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Evolutionary Heuristics for Fault Injection Parameter Space Search

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*Umjesto ove stranice umetnite izvornik Vašeg rada.
Da bi ste uklonili ovu stranicu obrišite naredbu \izvornik.*

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1. Introduction

The field of cryptography is a pretty large and well-developed one. As it is with most such fields, doing anything of worth means going down a rabbit hole into progressively greater and greater detail, until it becomes hard to describe where you are to someone standing on the surface.

This thesis is an attempt at covering one particular path down the rabbit hole.

Its structure is roughly this:

Chapter 1 lays out the general motivation and the current state of the art;

Chapter 2 contains some technical prerequisites, covering evolutionary algorithms (and genetic algorithms in particular), fault injection, and SHA-3;

Chapter 3 presents the setup I've used and describes the parameter space and the problem at hand;

Chapter 4 deals with the optimization algorithm, the simulator built to aid experimentation, and the results obtained;

Chapter 5 presents the procedure of exploiting the faulty outputs, and covers the exploitation part of the results

Chapter 6 just wraps it all up, and presents directions for future improvements.

1.1. Motivation

Cryptography is ubiquitous; as technology keeps advancing, the normal functioning of key infrastructure now depends on cryptographic algorithms. Billions of people worldwide rely on it daily to protect not only commerce, but also their privacy. But even with good cryptographic primitives, new attacks keep being discovered, commonly against implementations.

Zooming into this picture for something more concrete, we may find a service provider running attacker’s code on the same machine as a vulnerable encryption library, just waiting for a cache-timing side-channel attack; or a TLS implementation that will courteously say when the padding is wrong, thus letting an attacker steal a session; or perhaps, a smartcard that can be persuaded by a carefully placed glitch in its power supply to give out its secret PIN.

Surely, no one would want their bank account emptied just because someone had physical access to their debit card. But attacks like these do exist, and it’s this last case that’s most relevant for this thesis: fault attacks.

They’re usually not the easiest thing to do, and one part of *why?* is picking the right parameters. The core part of this thesis concerns finding a good algorithm for picking the parameters, and (if possible) mounting a successful fault attack.

This thesis is partly based on [18], and hence reuses some of the material.

1.2. Related work

While a lot of work has been done on fault injection itself (see e.g., [13, 8, 23, 2, 19]), very little of it concerns parameter optimization.

In [17], the authors develop an EMFI susceptibility criterion, which they use to rank the points of the chip surface depending on how susceptible they are to fault injection. The underlying assumption for the criterion is the Sampling Fault Model, described in [20]. The Sampling Fault Model could be summarized thus: faults are (mostly) induced by violating the setup time constraint of D-type flip-flops, and the length of the time window for fault injection does not depend on the clock frequency. (Early on during development, I considered this might provide a way to substantially decrease the search space size in the time-offset dimension; the practical problems of synchronizing to the internal clock and the comparatively low time resolution of the equipment ensured that this direction was not pursued.) The criterion itself is a combination of Power Spectral Density (measuring emitted power at the clock frequency) and Magnitude Squared Incoherence (measuring how linked the emitted signal is to the data being processed), weighted with a configurable parameter a like so:

$$emfisc_{x,y} = \sqrt{a \cdot psdn_{x,y}^2 + (1 - a) \cdot incn_{x,y}^2}$$

where $psdn$ and $incn$ are normalized Power Spectral Density and Magnitude Squared Incoherence, respectively.

They use a grid scan (in the 2 spatial dimensions) to measure all the points and rank them according to the criterion; a share α of the highest-ranking points are kept for further scanning; the rest is thrown away. They are able to reject over 50% of the chip surface (75% in their best case), while keeping 80% of the points causing faults. Figure 1.1 shows their coverage ratio – the share of preserved faulty points – dependent on α . However, note that by *fault*, they mean *any* perturbation of the normal behaviour of the algorithm.

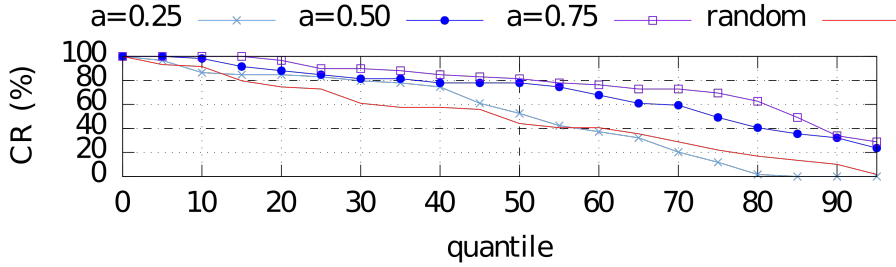


Figure 1.1: coverage ratio vs. α for EMFISC

In [9], the authors use several different methods to the problem of parameter optimization for supply voltage (VCC) glitching. They work with 3 parameters: glitch voltage, glitch length, and time offset. They reduce the dimensionality of the problem by splitting the search in two stages, effectively solving a “2.5-dimensional” problem, so to say. In the first stage, they look for the best (glitch voltage, glitch length) combination, i.e. the most promising shape of the glitch. All parameters not explicitly specified – in this case, time offset and the number of glitch repetitions – are set as random. In the second stage, 10 most promising (voltage, length) combinations are tried at each point in the specified time range (which is discretized into 100 instants), i.e. they perform a grid search in the time offset dimension.

The methods are compared at the first stage – random search, FastBoxing and Adaptive zoom&bound algorithms, and a genetic algorithm. While Adaptive zoom&bound comes out as the best strategy of these, the genetic algorithm shows some promise.

That work is extended in [21] where the authors use a combination of genetic algorithm and local search (called a memetic algorithm) in order to find faults even more efficiently. The authors consider power glitching with 3 parameters and are interested in fast characterization of the search space.

The evolutionary algorithm developed for the purpose of this thesis builds on

the ideas of the latter two papers.

2. Prerequisites

In order to understand what was done and how, several things must be understood first. These are:

1. genetic algorithms, used here for optimization
2. fault injection (FI) in general
3. the SHA-3 hash function, which is exploited here using algebraic fault analysis
4. algebraic fault analysis (AFA), which is used in conducting a real attack

SHA-3 and AFA are exposed first, so as to not interrupt the exposition of FI.

2.1. SHA-3/Keccak

In 2015., after a competition to choose the next SHA (Secure Hash Algorithm) algorithm, NIST standardized Keccak [5] as SHA-3. Strictly speaking, SHA-3 is not one algorithm, but several, which all share the same internal structure, and differ in a few parameters.

Its predecessors, SHA-1 and SHA-2, as well as some earlier algorithms which weren't standardized but are still widely used (MD4, MD5), were based on the Merkle-Damgård construction [10]. Figure 2.1 shows the general concept: the algorithm operates on blocks of data of size B . There exists an underlying function f , called the *compression function*, which takes $2B$ bits of input and produces B bits of output. f is essentially a small hash function itself, but one with fixed-length input and output, which the Merkle-Damgård construction uses to build a “big” hash function, with arbitrary-length input. It can be proven that the “big” hash function will be collision-resistant if and only if the compression function is collision-resistant [3].

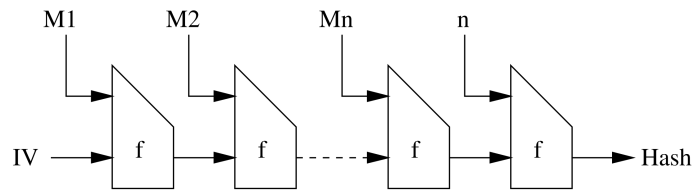


Figure 2.1: the Merkle-Damgård construction

SHA-3, however, is based on a different construction called a *sponge*. It's called a sponge because unlike the Merkle-Damgård construction, which takes an arbitrary amount of input and puts out a fixed-length output at the end, the sponge can alternate between taking in chunks of input (*absorbing*) and putting out chunks of output (*squeezing*); it has arbitrary-length output as well as arbitrary-length input. This is nicely illustrated in Figure 2.2.

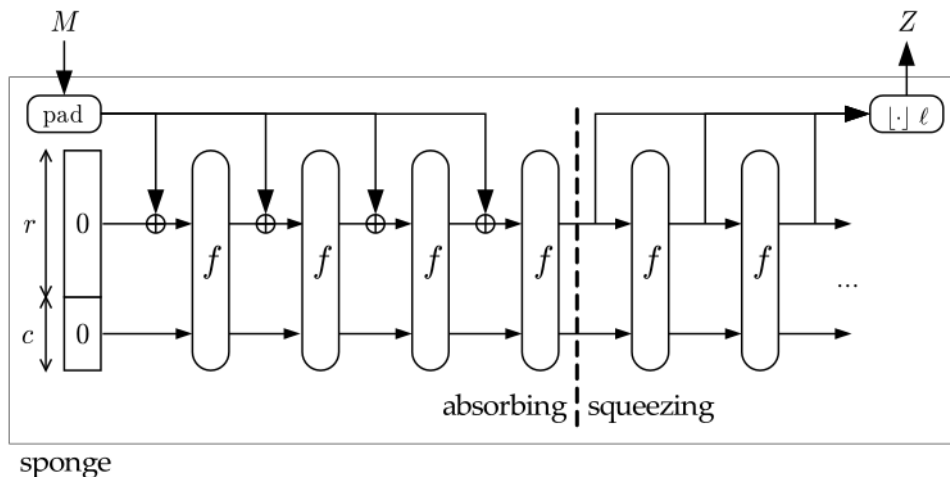


Figure 2.2: the sponge construction

Another way to put it would be this: the Merkle-Damgård construction has a compression function munging its internal state as well as chunks of input; the sponge has a permutation mixing its internal state with chunks of input, then mixing its internal state while spitting out chunks of output.

