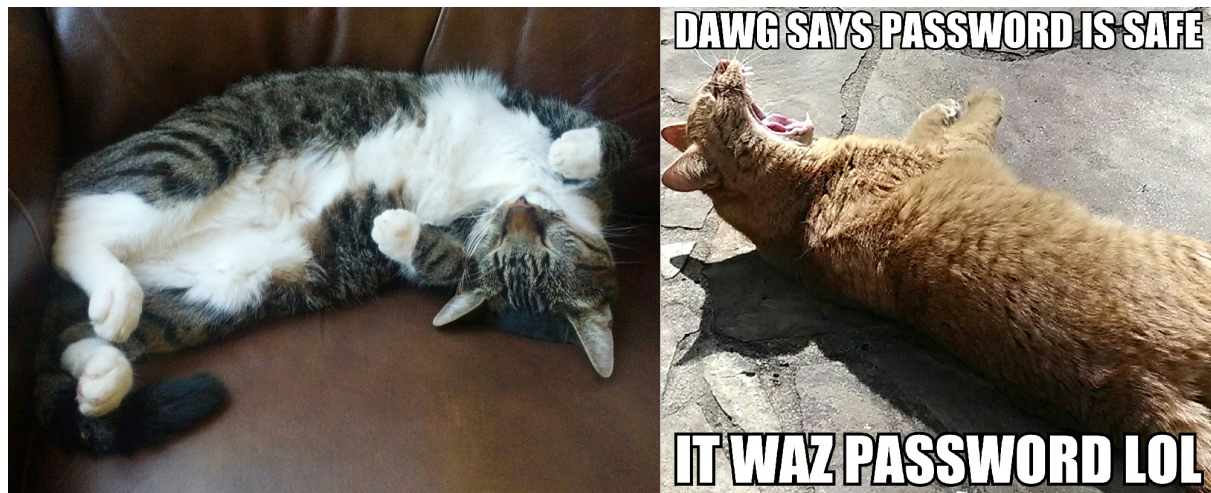


TwoCats:
A Compute Time and Sequential Memory Hard
Password Hashing Scheme



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Abstract. Scrypt demonstrated a new way to thwart off-line brute-force password guessing attacks, as the first successful sequential-memory-hard password hashing scheme (PHS). While Scrypt forces an attacker to use significant amounts of memory, custom ASICs can speed up Scrypt's inner loop substantially. Attackers also gain up to a 4X benefit in time*memory cost through a time-memory trade-off (TMTO). With cache timing information, an attacker can attack Scrypt in parallel on GPUs. TwoCats is a new “hybrid” sequential-memory-hard PHS which is compute time hardened through sequential multiply operations, limiting a custom ASIC's speed advantage to about 2X. TwoCats greatly increases the time*memory cost per guess of custom ASIC attacks, while greatly reducing benefits from time-memory trade-offs. TwoCats's “hybrid” design also provides good defense against cache timing attacks, without sacrificing time*memory performance.

1 Introduction

TwoCats is a sequential-memory and compute-time hard password hashing scheme (PHS) that maximizes an attackers time*memory cost for guessing passwords. TwoCats:

- Fills and hashes memory rapidly – $\frac{1}{2}$ as fast as memmove
- Hardens runtime through sequential multiplications
- Provides strong defense against GPU, FPGA, and ASIC attacks
- Reduces time-memory trade-off options
- Defends against cache-timing attacks
- Uses parallelism for improved protection
- Offers protection in case of leaked memory
- Is suitable for desktop PCs, web servers, mobile, and embedded applications
- Supports client independent updates
- Supports server relief
- Performs well hashing many GiB of DRAM, or a few KiB of cache

In this paper, memory-hard PHSs which do no password derived memory addressing are called “resistant”, while those that do so early in hashing are called “unpredictable”, and combinations of the two are called “hybrid”. “Resistant” memory-hard PHSs should be immune to cache-timing attacks, while “unpredictable” PHSs can be attacked on a massively parallel scale once an attacker knows what memory addresses are accessed when hashing a password. “Hybrid” PHSs can have some resistance against cache-timing attacks while being as effective against brute-force attacks as “unpredictable” PHSs. Scrypt[2] is a “hybrid” PHS, and has better cache-timing attack resistance than if it were “unpredictable”.

Like Scrypt, TwoCats uses a 2-loop architecture, where the first loop is “resistant”, and the second loop is “unpredictable”. Unlike Scrypt, both loops read two prior blocks, hash them together, and appends the result to memory, limiting an attacker's TMTO options. Like Scrypt, external memory is written once, and read on average once. A new fast memory

hashing function is employed that maximizes performance. Compared to single thread SSE optimized Script, single thread SSE optimized TwoCats achieves about a 6X speed increase when hashing 2 GiB of memory.

All else being equal, TwoCats has about a 5X lower time*peak memory cost against cache-timing attacks than resistant PHSs, and about a 7X lower time*average memory cost. At the same time, TwoCats will have about a 3.5X higher time*peak memory cost and a 2.3X higher time*average memory cost against the more common brute force attacks. An unpredictable PHS may have nearly zero time*memory cost in this case. This is discussed in section 4.

The importance of time*memory cost can be thought of as how much memory an attacker needs to buy per guessing core times how long that memory will be in use per guess. Without compute-time hardening, an ASIC attack would likely be limited in speed by memory bandwidth. A reasonably high end desktop PC might have 25GiB/s of memory bandwidth, while recent graphics cards have up to about 250GiB/s of bandwidth. A custom combined DRAM and hashing chip could greatly increase memory bandwidth per hashing core giving attackers a large advantage.

To counter this, TwoCats employs multiplication based compute-time hardening, forcing ASIC attackers to run no more than about 2X faster than a recent PC, regardless of his memory bandwidth. This multiplication chain will force FPGA attackers to run even slower. Modern GPUs are another matter, requiring rapid small unpredictable memory accesses for good defense. TwoCats does in the second loop. GPUs are discussed more in Section 3.

TwoCats currently runs using a 32-byte state and Blake2s in between block hashes. It runs well on 32-bit architectures. A 64-byte version of TwoCats is a natural extension, possibly using Blake2b.

TwoCats is free software. The source code for the reference implementation can be downloaded from:

<https://github.com/waywardgeek/TwoCats>

1.1 Credits

While I deserve credit for this document, my code, and the inspiration for naming a key derivation function after my cat¹, most of the good ideas found here come from the authors of Escrypt and Catena[1], as well as several other members of the PHC email list. The cache timing defense strategy is motivated by excellent work and generosity of ideas from Christian Forler, the author of Catena, while many of the other good ideas came from Alexander Peslyak, aka Solar Designer, author of Escrypt. I consider them both to be the unofficial primary authors of this work and invite them to be listed in the top spots officially at any time in the future. I hope that in some ways I have helped the eventual winning entry to be better. In particular, any PHC author should feel free to borrow any ideas in TwoCats to improve

¹ My wife informs me that naming a KDF after our cat was actually her idea.

their own entry. I will feel honored rather than offended by entries copying TwoCats's multiplication chain hardening, or even significant portions of TwoCats's algorithm directly.

