Accurately Benchmarking Efficiency of Pairing-Based Attribute-Based Encryption

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Motivation

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- Existing implementations may not be fairly comparable
- **Our goal:** accurately benchmarking and comparing schemes, efficiency analysis, new speed records

High-level overview

1. Introduction to ABE
2. Why is benchmarking ABE difficult?
3. ABE Squared
4. Towards automating ABE Squared
5. Conclusion

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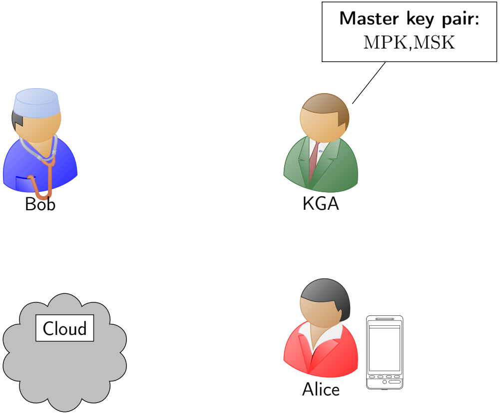
Ciphertext-policy attribute-based encryption (CP-ABE)

Setup:



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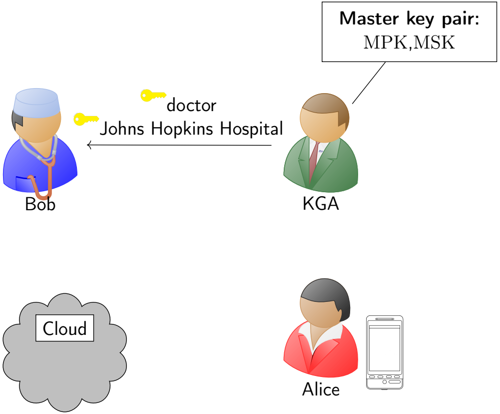

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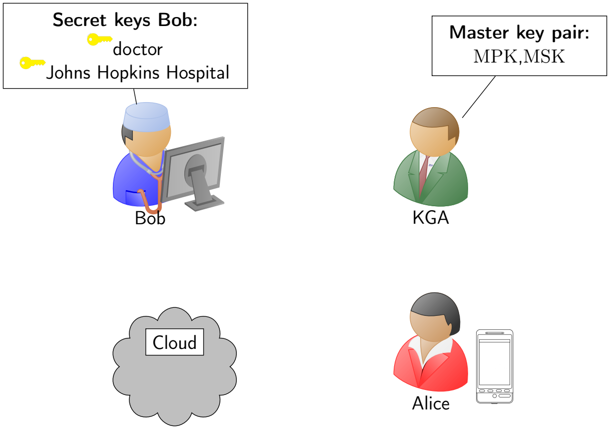

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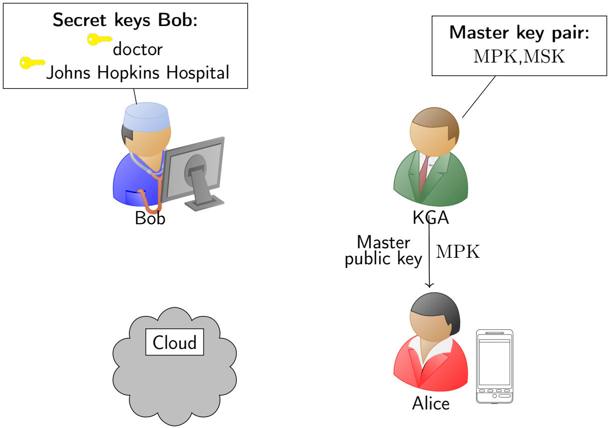

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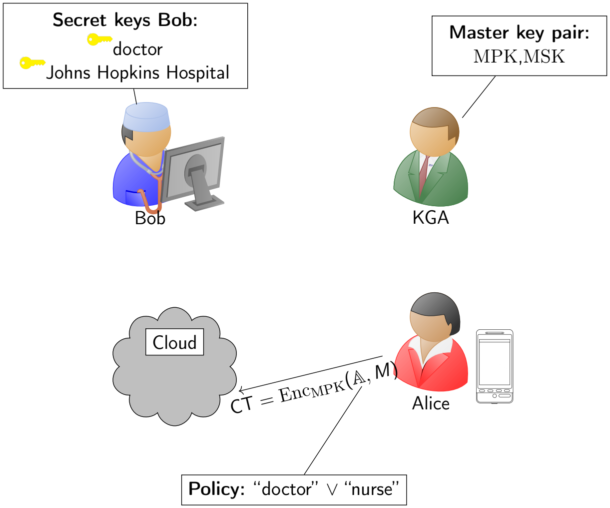

