Verification of Solana Programs

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Venice, May 26th 2023

Symposium on Challenges of Software Verification (CSV)

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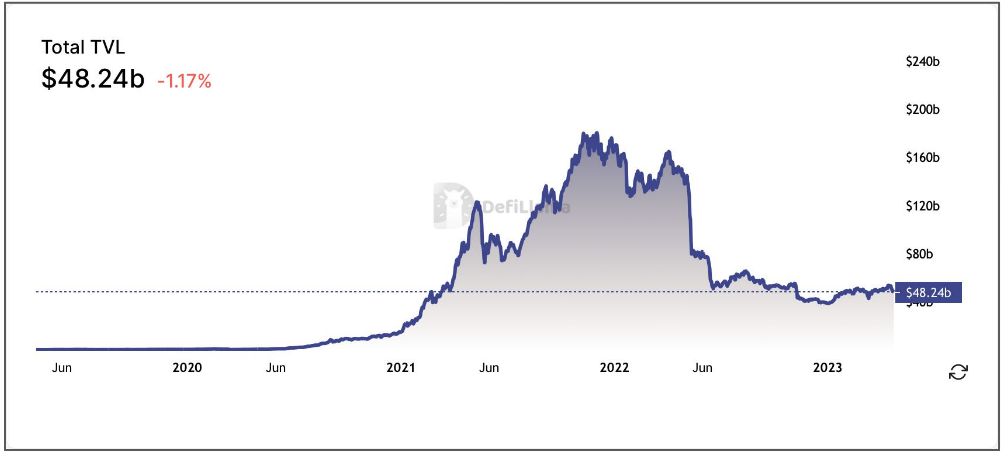
DeFi in one slide

- 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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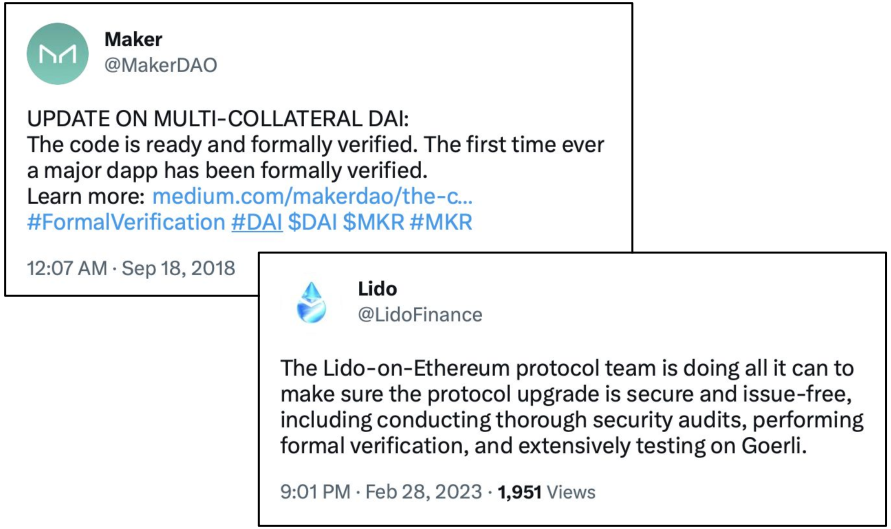
Interesting DeFi Bugs 2022/3

