# Using Fault Injection to weaken RSA public key verification

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SNE Research Project 2

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# What is Fault Injection?

Simply put:

> “Introducing faults in a target to alter its intended behavior”*

*(N. Timmers)

# What is Fault Injection?

- Use **physical** means to induce **logical** faults into a target
  - Electromagnetic
  - Temperature
  - Optical (laser)
  - Voltage
  - Etc.
- Can cause faults in instructions, execution flow, data.
  - Instruction corruption
  - Instruction skipping
  - Data corruption

# What can Fault Injection accomplish?

- Some examples:
  - Bypassing PIN/password verification
  - Escalating privileges
  - Bypassing Secure boot
  - Extracting RSA private key, AES keys
  - Firmware extraction
  - Modifying data in memory
- **We'll be using Voltage Fault Injection to modify data**
- Some excellent references I recommend to check out
  - Bellcore attack on RSA-CRT, Boneh et al. (1996)
  - Attacking RSA public modulus by Seifert (2005) and Muir (2005)
  - Low-voltage attacks on RSA and AES on ARM9 by Barenghi et al. (2009, 2010)
  - Building fault models for microcontrollers, SNE RP2, Spruyt (2012)
  - Proving the wild jungle jump, SNE RP2, Gratchoff (2015)
  - Controlling PC on ARM using Fault Injection, Timmers et al. (2017)

# Attacking RSA's public modulus

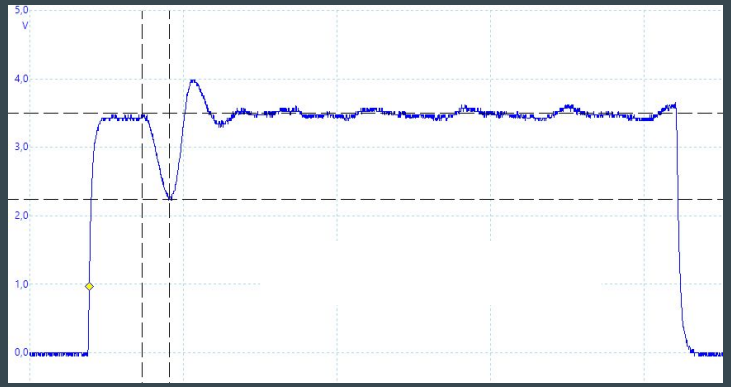
- An RSA public key consists of two values:
  - Public exponent *e*
  - Public modulus *N*
- *N* is (usually) a product of two large prime integers
- To get the private key, we need the factorization of *N*, but this is infeasible
- If we can **modify** *N*, we can make it easier to factor (call this modification *N')*
- With the factorization of *N'*, we can make a private key (*N', e, d')*
- As long as the target uses the modified *N*, our private key will work

# Voltage glitching to induce faults in data

- When copying data, we introduce a **glitch** in the supply voltage
- The processor will execute an instruction incorrectly and introduce a **fault**:

Source data: C3B5F25715A8D1

Destination data: C3B5F20055A8D1



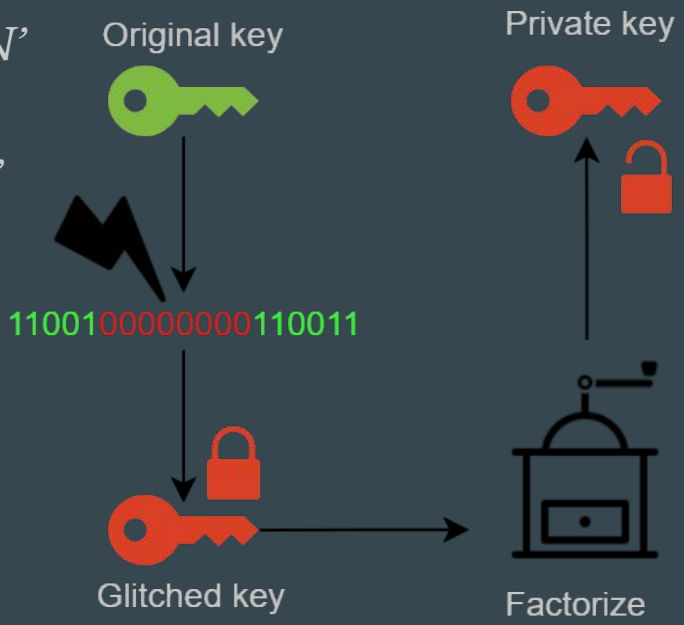

Example voltage glitch

**We can use this to change values in an RSA public key!**

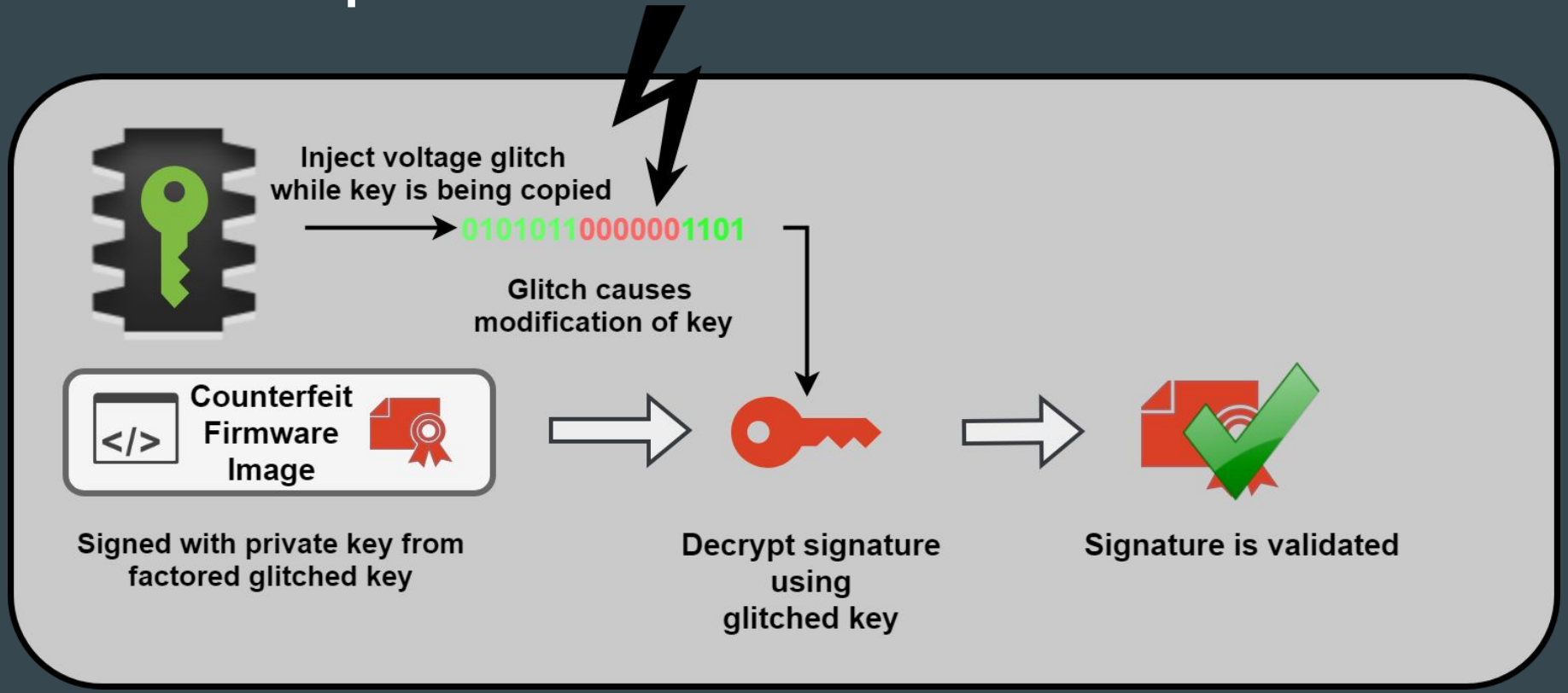
# The Attack

- While *N* is being copied, induce a fault to obtain *N'*
- We factor *N'* and create a private key *d'*
- Use *d'* to sign a message, which verifies against *N'*

**As long as the target has *N'* in memory, the signature will be valid.**



# Attack example - Secure Boot

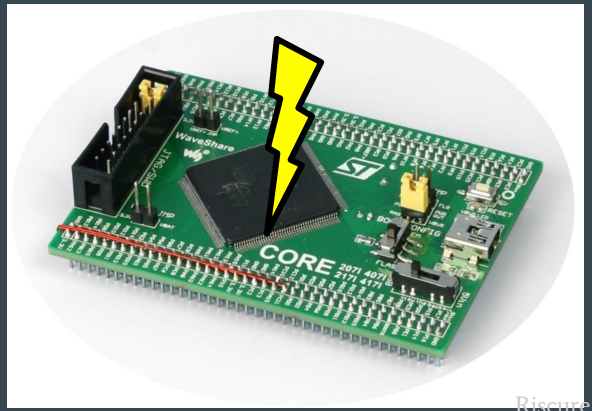


# Research questions

- Is modifying the RSA public modulus using voltage fault injection a practical means of weakening RSA signature verification?
  - How can an RSA public modulus be modified in a way that is beneficial to an attacker?
  - Which types of modifications reliably yield factorable moduli?
  - Can we create valid private keys from these factorizations?
  - Is it practical to apply this attack against RSA?

# Obtaining a fault model - Target Characterization

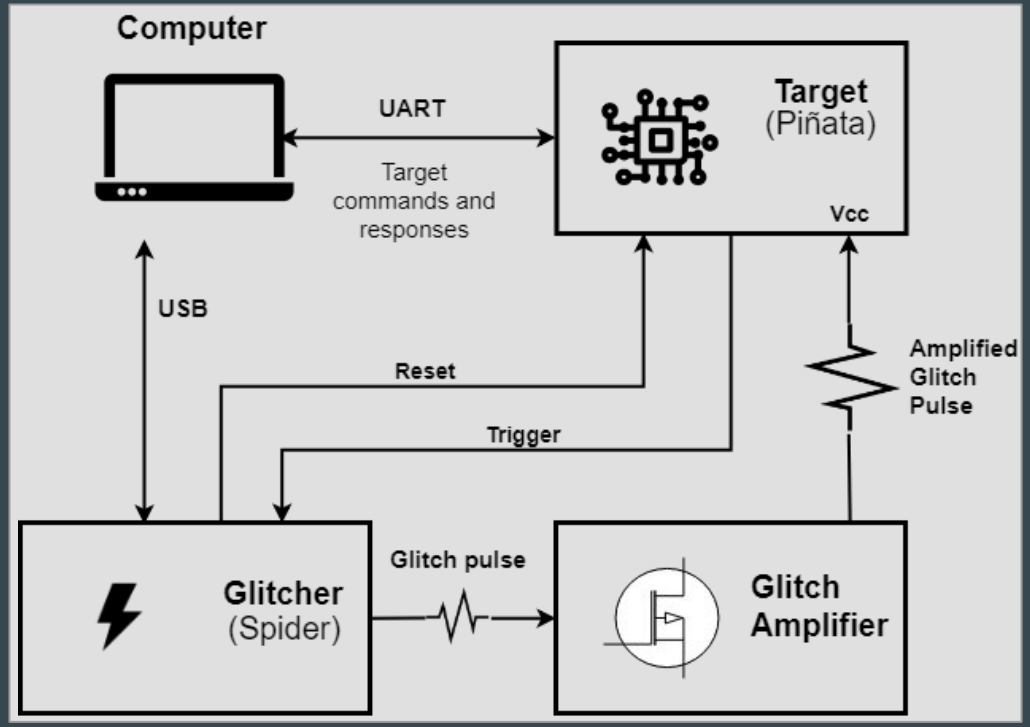
- Study the effects of V-FI on a memory copy
- Target device: ARM Cortex-M4F 32 bit
- Program target device to:
  - Copy data between buffers
  - Set trigger when copy starts and unset when finished
  - Return result
- Apply voltage glitch after trigger is set
- Record response and classify
  - Normal response, green color
  - Correct glitched response, red color
  - No response, yellow color