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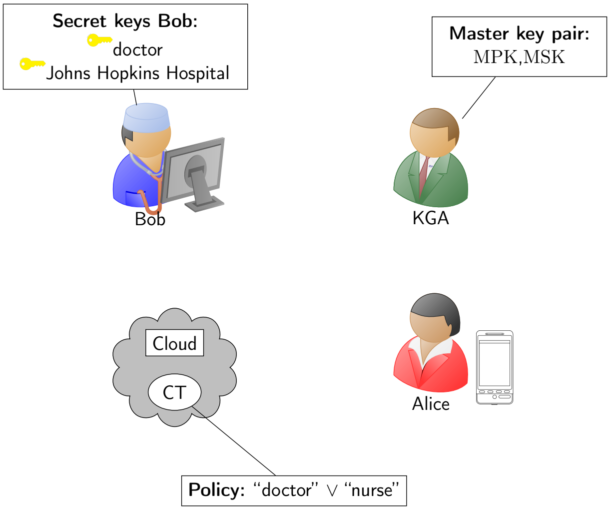

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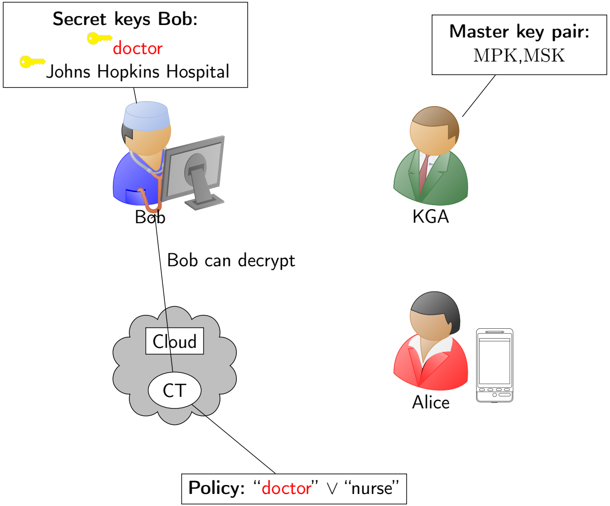

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- Popular in settings in which data has to be stored on untrusted platforms
- The European Telecommunications Standards Institute (ETSI) considers several use cases for ABE, e.g., Cloud, IoT
- More recently, Cloudflare has presented an updated version of their Geo Key Manager: Portunus

Requirements for ABE

These use cases share many common requirements for ABE:

- **Expressive policies:** policies should support Boolean formulas consisting of AND and OR operators
- **Large universes:** attribute could be any arbitrary string, e.g., names, roles, MAC addresses
- **Unbounded:** no bounds on any parameters, such as the length of the policies or attribute sets

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Storage and computational efficiency requirements may vary per use case.

Requirements for storage and computational efficiency

Examples:

- Portunus and cloud settings: fast decryption
- Internet of Things: small ciphertexts, fast encryption

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- Most established: many desirable practical properties, high security guarantees and efficient
- Unfortunately, not post-quantum secure
- Post-quantum secure schemes exist
- However, still heavily under development, e.g., to achieve the same desirable properties

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3 ABE Squared

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Typically, in ABE:

- Choose a framework for rapid prototyping, e.g., Charm [AGM+13]
- Implement, maybe optimize some parts

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Some of these really depend on what the designer tries to optimize, e.g., the decryption algorithm for Cloudflare's use case

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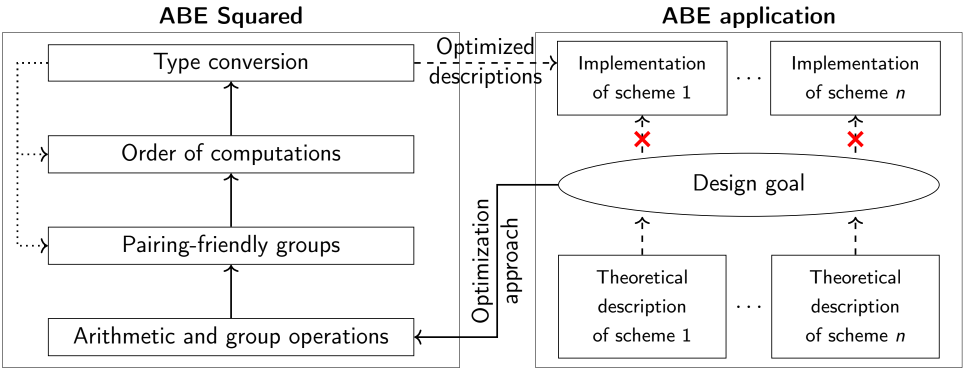
Overview of ABE Squared