- **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

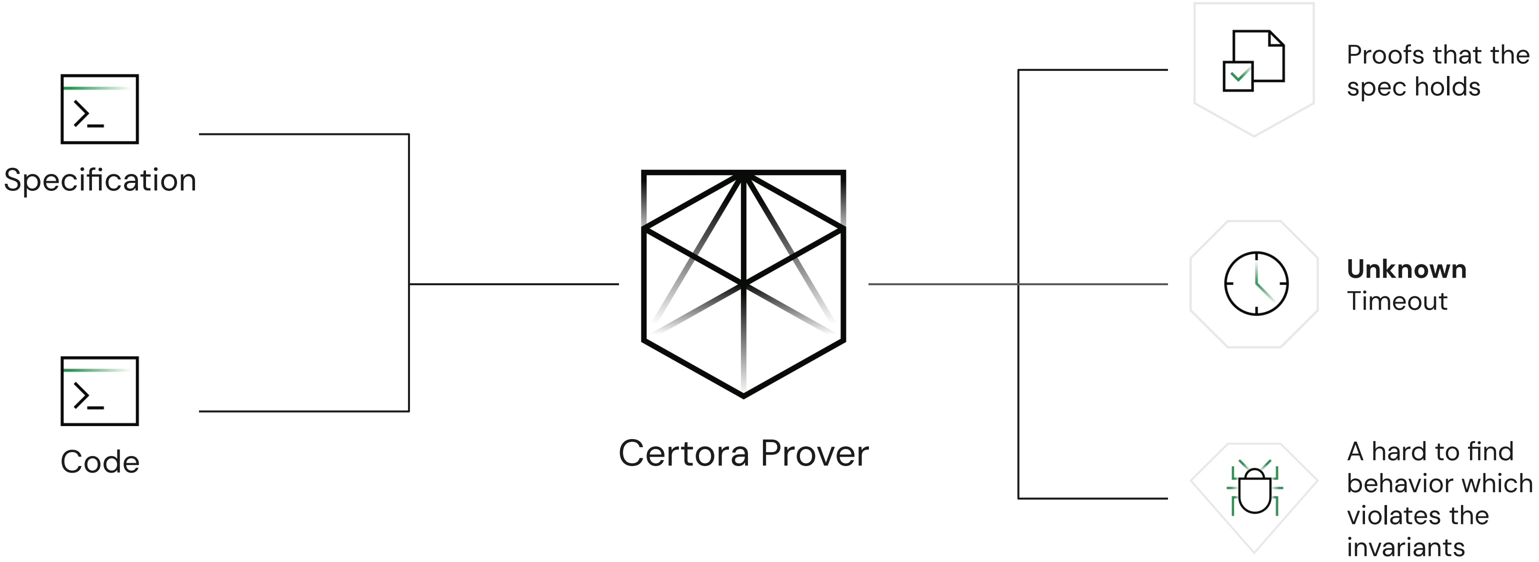
12:07 AM · Sep 18, 2018

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

The Certora Approach: Automatic Formal Verification



Specification

Code

Certora Prover

Proofs that the spec holds

Unknown
Timeout

A hard to find behavior which violates the invariants

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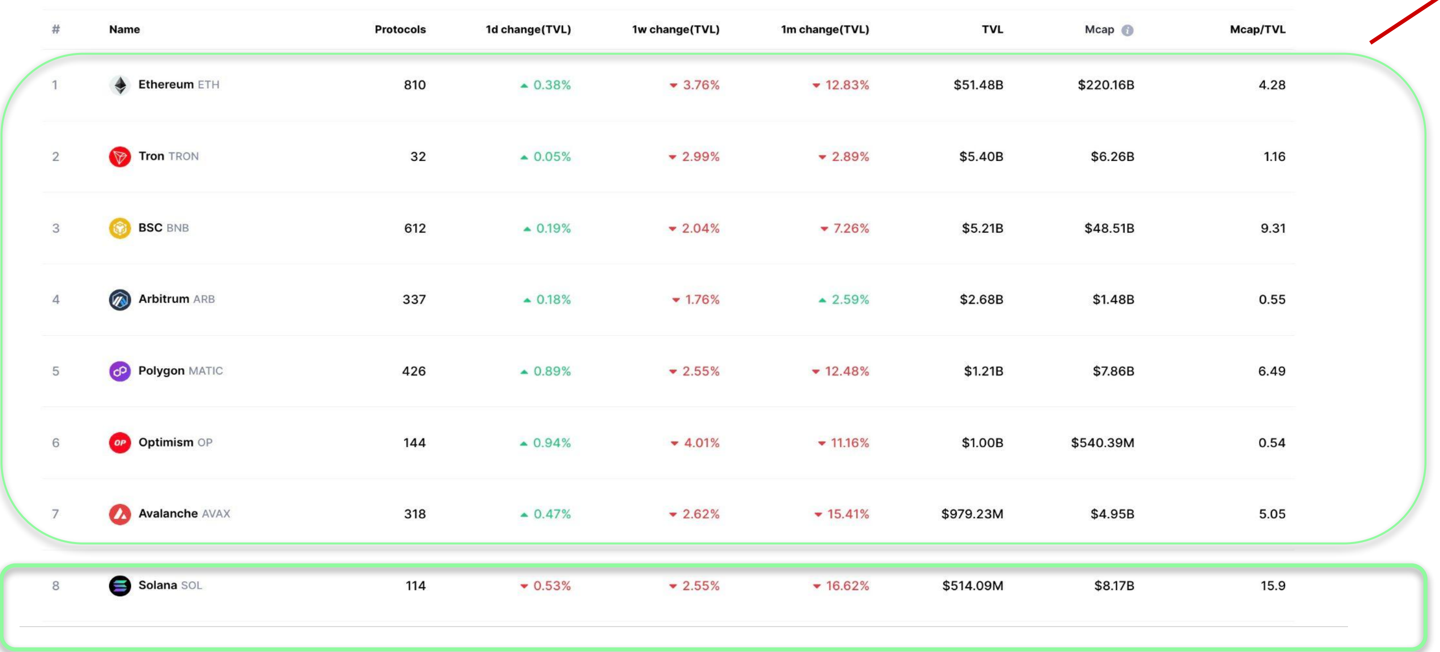
Why Formally Verify Solana (https://solana.com) ?



#	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

EVM

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/

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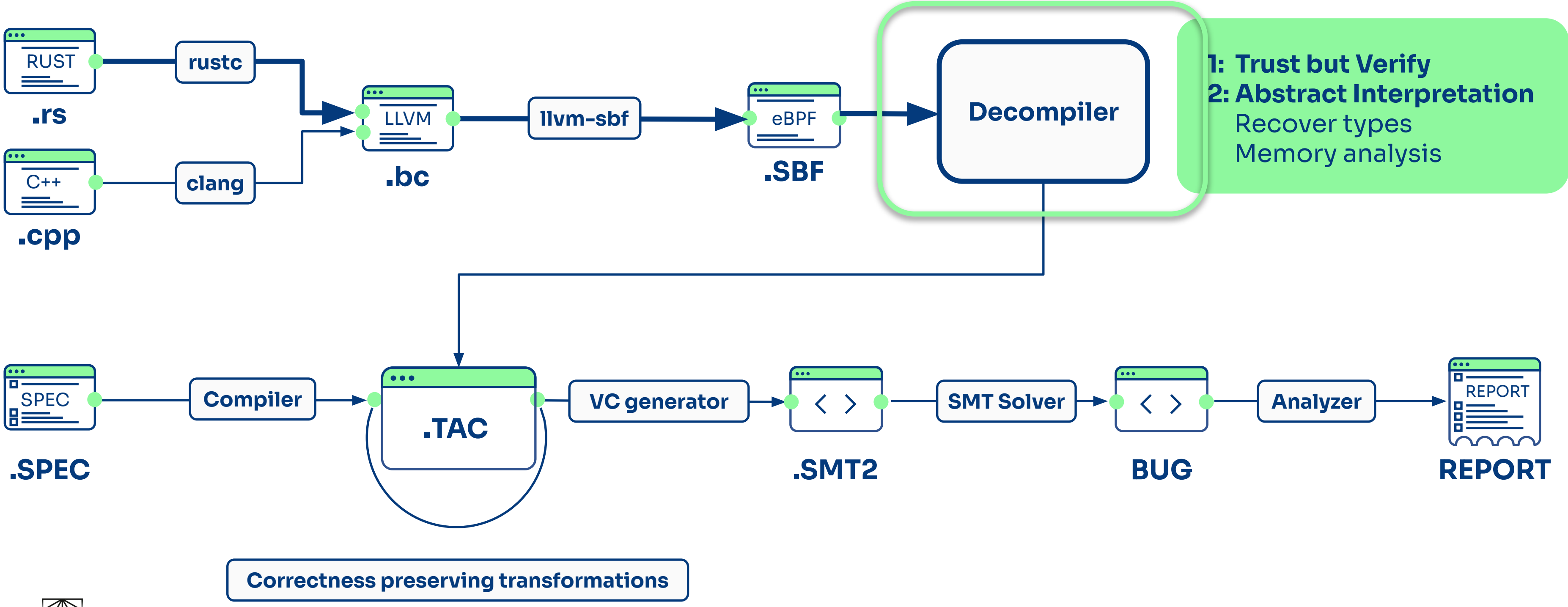
Certora Prover Architecture for Solana

