CS144 Notes: Security

- **Q: What are the goals of attackers?**
  - from machines
    * infiltration: take over machines/resources
      - defacement: replace legitimate content
    * denial of service

  - from users
    * get data
      - credit card, password, ...
    * get traffic
      - click = money
      - the real currency of our age is user's attention

- **Q: How do attackers achieve the goal?**

  Many, many different ways

  - phishing: spoof web site to look like the real one
  - pharming (DNS cache poisoning): wrong DNS resolution, for example
  - packet sniffing
  - man-in-the-middle attack
  - password brute-force attack

  - buffer overflow
  - client-state manipulation
  - cross-domain vulnerability
    * cross-site request forgery (XSRF)
    * cross-site script inclusion (XSSI)
    * cross-site scripting (XSS)
  - sql injection

  - note: some of these vulnerabilities can be controlled by "good" programming practice. more discussion later

- **Q: When we communicate over Internet, what type of "guarantee" do we want?**

- confidentiality
- message/data integrity
- authentication
- authorization

- **Q: How can we keep confidentiality of the messages?**
  - steganography: "embed" true message within harmless-looking message

    * e.g., Kathy is laughing loudly
      Osama bin laden video
      Change the lowest bit of image pixels

    * security by obscurity

  - encryption: "scramble" message with a key, so that it wouldn't make sense to others unless they have the key

    * e.g., bitwise XOR with k

      11110000 (message) XOR 10111001 (key) -> 01001001 (ciphertext)
      01001001 (ciphertext) XOR 10111001 (key) -> 11110000 (message)

Symmetric Key Cryptography

- **<explain the generalization referring to XOR example>**

  In general, an encryption algorithm requires:
    - c = F(m, k): encryption function (m XOR k)
        * m: message = plaintext. want to keep secret
        * c: ciphertext. transmitted over insecure channel
    - m = F'(c, k): decryption function. inverse of F (c XOR k)
        * From above, m = F'(F(m, k), k)
        * e.g., ((m XOR 10111001) XOR 10111001) = m
    - F(m, k), F'(m, k) are called "cipher"

- **Q: What other property should F(m, k) have?**

  Note: Ideally, one should never be able to guess m from c alone
  = ciphertext should not reveal any information about plaintext

    - Perfect secrecy
        * For all plaintext x and ciphertexts y, Pr[x|y] = Pr[x] (a.k.a. Shannon secrecy)
        * OTP (one time pad) encryption is proven to be perfectly secret, but due to practical limitation, cannot be used directly
            - many encryption algorithms try to "mimic" OTP, e.g., RC4

- **Commonly used ciphers:**
    - DES (data encryption standard)
        * 64 bit block cipher
        * vulnerable to brute-force attack due to short key -> Triple DES
    - AES (advanced encryption standard)
        * 128 bit block cipher
        * 128, 192, 256 bit keys

        * adopted by NIST (national institute of standard and technology) as a replacement of DES in 2000

    - IDEA, A5 (used by GSM), Blowfish, ...

- **<show AES encryption animation>**

Remark:

1. addition and multiplication used for MixColumn step are slightly different from standard definition.
2. MixColumn step "mixes" values from multiple bytes. Other steps do not mix values from multiple bytes.

- **Q: How can we agree on a key "secretly" over the Internet?**

    - Out-of-band communication?

- **Q: After A and B agreeing on secret key, how can we prevent B from impersonating A to C?**

    - Q: n parties. How many keys?

