Thinking about Cryptography:
Crypto Flaws and How to Avoid Them

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Some good news and some bad news…

The bad news

Implementing currently

^Crypto is ^hard…

…leading to many flaws

The good news

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Stupid encryption mistakes criminals make

Blown cover: Malware authors show how easy it is to get encryption wrong and, in the process, help security pros crack their code

Crypto flaws $\Rightarrow$ exploits

- Netscape
- Debian
- MSCHAP
- WEP
- Android/Bitcoin wallets
- PS3, XBox
- Flickr, Visa
- Yahoo, LinkedIn
- …

Scope of this talk

- In scope
  - Developer misuse of crypto (libraries)
- Out of scope
  - Crypto backdoors
  - Vulnerabilities in crypto libraries (incl. timing attacks, programming errors)
  - Clever attacks on complex protocols (BEAST, CRIME, …)

Examples…

- Using deterministic encryption
- Using nonrandom IV with CBC-mode encryption
- Using nonrandom encryption keys
- Using non-salted hashes
- Seeding PRNGs with fixed constants or low-entropy seeds

None of this is new!

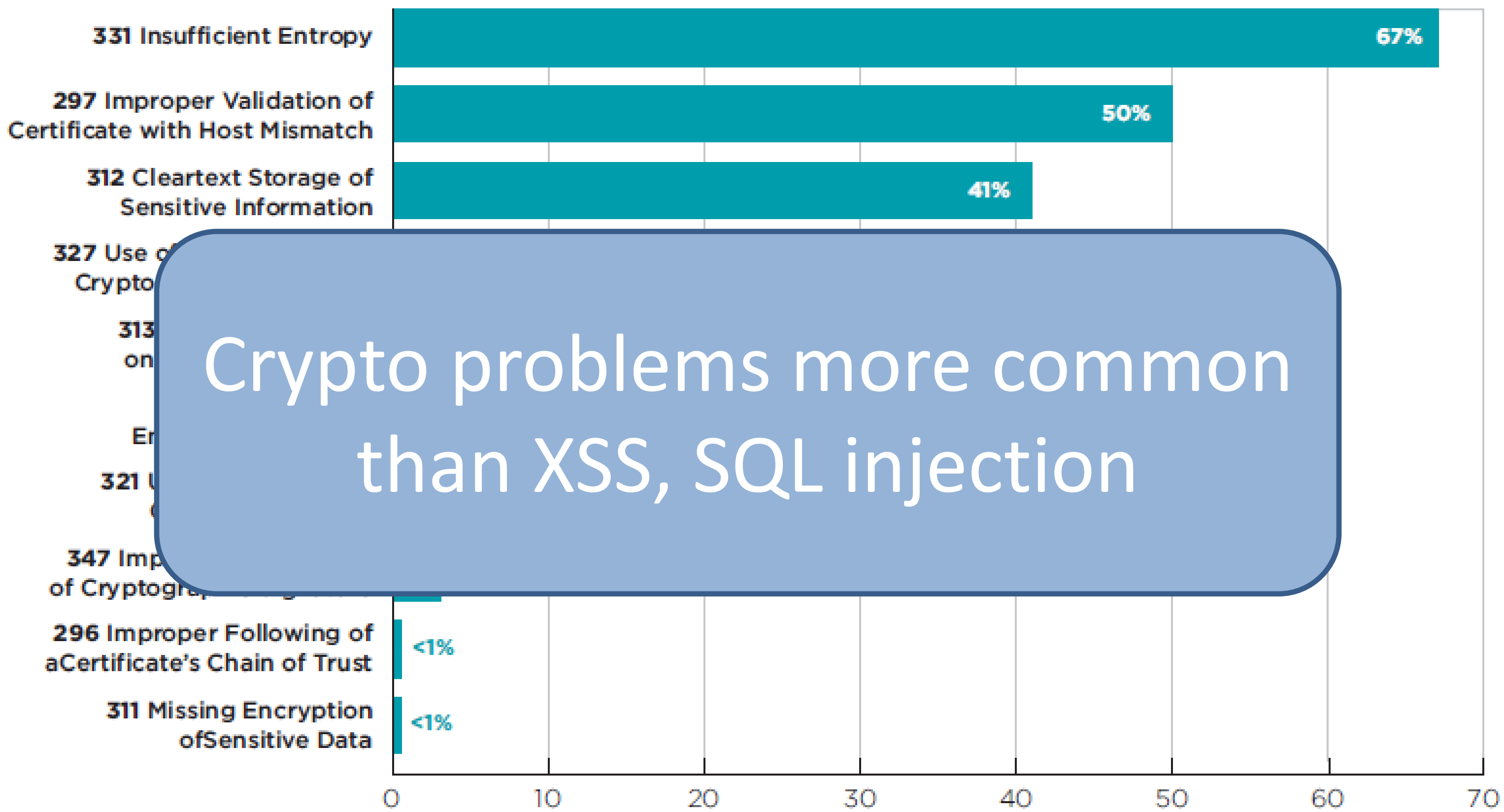
- Anderson, “Why Cryptosystems Fail,” ACM CCCS 1993
- Schneier, “Security Pitfalls in Cryptography,” 1998
- Gutmann, “Lessons Learned in Implementing and Deploying Crypto Software,” USENIX Security 2002

