Common Developer Crypto Mistakes (with illustrations in Java)

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Obligatory “It's all about me” page

- 35+ years developer experience, 15+ yrs security experience
  - 17 yrs at (now Nokia) Bell Labs; left as DMTS
  - 3.5 yrs as independent contractor (C++ & Java)
  - 14 years AppSec & InfoSec experience at CenturyLink / Qwest
- Currently: Information Security Engineer at Wells Fargo on Secure Code Review team (3 yrs)
- OWASP ESAPI for Java
  - Project co-leader
  - Cryptography developer (since Aug 2009)
- New OWASP Dev Guide – Crypto chapter
- Blog: http://off-the-wall-security.blogspot.com/
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- Email: <kevin.w.wall@gmail.com>
- Twitter: @KevinWWall
- CISSP, GIAC Web Application Defender (GWEB)

What I will cover

- Dev good news / bad news
- Mistakes in using the following:
  - Pseudo random number generators
  - Secure hashes
  - Symmetric encryption
  - Asymmetric encryption
- Miscellaneous topics (time permitting)
  - TLS issues
  - Key management
  - Transparent DB Encryption

Good News / Bad News

- Good news:
  - Devs no longer designing their own crypto
  - Devs rarely implementing standard algorithms
- Bad news:
  - Dev “expertise” from copy-&-paste from Stack Overflow, etc., so still get things wrong.
    - Confidentiality vs. authenticity
    - Confusion of cipher modes, padding schemes
  - Broken crypto for legacy applications
  - Even experts still get things wrong (e.g., OpenSSL, GPG, etc.).

Pseudo Random Number Generators
(PRNG)

PRNG Weaknesses

- Having a good source of (pseudo) randomness is essential to good cryptography.
  - –Poor randomness ==> broken crypto
  - –Cryptographers demand a “cryptographically secure” PRNG (CSRNG)
    - java.util.Random is *not* a CSRNG
    - java.security.SecureRandom is a CSRNG
  - –CSRNG must have unpredictable seed
    - Seed entropy must equal (and should exceed) the internal state of the CSRNG

PRNG Weaknesses: What to look for

- Using java.util.Random for *anything* related to crypto—this would include keys, IVs, nonces, etc.
- Seeding any CSRNG with insufficient entropy
  - If you initially require N-bits of randomness, then the entropy pool should have *at least* N-bits of randomness.
  - Generally not a problem with the default Oracle/Sun implementation of SecureRandom and SHA1PRNG.
    - Default SecureRandom CTOR uses /dev/urandom when available ***BUT*** may a problem if lots of randomness is required at boot time or if no /dev/urandom or /dev/random

Example of correct use / seeding of SecureRandom

```
SecureRandom csrng =
    SecureRandom.getInstance(“SHA1PRNG”,
                                            “BC”);
csrng.setSeed(
                         csrng.generateSeed(  160/8 )
                       );
```

For JDK 8 and later, consider using `SecureRandom.getInstanceStrong()` instead of `SecureRandom.getInstance()`.

Secure Cryptographic Hashing

Secure Hashing Weaknesses: What to look for (1/4)

- Use of completely broken algorithms: MD2, MD4, MD5 or algorithms that are not true message digests such as CRCs.
- Use of mostly broken algorithms: SHA1 (may be okay for legacy use for backward compatibility and some CSRNG cases).

Secure Hashing Weaknesses: What to look for (2/4)

- If concerned about *local* attacks…
  - Time-dependent comparison of hashes
    - E.g., Bad: String.equals() or Arrays.equals()
    - MessageDigest.isEqual() is okay *after* JDK 1.6.0_17
- Calling MessageDigest.digest(byte[]) or update(byte[]) methods on unbounded input under adversary’s control. (DoS attack)

Secure Hashing Weaknesses: What to look for (3/4)

- Misusing secure hash (MessageDigest) for message authentication codes (MAC):
  - MAC is a *keyed* hash, where the key is a secret key generally shared out-of-band.
  - Incorrect, naïve use:

    MAC(key, message) := H(key || message)

    Where '||' is bitwise concatenation.

Problem: Susceptible to "length extension attacks".

  - Correct use: Use an HMAC (RFC 2104)...

```
Mac hmac = Mac.getInstance("HmacSHA256", "SunJCE");
hmac.init(key);
```

Secure Hashing Weaknesses: What to look for (4/4)

- Misusing a secure hash to mask data where enumeration of all or most of the input space is feasible.
  - E.g., Use SHA-256(SSN) to store as key in database or to track in log file.
  - Problem: If adversary can observe hashes, she can enumerate SHA-256 hashes of all possible SSNs and compare these to stored hashes.

