scrypt: A key derivation function
Doing our best to thwart TLAs armed with ASICs

Colin Percival
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December 4, 2012
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- Examples of key derivation functions:
  - DES CRYPT [R. Morris, 1979]
  - MD5 CRYPT [P. H. Kamp, 1994]
  - bcrypt [N. Provos and D. Mazières, 1999]
  - PBKDF2 [B. Kaliski, 2000]
  - MD5 (not designed to be a key derivation function!)
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  - ... as long as the attacker is using the same software as you.
Hardware-based brute force attacks

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CREDIT: Randall Munroe / xkcd.com
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  - ...password-cracking ASICs get faster AND can fit more copies of a password-cracking circuit.
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An example of a “moderately large amount of RAM”: 1 kB.

If we use a *ridiculously* large amount of RAM, hardware attacks will be even more expensive.
Sequential memory-hard functions

**Definition**

A *sequential memory-hard function* is a function which

(a) can be computed on a Random Access Machine in \( T(n) \) operations using \( S(n) = O(T(n)) \) memory; and

(b) cannot be computed on a Parallel Random Access Machine with \( S^*(n) \) processors and \( S^*(n) \) space in expected time \( T^*(n) \) where \( S^*(n) T^*(n) = O(T(n)^{2-x}) \) for any \( x > 0 \).
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  spent by the defender, assuming he doesn’t run out of RAM.
- Note that this does not say how that area-time product is
  reached — in particular, it does not rule out using less area
  and more time (“time-memory trade-off”).
Algorithm (ROMix)

Given a random oracle \( H \), an input \( B \), and an integer parameter \( N \), compute

\[ V_i = H^i(B) \quad 0 \leq i < N \]

and \( X = H^N(B) \), then iterate

1. \( j \leftarrow \text{Integerify}(X) \mod N \)
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- ROMix fills $V$ with pseudorandom values, then accesses them in a pseudorandom order.
Lemma

For a fixed input $B$, given $M$ copies of a random oracle $H$ which can be simultaneously consulted in unit time, and an index of size $M$, there is no algorithm which for computing $H^x(B)$ for for a random $x \in \{0 \ldots N - 1\}$ completes in expected time less than $N \cdot \frac{4M+2}{4M+2} - \frac{1}{2}$. 

Proof (sketch).

Suppose an algorithm exists, and run $N$ copies of algorithm in parallel, one copy with each possible value of $x$. We can bound the number of values $H^x(B)$ which have been input to oracles in the first $i$ timesteps by $(2M + 1) \cdot (i + 1)$ by considering how many different oracles are “consistent with observations” up to that point. The result follows (with some algebra).
The class of functions ROMix are sequential memory-hard.

**Proof.**

Since $H$ is a random oracle, the values $j = \text{Integerify}(X) \mod N$ act as random values which cannot be computed prior to each value of $X$ being available; and computing each $V_j = H^j(B)$ takes (from the lemma) at least $\Omega(n/S^*(n))$ time. Since we iterate $n$ times, this provides $T^*(n) = \Omega(n^2/S^*(n))$ and thus $S^*(n)T^*(n) = \Omega(n^2) \neq O(T(n)^{2-x})$ as required, since $T(n) = O(n)$. \qed
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- Thanks to the “wrapping” with PBKDF2, we don’t need much cryptographic strength from ROMix — only that it takes a long time to compute.
Maximizing the constant factor

- $H$ doesn’t need to be a random oracle or even anything approximating one: The only real requirement is that it must not have any shortcuts to iteration.
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- Assuming there are no computational shortcuts, the cost to compute ROMix in hardware is proportional to:

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[\text{Memory required}] \cdot [\text{Time required}] = T_{\text{Software}} \cdot \frac{\text{[Size of } H \text{ output]}}{\text{[Time to compute } H \text{ in software]}} \cdot T_{\text{Software}} \cdot \frac{\text{[Time to compute } H \text{ in hardware]}}{\text{[Time to compute } H \text{ in software]}}
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- The area required to compute \( H \) is irrelevant, since the total area used will be determined almost completely by the RAM.
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  - If there’s a cryptographer in the audience working for a semiconductor company, I’d love to have more modern data...
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  - The permuting of outputs avoids any “pipelining” of multiple hash computations.
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- The “chained” computation ensures that there is no opportunity for parallelism.
- The permuting of outputs avoids any “pipelining” of multiple hash computations.

