

TigerKDF:
A Compute Time and Sequential Memory Hard
Key Derivation Function



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For Consideration in the Password Hashing Competition

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Chapel Hill, NC, February 2014

***Abstract.** Scrypt demonstrated a new way to thwart off-line brute-force password guessing attacks, as the first successful sequential-memory-hard key derivation function (KDF). 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 on a massively parallel scale. TigerKDF is a new “hybrid” sequential-memory-hard KDF which is compute time hardened through sequential multiply operations in its inner loop, limiting a custom ASIC core speed advantage to about 2X. TigerKDF greatly increases the time*memory cost per core of custom ASIC attacks, while greatly reducing any benefit from time-memory trade-offs. TigerKDF's “hybrid” design also provides good defense against cache timing attacks, without sacrificing time*memory performance.*

1 Introduction

TigerKDF is a sequential-memory and compute-time hard key derivation function (KDF) that maximizes an attackers time*memory cost for guessing passwords. TigerKDF:

- Insures high memory cost for an attacker by filling memory rapidly with a SIMD friendly memory hash function
- Insures high runtime for an attacker through serial multiply operations that are SIMD unfriendly, and difficult to speed up on an ASIC
- Mostly eliminates time-memory trade-off benefits to attackers
- Provides effective defense against cache-timing attacks
- Can use parallelism present on the machine for improved protection
- Is suitable for desktop PCs, web servers, and embedded applications
- Supports client independent hash updates
- Performs well hashing many GiB of DRAM, or just a few MiB of cache
- Can hamper GPU attacks through small unpredictable reads

In this paper, memory-hard KDFs which do no password derived memory addressing are called “pure”, while those that do so early in hashing are called “dirty”, and combinations of the two are called “hybrid”. “Pure” memory-hard KDFs are 100% immune to cache-timing attacks, while “dirty” KDFs can be attacked on a massively parallel scale once an attacker knows what memory addresses are accessed when hashing a correct password. “Hybrid” KDFs can have good resistance against cache-timing attacks while at the same time can be nearly as effective against brute-force guessing attacks as dirty KDFs. Scrypt[2] is a “hybrid” KDF, and suffers far less from cache-timing attacks than if it were “dirty”, but since it was not

designed specifically to thwart cache-timing attacks or TMTO attacks, its resistance can be improved.

Like Scrypt, TigerKDF uses a 2-loop architecture, where the first loop is a “pure” KDF. No password derived memory addresses are accessed in the first loop. The second loop is a “dirty” KDF, which significantly improves defense against offline brute-force guessing attacks as well as limiting TMTO options for an attacker. Unlike Scrypt, both loops read two prior blocks to hash a new block, limiting an attacker's TMTO options, and both loops write block hash results to memory.

In parallel with these two memory intensive loops runs a multiplication based compute-time hardened hash function which insures the main memory hashing loops cannot be significantly accelerated by an attacker using custom hardware.

Each loop hashes a “block” of memory, which by default is 16KiB, but is adjustable to values as low as 64 bytes. Both loops hash the previously generated block with a block generated earlier in memory. The prior block can be accessed pseudo-randomly in the second loop with sub-block memory segments as small as 32 bytes, frustrating GPU attacks in a manner similar to Bcrypt. This block/sub-block architecture provides good performance when accessing external DRAM, while making use of the flexibility of on-chip cache. Between block hashes, a cryptographically secure hash function randomizes the 256-bit “state” values used in both the memory hashing loops, as well as the multiplication hashing loop, which is hashed into the memory hashing states between blocks as well. By default Blaker2s is used for this purpose, as it provides excellent speed and security while matching the 256-bit state size well.

Against cache-timing attacks, TigerKDF has a time*memory cost about 16X lower than when no addressing information is known since the second loop can be aborted early, and the first loop can be computed efficiently with about 1/8th of the usual total memory. However, TigerKDF's “dirty” second loop provides about a 3-4X improved time*memory cost than “pure” KDFs. As a result, TigerKDF should have only about a 5-to-1 time*memory disadvantage against cache-timing attacks relative to “pure” KDFs. TigerKDF trades off some cache-timing attack resistance in order to retain full resistance against brute-force guessing attacks.