Is use of MD5 *ever* okay?

- Best collision attack against it is now about O($2^{24.1}$), which takes at most 5 or 6 seconds on a modern desktop / laptop.
- But…okay in following cases:
  - Used as a PRNG when we only need something that is more or less unique and unpredictable; example IV generation used with CBC for symmetric ciphers.
  - Used as an HMAC construct as defined in RFC 2104
    - Bellare, Canetti & Krawczyk (1996): Proved HMAC security doesn’t require that the underlying hash function be collision resistant, but only that it acts as a pseudo-random function.

Symmetric Encryption

Symmetric Encryption Weaknesses

- Inappropriate cipher algorithms
  - You aren’t still using RC4, are you?
- Insufficient key size: >= 128 bits
  - Java: DESede defaults to 2-key TDES (112-bit) unless the JCE Unlimited Strength Jurisdiction Policy files are installed.
- “ASCII” generated keys
- Inappropriate use of cipher modes
  - Related: IV abuses
- Assuming confidentiality implies data integrity.

ASCII Keys

- Keys generated from passwords or passphrases. E.g.,

```
String key = "#s0meSeCR3tK3y!!"; // Or from prop
SecretKeySpec skey =
    new SecretKeySpec( key.getBytes(), "AES");
Cipher cipher =
   Cipher.getInstance("AES/CBC/PKCS5Padding");
cipher.init(Cipher.ENCRYPT_MODE, skey);
...
```

Inappropriate use of cipher modes

Question: `Cipher.getInstance("AES")`
… what’s the default cipher mode?

- Block modes and stream modes
  - Block modes: ECB and CBC
  - Stream modes: pretty much everything else
- All modes except for ECB require an IV.
- Streaming modes: Must **not** reuse the same key / IV pair… ***EVER***!
- Streaming modes do not require padding.

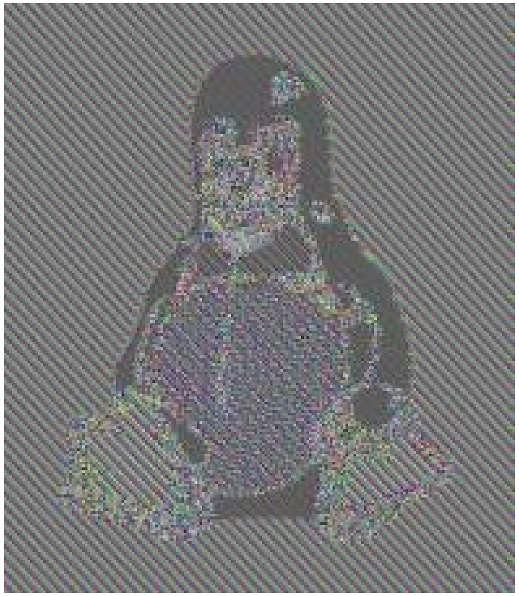
Inappropriate use of cipher modes: ECB

- ECB is the raw application of the cipher algorithm.
- Reasons why it is the most commonly misused:
  - First (and sometimes only) example in textbooks
  - Simplest to implement (no need to bother with IVs)
- Weaknesses:
  - Same plaintext blocks always encrypt to same ciphertext
  - Block replay attacks are possible

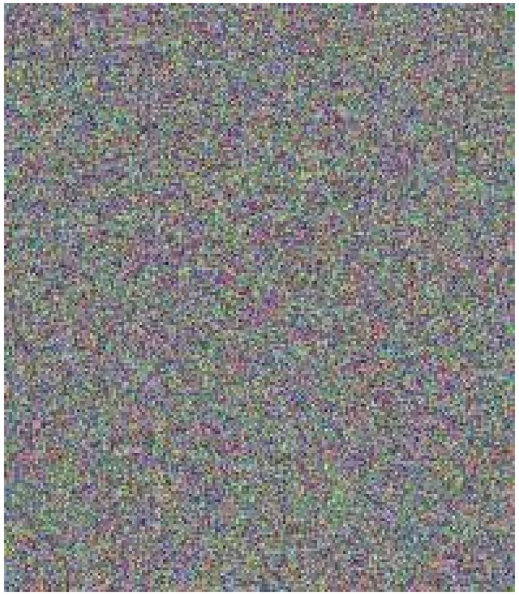
What's Wrong with ECB Mode?