With traditional hash functions, security is expressed in terms of number of output bits: a hash function with an n -bit output is supposed to have $n/2$ bits of security, i.e. the easiest attack has a complexity of $O(n/2)$. This corresponds to having a random oracle output n bits, and attacking it with the generic attack which relies on the birthday paradox.

But here, expressing its security in such a way obviously wouldn't make sense: with an arbitrary-length output, it would mean that we can get an arbitrarily

high level of security merely by squeezing more bits out of the sponge. Instead, this is expressed as a single parameter of the sponge construction.

2.1.1. The Keccak- $f[b]$ permutation

The central part of the sponge construction is the permutation. Keccak uses the Keccak- $f[b]$ permutation, where b is the size of its internal state; this is also called the *width* of the permutation. In the variant standardized as SHA-3, $b = 1600$. We define two parameters: **rate** (r) and **capacity** (c), with the constraint that $r + c = b$. The sponge will absorb r bits of input for each invocation of the permutation by XOR-ing the chunk of input with the first r bits of the internal state; the rate essentially tells us how fast is the input processed. The last c bits of the state are never directly touched from the outside, and are never output; the output is taken again from the first r bits of the state. Capacity is the single parameter that sums up the security level: $c/2$ bits for collision resistance, c bits for preimage and second preimage resistance. Several concrete SHA-3 hash functions are defined with different capacities, denoted SHA3- c : SHA3-224, SHA3-256, SHA3-384, and SHA3-512. Only the last one, SHA3-512, will be considered in this thesis.

And now, for the definition of the relevant variant of the permutation itself: the Keccak- $f[1600]$ is a sequence of operations on a 1600-bit state A , which we can represent as a three-dimensional array of bits: $A[5, 5, 64]$. Coordinates x and y should be taken modulo 5 and coordinate z should be taken modulo 64. If an index is omitted, this means the statement is valid for all values of the omitted indices, e.g. $A_{(x,z)}$ refers to the column of bits having coordinates of the form $(x, *, z)$. Figure 2.3 shows the notation used for different parts of the state.

The permutation is an iterated one, consisting of 24 rounds of R , where

$$R = \iota \circ \chi \circ \pi \circ \rho \circ \theta$$

is composed of five smaller phases:

θ – each bit $A_{(x,y,z)}$ is XOR-ed with the parities of neighbouring columns $A_{(x-1,z)}$ and $A_{(x,z-1)}$

ρ – a rotation along the z -axis, i.e. each lane (a 64-bit word) gets cyclically shifted by a certain amount

π – a permutation within each slice $A_{(z)}$

χ – a nonlinear operation, where a bit $A_{(x,y,z)}$ is flipped if the two bits two its right form a “01” pattern, i.e. it is XOR-ed with $\overline{A_{(x+1,y,z)}} \cdot A_{(x+2,y,z)}$

ι – an XOR with a round constant

You may notice how the algorithm is able to do most of the work just by operations on the 64-bit lanes, and largely independent ones at that: θ works only in columns, ρ only in lanes, χ only in rows, and π and χ only in slices. In fact, their composition $\chi \circ \pi$ merely rearranges the lanes, which implementations do “for free” by just swapping the lanes’ indices. Only bitwise operations (AND and XOR) are used, making the Keccak permutation easy to implement in hardware. Note that bitwise XOR and bitwise AND are occasionally referred to in literature as addition and multiplication in $GF(2)$, the Galois field of order 2.

For more details on Keccak, see [5].

In the rest of the thesis, I will refer to e.g. input of into π in round 14 and output of θ in the final round, as π_i^{14} and θ_o^{23} , respectively.

2.2. Algebraic fault analysis

Differential fault analysis (DFA) is an established technique for attacking cryptographic algorithms, introduced over twenty years ago in [6]. It assumes that a fault has occurred at a specific point in the execution of the algorithm, and analyzes the propagation of a *difference* between the original state and the new, faulty state. It has been applied to many well-known algorithms with great success, such as DES [6], AES [11, 24], and the SHA-1 compression function [12]. The direct predecessor of the DFA attack was used to break RSA [7]. SHA-3, likewise, has been shown to be vulnerable to fault injection with DFA, first with single-bit faults [4], and later with byte faults [15].

However, DFA can be very cumbersome, requiring complex and tedious analysis of how the differential propagates through the algorithm. Even with an algorithm such as Keccak, with algebraically simple internals, the differential propagation is not exactly easy to follow.¹

Algebraic fault analysis (AFA) sidesteps this problem. Instead of manually analyzing the propagation, AFA uses an appropriately constrained SAT solver. That is, it:

¹The reader is certainly invited to give it a try — the byte-fault propagation in [15] is quite bearable.

1. encodes (part of) the cryptographic algorithm as Boolean statements
2. encodes the fault model (assumptions about the fault: its position and effect) as Boolean statements
3. gives the above to the SAT solver as constraints
4. gives the (good output value, bad output value) pair to the SAT solver as constraints
5. uses the SAT solver to do the work of calculating the implied secret bits

SHA-3 is successfully attacked in [16] using AFA, and the attack is extended to an even more relaxed fault model (a 32-bit one) than was possible with DFA, since AFA makes better use of the faulty outputs. A more detailed description of AFA as it applies to SHA-3 specifically is given in chapter 5.

2.3. Implementation attacks and fault injection

Cryptographic algorithms that are perfectly safe in theory can be successfully attacked in practice by attacking not the algorithm itself, but its implementation. Any implementation which exists in the real world is a perfect black box: it can be observed and interacted with outside of its nominal inputs and outputs.

Implementation attacks can be roughly divided into passive and active ones.

Passive attacks, also called *side-channel attacks* (SCAs), do not interfere with the execution of the cryptographic algorithm, but observe the effects the implementation has on its surroundings, which leak secret information. There are many: power consumption, electromagnetic radiation, timing, even sound. These (unintended) side effects can be thought of as transmitting secret information over a noisy channel, hence the name.

Active attacks, on the other hand, interfere with the cryptographic algorithm somehow. They rely on inducing faulty behaviour, e.g. skipping instructions or flipping bits, hence the name *fault attacks*. They inject faults into the operation of the algorithm, so the practice is called fault injection. The common ones are:

- operating the device outside of its safe operating range (too high/low temperature or voltage, over- or underclocking the device)
- injecting transient voltage spikes in the supply voltage (a.k.a. V_{cc} glitching)

- exposing the board to an electromagnetic field, of a sinusoidal wave (harmonic EMFI) or short pulses (pulsed EMFI)

Since only pulsed EMFI is considered here, in the rest of the text EMFI refers to pulsed EMFI.

2.4. Genetic algorithms

Evolutionary algorithms (EAs) are metaheuristic optimization algorithms, inspired by biological evolutionary processes and phenomena such as mutation, recombination, and natural selection. In a way, they simulate the natural process of evolution: a solution (i.e. point in the solution space) becomes an individual in the population. These “individuals” are then valued using a *fitness function*; better solutions are fitter individuals, with a higher chance of surviving and procreating. Thus the objective function (which we are optimizing) gets mapped to the fitness function and, over a number of generations, the evolutionary process takes care of the optimization.

Every generation, a number of individuals are selected from the population to reproduce, i.e. to become parents; fitter individuals are given preference. Those individuals are in some way combined to produce offspring (new solutions). There is a small chance of mutations in the offspring: this allows the introduction of new elements to the solution, which otherwise may not have ever been generated from the initial population by just selection and reproduction.

After generating the offspring, the population is (whole or in part) replaced by the offspring: the next generation.

The outline of an evolutionary algorithm is given below as Algorithm 1.

Mind that this is a fairly general outline. The choice of selection and offspring generation makes all the difference. Usually, however, offspring generation consists of two phases:

- combining two (or more) parents to produce a child
- mutating the child with some probability p

It is not necessary for the entire population to be replaced in a generation. A portion of the fittest individuals surviving across generations is called *elitism*; this could also be regarded as “cloning” the old solutions into the next generation, so it fits in the outline given above.

Algorithm 1: evolutionary algorithm pseudocode

```
population  $\leftarrow$  generate initial population
repeat
  for individual  $\in$  population do
    evaluate fitness (individual)
  end for
  parents  $\leftarrow$  select (population)
  offspring  $\leftarrow$  generate offspring (parents)
  population  $\leftarrow$  offspring
until termination criterion met
return choose best individual (population)
```

This three-phase algorithm, when we represent the solution as a string of numbers, is called a *genetic algorithm* (GA). In analogy to real life (though not exactly the same), this representation is called the *chromosome* (or *genotype* or *individual*; they're interchangeable); multiple chromosomes are combined using *crossover* (or *recombination*) to produce offspring.

However, what exactly falls under genetic algorithms and the exact lines between GAs and other evolutionary algorithms can at times be a bit vague. That's alright, since it's a metaheuristic. To instance this *metaheuristic* into a *heuristic*, we need to replace these somewhat vague terms (selection, crossover, mutation, genetic representation) with concrete ones. This is left up to the implementer.

