Gimli: A cross-platform permutation

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What is a Permutation?

Definition: A Permutation is a keyless block cipher.

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“Wait, what?”

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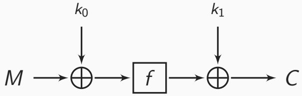

Even-Mansour construction

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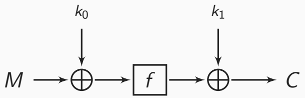
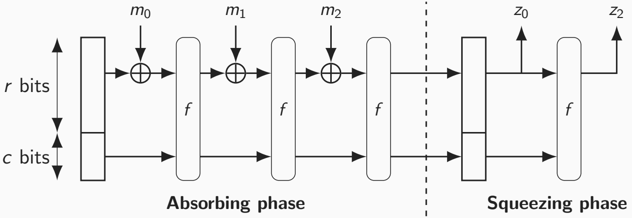


Even-Mansour construction



Sponge construction

Why Gimli?

Currently we have:

Permutation	width in bits	Benefits
AES	128	very fast *if the instruction is available.*
Chaskey	128	lightning fast *on Cortex-M0/M3/M4*
Keccak-f	200,400,800,1600	low-cost masking
Salsa20,ChaCha20	512	very fast *on CPUs with vector units.*

Why Gimli?

Currently we have:

Permutation	Hindrance
AES	**Not that fast without HW**.
Chaskey	**Low security margin, slow with side-channel protection**
Keccak-*f*	**Huge state (800,1600)**
Salsa20,ChaCha20	**Horrible on HW**.

Currently we have:

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Can we have a permutation that is not too big, nor too small and good in all these areas?

Yes!

Source: *Wikipedia*, *Fair Use*

What is Gimli?

GIMLI is:

- a 384-bits permutation (just the right size)
  - Sponge with $c = 256, r = 128 \implies$ 128bits of security
  - Cortex-M3/M4: full state in registers
  - AVR, Cortex-M0: 192bits (half state) fits in registers

What is Gimli?

GIMLI is:

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  - Sponge with $c = 256, r = 128 \implies$ 128bits of security
  - Cortex-M3/M4: full state in registers
  - AVR, Cortex-M0: 192bits (half state) fits in registers
- with high cross-platform performances
- designed for:
  - energy-efficient hardware
  - side-channel-protected hardware
  - microcontrollers
  - compactness
  - vectorization
  - short messages
  - high security level

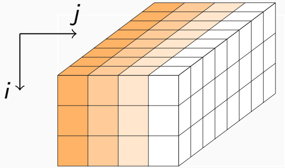
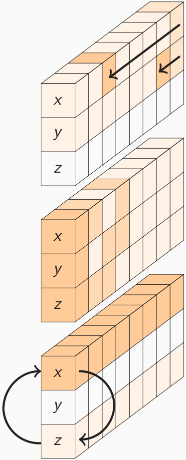


Figure: State Representation

384 bits represented as:

- a parallelepiped with dimensions $3 \times 4 \times 32$ (Keccak-like)
- or, as a 3×4 matrix of 32-bit words.

Specifications: Non-linear layer



In parallel:

$x \leftarrow x \lll 24$

$y \leftarrow y \lll 9$

In parallel:

$x \leftarrow x \oplus (z \ll 1) \oplus ((y \wedge z) \ll 2)$

$y \leftarrow y \oplus \quad x \quad \oplus ((x \vee z) \ll 1)$

$z \leftarrow z \oplus \quad y \quad \oplus ((x \wedge y) \ll 3)$

In parallel:

$x \leftarrow z$

$z \leftarrow x$

Figure: The bit-sliced 9-to-3-bits SP-box applied to a column

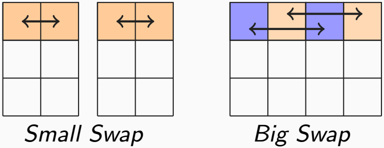


Figure: The linear layer

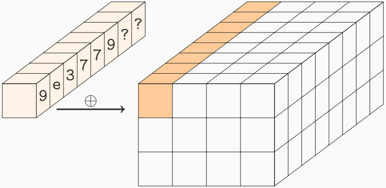


Figure: Constant addition `0x9e3779??`

Gimli in C

```c
extern void Gimli(uint32_t *state) {

  uint32_t round, column, x, y, z;

  for (round = 24; round > 0; --round) {

    for (column = 0; column < 4; ++column) {
      x = rotate(state[    column], 24);                    // x <<< 24
      y = rotate(state[4 + column],  9);                    // y <<< 9
      z =        state[8 + column];

      state[8 + column] = x ^ (z << 1) ^ ((y & z) << 2);
      state[4 + column] = y ^ x        ^ ((x | z) << 1);
      state[column]     = z ^ y        ^ ((x & y) << 3);
    }

    if ((round & 3) == 0) { // small swap: pattern s...s...s... etc.
      x = state[0]; state[0] = state[1]; state[1] = x;
      x = state[2]; state[2] = state[3]; state[3] = x;
    }
    if ((round & 3) == 2) { // big swap: pattern ..S...S...S. etc.
      x = state[0]; state[0] = state[2]; state[2] = x;
      x = state[1]; state[1] = state[3]; state[3] = x;
    }

    if ((round & 3) == 0) { // add constant: pattern c...c...c... etc.
      state[0] ^= (0x9e377900 | round);
    }
  }
}
```

Specifications: Rounds

Round 24 — Non-linear layer

Small Swap & Round constant addition

Round 23 — Non-linear layer

Round 22 — Non-linear layer

Big Swap

Round 21 — Non-linear layer

Round 20 — Non-linear layer

Small Swap & Round constant addition

Round 19 — Non-linear layer

Round 18 — Non-linear layer

Big Swap

...

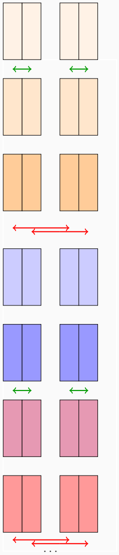
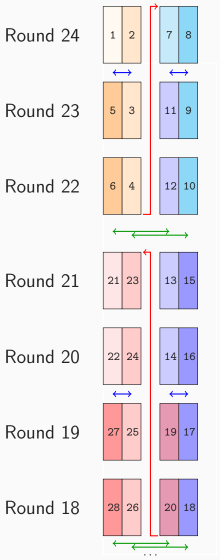


Figure: 7 first rounds of GIMLI



1. SP-box col. 0
2. SP-box col. 1

swap word $s_{0,0}$ and $s_{0,1}$

3. SP-box col. 1
4. SP-box col. 1
5. SP-box col. 0
6. SP-box col. 0

store columns 0,1 ; load columns 2,3

7. SP-box col. 2
8. SP-box col. 3

swap word $s_{0,2}$ and $s_{0,3}$

9. SP-box col. 3
10. SP-box col. 3
11. SP-box col. 2
12. SP-box col. 2

push word $s_{0,2}$, $s_{0,3}$; load word $s_{0,0}$, $s_{0,1}$

13. SP-box col. 2
14. SP-box col. 2
15. SP-box col. 3
16. SP-box col. 3

swap word $s_{0,2}$ and $s_{0,3}$

17. SP-box col. 3
18. SP-box col. 3
19. SP-box col. 2
20. SP-box col. 2

store columns 2,3 ; load columns 0,1

...

Figure: Computation order on AVR & Cortex-M0

Implementation in Assembly

# Rotate	# Compute x	# Compute y	# Compute z
$x \leftarrow x \lll 24$	$v \leftarrow z \ll 1$	$v \leftarrow y$	$u \leftarrow u \wedge v$
$y \leftarrow y \lll 9$	$x \leftarrow z \wedge y$	$y \leftarrow u \vee z$	$u \leftarrow u \ll 3$
$u \leftarrow x$	$x \leftarrow x \ll 2$	$y \leftarrow y \ll 1$	$z \leftarrow z \oplus v$
	$x \leftarrow u \oplus x$	$y \leftarrow u \oplus y$	$z \leftarrow z \oplus u$
	$x \leftarrow x \oplus v$	$y \leftarrow y \oplus v$	

The SP-box requires only 2 additional registers u and v.

