Security of ZKP projects: same but different

JP Aumasson
@veorq

CSO @ taurushq.com

Should you pay for security audits?

JP Aumasson
@veorq

CSO @ taurushq.com

This talk

My 2 cents on how to **optimize the RoI of "security audits"** of zkSNARKs

~10 years doing crypto audits, and more recently projects involving

- **Groth16**, the foundation of real-world zkSNARKs
- **Marlin**, a (universal) zkSNARK slightly less simple

(Most of the content applies to other systems: Plonk, SONIC, etc., and STARKs.)

Why study zkSNARKs security?

A major risk for decentralised platforms:

- Complexity + Novelty => Non-trivial **bugs**
- A lot **at stake** ($$$, user data, user privacy)

Why study zkSNARKs security?

A major risk for decentralised platforms

- Complexity + Novelty => Non-trivial **bugs**
- A lot **at stake** ($$$, user data, user privacy)

As a cryptographer since ~2005, **the most interesting** crypto I've seen:

- Intricate constructions with non-trivial components
- "Simple but complex" – non-interactive, but many moving parts
- "Multidimensional" way to reason about security
- "Real-worldness": not just papers – "code is specs"

What's zkSNARKs security? (it depends™)

Soundness, often the *highest risk* in practice:

- Invalid proofs should always be rejected – most obvious attack vector
- Forging, altering, replaying valid proofs should be impossible

What's zkSNARKs security? (it depends™)

Soundness, often the *highest risk* in practice:

- Invalid proofs should always be rejected – most obvious attack vector
- Forging, altering, replaying valid proofs should be impossible

Zero-knowledge: Proofs should not leak secret information (witness)

- In practice succinct proofs of large programs can leak only little data

What's zkSNARKs security? (it depends™)

Soundness, often the *highest risk* in practice:

- Invalid proofs should always be rejected – most obvious attack vector
- Forging, altering, replaying valid proofs should be impossible

Zero-knowledge: Proofs should not leak secret information (witness)

- In practice succinct proofs of large programs can leak only little data

Completeness, often a DoS/usability risk that may be further exploited:

- Valid proofs should always be accepted
- All programs/circuits supported should be correctly processed

Who can find bugs?

A. Developers of the code (manually or via testing)

B. Developers of other projects' code

C. External auditors of the code

D. Users of the code, accidentally 😇

E. External "attackers" 😈

Security goal: you want A|B|C to find bugs before D|E

Bug hunting challenges

Practical zkSNARKs are recent, thus auditors often have

- Limited **experience** auditing zkSNARKs
- Limited **knowledge** of the theory and of implementations' tricks
- Limited **"checklist"** of bugs and bug classes
- Limited **tooling** and methodologies
- Limited **documentation** from the projects

How to make useful work nonetheless?

New crypto, new approach

- More **collaboration** with the devs/designers (joint review sessions, Q&As, etc.)
- More **threat analysis**, to understand the application's unique/novel risks
- Practical **experience**: writing PoCs, circuits, proof systems, etc.
- Learn **previous failures**, for example from…
  - Public disclosures and exploits
  - Other audit reports
  - Issue trackers / PRs
  - Community

General workflow, and failure *examples*

Computation

↓

Circuit definition

↓

Arithmetization

↓

Non-interactive proof

↓

Integration

General workflow, and failure *examples*

Computation	The program's logic is not secure
↓ Circuit definition	The circuit is not equivalent to the program
↓ Arithmetization	The constraint system fails to enforce a constraint
↓ Non-interactive proof	Insecure choice of primitives/parameters/properties
↓ Integration	The application allows replays of previous proofs

How to break zkSNARKs? (1/2)

Break soundness, for example by exploiting

- Constraint system not effectively enforcing certain constraints
- Insecure generation or protection of private values

How to break zkSNARKs? (1/2)

Break soundness, for example by exploiting

- Constraint system not effectively enforcing certain constraints
- Insecure generation or protection of private values

Break zero-knowledge, for example by exploiting

- Private data treated as public variables
- Application-level “metadata attacks”

How to break zkSNARKs? (1/2)

Break soundness, for example by exploiting

- Constraint system not effectively enforcing certain constraints
- Insecure generation or protection of private values

Break zero-knowledge, for example by exploiting

- Private data treated as public variables
- Application-level “metadata attacks”

Break completeness, for example by exploiting

- Incorrect constraint synthesis behavior on edge cases (e.g. number of private vars)
- Gadget composition failure caused by type mismatch between gadget i/o values

How to break zkSNARKs? (2/2)

Break (off-chain) software, via any bug leading to

- Leakage of data, including via side channels (timing, oracles, etc.)
- Any form in insecure state (code execution, DoS)

Compromise the supply-chain, via

- Trusted setup's code and execution
- Build and release process integrity
- Software dependencies

How to break zkSNARKs? (2/2)

Break (off-chain) software, via any bug leading to

- Leakage of data, including via side channels (timing, oracles, etc.)
- Any form in insecure state (code execution, DoS)

