scrypt: A new key derivation function

Doing our best to thwart TLAs armed with ASICs

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Making bcrypt obsolete

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Are you sure your SSH keys are safe?

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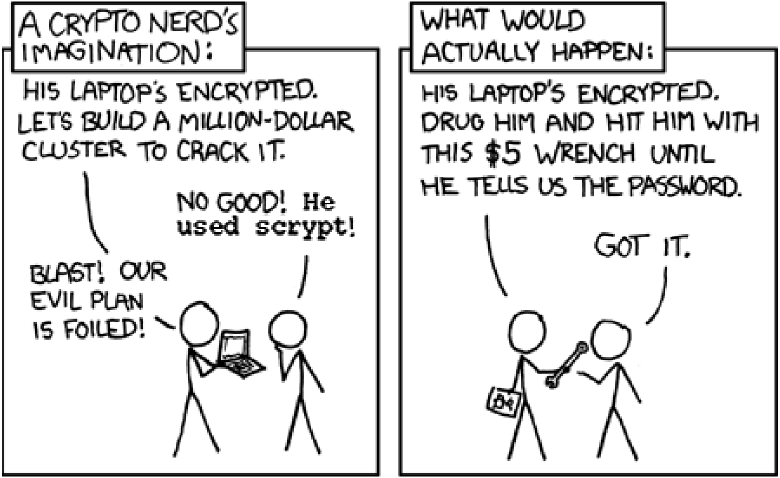
What are key derivation functions?

- You have a password.
- You want a generate a *derived key* from that password.
  - Verifying passwords for user authentication.
  - Encrypting or signing files.
- In most situations where passwords are used, they are passed to a key derivation function first.
  - In most situations where key derivation functions aren't used, they should be!
- 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 really a key derivation function!)

Security of key derivation functions

- Attack model: Assume that the attacker can mount an offline attack.
  - Attacker has access to `/etc/master.passwd` and wants to find the users' passwords.
  - Attacker has an encrypted file and wants to decrypt it.
- For all reasonable key derivation functions, the only feasible attack is to repeatedly try passwords until you find the right one.
  - This is called a "brute force" attack.
- If it takes twice as long to check if a password is correct, it will take twice as long to find the right password.
  - . . . as long as the attacker is using the same software as you.

Hardware-based brute force attacks



CREDIT: Randall Munroe / xkcd.com

Hardware-based brute force attacks

- Some organizations have the resources to design and fabricate custom password-cracking integrated circuits.
    - The US National Security Agency
    - The UK Government Communications Headquarters?
    - The Communications Security Establishment of Canada?
    - The Chinese government?
    - Organized crime?
    - The Electronic Frontier Foundation?
- Using ASICs, it is possible to pack many copies of a cryptographic circuit onto a single piece of silicon.
- 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.

Hardware brute-force attack cost

- The cost of a hardware brute-force attack is meaured in dollar-seconds.
  - Password cracking is embarrassingly parallel, so if you use twice as much hardware you can crack the key in half the time.
- Cost of ASICs $\asymp$ size of ASICs.
  - A strong key derivation function is one which can only be computed by using a large circuit for a long time.
- J. Kelsey, B. Schneier, C. Hall and D. Wagner, 1998: Use "32-bit arithmetic and moderately large amounts of RAM".
  - 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.

Memory-hard algorithms

Definition

A *memory-hard* algorithm on a Random Access Machine is an algorithm which uses $S(n)$ space and $T(n)$ operations, where $S(n) \in \Omega\left(T(n)^{1-\epsilon}\right)$.

- Conceptually, a memory-hard algorithm is one which comes close to using the largest amount of storage possible for an algorithm with the same running time.
  - . . . and consequently the largest circuit area possible.
- The HEKS key derivation algorithm [A.G. Reinhold, 1999] is memory-hard, but it isn't very secure, since it can be effectively parallelized.
- Secure key derivation functions require a large die area *and* a lot of time to compute.

Sequential memory-hard functions

Definition

A *sequential memory-hard function* is a function which
(a) can be computed by a memory-hard algorithm on a Random Access Machine in $T(n)$ operations; 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 $x > 0$.

- Not only do memory-hard functions require lots of storage, but they also cannot be parallelized efficiently.
- If we can find a key derivation function which is sequential memory-hard, it should be very secure against hardware attack.

ROMix

Algorithm (ROMix)

Given a hash function 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

$$j \leftarrow \mathit{Integerify}(X) \bmod N$$
$$X \leftarrow H(X \oplus V_j)$$

N times; and output X.

- The function *Integerify* can be any bijection from $\{0,1\}^k$ to $\{0 \ldots 2^k - 1\}$.
- ROMix fills V with pseudorandom values, then accesses them in a pseudorandom order.

ROMix

Theorem

Under the random oracle model, the class of functions ROMix are sequential memory-hard.

