Automated Repair of High Inaccuracies in Numerical Programs

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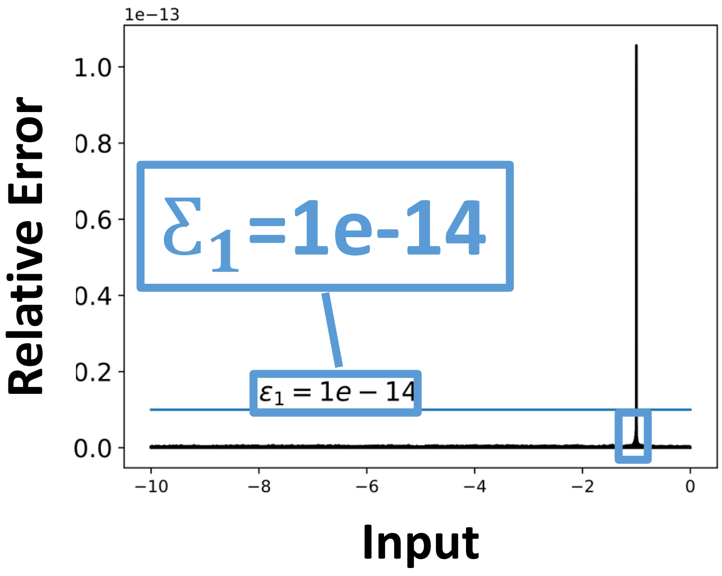
Introduction

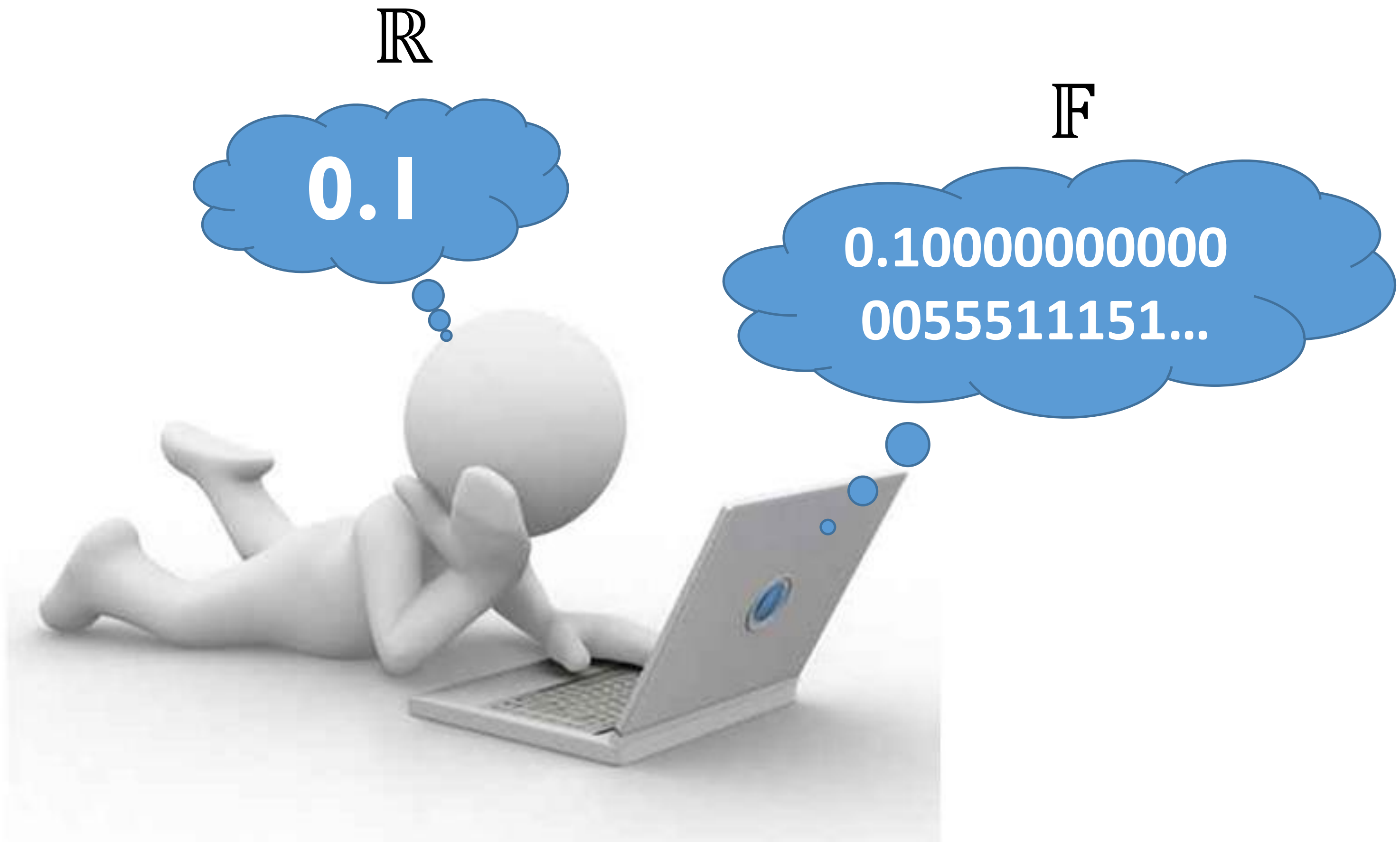
- High-inaccuracy bug
  - An input x
  - Real arithmetic output $O_r(x)$ (i.e., mathematical output)
  - Floating−point arithmetic output $O_f(x)$
  - Threshold ε