In this talk



1: Trust but Verify
2: Abstract Interpretation
Recover types
Memory analysis

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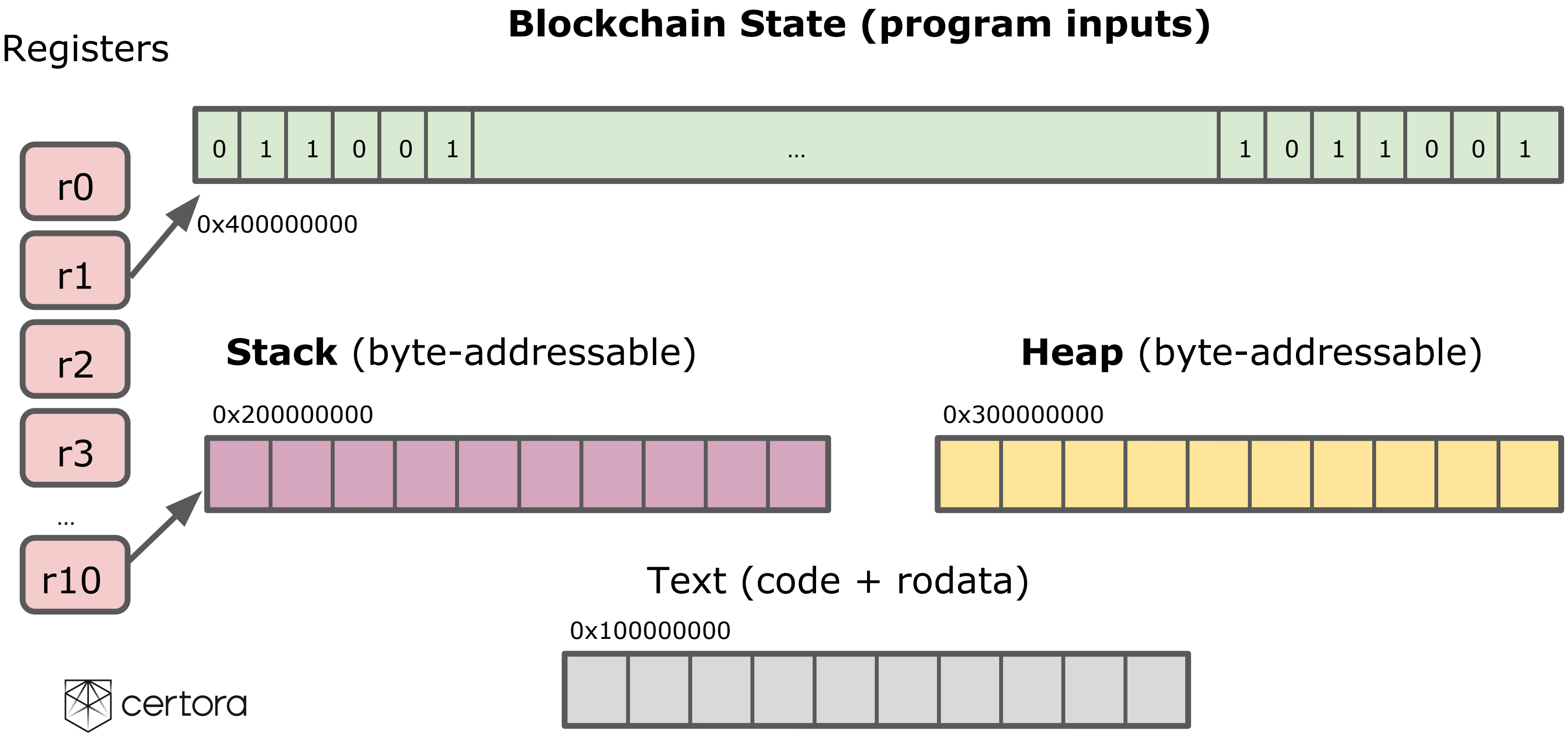
eBPF/SBF Virtual Machine



Registers

r0

r1

r2

r3

…

r10

Blockchain State (program inputs)

0 1 1 0 0 1 … 1 0 1 1 0 0 1

0x400000000

Stack (byte-addressable)

