# Efficient Side-Channel Protections of ARX Ciphers

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September 10, 2018

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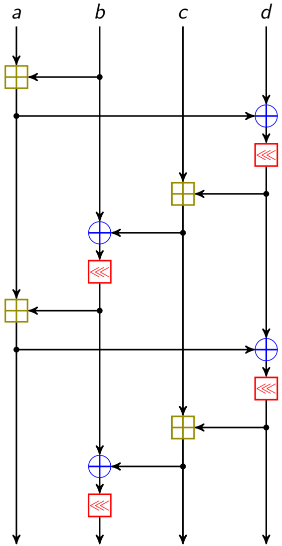

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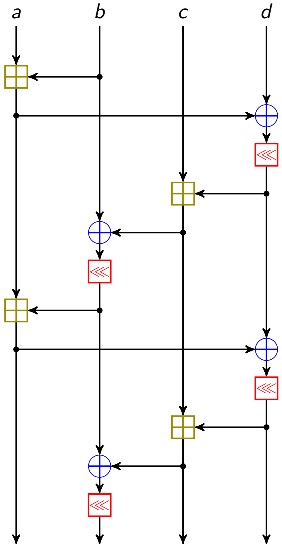

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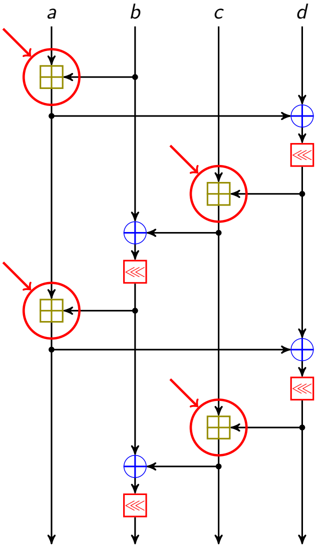

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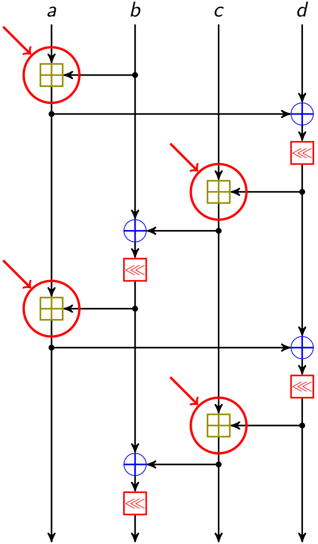

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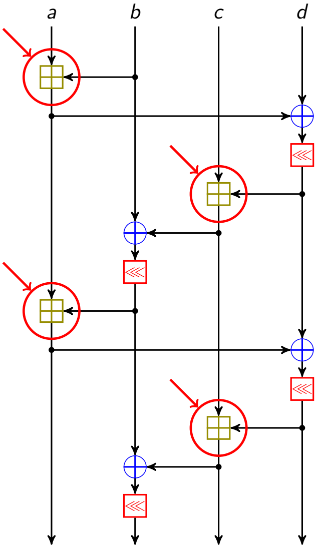

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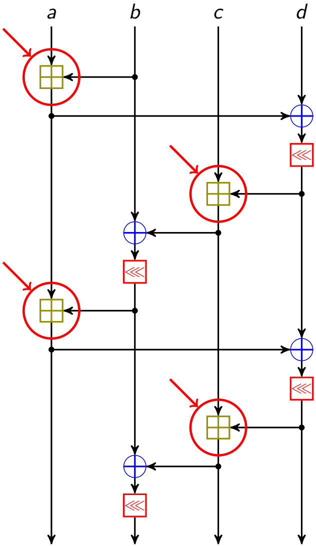
- Simpler: Apply Boolean masking directly to an Addition algorithm in *software*!