IEEE Top-10 Security Design Flaws

- Never assume trust
- Use authentication that cannot be bypassed
- Authorize after authentication
- Separate data and control
- Validate all data
- Use cryptography correctly
- Identify sensitive data and how to handle it
- Consider users
- Understand how external components affect attack surface
- Be flexible with future changes to objects/actors

The problem is still here…

- Veracode: "State of Software Security" (2015)



Crypto problems more common than XSS, SQL injection

Figure 5: Prevalence of cryptographic vulnerability types by CWE (percentage of applications affected)

The problem is still here…

- Egele et al., "An Empirical Study of Cryptographic Misuse in Android Applications," ACM CCCS 2013
  - 88% of Android applications using crypto APIs make mistakes
  - E.g.,
    - Weak keys/parameters
    - Deprecated/weak algorithms
    - Insufficient entropy
    - Ineffective password hashing

But it hasn't gone away…

- Lazar et al., "Why does cryptographic software fail?" APSys 2014
  - 269 crypto vulnerabilities in CVE database (Jan 2011 – May 2014)
  - 83% due to crypto misuse
  - E.g.,
    - Weak keys/parameters
    - Deprecated/weak algorithms
    - Insufficient entropy
    - Neglecting to encrypt sensitive data

Avoiding crypto flaws

- Don’t use weak keys/parameters
- Don’t use deprecated/weak algorithms
- Use sufficient entropy
- …

Avoiding crypto flaws

- Don’t use a keyed hash as a MAC
- Don’t use textbook RSA signatures/encryption
- Don’t use unauthenticated encryption
- Implement schemes exactly as defined
- Avoid timing vulnerabilities
- …