The importance of time*memory 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 based attack would likely be limited in speed only by external memory bandwidth, which attackers can buy at a substantial discount relative to defenders using their PCs for password hashing. For example, a reasonably high end desktop PC with an Ivy Bridge Core I7 processor with 2 banks of 1,666MHz DDR3 memory has around 25GiB/s of memory bandwidth, while there are graphics cards with 200GiB of bandwidth to GDDR5 memory. Multiplication based compute-time hardening forces the

attacker to run at, or likely even slower, than the defender, regardless of his memory bandwidth. For example, GPUs and FPGAs generally cannot run the multiplication hash loop as fast as most modern laptops, while a high-end GPU would typically have a 20-to-1 memory bandwidth advantage.

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 who also contributed ideas and feedback. The cache timing defense strategy is motivated by excellent work and generosity of ideas from Christian Forler, while many of the other good ideas came from Alexander Peslyak (aka Solar Designer). I consider them both to be the unofficial primary authors of this work until such time as they prefer to be listed in the top spots officially. Since they have generously offered their ideas to the other PHC entrants, I accept their help, and 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 TigerKDF to improve their own entry.

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

- Separate sequential multiplication hashing thread and multiple parallel SIMD optimized memory hashing threads. This architecture enables nearly optimum compute time hardening and memory hashing speed at the same time.
- Better GPU defense through randomized sub-block hashing from the “prev” block which is likely still in L1 cache.
- Blake2s hashing between SIMD “lanes” between block hashes. As SolarDesigner put it, there is no excuse for chaining a billion non-cryptographic hashes together.
- SSE optimized hashing in the memory hashing loops.

Solar Designer deserves both the 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 the way Bcrypt does, take advantage of modern SIMD instructions, and how to fix my lame billion long non-cryptographic hash chains.

He also deserves the credit and blame for goading me to rewrite my original “keystretch” algorithm as NoelKDF. We seemed to co-invent the idea of multiplication based compute hardening on the PHC discussion forum, and NoelKDF is the result.

I was motivated by Christian Forler's Catena paper and code for several features, including cache-timing defense, garlic, client-independent update, a client/server relief API, generating test vectors, and having a pluggable cryptographic hash function. I learned about pebbling

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

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 first loop.

I would also like to thank the Blake2 authors. Their efficiently optimized SSE code made a good example for me to follow while writing SSE code for TigerKDF, and Blake2 significantly improved the performance of TigerKDF. Colin Percival, who did such excellent work in Scrypt, deserves credit of course for the whole approach, and I also used his implementation of PBKDF2, and his Scrypt code as a roadmap for how to develop a memory-hard KDF. Steve Thomas deserves credit for pointing out some bugs and a severe weakness in the first version of NoelKDF, with a brilliant 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 “Dirty” TigerKDF

TigerKDF was originally a “dirty” KDF, until Christian Forler demonstrated an effective strategy against cache-timing attacks, which sent the other PHC authors scrambling. A simplified version of “dirty” TigerKDF is:

Simplified Dirty TigerKDF:

Inputs: hashlen, password, salt, memlen

Output: hash[hashlen]

mem[0 .. hashlen-1] = H(hashlen, password, salt)

value = 1

prevAddr = 0

destAddr = hashlen

for i = 1 .. memlen/hashlen:

 randAddr = value % i

 for j = 0 .. hashlen-1:

 value = value*(mem[prevAddr++] | 3) + mem[randAddr++]

 mem[destAddr++] = value

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

The function H is a cryptographically strong hash function such as PBKDF-SHA256, which is used in the reference implementation.

2.2 Multiplication-Hard KDFs

Speeding up multiplication on custom ASICs versus modern CPUs is difficult, and unlikely to result in a significant speed-up without exotic technologies such as liquid nitrogen cooling. In comparison, the Salsa20/8 hash function used in Scrypt[2] is likely to run at about

1ns per Salsa20/8 round per core, generating 64GiB/second of data on a well optimized advanced technology custom ASIC. In comparison, Scrypt on my development machine² hashes 0.5GiB twice in 1.8 seconds, which is about 100X slower. This is because it has only 16 levels of ADD/XOR logic per 32-bit register, of which there are 16, making Salsa20/8 it a bit less complex than 16 Booth-encoded 32x32 multipliers running in parallel. On the development machine, 32x32 bit multiplies have a 0.9ns latency.

