Structuring and optimizing KECCAK software

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Outline

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KECCAK-*f* in pseudo-code

```
KECCAK-F[b](A) {
  forall i in 0…nr-1
    A = Round[b](A, RC[i])
  return A
}

Round[b](A,RC) {
  θ step
  C[x] = A[x,0] xor A[x,1] xor A[x,2] xor A[x,3] xor A[x,4], forall x in 0…4
  D[x] = C[x-1] xor rot(C[x+1],1),                          forall x in 0…4
  A[x,y] = A[x,y] xor D[x],                                 forall (x,y) in (0…4,0…4)

  ρ and π steps
  B[y,2*x+3*y] = rot(A[x,y], r[x,y]),                       forall (x,y) in (0…4,0…4)

  χ step
  A[x,y] = B[x,y] xor ((not B[x+1,y]) and B[x+2,y]),        forall (x,y) in (0…4,0…4)

  ι step
  A[0,0] = A[0,0] xor RC

  return A
}
```

http://keccak.noekeon.org/specs_summary.html

Choice of parameters

Rate?

- $\{1152 \ldots 576\}$ bits for SHA3-224 to SHA3-512
- $\{1344 \ldots 1088\}$ bits for SHAKE128 and SHAKE256
  - Same for cSHAKE, KMAC, TupleHash, ... [NIST SP 800-185 draft]

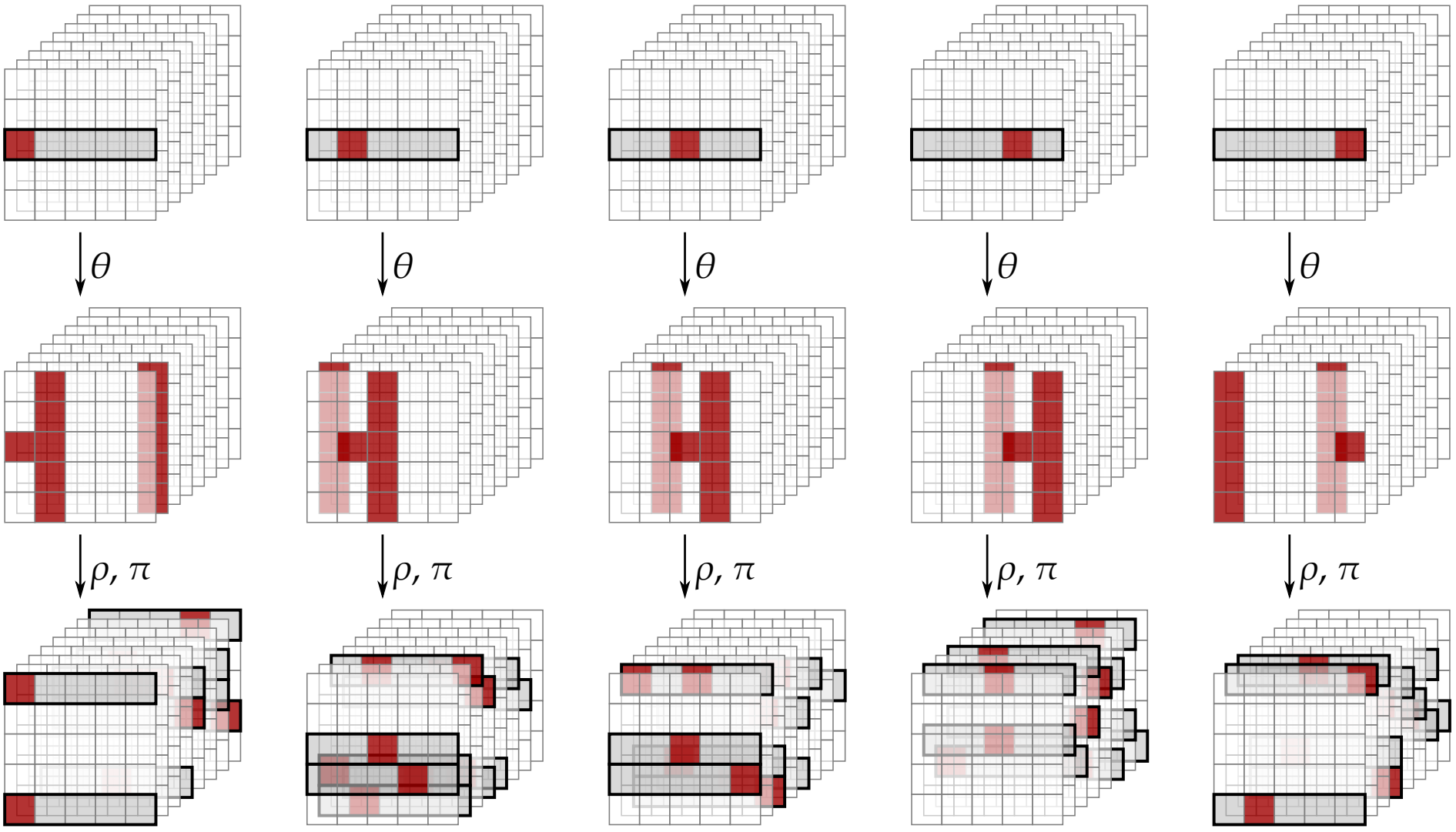
Number of rounds?

