Proving un-exploitability of parsers

An imaginary roadmap for unknown territories

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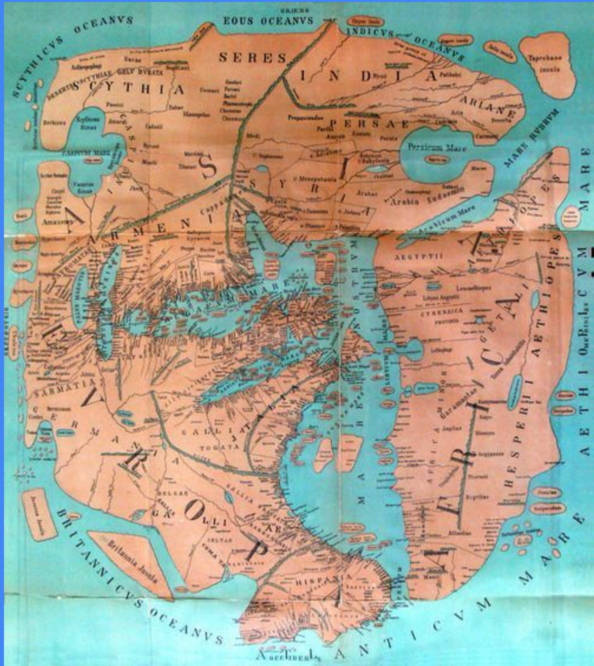
Google Project Zero



Introduction

- Wrote my first “exploit” in 1998
- Trained as a mathematician (cryptography, computational commutative algebra); some background with abstract interpretation etc.
- Since 2009 or 2010 increasingly interested in fundamental questions - “what is an exploit” ? - necessary to formalize “folklore”
- Work on “exotic” exploits (Rowhammer, JS Bytecode corruption etc.)

Introduction

- During sabbatical 2015/2016 and after my return to P0 I wrote a paper about theoretical foundations of “exploitability” and “weird machines”
- “Weird machines, exploitability, and provable unexploitability” [Paper][Talk]
- Key results of the paper:
    - Formalisation of “what is an exploit”
    - Formalisation of intended machines & weird machines
    - Insight that exploitability is a mostly orthogonal concept to correctness
    - Non-exploitability can be proven in some extremely restricted cases

What comes next?

- Results in the paper are quite “weak”
- 60%+ of the paper is just introducing concepts, clarifying definitions, and “learning to walk” with those definitions
- Now that we have the machinery, and have made the first two wobbly steps, where do we want to go?

This talk

1. **Recap** of the key concepts from the paper
2. What were the **important tricks** that helped us prove non-exploitability in the restricted case?
3. What extra scaffolding would we need if we wanted to prove non-exploitability of something more complex - like a parser?

This talk

1. **Recap** of the key concepts from the paper

2. What w itability in
   the res

Highly speculative and likely incomplete and wrong.

3. What extra scaffolding would we need if we wanted to prove non-exploitability of something more complex - like a parser?

Recap: Key concepts from the paper

Intended finite state machine (or transducer)

IFSM

Software PROG as emulator to simulate IFSM on real CPU

Concretization mapping: IFSM state to set of possible CPU states that represent it.

Abstraction mapping: Partial mapping from CPU states to valid IFSM states.

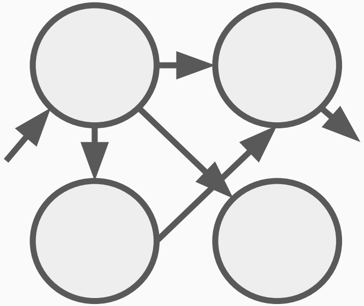
Sane, transitory, and weird states.

Security Properties as assertion over results of a game between ...

