What's Wrong with Poly1305?

Improving Poly1305 through a Systematic Exploration of Design Aspects of Polynomial Hash Functions

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Outline

Δ-Universal Hash in Practice

- **Definition:** Given $z \in \mathcal{T}$ and $M \neq M' \in \mathcal{M}$,

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- **Various practical applications:**
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  - Message Authentication Codes: UMAC, Badger, Poly1305-AES, GMAC [ISO/IEC 9797-3].
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- Good performance across all architectures without needing specific hardware support.
- Alternative and backup AEAD scheme to AES-GCM.
- Fast adoption even with the predominance of AES-GCM.
- Conservative and simple design, focused on performance with standard AEAD security.

Poly1305 [Ber05]

For $M = M_1 \| \cdots \| M_n$,

$$\text{Poly1305}(r, M) = (c_1 x^n + c_2 x^{n-1} + \cdots + c_n x^1 \mod 2^{130} - 5) \mod 2^{128},$$

where $c_i = M_i \| 1$ and $x = \text{clamp}(r, 22)$.

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- Tailored for 32-bit architectures.
- Limited security of ChaChaPoly in the multi-user setting due to Poly1305 [DGGP21].

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Given today's advancements and applications, would we still converge to this same design?

Systematization of Knowledge (SoK)

Current Standpoint:

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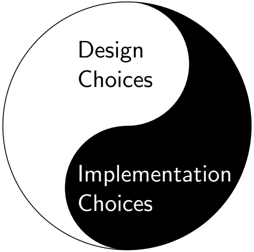
Our Exposition [DGGP24]:



Brief Description of the Design Space

key R message M $\in \{0,1\}^*$

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	M_1	M_2	$\cdots$	M_ℓ	$\in \{0,1\}^*$
$\downarrow$		$\downarrow$			$\downarrow$
r		$m_1, m_2, \ldots, m_\ell$			$\in \mathbb{F}_p^*$

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$\downarrow$

$P_r(m_1, m_2, \ldots, m_\ell)$ $\qquad$ Polynomial

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$$R \longrightarrow r$$

$$M \longrightarrow m_1, m_2, \ldots, m_\ell \in \mathbb{F}_p^*$$

$$m_1 \cdot r^\ell + m_2 \cdot r^{\ell-1} + \cdots + m_\ell \cdot r$$

Classical Polynomial

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$\in \{0,1\}^*$

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Classical Polynomial

Horner

Parallel Horner

2-level

Polynomial Evaluation Strategy

Brief Description of the Design Space

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$P_r(m_1, m_2, \ldots, m_\ell)$

Polynomial

t

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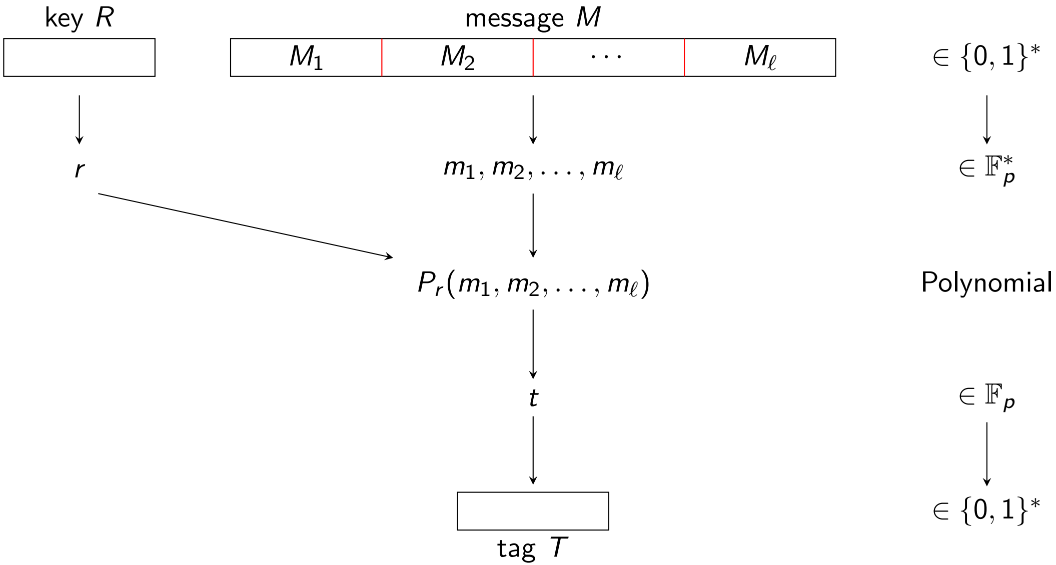

