TeTRIS:

General-purpose Fuzzing for Translation Bugs in Source-to-Source Code Transpilers

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FUTURES^3
LAB FUTURE TECHNOLOGY FOR USABLE, RELIABLE, & EFFICIENT SECURITY OF SOFTWARE & SYSTEMS

Transpilers: Automated Cross-language Code Translation

- **High-level goal:** translate code from one programming language to another

```c
int func(){
  int y, x, res;
  if (y < 5) {
      goto LABEL_RES;
  }
  if (x < 20) {
      goto LABEL_END;
  }
  LABEL_RES:
      res = x*y;
  LABEL_END:
      return res;
}
```

Original C code

Transpiler

(e.g., C2Rust)

```rust
pub unsafe extern "C" fn func() ->
libc::c_int {
  let mut y: libc::c_int = 0;
  let mut x: libc::c_int = 0;
  let mut res: libc::c_int = 0;
   if y < 5
     { cur_blk = 1;  }
   else if x < 20
     { cur_blk = 2;  }
   else
     { cur_blk = 1;  }
   match cur_blk {
       1 => { res = x*y; }
       _ => {}
   } return res;
}
```

Translated Rust code

Transpilers: Automated Cross-language Code Translation

- **High-level goal:** translate code from one programming language to another
  - An emerging backbone of modern **translation-oriented** software development tasks

Software Migration

Security Retrofitting

Code Interoperability

Transpilers: Automated Cross-language Code Translation

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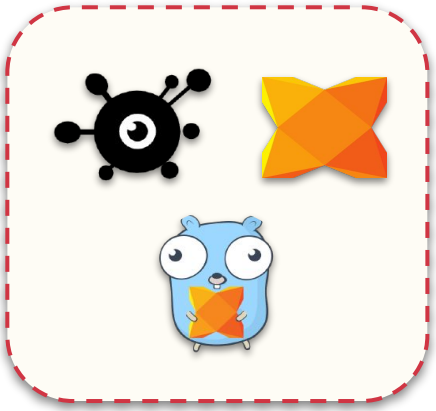
  - An emerging backbone of modern **translation-oriented** software development tasks
  - Success of these development tasks often undermined by **incorrect code translation**



Buggy Transpilers

Mis-translated Code

Downstream Failures

Transpilers: Automated Cross-language Code Translation

- **High-level goal:** translate code from one programming language to another
  - An emerging backbone of modern **translation-oriented** software development tasks
  - Success of these development tasks often undermined by **incorrect code translation**

Problem: what kinds of **translation errors** do transpilers face **in practice**?

Transpilers: Challenges to Successful Code Translation

- Manually distilled reported transpiler bugs into **three distinct categories**

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Bug Category	Transpiler	GitHub Issue No. & Error Description
Syntactic Mishandling	CxGo	#42: Mis-included variable re-declaration
	C2Go	#848: Mis-recovered switch-case values
	C2Nim	#217: Mis-recovered struct members

Example:
CxGo #42

```
#define func(arg){
    int x = arg;
}
if (0) {
    func(5);
    func(6);
}
```
Original C code

```
if false{
    var x int = 5
    _ = x
    var x int = 6
    _ = x
}
```
Mis-translated Go

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Type Conversion	C2Rust	#486: Mis-recovered int→float conversion
	Zig Translate-C	#20005: Mis-recovered bool→int conversion
	Zig Translate-C	#20638: Mis-recovered int→bool conversion

Example:
Zig #20005

```
#define func(x) (

    2 ? 4 : 8

)
```

Original C code

```
if(@as(c_int,2))
    @as(c_int,4);
else
    @as(c_int,8);
```

Mis-translated Zig

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Code Fragment Omissions	C2Nim	#240: Unrecovered standard int types
	C2Rust	#896: Unrecovered call instruction
	Go2Hx	#19: Unrecovered array size
	HxCpp	#225: Unrecovered optional int arguments

Example:
C2Rust #896

```c
int func() {
    g = 1;
    return g;
}
int main() {
    -func();
}
```
Original C code

```rust
fn func()-> c_int {
    g = 1 as c_int;
    return g;
}
fn main() {
    // -func();
}
```
Mis-translated Rust

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Example:
C2Rust #896

```
int func() {
    g = 1;
    return g;
}
int main() {
```

