Security of Key Derivation Functions

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Agenda

1. ~~Introduction~~
   - ~~Entropy~~
   - ~~Brute-force attacks~~
   - ~~Rainbow Tables~~
2. Attack platforms
   - Graphics Processing Units (GPUs)
   - Field Programmable Gate Arrays
3. Complexity of some attacks
   - PBKDF2
   - BCRYPT
   - SCRYPT
   - Lyra
4. Conclusions
   - Internal functions
   - Conclusions

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   - Brute-force attacks
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2. Attack platforms
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3. Complexity of some attacks
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   - BCRYPT
   - SCRYPT
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Attack platforms

- The most dangerous threats faced by KDFs comes from platforms that benefit from **economies of scale**, especially when cheap, **massively parallel** hardware is available;
- The most prominent examples of such platforms are Graphics Processing Units (**GPUs**) and custom hardware synthesized from **FPGAs** [DGK12].

GPUs – Evolution

- Following the increasing demand for **high-definition real-time rendering**, Graphics Processing Units (GPUs) have traditionally carried a large number of processing cores, boosting its parallelization capability;
- Only more recently, however, GPUs evolved from **specific platforms into devices for universal computation** and started to give support to standardized languages that help harnessing their computational power, such as CUDA [Nvi12a] and OpenCL [Khr12];
- As a result, they became more intensively employed for more general purposes, including **password cracking** [Spr11, DGK12].

GPUs – Examples

NVidia Tesla K20X [Nvi12b]:

- 2.688 cores operating at 732 MHz;
- 6 GB of shared DRAM, with a bandwidth of 250 GB/s.

NVidia GT540M (the vga card of my notebook):

- 96 cores operating at 900 MHz;
- 2 GB of shared DRAM, with a bandwidth of 28,8 GB/s.

GPUs – Possible scenario

Assume a scenario where the adversary have of a NVidia Tesla K20X.

- In case the passwords are stored using some KDF applied to the plaintext, and the KDF take only **2 ms to run**, consuming only **0.5 MB of memory**.

GPUs – Possible scenario

Assume a scenario where the adversary have of a NVidia Tesla K20X.

- In case the passwords are stored using some KDF applied to the plaintext, and the KDF take only **2 ms to run**, consuming only **0.5 MB of memory**.

In this scenario it is easy to conceive that the adversary will test 2.688 passwords every two ms. Resulting in 1.344.000 passwords tested per second, or 4.838.400.000 $\approx 2^{32,17}$ passwords tested per hour.

GPUs – Possible scenario

Assume a scenario where the adversary have of a NVidia Tesla K20X.

- In case the passwords are stored using some KDF applied to the plaintext, and the KDF take only **2 ms to run**, consuming only **0.5 MB of memory**.

In this scenario it is easy to conceive that the adversary will test 2.688 passwords every two ms. Resulting in 1.344.000 passwords tested per second, or 4.838.400.000 $\approx 2^{32,17}$ passwords tested per hour.

However, **if a sequential KDF requires 20 MB of DRAM**, the maximum number of cores that could be used simultaneously becomes 300, only 11 % of the total available.

FPGA

- An FPGA is a collection of configurable logic blocks wired together and with memory elements, forming a programmable and high-performance integrated circuit;
- As such devices are configured to perform a specific task, **they can be highly optimized** for its purpose (e.g., using pipelining [Dan08, KMM^{+}06]);
- Furthermore, When compared to GPUs, FPGAs may also be advantageous due to the latter's **considerably lower energy consumption** [CMHM10, FBCS12].

FPGA – A recent example of password-cracking [DGK12]

- The **small memory usage** of the PBKDF2 algorithm, as most of the underlying SHA-2 processing is performed using the device's memory cache (much faster than DRAM) [DGK12, Sec. 4.2];
- Dürmuth *et al*, using a RIVYERA S3-5000 cluster [Sci] with 128 FPGAs, reported a throughput of 356.352 passwords tested per second in an architecture having 5.376 password processed in parallel.