- 24 rounds for KECCAK, SHA-3, SHAKE
- 12 rounds for KEYAK, KANGAROOTWELVE

Hardware vs software

Where does the difference come from?

Choice of operations in KECCAK-f



Choice of operations in KECCAK-f

- Much dispersion per non-linear operation
- Benefits of weak alignment [Hash 2011]
- Wide dispersion: `mov reg, mem` (and back)

Unless there are more registers

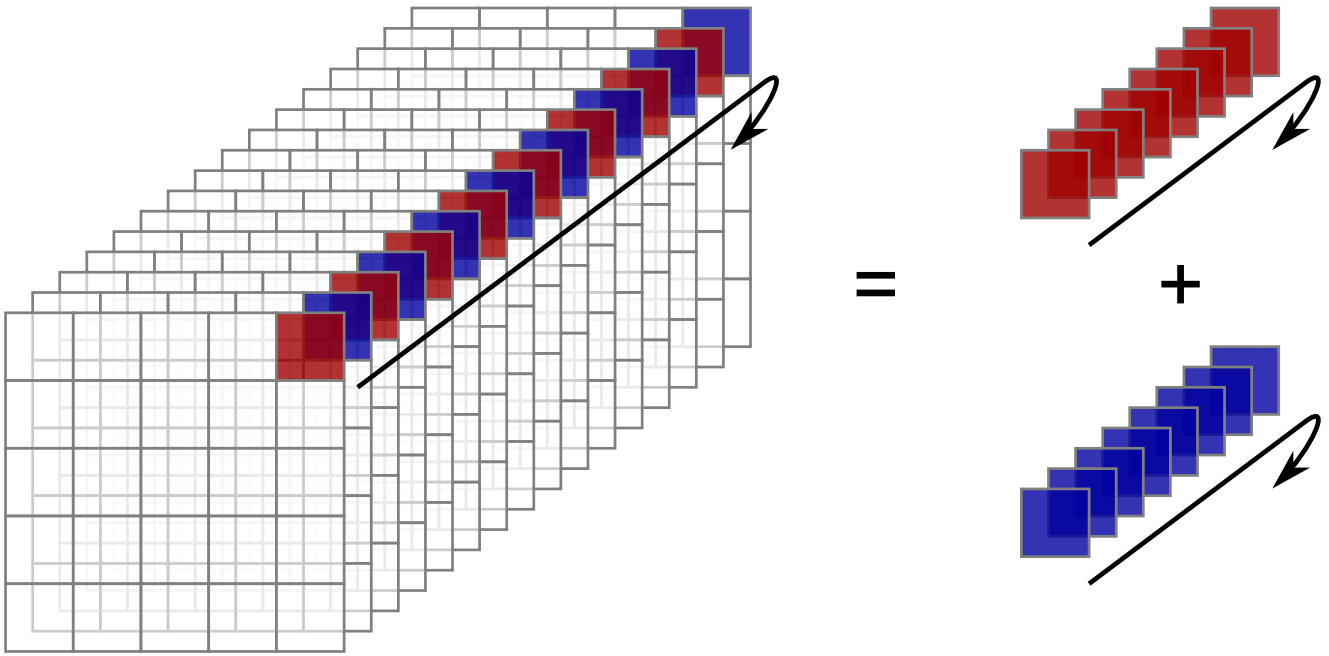
Parallelism

Parallelism inside KECCAK-f goes by 5×64.

