Demystifying Key Stretching and PAKEs

Steve “Sc00bz” Thomas

Who am I? Why am I here?

Who am I? Why am I here?

- Password cracker
- Cryptography enthusiast
- I just wanted a pw manager
  - Bugs and vulns galore
  - How would I make one?
- PHC Panelist
  - I broke Schvrch and old Makwa

Agenda

- Key Stretching
  - What?
  - Why?
  - Types
  - What goes wrong?
  - How?
  - Settings
- Password Authenticated Key Exchange (PAKE)
  - What?
  - Why?
  - Types
  - How?
  - Properties

Key Stretching

- Passwords
  - Hashing (Authentication)
  - KDF (Key Derivation Function)
- Fingerprints
  - Signal’s Safety Numbers ($2^{99.7} \rightarrow 2^{112}$)

Key Stretching – Why?

- Ashley Madison data breach (2015)
  - 36.15 million bcrypt cost 12 hashes
    - 113 H/s/GPU (GTX 980 Ti, the best at the time)
    - 89 GPU-hours/password

Key Stretching – Why?

- Ashley Madison data breach (2015)
  - 36.15 million bcrypt cost 12 hashes
    - 113 H/s/GPU (GTX 980 Ti, the best at the time)
    - 89 GPU-hours/password
  - 15.26 million salted, case-insensitive MD5 hashes[1]
    - 11.2 million bcrypt cracked in 10 days
    - 73% with MD5 hashes

Key Stretching – Types

- Computationally hard
  - Amount of work done (number of blocks hashed)
    - Parallel vs Sequential
- Memory hard
  - Amount of memory used
  - Bandwidth consumed
- Cache hard
  - Random small transactions

Key Stretching – Types

- Computationally hard
  - Parallel PBKDF2
  - PBKDF2
- Memory hard
  - Argon2
  - Balloon Hashing
  - scrypt
- Cache hard
  - bcrypt
  - bscrypt

Key Stretching – How?

1) seed = H(inputs)
   a) [optional] independent seed = H(non-secret inputs)
2) work = doWork(settings, seed[, independent seed])
3) key = KDF(output size, work, seed or inputs)

Key Stretching Bugs

- md5crypt (CVE-2012-3287)
- PBKDF2 (CVE-2013-1443)
- phpass (CVE-2014-9034)
- shacrypt (CVE-2016-20013)
- bcrypt's \$2\$, \$2a\$→\$2b\$, \$2x\$, truncation, and null characters

Key Stretching Bugs

- bcrypt silently truncates at 72 bytes

Code from
UK's "Police CyberAlarm"

```
$passhash = password_hash(
  phash('P3rv4d3_extrasalt') .
  $fields['password'] .
  phash('S0ftw4r3_extrapepper'),
  PASSWORD_BCRYPT);
```

Note "phash()" is SHA-256 hex output

Source: https://twitter.com/Paul_Reviews/status/1538124477317451777

Key Stretching Bugs

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Key Stretching Bugs

- Bouncy Castle's bcrypt compare .indexOf() vs .charAt() (CVE-2020-28052)
- Checks the first occurrences of ./0123456789
- $2y$10$UnluckySalt./3456789..HashValueWontMatter...........
  - 1 in 1,030,319 (for costs 11 and 12)
  - 1 in 197,153 (for all other normal costs)

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  - **How?**
  - Settings
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  - What?
  - Why?
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Key Stretching – How?

1) seed = H(inputs)
2) work = doWork(settings, seed)
3) key = KDF(outSize, work, seed)