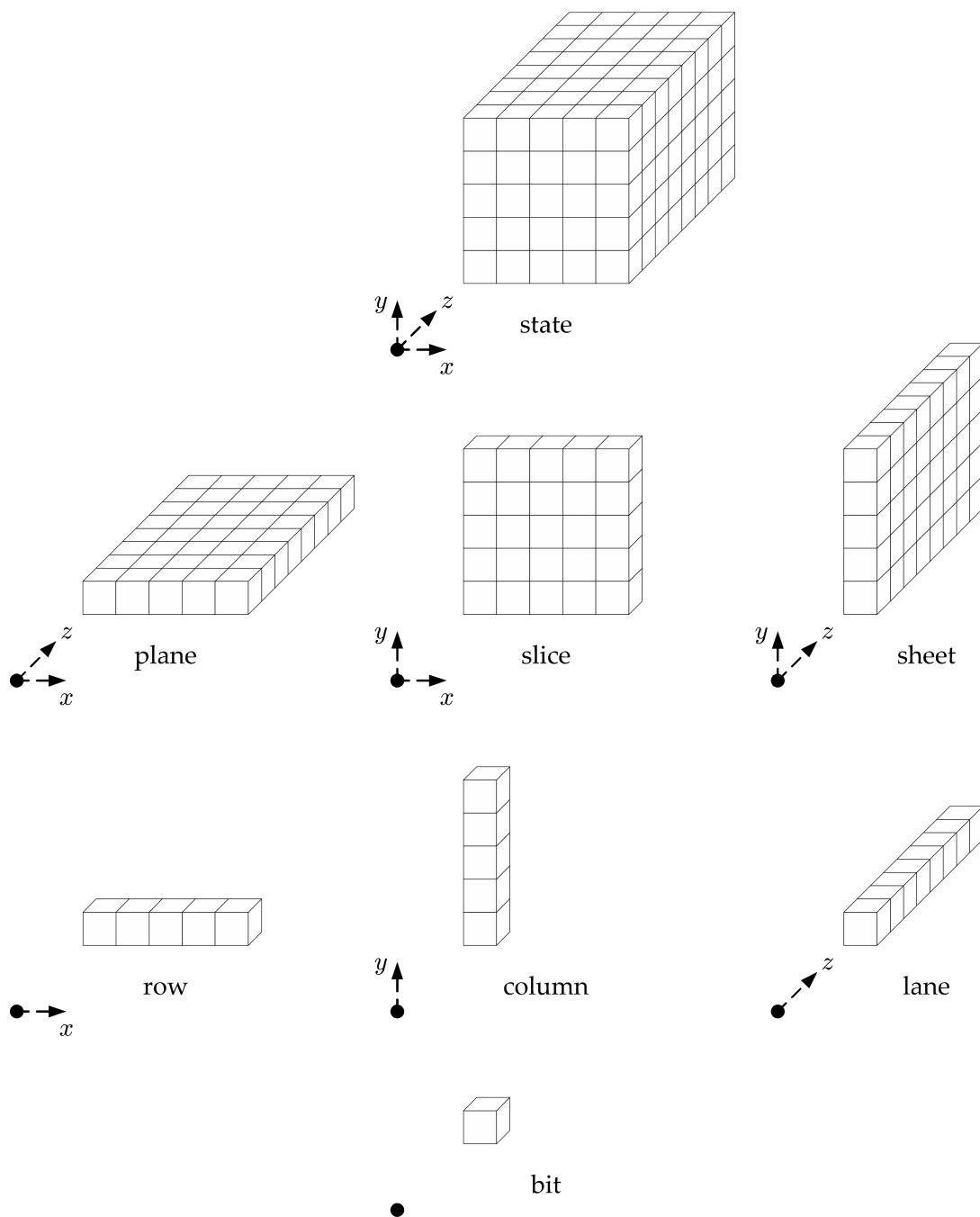


Figure 2.3: notation for parts of the Keccak state array

3. Fault injection

One obvious prerequisite for doing fault injection is a physical device running an actual algorithm to inject faults in. A cryptographic algorithm can be found easily; a susceptible one, with a bit of literature review. A device to attack, as well as the necessary equipment for glitching it, can be a bit harder to find.

This chapter is laid out thus: section 3.1 introduces the definitions used in the rest of the paper; section 3.2 covers the physical setup used for the experiments; section 3.3 presents the parameters used, and section 3.4 the big motivation for having a search at all. Sections 3.5 and 3.7 take care of the implicit assumptions on the search space and our requirements for the algorithm; section 3.6 covers the impact the underlying cryptographic algorithm on the parameter space; last, section 3.8 covers some practical implications of EM fault injection for the algorithm.

3.1. Definitions

When discussing the search and possible outputs of the algorithm,

a point is a distinct set of parameters, i.e. a point in the parameter space.

a measurement is the result of a single attempt at glitching the target with those parameters.

A single point may be measured multiple times, since trying the same parameters multiple times does not necessarily always yield the same response. In the rest of this thesis, only single-measurement and five-measurement points are used.

When counting the faulty measurements (i.e. those resulting in a faulty response), we distinguish between:

1. the total number of faulty measurements,

2. the number of distinct faulty responses (i.e. “unique faulty measurements”).

The difference is that if a measurement results in a before-seen faulty output, the second one will not be counted this second time around. To better illustrate this: say we find a set of parameters S_1 , which is measured five times, with one of the measurements giving a faulty output h_1 . Later, we find some other set of parameters S_2 that results in two faulty outputs, h_1 and h_2 . Out of the ten measurements performed in total, three of these are considered faulty, but with only two distinct faulty responses: h_1 and h_2 , since h_1 is not counted twice. For the purposes of exploitation, the number of distinct faulty responses is more interesting.

We classify the board response in one of the following classes:

NORMAL – for normal behaviour, meaning the board performs as if it wasn’t glitched

RESET – the board did not reply at all, requiring a reset to restore to normal operation

SUCCESS – the board produces an output/ciphertext/signature/hash different than the correct one

CHANGING – for each point, 5 measurements are performed. If all measurements are in the same class, the point is put into one of the first three classes; otherwise it goes into the CHANGING class.

Random search refers to just randomly choosing points to scan. *Grid search* is scanning points in a regularly-spaced grid that covers all or part of the search space. For the purposes of this thesis, random search is the baseline search algorithm.

3.2. Experimental setup

For the target, a Cortex-M4 STM32F407IG (Riscure “Piñata”) board was used, running a C implementation of SHA-3. This implementation was taken from the WolfSSL library [1], so as to have a real-world algorithm instead of a toy one. The board communicates to a PC by a serial interface and is powered by an external power supply (3.3 V DC). For inducing an electromagnetic pulse, the Riscure EM probe is used, as well as their VCGlitcher device that controls it. The board and

the EM probe are set up on an XYZ table which moves the probe around in space. The whole setup is controlled by code written in Python; for communicating with the Riscure equipment, Python bindings for the VCGLitcher C API are used.¹

Besides the serial interface, the board has a number of I/O pins which it can toggle to high or low; the only one here used is the “trigger” pin. This pin is used to signal to the VCGLitcher device that the cryptographic operation is in progress; this is used as a reference point for injecting the fault. While this slightly detracts from the realism of the attack, it greatly simplifies testing. (It does not make much difference for the vulnerability status of the device, since in real life the attacker only needs to spend more time figuring out the timing.)

In the case that the board gets stuck in an illegal state after a glitch, it needs to be reset. The only reliable way to reset this particular board is by cutting its power, which can take a significant fraction of a second, depending on the capacitors. A pause of 100 ms was used for this.

The physical dimensions of the chip package are 24×24 mm. Repositioning error of the XYZ table is 0.05 mm, which gives a spatial grid of at most 480×480 . However, the limiting factor here is most likely the size of the probe tip (and its internal coil), which is much larger.

All of these will, of course, vary depending on the chip and the equipment at hand; even for different variants of the Piñata, the capacitors differ. A more precise XYZ table, a smaller probe (such as in e.g. [20]), or a smaller chip will give different spatial resolutions.

3.3. Parameters

There are multiple parameters to vary to affect the probability of causing a fault: position of the probe tip (X, Y, and Z), pulse intensity, time offset of the pulse, pulse duration, shape and angle of the probe tip, and pulse shape.

In the experiments conducted, only a subset of these are considered:

position – two parameters (X and Y), since the distance from the board (Z) can be compensated by a change in intensity. The (x, y, z) position in real space is mapped by the interfacing code to an (x, y) position in the unit square $[0, 1]^2 \in \mathbb{R}$.

¹Currently, due to the provided DLL being a 32-bit one, a 32-bit Python interpreter is required. This may change in the future.

glitch intensity – regulates the voltage of the pulse. The SDK manual suggests that it is a percentage of power used [22], so it makes sense to map it to real values in $[0, 1]$.

time offset – between 367 and 375 μs , because that is where the injection point must be, for the code we are running. The offset is encoded as an integer value (number of 2 ns ticks).

number of repetitions of the pulse – a primitive form of pulse shape. This parameter is set to be in the (obviously, integral) range $[1, 10]$.

The pulse duration stays constant at a fixed value of 40 ns. Similarly, the shape and angle of the probe tip is not varied, since changing those cannot be easily automated.

Most parameters are within $[0, 1]$, but we can map the other ones to that interval as well, by taking its “percentage”: a parameter with range $[A, B]$, a value $x \in [A, B]$ is mapped to $y = \frac{x-A}{B-A}$, which is in $[0, 1]$. With everything mapped to $[0, 1]^5$, we can now define any length or distance to be the standard Euclidean distance in this image of the parameter space.

3.4. Search space size

One might wonder: why use a heuristic at all? What’s wrong with a “dumb” approach to parameter optimization? Let’s consider the straightforward approach: an exhaustive search.

The maximal spatial resolution, as I mentioned above, is 480×480 for this particular setup; a better setup would have an even higher one. For the time offset, the resolution is 2 ns; for a reasonable range, I’ll put the interval between 367 and 375 microseconds, since this was measured as the interval containing the fault injection point – this gives us a total of 4 000 different values; for the glitch intensity, there’s really no good rule for determining the smallest meaningful increment, but a 1% increment seems a fairly reasonable (if conservative) estimate based on visual estimates of the results, which would give a range of 100 values; the repetitions parameter in range $[1, 10]$ gives an extra 10 values.

The total size is therefore $480 * 480 * 4\,000 * 100 * 10 \approx 10^{12}$. At ≈ 0.16 seconds per measurement, and five measurements per point, this results in 29 203 years to conduct an exhaustive search. Even if completely ignoring everything but X, Y, and offset, an exhaustive search would still take 29.2 years to finish.