- Gain possible on SIMD units
  - E.g., $\times 1.7$ speed-up between x86_64 and XOP (AMD Bulldozer)
- Possible obstacles (SSE and AVX2)
  - No rotation instructions
  - No easy fit of 5-lane structures
- More processing per clock cycle
  - Larger SIMD units (e.g., AVX-512)
  - More general parallelism in instruction sets (remember IA64?)
  - Parallelism from the mode

Outline

Bit interleaving



$$\text{ROT}_{64} \leftrightarrow 2 \times \text{ROT}_{32}$$

Lane complementing

Remove NOTs using the De Morgan laws:

$$z \leftarrow x \wedge (y \oplus 1)$$
$$\Leftrightarrow$$
$$\bar{z} \leftarrow \bar{x} \vee y$$

Choose an *invariant* pair of complementing masks:

$$s \oplus m \xrightarrow{\chi} \chi(s) \oplus M \xrightarrow{\pi \circ \rho \circ \theta} s' \oplus m$$

with $m = \pi(\rho(\theta(M)))$.

80% of NOTs removed

In-place processing

Store $A[x, y]$ at round i in (x', y') with

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 1 & 2 \end{pmatrix}^i \begin{pmatrix} x \\ y \end{pmatrix}.$$

- Interacts with π: the output of χ can overwrite its input
- Matrix of order 4
  - $\Rightarrow$ no performance loss if 4 rounds unrolled

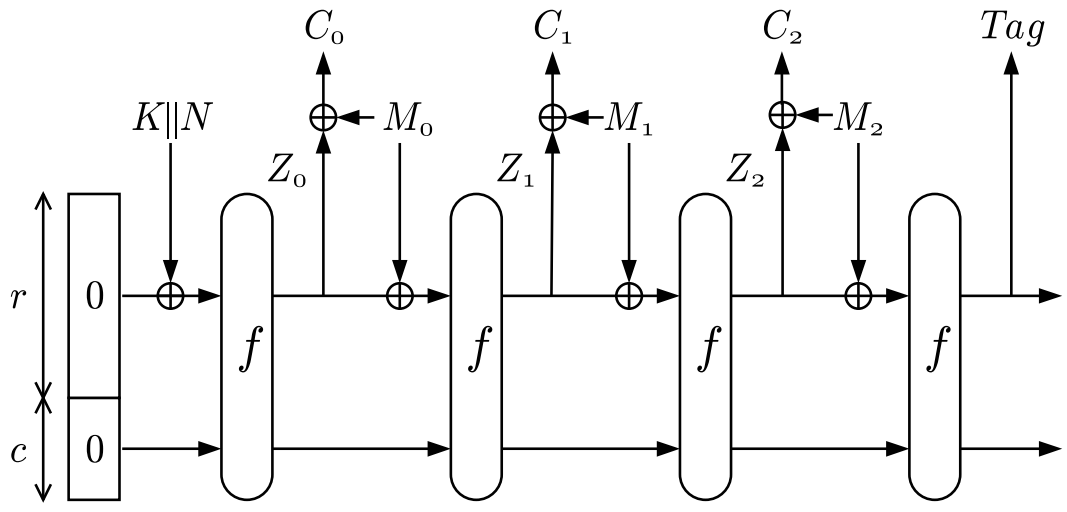
[Bertoni et al., KECCAK implementation overview]

Outline

Inventory

- KECCAK
  - sponge
  - KECCAK-$f[1600]$ for SHA-3, SHAKE, cSHAKE, etc.
  - KECCAK-$f[200]$ to KECCAK-$f[800]$
- KEYAK
  - full-state keyed duplex
  - 12 rounds
- KETJE
  - MonkeyDuplex
  - 1, 6, 12 rounds
- KEYAK, ParallelHash, KANGAROOTWELVE
  - parallelism
  - $n \times$ KECCAK-$f[1600]$

