# Physical Attacks and Countermeasures

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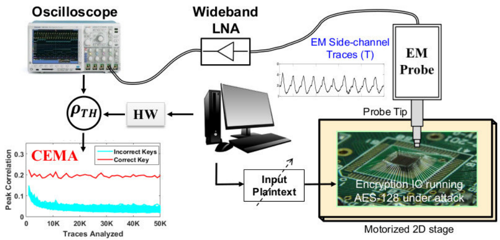
CS 579/ECE 599, February 28, 2022

# About Me: Stan Lyakhov

- TA for this course
- Graduate student at OSU in Dr. Immler's lab
- Formerly Multiparty Computation (MPC) with Mike Rosulek
- Work primarily on voltage fault injection and side channel analysis
- Fun fact: I grew up next to Technion (where DFA was proposed)

# Physical/Hardware Security (Part 1)

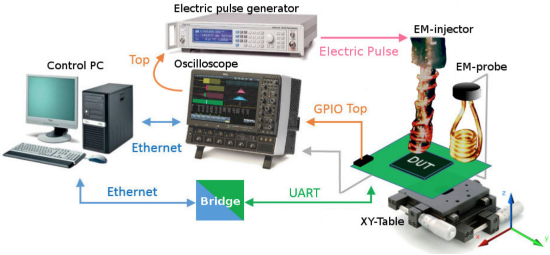
## Non-invasive Attacks




(source: "STELLAR: A Generic EM Side-Channel Attack […]")

- Eavesdrop signals from crypto hardware
- Massive data analysis + AI ('big data')
- Statistics that make you happy ☺
- Mostly Differential Power Analysis (DPA)
- Plus micro-architectural (timing) attacks

## Semi-invasive Attacks




(source: "Studying EM Pulse Effects on Superscalar Microarchitectures at ISA Level")

- Fault injection: change data/control flow
- Voltage, clock glitches; lasers
- High voltage/short rise EM pulses
- **Differential Fault Analysis (DFA)**
- Corresponding countermeasures

# What is Differential Fault Analysis (DFA)?

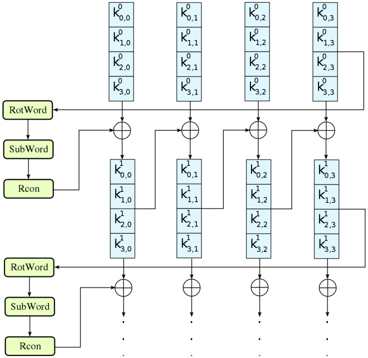
- Goal: extract a secret key by corrupting the state of a cipher
- Introduced for symmetric ciphers by Biham and Shamir in 1997
- Proposed using a laser or “cutting wires”
- Showed attack on DES/3DES (before AES was standardized)

# Review: Advanced Encryption Standard

- Three variants (AES128, AES192, AES256) with different key lengths
- Research interest in attacking all three
- Today: focusing on AES128
- AES Visualization:
  `https://www.cryptool.org/en/cto/aes-animation`
- AES Step-by-step tool:
  `https://www.cryptool.org/en/cto/aes-step-by-step`

# AES Key Schedule

- Recall: only the first KeyAdd xors with the key itself
- Key schedule creates subsequent keys using original
- Transformations between keys are:
  - Predicatable
  - **Invertible**
- Can recover original key if we find 10th round key



# DFA: Basic Idea

1. Observe output of encryption (no fault)
2. Observe output of an encryption with a strategically placed fault
3. Gain information by looking at the difference/comparing the two

# Fault Models: what can an attacker do?

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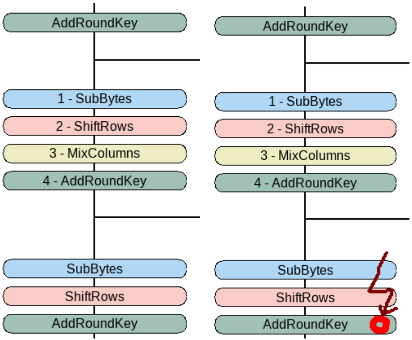
- What if we can set a specific value at a specific location?
  - Target KeyAdd: set some key bit to 0
  - Check if faulty ciphertext changes from non-faulty
  - Need 128 faults (at each bit position)

# Simple DFA

- Inputs: Two similar plaintexts
- For each bit position $i$ of the key:
  - Glitch: Set bit at position $i$ to 0
  - Compare: Are the outputs different?