TwoCats is a substantial improvement on my prior algorithm, NoelKDF. All of these improvements were suggested by Solar Designer, and include:

- Better GPU defense through randomized sub-block hashing from the “prev” block
- Blake2s hashing between SIMD “lanes” between block hashes. As SolarDesigner put it, there is no excuse for chaining a billion non-cryptographic hashes together.
- Better performance through SSE/AVX2 optimized memory hashing, in parallel with scalar multiplication compute-time hardening

Solar Designer deserves both credit and blame for goading me into this massive rewrite of NoelKDF. His suggestions simultaneously described how to dramatically improve performance, better defend against GPU attacks, take advantage of modern SIMD instructions, and how to fix my billion long non-cryptographic hash chains.

He also deserves credit and blame for goading me to rewrite my original “keystretch” algorithm as NoelKDF. We discussed multiplication based compute hardening on the PHC discussion forum, and NoelKDF was the result. TwoCats also gains it's TMTO resistance while supporting multiple threads from an idea Solar Designer posted, and his posts on multiplication techniques as well as SSE/AVX2 heavily impacted TwoCats, not to mention his generosity in providing access to a Core i7 Haswell machine and high memory bandwidth Sandy Bridge server.

I was motivated by Christian Forler's Catena paper to add several features, including cache-timing defense, garlic, client-independent update, a client/server relief API, and having a pluggable cryptographic hash function. I learned about pebbling algorithms initially from the Catena paper as well. I used his bit-reversal function and combined it with Solar Designer's sliding power-of-two window to create the memory access pattern used in the “resistant” first loop.

I would like to thank the Blake2 authors. Their efficiently optimized SSE code made a good example for me to follow while writing SSE code for TwoCats, and Blake2 significantly improved the performance of TwoCats. Colin Percival, who did such excellent work in Scrypt, deserves credit for the whole approach. Steve Thomas deserves credit for pointing out some bugs and a severe weakness in the first version of NoelKDF, with a modulo-4 attack against it, forcing me to revise and resubmit it. Gary Hvizdak was kind enough to review of the NoelKDF version of this paper, which readers will appreciate. Others on the forum have also been very generous.

2 Algorithm Specification

2.1 Simplified “Unpredictable” TwoCats

A simplified version of “unpredictable” TwoCats is:

Simplified unpredictable TwoCats:

Inputs: hashlen, password, salt, memlen

Output: hash[hashlen]

```
state[0 .. 7] = conv2Uint32(H(32, password, salt))
```

```
mem[0 .. hashlen-1] = H(hashlen, state)
```

```
prevAddr = 0
```

```
toAddr = hashlen
```

```
for i = 1 .. memlen/hashlen-1:
```

```
    fromAddr = state[0] % i
```

```
    for j = 0 .. hashlen/8-1:
```

```
        for k = 0 .. 7:
```

```
            state[k] = (state[k] + mem[prevAddr++]) ^ mem[fromAddr++]
```

```
            state[k] = ROTATE_RIGHT(state[k], 8)
```

```
            mem[toAddr++] = state[k]
```

```
output H(hashlen, conv2Uint8(mem[memlen-hashlen .. memlen-1]))
```

The function H is a cryptographically strong hash function such as Blake2s, which is used in the reference implementation.

In short, this algorithm hashes the previous hash block written to memory with a pseudo-random prior hash block to generate the next hash block to write to memory. It does this in 8 parallel “lanes” corresponding to the 8 32-bit state registers, and the lanes do not depend on each other. At the end, the last 8 values are hashed together with H to form the derived key.

While simple, this algorithm can be improved by (with credits for idea sources):

1. Introduce a sequential multiplication chain to compute-time harden the algorithm against ASIC attacks (Solar Designer & Bill Cox)
2. Hashing larger blocks than hashlen to reduce cache miss penalties (Scrypt)
3. Hash between lanes in between block hashes to mix data and introduce cryptographically strong hashes now and then (Solar Designer)
4. Introduce SSE/AVX2 parallelism to hash 8 chains in parallel (Solar Designer)
5. Introduce small unpredictable reads to thwart GPU attacks (Solar Designer)
6. Introduce repetitions to increase compute time and L1 cache bandwidth for memory-limited systems (Solar Designer & Bill Cox)
7. Introduce a “resistant” loop before the “unpredictable” loop to harden against cache-timing attacks (Catena)
8. Introduce inter-thread memory hashing to thwart TMTOs (Solar Designer)
9. Introduce thread level parallelism to take advantage of multi-core CPUs (Scrypt)
10. Introduce client-independent update (Catena)
11. Protect against memory leaking to attackers by overwriting early memory (Bill Cox)

Every one of these enhancements either increases speed or improves security. Since the security of a memory-hard PHS can be in part measured by its time*memory cost, increasing speed also increases security, since it allows us to hash more memory. Similarly, increasing CPU time through repetitions also increases security. Many potential enhancements have been left out of TwoCats to reduce complexity.

2.2 Multiplication-Hard Hash Function

Speeding up multiplication on custom ASICs versus modern CPUs is difficult, and unlikely to result in a significant speed-up. In comparison, the Salsa20/8 hash function used in Scrypt[2] is likely to run at about 1 or 2 nanoseconds per Salsa20/8 round per core on a 28nm custom ASIC. Solar Designer's SSE optimized version of scrypt on my development machine² hashes 2GiB twice in 2.71 seconds, which is about 30X slower. Salsa20/8 has only 16 levels of ADD/XOR logic per 32-bit register, of which there are 16, making about as complex as 16 Booth-encoded 32x32 → 64 multipliers running in parallel.

In contrast, TwoCats is hardened against ASIC attacks through the use of a multiplication-hard hash function, which cannot be substantially sped up, even on a carefully optimized custom ASIC. Each iteration depends on the previous, and must be computed with one sequential multiply followed by one sequential XOR. A lower bound on the runtime is:

$$T(memlen) \geq memlen \times multTime \times multsPerByte$$

On my development machine, a 32x32 → 64 multiply operation has latency $multTime = 0.88ns$. Hashing 2GiB of data this way with 8 serial multiplications per 32-bytes would require a minimum of $0.88ns * 231 * 8 / 32 = 0.47$ seconds. TwoCats performs this calculation in 0.83 seconds, which corresponds to being 57% multiplication compute-time hardened.

Definition: Multiplication-Hard Hash Function

A multiplication-hard hash function is a hash function that sequentially computes values using no more than a 1-to-3 ratio of sequential multiplication operations to simple operations, where simple operations are the usual single-cycle ALU operations such as: add, sub, XOR, AND, OR, complement, increment, decrement, and shift/rotate.

The reason for the choice of 1-to-3 is that current advanced Intel, AMD, and ARM processors have either 3 or 4 clock cycle latencies to compute a 32x32→64 multiplication, while all of the simple operations are computed in 1. This means in a multiplication-hard hash function, it should be possible to spend at least 50% of the compute time on multiplications, assuming other operations can execute in parallel. TwoCats has a multiplication to simple operation ratio of 1-to-1. It does one multiply and one XOR sequentially in every loop.

