

Symbolic Computation: Recent Progress and New Frontiers

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Erratum page 23 in the
proceedings: this is **not**

Philippe Baveye talk

*Significance of round-off
error propagation in two
codes used in environmental
modeling! ...*

... but (page 37)

**Symbolic Computation: Recent Progress
and New Frontiers**

Paul Zimmermann

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Abstract

*Symbolic computation and computer algebra systems are usually known to be either **very slow**, or **memory expensive**. However, some **specific symbolic computation problems** have received in the last years **new algorithmic solutions**, which enabled to push further the limits of what is doable within a reasonable amount of time and space. Some noticeable examples are polynomial factorisation, lattice reduction, Gröbner basis computation. We will present a few such algorithms, together with a **state-of-the-art** of what problems computer algebra systems can (or cannot) solve, and for each problem **what the current frontiers are**.*

Computer Algebra Systems

- **general purpose** (Maple, Mathematica, Macsyma, Reduce, MuPAD, Axiom, Derive):

proprietary, slow, have known pitfalls

- **special purpose** (GNU MP, Pari, Magma, NTL, Linbox):
free, fast, fewer bugs?

An Example

Cf. Fabienne Jézéquel talk “*Dynamical control of computations of multiple integrals*” (Tuesday, room Durand):

```
> f := exp(x) * cos(z) + sqrt(y) * sinh(z):
```

```
> int(int(int(f, x=2..5), y=1..3), z=2..3);
```

$$\begin{aligned}
 & \frac{1}{2} \exp(5) \sin(3) + \frac{1}{2} \exp(-3) + \frac{1}{2} \exp(3) - 2 \exp(2) \sin(3) \\
 & - \frac{1}{2} \exp(-3) - \frac{1}{2} \exp(3) - 2 \exp(5) \sin(2) - \frac{1}{2} \exp(2) \\
 & - \frac{1}{2} \exp(-2) + 2 \exp(2) \sin(2) + \exp(2) + \exp(-2)
 \end{aligned}$$

```
> evalf(%, 50);
```

```
-163.74566743673553320720440934473233062072278553592
```

```
> i := Int(Int(Int(f, x=2..5), y=1..3), z=2..3);
```

$$\frac{\frac{\frac{x^3}{2} \cos(z) + y \frac{x^3}{2} \sinh(z)}{1}, \frac{y^3}{1}}{\frac{z^2}{2}}$$

```
> st:=time(): evalf(i), time()-st;
```

```
-163.7456674, 30.790
```

Pitfalls?

```
[zimmerma@ecrouves scan]$ maple
  |\~/|      Maple 7 (IBM INTEL LINUX)
._|\|  |/_|. Copyright (c) 2001 by Waterloo Maple Inc.
 \  MAPLE /  All rights reserved. Maple is a registered trademark o
<____ ____> Waterloo Maple Inc.
      |      Type ? for help.
> Digits:=3:
> a:=1.0: b:=9e-5:
> Rounding := 0: # same with -infinity
> a - b;
```

1.0

You said slow?

```
> s:=numer(orthopoly[L](60, x)):
> st:=time(): readlib(realroot)(s), time()-st;
[[0, 1/8], [1/8, 1/4], [1/4, 1/2], [1/2, 3/4], [3/4, 1], [1, 3/2],
...
[176, 184], [184, 192], [192, 208], [208, 224]], 48.539
```

```
[zimmerma@ecrouves scan]$ time ./usp < laguerre60
1: 0/8..1/8
...
60: 208..224
60 real root(s)
0.200u 0.000s 0:00.44 45.4%      0+0k 0+0io 45pf+0w
```

What **size** of problem can we
solve in **one minute**?

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Computer Characteristics: Pentium II 366Mhz under RedHat 7.2,
with gcc 2.95.2, 128MB of main memory, and 256MB of swap.

What kind of problems?

Arithmetics: integer multiplication, gcd, modular exponentiation, floating-point and interval computation.

Number Theory: primality testing, integer factorisation.

Univariate Polynomials: factorisation over \mathbb{F}_p and \mathbb{Q} , approximation of complex roots, isolation of real roots.

Linear Algebra: minimal polynomial, determinant, lattice reduction.

Moore's law

The computer power increases by a **factor of 2** every **18 months**.