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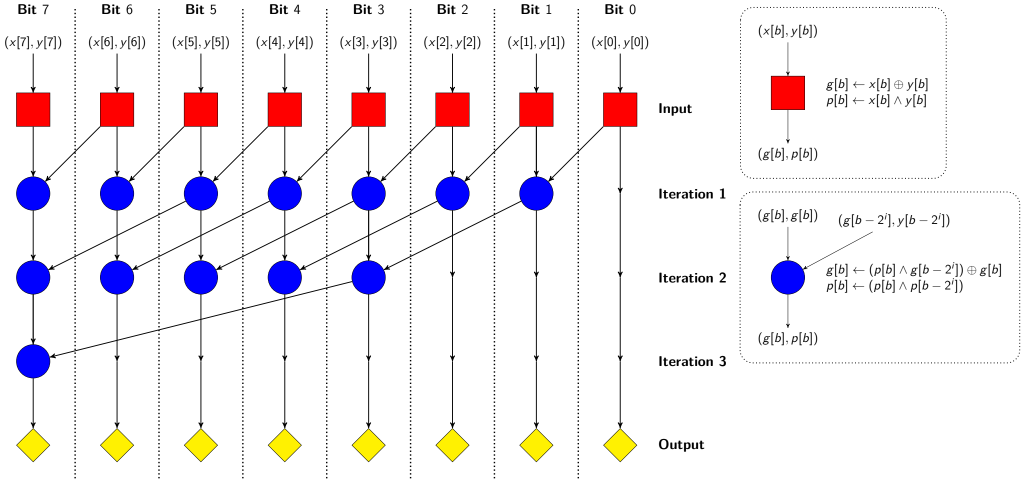
- Not in this presentation: We introduce a simpler algorithm for modular subtraction

# Kogge-Stone Adder (KSA)



$(x[b], y[b])$

$g[b] \leftarrow x[b] \oplus y[b]$
$p[b] \leftarrow x[b] \wedge y[b]$

$(g[b], p[b])$

$(g[b], g[b])$ $(g[b - 2^i], y[b - 2^i])$

$g[b] \leftarrow (p[b] \wedge g[b - 2^i]) \oplus g[b]$
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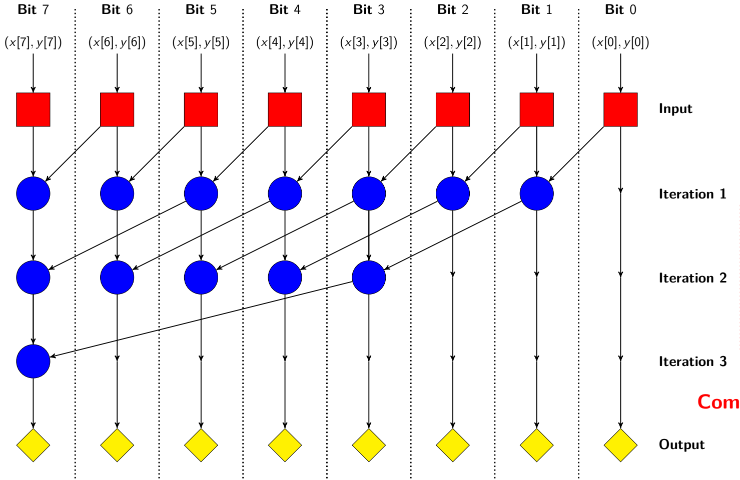

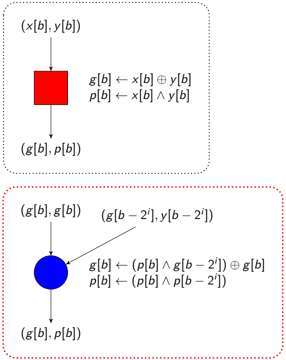

**Combined SHIFT-AND(-XOR) gates**

# TI AND(-XOR) Gate with 2 shares

$$(z_0 \oplus z_1) \leftarrow (x_0 \oplus x_1) \wedge (y_0 \oplus y_1)$$

$$\begin{aligned} s_0 &\leftarrow x_0 \wedge y_0, & s_1 &\leftarrow x_0 \wedge y_1 \\ s_2 &\leftarrow x_1 \wedge y_0, & s_3 &\leftarrow x_1 \wedge y_1 \\ z_0 &\leftarrow s_0 \oplus s_2, & z_1 &\leftarrow s_1 \oplus s_3 \end{aligned}$$