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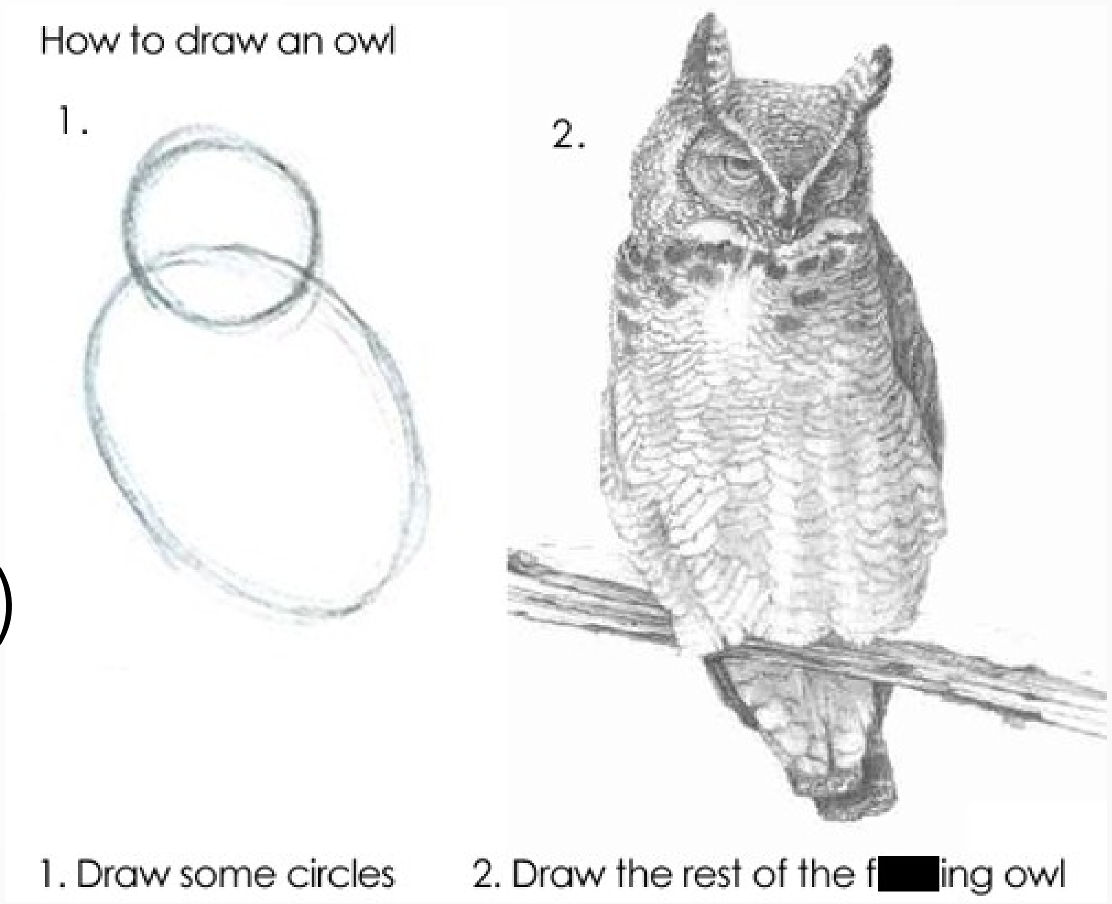
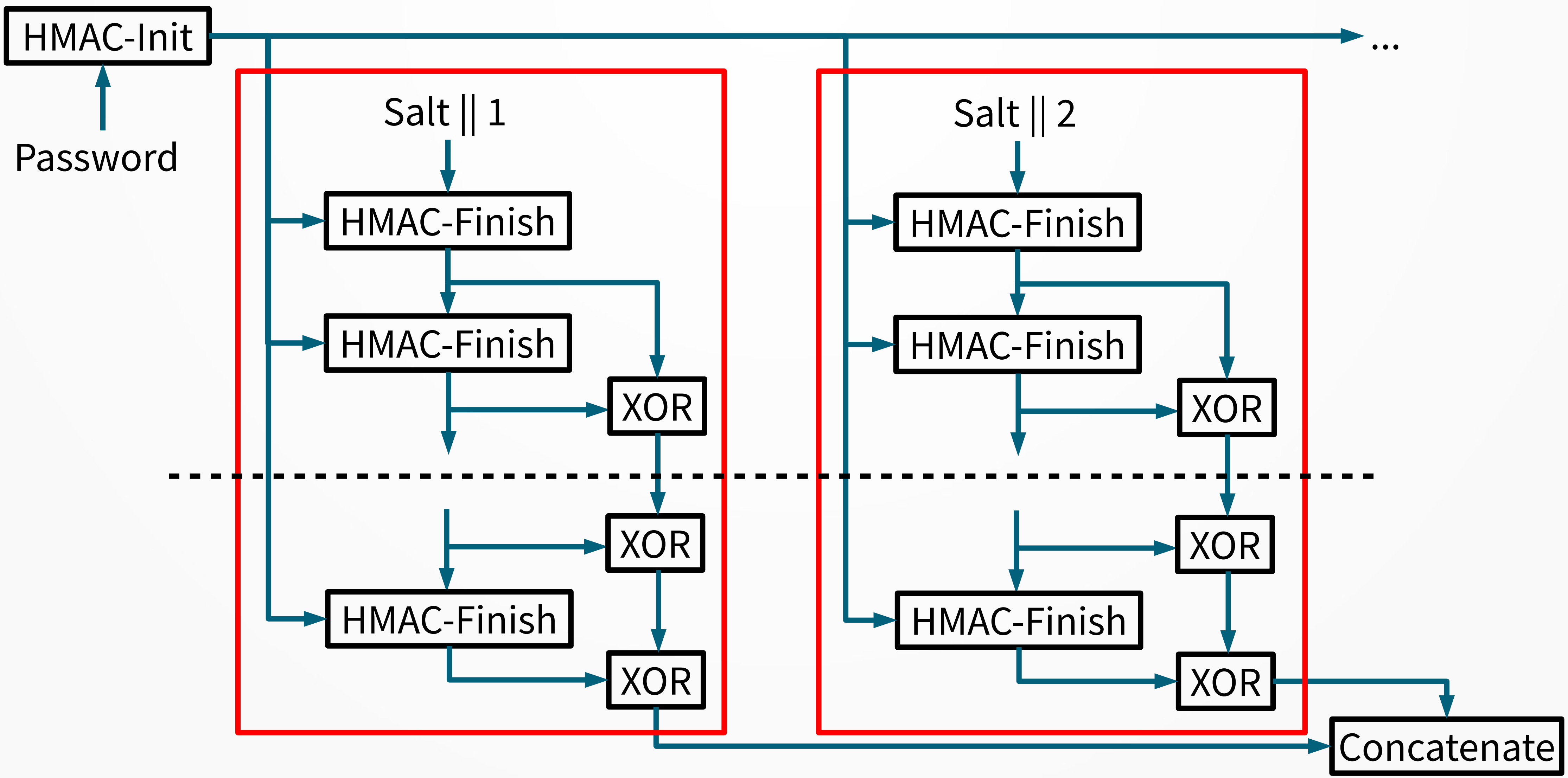


PBKDF2



HMAC-Init
Password
...
Salt || 1
HMAC-Finish
HMAC-Finish
XOR
XOR
HMAC-Finish
XOR
Salt || 2
HMAC-Finish
HMAC-Finish
XOR
XOR
HMAC-Finish
XOR
Concatenate