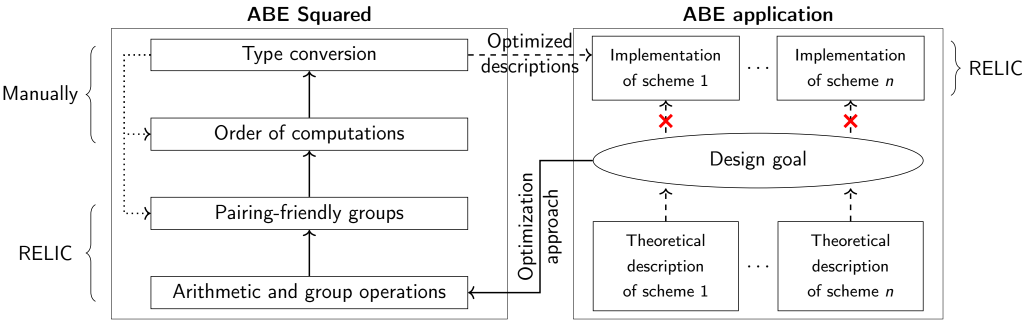
The arrows have the following meaning:

$a \longrightarrow b$ = "a influences b"

$a \cdots\rightarrow b$ = "a may require adjustment in b"

$a \dashrightarrow b$ = "a is input to b"/"b is output of a"

Overview of ABE Squared (continued)



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- Interaction between the upper two layers and how they interact with the lower two layers has not been investigated sufficiently for ABE yet
- Previous type-conversion methods typically only allow for optimized key or ciphertext sizes
- These cannot be used to optimize decryption
- We provide manual heuristics that take the interactions between the different layers into account
- Allows us to better optimize e.g., the decryption algorithm than previous methods allow

Optimized type conversion

Pairing: $e\colon \mathbb{G} \times \mathbb{H} \to \mathbb{G}_T$, where $\mathbb{G}, \mathbb{H}$ and $\mathbb{G}_T$ are groups of order p.

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Our heuristics: find most efficient instantiation in $\mathbb{G}$ and $\mathbb{H}$ given a specific design goal. (Also depends on the chosen group!)

Benchmarks for differently optimized schemes

Implementation of Wat11-I in RELIC, on the BLS12-381 curve, based on their optimization approaches[1] (OA). The costs are expressed in 10^3 clock cycles[2].

OA	Key generation				Encryption				Decryption			
	# of attributes				# of attributes				# of attributes			
	1	10	100	Increase	1	10	100	Increase	1	10	100	Increase
OE & OD	759	3029	25653	143.0%	**990**	**4540**	**39951**	-	**2005**	**7379**	**58515**	-
OK	**317**	**1249**	**10555**	-	1756	10814	101181	153.3%	2016	7611	63151	7.9%

[1] OE/OD/OK = optimized encryption/decryption/key generation.
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- Design goal influences the type conversion
- e.g., it yields a difference of a factor of ≈ 2.5 in computational costs for BLS12-381

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Performance analysis

To demonstrate the framework, we have implemented and benchmarked three schemes with the same practical properties (achieved in different ways) in RELIC:

- Wat11-IV [Wat11]: implemented in libraries such as Charm and OpenABE
- RW13 [RW13]: implemented in Charm, outperformed by Wat11-IV
- AC17-LU [AC17]: not implemented

Many follow-up works build on these schemes and are structurally similar. Note that all these schemes satisfy the three important properties that we mentioned earlier (i.e., expressive, large-universe and unbounded).

Benchmarks for 100 attributes

OA	Scheme	Curve	Key generation		Encryption		Decryption	
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OE	Wat11-IV	BLS12-381	42275	0.2%	77641	48.8%	58290	543.4%
	RW13	BLS12-381	51401	21.8%	54491	4.4%	112072	1137.1%
	AC17-LU	BLS12-381	**42196**	-	**52176**	-	9060	-
OK	Wat11-IV	BLS12-381	42135	94.6%	77898	48.9%	58441	543.9%
	RW13	BLS12-381	**21657**	-	128221	145.0%	118998	1211.2%
	AC17-LU	BLS12-381	41913	93.5%	**52326**	-	9076	-
OD	Wat11-IV	BLS12-381	**42275**	-	77641	42.5%	58290	1336.5%
	RW13	BLS12-381	51401	21.6%	**54491**	-	112072	2661.9%
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- For an optimized encryption or decryption, use AC17-LU
- For an optimized key generation, use RW13
- **Surprising result:** RW13 outperforms Wat11-IV in the key generation and encryption algorithms