TigerKDF is hardened against such attacks through the use of a multiplication-hard hash function, which cannot be significantly sped up on custom AISCs compared to advanced CPUs. Each iteration depends on the previous, and must be computed with one sequential multiply followed by one sequential addition. A lower bound on the runtime is:

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

On my development machine, a 32-bit multiply operation has latency $multTime = 0.9ns$. Hashing 2GiB of data this way would require a minimum of $0.9ns \times 2^{31}/4 = 0.48$ seconds. The reference version of TigerKDF performs this calculation in 0.69 seconds, or only 44% longer than an optimally multiplication bound loop.

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 sequential simple operations, where simple operations are the usual single-cycle ALU operations: 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 multiplication, while all of the simple operations are computed in 1. This means in a multiplication-hard hash function, it may be possible to spend at least 50% of the compute time on multiplications, assuming other tasks can execute in parallel. TigerKDF has a multiplication to simple operation ratio of 1-to-1. It does one multiply and one addition sequentially in every loop. The other operations, including increments, OR, and memory read and write can be done in parallel.

TigerKDF is sequential-memory-hard in the sense described in Catena[1]. Additional CPUs cannot significantly speed up its computations, since the random address computed in the second loop cannot be known until the prior loop iteration has completed. If an attacker decides to cheat and use less memory, he will suffer a penalty when he has to recompute the missing data, just as in Scrypt[2]. Even stronger, TigerKDF memory blocks written in the second loop depend on not just the previous, as in Scrypt, but also on another block earlier in memory. Attackers will have to recompute any missing input blocks that are accessed. With TigerKDF's 2-fanouts per node, this can grow exponentially through the computation DAG if an attacker has too little coverage of computed results in memory.

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

2.3 Algorithm Enhancements

By far, the most extensive enhancement over the original TigerKDF algorithm is the addition of a “pure” first loop. Several other enhancements were needed as well.

2.3.1 Speed Enhancements

For small hashlen, cache miss delays will dominate the runtime. Therefore TigerKDF has a separate blocklen parameter to enable high speed with short hash lengths.

The reference implementation, when run with 2 threads, achieves 12GiB/s memory bandwidth (when factoring out the memory allocation overhead) on a machine I estimate to have a 25GiB/s maximum. SIMD can be used to improve the time*memory cost, but there will be increased latency in the hash loop, which an ASIC attacker will not see, reducing the potential improvement of a SIMD optimized implementation. More threads do not significantly speed up hashing on the development machine, apparently because memory bandwidth becomes a bottleneck after 2 threads. A SIMD prototype using SSE 4.1 32x32->lower 32 unsigned multiply on my Core i7 Ivy Bridge processor sped up hashing by 2.5X using 4-way parallel SIMD.

While the original TigerKDF algorithm was optimized for external DRAM hashing, the current version is equally suitable for running in small amounts of memory entirely from CPU cache. This is enabled by choosing a few MiB rather than a GiB or more, setting blockSize to a small value such as 64, which is well matched to cache line sizes, and setting “repetitions” to high enough of a value to make the runtime long enough.

2.3.2 Improvements Over Pepper

Pepper is a small number of secret bits of the salt, which are sent as 0's to the user. When authenticating, he must try all the possible salt guesses until he guesses the correct salt. This has the impact of increasing the compute effort for both an attacker and defender. If pepper is chosen well, the user can try all the salt guesses in parallel, feeling little increase in latency, while an attacker feels the full impact.

This scheme has some problems. First, it gives an attacker a free TMTO, and eliminating these trade-offs is a major goal of TigerKDF. Second, if we use pepper in a server-relief system, it is likely that the user will attempt to authenticate with the server multiple times, increasing network traffic. Finally, it seems to be naturally applied externally to the password KDF, and won't be able to take full advantage of SIMD instructions when used that way, especially when the inner loop hash function is very simple as is the case with TigerKDF.

To overcome these limitations, TigerKDF executes with a user-specified level of parallelism. A pthread version of TigerKDF has been developed to demonstrate the use of this parameter, while the reference version simply computes the parallel tasks in series.