Parallel PBKDF2

```
work = xorBlocks(
  pbkdf2(password, salt,
    iterations:1024,
    length:128*cost*hashLength))
output =
  pbkdf2(password, work,
    iterations:1,
    length:outputLength)
```

Password Settings

- Minimum
  - Such that an attacker gets <10 KH/s/GPU[17]
- Maximum
  - Doesn’t take too much time $\lesssim$100 ms
  - Doesn’t use too much memory
  - Meets your needed throughput on your hardware

bscrypt Minimum Settings

- m=256 (256 KiB), t=8, p=1
- m=256 (256 KiB), t=4, p=2
- m=256 (256 KiB), t=3, p=3
- General
  - m=highest per core cache level in KiB
  - $t \geq \max(2, 1900000/1024/m/p)$
  - $p \leq$ cores

BSidesLV 2022 (PasswordsCon track)
bscrypt - A Cache Hard Password Hash

https://tobtu.com/minimum-password-settings/

bcrypt Minimum Settings

- Cost 9
  - Technically it's like “8.1” but it's an integer.
  - This should be about 5.3 kH/s on an RTX 3080 12GB.

https://tobtu.com/minimum-password-settings/

Argon2 Recommended Settings

- RFC9106
  1) Argon2id: m=2097152 (2 GiB), t=1, p=4
  2) Argon2id: m=65536 (64 MiB), t=3, p=4

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Argon2 Recommended Settings

- RFC9106
  1) Argon2id: m=2097152 (2 GiB), t=1, p=4
  2) Argon2id: m=65536 (64 MiB), t=3, p=4

Just kidding. Those are wildly different strengths.

https://tobtu.com/minimum-password-settings/

Argon2 Minimum Settings

- Argon2{id,d}: m=45056 (44 MiB), t=1, p=1
- Argon2{id,d}: m=18432 (18 MiB), t=2, p=1
- Argon2: m=11264 (11 MiB), t=3, p=1
- Argon2: m=8192 (8 MiB), t=4, p=1
- Argon2: m=7168 (7 MiB), t=5, p=1
- General
  - Argon2i: $m \geq 89062.5/(3*t-1)*\alpha$, $t \geq 3$, $p=1$
  - Argon2{id,d}: $m \geq 89062.5/(3*t-1)*\alpha$, $t \geq 1$, $p=1$

https://tobtu.com/minimum-password-settings/

scrypt Minimum Settings

- $N=2^{17}$ (128 MiB), r=8, p=1
- $N=2^{16}$ (64 MiB), r=8, p=2
- $N=2^{15}$ (32 MiB), r=8, p=3
- $N=2^{14}$ (16 MiB), r=8, p=5
- $N=2^{13}$ (8 MiB), r=8, p=9
- General
  - $N \geq 570000/r/p*\alpha$, r=8, $p \geq 1$

https://tobtu.com/minimum-password-settings/

PBKDF2 Settings Poll

A) 1’000’000 iterations

B) 100’000 iterations

C) 10’000 iterations

D) 1’000 iterations

PBKDF2 Minimum Settings

- PBKDF2-HMAC-BLAKE-512*
  - 170’000 iterations
- PBKDF2-HMAC-SHA-512
  - 130’000 iterations
- PBKDF2-HMAC-SHA-256
  - 350’000 iterations
- PBKDF2-HMAC-SHA-1
  - 860’000 iterations

Best but not a NIST approved hash

https://tobtu.com/minimum-password-settings/

Parallel PBKDF2 Minimum Settings

- PPBKDF2-SHA-256
  - Cost 3
- PPBKDF2-SHA-512
  - Cost 1
- Each cost is equivalent to 131’072 (2^{17}) iterations of PBKDF2

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- **Password Authenticated Key Exchange (PAKE)**
  - What?
  - Why?
  - Types
  - How?
  - Properties

PAKEs

- Password authentication
- Encrypted tunnels
- Sending files
  - https://github.com/magic-wormhole
- Fighting phone spoofing
  - https://commsrisk.com/?p=35506

Why not SCRAM?

- “Salted Challenge Response Authentication Mechanism”
- Untrusted channels
  - Messages are equivalent to a password hash

Types of PAKEs

- Balanced
  - Peer-to-Peer

Don't call these symmetric/asymmetric

- Augmented (aPAKE)
  - Client-Server
- Doubly Augmented[9]
  - Client-Server/Device-Server
- Identity
  - IoT

