Verification of Solana Programs

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Venice, May 26th 2023

Symposium on Challenges of Software Verification (CSV)

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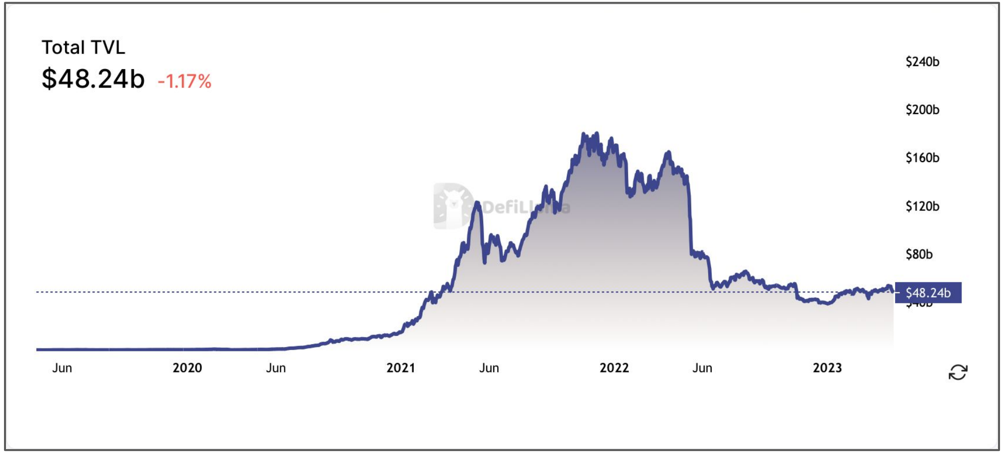
DeFi in one slide

- Economic process completely defined by code
- Fairly complex code
- Examples
  - Lending
  - Exchange
  - Options
  - Auctions
- 50 Billion dollars in the bear market



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Interesting DeFi Bugs 2022/3

- **Euler Finance $200M** – DonateToReserves() function didn't check for account debt health, allowing for bad debt to accrue and for the collateral to be liquidated at a large discount to the attacker
- **Yearn Finance V1 $10M** – Misconfiguration of one of the underlying asset addresses in the USDT pool allowed an attacker to drain the whole vault
- **Safemoon $9M** – Upgraded contract didn't use access control for the burn() function. The attacker burned tokens from the Safemoon pool on a DEX, inflated the price and sold tokens into the pool
- **Platypus $8.5M** – EmergencyWithdraw() didn't check for debt, so the attacker could take max loan for his collateral, and then simply emergency withdraw the collateral
- **Hundred $7.4M** – "First depositor" bug where the attacker could manipulate the exchange rate and borrow way more than allowed

Why Formally Verify DeFi?

❗ Code is law

💰 Billions of dollars at stake

Σ Code is typically medium-size/modular

🐛 But bugs are hard to find
Happens in rare scenarios

🔄 New code is produced frequently

Maker
@MakerDAO

UPDATE ON MULTI-COLLATERAL DAI:
The code is ready and formally verified. The first time ever a major dapp has been formally verified.
Learn more: medium.com/makerdao/the-c...
#FormalVerification #DAI $DAI $MKR #MKR

12:07 AM · Sep 18, 2018

Lido
@LidoFinance

The Lido-on-Ethereum protocol team is doing all it can to make sure the protocol upgrade is secure and issue-free, including conducting thorough security audits, performing formal verification, and extensively testing on Goerli.

9:01 PM · Feb 28, 2023 · **1,951** Views

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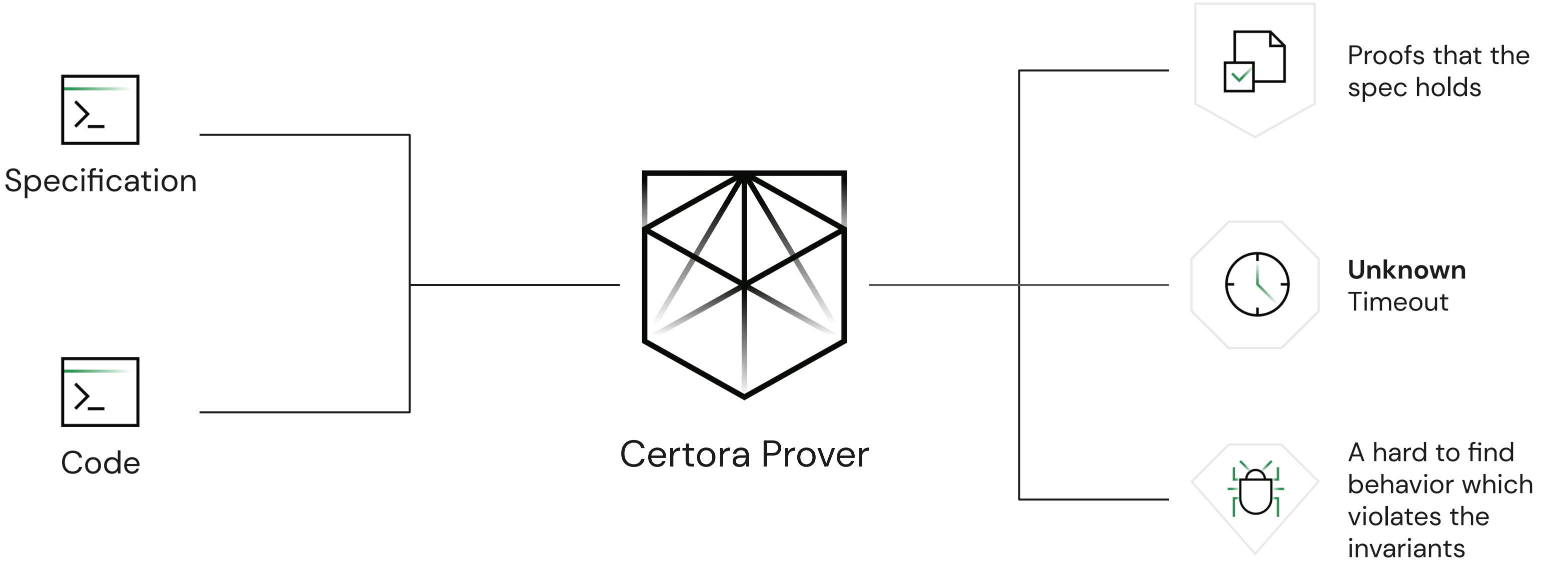
The Certora Approach: Automatic Formal Verification



Critical Bugs Found by Certora Prover

- **Solvency**
  If everybody runs to the bank
  Bank still fulfills all commitments

- Users' money cannot be locked or lost

Bugs prevented by the Certora-Prover missed in manual audits by top auditors

SushiSwap	$807M	AAVE	$6.5B	Compound	$2.7B	Balancer	$1.18B
Strategy	2	V3	1	Comet	5	V2	2
Trident	5	V2	2	V2	5		
KashiPair	3						
DutchAuction	1						

Solidity
@solidity_lang

"We thank all contributors who made this release possible. Special thanks goes to @johnadtoman of @CertoraInc for reporting the inline assembly memory side effects bug!"