Original Tux image

Tux image encrypted with ECB mode



Tux image encrypted with any other cipher mode



From: http://en.wikipedia.org/wiki/Block_cipher_mode_of_operation via Wikimedia Commons; Larry Ewing, lewing@isc.tamu.edu, and The GIMP.

ECB: Block Replay Attack (1/6)

- Adversary can modify encrypted message without knowing the key or even encryption algorithm.
  - Can mangle message beyond recognition.
    - Remove, duplicate, and/or interchange blocks
  - Can usurp meaning of message if structure known. Consider the following scenario...

ECB: Block Replay Attack (2/6)

[Example from Schneier, *Applied Cryptography*]*

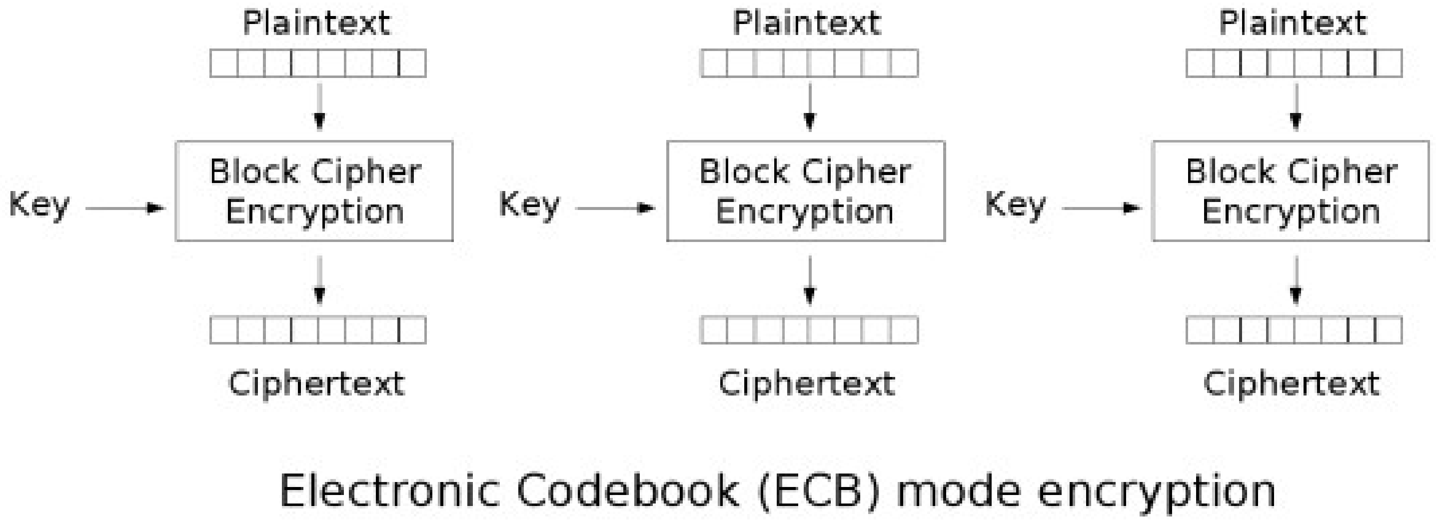
- Assume 8-byte encryption block size.
- Money transfer system to move $ btw banks
- Assume bank’s standard message format is:

Bank 1: Sending	1.5 blocks
Bank 2: Receiving	1.5 blocks
Depositor’s Name	6 blocks
Depositor’s Acct #	2 blocks
Deposit Amount	1 block

---

* First discussed by C. Campell, *IEEE Computer*, 1978

ECB: Block Replay Attack (3/6)



Each block is encrypted (and decrypted) independently

Image: Public domain, from Wikimedia Commons

ECB: Block Replay Attack (4/6)

- Mallory is MITM agent, listening to comm channel between Bank of Alice and Bank of Bob.
- Mallory sets up accounts in both banks and deposits seed money in Bank of Alice.
- Mallory transfers some fixed amount of the seed money to Bank of Bob and records transaction.
- Repeats later, and looks for identical blocks; eventually isolates acct transfer authorization.

ECB: Block Replay Attack (5/6)

- Mallory can now insert those message blocks into communication channel at will. Each time, that fixed amount will be deposited in Mallory’s account at the Bank of Bob.
- Two banks will notice by close of business when accts are reconciled. By that time, Mallory has already skipped town.