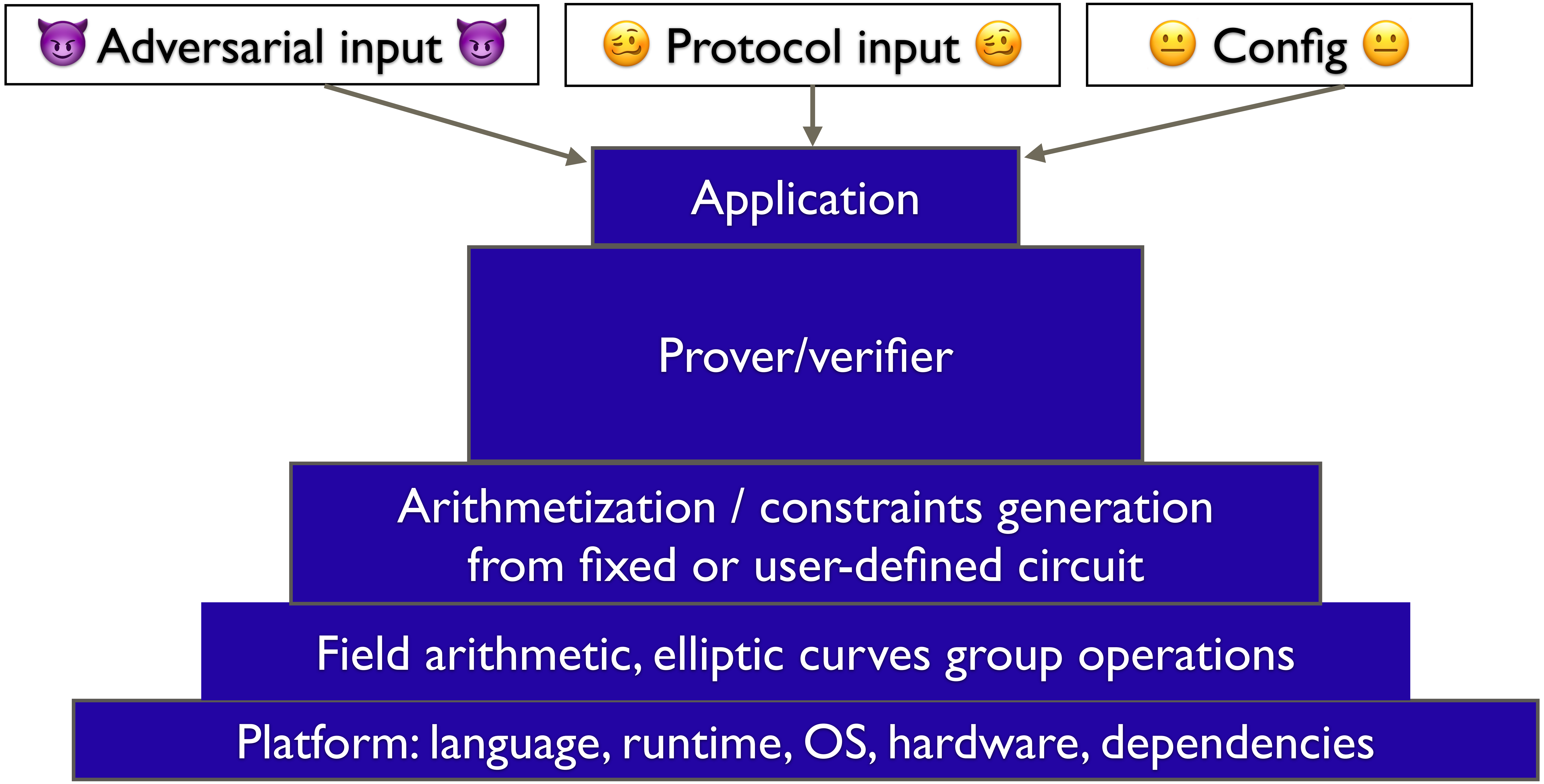
Compromise the supply-chain, via

- Trusted setup's code and execution
- Build and release process integrity
- Software dependencies

Break (on-chain) software (incl. verifier) via smart contract bugs, logic flaws, etc.

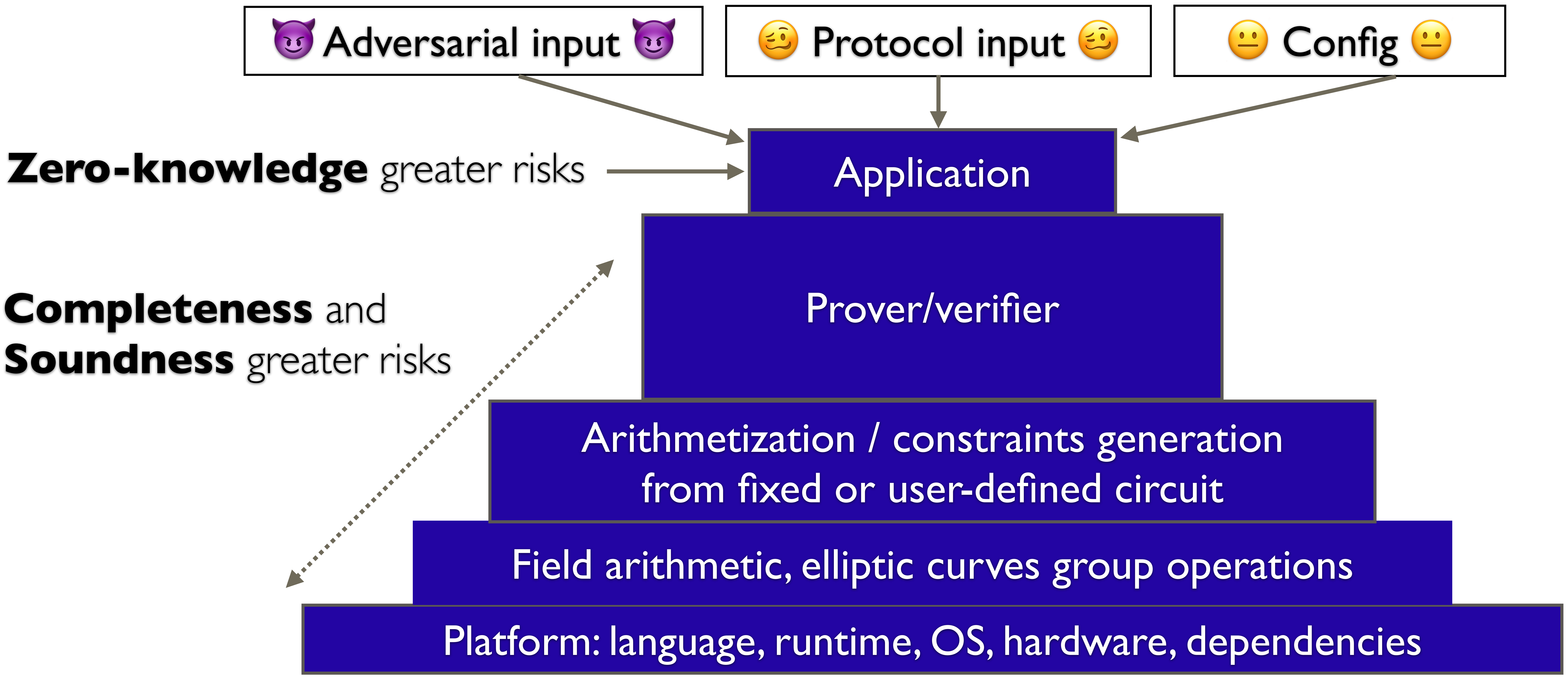
Need structure/methodology..

