

# MPRI – Cours 2.12.2



F. Morain



## Lecture III: Primality

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The slides are available on <http://www.lix.polytechnique.fr/Labo/Francois.Morain/MPRI/2014>

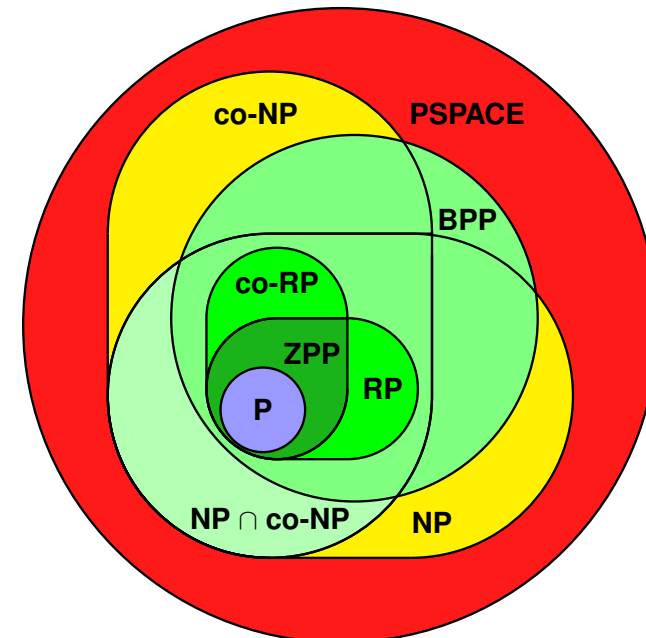
## Plan

- I. Compositeness tests.
- II. Primality tests.

## I. Compositeness tests

- Z) Definition and classification.
- A) Fermat.
- B) Euler-Solovay/Strassen.
- C) Artjuhov-Miller-Rabin.
- D) Other tests.

## Z) Definition and classification



## My view of randomized algorithms

**Def.** A **Monte Carlo algorithm** for deciding that  $X \in \mathbb{A}$  returns **yes** or **I don't know**:

$$\text{Proba}(\text{"yes"} \mid X \notin \mathbb{A}) = 0$$

$$\text{Proba}(\text{"I don't know"} \mid X \in \mathbb{A}) \leq 1 - \delta, \text{ for absolute } 0 < \delta < 1.$$

**Def.** A decision problem is in **RP** if there exists a polynomial time Monte Carlo algorithm that solves it.

**Rem.**  $\neq$  error on the answer; or a failure in the computer.

**Def.** A **Las Vegas algorithm** answers **yes**, **no** or **I don't know**:

$$\text{Proba}(\text{"yes"} \mid X \notin \mathbb{A}) = 0, \quad \text{Proba}(\text{"no"} \mid X \in \mathbb{A}) = 0$$

$$\text{Proba}(\text{"I don't know"} \mid X \in \mathbb{A}) \leq 1 - \delta.$$

**Def.**  $\text{ZPP} = \text{RP} \cap \text{co-RP}$ .

**Compositeness test:** deciding that  $N$  is composite.

**Primality test:** deciding that  $N$  is prime.

## A) Fermat

**Idea:** if  $\gcd(a, N) = 1$ , then  $a^{N-1} \equiv 1 \pmod{N}$ .

**But:**  $2^{340} \equiv 1 \pmod{341}$ : **pseudoprime** to base 2 (psp-2).

**Thm.** There exists an infinite number of psp-2 numbers.

**Thm.** (Pomerance) For  $x \geq x_0$ :  $x^{2/7} \ll P_2(x) \ll xL(x)^{-1/2}$  with  $L(x) = \exp\{\log x \log \log \log x / \log \log x\}$ .

**Def.**  $P(N) = \#\{a \in (\mathbb{Z}/N\mathbb{Z})^*, a^{N-1} \equiv 1 \pmod{N}\}$ .

**Thm.** If  $N = \prod_i p_i^{\alpha_i}$ ,  $P(N) = \prod_i \gcd(p_i - 1, N - 1)$ .

*Proof:* ■

## The test

**function** isComposite( $N$ )

1. Choose  $a$  at random in  $\mathbb{Z}/N\mathbb{Z} - \{0\}$ .
2. Compute  $g = \gcd(a, N)$ ; **if**  $g > 1$ , **then** return **(yes,  $g \mid N$ )**.
3. **if**  $a^{N-1} \not\equiv 1 \pmod{N}$ , **then** return **(yes,  $a$ )**  
**otherwise** return **I don't know**.