Field Multiplication

$$m \qquad \times \qquad r \qquad \in \mathbb{F}_p$$

Field Multiplication (Saturated Limb Representation)

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Saturated Limb Representation

w = word size, e.g., 32/64 bits

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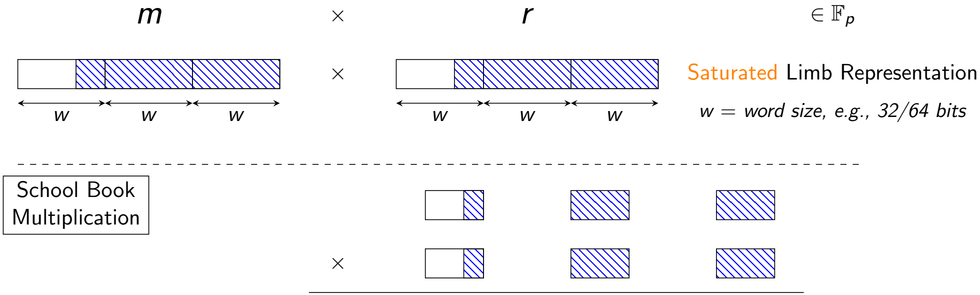

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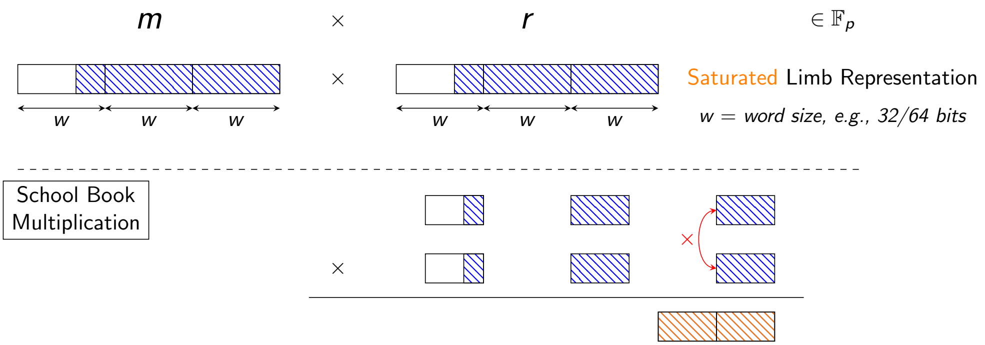

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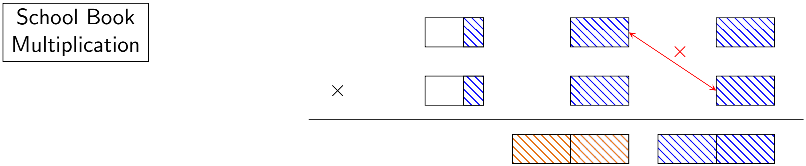

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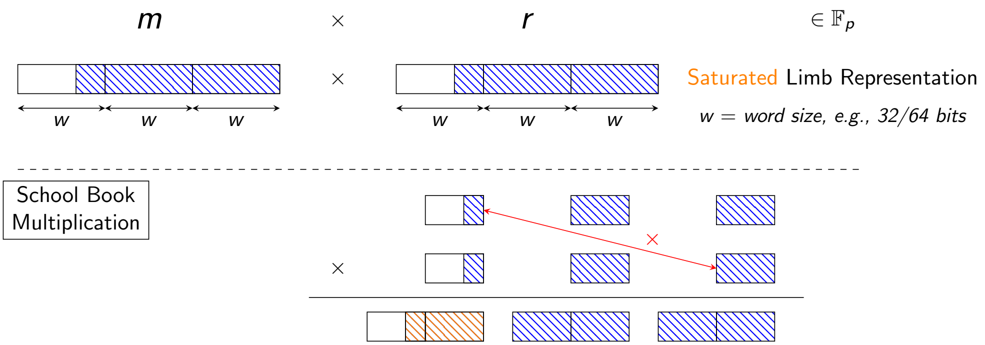

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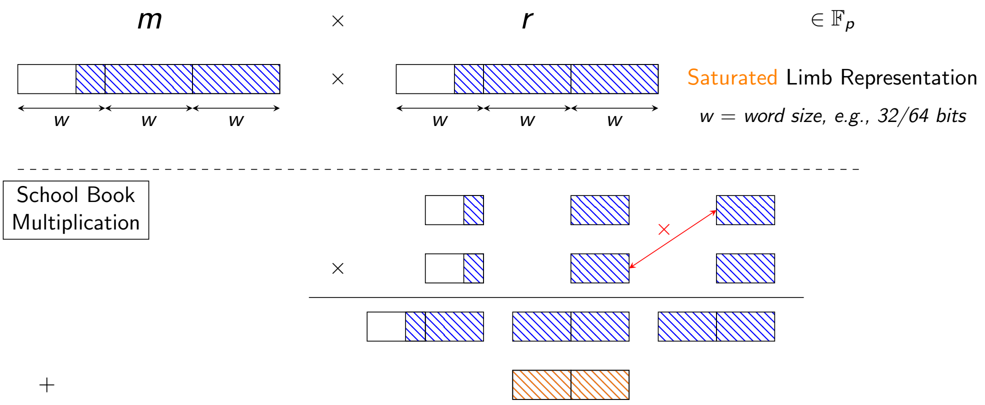