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s_2 &\leftarrow x_1 \wedge y_0, & s_3 &\leftarrow x_1 \wedge y_1 \\
t_0 &\leftarrow s_0 \oplus m, & t_1 &\leftarrow s_1 \oplus m \\
z_0 &\leftarrow t_0 \oplus s_2, & z_1 &\leftarrow t_1 \oplus s_3
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$$(z_0 \oplus z_1) \leftarrow (x_0 \oplus x_1) \wedge (y_0 \oplus y_1)$$

$$m \leftarrow (x_0 \gg 1) \oplus (u \ll k-1)$$

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- In the case of $z \leftarrow (x \wedge y) \oplus u$ no guard share is required

# Combined SHIFT-AND(-XOR) gate

$$m \leftarrow (x_0 \gg 1) \oplus (u \ll k - 1)$$

$$\begin{aligned} s_0 &\leftarrow x_0 \wedge (x_0 \ll i), & s_1 &\leftarrow x_0 \wedge (x_1 \ll i) \\ s_2 &\leftarrow x_1 \wedge (x_0 \ll i), & s_3 &\leftarrow x_1 \wedge (x_1 \ll i) \\ t_0 &\leftarrow s_0 \oplus m, & t_1 &\leftarrow s_1 \oplus m \\ z_0 &\leftarrow t_0 \oplus s_2, & z_1 &\leftarrow t_1 \oplus s_3 \end{aligned}$$

- The KSA heavily uses a combined SHIFT-AND (and SHIFT-AND-XOR) operation which lends itself well to the ARM “flexible second operand”

# Combined SHIFT-AND(-XOR) gate

$$\begin{aligned} s_0 &\leftarrow x_0 \wedge (y_0 \ll i), \\ s_2 &\leftarrow x_1 \wedge (y_0 \ll i), \\ t_0 &\leftarrow s_0 \oplus \color{red}{y_0}, \\ z_0 &\leftarrow t_0 \oplus s_2, \end{aligned} \qquad \begin{aligned} s_1 &\leftarrow x_0 \wedge (y_1 \ll i) \\ s_3 &\leftarrow x_1 \wedge (y_1 \ll i) \\ t_1 &\leftarrow s_1 \oplus \color{red}{y_1} \\ z_1 &\leftarrow t_1 \oplus s_3 \end{aligned}$$

- The KSA heavily uses a combined SHIFT-AND (and SHIFT-AND-XOR) operation which lends itself well to the ARM "flexible second operand"
- Again, in the case of $z \leftarrow (x \wedge (y << i)) \oplus y$ no guard share is required

# Protected KSA

```
Require: $x, y \in \mathbb{Z}_{2^k},\ k > 0$
Ensure: $z = (x + y) \bmod 2^k$
$n \leftarrow \max(\lceil \log_2(k - 1) \rceil, 1)$
$g \leftarrow x \wedge y$
$p \leftarrow x \oplus y$

for $i = 1$ to $n - 1$ do

    $g \leftarrow (p \wedge (g \ll 2^{i-1})) \oplus g$
    $p \leftarrow (p \wedge (p \ll 2^{i-1}))$

end for
$g \leftarrow (p \wedge (g \ll 2^{n-1})) \oplus g$
$z \leftarrow x \oplus y \oplus 2g$
return $z$
```