FPGA – A recent example of password-cracking [DGK12]

- The **small memory usage** of the PBKDF2 algorithm, as most of the underlying SHA-2 processing is performed using the device's memory cache (much faster than DRAM) [DGK12, Sec. 4.2];
- Dürmuth *et al*, using a RIVYERA S3-5000 cluster [Sci] with 128 FPGAs, reported a throughput of 356.352 passwords tested per second in an architecture having 5.376 password processed in parallel.

However – as in the GPU's example – **if a sequential KDF requires 20 MB of DRAM** in place of PBKDF2, the resulting throughput would presumably be much lower, especially considering that the FPGAs employed can have up to 64 MB of DRAM [Sci] and, thus, up to 3 passwords can be processed in parallel rather than 5.376.

Agenda

PBKDF2

Algorithm PBKDF2.

INPUT: pwd ▷ The password
INPUT: $salt$ ▷ The salt
INPUT: T ▷ The user-defined parameter
OUTPUT: K ▷ The password-derived key

if $k > (2^{32} - 1) \cdot h$ **then**
  return *Derived key too long.*
end if
$l \leftarrow \lceil k/h \rceil \;;\; r \leftarrow k - (l-1) \cdot h$
for $i \leftarrow 1$ **to** l **do**
  $U[1] \leftarrow PRF(pwd, salt || INT(i))$ ▷ INT(i): 32-bit encoding of i
  $T[i] \leftarrow U[1]$
  for $j \leftarrow 2$ **to** T **do**
    $U[j] \leftarrow PRF(pwd, U[j-1]) \;;\; T[i] \leftarrow T[i] \oplus U[j]$
  end for
  if $i = 1$ **then** $K \leftarrow T[1]$ **else** $K \leftarrow K \,||\, T[i]$ **end if**
end for
return K

Where:
k represents the desired size for the key generated by PBKDF2; and

h represents the size of the output of the function used internally.

PBKDF2

Algorithm PBKDF2.

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INPUT: $salt$ ▷ The salt
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OUTPUT: K ▷ The password-derived key

if $k > (2^{32} - 1) \cdot h$ **then**
  return *Derived key too long.*
end if
$l \leftarrow \lceil k/h \rceil \;\; ; \;\; r \leftarrow k - (l-1) \cdot h$ — l
for $i \leftarrow 1$ **to** l **do**
  $U[1] \leftarrow PRF(pwd, salt || INT(i))$ ▷ INT(i): 32-bit encoding of i
  $T[i] \leftarrow U[1]$ — $l.T$
  for $j \leftarrow 2$ **to** T **do**
    $U[j] \leftarrow PRF(pwd, U[j-1]) \;\; ; \;\; T[i] \leftarrow T[i] \oplus U[j]$
  end for
  if $i = 1$ **then** $K \leftarrow T[1]$ **else** $K \leftarrow K \,||\, T[i]$ **end if**
end for
return K

Where:
k represents the desired size for the key generated by PBKDF2; and
h represents the size of the output of the function used internally.

PBKDF2 – Summary

Let,

- τ be the amount of memory used by the system variables.

Attacks					
	Sequential (Default)		Intermediate states		Memory-free*
PBKDF2	Memory	Time	Memory	Time	Time
	$\mathcal{O}(\tau)$	$\mathcal{O}(l.T)$	-	-	-

Table: Complexity of attacks applicable to PBKDF2.

BCRYPT

Algorithm Bcrypt.

INPUT: pwd ▷ The password
INPUT: $salt$ ▷ The salt
INPUT: T ▷ The user-defined cost parameter]
OUTPUT: K ▷ The password-derived key