- **Q: Want to keep communication confidential between every party. How many keys do we need for n parties?**

Asymmetric Key Cryptography

- **Basic idea**
  - two pairs of keys
    - * e: encryption key
    - * d: decryption key

  - c = F(m, e): encryption function
    m = F'(m, d): decryption function

    - * From these, F'(F(m, e), d) == m

- **Q: How can we keep communication secret using this mechanism?**

- **Q: How do we use this to alleviate the key agreement problem?**
  - users share their "encryption" key -> public key
    - * others use the public key to encrypt the message to the user

  - users keep their "decryption" key secret -> private key
    - * users use their private key to decrypt message

  - no need to send the secret key over insecure channel

- **Q: What properties should F, F', e and d satisfy to make this work?**
  - "perfect secrecy" from F(m, e)
    - * one cannot get m from c without d

  - one should never get d from e

- **Q: n parties. How many keys do we need to keep all-pair confidentiality?**

- **Idea first developed by Ellis, Cocks, and Williams (working for British NSA)**
  - In early 70's, but could not publish
  - First public-key cryptosystem by Diffie and Hellman in 1976

- **RSA (Rivest, Shamir and Adleman)**
  - Most widely used asymmetric key cryptography
    * other example: ECC (elliptic curve cryptography)

  - used by many security protocols
    * e.g., SSL, PGP, CDPD, ...

  - algorithm
    * pick two *random* prime numbers p and q.

    * pick e < (p-1)(q-1)
      - does not have to be random
      - popular choice e = 2^16 + 1 = 65537 or others, like 3, 5, 35, ...

    * find d < (p-1)(q-1) such that "de mod (p-1)(q-1) = 1"
      - using extended-euclid algorithm in log[(p-1)(q-1)] time

  - two theorems
    1. there exists such unique d if e is a "coprime" to (p-1)(q-1)
       i.e. e does not share any factor with (p-1)(q-1)
    2. assuming n = pq, m = m^(ed) mod n

  - usage

    n, e: public key
    n, d: private key

    F(m, e): c = m^e mod n
    F'(c, d): m = c^d mod n

- now three things to verify
  1. F'(F(m, e), d) == m ?
  2. can we derive m from c = m^e mod n?
  3. can we derive d from de mod (p-1)(q-1) = 1 ?

- **Q: Is F'(F(m, e), d) == m ?**

- **Q: Can we compute m from c = m^e mod n?**

* RSA problem.

- **Q: can we compute d by solving de mod (p-1)(q-1) = 1?**

    * Q: Isn't it easy to get p and q from n = pq?

    * large-number factorization problem

  - Note: Security of RSA depends on the difficulty of factorization and RSA problems.

  - Note: asymmetric cryptography is 1000x slower than symmetric cryptography

Application of Asymmetric Key Cryptography

Recap: authentication, authorization, confidentiality, message integrity

- **Q: How can we keep message "confidential"?**

  - Performance and complexity issue

- **Q: How can we "authenticate" the other party?**
  - Main idea: F(F'(m, d), e) = m

    e.g., RSA   m = (m^e)^d = (m^d)^e

  - Challenge: generate random value r and send c = F'(r, d)
    Response: send back F(c, e) = r

- **Q: How can we check the message integrity?**

  - Q: How can we make sure others did not temper with checksum?

  - signature
    * secret key encrypted checksum of the text
    * others can ensure the authenticity of message by decrypting it using public key of the author

- **Q: How do we know the public key for A *really* belongs to A?**
  - CA (certificate authority)
    * guarantees that the public key really belongs to the person
      - out of band identity check

    * issues "certificate" to each person
      - "text" (XXXX is the public key of A) signed by CA's secret key
      - others can "trust" the public key if they trust CA

- SSL (https)
  - very high level description

    * when contacted by client, server presents its signed certificate "XXX is the public key of amazon.com. This certificate is valid until ../../...."
    * client "authenticates" server through challenge/response using the public key
    * client/server agrees on exchange symmetric key using public key encryption
    * client/server communicate securely through symmetric-key encryption

  - real protocol is much more complicated

    * mutual authentication
    * handshake of encryption algorithm
    * make sure freshness of conversation
    * ...