$$\left|\frac{O_r(x) - O_f(x)}{O_r(x)}\right| > \varepsilon$$



Introduction

Rounding error



Introduction

- Hard to debug and fix high-inaccuracy bugs manually
  - Huge search space (input domain)
    - More than 9.0e+15 floating-point (64 bits) numbers in [1,2]
  - Hard to localize the buggy code
    - Propagation and accumulation of round errors
  - Need of special knowledge on floating-point arithmetic to modify the buggy code

Introduction

Automated repair of numerical program:

Detecting + Localizing + Repairing
High-inaccuracy bugs

Our Approach

Four phases for automated repair

Detecting High-inaccuracy Bugs

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Localizing Buggy Code

↓

Generating and Validating Patches

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Patch Application and Simplification

Example

```
double F(double x){
  //assert(-10<x<100);
   double y,d,z;
   z = 0.0;
   if (x > 0.0){
        x = pow(x,5);
        y = x-1.0;
   }
   else{
        d = x*x;
        y = d-1.0;
   }
   while(z < 1e10){
        z = x*x-y*y;
        x = x*2.0+1.0;
  }
   y = y*z;
   return y;
}
```

Input intervals

- $I_1: [-10.0, 0.0)$
- $I_2: [0.0, 100.0]$

Our Approach

Phase 1: Detecting High-inaccuracy Bugs

- Obtaining (approximate) mathematical output
  - Shadow value execution in higher precision (64bits to 128 bits) (FPDebug) [Benz '12]
- Detecting algorithm to find negative test cases
  - Locality-Sensitive Genetic Algorithm (LSGA) [Zou '15]
  - Binary Guided Random Testing (BGRT) [Chiang '14]

