SPARKNaCl: a verified, fast re-implementation of TweetNaCl

or...

"What I did during lockdown..."

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- Goal and not goals...
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TweetNaCl?

- A complete implementation of the NaCl crypto API, written in C.

- Source code fits in 100 tweets!

- No comments at all in the code...

    - One 16-page technical paper describes how it works.

    - Assurance largely rests on dynamic test, lots of users and the formidable reputation of the authors.

TweetNaCl?

- Core algorithms:
    - Stream cipher: Salsa20
    - Authentication: Poly1305
    - Hash: SHA2-512
    - Signatures: Ed25519
    - Key exchange: X25519 (ECDH using Curve25519)

TweetNaCl?

- The code is very hard to understand...
  - No comments...
  - Cunning mathematical tricks to achieve acceptable performance...
  - “Constant Time” programming style to mitigate side-channel attack...
  - Somewhat terse overview in the paper...
- For example...

TweetNaCl?

There's a mistake in this paragraph...
Can you spot it?

- From the paper:

"**Arithmetic modulo the group order**. Signing requires reduction of a 512-bit integer modulo the order of the Curve25519 group, a prime $p = 2^{252}+\delta$ where $\delta \approx 2^{124.38}$. We store this integer as a sequence of limbs in radix 2^8. We eliminate the top limb of the integer, say $2^{504}b$, by subtracting $2^{504}b$ and also subtracting $2^{252}\delta b$; we then perform a partial carry so that 20 consecutive limbs are each between -2^7 and 2^7. We repeat this procedure to eliminate subsequent limbs from the top. We similarly eliminate any remaining multiple of 2^{252}, leaving an integer between $-1.1{\cdot}2^{251}$ and $1.1 \cdot 2^{251}$. We then multiply the final carry bit by p and add, obtaining an integer between 0 and $p - 1$, and carry in the traditional way so that each limb is between 0 and 255."

- Becomes...

```c
// Just for completeness...

typedef long long i64;

// Note that a "gf" is 1024 bits
// or 128 bytes
typedef i64 gf[16];

// Some tweet-saving abbreviations...
#define sv static void

#define FOR(i,n) for (i = 0;i < n;++i)
```

```
sv modL(u8 *r,i64 x[64])
{
  i64 carry,i,j;
  for (i = 63;i >= 32;--i) {
    carry = 0;
    for (j = i - 32;j < i - 12;++j) {
      x[j] += carry - 16 * x[i] * L[j - (i - 32)];
      carry = (x[j] + 128) >> 8;
      x[j] -= carry << 8;
    }
    x[j] += carry;
    x[i] = 0;
  }
  carry = 0;
  FOR(j,32) {
    x[j] += carry - (x[31] >> 4) * L[j];
    carry = x[j] >> 8;
    x[j] &= 255;
  }
  FOR(j,32) x[j] -= carry * L[j];
  FOR(i,32) {
    x[i+1] += x[i] >> 8;
    r[i] = x[i] & 255;
  }
}
```

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Why Bother?

- There is lots of other excellent work on formal verification of Crypto libraries – MSR Everest, AWS, Galois' Cryptol & SAW, Jasmin & EasyCrypt, HACSPEC, Fiat Cryptography etc. etc.

- There are several very highly respected implementations of NaCl out there, including LibSodium.

- Why bother with another one?

Why Bother?

- Can a modern deductive verification system and programming language cope with a library like NaCl?

  1. What can be proven anyway?

  2. What level of automation can be achieved?

Myth

“Formal is Slow...”

- So-called “Formal” languages have a reputation in industry for being “too slow” for production use.
- Put another way: “Our code has to go really fast, so we can only write it on C, C, C, or C... (or assembly language...)”
- Can a “formal” language like SPARK really compete?

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Goals...

- A re-implementation of TweetNaCl in SPARK, covering the whole library and NaCl API.
- It shall pass all NaCl regression tests.
- Retain "constant time" programming style.
- Fully "auto-active" proof of *at least* type- and memory safety for the whole thing.
  - It's all about the types... (and contracts...)
  - No "interactive" proof please...

Goals...

- Compatible with the “Zero Footprint” runtime library of GCC/GNAT
    - No COTS or libraries.
    - “Heap free” programming style, so will run on ”bare-metal” targets with no OS at all.
- *Same code* will compile and run on *any* target CPU/OS.

Goals...

- Performance and code size competitive with TweetNaCl.
- Will we find any bugs? En-passant, will we find bugs in TweetNaCl too?
  - We have form in this area: a subtle corner case bug was found in the Skein hash algorithm by re-implementing it in SPARK...