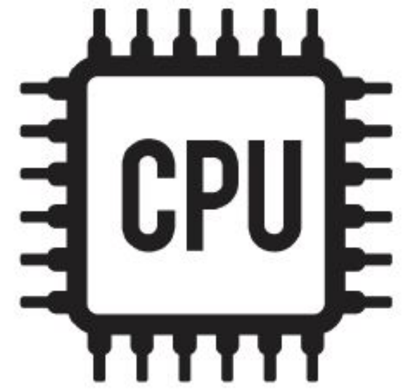
… two dueling transducers.

Weird machine programming

Intended Finite-State Machine (or transducer)



What I want



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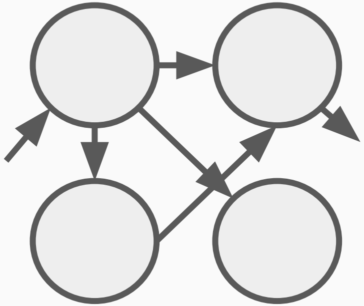
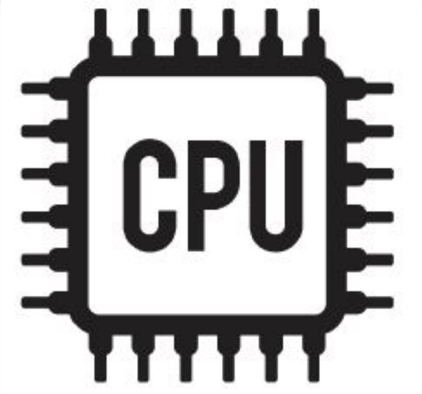
Instantiation mapping



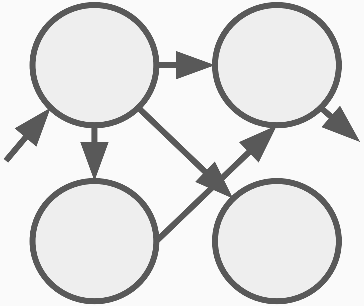
What I need



What I have

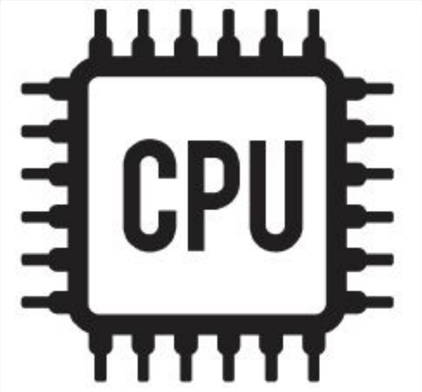
$$\gamma\theta, cpu, \rho : Q_\theta \rightarrow \mathfrak{P}(Q_{cpu})$$

Abstraction



What I need

partial



What I have

$$\alpha_{\theta,cpu,\rho} : Q_{cpu} \to Q_{\theta}$$

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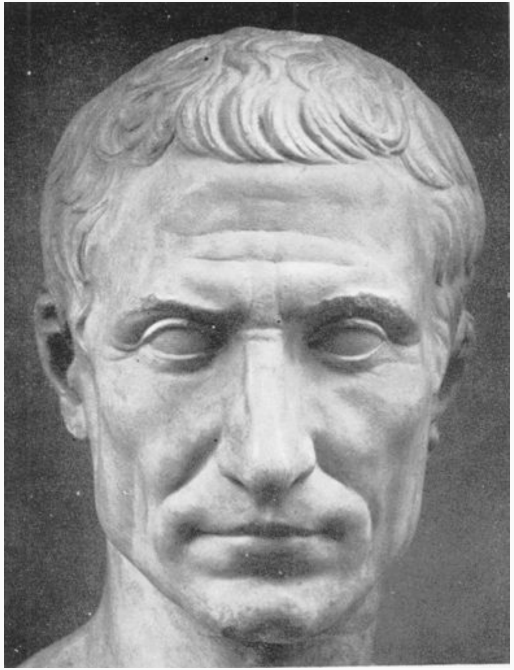
Sane, weird, and transitory states



CPU state space est omnis divisa in partes tres:

$$Q_{cpu} = Q_{cpu}^{\text{sane}} \dot\cup Q_{cpu}^{\text{trans}} \dot\cup Q_{cpu}^{\text{weird}}$$

