ENPM 809W
Introduction to Secure Software Engineering

Gananand Kini

Lecture 6

Cryptography related security bugs - Defenses

MITRE | SOLVING PROBLEMS FOR A SAFER WORLD™

Outline

- **Securing data flows**
  - Data encryption at rest and in-transit
  - Secure password storage (Adding flavor with SALT on both client and server)
  - Secrets storage (SecureString in .NET, alternatives in Java? Python?)
  - Managing PKI and digital certificates (Certificate Transparency)
- **Weaknesses associated with cryptography implementation**
  - Cryptographic secure random number generation
  - Key derivation
  - Defending against timing attacks
- **CPSA**

Securing data flows

Securing Data Flows

- **Software systems need to protect data flows (in transit).**
- **They also need to protect data at rest.**
- **Remember: Threat modeling was done using data flow diagrams.**
- **Good time to start looking at how to protect the data sources, sinks and flows.**
- **Also look at use and misuse cases to determine:**
  - What data needs protection? Example: Personably Identifiable Information
  - What are the protection requirements? Example: User profile information should only be accessible by Support staff and only after correctly identifying user and obtaining permission.

Weaknesses associated with cryptography application and implementation

Avoid …

- Using unknown or rolling your own cryptographic algorithm.
- Using weak cryptographic primitives (both for hashing or encryption/decryption).
- Going overboard with security because it will certainly hamper performance and usability.

Time of Check Time of Use problems in cryptography

- **Ensure transactional checking of:**
  - Identity
  - Signatures
- **And only use the content that was checked!**

Some hash collision countermeasures

- **Randomized hash function**
  - Typically best approach, but adds overhead, makes non-deterministic, & in many cases must be done at language implementation level
  - “Universal hash function” is an especially efficient hash function for use in adverse environment by a language infrastructure
  - Cryptographic hashes typically don’t help by themselves
  - If mapped to small number of buckets, attacker can still just precompute.
- **Use another data structure (e.g., treemaps) for mapping user data in app that isn’t vulnerable to a predictable worst-case situation**
- **Limit the number of worst-case situations in each HTTP request**
  - Limit the number of different HTTP request parameters
  - Limit HTTP POST and GET request lengths
- **Limit maximum CPU time or number of requests**
- **Add “random” data to value to be hashed when writing app**
  - Hand-create randomness, but extra work for developers
  - If you’re using Java HashMap or String.hashCode, consider this

Notes on Secure Password Storage

- From a cryptographic perspective, selection of a strong hash function for storing passwords is a must.
- Use of a unique salt or a secure random value that cannot be guessed should be used in order to prevent rainbow table types of attacks.
- We will discuss more on secure password storage in the section on Authentication and Authorization.

Random Number generation pitfalls (To avoid)

- **Use of predictable random number generators for cryptography is bad**
  - C: rand() – **DON'T USE**
  - Java: java.util.Random() **– DON'T USE**
- **Forgetting to seed the random number generator -or- Using the same seed every time will generate identical sequences of numbers is bad**
- **Instead of java.util.Random() use java.security.SecureRandom()**
  - (typically) uses the SHA1PRNG generator
  - seeds itself using /dev/urandom
    - collects random data from disk reads, mouse movement, keystrokes, etc.
  - be careful overriding the PRNG or seed, make sure you know what you are doing

.NET Random number generation

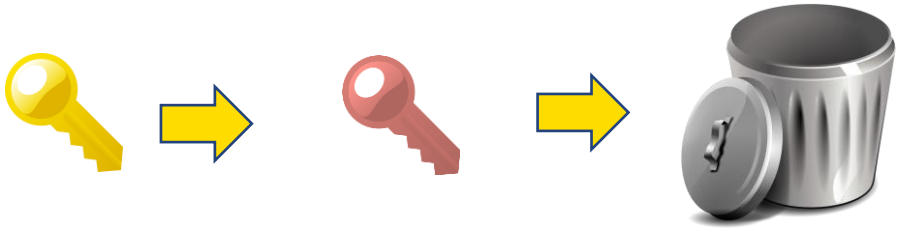
- **.NET provides System.Security.Cryptography.RandomNumberGenerator class.**
- **Provides secure random numbers for use in cryptographic algorithms.**
- **Operations**
  - Fill(Span<Byte>)
  - GetBytes(Span<Byte>|Byte[])
- **Use the right function! Predictable RNG vs. Crypto RNG:**
  - Java: Random vs. SecureRandom
  - C#: System.Random vs. System.Security.Cryptography.RandomNumberGenerator
  - Python: random vs. os.urandom
  - Javascript: Math.random vs. window.crypto.getRandomValues