CONSEQUENCE: Assume we have a computer whose frequency automatically increases following Moore's law. Then a computation that started at $t = -\infty$ until now can be reproduced in ???

Moore's law

The computer power increases by a **factor of 2** every **18 months**.

CONSEQUENCE: Assume we have a computer whose frequency automatically increases following Moore's law. Then a computation that started at $t = -\infty$ until now can be reproduced in **only 18 months!**

Moore's law vs Problem Size

Suppose we can solve in 2002 a problem with 10^{20} bit operations.
How large can we solve in 2010, 2100?

Complexity	2002	2010	2100
n	10^{20}	10^{22}	10^{40}
$n \log n$	10^{18}	10^{20}	10^{38}
n^2	10^{10}	10^{11}	10^{20}
n^3	10^7	10^7	10^{13}
n^6	2,000	4,000	10^7
$e^{cn^{1/3} \log^{2/3} n}$	159	186	681
2^n	66	72	132
2^{2^n}	6.05	6.17	7.04

Arithmetics: Integer Multiplication

Multiplication of integers has complexity $O(n \log n \log \log n)$ (using FFT). Current multiprecision libraries like GNU MP (GMP) can multiply in one minute (and 87MB) two 21M-digit numbers:

```
ecrouves% ./intmul 21000000  
x has 21000007 digits  
y has 21000007 digits  
x*y took 59040ms
```


Arithmetics: Integer GCD

Integer GCD has asymptotic complexity $O(M(n) \log n)$ where $M(n)$ is the multiplication complexity, *i.e.* $O(n \log^2 n \log \log n)$ using FFT. But the constant is so large that most libraries only implement quadratic algorithms.

Worst case for Euclid's algorithm: $\gcd(F_n, F_{n+1})$. Here with GMP:

```
ecrouves% ./intgcd 717745  
Fib[717745] has 150000 digits  
gcd(Fib[717745], Fib[717746]) took 12790ms
```

```
ecrouves% ./intgcd 1435490  
Fib[1435490] has 300000 digits  
gcd(Fib[1435490], Fib[1435491]) took 56410ms
```

Magma implements a subquadratic algorithm (but gains only a factor of 2):

```
> n := 2870981;  
> x := Fibonacci(n);  
> Ceiling(Log(x)/Log(10));  
600000  
> y := Fibonacci(n+1);  
> time z := Gcd(x,y);  
Time: 56.540
```

Arithmetics: Modular Exponentiation

Basic routine for RSA: compute $x^y \bmod m$ where both x , y and m have n digits. Theoretical asymptotic complexity is $O(nM(n))$, *i.e.* $\approx n^2 \log n$.

```
ecrouves% ./powm 4300  
x has 4305 digits  
y has 4306 digits  
m has 4306 digits  
x^y mod m took 58660ms
```

Arithmetics: Floating-Point Computations

Computation of $\exp(\pi)$ with the MPFR library [complexity $O(M(n) \log^2 n)$]:

```
[zimmerma@ecrouves scan]$ ./exp_pi 200000 > /tmp/exp_pi
```

```
mpfr_const_pi took 83770ms
```

```
mpfr_exp took 60500ms
```

```
mpfr_out_str took 4930ms
```

```
% cat /tmp/exp_pi
```

```
digits=200000 prec=664386
```

```
2.31406926327792690057290863679485473802661062426002119934450464
```

```
...
```

```
9930270981154056341199492439774176843224931910297732e1
```

Arithmetics: Interval Computations

```
> f := exp(x) * cos(z) + sqrt(y) * sinh(z):
```

```
> i:=int(int(int(f, x=2..5), y=1..3), z=2..3):
```

```
> codegen[optimize]([res=i]);
```

```

                                1/2
t1 = exp(5), t2 = sin(3), t5 = 3    , t6 = exp(-3), t9 = exp(3),
```

```

t12 = exp(2), t15 = sin(2), t20 = exp(-2), res = 2 t1 t2
```

```

+ 3 t5 t6 + 3 t5 t9 - 2 t12 t2 - t6 - t9 - 2 t1 t15 - 3 t5 t12
```

```

- 3 t5 t20 + 2 t12 t15 + t12 + t20
```

With MPFI 1.0 (cf. talk of Nathalie Revol), modified to include the sin function:

```
[zimmerma@ecrouves scan]$ time ./ex_mpfi 33000
Using 109627 bits
res=[-1.637456674...8300366317e2,
      -1.637456674...8300366316e2]
58.690u 0.050s 0:58.92 99.6%    0+0k 0+0io 69pf+0w
```

Number Theory

New: PRIME is in P (Agrawal, Kayal, Saxena, Aug. 2002), but complexity is $O(\log^{12} n)$ (proven) or $O(\log^6 n)$ (under conjecture)...

