Edwards coordinates for elliptic curves, part 2

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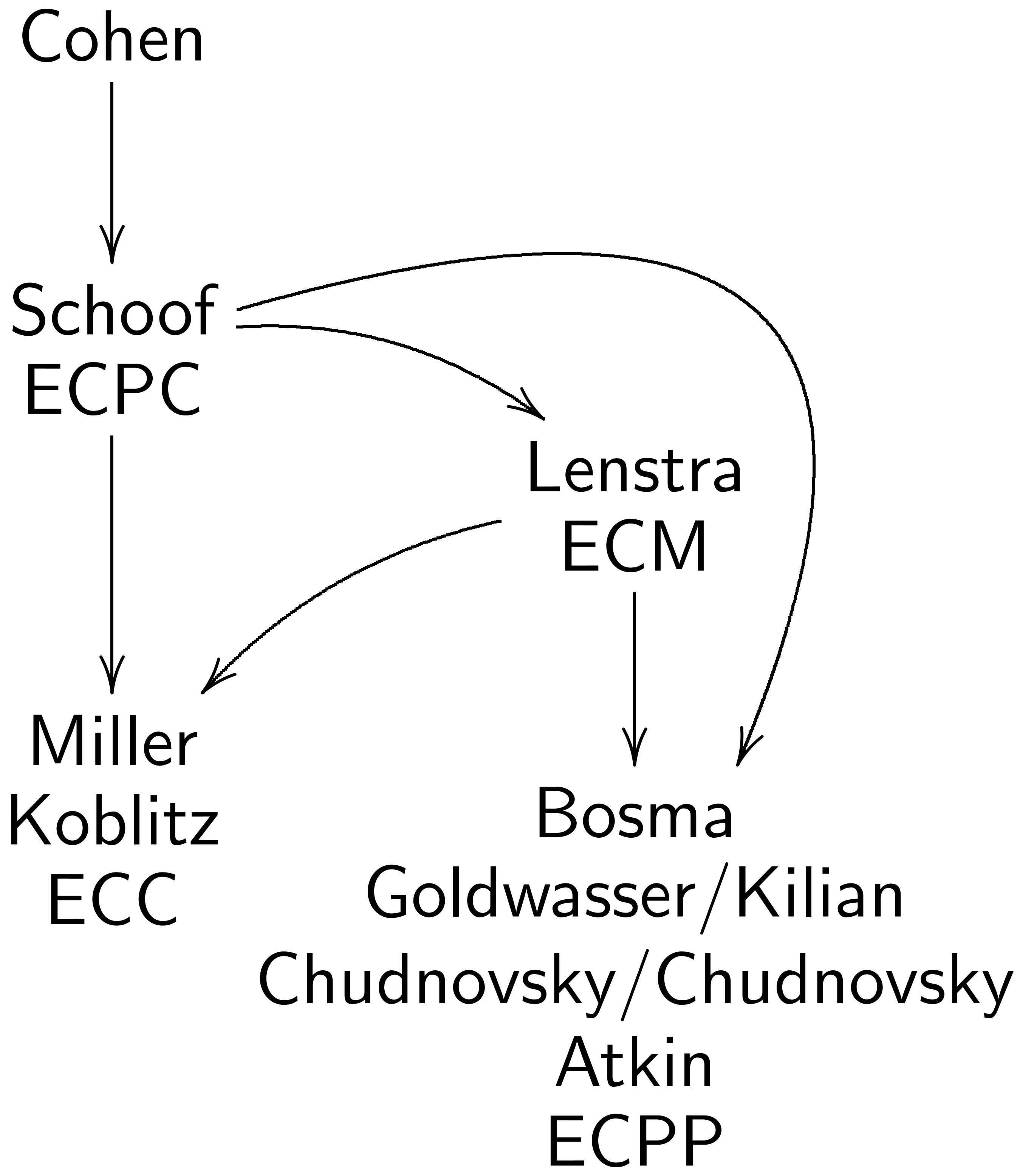
(Joint work with Tanja Lange)


Cohen
Schoof
ECPC
Lenstra
ECM
Miller
Koblitz
ECC
Bosma
Goldwasser/Kilian
Chudnovsky/Chudnovsky
Atkin
ECPP

Elliptic-curve signatures

Standardize a prime $p = 2^{255} - 19$.
Not too small; want hard ECDL!
Close to $2^{\cdots}$ for fast arithmetic.

Standardize a "safe" elliptic curve E over $\mathbf{F}_p$: $x^2 + y^2 = 1 + dx^2y^2$ where $d = 1 - 1/121666$.
$\#E(\mathbf{F}_p) = 8q$ where q is prime.
$2(p+1) - \#E(\mathbf{F}_p) = 4 \cdot \text{prime}$.

(2005 Bernstein "Curve25519: new Diffie-Hellman speed records" as $y^2 = x^3 + 486662x^2 + x$)

Standardize $B \in E(\mathbf{F}_p)$, order q.
Standardize a "hash function" H.