Ingredients

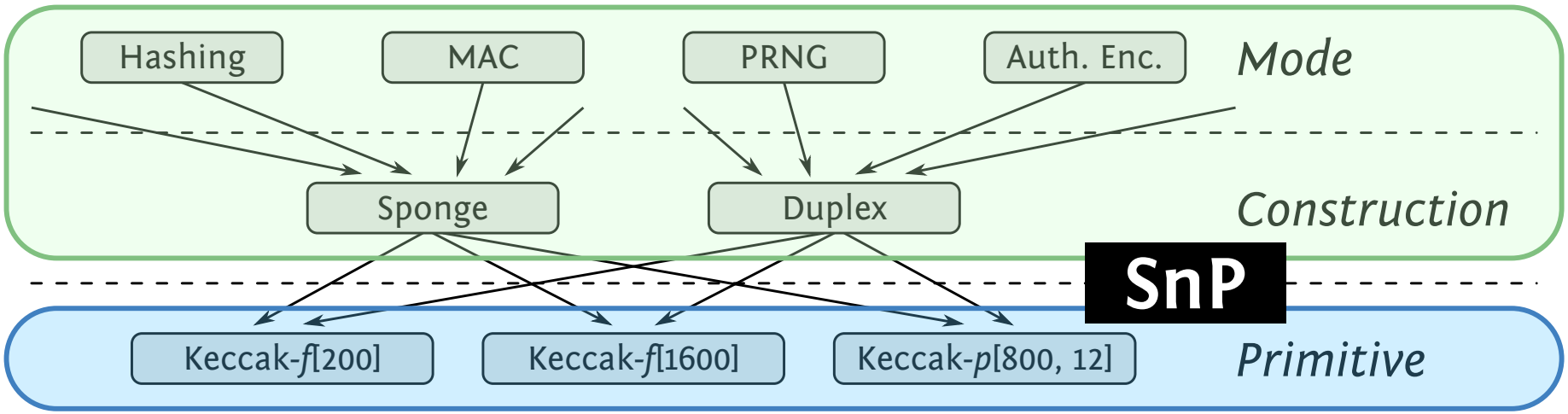


Absorbing and squeezing

- initialize the state
- apply the permutation f

- XOR/overwrite bytes into the state
- extract bytes from the state
  - and optionally XOR them

