Metamorphic Testing for Graphics Compilers

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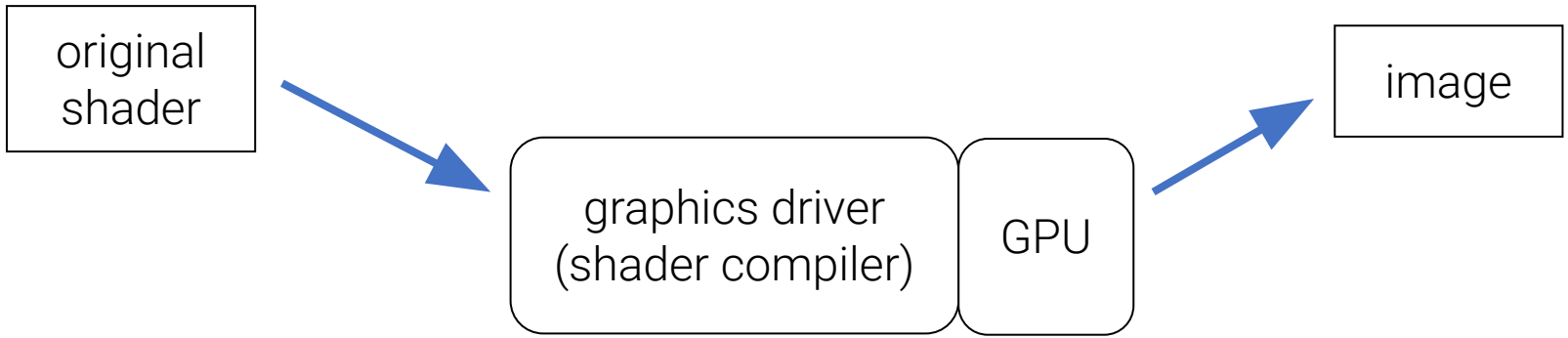
Outline

1. Overview of GraphicsFuzz
2. Growing the **Vulkan Conformance Test Suite** using GraphicsFuzz
3. Using GraphicsFuzz for **differential code coverage**
4. Finding **deeper vulnerabilities** using metamorphic testing

The GraphicsFuzz testing approach



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A kind of *metamorphic* testing

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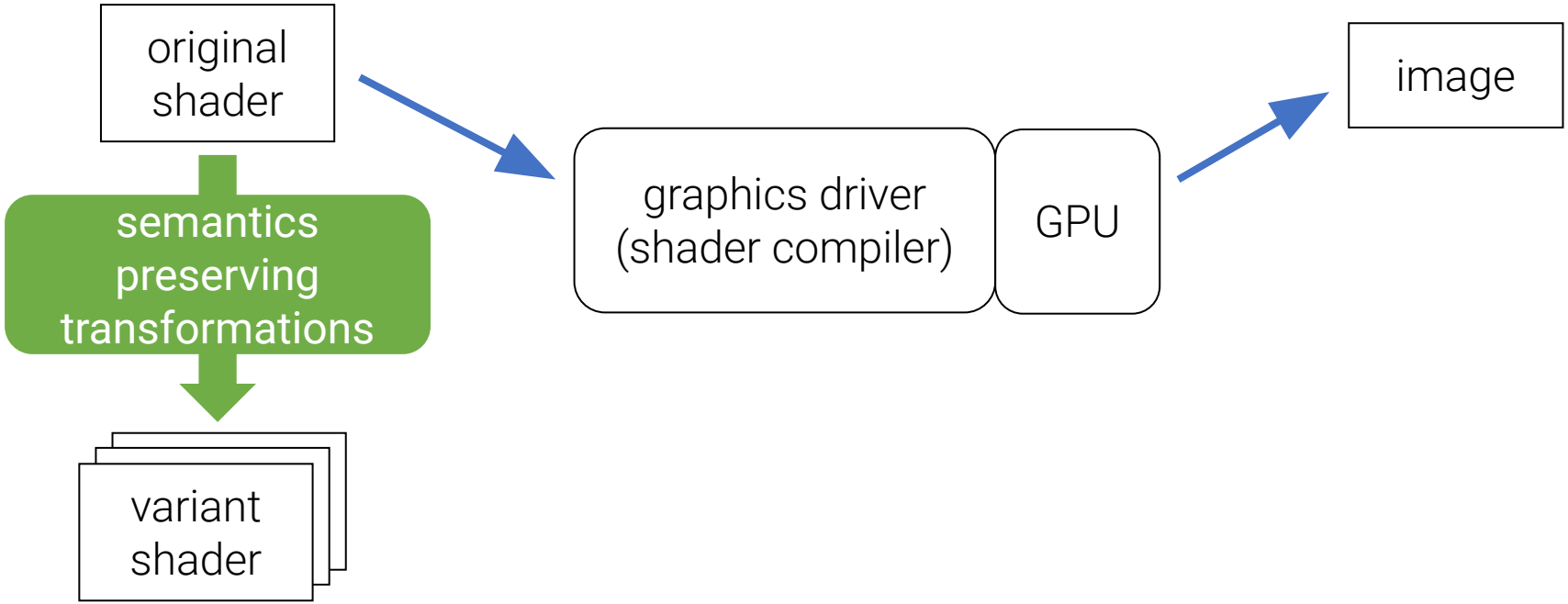

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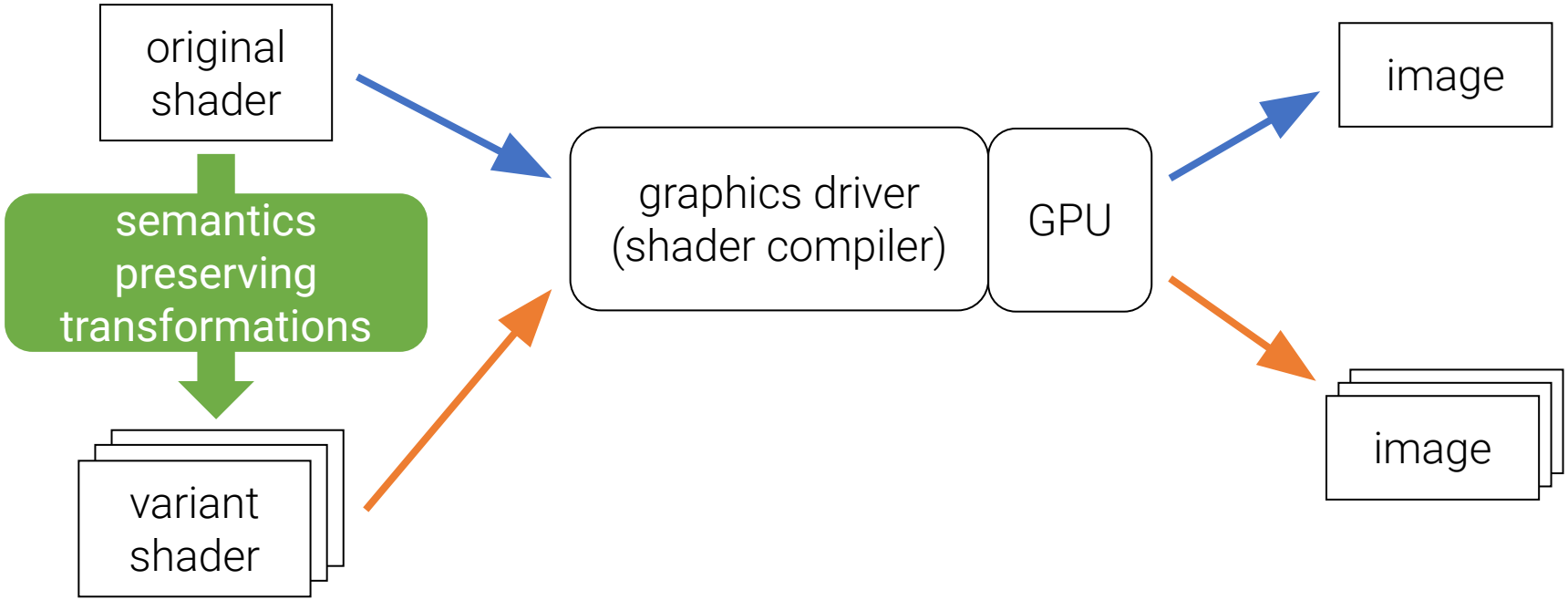

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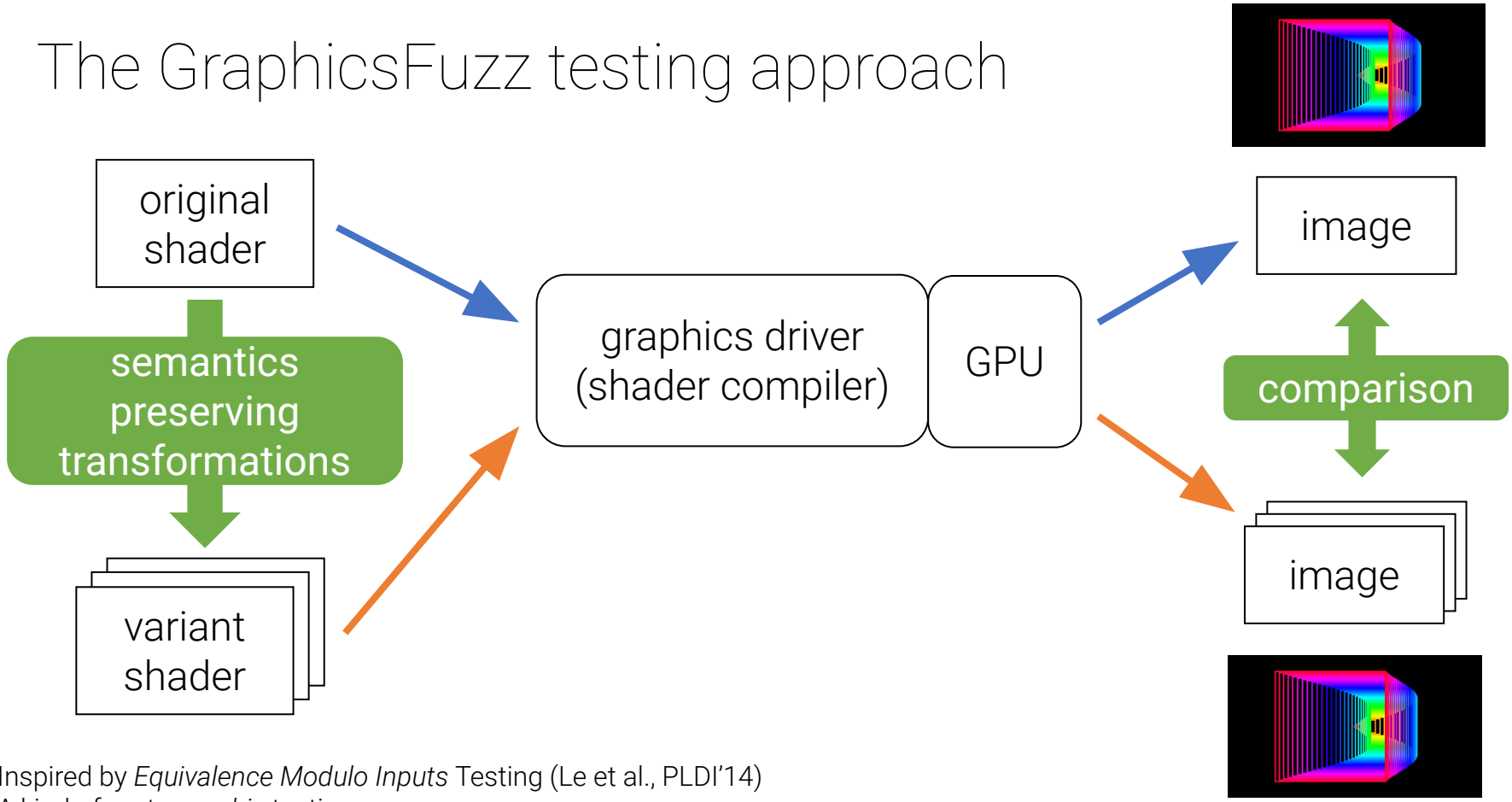