A failure in a **lower layer** can jeopardise the security of all upper layers



What to look for, and where?

A failure in a **lower layer** can jeopardise the security of all upper layers



Divide and conquer..

A failure in a **subcomponent** can jeopardise the security of all upper layers

Understand composability conditions..

Security 101: **Input validation** must be defined, implemented, and tested

😈 Adversarial input 😈 | 🥴 Protocol input 🥴 | 😐 Config 😐

Key management, Testing **Application** Interface, Side channels

Contracts between components must be defined to prevent **insecure composition**

Example: which component is responsible for **group membership** checks?

Elliptic curves, Pairings, Hash functions, PRF, Algebraic commitment
Randomness, Merkle trees **Prover/verifier** Linear algebra, Multi-exp.
Polynomial commitments, Fiat-Shamir transforms, etc. etc.

Real-word crypto bugs..

Soundness – Field arithmetic (1/n)

Vulnerability allowing double spend #16

Closed poma opened this issue on 26 Jul 2019 · 2 comments

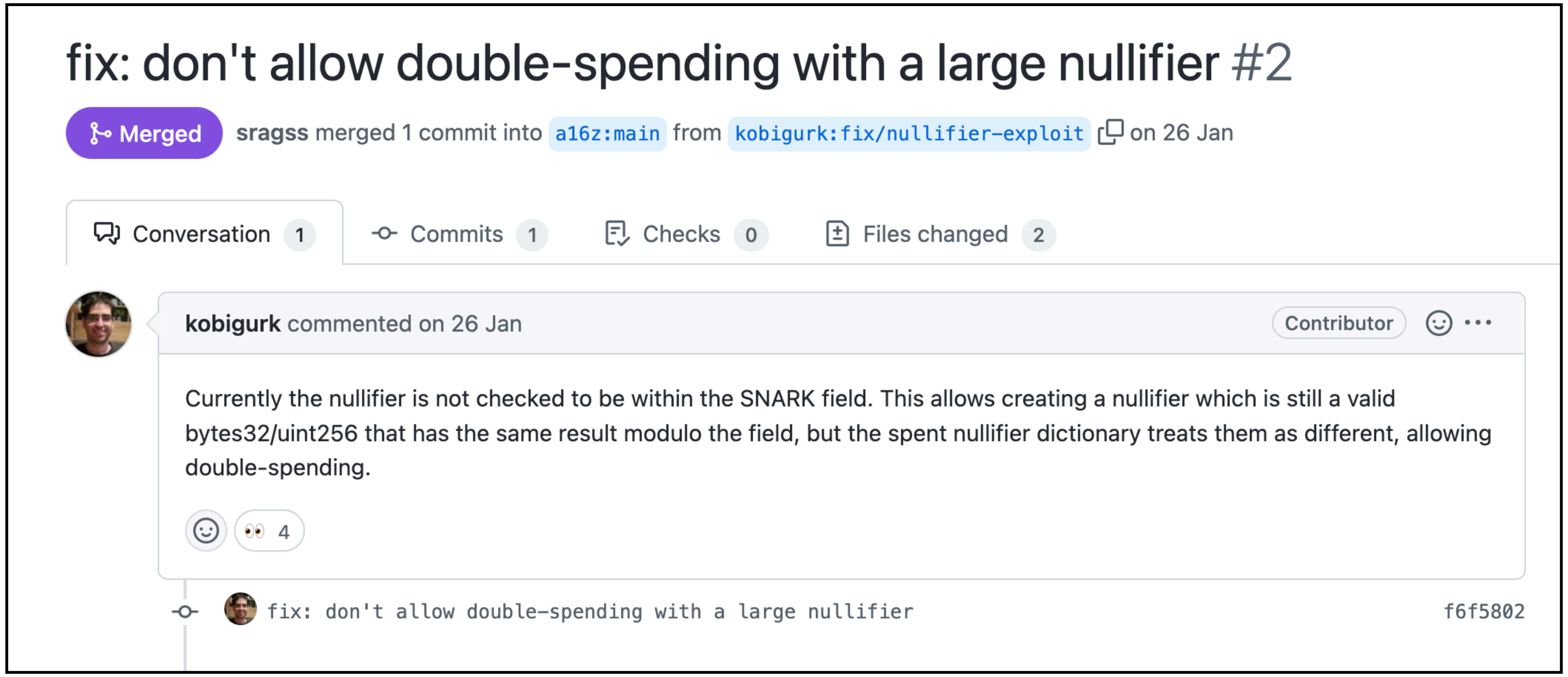
poma commented on 26 Jul 2019 • edited

Looks like in Semaphore.sol#L83 we don't check that nullifier length is less than field modulus. So `nullifier_hash + 21888242871839275222246405745257275088548364400416034343698204186575808495617` will also pass snark proof verification if it fits into uint256, allowing double spend.