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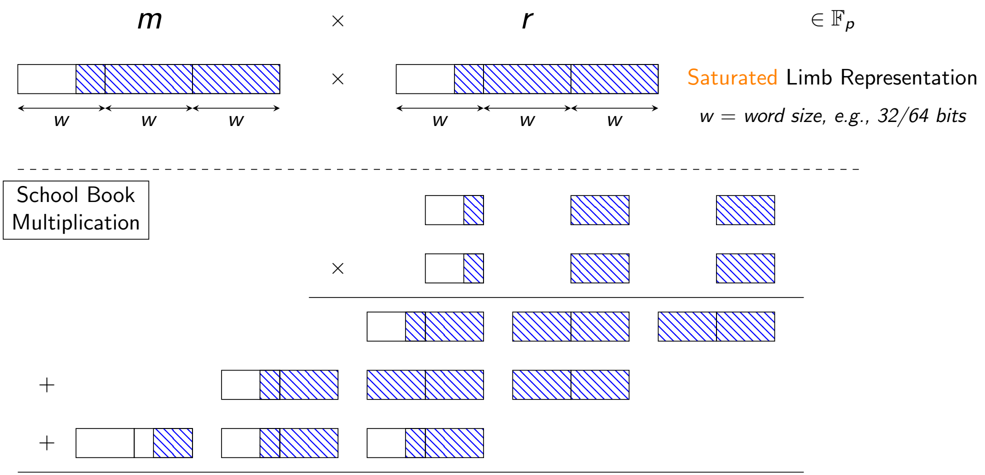

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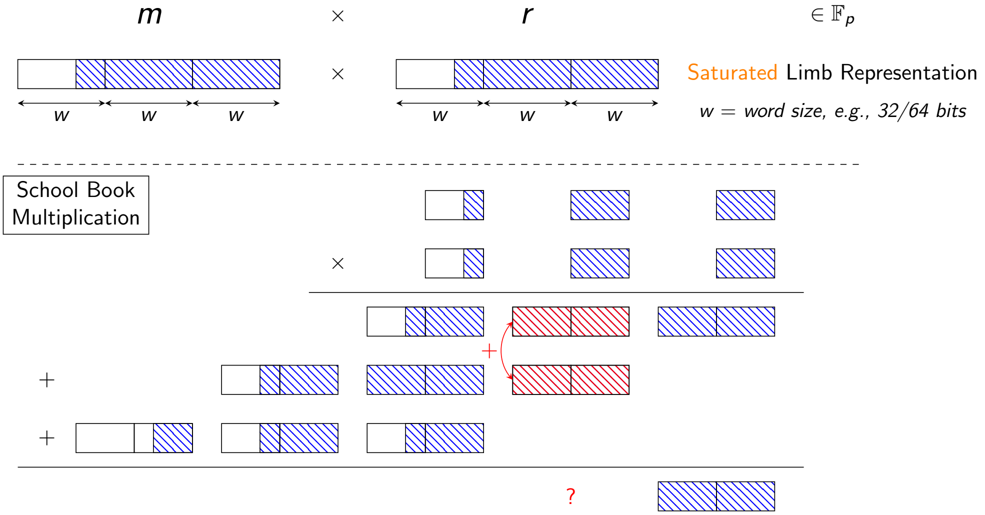