A layered approach



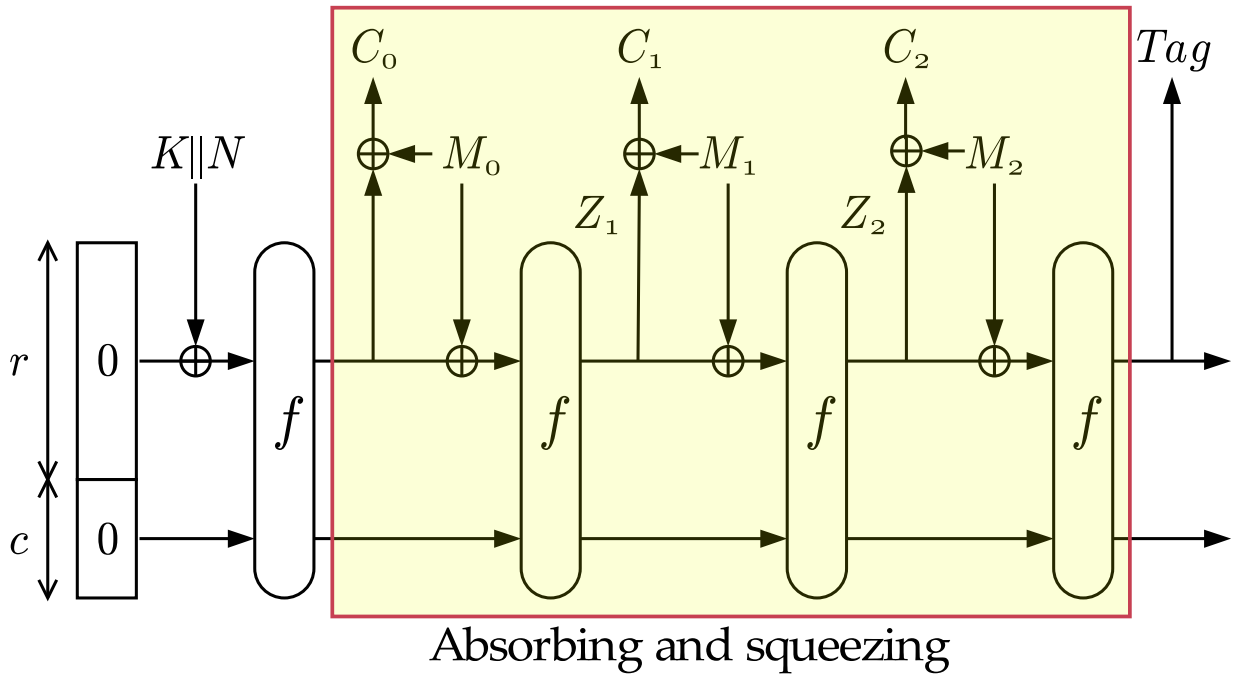
Generic

- focus on **user**
  - easy to use
  - e.g., message queue
- one implementation
  - pointers and arithmetic

Specific

- focus on **developer**
  - limited scope to optimize
  - unit tests
- tailored implementations
  - permutation
  - bulk data processing