3.5. Some assumptions on the search space

From the viewpoint of the optimization algorithm, the device should be as close as possible to a black box. That is to say, the algorithm should not have built-in assumptions that would be broken by running it for another device or cryptographic algorithm. However, I do make some assumptions: the objective function is not a golf-course. In a golf-course function, the gradient in the fitness landscape doesn't lead to optimal solutions, which tend to "pop out of nowhere", all of a sudden. Given the nature of EM glitching, the transition between different kinds of behaviour should be reasonably gentle; the reasoning behind it is that a very weak EM pulse will not affect the target at all, and we will observe normal behaviour. Conversely, a very strong EM pulse will completely dishevel its operation and even potentially damage it. Consequently, we should expect faulty behaviour to occur somewhere between those two extremes, i.e. along the class border; in other words, there are blobs of RESETs in a sea of NORMALs, wrapped in a thin layer of SUCCESSes and CHANGINGs.

Additionally, offset ranges (min. to max. offset) are set by the user, based on a rough expectation of the duration of the cryptographic algorithm.

3.6. A note on underlying algorithms

Some of the early scans and tests were done not on the Piñata running SHA3-512, but Piñata running EdDSA (also taken from WolfSSL). There exists a difference between their respective search spaces: the parameters and the parameter ranges are largely the same (there is a difference in the offset range, since EdDSA takes ≈ 30 ms to run, SHA3-512 only ≈ 0.4 ms), but underlying calculation and the "look" of the parameter space is different. In EdDSA, the vast majority of the time is spent performing a scalar multiplication on the Ed25519 curve, and the parameter space has one big blob of RESETs, the rest being filled by NORMALs. For SHA3-512, all the time is spent on the Keccak- f transformation, and the parameter space has not only the (substantially smaller) blob of RESETs, but also several blobs composed of mostly CHANGING points, with a number of RESETs and SUCCESSes. Figure 3.1 shows what the parameter space looks like for both of these.

CHANGING points (and some other features) were not present from the start; they were implemented just before switching to SHA-3, hence most scans on

EdDSA don't have them, and use single-measurement points instead. The process of selecting the algorithm and its hyperparameters was not a systematic one with extensive tuning, but a pragmatic one of choosing the most promising options within the timeframe.

3.7. Objectives

The requirements for this optimization algorithm are:

Good coverage of the parameter space – since we do not know where the exploitable faults are located, we need to explore the search space efficiently.

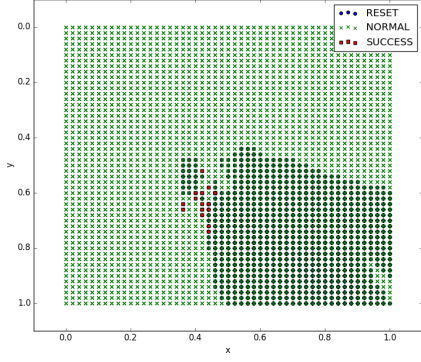
Speed – we require the algorithm to be fast in finding the faults, otherwise there is no advantage of using it when compared to the baseline.

These two requirements somewhat conflict with each other. Because most of the parameter space is useless (i.e. has no faults), covering enough space to be reasonably secure we did not miss anything important means potentially wasting a lot of measurements.

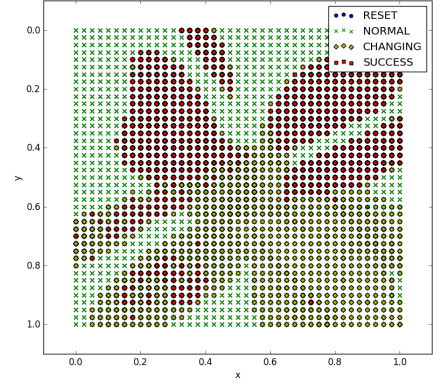
Usually, the objective function guides the optimization algorithm towards better solutions, and the algorithm ends when it finds what it considers to be the best one. Here, we don't want just a single "best" solution since not every fault that's found will also be exploitable, and there are situations where more than one are required; instead the aim is to obtain multiple good solutions.

3.8. Practical considerations

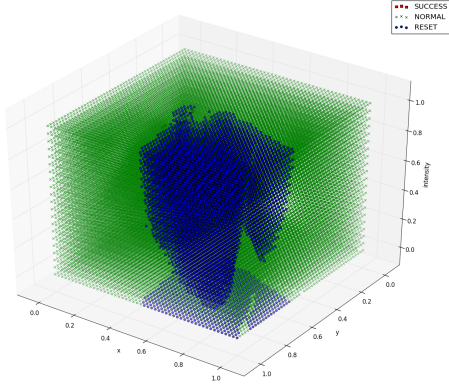
Commonly, optimization algorithms (and nature-inspired metaheuristics in particular) rely on a large number of iterations. Another assumption usually made is that the evaluation of possible solution points is uniform. Here, however, we have expensive measurements, where the cost of evaluation depends not only on the properties of the point itself, but also the context of its evaluation. When considering EM fault injection, the probe tip has to physically move to a different point. To do this with sufficient precision requires a non-negligible amount of time – the exact amount varies depending on the setup, but it can be up to several seconds per measurement. In comparison, a reset requires just a fraction of a second (for this board, ≈ 100 ms to do it reliably). The measurement part



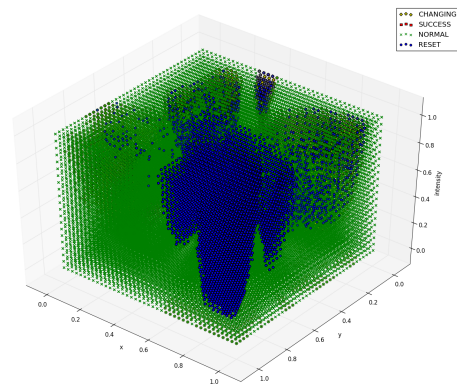
(a) EdDSA, in the 2 spatial dimensions



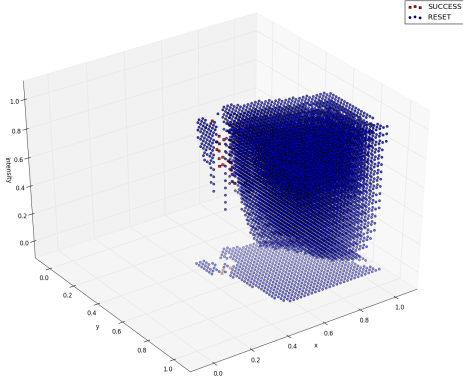
(b) SHA3-512, in the 2 spatial dimensions



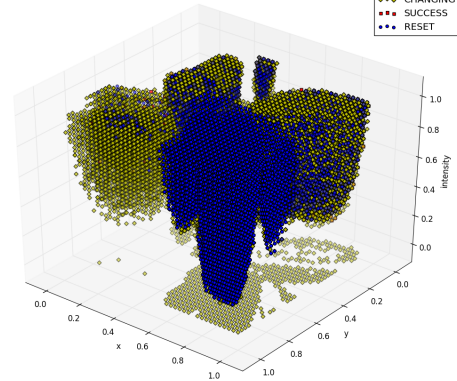
(c) EdDSA, 2 spatial dimensions and intensity



(d) SHA3-512, 2 spatial dimensions and intensity



(e) EdDSA, but without NORMAL points for clarity



(f) SHA3-512, but without NORMAL points for clarity

Figure 3.1: parameter space visualization, for EdDSA and SHA3-512

itself is even faster – 30 ms or less. Thus, the order in which points are evaluated matters.

Even with an optimal routing for any batch of N points, splitting the evaluation into more batches means more time wasted. For population-based algorithms, this translates to small population sizes being less efficient than large ones. Additionally, we may want to get a glimpse of the results even before the scan is finished, especially for long-running scans. In the case of a random or grid scan, this requires splitting the scan into batches where each covers more or less the whole parameter space, since scanning points in the optimal (or nearly-optimal) order results in uneven coverage: as a general rule, a segment the shortest Hamiltonian path from any given starting point will not evenly cover the XY-plane, but instead a small part of it.

4. Optimization

Now, to deal with the optimization itself.

Since EM fault injection is an *expensive* optimization problem, I created an emulator of the board to respond in its stead. While most scans were in the end done on the actual Piñata board, the emulator helps to predict and visualize behaviour of different algorithms (or the same algorithm, but differently parametrized) over multiple runs, with only a fraction of the runtime cost. However, we can only expect this if the behaviour of the emulator closely matches that of the board. This poses a problem: how do we achieve this? Obviously, without modelling the chip itself (which would be a large problem in and of itself), the emulator must rely on samples of the objective function.

The straightforward solution would be to exhaustively sample the parameter space and use a lookup table, but as mentioned in section 3.4, it's impossible in terms of time, and very hard in terms of space ($\approx 5 \cdot 10^{12}$ measurements!). What *is* possible, however, is a lower-resolution grid scan, with interpolation between points. This was, in fact, performed: the largest of these is a grid scan with 1/40 resolution in the XY-plane, 1/20 resolution in the intensity dimension, 9 offset values (from 367 μ s to 375 μ s, with 1 μ s step), and with repetitions set to 1. This gives $41 \times 41 \times 21 \times 9 = 317709$ points; with an average of 1.125 s per point, this takes around 100 hours, or a bit over four days. Given that this is a grid scan, it greatly simplifies storage and nearest-neighbour lookup: caching it as a bare NumPy array in a binary file takes up less than 3 MiB of space, the loading takes just a fraction of a second, and once in RAM, the lookup is as trivial as it gets. This is relatively easy to extend to k -nearest neighbours.

Another variant, made convenient by the availability of a number of scans of the parameter space, would be to abandon the notion of a regular grid, aggregate all those scans, and use that as the underlying information.

In any case, the emulator will be intrinsically limited due to being bound to actual data.