0x200000000

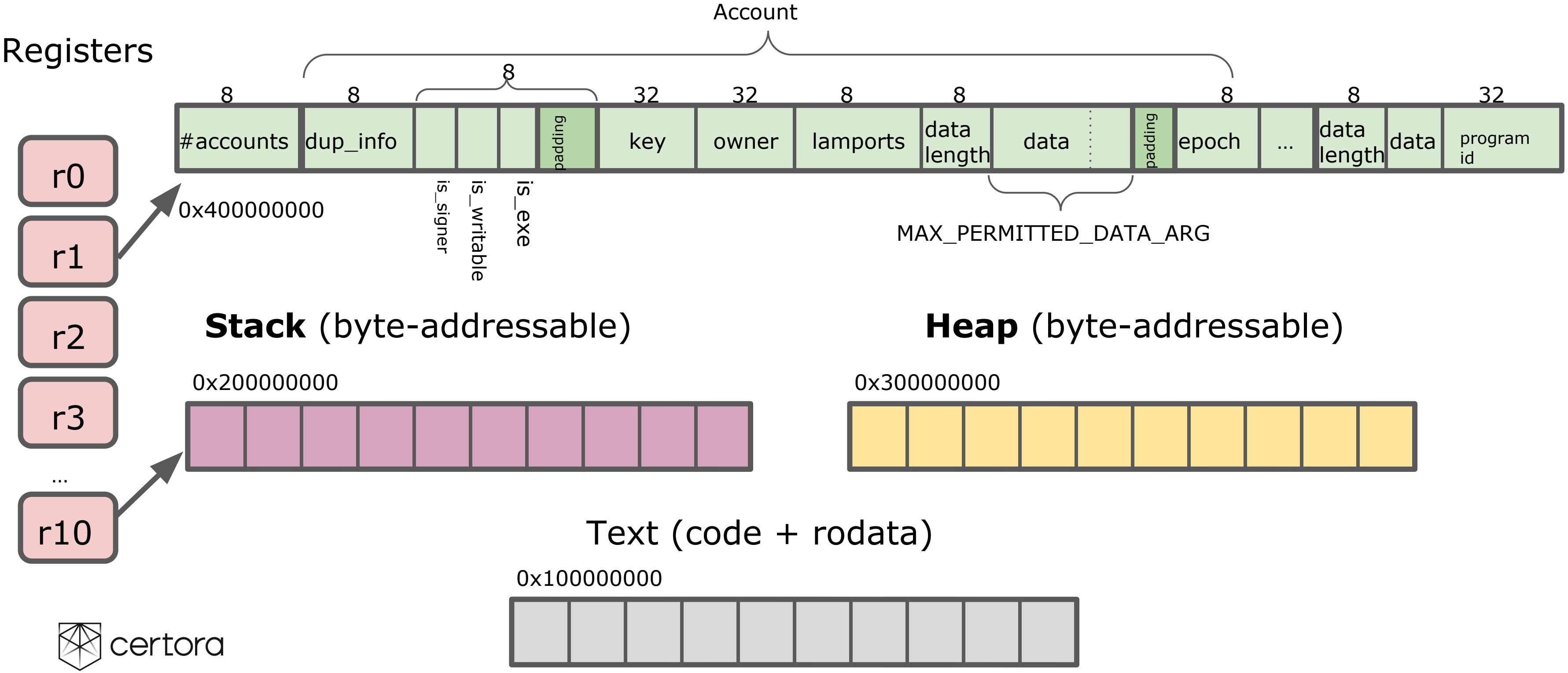
Heap (byte-addressable)

0x300000000

Text (code + rodata)

0x100000000

eBPF/SBF Virtual Machine



(Deserialized) Blockchain State

Account

8	8	8				32	32	8	8			8		8		32
#accounts	dup_info	is_signer	is_writable	is_exe	padding	key	owner	lamports	data length	data	padding	epoch	…	data length	data	program id

0x400000000

MAX_PERMITTED_DATA_ARG

Registers

r0

r1

r2

r3

…

r10

Stack (byte-addressable)

0x200000000

Heap (byte-addressable)

0x300000000

Text (code + rodata)

0x100000000

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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

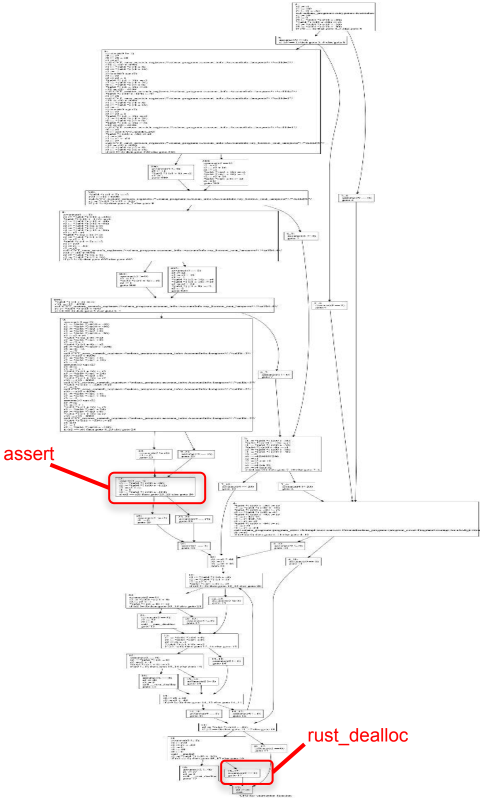
1. Translate ELF to a sequence of three-address instructions
    - Resolve Solana-specific relocations
2. CFG and Call graph construction: one per function
    - Indirect calls not supported
3. Inline all internal functions
    - Explicit modeling of call semantics
4. Compute Cone-of-Influence and slice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