$s \leftarrow InitState()$ ▷ Copies the digits of π into the sub-keys and S-boxes S_i
$s \leftarrow ExpandKey(s, salt, pwd)$
for $i \leftarrow 1$ **to** 2^T **do**
    $s \leftarrow ExpandKey(s, 0, salt)$; $s \leftarrow ExpandKey(s, 0, pwd)$
end for
$ctext \leftarrow$ "$OrpheanBeholderScryDoubt$"
for $i \leftarrow 1$ **to** 64 **do** { $ctext \leftarrow BlowfishEncrypt(s, ctext)$ } **end for**
return $T \,||\, salt \,||\, ctext$
function EXPANDKEY($s, salt, pwd$)
    for $i \leftarrow 1$ **to** 32 **do** { $P_i \leftarrow P_i \oplus pwd[32 * (i-1) \ldots 32 * i - 1]$ } **end for**
    for $i \leftarrow 1$ **to** 9 **do**
        $temp \leftarrow BlowfishEncrypt(s, salt[64 * (i-1) \ldots 64 * i - 1])$
        $P_{0+(i-1)*2} \leftarrow temp[0 \ldots 31]$; $P_{1+(i-1)*2} \leftarrow temp[32 \ldots 64]$
    end for
    for $i \leftarrow 1$ **to** 4 **do**
        for $j \leftarrow 1$ **to** 128 **do**
            $temp \leftarrow BlowfishEncrypt(s, salt[64 * (j-1) \ldots 64 * j - 1])$
            $S_i[(j-1) * 2] \leftarrow temp[0 \ldots 31]$; $S_i[1 + (j-1) * 2] \leftarrow temp[32 \ldots 63]$
        end for
    end for
    return s
end function

BCRYPT

Algorithm Bcrypt.

INPUT: pwd ▷ The password
INPUT: $salt$ ▷ The salt
INPUT: T ▷ The user-defined cost parameter]
OUTPUT: K ▷ The password-derived key

```
s ← InitState()   ▷ Copies the digits of π into the sub-keys and S-boxes S_i
s ← ExpandKey(s, salt, pwd)
for i ← 1 to 2^T do
    s ← ExpandKey(s, 0, salt)  ;  s ← ExpandKey(s, 0, pwd)
end for
ctext ← "OrpheanBeholderScryDoubt"
for i ← 1 to 64 do { ctext ← BlowfishEncrypt(s, ctext) } end for
return T || salt || ctext
function ExpandKey(s, salt, pwd)
    for i ← 1 to 32 do { P_i ← P_i ⊕ pwd[32 * (i − 1) ... 32 * i − 1] } end for
    for i ← 1 to 9 do
        temp ← BlowfishEncrypt(s, salt[64 * (i − 1) ... 64 * i − 1])
        P_{0+(i−1)*2} ← temp[0 ... 31]  ;  P_{1+(i−1)*2} ← temp[32 ... 64]
    end for
    for i ← 1 to 4 do
        for j ← 1 to 128 do
            temp ← BlowfishEncrypt(s, salt[64 * (j − 1) ... 64 * j − 1])
            S_i[(j − 1) * 2] ← temp[0 ... 31]  ;  S_i[1 + (j − 1) * 2] ← temp[32 ... 63]
        end for
    end for
    return s
end function
```

2^T

$\approx 2^9.2^T + 2^6$

2^6

2^5

9

2^2

$2^2.2^7$

BCRYPT – Summary

Let,

- τ be the amount of memory used by the system variables;
- β be the 4 KBytes of memory used by the S-Boxes and sub-keys of Blowfish algorithm [PM99].

Attacks					
	Sequential (Default)		Intermediate states		Memory-free*
BCRYPT	Memory	Time	Memory	Time	Time
	$\mathcal{O}(\tau + \beta)$	$\mathcal{O}(2^{9+T})$	-	-	-

Table: Complexity of attacks applicable to BCRYPT.

SCRYPT

Algorithm Scrypt.

PARAM: h ▷ The output length of *BlockMix*'s internal hash function
INPUT: pwd ▷ The password
INPUT: $salt$ ▷ A random salt
INPUT: k ▷ The key length
INPUT: b ▷ The block size, satisfying $b = 2r \cdot h$
INPUT: R ▷ Cost parameter (memory usage and processing time)
INPUT: p ▷ Parallelism parameter
OUTPUT: K ▷ The password-derived key