Use secure initialization vectors (IV)

- ***Never* reuse IVs**
  - Create new IV each session/encryption
  - In general, don't reuse values for crypto algorithms unless it is *specifically* documented as being fine
- **Use cryptographically random values**
  - For example, from a cryptographic pseudo-random number generator (PRNG)
  - In general, don't use non-cryptographic random values whenever using crypto algorithms

Cryptographic material management

- **How do you manage the process of protecting data?**
- **Lots of developers focus on these:**
  - Crypto material generation or retrieval
  - Crypto operations
- **Lots of developers forget to:**
  - Cleanup
    - What about removing traces of the protected information?
    - What about ensuring compromised cryptographic material isn't used again?



.NET Ephemeral String Storage

- **You don't want to keep cryptographic material around in memory:**
  - System.Security.SecureString class tried to solve the problem… Emphasis on **tried**.
  - However, it does **not** secure the string in memory!
  - Provides an immutable String storage space and makes sure the object gets disposed after use.
  - Idea is to accept input directly into a SecureString and then Clear() after use.
- **Operations:**
  - AppendChar(Char) //Add to the string
  - SetAt(Int32, Char) // to modify only if necessary
  - Clear() // Clears the memory of all the values stored there
  - Dispose() // Frees up memory

Timing attacks: Solutions

- **Use timing-independent (sometimes called "constant-time") algorithms**
  - *Not* the same as O(1) algorithms!!
- **E.g., "is equal to" in Java [Lawson2010] [Hale2009]:**

```
public static boolean isEqual(byte[] a, byte[] b) {
 if (a.length != b.length) { return false; } // Omitting this is a bad bug
 int result = 0;
 for (int i = 0; i < a.length; i++) { // Note that we always examine everything
   result |= a[i] ^ b[i];  // Do not use +… not constant-time on some systems
 }
 return result == 0;
}
```

- **Crypto library implementations have to worry about this broadly**
- **Consider if you need timing-independent, *especially* when using crypto**
  - Use them when comparing secret values (e.g., session values) where an attacker could incrementally guess a next value
  - Not a problem for iterated salted hashes (too slow for attacker to get value)
  - Timing attacks apply broadly, but "is equal to" is especially common issue
  - MessageDigest.equal() was fixed in Java SE 6 Update 17

Nate Lawson. January 7, 2010. Timing-independent array comparison. http://rdist.root.org/2010/01/07/timing-independent-array-comparison/
Hale. Hale, Coda. http://codahale.com/a-lesson-in-timing-attacks/. A Lesson In Timing Attacks (or, Don't use MessageDigest.isEquals) 13 Aug 2009

Credit: Prof. David A. Wheeler

OWASP Resources

- **Cryptographic storage cheat sheet:**
  - https://cheatsheetseries.owasp.org/cheatsheets/Cryptographic_Storage_Cheat_Sheet.html
- **Transport Layer Protection cheat sheet:**
  - https://cheatsheetseries.owasp.org/cheatsheets/Transport_Layer_Protection_Cheat_Sheet.html
- **Both are included as pdfs in your module.**
- **Also best settings for crypto on various platforms/software systems (from OWASP page): https://bettercrypto.org/**

Cryptographic Protocol Shapes Analyzer (CPSA)

Cryptographic Protocols Shapes Analyzer (CPSA)

- **Created at MITRE by Moses D. Liskov, John D. Ramsdell, Joshua D. Guttman, and Paul D. Rowe and written in Haskell.**
- **https://hackage.haskell.org/package/cpsa**
- **Assists in the design and test of cryptographic protocols given:**
  - Protocol definition
  - Partial description of an execution
- **Only tries to show executions that are different.**
- **Each execution is called a shape.**
- **Helps to identify where cryptographic protocols could go wrong.**
- **Uses the Dolev-Yao model for cryptographic analysis and underlying algebra.**

Sources:

1. M. Liskov, J. Ramsdell, J. Guttman, and P. Rowe. Cryptographic Protocol Shapes Analyzer: A Manual v3. June 24, 2016. Retrieved July 20, 2021.