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Why Formally Verify Solana (https://solana.com) ?

EVM

#	Name	Protocols	1d change(TVL)	1w change(TVL)	1m change(TVL)	TVL	Mcap	Mcap/TVL
1	Ethereum ETH	810	▲ 0.38%	▼ 3.76%	▼ 12.83%	$51.48B	$220.16B	4.28
2	Tron TRON	32	▲ 0.05%	▼ 2.99%	▼ 2.89%	$5.40B	$6.26B	1.16
3	BSC BNB	612	▲ 0.19%	▼ 2.04%	▼ 7.26%	$5.21B	$48.51B	9.31
4	Arbitrum ARB	337	▲ 0.18%	▼ 1.76%	▲ 2.59%	$2.68B	$1.48B	0.55
5	Polygon MATIC	426	▲ 0.89%	▼ 2.55%	▼ 12.48%	$1.21B	$7.86B	6.49
6	Optimism OP	144	▲ 0.94%	▼ 4.01%	▼ 11.16%	$1.00B	$540.39M	0.54
7	Avalanche AVAX	318	▲ 0.47%	▼ 2.62%	▼ 15.41%	$979.23M	$4.95B	5.05
8	Solana SOL	114	▼ 0.53%	▼ 2.55%	▼ 16.62%	$514.09M	$8.17B	15.9

Non-EVM

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https://coinmarketcap.com/chain-ranking

Why Formally Verify Solana?

- Benefits:
  - Based on general purpose programming languages: Rust, C/C++
  - Reusing existing eBPF virtual machine:
    - Support multiple (or even combination of) input languages
  - Programs are stateless: all data is passed as function arguments
    - Non-interference (easier to shard)

- Challenges:
  - Verification of low-level eBPF/SBF is harder
  - No common format between apps (data format is up to the app):
    - Inputs are just array of bytes
    - Serialization/deserialization
  - Compiled Rust can be harder to verify than human-written C
    - Rust union types, dangling pointers, etc.

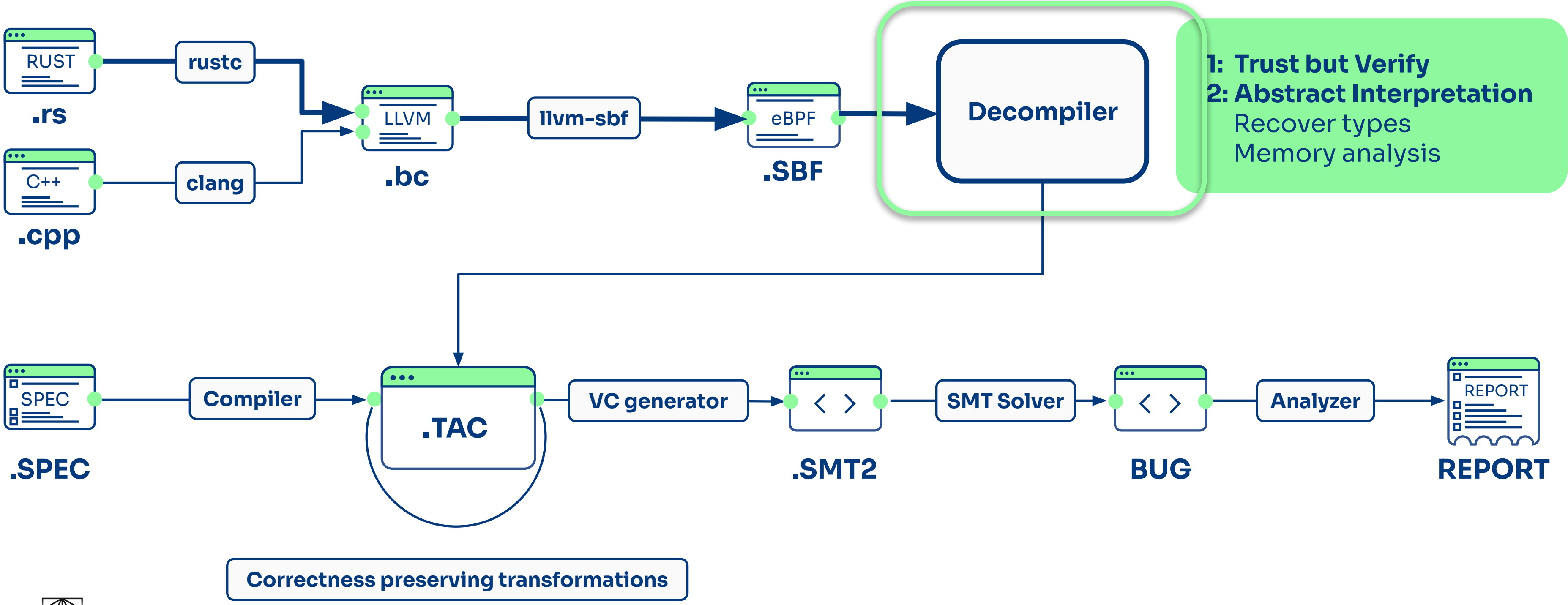
Solana Programming (not in this talk)

- **Accounts**
  - Fields: lamports, owner, executable, data, rent epoch
  - Program and Data accounts
- **Transactions** consist of **instructions**
- All programs are *stateless*: any data they interact with is stored in separate accounts that are passed in via instructions
- **PDAs** (Program Derived Address): data account owned by programs instead of users
  - Used to implement associative maps
- **CPI** (Cross Program Invocations)
- **Deserialize/Serialize**