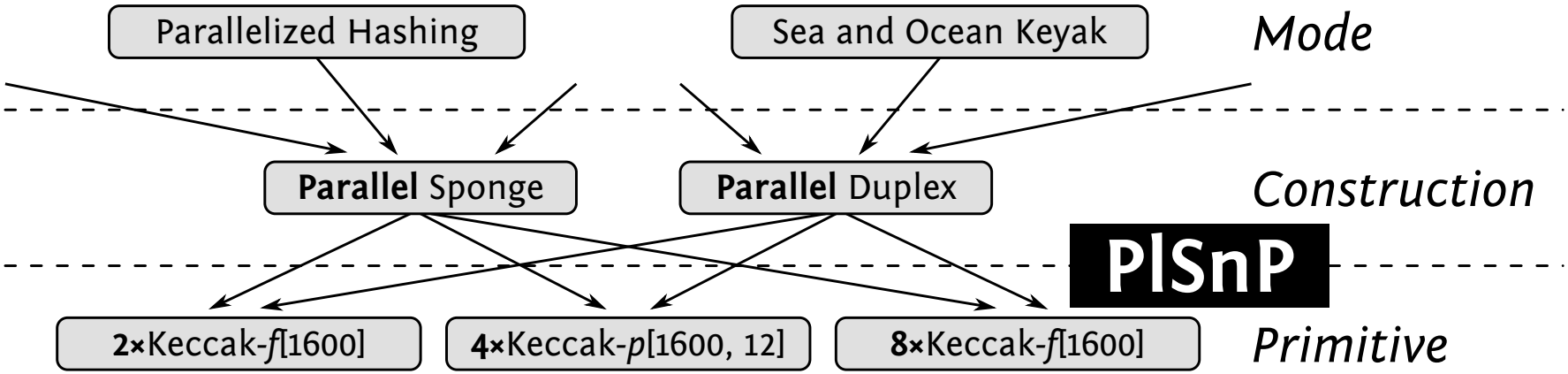
SnP fast loop optimization



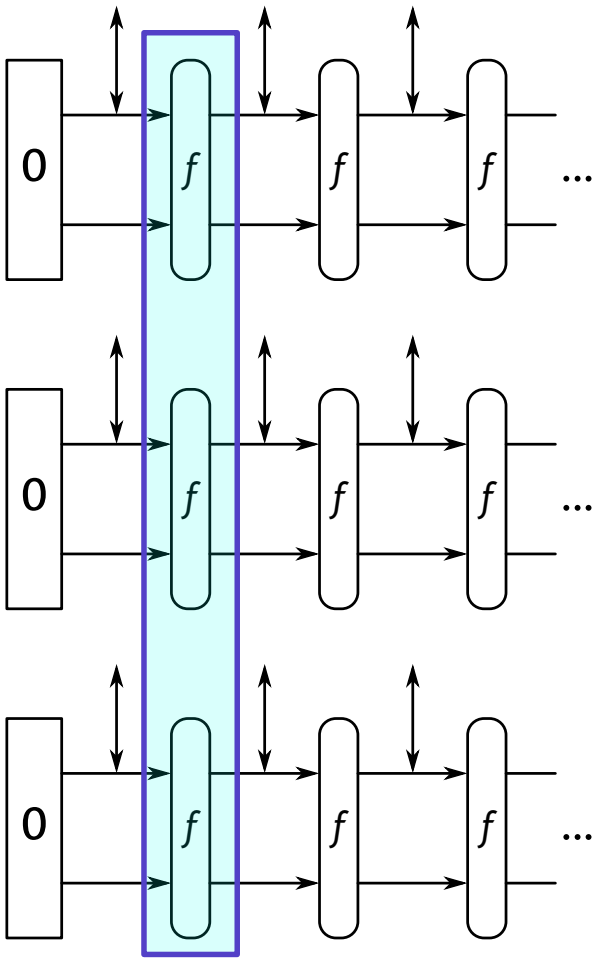
Specialized repeated application of some operations

(optional)