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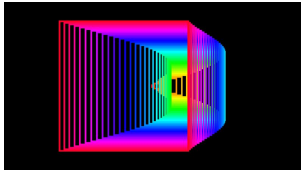


original shader

semantics preserving transformations

variant shader

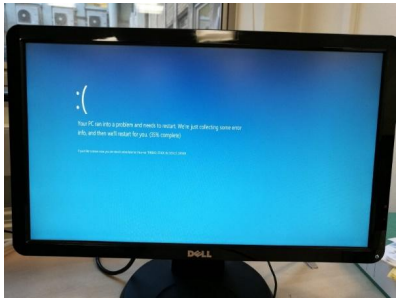
graphics driver (shader compiler)

GPU

image

diff/crash

image



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A kind of *metamorphic* testing

Example transformations

Inject dead code

```
if (false) {

    // arbitrary code

}
```

Use *uniforms* - shader inputs - to fool the compiler:

```
uniform float f; // set to 1.0 at runtime

...

if (f < 0.0) { // evaluates to false

    // arbitrary code

}
```

Example transformations

Wrap code in single iteration loop

```
// existing code
```

```
for (int i = 0; i < 1; i += 1) {

  // existing code

}
```

Again, fool the compiler with uniforms

```
// existing code
```

```
uniform int a; // set to 0

uniform int b; // set to 1

uniform int c; // set to 1

for (int i = a; i < b; i += c) {

  // existing code

}
```

Example transformations

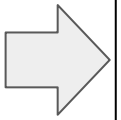
Pack scalars into vector

```
float d = 42.0;

vec2 v = vec2(1.0, 0.0)

…

d = v.x + v.y;
```



```
vec3 d_v = vec3(42.0, 1.0, 0.0);



…

d_v.x = d_v.y + d_v.z;
```

Example transformations

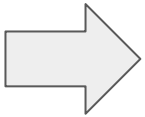
Add **barrier synchronization** in **compute shaders**

```
for (int i = 0; i < 10; i++) {

    // do something

    // do some more

}
```



```
for (int i = 0; i < 10; i++) {

    // do something

    barrier();

    // do some more

}
```

Example transformations

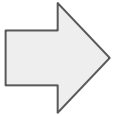
Do not add barriers where control flow is **divergent**

```
for (int i = 0;
     i < gl_GlobalInvocationID.x;
     i++) {

   // do something

   // do some more

}
```



```
for (int i = 0;
     i < gl_GlobalInvocationID.x;
     i++) {

   // do something

   barrier(); // illegal

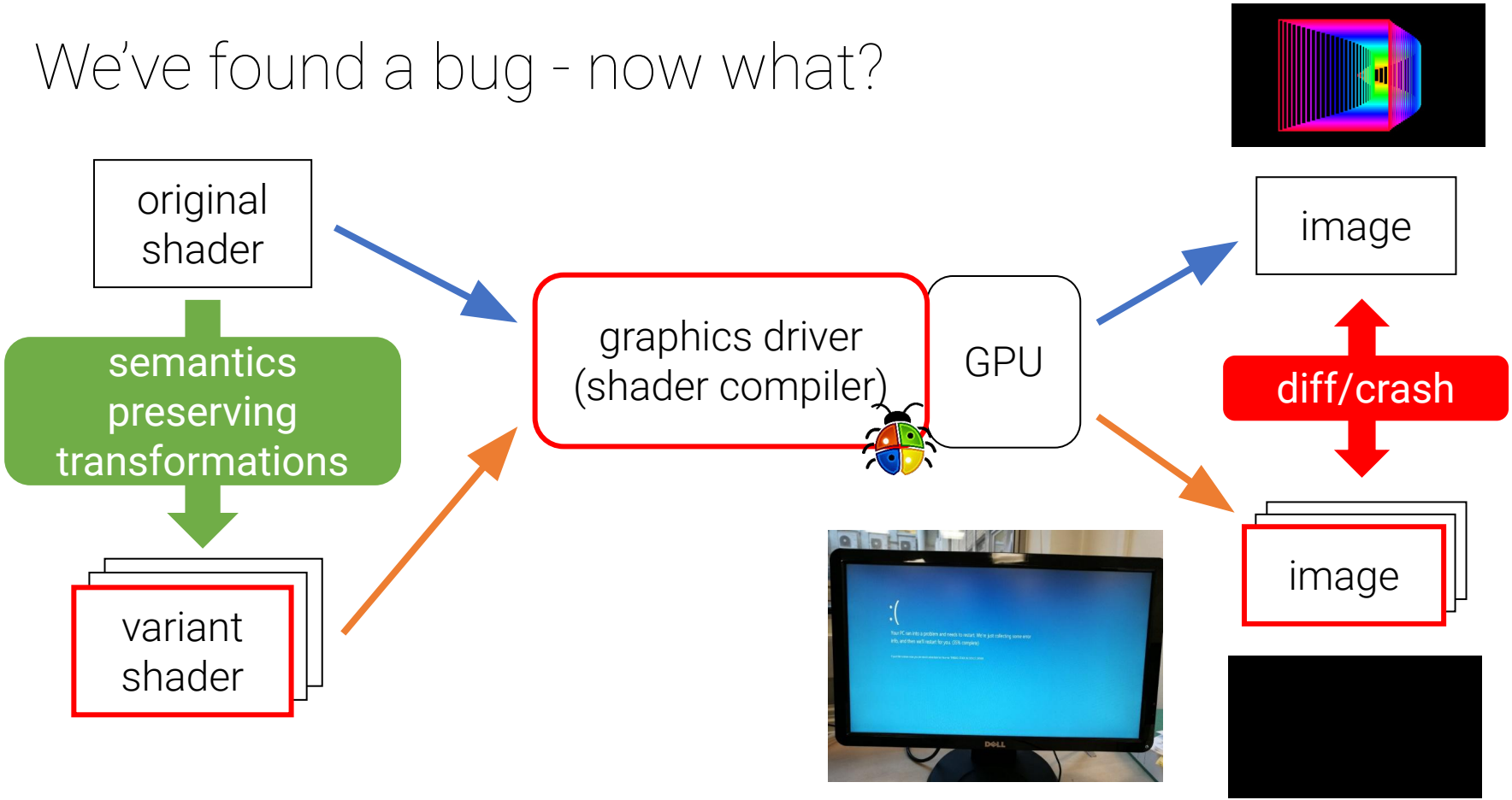
   // do some more

}
```

Concurrency and determinism

- Our metamorphic testing approach requires shaders to have *deterministic output*
- Concurrency is acceptable as long as the end result is unique
- Transformations must respect this

We've found a bug - now what?

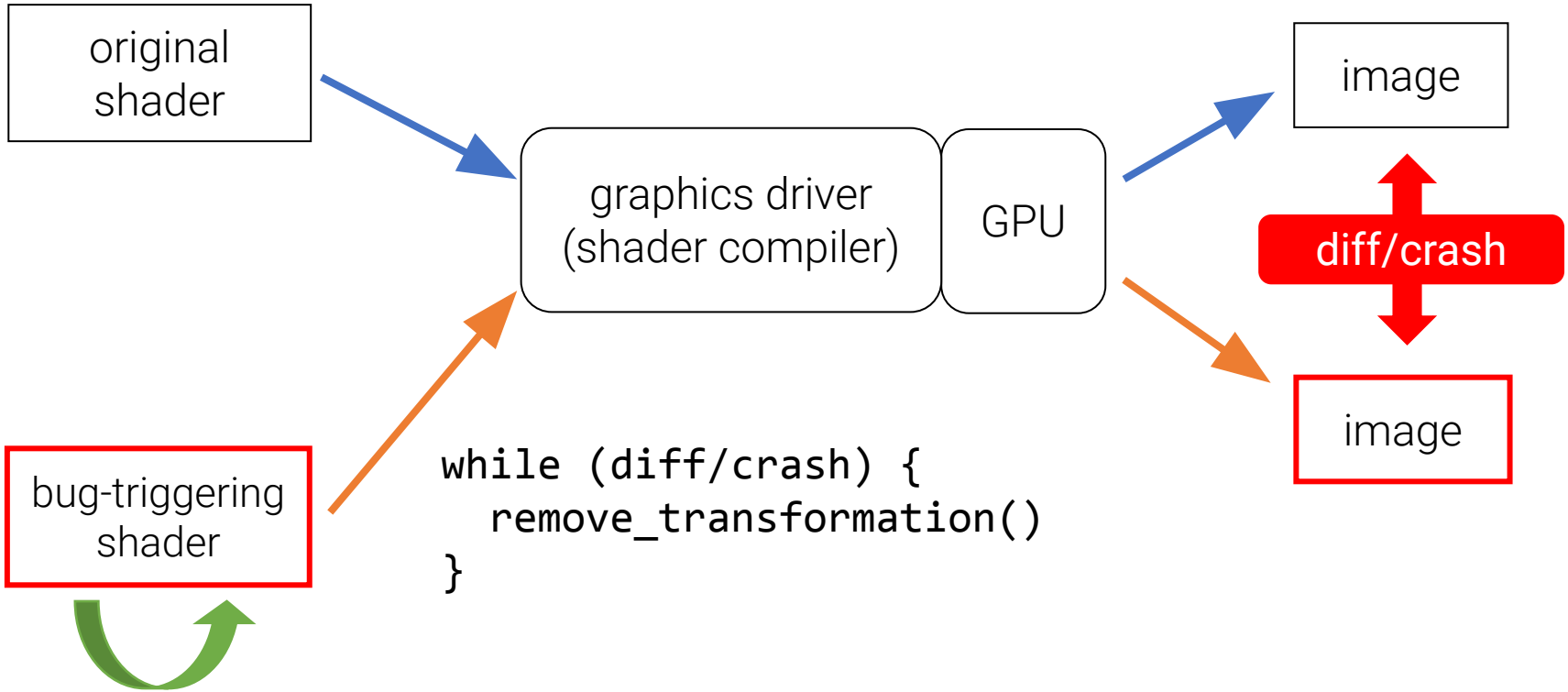


Useful?