The TwoCats hash function below implements upgrades 1-6 mentioned above:

² My “development machine” is my son's 3.4 GHz quad-core i7-3770 Manjaro Linux MineCraft server.

```

hashBlocks(uint32 state[8], uint32 mem[], uint32 blocklen, uint32 subBlocklen,
           uint64 fromAddr, uint64 prevAddr, uint64 toAddr,
           uint8 multiplies, uint32 repetitions):
    numSubBlocks = blocklen/subBlocklen
    for i = 0 .. 7:
        oddState[i] = state[i] | 1
    v = 1
    for r = 0 .. repetitions-1:
        for i = 0 .. numSubBlocks-1:
            randVal = mem[fromAddr]
            p = prevAddr + subBlocklen*(randVal & (numSubBlocks - 1))

            # Compute the multiplication chain, preferably in CPU registers
            for j = 0 .. subBlocklen/8 - 1:
                for k = 0 .. multiplies:
                    v = v * oddState[k]
                    v ^= randVal
                    randVal += v >> 32

            # Hash 32 bytes of memory, preferably in the SIMD unit
            for k = 0 .. 7:
                state[k] = (state[k] + mem[p++]) ^ mem[fromAddr++]
                state[k] = (state[k] >> 24) | (state[k] << 8)
                mem[toAddr++] = state[k]

hashWithSalt(state, v)

```

On machines supporting SSE or AVX2, the multiplication computations occur in CPU registers, and run in parallel with the memory hashing loop, which is done in the SSE/AVX2 unit. This hash function can compute from 0 to 8 32x32->64 multiplies per inner loop, along with every 32 bytes of hashed memory. A block is 4094 32-bit values by default. When this function is called in the first “resistant” loop, subBlocklen is set to blocklen, since predictable sub-block hashing gains us little. In the second “unpredictable” loop, subBlocklen is 16 which causes modern GPUs difficulty. After the new hashed block is written to memory, hashWithSalt calls Blake2s to mix bits between the state registers.

2.3 The “Resistant” loop

To provide stronger resistance against offline brute-force guessing attacks, TwoCats runs an “unpredictable” second loop called “hashWithPassword”. This function implements features 7 and 8 above. The function is:

```

hashWithoutPassword(uint32 state[8], uint32 mem[], uint32 p, uint64 blocklen,
                    uint32 blocksPerThread, uint32 multiplies, uint32 repetitions,
                    uint32 parallelism, uint32 completedBlocks):

    uint64 start = blocklen*blocksPerThread*p
    uint32 firstBlock = completedBlocks
    if completedBlocks == 0:
        # Initialize the first block of memory
        for i = 0 .. blocklen/8 - 1:
            hashWithSalt(mem + start + 8*i, state, i)
            firstBlock = 1

    # Hash one "slice" worth of memory hashing
    numBits = 1
    for i = firstBlock .. completedBlocks + blocksPerThread/SLICES - 1:
        while 1 << numBits <= i:
            numBits++

        # Compute the "sliding reverse" block position
        reversePos = reverse(i, numBits-1)
        if reversePos + (1 << (numBits-1)) < i:
            reversePos += 1 << (numBits-1)
        uint64 fromAddr = blocklen*reversePos

        # Compute which thread's memory to read from
        if fromAddr < completedBlocks*blocklen:
            fromAddr += blocklen*blocksPerThread*(i % parallelism)
        else:
            fromAddr += start

        uint64 toAddr = start + i*blocklen
        uint64 prevAddr = toAddr - blocklen
        hashBlocks(state, mem, blocklen, blocklen, fromAddr, prevAddr, toAddr,
                  multiplies, repetitions)

```

This function is called SLICE/2 number of times, where SLICE is 4. This is because we execute this function from “parallelism” threads (when pthreads are enabled). It is desirable to allow one thread to hash another thread's memory into it's hash block in order to force attackers to keep all the thread memory loaded at once, rather than running them sequentially with only one thread's memory loaded at a time. Since threads do not run at the same speed, memory for each thread is broken into SLICE slices, and we run “parallelism” threads in parallel to generate one slice of hashed memory, and then join the threads.

This function finds the prior block to hash using the “sliding power of 2” window suggested by Solar Designer, with a bit-reversal addressing pattern from Catena. This tested

most resistant to cache timing attacks in my benchmarks. This is discussed more in the Efficiency section below.

2.4 The “Unpredictable” Loop

The unpredictable loop follows execution of the resistant loop. This loop provides TwoCats its “sequential-memory-hardness”. Its primary purpose is providing solid defense against offline brute-force guessing attacks. Because an attacker cannot know what address will be accessed in the immediate future, he risks considerable recomputation if he tries to implement a TMTO attack with 1/4th memory or less. Also, the unpredictability of this loop keeps him from using parallel cores to recompute values before they are needed. A “resistant” PHS has a simple “free” 1/2 memory TMTO which results in zero recomputations, and typically 1/4 memory TMTO attacks have few recomputations. This loop gives an attacker no such free ride.

The function is:

```
hashWithPassword(uint32 state[8], uint32 mem[], uint32 p, uint64 blocklen,
                uint32 blocksPerThread, uint32 multiplies, uint32 repetitions,
                uint32 parallelism, uint32 completedBlocks):

    uint64 start = blocklen*blocksPerThread*p;

    # Hash one "slice" worth of memory hashing
    for i = completedBlocks .. completedBlocks + blocksPerThread/SLICES - 1:

        # Compute rand()^3 distance distribution
        uint64 v = state[0]
        uint64 v2 = v*v >> 32
        uint64 v3 = v*v2 >> 32
        uint32 distance = (i-1)*v3 >> 32

        # Hash the prior block and the block at 'distance' blocks in the past
        uint64 fromAddr = (i - 1 - distance)*blocklen

        # Compute which thread's memory to read from
        if fromAddr < completedBlocks*blocklen:
            fromAddr += blocklen*(state[1] % parallelism)*blocksPerThread
        else:
            fromAddr += start

        uint64 toAddr = start + i*blocklen
        uint64 prevAddr = toAddr - blocklen
        hashBlocks(state, mem, blocklen, TWOCATS_SUBBLOCKLEN, fromAddr,
                  prevAddr, toAddr, multiplies, repetitions)
```

This function differs from the simplified version of TwoCats in that instead of selecting a prior block to hash uniformly, it biases selection to more recently generated blocks. If

uniform were used, the average distance would be $i/2$. With this cubed distribution, the average is $i/4$, which is still very good, and at the same time the number of very short edges is greatly increased. Short edges cause an attacker more recomputations than long edges if he has dropped blocks from memory. This is discussed more in the Efficiency section.

The average edge length from node i is computed as:

$$l = i \int_0^1 x^3 dx = \frac{1}{4}i$$

2.5 Thread Management

The function `hashMemory` initializes thread states, and launches the threads once per slice, first on `hashWithoutPassword`, and then `hashWithPassword`. It implements feature 9 above: thread level parallelism. The decision to support multithreading was difficult, but in the end, the huge performance and security improvement warrants the additional complexity. In comparison, pepper can take advantage of multiple CPU cores, but not without giving an attacker a simple TMT0. The function is:

`hashMemory(uint8 hash[], uint32 hashSize, uint32 mem[], uint8 memCost, uint8 timeCost, uint8 multiplies, uint8 parallelism, uint32 resistantSlices):`

```
# Determine parameters that meet the memory goal
repetitions = 1 << timeCost
(parallelism, blocklen, blocksPerThread) =
    TwoCats_ComputeSizes(memCost, timeCost, parallelism)

# Convert hash to 8 32-bit ints.
uint32 hash256[8]
hash256 = TwoCats_hkdfExtract(hash, hashSize)

# Initialize thread states
uint32 states[parallelism]
for p = 0 .. parallelism-1:
    states[p] = copy(hash256)
    hashWithSalt(states[p], p)

for slice = 0 .. SLICES - 1:
    for p = 0 .. parallelism-1:
        if slice < resistantSlices:
            hashWithoutPassword(states[p], mem, p, blocklen,
                                blocksPerThread, multiplies, repetitions, parallelism,
                                slice*blocksPerThread/SLICES)
        else:
            hashWithPassword(states[p], mem, p, blocklen,
                              blocksPerThread, multiplies, repetitions, parallelism,
                              slice*blocksPerThread/SLICES)

# Apply a crypto-strength hash
```

```
addIntoHash(hash256, mem, parallelism, blocklen, blocksPerThread)
hash = TwoCats_hkdfExpand(hashSize, hash256);
```