ECB: Block Replay Attack (6/6)

- Can *not* be defeated by simply prepending date/time stamp to bank transfer authorization message. Mallory can replay individual blocks that lie on whole block boundaries (e.g., in this case the Depositor’s Name and account #).
- *Can* be defeated by adding secure *keyed* hash to entire message (or using another cipher mode).

ECB: What to look for

- No cipher mode specified at all. E.g.,

```
Cipher cipher = Cipher.getInstance(“AES”);
```

In Java, this is the same as:

```
Cipher cipher =
      Cipher.getInstance(“AES/ECB/PKCS5Padding”);
```

- No evidence that an IV is used
  - In Java, look for *absence* of both IVParameterSpec and Cipher.getIV()
  - Check lengths of resulting encryption
    - Generally IV is prepended to the raw ciphertext. (Exception might be where IV is fixed (bad) or determined algorithmically; discussed later.)

ECB: Is it ever okay?

- Yes, when:
  - Encrypting plaintext with a less than 1 cipher block and ciphertext attacks not feasible:
    - Blowfish and DES (and hence DESede) block size: 64 bits
    - AES block size (and most other AES candidates): 128 bits
  - OR when encrypting *random* data
    - E.g., nonces, session IDs, *random* secret keys; maybe passwords if strong passwords enforced (LOL!).
- AND padding is used when appropriate (random data)
- AND block replay attacks are not an issue
- OR, using it for asymmetric encryption (only applicable mode!)

If use of ECB *seems* okay…

- Make sure it is not used in a scenario where a block replay attack is possible.
- Ask yourself:
  - Are multiple blocks of ciphertext encrypted with ECB used?
  - Are these multiple ciphertext blocks exposed to an “adversary”?
  - Will block re-ordering ever fail to be detected in any cases? (I.e., are there cases where data integrity not always ensured?)
- If answer to these is “yes” for all questions, block replay is probably possible.

Key / IV reuse in streaming mode (1/9)

- Stream ciphers and block ciphers operating in streaming modes create a cipher bit stream that is XOR’d with the plaintext stream.
- For a given key / IV pair, the same cipher bit stream is generated each time. Let’s call this cipher bit stream, C(K, IV).
- Let the encryption function for such a streaming mode be designated as E(K, IV, msg).
  - Then E(K, IV, msg) = msg XOR C(K, IV)

Key / IV reuse in streaming mode (2/9)

- Let's see what happens if we encrypt 2 different plaintext messages, A and B, this way

  E(K, IV, A) = A XOR C(K, IV)
  E(K, IV, B) = B XOR C(K, IV)

- If an adversary intercepted both of these ciphertext results, they can compute the XOR of them, which is

  E(K, IV, A) XOR E(K, IV, B) =
  A XOR C(K, IV) XOR B XOR C(K, IV)

which, since XOR is commutative, is:

A XOR B XOR C(K, IV) XOR C(K, IV) = A XOR B

That is, the XOR of the 2 plaintext messages, A and B.

Key / IV reuse in streaming mode (3/9)

- So what do we do with the XOR of 2 plaintext messages, A and B?
- If messages A and B are both written in some normal language (or character set, like ASCII), we can make that as a guess and use frequency distribution of some anticipated language (or format, such as CC#s, etc.) and guess likely plaintext bits (characters). If the result resembles something intelligible (e.g., ASCII letter), guess was probably right.
- Modest computers can crack this in matter of few minutes for modest length messages.

Key / IV reuse in streaming mode (4/9)

- The more ciphertexts created using the same key / IV pair and observed by an adversary, the better.
- Fixed message formats / structures (e.g., knowing you have all numeric fields such as SSN or credit card #) make it even more trivial.
- Eventually, both plaintexts (or shortest part if different lengths) get revealed.