2.3.3 *Garlic and Data*

TigerKDF “borrows” the concept of “garlic” from Catena[1], along with other goodies such as “client independent update”, and of course a cache-timing resistance strategy. I also copied `catena_test_vectors.c` to generate vectors for TigerKDF. Please read the Catena paper for a more in-depth description of these features. Client independent updates are where a sysadmin can increase the difficulty of computing a password hash without having to know the user's password.

A data input has also been added, following Catena's naming convention, which allows a software developer to provide application specific data such as secondary authentication keys to the hash. For example, when a server has a password specific key that is decrypted using the server's master key during password authentication, that password specific key can be added as data to the hash. This renders brute force attacks impractical to attackers who do not have the master key. Similarly, if a user provides a key file, a hash of that file can be used as data, again making brute-force attacks impractical. A similar concept appears in Escrypt (local parameters) and Blakerypt (session keys).

2.3.4 *Additional Enhancements*

In the second “dirty” loop, the prior memory block to hash is no longer chosen uniformly randomly. Instead it follows a cube-law, reducing the average edge length from $\frac{1}{2}$ to $\frac{1}{4}$, significantly improving TMTD resistance. Having short edges causes the computation DAG depth to be considerably higher, with typical sub-DAGs of attackers using only 1/8th of memory being on average around 1/8th the size of the entire DAG, even with decent strategies for pebble placement, such as evenly spacing them, covering high degree nodes, and covering nodes with short incoming edges. With a uniform distribution for selecting the prior memory block to hash, only 1 in 100 edges are shorter than 1% of the node number, while with the cubed distribution, 21.5% are this short. The average edge length from node i is computed as:

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

One intended use for TigerKDF is specifically in applications like TrueCrypt where only parameters that are indistinguishable from true random data can be used. Salt is such a parameter, but garlic, memory-size, and such are not. In these cases, the application can choose default settings for most values, and select an appropriate garlic level. After hashing the user's password, the resulting derived key is hashed one more time with a strong cryptographic hash and stored along with the salt in the encrypted volume. When verifying a password later, the application compares the resulting hash after each level of garlic is applied, and stops if it matches.

2.4 The TigerKDF Algorithm

All integers are unsigned 32-bit, unless they specify a memory index, in which case they are 64-bits to allow for hashing more than 4GiB of memory. They may be 32-bits instead on 32-bit platforms. Implementers need to be careful to insure that 32-bit values are cast to 64-bits during computations resulting in a 64-bit results. Hashsize and blocksize must be multiples of 4. Ranges are kept low enough to allow signed integers to be used rather than unsigned. Total memory, which is $2^{20} * \text{memsize} * 2^{\text{garlic}}$ should be $\leq 2^{50}$, and the total memory size/blocksize should be $< 2^{31}$. Memlen, specified in MiB, must be long enough for at least 2 blocks per parallel task. If ranges are invalid, or memory cannot be allocated, the algorithm returns null for versions that return byte arrays such as Python, and false for versions that write to a user-supplied buffers such as the C reference version.

The algorithm for TigerKDF is:

TigerKDF Algorithm:

Inputs: hashsize, an integer from 12 .. 1024 specifying byte length of hash result in bytes
password: byte array of length 1 .. 1024
salt: byte array of length 1 .. 1024
memsize: 32-bit int 1 .. 2^{30} specified in MiB
garlic: 8-bit integer 0 .. 30 specifies multiplier on memsize of 2^{garlic}
data: byte array of length 0 .. 1024, may be null
blocksize: integer 4 .. 2^{30} specifies memory hashed at once in bytes
parallelism: integer 1 .. 2^{20}
repetitions: integer 1 .. 2^{30}

Output: hash result in byte array of length hashsize, or null if there is an error

```
function TigerKDF_HashPassword(hashsize, password, salt, memsize, garlic, data,
    blocksize, parallelism, repetitions):
    if input ranges are invalid:
        return null
    if data != null:
        derivedSalt = H(hashsize, data, salt)
        hash = H(hashsize, password, derivedSalt)
    else:
        hash = H(hashsize, password, salt)
    memlen =  $2^{20} * \text{memsize} / 4$ 
    blocklen = blocksize / 4
    numblocks = memlen / (2 * parallelism * blocklen)
    mem = array of  $2 * \text{numblocks} * \text{blocklen} * \text{parallelism} * 2^{\text{garlic}}$  32-bit integers
    if mem allocation failed:
        return null
    for i = 0 .. garlic:
        for p = 0 .. parallelism-1:
            hashWithoutPassword(p, hash, mem, blocklen, numblocks, repetitions)
```

```

    for p = 0 .. parallelism-1:
        hashWithPassword(p, mem, blocklen, numblocks, parallelism, repetitions)
    xorIntoHash(hash, mem, blocklen, numblocks, parallelism)
    numblocks *= 2
    hash = H(len(hash), hash, i)
return hash

