Analysis of Arbitrary Waveform Generation for Voltage Glitches

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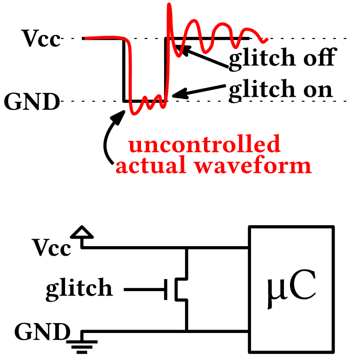
Fault Injection (FI) by Voltage Glitching

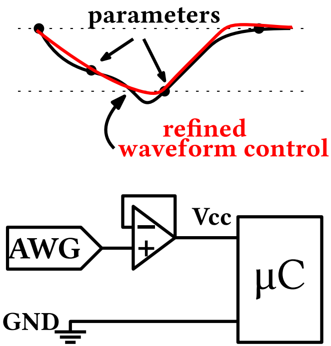
Traditional

square pulse (idealized)



Arbitrary

polynomial interpolation



Why? → Differential Fault Analysis, bypass code read-out protection, fun …

Previous Work

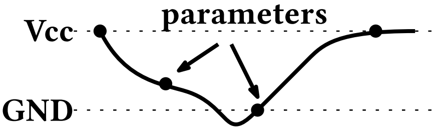
"*Shaping the Glitch*" [1] at CHES 2019

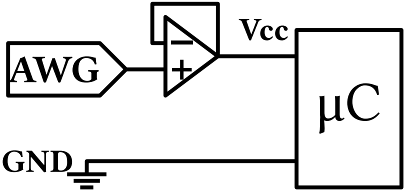
Their approach:

- Cubic interpolation over random points
- Better waveform control vs. traditional glitch
- Shown to improve success rate
- Enabled vulnerabilities in 6 microcontrollers
- Genetic algorithm "discovers" waveform

Limitations:

- High reset rate when glitching (why?)
- Blindly trusting genetic algorithm to do the job
- What features (do not) work in a waveform?





[1] Claudio Bozzato, Riccardo Focardi, and Francesco Palmarini. "Shaping the Glitch: Optimizing Voltage Fault Injection Attacks". In: *IACR Transactions on Cryptographic Hardware and Embedded Systems* (Feb. 28, 2019), pp. 199–224. ISSN: 2569-2925. URL: https://tches.iacr.org/index.php/TCHES/article/view/7390

Our Work and Why it May Matter to You

- **Questions we investigate**
  - How to move away from *random* supporting points?
  - Is it possible to constrain the waveform to hardware-limits?
  - Can we limit the search-space prior to automated learning?
- **Challenges we want to solve**
  - Find properties of a glitch that promote *success* and reduce *reset* rate
  - Generate waveforms more *systematically* while respecting hardware-constraints
  - Provide safety *guarantees* on all generated waveforms
- **Scope of this work**
  - Focus on the properties of the waveform generation prior to automated learning
  - In other words: this is <u>not</u> about the efficiency of the search (*covered separately*)

→ targeted improvements important to perform security testing more economically!

Outline of our Work

1. **Waveform Parametrization**
   - Defining “valid” waveforms
   - Polynomial basis: what can go wrong
   - Our proposed approach: *Modular Splines* for generating waveforms
2. **Awgsomefi: Fault Injection Framework (see paper)**
3. **Case Studies**
   - Loop escape on the STM32F0 with *specificity*
   - Improved firmware extraction from the 78K0R
4. **Conclusion**
   - Summary
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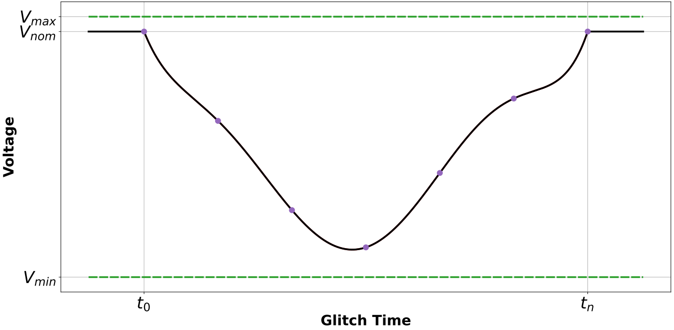
Waveform Parametrization: Our Constraints