4.1. Simple GA

First, a simple genetic algorithm was tried out, with a single elite individual. The initial population is generated by sampling uniformly at random within the parameter ranges.

4.1.1. Selection and crossover

Several selection algorithms were used: roulette-wheel selection, 3-tournament selection, and a variation on roulette-wheel selection with class awareness. This last one was inspired by the work in [9]; its pseudocode is given below:

Algorithm 2: pseudocode for the class-aware roulette-wheel selection

```
 $N \leftarrow \text{length}(\text{population})$ 
 $\text{elite size} \leftarrow 1$ 
 $\text{population}_{\text{new}} \leftarrow \emptyset$ 
for  $i$  in range( $N - \text{elite size}$ ) do
     $\text{parent}_1 \leftarrow \text{random choice}(\text{population})$ 
    if there exist individuals  $\notin$  class( $\text{parent}_1$ ) then
         $\text{parent}_2 \leftarrow \text{random choice}(\text{other classes})$ 
    else
         $\text{parent}_2 \leftarrow \text{random choice}(\text{population} \setminus \{\text{parent}_1\})$ 
    end if
     $\text{child} \leftarrow \text{class-aware crossover}(\text{parent}_1, \text{parent}_2)$ 
     $\text{child} \leftarrow \text{mutate}(\text{child})$ 
     $\text{population}_{\text{new}} \leftarrow \text{population}_{\text{new}} \cup \{\text{child}\}$ 
end for
```

The class-aware crossover here simply returns a point halfway between the parents, if the parents are from different classes; otherwise it acts as a normal crossover. The idea behind this is simple: after finding a RESET, use it to locate the class border area, and concentrate there.

Of the selections, roulette-wheel selection was chosen for further testing. As it turns out, the class-aware selection did find a part of the class border area very fast, and converge there; however this was only a very small part of the border, and the algorithm is not able to “recover” from this convergence, but it will instead stay on the same small area, nor mapping out the rest of the space. 3-tournament selection was not chosen, since it appeared to be too aggressive,

i.e. it exerted overly high selection pressure for the problem at hand. It works by randomly choosing individuals three at a time, in “tournaments”. The lowest-ranking of the three is discarded, and the other two are used as parents. The tournaments are held until enough children have been produced.

The “normal” crossover, however, is not a standard GA crossover, but different. Its pseudocode is given below in Algorithm 3.

Algorithm 3: pseudocode for custom GA crossover

Input: $parent_1, parent_2$, two chromosomes, each a list of FI parameters
Output: $child$, the resulting child
for each parameter p in $\text{range}(N - \text{elite size})$ **do**
 $child.p \leftarrow$ random value in interval $[parent_1.p, parent_2.p]$
end for
return $child$

For comparison, the standard single-cut crossover is given as Algorithm 4; the uniform crossover is not much different. In terms of behaviour, it would be best to consider the geometric interpretation. A vector of k parameters can be viewed as a point in k -dimensional space. Two such points – the parents – define an axis-aligned k -dimensional hypercube. The “normal” crossover calculates the child as a random point from within that hypercube; the standard crossovers, in contrast, calculate the child as one of the corners of the hypercube. If the child has l parameters of $parent_1$, it will be at a Hamming¹ distance of $k - l$ from $parent_1$, and l from $parent_2$.

Algorithm 4: pseudocode for standard GA crossover

Input: $parent_1, parent_2$, two chromosomes, each a list of FI parameters
Output: $child$, the resulting child
for each parameter p in $\text{range}(N - \text{elite size})$ **do**
 $child.p \leftarrow$ random choice ($parent_1.p, parent_2.p$)
end for
return $child$

¹*Hamming distance* might not be the technically correct term here, but it is easy to see the 1-to-1 correspondence between the edges of *this* k -dimensional hypercube and the set $\{0, 1\}^k$ of length- k bitstrings: strings are corners, edges are bitflips.

4.1.2. Mutation

As for the mutation, its task is to ensure adequate exploration of the search space. Its exact form shouldn't make a great difference for the successfulness of the algorithm, as long as the final algorithm doesn't have any "blind spots", i.e. it doesn't leave some parts of the search space unreachable by the algorithm. The pseudocode of the mutation I used for this algorithm is given in Algorithm 5.

Algorithm 5: pseudocode for mutation

Input: p_{MUT} , the mutation probability
 Q , an upper limit on the step size
 $individual$, a solution to mutate

Output: $individual'$, the mutant
 $individual' \leftarrow \text{copy}(individual)$

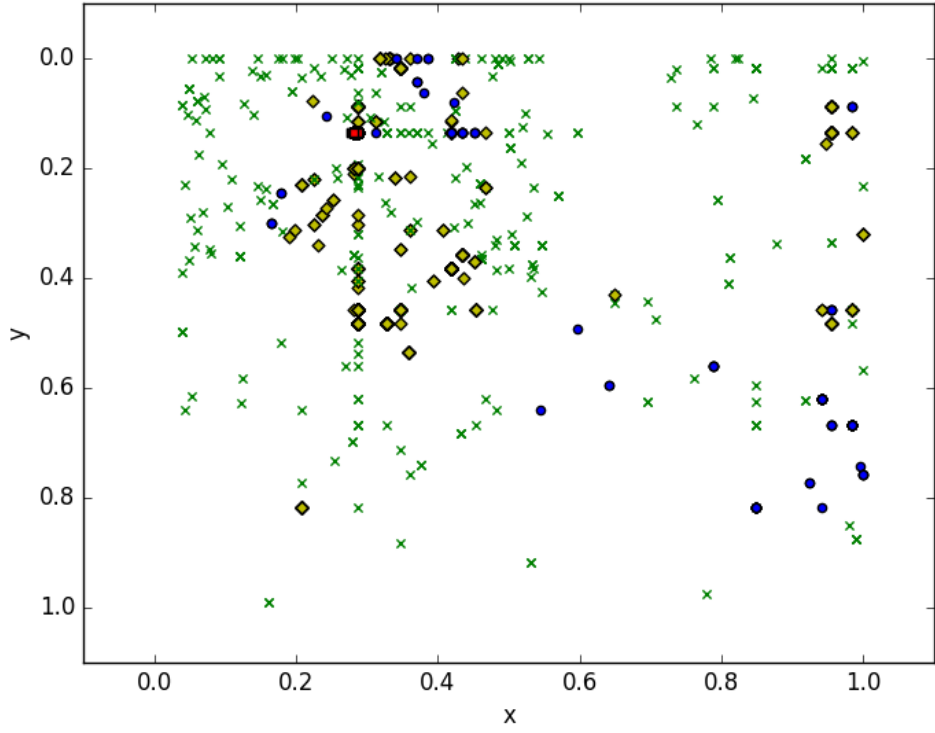
for each parameter P except repetitions **do**
 with probability p :
 $individual'.P \leftarrow individual.P + \text{random choice from interval } [-\frac{Q}{2}, \frac{Q}{2}]$
 clip value of $individual'.P$ to within allowed range
end for

with probability p :
 $individual'.repetitions \leftarrow \text{random integer from the allowed range}$

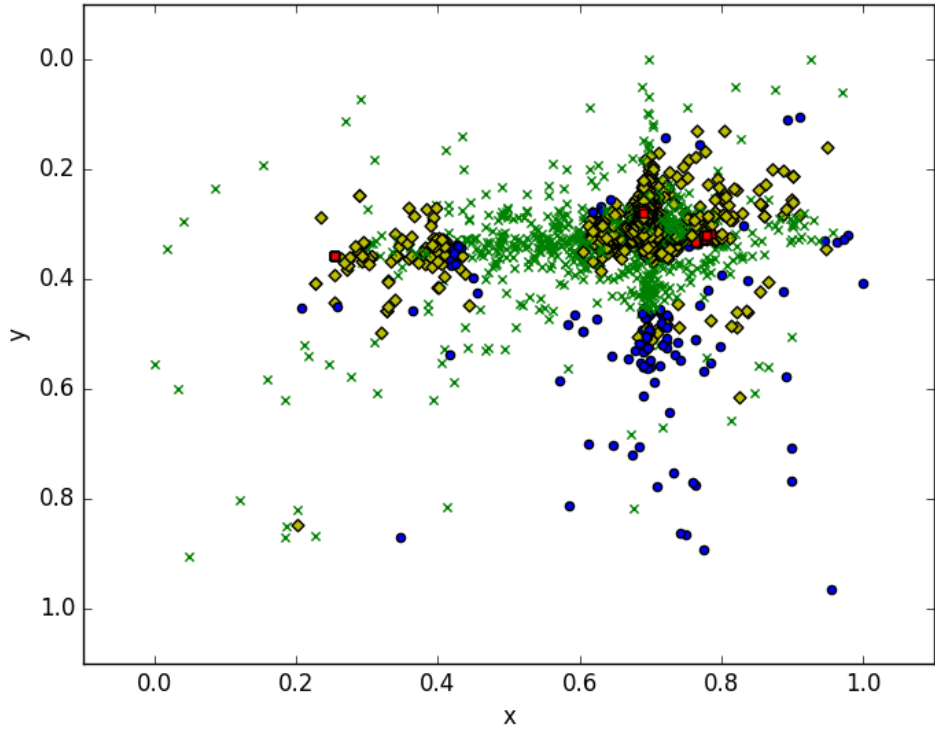
Its per-parameter nature increases the probability that at least *some* mutation will happen. It also means that significant jumps will tend to be mostly axis-aligned. The effect is somewhat similar to having a traditional crossover: many points on perpendicular lines, seemingly radiating from a hotspot; however the effect is weaker than with a single-cut crossover and a standard mutation which twiddles all the parameters at once. See Figure 4.1 for a picture of this.