Riscure

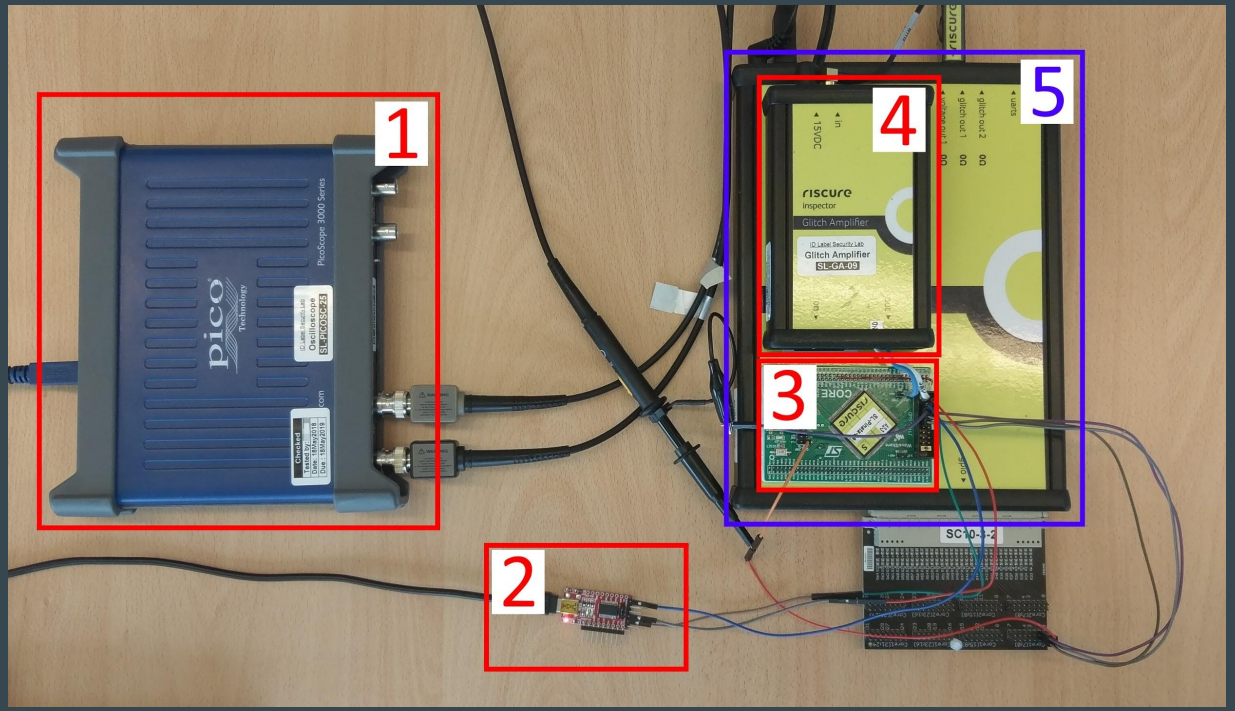
# Experimental Setup

- Target running our test code (Riscure Piñata)
- Glitcher and glitch amplifier (Riscure Spider and GA)
- Computer
  - Control glitcher over USB
  - Control target over UART
  - Record responses from target