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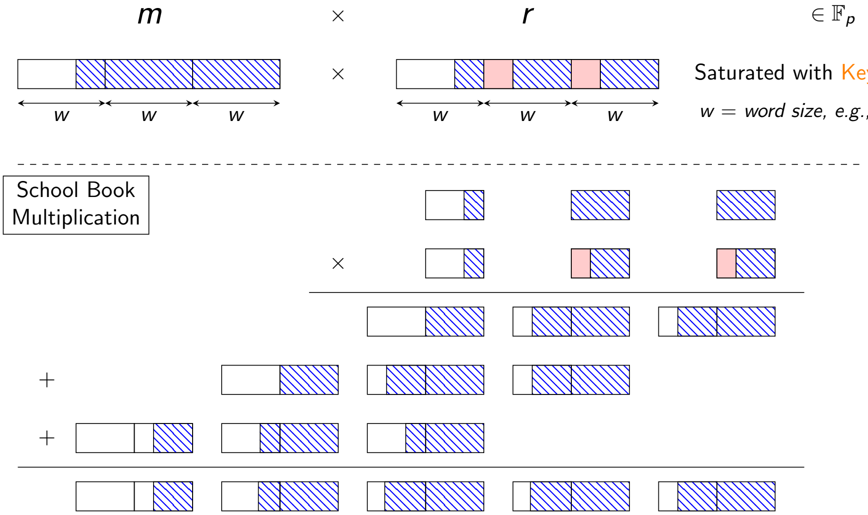

Saturated with Key-Clamping

w = *word size, e.g., 32/64 bits*

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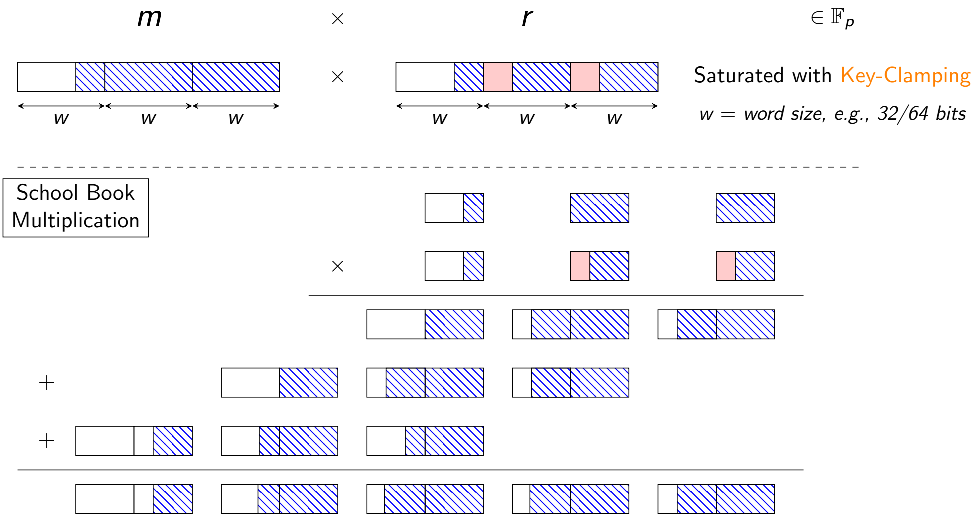

Limitation: Not exploitable using parallel Horner and 2-level evaluation algorithms.

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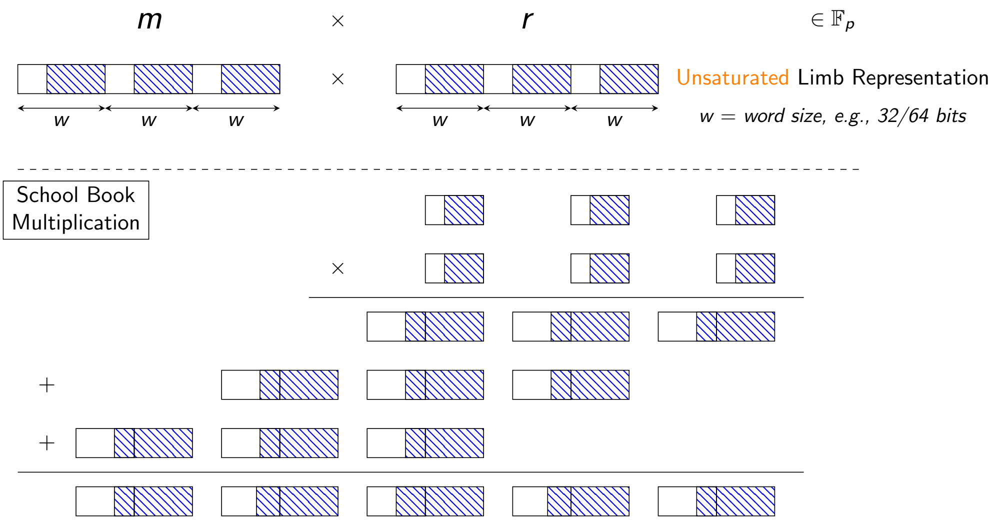

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Problem:

- How do we pick a concrete design from this huge space?
- We want to be able to understand and test different combinations.
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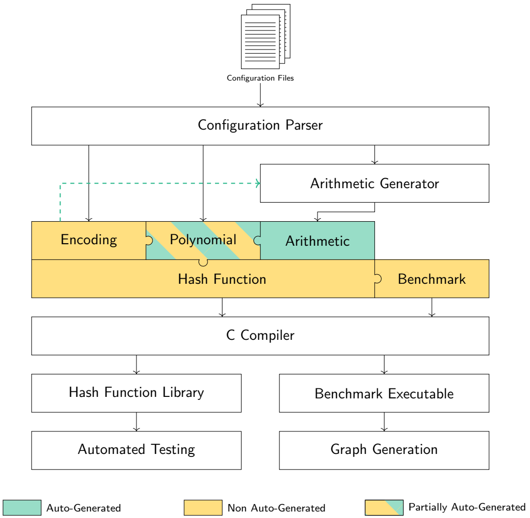
Solution:

- Modularize!
  - We use our systematization to define modular *configurations*.
- Generic Implementations and Auto-Generation!
  - Write generic implementations, setting specific parameters at compile time.
  - However, fully generic code can lead to bad performance.
  - Where this is likely to occur we automatically generate efficient implementations.

Modular Benchmarking Framework



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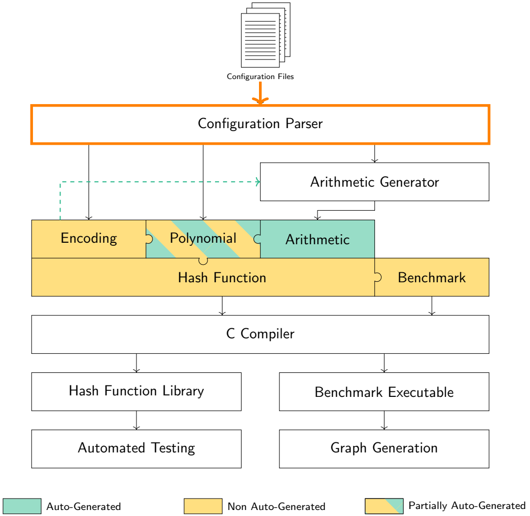

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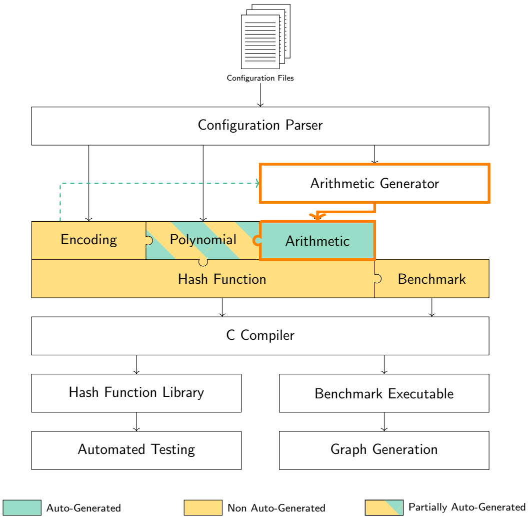

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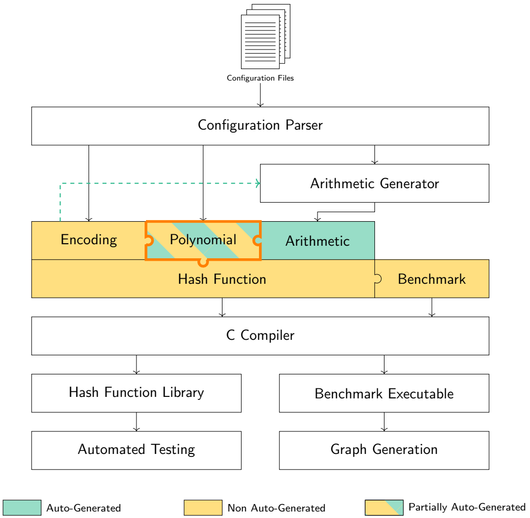

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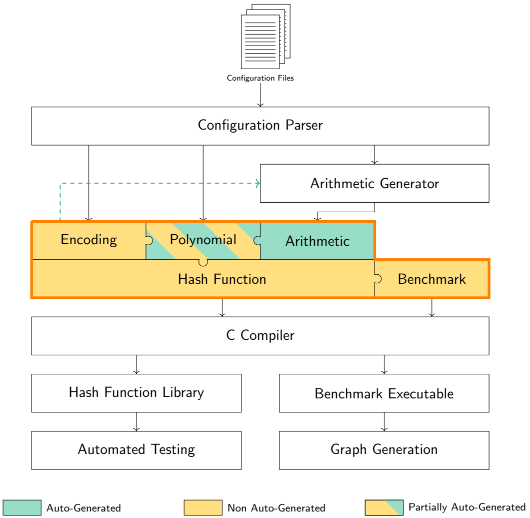

