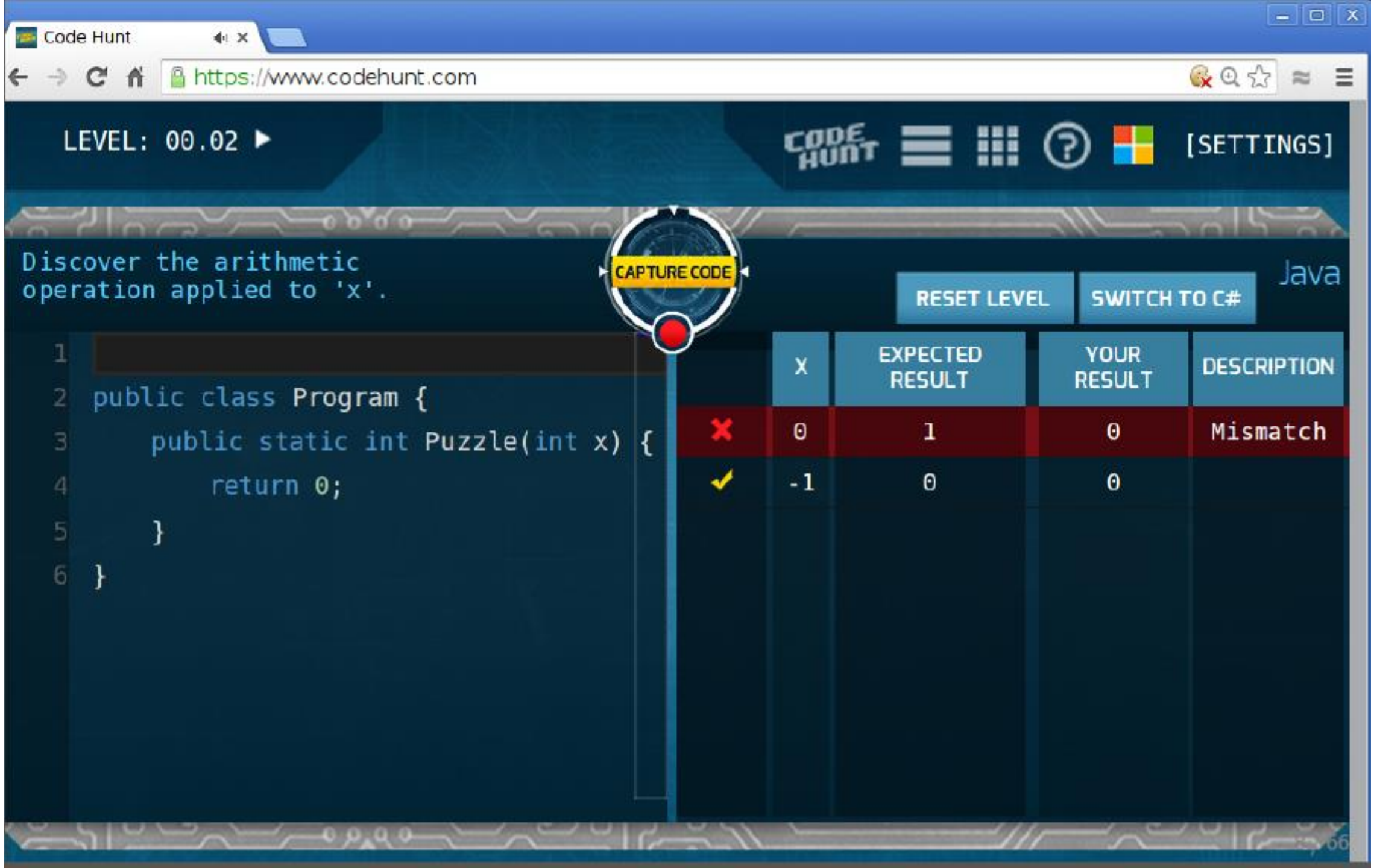
Code Hunt programming game

Code Hunt programming game

Code Hunt programming game




Code Hunt
https://www.codehunt.com
LEVEL: 00.02
[SETTINGS]
Discover the arithmetic operation applied to 'x'.
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
1
2 public class Program {
3 public static int Puzzle(int x) {
4 return 0;
5 }
6 }