# Experimental Setup (cont.)

1. PC oscilloscope
2. UART interface target <-> PC
3. Target (Piñata)
4. Glitch Amplifier
5. Glitcher (Spider)

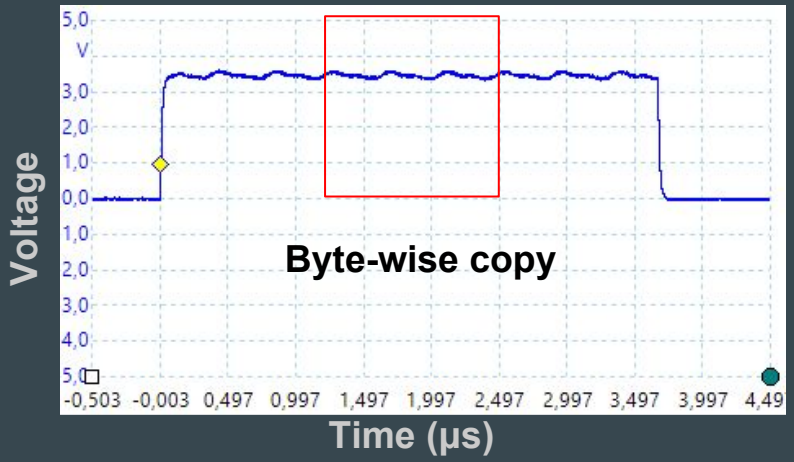


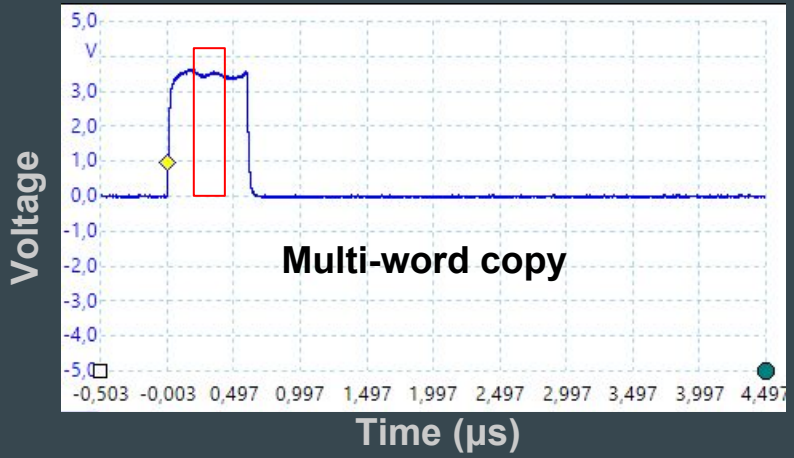
# Prepare target device

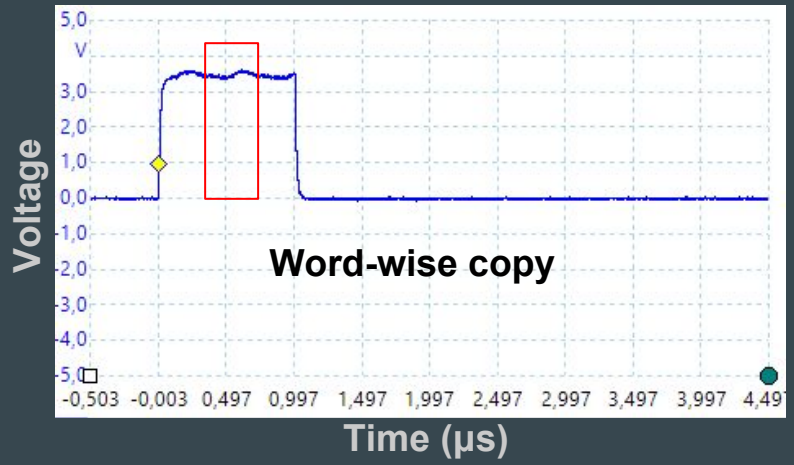
- Prepare two buffers:
  - Fill **source** with 0x55
  - Fill **destination** with 0x44
  - (Normally memory is initialized with 0x00. We use 0x44 to distinguish between faults)
- Initialize unused registers to known pattern
  - C4 F4 B4 D4 for r4, C5 F5 B5 D5 for r5 etc.
- Copy **source** to **destination**
- Three variants, implemented in ARM assembly:
  - Byte-per-byte using LDRB / STRB
  - Word-per-word (4 bytes) using LDR / STR
  - Multi-word (16 bytes) using LDM / STM
- Output destination buffer over UART, bookended with 0xAA, 0xBB

# Loop timing measurement

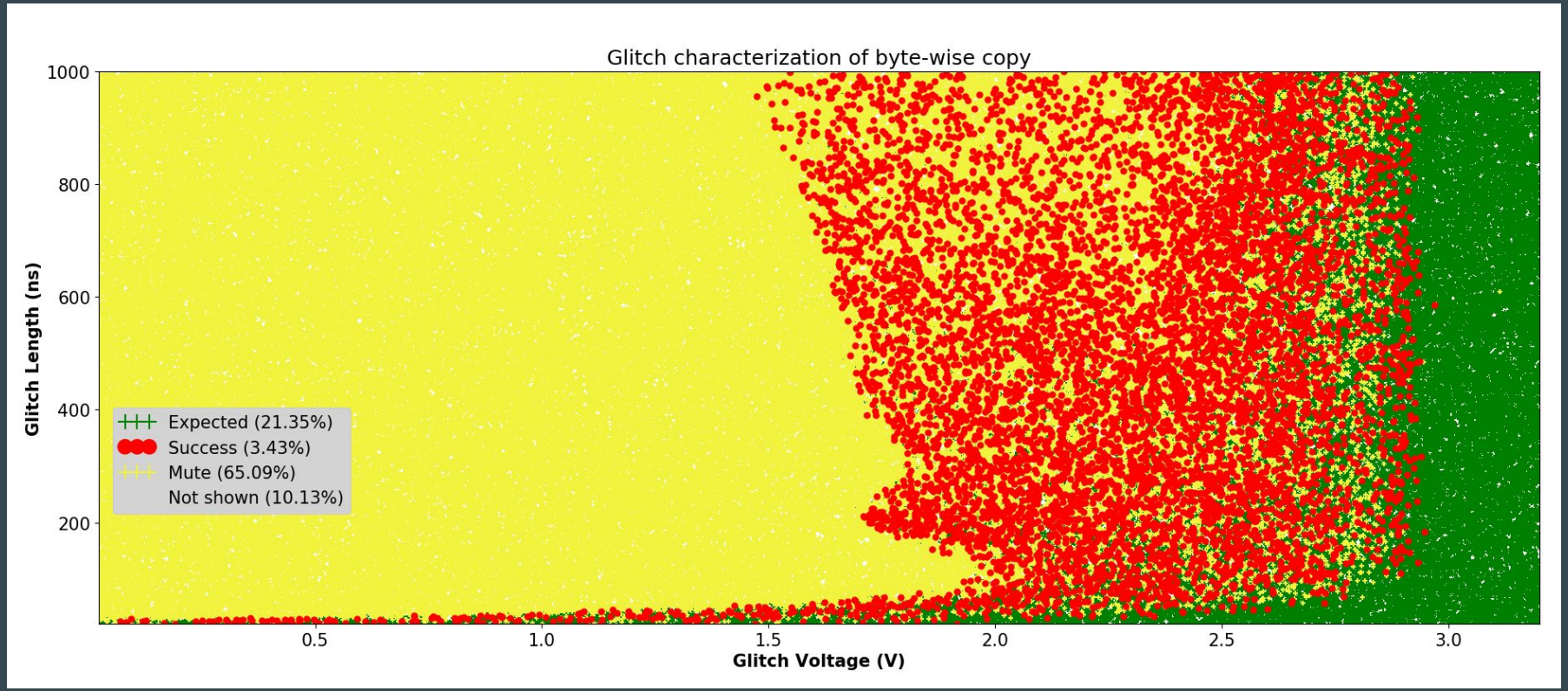
- We determine the time each loop takes using the oscilloscope
- Select glitch timings to hit the middle third (focus on area highlighted in red)