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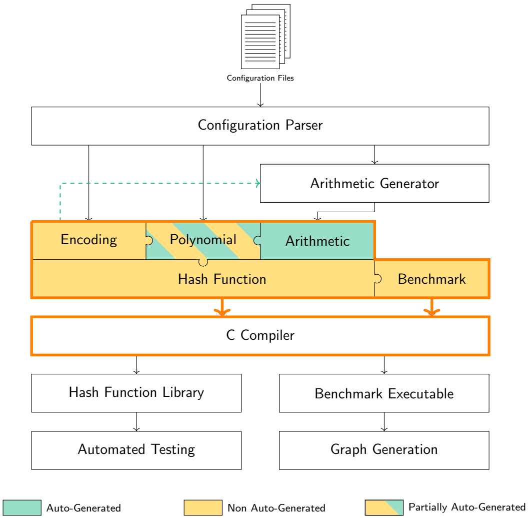

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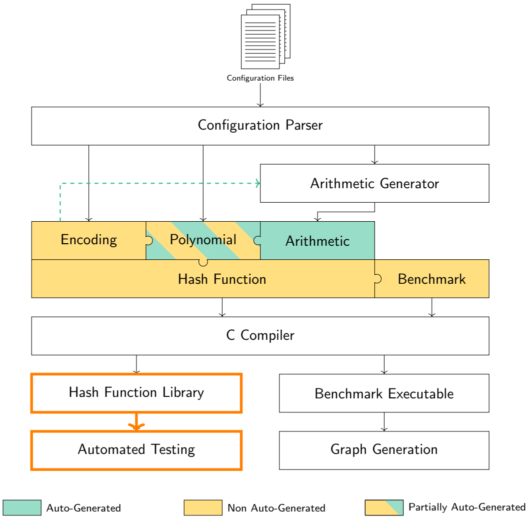

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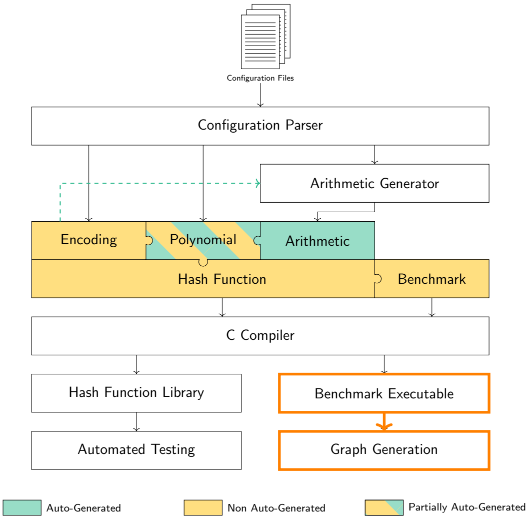

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openssl poly1305-x86.pl

> *[B]esides SSE2 there are floating-point and AVX options; FP is deemed unnecessary, because pre-SSE2 processor are too old to care about, while it's not the fastest option on SSE2-capable ones;*

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- Keep things simple, familiar to developers.
- Allow various optimization strategies to tune implementations to different hardware.
- But without tailoring the design towards a specific implementation.
  - Don't design for FPUs!

New Designs

- No clamping to support FPU implementations as these are not worth the security loss.
- Stick with Classical Polynomial over $\mathbb{F}_p$. Pack limbs as full as we can.
- Designs allow: Delayed reduction, 2-level polynomial evaluation, exploiting CPU parallelism.

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Security Level:	≈107 bits	≈137 bits

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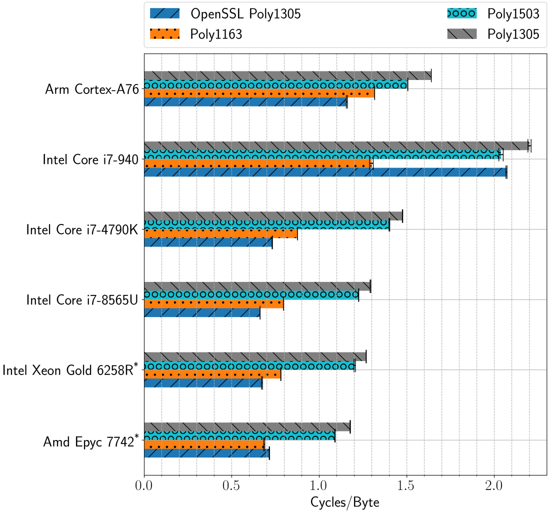
- Designs allow: Delayed reduction, 2-level polynomial evaluation, exploiting CPU parallelism.