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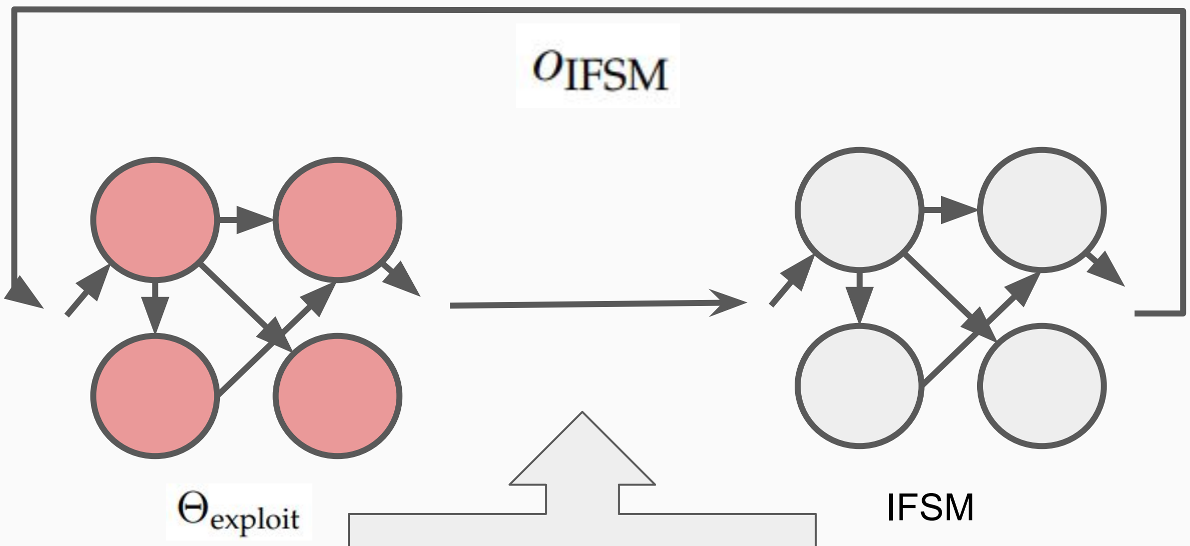
Dueling transducers

Output of the IFSM is sent to the exploit.



Output of exploit is sent to the IFSM to interact with it.

Security properties

- Define the game between the dueling transducers.
- Decide what you do not want to happen.
- Phrase this as statement about the communication between the transducers and the possible final states of the IFSM
- This “game structure” is adopted from security proofs in Cryptography