The function `TwoCats_ComputeSizes` does the following:

- Compute `blocksPerThread` as $(1024 \ll \text{memCost}) / (\text{parallelism} * \text{blocklen})$
- If `blocksPerThread` is < 256 , set it to 256
- If needed, lower `blocklen` to nearest power of 2 to keep from having too much memory
- If `blocklen` is < 64 , set it to 64
- If needed to reduce memory further, decrease `parallelism`

This heuristic hides the complexity of choosing reasonable values for `blocklen` and `blocksPerThread`, from the user, simplifying the API.

The function `addIntoHash` simply adds the last 8 words written to memory by each thread into `hash256`.

2.6 Garlic (aka memCost)

The final upgrade is adding Catena style “garlic” and protecting against memory leaks, which are features 10 and 11 above. Catena's “garlic” which I implemented in `TwoCats`, enables a very cool feature called “client independent update”. What this does is make it possible for a system administrator to increase the hashing difficulty of any password in his database at any time, without having to know the password. Basically, it's just a wrapper around `hashMemory` which calls it over and over with increasing `memCost`. If an administrator wants to increase difficulty, he can simply call `TwoCats` with `startMemCost == oldMemCost`, and `stopMemCost == desiredMemCost`. The output from `hashMemory` is the input to the next call to `hashMemory` with 1 higher `memCost`.

This loop also is a good place to deal with a major security issue in memory-hard PHSs: attackers have a much higher chance of gaining access to leaked memory, enabling him to abort incorrect password guesses early. Because memory-hard PHSs are so memory hungry and run for so long, they can segv, get swapped to disk during hibernation or if memory is full, the process might core dump, or a compromised peripheral might have enough time to detect the password hashing in progress and somehow gain access to RAM data, possibly through DMA.

To reduce the chance of leaking the most critical earliest memory to attackers, `TwoCats` overwrites 1/32nd of memory, in increasing levels of `memCost`. This causes the first 1 KiB to be hashed, then overwritten, then 2 KiB, then 4 KiB, and so on until 1/64th of memory is filled. At this point, `TwoCats` jumps ahead to the user's specified `startMemCost` and applies levels of garlic the same way Catena does. This slows down the algorithm about 3%, but the extra protection warrants this performance hit.

The `TwoCats` main hash function is:

```

bool TwoCats(uint8 hash[], uint32 hashSize, uint8 startMemCost, uint8 stopMemCost,
             uint8 timeCost, uint8 multiplies, uint8 parallelism,
             bool updateMemCostMode):

    uint32 mem[1024 << stopMemCost]

    # Iterate through the levels of garlic. Throw away some early memory to reduce the
    # danger from leaking memory to an attacker.
    for i = 0 .. stopMemCost-1:
        if i >= startMemCost || (!updateMemCostMode && i + 6 < startMemCost):
            resistantSlices = SLICES/2
            if i < startMemCost:
                resistantSlices = SLICES
            hashMemory(hash, hashSize, mem, i, timeCost, multiplies,
                      parallelism, resistantSlices)
            if i != stopMemCost:
                # Not doing the last hash is for server relief support
                TwoCats_hkdf(hash, hashSize)

    # The light is green, the trap is clean
    return true

```

There are a few range restrictions on inputs:

- hashSize = 1 .. 255*32
- startMemCost <= stopMemCost
- stopMemCost <= 30
- timeCost <= 30
- multiplies <= 8
- parallelism != 0

Variable sized inputs may have 0 length.

This simple outer wrapper provides support for client independent updates, server relief, and memory leak protection. Feel free to copy it for your PHC entry.

There are some details in `twocats-common.c` that are boiler-plate for a PHS, such as hashing the password, salt and data with HKDF. Refer to the reference source code for these details. The derivation of “hash” from inputs is described in the next section.

3 Security Analysis

There are reasons to believe the design of TwoCats is secure. The analysis of TwoCats security will be covered in detail in this section.

There are many security measures by which to judge an algorithm. Breaking them down, the first category is “critical” features, which if circumvented would be disastrous for any passwords still protected by the algorithm. Since this is an analysis of a memory-hard PHS,

critical features also include memory-hard specific features that if compromised would render the algorithm susceptible to massively parallel attacks without the memory cost. Then comes “important” features, which would somehow limit the effectiveness of an algorithm if circumvented.

Critical features include:

- The derived key cannot be reversed to reveal the password with significantly fewer guesses than brute-force
- “The hash should behave randomly with respect to any of its input” - PHC FAQ
- The time*memory cost cannot be significantly reduced, forcing an attacker to devote a comparable amount of resources as the defender for each password guess

In this context, “significantly reduced” and “significantly fewer” are fuzzy, but striving for no more than a 10X cost advantage per guess for an attacker is a good goal for a memory-hard PHS. Any algorithm showing 10,000X or more cost advantage for an attacker should be avoided, as better algorithms exist. This includes defense against attackers using GPUs, FPGAs, and advanced custom ASICs.

Important features include:

- Low flexibility in TMTO attacks
- Cache timing attack resistance, through password independent memory addressing
- Defense against modern GPU architectures
- Simplicity, enabling better cryptanalysis and more secure implementations
- Resistance to memory leak attacks such as when memory is written to swap

3.1 Key Reversal and Derived Key Randomization

TwoCats uses HKDF-SHA256[9] at the start of the algorithm to derive a cryptographic pseudorandom key from the input data. Every single input, assuming `startMemCost == stopMemCost`, is passed to `HKDF_Extract`, including sizes of all variable sized data, making the initial key derivation in TwoCats “strongly secure”, according to Yao and Yin's definition[10].

```
hash256 = hkdfExtract(SHA256, salt, hashSize || passwordSize || password ||
                      dataSize || datastartMemCost || timeCost || multiplies || parallelism)
```

When `startMemCost < stopMemCost`, the first iteration of memory cost is strongly secure, and the rest are simply client-independent updates made without knowledge of the password, making them more computationally difficult. Attacks such as the chosen-c attack on

PBKDF2 are not possible when all the inputs are hashed upfront. Also, input collisions such as PBKDF2 has when adding additional 0's to short passwords, or when hashing long passwords, cannot happen in TwoCats because the password length is hashed upfront

By default, SHA-256 is used as the hashing algorithm (PRF) for HKDF, but this is configurable. This insures there is no currently known way of reversing the key which is better than brute-force guessing, and also that changes in the password and associated data cause only randomized effects in the derived key. In addition, HKDF-SHA256 is called again at the end of the algorithm with only the final hash as input. In between, memory hashing and multiplication-intensive hashing strive to lose little entropy, but the results are isolated from the starting application of the cryptographic hash, and are added into the hash. This loop is repeated per level of applied “garlic”, meaning the total entropy loss should be no higher than what is lost for $2 + 3 \times \text{garlic}$ rounds of the cryptographic hash function: 2 for the initial HKDF, and 3 for each application of garlic for the isolation hash and HKDF.