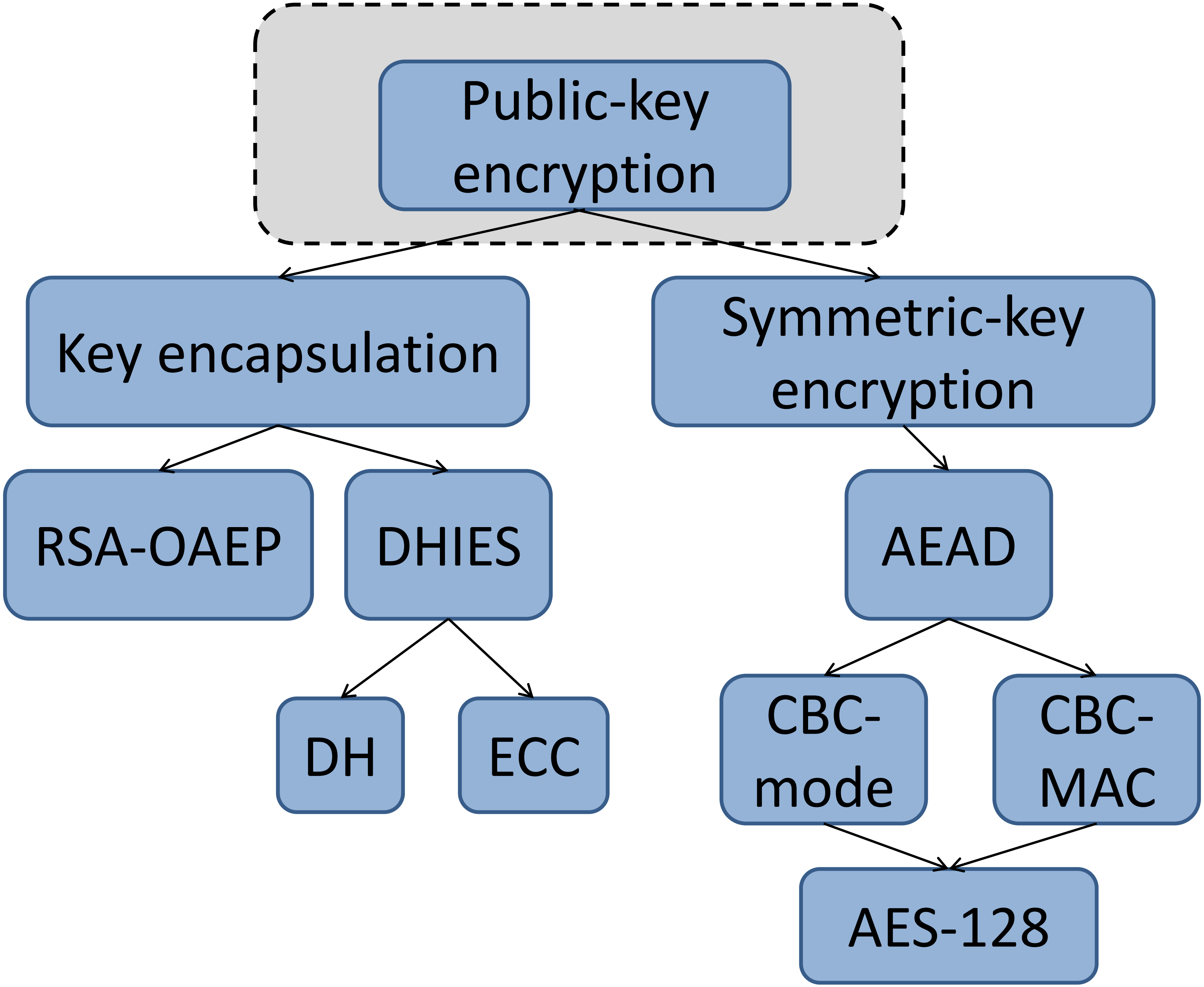
Common themes?

Common themes

- Unusable cryptography
- Misunderstanding cryptography

Same underlying cause!

- Incomplete separation between specification (API) and implementation (mechanism)