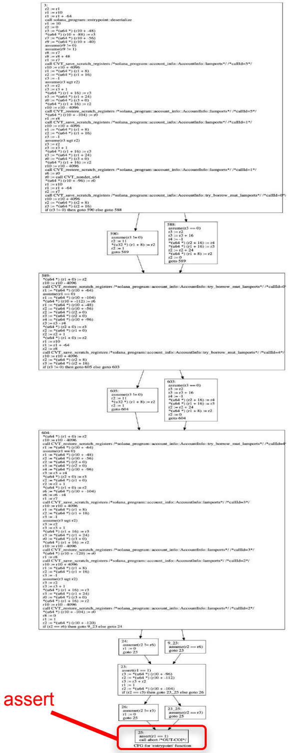
Memory Analysis Assumptions

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

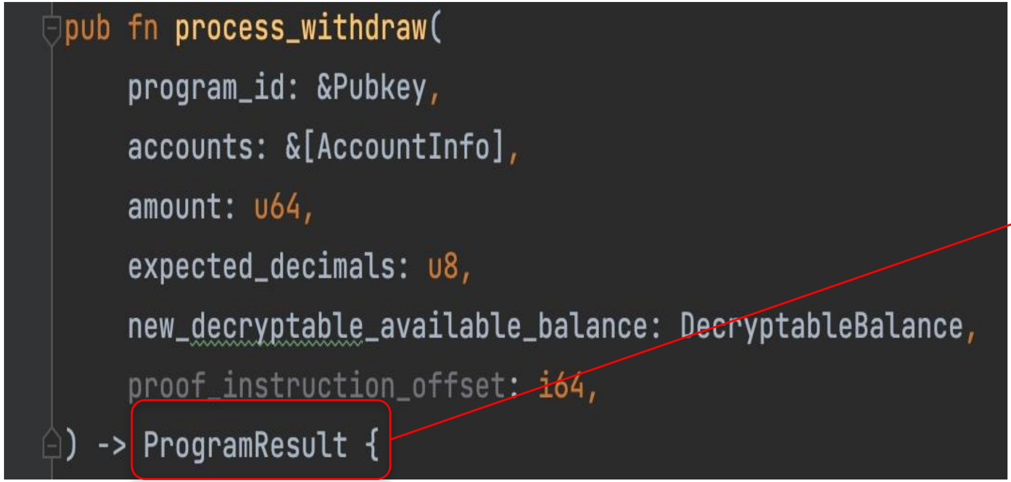




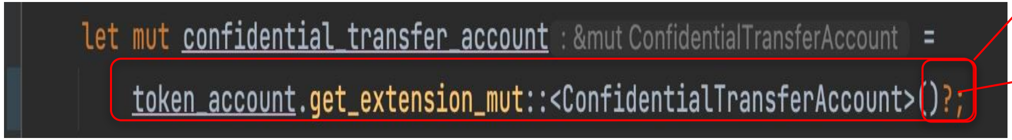
- Many irrelevant paths:
  - error paths
  - free pointers
- We only care about paths that can influence the evaluation of assertions

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

Rust enum types



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



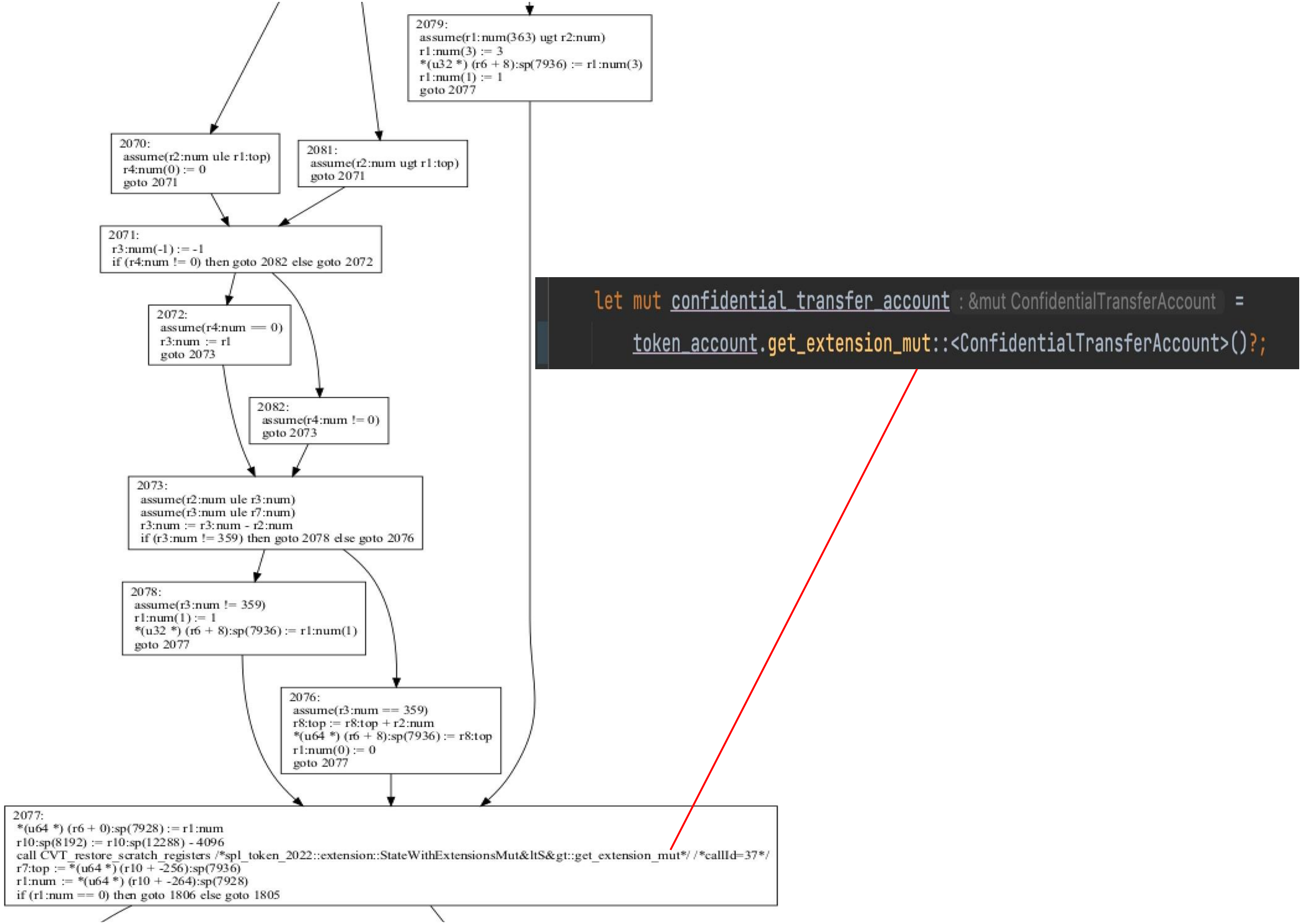
```
    let mut confidential_transfer_account : &mut ConfidentialTransferAccount =
        token_account.get_extension_mut::<ConfidentialTransferAccount>()?;
```