$(B_0 ... B_{p-1}) \leftarrow PBKDF2_{HMAC-SHA-256}(pwd, salt, 1, p \cdot b)$
for $i \leftarrow 0$ **to** $p-1$ **do** $\{ B_i \leftarrow ROMix(B_i, R) \}$ **end for**
$K \leftarrow PBKDF2_{HMAC-SHA-256}(pwd, B_0 || B_1 || ... || B_{p-1}, 1, k)$
return K ▷ Outputs the k-long key
function ROMIX(B, R) ▷ Sequential memory-hard function
    $X \leftarrow B$
    for $i \leftarrow 0$ **to** $R-1$ **do** ▷ Initializes memory array V
        $V_i \leftarrow X$; $X \leftarrow BlockMix(X)$
    end for
    for $i \leftarrow 0$ **to** $R-1$ **do** ▷ Reads random positions of V
        $j \leftarrow Integerify(X) \bmod R$; $X \leftarrow BlockMix(X \oplus V_j)$
    end for
    return X
end function
function BLOCKMIX(B) ▷ Hash function with (b-long) inputs/outputs
    $Z \leftarrow B_{2r-1}$ ▷ $r = b/2h$, where $h = 512$ for Salsa20/8
    for $i \leftarrow 0$ **to** $2r-1$ **do** $\{ Z \leftarrow Hash(Z \oplus B_i)$; $Y_i \leftarrow Z \}$ **end for**
    return $(Y_0, Y_2, ..., Y_{2r-2}, Y_1, Y_3, Y_{2r-1})$
end function

SCRYPT – Sequential (Default)

Algorithm Scrypt.

PARAM: h ▷ The output length of *BlockMix*'s internal hash function
INPUT: pwd ▷ The password
INPUT: $salt$ ▷ A random salt
INPUT: k ▷ The key length
INPUT: b ▷ The block size, satisfying $b = 2r \cdot h$
INPUT: R ▷ Cost parameter (memory usage and processing time)
INPUT: p ▷ Parallelism parameter
OUTPUT: K ▷ The password-derived key

Memory cost ≈ p.R.2r
Processing cost ≈ p.R.2r

$(B_0 ... B_{p-1}) \leftarrow PBKDF2_{HMAC-SHA-256}(pwd, salt, 1, p \cdot b)$
for $i \leftarrow 0$ **to** $p-1$ **do** { $B_i \leftarrow ROMix(B_i, R)$ } **end for** — *p*
$K \leftarrow PBKDF2_{HMAC-SHA-256}(pwd, B_0 || B_1 || ... || B_{p-1}, 1, k)$
return K ▷ Outputs the k-long key

function ROMIX(B, R) ▷ Sequential memory-hard function
  $X \leftarrow B$
  for $i \leftarrow 0$ **to** $R-1$ **do** ▷ Initializes memory array V — *R*
    $V_i \leftarrow X$; $X \leftarrow BlockMix(X)$
  end for
  for $i \leftarrow 0$ **to** $R-1$ **do** ▷ Reads random positions of V — *R*
    $j \leftarrow Integerify(X) \bmod R$; $X \leftarrow BlockMix(X \oplus V_j)$
  end for
  return X
end function

function BLOCKMIX(B) ▷ Hash function with (b-long) inputs/outputs
  $Z \leftarrow B_{2r-1}$ ▷ $r = b/2h$, where $h = 512$ for Salsa20/8
  for $i \leftarrow 0$ **to** $2r-1$ **do** { $Z \leftarrow Hash(Z \oplus B_i)$; $Y_i \leftarrow Z$ } **end for** — *2r*
  return $(Y_0, Y_2, ..., Y_{2r-2}, Y_1, Y_3, Y_{2r-1})$
end function

SCRYPT – Memory-free*

Algorithm Scrypt.

```
PARAM: h       ▷ The output length of BlockMix's internal hash function
INPUT: pwd     ▷ The password
INPUT: salt    ▷ A random salt
INPUT: k       ▷ The key length
INPUT: b       ▷ The block size, satisfying b = 2r · h
INPUT: R       ▷ Cost parameter (memory usage and processing time)
INPUT: p       ▷ Parallelism parameter
OUTPUT: K      ▷ The password-derived key

(B_0...B_{p-1}) ← PBKDF2_{HMAC-SHA-256}(pwd, salt, 1, p · b)
for i ← 0 to p − 1 do { B_i ← ROMix(B_i, R) } end for                    p
K ← PBKDF2_{HMAC-SHA-256}(pwd, B_0||B_1||...||B_{p-1}, 1, k)
return K    ▷ Outputs the k-long key
function ROMix(B, R)    ▷ Sequential memory-hard function
    X ← B
    for i ← 0 to R − 1 do    ▷ Initializes memory array V
        V_i ← X ; X ← BlockMix(X)                                          R
    end for
    for i ← 0 to R − 1 do    ▷ Reads random positions of V
        j ← Integerify(X) mod R ; X ← BlockMix(X ⊕ V_j)                    R
    end for
    return X
end function
function BlockMix(B)    ▷ Hash function with (b-long) inputs/outputs
    Z ← B_{2r-1}    ▷ r = b/2h, where h = 512 for Salsa20/8
    for i ← 0 to 2r − 1 do { Z ← Hash(Z ⊕ B_i) ; Y_i ← Z } end for        2r
    return (Y_0, Y_2, ..., Y_{2r-2}, Y_1, Y_3, Y_{2r-1})
end function
```