Types of PAKEs

- Balanced
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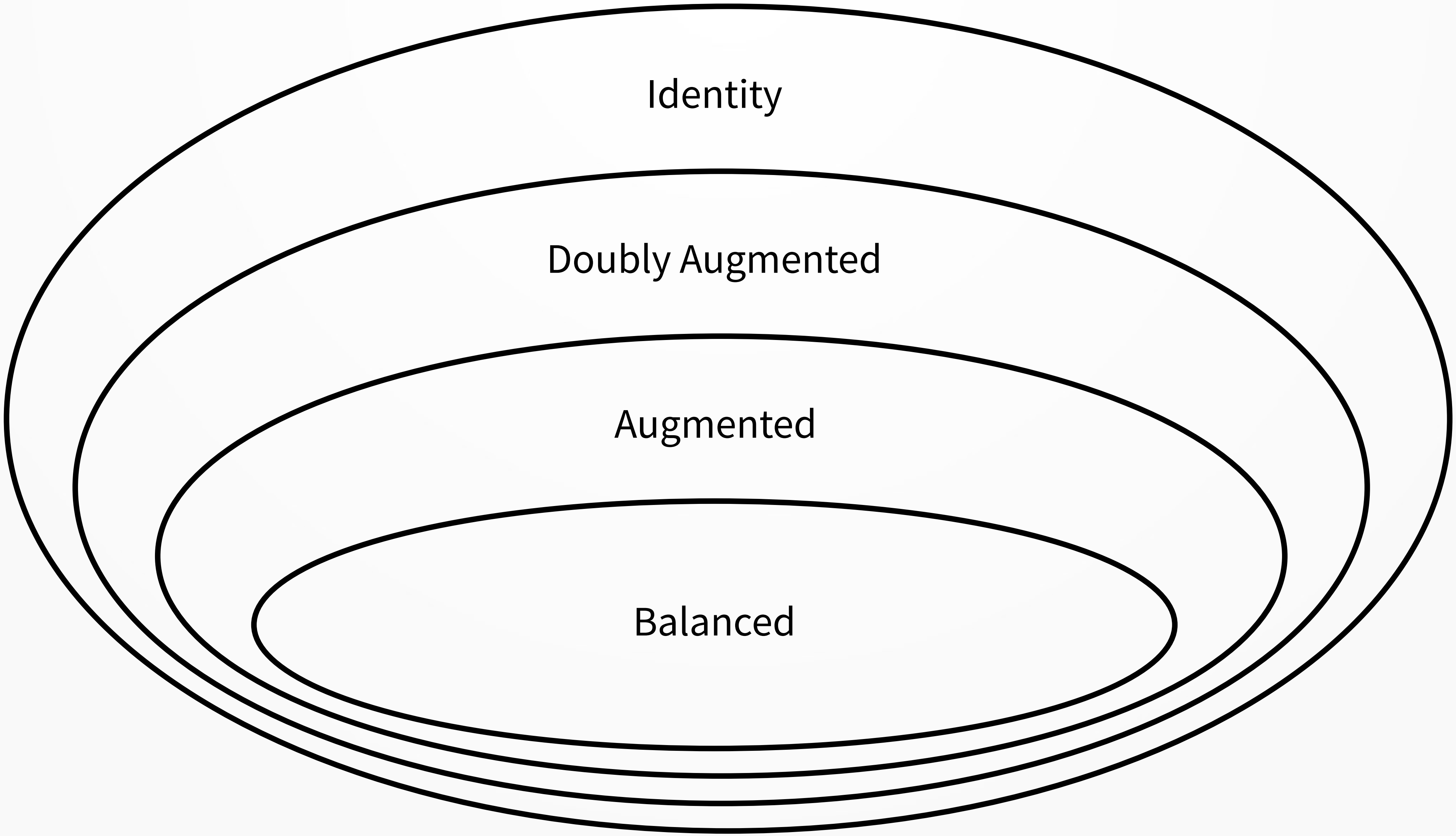
PAKE Hierarchy



Balanced	Augmented
Identity	Doubly Augmented

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  - What?
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  - Properties

Standard Diffie-Hellman

```
A:     a = random()
A:     A = a*G
A->B:  A
   B:  b = random()
   B:  B = b*G
   B:  S_B = b*A
A<-B:  B
A:     S_A = a*B
```

Hide the Ephemeral Keys

Standard Diffie-Hellman

```
A:     a = random()
A:     A = a*G
A->B:  A
   B:  b = random()
   B:  B = b*G
   B:  S_B = b*A
A<-B:  B
A:     S_A = a*B
```

```
Both: P = hashToCurve(H(pw))
A:    a = random()
A:    A = a*G+P
A->B: A
   B: b = random()
   B: B = b*G+P
   B: S_B = b*(A-P)
A<-B: B
A:    S_A = a*(B-P)
```

Hide the Generator

Standard Diffie-Hellman

A: $a = \text{random}()$

A: $A = a*G$

A->B: A

B: $b = \text{random}()$

B: $B = b*G$

B: $S_B = b*A$

A<-B: B

A: $S_A = a*B$

Both: $P = \text{hashToCurve}(H(pw))$

A: $a = \text{random}()$

A: $A = a*P$

A->B: A

B: $b = \text{random}()$

B: $B = b*P$

B: $S_B = b*A$

A<-B: B

A: $S_A = a*B$

Hide the Generator

Standard Diffie-Hellman

A: a = random()
A: A = a*G
A->B: A
B: b = random()
B: B = b*G
B: S_B = b*A
A<-B: B
A: S_A = a*B

Both: P = hashToCurve(H(pw))
A: a = random()
A: A = a*P
A->B: A
B: b = random()
B: B = b*P
B: S_B = b*A
A<-B: B
A: S_A = a*B

Patent Expired
2017

Hide the Salt (OPRF)

```
C:     P = hashToCurve(pw, id, …)
C:     r = random()
C:     R = r*P
C->S: id, R
   S: salt = dbLookup(id)
   S: R' = salt*R
C<-S: R'
C:     BlindSalt = (1/r)*R'
BlindSalt == (1/r)*r*salt*P == salt*P
```

PAKEs – How?

