Fast, Safe, Pure-Rust Elliptic Curve Cryptography

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Noisebridge 10th Anniversary
September 2017

Introductions

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- Don't worry! We'll cover the basic terminology, and — with a tad of high-school level algebra — you should be able to follow along just fine.
- If not, still don't worry! All questions are welcome, and if you're shy please feel free to talk to us privately afterwards, either in person or online.

Overview

What is `curve25519-dalek`?

Rust is excellent

Implementing cryptography with `-dalek`

What is `curve25519-dalek`?

Anatomy of an elliptic curve cryptography implementation

Applications	
Protocol	Protocol-specific library
Group	`curve25519-dalek`
Elliptic Curve	
Finite Field	
CPU	

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Our implementation was originally based on Adam Langley's `ed25519` Go code, which was in turn based on the reference `ref10` implementation.

Historical Implementations

In order to talk about what `curve25519-dalek` is, and why we made it, it's important to revisit other elliptic curve libraries, their designs, and common problems.

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- Assumptions about how these lower-level pieces will be used aren't necessarily correct if someone wanted to reuse the code to implement a different protocol.
- Excessive copy-pasta with minor tweaks by other cryptographers (worsened by the fact that some cryptographers think that releasing unsigned tarballs of their implementations *inside* another tarball of a benchmarking suite is somehow an appropriate software distribution mechanism).

Historical Implementations: Part I (cont.)

This leads to large, monolithic codebases which are idiosyncratic, incompatible with one another, and highly specialised to perform only the single protocol they implement (usually, a signature scheme or Diffie-Hellman key exchange).

The modus operandi for implementing cryptographic software is writing microarchitecture-optimised, *artisinal assembly*, with the purported goals of lower clock cycles and constantimedness. (However the neither goal is guaranteed, as we'll see later.)

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```
:name:fe:t0:t1:t2:t3:t4:t5:t6:t7:t8:t9:z:out:
fe r:var/r=fe:
enter f:enter/f:>z1=fe#11:
return:nofallthrough:<z_252_3=fe#12:leave:
h=f*g:<f=fe:<g=fe:>h=fe:asm/fe_mul(>h,<f,<g);:
h=f^2^k:<f=fe:>h=fe:#k:asm/fe_sq(>h,<f); for
#(i = 1;i !lt; k;++i) fe_sq(>h,>h);:
:
[...]
fe z_100_50
fe z_100_0
fe z_200_100
fe z_200_0
fe z_250_50
fe z_250_0
fe z_252_2
fe z_252_3

enter pow22523

[...]
z_10_5 = z_5_0^2^5
z_10_0 = z_10_5*z_5_0
z_20_10 = z_10_0^2^10
z_20_0 = z_20_10*z_10_0
z_40_20 = z_20_0^2^20
z_40_0 = z_40_20*z_20_0
z_50_10 = z_40_0^2^10
z_50_0 = z_50_10*z_10_0
z_100_50 = z_50_0^2^50
z_100_0 = z_100_50*z_50_0
z_200_100 = z_100_0^2^100
z_200_0 = z_200_100*z_100_0
z_250_50 = z_200_0^2^50
z_250_0 = z_250_50*z_50_0
z_252_2 = z_250_0^2^2
z_252_3 = z_252_2*z1
return
```

→

```
/* qhasm: z_20_10 = z_10_0^2^10 */
/* asm 1: fe_sq(>z_20_10=fe#2,<z_10_0=fe#1); for (i = 1;i < 10;++i) fe_sq(>z_20_10=fe#2,>z_20_10=fe#2); */
/* asm 2: fe_sq(>z_20_10=t1,<z_10_0=t0); for (i = 1;i < 10;++i) fe_sq(>z_20_10=t1,>z_20_10=t1); */
fe_sq(t1,t0); for (i = 1;i < 10;++i) fe_sq(t1,t1);

/* qhasm: z_20_0 = z_20_10*z_10_0 */
/* asm 1: fe_mul(>z_20_0=fe#2,<z_20_10=fe#2,<z_10_0=fe#1); */
/* asm 2: fe_mul(>z_20_0=t1,<z_20_10=t1,<z_10_0=t0); */
fe_mul(t1,t1,t0);