- The random oracle model is a very standard assumption in proofs relating to hash functions.
- The proof is roughly 2 pages long.
  - I could probably spend my entire talk explaining the proof.
  - . . . but I won't.
  - If you're interested, go read the paper I wrote about this.
- It's much easier to prove that an algorithm runs in specified time and space than to prove a minimum bound on the time and space used by *any* algorithm which computes a function.

- Use PBKDF2 to convert a password into a bitstream.
- Feed this bitstream to ROMix.
- Feed the output of ROMix back to PBKDF2 to generate the derived key.
- Cryptographic primitives used:
  - HMAC-SHA256
  - Salsa20/8 core
- The Salsa20/8 core outputs lots of bits very fast, which means that scrypt can use lots of memory.
  - Approximately 1 byte of RAM per 10 clock cycles on a Core 2 processor.
  - We can quickly require a large semiconductor area.

Estimating hardware brute force attack costs

- It's hard to get accurate information about how much it costs to build password-cracking machines.
  - Oddly enough, the NSA doesn't publish this data.
- The best we can do for most KDFs is to count cryptographic operations and assume that they are responsible for most of the time and die area.
  - This is probably a fairly accurate approximation, since key derivation functions only have a very small amount of non-cryptographic computations.
- For scrypt we also need to look at the die area required for storage.

Estimating hardware brute force attack costs

- Approximate circuit complexity and performance for cryptographic primitives, based on a 130 nm semiconductor process:
  - A DES circuit with ≈ 4000 gates of logic can encrypt data at 2000 Mbps.
  - An MD5 circuit with ≈ 12000 gates of logic can hash data at 2500 Mbps.
  - A SHA256 circuit with ≈ 20000 gates of logic can hash data at 2500 Mbps.
  - A Blowfish circuit with ≈ 22000 gates of logic and 4 kiB of SRAM can encrypt data at 1000 Mbps.
  - A Salsa20/8 circuit with ≈ 24000 gates of logic can output a keystream at 2000 Mbps.
- I'm using 130 nm as a reference point because this is what I could get the most data for.

Estimating hardware brute force attack costs

- Very approximate estimates of VLSI area and cost:
  - Each gate of random logic requires $\approx 5\ \mu\mathrm{m}^2$ of VLSI area.
  - Each bit of SRAM requires $\approx 2.5\ \mu\mathrm{m}^2$ of VLSI area.
  - Each bit of DRAM requires $\approx 0.1\ \mu\mathrm{m}^2$ of VLSI area.
  - VLSI circuits cost $\approx 0.1\$/\mathrm{mm}^2$.
- These values are based on a 130 nm process circa 2002.
- These values have a very wide error margin.
  - Non-cryptographic parts of ASICs (e.g., I/O), chip packaging, boards, power supplies, and operating costs could increase password-cracking costs by a factor of 10.
  - Improvements in semiconductor technology since 2002 could reduce password-cracking costs by a factor of 10.
  - Improved cryptographic circuits could reduce costs by a factor of 10.

Key derivation functions

- Non-parameterized KDFs:
  - DES CRYPT
  - MD5 CRYPT
  - MD5
- KDFs tuned for interactive logins ($t \leq 100 \text{ ms}$):
  - PBKDF2-HMAC-SHA256, $c = 86000$
  - bcrypt, $cost = 11$
  - scrypt, $N = 2^{14}, r = 8, p = 1$
- KDFs tuned for file encryption ($t \leq 5 \text{ s}$):
  - PBKDF2-HMAC-SHA256, $c = 4300000$
  - bcrypt, $cost = 16$
  - scrypt, $N = 2^{20}, r = 8, p = 1$
- Running time based on a 2.5 GHz Core 2 (aka. my laptop).

Passwords

- 6 lower-case letters; e.g., "sfgroy".
- 8 lower-case letters; e.g., "ksuvnwyf".
- 8 characters selected from the 95 printable 7-bit ASCII characters; e.g., "6,uh3y[a".
- 10 characters selected from the 95 printable 7-bit ASCII characters; e.g., "H.*W8Jz&r3".
- 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.

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

KDF brute force attack costs

- When used for interactive logins, scrypt is . . .
  - $\approx 2^5$ times more expensive to attack than bcrypt,
  - $\approx 2^8$ times more expensive to attack than PBKDF2,
  - and $\approx 2^{15}$ times more expensive to attack than MD5 CRYPT.
- When used for file encryption, scrypt is . . .
  - $\approx 2^{12}$ times more expensive to attack than bcrypt,
  - $\approx 2^{15}$ times more expensive to attack than PBKDF2,
  - and $\approx 2^{37}$ times more expensive to attack than MD5.
- `openssl enc` uses MD5 as a key derivation function.
- OpenSSH uses MD5 as a key derivation function for passphrases on key files.
  - Are you sure that your SSH keys are safe?

Availability

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

Questions?