CPSA Quick Tutorial

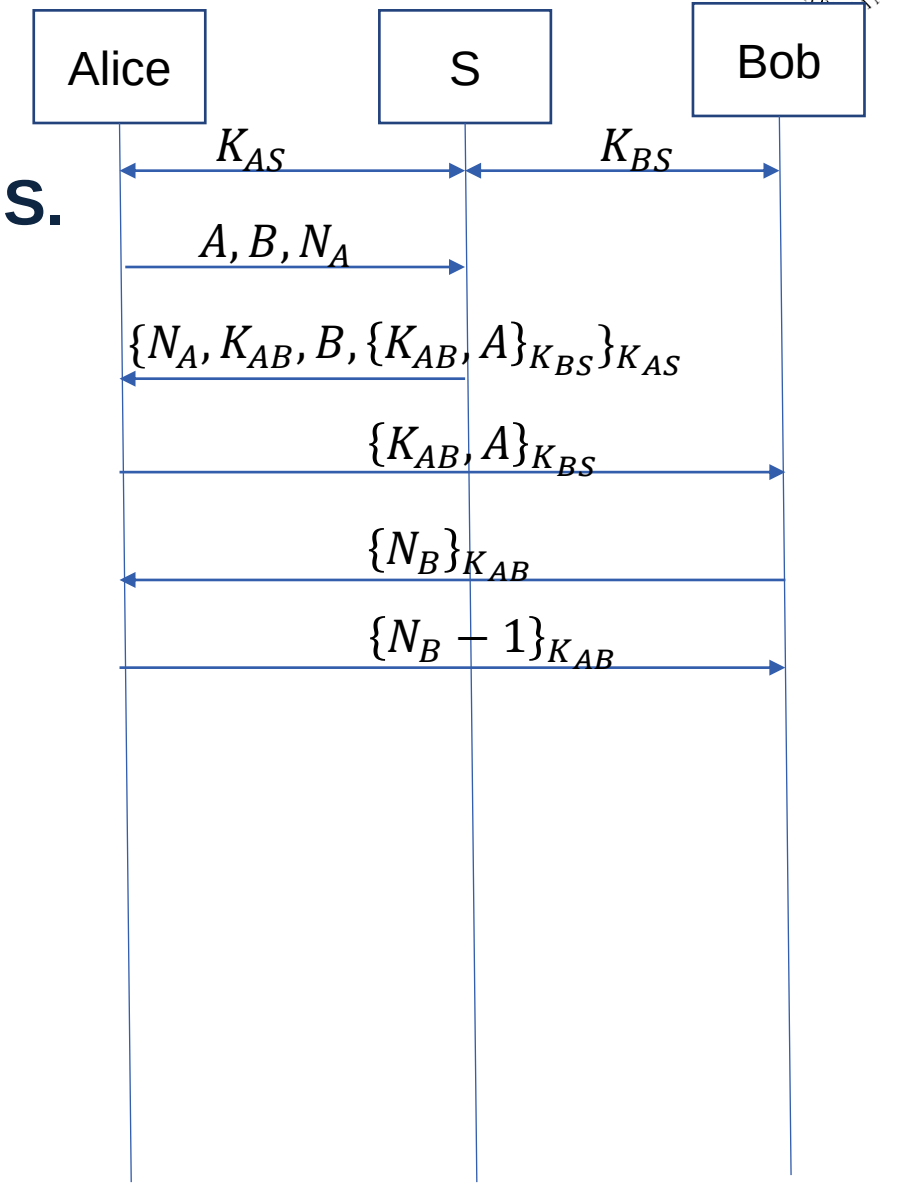
- **How do you use CPSA?**
  - **Do** model roles that are involved in the protocol not individual actors.
    - So CPSA ignores that a message is supposed to be received by a recipient and models the network itself as an attacker. Since the attacker is free to drop the message, the intended recipient might never get the message.
  - Similarly, the intended recipient does not have to respond to messages and so you **do not** model specific responses.
  - **Do** model messages using cryptographic materials such as keys, nonces, cryptographic operations
  - **Do** create a skeleton that describes a partial execution of a protocol.
    - A skeleton has instances (viewpoint of honest parties assuming the role along with variable values) of the roles modeled earlier.

