CRYPTOGRAPHY ENGINEERING

Design Principles and Practical Applications

Niels Ferguson
Bruce Schneier
Tadayoshi Kohno

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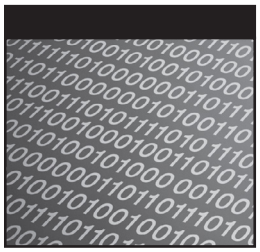

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To Denise, who has made me truly happy.

—Niels Ferguson

To Karen; still, after all these years.

—Bruce Schneier

To Taryn, for making everything possible.

—Tadayoshi Kohno

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About the Authors

Niels Ferguson has spent his entire career working as a cryptographic engineer. After studying mathematics in Eindhoven, he worked for DigiCash analyzing, designing, and implementing advanced electronic payment systems that protect the privacy of the user. Later he worked as a cryptographic consultant for Counterpane and MacFergus, analyzing hundreds of systems and designing dozens. He was part of the team that designed the Twofish block cipher, performed some of the best initial analysis of AES, and co-designed the encryption system currently used by WiFi. Since 2004 he works at Microsoft where he helped design and implement the BitLocker disk encryption system. He currently works in the Windows cryptography team that is responsible for the cryptographic implementations in Windows and other Microsoft products.

Bruce Schneier is an internationally renowned security technologist, referred to by *The Economist* as a ''security guru.'' He is the author of eight books—including the best sellers *Beyond Fear: Thinking Sensibly about Security in an Uncertain World*, *Secrets and Lies*, and *Applied Cryptography*—as well as hundreds of articles and essays in national and international publications, and many more academic papers. His influential newsletter *Crypto-Gram*, and his blog *Schneier on Security*, are read by over 250,000 people. He is a frequent guest on television and radio, and is regularly quoted in the press on issues surrounding security and privacy. He has testified before Congress on multiple occasions, and has served on several government technical committees. Schneier is the Chief Security Technology Officer of BT.

Tadayoshi Kohno (Yoshi) is an assistant professor of computer science and engineering at the University of Washington. His research focuses on improving the security and privacy properties of current and future technologies. He conducted the initial security analysis of the Diebold AccuVote-TS electronic voting machine source code in 2003, and has since turned his attention to securing emerging technologies ranging from wireless implantable pacemakers and defibrillators to cloud computing. He is the recipient of a National Science Foundation CAREER Award and an Alfred P. Sloan Research Fellowship. In 2007 he was awarded the MIT Technology Review TR-35 Award for his work in applied cryptography, recognizing him as one of the world's top innovators under the age of 35. He received his PhD in computer science from the University of California at San Diego.

Niels, Bruce, and Yoshi are part of the team that designed the Skein hash function, one of the competitors in NIST's SHA-3 competition.

Acknowledgments for *Cryptography Engineering*

We are deeply indebted to the cryptography and security community at large. This book would not have been possible without all of their efforts in advancing the field. This book also reflects our knowledge and experience as cryptographers, and we are deeply grateful to our peers and mentors for helping shape our understanding of cryptography.

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Part of this book was developed and refined in an undergraduate computer security course at the University of Washington. We thank all those students, teaching assistants, and student mentors for the course. We especially thank Joshua Barr, Jonathan Beall, Iva Dermendjieva, Lisa Glendenning, Steven Myhre, Erik Turnquist, and Heather Underwood for providing specific comments and suggestions on the text.

We thank Melody Kadenko and Julie Svendsen for all their administrative support throughout this process. We are indebted to Beth Friedman for all her work copyediting this manuscript. Finally, we thank Carol Long, Tom Dinse, and the entire Wiley team for encouraging us to prepare this book and helping us all along the way.

We are also indebted to all the other wonderful people in our lives who worked silently behind the scenes to make this book possible.

Acknowledgments for *Practical Cryptography* (the 1st Edition)

This book is based on our collective experience over the many years we have worked in cryptography. We are heavily indebted to all the people we worked with. They made our work fun and helped us reach the insights that fill this book. We would also like to thank our customers, both for providing the funding that enabled us to continue our cryptography research and for providing the real-world experiences necessary to write this book.

Certain individuals deserve special mention. Beth Friedman conducted an invaluable copyediting job, and Denise Dick greatly improved our manuscript by proofreading it. John Kelsey provided valuable feedback on the cryptographic contents. And the Internet made our collaboration possible. We would also like to thank Carol Long and the rest of the team at Wiley for bringing our ideas to reality.

And finally, we would like to thank all of the programmers in the world who continue to write cryptographic code and make it available, free of charge, to the world.