“Trust me: there’s a bug in your GPU compiler. Good luck!”

```
void main(void)
{
    vec2 uv = (gl_FragCoord.xy / resolution.xy) * 2.0 - 1.0;
    uv.x *= resolution.x / resolution.y;
    if(_GLF_DEAD(_GLF_FALSE(false, (injectionSwitch.x > injectionSwitch.y))))
        return;
    vec3 finalColor = RenderScene(uv);
    if(_GLF_DEAD(_GLF_IDENTITY(false, (false) || false)))
        {
            vec3 donor_replacementp = _GLF_FUZZED(faceforward(((++ finalColor) - faceforward(vec3(4.8, 7582.5251,
-3.4), vec3(-369.491, -9.0, 6172.7474), finalColor)), vec3(6108.1119, -181.078, 495.885), (finalColor).yzx));
            float donor_replacementtw = _GLF_FUZZED(sign(dot((EPS / vec3(53.44, 6.0, -752.725)), fract(finalColor))))
            float donor_replacementstrength = _GLF_FUZZED(38.04);
            float donor_replacementprev = _GLF_FUZZED(clamp((+ distance(time, -47.91)), (-- finalColor.g), (mouse /
EPS)[1]));
            if(_GLF_DEAD(_GLF_FALSE(false, (injectionSwitch.x > injectionSwitch.y))))
                return;
            float donor_replacementaccum = _GLF_FUZZED(distance(vec2(-349.170, -4419.3875), (- vec4(-359.006, 69.29,
-96.95, -243.116)).wz));
            if(_GLF_DEAD(_GLF_IDENTITY(false, (false ? _GLF_FUZZED((-28449 < shadowType)) : false))))
                return;
            for(
                int i = 0;
                i < 16;
```

Test-case reduction



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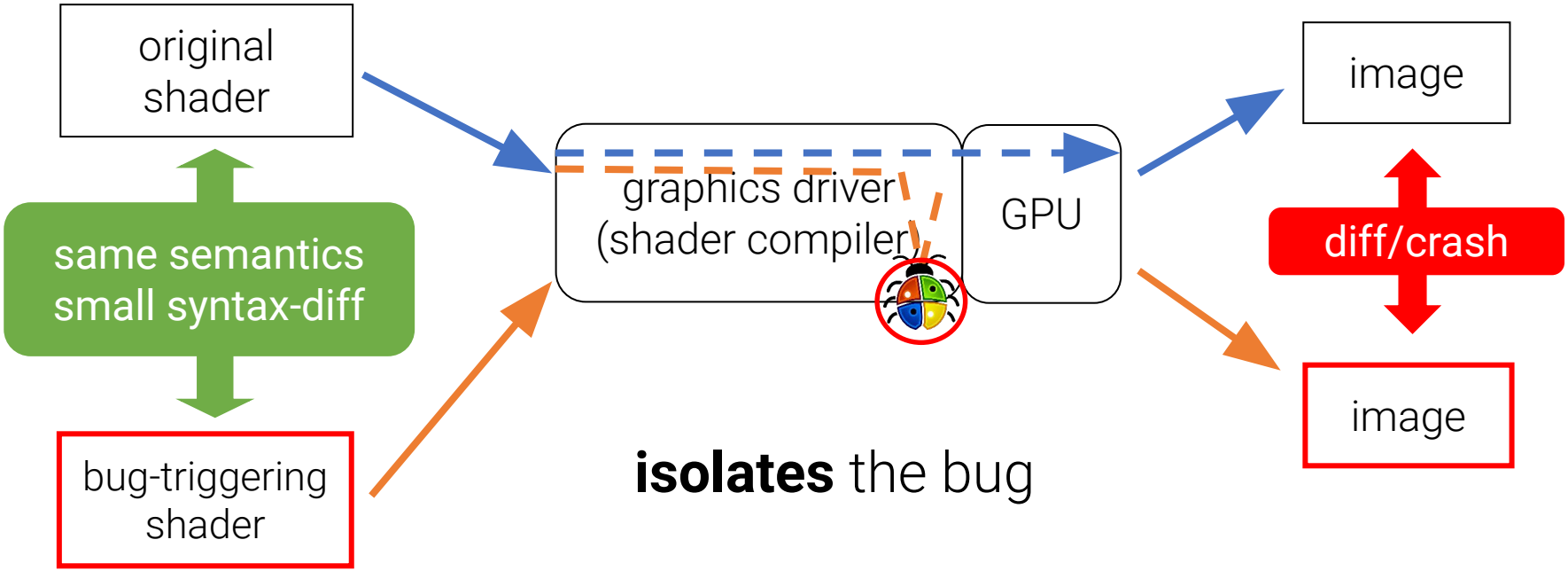
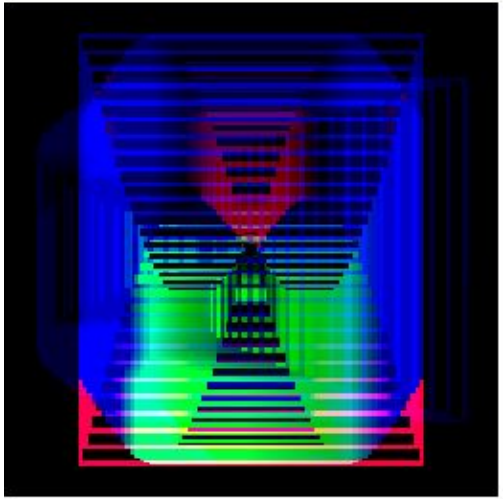
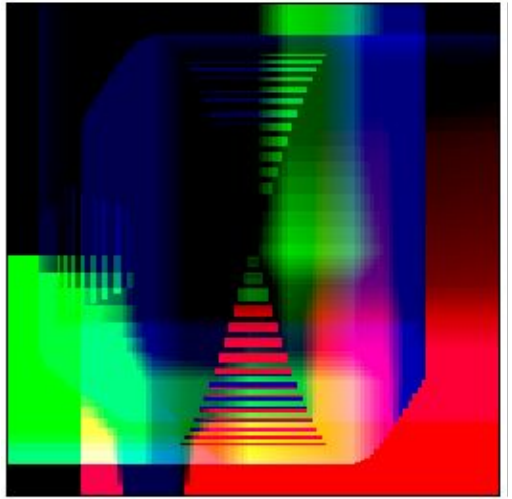


isolates the bug

A **wrong image** compiler bug



Original



Variant

Diff:

```
-   return defaultColor();
+   switch(0)
+   {
+     case 0:
+     return defaultColor();
+     break;
+   }
```

A **crash** compiler bug

```
precision highp float;

void main() {
  vec2 a = vec2(1.0);
  vec4 b = vec4(1.0);
  // Crash:
  pow(vec4(a, vec2(1.0)), b);
}
```

A **crash** compiler bug

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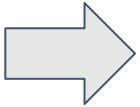


```
SIGSEGV

#00 pc 01e214  /vendor/compiler.so (LLVMGen::genPow(Operand*, Operand*))
...
```

Another **crash** compiler bug

```
precision highp float;

vec3 GLF_live6mand() {
 return mix(
  uintBitsToFloat(uvec3(38730u, 63193u, 63173u)),
  floor(vec3(463.499, 4.7, 0.7)),
  vec3(1.0) + vec3(1.0)
 );
}
void main() {
 GLF_live6mand();
 _GLF_color = vec4(1.0, 0.0, 0.0, 1.0);
}
```

```
ASSERTION FAILURE

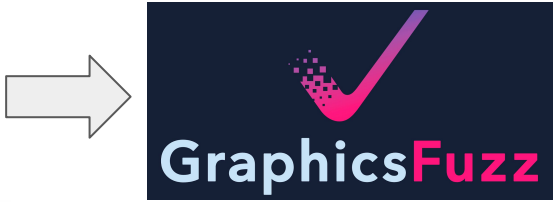
amdllpc: external/llvm/lib/Support/APFloat.cpp:1521:

llvm::lostFraction llvm::detail::IEEEFloat::
addOrSubtractSignificand(const llvm::detail::IEEEFloat &, bool):

Assertion `!carry' failed.
```

GraphicsFuzz: secure and reliable graphics drivers

Imperial College London



https://github.com/google/graphicsfuzz

When we joined Google...

The **Vulkan** API is the future of graphics

Our goal: use GraphicsFuzz to improve Vulkan shader compilers

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Problem:

- GraphicsFuzz was designed for OpenGL, not Vulkan!

Testing Vulkan compilers via OpenGL

GLSL: the OpenGL shading language

SPIR-V: the Vulkan shading language

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glslang: compiles GLSL into SPIR-V

Gets us into Vulkan world

Testing Vulkan compilers via OpenGL

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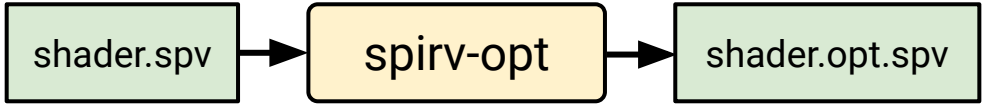
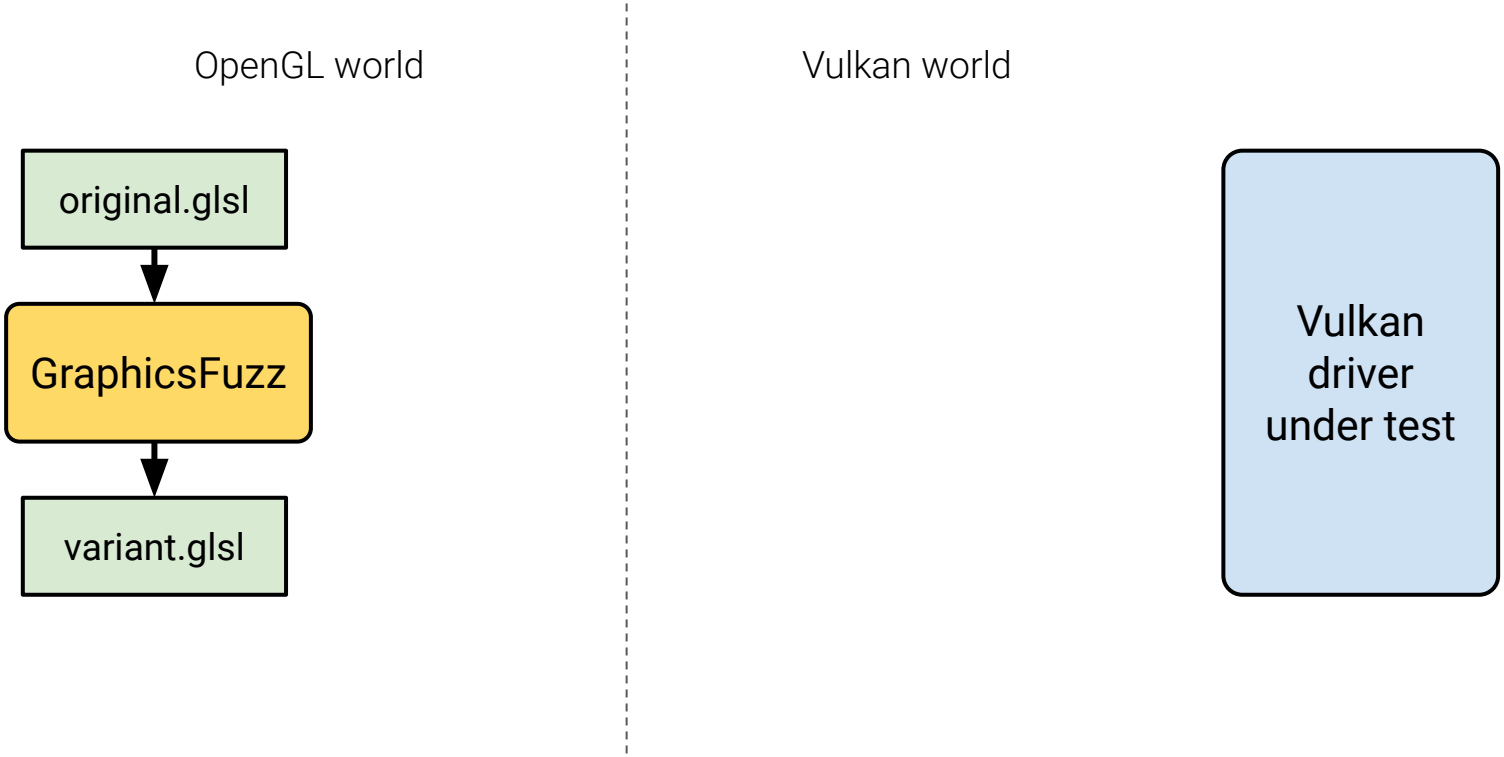
Gets us into Vulkan world

spirv-opt: source-to-source SPIR-V optimizer



Makes Vulkan world more interesting!