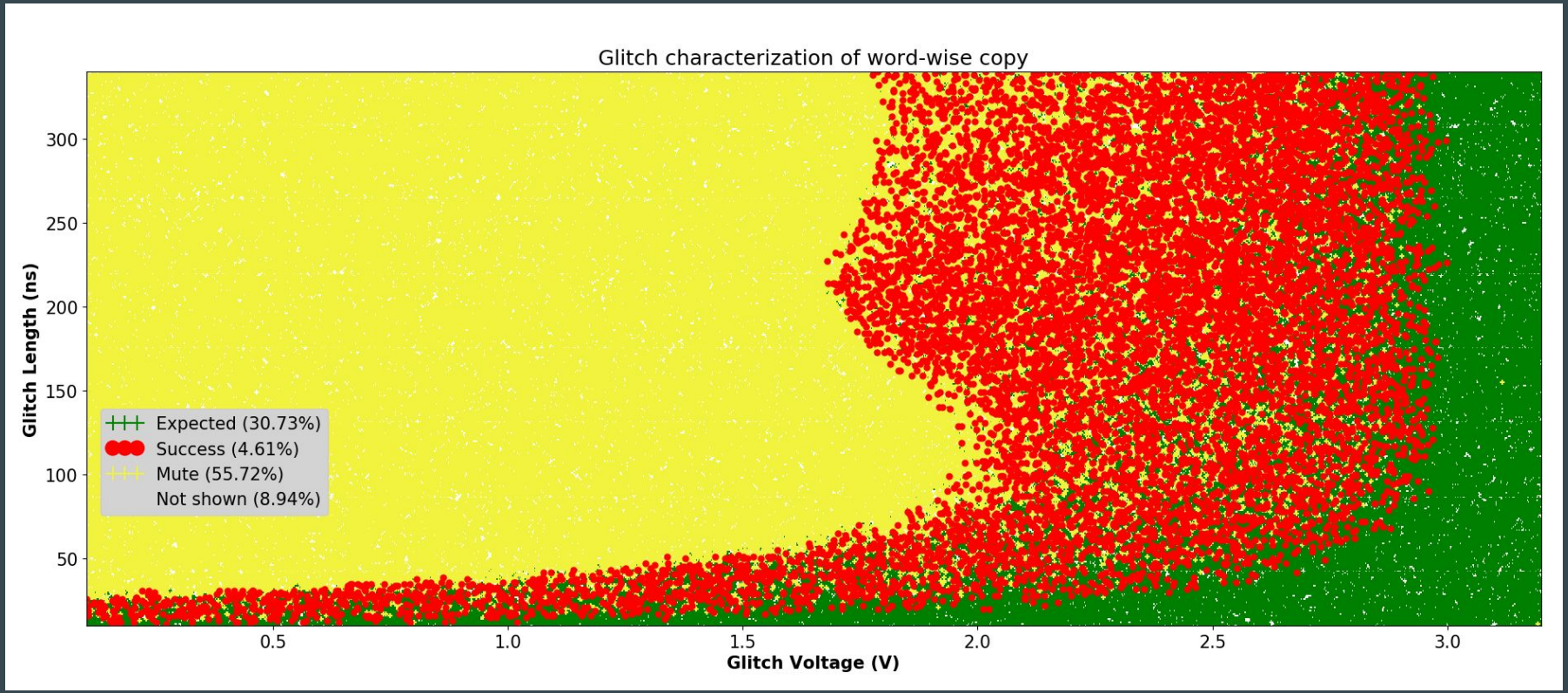



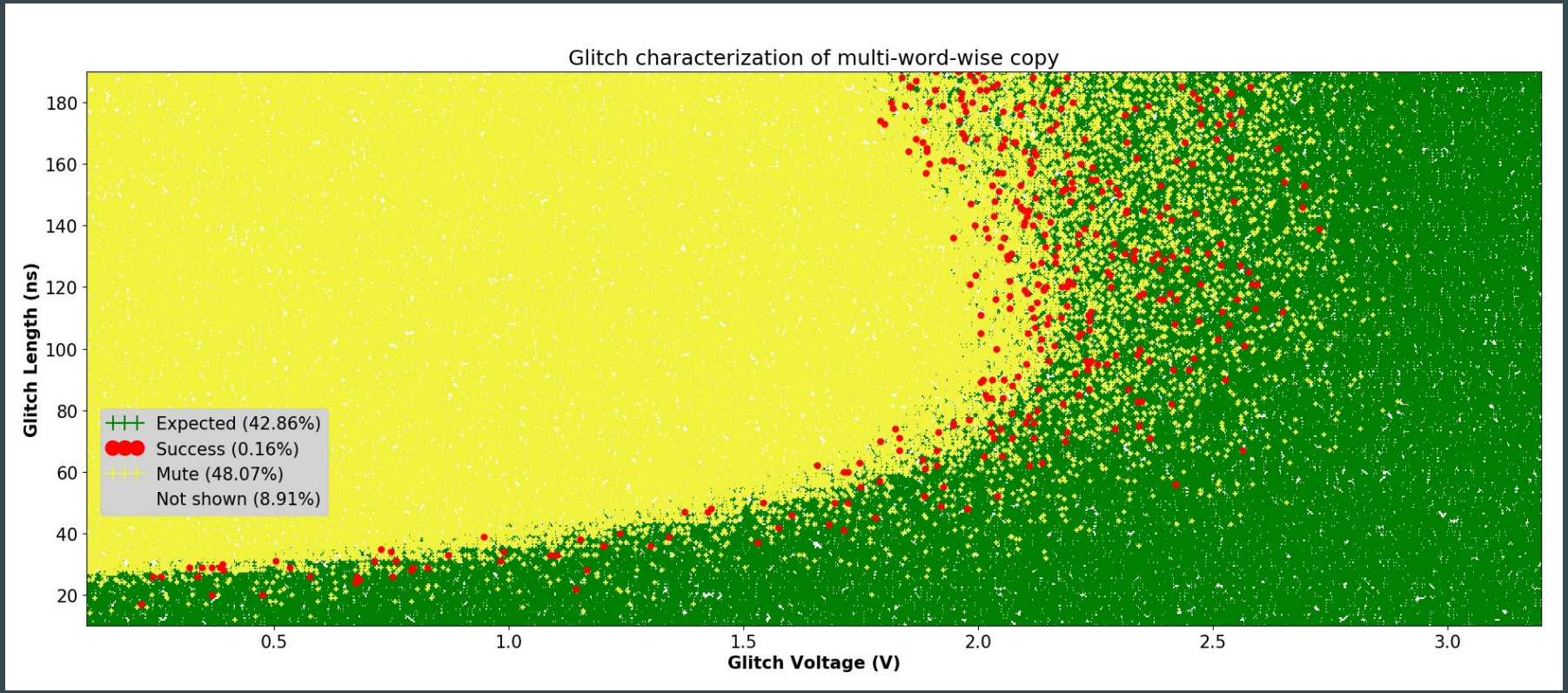
# Glitch characterization, byte-wise, (229815 tests)