- Starts at t_0 and ends at t_n
- Begins and ends at V_{nom}
- Must stay within $[V_{min}, V_{max}]$ to avoid damaging the chip



Naive Interpolation

- For simplicity, let's interpolate polynomial on equispaced points
- We set $\mathrm{waveform}(t_0) = \mathrm{waveform}(t_n) = V_{nom}$
- The rest randomly picked to be within $[V_{min}, V_{max}]$
- What can possibly go wrong? (paper=more explanations, discussing cubic interpolation)

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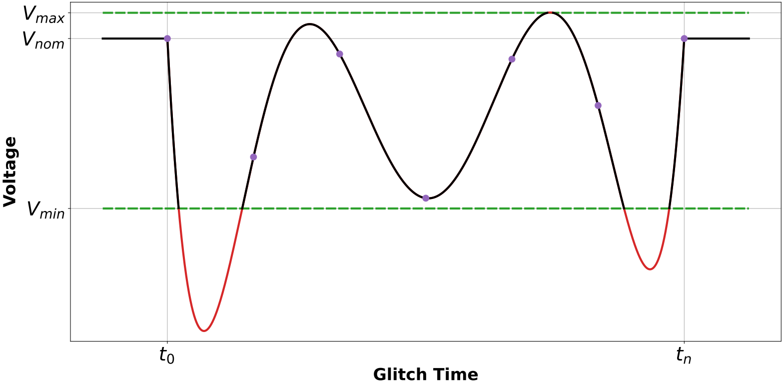
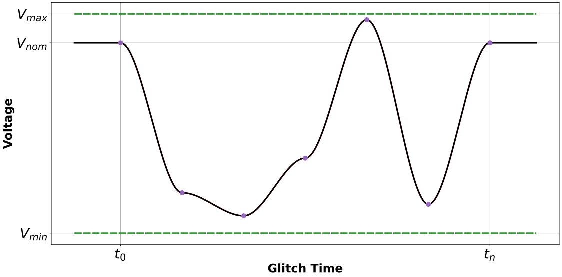


Cubic Hermite Splines as Waveforms

- **Needed:** Smoothness/control tradeoff
- Set first derivative at interpolation points
- Interpolation points once differentiable



- **Idea:** What if we set the derivative at each breakpoint to 0?
- Only interpolation points can be minima/maxima in interval…

→ Benefit: waveform will *always* stay inbounds!

Selection of Glitch Duration

- t_0 mostly picked analytically (e.g. by doing side-channel analysis)
- Instead of selecting t_n we look for $t_\Delta = t_n - t_0$
- In previous works this is an additional parameter for exhaustive testing
- **Observation:** Not all durations make sense for complicated waveforms

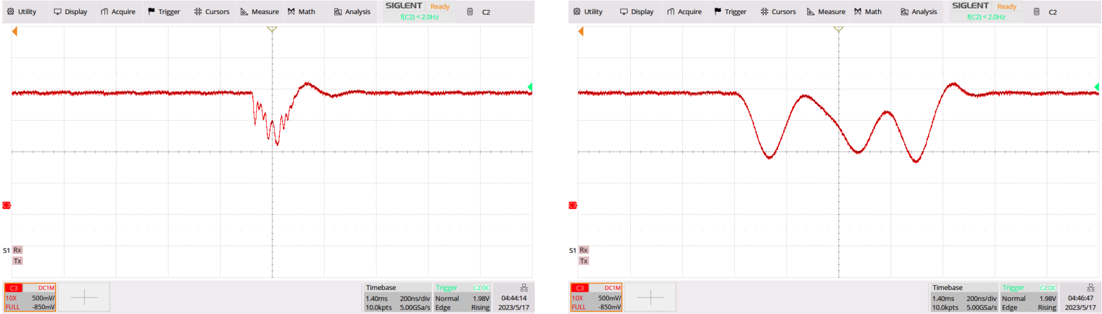


Figure: 120 ns vs. 800 ns glitch.