NOT Goals...

- Don’t try to compete with LibSodium’s performance...
- Don’t try to prove partial correctness (unless strictly necessary).
- Don’t try to prove mathematical security-related properties of Curve25519, Ed25519 and so on...

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Some stats

- SPARKNaCl is 1786 *logical* lines of code, of which 664 statements and 1122 declarations.

- 111 subprogram bodies, comprising 74 procedures and 37 functions.

Contracts...

- Types and subtypes: LOTS!
- Precondition: 27
- Postcondition: 20
- Dynamic_Predicate on subtype: 8
- Assert: 51

Some stats

- Loop statements: 56
  - User-written loop invariant not required (auto-generated invariant is good enough): 25
  - User-written loop invariant required, but trivial: 18
  - User-written loop invariant, but hard: 13
- "Hard" = "Hours or days of effort to understand the algorithm, and get the proof to automate OK"

The hard bits...

- The most “difficult” (for formal verification) loops are in:
  - “*” operator for type GF (256-bit large integer)
  - The “Carry-and-Reduce (Car)” functions for reducing a GF large integer modulo 2^{255}-19.
  - The “Modulo L” operation (see above...) within the Ed25519 Sign and Open functions.
  - The first two are *also* the most performance-critical inner loops of the Sign algorithm...

What has been proven?

- “Type and Memory Safety”
    - No undefined behaviour
    - No dependence on unspecified behaviour
    - Nothing that would normally raise an exception: range violation, arithmetic overflow, buffer overflow, division-by-zero etc.
    - (Note: there are no pointers! And no heap...)
    - All object values satisfy all type declarations.
- All user-supplied contracts are true (pre, post, loop invariants, asserts...)

What has been proven?

- Observations:

    1. Types are cool. Better (i.e. “stronger”) types get you better proof. Never write a “Pre” or an “Assert” where a type could do the job just as well.

    2. Expressive use of types is the key to achieving proof automation and completeness.

    3. “Type safety” is not a “fixed price” concept in SPARK.
    More types -> More proof.

    4. Types serve as a (weak-ish) specification of correctness properties...

    5. Fully predicated types from Ada2012 (aka “Liquid Types” in Haskell and OCAML) are awesome.

Predicated types? Eh?

```
LM    : constant := 65536; -- Limb Modulus
LMM1  : constant := 65535; -- "LM Minus 1”
R2256 : constant := 38; -- We’ll come back to this one...
--  "Maximum GF Limb Coefficient”
MGFLC : constant := (R2256 * 15) + 1;
--  "Maximum GF Limb Product”
MGFLP : constant := LMM1 * LMM1;

subtype GF64_Any_Limb is I64 range -LM .. (MGFLC * MGFLP);
type GF64 is array (Index_16) of GF64_Any_Limb;
subtype GF64_Normal_Limb is GF64_Any_Limb range 0 .. LMM1;
subtype Normal_GF64 is GF64
  with Dynamic_Predicate =>
    (for all I in Index_16 => Normal_GF64 (I) in
                                    GF64_Normal_Limb);
```

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What has been proven?

- The code generates 907 Verification Conditions.
- Final result: 100% automation/completeness for all VCs using Z3, CVC4 and Alt-Ergo provers.
- Of those 907
  - 777 are trivial and proven by all 3 provers.
  - 130 are “hard” in that at least one prover fails to prove it.

Proof Performance

- Proof of the whole library takes about 4.5 minutes from scratch on my laptop (using 16 threads).
- Results are cached to improve re-proof of units that haven't changed.
- Generating lots of independent VCs parallelizes very well... Just throw more CPU cores at it...
    - but...relies on strict modularity and contracts in SPARK...so "whole program" or "inter-procedural" proof is never required...