Contents at a Glance

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Preface to *Cryptography Engineering*

Most books cover what cryptography is—what current cryptographic designs are and how existing cryptographic protocols, like SSL/TLS, work. Bruce Schneier's earlier book, *Applied Cryptography*, is like this. Such books serve as invaluable references for anyone working with cryptography. But such books are also one step removed from the needs of cryptography and security engineers in practice. Cryptography and security engineers need to know more than how current cryptographic protocols work; they need to know how to use cryptography.

To know how to use cryptography, one must learn to think like a cryptographer. This book is designed to help you achieve that goal. We do this through immersion. Rather than broadly discuss all the protocols one might encounter in cryptography, we dive deeply into the design and analysis of specific, concrete protocols. We walk you—hand-in-hand—through how we go about designing cryptographic protocols. We share with you the reasons we make certain design decisions over others, and point out potential pitfalls along the way.

By learning how to think like a cryptographer, you will also learn how to be a more intelligent user of cryptography. You will be able to look at existing cryptography toolkits, understand their core functionality, and know how to use them. You will also better understand the challenges involved with cryptography, and how to think about and overcome those challenges.

This book also serves as a gateway to learning about computer security. Computer security is, in many ways, a superset of cryptography. Both computer security and cryptography are about designing and evaluating objects (systems or algorithms) intended to behave in certain ways even in the presence

of an adversary. In this book, you will learn how to think about the adversary in the context of cryptography. Once you know how to think like adversaries, you can apply that mindset to the security of computer systems in general.

History

This book began with *Practical Cryptography* by Niels Ferguson and Bruce Schneier, and evolved with the addition of Tadayoshi Kohno—Yoshi—as an author. Yoshi is a professor of computer science and engineering at the University of Washington, and also a past colleague of Niels and Bruce. Yoshi took *Practical Cryptography* and revised it to be suitable for classroom use and self-study, while staying true to the goals and themes of Niels's and Bruce's original book.

Example Syllabi

There are numerous ways to read this book. You can use it as a self-study guide for applied cryptographic engineering, or you can use it in a course. A quarter- or semester-long course on computer security might use this book as the foundation for a 6-week intensive unit on cryptography. This book could also serve as the foundation for a full quarter- or semester-long course on cryptography, augmented with additional advanced material if time allows. To facilitate classroom use, we present several possible syllabi below.

The following syllabus is appropriate for a 6-week intensive unit on cryptography. For this 6-week unit, we assume that the contents of Chapter 1 are discussed separately, in the broader context of computer security in general.

- **Week 1:** Chapters 2, 3, and 4;
- **Week 2:** Chapters 5, 6, and 7;
- **Week 3:** Chapters 8, 9, and 10;
- **Week 4:** Chapters 11, 12, and 13;
- **Week 5:** Chapters 14, 15, 16, and 17;
- **Week 6:** Chapters 18, 19, 20, and 21.

The following syllabus is for a 10-week quarter on cryptography engineering.

- **Week 1:** Chapters 1 and 2;
- **Week 2:** Chapters 3 and 4;

- **Week 3:** Chapters 5 and 6;
- **Week 4:** Chapters 7 and 8;
- **Week 5:** Chapters 9 and 10;
- **Week 6:** Chapters 11 and 12;
- **Week 7:** Chapters 13 and 14;
- **Week 8:** Chapters 15, 16, and 17;
- **Week 9:** Chapters 18, 19, 20;
- **Week 10:** Chapter 21.

The following syllabus is appropriate for schools with 12-week semesters. It can also be augmented with advanced materials in cryptography or computer security for longer semesters.

- **Week 1:** Chapters 1 and 2;
- **Week 2:** Chapters 3 and 4;
- **Week 3:** Chapters 5 and 6;
- **Week 4:** Chapter 7;
- **Week 5:** Chapters 8 and 9;
- **Week 6:** Chapters 9 (continued) and 10;
- **Week 7:** Chapters 11 and 12;
- **Week 8:** Chapters 13 and 14;
- **Week 9:** Chapters 15 and 16;
- **Week 10:** Chapters 17 and 18;
- **Week 11:** Chapters 19 and 20;
- **Week 12:** Chapter 21.

This book has several types of exercises, and we encourage readers to complete as many of these exercises as possible. There are traditional exercises designed to test your understanding of the technical properties of cryptography. However, since our goal is to help you learn how to think about cryptography in real systems, we have also introduced a set of non-traditional exercises (see Section 1.12). Cryptography doesn't exist in isolation; rather, cryptography is only part of a larger ecosystem consisting of other hardware

and software systems, people, economics, ethics, cultural differences, politics, law, and so on. Our non-traditional exercises are explicitly designed to force you to think about cryptography in the context of real systems and the surrounding ecosystem. These exercises will provide you with an opportunity to directly apply the contents of this book as thought exercises to real systems. Moreover, by weaving these exercises together throughout this book, you will be able to see your knowledge grow as you progress from chapter to chapter.