/* qhasm: z_40_20 = z_20_0^2^20 */
/* asm 1: fe_sq(>z_40_20=fe#3,<z_20_0=fe#2); for (i = 1;i < 20;++i) fe_sq(>z_40_20=fe#3,>z_40_20=fe#3); */
/* asm 2: fe_sq(>z_40_20=t2,<z_20_0=t1); for (i = 1;i < 20;++i) fe_sq(>z_40_20=t2,>z_40_20=t2); */
fe_sq(t2,t1); for (i = 1;i < 20;++i) fe_sq(t2,t2);

/* qhasm: z_40_0 = z_40_20*z_20_0 */
/* asm 1: fe_mul(>z_40_0=fe#2,<z_40_20=fe#3,<z_20_0=fe#2); */
/* asm 2: fe_mul(>z_40_0=t1,<z_40_20=t2,<z_20_0=t1); */
fe_mul(t1,t2,t1);

/* qhasm: z_50_10 = z_40_0^2^10 */
/* asm 1: fe_sq(>z_50_10=fe#2,<z_40_0=fe#2); for (i = 1;i < 10;++i) fe_sq(>z_50_10=fe#2,>z_50_10=fe#2); */
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/* qhasm: z_100_50 = z_50_0^2^50 */
/* asm 1: fe_sq(>z_100_50=fe#2,<z_50_0=fe#1); for (i = 1;i < 50;++i) fe_sq(>z_100_50=fe#2,>z_100_50=fe#2); */
/* asm 2: fe_sq(>z_100_50=t1,<z_50_0=t0); for (i = 1;i < 50;++i) fe_sq(>z_100_50=t1,>z_100_50=t1); */
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/* qhasm: z_200_100 = z_100_0^2^100 */
/* asm 1: fe_sq(>z_200_100=fe#3,<z_100_0=fe#2); for (i = 1;i < 100;++i) fe_sq(>z_200_100=fe#3,>z_200_100=fe#3); \
*/
/* asm 2: fe_sq(>z_200_100=t2,<z_100_0=t1); for (i = 1;i < 100;++i) fe_sq(>z_200_100=t2,>z_200_100=t2); */
fe_sq(t2,t1); for (i = 1;i < 100;++i) fe_sq(t2,t2);
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"THE DEATH OF OPTIMISING COMPILERS"

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- *I can keep going.*

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Rust is excellent

Constant-time code and LLVM

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In the future, we'd like to do CI testing of the generated binaries: Rust, but verify.

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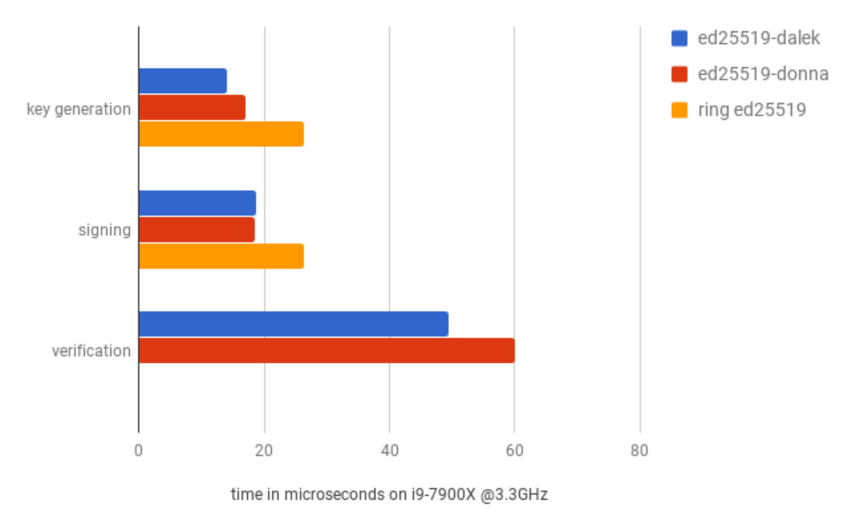
Filippo Valsorda (@FiloSottile)'s `rustgo` allows coordinating Rust function calls with the Go runtime with minimal overhead, and used calling `curve25519-dalek` as an example. (It's $3\times$ faster than the implementation in the Go standard library).

How fast is it?