  - enabling SSL on tomcat
    * uncomment the "SSL HTTP/1.1 Connector" entry in $CATALINA_HOME/conf/server.xml

Key Management

- **Q: How to generate keys?**
    - user selection vs random-number generator
    - random-number generator + encryption by user password

      Note:
        * the need for perfect random number generator
        * the need for "safe" key storage

- **Q: What if a key/password is stolen?**
    - Multi-factor authentication
        * to minimize possibility of compromised keys, systems authenticate users based on combinations of
            - what you have (e.g., physical key, id card)
            - what you know (e.g., password)
            - who you are (e.g., fingerprint)
        * 2-factor authentication
    - smartcard
        * temper-resistant
        * stores password (or digital certificate)
        * some performs on-board RSA encryption/decryption to avoid revealing the password to the reader

    - OTP (one time password) card: e.g. SecurID by RSA security
        * a physical card flashing a new security code, say, every minute
            - temper resistant
        * keys are generated from current time + "seed key"
            - the server knows the security code generation algorithm
            - the need for time synchronization
        * user provides the security code to the server for logging in
            - often requires additional PIN from the user
        * prevents password replay attack
    - a physical device such as your laptop and smart phone

Common vulnerabilities

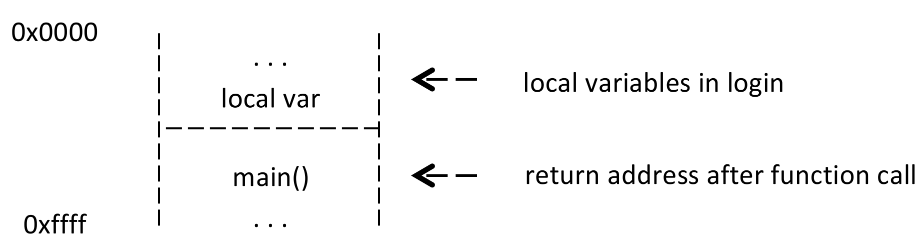
- **common vulnerabilities to discuss**
  - buffer overflow
  - client state manipulation
  - SQL/command injection
  - cross-site scripting
  - cross-site request forgery
- https://www.owasp.org/index.php/Top_10_2013-Top_10

**** buffer overflow ****

```
<example>

int main() {
   if (login()) {
      start_session();
   }
   return 0;
}

int login() {
   char passwd[10];
   gets(passwd);
   return (strcmp(passwd, "mypasswd") == 0);
}

int start_session() {
   ...
}
```

- **Q: main() -> login() -> start_session().**
  How does the system remember where to return inside a function call?
  - structure of stack after function call

main() -> login()



        * stacks typically grow bottom up

- **What will happen if the user-input is longer than 10 characters?**

  <illustrate the possibility by drawing the information in the stack>

    - by making a local variable "overflow", a malicious user may jump to any part of the program
    - "attack string": carefully constructed user input for attack

- **Java c#, or c++ string: "mostly" safe from buffer overflow attack**
    - most java run time actively check incorrect address, buffer overflow, array bound checking.
    - c++ stl string class also actively checks overflow.
    - do not use c str functions: gets, strcpy, strcat, sprintf, ...

- **Q: Any general solution?**

    - stackguard: inserts random "canary" before return addr and checks corruption before return.
        * not a complete protection against buffer overflow.
        * /GS flag for ms c++ compiler
        * -fstack-protector-all for some gcc

    - Also, never trust user input!!!

**** Client state manipulation ****

```
<example>

<form ...>
  <input type="hidden" name="price" value="5.50">
  ...
</form>
```

- **Q: what is the problem?**

- Note: the same goes for information stored in Cookie
- Note: again, never trust user's input!!!

- **Q: How do we avoid the problem?**
  - authoritative state stays at the server
    - * store values at the server and send session id only
      session id: random number generated by the server
      Note: to avoid stolen session id attack
      - pick a random session id from a large pool
      - use "client ip" for session id generation
      - make session id short lived

  - signed-state sent to client
    - * verify whether the parameters from client matches the signature
      Note:
      - sign every parameter. e.g., signature on price only
      - make the signature short lived. e.g., price fluctuation over time

- **Q: Pro/con of each approach?**

**** SQL/command injection attack ****

- **Q: Is there any problem with the following code?**

```
"SELECT name, price FROM Product WHERE prod_id = " + user_input + ";"
```

  - Q: What if user_input = "1002 OR TRUE"?