CPSA assumptions

- **Cryptography mechanisms being used are strong (for example enc operation cannot be broken by the adversary)**
- **Other assumptions about nonces are specified in the cpsa program:**
  - uniq-orig – Unique origination role (Generated unique for a given role)
  - uniq-gen – Similar to uniq-orig but also unique to transmission strand

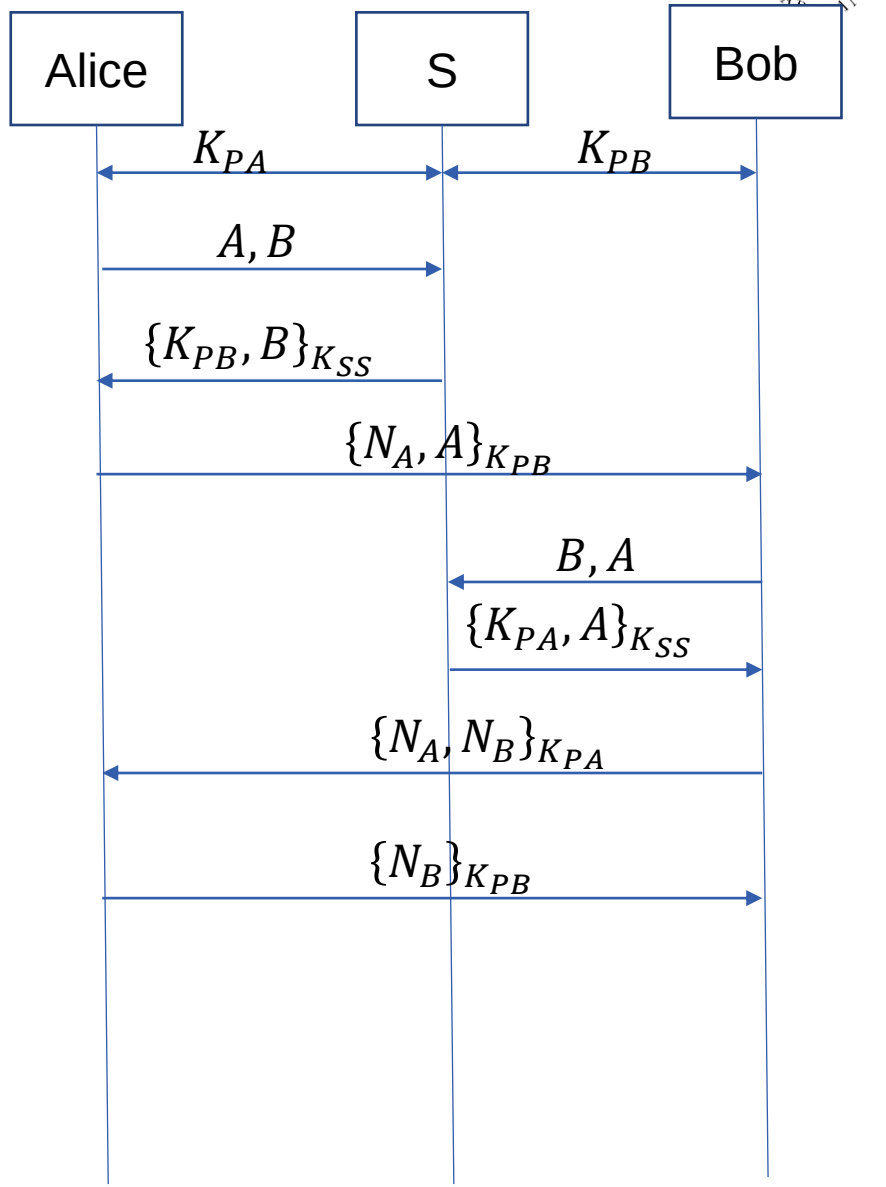
Needham-Schroder Protocol (Symmetric)

- Alice and Bob want to exchange secrets over an insecure network but with help of trusted server S.
- They want to establish a shared symmetric key that encrypts and decrypts only their communications. How do they do it?
- N_A is Alice's chosen nonce.
- N_B is Bob's chosen nonce.
- K_{AS} is symmetric key known only to S and Alice.
- K_{BS} is symmetric key known only to S and Bob.
- Another notation: $A \rightarrow S: A, B, N_A$
- What is the problem here?



Needham-Schroder Protocol (Asymmetric)

- Alice and Bob want to exchange secrets over an insecure network but with help of trusted server S.
- They want to establish a session key that encrypts and decrypts only their communications. How do they do it?
- N_A is Alice's randomly chosen nonce.
- N_B is Bob's randomly chosen nonce.
- K_{PA} and K_{SA} are Alice's public and secret keys respectively. S is for secret …
- K_{PB} and K_{SB} are Bob's public and secret keys respectively.
- K_{SS} is the key used by server to sign.
- What is the problem here?