Code Hunt
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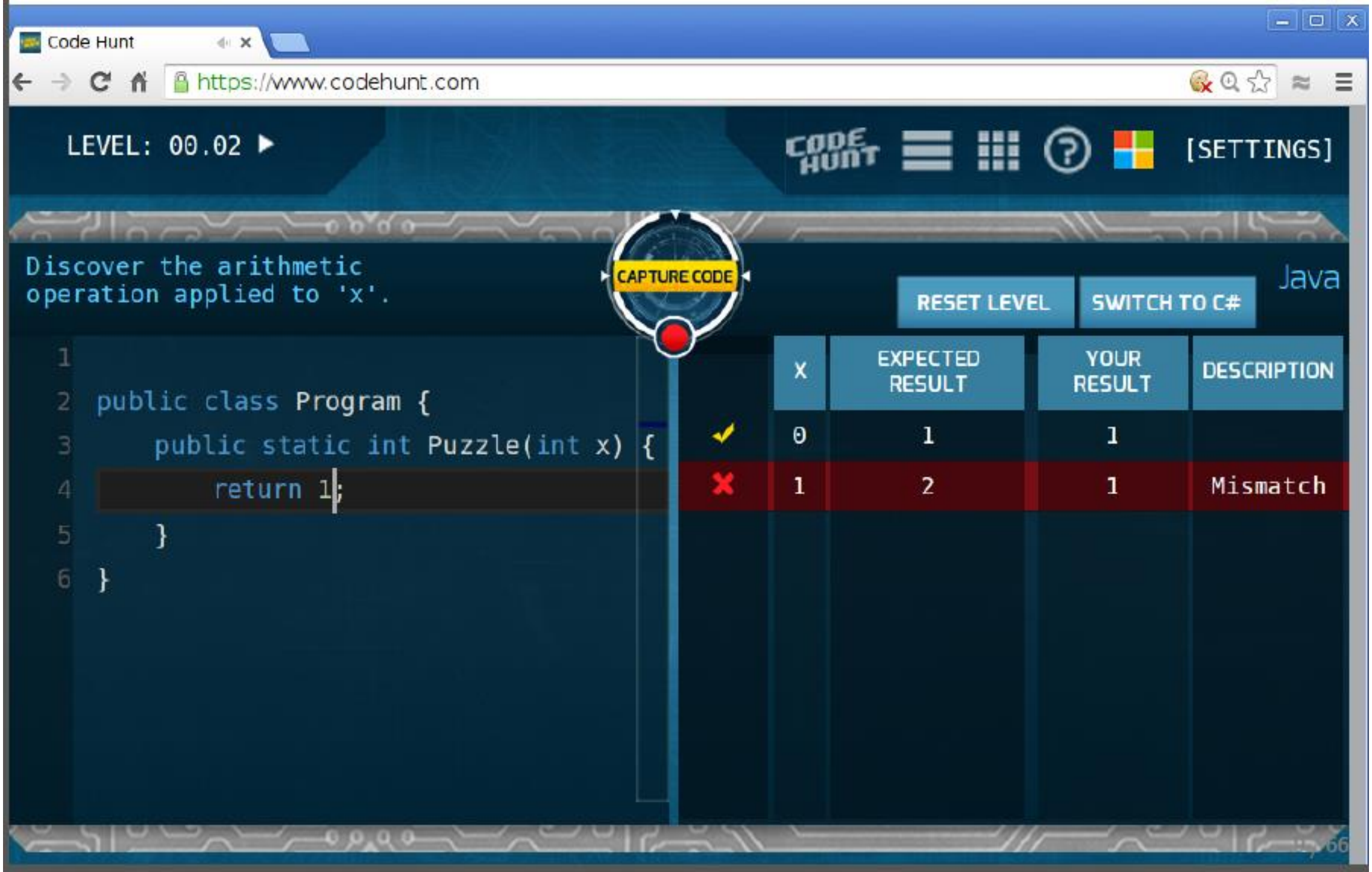
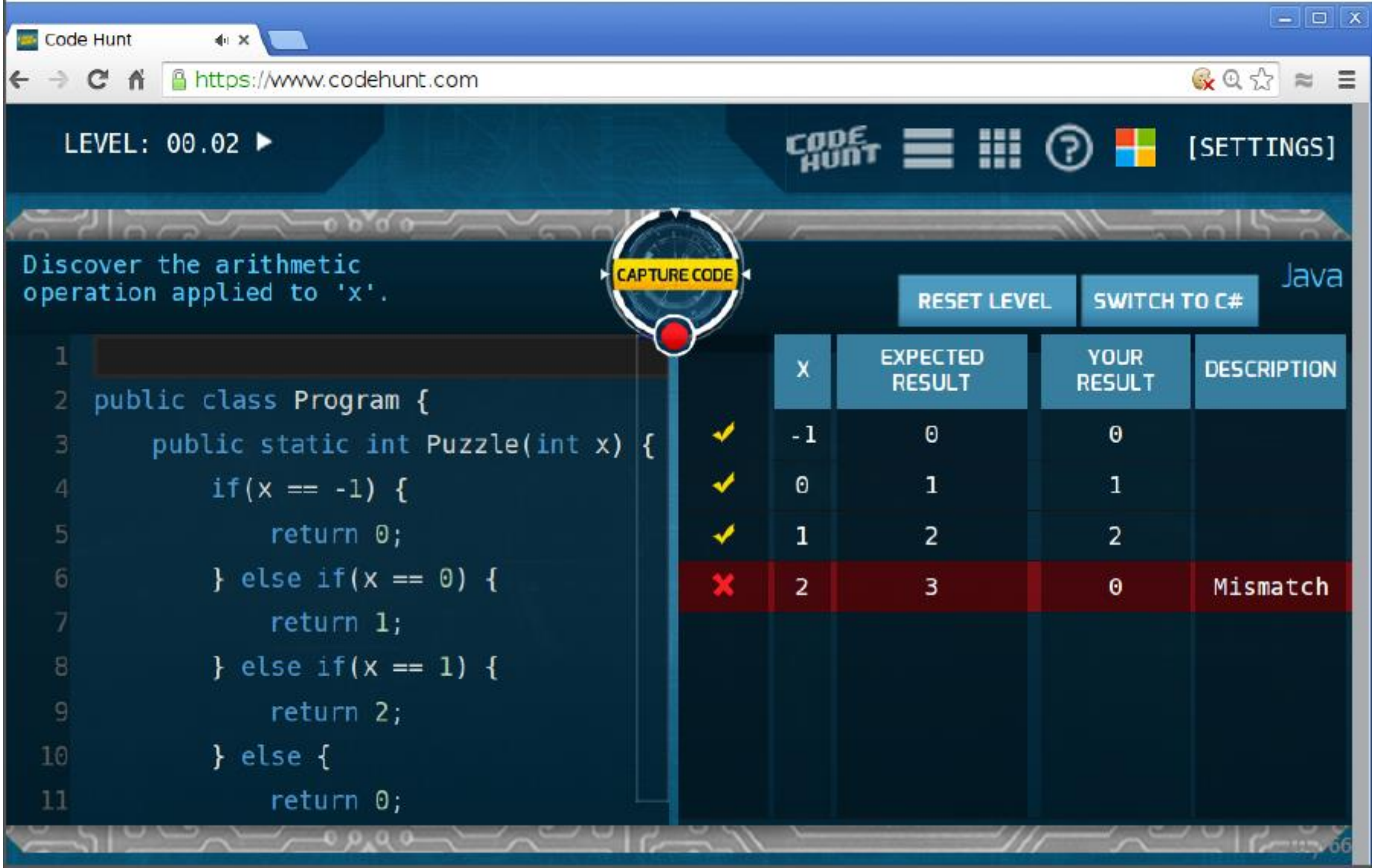
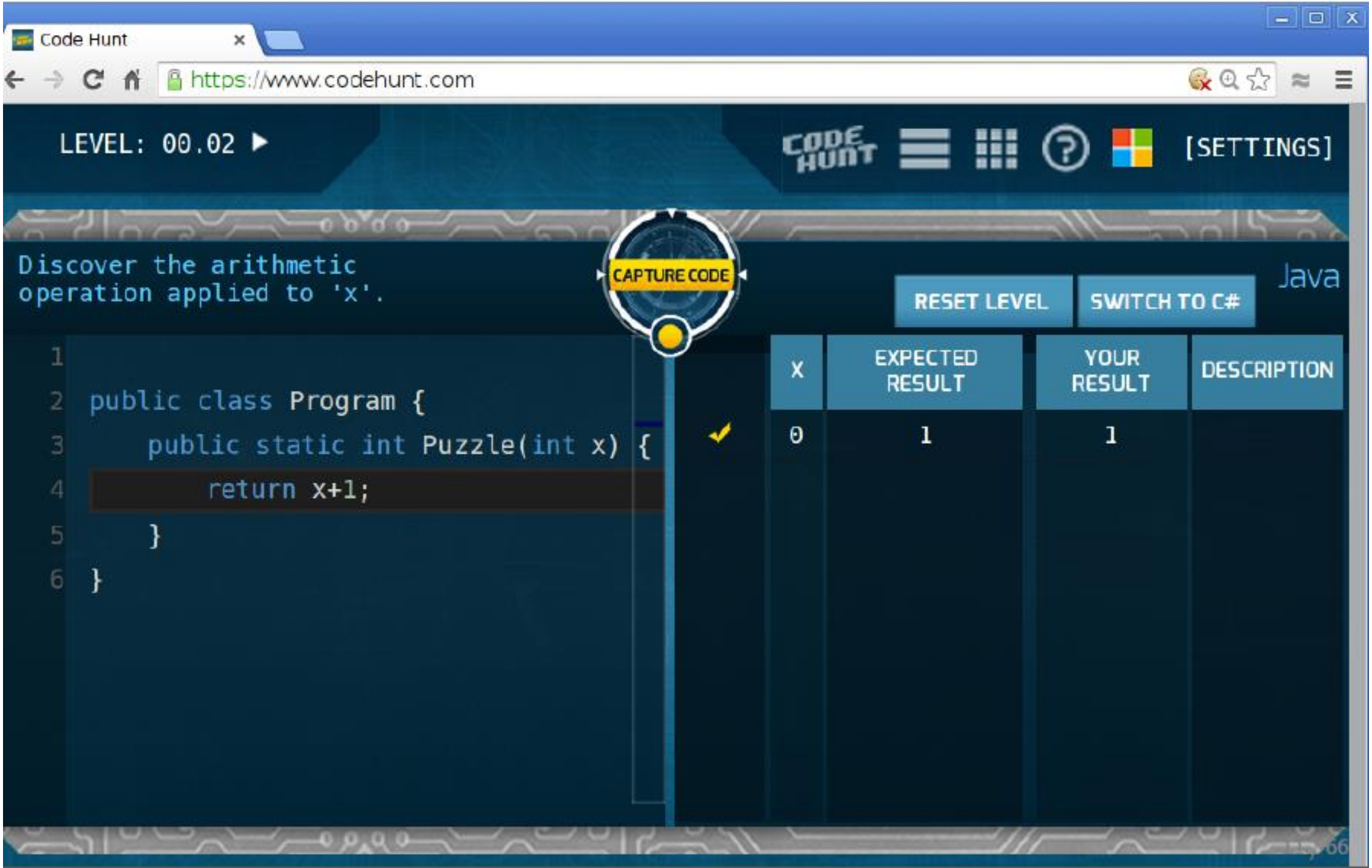