`Result<(),ProgramError>`

`Result<&mut V, ProgramError>`

question mark (`?`) operator

Rust enum types



```
2079:
 assume(r1:num(363) ugt r2:num)
 r1:num(3) := 3
 *(u32 *) (r6 + 8):sp(7936) := r1:num(3)
 r1:num(1) := 1
 goto 2077
```

```
2070:
 assume(r2:num ule r1:top)
 r4:num(0) := 0
 goto 2071
```

```
2081:
 assume(r2:num ugt r1:top)
 goto 2071
```

```
2071:
 r3:num(-1) := -1
 if (r4:num != 0) then goto 2082 else goto 2072
```

```
2072:
 assume(r4:num == 0)
 r3:num := r1
 goto 2073
```

```
2082:
 assume(r4:num != 0)
 goto 2073
```

```
2073:
 assume(r2:num ule r3:num)
 assume(r3:num ule r7:num)
 r3:num := r3:num - r2:num
 if (r3:num != 359) then goto 2078 else goto 2076
```

```
2078:
 assume(r3:num != 359)
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```
2076:
 assume(r3:num == 359)
 r8:top := r8:top + r2:num
 *(u64 *) (r6 + 8):sp(7936) := r8:top
 r1:num(0) := 0
 goto 2077
```

```
2077:
 *(u64 *) (r6 + 0):sp(7928) := r1:num
 r10:sp(8192) := r10:sp(12288) - 4096
 call CVT_restore_scratch_registers /*spl_token_2022::extension::StateWithExtensionsMut&ltS&gt::get_extension_mut*/ /*callId=37*/
 r7:top := *(u64 *) (r10 + -256):sp(7936)
 r1:num := *(u64 *) (r10 + -264):sp(7928)
 if (r1:num == 0) then goto 1806 else goto 1805
```

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let mut confidential_transfer_account : &mut ConfidentialTransferAccount =
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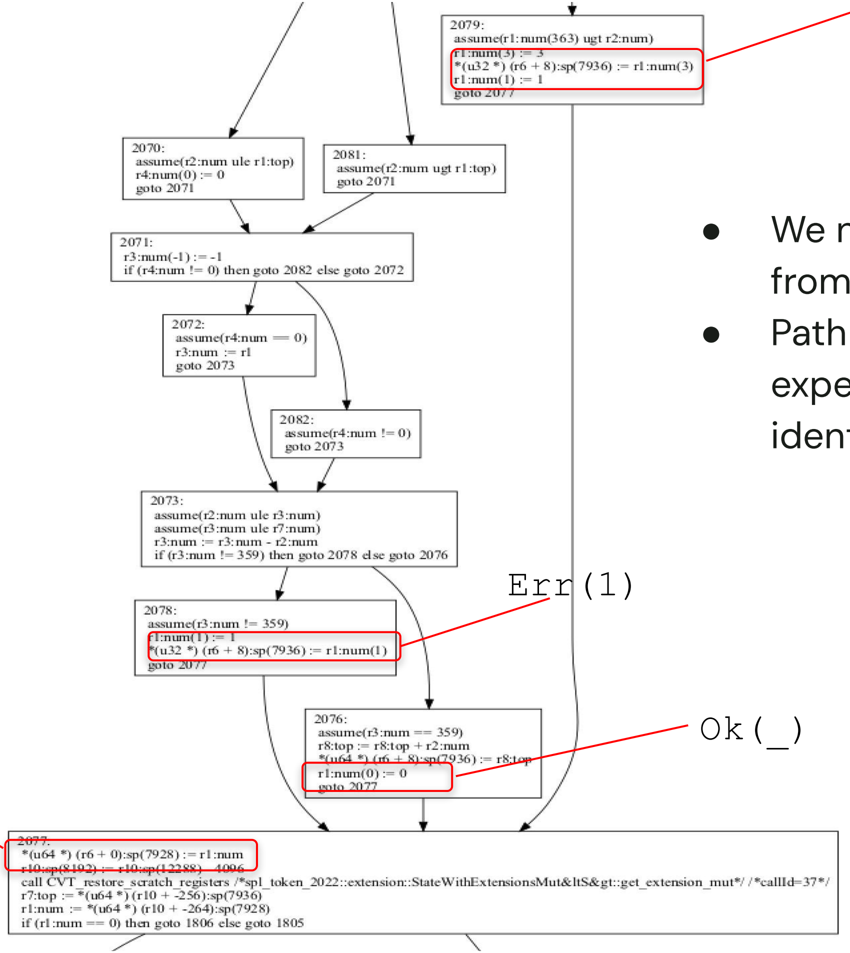
Rust enum types



