scrypt: A key derivation function

Doing our best to thwart TLAs armed with ASICs

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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.

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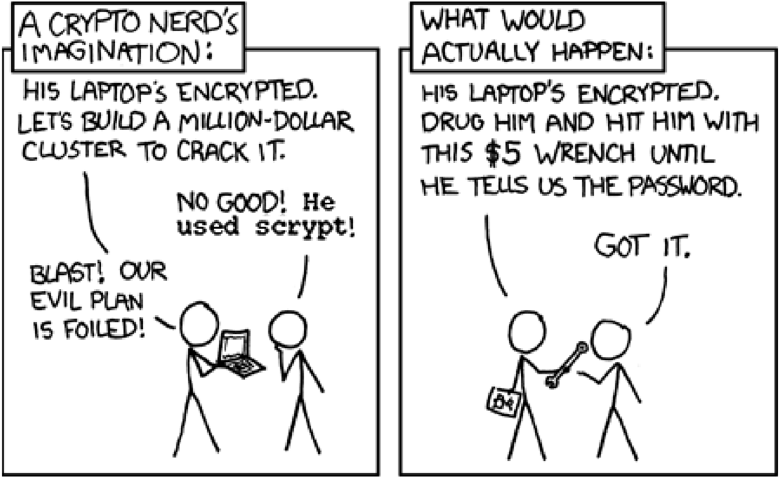

CREDIT: Randall Munroe / xkcd.com

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- Moore's law: Every 18–24 months, a new generation of semiconductor manufacturing processes makes CPUs faster.
    - ... 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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- 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").

ROMix

Algorithm (ROMix)

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

$$V_i = H^i(B) \qquad 0 \leq i < N$$

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

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

ROMix

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 $\frac{N}{4M+2} - \frac{1}{2}$.

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 $H^\alpha(B)$ 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). $\square$

Theorem

The class of functions ROMix are sequential memory-hard.

Proof.

Since H is a random oracle, the values $j = \mathrm{Integerify}(X) \bmod N$ 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 $S^*(n)T^*(n) = \Omega(n^2) \neq \mathrm{O}(T(n)^{2-x})$ as required, since $T(n) = \mathrm{O}(n)$. $\square$

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- We use ROMix to make the computation expensive.
  - Thanks to the "wrapping" with PBKDF2, we don't need much *cryptographic* strength from ROMix — only that it takes a long time to compute.

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- Assuming there are no computational shortcuts, the cost to compute ROMix in hardware is proportional to:

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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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SHA256	450 Mbps	1250 Mbps	160 Mbps
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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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- 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.

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- Running time based on a 2.5 GHz Core 2 (aka. my laptop).

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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.

KDF	6 letters	8 letters	8 chars	10 chars	40-char text
DES CRYPT	$< \$1$	$< \$1$	$< \$1$	$< \$1$	$< \$1$
MD5	$< \$1$	$< \$1$	$< \$1$	\$1.1k	\$1
MD5 CRYPT	$< \$1$	$< \$1$	\$130	\$1.1M	\$1.4k
PBKDF2 (100 ms)	$< \$1$	$< \$1$	\$18k	\$160M	\$200k
bcrypt (95 ms)	$< \$1$	\$4	\$130k	\$1.2B	\$1.5M
scrypt (64 ms)	$< \$1$	\$150	\$4.8M	\$43B	\$52M
PBKDF2 (5.0 s)	$< \$1$	\$29	\$920k	\$8.3B	\$10M
bcrypt (3.0 s)	$< \$1$	\$130	\$4.3M	\$39B	\$47M
scrypt (3.8 s)	\$900	\$610k	\$19B	\$175T	\$210B

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  - Are you sure that your SSH keys are safe?

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Questions?