Modular Splines: Limiting the Slew Rate

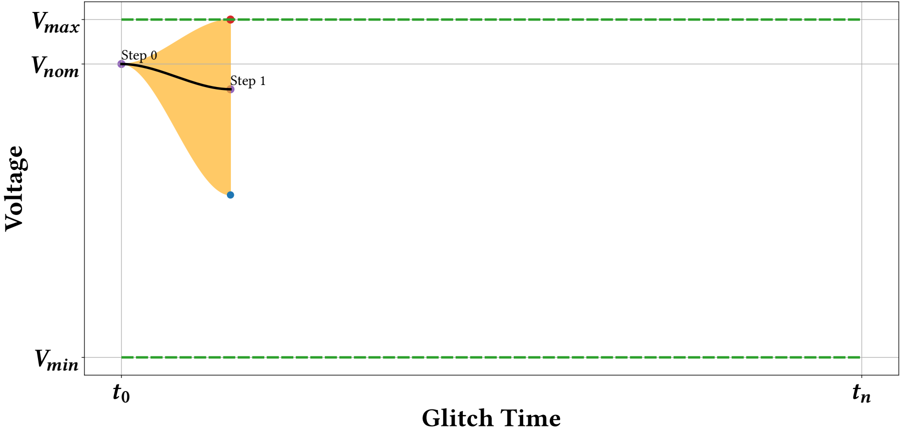
- **Idea:** construct the Hermite spline one segment at a time
  1. Begin at t_0 and $V_0 = V_{nom}$
  2. Choose $t_{i+1} > t_i$
  3. Choose V_{i+1} such that $\left|\frac{V_{i+1}-V_i}{t_{i+1}-t_i}\right| < limit_{\Delta V}$
  4. Repeat from step 2 until $i = n-1$
  5. Choose large enough t_n so that $\left|\frac{V_{nom}-V_{n-1}}{t_n-t_{n-1}}\right| < limit_{\Delta V}$

- For very **small** $t_{i+1} - t_i \implies V_{i+1} \approx V_i$
- For **large** enough $t_{i+1} - t_i \implies V_{i+1}$ chosen from $[V_{min}, V_{max}]$

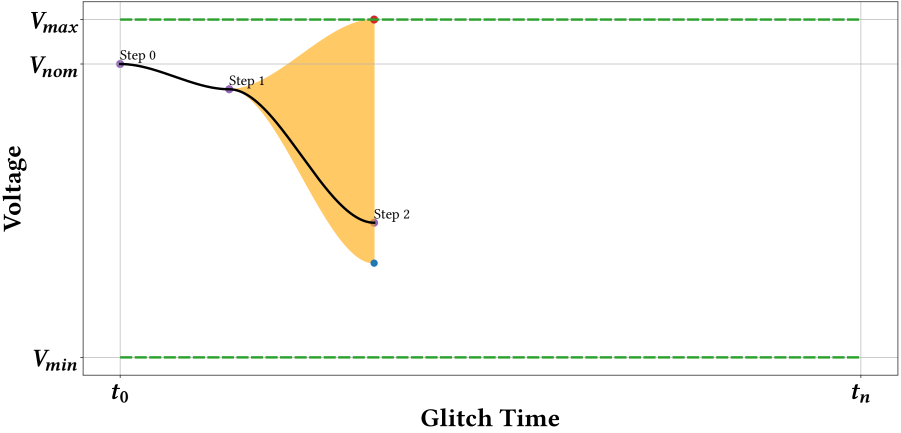
- t_Δ no longer chosen arbitrarily: sum of segments!
- The more "complex" the glitch the higher its average duration

$\rightarrow$ Benefit: search space for t_n determined by OPAMP capability

Modular Splines in Action



Modular Splines in Action



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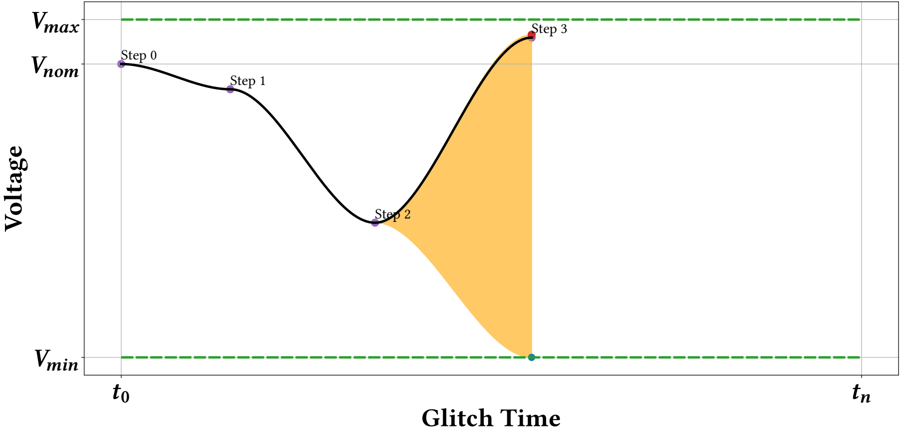