Additional Information

While we strove to make this book as error-free as possible, errors have undoubtedly crept in. We maintain an online errata list for this book. The procedure for using this errata list is below.

- Before reading this book, go to `http://www.schneier.com/ce.html` and download the current list of corrections.
- If you find an error in the book, please check to see if it is already on the list.
- If it is not on the list, please alert us at `cryptographyengineering@schneier.com`. We will add the error to the list.

We wish you a wonderful journey through cryptography engineering. Cryptography is a wonderful and fascinating topic. We hope you learn a great deal from this book, and come to enjoy cryptography engineering as much as we do.

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Preface to *Practical Cryptography* (the 1st Edition)

In the past decade, cryptography has done more to damage the security of digital systems than it has to enhance it. Cryptography burst onto the world stage in the early 1990s as the securer of the Internet. Some saw cryptography as a great technological equalizer, a mathematical tool that would put the lowliest privacy-seeking individual on the same footing as the greatest national intelligence agencies. Some saw it as the weapon that would bring about the downfall of nations when governments lost the ability to police people in cyberspace. Others saw it as the perfect and terrifying tool of drug dealers, terrorists, and child pornographers, who would be able to communicate in perfect secrecy. Even those with more realistic attitudes imagined cryptography as a technology that would enable global commerce in this new online world.

Ten years later, none of this has come to pass. Despite the prevalence of cryptography, the Internet's national borders are more apparent than ever. The ability to detect and eavesdrop on criminal communications has more to do with politics and human resources than mathematics. Individuals still don't stand a chance against powerful and well-funded government agencies. And the rise of global commerce had nothing to do with the prevalence of cryptography.

For the most part, cryptography has done little more than give Internet users a false sense of security by promising security but not delivering it. And that's not good for anyone except the attackers.

The reasons for this have less to do with cryptography as a mathematical science, and much more to do with cryptography as an engineering discipline. We have developed, implemented, and fielded cryptographic systems over the

past decade. What we've been less effective at is converting the mathematical promise of cryptographic security into a reality of security. As it turns out, this is the hard part.

Too many engineers consider cryptography to be a sort of magic security dust that they can sprinkle over their hardware or software, and which will imbue those products with the mythical property of ''security.'' Too many consumers read product claims like ''encrypted'' and believe in that same magic security dust. Reviewers are no better, comparing things like key lengths and on that basis, pronouncing one product to be more secure than another.

Security is only as strong as the weakest link, and the mathematics of cryptography is almost never the weakest link. The fundamentals of cryptography are important, but far more important is how those fundamentals are implemented and used. Arguing about whether a key should be 112 bits or 128 bits long is rather like pounding a huge stake into the ground and hoping the attacker runs right into it. You can argue whether the stake should be a mile or a mile-and-a-half high, but the attacker is simply going to walk around the stake. Security is a broad stockade: it's the things around the cryptography that make the cryptography effective.

The cryptographic books of the last decade have contributed to that aura of magic. Book after book extolled the virtues of, say, 112-bit triple-DES without saying much about how its keys should be generated or used. Book after book presented complicated protocols for this or that without any mention of the business and social constraints within which those protocols would have to work. Book after book explained cryptography as a pure mathematical ideal, unsullied by real-world constraints and realities. But it's exactly those real-world constraints and realities that mean the difference between the promise of cryptographic magic and the reality of digital security.

Practical Cryptography is also a book about cryptography, but it's a book about sullied cryptography. Our goal is to explicitly describe the real-world constraints and realities of cryptography, and to talk about how to engineer secure cryptographic systems. In some ways, this book is a sequel to Bruce Schneier's first book, *Applied Cryptography*, which was first published ten years ago. But while *Applied Cryptography* gives a broad overview of cryptography and the myriad possibilities cryptography can offer, this book is narrow and focused. We don't give you dozens of choices; we give you one option and tell you how to implement it correctly. *Applied Cryptography* displays the wondrous possibilities of cryptography as a mathematical science—what is possible and what is attainable; *Practical Cryptography* gives concrete advice to people who design and implement cryptographic systems.

Practical Cryptography is our attempt to bridge the gap between the promise of cryptography and the reality of cryptography. It's our attempt to teach engineers how to use cryptography to increase security.