Gimli: A cross-platform permutation

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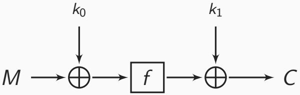
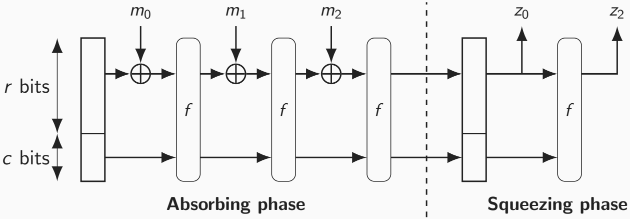
What is a Permutation?

Definition: A Permutation is a keyless block cipher.



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**.

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

Specifications: State

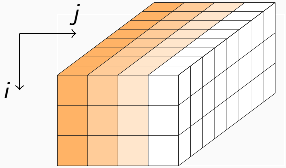
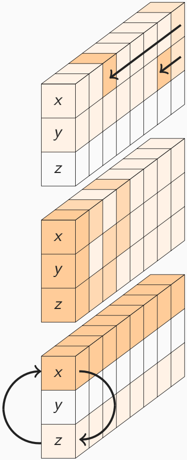


Figure: State Representation

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:

$$
\begin{aligned}
x &\leftarrow x \oplus (z \ll 1) \oplus ((y \wedge z) \ll 2)\\
y &\leftarrow y \oplus \quad x \quad \oplus ((x \vee z) \ll 1)\\
z &\leftarrow z \oplus \quad y \quad \oplus ((x \wedge y) \ll 3)
\end{aligned}
$$

In parallel:

$x \leftarrow z$

$z \leftarrow x$

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

Specifications: Linear layer

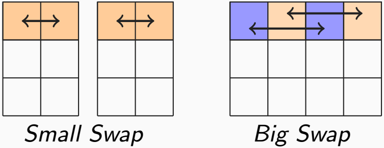


Figure: The linear layer

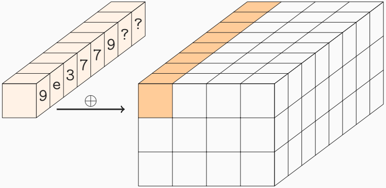
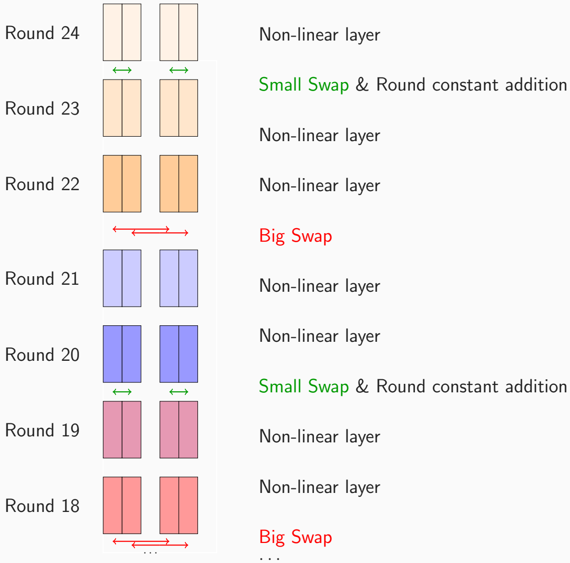


Figure: Constant addition `0x9e3779??`

Gimli in 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

Non-linear layer

Round 20

Small Swap & Round constant addition

Round 19

Non-linear layer

Non-linear layer

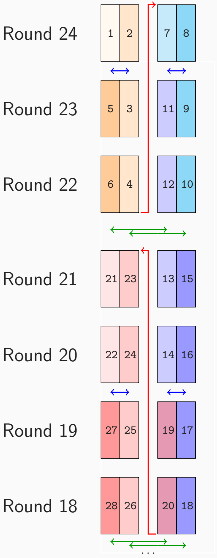
Round 18

Big Swap

. . .

Figure: 7 first rounds of GIMLI

Unrolled AVR & Cortex-M0



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
x ← x ⋘ 24
y ← y ⋘ 9
u ← x
```

```
# Compute x
v ← z ≪ 1
x ← z ∧ y
x ← x ≪ 2
x ← u ⊕ x
x ← x ⊕ v
```

```
# Compute y
v ← y
y ← u ∨ z
y ← y ≪ 1
y ← u ⊕ y
y ← y ⊕ v
```

```
# Compute z
u ← u ∧ v
u ← u ≪ 3
z ← z ⊕ v
z ← z ⊕ u
```

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

Rotate for free on Cortex-M3/M4

```
# Rotate
x ← x ⋘ 24

u ← x
```

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

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

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

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
x ← x ⋘ 24
.
.
.
.
```