Signer has 32-byte secret key
$n \in \{0, 1, \ldots, 2^{256} - 1\}$.

Everyone knows signer's 32-byte public key: compressed nB.

To sign a message m:
generate a secret s;
compute $R = sB$;
compute $t = H(R, m)s + n \bmod q$;
transmit (m, compressed R, t).

To verify (m, compressed R, t):
verify $tB = H(R, m)R + nB$.

(first similar idea: 1985 ElGamal;
many generalizations, variations;
these choices: 2006 van Duin)

Bottleneck: Several types of elliptic-curve scalar multiplication.

Generating key:
given 256-bit integer n,
fixed $B \in E(\mathbf{F}_p)$, compute nB.

Generating signature: Same.

Verifying signature:
given 256-bit t, 256-bit h,
fixed B, variable R,
compute $tB - hR$.

Similar bottleneck for ECDH:
given 256-bit n, variable R,
compute nR.

Optimizing scalar multiplication

Crypto 1985, Miller, "Use of elliptic curves in cryptography":

Using division-polynomial recursions can compute nP given P "in $26 \log_2 n$ multiplications"; but can do better!

"It appears to be best to represent the points on the curve in the following form: Each point is represented by the triple (x, y, z) which corresponds to the point $(x/z^2, y/z^3)$."

1986 Chudnovsky/Chudnovsky, "Sequences of numbers generated by addition in formal groups and new primality and factorization tests":

"The crucial problem becomes the choice of the model of an algebraic group variety, where computations mod p are the least time consuming."

For "traditional" $(X/Z^2, Y/Z^3)$:
Chudnovsky/Chudnovsky
state explicit formulas using
8**M** for DBL if $a_4 = -3$;
16**M** for ADD.

"We suggest to write
addition formulas involving
(X, Y, Z, Z^2, Z^3)."
9**M** DBL if $a_4 = -3$; 14**M** ADD.

Also operation counts for
projective coordinates $(X : Y : Z)$
representing $(X/Z, Y/Z)$;
Hessian curves; Jacobi quartics;
Jacobi intersections.

Asiacrypt 1998,
Cohen/Miyaji/Ono, “Efficient elliptic curve exponentiation using mixed coordinates”:

1. Faster X, Y, Z, Z^2, Z^3 formulas than Chudnovsky/Chudnovsky!
Compute Z^2, Z^3 only for points that will be added.

2. A new coordinate system; speedups in some cases.

3. A new inversion strategy.

4. The first serious analysis of parameter choices.

"Sliding windows" (1939 Brauer, improved by 1973 Thurber): popular method to compute nP from P using very few additions, subtractions, doublings.

Precompute $2P, 3P, 5P, 7P$.

If n is even, recursively compute $(n/2)P$ and then double.

If n is odd, recursively compute $(n \pm 1)P$ or $(n \pm 3)P$ or $(n \pm 5)P$ or $(n \pm 7)P$, whichever involves the largest power of 2, and then add $\mp P$ or $\mp 3P$ or $\mp 5P$ or $\mp 7P$.

Why not $2P, 3P, 5P, \ldots, 15P$?
Or $2P, 3P, 5P, \ldots, 31P$?

For $2P, 3P, 5P, \ldots, (2^w - 1)P$:
$\approx 2^{w-1}$ adds in precomputation;
on average $\approx 256/(w + 2)$
adds in main computation.

Cohen/Miyaji/Ono introduce
an option to speed up the adds:
compute $2P$, convert to affine,
compute $3P, 4P$, convert,
compute $5P, 7P, 8P$, convert,
etc.

Cohen/Miyaji/Ono
analyze #adds carefully;
account for different
types of additions;
analyze several different
coordinate systems; and
identify optimal choices of w,
depending on $\mathbf{I}/\mathbf{M}$,
for 160 bits, 192 bits, 224 bits.

Example of results for 160 bits,
assuming $\mathbf{S}/\mathbf{M} = 0.8$:
Cohen/Miyaji/Ono recommend
one method using "$1610.2\mathbf{M}$"
and one using "$4\mathbf{I} + 1488.4\mathbf{M}$."

Subsequent improvements:

1. Faster addition/doubling formulas for old coordinates. Many sources; for survey see Explicit-Formulas Database.

2. Fast new coordinates: e.g. Edwards curves, extended Jacobi quartics, inverted Edwards coordinates.

3. "Fractional windows" and other addition-chain tweaks: e.g. $2P, 3P, 5P, 7P, 9P, 11P, 13P$.

4. More inversion strategies.

Asiacrypt 2007, Bernstein/Lange, "Faster addition and doubling on elliptic curves": fast Edwards computations; comparison to other coordinates for scalar multiplication.

Comparison unjustifiably assumed $2P, 3P, 5P, \ldots, 15P$; ignored possibility of inversions.