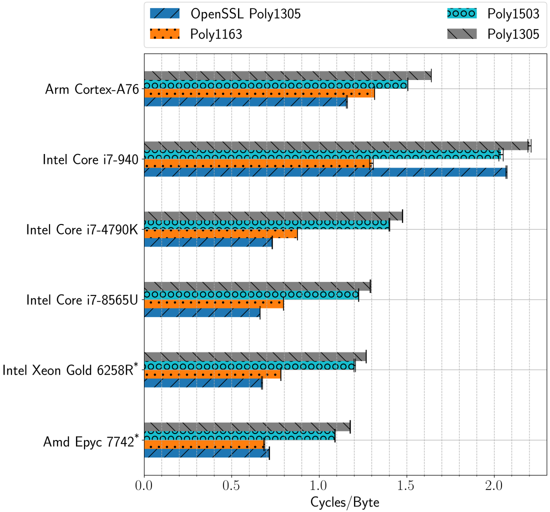
Options:	Fewer limbs to increase performance	Same number of limbs and increase security
Prime for fast reduction:	$p_1 = 2^{116} - 3$	$p_2 = 2^{150} - 3$
Bits per limb (32/64):	29/58	30/50
Security Level:	≈107 bits	≈137 bits
Resulting Hash function:	**Poly1163**	**Poly1503**

Benchmarking



*Turbo Boost/Core Adjusted

Benchmarking

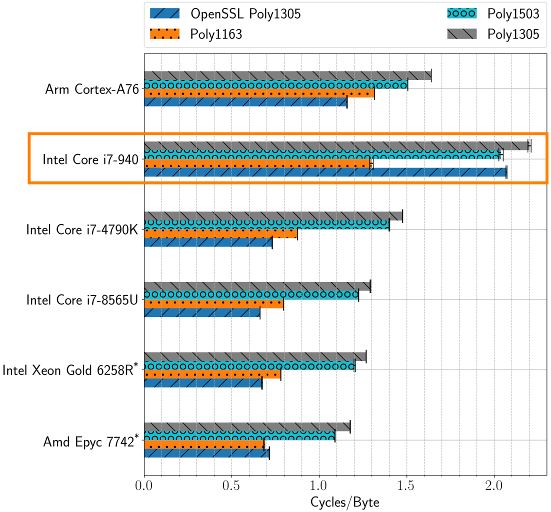


*Turbo Boost/Core Adjusted

Results:

- Our modular implementations achieve **high performance without vectorization or hand-optimization.**

Benchmarking



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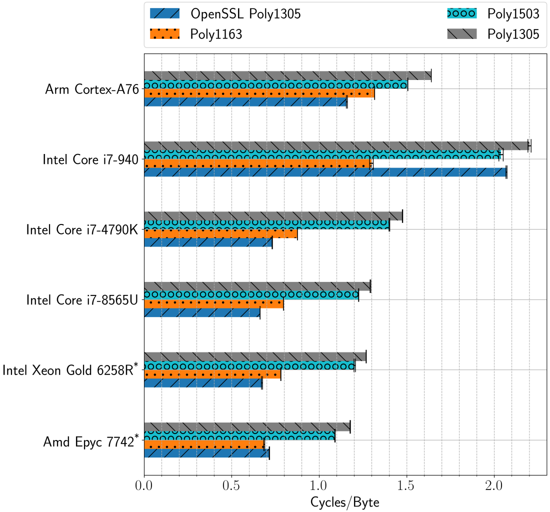
Benchmarking



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Results:

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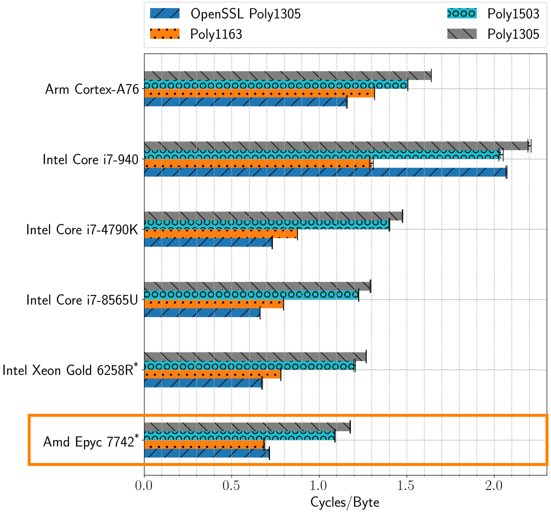
- Poly1163 performance makes it **suitable as drop-in replacement for Poly1305.**