# Glitch characterization, word-wise, (230123 tests)

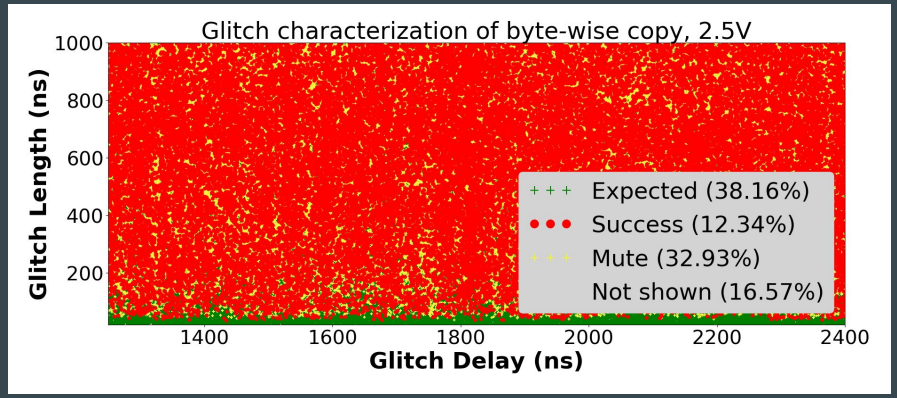


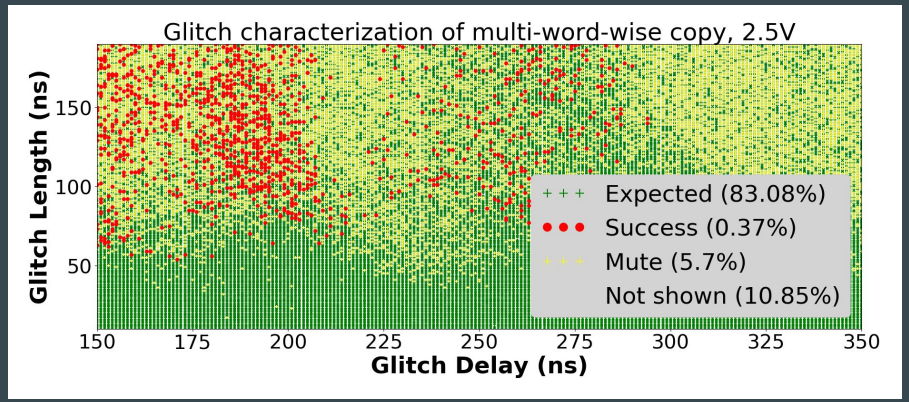
# Glitch characterization, multi-word-wise (231069 tests)

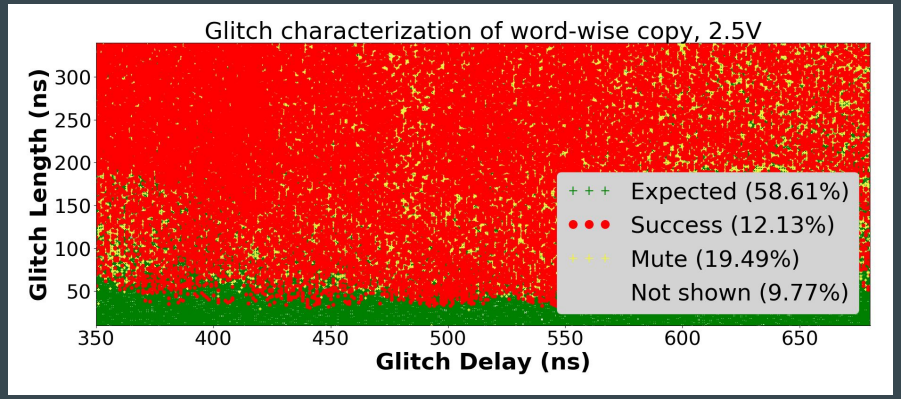


# Refine parameters -> Fix voltage at 2.5V

- Higher success rate
- Multi-word still difficult, but shows a clear area to focus on
- Further refinement is possible



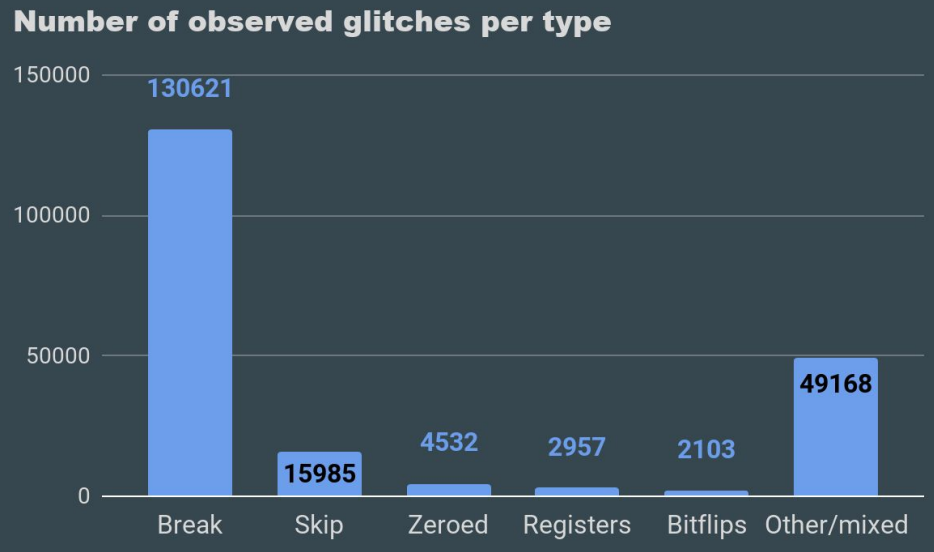



# Fault Models observed - some examples

- Early Break: AA5555...5555555555555544444444444444BB
- Skip: AA5555...5555555555554455555555555555555BB
- Zeroed: AA5555...55550000555555555555555555555BB
- Registers: AA5555...5555DABAFACA55555555C7555555555BB
- Bitflips: AA5555...55555455555555555555555...55BB (01010100)
- Mixed: AA5555...5555D7B7F7C7555500005555555544444BB
- Other: AA5555...55554400230120AD2C0008152D000851...BB

# Determine Fault Model

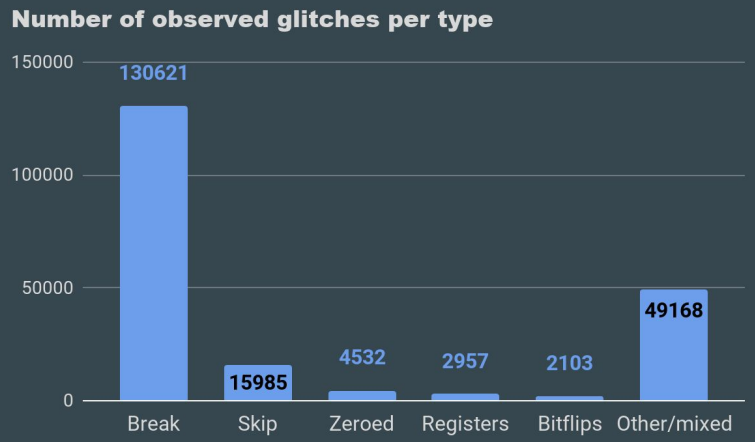
Out of 3.191.236 total tests, we observed 205.366 desired (red) glitches. These glitches are categorized and tallied as follows:




| Type of fault | Percentage of total |
|---|---|
| Early break | 63,6% |
| Single skip | 7,8% |
| Zeroed | 2,2% |
| Other registers | 1,5% |
| Flipped bits | 1% |
| Other/mixed | 23.9% |

