

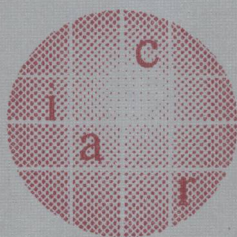
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Jacques Stern (Ed.)

Advances in Cryptology – EUROCRYPT '99

International Conference on the Theory
and Application of Cryptographic Techniques
Prague, Czech Republic, May 1999
Proceedings



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Preface

EUROCRYPT '99, the seventeenth annual Eurocrypt Conference, was sponsored by the International Association for Cryptologic Research (IACR), in cooperation with the Group of Cryptology within the Union of Czech Mathematicians and Physicists. The General Chair, Jaroslav Hruby, was responsible for the overall organization of the conference in the beautiful city of Prague. Let me mention that it was a pleasure to work together: although we were in different locations, we managed to stay in close contact and maintain a smooth organization of the conference.

The Program Committee, consisting of 21 members, considered 120 papers and selected 32 for presentation. In addition, Ross Anderson kindly agreed to chair the traditional rump session for informal short presentations of new results. These proceedings include the revised versions of the 32 papers accepted by the Program Committee. These papers were selected on the basis of originality, quality, and relevance to cryptography. As a result, they should give a proper picture of how the field is evolving. Revisions were not checked and the authors bear full responsibility for the contents of their papers.

The selection of papers was a difficult and challenging task. Each submission was refereed by at least three reviewers and most had four reports or more. I wish to thank the program committee members, who did an excellent job. In addition, I gratefully acknowledge the help of a large number of colleagues who reviewed submissions in their areas of expertise. They are: Michel Abdalla, Josh Benaloh, Charles Bennett, Simon Blackburn, Matt Blaze, Christian Cachin, Jan Camenisch, Ran Canetti, Benny Chor, Galdi Clemente, Jean-Sébastien Coron, Paolo D'Arco, Anand Desai, Uri Feige, Marc Fischlin, Roger Fischlin, Matt Franklin, Steven Galbraith, Rosario Gennaro, Pierre Girard, Dieter Gollmann, Shai Halevi, Helena Handschuh, Yuval Ishai, Markus Jakobsson, Mike Just, Ted Krovetz, Kaoru Kurosawa, Eyal Kushilevitz, Keith Martin, Barbara Massignetti, Johannes Merkle, Daniele Micciancio, Victor S. Miller, Fauzan Mirza, Serge Mister, Peter L. Montgomery, Tal Mor, David M'Raihi, Luke O'Connor, Andrew Odlyzko, Wakaha Ogata, Koji Okada, Pascal Paillier, Pino Persiano, David Pointcheval, Bart Preneel, Tal Rabin, Omer Reingold, Phil Rogaway, Ludovic Rousseau, Berry Schoenmakers, Peter Shor, Jean-Pierre Seifert, Othmar Staffelbach, Ugo Vaccaro, Serge Vaudenay, Ruizhong Wei, Mike Wiener, Rebecca Wright, Xian-Mo Zhang, and Robert Zuccherato. I apologize for any inadvertent omission.

I also wish to thank my PhD students Phong Nguyen, Thomas Pornin, and Guillaume Poupard, who helped me a great deal at various steps of the whole process. Their computer skills and the time and effort they invested were a crucial ingredient of my ability to run the program committee. Thomas ran the electronic submission phase and was able to print all postscript files, including those produced by non-standard word processors. Guillaume opened a private

FTP server and Web site for PC members, and Phong did the editing work, both in paper and in electronic form. I hope I did not distract them too much from their research, but they were kind enough to tell me they had learnt a lot. Thanks also to Joelle Isnard and Nadine Riou, who organized the PC meeting in Paris.

Following the example of CRYPTO '98, EUROCRYPT '99 was the first of the Eurocrypt series with electronic submissions. The electronic submission option was a clear choice for almost all authors, with only 5% of the papers submitted by regular mail. I believe that the time has come to make e-submission mandatory, but it will be the choice of future Crypto and Eurocrypt PC chairs. I wish to thank Joe Kilian, who forwarded us the electronic submission software used for CRYPTO '98 and helped us run it. This software was originally developed by ACM's SIGACT group and I thank the ACM for allowing us to use their system.