# Protected KSA

```
Require: $x_0, x_1, y_0, y_1 \in \mathbb{Z}_{2^k}$, $k > 0$, $u \in \{0, 1\}$, with $x = x_0 \oplus x_1$ and $y = y_0 \oplus y_1$
Ensure: $z = (x + y) \bmod 2^k$, with $z = z_0 \oplus z_1$
$n \leftarrow \max(\lceil \log_2(k - 1) \rceil, 1)$
$(g_0, g_1) \leftarrow \texttt{SecAnd}(x_0, x_1, y_0, y_1, u)$                # Shared AND
$(p_0, p_1) \leftarrow \texttt{SecXor}(x_0, x_1, y_0, y_1)$                   # Shared XOR
$u \leftarrow x_0 \bmod 2$                                                    # Update guard share
for $i = 1$ to $n - 1$ do
    $v \leftarrow p_0 \bmod 2$                                                # Save next guard share
    $(g_0, g_1) \leftarrow \texttt{SecAndShiftXor}(p_0, p_1, g_0, g_1, 2^{i-1})$   # Shared AND-SHIFT-XOR
    $(p_0, p_1) \leftarrow \texttt{SecAndShift}(p_0, p_1, u, 2^{i-1})$        # Shared AND-SHIFT
    $u \leftarrow v$                                                          # Update guard share
end for
$(g_0, g_1) \leftarrow \texttt{SecAndShiftXor}(p_0, p_1, g_0, g_1, 2^{n-1})$       # Shared AND-SHIFT-XOR
$(z_0, z_1) \leftarrow (x_0 \oplus y_0 \oplus 2g_0, x_1 \oplus y_1 \oplus 2g_1)$   # Compute final output
return $(z_0, z_1, u)$
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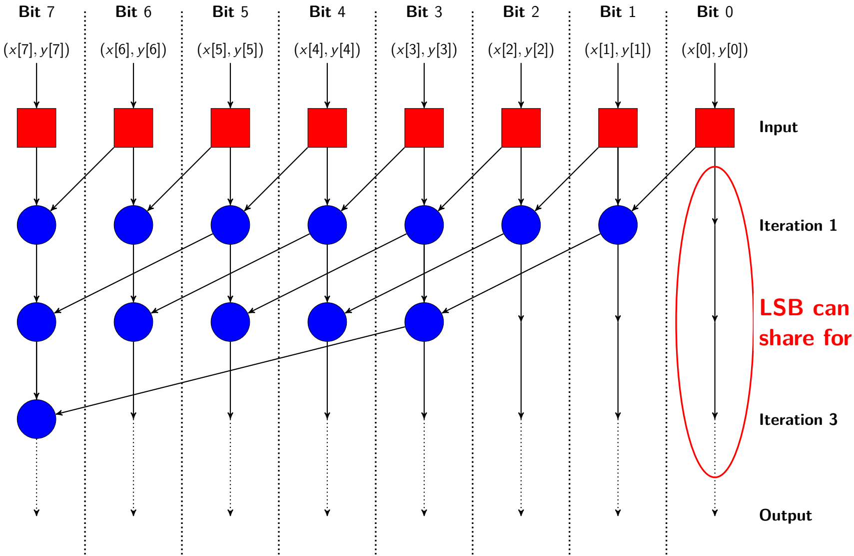

**LSB can be used as guard share for next iteration**

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# Further optimization