```

```

function hashWithoutPassword(p, hash, mem, blocklen, numblocks, repetitions):
    uint64 start = 2*p*numblocks*blocklen
    mem[start .. start+blocklen-1] = toUint32Array(H(blocklen*4, hash, p))
    value = 1
    mask = 1
    uint64 toAddr = start + blocklen
    for i = 1 .. numblocks-1:
        if mask << 1 <= i:
            mask = mask << 1
        reversePos = bitReverse(i, mask)
        if reversePos + mask < i:
            reversePos += mask
        uint64 fromAddr = start + blocklen*reversePos
        value = hashBlocks(value, mem, blocklen, fromAddr, toAddr, repetitions)
        toAddr += blocklen

```

```

function hashWithPassword(p, mem, blocklen, numblocks, parallelism, repetitions):
    startBlock = 2*p*numblocks + numblocks
    // start, toAddr, v, v2, v3, and distance are 64-bit ints
    uint64 start = startBlock*blocklen
    value = 1
    uint64 toAddr = start
    for i = 0 .. numblocks-1:
        uint64 v = value
        uint64 v2 = v*v >> 32
        uint64 v3 = v*v2 >> 32
        uint64 distance = (i + numblocks - 1)*v3 >> 32
        if distance < i:
            uint64 fromAddr = start + (i - 1 - distance)*blocklen
        else:
            q = (p + i) % parallelism
            b = numblocks - 1 - (distance - i)
            uint64 fromAddr = (2*numblocks*q + b)*blocklen
        value = hashBlocks(value, mem, blocklen, fromAddr, toAddr, repetitions)
        toAddr += blocklen

```

```

function hashBlocks(value, mem, blocklen, fromAddr, prevAddr, toAddr, repetitions):
    uint64 prevAddr = toAddr - blocklen
    for r = 0 .. repetitions-1:
        for i = 0 .. blocklen-1:
            // This truncates to 32-bits

```

```

        value = value*(mem[prevAddr + i] | 3) + mem[fromAddr + i]
        mem[toAddr + i] = value
    return value

```

```

function xorIntoHash(hash, mem, blocklen, numblocks, parallelism):
    for p = 0 .. parallelism-1:
        uint64 pos = 2*(p+1)*numblocks*blocklen - length(hash)/4
        data = toUInt8Array(mem[pos:pos+len(hash)/4])
        for i = 0 .. length(hash)-1:
            hash[i] ^= mem[pos+i]
    return hash

```

```

function bitReverse(value, mask):
    result = 0
    while mask != 1:
        result = (result << 1) | (value & 1)
        value >>= 1
        mask >>= 1
    return result

```

The first “pure” loop uses a power-of-two sliding window with a bit-reversal function to select the target within this window. Alexander Peslyak suggested the power-of-two sliding window to provide a more uniform distribution of incoming edges, while Christian Forler invented using a bit-reversal distribution of edges to thwart cache-timing attacks.

The second “dirty” loop is the TigerKDF cubed-distribution. When running on multiple threads, each thread computes its results from all of the threads results computed in the first loop. This forces an attacker to keep all of the first loop results in memory while the second loops run. While an attacker can run the second loop sequentially, he will still be forced to have most of memory loaded at once (or suffer a substantial recomputation penalty), greatly increasing his time*memory cost.