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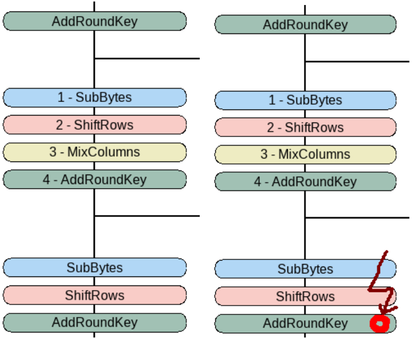
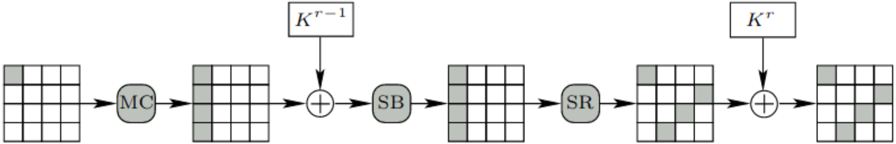



- Faulty ciphertexts required: 128
- Pros: simple algorithm
- Cons: unreasonable fault model

# DFA by Piret and Quisquater ('03)

- Fault model: any **single byte** in round 9 changed to any value
- Extract 4 bytes of key ($K^r$) at a time



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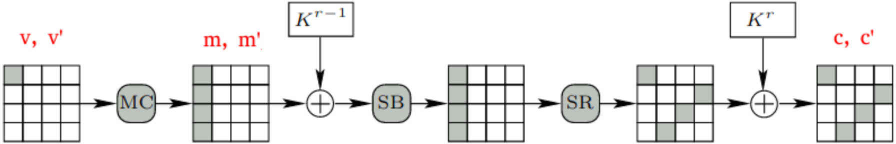

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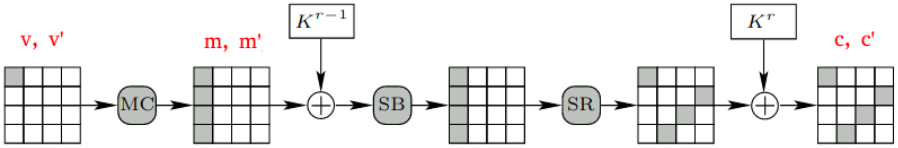


- *Inputs (1 byte apart):* $v \oplus \mathrm{glitch} = v'$
- **MixColumns**

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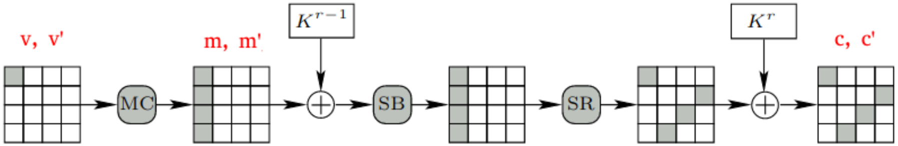


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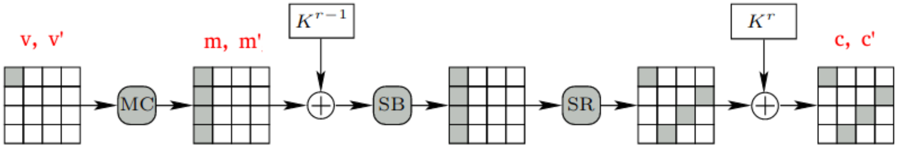


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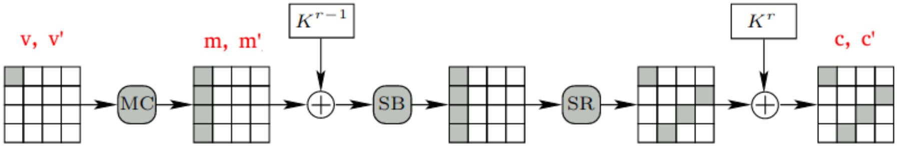


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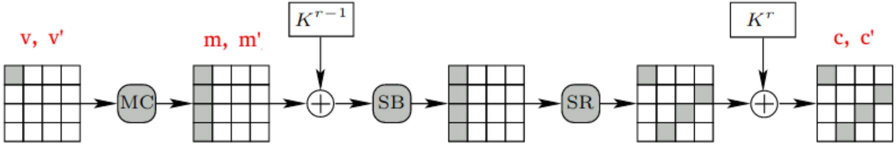
# Idea: recover $m$ from $c$?