Testing Vulkan from OpenGL



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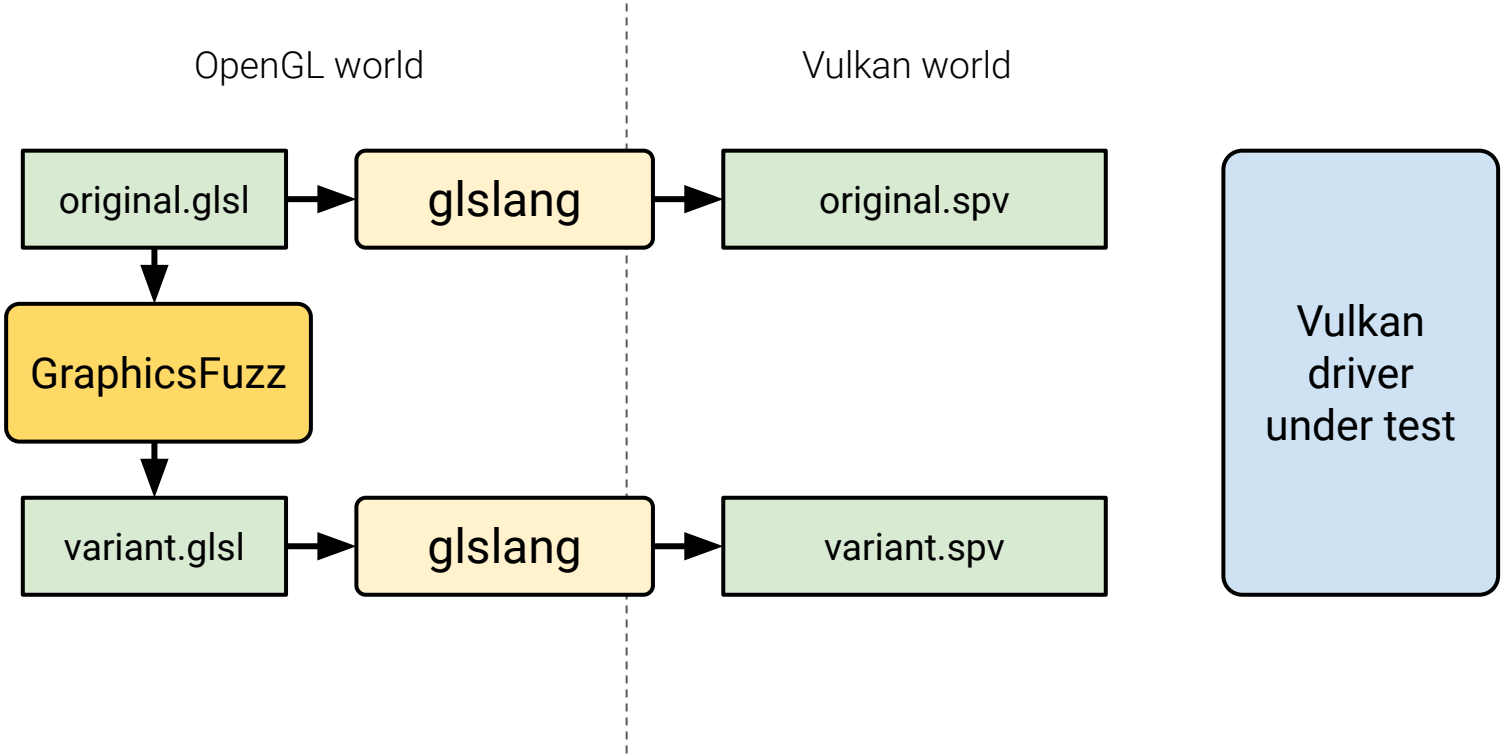

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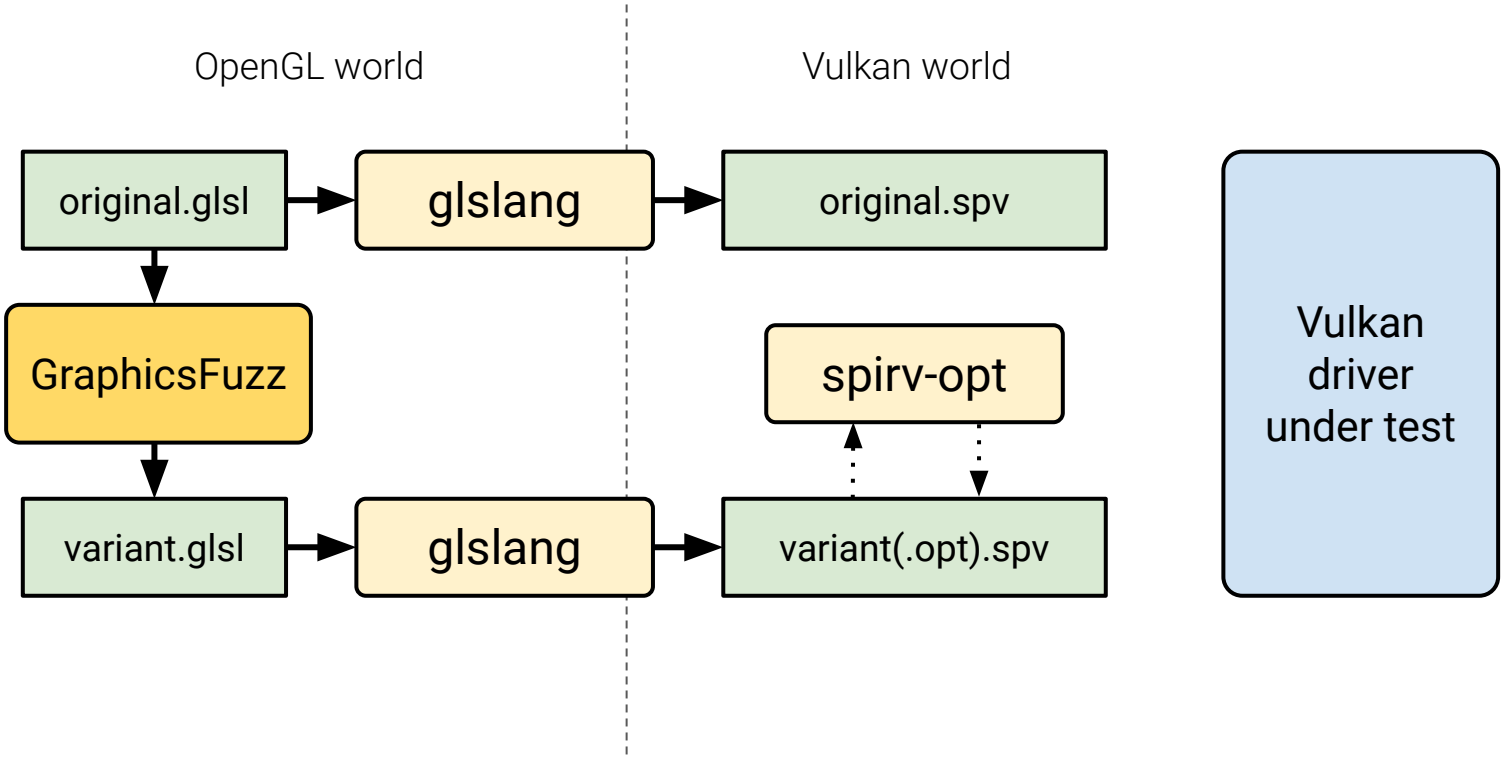

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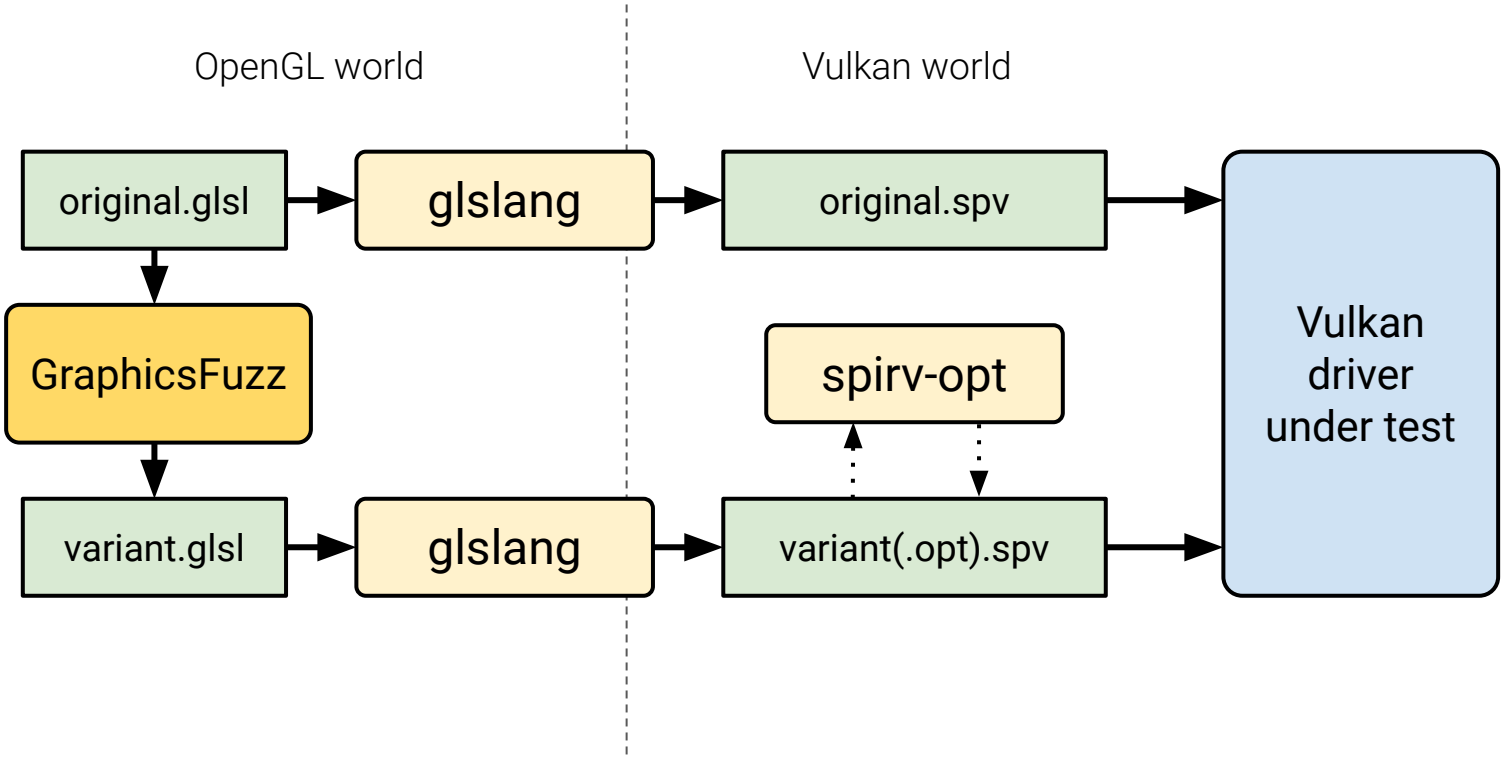