- Balanced (Noise-NN)
- Augmented (Noise-KN)
- Doubly Augmented (“Noise-KK” but 3DH)
- Identity (Identity exchange+Balanced PAKE)

Balanced (Noise-NN)

Alice

Bob

Ephemeral Key ⟷ Ephemeral Key

Augmented (Noise-KN)

Alice

Bob

Static Key

Ephemeral Key

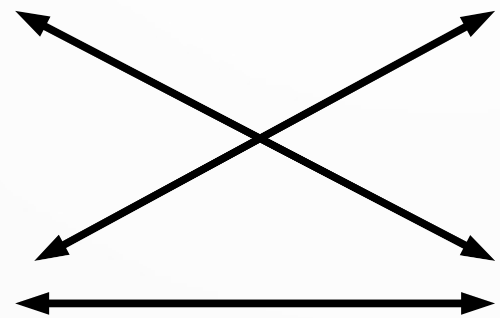
Ephemeral Key

Doubly Augmented (3DH)

Alice | Bob

Static Key | Static Key

Ephemeral Key | Ephemeral Key



PAKE Algorithms

- Balanced
  - CPace
  - SPEKE[7]
  - SPAKE2[8]
  - SPAKE2-EE[9]
- Augmented
  - (strong) AuCPace*
  - B-SPEKE
  - BS-SPEKE*
  - SPAKE2+[8]
  - SPAKE2+EE[9]
  - SRP6a
- Identity
  - CHIP[12]
  - CRISP[12]

Note not red

- Doubly Augmented
  - Double BS-SPEKE*
  - OPAQUE[11]

Hiding the: Generator, Ephemeral Keys, Salt

PAKE Algorithms

- Balanced
  - CPace
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- Identity
  - CHIP[12]
  - CRISP[12]
  - “FRY”

Note not red

- Doubly Augmented
  - Double BS-SPEKE*
  - OPAQUE[11]

Hiding the: Generator, Ephemeral Keys, Salt

PAKE Properties

0) Forward secrecy (every PAKE has this)
1) Prevent precomputation
2) Secure registration
3) Quantum annoying (Paper[13], PQCrypto 2021[14])
4) Fragile
5) Number of trips (3 vs 4)

PAKE Properties

0) Forward secrecy (every PAKE has this)
1) Prevent precomputation
2) Secure registration
3) Quantum annoying (Paper[13], PQCrypto 2021[14])
4) Fragile
5) Number of trips (3 vs 4)

Discrete Log Problem (DLP)
"Break Diffie-Hellman"

Quantum Annoying

- "It is noted in [BM92] that if we assume that a discrete log pre-computation has been made for the modulus, a password attack must also compute the specific log for each entry in the password dictionary (until a match is found)."
  - SPEKE paper 1996[7]
- "With EKE, the password *P* is used to superencrypt such values; it is not possible to essay a discrete logarithm calculation except for all possible guesses of *P*."
  - EKE paper 1992[16]

PAKE Properties

1) Prevent precomputation
2) Secure registration
3) Quantum annoying
4) Fragile
5) 3 Trips

- (strong) AuCPace
- CPace
- BS-SPEKE
- Double BS-SPEKE
- OPAQUE

PAKE Costs

- BS-SPEKE
- `C: fHI**ii   f***xiiH`
- `S: f*i      f***i`

- OPAQUE-3DH
- `C: fHI**ii   f***xi`
- `S: f*i      f***x`

- `*`: Scalar point multiply
- `x`: Scalar base point multiply
- `H`: Hash to point
- `i`: Field invert
- `I`: Scalar invert
- `f`: From bytes

PAKE API

```
message, status =
  start(myId, otherId, secret,
    pakeUser = PAKE_USER_CLIENT,
    pakeMode = PAKE_MODE_USE)

message, status =
  receiveMessage(message)
```

https://gist.github.com/Sc00bz/9d5c8e98143f68377e17dc82c5955f2b “pake-api.md”

PAKE API

```
sessionKey    = getPakeKey()
storedSecret = getStoredSecret()

passwordKey   = getPasswordKey()
```

https://gist.github.com/Sc00bz/9d5c8e98143f68377e17dc82c5955f2b "pake-api.md"

Cheat Sheet

- Balanced
  - CPace
- Augmented
  - BS-SPEKE
- Doubly Augmented
  - Double BS-SPEKE
- Identity
  - CHIP

- Balanced PAKEs don't need key stretching
- bscrypt (minimums)
  - m=256 (256 KiB), t=8, p=1
  - m=256 (256 KiB), t=4, p=2
  - m=256 (256 KiB), t=3, p=3
  - General
    - m=highest per core cache level in KiB
    - t≥max(2, 1900000/1024/m/p)
    - p≤cores

Agenda

- Key Stretching
  - What? [Slide 5]
  - Why? [Slide 6]
  - Types [Slide 8]
  - What goes wrong? [Slide 11]
  - How? [Slide 16]
  - Settings [Slide 20]
- Password Authenticated Key Exchange (PAKE)
  - What? [Slide 30]
  - Why? [Slide 31]
  - Types [Slide 33]
  - How? [Slide 38]
  - Properties [Slide 48]

Questions?