Processing cost ≈ p.R.R.2r

SCRYPT – Summary

	Attacks				
	Sequential (Default)		Intermediate states		Memory-free*
SCRYPT	Memory	Time	Memory	Time	Time
	$\mathcal{O}(R)$	$\mathcal{O}(R)$	-	-	$\mathcal{O}(R^2)$

Table: Complexity of attacks applicable to SCRYPT.

Lyra

Algorithm The Lyra Algorithm.

PARAM: $Hash$ ▷ Sponge with block size b (in bits) and underlying permutation f
PARAM: ρ ▷ Number of rounds of f in the Setup and Wandering phases
INPUT: pwd ▷ The password
INPUT: $salt$ ▷ A random salt
INPUT: T ▷ Time cost, in number of iterations
INPUT: R ▷ Number of rows in the memory matrix
INPUT: C ▷ Number of columns in the memory matrix
INPUT: k ▷ The desired key length, in bits
OUTPUT: K ▷ The password-derived k-long key

▷ **Setup**: Initializes a $(R \times C)$ memory matrix whose cells have b bits each
$Hash.absorb(\text{pad}(salt \,\|\, pwd))$ ▷ Padding rule: 10*1
$M[0] \leftarrow Hash.squeeze_{\rho}(C \cdot b)$
for $row \leftarrow 1$ **to** $R - 1$ **do**
    for $col \leftarrow 0$ **to** $C - 1$ **do**
        $M[row][col] \leftarrow Hash.duplexing_{\rho}(M[row-1][col], b)$
    end for
end for
▷ **Wandering**: Iteratively overwrites blocks of the memory matrix
$row \leftarrow 0$
for $i \leftarrow 0$ **to** $T - 1$ **do** ▷ **Time Loop**
    for $j \leftarrow 0$ **to** $R - 1$ **do** ▷ **Rows Loop**: randomly visits R rows
        for $col \leftarrow 0$ **to** $C - 1$ **do** ▷ **Columns Loop**: visits blocks in row
            $M[row][col] \leftarrow M[row][col] \oplus Hash.duplexing_{\rho}(M[row][col], b)$
        end for
        $col \leftarrow M[row][C-1] \bmod C$
        $row \leftarrow Hash.duplexing(M[row][col], |R|) \bmod R$
    end for
end for
▷ **Wrap-up**: key computation
$Hash.absorb(\text{pad}(salt))$ ▷ Uses the sponge's current state
$K \leftarrow Hash.squeeze(k)$
return K ▷ Outputs the k-long key

Lyra – Sequential (Default)

Algorithm The Lyra Algorithm.