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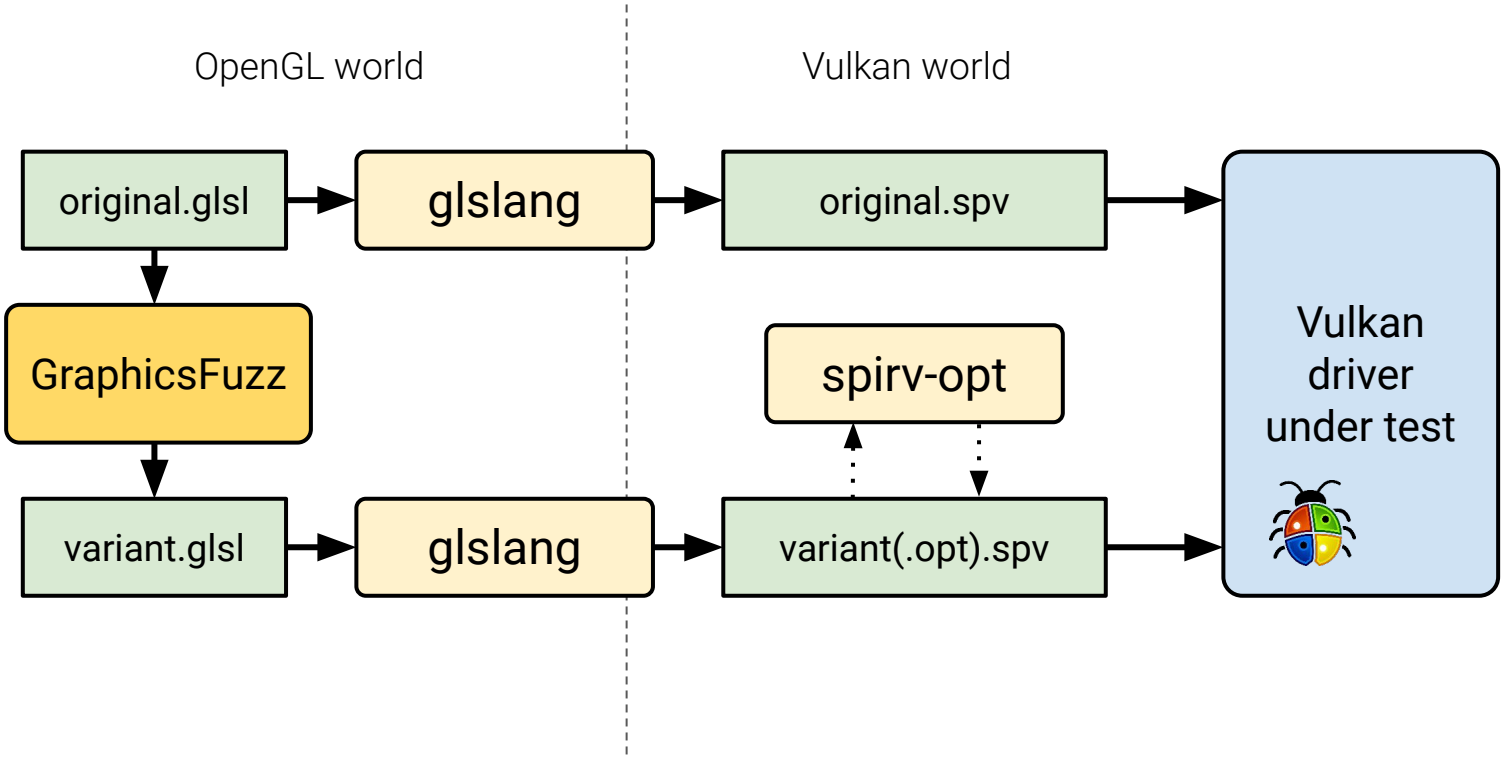

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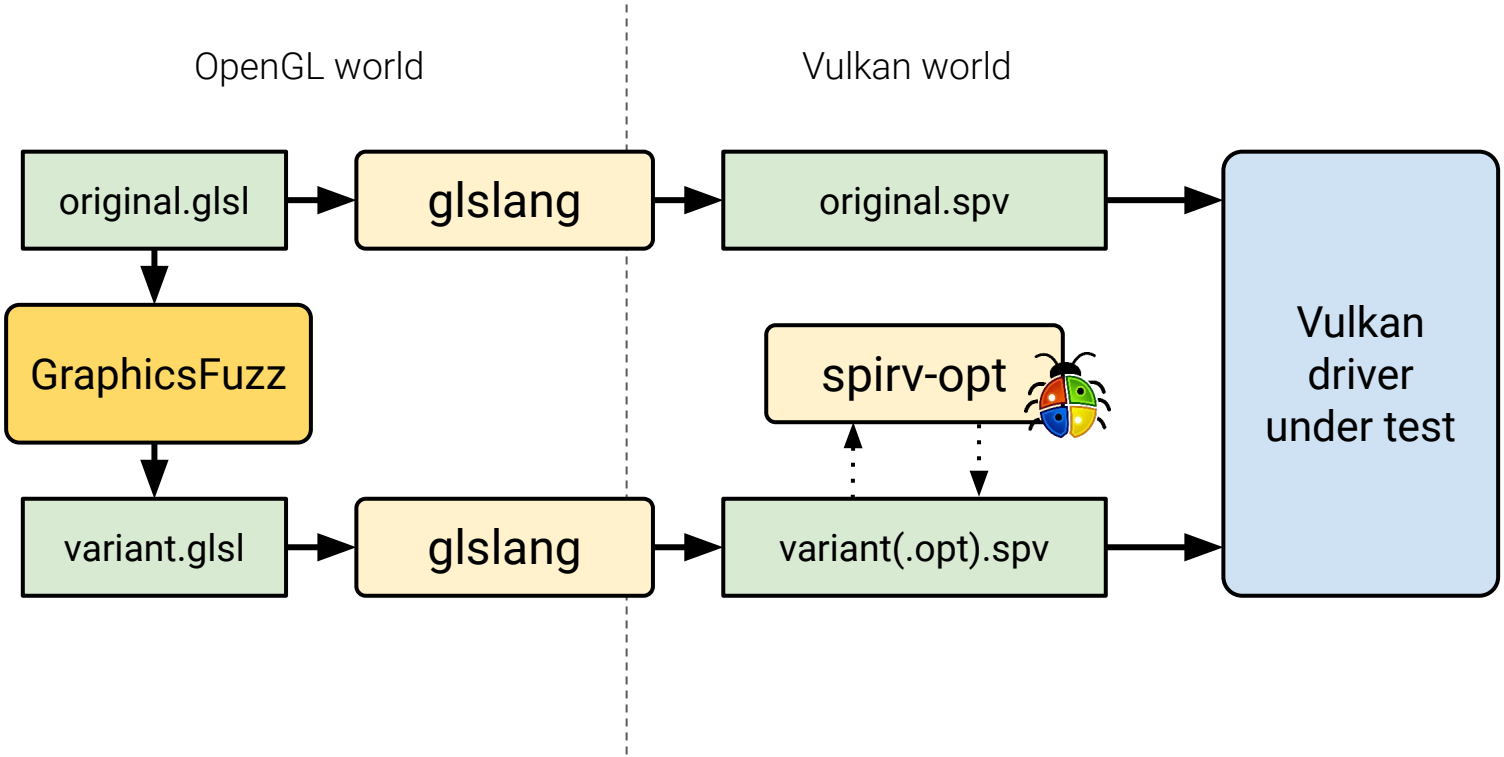

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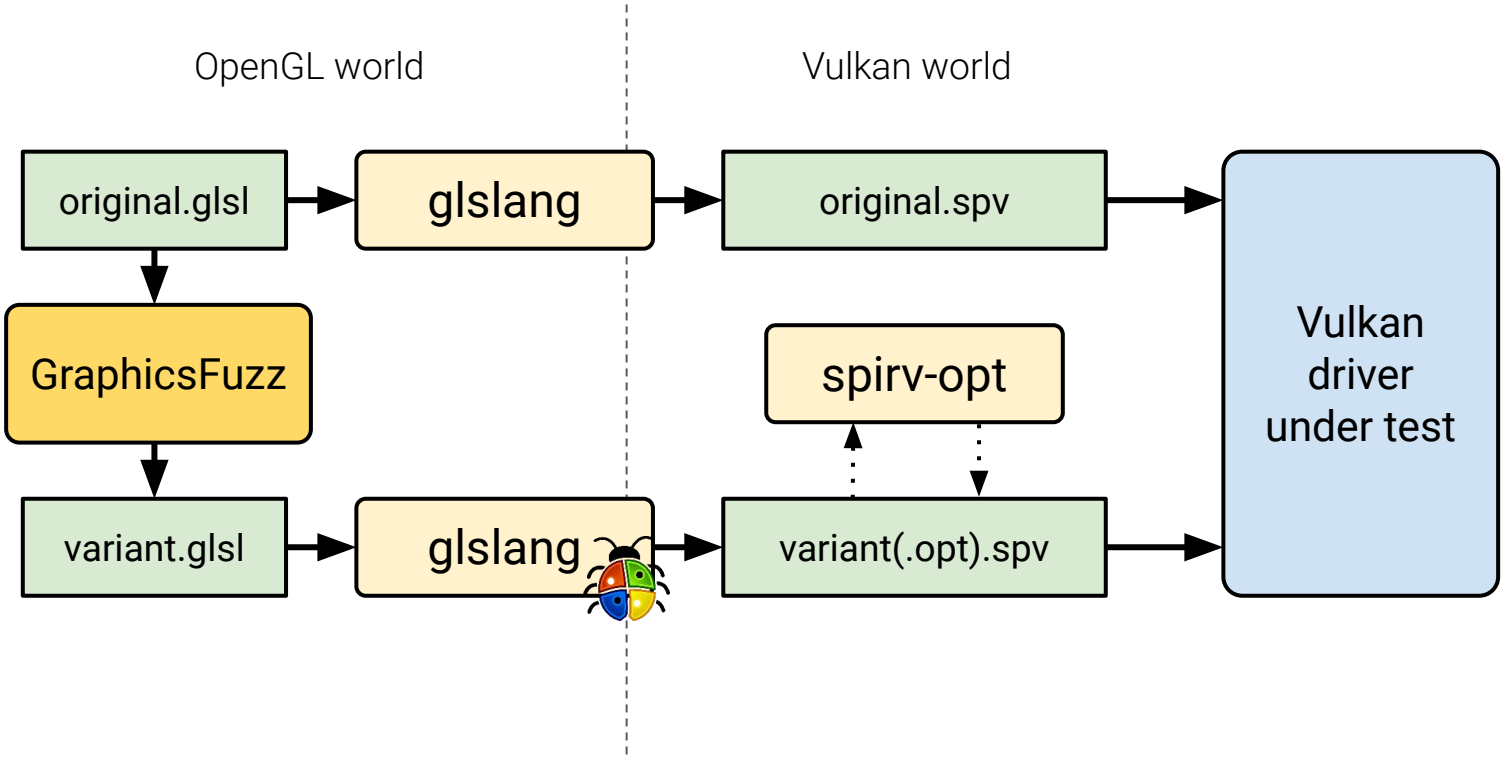

Where Should Bug Reports Go?