Finally, I wish to thank the all authors who submitted papers for making this conference possible by creating the scientific material, and especially the authors of accepted papers. I would also like to thank the publisher, Springer-Verlag, for working within a tight schedule in order to produce these proceedings in due time.

February 1999

Jacques Stern
Program Chair
EUROCRYPT '99

EUROCRYPT '99

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Table of Contents

Cryptanalysis I

Cryptanalysis of RSA with Private Key d Less than $N^{0.292}$	1
<i>Dan Boneh and Glenn Durfee (Stanford University)</i>	
Cryptanalysis of Skipjack Reduced to 31 Rounds Using Impossible Differentials	12
<i>Eli Biham, Alex Biryukov (Technion), and Adi Shamir (Weizmann Institute of Science)</i>	

Hash Functions

Software Performance of Universal Hash Functions	24
<i>Wim Nevelsteen and Bart Preneel (Katholieke Universiteit Leuven)</i>	

Foundations I

Lower Bounds for Oblivious Transfer Reductions	42
<i>Yevgeniy Dodis and Silvio Micali (MIT)</i>	
On the (Im)possibility of Basing Oblivious Transfer and Bit Commitment on Weakened Security Assumptions	56
<i>Ivan Damgård (University of Århus), Joe Kilian (NEC Research Institute), and Louis Salvail (University of Århus)</i>	
Conditional Oblivious Transfer and Timed-Release Encryption	74
<i>Giovanni Di Crescenzo (University of California San Diego), Rafail Ostrovsky, and Sivaramakrishnan Rajagopalan (Bellcore)</i>	

Public Key

An Efficient Threshold Public Key Cryptosystem Secure Against Adaptive Chosen Ciphertext Attack	90
<i>Ran Canetti (IBM T.J. Watson) and Shafi Goldwasser (MIT)</i>	
Proving in Zero-Knowledge that a Number Is the Product of Two Safe Primes	107
<i>Jan Camenisch (University of Aarhus) and Markus Michels (Entrust Technologies Europe)</i>	
Secure Hash-and-Sign Signatures Without the Random Oracle	123
<i>Rosario Gennaro, Shai Halevi, and Tal Rabin (IBM T.J. Watson)</i>	

Watermarking and Fingerprinting

A Note on the Limits of Collusion-Resistant Watermarks	140
<i>Funda Ergun (Bell Laboratories), Joe Kilian (NEC Research Institute), and Ravi Kumar (IBM Almaden)</i>	
Coin-Based Anonymous Fingerprinting	150
<i>Birgit Pfitzmann and Ahmad-Reza Sadeghi (Universität des Saarlandes)</i>	

Elliptic Curves

On the Performance of Hyperelliptic Cryptosystems	165
<i>Nigel P. Smart (Hewlett-Packard Laboratories)</i>	
Fast Elliptic Curve Algorithm Combining Frobenius Map and Table Reference to Adapt to Higher Characteristic	176
<i>Tetsutaro Kobayashi, Hikaru Morita, Kunio Kobayashi, and Fumitaka Hoshino (NTT Laboratories)</i>	
Comparing the MOV and FR Reductions in Elliptic Curve Cryptography	190
<i>Ryuichi Harasawa, Junji Shikata, Joe Suzuki (Osaka University), and Hideki Imai (University of Tokyo)</i>	

New Schemes

Unbalanced Oil and Vinegar Signature Schemes	206
<i>Aviad Kipnis (NDS Technologies), Jacques Patarin, and Louis Goubin (Bull SmartCards and Terminals)</i>	
Public-Key Cryptosystems Based on Composite Degree Residuosity Classes	223
<i>Pascal Paillier (Gemplus and ENST)</i>	
New Public Key Cryptosystems Based on the Dependent-RSA Problems .	239
<i>David Pointcheval (École Normale Supérieure)</i>	