As this is negligible entropy loss between the initial and final calls to HKDF, TwoCats provides comparable base security with respect to reversibility and derived key randomization as HKDF-SHA256.

3.2 Memory Hardness

Scrypt appears to have a hardened time*memory cost of about $\frac{1}{4}$ for an attacker vs defenders. To achieve this, an attacker reduces memory by a high factor, and increases his compute effort by a bit more than $\frac{1}{4}$ of this factor. No better TMTO attack is currently known against Scrypt. If one exists, the Litecoin community would be very interested.

TwoCats starts with this level of time*memory cost hardening and enhances it by limiting an attacker's TMTO options. Each hashed memory block depends on the previous as in Scrypt, and also on a randomized prior block, frustrating the DAG-cut attack used in an Scrypt TMTO attack, by increasing the data in any DAG cut to a number comparable to the graph size – the mid-cut is about 18% of the number of nodes in the computation DAG. A TMTO attack has been identified, which reduce time*cost by about 10%, though the complexity of memory tracking in this attack limits it's usefulness to an attacker. In this attack, the fact that memory locations near the end of each loop have low probability of being accessed is used to save some memory without a high recomputation cost. The TMTO hardness of TwoCats is further discussed in the Efficiency Analysis section.

3.3 Secure Memory Hash Function

It may be simpler to focus on two separate functions performed in hashBlocks: memory hashing, and compute-time hardening. Memory hashing is not impacted by the multiplication chain computation, and when this is removed, we get a simpler memory-hashing only loop that writes the same data to memory:

```
for i = 0 .. numSubBlocks-1:  
    randVal = mem[f]
```

```

p = prevAddr + subBlocklen*(randVal & mask)
for j = 0 .. subBlocklen/8 - 1:
    for k = 0 .. 7:
        state[k] = (state[k] + mem[p++]) ^ mem[fromAddr++]
        state[k] = ROTATE_LEFT(state[k], 8)
        mem[toAddr++] = state[k]

```

The memory hash function is designed to be fast, SIMD friendly, lose negligible entropy, and to force an attacker to compute `mem[0 .. i-1]` before he can compute `mem[i]`. It uses addition, rotation, and XOR (ARX)[7]. These are the primitives behind several popular fast cryptographically strong hash functions, including SHA-3 competitors Skein, Blake, CubeHash, and Salsa20[7]. These operations are not combined in a manner to make the hashing cryptographically secure, but they still have to be computed, which is what counts.

The memory being hashed into the state is separated by at least one application of the cryptographically strong hash function `H`, and many rounds of memory block hashing are applied. It is important that the hash function lose little entropy, which is assured by the reversible ARX operations. The data written to memory passes the dieharder tests, and the number of 32-bit collisions in the data written to memory is as expected.

It is critical to force an attacker to compute each memory location's value, and to have no short-cuts that allow `mem[i]` to be computed without first computing `mem[0..i-1]`. Confidence that this is the case comes from the similarity of this hash function to other ARX hash functions. If it were possible to compute the last round of Salsa20 hashing without first taking time to compute all the prior rounds, attackers would be very interested in hearing about it.

3.4 Hardened Compute Time Cost

TwoCats introduces the concept of multiplication based compute-time hardening of a PHS. By sequentially calling a hash function dominated by the runtime of serial multiplications, an attacker is forced to spend a comparable time computing the TwoCats hash function as the defender, even on a custom ASIC.

What matters in the multiplication hardened hash function is that the attacker needs to be forced to compute the multiplications sequentially, and there should be as little non-multiplication computation as possible. The interesting portion of the hashing loop for multiplication hashing:

```

uint64 v = 1
for i = 0 .. 7:
    oddState[i] = state[i] | 1
for i = 0 .. numSubBlocks-1:
    randVal = mem[f++]
    for j = 0 .. subBlocklen/8 - 1:
        for k = 0 .. 7:
            v = (uint32)v * (uint64)oddState[k]
            v ^= randVal

```

```
        randVal += v >> 32
    hashWithSalt(state, v)
```

The oddState variables are allocated in regular CPU registers, while the stat variables are loaded into SSE/AVX2 registers. The memory hashing function runs very well on SSE and AVX2 SIMD units in Sandy Bridge, Ivy Bridge, and Haswell CPUs, but moving data from between the SIMD unit and the scalar integer unit is very slow. The value of mem[f] is updated pseudorandomly by the memory hashing code, and only interacts with the compute-time hardening code through randValue. At the end of the loop, the resulting value of v is used as salt when state is hashed with Blake2s.

If addition were used rather than bitwise XOR, then the multiplications could be distributed, and parallel computation could be used to accelerate computation. Since XOR does not distribute with multiplication, the multiplications must be computed sequentially.

3.5 Cache Bandwidth Hardening

In addition to compute-time hardening through sequential multiplies, TwoCats has a timeCost parameter, which causes its 16 KiB block hashes to be repeated 2^{timeCost} times, but results are only written on the last iteration. With high timeCost values, bandwidth to L1 cache can be very high. As benchmarks show, about 79 GiB/s can be sustained to L1 cache using this parameter with one thread on Intel Haswell CPUs, or about 36% of the theoretical maximum, and 57 GiB/s on Ivy Bridge, or 52% of the maximum possible. This represents yet another barrier, in addition to multiplication compute-time hardening, which will make it difficult for ASIC attackers to significantly speed up attacks on TwoCats.

3.6 GPU, FPGA, and ASIC Attack Resistance

GPUs naturally run with long instruction latency, and the multiplication chain will perform only a bit worse than an addition chain. There are two approaches to defeating graphics card attacks. First, use a lot of memory. Scrypt runs at near parity with GPUs at around 4MiB, and at 1GiB, Scrypt is not practical to attack with GPUs. However, Bcrypt runs at parity with GPUs in only 4KiB of memory. The difference is the way Bcrypt does many small unpredictable reads in series, which GPUs do poorly. TwoCats includes similar small random reads in the second loop (but not the first), which by default is 64 bytes compared to Bcrypt's 16. Exactly where TwoCats achieves memory parity with GPUs has not yet been benchmarked, but I expect it to be in between that of Scrypt and Bcrypt.

Against ASICs, TwoCats deploys a multiplication computation time hardened inner loop. A custom ASIC in the same technology node as a modern CPU should not have any advantage in the speed of multiplication. TwoCats's inner loop is typically about 50% dominated by multiplication, meaning an ASIC attacker has to spend about 50% as long as the defender computing the hash. This is a dramatic improvement over prior algorithms that only use addition, rotation, and XOR in their hashing loops.

FPGAs will fare even worse from the multiplication computation time hardening, due to slower clock cycles, and multiple clocks per 32-bit multiplication.

3.7 Memory Leak Attacks

The single greatest weakness in memory-hard PHSs is likely what happens when an attacker gains access to hashed memory. Writing password derived data to large amounts of memory greatly increases the odds that password derived data will be leaked to an attacker, through swap, hibernation, memory recycling without reinitialization, core dumps, DMA transfers to a compromised device, etc. With this data, an attacker can abort incorrect password guesses early, and mount a massively parallel attack with little time and memory per guess.