I believe this improves software performance more than it improves hardware performance, but I have no proof.
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For scrypt we also need to look at the die area required for storage.
Very approximate estimates of VLSI area and cost on a 130 nm process:

- Each gate of random logic requires $\approx 5 \, \mu m^2$ of VLSI area.
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Key derivation functions

- Non-parameterized KDFs:
  - DES CRYPT
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KDFs tuned for interactive logins ($t \leq 100 \text{ ms}$):
- PBKDF2-HMAC-SHA256, $c = 86000$
- bcrypt, $cost = 11$
- scrypt, $N = 2^{14}, r = 8, p = 1$
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- Running time based on a 2.5 GHz Core 2 (aka. my laptop).
6 lower-case letters; e.g., “sfgroy”.
Passwords

- 6 lower-case letters; e.g., “sfgroy”.
- 8 lower-case letters; e.g., “ksuvnwyf”.

Colin Percival
Tarsnap
cperciva@tarsnap.com

scrypt: A key derivation function
Passwords

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- 8 characters selected from the 95 printable 7-bit ASCII characters; e.g., “6,u$h3y[a”.

Colin Percival  Tarsnap  cperciva@tarsnap.com  
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- 10 characters selected from the 95 printable 7-bit ASCII characters; e.g., “H.*W8Jz&r3”.

Colin Percival  Tarsnap  cperciva@tarsnap.com  scrypt: A key derivation function
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- 8 characters selected from the 95 printable 7-bit ASCII characters; e.g., “6,uh3y[a”.
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- A 40-character string of text; e.g., “This is a 40-character string of English”.
  - Entropy estimated according to formula from NIST: 1st character has 4 bits of entropy; 2nd–8th characters have 2 bits of entropy each; 9th–20th characters have 1.5 bits of entropy each; 21st and later characters have 1 bit of entropy each.
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  - This formula is not very good, but it’s the best I have available...
### Estimated brute force attack costs

Estimated cost of hardware to crack a password in 1 year.

<table>
<thead>
<tr>
<th>KDF</th>
<th>6 letters</th>
<th>8 letters</th>
<th>8 chars</th>
<th>10 chars</th>
<th>40-char text</th>
</tr>
</thead>
<tbody>
<tr>
<td>DES CRYPT</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
</tr>
<tr>
<td>MD5</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>$1.1k</td>
<td>$1</td>
</tr>
<tr>
<td>MD5 CRYPT</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>$130</td>
<td>$1.1M</td>
<td>$1.4k</td>
</tr>
<tr>
<td>PBKDF2 (100 ms)</td>
<td>&lt; $1</td>
<td>&lt; $1</td>
<td>$18k</td>
<td>$160M</td>
<td>$200k</td>
</tr>
<tr>
<td>bcrypt (95 ms)</td>
<td>&lt; $1</td>
<td>$4</td>
<td>$130k</td>
<td>$1.2B</td>
<td>$1.5M</td>
</tr>
<tr>
<td>scrypt (64 ms)</td>
<td>&lt; $1</td>
<td>$150</td>
<td>$4.8M</td>
<td>$43B</td>
<td>$52M</td>
</tr>
<tr>
<td>PBKDF2 (5.0 s)</td>
<td>&lt; $1</td>
<td>$29</td>
<td>$920k</td>
<td>$8.3B</td>
<td>$10M</td>
</tr>
<tr>
<td>bcrypt (3.0 s)</td>
<td>&lt; $1</td>
<td>$130</td>
<td>$4.3M</td>
<td>$39B</td>
<td>$47M</td>
</tr>
<tr>
<td>scrypt (3.8 s)</td>
<td>$900</td>
<td>$610k</td>
<td>$19B</td>
<td>$175T</td>
<td>$210B</td>
</tr>
</tbody>
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When used for interactive logins, scrypt is \ldots

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KDF brute force attack costs

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\text{openssl enc uses MD5 as a key derivation function.}

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OpenSSH uses MD5 as a key derivation function for passphrases on key files.
- Are you sure that your SSH keys are safe?
Availability

  - Source code for scrypt.
  - A simple file encryption/decryption utility.
  - A 16-page paper.
More details at http://www.tarsnap.com/scrypt/.

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Questions?