Motivation: how can **mis-translation errors** be uncovered **automatically**?

```
fn func()-> c_int {
    g = 1 as c_int;
    return g;
}
fn main() {
    // -func();
}
```

Mis-translated Rust

Prior Work: Approaches for Fuzzing Code Processors

- **Observation:** current approaches **ill-suited** to today's diverse transpilers

Fuzzer
AFL++
libFuzzer
AFL-Comp-Fuzz
Polyglot
CSmith
YARPGen

Prior Work: Approaches for Fuzzing Code Processors

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Fuzzer	C1: Language Agnostic
AFL++	✔
libFuzzer	✔
AFL-Comp-Fuzz	✔
Polyglot	✔
CSmith	✘
YARPGen	✘

Supports **only C** (e.g., Clang, GCC)

Any language (e.g., C, Py, Go)

Prior Work: Approaches for Fuzzing Code Processors

- **Observation:** current approaches **ill-suited** to today's diverse transpilers

Fuzzer	C1: Language Agnostic	C2: Minimal Lang. Spec.
AFL++	✔	None
libFuzzer	✔	None
AFL-Comp-Fuzz	✔	None
Polyglot	✔	✔
CSmith	✘	✘
YARPGen	✘	✘

Supports **only C** (e.g., Clang, GCC)

Fuzzer	Core	Spec
CSmith	~38.9 K LoC	
Polyglot	~7.0 K	~1.5 K

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Fuzzer	C1: Language Agnostic	C2: Minimal Lang. Spec.	C3: Upholds Code Validity
AFL++	✔	None	✘
libFuzzer	✔	None	✘
AFL-Comp-Fuzz	✔	None	✘
Polyglot	✔	✔	✘
CSmith	✘	✘	✔
YARPGen	✘	✘	✔

Supports **only C** (e.g., Clang, GCC)

Fuzzer	Semantic Validity
CSmith	~100%
Polyglot	~20%

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AFL-Comp-Fuzz	✔	None	✘
Polyglot	✔	✔	✘
CSmith	✘	✘	✔
YARPGen	✘	✘	✔

Supports **only C** (e.g., Clang, GCC)

Fuzzer	Semantic Validity
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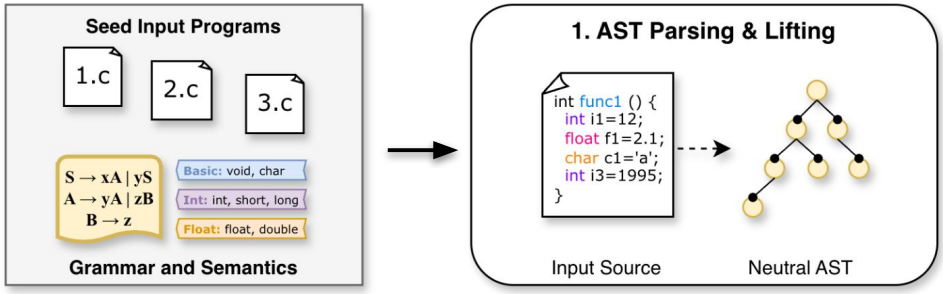
- **Takeaways:** transpiler fuzzing must balance **both generality *and* code validity**

TeTRIS: Testing Transpilers Regardless of Input Source

- **Key idea: grammar-guided mutation** with **language-level semantic guardrails**