3 Security Analysis

3.1 Results are Indistinguishable from Random

The resulting hash from TigerKDF will appear indistinguishable from true random data, and no change in input will produce a predictable change in the output. This is because it starts by creating an intermediate derived key using PBKDF2, and in the reference implementation, the hash function is SHA-256. The intermediate derived key, stored in “hash”, thus has these properties, to the extent that we believe PBKDF2-SHA256 has them. Once the intermediate derived key is computed, the password and input data are never accessed again, and can (and should) be cleared from memory. The derived key is hashed by PBKDF2 again to create the first block of data for each thread, using the thread ID, p , as the salt, and the intermediate derived key as the password. Therefore, we can be confident that the seed data for each

thread is no more correlated with the derived key than PBKDF2-SHA256 allows. To compute the final hash, the results from each thread are XOR-ed into the intermediate derived key, and since the seed for each thread is uncorrelated with the derived key, the results from each thread also are uncorrelated with the derived key. No matter how apparently non-random the output of each thread may be, XOR-ing these outputs into the derived key makes it no less indistinguishable from true random data. Because we also want hash results between applied levels of garlic to be completely unpredictable, an application of H is also made to the hash after each level of garlic.

Because of this architecture, the inner loop hash function used to fill memory need not be cryptographically strong. TigerKDF takes advantage of this for improved speed and compute-time hardness.

3.2 The TigerKDF Hash Function

TigerKDF uses a new multiplication hardened hash function, and a new fast memory intensive hash function. The multiplication hash function is reversible, and should not lose entropy. The multiplication is reversible since one operand is odd[6]. For each block of memory hashed in sequence, the following loop is executed, and the resulting state is hashed into the memory hashing state:

```
for i = 0 .. multipliesPerBlock - 1:
    state[j&7] = (state[j&7]*(state[(j+1)&7] | 1)) ^ (state[(j+2)&7] >> 1)
```

TigerKDF introduces a new non-cryptographic hash function that is meant to be compute time hardened and fast rather than producing data that is undetectably non-random. There is no need for this hash function in the inner loop to produce cryptographically pseudo-random data, as the output is cryptographically pseudo-random regardless. For the inner loop hash function, there are two primary concerns:

1. Entropy loss needs to be insignificant
2. To compute $\text{mem}[i]$, an attacker must first compute $\text{mem}[0 \dots i-1]$

TigerKDF uses the following inner loop hash function:

```
value = value * (mem[prevAddr] | 3) + mem[randAddr]
```

This is motivated from a desire for the hash function to be similar to a permutation. With permutations, no entropy is lost. If $\text{mem}[\text{prevAddr}]$ and $\text{mem}[\text{randAddr}]$ were replaced with a PRNG stream seeded only from the password and salt, then this would be a true permutation, and would be reversible. Being reversible is undesirable, as it gives attackers more TMTO options.

For this hash function to work well and not lose significant entropy, $\text{mem}[\text{prevAddr}]$ needs to be highly scrambled relative to value . With a default block size of 20,000, value is hashed 20,000 times since the last time $\text{mem}[\text{prevAddr}]$ was hashed into value . Block sizes of 256 passed the dieharder tests, indicating that even 256 iterations of the hash is far enough away. A side benefit of choosing Alexander's sliding-power-of-two window in the first loop is that

the 1st block, which is generated using PBKDF-SHA256, is rehashed into the stream at every node in the DAG that is a power of two, potentially reintroducing lost entropy in case there were any.

Besides making one input odd, so that the multiplication is reversible, the OR seems to reduce the possibility that an attacker can compute $\text{mem}[i]$ in a closed form, enabling him to compute $\text{mem}[i]$ without first computing $\text{mem}[0 \dots i-1]$.

Passing the dieharder tests is not a goal in itself, but simply additional evidence that TigerKDF does not leak entropy quickly. Dieharder tests are run with a blocklen of 256 rather than 4096. This is because the 32-bit value used to mix between values in a block is an awfully thin pipe for mixing 4KB quickly. The dieharder tests seem to detect correlations between sequential memory blocks if they are too long. However, this does not mean the hash function is losing entropy. It simply means that the dieharder tests can detect the low amount of mixing between large adjacent blocks. The effect is similar to what would happen if we wrote out every value as it is computed in Salsa20/8. Writing out data every 8 rounds easily passes the dieharder tests, but if we wrote out all 64 computed values for every round of Salsa20/2, there is no way this stream would pass tests for randomness. However, it would generate considerably more data much more quickly while not losing entropy, and attackers would still be forced to compute it all. This would be a very effective strategy for a fast memory-hard KDF hash function, except that Salsa20/8, as well as most cryptographically strong hashes, use CPU operations like ADD, SHIFT, and XOR which can be sped up in custom ASICs by a large factor.