**Cost.**  $O((\log N)M(\log N))$ ; typically  $O((\log N)^3)$ , asymptotically  $\tilde{O}((\log N)^2)$ .

**Prop.**  $\text{Proba}(\text{"I don't know"}) = P(N)/(N - 1)$ .

**Proof.** Probability of yes is:

$$\left(1 - \frac{\varphi(N)}{N-1}\right) + \frac{\varphi(N)}{N-1} \left(1 - \frac{P(N)}{\varphi(N)}\right). \square$$

**Rem.** if  $N$  is prime, proba is 1...!

## Carmichael numbers

**Def.** composite  $N$  s.t.  $P(N) = \varphi(N)$ .

**Ex.** 561.

**Rem.**  $P(N)/(N - 1) = \varphi(N)/(N - 1)$  close to 1.

**Thm.**(Alford, Granville, Pomerance, 1992) There are infinitely many Carmichael numbers.

**More properties of Carmichael numbers:**

1.  $N$  is squarefree.
2. For all  $p \mid N$ ,  $p - 1 \mid N - 1$  (equivalently  $\lambda(N) \mid N - 1$ ).
3.  $N$  has at least three prime factors.

## B) Euler and Solovay-Strassen

**Idea:** (Euler) if  $N$  is prime and  $\gcd(a, N) = 1$ , then

$$a^{(N-1)/2} \equiv \left(\frac{a}{N}\right) \pmod{N}.$$

**Pb:**  $2^{(1105-1)/2} \equiv \left(\frac{2}{1105}\right) \pmod{1105}$ ; this is an **Euler pseudoprime** to base 2 (epsp-2). There are an infinite number of them.

**Prop.**  $E_2(x) \leq P_2(x)$ .

**Def.**  $\mathcal{E}(N) = \{a \in (\mathbb{Z}/N\mathbb{Z})^*, a^{(N-1)/2} \equiv \left(\frac{a}{N}\right) \pmod{N}\}$ ;  
 $E(N) = \#\mathcal{E}(N)$ .

**Prop.**  $\mathcal{E}(N)$  is proper subgroup of  $(\mathbb{Z}/N\mathbb{Z})^*$ .

**Coro.**  $E(N)/\varphi(N) \leq 1/2$ .

## The exact value of $E(N)$

**Thm. (Monier)** Write  $N = \prod_{i=1}^k p_i^{\alpha_i}$  where  $p_i$  are distinct odd primes,  $\alpha_i \geq 1$ . Write  $N = 1 + 2^s t$  with  $t$  odd and  $p_i = 1 + 2^{s_i} t_i$  with  $t_i$  odd. Assume  $s_1 \leq s_2 \leq \dots \leq s_k$  and put  $T_i = \gcd(t, t_i)$ ,  $n_i = \gcd((N-1)/2, p_i - 1)$  and  $\mathcal{N} = \prod_i n_i$ . Then

$$E(N) = \delta(N)\mathcal{N}$$

where

$$\delta(N) = \begin{cases} 2 & \text{if } s = s_1 \\ 1/2 & \text{if } \exists i, \alpha_i \text{ odd and } s_i < s \\ 1 & \text{otherwise.} \end{cases}$$

**Proof.** exercise.

## The test

**function** isComposite2( $N$ )

1. Choose  $a$  at random in  $\mathbb{Z}/N\mathbb{Z} - \{0\}$ .
2. Compute  $g = \gcd(a, N)$ ; if  $g > 1$ , **then** return (yes,  $g \mid N$ ).
3. If  $a^{(N-1)/2} \not\equiv \left(\frac{a}{N}\right) \pmod{N}$  **then** return (yes,  $a$ )  
**else** return I don't know.

**Prop.**  $\text{Proba}(\text{"I don't know"}) = E(N)/(N-1) \leq 1/2$ .

**Coro.** isComposite?  $\in$  **RP** (hence **isPrime?**  $\in$  **co-RP**).

**Miller (1975):**  $a = 2, 3, \dots$ ; Ankeny–Montgomery–Lenstra–Bach: if an adequate Riemann hypothesis is true, then the smallest witness is  $< 2(\log N)^2$ , yielding a deterministic  $O((\log N)^3 M(\log N))$  algorithm.