Report to developer?

Limited value:

- Might not get fixed at all
- Fix might not propagate to end user devices
- No value to the rest of the ecosystem

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Add to Vulkan Conformance Test Suite?

High value:

- All GPU makers run this daily
- Devices must pass CTS -> bug fixed for all future devices
- Contributes bug-inducing test to everyone

Vulkan Conformance Test Suite (CTS)

Search or jump to… / Pull requests Issues Trending Explore

KhronosGroup / **VK-GL-CTS** Watch Star 312 Fork

Code Issues 21 Pull requests 4 Actions Wiki Releases 64 ···

master **22** branches **64** tags

alegal-arm Update vk.xml revision ··· 483a71c 7 days ago **16,719** commits

.github	Add CONTRIBUTING.md for Github	3 years ago
android	Add cube compat. to array image copy tests	7 days ago
data	Add const matrix multiply test	2 years ago
doc	Add support for properly styling SPIR-V sources from …	7 months ago

About

Khronos Vulkan, OpenGL, and OpenGL ES Conformance Tests

www.khronos.org/

opengl-es vulkan opengl opengl-es-cts vulkan-cts opengl-cts

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Test outcome cannot depend on **undefined** or **implementation-defined** behaviour

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Test outcome cannot depend on **undefined** or **implementation-defined** behaviour

Worst-case scenario: an invalid test gets admitted to CTS

Challenging undefined behaviours

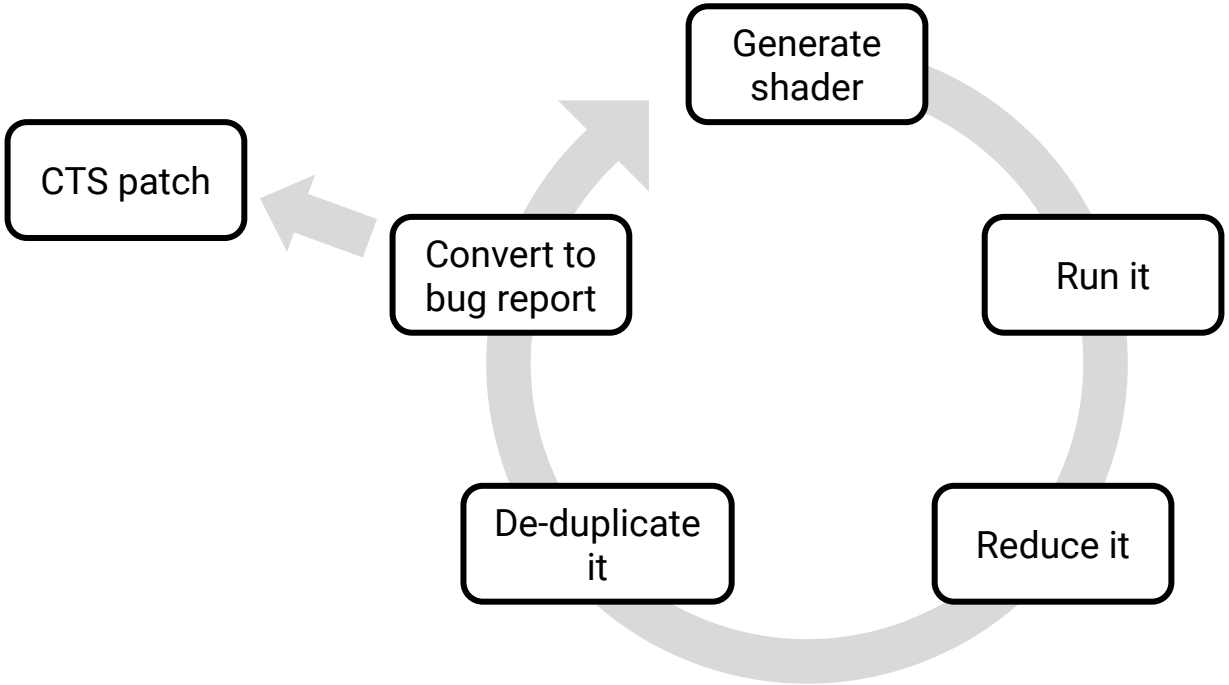
- Infinite loops
- Out-of-bounds accesses
- Uninitialized accesses

Challenging implementation-defined behaviour

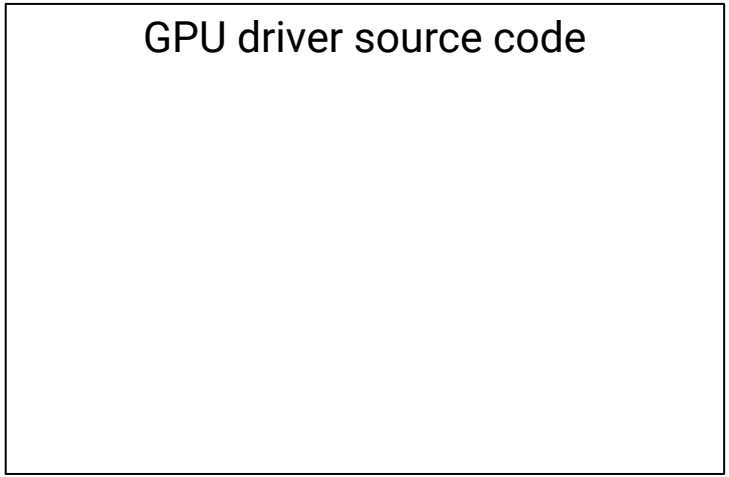
- Floating-point precision

Safeguards against these discussed in ECOOP 2020 paper

GraphicsFuzz → CTS workflow



Beyond Bugs: Differential Code Coverage



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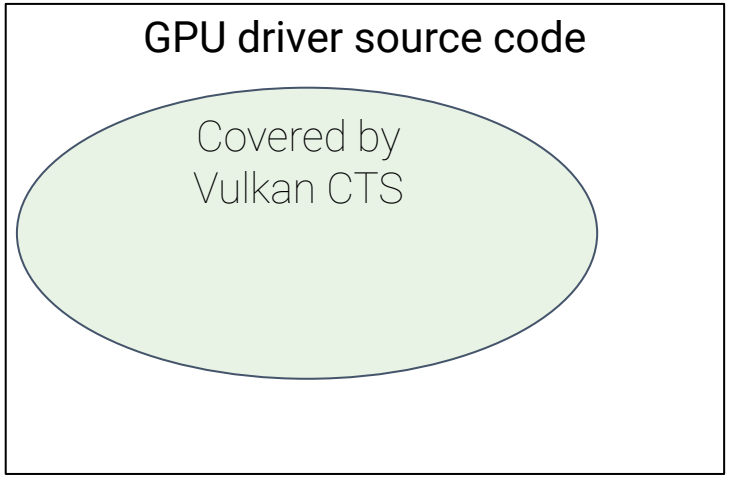

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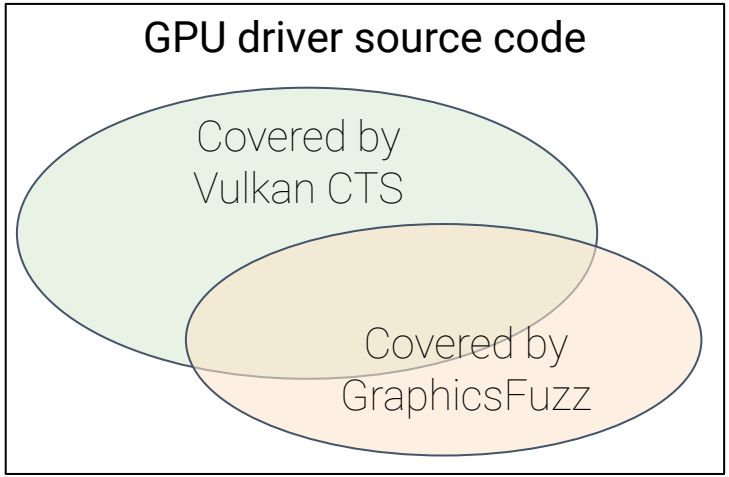

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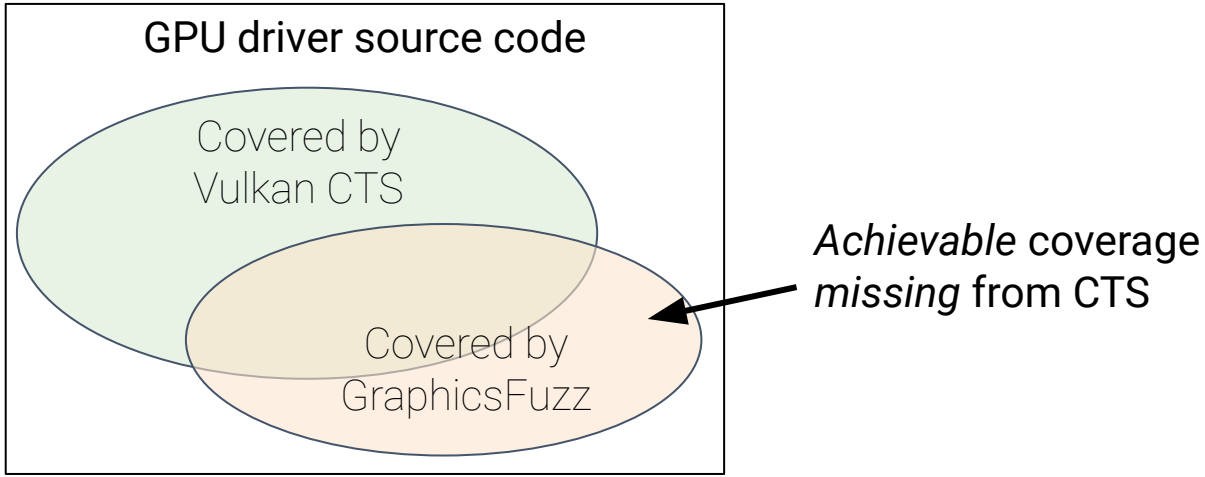
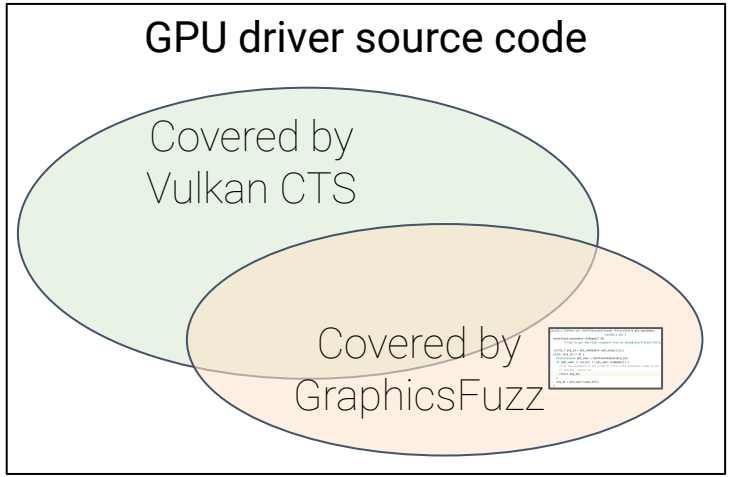