$$\begin{aligned} s_0 &\leftarrow x_0 \wedge y_0, & s_1 &\leftarrow x_0 \vee \neg y_1 \\ s_2 &\leftarrow x_1 \wedge y_0, & s_3 &\leftarrow x_1 \vee \neg y_1 \\ z_0 &\leftarrow s_0 \oplus s_1, & z_1 &\leftarrow s_2 \oplus s_3 \end{aligned}$$

- Biryukov et al. (2017) introduced a further optimized secure AND gate (`SecAndOpt`/`SecAndShiftOpt`) which can be combined with our approach

# Comparision of masked operations

| | `SecXor` | `SecShift` | `SecAnd` | `SecAndShift` / `-Opt` | `SecAndShiftXor` |
|---|---|---|---|---|---|
| Generic [Coron et al.] | 2 | 4 | 8 | $8 + 2$ | $8 + 4 + 2$ |
| ARM [Coron et al.] | 2 | 4 | 8 | $8 + 2$ | $8 + 4 + 2$ |
| Generic [Biryukov et al.] | 2 | 2 | 7 | $7 + 2$ | $7 + 2 + 2$ |
| ARM [Biryukov et al.] | 2 | 2 | 6 | $6 + 2$ | $6 + 2 + 2$ |
| Generic [new] | 2 | - | 8 | 10 / 9 | 10 |
| ARM [new] | 2 | - | 8 | 8 / 6 | 8 |

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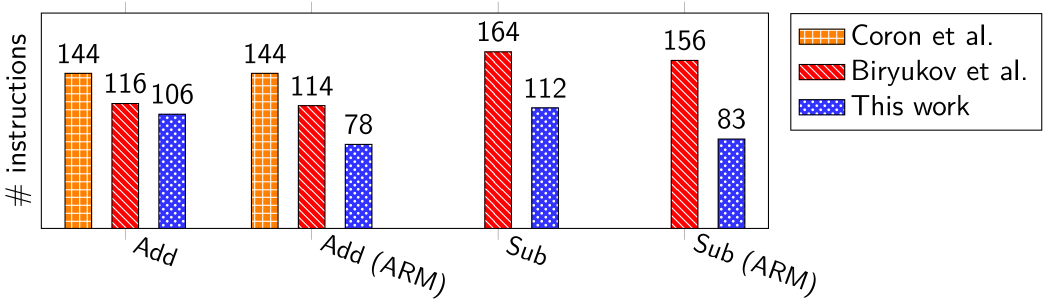
- Combined AND-SHIFT operations save most of the instructions
- Especially when combined with optimizations proposed by Biryukov et el.
- Generation of refresh mask takes only 3 instructions

# Comparision of masked 32-bit modular addition



- ARM implementation improved by 31% when combined with approach by Biryukov et al.

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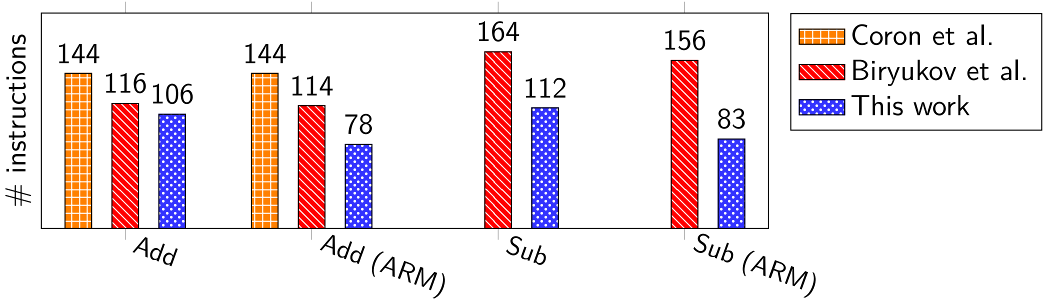

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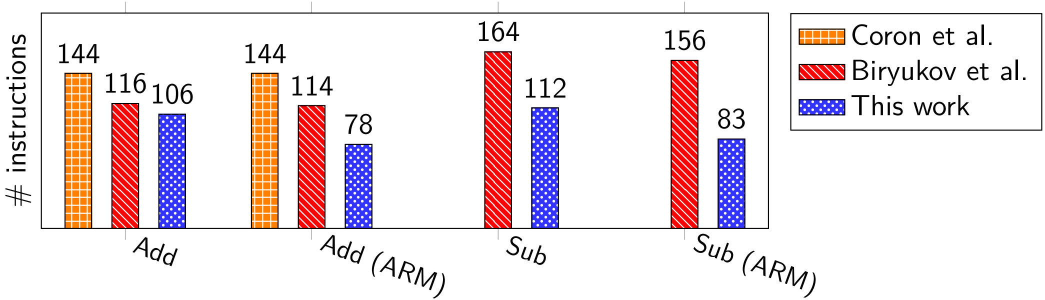