# Rotate	# Compute x	# Compute y	# Compute z
x ← x ⋘ 24	v ← z ≪ 1	v ← y	u ← u ∧ (v ⋘ 9)
	x ← z ∧ (y ⋘ 9)	y ← u ∨ z	u ← u ≪ 3
u ← x	x ← x ≪ 2	y ← y ≪ 1	z ← z ⊕ (v ⋘ 9)
	x ← u ⊕ x	y ← u ⊕ y	z ← z ⊕ u
	x ← x ⊕ v	y ← y ⊕ (v ⋘ 9)	

Remove y <<< 9.

Shift for free on Cortex-M3/M4

```
# Rotate
x ← x ⋘ 24

u ← x
```

```
# Compute x

x ← z ∧ (y ⋘ 9)

x ← u ⊕ (x ≪ 2)
x ← x ⊕ (z ≪ 1)
```

```
# Compute y
v ← y
y ← u ∨ z

y ← u ⊕ (y ≪ 1)
y ← y ⊕ (v ⋘ 9)
```

```
# Compute z
u ← u ∧ (v ⋘ 9)

z ← z ⊕ (v ⋘ 9)
z ← z ⊕ (u ≪ 3)
```

Get rid of the other shifts.

Free mov on Cortex-M3/M4

```
# Rotate
x ← x ⋘ 24
.
.
.
.
```

```
# Compute x
.
u ← z ∧ (y ⋘ 9)
.
u ← x ⊕ (u ≪ 2)
u ← u ⊕ (z ≪ 1)
```

```
# Compute y
v ← y
y ← x ∨ z
.
y ← x ⊕ (y ≪ 1)
y ← y ⊕ (v ⋘ 9)
```

```
# Compute z
x ← x ∧ (v ⋘ 9)
.
z ← z ⊕ (v ⋘ 9)
z ← z ⊕ (x ≪ 3)
.
```

Remove the last mov:

u contains the new value of x

y contains the new value of y

z contains the new value of z

Free mov on Cortex-M3/M4

# Rotate	# Compute x	# Compute y	# Compute z
x ← x ⋘ 24			x ← x ∧ (y ⋘ 9)
	u ← z ∧ (y ⋘ 9)	v ← x ∨ z	
			z ← z ⊕ (y ⋘ 9)
	u ← x ⊕ (u ≪ 2)	v ← x ⊕ (v ≪ 1)	z ← z ⊕ (x ≪ 3)
	u ← u ⊕ (z ≪ 1)	v ← v ⊕ (y ⋘ 9)	

Remove the last mov:

u contains the new value of x

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z contains the new value of z

Free swap on Cortex-M3/M4

# Rotate	# Compute x	# Compute y	# Compute z
$x \leftarrow x \lll 24$	$u \leftarrow z \wedge (y \lll 9)$	$v \leftarrow x \vee z$	$x \leftarrow x \wedge (y \lll 9)$
	$u \leftarrow x \oplus (u \ll 2)$	$v \leftarrow x \oplus (v \ll 1)$	$z \leftarrow z \oplus (y \lll 9)$
	$u \leftarrow u \oplus (z \ll 1)$	$v \leftarrow v \oplus (y \lll 9)$	$z \leftarrow z \oplus (x \ll 3)$

Swap x and z:

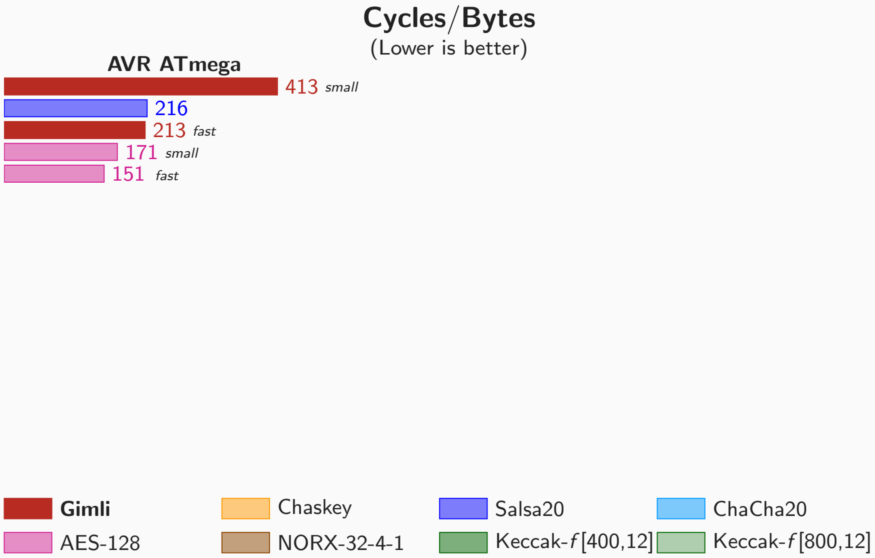
u contains the new value of z

v contains the new value of y

z contains the new value of x

SP-box requires a total of 10 instructions.

How fast is Gimli? (Software)



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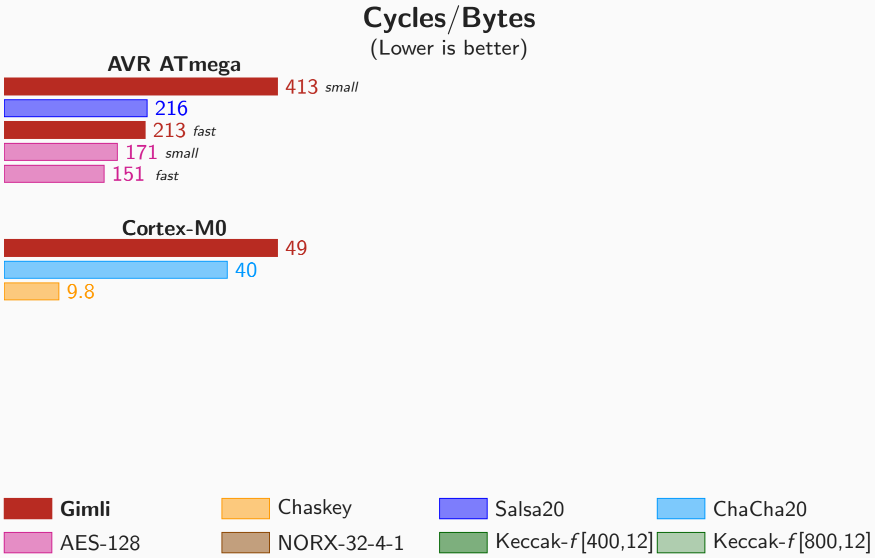

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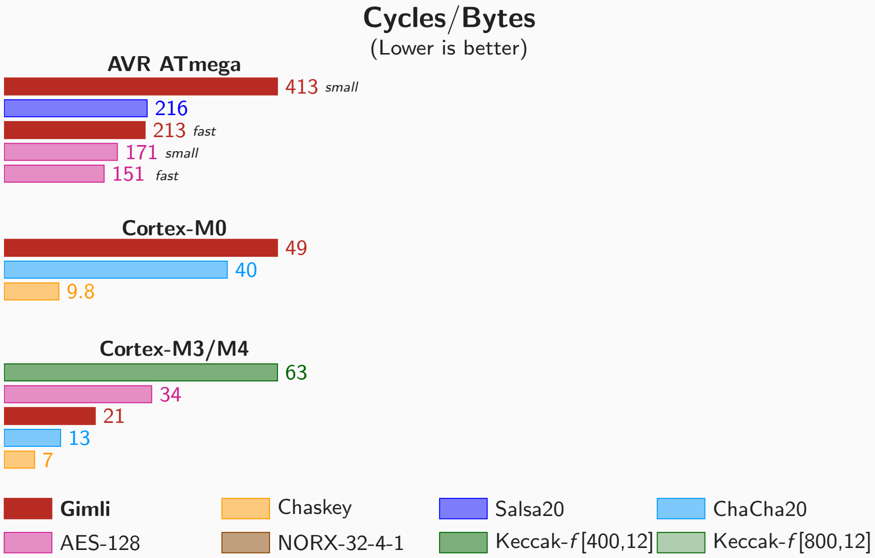