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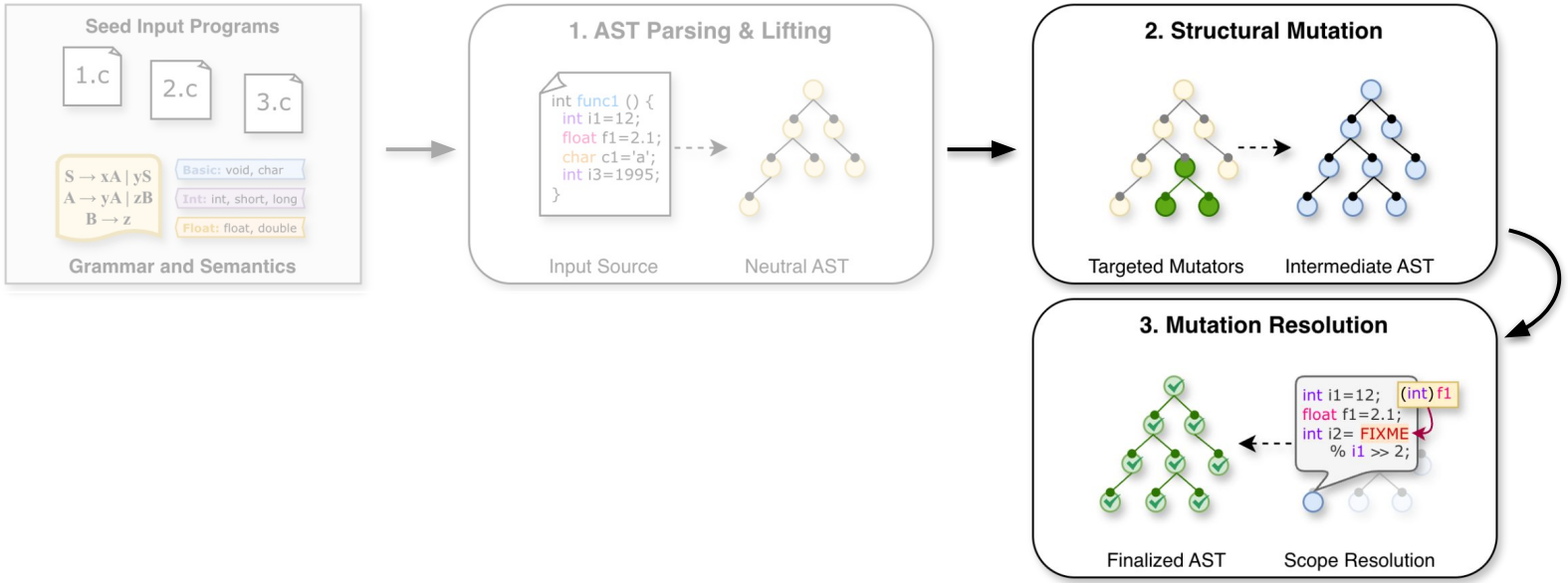

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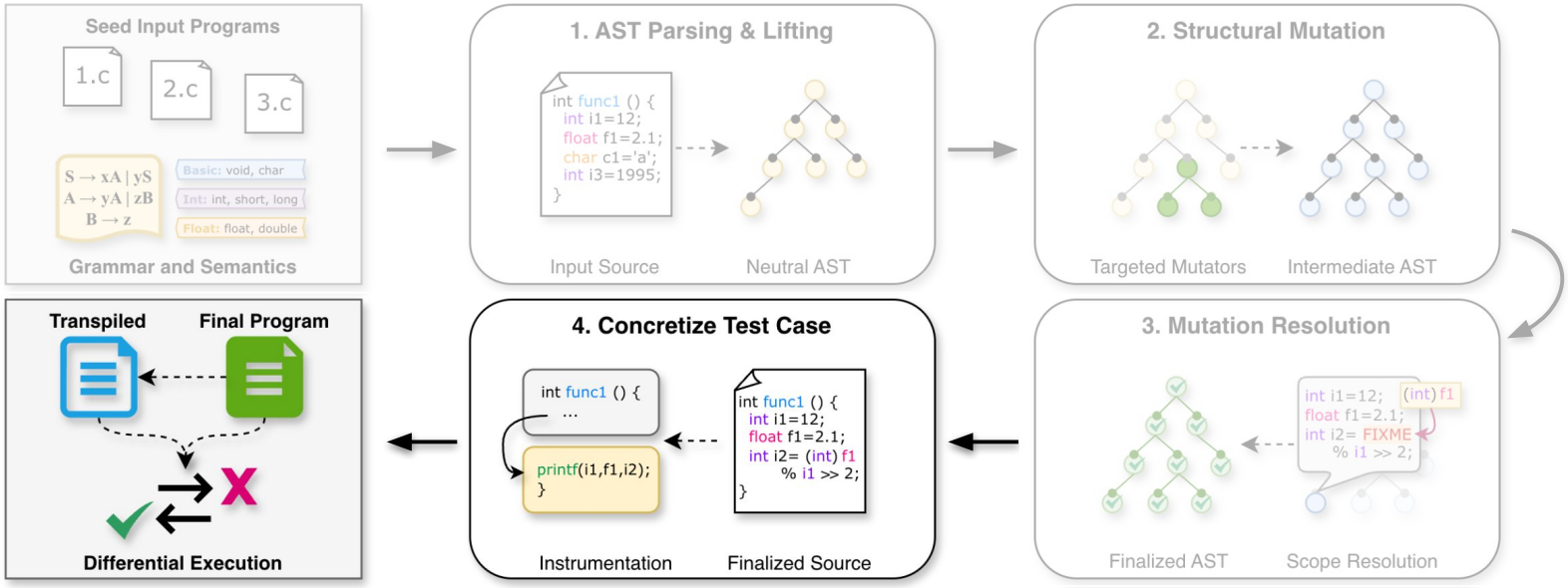
  - **Transpiler-specific bug oracles:** transpiler crashes, non-runnable code, differential execution