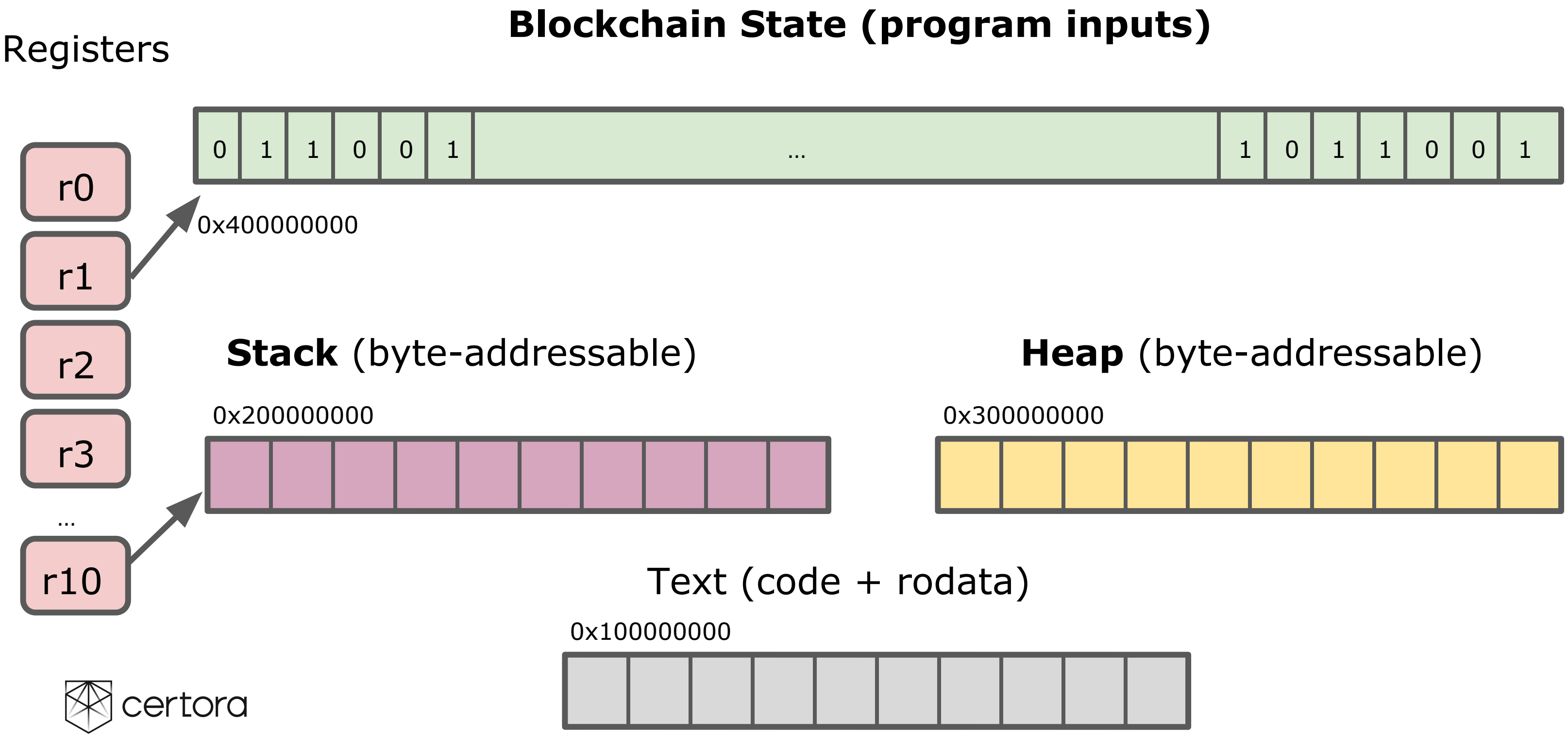
https://solanacookbook.com/

Certora Prover Architecture for Solana

In this talk



eBPF/SBF Virtual Machine



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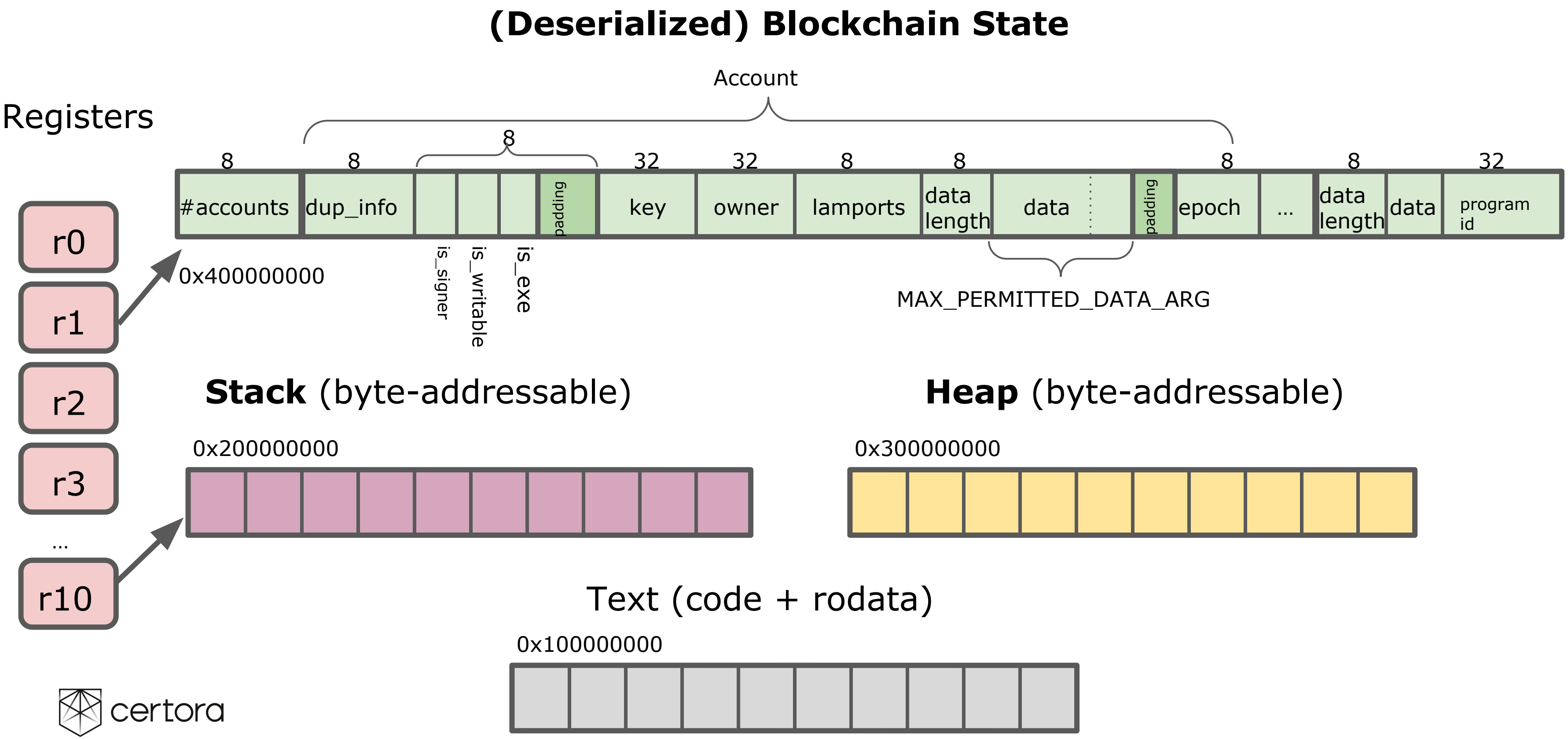
eBPF/SBF Virtual Machine