TwoCats provides some resistance against memory leaks by overwriting early hashed memory. It repeatedly hashes memory with the “resistant” hash algorithm, starting with just 256 blocks, and increases the size by a factor of two until it reaches at least 1/64th of memory. After that, it starts from scratch, doing the “resistant” first loop on the first half of memory, followed by the “unpredictable” second loop on the second half of memory. The compute overhead is roughly 1/32 or about 3%.

This algorithm initially presents a minimal attack surface to an attacker. If memory leaks after this phase has completed, an attacker will potentially gain a 2048X time*cost reduction, or about 11 bits of strength. With a TMTO additional attack, memory can be cut another 4X, leading to a 13 bit combined loss in password strength. I feel this is a reasonable trade-off for a 3% increase in runtime.

3.8 Weaknesses

TwoCats inherits any weaknesses in HKDF-SHA256, just as Scrypt inherited weakness from PBKDF2-SHA256. However, HKDF was designed by the author of HMAC to be a secure next-generation KDF which is free from the known flaws in previous algorithms such as PBKDF2. Unlike PBKDF2, HKDF-SHA256 has no known input collisions, and there are no chosen-input attacks. I can find only one security weakness in HKDF: the input key material is not padded in any way other than by SHA256. I recommend that users of TwoCats use fixed-length password buffers initialized to 0's, and to reject passwords with non-printable characters, when that makes sense for their application, or which do not fit in the buffer. This insures no branching or memory addressing specific to the password length ever happens.

It is possible for an attacker to make better use of TwoCats leaked memory than if cryptographically secure data were written to memory. In particular, an attacker might more easily determine which data block is the first block, minimizing his time to abort an incorrect password guess. He might also be able to search swap or data on an SSD specifically for TwoCats hash data, which would be more difficult if the data written to memory were cryptographically indistinguishable from random. The decision to accept this weakness in TwoCats is deliberate: the alternative is to slow down memory hashing considerably.

Slowing down the algorithm by even 2X would give an attacker with a leaked password database a potential 4X faster cracking time, since he only needs $\frac{1}{2}$ the memory per core, and $\frac{1}{2}$ the time per core. Because time*memory security with a memory-hard PHS increases as the square of the hashing speed, this was an easy decision to make. However, TwoCats overwrites memory early on, providing some defense even if memory is leaked. If the first 1/64th of memory is overwritten before an attacker gains access, he will gain only about an 11-13 bit advantage in cracking the password.

My lack of understanding of GPU attacks may have contributed to weaknesses against current GPU architectures relative to algorithms such as Bcrypt. More benchmarking will be required to determine TwoCats's strength against GPUs. However, small (64-byte) unpredictable reads are done in the inner hashing loop in the second half of the algorithm, which I believe makes it harder for GPUs to be effective.

With cache timing information, an attacker gains an estimated 16X lower peak time*memory cost (though only 5X worse than a resistant PHS). However, this relies on the assumption that the sliding-reverse window DAGs cannot be efficiently pebbled with less than about $\frac{1}{4}$ memory versus the first-loop DAG size. The TwoCats first loop uses the DAG architecture that tested most resistant in this respect, but only upper bounds on recomputation penalties have been established. There is some risk that significantly better pebbling algorithms can be found, reducing the effectiveness of defending against cache-timing attacks. Other algorithms come with proofs for lower bounds on recomputation, but the proven lower bounds are 2 orders of magnitude lower than the efficiency of the best currently known pebbling attacks³. TwoCats uses the algorithm that proved most resistant computationally to the pebbling code I designed. I believe it will remain more resistant over time than the alternatives considered. This is the best choice, in my opinion, for a first-loop algorithm in a hybrid PHS, based on my experience with pebbling attacks, and I know of no better pebbling algorithm.

Against simple brute-force attacks, TwoCats is resistant to TMTOs. The best TMTO found so far reduces the time*memory cost by 10% by keeping every other value in memory near the end of both loop ranges, since this memory is not likely to be read. There is some risk that better TMTOs can be found with more clever memory coverage of computed values. However, the 4X TMTO improvement we see attackers use against Scrypt cannot be used against TwoCats, so the security risk here is low.

While simplicity has been a major goal of TwoCats from the start, improved security has been a higher concern. Several decisions were made in favor of security over simplicity, including the two-loop “hybrid” architecture.

The mathematical analysis of TwoCats's hashing functions could be improved. The multiplier/XOR chains have no formal proof that there exists no simple mathematical

³ Catena-3 has a proven lower bound of $T \geq G^3 / 128S^2$ where G is $\frac{1}{4}$ the size of the DAG

shortcut to reduce the computation time. I have a little number theory background, but I am certainly no expert. However, I do have extensive experience representing Boolean equations and manipulating them to reduce their size and delay in ASICs. Multiplications have no efficient Boolean level canonical representation that I am aware of (BDDs and related forms are all exponential), and a logic equation representation of the multiplication chain that it will explode exponentially if I push the XOR operations through the multipliers using any common circuit design techniques such as Shannon Decomposition.

The use of Blake2s is not a significant weakness, even if a weakness is found in Blake2s in the future. HKDF-SHA256 is used for the initial key derivation, rather than Blake2s, and the function served by Blake2s during hashing has much weaker security requirements: that it mixes the lane data well, be slightly difficult to invert (harder than just performing the TwoCats computation), and that it lose little entropy.

While I have considerable experience with ASIC and FPGA architectures, I have little cryptography experience. Extensive expert review of TwoCats will be required before it can be considered secure.

4 Efficiency Analysis

TwoCats introduces an efficient compute-time hardened hash function, in addition to being sequential-memory-hard. This hash function on most machines will take from 4 to 8 clock cycles per 32-bit result written to memory, with one thread, because the multiply operation takes 3-4 cycles, the addition takes 1, and the rest (memory read/write, OR, and increments) can often be done in parallel. With multiple threads, throughput can be increased to fill about half of the memory bandwidth before the memory bottleneck begins to heavily impact runtime.

4.1 The Cost of Cache Timing Attack Resistance

The “resistant” PHSs proposed so far seem to allow an attacker to use about $\frac{1}{4}$ of the memory compared to the computed DAG size, with little or no recomputation penalty. There are good reasons for this. First, there is a recomputation-free $\frac{1}{2}$ memory attack against all “resistant” PHSs which have computation DAGs with max fanout degree 2. When pebbling a resistant PHS's DAG, simply pick up one of the pebbles used to compute the next node, or if those pebbles will be needed in future computations, pick a pebble which is not pointed to by any node beyond the node being pebbled. This always works for DAGs with max fan-out degree ≤ 2 .

For DAG pebbling with $\frac{1}{3}$ the pebbles compared to the DAG size, we can always pebble to the $\frac{2}{3}$ mark with no recomputation. For every new node pebbled after that, we gain a pebble that is not needed to cover some node that is still pointed to by the remaining unpebbled nodes. This makes it very hard to design a hard-to-pebble DAG where an attacker

has 1/3 pebbles. This results in resistant PHSs having a 3-4X lower memory cost than unpredictable or hybrid PHSs.

