



Primality testing

- Let $\pi(N)$ be number of prime numbers that are less than or equal to N .
- Prime number theorem: $\pi(N) \approx N/\ln(N)$
 - If $n \geq 17$, $N/\ln(N) < \pi(N) < 1.26 N/\ln(N)$
- e. g. $N = p$ or q in $n=pq$. $p \approx q \approx 2^{512}$.
 - $\Pr(N \text{ is a prime} | \text{ odd } N \approx 2^{512}) \approx 1/\ln(2^{512}) = 1/355$.
- Easier to prove "N" is composite than to prove "N" is a prime. (why ?)



Definition 5.1

- **yes-biased Monte Carlo algorithm:** a randomized algorithm in which "yes" is always correct, "no" may be incorrect.
 - "yes" or "no" is a decision by an algorithm for a problem (e.g. Is N composite ?)
 - $\Pr(\text{incorrect answer} | \text{"yes"}) = 0$.
- If $\Pr(\text{incorrect answer} | \text{"no"}) \leq \epsilon$, then the algorithm has **error probability of ϵ** .



Problem 5.1 (page 179)

- Q: Is N a composite ?
- If we answer "yes" because a factor found (or other method), then it is definitely composite.
 - for yes-biased Monte Carlo algorithm $\Pr(\text{composite} | \text{"yes"}) = 1$.
- error probability $\Pr(\text{composite} | \text{"no"}) \leq \epsilon$.
 - $\Pr(\text{prime} | \text{"no"}) > 1 - \epsilon$.

Primality test for a large integer

- probabilistic test:
 - can be highly efficient
 - tiny probability of making an error
- deterministic test:
 - no general polynomial-time algorithm available until Agrawal, Kayal, and Saxena (2002) [AKS algorithm]
 - AKS algorithm is still not yet practical for a large prime number.

Probabilistic composite tests

- Solovay-Strassen Algorithm (Algorithm 5.6, page 182) is a yes-biased algorithm with error probability at most $1/2$.
- Miller-Rabin Algorithm (Algorithm 5.7, page 188) is a yes-biased algorithm with error probability at most $1/4$.
- We can perform several independent random tests to drastically reduce the error probability.

Miller-Rabin Algorithm

- Let $n-1 = 2^k m$, m is odd.
- Choose "a" randomly between 1 to $n-1$.
- $b \leftarrow a^m \pmod n$.
- if $b = 1$, then return ("prime")
- for $i=0$ to $k-1$ do
 - if $b = -1 \pmod n$, then return ("prime")
 - else $b \leftarrow b^2 \pmod n$.
- return ("composite")



Miller-Rabin Algorithm

- $n-1 = 2^k m$, m is odd.
 - Choose "a" randomly between 1 to $n-1$.
 - $b \leftarrow a^m \bmod n$.
 - if $b = 1$, then return ("prime")
 - for $i=0$ to $k-1$ do
 - if $b = -1$, then return ("prime")
 - else $b \leftarrow b^2 \bmod n$.
 - return ("composite")
- Recall that for a prime n ,
 - $a^{n-1} = 1 \bmod n$.
 - If $a^{n-1} = 1 \bmod n$, then n can be a possible prime.
 - If many such "a" are found, it is very likely n is a prime.



Factoring Algorithms

- Factorization is much harder than primality testing.
 - no known polynomial time algorithm.
- Trial division: try all primes $p \leq n^{0.5}$.
 - simple but not very efficient for a large n .
 - suitable when n has many small prime factors.
 - not effective for RSA (why not ?).



Pollard p-1 Algorithm (n,B)

- Choose a "suitable" bound B
- $a \leftarrow 2$
- for j from 2 to B do
 - $a \leftarrow a^j \bmod n$
- $d = \gcd(a-1, n)$
- if $(1 < d < n)$ return (d) else return ("fail")
 - useful when all prime factor of $(p-1) < B$, where $p|n$.

Pollard rho Algorithm (n, x_1)

- Choose a initial sees x_1 and $f(x)=x^2+1$
- $x \leftarrow x_1, x' \leftarrow f(x) \bmod n,$
- $p \leftarrow \gcd(x-x', n).$
- while ($p=1$) do
 - $x \leftarrow f(x) \bmod n,$
 - $x' \leftarrow f(x') \bmod n, x' \leftarrow f(x') \bmod n$
 - $p \leftarrow \gcd(x-x', n)$
- if($p < n$) return (p) else return ("fail")

Factoring Algorithm in Practice

Factoring Algorithms	Asymptotic Running Time
quadratic sieve	$O(\exp[(1+o(1)) ((\ln n) \ln \ln(n))^{0.5}])$
elliptic curve (p is smallest prime $ n$)	$O(\exp[(1+o(1)) (\ln p \ln \ln(p))^{0.5}])$
number field sieve	$O(\exp[(1.92+o(1)) (\ln n)^{1/3} (\ln \ln(n))^{2/3}])$

RSA Challenges

- Early 1990s. RSA-d, d =#of digits in $n=pq$. RSA-100, RSA-110, ..., RSA-500.
 - RSA-160 found in 2003.
- Since 2001. RSA-b, b =#of bits in $n=pq$.
 - RSA-576, RSA-640, RSA-704, RSA-768, RSA-896, RSA-1024, RSA-1576.
 - Prizes: from \$10,000 to \$200,000.
 - <http://mathworld.wolfram.com/>



Other Attacks on RSA

- computing $\phi(n)$
- find decryption exponent (d) of RSA
- Wiener's low decryption exponent attack.