ECPP is believed to be $O(\log^4 n)$. With Morain's ECPP-V6.4.5a:

```
ecrouves% time xrunecpp -f p290 -C p290.cert
```

```
Working on 1415132764414474869524500144421965690639918680434754208024734\  
336546038394919409611888752637626014128980726045296225927308489322042914\  
836340003691320909724764365042424859088382828895499502881883260433667686\  
909076137633236197675088250191255604277652097861010838659146460381197447\  
3290309003941
```

```
...
```

```
% N_56=1061
```

```
% Proofs: [0] [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] ...
```

```
% Total time is          58.820000 s
```

```
This number is prime
```

Checking the certificate

```
ecrouves% time xcheckcertif -f p290.cert
```

```
0:      43 y      0.60s
```

```
...
```

```
57:     -1 y      0.00s
```

```
% Total time is      7.72 s
```



```

ecrouves% ./xcheckcertif -f /tmp/cert -v # 572 digits
% Each line has the following shape:
%
% i: D y/n time
% where i is the rank of the certificate,
% D the discriminant
% y if the certificate is correct and n otherwise,
% time is the time needed
  0:      872 y          3.59s
  1:      643 y          3.40s
  2:     1659 y          3.18s
...
 75:       -1 y          0.00s

% Total time is          58.73 s

```

Integer Factorisation

Factor is $O(\exp^{c(\log n)^{1/3}(\log \log n)^{2/3}})$ (Number Field Sieve, Pollard 1988) where the best known $c = \frac{(92+26\sqrt{13})^{1/3}}{3} \approx 1.902$:

```
[zimmerma@ecrouves scan]$ gp
```

```
GP/PARI CALCULATOR Version 2.1.4 (released)
```

```
i686 running linux (ix86 kernel) 32-bit version
```

```
(readline v4.2 enabled, extended help available)
```

```
? n=885684319731911762861578039559042994165374347516240073;
```

```
? factorint(n,14)
```

```
...
```

```
time = 1mn, 1,370 ms.
```

```
%7 =
```

```
[812628396211489583584572751 1]
```

```
[1089900776124748047286366823 1]
```

Polynomials: Finding Roots over \mathbb{F}_p

Over \mathbb{F}_p , the basic operation is $x^p \bmod f$. Von zur Gathen challenge: **sparse polynomials** $x^n + x + 1$ modulo $p_n = \text{nextprime}(\lfloor \pi 2^n \rfloor)$. With NTL, which implements a $O(n^{1/2}M^2(n))$ algorithm:

```
[zimmerma@ecrouves scan]$ ./findroots 300
[44345865210347378455039303391189968223765785066\
 52416409072300108508446099286502968211870461
307586035062755037465897132111694408734936944546\
 4525867407410390170897335961232390185479061
929648767065408656206963825355501716750056182793\
 995242182606713121254050008124435641493106
305109539053340478959105603919976203366612383268\
 0831719240533010715122292526387954862254865] 61.2
```

Magma faster for sparse poly.: 34s for $n = 300$, 59s for $n = 450$.