Using Reduction to Synthesise High Coverage Tests



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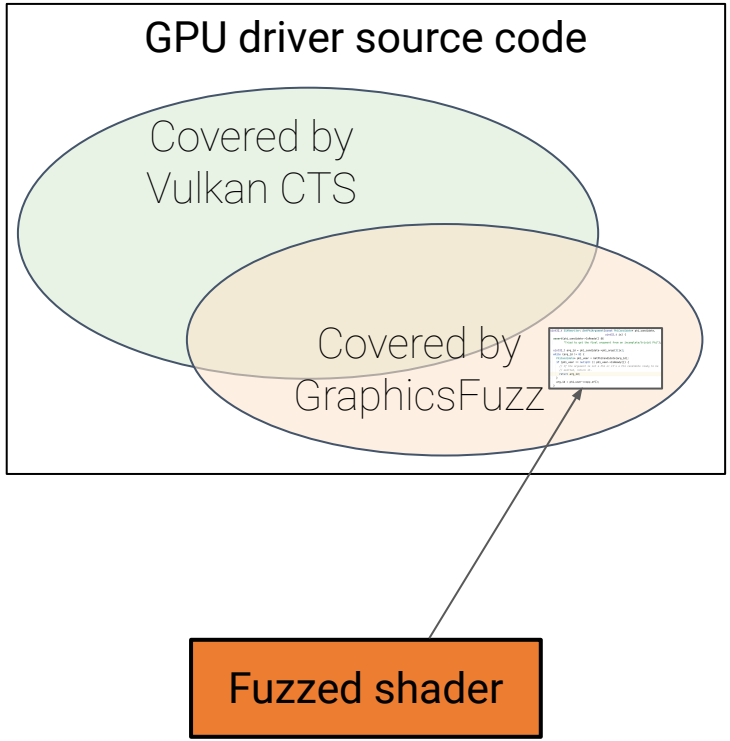

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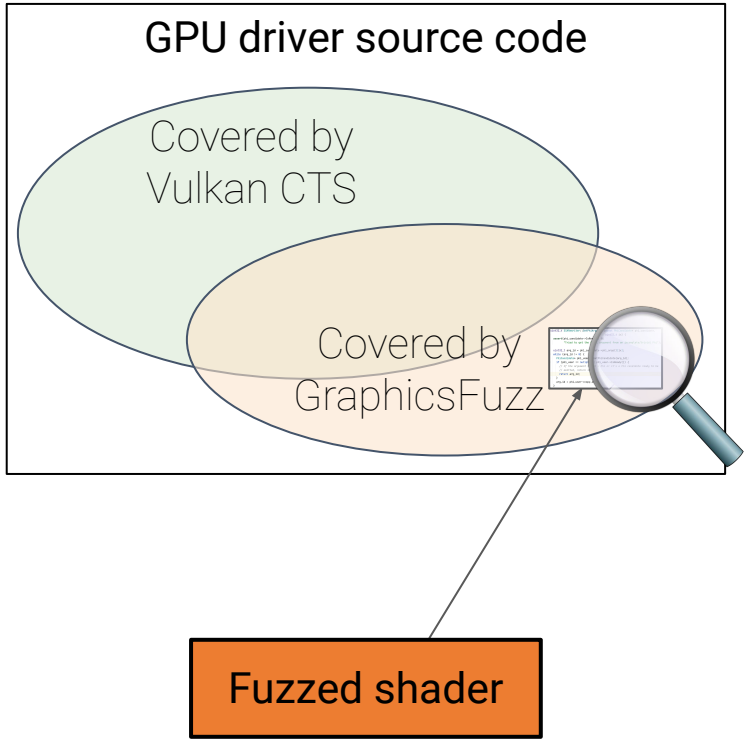

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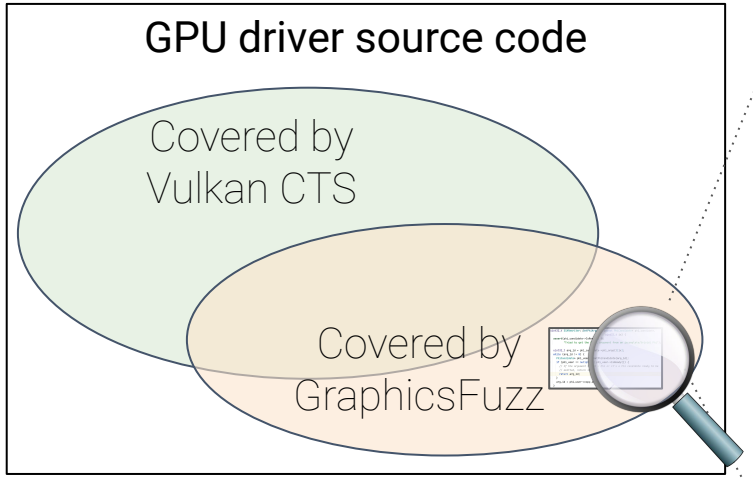
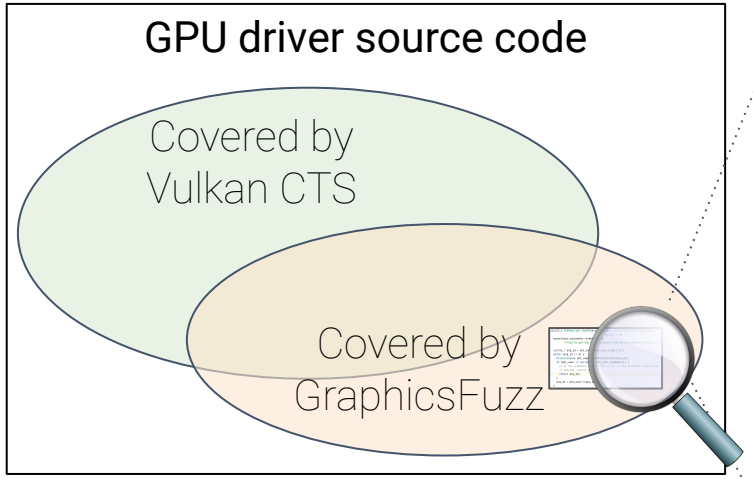



```
uint32_t SSARewriter::GetPhiArgument(const PhiCandidate* phi_candidate,
                                     uint32_t ix) {
  assert(phi_candidate->IsReady() &&
         "Tried to get the final argument from an incomplete/trivial Phi");

  uint32_t arg_id = phi_candidate->phi_args()[ix];
  while (arg_id != 0) {
    PhiCandidate* phi_user = GetPhiCandidate(arg_id);
    if (phi_user == nullptr || phi_user->IsReady()) {
      // If the argument is not a Phi or it's a Phi candidate ready to be
      // emitted, return it.
      return arg_id;
    }
    arg_id = phi_user->copy_of();
  }
```

Fuzzed shader

Using Reduction to Synthesise High Coverage Tests

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    if (phi_user == nullptr || phi_user->IsReady()) {
      // If the argument is not a Phi or it's a Phi candidate ready to be
      // emitted, return it.
      assert (false && "GraphicsFuzz COVERAGE");
      return arg_id;
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Fuzzed shader

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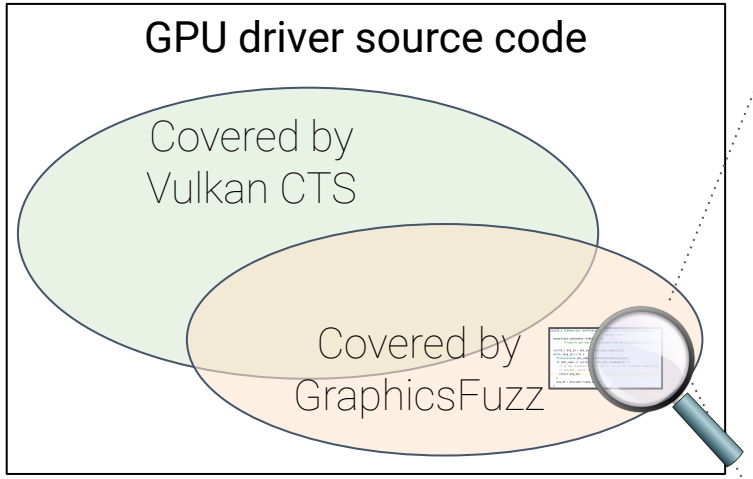


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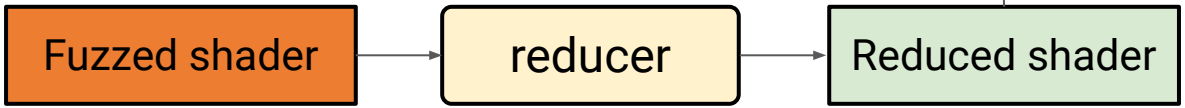
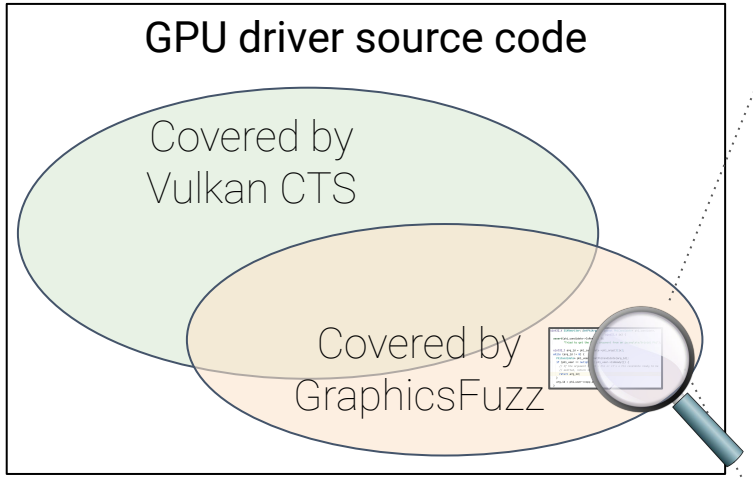
    PhiCandidate* phi_user = GetPhiCandidate(arg_id);
    if (phi_user == nullptr || phi_user->IsReady()) {
      // If the argument is not a Phi or it's a Phi candidate ready to be
      // emitted, return it.
      assert (false && "GraphicsFuzz COVERAGE");
      return arg_id;
    }
    arg_id = phi_user->copy_of();
  }
```



A form of *cause reduction* (Groce et al., ICST'14)

Using Reduction to Synthesise High Coverage Tests




```
uint32_t SSARewriter::GetPhiArgument(const PhiCandidate* phi_candidate,
                                     uint32_t ix) {
  assert(phi_candidate->IsReady() &&
         "Tried to get the final argument from an incomplete/trivial Phi");

  uint32_t arg_id = phi_candidate->phi_args()[ix];
  while (arg_id != 0) {
    PhiCandidate* phi_user = GetPhiCandidate(arg_id);
    if (phi_user == nullptr || phi_user->IsReady()) {
      // If the argument is not a Phi or it's a Phi candidate ready to be
      // emitted, return it.
      return arg_id;
    }
    arg_id = phi_user->copy_of();
  }
```

Reduced shader

A small shader that obtains the extra coverage!

Manually improve oracle then submit to Vulkan CTS

Improving the Oracle

Automatically-reduced test that increases coverage

```
void main() {

  dot(vec2(1.0, 0.0), vec2(0.0))