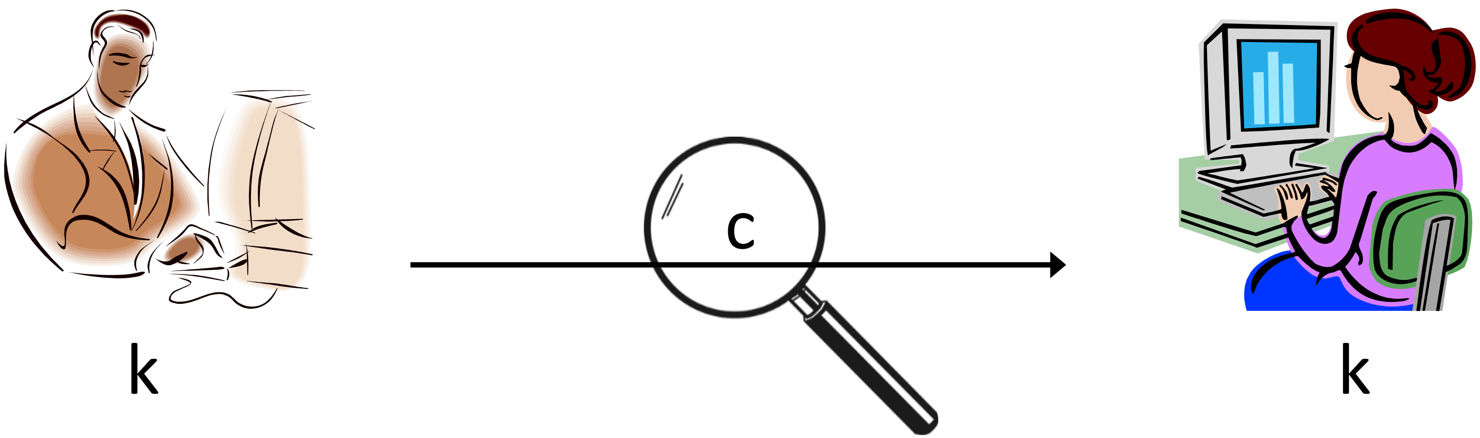

Public-key encryption
Key encapsulation
Symmetric-key encryption
RSA-OAEP
DHIES
AEAD
DH
ECC
CBC-mode
CBC-MAC
AES-128

Usable cryptography?

Usable by whom?

- The users
  - E.g., Whitten-Tygar, “Why Johnny Can’t Encrypt,” USENIX Security 1999
- Developers!
- Let’s look at a problem developers face…