Shoup: **dense polynomials** $F_n = \sum a_i x^{n-i}$ modulo
 $p_n = \text{nextprime}(\lfloor \pi 2^{n-2} \rfloor)$ (JSC 1995), where $a_0 = 1, a_{i+1} = a_i^2 + 1$:

```
[zimmerma@ecrouves scan]$ ./findroots2 298
```

```
[21657151942655967049428580353256300555690137481\
```

```
798967577768513583081762652641723649497420] 62.02
```

Factoring over small fields

Factoring $F_n \bmod 3$ where F_n is Shoup's polynomial, with Magma [$O(nM(n))$]:

```
> time Shoup_mod3(4000);  
[ 1, 3, 30, 201, 611, 645, 1083, 1426 ]  
Time: 58.920
```

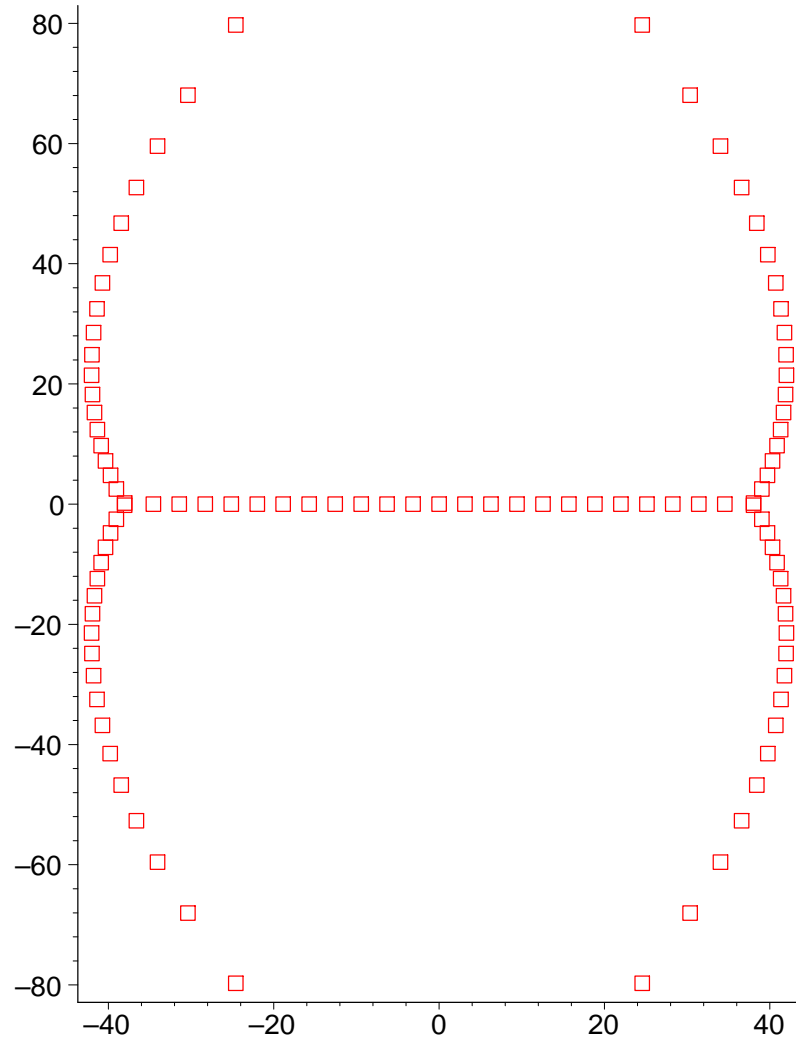
(NTL is much slower: 60s for $n = 1200$, and Pari/GP lies between: 17s for $n = 1200$.)

Factoring over $GF(2)$

Squaring a polynomial takes linear time! Factoring $x^n + x + 1$ takes $O(n^2)$. With Magma (NTL needs 400s):

```
> time VZG_mod2(21000);  
[ 5, 22, 28, 31, 72, 156, 1510, 1855, 6898, 10423 ]  
Time: 60.110
```

Complex Roots



Let S_n be the truncated Taylor expansion of order n of $\sin x$ at $x = 0$.

Approximating **all complex roots** of S_n with MPSolve (Bini, Fiorentino):

```
[zimmerma@ecrouves MPSolve2.0]$ time ./unisolve < sin317
(0, 0)
(-0.1300071725200322792e3, -0.6675106985812535385e2)
...
(0.1300071725200322792e3, -0.6675106985812535385e2)
60.110u 0.040s 1:00.80 98.9%    0+0k 0+0io 188pf+0w
```


Isolating Real Roots

Uspensky's algorithm based on **Descartes' rule** (Rouillier, Z., 2002, $O(n^3)$ conjectured):

```
[zimmerma@ecrouves scan]$ time ./usp < sin449
initial interval is -0.1024e4..0.1024e4
1: 0..0
2: -168..-167
...
109: 167..168
109 real root(s)
58.240u 0.010s 0:58.81 99.0%    0+0k 0+0io 47pf+0w
```

Polynomial Factoring

First polynomial algorithm: Lenstra, Lenstra, Lovász (1982), but **impractical** [$O(n^{10})$], even of worst cases for Zassenhaus' exponential algorithm!

van Hoeij (2000): new polynomial algorithm based on LLL, **very practical**, implemented in NTL.