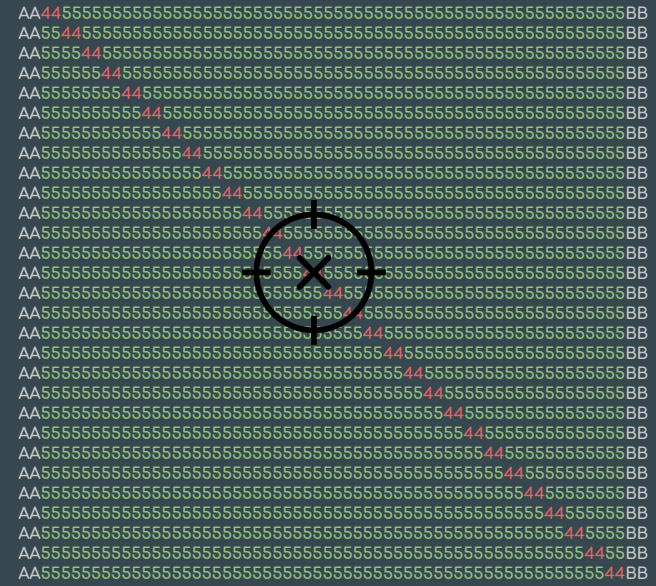
# Most suitable for breaking RSA

- By far the most common is an early break scenario
- This is not the most suitable for breaking RSA
  - Every byte set to 0 at the end adds $2^8$ as a factor
  - In this scenario, about half of the messages fail to decrypt properly
  - RSA requires that message and n are coprime
  - You could modify the message to make it work
- More suitable is a single skip
  - It's the second most common
  - It's predictable
  - Less likely to add repeating factors



# But can we hit every single loop iteration?

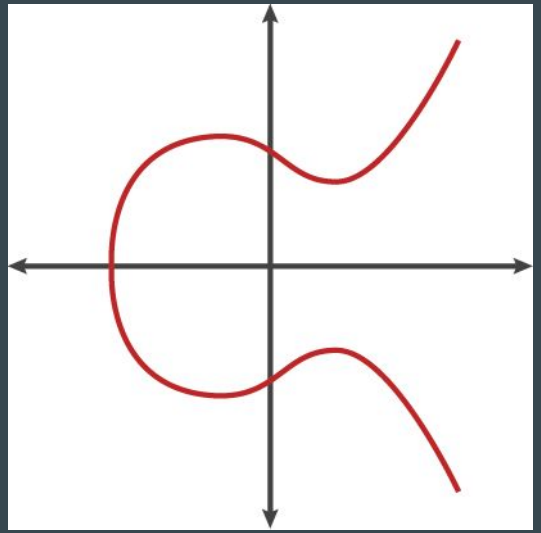
- Yes, we can incur single skips in every single byte or word
  - More difficult with multi-word
- We can hit a single iteration with a probability of 95% within about 2,5 minutes.
- If a secure boot takes 10 seconds this scales up to once in every 5 hours or so.
- But we only need one hit for this attack to work!



# Factoring glitched moduli

- For “normal” RSA General Number Field Sieve is currently the most efficient
- We can expect multiple smaller factors, so there is a better solution
- ECM: Lenstra’s Elliptic Curve Method
- Can find factors up to 128 bits efficiently
- We used SAGE’s implementation of ECM

SAGE: an open-source mathematics framework



Source: Cloudflare

# Factorization testing method

Based on most suitable fault model of skipping a single loop iteration.

1. Generate a random RSA key, selecting a size between 512 and 4096 bits
2. Apply glitch to each unit of data in the key separately
3. Attempt factoring of all resulting moduli using ECM
    - Divide ECM threads over each core
    - Use a timeout to keep things manageable
4. Repeat many times with a freshly generated key each time