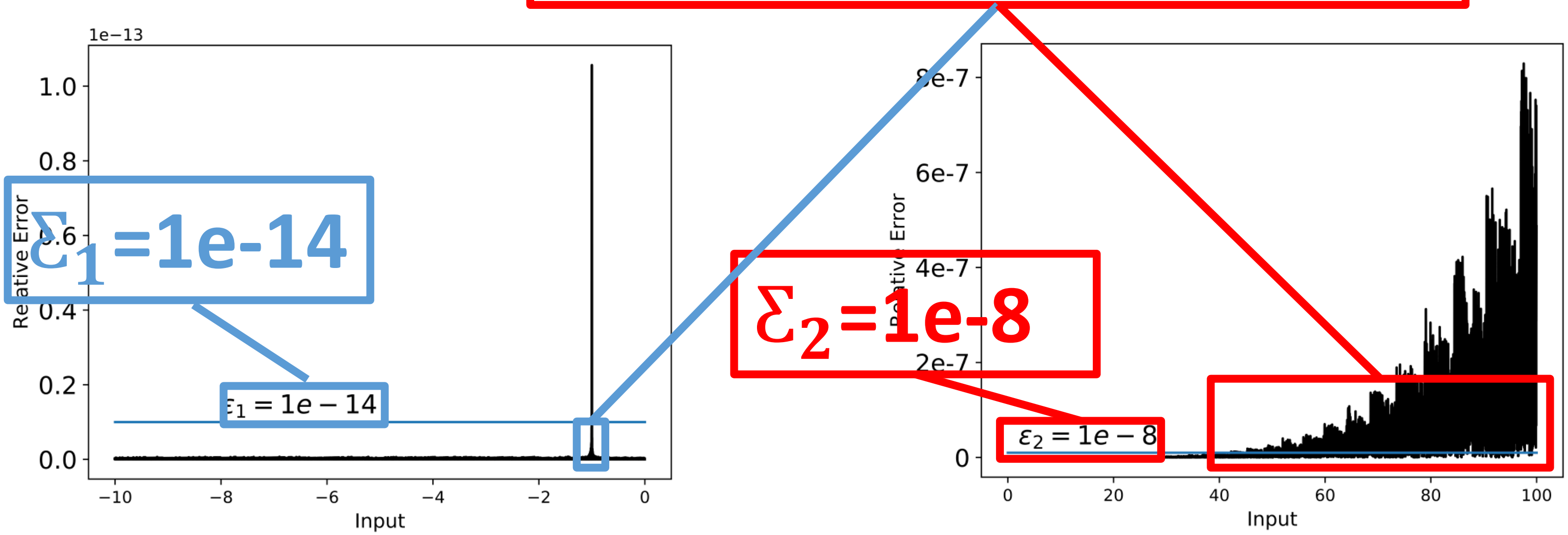
Our Approach

Phase 1: Detecting High-inaccuracy Bugs

- Using FPDebug to approximate the real arithmetic results and Binary Guided Random Testing to search inputs.

Input intervals triggering bugs

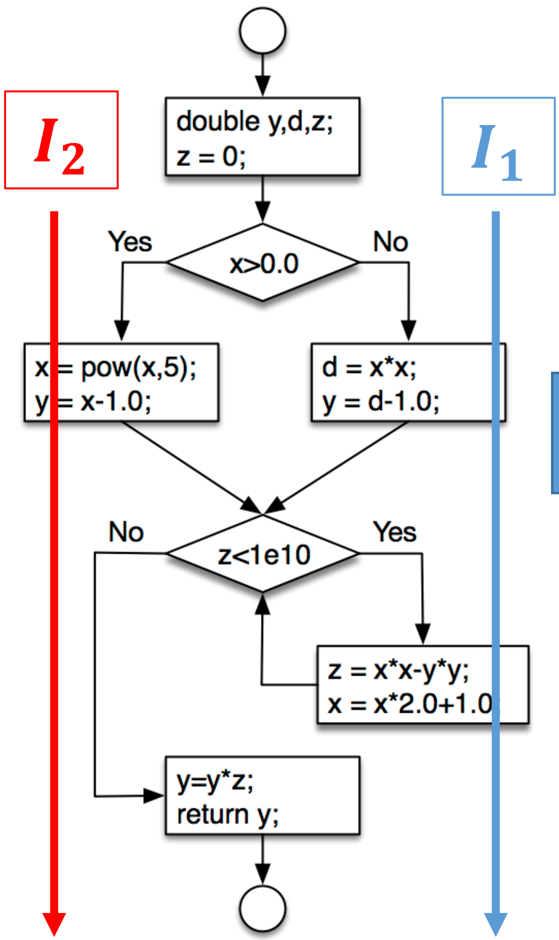
- $I_1: x \in [-1.0042, -0.9982]$
- $I_2: x \in [39.5303, 100.0000]$