Root cause: Missing overflow check of a nullifier (~ unique ID of a shielded payment)

https://github.com/appliedzkp/semaphore/issues/16

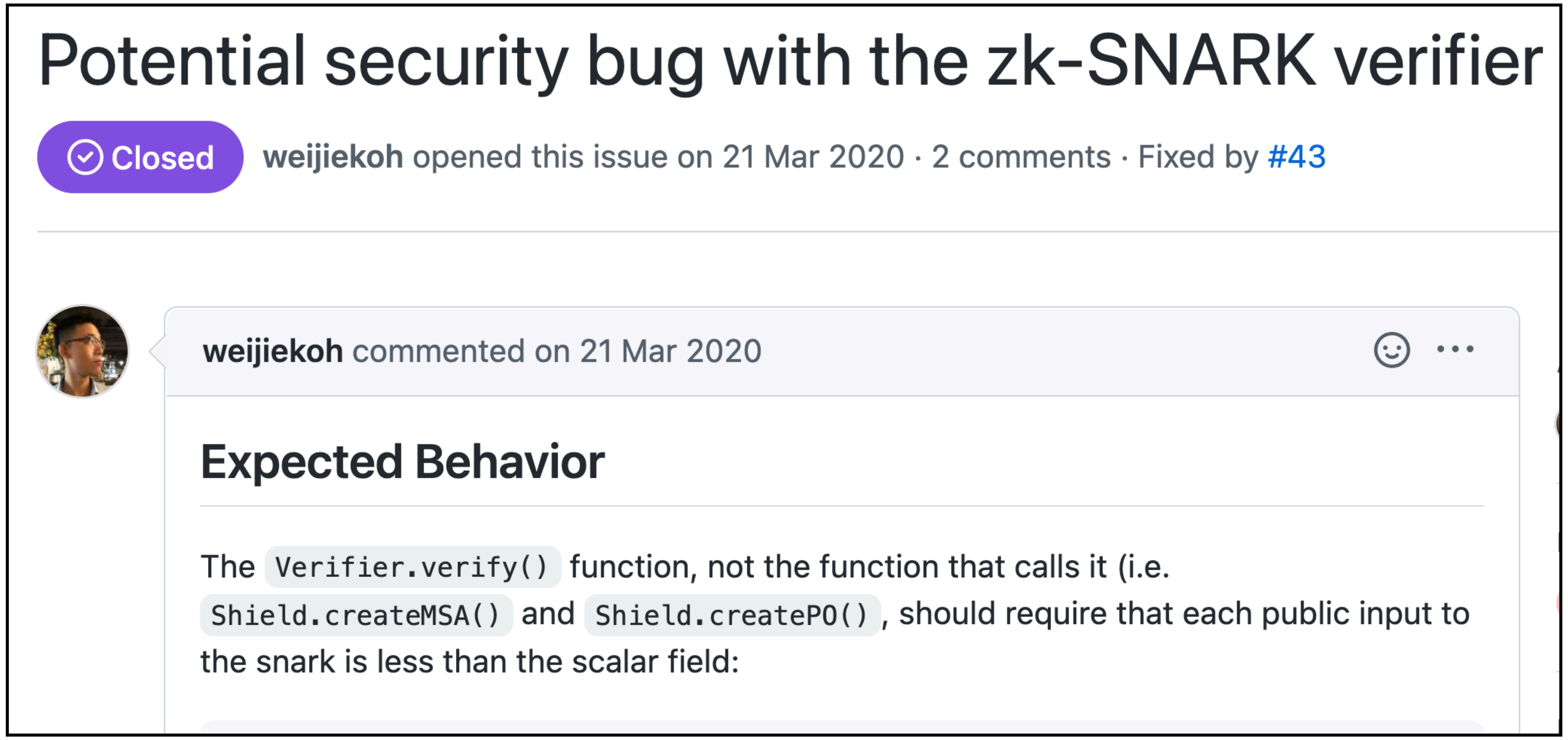
Soundness – Field arithmetic (2/n)



Root cause: Missing overflow check of a nullifier (~ unique ID of a shielded payment)

https://github.com/a16z/zkp-merkle-airdrop-contracts/pull/2

Soundness – Field arithmetic (3/n)



Missing overflow check (of a public circuit input)

https://github.com/eea-oasis/baseline/issues/34

Soundness – Field arithmetic (4/n)

```
- // If the values are not in the correct range, the pairing check will fail.
+ // If the values are not in the correct range, the pairing check will fail
+ // because by EIP197 it verfies all input.
  Proof memory proof;
  proof.A = Pairing.G1Point(a[0], a[1]);
  proof.B = Pairing.G2Point([b[0][0], b[0][1]], [b[1][0], b[1][1]]);
@@ -219,7 +221,7 @@ contract Verifier {
  if (input.length + 1 != vk.IC.length) revert Pairing.InvalidProof();
  Pairing.G1Point memory vk_x = vk.IC[0];
  for (uint256 i = 0; i < input.length; i++) {
-   if (input[i] >= Pairing.SCALAR_MODULUS) revert Pairing.InvalidProof();
+   // By EIP196 the scalar_mul verifies it's input is in the correct range.
    vk_x = Pairing.addition(vk_x, Pairing.scalar_mul(vk.IC[i + 1], input[i]));
```