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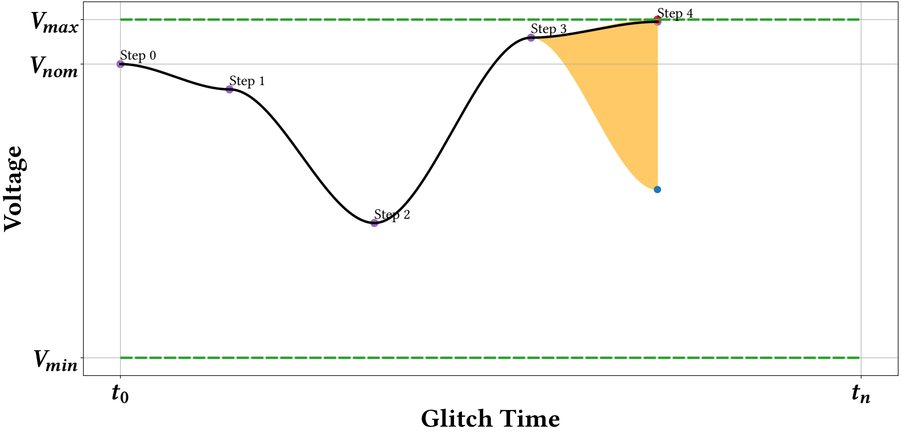

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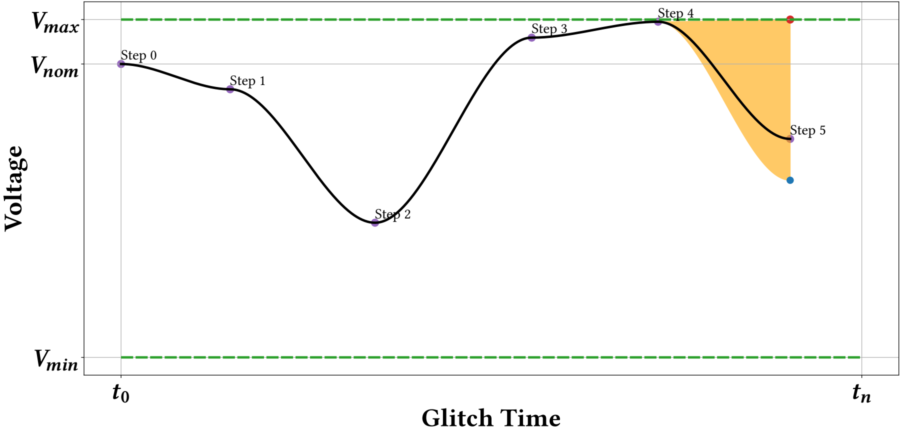

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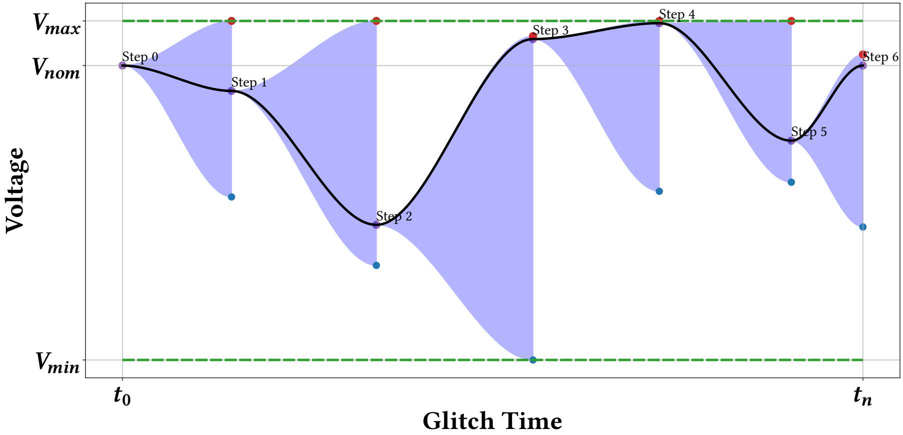

Modular Splines: Summary

- Proposed option is the only one that is *guaranteed* to be in bounds
- Searchspace reduced by bounding voltages at interpolation points based on slew rate

- Full parameters list:
  1. Start time of glitch, t_0
  2. Total number of spline segments, n
  3. Segments t_i (n total)
  4. Inner voltages, V_i ($n-1$ total) bounded by slew rate!