When CPU limited, run-times should be approximately the same for resistant, hybrid, and unpredictable PHSs when using the same hashing algorithm, though some PHSs do not write to memory corresponding to DAG nodes that have in-degree 1, saving on memory bandwidth. This can lead to a lower performance penalty than my estimated 3-4X, and this is in fact the case for Catena-2, which has between a 2-3X reduction in the time*memory cost compared to unpredictable PHSs. However, resistant PHSs do not suffer from a memory bandwidth degradation in comparison to hybrid and unpredictable PHSs. Attackers will have to pay a bit more for the extra RAM, but this is likely to be a small factor, typically less than 2X.

I have written a pebbling application that attempts to pebble TwoCats, Catena-3, and what I believe is similar to Escrypt's sliding power-of-two window. In the pebbling algorithm, I assume an attacker knows every detail about the computation DAG ahead of time, and can plan his memory usage strategy carefully. Automated pebbling confirms that all DAG types tested are easily pebbled with $\frac{1}{4}$ pebbles compared to number of nodes.

In summary, the cost for resistant PHSs versus unpredictable PHSs is typically about a 3-4X penalty in time*memory cost, though in some cases it may be in the 2-3X range.

4.2 Computation DAGs

The original Script algorithm writes a linear chain of hashed blocks to memory, each hashed block depending sequentially on the data computed for the previous. Its directed acyclic computation graph is a linear chain:

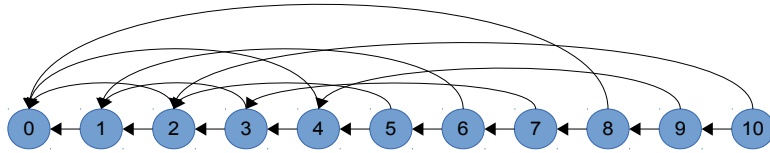
Script Computation DAG:



Script is vulnerable to TMTO attacks. An attacker covering nodes 3 and 7 sees an average recomputation of 1.5 nodes + second loop hashing, for a 2.5 computations per node in the second loop. Adding first loop computations gets the total to 3.5 computations per node, compared with 2 computations per node when keeping all nodes in memory. That's a 1.75X computation penalty, but the attacker only covered 1 in 4 nodes, so his time*memory is down

to 0.44X of his original cost. As an attacker reduces his memory coverage, his time*memory cost converges to $\frac{1}{4}$ of the original.

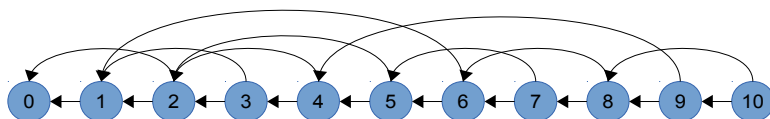
TwoCats's “resistant” Computation DAG:



One visual give-away that this is a sliding-power-of-two bit-reversal DAG is that every power of 2 node points to node 0. To compute the destination of an edge, take the binary representation of the source node, remove the leading 1, and reverse the bits. For example, node 6 is 110, which becomes 10 after removing the leading 1, and then 01 with bit-reversal, so node 6 points to node 1. If an edge length is 2 greater than largest power of 2 less than the source node number, then add that power of two. So, for example, if the graph were larger, we'd see node 11000 (node 24) would point to node 0001 (node 1), but since $1 + 16 + 2 = 19 < 24$, we add 16. Therefore, node 24 points to node 17. This causes the destination node to always fall within the “sliding” power-of-two window preceding a node (actually it follows 2 pebbles behind to avoid 1-long edges).

This DAG architecture was chosen after it demonstrated the strongest resistance of all DAG architectures tested to my automated pebbling algorithm. An attacker attempting to pebble such graphs with a combination of fixed-spaced pebbles, fixing pebbles on high degree nodes, and fixing pebbles on destinations of short edges will find this graph requires more pebbles and recomputation than the other DAGs tested.

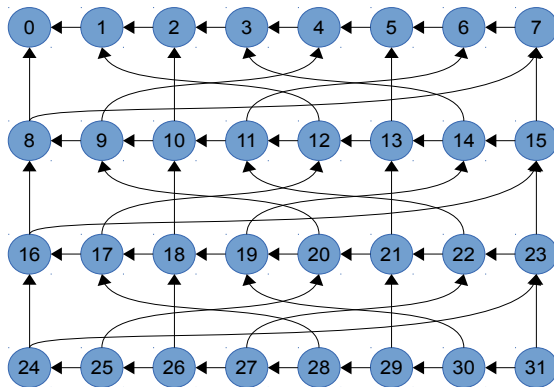
TwoCats's “unpredictable” Computation DAG:



TwoCats “unpredictable” computation DAGs have the same linear chain, but instead of waiting until all memory is written before doing password dependent pseudo-unpredictable reads, it reads and hashes while writing. This creates a unpredictable-ish looking graph where edges on average point back $\frac{1}{4}$ from their position, and there are lots of short edges. This keeps the midpoint cut size around 17% of the number of nodes. In this case, the cut size to the right of node 5 is 4.

If an attacker has covered only nodes 3 and 7 only, then to compute node 8 requires recomputation of every single missing node because 8 points to 6, which points to 5 which points to 4, which points to 2 and then onto 0. Similarly, computing 9 and 10 also require full recomputation of every missing node, since they point to 8. In general, a TwoCats graph recomputation penalty grows to a substantial portion of the entire graph for each missing node requiring recomputation by the time an attacker has only 1/8th of the nodes in memory, resulting in a runtime proportional to the square of the graph size. While a $\frac{1}{2}$ memory TMTO with every other memory block kept results in no significant change in memory*time cost, anything lower than $\frac{1}{2}$ rapidly becomes too expensive to compute. An attacker keeping every 4th node in memory suffers an additional computation factor of over 2000X for a 1M node graph. A reasonable attack against TwoCats would be to save $\frac{1}{2}$ of the last $\frac{1}{2}$ of memory. For 1,000,000 node graphs the gain is < 2% in the time*memory cost. If we increase spacing to 3 in the last $\frac{1}{4}$, then to 4 in the last 8th, and so on, the memory*time cost drops 3% versus the normal algorithm.

Catena-3 Computation DAG:



The Catena-3 DAG is computed using $\frac{1}{4}$ of the memory requirement compared to the size of its computation DAG. However, an attacker is unlikely to succeed at improving his time*memory cost while using even one less memory location than $\frac{1}{4}$. Our algorithm pebbles Catena with 0 recomputation penalty for a $\frac{1}{4}$ pebble coverage just like TwoCats and Escrypt.

With one fewer pebbles, the Catena pebbling penalty jumps to 1.8X for a 1024 node graphs, using fixed pebbles every 4. The penalty seems independent of graph size. When a Catena-3 sub-DAG is embedded in the first row, the penalty jumps to 3X, when using fixed pebbles every 4 and pebbling nodes pointed to by short edges, which improves the situation on the first row.

Code for the pebbling application can be found at:

<https://github.com/waywardgeek/TwoCats/tree/master/predict>

5 Benchmark Results

The following benchmarks were run on my quad-core 3.4GHz i7-3660 Ivy Bridge development machine with 2 banks of 4GB CORSAIR Vengeance RAM, running Manjaro (Arch) Linux. Script version 1.1.6 was locally compiled with SSE2, and -O3 -march-native optimization. Catena was compiled from the available on 1/24/14 from github, using the waywardgeek branch I created. Escript was version 0.3.1, patched to upgrade it to 0.3.2, run in Scrypt-compatibility mode, and hand modified to only run a single print_scrypt call and then exit. Multiple threads did not seem to work properly in Scrypt, so it was run only single-threaded. However, the Escript implementation of Scrypt is currently the fastest implementation of Scrypt available. All of these benchmarks include memory allocation overhead. Executable were run with another CPU intensive task running and without, three times, and the best time was listed.