Key / IV reuse in streaming mode (5/9)

Next 4 slides from Dr. Rick Smith, Univ of St. Thomas, MN
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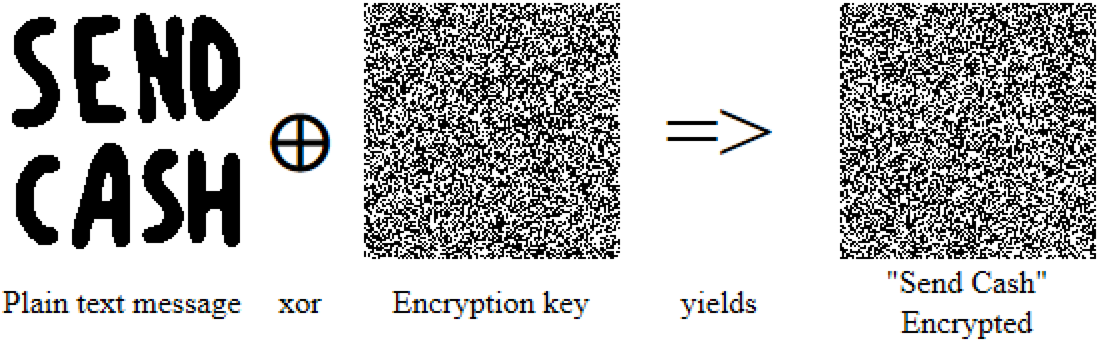
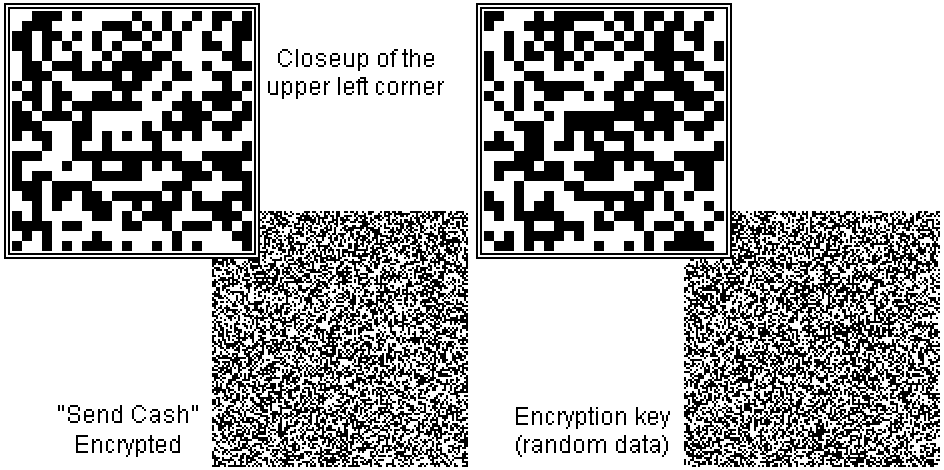




Key / IV reuse in streaming mode (6/9)

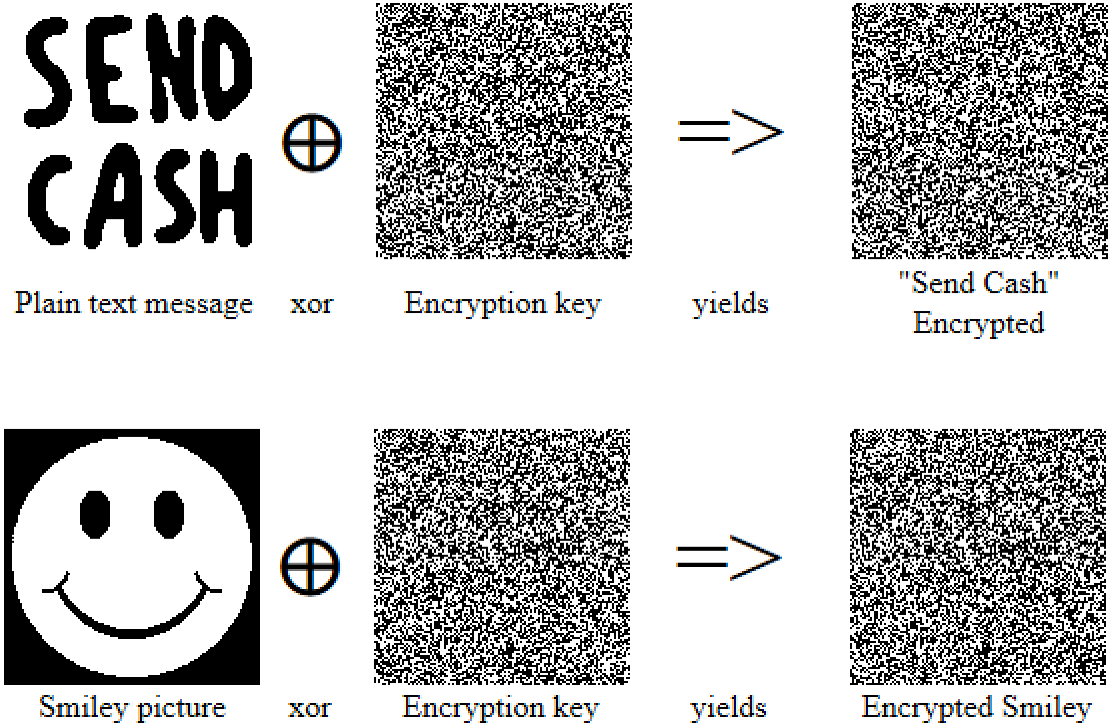
- To recover the original message (image), we XOR the encrypted “Send Cash” image with the encryption key again:

“Send Cash” encrypted

Encryption key

“Send Cash” Plaintext image

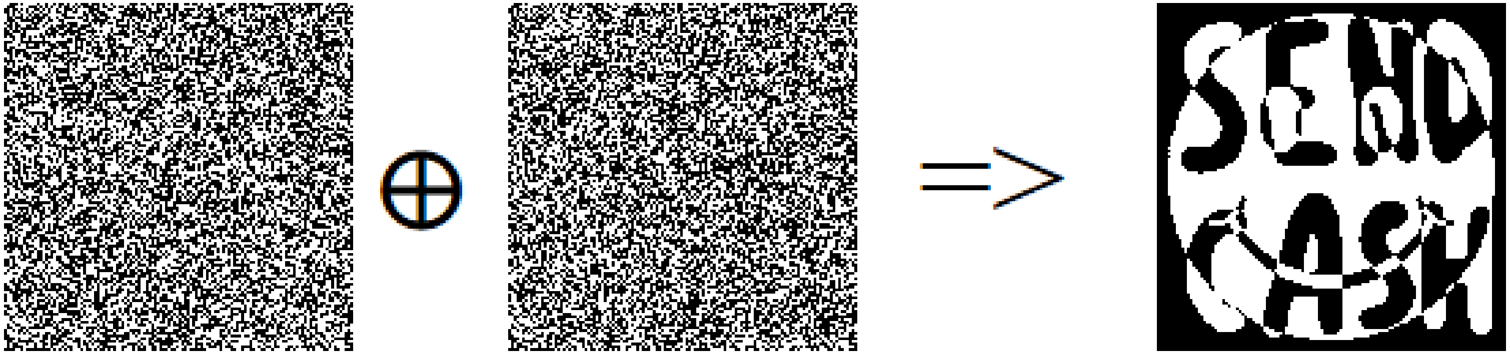
Key / IV reuse in streaming mode (7/9)



Note that we have the ***same*** encryption key XOR’ing both images.

Key / IV reuse in streaming mode (8/9)

Here’s what happens when we XOR the 2 images that both used the same encryption key together:



"Send Cash" Encrypted xor Smiley Encrypted yields Both messages overlaid

Key / IV reuse in streaming mode (9/9)

- *But wait!* It gets worse. It an application is doing this and an adversary can decrypt a message, they may be able to use a MITM attack to actually *alter* the ciphertext.
- Wikipedia example (Stream_cipher_attack):

(*C(K) xor "$1000.00") xor ("$1000.00" xor "$9500.00")* = C(K) xor "$1000.00" xor "$1000.00" xor "$9500.00" = C(K) xor "$9500.00"

Detour: Authenticated Encryption

- Encryption provides confidentiality, not integrity. (Integrity, aka authenticity)
- Approaches to authenticated encryption
  - Encrypt-then-MAC (EtM): Encrypt, then apply MAC over IV+ciphertext and append the MAC.
  - Encrypt-and-MAC (E&M): Encrypt the plaintext and append a MAC of the plaintext.
  - MAC-then-Encrypt (MtE): Append a MAC of the plaintext and encrypt them both together.
- Decryption operation applied in reverse order.
- EtM built into some cipher modes such as CCM, GCM, EAX, etc.