}
```

Manually edited test with stronger oracle

```
void main() {
 if(dot(vec2(1.0, 0.0), vec2(0.0)) == 0.0) // precise check
     _GLF_color = RED;  // we expect red
 else
     _GLF_color = BLACK;
}
```

Impact of GraphicsFuzz on CTS so far

442 tests added

- 178 bug tests
- 264 coverage tests

master VK-GL-CTS / external / vulkancts / data / vulkan / amber / **graphicsfuzz** / Add

afd and **alegal-arm** Add a batch of GraphicsFuzz tests ··· 248a497 14 day

..

access-new-vector-inside-if-condition.amber	dEQP-VK.graphicsfuzz.access-new-vector-inside-if-condition
always-discarding-function.amber	dEQP-VK.graphicsfuzz.always-discarding-function
always-false-if-in-do-while.amber	Fix invalid SPIR-V in GraphicsFuzz tests
always-false-if-with-discard-return.amber	dEQP-VK.graphicsfuzz.always-false-if-with-discard-return
arr-value-set-to-arr-value-squared.amber	dEQP-VK.graphicsfuzz.arr-value-set-to-arr-value-squared
array-idx-multiplied-by-for-loop-idx.amber	Add a batch of GraphicsFuzz tests
assign-array-value-to-another-array-2.amber	Add a batch of GraphicsFuzz tests
assign-array-value-to-another-array.amber	Add a batch of GraphicsFuzz tests
barrier-in-loop-with-break.amber	dEQP-VK.graphicsfuzz.barrier-in-loop-with-break
break-in-do-while-with-nested-if.amber	dEQP-VK.graphicsfuzz.break-in-do-while-with-nested-if

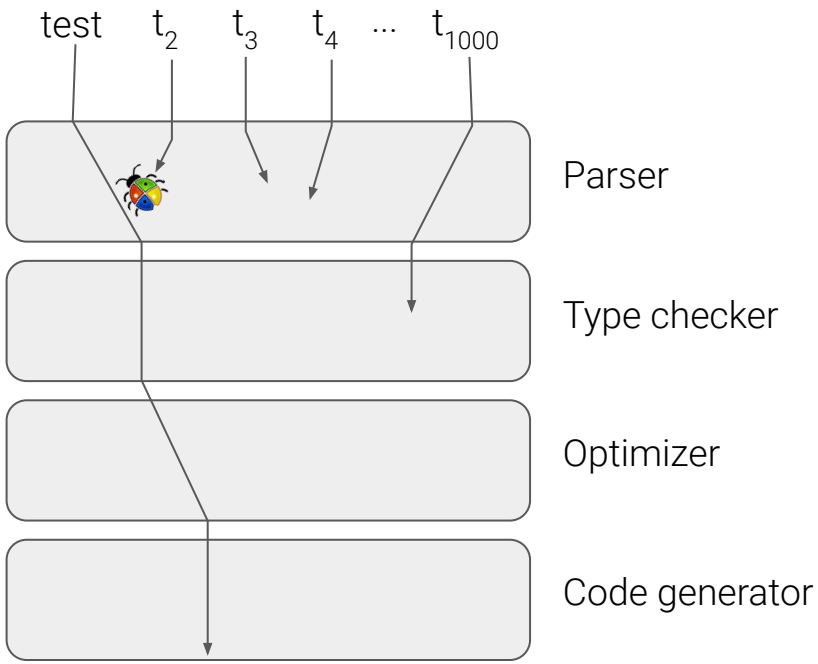
Metamorphic testing for finding vulnerabilities

- Chrome web browser: billions of users -> lots of **attackers**
- **ClusterFuzz**: continuous fuzzing of Chrome
- WebGL vulnerabilities are thus a concern
- Chrome security **do not** care about wrong images (not exploitable!)

How does metamorphic testing help?

Mutation-based fuzzing (AFL)

- Most mutated inputs: **invalid**
- Great for finding vulnerabilities in parsers
- Parsers are a first point of attack
- Not good for finding bugs deeper in system under test

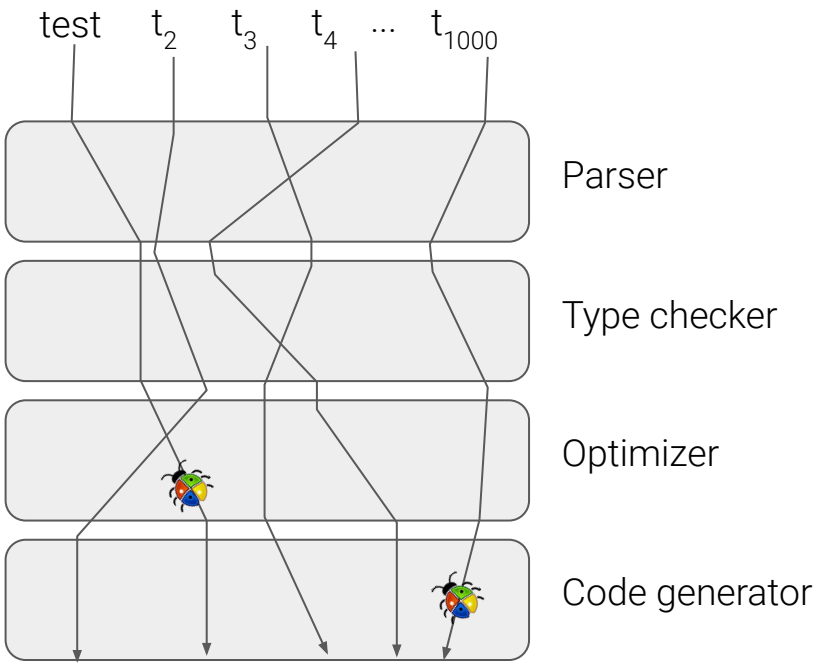


Layered SUT, e.g. a compiler

Metamorphic testing

- Original valid => variants valid
- Finds **deep** vulnerabilities
- Does not find bugs triggered by malformed inputs

Metamorphic testing conveniently produces well-formed inputs



Layered SUT, e.g. a compiler

GraphicsFuzz + ClusterFuzz finds WebGL vulnerabilities

Issue 912508: Heap-buffer-overflow in sh::SetUnionArrayFromMatrix

Code

Reported by ClusterFuzz on Thu, Dec 6, 2018, 6:06 AM EST

Detailed report: https://clusterfuzz.com/testcase?key=5177583668559872

Fuzzer: metzman_graphicsfuzz_crash_fuzzer
Job Type: linux_asan_chrome_mp
Platform Id: linux

Crash Type: Heap-buffer-overflow WRITE 4
Crash Address: 0x6250005fc100
Crash State:
  sh::SetUnionArrayFromMatrix
  sh::TIntermConstantUnion::FoldAggregateBuiltIn
  sh::TIntermAggregate::fold

Sanitizer: address (ASAN)

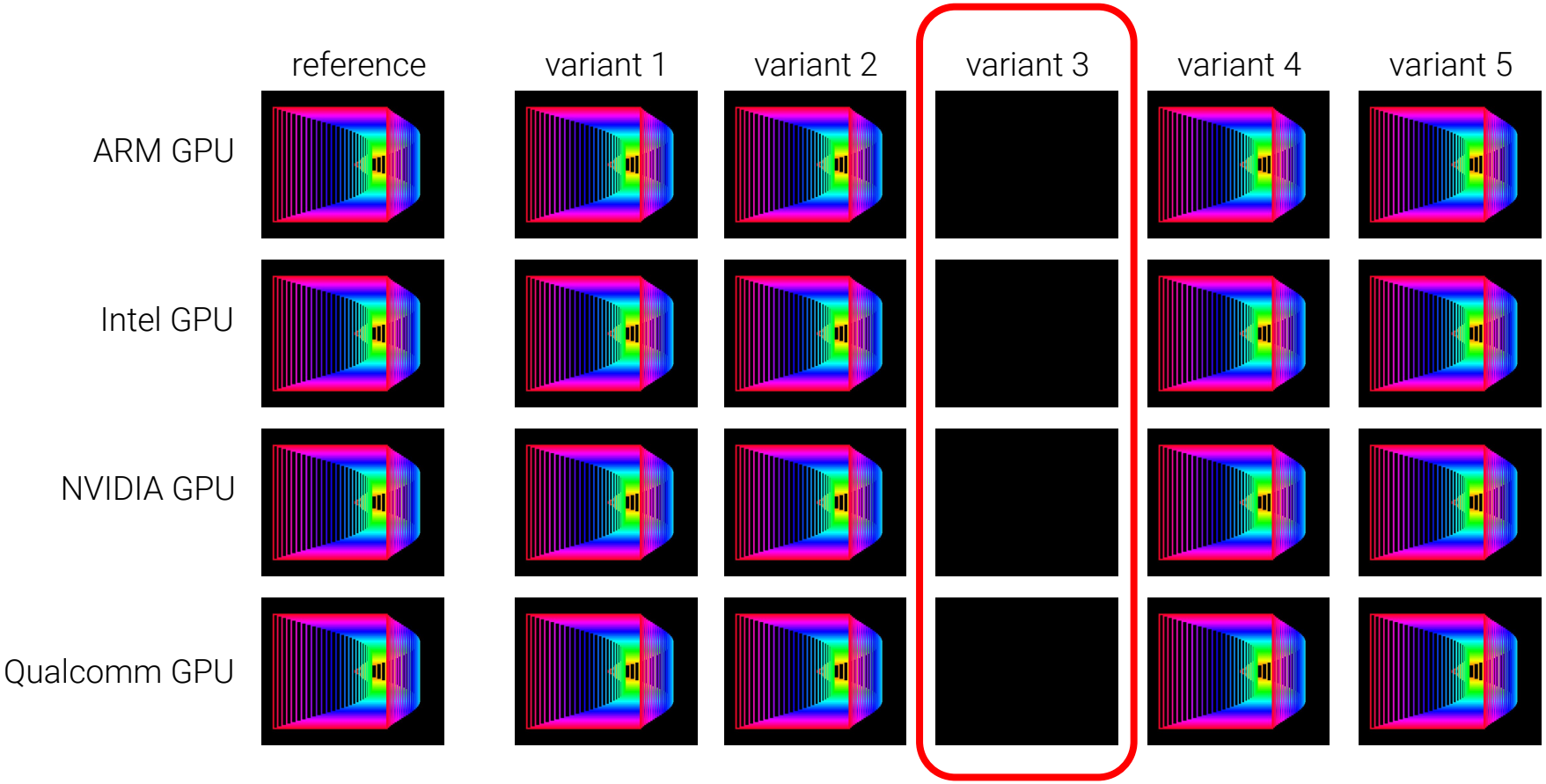
Recommended Security Severity: High

The metamorphic approach complements mutation-based fuzzing

Metamorphic + coverage-guided would be nice to try!

GraphicsFuzz tests itself!

Bug in GraphicsFuzz



Summary and Ongoing Work

- GraphicsFuzz finds bugs in shader compilers
- Cross-compilation allows us to target Vulkan
- On finding bugs we contribute **conformance tests**
- Differential coverage + test case reduction allows us to find and fill conformance test suite **coverage gaps**
- Metamorphic testing complements mutation-based fuzzing for finding **vulnerabilities**

Current work: direct fuzzing techniques for Vulkan shader compilers

Summary and Ongoing Work

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Current work: direct fuzzing for SPIR-V, and the WebGPU shading language

Thank you! Questions?