$\longrightarrow$ Modular Splines prove a much more systematic approach with smaller search-space!

Outline of this Work

1. **Waveform Parametrization**
   - Defining “valid” waveforms
   - Polynomial basis: what can go wrong
   - *Modular Splines* for generating waveforms
2. **Awgsomefi: Fault Injection Framework (see paper)**
3. **Case Studies**
   - Loop escape on the STM32F0 with *specificity*
   - Improved firmware extraction from the 78K0R
4. **Conclusion**
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   - Future Work

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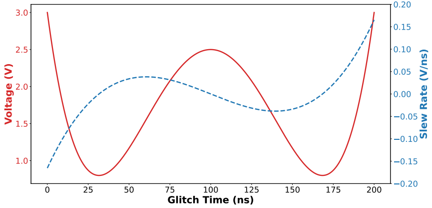
Case Study: STM32 Loop Escape

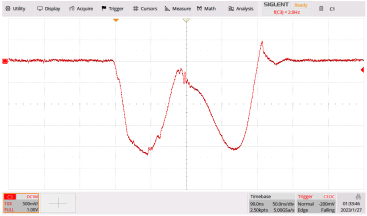
```
while (glitched) // <- Glitch
{
;
}
glitched++;
asm("NOP");
asm("NOP");
// continue NOP slide

if (glitched == 0x01u) {
   sigTermOne();
   sigEnabTwo();
} else if (glitched == 0x02u) {
   sigTermOne();
   sigTermTwo();
}
// Check other possible signals
```

- Goal: escape from loop
- How many instructions skipped?
- Can we control number of skips?

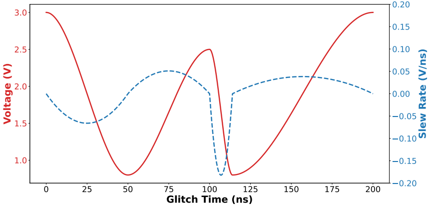
STM32: Waveform Base Comparison



(a) Chebyshev polynomial and its derivative.



(b) Polynomial-glitch applied to STM32.



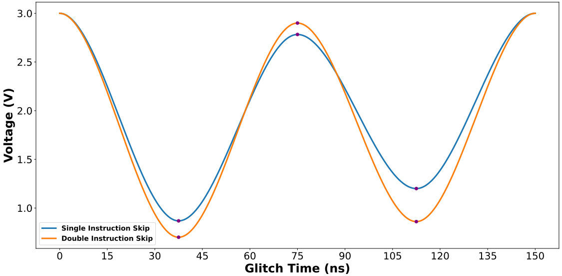
(c) Spline glitch waveform and its derivative.

(d) Spline-glitch applied to STM32.

Figure: Polynomial (0% glitch success) vs. Hermite spline (40% glitch success).

STM32: Exploring Specificity

- Can we look for waveforms that achieve single vs double instruction skips?
- Small difference in waveform: big difference in outcome!



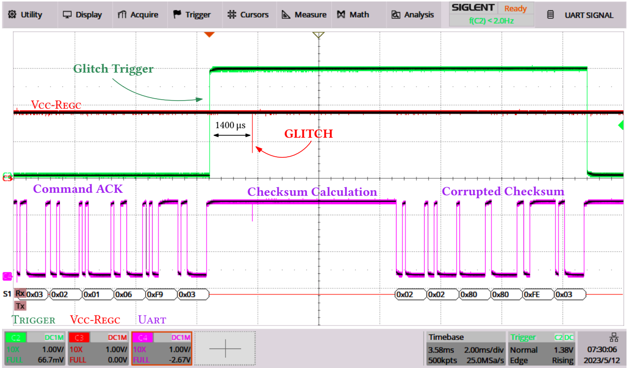
	Single Skip Success Rate	Double Skip Success Rate
Single Skip Waveform	55%	$\approx 0\%$
Double Skip Waveform	6%	41%