## C) Artjuhov-Miller-Rabin

$N$  being odd, write  $N - 1 = 2^s t$  with  $s \geq 1$  and odd  $t$ .

$$a^{N-1} - 1 = (a^t - 1)(a^t + 1)(a^{2t} + 1) \dots (a^{2^{s-1}t} + 1)$$

$$(AMR_a) : a^t \equiv 1 \pmod{N} \text{ or } \exists j, 0 \leq j < s, a^{2^j t} \equiv -1 \pmod{N}.$$

**Pb:**  $N = 2047 = 23 \times 89$  is s.t.  $N - 1 = 2 \times 1023$  and  $2^{(N-1)/2} \equiv 1 \pmod{N}$ : **strong-pseudoprime to base 2** (spsp-2).

**Thm.**  $\text{spsp-}a \Rightarrow \text{epsp-}a$ .

**Def.**  $F(N) = \#\{a \in (\mathbb{Z}/N\mathbb{Z})^*, (AMR_a) \text{ is satisfied}\}$ .

**Thm. (Monier)**

$$F(N) = \left[1 + \frac{2^{ks_1} - 1}{2^k - 1}\right] \prod_{i=1}^k T_i.$$

**Coro.**  $F(N)/(N-1) \leq 1/4$ .

## The test

**function** isComposite3( $N$ )

1. Choose  $a$  at random in  $\mathbb{Z}/N\mathbb{Z} - \{0\}$ .
2. Compute  $g = \gcd(a, N)$ ; **if**  $g > 1$ , **then** return (yes,  $g \mid N$ ).
3. **If**  $(AMR_a)$  **then** return (yes,  $a$ )  
**else** return I don't know.

**Prop.**  $\text{Proba}(\text{"I don't know"}) = F(N)/(N - 1)$ .

## Numerical tables

$x$	$P_2(x)$	$E_2(x)$	$F_2(x)$	$C(x)$	$\pi(x)$
$10^4$	22	12	5	7	1229
$10^5$	78	36	16	16	9592
$10^6$	245	114	46	43	78498
$10^7$	750	375	162	105	664579
$10^8$	2057	1071	488	255	5761455
$10^9$	5597	2939	1282	646	50847534
$10^{10}$	14884	7706	3291	1547	455052511
$25 \times 10^9$	21853	11347	4842	2163	1091987405
$10^{11}$	38975	20417	8607	3605	4118054813
$10^{12}$	101629	53332	22407	8241	37607912018
$10^{13}$	264239	139597	58897	19279	346065536839
$10^{14}$				44706	3204941750802
$10^{15}$				105212	29844570422669
$10^{16}$				246683	279238341033925

## Building primes?

**function** randomProbablePrime( $b$ )

**repeat**

choose odd  $N$  at random in  $[2^{b-1}, 2^b[$

**until**  $N$  passes  $k$  tests.

$p_{b,k} = \text{Proba}(X = N \text{ is composite} \mid Y_k = N \text{ passes } k \text{ tests}) = ?$

**Rem.** What we know is

$\text{Proba}(Y_k = N \text{ passes } k \text{ tests} \mid X = N \text{ is composite}) \leq (1/4)^k$ .

**Thm.** (Burthe, 1996)  $\forall b \geq 2, \forall k \geq 1, p_{b,k} \leq 4^{-k}$ .

## Other tests

**Goal:** reduce the non-answer probability while keeping the computations fast.

- Algebraic extensions: Lucas (degree 2), Adams & Shanks, Gurak.
- Elliptic curves: Gordon.
- Combinations of the preceding: no examples known of sssp- $a$  and Lucas pseudoprime, for instance.
- Frobenius pseudoprimes à la Grantham:  $\leq 1/7710$ . Cf. also Zhang.

## II. Primality tests

A) Fermat

B) En route for **P**.

C) Agrawal, Kayal, Saxena.