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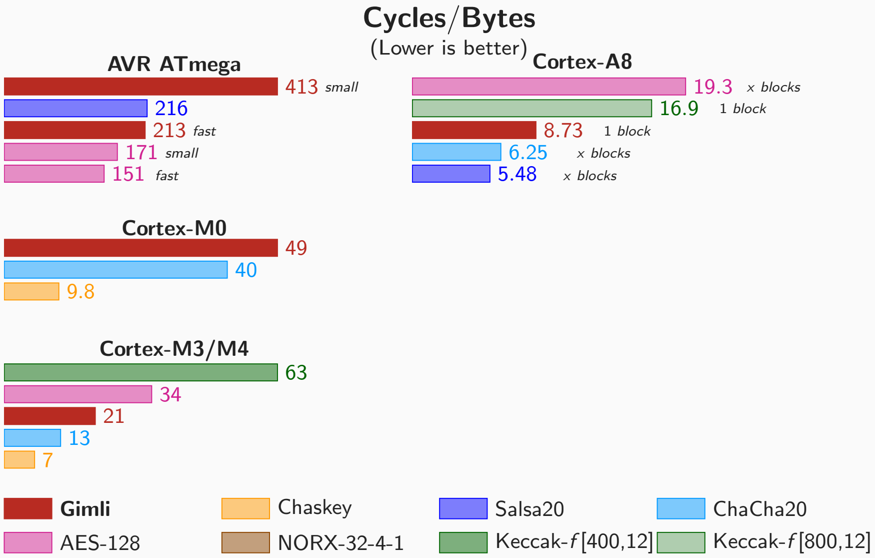

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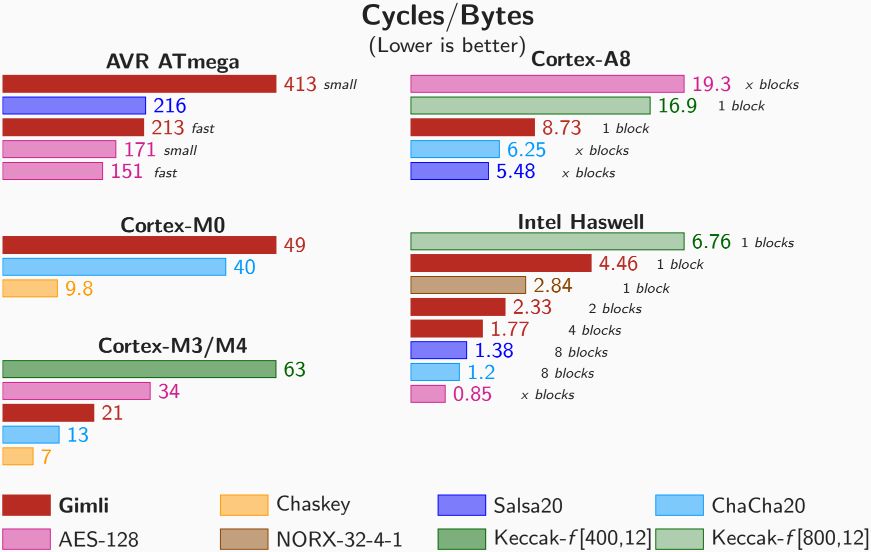
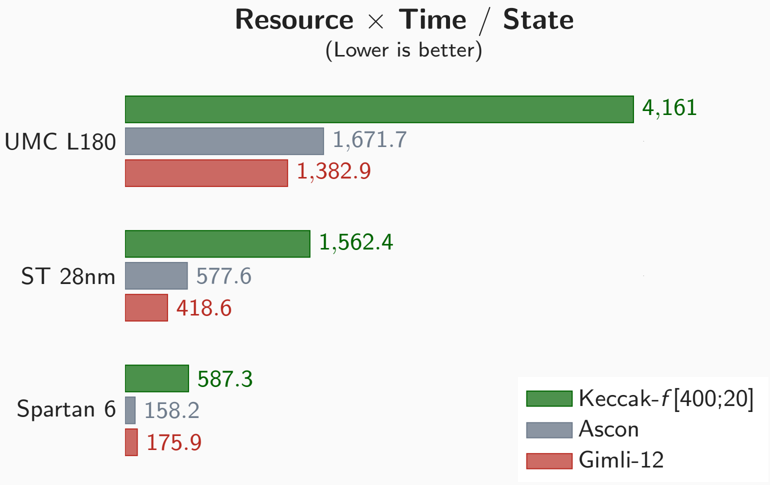


How efficient is Gimli? (Hardware)



latency : 2 cycles

How secure is Gimli?