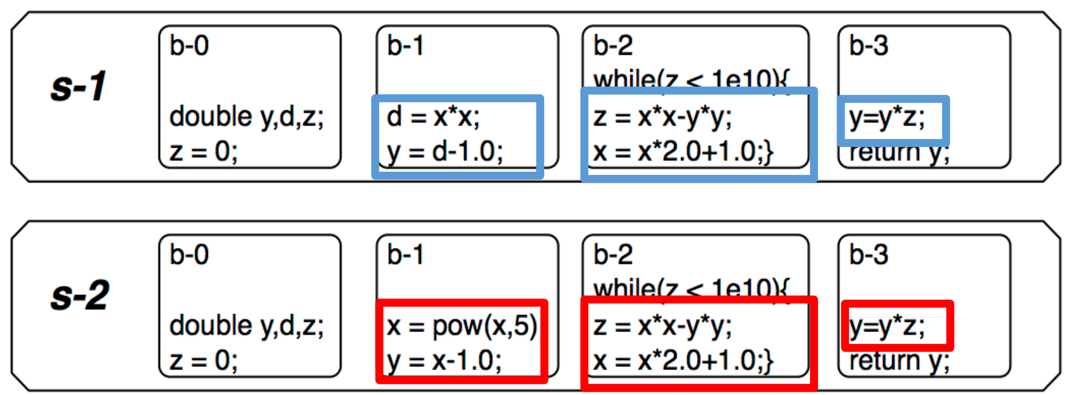


Our Approach

Phase 2: Localizing buggy code

control flow graph → **Slices and Blocks**





Input intervals triggering bugs

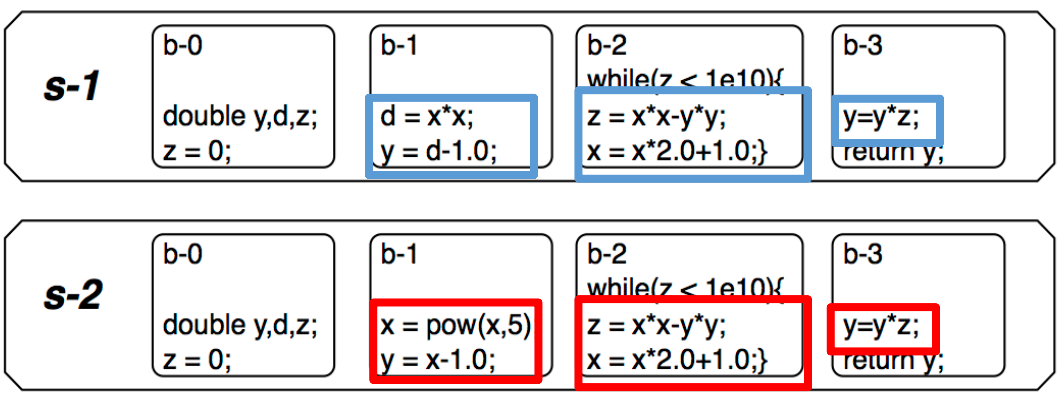
- $I_1 : x \in [-1.0042, -0.9982]$
- $I_2 : x \in [39.5303, 100.0000]$

Our Approach

Phase 2: Localizing buggy code

- Ranking blocks according to the relative error that each block introduces

Slices and Blocks



Ranking list of Blocks

s-1	*s-2*
b-1	*b-2*
b-2	*b-3*
b-3	*b-1*

Our Approach

Phase 3: Generating and Validating Patches

- **Generating patches**
  - symbolical calculation
  - mathematically equivalent transformation