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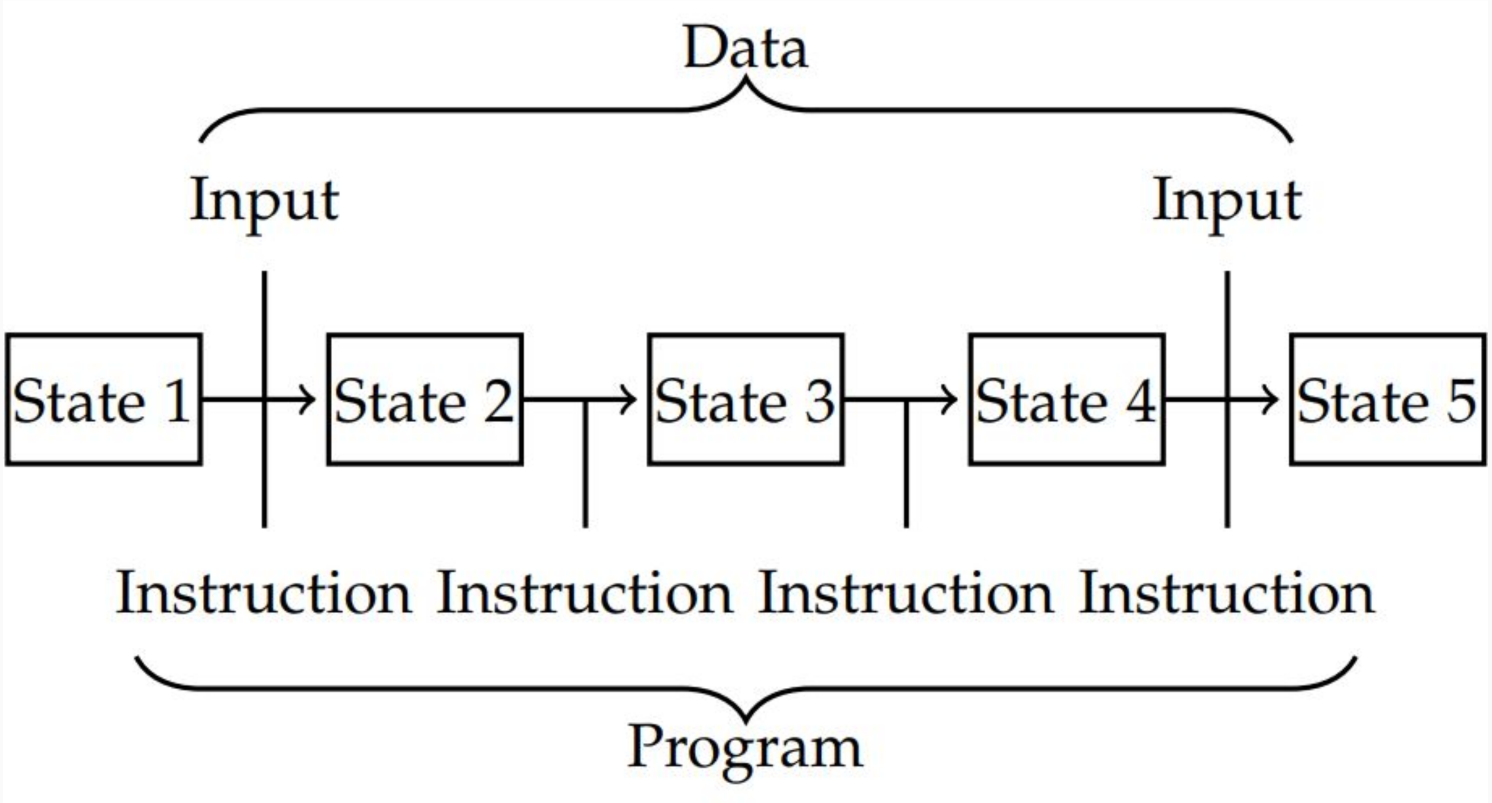