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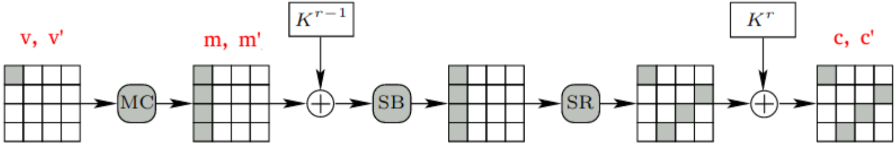


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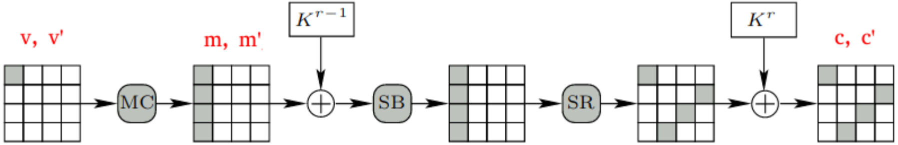


- $m$ (and $m'$) is completely unknown. Can we get from $c$ to $m$?
- $m = ISBOX(\text{unshift}(c \oplus K^{10})) \oplus K^9$
- $m' = ISBOX(\text{unshift}(c' \oplus K^{10})) \oplus K^9$

$$\begin{aligned} m \oplus m' &= \text{mixcol}(v) \oplus \text{mixcol}(v') \\ &= \text{mixcol}(v) \oplus \text{mixcol}(v \oplus \text{glitch}) \\ &= \text{mixcol}(v) \oplus \text{mixcol}(v) \oplus \text{mixcol}(\text{glitch}) \\ &= \text{mixcol}(\text{glitch}) \end{aligned}$$

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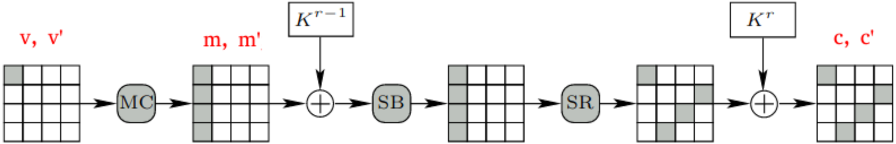


$$
\begin{aligned}
\text{mixcol}(\text{glitch}) &= m \oplus m' \\
&= \mathit{ISBOX}(\text{unshift}(c' \oplus K^{10})) \oplus K^9 \oplus \mathit{ISBOX}(\text{unshift}(c \oplus K^{10})) \oplus K^9 \\
&= \mathit{ISBOX}(\text{unshift}(c' \oplus K^{10})) \oplus \mathit{ISBOX}(\text{unshift}(c \oplus K^{10}))
\end{aligned}
$$

# Computing all possibilities of $\mathrm{mixcol}(\mathrm{glitch})$

- Let $x = 1$ to $255$
- **Note**: all multiplication is galois field multiplication!

$$\mathrm{glitch} = \begin{bmatrix} x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad \mathrm{mixcol} = \begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix}$$

$$m \oplus m' = \mathrm{mixcol} \times \mathrm{glitch} = \begin{bmatrix} 2 \times x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ 3 \times x & 0 & 0 & 0 \end{bmatrix}$$

Only 255 possibilities for $\mathrm{mixcol}(\mathrm{glitch})$! Can precomute

# Plan of attack

- Guess $K^{10}$
- $m \oplus m' = ISBOX(\mathrm{unshift}(c' \oplus K^{10})) \oplus ISBOX(\mathrm{unshift}(c \oplus K^{10}))$
- If $m \oplus m'$ does not equal to $\mathrm{mixcol}(\mathrm{glitch})$ for some $x$
- $K^{10}$ cannot be the correct key!

$$m \oplus m' = \mathrm{mixcol}(\mathrm{glitch}) = \begin{bmatrix} 2 \times x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ 3 \times x & 0 & 0 & 0 \end{bmatrix}$$