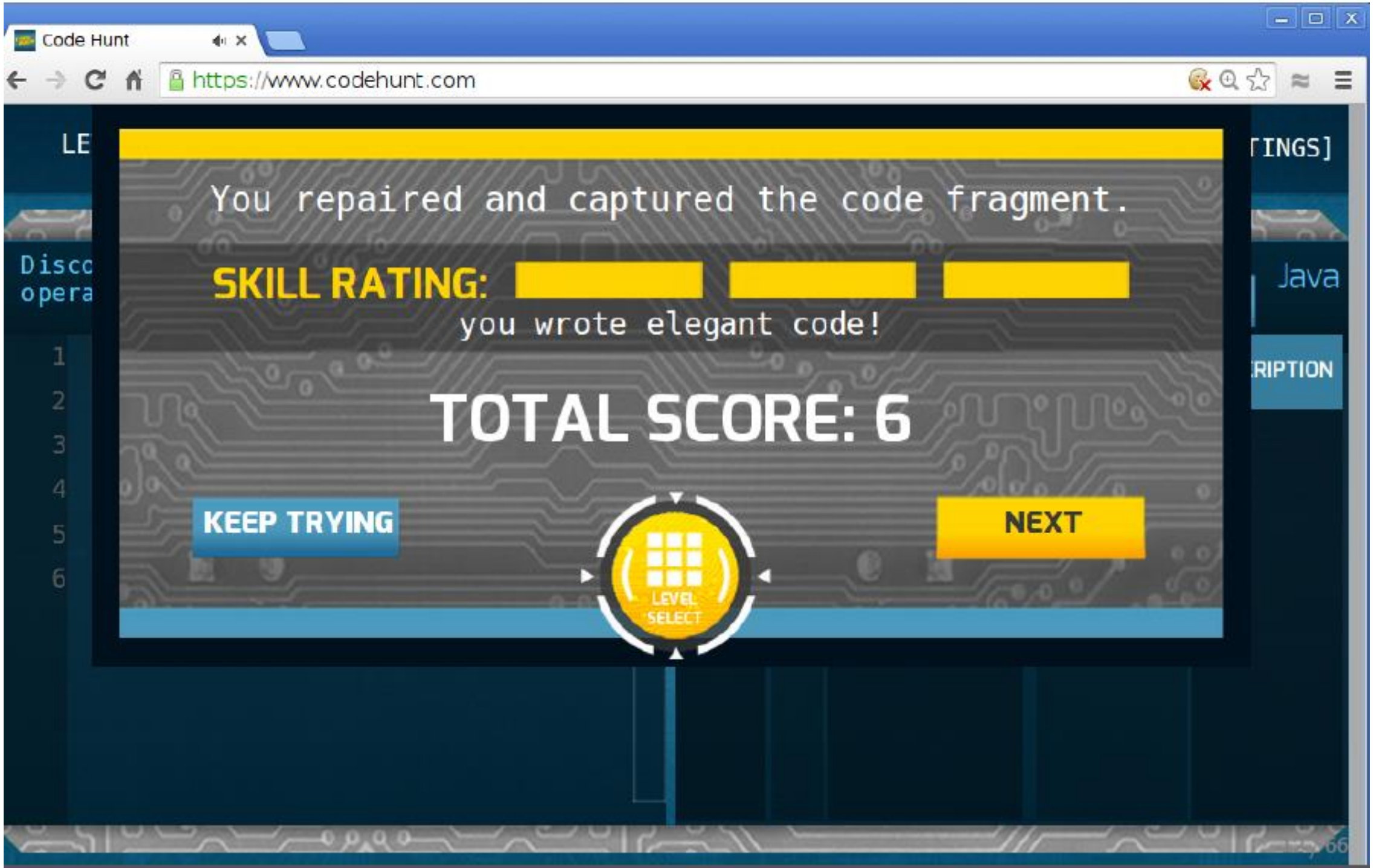
LEVEL: 00.02
[SETTINGS]
Discover the arithmetic operation applied to 'x'.
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
1
2 public class Program {
3 public static int Puzzle(int x) {
4 return 0;
5 }
6 }
X
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
0
1
0
Mismatch
-1
0
0