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SBF Instruction Set

- Currently, three different dialects with similar bytecodes: bpf/sbf/sbfv2
- RISC-like instruction set
- 11 general-purpose, 64-bit registers
  - r10 is read-only frame pointer to access to stack
- ALU, JUMP, LOAD, STORE, MOVE
  - Jumps use only relative constant offsets: CFG construction is decidable
- Syscalls and eBPF-to-eBPF (internal) calls
  - r0: return
  - r1, ..., r5: caller-saved (volatile) registers
  - r6, ..., r9: callee-saved (non-volatile) registers
- No type information: no distinction between numbers and pointers
- Direct and indirect function calls: call graph construction is undecidable

SBF Disassembler

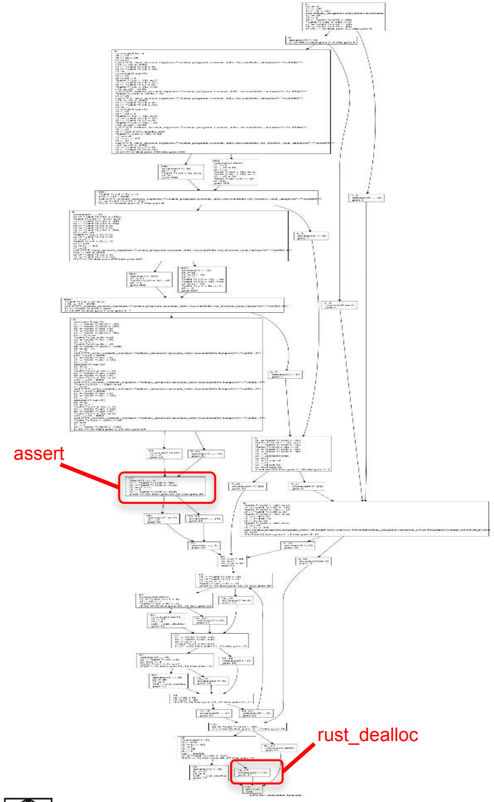
1. Translate ELF to a sequence of three-address instructions
    - Resolve Solana-specific relocations
2. CFG and Call graph construction: one per function
    - Indirect calls not supported
3. Inline all internal functions
    - Explicit modeling of call semantics
4. Compute Cone-of-Influence and slice program
5. Memory analysis
6. Translation to TAC program

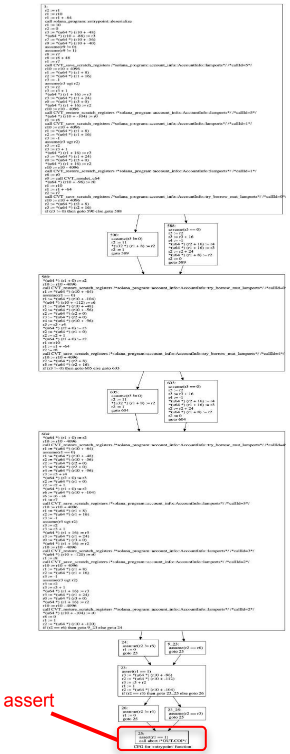
Memory Analysis Assumptions

The analysis is sound under the following assumptions:

1. Memory safety
   - Absence of out-of-bounds accesses
   - Stack/Heap/Blockchain memory is initialized
2. First read from blockchain state returns non-deterministic values
   - Pointers do not alias with any other pointer
3. Each memory read accesses the same number of bytes last written
   - Checked by the analysis

Rust compiles to large programs





- Many irrelevant paths:
  - error paths
  - free pointers
- We only care about paths that can influence the evaluation of assertions

Solution: dataflow analysis that removes any path that is not in the Cone-Of-Influence (CoI)

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Rust enum types

```rust
pub fn process_withdraw(
    program_id: &Pubkey,
    accounts: &[AccountInfo],
    amount: u64,
    expected_decimals: u8,
    new_decryptable_available_balance: DecryptableBalance,
    proof_instruction_offset: i64,
) -> ProgramResult {
```