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

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

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

Remove the last `mov`:

`u` contains the new value of `x`

`v` contains the new value of `y`

`z` contains the new value of `z`

Free swap 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 ← x ∨ z
v ← x ⊕ (v ≪ 1)
v ← v ⊕ (y ⋘ 9)
```

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

Swap x and z:

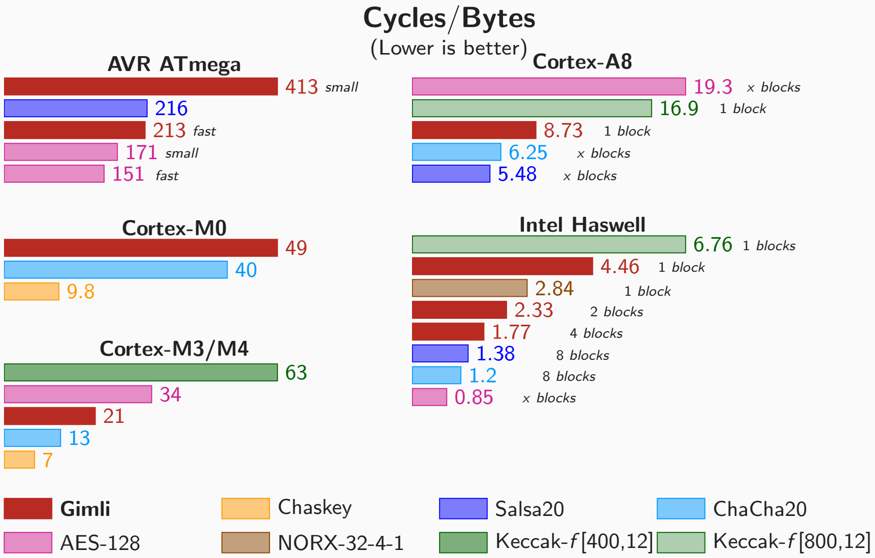
u contains the new value of z

v contains the new value of y

z contains the new value of x

SP-box requires a total of 10 instructions.

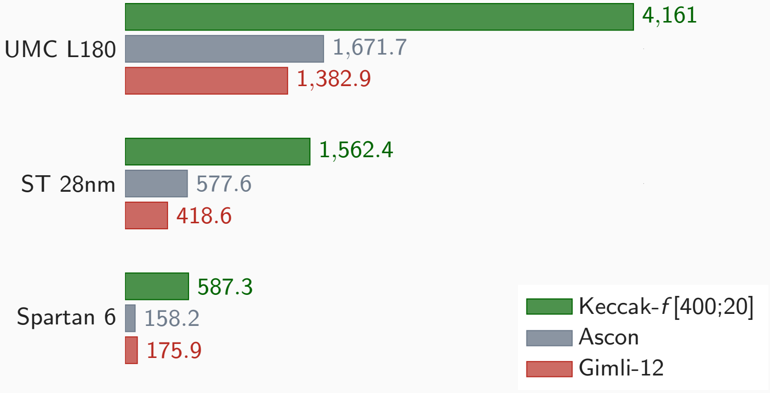
How fast is Gimli? (Software)



How efficient is Gimli? (Hardware)

Resource × Time / State

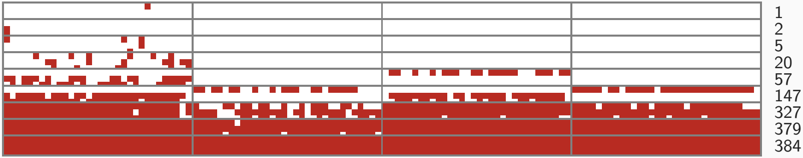
(Lower is better)



latency : 2 cycles

How secure is Gimli?

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



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?

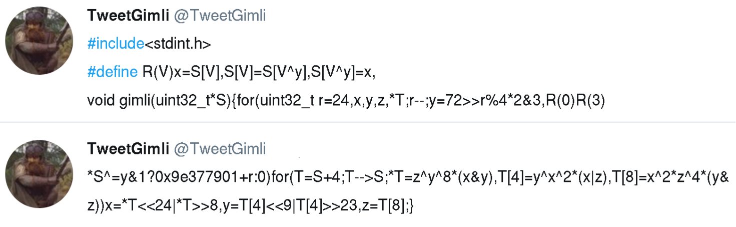
- Differential propagation
  - Optimal 8-round trail with probability of 2^{-52}
- Algebraic Degree and Integral distinguishers
  - z_0 has an algebraic degree of 367 after 11 rounds (upper bound)
  - 11-round integral distinguisher with 96 active bits.
  - 13-round integral distinguisher with 192 active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

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