ECE459: Programming for Performance Winter 2018

Lecture 23 — Password Cracking, Software Transactional Memory

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GPU Application: Password Cracking

GPUs are good—too good, even—at password cracking. We'll discuss a paper that proposes a technique to make it harder to crack passwords. This technique is scrypt, the algorithm behind DogeCoin [Per09]. See also `http://www.tarsnap.com/scrypt.html`

First, let's talk about acceptable practices for password storage. It is *not* acceptable engineering practice to store passwords in plaintext. The inevitable security breach will end with your company sending a "sorry" disclosure email to its clients, and you will be responsible for the ensuing bad publicity.

Acceptable practices: **not** plaintext; hashed and salted. (We're not going to talk about what "salted" means here. Look it up if you need it. Hint: ECE 155.)

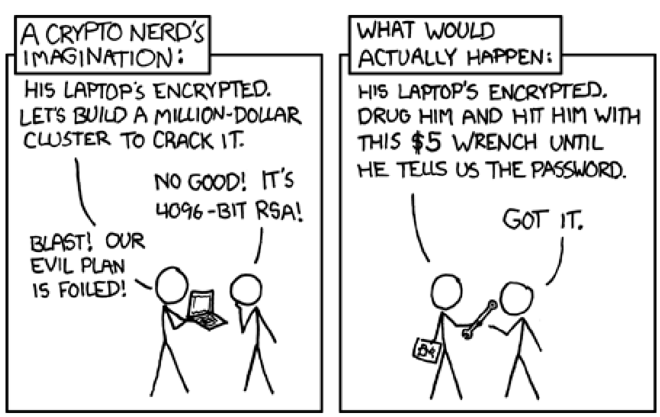
Cryptographic hashing. Instead of storing the plaintext password, you store a hash of the password, under a cryptographic hash function. One important property of a cryptographic hash function is that it must be (believed to be a) one-way function; that is: $x \mapsto f(x)$, the forward direction, must be easy to compute, but $f(x) \mapsto x$, the inverse mapping, must be hard to compute. Examples of such functions include SHA1 and scrypt.

Breaking the hash. Even if there is no known short computation for the inverse function, it's always possible to brute-force the password computation by trying all possible passwords. Think about how GPUs work. Each potential password is a point in the computation space, and we compute the hash over all of them simultaneously. That's a lot of speedup. Custom hardware is also good, and those of you who know something about hardware could think about implementing it. Oh, hello, Bitcoin miners.

Arms race: making cracking difficult. The idea has always been to make it more difficult to compute the hash function, so that it's OK to try one password, but it's intractable to try one billion passwords. Even way back, UNIX passwords forced repeated applications of the hash function to accomplish these.

The main idea behind scrypt is to make hashing expensive in both time and space, increasing both the number of operations and the cost of brute-forcing. Hence crackers will need to use more circuitry to break passwords.

Of course, there's always this form of cracking:



(Source: xkcd 538)

Formalization. Let's make the notion of "expensive" a bit more formal. The idea is to force the use of the "most memory possible" for a given number of operations. More memory implies more circuitry required to implement.

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

Memory-hard algorithms are expensive to implement in either hardware or software.

Now, we want to move from particular algorithms to the underlying functions (that is, we would like to quantify over all possible algorithms). Intuitively, a *sequential memory-hard function* is one where (1) the fastest sequential algorithm is memory-hard; and (2) it is impossible for a parallel algorithm to asymptotically achieve lower cost.

Existence proof. Of course anyone can define anything. It's much better if the thing being defined actually exists. The scrypt paper then goes on to exhibit ReMix, which is a concrete example of a sequential memory hard function.

Finally, the paper concludes with an example of a more realistic (cache-aware) model and a hard function in that context, BlockMix.

Reduced-resource computation

In an n-body simulation, you can implement an optimization that trades off accuracy for performance. In that specific case, domain knowledge would enable you to skimp out on some unnecessary computation: points that are far away contribute only very small forces.

In [RHMS10], Martin Rinard summarizes two of his novel ideas for automatic or semiautomatic optimizations which trade accuracy for performance: early phase termination [Rin07] and loop perforation [HMS$^+$09]. Both of these ideas are applicable to code we've learned about in this class.

Early phase termination

We've talked about barriers quite a bit. Recall that the idea is that no thread may proceed past a barrier until all of the threads reach the barrier. Waiting for other threads causes delays. Killing slow threads obviously speeds up the program. Well, that's easy.

"Oh no, that's going to change the meaning of the program!"

Let's consider some arguments about when it may be acceptable to just kill (discard) tasks. Since we're not completely crazy, we can develop a statistical model of the program behaviour, and make sure that the tasks we kill don't introduce unacceptable distortions. Then when we run the program, we get an output and a confidence interval.

Two Examples. When might this work? Monte Carlo simulations are a good candidate; you're already picking points randomly. Raytracers can work as well. Both of these examples could spawn a lot of threads and wait for all threads to complete. In either case, you can compensate for missing data points, assuming that they look like the ones that you did compute.