Implementing cryptography with `-dalek`

Implementing EdDSA signatures in `ed25519-dalek`

To create an EdDSA signature on a message, m, we first generate our keypair (sk, pk) by choosing the secret scalar, $sk \xleftarrow{\$} \mathbb{Z}/2^{32}\mathbb{Z}$, that is, a random 32-byte string.

Implementing EdDSA signatures in `ed25519-dalek`

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```
impl SecretKey {
    pub fn generate(csprng: &mut Rng) -> SecretKey {
        let mut sk: SecretKey = SecretKey([0u8; 32]);

        csprng.fill_bytes(&mut sk.0);

        sk
    }
}
```

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We then hash sk (RFC8032 specifies SHA-512), take the lower 256 bits of the digest, reduce it as a scalar $x \in \mathbb{Z}/\ell\mathbb{Z}$, and then compute the public key as a point on the curve, $pk \leftarrow xB$ where B is the distinguished basepoint.

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```rust
impl PublicKey {
    pub fn from_secret<D>(secret_key: &SecretKey) -> PublicKey
            where D: Digest<OutputSize = U64> + Default {
        let mut h:         D = D::default();
        let mut hash: [u8; 64] = [0u8; 64];
        let     pk:   [u8; 32];
        let mut digest: &mut [u8; 32];

        h.input(secret_key.as_bytes());
        hash.copy_from_slice(h.fixed_result().as_slice());

        digest = array_mut_ref!(&mut hash, 0, 32);
        digest[0]  &= 248;
        digest[31] &= 127;
        digest[31] |= 64;

        pk = (&Scalar(*digest) * &constants::ED25519_BASEPOINT_TABLE).compress_edwards().to_bytes();
        PublicKey(CompressedEdwardsY(pk))
    }
```

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To sign the message m, we “expand” sk by hashing it and reduce the low 256-bits to a scalar `sk_expanded` $\in \mathbb{Z}/\ell\mathbb{Z}$. We then hash the concatenation of the high 256-bits of the digest and the message, and reduce the resulting digest into a scalar $r_0 \in \mathbb{Z}/\ell\mathbb{Z}$ which we multiply by the basepoint to produce the point $r \leftarrow r_0 \times B$.

Next, because relying on the sanctity of hash functions is an enormously appropropriate model for real world scenarios, we now compress r into its Edwards y-coordinate (as a 32-byte array). We concentenate the compressed form with the public key (also compressed), as well as — again — the message. The output digest is again reduced as a scalar `hram_digest` $\in \mathbb{Z}/\ell\mathbb{Z}$.

Finally, we compute $s \leftarrow$ `hram_digest` $\times$ `sk_expanded` $+ r_0$ and t as the compressed Edwards y-coordinate of r.

The signature now consists of 32 bytes of t concatenated with 32 bytes of s.

Implementing EdDSA signatures in `ed25519-dalek`

```rust
impl Keypair{
    pub fn sign<D>(&self, message: &[u8]) -> Signature
            where D: Digest<OutputSize = U64> + Default {
        let mut h: D = D::default();
        let mut hash: [u8; 64] = [0u8; 64];
        let mut signature_bytes: [u8; 64] = [0u8; SIGNATURE_LENGTH];

        h.input(self.secret.as_bytes());
        hash.copy_from_slice(h.fixed_result().as_slice());

        let expanded_key_secret: Scalar = expand_key(&hash);

        h = D::default(); h.input(&hash[32..]); h.input(&message);
        hash.copy_from_slice(h.fixed_result().as_slice());

        let mesg_digest: Scalar = Scalar::reduce(&hash);

        let r: ExtendedPoint = &mesg_digest * &constants::ED25519_BASEPOINT_TABLE;

        h = D::default(); h.input(&r.compress_edwards().to_bytes()[..]); h.input(self.public.as_bytes()); h.input(&message);
        hash.copy_from_slice(h.fixed_result().as_slice());

        let hram_digest: Scalar = Scalar::reduce(&hash);

        let s: Scalar = Scalar::multiply_add(&hram_digest, &expanded_key_secret, &mesg_digest);
        let t: CompressedEdwardsY = r.compress_edwards();

        signature_bytes[..32].copy_from_slice(&t.0); signature_bytes[32..64].copy_from_slice(&s.0);
        Signature(*array_ref!(&signature_bytes, 0, 64))
    }

    /// Verify a signature on a message with this keypair's public key.
    pub fn verify<D>(&self, message: &[u8], signature: &Signature) -> bool
            where D: FixedOutput<OutputSize = U64> + BlockInput + Default + Input {
        self.public.verify::<D>(message, signature)
    }
}
```