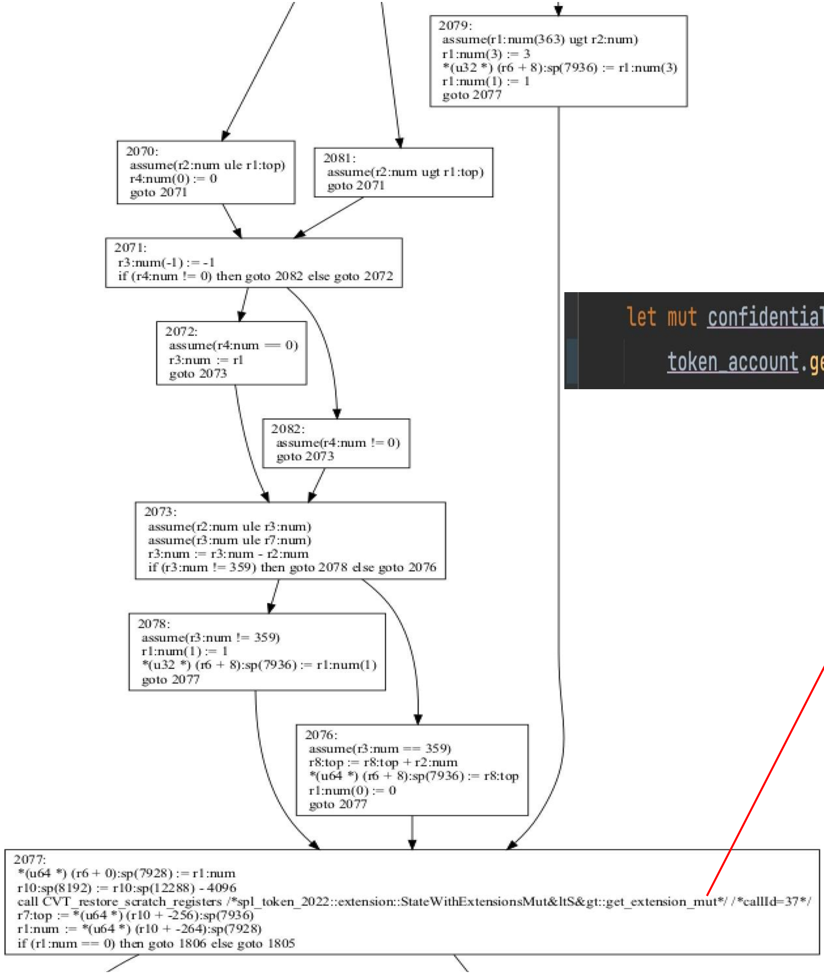
`Result<(),ProgramError>`

`Result<&mut V, ProgramError>`

```rust
let mut confidential_transfer_account : &mut ConfidentialTransferAccount =
    token_account.get_extension_mut::<ConfidentialTransferAccount>()?;
```

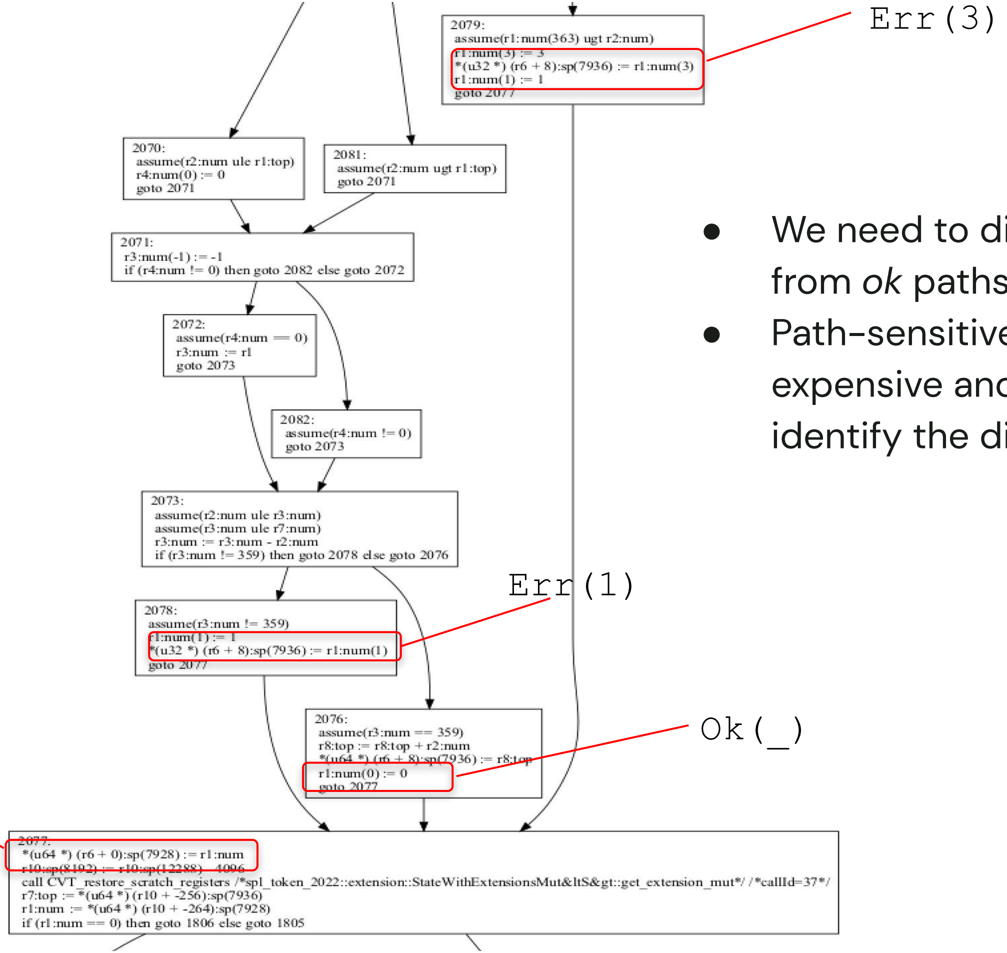
question mark (`?`) operator

Rust enum types




```rust
let mut confidential_transfer_account : &mut ConfidentialTransferAccount =
    token_account.get_extension_mut::<ConfidentialTransferAccount>()?;
```

Rust enum types



- We need to discriminate *error* from *ok* paths
- Path-sensitive analysis is expensive and it is not easy to identify the discriminants