- Simple diffusion
  - avalanche effect shown after 10 rounds.
  - each bit influences the full state after 8 rounds.


1

Worse case propagation in Gimli over 8 rounds.

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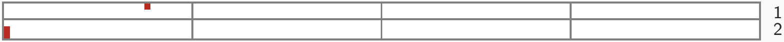

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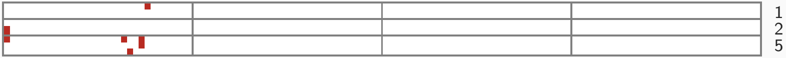

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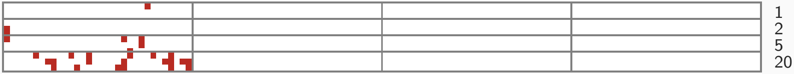

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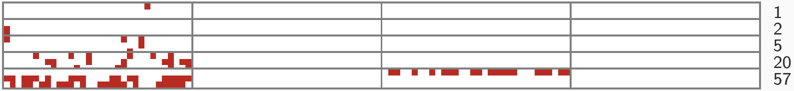

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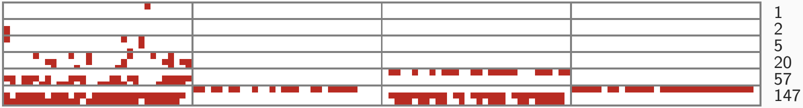

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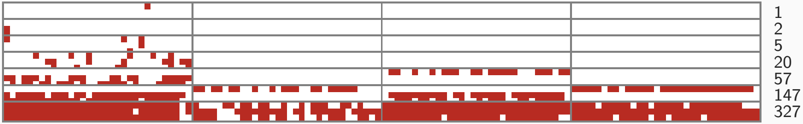

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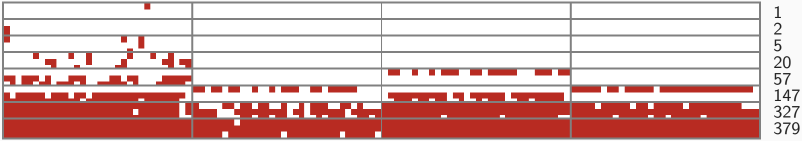

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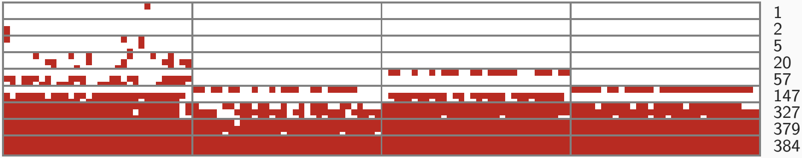

Worse case propagation in Gimli over 8 rounds.

How secure is Gimli?

Round	col_0	col_1	col_2	col_3	Weight
0	0x80404180 0x80002080 0x80002080	0x00020100 - 0x80010080	- - -	- - -	18
1	0x80800100 0x80400000 0x80400080	- - -	- - -	- - -	8
2	0x80000000 0x80000000 0x80000000	- - -	- - -	- - -	0
3	- - 0x80000000	- - -	- - -	- - -	0
4	0x00800000 - -	- - -	- - -	- - -	2
5	- 0x00000001 0x00800000	- - -	- - -	- - -	4
6	0x01008000 0x00000200 0x01000000	- - -	- - -	- - -	6
7	- 0x01040002 0x03008000	- - -	- - -	- - -	14
8	0x02020480 0x0a00040e 0x06010000	- - -	- 0x06000c00 0x00010002	- - -	-

Optimal differential trail for 8-round probability 2^{-52}

How secure is Gimli?

- Differential propagation
  - Optimal 8-round trail with probability of 2^{-52}
- Algebraic Degree and Integral distinguishers
  - z_0 has an algebraic degree of 367 after 11 rounds (upper bound)
  - 11-round integral distinguisher with 96 active bits.
  - 13-round integral distinguisher with 192 active bits.

Mike Attacks!