For signature verification,

Implementing EdDSA signatures in ed25519-dalek

```
impl PublicKey {
    pub fn verify<D>(&self, message: &[u8], signature: &Signature) -> bool
            where D: Digest<OutputSize = U64> + Default {
        use curve25519_dalek::edwards::vartime;

        let mut h: D = D::default();
        let mut a: ExtendedPoint;
        let ao:  Option<ExtendedPoint>;
        let r: ExtendedPoint;
        let digest: [u8; 64];
        let digest_reduced: Scalar;

        if signature.0[63] & 224 != 0 {
            return false;
        }
        ao = self.decompress();

        if ao.is_some() {
            a = ao.unwrap();
        } else {
            return false;
        }
        a = -(&a);

        let top_half:    &[u8; 32] = array_ref!(&signature.0, 32, 32);
        let bottom_half: &[u8; 32] = array_ref!(&signature.0,  0, 32);

        h.input(&bottom_half[..]);
        h.input(&self.to_bytes());
        h.input(&message);

        let digest_bytes = h.fixed_result();
        digest = *array_ref!(digest_bytes, 0, 64);
        digest_reduced = Scalar::reduce(&digest);
        r = vartime::double_scalar_mult_basepoint(&digest_reduced, &a, &Scalar(*top_half));

        if slices_equal(bottom_half, &r.compress_edwards().to_bytes()) == 1 {
            return true
        } else {
            return false
        }
    }
}
```

```rust
impl PublicKey {
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```

To sign the message m, we "expand" sk by hashing it and reduce the low 256-bits to a scalar `sk_expanded` $\in \mathbb{Z}/\ell/ZZ$. We then hash the concatenation of the high 256-bits of the digest, the public key (compressed to only the Edwards y-coordinate, as an array of 32 bytes), and the message, and reduce the resulting digest into a scalar $r_0 \in \mathbb{Z}/\ell\mathbb{Z}$

Implementing rangeproofs with `-dalek`

Another type of zero-knowledge proof is a rangeproof: proving that a secret number lies in a particular range, without revealing any other information.

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Basic idea: to prove $x \in [0, b^n]$, write x in base b as $x = \sum_{i=0}^{n-1} x_i b^i$, and prove that each digit is in range: $x_i \in [0, b]$.

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We implemented the Back-Maxwell rangeproof, which uses $b = 3$ and shares data between digits to save space.

Implementing rangeproofs with -dalek: (partial) code

```
// mi_H[i] = m^i * H = 3^i * H in the loop below, construct these serially here:
let mut mi_H = vec![*H; n];
let mut mi2_H = vec![*H; n];
for i in 1..n {
    mi2_H[i-1] = &mi_H[i-1] + &mi_H[i-1];
    mi_H[i] = &mi_H[i-1] + &mi2_H[i-1];
}
mi2_H[n-1] = &mi_H[n-1] + &mi_H[n-1];

// Need to collect into a Vec to get par_iter()
let indices: Vec<_> = (0..n).collect();
let compressed_Ris: Vec<_> = indices.par_iter().map(|j| {
    let i = *j;

    let Ci_minus_miH = &self.C[i] - &mi_H[i];
    let P = vartime::multiscalar_mult(&[self.s_1[i], -&self.e_0], &[G, Ci_minus_miH]);
    let ei_1 = Scalar::hash_from_bytes::<Sha512>(P.compress().as_bytes());

    let Ci_minus_2miH = &self.C[i] - &mi2_H[i];
    let P = vartime::multiscalar_mult(&[self.s_2[i], -&ei_1], &[G, Ci_minus_2miH]);
    let ei_2 = Scalar::hash_from_bytes::<Sha512>(P.compress().as_bytes());

    let Ri = &self.C[i] * &ei_2;

    Ri.compress()
}).collect();
```

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- `zkp` https://github.com/hdevalence/zkp
  A DSL resembing Camenisch-Stadler notation for proving statements about discrete logarithms in the Decaf group on curve25519

Thank you!

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