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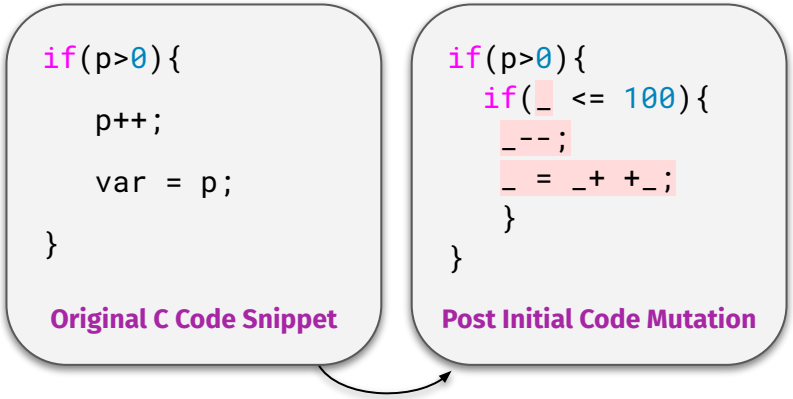

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- **Key idea: grammar-guided mutation** with **language-level semantic guardrails**
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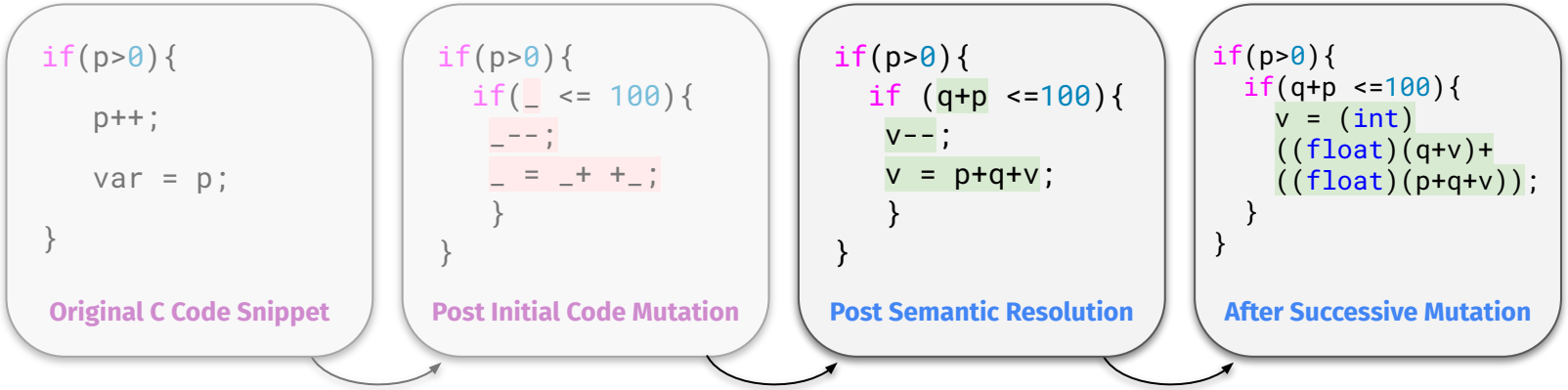
  - Generated programs gradually cover deeper language **syntax and semantic combinations**



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  - Generated programs gradually cover deeper language **syntax and semantic combinations**

Fuzzer	Core	C Spec	Go Spec	Haxe Spec
CSmith	~38.9K LoC		✘	✘
Polyglot	~7.0 K	~1.5 K	✘	✘
TeTRIS	~5.6 K	811 LoC	797 LoC	785 LoC

- **Outcome: broad transpiler support** with only minimal language specification

Evaluation: Overview

- **Fundamental questions:**
  1. Is TeTRIS capable of **generating valid inputs**?
  2. Can TeTRIS **more thoroughly** test transpilers?
  3. Does TeTRIS uncover **more translation bugs**?