Horton Principle

- David Wagner and Bruce Schneier
- Relevant when considering what to data to include in a MAC
- Semantic authentication: “Authenticate what is meant, not what is said”
  - Avoid unauthenticated data: either don’t send / rely on it, or include it in the MAC
  - Relevant in message formats and protocols
- E.g., Alice sends: “metadata||IV||ciphertext||MAC”

Symmetric Encryption Weaknesses: CBC

- Overall, CBC probably most robust mode when used correctly.
- Use correctly means:
  - Random key and random IV with padding
  - HMAC over the IV+ciphertext applied as “encrypt-then-MAC” approach.
- Common mistakes:
  - Fixed IV or predictable IV (e.g., counter, time, etc.)
  - Failure to MAC correctly (e.g., no MAC at all, encrypt-and-MAC, or MAC-then-encrypt)

Why is AE needed?

- When ciphertext’s authenticity is in doubt, certain cryptographic attacks are possible that will either divulge the plaintext (or portions thereof) or possibly even real the secret key.
- Padding oracle attack, Serge Vaudenay, 2002
  - Originally discussed as deficiency in IPSec and SSL
  - Dismissed as being impractical until Rizzo and Duong research and POET software in 2010

Symmetric Encryption Weaknesses: Assuming confidentiality implies data integrity

- Only true if one is using an AE cipher mode such as CCM or GCM (the only 2 AE modes that are NIST approved) or using a correctly implemented EtM approach.
- If confidentiality is not required, better (and faster) to just use an HMAC.
- Look for cases where plaintext is already known to attacker and encryption is used to prevent tampering.

Asymmetric Cryptography: Encryption

Common Asymmetric Padding Schemes

- No padding
- PKCS#1 v1.5 (simply called "PKCS1Padding" in Java)
- Optimal Asymmetric Encryption Padding (OAEP)

Asymmetric Ciphers and Chosen Plaintext Attacks (1/3)

- All asymmetric ciphers are prone to chosen plaintext attacks (CPA).
  - CPA is a cryptanalytic attack where an attacker can chose which plaintext to encrypt and then observe the resulting ciphertext.
  - CPA is always possible with asymmetric ciphers because we assume the algorithm details is known as well as the *public* key.

Asymmetric Ciphers and Chosen Plaintext Attacks (2/3)

- Why might this be a problem?
  - Normally it’s not because:
    - We usually are encrypting highly unpredictable plaintext that is too large to be enumerated. E.g., symmetric session keys, cryptographic hash values
    - Or using OAEP padding.
  - It becomes a problem when the is highly regular or short enough to enumerate all possible values and/or PKCS1 (or 1.5) padding (or no padding) is used.

Asymmetric Ciphers and Chosen Plaintext Attacks (3/3)

- Real-life (bad) example
  - Application uses RSA algorithm to encrypt credit-card #s and store the resulting ciphertexts in application DB.
  - Consider inside attacker with access to DB records (e.g., DBA, developer, tester) as well as the *public* key.
  - Attacker encrypts all possible credit card #s with public key and saves mapping of plaintext / ciphertext pairs.
  - Lookup into application DB records via CC# ciphertext allows discovery of credit card holder as well as revealing plaintext CC#.

Miscellaneous Topics

- Key Management
- Database Encryption
- TLS/SSL issues

Key Management: Re-keying Frequency(1/2)

- PCI DSS 2.0 and later says that you *must* change symmetric crypto keys *at least* yearly? Is that enough?
- Steve Bellovin says in http://osdir.com/ml/encryption.general/2005-02/msg00005.html:
  - For 3DES in CBC mode, re-key at least every 2^{32} * 64-bits of plaintext
  - For AES in CBC mode, every 2^{64} * 128-bits
  - General: every $2^{N/2}$ * cipher_block_size bits, where N is key size in bits.

Key Management: Re-keying Frequency (2/2)

- “Sweet32”, a TLS attack on legacy 32-bit cipher suites is example:
- https://sweet32.info/
- https://sweet32.info/SWEET32_CCS16.pdf
- Matthew Green blog post provides more explanation:
  - http://blog.cryptographyengineering.com/2016/08/attack-of-week-64-bit-ciphers-in-tls.html

Key Management: Secure Key Storage

So where do you store your keys?

- Ideally: an HSM or a TPM
- FAIL: If hard-coded in source code or put into properties file.
  - Both situations usually under version control!
- Ok: Config file, locked down & controlled by ops staff and unavailable to all others.
- Better: For .NET, DPAPI, WebLogic Encryption Services, Java Key Store
- NEVER put encryption key in *same* file with data that's being encrypted.

Encrypting Data in a DB

Three ways to encrypt data for a database:

1. DB Engine itself does it via (mostly) Transparent Data Encryption (TDE)
2. Done via a proxy; e.g., MIT's CryptDB
3. Done via application code

From application perspective, TDE approach is simplest.