Factoring $L_n L_{n+1}$ with NTL

$$L_0 = 1, \quad L_1 = 1 - x, \quad nL_n = (2n - 1 - x)L_{n-1} - (n - 1)L_{n-2}$$

```
[zimmerma@ecrouves src]$ ./ZZXFacTest < L205_L206
```

```
...
```

```
*** end SFFactor.   degree sequence:
```

```
206 205
```

```
total time: 59.38
```

Linear Algebra

Arne Storjohann (ISSAC'02) proved that $A^{-1}b$ and $\det(A)$ over $K[x]^{n \times n}$ have arithmetic complexity $\mathcal{O}(n^\theta \deg A)$ (Las Vegas model), using “High-Order Lifting”.

Seems to extend well to the integer case: $\mathcal{O}(n^\theta)$ bit complexity?

Trefethen's Challenge

Let A be a $n \times n$ sparse matrix with $A_{i,i}$ the i th prime, and $A_{i,j} = 1$ for $|i - j| = 2^k$.

2	1	1		1				1										
1	3	1	1			1				1								
1	1	5	1	1			1					1						
		1	1	7	1	1		1						1				
1			1	1	11	1	1		1							1		
		1			1	1	13	1	1		1							1
			1			1	1	17	1	1		1						1
				1			1	1	19	1	1		1					
1					1			1	1	23	1	1		1				
		1						1		1	29	1	1		1			
			1						1	1	1	31	1	1				1
				1						1	1	1	37	1	1			
					1						1	1	1	41	1	1		
						1						1	1	1	43	1		
							1						1	1	1	47		

The Challenge: for $n = 20000$, compute $B = A^{-1}$, then $B_{1,1}$ (rational with numerator/denominator of 100,000 digits each). Solved by LinBox in about 2 years of CPU time.

```
[zimmerma@ecrouves blackbox]$ time ./load-det 2500 test.matrix
Massey...Done
Determinant is 665 (mod 65521)
58.180u 0.060s 0:58.30 99.8%      0+0k 0+0io 210pf+0w
```