- Twitter: @Sc00bzT
- Github: Sc00bz
- steve at tobtu.com

References

[1] https://blog.cynosureprime.com/2015/09/how-we-cracked-millions-of-ashley.html

[2] Police CyberAlarm https://twitter.com/Paul_Reviews/status/1538124477317451777

[3] Police CyberAlarm https://twitter.com/Paul_Reviews/status/1544735763807539200

[4] Password settings https://tobtu.com/minimum-password-settings/

[5] Send files https://github.com/magic-wormhole

[6] Phone spoofing https://commsrisk.com/?p=35506

[7] SPEKE https://jablon.org/jab96.pdf / https://jablon.org/jab97.pdf

[8] SPAKE2 https://www.di.ens.fr/~mabdalla/papers/AbPo05a-letter.pdf

[9] SPAKE2-EE https://moderncrypto.org/mail-archive/curves/2015/000424.html

References

[10] (strong) AuCPace https://ia.cr/2018/286

[11] OPAQUE https://ia.cr/2018/163

[12] CHIP, CRISP https://ia.cr/2020/529

[13] Quantum annoying formal definition https://ia.cr/2021/696

[14] Quantum annoying talk https://pqcrypto2021.kr/program.php / https://youtu.be/Ikco7zuAixY

[15] pake-api.md https://gist.github.com/Sc00bz/9d5c8e98143f68377e17dc82c5955f2b

[16] EKE https://www.cs.columbia.edu/~smb/papers/neke.pdf

[17] 10 kH/s/GPU quote https://arstechnica.com/?p=685505

Bonus Slides

- BS-SPEKE secure registration
- bscrypt
- Preserve clamped scalar invert

BS-SPEKE Secure Registration

```
    S: Check client verifier
    S: verifierS  = H(...)
    S: sessionKey = H(...)
    S: encReg = aead_encrypt(sessionKey, reg || regMac)
 C<-S: verifierS, encReg
 C:    Check server verifier
 C:    sessionKey = H(...)
 C:    reg || regMac = aead_encrypt(sessionKey, encReg)
 C:    Checks regMac == MAC(macKey, reg * G)
```

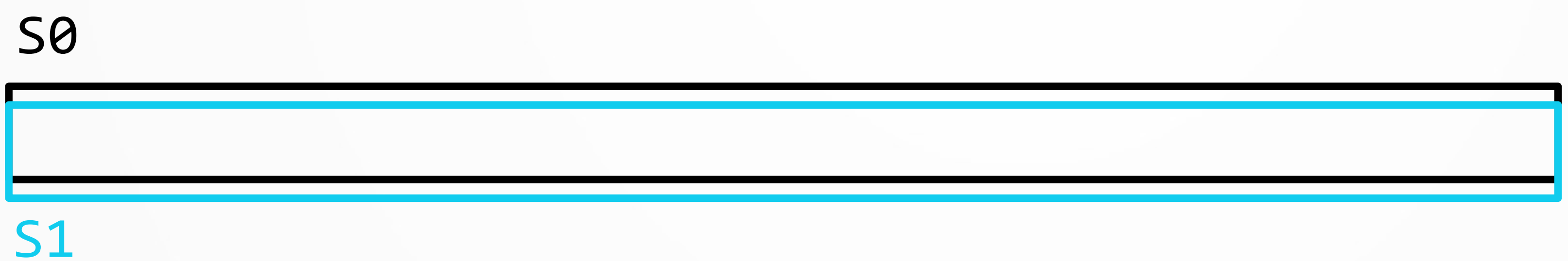
bscrypt

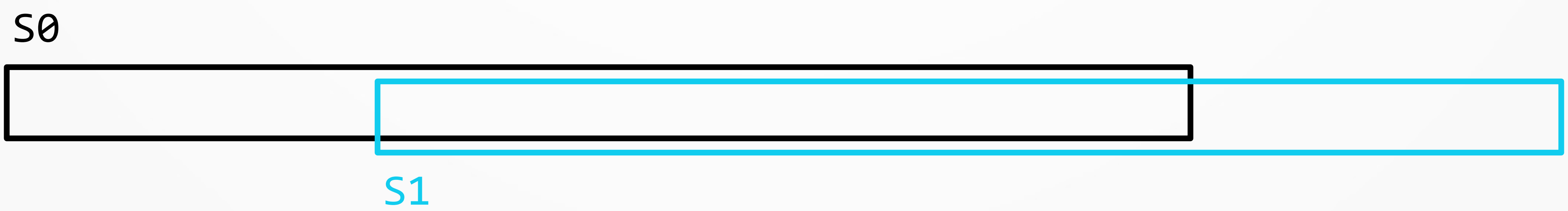
- The fun slides from my BSidesLV 2022 talk
- But first one info slide