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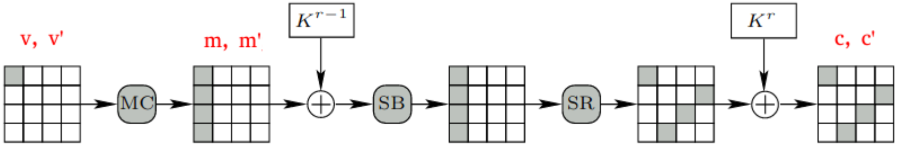
- **Problem**: $K^{10}$ is 128 bits long! Are we guessing the whole thing?
- **Solution**: No, only guess part of $K^{10}$ (the 4 bytes that differ)

$$\begin{bmatrix} 2 \times x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ 3 \times x & 0 & 0 & 0 \end{bmatrix}$$

# Attacking Partial $K^{10}$




- $m_0 \oplus m_0' = ISBOX(c_0 \oplus K_0) \oplus ISBOX(c_0' \oplus K_0)$
- $m_1 \oplus m_1' = ISBOX(c_{13} \oplus K_{13}) \oplus ISBOX(c_{13}' \oplus K_{13})$
- $m_2 \oplus m_2' = ISBOX(c_{10} \oplus K_{10}) \oplus ISBOX(c_{10}' \oplus K_{10})$
- $m_3 \oplus m_3' = ISBOX(c_7 \oplus K_7) \oplus ISBOX(c_7' \oplus K_7)$

# Revised Plan of Attack

- Guess $K_0, K_{13}, K_{10}, K_7$
- Let $m_c \oplus m'_c = [m_0 \oplus m'_0, m_{13} \oplus m'_{13}, m_{10} \oplus m'_{10}, m_7 \oplus m'_7]^T$
- If $m_c \oplus m'_c$ does not equal to **first column** of $\text{mixcol}(\text{glitch})$ for some $x$
- $K_0, K_{13}, K_{10}, K_7$ can't all be the correct bytes!

$$\text{mixcol}(\text{glitch})[0] = \begin{bmatrix} 2 \times x \\ x \\ x \\ 3 \times x \end{bmatrix}$$

- We started with $2^{32}$ possible bytes
- After filtering impossible values, we are left with around $2^{10} \approx 1036$ possibilities

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- We can narrow those down to just 1 (more on that later)

# Analysis: Revised Plan of Attack

- Given $c$ and $c'$, we can remove from consideration most values of 4 impacted bytes
- Have to bruteforce $\{K_0, K_{13}, K_{10}, K_7\}$, which means $(2^8)^4 = 2^{32}$ possibilities
- Not impossible, but can we do better?

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- Not impossible, but can we do better?
- Yes! Filter 2 bytes, then 3 bytes, and then 4 bytes at the end

# Simple Attack Outline

# Simple Attack: Filtering

- Let $m_{c2} = [m_0 \oplus m'_0, m_{13} \oplus m'_{13}]^T$. Iterations: $256 \times 256$
- Let $m_{c3} = [\text{filtered}(m_{c2}), m_{10} \oplus m'_{10}]^T$. Iterations: $|\text{filtered}(m_{c2})| \times 256$
- Let $m_{c4} = [\text{filtered}(m_{c3}), m_7 \oplus m'_7]^T$. Iterations: $|\text{filtered}(m_{c3})| \times 256$
- Our key candidates $\{K_0, K_{13}, K_{10}, K_7\}_i$ are the keybytes used in $\text{filtered}(m_{c4})$

Filter defined as:

$$m_{c2} \stackrel{?}{=} [2 \times x, x]^T$$

$$m_{c3} \stackrel{?}{=} [2 \times x, x, x]^T$$

$$m_{c4} \stackrel{?}{=} [2 \times x, x, x, 3 \times x]^T$$

# Simple Attack: End

- After filtering, we are left with $|\text{filtered}(m_{c4})| \approx 1036$ possibilities
- Need one more faulty pair: $p^* \implies (c^*, c^{*\prime})$
- For the remaining candidates, check that $m^* \oplus m^{*\prime}$ is in $[2 \times x, x, x, 3 \times x]^T$ as well

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$$ISBOX(c_0^* \oplus K_0) \oplus ISBOX(c_0^{*\prime} \oplus K_0) \stackrel{?}{=} 2 \times x$$

$$ISBOX(c_{13}^* \oplus K_{13}) \oplus ISBOX(c_{13}^{*\prime} \oplus K_{13}) \stackrel{?}{=} x$$

$$ISBOX(c_{10}^* \oplus K_{10}) \oplus ISBOX(c_{10}^{*\prime} \oplus K_{10}) \stackrel{?}{=} x$$