Computing $\phi(n)$

- If both n and $\phi(n)$ are known, then we can find the factorization of n. why ?
- $n=pq$, $\phi(n) =(p-1)(q-1)$.
- Plug $q=n/p$ in the equation for $\phi(n)$,
 - $p^2 - (n- \phi(n)+1) p + n = 0$.
- we can then easily solve the quadratic equation of p.




Example 5.13 (page 201)

- $n=84773093$,
- $\phi(n) = 84754668$.
 - $n- \phi(n) = 18425$.
- quadratic equation for p is
 - $p^2 - (n- \phi(n)+1) p + n = 0$.
- $p^2 - 18426 p + 84773093 = 0$.
- Solutions (how ?) are: 9539 and 8887.



Find decryption exponent

- If the information about d (decryption exponent) is known, the n can be factored.
 - implication: we cannot not simply change other d 's with n unchanged.
 - Algorithm 5. 10: randomized algorithm that can factor n in a polynomial time (page 204)



Wiener's low decryption exponent attack

- If d (decryption exponent) is too small, the n can be factored.
 - Algorithm 5. 11: based on extended Euclidean algorithm and continued fraction technique (page 204)
 - implication: we cannot not use too small d 's as decryption exponent.
 - we choose simpler "e" as a public key then solve for "d" which is usually not too small.



Rabin Cryptosystem

- Another example of public key cryptosystem which is computationally secure against a chosen-plaintext attack (assuming $n=pq$ is hard to be factored)
- **Drawback:** the encryption function is not 1-1. Decryption function may yield 4 possible plaintexts for a given ciphertext.



Algorithm 5.2 (Rabin)

- Let $n=pq$, $p=3 \pmod 4$, $q=3 \pmod 4$.
- $P=C=Z_n^*$. $K=\{(n,p,q)\}$. n is public key.
- Encryption:
 - $e_k(x) = x^2 \pmod n$
- Decryption:
 - $d_k(y) = y^{1/2} \pmod n$ (how ?)



Find $y^{1/2} \pmod n$?

- Require $n=pq$, $p=3 \pmod 4$ and $q=3 \pmod 4$.
- Recall $y^{(p-1)} = 1 \pmod p$ (and $y^{(q-1)} = 1 \pmod q$)
- Since $y=x^2 \pmod p$, we have $y^{(p-1)/2} = 1 \pmod p$.
- We can show that $x = \pm y^{(p+1)/4} \pmod p$ satisfies $x^2 = y \pmod p$.
- Likewise, $x = \pm y^{(q+1)/4} \pmod q$ satisfies $x^2 = y \pmod q$.
- We can find four solutions using Chinese Remainder Theorem.



Example 5.18

- Choose small $n=77=7 \times 11$.
- $e_k(x) = x^2 \pmod 77$, $d_k(y) = y^{1/2} \pmod 77$.
- Suppose $y=23$ received. Find x ?
 - $x = 23^{(7+1)/4} \pmod 7 = 2^2 \pmod 7 = 4$.
 - $x = 23^{(11+1)/4} \pmod 11 = 1^3 \pmod 11 = 1$.
- Use CRT, $x = \pm 4 \pmod 7$, $x = \pm 1 \pmod 11$, we find $x = \pm 10$ and $\pm 32 \pmod 77$
 - $x = 10, 32, 45, 67$.



Security of Rabin Cryptosystem

- Rabin Cryptosystem can be proved using "Turing reduction". (page 213)
- Factorization \leq_T Rabin decryption.
 - if we can solve Rabin decryption in polynomial time, then we can solve factorization problem in polynomial time.
 - factorization is hard, so is Rabin decryption.



Sematic Security of RSA

- total break: the private key is known to your adversary.
- partial break: some unseen ciphertexts can be decrypted by your adversary.
- distinguishability of ciphertexts: $> 1/2$ chance to distinguish between encryption of two plaintexts.



Multi-precision arithmetic software packages

- Modular arithmetic operations are provided to compute residues, perform exponentiation, and compute multiplicative inverses:
- `BigInteger` class in Java:
 - <http://java.sun.com/j2se/1.4.2/docs/api/java/math/BigInteger.html>
- NTL (for C++): <http://www.shoup.net/>
- GMP (for C): <http://www.swox.com/gmp/>
- MAPLE or MATHEMATICA.



Summary

- Primality testing algorithms
- Factorization algorithms
- Attacks on RSA
- Rabin Cryptosystem



HW5

- (written assignment)
 - 5.3, 5.5, 5.6, 5.7, 5.33
- (program assignment)
 - 5.12.