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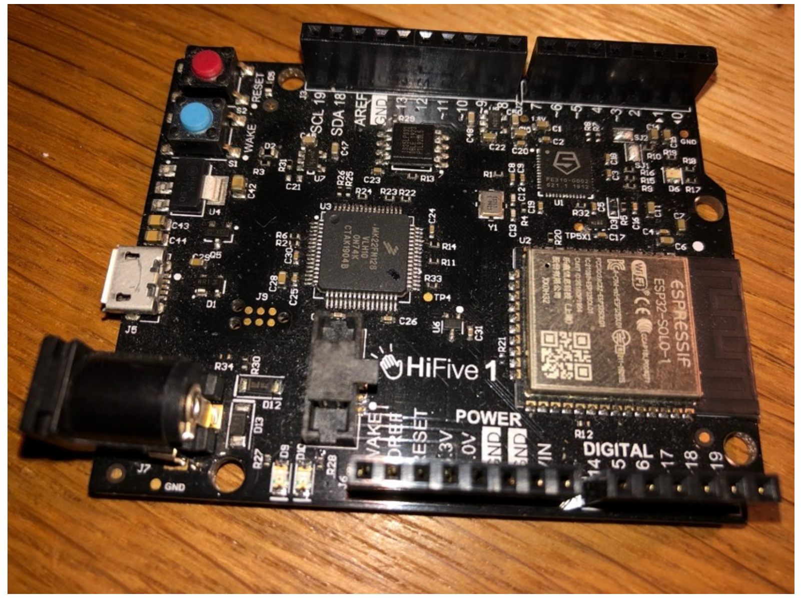
Performance



- Test setup:
  - HiFive 1 Rev B board
  - SiFive FE310 32-bit RISC-V
  - GNAT Community 2020 (GCC 8.4.1) for both C and Ada
  - Test an Ed25519 “Sign” operation on a 256 byte message using both SPARKNaCl and TweetNaCl.

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Expectations...

- Why SPARK might be slower than C...
  - Functional programming style (and first-class array types) implies return-by-copy for function return values, which can be large blocks of data. Therefore: slow!
  - TweetNaCl only does *two* normalization calls after “*” on GF type, but this cannot be proven in SPARKNaCl which does *three* normalization calls.
  - SPARKNaCl sanitizes local variables before return from subprograms. TweetNaCl does not.

Expectations...

- Why SPARK might be faster than C...
  - SPARK is proven to be free of "runtime errors", so can be compiled with no dynamic type checking – just like C!
  - SPARK has many intrinsic properties that make it amenable to optimization: no aliasing, no undefined behaviour, no side-effects in expressions etc.
  - So... Let's experiment with several of the standard optimization levels...

Baseline results

- Numbers are Millions of CPU cycles, so *smaller is better*.

Optimization Level	C	SPARK
0	241.83	198.03
1	97.65	98.03
2	84.99	93.86

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Baseline results

- SPARK wins at –O0! What happened?
    - Inlining of expression functions and Intrinsic Shift/Rotate functions work properly in SPARK at –O0...
    - Jason Donenfeld's "Carry-and-Reduce" code from WireGuard is a bit faster (and easier to prove...)
    - "Return-Slot Optimization" (even at –O0) removes the cost of functional return-by-copy in many cases.

Improvement

- The golden rule: improve performance, but *never break the proof!*
    - All improvements retain 100% completeness and automation of the proof.
- Proof actually stops me making dumb mistakes (e.g. making the code faster, but introducing a type-safety bug...)
- Proof can *suggest* or *guide* improvements (more of which later...)
    - (Optional skip to slide 75 here)

Round 1...

- Not enough time to go over all the optimizations...
- In the order I discovered them...
  - Optimal initialization of large objects (using proof rather than data-flow analysis)
  - Manual partial redundancy elimination.
  - Manual unroll of “*” inner loop
  - Removal of array “slices” in SPARK Code
  - Application of these changes to TweetNaCl as well as SPARK to get a “level playing field...”

Round 1 Results

- Numbers are Millions of CPU cycles, so *smaller is better*.

Optimization Level	Original C	Revised C	Original SPARK	Revised SPARK
0	241.83	175.74	198.03	181.74
1	97.65	62.32	98.03	69.96
2	84.99	51.00	93.86	57.82

Round 2...

- Observation: TweetNaCl stores a 256-bit integer using 16 64-bit “digits” (so 1024 bits) to accommodate the worst-case range of the digits during a “*” operation.
  - This makes for compact code, but
  - ...is wasteful of storage...
  - All mathematical operations on digits are 64-bit integer, which is *really slow* on 32-bit RISC-V (6 instructions for a multiplication instead of 1...)

Round 2...

- Observation 2: We have proved that 64 bits are required to accommodate the intermediate result of a "*" operation.

- BUT... Subsequent operations can be done in 32-bit arithmetic (e.g. the *second* call to "carry and reduce" can be all 32-bit...) and we can store a GF value in exactly 256 bits with no waste.

  - Assignments are faster. Possibly better performance from data cache too...

- Use the proof system and predicated types to prove that all these transformations are OK...

- I have NOT even tried to port these changes to the C code...