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$\approx 98\%$ of the time, the equations will hold for just a single candidate

# Simple Attack Algorithm

# Simple Attack Algorithm: Preparation

1. Compute $D = \mathrm{mixcol}(\mathrm{glitch}) = [2 \times x, x, x, 3 \times x]^T$ for every $x \in 1$ to $255$
2. Encrypt some plaintext $p$ and observe the output $c$
3. Inject fault in the first byte in the 9$^{\text{th}}$ round to get $c'$
4. Encrypt another plaintext $p^*$ and observe the output $c^*$
5. Inject another fault in the same place to get $c^{*\prime}$

# Simple Attack Algorithm: Filtering

1. For each $K_0 \in 0$ to $255$ and $K_{13} \in 0$ to $255$, and $x \in 1$ to $255$
   - 1.1 $ISBOX(K_0 \oplus c_0) \oplus ISBOX(K_0 \oplus c'_0) \stackrel{?}{=} D[x, 0]$
   - 1.2 $ISBOX(K_{13} \oplus c_{13}) \oplus ISBOX(K_{13} \oplus c'_{13}) \stackrel{?}{=} D[x, 1]$
   - 1.3 If both are true, add candidates $\{K_0, K_{13}\}$ to group $K_{c2}$
2. For each $K_{10} \in 0$ to $255$, and $\{K_0, K_{13}\} \in K_{c2}$, and $x \in 1$ to $255$
   - 2.1 $ISBOX(K_0 \oplus c_0) \oplus ISBOX(K_0 \oplus c'_0) \stackrel{?}{=} D[x, 0]$
   - 2.2 $ISBOX(K_{13} \oplus c_{13}) \oplus ISBOX(K_{13} \oplus c'_{13}) \stackrel{?}{=} D[x, 1]$
   - 2.3 $ISBOX(K_{10} \oplus c_{10}) \oplus ISBOX(K_{10} \oplus c'_{10}) \stackrel{?}{=} D[x, 2]$
   - 2.4 If so, add candidates $\{K_0, K_{13}, K_{10}\}$ to group $K_{c3}$
3. For each $K_7 \in 0$ to $255$, and $\{K_0, K_{13}, K_{10}\} \in K_{c3}$, and $x \in 1$ to $255$
   - 3.1 $ISBOX(K_0 \oplus c_0) \oplus ISBOX(K_0 \oplus c'_0) \stackrel{?}{=} D[x, 0]$
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   - 3.4 $ISBOX(K_7 \oplus c_7) \oplus ISBOX(K_7 \oplus c'_7) \stackrel{?}{=} D[x, 3]$
   - 3.5 If so, add candidates $\{K_0, K_{13}, K_{10}, K_7\}$ to group $K_{c4}$

# Simple Attack Algorithm: End

1. For each $\{K_0, K_{13}, K_{10}, K_7\} \in K_{c4}$, and $x \in 1$ to $255$
   1.1 $ISBOX(K_0 \oplus c_0^*) \oplus ISBOX(K_0 \oplus c_0^{*\prime}) \stackrel{?}{=} D[x, 0]$
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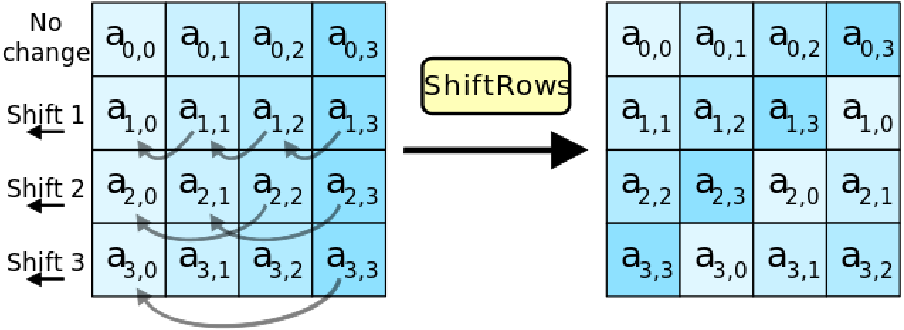
   1.4 $ISBOX(K_7 \oplus c_7^*) \oplus ISBOX(K_7 \oplus c_7^{*\prime}) \stackrel{?}{=} D[x, 3]$
   1.5 If all are true $\{K_0, K_{13}, K_{10}, K_7\}$, are likely correct keybytes

# Converting Simple Attack to Full Attack

# Limitations of Simple Attack: leaks 4 out of 16 bytes

- We only showed how to attack the first column to leak 4 bytes.
- Same strategy applies for the rest!
  - We need to inject the glitch in a different place (e.g. in the first entry of the second column)
  - Instead of working with $\{K_0, K_{13}, K_{10}, K_7\}$ we use something else
  - For column 2: $\{K_4, K_1, K_{14}, K_{11}\}$. Can you figure out the rest?