Accumulators

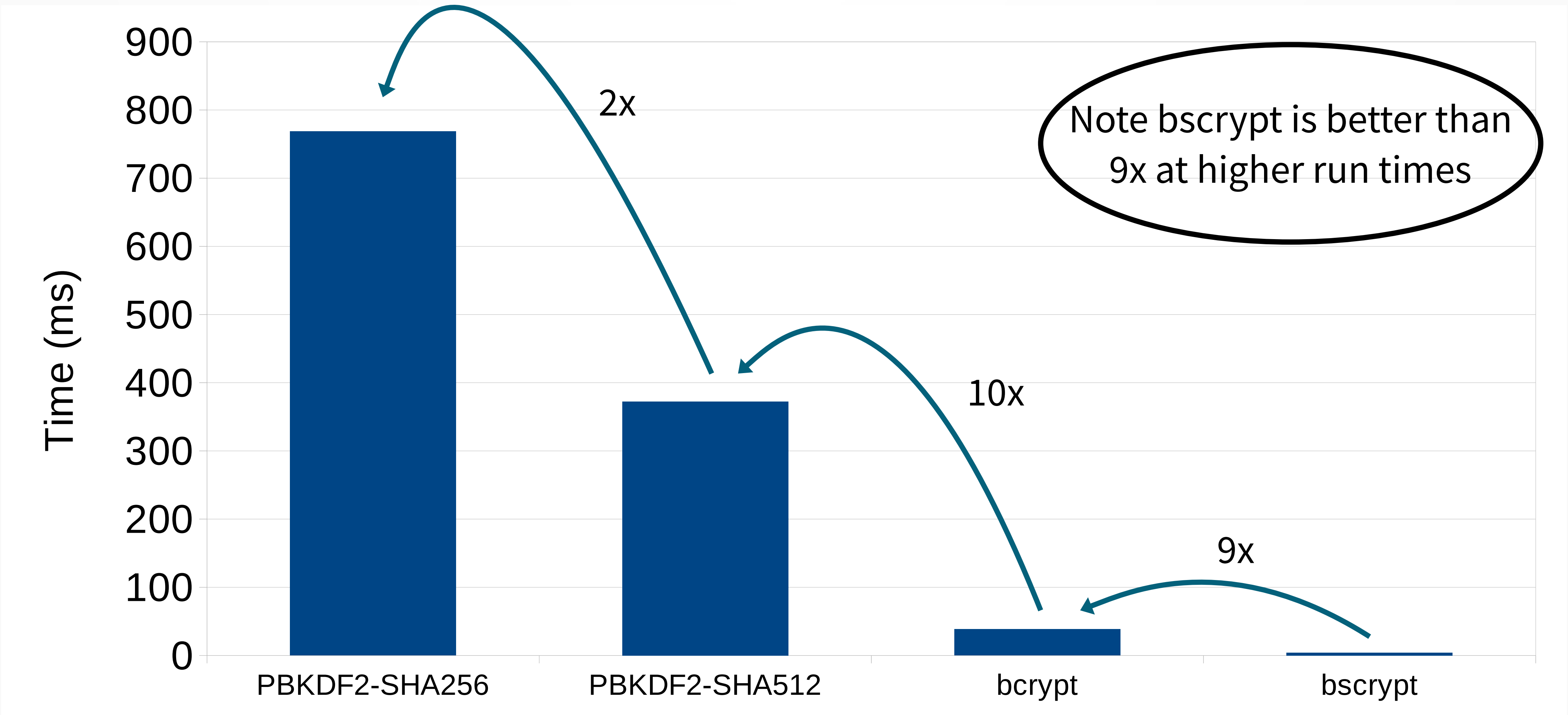
```
R ^= sbox0[L >> 32 & mask];
R += sbox1[L       & mask];
L ^= sbox0[R >> 32 & mask];
L += sbox1[R       & mask];
...
```