Missing overflow check (of a public circuit input)

https://github.com/appliedzkp/semaphore/pull/96/

Soundness – R1CS

Discuss: enforce `mul_by_inverse` #70

Merged **weikengchen** merged 7 commits into `master` from `fix-mul-by-inverse` on 6 Jul

Conversation 12 · Commits 7 · Checks 5 · Files changed 3

weikengchen commented on 4 Jul 2021 • edited · Member

Description

It seems that the `mul_by_inverse` implementation has a soundness issue that the newly allocated `d_inv` does not need to be the inverse of `d` but could be any value. This can be a soundness issue as the `poly` gadgets have used this API.

```
fn mul_by_inverse(&self, d: &Self) -> Result<Self, SynthesisError> {
    let d_inv = if self.is_constant() || d.is_constant() {
        d.inverse()?
    if self.is_constant() || d.is_constant() {
        let d_inv = d.inverse()?;
        Ok(d_inv * self)
    } else {
```

RUSTSEC-2021-0075 History

Flaw in `FieldVar::mul_by_inverse` allows unsound R1CS constraint systems

Field element inverse property not enforced by the constraint system

https://github.com/arkworks-rs/r1cs-std/pull/70

Soundness – Hash validation

Technical Details

The bug was found by Kobi Gurkan in the zk-SNARK implementation of the MIMC hash function in circomlib, that is used in Tornado for building the merkle tree of deposits. If everything works as expected, users prove that they have committed a leaf to that tree during deposit without revealing the commitment itself. The buggy version did not check that resulting MIMC hash is correct. The fix is simple: instead of using the `=` operator the `<==` operator should be used.

Coding error, allowing to fake the witness' Merkle root and forge proofs

https://tornado-cash.medium.com/tornado-cash-got-hacked-by-us-b1e012a3c9a8

Soundness – Trusted setup (paper)

Background

On March 1, 2018, Ariel Gabizon, a cryptographer employed by the Zcash Company at the time, discovered a subtle cryptographic flaw in the [BCTV14] paper that describes the zk-SNARK construction used in the original launch of Zcash. The flaw allows an attacker to create counterfeit shielded value in any system that depends on parameters which are generated as described by the paper.

This vulnerability is so subtle that it evaded years of analysis by expert cryptographers focused on zero-knowledge proving systems and zk-SNARKs. In an analysis [Parno15] in 2015, Bryan Parno from Microsoft Research discovered a different mistake in the paper. However, the vulnerability we discovered appears to have evaded his analysis. The vulnerability also appears in the subversion zero-knowledge SNARK scheme of [Fuchsbauer17], where an adaptation of [BCTV14] inherits the flaw. The vulnerability also appears in the ADSNARK construction described in [BBFR14]. Finally, the vulnerability evaded the Zcash Company's own cryptography team, which includes experts in the field that had identified several flaws in other parts of the system.

Theoretical flaw in the paper's setup description (sensitive values not cleared)

https://electriccoin.co/blog/zcash-counterfeiting-vulnerability-successfully-remediated/

Soundness – Fiat-Shamir (code and papers)

Coordinated disclosure of vulnerabilities affecting Girault, Bulletproofs, and PlonK

POST APRIL 13, 2022 LEAVE A COMMENT

By Jim Miller

- ZenGo's `zk-paillier`
- ING Bank's `zkrp` (deleted)
- SECBIT Labs' `ckb-zkp`
- Adjoint, Inc.'s `bulletproofs`
- Dusk Network's `plonk`
- Iden3's `SnarkJS`
- ConsenSys' `gnark`

The Problem

Why is this type of vulnerability so widespread? It really comes down to a combination of ambiguous descriptions in academic papers and a general lack of guidance around these protocols.

The vulnerabilities in one of these proof systems, Bulletproofs, stem from a mistake in the original academic paper, in which the authors recommend an insecure Fiat-Shamir generation. In addition to disclosing these issues to the above repositories, we've also reached out to the authors of Bulletproofs who have now fixed the mistake.

Incomplete Fiat-Shamiring of protocol transcript

https://blog.trailofbits.com/2022/04/13/part-1-coordinated-disclosure-of-vulnerabilities-affecting-girault-bulletproofs-and-plonk/

Zero-knowledge – Application (Aztec)

Issue #2

We discovered our method for removing spending keys involving an account nullifier, broke the sender privacy of transactions from the account; and consequently changed our key removal procedure to use an “Account Nonce” instead of the nullifier.

Issue #3

Our privacy circuit was not correctly including the user account nonce within the encrypted note cipher-text. This would have mean that a deprecated account, with an old nonce, would be able to spend any note owned by the account. We modified our circuit to include the account nonce when encrypting notes.