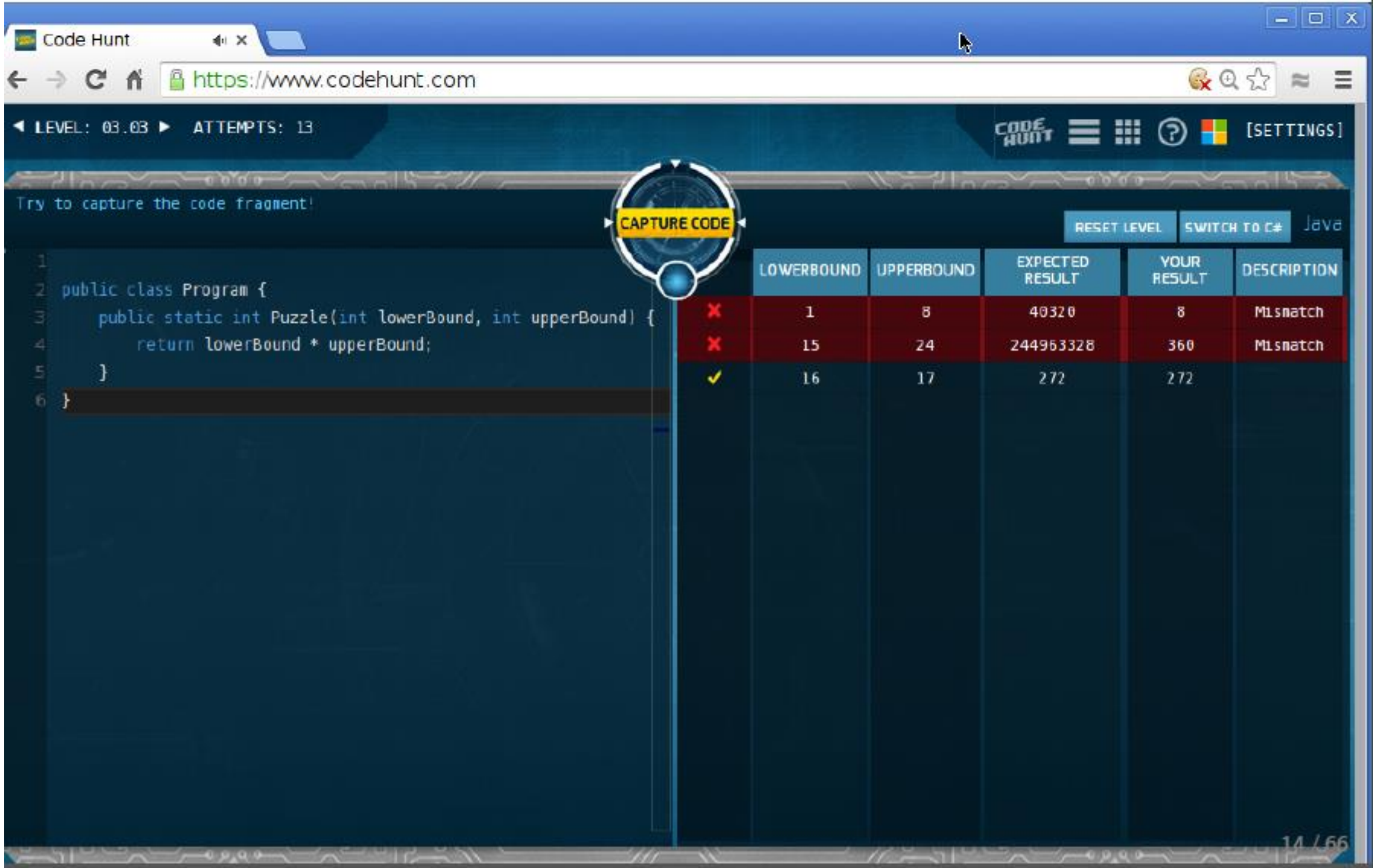

Code Hunt
https://www.codehunt.com
LEVEL: 00.02
[SETTINGS]
Discover the arithmetic operation applied to 'x'.
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
1
2 public class Program {
3 public static int Puzzle(int x) {
4 return 1;
5 }
6 }
X
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
0
1
1
1
2
1
Mismatch

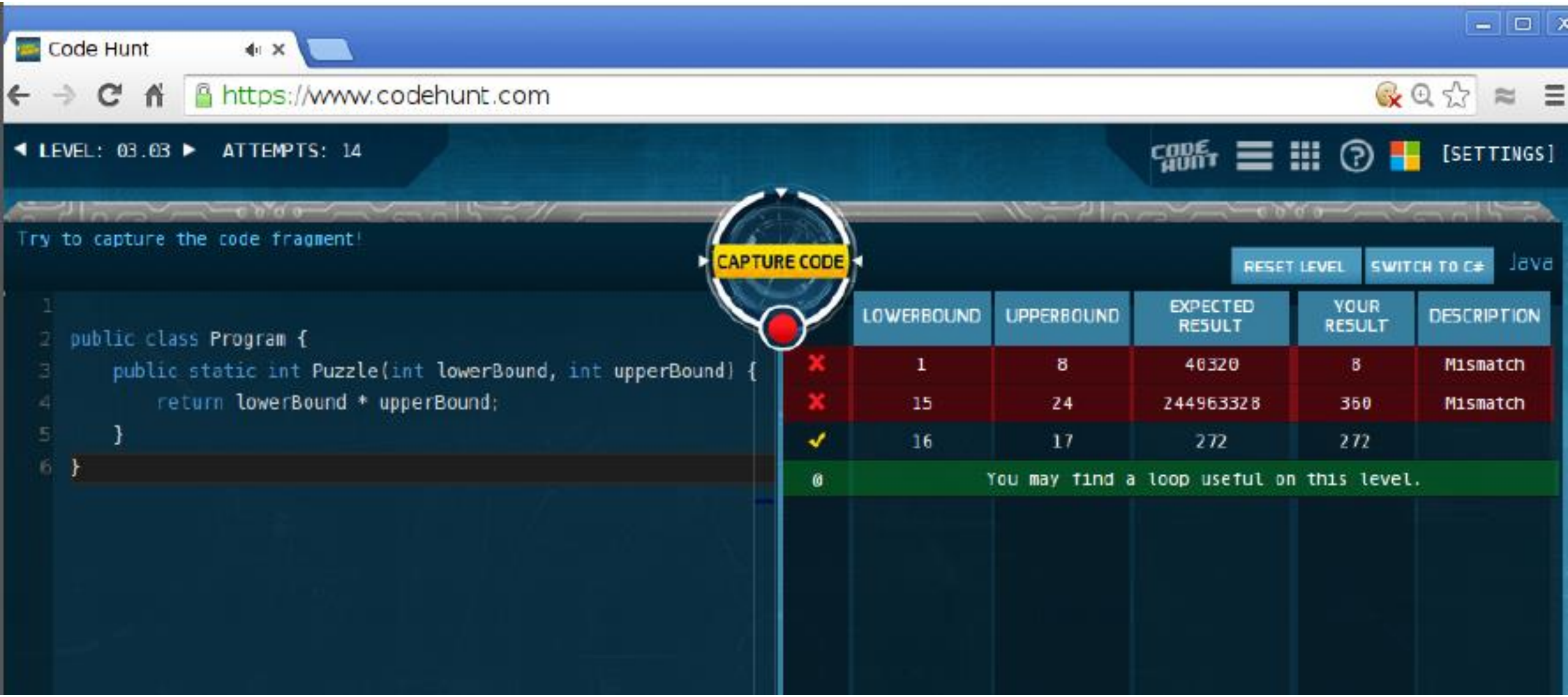

Code Hunt
https://www.codehunt.com
LEVEL: 00.02
[SETTINGS]
Discover the arithmetic operation applied to 'x'.
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
public class Program {
public static int Puzzle(int x) {
if(x == -1) {
return 0;
} else if(x == 0) {
return 1;
} else if(x == 1) {
return 2;
} else {
return 0;
X
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
-1
0
0
0
1
1
1
2
2
2
3
0
Mismatch