### Example of use

**Hyp.** We know how to find all prime factors  $< 20$ .

$$\begin{aligned} N_0 &= 100003, & N_0 - 1 &= 2 \times 3 \times 7 \times N_1, \\ N_1 &= 2381, & N_1 - 1 &= 2^2 \times 5 \times 7 \times 17 \end{aligned}$$

$p$	2	5	7	17
$3^{(N_1-1)/p} \bmod N_1$	2380	1347	1944	949

$\Rightarrow N_1$  is prime

$$s = N_1 > \sqrt{N_0}$$

$$2^{N_0-1} \equiv 1 \pmod{N_0}, \gcd(2^{(N_0-1)/N_1} - 1, N_0) = 1$$

$\Rightarrow N_0$  is prime

**Rem.** We have got a (recursive) primality proof of depth  $O(\log N)$ .

## A) Fermat

**Thm.**  $N$  is prime if and only if  $(\mathbb{Z}/N\mathbb{Z})^*$  is cyclic of order  $N - 1$ :

$$\left. \begin{aligned} a^{N-1} &\equiv 1 \pmod{N} \\ \forall p \mid N-1, &a^{\frac{N-1}{p}} \not\equiv 1 \pmod{N} \end{aligned} \right\} \Rightarrow N \text{ is prime}$$

**Certificate:**  $(N, \{p \mid N-1\}, a) \Rightarrow \text{isPrime?} \in \text{NP}$ .

**Thm. (Pocklington, 1914)** Let  $s$  s.t.  $s \mid N-1$

$$\left. \begin{aligned} a^{N-1} &\equiv 1 \pmod{N} \\ \forall q \text{ prime } \mid s, &\gcd(a^{\frac{N-1}{q}} - 1, N) = 1 \end{aligned} \right\} \Rightarrow \forall p \mid N, p \equiv 1 \pmod{s}$$

**Coro.**  $s > \sqrt{N} \Rightarrow N$  is prime.

**Rem.** factorisation is not polynomial time in the classical world (see later), but polynomial quantic; search for  $a$  is not either (except if Riemann is true or randomized approach).

### The $N + 1$ test

For  $a_0$  and  $a_1$  integers, let:

$$A_N = A_N(a_0, a_1) = \mathbb{Z}/N\mathbb{Z}[T]/(T^2 + a_1T + a_0)$$

and  $\Delta = a_1^2 - 4a_0$ .

Elements of  $A_N$  are  $u + v\alpha$  with  $u, v$  dans  $\mathbb{Z}/N\mathbb{Z}$ , computations made using  $\alpha^2 = -a_1\alpha - a_0$ .

**Thm.** Let  $p$  be a prime  $\nmid \Delta$ .

- if  $(\Delta/p) = -1$ , then  $A_p \sim \mathbb{F}_{p^2}$  ;
- if  $(\Delta/p) = +1$ , then  $A_p \sim \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}$ .

**Proof :** If  $(\Delta/p) = -1$ ,  $T^2 + a_1T + a_0$  is irreducible, hence we recover the classical construction of  $\mathbb{F}_{p^2}$ .

If  $(\Delta/p) = +1$ ,  $T^2 + a_1T + a_0 = (T - u)(T - v)$  with  $u \not\equiv v \pmod{p}$ .

Therefore

$$A_p \sim (\mathbb{Z}/p\mathbb{Z})[T]/(T - u) \times (\mathbb{Z}/p\mathbb{Z})[T]/(T - v) \sim \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}. \square$$

**Thm.** Let  $N$  be an odd integer. Assume that we found  $a_0, a_1$  s.t.  $\Delta = a_1^2 - 4a_0$  satisfies  $(\Delta/N) = -1$ . Write  $N + 1 = \prod_i q_i^{\beta_i}$ . Suppose we have found  $\theta \in A_N = A_N(a_0, a_1)$  s.t.

$$\theta^{N+1} = 1 \text{ in } A_N,$$

and for all  $i$  :

$$\theta^{(N+1)/q_i} = u_i + v_i\alpha \text{ with } (u_i - 1, v_i, N) = 1.$$

Then  $N$  is prime.

*Proof* : assume  $N$  is composite and let  $p \mid N$  with  $p \leq \sqrt{N}$ . Reduce  $A_N \bmod p$  towards  $A_p$  :

$$\tau = \theta \bmod p = (u \bmod p) + (v \bmod p)\alpha.$$

We get

$$\tau^{N+1} = 1 \text{ in } A_p,$$

and

$$\tau^{(N+1)/q_i} \neq 1 \text{ in } A_p$$

which proves  $\tau$  has ordre  $N + 1$  in  $(A_p)^*$ .