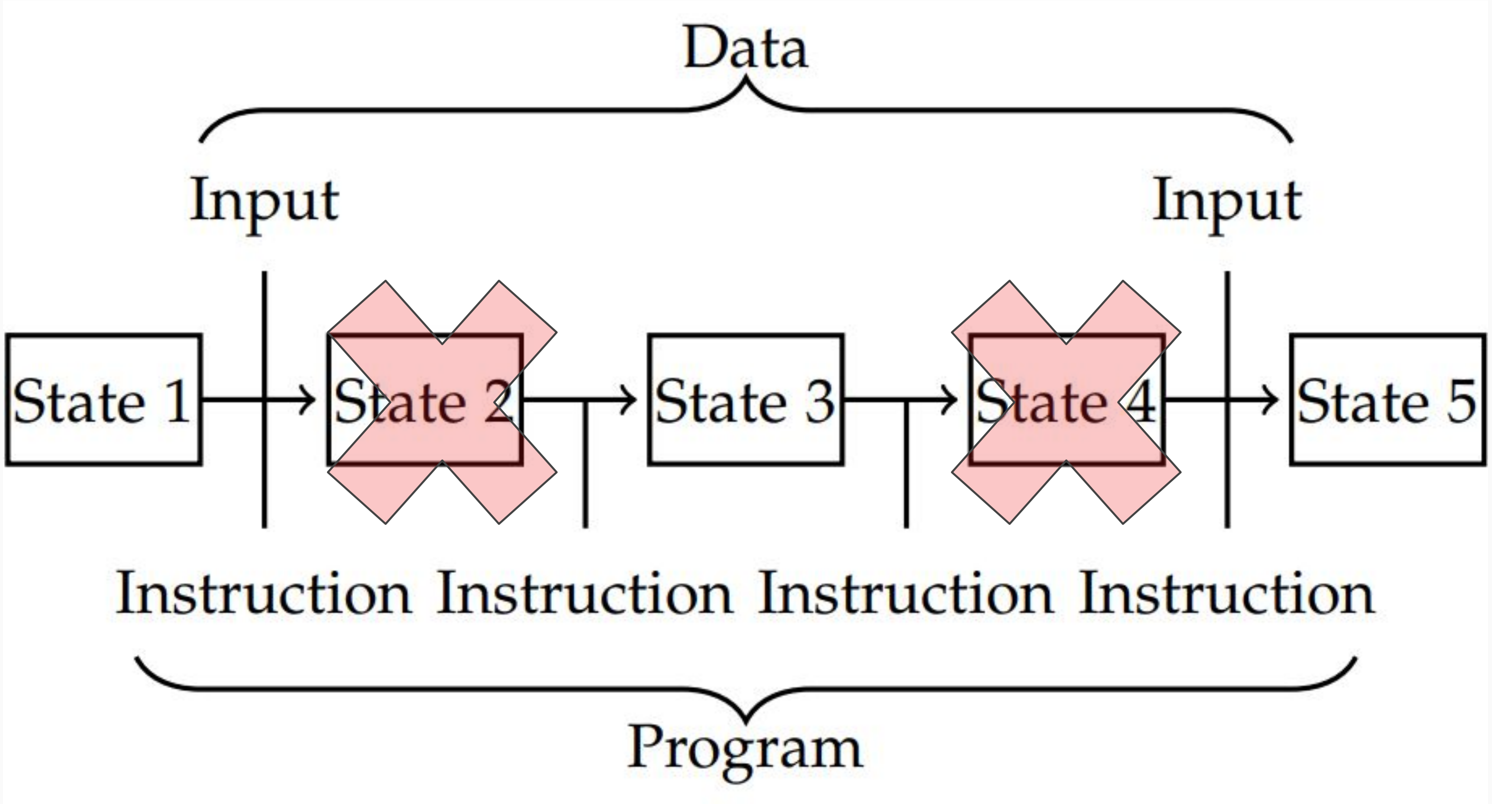
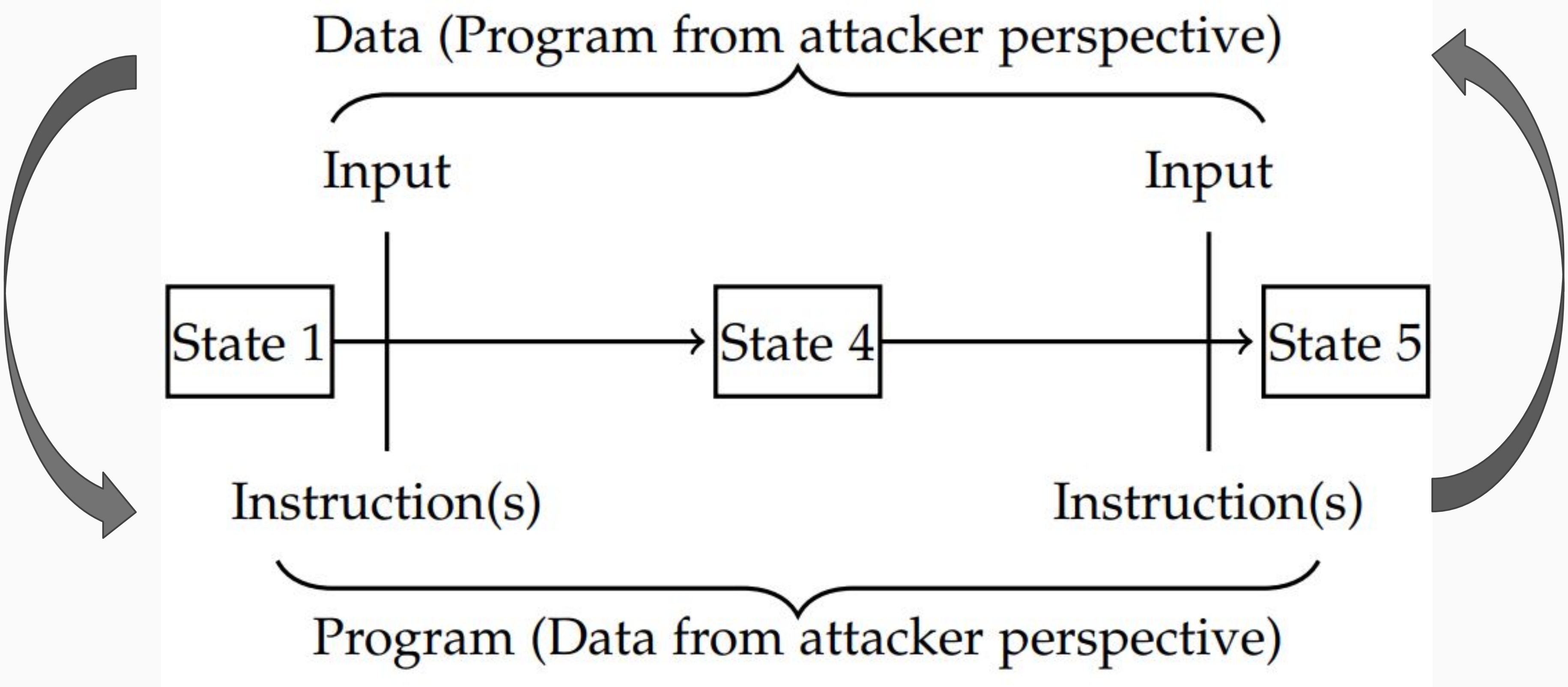
Classical view of programming