Missing “account nonce” in encrypted notes processing, breaking privacy

https://medium.com/@jaosef/54dff729a24f (Aztec 2.0 Pre-Launch Notes)

Zero-knowledge – Application (Zcash, Monero)

Remote Side-Channel Attacks on Anonymous Transactions

Florian Tramèr*
Stanford University
tramer@cs.stanford.edu

Dan Boneh
Stanford University
dabo@cs.stanford.edu

Kenneth G. Paterson
ETH Zürich
kenny.paterson@inf.ethz.ch

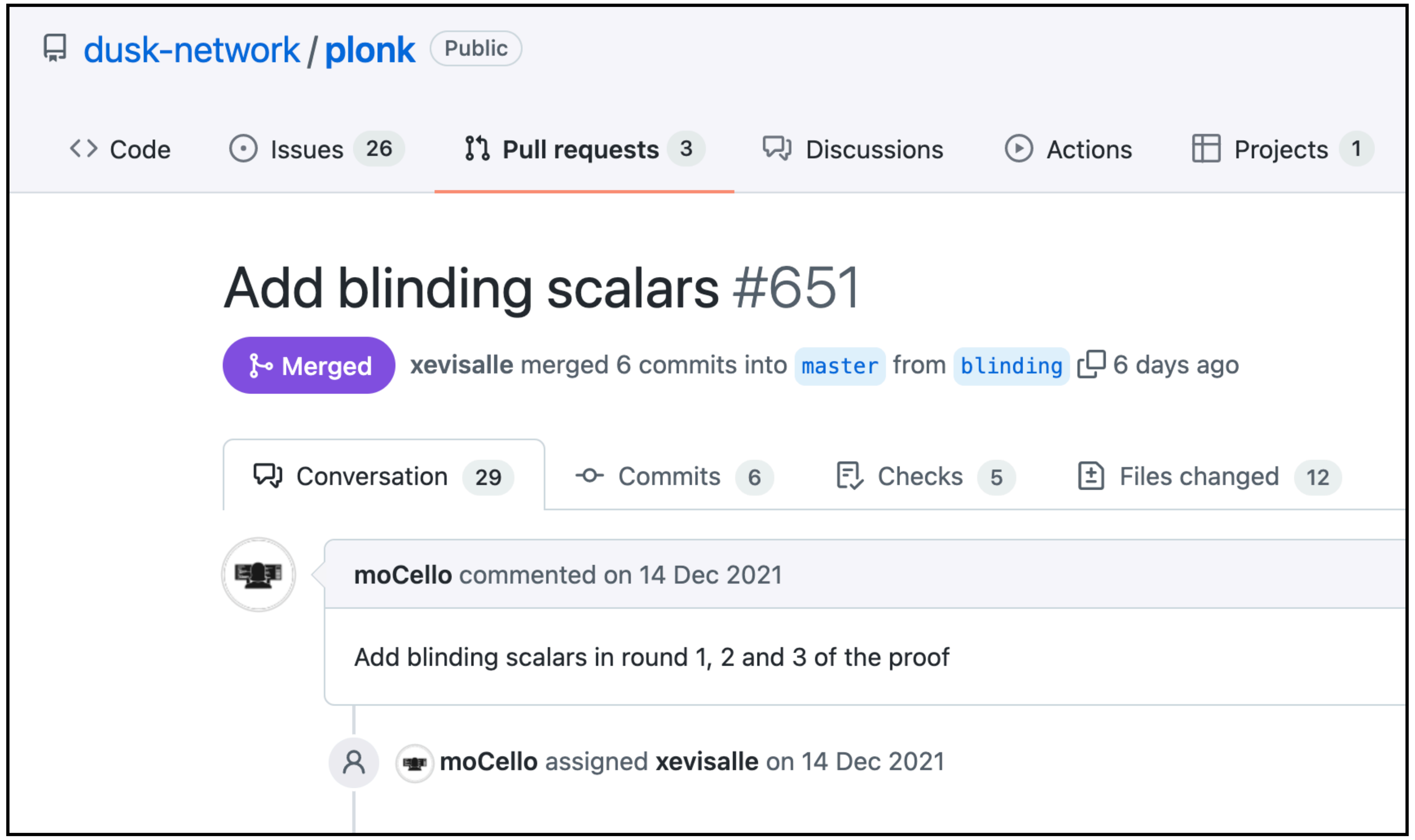
We exploit the fact that the time to produce a proof is correlated with the value of the prover's witness. As the witness contains the transaction amount, we expect this amount to be correlated with the proof time. For example, Zcash's proofs decompose the transaction amount into bits and compute an elliptic curve operation for each *non-zero* bit. The proof time is thus strongly correlated with the Hamming weight of the transaction amount, which is in turn correlated with its value.

Abstract: Privacy-focused crypto-currencies, such as Zcash or Monero, aim to provide strong cryptographic guarantees for transaction confidentiality and unlinkability. In this paper, we describe side-channel attacks that let remote adversaries bypass these protections. We present a general class of timing side-channel and traffic-analysis attacks on receiver privacy. These attacks enable an active remote adversary to identify the (secret) payee of any transaction in Zcash or Monero. The attacks violate the privacy goals of these crypto- currencies by exploiting side-channel information leaked by the implementation of different system components. Specifically, we show that a

Timing dependencies exploited to leak secrets and obtain oracles

https://eprint.iacr.org/2020/627.pdf

Zero-knowledge – Prover (Plonkup)



Missing (randomized) blinding to hide private inputs – *potential* ZK loss

https://github.com/dusk-network/plonk/pull/651

Completeness? – DSL / Signatures

veorq commented yesterday

`crypto.signature.signature.verify()` rejects signatures with an `r`, inverse `s`, or message (hash) greater than `2**251 < EC_ORDER`:

cairo-lang/src/starkware/crypto/starkware/crypto/signature/signature.py
Lines 199 to 201 in 4e23351

```
199    assert 1 <= r < 2 ** N_ELEMENT_BITS_ECDSA, "r = %s" % r
200    assert 1 <= w < 2 ** N_ELEMENT_BITS_ECDSA, "w = %s" % w
201    assert 0 <= msg_hash < 2 ** N_ELEMENT_BITS_ECDSA, "msg_hash = %s" % msg_hash
```

There's a gap of ~2^196 values, thus a probability to hit an invalid `r` or `s` that is of the order of 2^(196-251)/2 = 2^54, when generating an ECDSA sig for some fixed message using a standard algorithm (rather than Cairo's `sign()`, which enforces these constraints).