Case Study: 78K0R Firmware Extraction

78K0R Plan of Attack: verify-only microcontroller

Need `ChecksumLeak` and `ShortVerify` as gadgets

- `ChecksumLeak`: Omit a byte from the checksum
  - Subtract corrupted checksum from correct checksum to leak a byte!
  - We found waveform that can leak one or **two** bytes
  - Noisy gadget $\implies$ need `ShortVerify`



78K0R Plan of Attack: `ShortVerify`

- `ShortVerify`: Verify multiples of 4 bytes
  - Normally can only verify multiples of 256 bytes
  - Verifications must be 256 byte aligned
  - In previous works, fault injection is used
  - In this work: “properly configured software bypass”

Verify Command (as intended)

Programmer — **78K0R**

- VERIFY[STARTADDR][ENDADDR] →
- ← STATUS FRAME
- DATA FRAME[LEN][DATA][ETB/ETX] →
- ← STATUS FRAME (ST1/ST2)

ShortVerify Command (proposed)

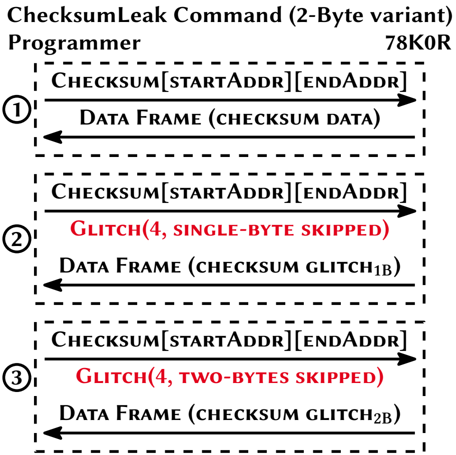
Programmer — **78K0R**

- VERIFY[STARTADDR][STARTADDR+256] →
- ← STATUS FRAME
- DATA FRAME[LEN=4][DATAWORD][ETX] →
- ← STATUS FRAME (ST1/ST2)

Our Attack

Idea: Extract 4 bytes at a time
Let's try to extract bytes $4-7$.

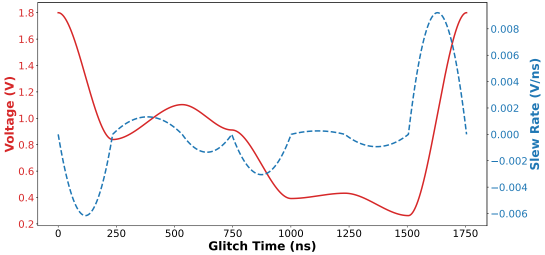
1. Find the reference checksum (no glitch) ①
2. Leak candidates for couplet $4, 5$
   - Use `ChecksumLeak` to omit byte 4 ②
   - Use `ChecksumLeak` again to omit bytes $4, 5$ ③
3. Leak candidates for couplet $6, 7$
   - Use `ChecksumLeak` to omit byte 6 ②
   - Use `ChecksumLeak` again to omit bytes $6, 7$ ③
4. Concatenate candidate couplets and run `ShortVerify` to find the correct bytes!



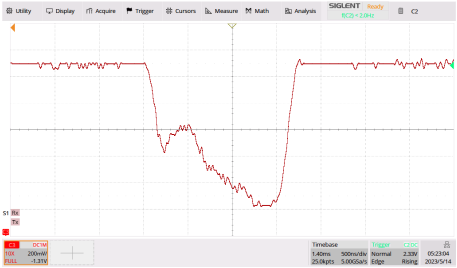
Our Glitch Waveform

- About 2x longer than used in original work
- Allows double glitches

- Smooth: no overshoots
- Lower reset rate $\implies$ more glitches per given time interval



(a) Fault injection waveform.



(b) Scope measurement of fault injection.

Benchmark Comparison

After 10 minutes of glitching (same condition as [1])

Vulnerability	Technique	Success (S)	Reset (R)	R/S	Glitches
ShortVerify	AWG [1]	1291 (6.8%)	2786 (14.6%)	2.16	19044
	this work [2]	**10216 (100%)**	–	–	0
ShortChecksum	AWG [1]	728 (4.4%)	2912 (17.7%)	4.01	16475
	this work [3]	–	–	–	–
ChecksumLeak	AWG [1]	687 (8.6%)	2515 (31.5%)	**3.66**	7977
	this work [4]	1427 (8.8%)	389 (2.4%)	**0.27**	16216

→ Overall, new techniques made this a much more powerful attack!