Peak cost is memory/CPU time. Average cost is computed based on my understanding of how each algorithm fills memory, and is an attempt to show the average memory usage / CPU time. In particular, Scrypt fills memory linearly in the first pass, and hashes it in the second leading to an average memory of about 0.75 of the peak, while Catena-3 fills memory linear in the first write pass, and holds steady in the next 5 read/write passes, leading to an average memory of $11/12 = 0.92$. TwoCats does the worst of the three on average memory, as it fills linearly continuously, at 0.5.

Bandwidth is total read/write passes * memory/CPU time. Catena can be done in 6 passes, which is what I assume in the table, though the implementation currently has 8, so Catena's bandwidth and runtime still have room for optimization.

I apologize to Alexander, the Escript author, and Christian, the Catena author, for using benchmarks from their pre-released code. Please feel free to ask me to correct/update/remove any data I have listed, and to request that new data be added. I feel it is important to list Catena data, since it shows the 3-4X peak time*cost reduction that I expect for a “resistant” PHS, and I have only listed data when using the same hash function as I had used in NoelKDF, which shows Catena in a good light from a benchmark perspective. Alexander mentioned that I should list the best Scrypt data available, and his Escript implementation run in Scrypt compatibility mode is the best available. Also, as Alexander suggested, I have

benchmarked a Escript Salsa20/2 version, which I built by deleting 3 of the 4 2-round calls in SALSA20_8_BASE. The idea is to show how much faster Scrypt could be with a simple 3-line change.

	Memory	CPU Time (s)	Compute Hardness	Bandwidth (GiB/s)	Peak Cost	Average Cost
Scrypt (1 thread)	500 MiB	0.83		1.2	1.0X	0.75X
Escript (1 thread)	2 GiB	2.71		1.5	1.2X	0.90X
Escript (2 threads)	2 GiB	1.40		2.9		
Escript (4 threads)	2 GiB	0.81		4.9		
Escript (8 threads)	2 GiB	0.61		6.6		
Escript/Salsa20/2 (1 thread)	2 GiB	.98		4.1		
Escript/Salsa20/2 (8 threads)	2 GiB	.50		8.0		
Catena-3	1 GiB	1.37		4.4	1.2X	1.1X
Catena-2	1 GiB	1.06		5.7	1.6X	1.4X
TwoCats (1 thread)	2 GiB	0.52	52% (-M4)	7.7	6.4X	3.2X
TwoCats (1 thread)	2 GiB	0.45	40% (-M3)	8.9		
TwoCats (2 threads)	2 GiB	0.33	36% (-M4)	12.1		
Memmove (1 thread)	2 GiB	0.23		17		
Memmove (2 threads)	2 GiB	0.18		22		

Compute hardness is calculated as the time spent doing serial multiplications compared to the total runtime. On the 3.4GHz quad-core i7 Ivy Bridge processor used in these benchmarks, multiplication takes 3 cycles, or 0.88ns. An additional cycle is required for the XOR operation, making 75% the maximum possible compute time hardness. Memory allocation overhead is on the order of 15-20%, making it difficult to achieve compute time hardness over 50% while hashing external RAM. A dedicated authentication server which allocates memory once for many authentications would achieve higher compute-time hardness.

For small memory in-cache hashing, TwoCats runs very fast, especially with SSE or AVX2 enabled. The Haswell machine was provided by Solar Designer, and is an Intel quad-core i7-4770. These numbers are for 1, 4, and 8 threads, with either 0 or 1 multiplication in the inner loop per 32 bytes hashed. Each hash requires 2 reads, doubling the bandwidth. All runs were made with the blocksize equal to 16KiB and subblocks size equal to 64, meaning there were many small random reads. In general, this slows down L1 cache limited loops by about 2X compared to having no small random reads. Each run was made hashing 1MiB repeated 2^{16} times.

	1T 0M	4T 0M	8T 0M	1T 1M	4T 1M	8T 1M
Haswell AVX2	79 GiB/s	260 GiB/s	350 GiB/s	57 GiB/s	199 GiB/s	277 GiB/s
Ivy Bridge SSE2	57 GiB/s	191 GiB/s	191 GiB/s	45 GiB/s	142 GiB/s	155 GiB/s

AVX2 showed the most improvement over SSE2 when running in L1 cache, and with 8 threads. Even a single multiplication in the inner loop results in a multiplication time limited loop when running in L1 cache.

The L1 data bus in Ivy Bridge and Sandy Bridge is 16 bytes wide, with two lanes. On Haswell the data widths are doubled, and we can read 32 bytes at once. The theoretical top read bandwidth in Ivy bridge was 109 GiB/s, so it seems TwoCats is achieving about 50% with 1 thread. Similarly, it achieves about 36% of the possible L1 read bandwidth on Haswell. When sequential rather than random 64-byte reads are done, almost the full possible bandwidth is achieved on Ivy Bridge, at 92 GiB/s.

I compared resistance to cache timing attacks using my automated pebbler. Catena-3 seems to be the clear winner for a “resistant” PHS, as even reducing 1 pebble punishes an attacker significantly. However “hybrid” PHSs fill memory with all the computed results, so users do not benefit from the reduced memory consumption the way they do with Catena. For TwoCats, I tested Catena-2 and Catena-3, with and without an embedded Catena-3 graph in the first row (“Enhanced Catena”), and various other DAG styles, including the combination of Alexander’s power-of-two sliding window and Christian’s bit-reversal. As I enhanced the algorithm, the recomputation penalties decreased, but the relative order of results has not changed. To improve pebbling, I manually tuned my 3 parameters to minimize the recomputation penalty. Fixed pebbles at fixed spacing had the greatest impact. Enhanced Catena needs a heuristic to cover nodes pointed to by short edges, and the sliding-reverse DAGs needed a heuristic for fixing pebbles on nodes of high in degree.

	Spacing	Max Degree	Min Edge Length	Recomputation Penalty
Catena-3	7	0	0	10X
Catena-2	5	0	0	2.6X
Enhanced Catena-3	8	0	25	89X
Enhanced Catena-2	5	0	25	6.5X
Sliding-Reverse	16	3	0	1176X

All of these runs pebbled graphs with 128 pebbles. The Catana-3 and sliding-reverse graphs had 1024 nodes, while the Catena-2 graphs had 768 nodes.

6 Intellectual Property Statement

I, Bill Cox, place TwoCats, both the algorithm and all files and intellectual property associated with this project, into the public domain. I will file no patents on any idea used in this project. TwoCats includes source code from the official references for Blake2 and HKDF, and are released under the MIT-like licenses. Also, `twocats-test.c` was copied from Catena's `catena_test_vectors.c` and is released under the MIT license.

TwoCats is and will remain available worldwide on a royalty free basis, and I am unaware of any patent or patent application that covers the use or implementation of the TwoCats algorithm.

7 No Hidden Weaknesses

I, Bill Cox, assert that TwoCats has no deliberately hidden weakness such as back doors, and I know of no weaknesses other than those discussed in this document in the Weaknesses section. No unusual constants are used in the code.

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