4.1.3. Fitness function

Fitness values are set according to the class: SUCCESS has the highest fitness (10), followed by CHANGING (variable), then RESET (5), and finally, NORMAL (2). CHANGING points' fitness depends on its underlying measurements: a mix of NORMAL and RESET points is somewhat better than all measurements being RESET or NORMAL points, and adding SUCCESSful individual measurements into the mix moves the fitness close to an all-SUCCESS point. With these requirements in mind, the following formula was chosen for the fit-



(a) single-cut crossover with a standard all-parameters-simultaneously mutation



(b) the custom within-hypercube crossover with a per-parameter mutation

Figure 4.1: A comparison of the effects of a per-parameter mutation with custom crossover vs. all-parameter mutation with single-cut crossover. Both runs have 50 generations of 50 units each, and use the same $PMUT$.

ness of a CHANGING point:

$$fitness_{\text{CHANGING}} = 4 + 1.2 * N_{\text{SUCCESS}} + 0.2 * N_{\text{NORMAL}} + 0.5 * N_{\text{RESET}}$$

The factors 0.2 and 0.5 are chosen in analogy to the values for NORMAL and RESET (2 and 5, respectively); the other numbers are what they are to provide nice scaling. For example: 4 NORMAL and 1 RESET measurement give fitness 5.3, which is higher than the fitness of a RESET point (with all 5 RESET measurements). Similarly, 4 SUCCESS and 1 RESET measurements give a fitness of 9.3, which is lower than the fitness of a SUCCESS point (with all 5 SUCCESS measurements).

4.2. Extending the simple GA

Recall, the early scans did not have a CHANGING class, and the landscape consisted of blobs of RESETs in a sea of NORMALs. So, a second phase was added: a series of binary searches to find and map out the border.

The initial GA phase, if it covered most of the search space, can serve to map out the general landscape. In the second phase, first a point deep within the RESET blob is found. Since there was only one major blob of RESETs, this was not difficult: it was implemented as finding the centroid of all RESET points seen so far. Having found the centroid, a number of seen NORMAL points are randomly chosen. Now, for each of those NORMAL points, we have a line connecting it to the RESET centroid. This line must at some point pass through border between the NORMAL and RESET classes, so a binary search is performed on that line in order to find it. With a maximal spatial resolution of 480×480 , each binary search requires measuring at most 9 points.

For each binary search, after the intersection of the line with the class border is found, a small local search is performed to map out that part of the border. (We consider the class border area to be of interest.)

The third phase, which comes after the binary searches, is a separate local search phase. It consists of taking very promising points – SUCCESSful ones – and doing a scan of their neighbourhoods. This phase is merely additional exploitation of already discovered points, for extra effect.

In this early landscape, this three-phase algorithm makes a lot of sense. First, map out the general landscape; then map out the border and discover good points; then focus on exploiting what you have. In a situation where the overwhelming

majority of the search space are not good points, the local searches make sense: they are necessary to exploit the little good points there are.

Introducing local search also opens up the question of what should be considered “close”, i.e. how big is the neighbourhood of a point? There seems to be no good answer to this question, or at least not one that could be convincingly justified over other ones. So, I used values that seemed about right, tweaking them a bit and looking at the results, as well as visually estimating by the size of landscape features. For lack of a better answer to “what is a neighbourhood of a point?”, it is “an axis-aligned cube centered on the point, with edge length $CUBE_SIZE = 0.1$ ”.

Figure 4.2 shows one such three-phase scan. The GA phase used 20 generations of 15 units, with $p_{MUT} = 0.01$. The second-phase was 20 binary searches with 40 points scanned around the class border; the second-phase local searches had a neighbourhood cube of edge length 0.1. The final phase was local searches around each SUCCESSful point, with cube size 0.02. The effect of the second phase is visible in the shape of the point clouds.

In the general case where there are multiple blobs of unknown size, number, and positioning with respect to each other, the situation is more complicated. The problem of determining even how many blobs there are is nontrivial, especially with a rather limited amount of information available. (Remember, evaluations are expensive.) There is also the question of how to pick NORMAL points so that no other blobs lie on the connecting line. A way to solve all this would be to segment the search space in “BLOB” and “not BLOB” and so turn it into a geometric problem, but again, the algorithm has limited information at its disposal. The introduction of CHANGING points additionally muddles the notion of the exact class border and brings in more hyperparameters.

While this problem might be an interesting one to solve, it runs the risk of becoming a significant piece of work by itself. With the given time constraints, it seemed logical not to pursue this approach for the time being.

4.2.1. Alternative variants of the algorithm

Certain other variants were tried out or under trial: a simple particle swarm optimization (PSO) algorithm, which turned out to be good at traversing the parameter space, but would take many more iterations than was reasonable given the expensive nature of point evaluation; one memetic algorithm, which inter-

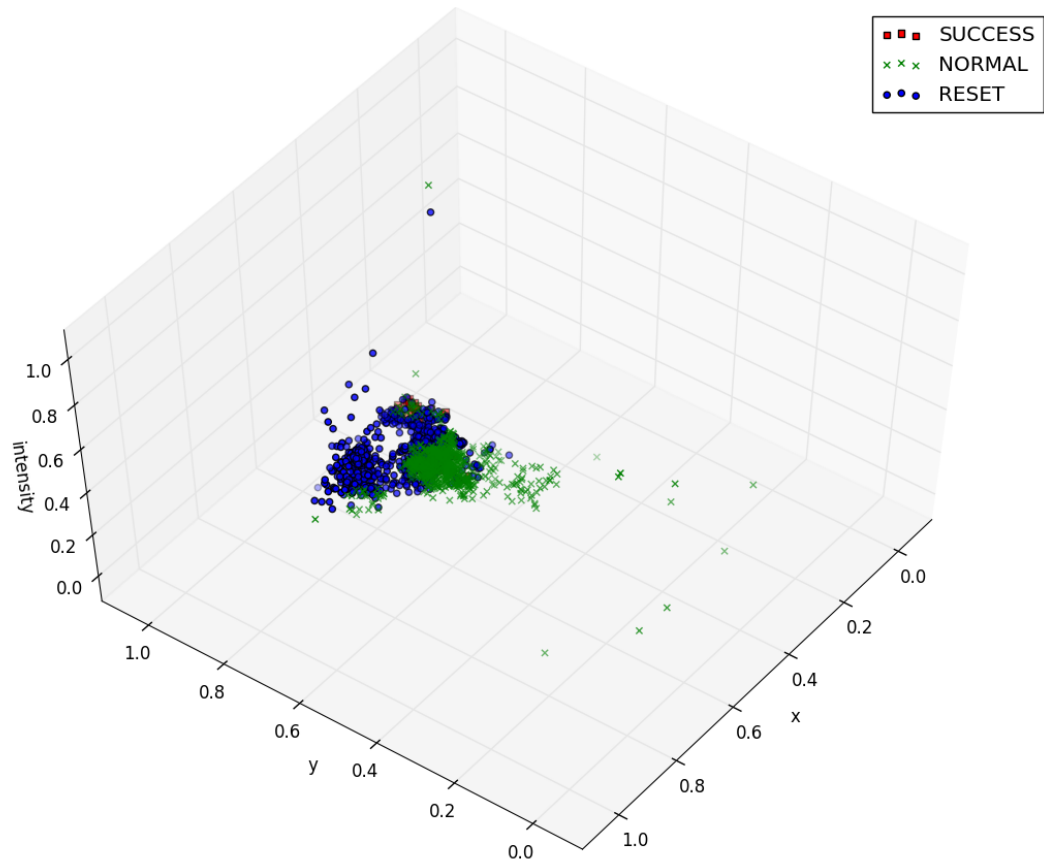


Figure 4.2: an example of the three-phase (GA + binary search + local search) algorithm

leaves generations of the GA with local modification of the point was also on trial, but its development was given low priority since it did not do too well in initial testing.

4.2.2. Final version

For the final version of the evolutionary algorithm, a variation on the three-phase version was used; more specifically, the binary search phase was thrown out, and the hyperparameters were set to values meant to ensure a reasonable execution time of the algorithm – the EA does not terminate after a fixed number of evaluations, but the execution time depends on the results it finds.

Additionally, the probe tip was replaced with a smaller, more precise one; the result of this was that, on random scans, the share of faulty responses fell almost fivefold, and the share of unique faulty responses slightly increased. A similar effect occurred for the EA. This is expected: the probe affects not a single point, but an area. Hitting a smaller area means that points otherwise near, which would before have affected each other enough not to be distinguishable, now produce a different effect.

To sum it up in one place, the final version is given below:

1. first phase is a genetic algorithm, with the above-described custom crossover and mutation, with $p_{MUT} = 0.05$, and 20 generations of size 50.
2. second phase is local search, which takes 10 randomly chosen points in the neighbourhood of each SUCCESS point.

Note how the parameters are set to stimulate exploration: both the custom within-hypercube crossover and the per-parameter mutation promote the many slight variations so nicely seen in Figure 4.1. A lower number of generations with a larger population size (and the relatively high mutation rate) prevent the algorithm from converging too quickly, thus forcing it to spend some time exploring the search space, which gives a better idea of its shape.

4.3. Parameter optimization results

This section presents the results of injecting faults into SHA3-512.

The duration of the EA is determined by the number of faults it finds. Five independent runs were conducted, with 2 074, 2 343, 3 353, 3 606, and 5 132 points,

respectively. Each individual run will be different due to the stochastic nature of the algorithm, as well as of the target’s response. To obtain statistically meaningful results, the reported values are averages over all runs. On average, in each run there are 3 301.6 points, of which:

- 662.8 (18.9%) NORMAL
- 496.4 (15.0%) RESET
- 375.2 (11.4%) CHANGING
- 1 807.2 (54.7%) SUCCESS

This also means there are 16 508 individual measurements on average. Out of these, 9 700.4 (58.8%) are faulty, and 3 288.4 (19.9%) are unique/distinct. Comparing this with random search with 3 302 points, we get:

- 2 995.8 (90.7%) NORMAL
- 65.0 (2.0%) RESET
- 232.4 (7.0%) CHANGING
- 8.8 (0.3%) SUCCESS

Again, this would represent 16 510 individual measurements. Out of these, 228.2 (1.3%) are faulty, and 160.8 (1.0%) are unique/distinct. To conclude, when averaged over 5 runs, the EA algorithm gives 42.5 times more faulty measurements, and 20.5 times more distinct faulty ones. The somewhat lower share of distinct measurements for the EA algorithm can be explained by many SUCCESS points being close to each other due to the local search phase, thus being more likely to cause the same response.