- August 1^{st}, `eprint.iacr.org/2017/743`
- Claim against 192-bit key.
- Requires:
  - "$2^{138.5}$ work".
  - "2^{129} bits of memory".

i.e. more hardware and more time than naive brute-force attack. (2^{80} parallel units, each searching 2^{112} keys.)

Image: *Wikipedia, Fair Use*

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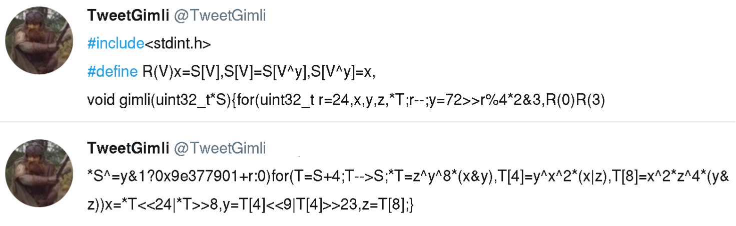
  (2^{80} parallel units, each searching 2^{112} keys.)
- "golden collision" techniques by van Oorschot–Wiener (1996) reduce the cost in memory but increase the work. Still worse than brute-force.
- Standard practice in designing PRF such as ChaCha20 add words to positions that **maximize** diffusion.
  Hamburg's attack requires to add key words to positions selected to *minimize* diffusion.
- Practical attack not feasible in the foreseeable future, even with quantum computers.

Image: *Wikipedia, Fair Use*


TweetGimli @TweetGimli

```
#include<stdint.h>
#define R(V)x=S[V],S[V]=S[V^y],S[V^y]=x,
void gimli(uint32_t*S){for(uint32_t r=24,x,y,z,*T;r--;y=72>>r%4*2&3,R(0)R(3)
```

TweetGimli @TweetGimli

```
*S^=y&1?0x9e377901+r:0)for(T=S+4;T-->S;*T=z^y^8*(x&y),T[4]=y^x^2*(x|z),T[8]=x^2*z^4*(y&
z))x=*T<<24|*T>>8,y=T[4]<<9|T[4]>>23,z=T[8];}
```

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BACKUP SLIDES

How efficient is Gimli? (Hardware)

Permutation	Cycles	Resources	Period (ns)	Time (ns)	Res.×Time/state
FPGA – Xilinx Spartan 6 LX75					
Ascon	2	732 S(2700 L+325 F)	34.570	70	**158.2**
GIMLI 12*r*	2	1224 S(4398 L+389 F)	27.597	**56**	175.9
Keccak	2	1520 S(5555 L+405 F)	77.281	155	587.3
GIMLI 24*r*	1	2395 S(8769 L+385 F)	56.496	57	352.4
GIMLI 8*r*	3	831 S(2924 L+390 F)	24.531	74	159.3
GIMLI 6*r*	4	646 S(2398 L+390 F)	18.669	75	**125.6**
GIMLI 4*r*	6	415 S(1486 L+391 F)	8.565	**52**	**55.5**
GIMLI (Serial)	108	139 S(492 L+397 F)	3.996	432	156.2
28nm ASIC – ST 28nm FDSOI technology					
GIMLI 12*r*	2	35452 GE	2.2672	**5**	**418.6**
Ascon	2	32476 GE	2.8457	6	577.6
Keccak	2	55683 GE	5.6117	12	1562.4
GIMLI 24*r*	1	66205 GE	4.2870	5	739.1
GIMLI 8*r*	3	25224 GE	1.5921	**5**	313.7
GIMLI 4*r*	6	14999 GE	1.0549	7	**247.2**
GIMLI (Serial)	108	5843 GE	1.5352	166	2522.7
180nm ASIC – UMC L180					
GIMLI 12*r*	2	26685 GE	9.9500	**20**	**1382.9**
Ascon	2	23381 GE	11.4400	23	1671.7
Keccak	2	37102 GE	22.4300	45	4161.0
GIMLI 24*r*	1	53686 GE	17.4500	18	2439.6
GIMLI 8*r*	3	19393 GE	7.9100	24	**1198.4**
GIMLI 4*r*	6	11008 GE	10.1700	62	1749.1
GIMLI (Serial)	108	3846 GE	11.2300	1213	12146.0

Gates Equivalent(GE). Slice(S). LUT(L). Flip-Flop(F).