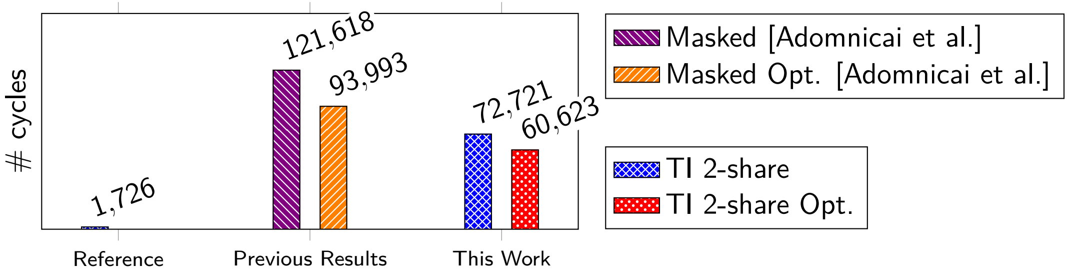


- ARM implementation improved by 31% when combined with approach by Biryukov et al.
- Significantly improved subtraction instruction counts
- Needs one random bit, outputs one random bit

# Application to ChaCha20 cipher

- We implemented an unprotected reference and two protected variants



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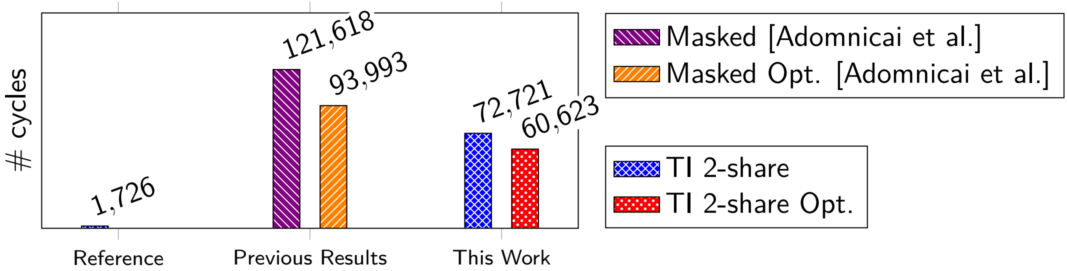

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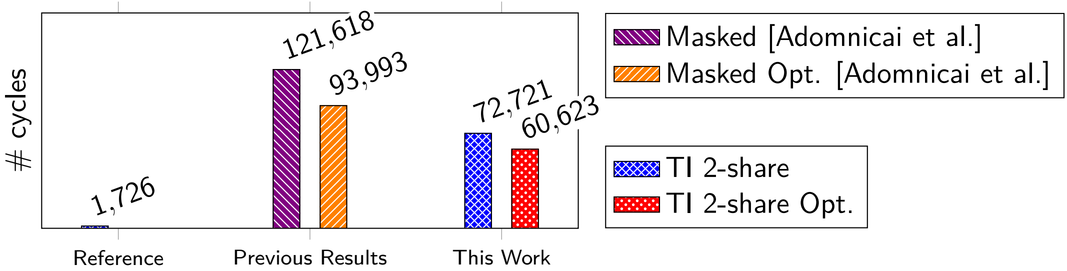
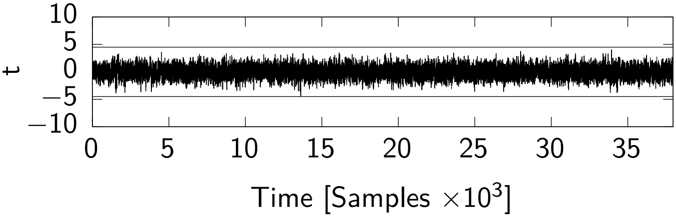
- Note: cycle-counts not entirely comparable due to possible differences in memory architecture



# Simulation

- ChaCha implementation was simulated with Micro-Architectural Power Simulator (MAPS)[1]
- Simulator was extended by 11 instructions
- Hamming distance is sampled for each register assignment
- $t$-Test with a fixed vs. random setup and $10^5$ noise free traces
- Noise amplification methods like shuffling should still be used



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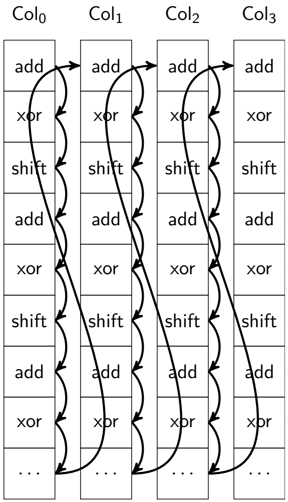
[1] https://github.com/cryptolu/maps

Thank you for listening

# Chacha Shuffling (Backup Slide)



- In the case of ChaCha, shuffling can be used to amplify the noise
- ChaCha State consists of 4 columns which are processed independently (within a round)
- Instead of processing columns sequentially, one can jump between columns
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