Parallel processing

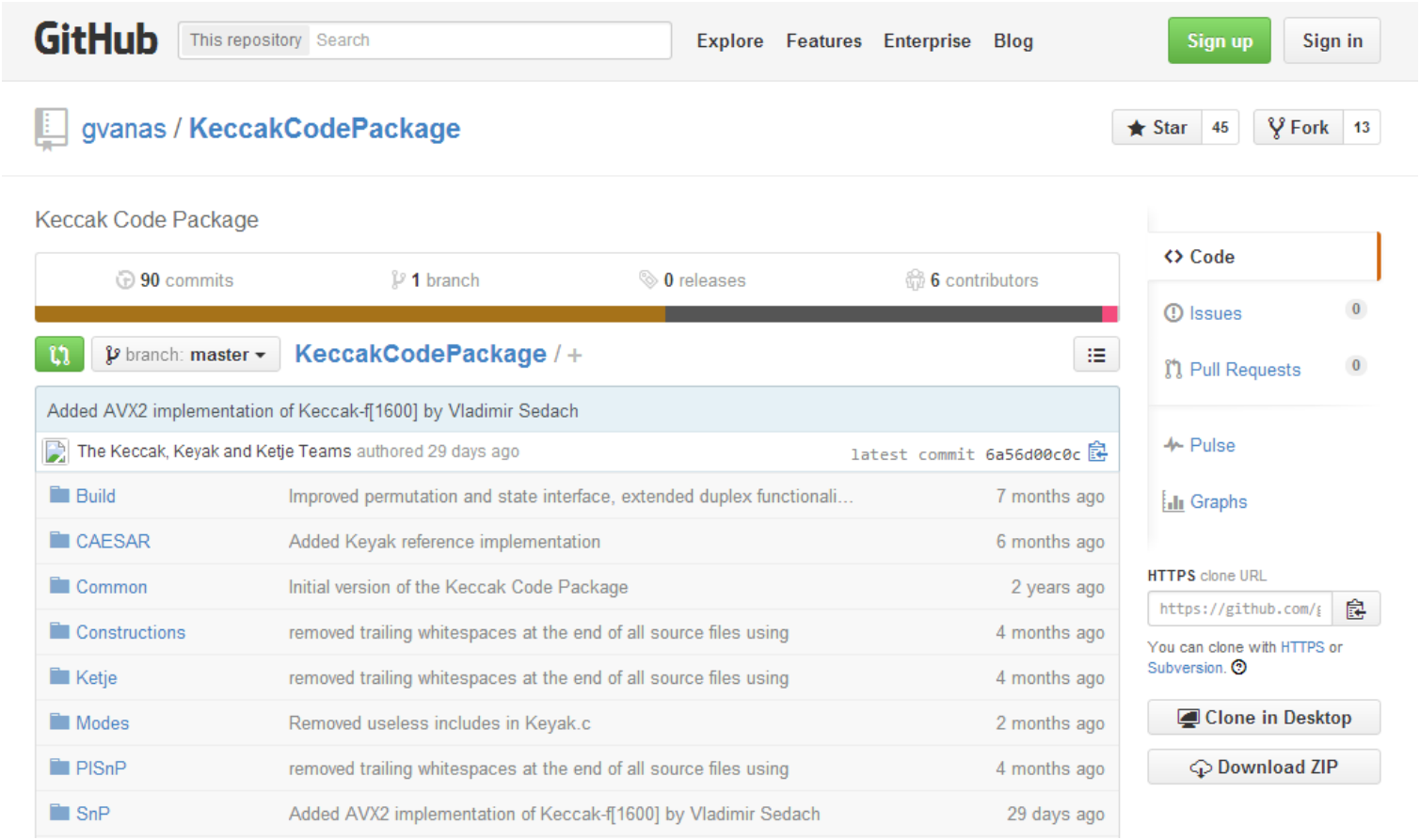


PlSnP (= Parallel States and Permutations)



- Functions on individual instances
- Functions on **all instances**
  - Parallel application of f
  - XOR blocks into state
- Optional **fast loop**
- Fallback stubs
  - to serial implementation
  - to parallel with lower degree

The KECCAK code package



https://github.com/gvanas/KeccakCodePackage

Outline

Safety margin: from *rock-solid* to *comfortable*

- Keccak's round function unchanged since 2008
- How many rounds?
  - **24** rounds: Keccak/SHA-3/SHAKE
  - **12** rounds: Keyak
  - **5** rounds: best collision attacks [Dinur et al.] [Qiao et al.]

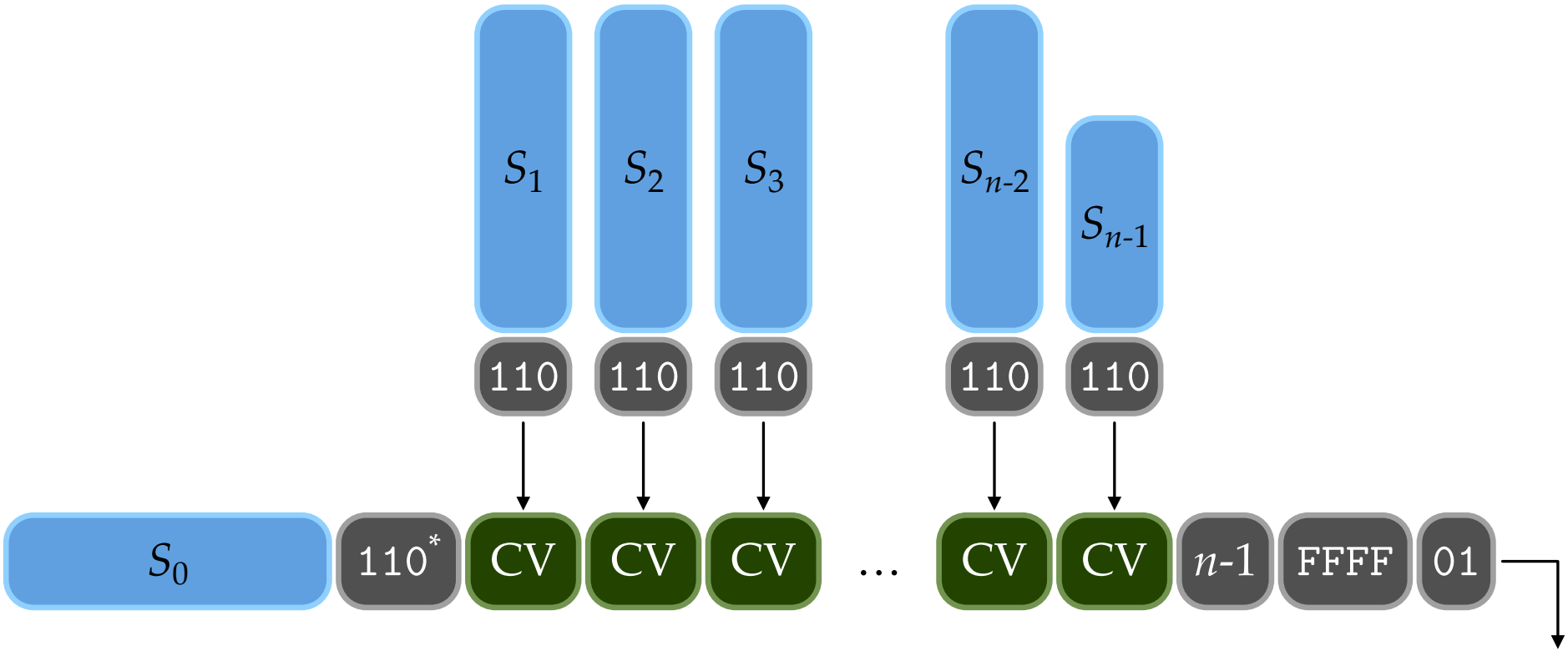
$\Rightarrow$ let's do hashing with **12** rounds