s-1: b-1

$$d = x * x \qquad y = d - 1.0$$

symbolical calculation

$$d = x * x \qquad y = x * x - 1$$

mathematically equivalent transformation

$$d = x * x \qquad y = (x - 1) * (x + 1)$$

Our Approach

Phase 3: Generating and Validating Patches

- **Validating Patches**
  - **Regression testing**

Input intervals trigger bugs

- $I_1 : x \in [-1.0042, -0.9982]$
- $I_2 : x \in [39.5303, 100.0000]$

```
d = x*x;
y = d-1.0;
```

```
if ((x>= -1.0042)
  &&(x<-0.9982)){
    d = x*x;
    y = (x-1.0)*(x+1.0);
}else{
    d = x*x;
    y = d-1.0;}
```

```
while(z < 1e10){
        z = x*x-y*y;
        x = x*2.0+1.0;
}
```

```
if ((x>=35.5303)
  &&(x<=100)){
  while(z<1e10){
       z = (x-y)*(x+y);
       x = x*2.0+1.0;
  }else{
  while(z < 1e10){
       z = x*x-y*y;
       x = x*2.0+1.0;
}}
```

Our Approach

Phase 4: Patch Application

```
double F(double x){
  //assert(-10<x<100);
   double y,d,z;
   z = 0.0;
   if (x > 0.0){
       x = pow(x,5);
       y = x-1.0;
   }
   else{
       d = x*x;
       y = d-1.0;
   }
   while(z < 1e10){
       z = x*x-y*y;
       x = x*2.0+1.0;
  }
   y = y*z;
   return y;
}
```

```
double F(double x){
  //assert(-10<x<100);
   double y,d,z;
   z = 0.0;
   if (x > 0.0){
       x = pow(x,5);
       y = x-1.0;
   }
   else{
   if ((x>= -1.0042)
     &&(x<-0.9982)){
       d = x*x;
       y = (x-1.0)*(x+1.0);
   }else{
       d = x*x;
       y = d-1.0;}
   }
   if ((x>=35.5303)
   &&(x<=100)){
   while(z<1e10){
       z = (x-y)*(x+y);
       x = x*2.0+1.0;
   }else{
   while(z < 1e10){
       z = x*x-y*y;
       x = x*2.0+1.0;
  } }
   y = y*z;
   return y;
}
```

Our Approach

Phase 4: Patch Simplification

```
if ((x>= -1.0042)
   &&(x<-0.9982)){
    d = x*x;
    y = (x-1.0)*(x+1.0);
}else{
    d = x*x;
    y = d-1.0;}
```

↓

```
d = x*x;
y = d-1.0;
```

```
if ((x>=35.5303)
  &&(x<=100)){
  while(z<1e10){
      z = (x-y)*(x+y);
      x = x*2.0+1.0;
  }else{
  while(z < 1e10){
      z = x*x-y*y;
      x = x*2.0+1.0;
} }
```