  - Q: What if user_input = "0; SELECT * from CreditCard"?

  - CardSystems lost 263,000 card numbers through SQL injection vulnerability and was acquired by another company

- **Q: Any problem?**

```
system("cp file1.dat $user_input");
```

- Protection:
  - Never trust user input!!!! reject unless it is absolutely safe

  - For SQL: prepared statements and bind variables

```
<example>

PreparedStatement s =
    db.prepareStatement("SELECT * from Product WHERE id = ?");
s.setInt(1, Integer.parseInt(user_input));

ResultSet rs = s.executeQuery();
```

    Note: invalid input cannot make it into the SQL statement filtered out during parsing
    * similar support for other languages

  - Java Runtime.exec(command_string) executes the first word in the string as the command and the rest as the parameters.
    * Not as vulnerable as C/C++/php/...

  - "taint" propagation support in Perl/Ruby
    * user supplied strings are marked "tainted"
    * if tainted string is used inside sensitive commands (SQL, shell,...) system generates error
    * tainted string needs to be explicitly "untainted" by programmer

  - to minimize the damage in case of successful attack
    * give only the necessary privilege to your application
    * encrypt sensitive data in dbms

**** cross site scripting (XSS) ****

```
<example>

$user_name$'s profile
```

- **Q: Any problem?**

- Q: What will happend if $user_name is "<script>hack()</script>"?

- Note: if page includes user input, users may execute *any* script

- **Q: How to prevent it?**

  - Q: not allow any html tag?

    * At the minimum, escape &, <, >, ", '

  - Q: What if html tags should be allowed (like html email)?

  - Q: What about <img src=$user_url>?
    $user_url can be "javascript:attack-code;"

    * Note: Be very careful with html attributes, scripts, URLs to other sites

Note:

- General protection against all XSS attack is VERY difficult
- Importance of white listing as opposed to black listing
- Both input validation and output sanitization

**** cross site request forgery (XSRF) ****

- **review of HTTP cookie**

  - arbitrary name/value pair set by the server and stored by client
  - server -> client
    * Set-Cookie: foo=bar; path=/; domain=cs188.edu; expires=Mon, 09-Dec ...

      - path and domain specify when to return the cookie
      - if expiration date is set in the future, the cookie becomes "permanent" and is stored in the hard drive

- if unspecified, the cookie becomes transient (= session cookie)
- to erase a cookie:
  1. change the expiration date to a past time
  2. set the value to null

- client -> server
  * Cookie: foo=bar

- often used to track a user login session
  * cookies are "valid" during a web browser session

- Q: Can a malicious page "access" cookie from another site?

  * same domain policy
    - basic security mechanism to protect data from malicious web site
    - a script can access documents and cookies that are from the same "domain" (= site)
    - cookies are sent back only to the same domain

```
<example>  http://evilsite.com
   The user has visited http://victim.com and has not logged out

   <form ... name="hack" action="http://victim.com">
       <input type="hidden" name="newpassword" value="hacked">
       ...
   </form>

   <script>
       document.hack.submit()
   </script>
```

- Q: What will happen? Will http://victim.com reject the request?

- Note:
  * XSRF allows attacker only to "write" to the server
  * due to same-domain policy, "read" from the server is not possible

- Q: How to prevent it?

* S1: Check Referrer header?
    - Note: Referrer header may be missing for legitimate reasons
* S2: Ask user password for every request?
* Q: Any other way?

- "action token"
    * basic idea: make sure requests from our pages include a "signature" that a malicious page cannot get
    * procedure
        1. generate "action token":
            a. action token: secret-key signed signature of session id
            b. we assume session id is random, unique per session, short lived and hard to guess
        2. embed the action token as a hidden field of the form

        - for every request
        1. compute the action token of the request
        2. take action only if it matches with the session id
    * Q: can a malicious page obtain the action token from our page?
    * Q: any other way to obtain the action token?