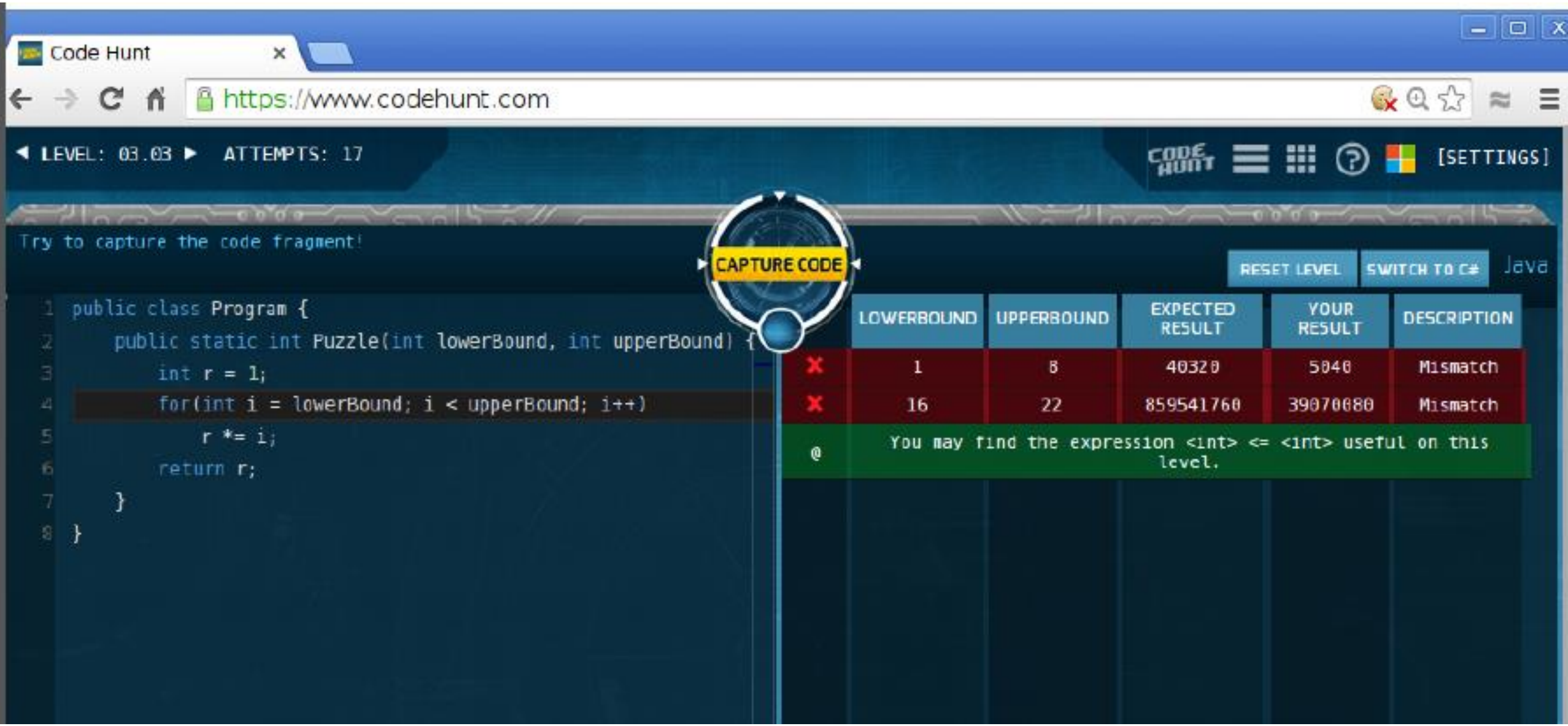

Code Hunt
https://www.codehunt.com
LEVEL: 00.02
[SETTINGS]
Discover the arithmetic operation applied to 'x'.
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
1
2 public class Program {
3 public static int Puzzle(int x) {
4 return x+1;
5 }
6 }
X
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
0
1
1


Code Hunt
https://www.codehunt.com
You repaired and captured the code fragment.
SKILL RATING:
you wrote elegant code!
TOTAL SCORE: 6
KEEP TRYING
LEVEL SELECT
NEXT
Java

More difficult level

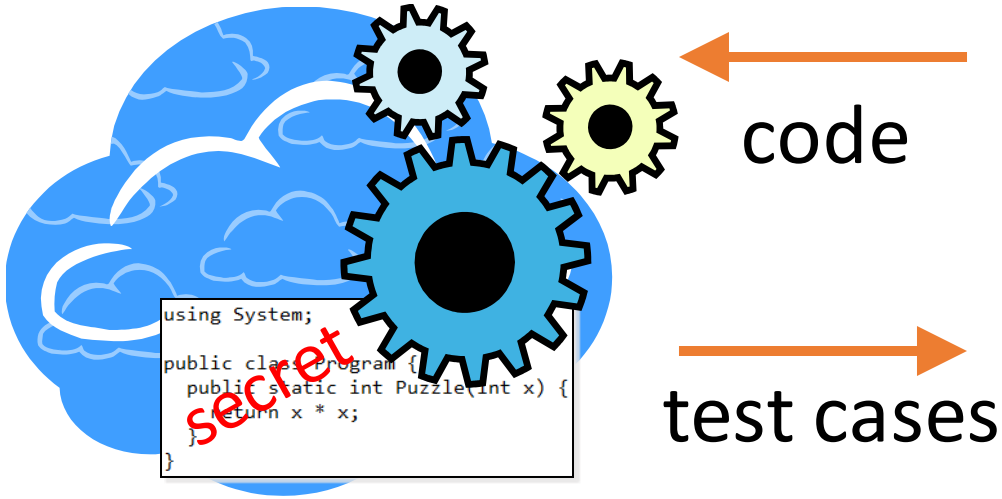

Code Hunt
https://www.codehunt.com
LEVEL: 03.03
ATTEMPTS: 13
[SETTINGS]
Try to capture the code fragment!
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
public class Program {
public static int Puzzle(int lowerBound, int upperBound) {
return lowerBound * upperBound;
}
}
LOWERBOUND
UPPERBOUND
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
1
8
40320
8
Mismatch
15
24
244963328
360
Mismatch
16
17
272
272
14 / 66