I can't think of a specific attack scenario at the moment, but I would expect to find applications where either

1. that accidental failure rate would be unacceptably high, or
2. adversaries could bruteforce invalid sigs to do some kind of DoS, or worse (with plausible deniability)

I probably miss some of the context, and you may have a good reason to verify sigs that way.

Valid signatures rejected, risk initially deemed negligible

https://github.com/starkware-libs/cairo-lang/issues/39

Conclusions

😌 **Why not be too scared?**

- Robust code and frameworks (e.g. Rust projects such as arkworks and zkcrypto)
- Safe code easier to write with DSLs (Cairo, Leo, etc.) and reusable gadgets/chips
- Relatively narrow attack surface in practice

Conclusions

😌 **Why not be too scared?**

- Robust code and frameworks (e.g. Rust projects such as arkworks and zkcrypto)
- Safe code easier to write with DSLs (Cairo, Leo, etc.) and reusable gadgets/chips
- Relatively narrow attack surface in practice

😱 **Why be scared?**

- Few people understand zkSNARKs, even fewer can find bugs
- Lack of tooling (wrt testing, fuzzing, verification)
- More ZKPs used => more $$$ at stake => greater RoI for vuln researchers

Conclusions

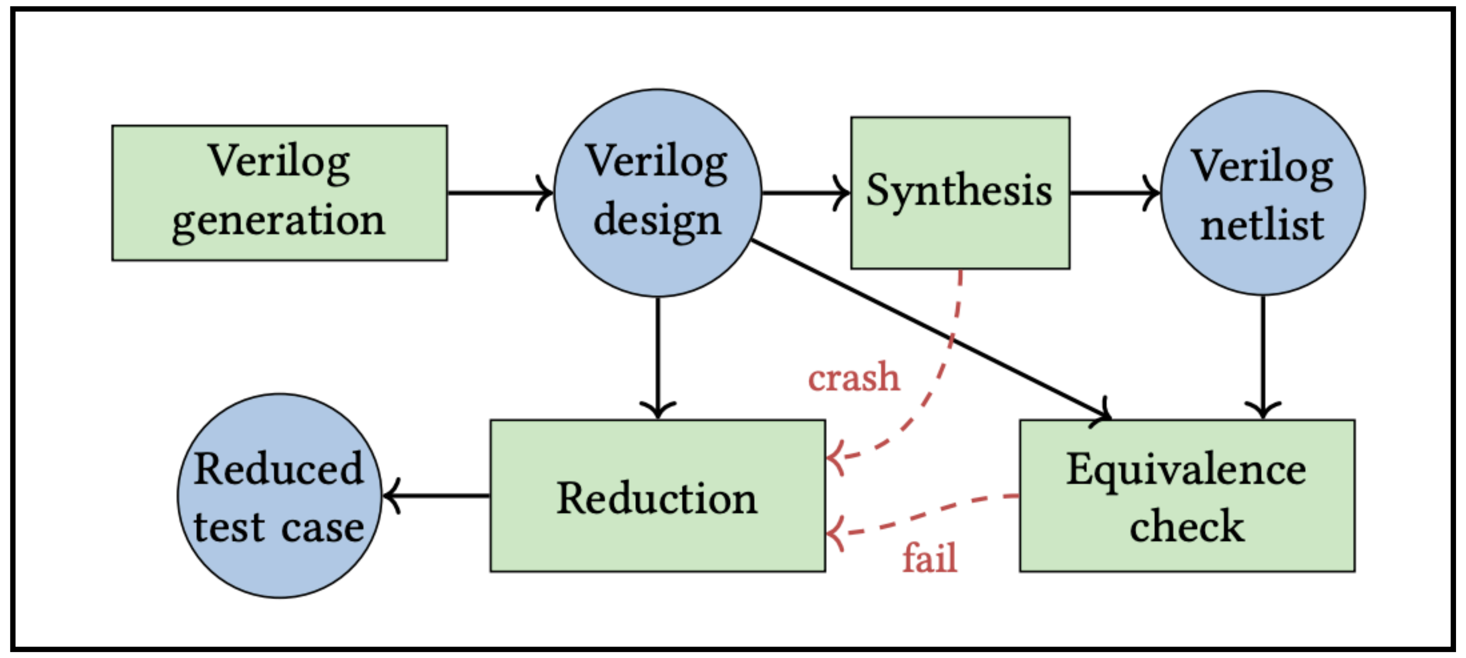
We need **more**…

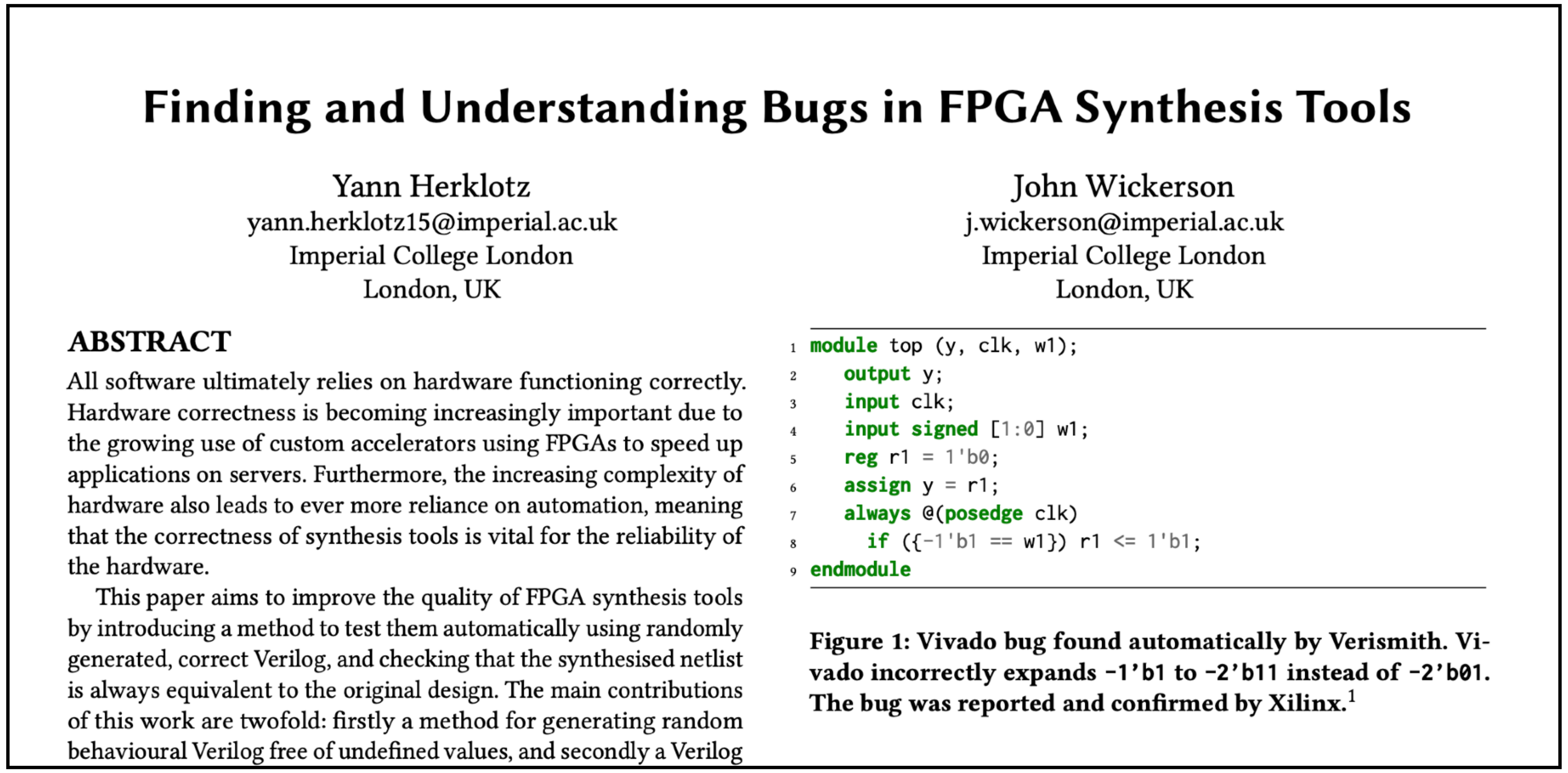
- **Testing** and (smart) fuzzing, formal verification can probably help too
- Real-world **specifications** (ex: https://eng-blog.o1labs.org/posts/cargo-spec/)
- **Information sharing**, with detailed and accessible **write-ups**, such as https://blog.trailofbits.com/2022/04/13/part-1-coordinated-disclosure-of-vulnerabilities-affecting-girault-bulletproofs-and-plonk/

Conclusions

Learn from **hardware circuit synthesizers**?