Better exploit parallelism

- SIMD with growing widths
  - 128, 256 and soon 512 bits
- Multiple cores

$\Rightarrow$ let's exploit this parallelism

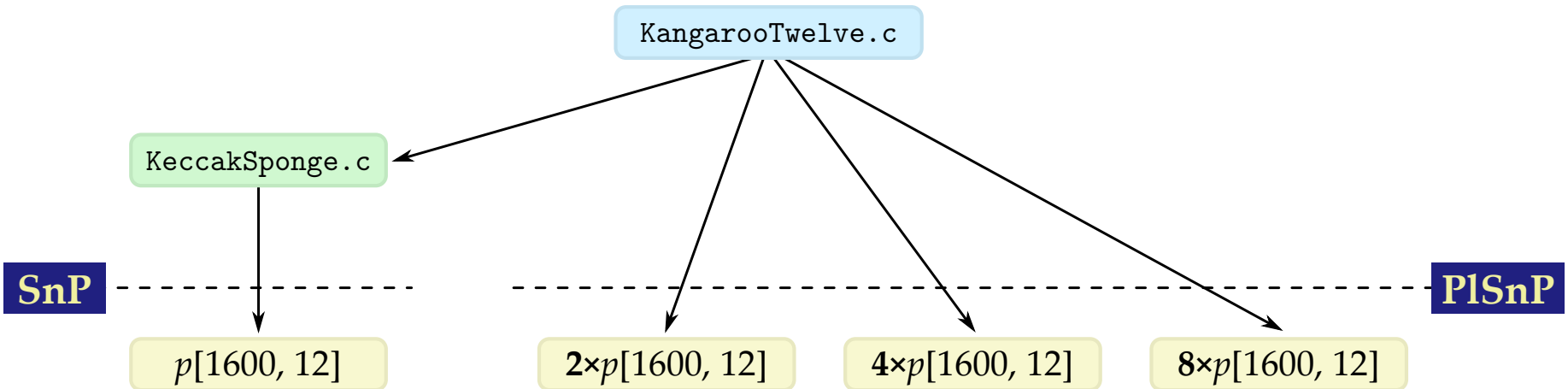
KangarooTwelve's mode



Final node growing with kangaroo hopping and SAKURA coding

[ACNS 2014]

Structure in the Keccak code package



KangarooTwelve performance

	Short input	Long input
Intel® Core™ i5-4570 (Haswell)	4.15 c/b	1.44 c/b
Intel® Core™ i5-6500 (Skylake)	3.72 c/b	1.22 c/b
Intel® Xeon Phi™ 7250 (Knights Landing)*	(4.56 c/b)	0.74 c/b

* Thanks to Romain Dolbeau

[Bertoni et al., IACR ePrint 2016/770]

Outline

AVX-512

AVX-512 = SIMD with 512-bit registers

Benefits for KECCAK-f:

- $8 \times$ KECCAK-$f[1600]$
- Rotation instructions
- Three-input binary functions
  - $r \leftarrow a \oplus b \oplus c$
  - $r \leftarrow a \oplus ((b \oplus 1) \wedge c)$
- 32 registers

A near collision...

Questions?

By Marcello Maria Perongini (flickr.com)

https://github.com/gvanas/KeccakCodePackage
http://keccak.noekeon.org/Keccak-implementation-3.2.pdf
http://keccak.noekeon.org/KangarooTwelve.pdf