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Future work: automation and more curves

- For future work, it would be valuable to automate ABE Squared
- Furthermore, it would be valuable to analyze the efficiency of schemes for more curves
- Existing libraries for curve arithmetic often support very few curves
- There exist many curves at the 128-bit security level (see `https://members.loria.fr/AGuillevic/pairing-friendly-curves/`):

Curve	k	D	u	ref	p (bits)	r (bits)	$p^{k/d}$ ($\mathbb{G}_2$, bits)	p^k (bits)
Curve for fastest pairing								
Barreto–Lynn–Scott BLS12, cyclotomic $r(x)$	12	3	$-(2^{73}+2^{72}+2^{50}+2^{24})$	eprint 2017/334	440	295	p^2, 880	5280
Barreto–Lynn–Scott BLS12, cyclotomic $r(x)$	12	3	$-(2^{12}-2^{48}-2^{71}+2^{74})$	eprint 2017/334	442	296	p^2, 884	5296
Barreto–Lynn–Scott BLS12, cyclotomic $r(x)$	12	3	$-(2^{74}+2^{73}+2^{63}+2^{57}+2^{50}+2^{17}+1)$	eprint 2019/885	446	299	p^2, 892	5352
Fotiadis–Martindale FM17, Aurifeuillean $r(x)$	12	3	$-2^{72}-2^{71}-2^{36}$	eprint 2019/555	447	296	p^2, 894	5356
Kachisa–Schaefer–Scott KSS16	16	1	$-2^{34}+2^{27}-2^{23}+2^{20}-2^{11}+1$	eprint 2017/334	330	257	p^4, 1320	5280
Kachisa–Schaefer–Scott KSS16	16	1	$2^{34}-2^{30}+2^{26}+2^{23}+2^{14}-2^5+1$	eprint 2019/1371	330	256	p^4, 1320	5268
Kachisa–Schaefer–Scott KSS16	16	1	$2^{35}-2^{32}-2^{18}+2^8+1$	eprint 2017/334	339	263	p^4, 1356	5411
Curve with small embedding degree k								
Cocks–Pinch modified	6	3	$2^{128}-2^{124}-2^{69}$, $h_t=-1$, $h_y=2^{80}-2^{70}-2^{66}-$ `0x3fe0` = `0xffbbffffffffffffc020`	eprint 2019/431	672	256	p, 672	4028
Cocks–Pinch modified	8	1	$2^{64}-2^{54}+2^{37}+2^{32}-4$, $h_t=1$, $h_y=$ `0xdc04`	eprint 2019/431	544	256	p^2, 1088	4349
Curve with smallest $\mathbb{G}_1$								

Finding the best curve

- Implementing curve arithmetic for over 20 curves is (too) ambitious
- Perhaps a better approach: theoretically approximate the efficiency for each curve
- Extrapolate the efficiency of schemes using these approximations
- Implement those that we believe are the best choices for ABE (applications)

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- Perhaps, BLS12-381 is already good enough
- BLS12-381 believed to currently provide 126 bits of security
- ABE schemes typically lose some extra bits of security
- Could be better to use a curve with $>$ 128 bits of security
- Additionally, different curves have different efficiency trade-offs
- Natural to think that, for each scheme and design goal, there may be a different optimal curve

Performance estimations for some curves

We estimate the costs (very roughly!) for RW13 using the field-arithmetic benchmarks in [GMT20], in milliseconds:

OA	Curve	Key generation	Encryption	Decryption
OE/OD	BLS12-446	400	332	141
	CP8-544	**173**	431	122
	KSS16-330	874	**218**	**102**
OK/OD	BLS12-446	133	994	141
	CP8-544	173	**431**	122
	KSS16-330	**87**	2169	**102**

- KSS16-330 may yield better efficiencies for the one-algorithm optimization strategies (OK/OE/OD)
- More "balanced" curves such as CP8-544 may be more suitable for more "balanced" efficiencies among the algorithms

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- By optimizing multiple schemes with respect to the same goal, they can be compared more fairly
- Existing open-source libraries providing ABE implementations, e.g., Charm, OpenABE, can greatly benefit from our heuristics
- **Design goals matter:** for different goals, different schemes may perform the best

Questions?

Thank you for your attention!

- Our paper:
  - TCHES: `tches.iacr.org/index.php/TCHES/article/view/9486`
  - eprint: `https://eprint.iacr.org/2022/038`
- Our code: `https://github.com/abecryptools/abe_squared`

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