New, 2007 Bernstein/Lange, "Analysis and optimization of elliptic-curve single-scalar multiplication": Much more comprehensive comparison.

"This paper is dedicated to Henri Cohen on the occasion of his sixtieth birthday."

Example of new results for 160-bit scalars:

$1\mathbf{I} + 1495.8\mathbf{M}$

for Jacobian coordinates;

$1\mathbf{I} + 1434.1\mathbf{M}$

for Jacobian with $a_4 = -3$;

$1287.8\mathbf{M}$

for inverted Edwards.

Could also use
"Montgomery coordinates."
No fast additions, but
fast differential additions
$P - Q, P, Q \mapsto P + Q$.

(1986 Chudnovsky/Chudnovsky;
independently 1987 Montgomery
with faster formulas)

$P \mapsto nP$ using 8.2**M** per bit.
Conventional wisdom:
Faster than Jacobian;
therefore the fastest method.

Our prediction: Edwards
will be faster than Montgomery
for cryptographic applications.

Larger advantage
with larger scalars.

Much larger advantage
with more scalars: $mP + nQ$.

Need to account carefully
for differences between
simple multiplication counts
and real software speeds.
In progress: implementation.

Double-base chains

Are triplings useful
for scalar multiplication?

Can write nP as sum of
very few points $c_i 2^{a_i} 3^{b_i} P$
with $c_i = \pm 1$.
But need many doublings,
triplings to compute those points.

Asiacrypt 2005,
Dimitrov/Imbert/Mishra: Require
$a_0 \ge a_1 \ge \cdots$ and $b_0 \ge b_1 \ge \cdots$.
Only a_0 doublings, b_0 triplings.
But need more points.

Indocrypt 2006, Doche/Imbert:
Use precomputation to expand range of c_i's. Fewer points.

Indocrypt 2007,
Bernstein/Birkner/Lange/Peters:
Analysis of double-base single-scalar multiplication with various doubling/tripling ratios, various coordinate systems, various addition formulas (including new tripling formulas for Edwards curves), etc.

Basic conclusions: Triplings help Jacobian coordinates,
Hessian curves, and tripling-oriented Doche/Icart/Kohel.

But the best resulting speeds are still slower than pure-doubling Edwards.

Analysis assumes 0 inversions.
In progress: expand analysis for more inversion strategies.
"Grand unified optimization."
And then more scalars. . .

Many-scalar multiplication

Batch verification of many
$t_i B - h_i R_i = S_i$: check
$\sum_i v_i t_i B - \sum_i v_i h_i R_i - \sum_i v_i S_i$
$= 0$ for random 128-bit v_i.
(Naccache et al., Eurocrypt 1994;
Bellare et al., Eurocrypt 1998)

Also encounter many scalars
in computing nB as
$n_0 B + n_1 2^{16} B + \cdots$
using precomputed $2^{16} B$ etc.

Use subtractive multi-scalar multiplication algorithm: if $n_1 \geq n_2 \geq \cdots$ then $n_1 P_1 + n_2 P_2 + n_3 P_3 + \cdots = (n_1 - q n_2) P_1 + n_2 (q P_1 + P_2) + n_3 P_3 + \cdots$ where $q = \lfloor n_1 / n_2 \rfloor$. (credited to Bos and Coster by de Rooij, Eurocrypt 1994; see also tweaks by Wei Dai, 2007)

Addition speed is critical. Inverted Edwards coordinates: $9\mathbf{M} + 1\mathbf{S}$, speed record.

Elliptic-curve factorization

Bernstein/Birkner/Lange/Peters, in progress: Edwards ECM.

First-stage ECM analysis: similar to ECC analysis. Can use larger scalars, increasing the advantage of Edwards over Montgomery.

Second stage: more complicated.

Also some improvements in curve selection.

Elliptic-curve primality proving

Is n prime? Maybe.

Want computation of kP in $E(\mathbf{Z}/n)$ to *prove* that $kP = 0$ in $E(\mathbf{Z}/p)$ for every prime divisor p of n; use this to prove that n is prime.

Proper definition of $E(\mathbf{Z}/n)$ achieves this, but also requires many invertibility tests, each costing at least $1\mathbf{M}$ and extra implementation effort.

For simplicity and speed,
current ECPP software
omits various tests.

Bernstein question to Morain:
"Do the resulting computations
actually prove primality?"

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omits various tests.

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Morain answer to Bernstein:
"Feel free to look for a
non-prime counterexample."

Disclaimer: There is no evidence
that this conversation took place.

Often ECPP uses curves
that can be transformed to
Montgomery, Edwards, etc.
(Chance $\to 1$ as $n \to \infty$?)

With detailed case analysis
can eliminate tests for zero
from a Montgomery-style ECPP.
(2006 Bernstein)

Bernstein/Lange, with
Jonas Lindstrøm Jensen, in
progress: Aiming for simpler,
faster ECPP using Edwards.