Round 2 Results

- Numbers are Millions of CPU cycles, so *smaller is better*.

Optimization Level	Original C	Revised C	Original SPARK	Revised SPARK
0	241.83	175.74	198.03	167.48
1	97.65	62.32	98.03	32.60
2	84.99	51.00	93.86	27.43

Round 3...

- Introduce –O3 (but with explicit No_Unroll pragma applied to all loops)
- Introduce –Os
- Try RV32IMC (Compressed) instruction set.
    - Smaller code size, so possibly better I-Cache hit rate?
    - Penalty for branch to mis-aligned instruction, though (on the FE310 core...)
- So, try RV32IMC but with forced 4-byte alignment on all basic block headers.

Round 3 Results

- Numbers are Millions of CPU cycles, so *smaller is better*.

Optimization Level	Original C	Revised C	Original SPARK	Revised SPARK
0	241.83	175.74	198.03	174.47
1	97.65	62.32	98.03	32.54
2	84.99	51.00	93.86	41.10
3				25.69
s				30.52

Round 3 – Summary

- Best performance: 25.69 Million cycles at –O3 and RV32IMC_align_4
- Smallest worst-case stack usage: 2512 bytes at –Os
- Smallest code size: 18280 bytes at –Os (for the whole library)

Round 4...

- Manual loop fusion in “+” and “-” functions with first “Car” operation on GF.

- Narrowing of integer “*” in multiplication of GF digits. (If all digits are always 16-bit unsigned, then multiplying two digits is always OK in 32-bit arithmetic, right?)

    - Proof system says “Yes”...

- Unroll first iteration of “*” on GF to avoid double-initialization of the digits of the intermediate result.

Round 4 Results

- Numbers are Millions of CPU cycles, so *smaller is better*.

Optimization Level	Original C	Revised C	Original SPARK	Revised SPARK
0	241.83	175.74	198.03	109.20
1	97.65	62.32	98.03	30.21
2	84.99	51.00	93.86	24.52
3				23.58
s				27.99

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Round 5

- New compiler! GNAT Community 2021 is GCC 10.3.1 and incorporates improvements to Return-Slot Optimization, so RSO gets enabled for more function calls in SPARK code...

    - Thanks to Eric Botcazou at AdaCore for this work...

- ...and any other improvements that come along...

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Round 5 Results

- Numbers are Millions of CPU cycles to form an Ed25519 Signature of a 256 byte message, so *smaller is better*.

Optimization Level	Original C	Revised C	Original SPARK	Final SPARK
0	241.83	175.74	198.03	110.20
1	97.65	62.32	98.03	30.06
2	84.99	51.00	93.86	24.37
3				23.22
s				27.62

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Observations

- Optimization comes in many flavours:
    - Language-specific (e.g. array slices and RSO in SPARK)
    - Micro-architecture specific (RV32IM or RV32IMC with or without instruction alignment?)
    - Algorithmic (with proof support)
    - “Back porting” of optimizations (such as PRE and loop unrolling) so the benefit of them appears at –O0...

Observations

- It's very hard to predict what you're gonna get... No substitute for measurement and experimentation...
- "Proof driven optimization" is great. It stops me making dumb mistakes and proves that transformations are semantics-preserving...
  - For example, operator narrowing and storage compression of the GF type and its operators.

Observations

- Does your project still compile at –O0? Why? Optimization of SPARK is semantics-preserving!
- Loop invariants are still too hard to find for anything that's remotely non-trivial...
- Reproducibility of results with SMT provers is poor...
    - New version of prover? Might break proof... ☹
    - Prover timeouts are a *terrible* idea! ☹

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A few ideas...

- Do all the performance analysis again on an RV64 target.
- Do it all again using LLVM.
- Submit bug reports against CVC4, Z3 etc. for all the unproven VCs... Perhaps CVC5 will prove the whole thing alone?
- Prove that *two* applications of "Car" following "*" really is all you need. (Hint: this has been done in Coq so it must be possible, but can it be automated?)
- Verification of "Constant Time" property using Info-flow analysis of program-dependence graph. TBD...

Resources

- SPARKNaCl

https://github.com/rod-chapman/SPARKNaCl

- Long explanations of performance optimization:

https://blog.adacore.com/performance-analysis-and-tuning-of-sparknacl
https://blog.adacore.com/doubling-the-performance-of-sparknacl-again
https://blog.adacore.com/sparknacl-with-gnat-and-spark-community-2021-port-proof-and-performance

- GNAT/GCC and SPARK Toolsets,

https://www.adacore.com/download/more