↓

```
while(z < 1e10){
      z = (x-y)*(x+y);
      x = x*2.0+1.0;
}
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```
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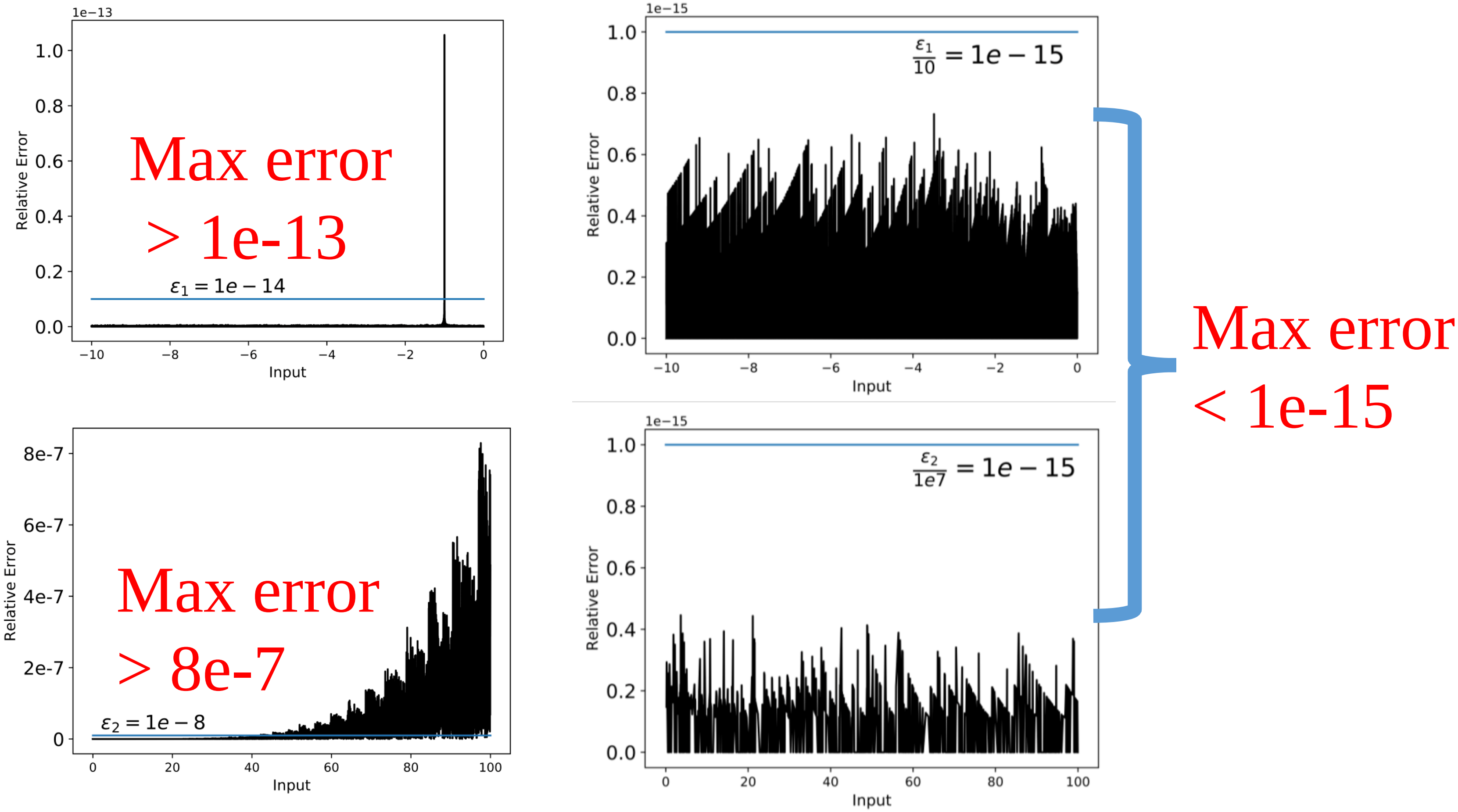
       y = x-1.0;
   }
   else{
       d = x*x;
       y = (x-1)*(x+1);
   }
   while(z < 1e10){
       z = (x-y)*(x+y);
       x = x*2.0+1.0;
  }
   y = y*z;
   return y;
}
```

Our Approach

Before repair

After repair



Experiments

Program	Input Domain	Time(s)			Max. Relative Error	
		Time for Detecting	Time for Patches	Total Time	Before Repair	After Repair
frac2	(0,1e5]	120.22	5.06	125.29	1.38E-11	9.33E-17
frac3	(1,200]	75.54	14.87	90.41	4.80E-12	1.46E-16
sqrt2	(0,1e7]	123.71	5.04	128.76	1.43E-09	1.53E-16
sqr2	(0,1e10]	217.94	3.11	221.05	7.87E-07	0.00E+00
rsqrt	(0,700]	93.76	9.58	103.35	2.33E-13	2.64E-16

Benchmark: 5 programs from FPBench (a benchmark for floating point analysis [Damouche '16])

Conclusion

- Propose a novel approach for automatically detecting, localizing, and repairing high-inaccuracy bugs in numerical programs
- Develop an automated repair prototype tool , evaluate it on several benchmark programs and achieve promising results

Future Work

- Design more efficient detecting algorithm to find negative test cases
- Improve our tool and evaluate it on real-world scientific numerical programs, e.g., the GNU Scientific Library (GSL)

Thank you!