- Competing code processor fuzzers:
  - CSmith (language-specific C compiler fuzzer)
  - AFL++, AFL-Compiler-Fuzzer, Polyglot (gen.-purpose)

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- Competing code processor fuzzers:
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- Benchmarked on **seven transpilers** spanning **six distinct** language-to-language pairings
  - Standard evaluation procedure (5 × 24hr trials each)

Transpiler	In Lang.	Out Lang.
C2Rust	C	Rust
CxGo, C4go	C	Go
Zig Translate-C	C	Zig
Go2Hx	Go	Haxe
HxCpp	Haxe	C++
HxPy	Haxe	Python3

Evaluation: Generated Code Validity

- Measured **mean generated code validity** across all fuzzers per transpiler
  - Proportion of each fuzzer's 24-hr corpora accepted as valid by each targeted transpiler
  - Evaluated on transpilers compatible with grey-box fuzzing (CxGo, C4Go, C2Rust, HxCpp, HxPy)

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Metric	TeTRIS vs. CSmith
Code Validity	**- 0.25×**

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Metric	TeTRIS vs. CSmith	TeTRIS vs. Polyglot	TeTRIS vs. AFL-Comp-Fuzz	TeTRIS vs. AFL++
Code Validity	**- 0.25×**	**+ 5.24×**	**+ 27.42×**	**+ 30.69×**

- **Takeaways:** TeTRIS balances **code validity *and* broad transpiler support**
  - Comparable performance to C-specific CSmith despite supporting many more languages

Evaluation: Transpiler Code Coverage

- Measured **mean transpiler code coverage** for all fuzzers per transpiler
  - Enumerated basic block coverage of transpiler binaries using AFL-QEMU binary tracing
  - Evaluated on transpilers compatible with QEMU coverage tracing (CxGo, C2Rust, HxCpp, HxPy)

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Code Coverage	**- 10.25%**

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Metric	TeTRIS vs. CSmith	TeTRIS vs. Polyglot	TeTRIS vs. AFL-Comp-Fuzz	TeTRIS vs. AFL++
Code Coverage	**- 10.25%**	**+ 11.31%**	**+ 23.62%**	**+ 21.70%**

- **Takeaways:** TeTRIS probes more of transpilers' **overall translation logic**
  - Trades-off some **transpiler-specific depth** for covering a **broader range of behaviors**

Evaluation: Discovered Transpiler Bugs

- Analyzed **total unique bugs** throughout all transpiler fuzzing campaigns
  - **Bug categories:** transpiler crashes, post-translation crashes, divergent runtime outputs
  - All bugs manually deduplicated and reported to their respective transpiler developers

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Metric	CSmith
Total (old +new)	**2**

Evaluation: Discovered Transpiler Bugs

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Metric	CSmith	Polyglot	AFL-Comp-Fuzz	AFL++	TeTRIS
Total (old +new)	2	0	0	0	16

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Metric	CSmith	Polyglot	AFL-Comp-Fuzz	AFL++	TeTRIS
Total (old +new)	2	0	0	0	16
Newly-Found	0	0	0	0	12

- **Takeaways:** TeTRIS's diverse test cases expose **more transpiler defects**
  - Since submission, **all 12** TeTRIS-found new bugs **are confirmed and/or fixed**

Case Studies: TeTRIS-found Transpiler Bugs

- **CxGo #76:** unhandled **bool-to-float implicit type conversion**
  - CxGo adds **external functions** to accommodate Go's lack of implicit type conversion

```
float x = 1.25;

x += 100 + (4 < 4.5);

x += 9.9 + (4 < 4.5);
```

Original C code


```
var x float32 = 1.25
x += 100 + float32(
   int(libc.BoolToInt(4<4.5))
)
x += 9.9 + float32(
   float64(4<4.5)
)
```

Case Studies: TeTRIS-found Transpiler Bugs

- **CxGo #76:** unhandled **bool-to-float implicit type conversion**
  - CxGo adds **external functions** to accommodate Go's lack of implicit type conversion
  - Although bool-to-integer conversions supported, CxGo **missed conversions to floats**

```
float x = 1.25;

x += 100 + (4 < 4.5);

x += 9.9 + (4 < 4.5);
```