Tables 4.1 until 4.3 contain results for the random search and evolutionary algorithms when considering the first 500, 1 000, and 2 000 points, respectively. Note how the results for random search do not change significantly with more measurements. At the same time, we see that the EA is very successful already for the smallest case where with only 500 points, and as we add more points, the percentage of SUCCESS points increases.

Finally, the search space after random search or EA is shown in Figures 4.3a until 4.3f. Figures 4.3a and 4.3b give results projected down onto the XY-plane, i.e. by just the X and Y parameters. Figures 4.3c until 4.3f depict depict intensity as a third parameter. For less clutter, versions without NORMAL points are also provided. The number of points in case of random search is always 3 302; for the

Table 4.1: 500 points.

| | Random | EA |
|-----------|---------------|---------------|
| NORMAL | 452.6 (90.5%) | 315.2 (63.0%) |
| RESET | 9.8 (2.0%) | 73.4 (14.7%) |
| CHANGING | 36.0 (7.2%) | 79.0 (15.8%) |
| SUCCESS | 1.6 (0.3%) | 32.4 (6.5%) |
| #faults | 33.4 (1.3%) | 260.8 (10.4%) |
| #distinct | 22.6 (0.9%) | 158.8 (6.3%) |

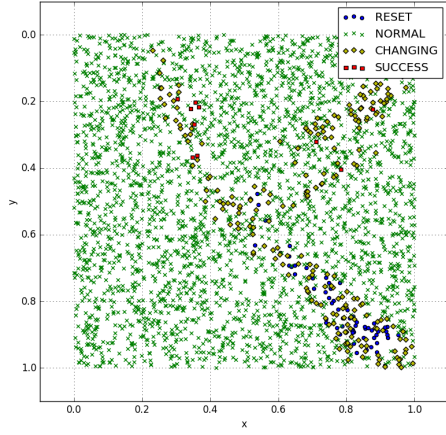
Table 4.2: 1 000 points.

| | Random | EA |
|-----------|---------------|-----------------|
| NORMAL | 910.4 (91.0%) | 381.8 (38.2%) |
| RESET | 19.6 (2.0%) | 198.0 (19.8%) |
| CHANGING | 67.2 (6.7%) | 169.2 (16.9%) |
| SUCCESS | 2.8 (0.3%) | 251.0 (25.1%) |
| #faults | 58.8 (1.2%) | 1 530.4 (30.6%) |
| #distinct | 40.4 (0.8%) | 956.6 (19.1%) |

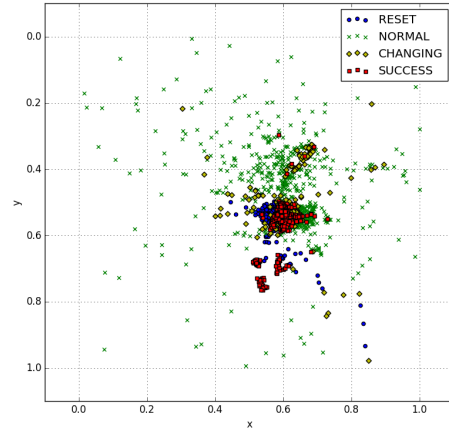
Table 4.3: 2 000 points.

| | Random | EA |
|-----------|-----------------|-----------------|
| NORMAL | 1 814.6 (90.7%) | 541.6 (27.1%) |
| RESET | 36.6 (1.8%) | 351.2 (17.6%) |
| CHANGING | 144.2 (7.2%) | 285.0 (14.2%) |
| SUCCESS | 4.6 (0.2%) | 822.2 (41.1%) |
| #faults | 130.6 (1.3%) | 4 606.4 (46.0%) |
| #distinct | 93.4 (0.9%) | 2 030.4 (20.3%) |

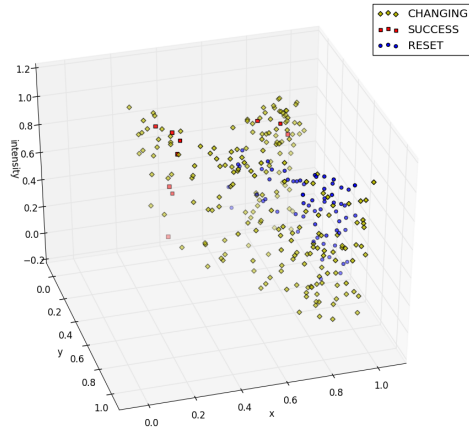
EA, the run with 3 606 points is shown. Naturally, figures without the NORMAL points have less points.



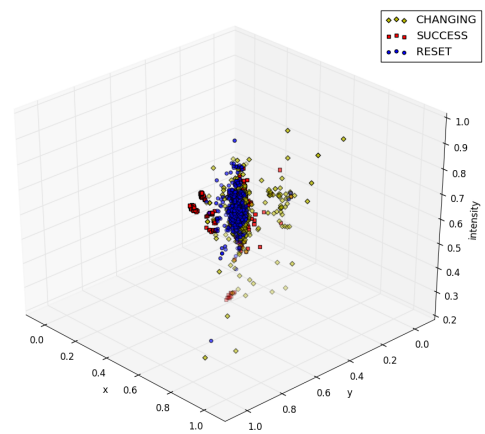
(a) Random search in 2D



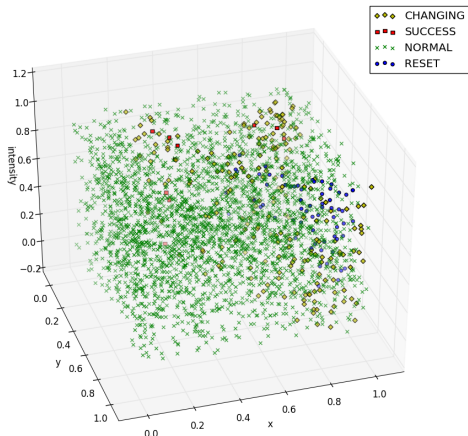
(b) GA and local search in 2D



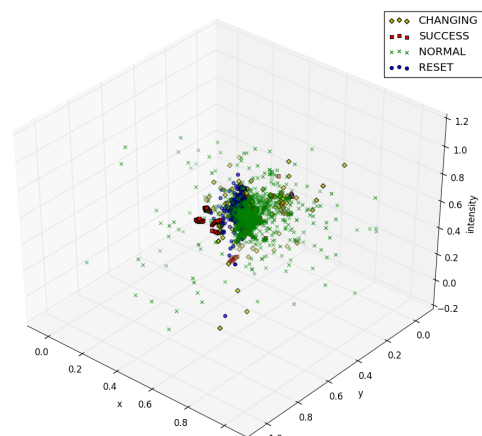
(c) Random search without NORMAL points



(d) GA and local search without NORMAL points



(e) Random search



(f) GA and local search

Figure 4.3: results for EA (GA with local search) and random search

5. Attacking SHA-3

The ultimate goal of optimizing fault injection parameters is, of course, to do fault injection attacks. This chapter presents exactly that: a fault attack on SHA-3 (specifically, SHA3-512) in practice.

5.1. State of the art

To the best of my knowledge, no implementation of SHA-3 has yet been attacked in practice. The attacks which do exist are only simulated: [4] show that differential fault analysis (DFA) can be used to recover the complete state in around 80 faults on average, if the attacker is able to inject single-bit faults in the input of the penultimate round (i.e. θ_i^{22}), though they rely on brute-forcing the last few bits. According to [15] (itself an extension of [14]), this is around 500 single-bit random faults for the whole state. In [15], the attack is generalized to a single-byte fault model, recovering the state in around 120 random faults.

Algebraic fault analysis (AFA) is more promising: in the progress through [14], [15], and [16], the authors manage to bring down the number of faults needed to recover the internal state with SHA3-512 down to under 10 with AFA and the 32-bit fault model.

Besides being more efficient at recovering state, AFA has several advantages:

- it does not require analysis of fault propagation through the algorithm, making it much easier to abstract the internal details.
- the fault model can be easily changed, by just changing the appropriate constraints.
- perhaps most importantly, it works for more relaxed fault models.

5.2. Attack description

The attack used here is the one in [16]. Again, like the other papers concerning fault injection into Keccak, it requires the attacker to be able to inject multiple faults in the input of round 22 of Keccak. These faults are allowed to affect up to 1 unit of the state, where units are sized 8b, 16b, or 32b, depending on the fault model. This means that, for example, with a 32-bit fault model and the internal state $A[200]$, the fault model allows us to fault bytes $A[0]$ through $A[3]$ inclusive, but not bytes $A[1]$ through $A[4]$, since that crosses the line between two 32-bit units ($A[0]$ to $A[3]$ is the first such unit, $A[4]$ to $A[7]$ the second, etc.).

The Keccak permutation, by virtue of being a permutation, is invertible. The same applies to its individual rounds. This means it is enough to recover the entire state at *some* point in the execution. As in previous work, the chosen target state is χ_i^{22} , the input to the nonlinear χ transformation of round 22. For state recovery, we reused their C++ retrieval code (which uses CryptoMiniSAT for SAT solving).

The general idea behind AFA on SHA-3/Keccak is simple: use a SAT solver to do the work for us: all we need is to provide appropriate constraints for it. We start with 1 600 Boolean variables representing the state (θ_i^{22}) and then provide constraints:

Fault Model – what kind of a fault do we cause?