3.3 Weaknesses

The single largest weakness in TigerKDF seems to be shared among all memory-hard KDFs. Writing password derived data to large amounts of memory increases the odds that password derived data will be leaked to an attacker, through swap, hibernation, memory recycling without reinitialization, or core dumps. With this data, an attacker can abort incorrect password guesses early, and mount a massively parallel attack with little CPU time or memory per guess.

With cache timing information, an attacker gains an estimated 16X lower time*memory cost. However, this relies on the assumption that the sliding-reverse window DAGs cannot be efficiently pebbled with little recomputation with less than $\frac{1}{4}$ memory versus the first-loop DAG size. The TigerKDF 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 lower upper bounds can be found, reducing the effectiveness of defending against cache-timing attacks.

Against the simple brute-force attacks, TigerKDF is resistant to TMTOs. The best TMT0 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.

While compute-time hardening is desirable, in reality an attacker will most likely run multiple cores in parallel until his memory bandwidth becomes the limiting factor. For best defense, users should run TigerKDF with enough parallelism to fill about half of their memory bandwidth, which matches the CPU effort to memory bandwidth while hashing more memory than a single thread.

4 Efficiency Analysis

TigerKDF 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 Importance of Memory Bandwidth

In reality, an attacker will most likely pay for enough memory to match his GPU, FPGA, or ASIC, and the memory cost is unlikely to dominate the cost. We make his system more expensive by hashing more memory, but it is likely that his FPGA, GPU, or ASIC will cost a more than his DRAM. We can make a hash function take a long time for him to compute, by using multiplication hardening. However, an attacker easily gets around the compute time by adding more cores. Assuming he has bought enough memory, the only thing stopping him from running more cores in parallel is memory bandwidth. When a password cracker compares systems for cracking memory-hard KDFs, it is likely that memory bandwidth per dollar will be his primary metric.

Some KDFs are being designed to run out of cache memory, which is much more expensive than off-chip DRAM. However, “pure” KDFs should avoid this strategy because an attacker can interleave memory from parallel guessing cores to make it very cost effective to use off-chip DRAM. Since all the cores access the same memory location at the same time, an attacker can efficiently stream data in and out of his FPGA with little penalty for switching addresses.

4.2 The Cost of Pure Cache Timing Resistance

The “pure” KDFs 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 “pure” KDFs which have computation DAGs with max fanout degree 2. When pebbling a pure KDF'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 $1/3$ the pebbles compared to the DAG size, we can always pebble to the $2/3$ 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 pure KDFs having a 3-4X lower memory cost than dirty or hybrid KDFs.

When CPU limited, run-times should be approximately the same for pure, hybrid, and dirty KDFs when using the same hashing algorithm, though some KDFs 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 dirty KDFs. However, pure KDFs do not suffer from a memory bandwidth degradation in comparison to hybrid and dirty KDFs. 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 TigerKDF, 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 $1/4$ pebbles compared to number of nodes.

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

4.3 SIMD Optimization

Having a parallelism parameter enables TigerKDF to be SIMD optimized. In particular, if parallelism is a multiple of 2 or 4, the inner hashing loop should be executable as 2 or 4 32-bit loops in parallel. Memory for first loop can be interleaved, enabling efficient 128-bit parallel operations. The second loop has each parallel task reading from a pseudo-random memory location (fromAddr), and will require more memory bandwidth as a result, but interleaving memory still enables reading from prevAddr and writing to toAddr 128-bits at a time for 4 parallel tasks.

4.4 Computation DAGs

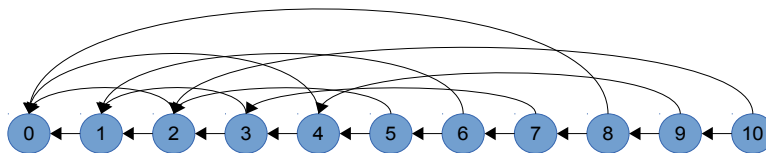
The original Script algorithm writes a linear chain of hashed blocks to memory, each hashed block depending sequentially on the data computed for the previous. Its directed acyclic computation graph is a linear chain:

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.