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```

`Err(3)`

`Err(1)`

`Ok(_)`

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

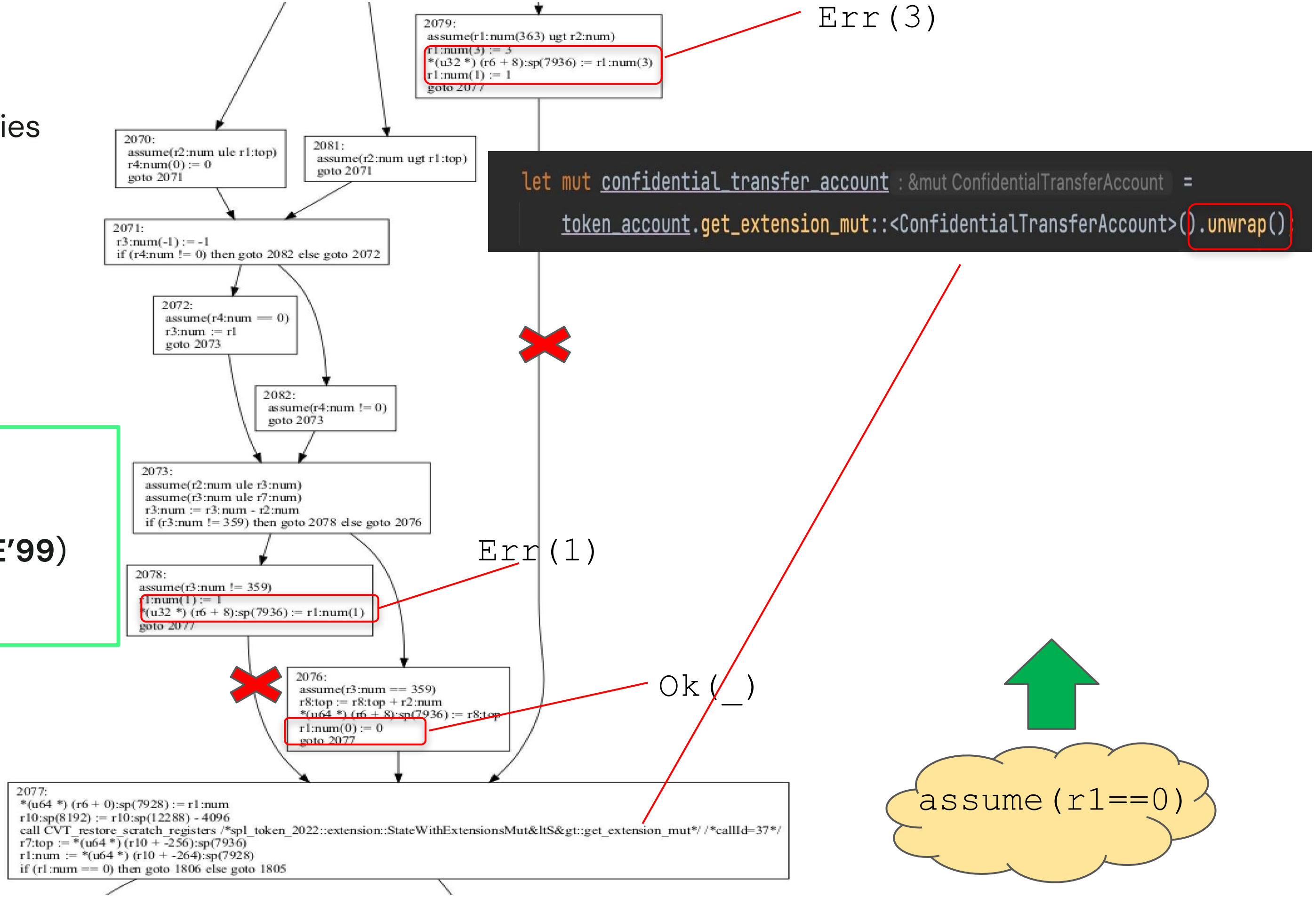
`r1` is the discriminant

0 = `Ok`

1 = `Err`

Rust enum types

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



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

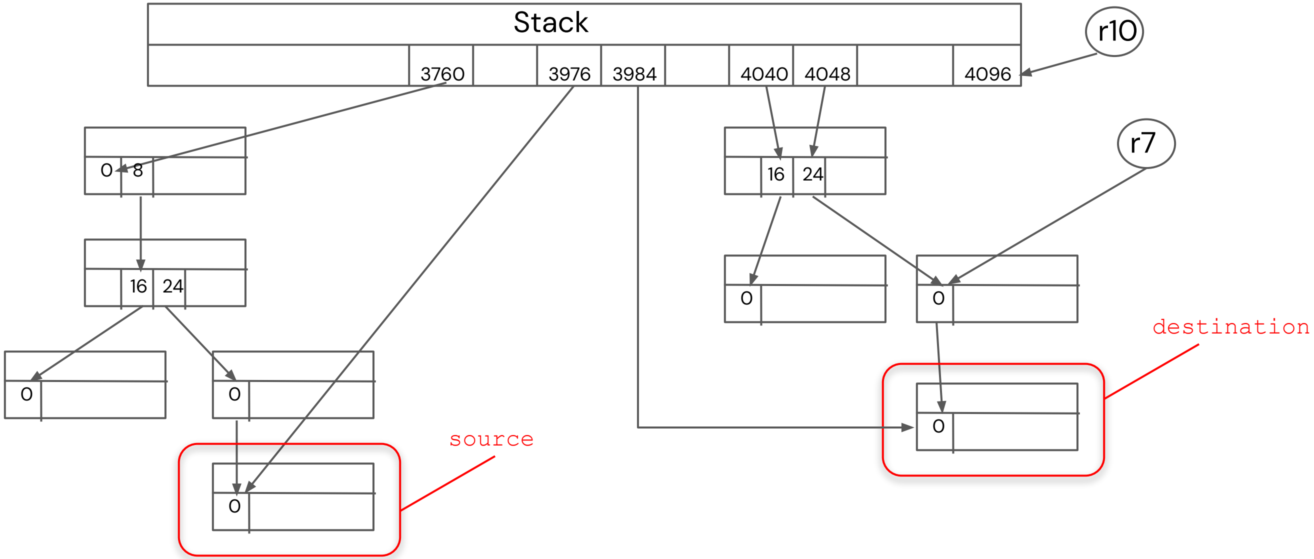
Solution: iterative forward+backward analysis (**Cousot&Cousot JLP'92/ASE'99**) to prune error paths