Overlapping S-boxes

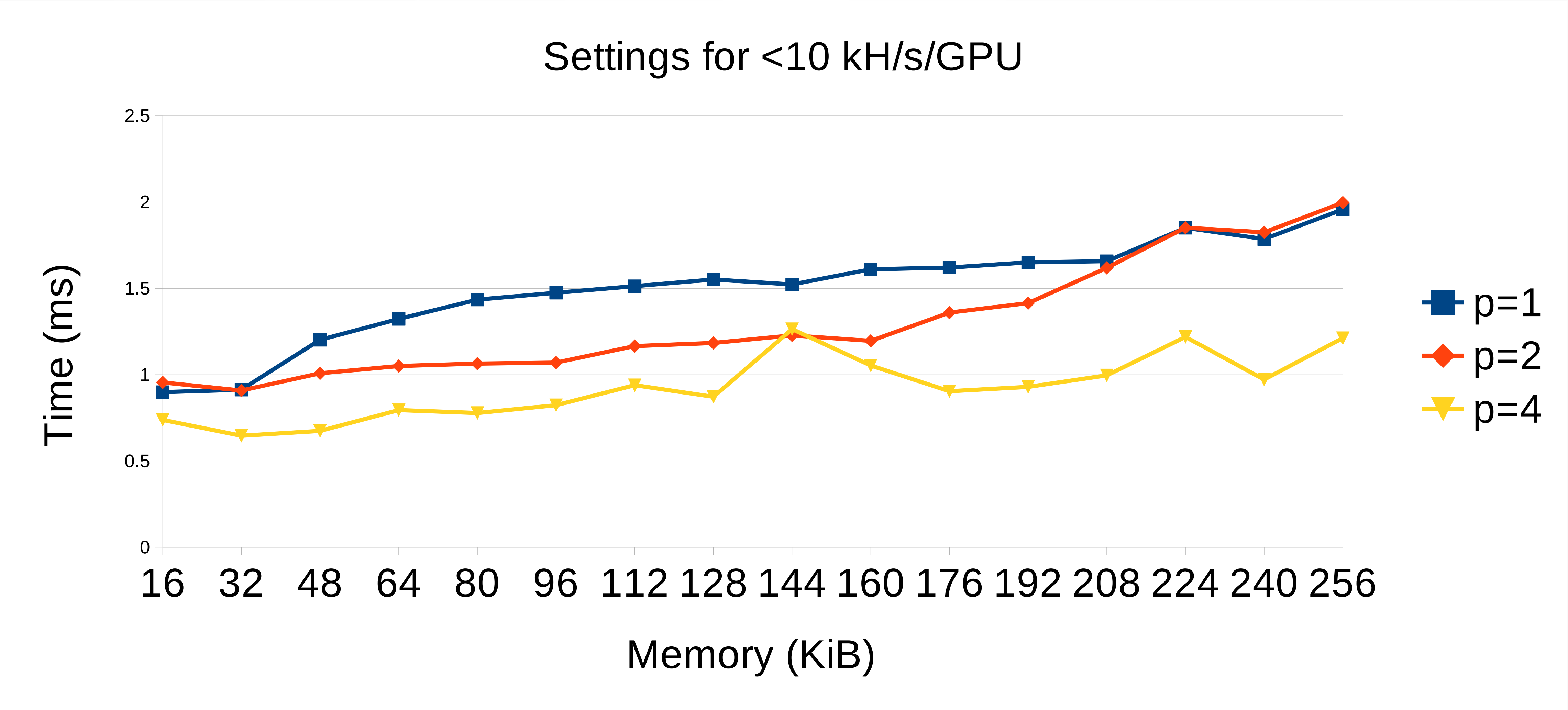




i5-6200U: Settings for ~5300 KH/s/GPU



i5-6500: 32 KiB L1, 256 KiB L2, 6 MiB L3



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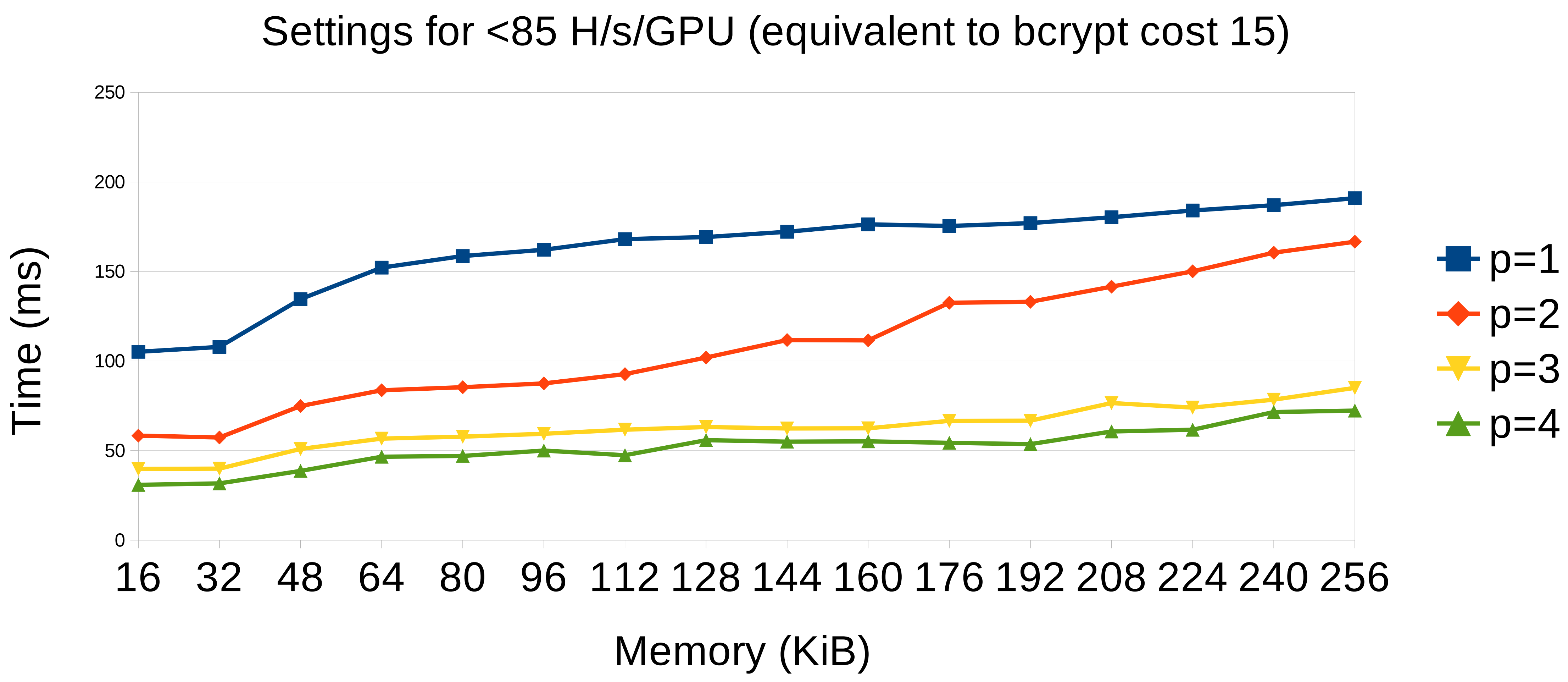

Clamped Scalar Invert (Curve25519)

- Prime sub group
  - L = 2**252 + 0x14def9dea2f79cd65812631a5cf5d3ed
- Normal scalar invert
  - InvertedScalar = power_mod(Scalar, L - 2, L)

Clamped Scalar Invert (Curve25519)

- Prime sub group
  - L = 2**252 + 0x14def9dea2f79cd65812631a5cf5d3ed
- InvertedScalar1 = power_mod(Scalar, L - 2, 8 * L)
- InvertedScalar2 = 8 * L - InvertedScalar1
- checkBit(InvertedScalar1, 254) != 0
  - InvertedScalar1
  - Otherwise InvertedScalar2

Clear the Cofactor (Curve25519)

- Prime sub group
  - L = 2**252 + 0x14def9dea2f79cd65812631a5cf5d3ed
- Multiply scalar by “inverse of 8 multiplied 8”
  - That’s “8/8” which is “1”
- Clear = 8 * power_mod(8, L - 2, L)
- NewScalar = Clear * Scalar (mod 8*L)