Private-key encryption



k   k

$c \leftarrow Enc_k(m)$ $m = Dec_k(c)$

Given c, attacker learns nothing about m

Message authentication

c_1

c_2

c_3

c^*

k

k

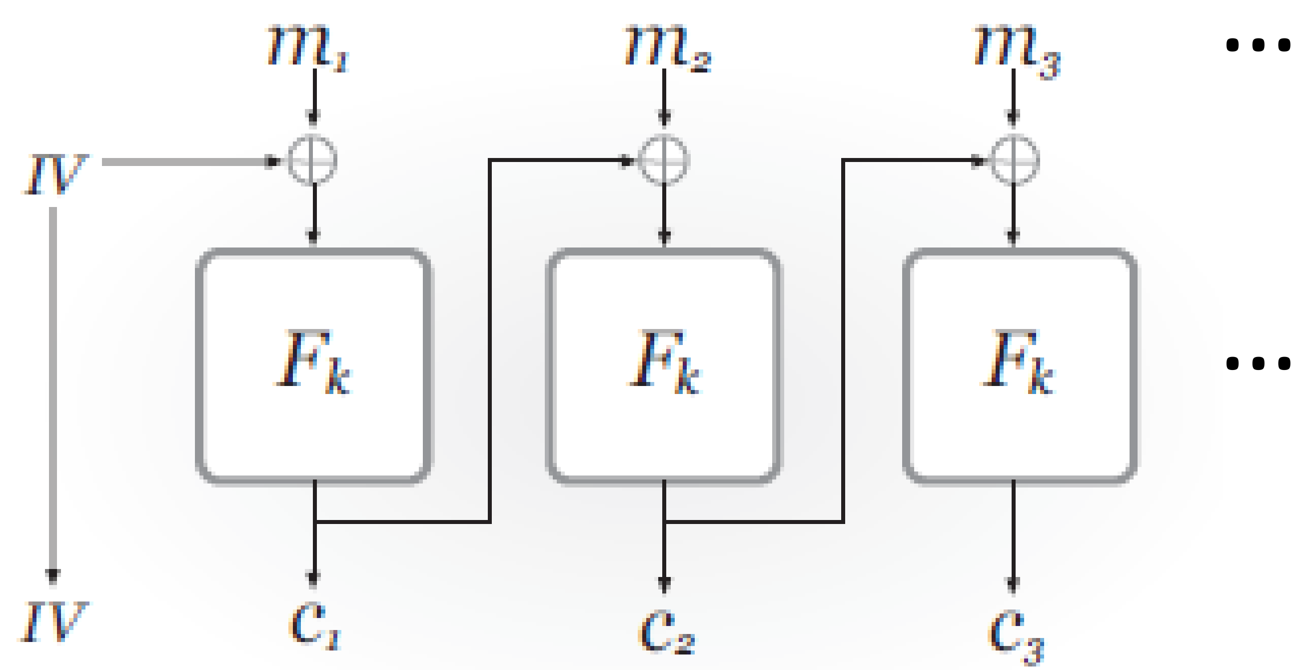
$c_1 \leftarrow \text{Encode}_k(m_1)$

$m_1 = \text{Decode}_k(c_1)$

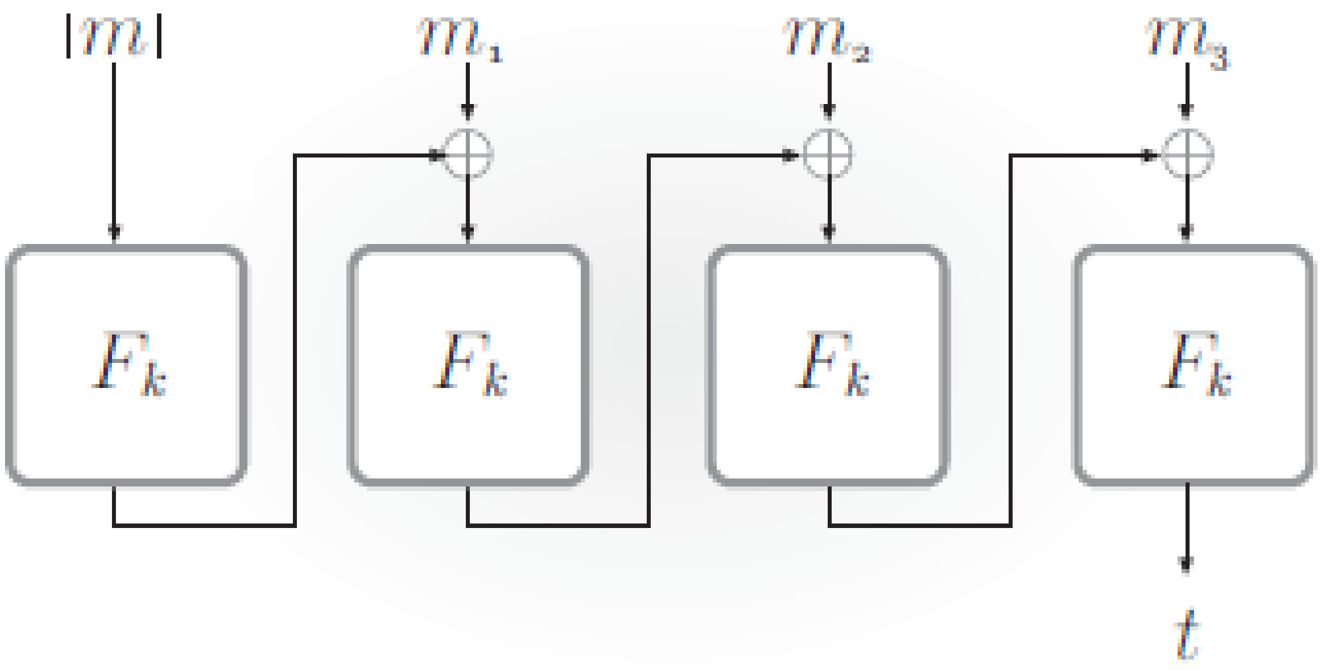
$\perp = \text{Decode}_k(c^*)$

Given c_1, …, attacker cannot generate c^* that fools receiver to output new m^*

CBC-mode encryption



CBC-MAC



CBC in OpenSSL

- Provides a “CBC” function that takes as input a key, an IV, and a message
  - Cl ı, then
    ca ·esult
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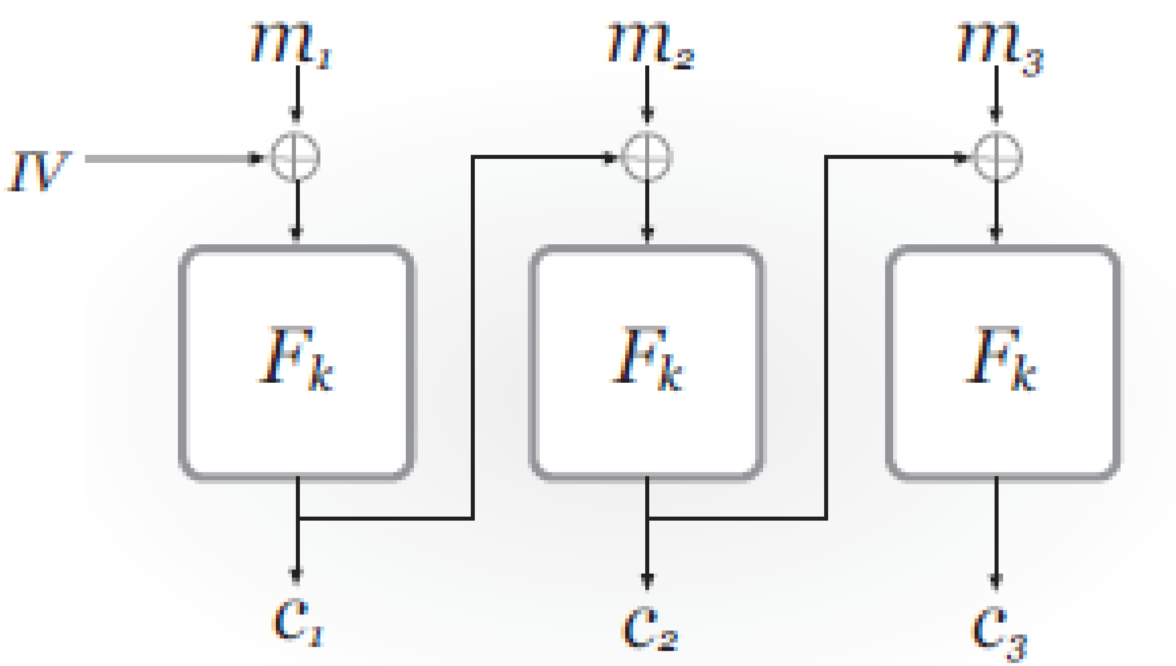

CBC-mode encryption

- CBC-mode encryption is only secure when used with an *unpredictable* IV
  - $CBC_k(0…0, m_1, …, m_n)$ is not secure
  - $CBC_k(ctr, m_1, …, m_n)$ is not secure

- Correctness
  - $CBC_k(IV, m_1, …, m_n)$ without the IV is not (fully) decryptable

CBC-MAC

- CBC-MAC is very brittle!
  - Returning $CBC_k(0…0, |m|, m_1, …, m_n)$ is insecure
    - Returning too many or too few bytes from the end can also be insecure
  - Returning last block of $CBC_k(0…0, m_1, …, m_n)$ is insecure
  - Using $CBC_k(IV, |m|, m_1, …, m_n)$ can be insecure and/or incorrect

Interactions

- Using CBC-mode encryption and CBC-MAC (properly!) with the same key is insecure

- Even if CBC-mode/CBC-MAC correct, need to use with secure block cipher, random key, …