Block Ciphers

Resistance Against General Iterated Attacks	255
<i>Serge Vaudenay (École Normale Supérieure)</i>	
XOR and Non-XOR Differential Probabilities	272
<i>Philip Hawkes (Qualcomm International) and Luke O'Connor (IBM Zürich)</i>	

S-boxes with Controllable Nonlinearity	286
<i>Jung Hee Cheon, Seongtaek Chee, and Choonsik Park (ETRI)</i>	

Distributed Cryptography

Secure Distributed Key Generation for Discrete-Log Based Cryptosystems	295
<i>Rosario Gennaro (IBM T.J. Watson), Stanisław Jarecki (MIT), Hugo Krawczyk (Technion and IBM), and Tal Rabin (IBM T.J. Watson)</i>	
Efficient Multiparty Computations Secure Against an Adaptive Adversary	311
<i>Ronald Cramer (ETH Zurich), Ivan Damgård, Stefan Dziembowski (Aarhus University), Martin Hirt (ETH Zurich), and Tal Rabin (IBM T.J. Watson)</i>	
Distributed Pseudo-random Functions and KDCs	327
<i>Moni Naor, Benny Pinkas, and Omer Reingold (Weizmann Institute of Science)</i>	

Cryptanalysis II

Improved Fast Correlation Attacks on Stream Ciphers via Convolutional Codes	347
<i>Thomas Johansson and Fredrik Jönsson (Lund University)</i>	
Cryptanalysis of an Identification Scheme Based on the Permuted Perceptron Problem	363
<i>Lars R. Knudsen (University of Bergen) and Willi Meier (FH-Aargau)</i>	

Tools from Related Areas

An Analysis of Exponentiation Based on Formal Languages	375
<i>Luke O'Connor (IBM Zürich)</i>	
Dealing Necessary and Sufficient Numbers of Cards for Sharing a One-Bit Secret Key	389
<i>Takaaki Mizuki, Hiroki Shizuya, and Takao Nishizeki (Tohoku University)</i>	

Foundations II

Computationally Private Information Retrieval with Polylogarithmic Communication	402
<i>Christian Cachin (IBM Zurich), Silvio Micali (MIT), and Markus Stadler (Crypto AG)</i>	

On the Concurrent Composition of Zero-Knowledge Proofs	415
<i>Ransom Richardson (Groove Networks) and Joe Kilian (NEC Research Institute)</i>	

Pseudorandom Function Tribe Ensembles Based on One-Way Permutations: Improvements and Applications	432
<i>Marc Fischlin (Universität Frankfurt)</i>	

Broadcast and Multicast

Secure Communication in Broadcast Channels: The Answer to Franklin and Wright's Question	446
<i>Yongge Wang and Yvo Desmedt (University of Wisconsin)</i>	

Efficient Communication-Storage Tradeoffs for Multicast Encryption	459
<i>Ran Canetti (IBM T. J. Watson), Tal Malkin (MIT), and Kobbi Nissim (Weizmann Institute of Science)</i>	

Author Index	475
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Cryptanalysis of RSA with Private Key d Less than $N^{0.292}$

Dan Boneh* and Glenn Durfee**

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Abstract. We show that if the private exponent d used in the RSA public-key cryptosystem is less than $N^{0.292}$ then the system is insecure. This is the first improvement over an old result of Wiener showing that when $d < N^{0.25}$ the RSA system is insecure. We hope our approach can be used to eventually improve the bound to $d < N^{0.5}$.

1 Introduction

To provide fast RSA signature generation one is tempted to use a small private exponent d . Unfortunately, Wiener [10] showed over ten years ago that if one uses $d < N^{0.25}$ then the RSA system can be broken. Since then there have been no improvements to this bound. Verheul and Tilborg [9] showed that as long as $d < N^{0.5}$ it is possible to expose d in less time than an exhaustive search; however, their algorithm requires exponential time as soon as $d > N^{0.25}$.