Original C code


```
var x float32 = 1.25
x += 100 + float32(
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)
```

Uncompilable Go code

- **Takeaways:** real-world codebases span a **wide range of type semantics**
  - TeTRIS's random programs surface mishandling of **expected type-to-type conversions**

Case Studies: TeTRIS-found Transpiler Bugs

- **Zig Translate-C #21871:** mis-inclusion of **unreachable code statements**
  - While **unreachable code** is permitted in C, it is strictly prohibited in the Zig language

```c
return x += y * 3;

x++;

return 0;
```

Original C code


```
return blk: {
    const ref = &x;
    ref.* += y *@as(c_int,3);
    break :blk ref.*;
};
```

Case Studies: TeTRIS-found Transpiler Bugs

- **Zig Translate-C #21871:** mis-inclusion of **unreachable code statements**
  - While **unreachable code** is permitted in C, it is strictly prohibited in the Zig language
  - Zig Translate-C correctly prunes most unreachable statements, **but wrongly kept these**

```c
return x += y * 3;

x++;

return 0;
```

Original C code


```
return blk: {
    const ref = &x;
    ref.* += y *@as(c_int,3);
    break :blk ref.*;
};
x += 1;
return 0;
```

Uncompilable Zig code

- **Takeaways:** transpilers' **internal code analyses** are also error-prone
  - TeTRIS uncovers how these analyses fail toward **enhancing transpilers' reliability**

Case Studies: TeTRIS-found Transpiler Bugs

- **Go2Hx #179:** non-equivalent **comparisons between zeroed arrays**
  - Go supports **value-level array comparisons**, while Haxe only by reference

```
x := [4]int{0,0,0,0}

if x != [4]int{0,0,0,0} {
    panic("ERR: unequal!")
}
```

Original Go code (branch = **FALSE)**


```
var x = new Array<Int>
    ([0,0,0,0]);
if (
                ){
    throw "ERR: unequal!";
}
```

Case Studies: TeTRIS-found Transpiler Bugs

- **Go2Hx #179:** non-equivalent **comparisons between zeroed arrays**
  - Go supports **value-level array comparisons**, while Haxe only by reference
  - Go2Hx fails to properly account for this, resulting in **divergent executions**

```
x := [4]int{0,0,0,0}

if x != [4]int{0,0,0,0} {
    panic("ERR: unequal!")
}
```

✘

Original Go code (branch = **FALSE**)


```
var x = new Array<Int>
    ([0,0,0,0]);
if (x != new Array<Int>
    ([0,0,0,0])){
    throw "ERR: unequal!";
}
```

✔

Non-equivalent Haxe code (branch = **TRUE**)

- **Takeaways:** transpilers need to resolve **language-level feature differences**
  - TeTRIS's coverage of diverse code constructs surfaces **subtle translation edge-cases**

Conclusion: Why TeTRIS?

- Transpiler bugs **impede translation-oriented tasks**
  - Code migration, interoperability, and security retrofitting
  - Hence, **testing transpilers proactively** is key to fixing them
- Prior fuzzers are **ineffective on today's transpilers**
  - Language-specific fuzzers (e.g., CSmith) remain **inflexible**
  - General-purpose fuzzers (e.g., Polyglot) face **invalid code**
  - Hence, vast majority of transpiler logic **remains untested**

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  - Hence, vast majority of transpiler logic **remains untested**
- **Our solution: TeTRIS**
  - The first fuzzer designed specifically for transpilers' needs
  - **Outcome:** effective fuzzing for today's diverse transpilers, spanning **C**-, **Go**-, and **Haxe**-targeting translation workflows

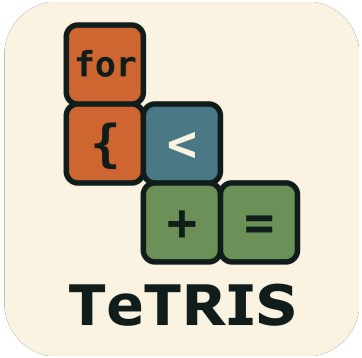
Key Results:

5–30× higher validity

11–23% more coverage

12 new transpiler bugs (*all since confirmed*)

Thank you!



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