Benchmarking



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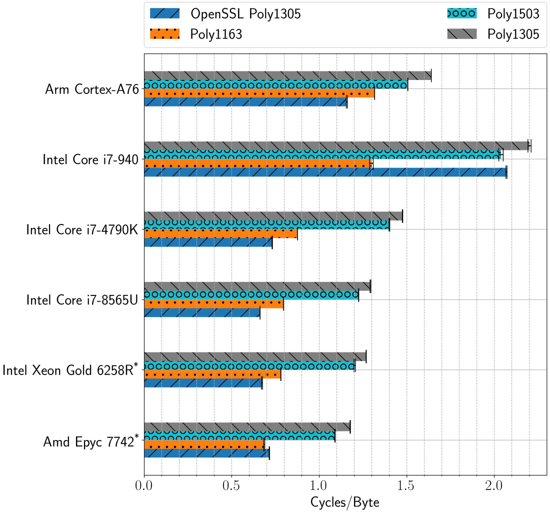

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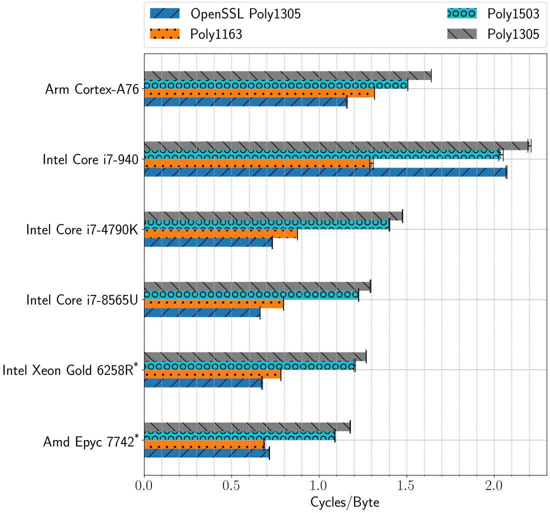
- Poly1163 performance makes it **suitable as drop-in replacement for Poly1305.**

Our Expectations for Vectorization:

- Poly1163: Significantly outperforms Poly1305 at the same security level.

Benchmarking



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Results:

- Our modular implementations achieve **high performance without vectorization or hand-optimization.**
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Our Expectations for Vectorization:

- Poly1163: Significantly outperforms Poly1305 at the same security level.
- Poly1503: Replacement for Poly1305 with 34 bits of extra security ($103 \rightarrow 137$) at similar performance.

Where to Find More Details

SoK on Polynomial Hash:

https://doi.ieeecomputersociety.org/10.1109/SP54263.2024.00132

Code of Polynomial Hash Framework:

https://github.com/jangilcher/polynomial_hashing_framework

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In Henri Gilbert and Helena Handschuh, editors, *FSE 2005*, volume 3557 of *LNCS*, pages 32–49. Springer, Heidelberg, February 2005.

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Universal classes of hash functions.
Journal of computer and system sciences, 18(2):143–154, 1979.

Jean Paul Degabriele, Jérôme Govinden, Felix Günther, and Kenneth G. Paterson.
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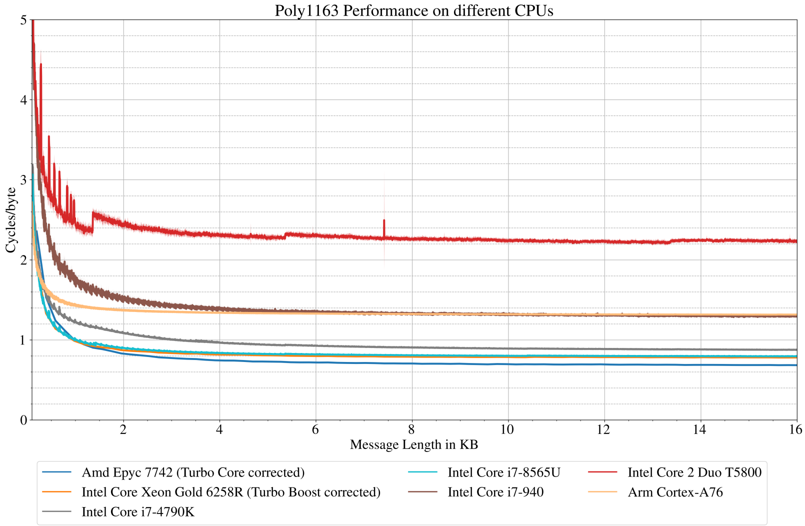
Jean Paul Degabriele, Jan Gilcher, Jérôme Govinden, and Kenneth G. Paterson.
Sok: Efficient design and implementation of polynomial hash functions over prime fields.
In *2024 IEEE Symposium on Security and Privacy (SP)*, pages 131–131, Los Alamitos, CA, USA, may 2024. IEEE Computer Society.

Benchmarks: Poly1163



Benchmarks: Poly1503