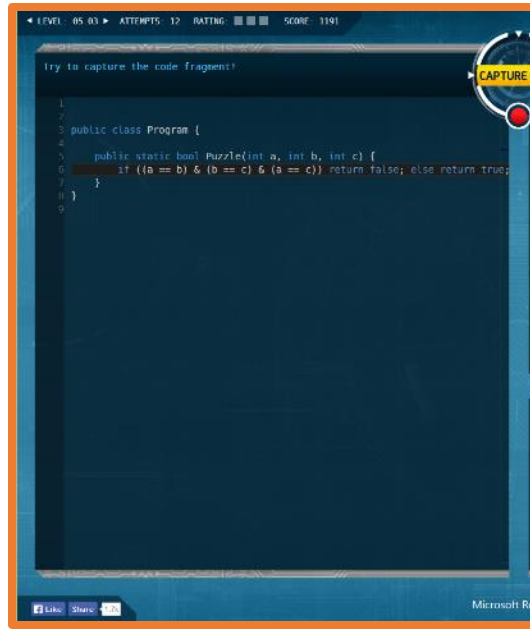

Code Hunt
https://www.codehunt.com
◄ LEVEL: 03.03 ► ATTEMPTS: 14
[SETTINGS]
Try to capture the code fragment!
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
1
2 public class Program {
3 public static int Puzzle(int lowerBound, int upperBound) {
4 return lowerBound * upperBound;
5 }
6 }
LOWERBOUND
UPPERBOUND
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
1
8
40320
8
Mismatch
15
24
244963328
360
Mismatch
16
17
272
272
0
You may find a loop useful on this level.


Code Hunt
https://www.codehunt.com
LEVEL: 03.03
ATTEMPTS: 17
[SETTINGS]
Try to capture the code fragment!
CAPTURE CODE
RESET LEVEL
SWITCH TO C#
Java
public class Program {
public static int Puzzle(int lowerBound, int upperBound) {
int r = 1;
for(int i = lowerBound; i < upperBound; i++)
r *= i;
return r;
}
}
LOWERBOUND
UPPERBOUND
EXPECTED RESULT
YOUR RESULT
DESCRIPTION
1
8
40320
5040
Mismatch
16
22
859541760
39070080
Mismatch
You may find the expression <int> <= <int> useful on this level.

It’s a game!

iterative gameplay
adaptive
personalized
no cheating
clear winning criterion





How it works

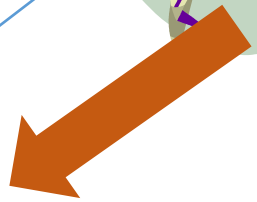
Secret Implementation

```
class Secret  {
    public static int Puzzle(int  x) {
      if (x <= 0) return 1;
      return x * Puzzle(x-1);
    }
}
```

Secret Impl behavior == **Player Impl**

Player Implementation

```
class Player {
    public static int Puzzle(int  x) {
          return x;
    }
}
```



```
class Test {
   public static void Driver(int  x) {
      if (Secret.Puzzle(x) != Player.Puzzle(x))
          throw new Exception("Mismatch");
     }
}
```

	x	your result	secret implementation result	Output/Exception
✓	1	1	1	
✓	2	2	2	
✗	3	3	6	Mismatch

Pex in the cloud @ api.codehunt.com

- Pex performs dynamic symbolic execution in a sandbox
- 32KB compressed code limit
  (deflate compression of UTF8-encoded program text)
- Single-threaded code only
- Default Pex search strategy for path selection
- 2s timeout for each Z3 query, 30s overall timeout
- If any discovered path exceeds some instruction limit (~100,000), you lose (likely termination issue)
- If Pex doesn’t find counterexample, you win
- Secret program can trim / shape input space via assumptions

Inputs and outputs

- The puzzle signature (parameters and result) may refer to…
  - simple datatypes (byte, bool, char, int, double, string, …) (however, avoid floating point number computations)
  - arrays of simple data types
  - that's it.
- Generated driver code…
  - First calls secret program, then user program
  - Passes inputs to both
  - Compares results: values have to be equal (deep equality for arrays / strings), exceptions types (if any) have to match

```
class Player {
    public static int Puzzle(int  x) {
        return x;
    }
}
```

```
class Secret  {
    public static int Puzzle(int  x) {
      if (x <= 0) return 1;
      return x * Puzzle(x-1);
    }
}
```

```
class Test {
   public static void Driver(int  x) {
      // simplified, similar for exceptions
      if (Secret.Puzzle(x) != Player.Puzzle(x))
          throw new Exception("Mismatch");
     }
}
```

Assumptions

```
using Microsoft.Pex.Framework;
[…]
PexAssume.IsTrue(…)
```

- Assumptions act as filters on input values
- Only the secret code is allowed to contain assumptions

Overflows

- Pex faithfully models the default behavior of C# / .NET.

```
public static void Puzzle(int x) {
  if (x + 10 < x) throw new Exception("what?");
}
```

Use an assumption to limit input space if you don’t want to confuse people.

```
PexAssume.IsTrue(x <= int.MaxValue - 10);
```

Path explosion

- Pex tries to flip execution at each MSIL branching instruction => avoid branches!
- Prefer strict Boolean expressions over short circuit
- Use PexAssume to impose bounds.

```
public static void Puzzle(int[] a) {
   PexAssume.IsTrue(a != null && a.Length == 100);
   bool condition = true;
   for (int i=0; i<100; i++) {
     condition = condition & a[i] > i;
   }
   PexAssume.IsTrue(condition);
 }
```

Reminder: Pex actually runs your code…

- In Code Hunt, white-list of APIs for sandboxing

  System.IO.Directory.Delete("c:\");

  => “*Disallowed dependencies*”

- Interaction with PexSymbolicValue

```
using Microsoft.Pex.Framework;
[…]
var pc = PexSymbolicValue.GetPathConditionString();
Console.WriteLine(pc);
```