Classical view of programming



Attacker view of programming



Data (Program from attacker perspective)

Input

Input

State 1

State 4

State 5

Instruction(s)

Instruction(s)

Program (Data from attacker perspective)

Attacker view of programming

There is now a new computational device: ***The weird machine.***

- Transforms states in Q_{cpu}^{weird} via emulated transitions designed to transform IFSM states.
- Takes the input stream of the IFSM as instruction stream
- $Q_{cpu}^{\text{sane}} \cup Q_{cpu}^{trans}$ are terminating states for the weird machine (because the IFSM resumes execution)

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Example in the paper: Secret-keeping machine

- Simple IFSM that keeps up to 5000 pairs of (password, secret).
- Attackers should not be able to retrieve a secret for which they do not know the password faster than guessing.
- Attacker model: Attacker is allowed to corrupt one chosen bit, exactly once.
- Two implementations: One linked-list based (exploitable), one based on flat arrays that are linearly traversed that can be proven “unexploitable” by that attacker.

Game in the paper:

- Game flow:
  a. Attacker chooses a distribution over finite-state transducers that have as input alphabet the output alphabet of the IFSM, and that have as output alphabet the input alphabet of the IFSM
  b. Defender draws p, s uniformly at random from $bits_{32}$
  c. Attacker draws a finite-state transducer Θ_{exploit} from his distribution and connects it to the IFSM. The transducer is allowed to interact with the IFSM for n_{setup} steps
  d. The defender sends p,s to the IFSM
  e. The attacker is allowed to have his transducer interact with the IFSM for n_{exploit} steps. **At any step, but only once, he is allowed to flip an attacker-chosen bit in memory (not in registers).**

Idea underlying the proof of non-exploitability

- Begin by showing (or assuming) that attacker without bit-flip cannot violate security properties (get secret much faster than guessing)
- Assume attacker with bit-flip **can** violate security properties (e.g. get secret much faster than guessing)
- Demonstrate that anything that can be achieved by the attacker with bit-flips **could also** be achieved by an attacker without bitflips with just a small overhead.
- **Contradiction**. This shows that an attacker with bit flips cannot get a significant advantage over an attacker without bit flip.