Needham-Schroder in CPSA

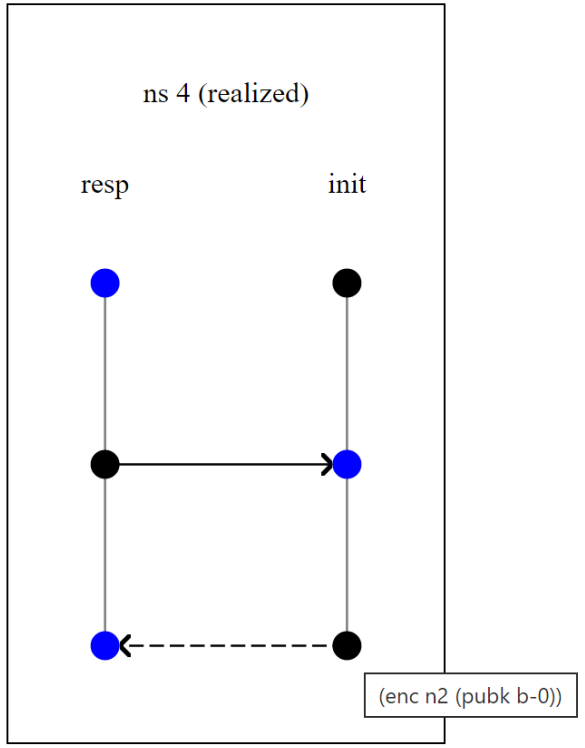
- **CPSA uses a `herald` for title of the code.**
- **The `comment` is shown below the title.**
- **Three semicolons also are used for inline comments.**
- **Define protocol using `defprotocol`**
- **Define roles using `defrole`**
  - In this case initiator (init) and responder (resp)
- **Define a skeleton containing "strands" using `defskeleton`.**
  - Strands are S-expressions (Lisp) that define an instance of the protocol from the provided role's view along with some "maplets" or variable values to use for various parts of the protocol.

```
(herald "Needham-Schroeder Public-Key Protocol"
                (comment "This protocol contains a man-in-the-middle"
                                "attack discovered by Galvin Lowe."))

;;; Used to generate output for inclusion in the primer.
;;; Use margin = 60 (-m 60) to generate the output.

(defprotocol ns basic
  (defrole init
    (vars (a b name) (n1 n2 text))
    (trace
     (send (enc n1 a (pubk b)))
     (recv (enc n1 n2 (pubk a)))
     (send (enc n2 (pubk b)))))
  (defrole resp
    (vars (b a name) (n2 n1 text))
    (trace
     (recv (enc n1 a (pubk b)))
     (send (enc n1 n2 (pubk a)))
     (recv (enc n2 (pubk b)))))
  (comment "Needham-Schroeder"))

;;; The initiator point-of-view
(defskeleton ns
  (vars (a b name) (n1 text))
  (defstrand init 3 (a a) (b b) (n1 n1))
  (non-orig (privk b) (privk a))
  (uniq-orig n1)
  (comment "Initiator point-of-view"))

;;; The responder point-of-view
(defskeleton ns
  (vars (a b name) (n2 text))
  (defstrand resp 3 (a a) (b b) (n2 n2))
  (non-orig (privk a) (privk b))
  (uniq-orig n2)
  (comment "Responder point-of-view"))
```

Maplet (role name, role value)

Needham-Schroder: identifying the problem

- Nodes represent events (transmission/reception)
- Blue and red nodes indicate reception of message
- Black nodes indicate sending of message
- Solid arrow represents a successful transmission of message
- Dashed arrow represents an inconsistency between sender and receiver
- Red node indicates that constraints are not met.
- CPSA tries using a different value in place of the variables and appends a counter: For example n2-0.




```
(defskeleton ns
  (vars (n2 n1 text) (a b b-0 name))
  (defstrand resp 3 (n2 n2) (n1 n1) (b b) (a a))
  (defstrand init 3 (n1 n1) (n2 n2) (a a) (b b-0))
  (precedes ((0 1) (1 1)) ((1 2) (0 2)))
  (non-orig (privk a) (privk b))
  (uniq-orig n2)
  (operation nonce-test (added-strand init 3) n2 (0 2)
    (enc n1 n2 (pubk a)))
  (label 4)
  (parent 3)
  (unrealized)
  (shape)
  (maps ((0) ((a a) (b b) (n2 n2) (n1 n1))))
  (origs (n2 (0 1))))
```

Next time …

- **Authentication and Authorization related bugs - Attacks**