- Transparent to the application.
- Available for Oracle and Microsoft SQL Server
- Probably satisfies “letter of the law” for PCI DSS compliance (not verified).

30k' view of TDE

- Offers encryption at the column, table, and tablespace levels.
- Limited ciphersuite available; e.g., AES & 3DES
- Key management: usually 2 keys involved:
  - DB “master” key – a key encryption key, secured w/ password
  - Table / column / tablespace keys, encrypted by DB master key
- Usually CBC mode used, with usually with same IV for all encryptions
  - Same IV required for deterministic encryption so indexing works as expected
  - “Salt” allows non-deterministic encryption

WIYTM? Why TDE fails

- If any application has that DB table / column open, then any other application with access to that table / column has access to encrypted data!
  - Not problem if data properly partitioned via “views”.
  - Backups, depending on how done, can be in plaintext!
- Usually the data we are encrypting in DB is:
  - Less than 20 bytes
  - Has particular format
  - Limited possible values

Result: Patterns may allow enumeration of values.

SSLSocket & Server AuthN

- SSLSocket (or subclass) created by SSLSocketFactory does not do host name verification or cert pinning by default. Hence, MITM attacks are possible.
  - Must implement your own. 2 approaches:
    - Subclass SSLSocket; see http://www.velocityreviews.com/forums/t958287-adding-hostname-verification-to-sslsocket.html
    - Create an SSLContext that does host name verification; see http://stackoverflow.com/questions/8545685/writing-a-ssl-checker-using-java

Specifying JCE Providers

- Java has a concept of security providers.
  - Statically added via:
    - JRE: $JAVA_HOME/lib/security/java.security
    - JDK: $JAVA_HOME/jre/lib/security/java.security
  - Dynamically added via:
    - Security.addProvider(Provider provider)
    - Security.insertProviderAt(Provider provider, int pos)
    - Various getInstance() methods take Provider as 2nd arg
- Determined by position; defaults to what is in java.security.
- This concept extends to crypto providers

What could possibly go wrong?

```
import org.bouncycastle.jce.provider.*;
...
int pos = Security.addProvider(
    new BouncyCastleProvider()  );
```

Static setting in java.security

- Default list of providers ordered by preference:

```
security.provider.1=sun.security.provider.Sun
security.provider.2=sun.security.rsa.SunRsaSign
security.provider.3=sun.security.ec.SunEC
...
security.provider.9=sun.security.smartcardio.SunPCSC
security.provider.10=sun.security.mscapi.SunMSCAPI
security.provider.11=org.bouncycastle.jce.provider.BouncyCastleProvider
```

How about this?

```
import org.bouncycastle.jce.provider.*;
...
Security.insertProviderAt(
    new BouncyCastleProvider(), 1 );
```

Equivalent static setting in java.security

- Equivalent as if we did this:

```
security.provider.1=org.bouncycastle.jce.provider.BouncyCastleProvider
security.provider.2=sun.security.provider.Sun
security.provider.3=sun.security.rsa.SunRsaSign
security.provider.4=sun.security.ec.SunEC
…
security.provider.10=sun.security.smartcardio.SunPCSC
security.provider.11=sun.security.mscapi.SunMSCAPI
```

What could possibly go wrong?

- Consider this in Logger.getLogger() method in *rogue* copy of log4j.jar someone downloaded:

```
 …
 Security.insertProviderAt(
new MyEvilProvider(), 1 );
 …
```

How do we address this?

- Specify the Provider instance as part of the getInstance() methods; e.g.,

```
Cipher.getInstance(“AES/CBC/PKCS5Padding”,
                                   new BouncyCastleProvider() );
```

OR

- Use a Java Security Manager and restrict what classes may call Security.addProvider() and Security.insertProviderAt()

What to look for

- Calls to either

  Security.addProvider()

OR

  Security.insertProviderAt()

without the use of a Java Security Manager (JSM)

Caveat: Java Security Manager is rarely used and if it is used, usage of a properly restrictive security policy is hardly ever set. Also, if the jars are not signed and validated before use, using the JSM matters little.

Additional References

- New OWASP Dev Guide, chapter 11 (Cryptography) [still a work in progress]
  - https://github.com/OWASP/DevGuide/blob/master/03-Build/0x11-Cryptography.md
  - And those references therein

Questions?

(Now, or email me at
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