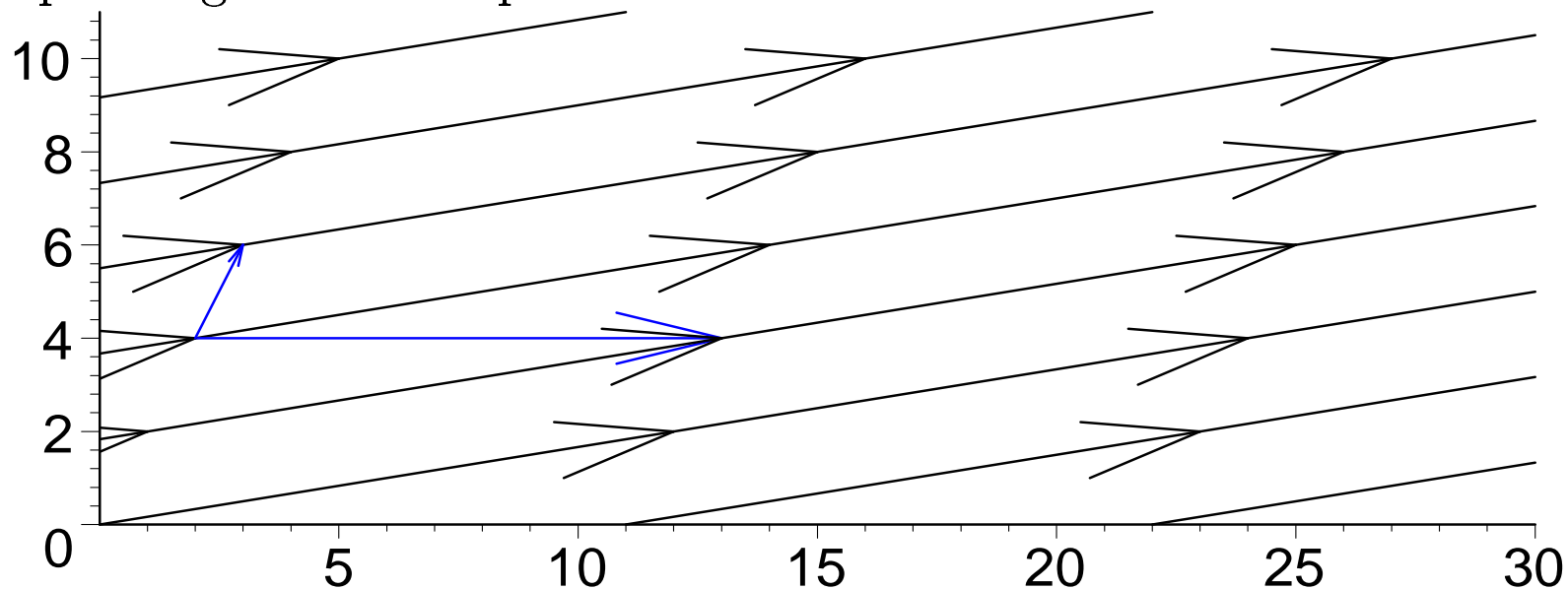
Minimal Polynomial

Compute the minimal polynomial of $A \bmod 65521$ (Linbox using black box algorithms):

```
$ time linbox-0.1.2/examples/blackbox/example 3300
Minimal polynomial...done
58.730u 0.030s 0:58.79 99.9%    0+0k 0+0io 194pf+0w
```

Lattice reduction

Problem: given a set of n vectors in \mathbb{Z}^n , find a basis of **short vectors** spanning the same space



Complexity: $\mathcal{O}(n^5 \log^2 A)$ (theoretical) $\mathcal{O}(n^4 \log^2 A)$ (experimental)

New developments: Koy and Schnorr (2002): saves a factor n .

Applications

Knapsack problem: find $\sum_{i=1}^n \epsilon_i b_i = S \pmod{M}$.

```
[zimmerma@ecrouves scan]$ time ./111 350 < in
```

```
...
```

```
norm(B[1])=2.000000e+00
```

```
smallest norm=2.000000e+00
```

```
largest norm=1.100000e+01
```

```
59.910u 0.170s 1:02.19 96.6%      0+0k 0+0io 47pf+0w
```

Summary

Problem	1 minute	record
IntMul	21M dig.	$\approx 10^{10}$
IntGcd	600K dig.	$\approx 10^8$
Float	200K dig.	$\approx 10^7$
PowMod	4300 dig.	$\approx 10^5$
IntPrime	290 dig.	5020 dig. (13 weeks, 1.3Ghz Athlon)
IntCheckPrime	572 dig.	$\approx 10^5$ dig.
IntFactor	54 dig.	158 dig. (52 months 800Mhz Athlon)

Problem	1 minute	record
RootMod (sparse)	450	$\approx 10^4$
RootMod (dense)	300	$\approx 10^4$
RootMod (dense, GF(3))	4000	$\approx 10^5$
RootMod (dense, GF(2))	21000	$\approx 10^7$
ComplexRoots	317	$\approx 10^4$
RealRoots	449	$\approx 10^4$
Factor	411	$\approx 10^4$
LinDep (sparse, \mathbb{F}_2)		$\approx 10^7$
Det (sparse, \mathbb{F}_{65521})	2500	$\approx 10^5$
MinPoly (sparse, \mathbb{F}_{65521})	3300	$\approx 10^5$
LLL	350	10^3

Conclusion

- computer algebra tools can tackle **large problems**

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Conclusion

- computer algebra tools can tackle **large problems**
- ... but you have to use **special-purpose** software
- ... and **choice** of software is crucial!
- for several problems, the new frontier is **memory**

Many thanks to the following software (and their authors): GNU MP 4.1, Pari-2.1.4 (and 2.2.4 alpha), Magma V2.8-3, NTL 5.3, Linbox 0.1.2, ECPP-V6.4.5a, MPFR 2.0.1, MPFI 1.0.