`r1` is the discriminant
0 = `Ok`
1 = `Err`

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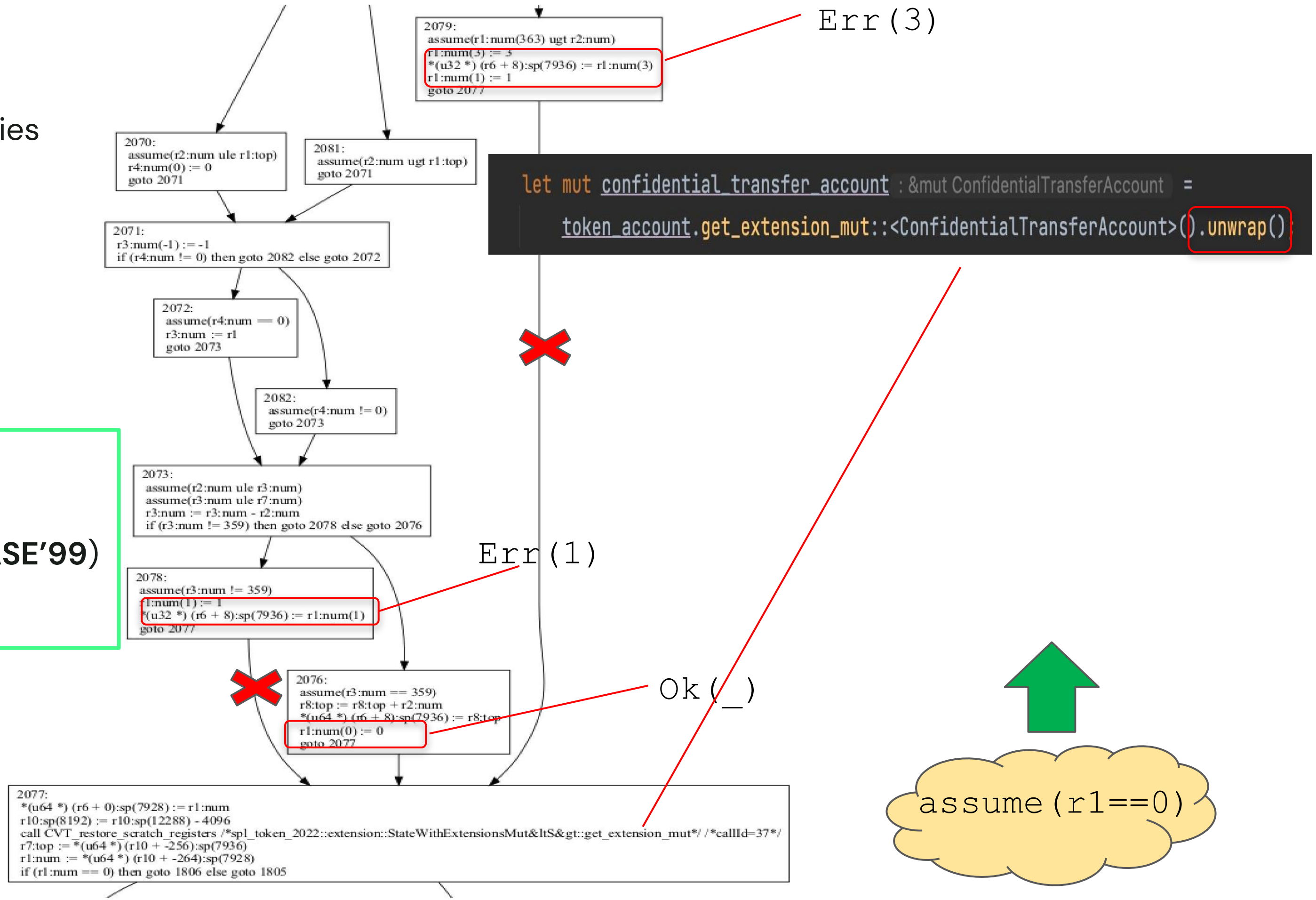
Rust enum types

We typically prove properties under the assumption that functions return `ok`

Solution: iterative forward+backward analysis (**Cousot&Cousot JLP’92/ASE’99**) to prune error paths



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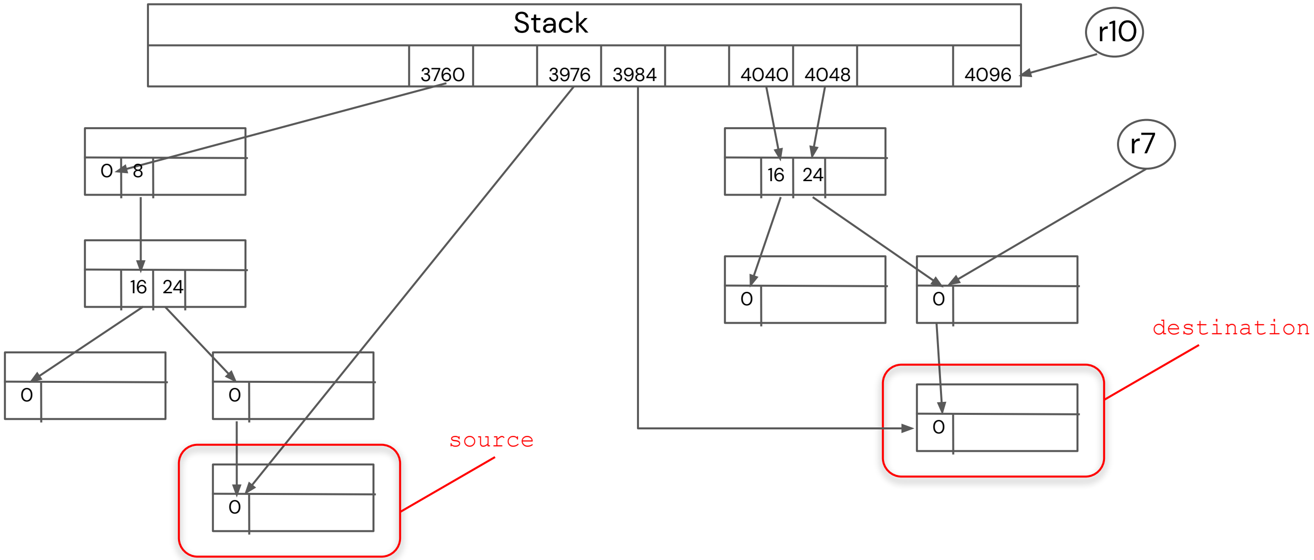
Analysis of SBF code