- HDL-to-netlist ≈ Program-to-constraints – same, but different
- History of bugs and tooling
- Testing methodologies





Finding and Understanding Bugs in FPGA Synthesis Tools

Yann Herklotz
yann.herklotz15@imperial.ac.uk
Imperial College London
London, UK

John Wickerson
j.wickerson@imperial.ac.uk
Imperial College London
London, UK

ABSTRACT

All software ultimately relies on hardware functioning correctly. Hardware correctness is becoming increasingly important due to the growing use of custom accelerators using FPGAs to speed up applications on servers. Furthermore, the increasing complexity of hardware also leads to ever more reliance on automation, meaning that the correctness of synthesis tools is vital for the reliability of the hardware.

This paper aims to improve the quality of FPGA synthesis tools by introducing a method to test them automatically using randomly generated, correct Verilog, and checking that the synthesised netlist is always equivalent to the original design. The main contributions of this work are twofold: firstly a method for generating random behavioural Verilog free of undefined values, and secondly a Verilog


```
module top (y, clk, w1);
  output y;
  input clk;
  input signed [1:0] w1;
  reg r1 = 1'b0;
  assign y = r1;
  always @(posedge clk)
    if ({-1'b1 == w1}) r1 <= 1'b1;
endmodule
```

Figure 1: Vivado bug found automatically by Verismith. Vivado incorrectly expands -1'b1 to -2'b11 instead of -2'b01. The bug was reported and confirmed by Xilinx.[1]

https://johnwickerson.github.io/papers/verismith_fpga20.pdf

Thank you!

JP Aumasson
@veorq

CSO @ taurushq.com

Big thank yous for their help and feedback to:
Aleo, Protocol Labs, Kobi Gurkan, Adrian Hamelink, Daira Hopwood, Daniel Jacob Bilar, David Wong, Lúcás Meier, Mathilde Raynal