Side effects

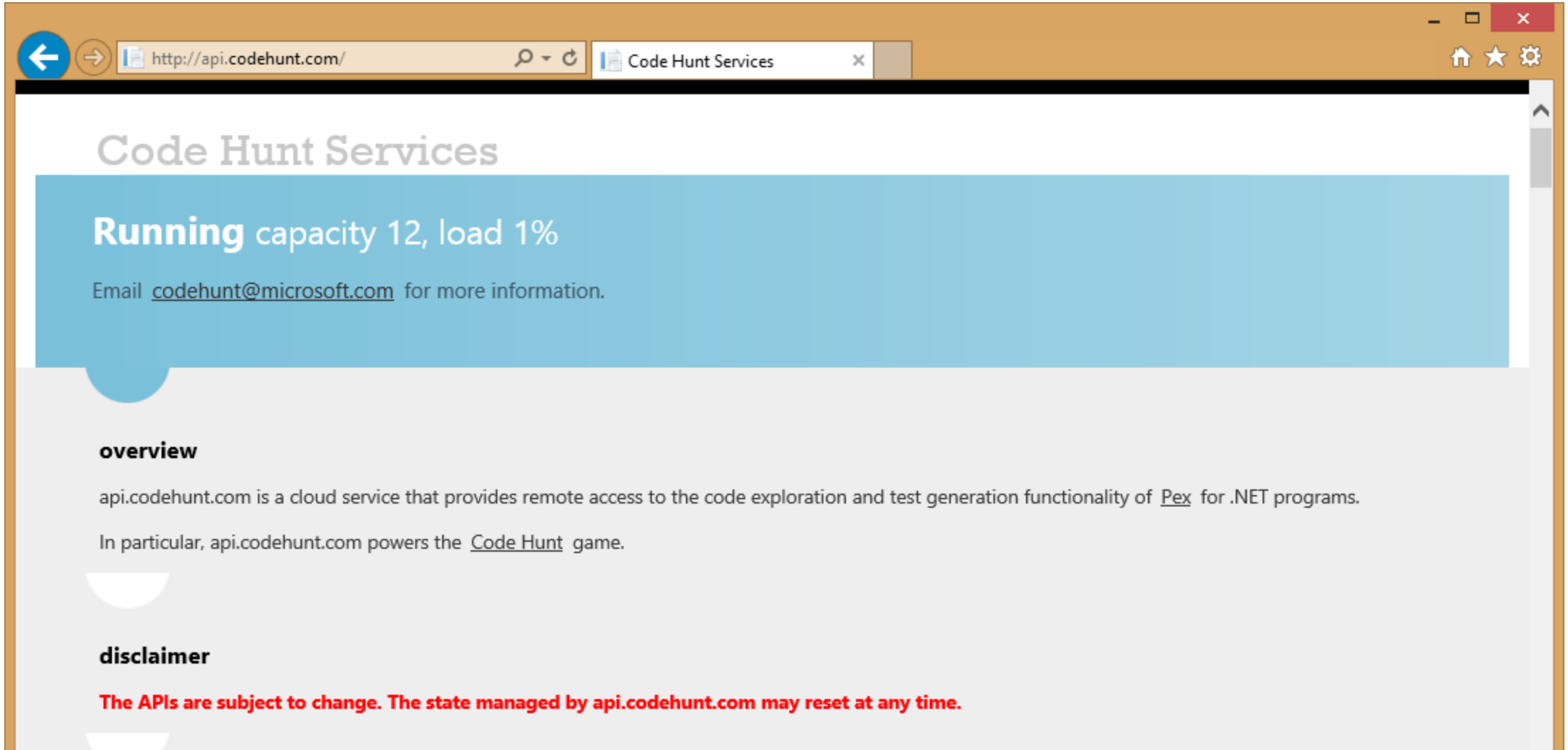
- White-listed APIs: many non-deterministic APIs excluded (e.g., System.Random)
- In code:
  - Avoid static fields (except possible for deterministic initialize-once cases)
  - Do not mutate incoming arrays: effects are visible to user code

Forcing values

- You can introduce benign branches to force Pex to generate certain test cases

```
public static void Puzzle(int[] a) {
    if (a != null && a.Length == 10 && a[3] == 27) {}
    if (a != null && a.Length == 20 && a[13] == 42) {}
 }
```

Back end @ api.codehunt.com



Statistics

Users: 2044477
User Programs: 9458818
User Explorations: 7490881
Programs: 5309700
Explorations: 4099675

APIs

Each API is given via its method (`GET` or `POST`), its path (`/api/something`), an optional request body, and a list of possible response codes and bodies. Requests and response bodies, if any, are in JSON format, and are specified using TypeScript interface syntax.

authorization

Most APIs require a special authorization header with a bearer token. If you do not send the following header with the APIs, you will get a `401 Unauthorized` status code.

```
Authorization: Bearer $ACCESS_TOKEN
```

There are two ways to get an access token: 1) anonymously (which creates a new anonymous user account on-the-fly), or 2) by referring to a regular user account. To get an anonymous `$ACCESS_TOKEN`, do the following.

```
POST /api/token?grant_type=client_credentials&client_id=anonymous&client_secret=anonymous
    response 200 OK                    body: TokenInfo

interface TokenInfo {
    access_token: string;
}
```

Anonymously obtained access tokens have severe usage restrictions. If you want to obtain a regular user account (represented by the pair `client_id` and `client_secret`), send a request by email to codehunt@microsoft.com .

merging

You can merge all data from an anonymously obtained account into a regular user account. You need to obtain an access token for the anonymous account from which data will be taken; then call the following API authorized by the regular target user to whom the data is copied.

```
POST /api/merge
```

Summary

Code Hunt is a serious programming game
powered by Pex,
an industrial-strength dynamic symbolic execution engine.

www.codehunt.com
api.codehunt.com
research.microsoft.com/Pex
research.microsoft.com/CodeHunt