- Disassembler needs to translate SBF into a TAC program **without side effects**
  - TAC memory operations have an explicit argument "mem" that represents the (possibly infinite) set of memory locations being accessed
  - Two TAC memory ops do not alias if they have different "mem" names
- How: static memory partitioning
    - Split all program memory (stack, heap, and inputs) into a **finite** set of **disjoint** regions
    - For each memory instruction, map the memory location to a region
- Challenges:
  - No explicit allocation sites for program inputs because they are allocated either before the SBF program is loaded or by deserialization
  - Strong vs weak updates

Analysis of SBF code

- Solution 1: flow-insensitive/field-sensitive pointer analysis (**Gurfinkel&Navas SAS'17**)
  - Adopted in LLVM-based verifiers such as SeaHorn and SMACK
  - Easy to model in SMT: one single points-to graph for the whole program



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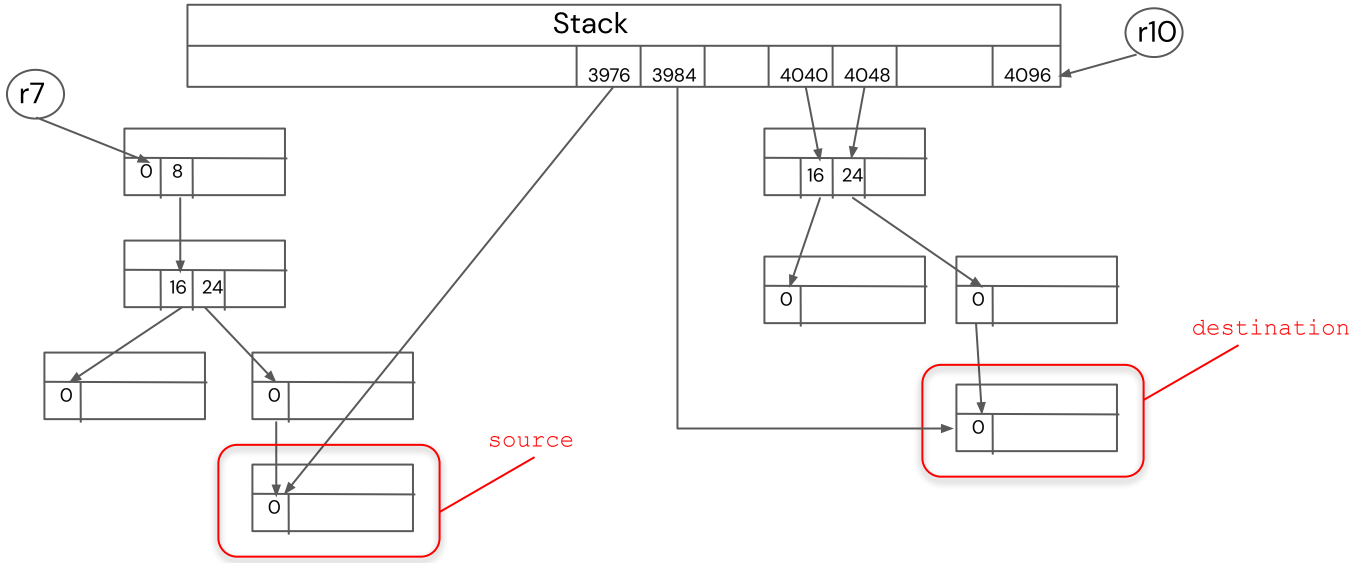
Analysis of SBF code



- Registers must be tracked flow-sensitively
    - They can be re-assigned at each instruction

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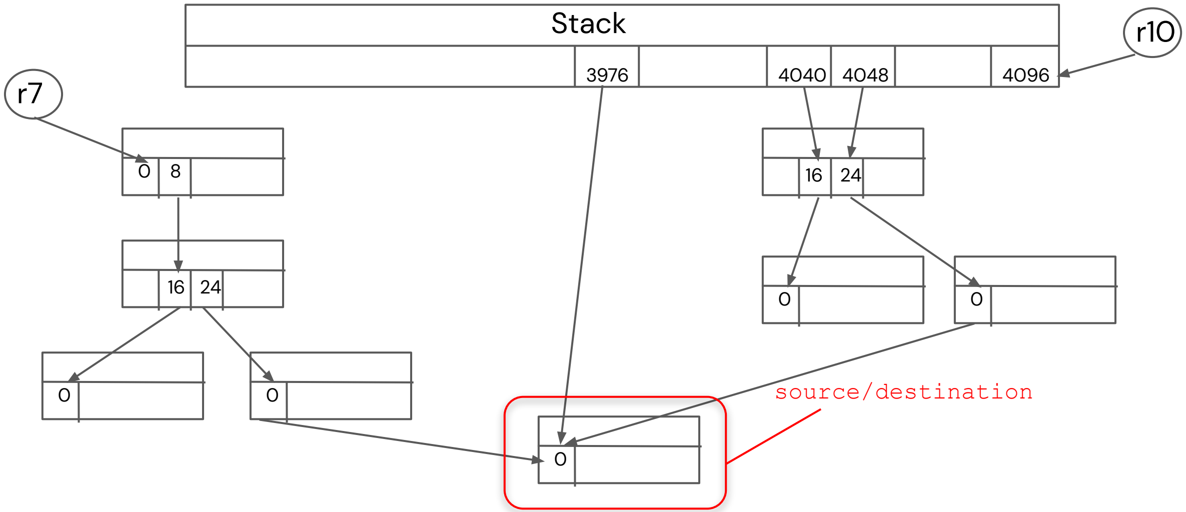
Analysis of SBF code



- Registers must be tracked flow-sensitively
    - They can be re-assigned at each instruction

- Stack must be tracked flow-sensitively

- LLVM back-end reuses stack allocations

```
lifetime.start.p0i8(%p1)
call try_borrow_mut_lamports(%p1) // %p1 points to src
lifetime.end.p0i8(%p1)
lifetime.start.p0i8(%p2)
call try_borrow_mut_lamports(%p2) // %p2 points to dst
lifetime.end.p0i8(%p2)
```

- Same slot 3976 in SBF for `%p1` and `%p2`

Analysis of SBF code

- Solution 2: flow-sensitive pointer analysis
  - Solution adopted by verifiers such as Predator
  - Very precise but expensive: one points-to graph per basic block
  - Harder to model in SMT: a memory instruction can use different “mem” depending on which predecessor reaches the instruction

Analysis of SBF code

- Our solution:
    - Flow-sensitive stack and registers
    - Flow-insensitive heap and program inputs
    - **Stack scalarization:**
        - Each stack slot is translated to a scalar variable
        - This allows **strong updates** on local variables
        - Precise and easy to model in SMT
    - Weak updates on heap and program inputs
        - Still easy to model in SMT

Conclusions

- Solidity/EVM has attracted most of the attention of the verification community
- Verification of Solana contracts is a very exciting new research area
- Based on thrilling Rust and eBPF technology
  - A lot of the ideas and solutions can be reused in different contexts
- Both (compiled) Rust and SBF pose unique challenges to verification
- **Certora is building the first automatic verifier for Solana contracts!**

Many challenges are still to solve ...