Bijectivity

$$f_0 = \begin{cases} x_0' \leftarrow x_0 \\ y_0' \leftarrow y_0 \oplus x_0 \\ z_0' \leftarrow z_0 \oplus y_0 \end{cases} \qquad f_0^{-1} = \begin{cases} x_0 \leftarrow x_0' & = x_0' \\ y_0 \leftarrow y_0' \oplus x_0 & = y_0' \oplus x_0' \\ z_0 \leftarrow z_0' \oplus y_0 & = z_0' \oplus y_0' \oplus x_0' \end{cases}$$

$$f_1 = \begin{cases} x_1' \leftarrow x_1 \oplus z_0 \\ y_1' \leftarrow y_1 \oplus x_1 \oplus (x_0 \vee z_0) \\ z_1' \leftarrow z_1 \oplus y_1 \end{cases} \qquad f_1^{-1} = \begin{cases} x_1 \leftarrow x_1' \oplus z_0 & = x_1' \oplus z_0 \\ y_1 \leftarrow y_1' \oplus x_1 \oplus (x_0 \vee z_0) & = y_1' \oplus x_1' \oplus z_0 \oplus (x_0 \vee z_0) \\ z_1 \leftarrow z_1' \oplus y_1 & = z_1' \oplus y_1' \oplus x_1' \oplus z_0 \oplus (x_0 \vee z_0) \end{cases}$$

$$f_2 = \begin{cases} x_2' \leftarrow x_2 \oplus z_1 \oplus (y_0 \wedge z_0) \\ y_2' \leftarrow y_2 \oplus x_2 \oplus (x_1 \vee z_1) \\ z_2' \leftarrow z_2 \oplus y_2 \end{cases} \qquad f_2^{-1} = \begin{cases} x_2 \leftarrow x_2' \oplus z_1 \oplus (y_0 \wedge z_0) & = x_2' \oplus z_1 \oplus (y_0 \wedge z_0) \\ y_2 \leftarrow y_2' \oplus x_2 \oplus (x_1 \vee z_1) & = y_2' \oplus x_2' \oplus z_1 \oplus (y_0 \wedge z_0) \oplus (x_1 \vee z_1) \\ z_2 \leftarrow z_2' \oplus y_2 & = z_2' \oplus y_2' \oplus x_2' \oplus z_1 \oplus (y_0 \wedge z_0) \oplus (x_1 \vee z_1) \end{cases}$$

and

$$f_n = \begin{cases} x_n' \leftarrow x_n \oplus z_{n-1} \oplus (y_{n-2} \wedge z_{n-2}) \\ y_n' \leftarrow y_n \oplus x_n \oplus (x_{n-1} \vee z_{n-1}) \\ z_n' \leftarrow z_n \oplus y_n \oplus (x_{n-3} \wedge z_{n-3}) \end{cases}$$

and

$$f_n^{-1} = \begin{cases} x_n \leftarrow x_n' \oplus z_{n-1} \oplus (y_{n-2} \wedge z_{n-2}) \\ y_n \leftarrow y_n' \oplus x_n' \oplus z_{n-1} \oplus (y_{n-2} \wedge z_{n-2}) \oplus (x_{n-1} \vee z_{n-1}) \\ z_n \leftarrow z_n' \oplus y_n' \oplus x_n' \oplus z_{n-1} \oplus (y_{n-2} \wedge z_{n-2}) \oplus (x_{n-1} \vee z_{n-1}) \oplus (x_{n-3} \wedge z_{n-3}) \end{cases}$$

SP^{-1} is fully defined by recurrence. SP is therefore bijective.

Gimli in C99 (268 chars)

```c
#include<stdint.h>
#define R(V)x=S[V],S[V]=S[V^y],S[V^y]=x,
void gimli(uint32_t*S){
  for(uint32_t r=24,x,y,z,*T;
    r--;
    y=72>>r%4*2&3,R(0)R(3)*S^=y&1?0x9e377901+r:0)
    for(T=S+4;
      T-->S;
      *T=z^y^8*(x&y),T[4]=y^x^2*(x|z),T[8]=x^2*z^4*(y&z))
      x=*T<<24|*T>>8,y=T[4]<<9|T[4]>>23,z=T[8];
  }
```

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