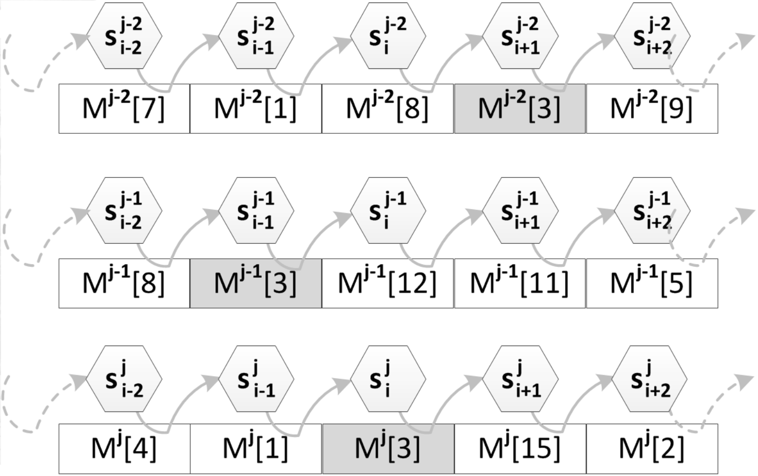
```
PARAM: Hash    ▷ Sponge with block size b (in bits) and underlying permutation f
PARAM: ρ    ▷ Number of rounds of f in the Setup and Wandering phases
INPUT: pwd    ▷ The password
INPUT: salt    ▷ A random salt
INPUT: T    ▷ Time cost, in number of iterations
INPUT: R    ▷ Number of rows in the memory matrix
INPUT: C    ▷ Number of columns in the memory matrix
INPUT: k    ▷ The desired key length, in bits
OUTPUT: K    ▷ The password-derived k-long key

▷ Setup: Initializes a (R × C) memory matrix whose cells have b bits each
Hash.absorb(pad(salt || pwd))    ▷ Padding rule: 10*1
M[0] ← Hash.squeeze_ρ(C · b)
for row ← 1 to R − 1 do
    for col ← 0 to C − 1 do
        M[row][col] ← Hash.duplexing_ρ(M[row − 1][col], b)
    end for
end for
▷ Wandering: Iteratively overwrites blocks of the memory matrix
row ← 0
for i ← 0 to T − 1 do    ▷ Time Loop
    for j ← 0 to R − 1 do    ▷ Rows Loop: randomly visits R rows
        for col ← 0 to C − 1 do    ▷ Columns Loop: visits blocks in row
            M[row][col] ← M[row][col] ⊕ Hash.duplexing_ρ(M[row][col], b)
        end for
        col ← M[row][C − 1] mod C
        row ← Hash.duplexing(M[row][col], |R|) mod R
    end for
end for
▷ Wrap-up: key computation
Hash.absorb(pad(salt))    ▷ Uses the sponge's current state
K ← Hash.squeeze(k)
return K    ▷ Outputs the k-long key
```

R.C (setup loop, lines 4–8)

T (time loop, lines 11–19)

R (rows loop, lines 12–18)

Lyra – Intermediate states



Lyra – Intermediate states

Algorithm The Lyra Algorithm.

PARAM: *Hash* ▷ Sponge with block size b (in bits) and underlying permutation f
PARAM: ρ ▷ Number of rounds of f in the Setup and Wandering phases
INPUT: *pwd* ▷ The password
INPUT: *salt* ▷ A random salt
INPUT: T ▷ Time cost, in number of iterations
INPUT: R ▷ Number of rows in the memory matrix
INPUT: C ▷ Number of columns in the memory matrix
INPUT: k ▷ The desired key length, in bits
OUTPUT: K ▷ The password-derived k-long key

Processing cost ≈ (R+T).R.T/2
Memory cost ≈ R.(T-1)

```
▷ Setup: Initializes a (R × C) memory matrix whose cells have b bits each
Hash.absorb(pad(salt || pwd))   ▷ Padding rule: 10*1
M[0] ← Hash.squeeze_ρ(C · b)
for row ← 1 to R − 1 do
    for col ← 0 to C − 1 do
        M[row][col] ← Hash.duplexing_ρ(M[row − 1][col], b)
    end for
end for
▷ Wandering: Iteratively overwrites blocks of the memory matrix
row ← 0
for i ← 0 to T − 1 do   ▷ Time Loop                                  T
    for j ← 0 to R − 1 do   ▷ Rows Loop: randomly visits R rows
        for col ← 0 to C − 1 do   ▷ Columns Loop: visits blocks in row
            M[row][col] ← M[row][col] ⊕ Hash.duplexing_ρ(M[row][col], b)
        end for                                                     R
        col ← M[row][C − 1] mod C
        row ← Hash.duplexing(M[row][col], |R|) mod R
    end for
end for
▷ Wrap-up: key computation
Hash.absorb(pad(salt))   ▷ Uses the sponge's current state
K ← Hash.squeeze(k)
return K   ▷ Outputs the k-long key
```

Lyra – Memory-free*

Algorithm The Lyra Algorithm.