# Limitations of Simple Attack: only works on first row glitch

- What if we can't control exactly what single byte is glitched?
  - We can tell which column was affected by comparing $c$ and $c'$
  - Modify $D$ to include possibilities that any of the 4 bytes in the column can be glitched
  - Size of $D$: $255 \times 4 = 1020$. Still easy to precomute.

$$\text{glitch}_0 = \begin{bmatrix} 1 \text{ to } 255 & 0 & 0 & 0 \end{bmatrix}^T$$
$$\text{glitch}_1 = \begin{bmatrix} 0 & 1 \text{ to } 255 & 0 & 0 \end{bmatrix}^T$$
$$\text{glitch}_2 = \begin{bmatrix} 0 & 0 & 1 \text{ to } 255 & 0 \end{bmatrix}^T$$
$$\text{glitch}_3 = \begin{bmatrix} 0 & 0 & 0 & 1 \text{ to } 255 \end{bmatrix}^T$$

$$\begin{aligned} D = & (\text{mixcol} \times \text{glitch}_0) \cup (\text{mixcol} \times \text{glitch}_1) \\ & \cup (\text{mixcol} \times \text{glitch}_2) \cup (\text{mixcol} \times \text{glitch}_3) \end{aligned}$$

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- Let’s say we did this attack on all 4 columns and got all 16 keybytes
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- We recovered the round 10 key. We want the original key
- Recall: AES key schedule is invertible
- Can find original round key based on round 10 key

# Summary: DFA by Piret and Quisquater ('03)

- Need 2 different faults in the same column to recover 4 bytes
- 8 faults total for the entire key
- Can we do it with 1 fault per column instead?
  - We are left with about $2^{10}$ values per each 4 bytes
  - Guessing $(2^{10})^4 = 2^{40}$ is possible but a little painful if you don't have strong computer
  - Still powerful: going from 128 bit security to 40 bit security

# DFA by Saha et al. ('09)

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- Fault injected in $8^{th}$ round

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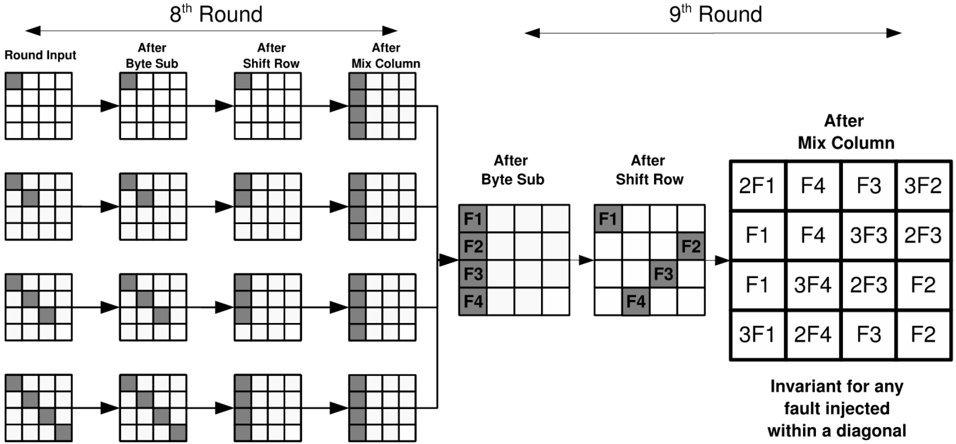
- 1 fault to rule them all: recover key with 1 fault
- Fault injected in $8^{th}$ round
- Pro: 1 fault is all you need!
- Con: Must bruteforce $2^{32}$ keys at the end

# DFA by Saha et al. (’09)



# References


- Biham and Shamir
  `https://link.springer.com/chapter/10.1007/BFb0052259`
- Piret and Quisquater
  `https://eprint.iacr.org/2010/440`
- Saha et al.
  `https://eprint.iacr.org/2009/581.pdf`