- Solana
    a. Cross-program invocations (CPI)
    b. Automatic handling of serialization/deserialization
    c. Verifying multiple transactions/instructions
        - For now, we focus on one instruction at the time, and manually provide context invariants
        - However, most exploited vulnerabilities used multiple instructions and transactions
    d. Fuller model of transaction state
        - e.g., support instruction introspection (heavily used for implementing confidentiality)
    e. Richer model of the blockchain environment: e.g., PDA-based links between accounts

- Rust/SBF
    a. More precise memory abstraction to support Rust enum types
    b. More precise abstractions for the heap (e.g., Box, Vec, ...)
- SMT
    a. Improve domain-specific treatment of non-linear arithmetic

Demo: SPL Token 2022

https://spl.solana.com/token-2022

Verification harness for `process_withdraw`

```rust
fn cvt_harness_process_withdraw(
    program_id: &Pubkey,
    _accounts: &[AccountInfo],
    _instruction_data: &[u8],
) -> ProgramResult {
    // Create non-deterministic inputs for process_withdraw
    let token_account_info = CVT_nondet_account_info();
    let mint_account_info = CVT_nondet_account_info();
    let instructions_sysvar_info = CVT_nondet_account_info();
    let authority_info = CVT_nondet_account_info();
    let acc_infos : [?; 4] = [token_account_info.clone(), mint_account_info.clone(), instructions_sysvar_info.clone(), authority_info.clone()];
    let amount = CVT_nondet_u64();
    let expected_decimals = CVT_nondet_u8();
    let new_decryptable_available_balance: DecryptableBalance = cvt_confidential::CVT_mk_decryptable_balance();
    let proof_instruction_offset = CVT_nondet_i64();
    // Call the function under verification
    process_withdraw(program_id, accounts: &acc_infos, amount, expected_decimals, new_decryptable_available_balance, proof_instruction_offset).unwrap();
    // Check the property
    let token_account_data : &? = &acc_infos[0].data.borrow();
    let token_account : StateWithExtensions<Account> = StateWithExtensions::<Account>::unpack( input: token_account_data).unwrap();
    let confidential_transfer_account : &ConfidentialTransferAccount =
        token_account.get_extension::<ConfidentialTransferAccount>().unwrap();
    cvt::CVT_assert(confidential_transfer_account.encryption_pubkey == cvt_confidential::get_proof_withdraw_account().pubkey);
    Ok(())
}
```

Non-deterministic inputs

function under verification

property

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process_withdraw

```
// ZK-proof certifies that the account has enough available balance to withdraw the amount.
let zkp_instruction : Instruction =
    get_instruction_relative( index_relative_to_current: proof_instruction_offset,
                              instruction_sysvar_account_info: instructions_sysvar_info)?;
let proof_data : &WithdrawData = decode_proof_instruction::<WithdrawData>(
    expected: ProofInstruction::VerifyWithdraw,
    &zkp_instruction,
)?;

// Check that the encryption public key associated with the confidential extension is
// consistent with the public key that was actually used to generate the zkp.
// ============== THIS CHECK WAS ADDED BY AUDITOR =======================
// SEE https://github.com/solana-labs/solana-program-library/pull/3768/
if confidential_transfer_account.encryption_pubkey != proof_data.pubkey {
    return Err(TokenError::ConfidentialTransferElGamalPubkeyMismatch.into());
}

// Prevent unnecessary ciphertext arithmetic syscalls if the withdraw amount is zero
if amount > 0 {
    confidential_transfer_account.available_balance =
        syscall::subtract_from( ciphertext: &confidential_transfer_account.available_balance, amount)
            .ok_or( err: ProgramError::InvalidInstructionData).unwrap();
}

// Check that the final available balance ciphertext is consistent with the actual ciphertext
// for which the zero-knowledge proof was generated for.
if confidential_transfer_account.available_balance != proof_data.final_ciphertext {
    return Err(TokenError::ConfidentialTransferBalanceMismatch.into());
}
```

ZK-Proof

Bug source

Mocking `process_withdraw`

mock

```
    // ZK-proof certifies that the account has enough available balance to withdraw the amount
    let proof_data : &WithdrawData  = cvt_confidential::get_proof_withdraw_account();

    // Check that the encryption public key associated with the confidential extension is
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    if confidential_transfer_account.available_balance != proof_data.final_ciphertext {
        return Err(TokenError::ConfidentialTransferBalanceMismatch.into());
    }

    confidential_transfer_account.decryptable_available_balance = new_decryptable_available_balance;
```

Usage of Certora Prover

- Compile Solana Program to generate SBF

```
% cargo build-sbf —-arch=sbfv2
  Finished release [optimized] target(s) in 6.24s
```

- Run Certora Prover on buggy version:

```
% certoraRun.py target/sbf-solana-solana/release/spl_token_2022.so
  Violated: cvt_harness_process_withdraw
  cvt_harness_process_withdraw: A property is violated
  Done Sat May 20 14:14:45 MDT 2023
  Reports in file:///Users/jorge/SPL/token/program-2022/src/certora_files/emv-1-
release-spl_token_2022.so-20-May--14-14/Reports
```

- Run Certora Prover on fixed version (https://github.com/solana-labs/solana-program-library/pull/3768/):

```
% certoraRun.py target/sbf-solana-solana/release/spl_token_2022.so
  Verified: cvt_harness_process_withdraw
  cvt_harness_process_withdraw: Properties successfully verified on all inputs
```

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