[2] **software-only bypass: *always* successful!**

[3] **not needed: search-space small enough**

[4] **Reset/Success rate improved from 3.66 to 0.27**

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Summary and Future work

Summary:

- Arbitrary wave voltage glitches provide interesting new opportunities
- Full potential has not been realized yet
- We proposed and demonstrated a new waveform parametrization method
- Using *specificity*, we vastly improved an existing firmware extraction attack

Future work:

- Do we have to interpolate or are there even better options?
- Modular Splines will benefit from new search strategies (work in progress)
- X-device profiling and how well does this perform when facing countermeasures?

Thank you for your attention!
Questions?

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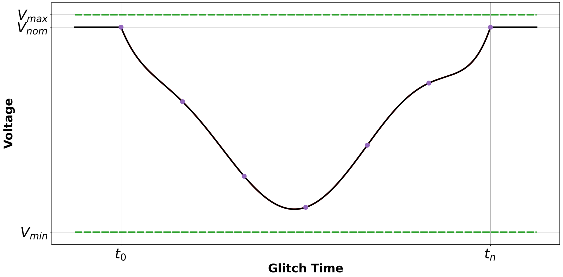
Backup Slides for Q&A

Arbitrary Waveform Glitches: Polynomials

- **Property 1:** Polynomials can approximate any waveform in the $[t_0, t_n]$ interval
- **Property 2:** Degree n polynomials are *uniquely* determined by $n + 1$ points



- **Idea:** Interpolate polynomials on $n + 1$ points within $[t_0, t_n]$ to generate waveforms
- **Question:** What points t to interpolate on? Does it matter? Yes!

Fixing Oscillations

- **Insight:** even if our interpolation points only pass through $[V_{min}, V_{max}]$, the waveform may still *significantly* oscillate out of bounds
- Why does this happen? Runge Phenomenon!
- Instead we interpolate on *Chebyshev nodes*

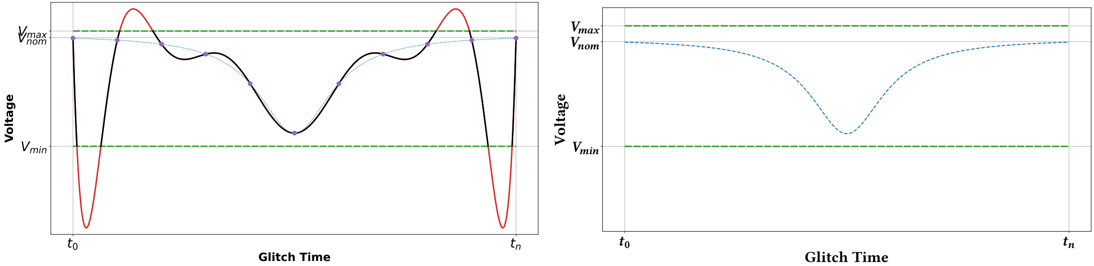
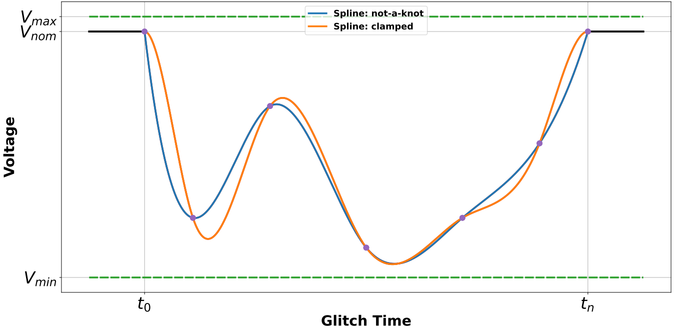


Figure: Interpolating shifted Runge function on equispaced points and Chebyshev nodes.

Cubic Splines as Waveforms

- Used in *all* previous works on arbitrary waveform voltage glitching
- Build complicated waveforms by “stitching” together cubic polynomials
- Spline is twice differentiable at knots + resilient to oscillations!
- Multiple configurations available (clamped, not-a-knot)
- However: slew-rate left uncontrolled!



Cubic Splines: Summary

- Less smooth than polynomials but still twice differentiable everywhere
- Potentially much larger search space (but also better control)
- Stays in bounds (mostly) even on equidistant points