Analysis of SBF code

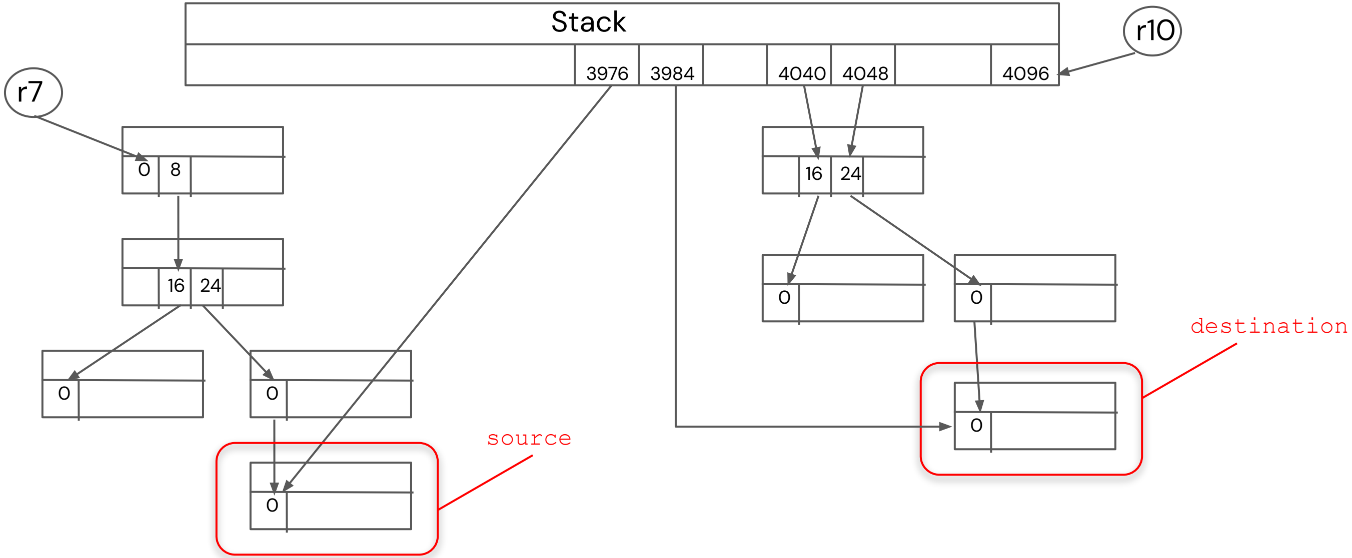
- Disassembler needs to translate SBF into a TAC program **without side effects**
  - TAC memory operations have an explicit argument “mem” that represents the (possibly infinite) set of memory locations being accessed
  - Two TAC memory ops do not alias if they have different “mem” names
- How: static 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



Analysis of SBF code



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

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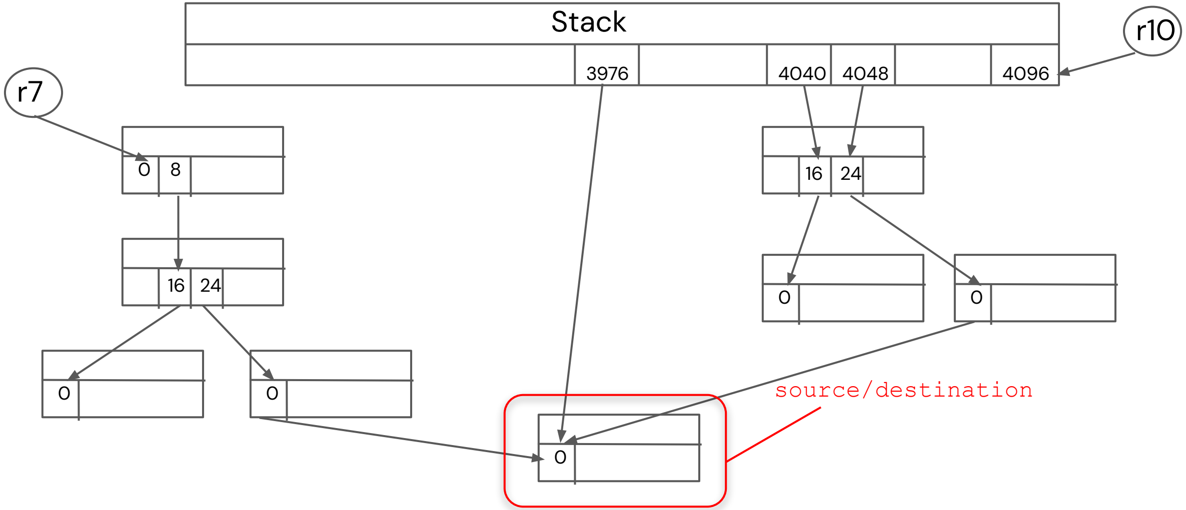
Analysis of SBF code



- 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`

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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