Proof sketch

- Cleverly summarize possible states of CPU/PROG into a few understandable equivalence classes.
- Show that attacker memory corruption can only lead to a few different equivalence classes of weird or sane states.
- Show that all sane -> sane transitions attacker can cause can be emulated by the weaker attacker.
- Show that all weird -> weird -> weird … transitions reach only a controlled number of equivalent states; show that any output could also be emulated by the weaker attacker.

Paper result ...

- For a very simple and limited IFSM ...
- … and a restricted, but also powerful memory-corrupting attacker ...
- … it is possible to prove unexploitability

What next?

… Sergey asked me ...

… “can you talk about how one could prove non-exploitability of parsers?”

Like asking someone who travelled twenty miles by feet “what is the best way to walk to India from here?”

Here be dragons.

Non-exploitable parsers

- A parser is a transducer that emits a program state at the end
- Any sane input language should lead to a formally-describable IFSM
- Safe compilation from IFSM-description to emulated IFSM is necessary
- This can, if done properly, yield a **correct** parser.

Non-exploitable parsers

- Exploitability is mostly orthogonal to correctness
- A correct program can be exploitable if an attacker has the means to enter a weird state (hardware fault etc.)
- An incorrect program gives the attacker means to enter weird states
- What would we need to build a compiler that can compile a spec of an IFSM to a **non-exploitable** implementation PROG ?

Ingredients needed

- Spec of the IFSM, specification of CPU
- Security Game
- Security Properties
- Attacker model for the weak and strong attacker

Security properties for parsers

- Parsers map input sequences to program states
- A good security property for parsers could be:

No attacker should be able to get the parser to emit an invalid state.

Recipe for proving non-exploitability ...

- Show that PROG (and/or IFSM) preserves the security property against the weak attacker. This should be comparatively “easy”.
- Show that all sane-to-sane transitions the the strong attacker can cause are either intended sane-to-sane transitions, or can be emulated easily by a weak attacker.
- Show that the strong attacker can only cause weird-weird transitions to a small number of equivalence classes of weird states, cannot produce output from the weird states, and when reverting back to a sane state only achieves a transition achievable by a weak attacker.

What would the compiler need to do?

The compiler will need to do the heavy lifting of ensuring that only a few, well-specified equivalence classes of states are reachable.

Controlling **sane** transitions

- **Controlling sane transitions:** Ensure that the attacker can only achieve benign sane-sane transitions. Can probably be done with clever design & layout of data structures in memory.

- Will be very dependent on precise semantics of CPU, and precise capabilities of the attacker

Controlling **weird** transitions

- Ensure that any program state that can be emitted using transitions through weird states can be emitted without those transitions.

- Easiest solution if computational cost is not an issue: Build code that can check whether CPU state is sane, run it before consuming a byte of input.

- Memory tagging is a much weaker, probabilistic variant of this.

- Sanity checks on data structure internals before operating on this are also weak, probabilistic variants of this.

Other possible avenues

- Validating CPU state is sane may be too expensive?
- Commonly done in some high-security embedded circuits (failure on invalid combination of state bits)
- Is doing this cheaply in software possible?
- Is there another way - perhaps “trapping” the attacker in a few harmless equivalence classes of weird states?

Closing words

- We are only slowly coming to grips with what “exploitation” means
- Computers are big recurrence equations that tend to exhibit deterministic chaos
- Security implies making sure that only few points in the state space are reachable, and that those points are well-understood
- Please take my speculation on “the way forward” with a rather huge grain of salt. Sergey Bratus made me do it.

Questions?