Hence  $N + 1 \leq \#A_p = p^2$ , contradiction.  $\square$

**Choosing  $\theta$** : using  $\bar{\alpha} = -a_1 - \alpha$  (conjugate), enough to choose

$$\theta = \frac{\alpha + m}{\bar{\alpha} + m} = \frac{(m^2 - a_0) + (2m - a_1)\alpha}{m(m - a_1) + a_0}$$

for varying  $m$ .

**Ex.** Consider  $N = 101$ ;  $N + 1 = 2 \times 3 \times 17$ . Take  $a_1 = -2, a_0 = -1, \Delta = 8$  and  $\left(\frac{8}{101}\right) = \left(\frac{2}{101}\right) = -1$ . Take  $\theta = 1 + 2\alpha$  (using  $m = 1$ )

$$\theta^{102} = 1, \theta^{102/2} = 100, \gcd(100 - 1, N) = 1,$$

$$\theta^{102/3} = 47T + 3, \gcd(3 - 1, 47, N) = 1,$$

$$\theta^{102/17} = 23T + 85, \gcd(85 - 1, 23, N) = 1.$$

## Remarks

- Pocklington-like theorems exist.
- Deduce from this the degree 2 pseudoprimes.
- All this can be reformulated in terms of Lucas sequences (bouhhhh!).
- **Lucas-Lehmer**:  $M_m = 2^m - 1$  is prime iff for  $L_0 = 4, L_{n+1} = L_n^2 - 2 \bmod M_m$ , one has  $L_{m-2} = 0$  [using  $\sqrt{3}$ ].  
 $\Rightarrow$  largest known primes, e.g.,  $M_{43112609}$  with 12, 978, 189 decimal digits.

Lower bound (?) for primality proving algorithms:  
 $O((\log N)M(M_p))$  (super fast arithmetic!).

## B) En route for P

- Gauss and Jacobi sums: L. Adleman, C. Pomerance, S. Rumely (1980, 1983); H. Cohen, H. W. Lenstra, Jr (1981 – 1984) ; H. Cohen, A. K. Lenstra (1982, 1987). W. Bosma & M.-P. van der Hulst (1990) ; P. Mihăilescu (1998). **deterministic**  $O((\log N)^{c_1 \log \log \log N})$ .
- almost **RP**: Goldwasser and Kilian using elliptic curves (1986); practical algorithm by Atkin (1986; later FM). See Smith's part.
- **RP**: Adleman and Huang using hyperelliptic curves (1986ff). See Smith's part.

**First idea:** (Agrawal, Biswas – 1999)

**Prop.**  $N$  is prime iff  $P(X) = (X + 1)^N - X^N - 1 \equiv 0 \pmod{N}$ .

**In practice:** choose  $Q(X) \in \mathbb{Z}/N\mathbb{Z}[X]$  at random of degree  $O(\log N)$ . If

$$(X + 1)^N \not\equiv X^N + 1 \pmod{(Q(X), N)}$$

then  $N$  is composite.

The probability of failure is bounded by  $1 - 1/(4 \log N)$ .

**Conjecture:** If  $N$  is composite, there exists  $1 \leq r \leq \log N$  s.t.  $P(X)$  is not divisible by  $X^r - 1$  modulo  $N$ .

**Thm.** Let  $N, s$  be integers,  $r$  a prime number and  $q = P(r - 1)$ . If:

(0)

$$\binom{q - 1 + s}{s} > N^{2\lfloor\sqrt{r}\rfloor};$$

(i)  $N \neq M^k, k > 1$ ;

(ii)  $N$  has no prime factor  $\leq s$ ;

(iii)  $N^{(r-1)/q} \pmod{r} \notin \{0, 1\}$ ;

(iv)  $\forall a, 1 \leq a \leq s, (X - a)^N \equiv X^N - a \pmod{(X^r - 1, N)}$ ;

then  $N$  is prime.

For a proof, see FM's Bourbaki article.