In this paper we give the first substantial improvement to Wiener's result. We show that as long as $d < N^{0.292}$ one can efficiently break the system. We hope our approach will eventually lead to what we believe is the correct bound, namely $d < N^{0.5}$. Our results are based on the seminal work of Coppersmith [2].

Wiener describes a number of clever techniques for avoiding his attack while still providing fast RSA signature generation. One such suggestion is to use a large value of e . Indeed, Wiener's attack provides no information as soon as $e > N^{1.5}$. In contrast, our approach is effective as long as $e < N^{1.875}$. Consequently, larger values of e must be used to defeat the attack. We discuss this variant in Section 5.

2 Overview of Our Approach

Recall that an RSA public key is a pair $\langle N, e \rangle$ where $N = pq$ is the product of two n -bit primes. For simplicity, we assume $\gcd(p-1, q-1) = 2$. The corresponding private key is a pair $\langle N, d \rangle$ where $e \cdot d \equiv 1 \pmod{\frac{\phi(N)}{2}}$ where $\phi(N) = N - p - q + 1$.

* Supported by DARPA.

** Supported by Certicom and an NSF Graduate Research Fellowship.

Note that both e and d are less than $\phi(N)$. It follows that there exists an integer k such that

$$ed + k \left(\frac{N+1}{2} - \frac{p+q}{2} \right) = 1. \quad (1)$$

Writing $s = -\frac{p+q}{2}$ and $A = \frac{N+1}{2}$, we know:

$$k(A + s) \equiv 1 \pmod{e}.$$

Throughout the paper we write $e = N^\alpha$ for some α . Typically, e is of the same order of magnitude as N (e.g. $e > N/10$) and therefore α is very close to 1. As we shall see, when α is much smaller than 1 our results become even stronger.

Suppose the private exponent d satisfies $d < N^\delta$. Wiener's results show that when $\delta < 0.25$ the value of d can be efficiently found given e and N . Our goal is to show that the same holds for larger values of δ . By equation (1) we know that

$$|k| < \frac{2de}{\phi(N)} \leq 3de/N < 3e^{1+\frac{\delta-1}{\alpha}}.$$

Similarly, we know that

$$|s| < 2N^{0.5} = 2e^{1/2\alpha}.$$

To summarize, taking $\alpha \approx 1$ (which is the common case) and ignoring constants, we end up with the following problem: find integers k and s satisfying

$$k(A + s) \equiv 1 \pmod{e} \quad \text{where} \quad |s| < e^{0.5} \quad \text{and} \quad |k| < e^\delta. \quad (2)$$

The problem can be viewed as follows: given an integer A , find an element “close” to A whose inverse modulo e is “small”. We refer to this is the *small inverse problem*. Clearly, if for a given value of $\delta < 0.5$ one can efficiently list all the solutions to the small inverse problem, then RSA with private exponent smaller than N^δ is insecure (simply observe that given s modulo e one can factor N immediately, since $e > s$). Currently we can solve the small inverse problem whenever $\delta < 1 - \frac{1}{2}\sqrt{2} \approx 0.292$.

Remark 1. A simple heuristic argument shows that for any $\epsilon > 0$, if k is bounded by $e^{0.5-\epsilon}$ (i.e. $\delta < 0.5$) then the small inverse problem (equation (2)) is very likely to have a unique solution. The unique solution enables one to break RSA. Therefore, the problem encodes enough information to prove that RSA with $d < N^{0.5}$ is insecure. For $d > N^{0.5}$ we have that $k > N^{0.5}$ and the problem will no longer have a unique solution. Therefore, we believe this approach can be used to show that $d < N^{0.5}$ is insecure, but gives no results for $d > N^{0.5}$.

The next section gives a brief introduction to lattices over \mathbb{Z}^n . Our solution to the small inverse problem when α is close to 1 is given in Section 4. In Section 5 we give a solution for arbitrary α . Section 6 describes experimental results with the algorithm.