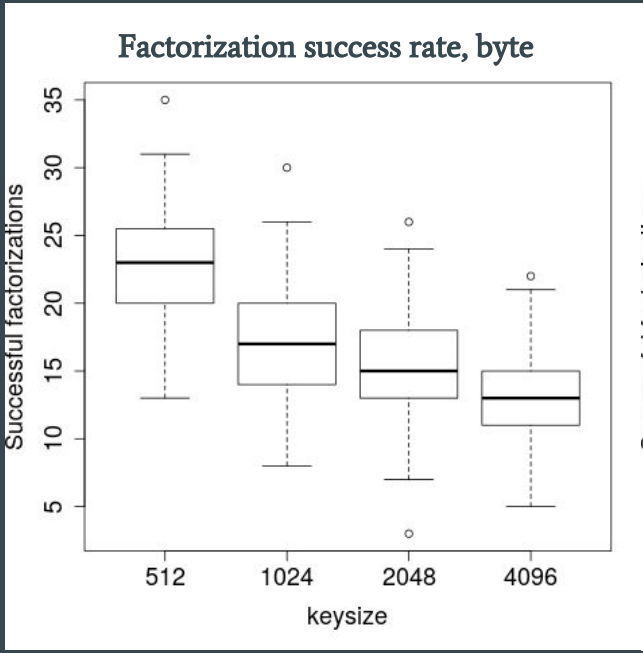
# Results

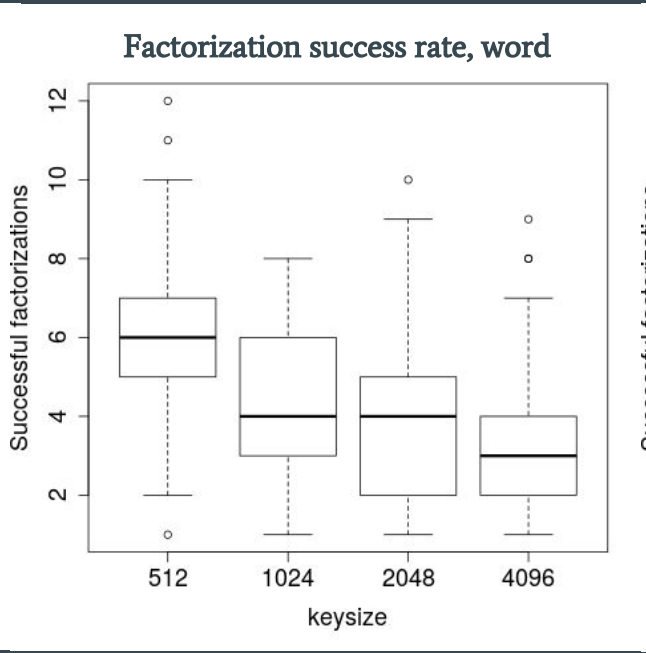
- 1234 unique RSA keys were tried:
  - 339 512-bit keys
  - 319 1024-bit keys
  - 307 2048-bit keys
  - 269 4096-bit keys

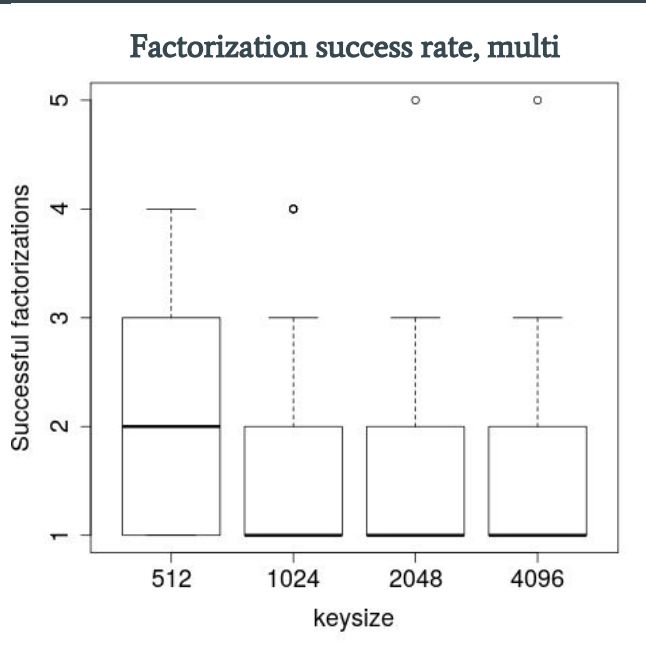
- In total 146512 perturbations of these 1234 keys were attempted!
- Of those, 11150 were factored successfully within 60 seconds, or 7,6%
- But, **ALL** keys had at least one successfully factored perturbation
- Including every single 4096 bit key!

# Factorization success rates by fault model

Please note the scale difference. Timeout used: 60 seconds.



# Creating private keys from factorizations

- Private key: $d \equiv e^{-1} \mod \phi(n)$
- $\phi(n)$ is easy to calculate if we know the factorization
- Usually more than two primes, different from “textbook” RSA
  - Ask me later for details if you’re interested!
- No further alterations to RSA are needed
- Also implemented this using SAGE

Leonhard Euler, Portrait by Jakob Emanuel Handmann (1753)

# Key takeaways

- We've shown that it's possible to reliably modify a public key using V-FI
- Even though RSA public values don't have to be kept secret, they should be protected against modification!
- We can factor all keys efficiently and create a private key
- All keys, even of 4096 bit size, have at least one easily factored modification
- With careful timing, this attack can succeed in minutes

**Weakening the public modulus using Voltage Fault Injection is a practical means of attacking RSA signature verification.**

# Discussion / Future work

- Specialized equipment was used in our experiments
  - But this attack should also work with cheaper, open source hardware, such as a ChipWhisperer
- We had control over the target's code, allowing easy triggering
  - For targets not under our control, Side Channel Analysis can be used to determine timings
- Signature verification was not tested on target
  - Suggest implementing
- We suggest applying this to a secure boot implementation
- Suggest looking into the effect on various signing schemes
  - PKCS#1 v1.5, RSA-PSS, RSA-OAEP, etc.
  - RSA-CRT signature generation will not work with these keys

# Thank You!


GitHub https://github.com/ivovanderelzen/GlitchRSA/

# Questions?

# Extra bits

# Odds of hitting a single byte

- If we target a single byte we can hit it about 1,7/1000 or 0,17% of the time
- We need to do 1761 tests to get a 95% chance of hitting this byte at least once
  - $\frac{\ln(1-0.95)}{\ln(1-0.0017)} = 1760.7$
- With a glitch rate of 12 per second, this will take 147 seconds, about 2,5 minutes
- With a (conservative) rate of one every 10 seconds
  - 1761 * 10 / 360 = 292 minutes, or about 5 hours

# Calculating Euler's totient

- Generalized formula:
  - $\phi(n) = \phi(p_1) \cdot \phi(p_2) \ldots \cdot \phi(p_n)$
- Normally RSA works with two prime factors
  - $\phi(n) = \phi(p) \cdot \phi(q)$
  - $\phi(n) = (p-1) \cdot (q-1)$
- More than two factors
  - $\phi(n) = (p-1) \cdot (q-1) \cdot (r-1) \ldots$
- Prime power factors
  - $\phi(p^k) = p^{k-1} \cdot (p-1)$ (Where p is the prime factor and k is its exponent)
- If *N* is prime
  - $\phi(n) = n - 1$

Leonhard Euler, Portrait by Jakob Emanuel Handmann (1753)

# Message Coprimality

- RSA states that the message should be coprime with the modulus
  - $gcd(m, n) = 1$
- Other situations also work
  - Let $p$, $q$, $r$ be prime (power) factors of $n$
  - $gcd(m,n) = p$ (a factor of $n$ divides the message)
  - $gcd(m,n) = p * q * r$, etc... (product of any of the factors)
- With prime power factors, we can run into an issue
  - Let $p^k$ be a prime power factor of n
  - $gcd(m,n) = p^k$ decrypts correctly
  - $gcd(m,n) = p^x$ where $x != k$, does not decrypt correctly