PARAM: *Hash* ▷ Sponge with block size b (in bits) and underlying permutation f
PARAM: ρ ▷ Number of rounds of f in the Setup and Wandering phases
INPUT: *pwd* ▷ The password
INPUT: *salt* ▷ A random salt
INPUT: T ▷ Time cost, in number of iterations
INPUT: R ▷ Number of rows in the memory matrix
INPUT: C ▷ Number of columns in the memory matrix
INPUT: k ▷ The desired key length, in bits
OUTPUT: K ▷ The password-derived k-long key

Processing cost $\approx R.(R/2)^T$

▷ **Setup**: Initializes a $(R \times C)$ memory matrix whose cells have b bits each
$Hash.absorb(pad(salt \| pwd))$ ▷ Padding rule: 10*1
$M[0] \leftarrow Hash.squeeze_\rho(C \cdot b)$
for $row \leftarrow 1$ **to** $R-1$ **do**
  for $col \leftarrow 0$ **to** $C-1$ **do**
    $M[row][col] \leftarrow Hash.duplexing_\rho(M[row-1][col], b)$
  end for
end for
▷ **Wandering**: Iteratively overwrites blocks of the memory matrix
$row \leftarrow 0$
for $i \leftarrow 0$ **to** $T-1$ **do** ▷ **Time Loop**
  for $j \leftarrow 0$ **to** $R-1$ **do** ▷ **Rows Loop**: randomly visits R rows
    for $col \leftarrow 0$ **to** $C-1$ **do** ▷ **Columns Loop**: visits blocks in row
      $M[row][col] \leftarrow M[row][col] \oplus Hash.duplexing_\rho(M[row][col], b)$
    end for
    $col \leftarrow M[row][C-1] \bmod C$
    $row \leftarrow Hash.duplexing(M[row][col], |R|) \bmod R$
  end for
end for
▷ **Wrap-up**: key computation
$Hash.absorb(pad(salt))$ ▷ Uses the sponge's current state
$K \leftarrow Hash.squeeze(k)$
return K ▷ Outputs the k-long key

T

R

Lyra – Summary

Attacks					
	Sequential (Default)		Intermediate states		Memory-free*
Lyra	Memory	Time	Memory	Time	Time
	$\mathcal{O}(R.C)$	$\mathcal{O}(R.T)$	$\mathcal{O}(R.T)$	$\mathcal{O}(R^2.T + R.T^2)$	$\mathcal{O}(R^{T+1})$

Table: Complexity of attacks applicable to Lyra.

Summary

Let,

- τ be the amount of memory used by the system variables;
- β be the 4 KBytes of memory used by the S-Boxes and sub-keys of Blowfish algorithm [PM99].

Attacks					
	Sequential (Default)		Intermediate states		Memory-free*
PBKDF2	Memory $\mathcal{O}(\tau)$	Time $\mathcal{O}(l.T)$	Memory -	Time -	Time -
BCRYPT	$\mathcal{O}(\tau+\beta)$	$\mathcal{O}(2^{9+T})$	-	-	-
SCRYPT	$\mathcal{O}(R)$	$\mathcal{O}(R)$	-	-	$\mathcal{O}(R^2)$
Lyra	$\mathcal{O}(R.C)$	$\mathcal{O}(R.T)$	$\mathcal{O}(R.T)$	$\mathcal{O}(R^2.T+R.T^2)$	$\mathcal{O}(R^{T+1})$

Table: Complexity of attacks applicable to the main KDFs.

Agenda

Internal functions

- The security of the key derivation function is directly linked to the security of the function used internally;
- The hash function SHA-1 adopted by the PBKDF2 algorithm and the hash function Salsa20/8 adopted by the Scrypt algorithm **have known vulnerabilities** [WYY05, AFK^{+}08];
- While the sponge function BLAKE2 adopted by Lyra **remains safe** [MQZ10].

Conclusions

- Lyra is Lyra, a password-based key derivation scheme that allows legitimate users to **fine tune memory and processing costs** according to the desired level of security and resources available in the target platform;
- Moreover, the combination of a strictly sequential design, the high costs of exploring memory-processing trade-offs, and the ability to raise the memory usage beyond what is attainable with similar-purpose solutions (e.g., scrypt) for a similar security level and processing time, make **Lyra an appealing KDF alternative**.

Questions?

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