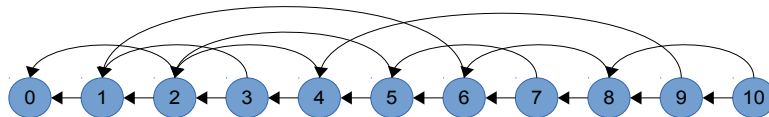
TigerKDF's "Pure" Computation DAG:



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.

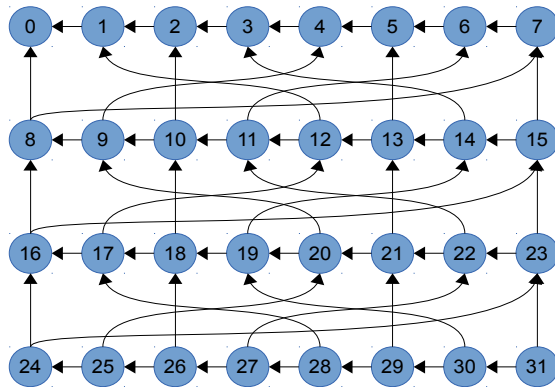
TigerKDF's "Dirty" Computation DAG:



TigerKDF “dirty” computation DAGs have the same linear chain, but instead of waiting until all memory is written before doing password dependent pseudo-random reads, it reads and hashes while writing. This creates a random-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 TigerKDF 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 $\frac{1}{8}$ th 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 TigerKDF 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 $\frac{1}{8}$, 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 TigerKDF 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/TigerKDF/tree/master/predict>

5 Results

The following benchmarks were run on our quad-core i7 CPU development machine running Manjaro (Arch) Linux, using the default install package for Scrypt, and the version of Catena available on 1/24/14 from github, using the waywardgeek branch I created. All were run in single-threaded mode. For completeness, I also compiled Scrypt from source with `--enable-sse2`, and include this in the benchmarks. It is interesting to note, that although Scrypt was hand SSE optimized, the default Arch distribution does not enable it.

	Memory	CPU Time (s)	Compute Hardness	Bandwidth (GiB/s)	Speedup
Scrypt (nosee)	500 MiB	1.8		0.56	1.0X
Scrypt (see)	500 MiB	1.0		1.0	1.8X

Catena-3	1 GiB	1.37		4.4	2.6X
Catena-2	1 GiB	1.06		5.7	3.4X
TigerKDF (2 threads)	2 GiB	0.43	64%	10	17X
TigerKDF (3 threads)	2 GiB	0.31	60%	13	23X
Memmove	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.

The Catena-3 code used the same exact hash function as my previous hashing algorithm, NoelKDF. I literally copied and pasted the hashing code from TigerKDF-ref.c into catena-multihash.c.

Next, I compared resistance to cache timing attacks with my automated pebbler. Catena-3 seems to be the clear winner for a “pure” KDF, as even reducing 1 pebble punishes an attacker. However “hybrid” KDFs fill memory with all the computed results, so users do not benefit from the reduced memory consumption the way they do with Catena. For TigerKDF, 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 Catena-3 and sliding-reverse graphs had 1024 nodes, while the Catena-2 graphs had 768 nodes.

Not too much should be read into these numbers as they are simply upper bounds. However, sliding-reverse was chosen for hybrid-TigerKDF based in part on these results.

Also, the sliding-reverse DAG does a better job in the second loop at forcing attackers to keep results in memory.

6 Conclusion

A natural choice for memory-hard KDFs seems to exist between the extremes of “pure” and “dirty” KDFs. “Hybrid” KDFs, while maybe 5X-ish less resistant to cache-timing attacks are 3-4X-ish more resistant against the more common brute-force guessing attacks, all else being equal.

Further, substantial resistance to ASIC attacks can be had through multiplication-time hardened hashing functions.

TigerKDF is just such a hybrid KDF.

7 Intellectual Property Statement

I, Bill Cox, place TigerKDF-ref.c, the algorithm it contains, and all other files and intellectual property associated with this project into the public domain. I will file no patents on any idea used in this project. TigerKDF includes sha.c and sha.h which I copied from the script source code, and which is released under the BSD license, and TigerKDF-test.c was copied from Catena's catena_test_vectors.c and is released under the MIT license.

TigerKDF 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 TigerKDF algorithm.

8 No Hidden Weaknesses

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

9 Bibliography

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