CBC in OpenSSL

- OpenSSL documentation:
  - Normally, [CBC] is found as the function alg_cbc_encrypt(). Be aware that alg_cbc_encrypt() is not really CBC (it does not update the IV); use alg_ncbc_encrypt() instead
  - The use of different starting variables prevents the same plaintext enciphering to the same ciphertext

CBC in OpenSSL

- OpenSSL wiki:
  - [Set] up a 256-bit key and a 128-bit IV … Make sure you use the right key and IV length for [the] cipher … or it will go horribly wrong!!
  - [Set] up a buffer for the ciphertext…It is important to ensure that this buffer is sufficiently large … or you may see a program crash (or potentially introduce a security vulnerability …)

Developers need help

- Acar et al., “You Get Where You’re Looking For…,” IEEE S&P 2016
- App developers often turn to StackOverflow for programming help
- How valuable/dangerous is this?
  - Only 17% of StackOverflow posts had secure code
  - User study: developers using StackOverflow have higher chance of writing *functional* code, but lower chance of writing *secure* code

Fundamental problem

- Why should a developer need to know *anything* about the low-level crypto details?
- Should instead be provided with an interface to *encrypt* and an interface to *authenticate*
  - Newer crypto libraries (NaCl, Keyczar) work this way
  - Safer defaults
- API documentation needs to improve
  - Listed in OpenSSL roadmap since mid-2015

Misunderstanding cryptography

Core principles of modern crypto

- Formal definitions
  - Precise, mathematical model and definition of what security means
- Assumptions
  - Clearly stated and unambiguous
- Proofs of security
  - Move away from design-break-patch cycle

Formal definitions

- Defines the syntax of an API…
- Allows for an *understanding of the security guarantees* provided by that API
  - I.e., semantically secure encryption ensures that a passive adversary learns nothing about the message from the ciphertext
- This is all that should be exposed by a proper crypto library

Formal definitions

- Definitions are *central* to modern crypto
- Definitions as a “first-class object”
- Specifying a threat model is critical

Assumptions

- (Most) modern cryptography relies on unproven assumptions
  - Get over it

- Be vaguely aware when an assumption is (close to being) falsified
  - E.g., RSA-1024

- Should be handled automatically if using a proper crypto library

Proofs

- Crypto schemes can be *proven* secure!
  - Relative to some definition
  - Based on certain assumption(s)

- These proofs are brittle
  - Schemes must be implemented as described
  - Don’t design your own crypto

Constructions?

- No!

- When teaching crypto to a general audience, focus on *definitions* and *secure usage*
  - Details of schemes *irrelevant* to average developer

Avoiding flaws?

- "CBC-mode encryption produces random-looking ciphertexts"
- "View encryption as a black box that completely scrambles the message"

$\Rightarrow$ Encryption provides message integrity!

(Many authentication protocols built/broken based on this incorrect reasoning)

How could this have gone?

- What is the desired security (threat model)?
  - Impersonator should be unable to properly encode a random challenge from verifier
- Does semantically secure encryption imply it?
  - Nothing in the definition says it does…
- What is the appropriate primitive here?
  - Message authentication code

Avoiding flaws?

- “Hash functions produce completely random-looking output”
- “Changing even one bit of input results in completely unpredictable output”

$\Rightarrow$ Hash(key, m) must be a good MAC!

(Many integrity mechanisms built/broken based on this incorrect reasoning)

How could this have gone?

- What is the desired security (threat model)?
  - Message integrity
- Does a collision-resistant hash imply it?
  - Nothing in the definition says it does…
- What is the appropriate primitive here?
  - Message authentication code

Summary

- Many crypto flaws result from developers' exposure to *implementations* rather than *specifications*
  - Schemes vs. clean, easy, clear APIs
  - Constructions vs. definitions
- Crypto libraries should *only* expose an API for desired high-level tasks
- Developers should *focus on security goals* rather than low-level details about schemes

Questions?