There’s a separate set of (up to) 1 600 Boolean variables ($\Delta\theta_i^{22}$) representing the induced fault. $\theta_i^{22} \oplus \Delta\theta_i^{22}$ is the faulted state, before propagating through the final two rounds of the algorithm. Depending on what the fault model is, we add constraints such as “exactly one bit of $\Delta\theta_i^{22}$ is non-zero”, corresponding to a one-bit fault model, or slightly more verbose ones for specifying things such as “we faulted a word-aligned 32-bit word”, which would correspond to a 32-bit fault model in [16].

Keccak – how does the (faulted) internal state propagate?

For Keccak, the internal transformations can be relatively simply encoded as Boolean expressions. This implicitly tells the solver everything it needs to know about fault propagation, regardless of the fault model constraints. There are two cases we consider:

$$H = \iota^{23} \circ \chi \circ \pi \circ \rho \circ \theta \circ \iota^{22} \circ \chi \circ \pi \circ \rho \circ \theta(\theta_i^{22})$$

where H is the correct hash output, and

$$H' = \iota^{23} \circ \chi \circ \pi \circ \rho \circ \theta \circ \iota^{22} \circ \chi \circ \pi \circ \rho \circ \theta(\theta_i^{22} \oplus \Delta\theta_i^{22})$$

where H' is the faulty hash output.

Outputs – which are the concrete outputs?

We give the SAT solver the actual values of H and H' . After so constraining the SAT solver, we can let it find a solution – an internal state satisfying all the constraints. Once it finds the first such solution, we ban this newly-found solution by adding it as an additional constraint, and let the SAT solver find another one. This process is repeated until no new solutions can be found.

The bits of the state which are the same in all solutions are the ones we can recover; as for those which take different values in different solutions, their values are not entailed by the combined constraints of the fault model, the algorithm, and the outputs (i.e. the “real” constraints).

Depending on the fault model and the version of SHA-3 (SHA3-512, SHA3-224, etc.), these constraints may or may not be enough to recover part of the state. If this happens, additional constraints can be introduced, such as using *two* faulty hashes at a time, H'_1 and H'_2 , at a cost of having extra Boolean variables, making the problem harder for the SAT solver (this is Method II from [16]); or, if we can first somehow recover part of the χ_i^{23} bits, we can use them to additionally constrain the SAT solver (this is Method III from [16]).

As for the choice of fault model and method: 32-bit fault model and Method III from [16] was chosen. While the standard approach (Method I – single faulty output, no extra χ_i^{23} bits) approach would be preferable, it is not possible according to the authors, at least when using two (and not more) faults at once. In principle, there is no limit on the number of faults we can use to constrain the SAT solver, but increasing this number quickly brings us where running the solver is *very* hard, and obtaining another exploitable fault is cheaper than the extra SAT solving. The main reason for choosing the 32-bit fault model was, the fact that the target board has a 32-bit word size. This also being the most relaxed fault model means that any 8-bit or 16-bit faults do not go to waste, but are also exploited.

Table IV in [16] neatly presents what is possible in reasonable time with the current state of the art in SAT solving: going from longer-output SHA-3 functions to shorter-output ones, less information is available to us, and state retrieval becomes progressively harder. For SHA3-512 in particular, Method I is still usable in the 8-bit and 16-bit fault models, requiring 45 and 23 faults on average to recover the state. The 32-bit fault model requires using at least Method II; this comes at a substantial cost in SAT solving time, but also a reduction in the number of faults needed: on average 7 faults for Method II, and 6 for Method III. Intuitively, this is because a fault can only leak so much information; so we need either more faults, or larger faults.

With the 32-bit fault model, each fault usually allows the recovery of hundreds of bits, according to [16]. With Method II the distribution is bimodal, with a part of faults allowing for <100 bits, and the rest around 500 bits; with Method III the lower mode vanishes, and the upper one stays more-or-less where it is. We can conclude that, while the addition of extra χ_i^{23} bits does make a difference in the total number of faults required, it is not large. What it *does* do, however, is drastically reduce the time needed for retrieval — by an order of magnitude.

This is the main reason for choosing Method III: it lets us approximate Method II, with a *lot* less computing power. Since many more faults were generated for the purposes of this thesis than is necessary for a single successful attack, great efficiency was needed to check them all for exploitability. So, the following method was used:

1. obtain the bottom 640 bits of Keccak state ($\chi_i^{23}(X, 0, Z)$ and $\chi_i^{23}(X, 0, Z)$), not by performing a separate recovery phase, but by using `memcpy()`
2. generate a single faulty hash that is known to be the result of a good fault (in the 32-bit fault model); this is H'_1
3. take a faulty hash generated by the real board; this is H'_2
4. add those hashes as constraints and run the SAT solver

If the recovery is unsuccessful, this means that the candidate hash H'_2 was not an exploitable one. This method allows a $O(\text{number of faults to test})$ time complexity, which is absolutely needed to check the thousands of faults obtained.

5.3. Algebraic fault analysis results

The exploitability of all distinct faulty hashes obtained by the evolutionary algorithm, as well as of all those obtained by the random scan, was tested. While the share of distinct/unique faulty hashes depends on the size of the scan, the exploitability of a faulty hash does not. For this reason, I calculated the share of exploitable individual faults on all the samples obtained (with the same hyperparameters).

The results are as follows: the EA generated a total of 14 979 distinct faults (out of 82 540 individual measurements); 106 of these were exploitable 32-bit faults, for a share of 0.71%. Random search generated 947 distinct faults (out of 100 000 individual measurements); 110 of these were exploitable 32-bit faults, for a share of 11.61%. When translated into exploitable faults per individual measurement, this gives about 1.41×10^{-3} and 1.13×10^{-3} for EA and random search, respectively – an improvement of 24.6%.

Despite the fact that the EA is still significantly more successful than random search, we see that actually most of the faults obtained with the EA cannot be translated into exploitable faults. This results in a decrease between the performance difference of the EA and random search. Still, such results are not entirely unexpected: the EA was given no information on the exploitability of a fault that it could use to guide its search. This could be addressed by having its fitness function integrate an analysis of fault exploitability.

6. Conclusion

In the end, the developed algorithm did not turn out to be really complex, partly due to the short development schedule; however, even though fault injection is widely used, the amount of work on its parameter optimization is surprisingly small, and plenty of work still needs to be done. It is therefore not particularly surprising that the developed algorithm ended up being substantially better than the baseline: over 20 times more distinct faults per individual measurement than random search; and almost 25% more exploitable faults compared to random search.

To my knowledge, there is presently only one other method for EMFI parameter optimization, the one given in [17], and described in section 1.2. However, they consider RESET points to also be *faults* worth preserving, meaning we cannot do a direct comparison – their task appears to be an easier one. But if we look at their best case – keeping 80% of the faults while rejecting 75% of the chip surface – this is an increase in fault concentration by a factor of merely 3.2, for a price of a full 2-dimensional grid scan. Considering that the EA developed here likely runs in a comparable amount of time, it is evident that their EMFISC approach is, as it stands, inferior.

Since there are few works looking at FI parameter optimization, there is a number of potentially interesting research topics. The most obvious one is certainly adding exploitability analysis to the fitness function – filtering out the non-exploitable SUCCESS points would be a great improvement to this algorithm. I expect that making it run in real-time on a single workstation would not be easy. One less obvious follow-up topic would be: what is a neighbourhood? A way to figure out the effective lowest resolution would potentially make the search space considerably smaller.

And, of course, this algorithm should be tested on other boards as well. As it turns out, there are good reasons why this particular board is named the *Piñata*: one, it is fairly susceptible to being exploited by various means; this makes it an

excellent practice target for fault injection. Two, like the real thing, it is meant to take a beating: millions of glitches, day in, day out. This second reason is why it was chosen – nobody wants a dead board in the middle of a five-day scan – but the first reason might be the cause for what seems an unusually high number of faults in total.

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Evolucijske heuristike za pretragu prostora parametara napada umetanjem pogreške

Sažetak

Kriptografija je u temeljima velikog dijela moderne računalne infrastrukture, stoga je vrlo bitno da se u nju možemo pouzdati. Sigurnost malih, ugradbenih uređaja čini jedan dio tog.

Elektromagnetsko umetanje greške (EMFI) je moćna tehnika za izvođenje napada umetanjem pogreške, ali zahtijeva odabir dobrih parametara u prostoru daleko prevelikom da bi se mogao iscrpno pretražiti. U ovom radu se iznosi evolucijski algoritam za pretragu prostora parametara za umetanje greške, kao i logika iza njegovog razvoja. Ovaj algoritam se potom koristi za pronalazak grešaka koje se koriste za algebarsku analizu grešaka (AFA) na SHA-3 (Keccak) kriptografskom heš algoritmu; dana je usporedba rezultata sa slučajnom osnovicom.

Ključne riječi: umetanje pogreške, evolucijski algoritam, SHA-3, algebarska analiza grešaka, optimizacija parametara

Evolutionary Heuristics for Fault Injection parameter Space Search

Abstract

Cryptography underpins a large part of modern computer infrastructure, making its reliability very important. The security of embedded devices and their tamper-resistance is a small part of this.

Electromagnetic fault injection (EMFI) is a powerful fault injection technique for conducting fault injection (FI) attacks, however it requires choosing parameters in a parameter space that's far too large to perform an exhaustive search, and presently there appears to be no good method for conducting the search for good parameters. In this thesis, an evolutionary algorithm for FI parameter search is presented, along with the rationale used in its development. This algorithm is used to find faults for an algebraic fault attack (AFA) on the SHA-3 (Keccak) cryptographic hash algorithm, and its results are compared with the random baseline.

Keywords: electromagnetic fault injection, evolutionary algorithm, SHA-3, algebraic fault attack, parameter optimization