## Analysis

**Cost:**  $s$  computations of  $X^N$  modulo  $(X^r - 1, N)$ ; one computation costs  $O(\log N)$  products of degree  $r$  polynomials, hence:

$$O(s(\log N)M_P(r)M(\log N)).$$

**Prop.** If  $s = \lfloor 2\lfloor\sqrt{r}\rfloor \log N / \log 2 \rfloor + 1$  and  $q \geq 2s$ , then

$$\binom{q - 1 + s}{s} > N^{2\lfloor\sqrt{r}\rfloor}.$$

*Proof:*

$$\binom{q - 1 + s}{s} > (q/s)^s \geq 2^s > N^{2\lfloor\sqrt{r}\rfloor}.$$

**Coro.**  $O((\log N)^2 r^{1/2} M_P(r) M(\log N))$ .

**Analytical number theory:** we can find  $r = (\log N)^{2/(2\delta-1)}$  for  $\delta \in ]0.5, 0.676]$ .

## At last...

Using  $r = (\log N)^{2/(2\delta-1)}$ .

**Coro.** There exists a deterministic primality proving algorithm whose running time is

$$O((\log N)^{(8\delta+1)/(2\delta-1)})$$

using  $M_P(r) = r^2, M(\log N) = (\log N)^2$ ; and

$$\tilde{O}((\log N)^{6\delta/(2\delta-1)})$$

with  $M_P(r) = \tilde{O}(r), M(\log N) = \tilde{O}(\log N)$ .

*Proof:*

$$L^2 r^{1/2} M_P(r) M(\log N) = L^{2+2/(2\delta-1)+4/(2\delta-1)+2} \square$$

**Ex.** (AKS original)  $\delta = 2/3$ : 19, 12;  $\delta = 1$  (Sophie Germain): 9, 6.

**Rem.** Jacobi  $O((\log N)^{c \log \log \log N})$ , ECPP  $\tilde{O}((\log N)^4)$ .

**Rem.** Non effective.

## What next?

- cf. D. Bernstein homepage for more on the history of improvements to the basic test.
- Including: **H. W. Lenstra, Jr.** ( $\tilde{O}_{\text{eff}}((\log N)^{12})$  or  $\tilde{O}((\log N)^8)$ ), **S. David**.
- Cleaner version of **AKS**:  $\tilde{O}_{\text{eff}}((\log N)^{10.5})$  or  $\tilde{O}((\log N)^{7.5})$ .
- **H. W. Lenstra, C. Pomerance** :  $\tilde{O}_{\text{eff}}((\log N)^6)$ .
- **P. Berrizbeitia / Q. Cheng** :  
Let  $r$  prime s.t.  $r^\alpha \parallel N - 1$ ,  $r \geq \log^2 N$ ;  $1 < a < N$  s.t.  
 $a^{r^\alpha} \equiv 1 \pmod N$ ,  $\gcd(a^{r^{\alpha-1}} - 1, N) = 1$ ,  
 $(X + 1)^N = X^N + 1 \pmod{(X^r - a, N)}$ , then  $N$  is prime. Heuristic complexity would be  $\tilde{O}((\log N)^4)$  for these numbers.
- **D. Bernstein, P. Mihăilescu**: use  $e \mid N^d - 1$ ; inject cyclotomic ideas,  $\tilde{O}((\log N)^4)$ .

## V. Conclusions for primality

### Which algorithm?

- **easy to understand / implement, fast**: compositeness tests;
- **fast, proven**: Jacobi;
- **fast, heuristic**: ECPP;
- **certificate**: ECPP;
- **deterministic polynomial**: AKS.

D. Bernstein has an AKS example for  $2^{1024} + 643$  (13 hours on 800 MHz PC, 200 Mb memory).

To be compared to FASTECPP:

**14/07/03**: FM, **7000dd** with mpifastECPP.

**19/08/03**: J. Franke, T. Kleinjung, T. Wirth, **10000dd**.

**15/10/10**: FM, **25,050 dd** with mpifastECPP (2000 CPU days).

**Rem. 2013**: Franke et al., **30,008 dd** with combination CIDE.

## What's left to be done?

### Open questions:

- Is  $\tilde{O}((\log N)^4)$  the best running time for all numbers?  
**Compare**:  $\tilde{O}((\log N)^2)$  for Fermat or Mersenne numbers.  
**Claim** (Lukes, Patterson, Williams):  $\tilde{O}((\log N)^3)$  under GRH? (pseudosquares or pseudocubes).
- Combination of tests?