Also recall that, in scientific computations, you're entering points that were measured (with some error) and that you're computing using machine numbers (also with some error). Computers are only providing simulations, not the ground truth; the question is whether the simulation is good enough.

Loop perforation

You can also apply the same idea to sequential programs. Instead of discarding tasks, the idea here is to discard loop iterations. Here's a simple example: instead of the loop,

```
for (i = 0; i < n; i++) sum += numbers[i];
```

simply write,

```
for (i = 0; i < n; i += 2) sum += numbers[i];
```

and multiply the end result by a factor of 2. This only works if the inputs are appropriately distributed, but it does give a factor 2 speedup.

Example domains. In [RHMS10], we can read that loop perforation works for evaluating forces on water molecules (in particular, summing numbers); Monte-Carlo simulation for swaption pricing; and video encoding. In that example, changing loop increments from 4 to 8 gives a speedup of 1.67, a signal to noise ratio decrease of 0.87%, and a bitrate increase of 18.47%, producing visually indistinguishable results. The computation looks like this:

```
min = DBL_MAX;
index = 0;
for (i = 0; i < m; i++) {
  sum = 0;
  for (j = 0; j < n; j++) sum += numbers[i][j];
  if (min < sum) {
    min = sum;
    index = i;
  }
}
```

The optimization changes the loop increments and then compensates.

Software Transactional Memory

Developers use software transactions by writing `atomic` blocks. These blocks are just like `synchronized` blocks, but with different semantics.

```
atomic {
  this.x = this.z + 4;
}
```

You're meant to think of database transactions, which I expect you to know about. The `atomic` construct means that either the code in the atomic block executes completely, or aborts/rolls back in the event of a conflict with another transaction (which triggers a retry later on).

Benefit. The big win from transactional memory is the simple programming model. It is far easier to program with transactions than with locks. Just stick everything in an atomic block and hope the compiler does the right thing with respect to optimizing the code.

Motivating Example. We'll illustrate STM with the usual bank account example[1].

[1]Apparently, bank account transactions aren't actually atomic, but they still make a good example.

```
transfer_funds(Account* sender, Account* receiver, double amount) {
  atomic {
    sender->funds -= amount;
    receiver->funds += amount;
  }
}
```

Using locks, we have two main options:

- Big Global Lock: Lock everything to do with modifying accounts. (This is slow; and you might forget to grab the lock).
- Use a different lock for every account. (Prone to deadlocks; may forget to grab the lock).

With STM, we do not have to worry about remembering to acquire locks, or about deadlocks.

Drawbacks. As I understand it, three of the problems with transactions are as follows:

- I/O: Rollback is key. The problem with transactions and I/O is not really possible to rollback. (How do you rollback a write to the screen, or to the network?)
- Nested transactions: The concept of nesting transactions is easy to understand. The problem is: what do you do when you commit the inner transaction but abort the nested transaction? The clean transactional fa cade doesn't work anymore in the presence of nested transactions.
- Transaction size: Some transaction implementations (like all-hardware implementations) have size limits for their transactions.

Implementations. Transaction implementations are typically optimistic; they assume that the transaction is going to succeed, buffering the changes that they are carrying out, and rolling back the changes if necessary.

One way of implementing transactions is by using hardware support, especially the cache hardware. Briefly, you use the caches to store changes that haven't yet been committed. Hardware-only transaction implementations often have maximum-transaction-size limits, which are bad for programmability, and combining hardware and software approaches can help avoid that.

Implementation issues. Since atomic sections don't protect against data races, but just rollback to recover, a datarace may still trigger problems in your program.

```
atomic {
  x++;
  y++;
}
```

```
atomic {
  if (x != y)
     while (true) { }
}
```

In this silly example, assume initially `x = y`. You may think the code will not go into an infinite loop, but it can.

References

[HMS+09] Henry Hoffmann, Sasa Misailovic, Stelios Sidiroglou, Anant Agarwal, and Martin Rinard. Using code perforation to improve performance, reduce energy consumption, and respond to failures. Technical Report MIT-CSAIL-TR-2009-042, MIT CSAIL, Cambridge, MA, September 2009.

[Per09] Colin Percival. Stronger key derivation via sequential memory-hard functions, 2009. Online; accessed 6-January-2016. URL: `http://www.bsdcan.org/2009/schedule/attachments/87_scrypt.pdf`.

[RHMS10] Martin Rinard, Henry Hoffmann, Sasa Misailovic, and Stelios Sidiroglou. Patterns and statistical analysis for understanding reduced resource computing. In *Proceedings of Onward! 2010*, pages 806–821, Reno/Tahoe, NV, USA, October 2010. ACM. URL: `http://doi.acm.org/10.1145/1932682.1869525`.

[Rin07] Martin Rinard. Using early phase termination to eliminate load imbalances at barrier synchronization points. In *Proceedings of OOPSLA 2007*, pages 369–386, Montreal, Quebec, Canada, October 2007.