COMP90015 Distributed Systems

Security

Aaron Harwood

School of Computing and Information Systems

2022 Semester II

1. Overview of Security for Distributed Systems

2. Cryptographic Techniques

Policies and Mechanisms

- The challenges of security arise as a result of the need to share or to distribute resources. If a resource is not to be shared or distributed then it can be physically isolated from external access.
- A *security policy* provides a statement of the required integrity privacy of shared information and other limits to the allowable usage of a shared resource.
- A security policy is enforced using a *security mechanism*.
- Digital cryptography provides the basis for most computer security mechanisms, though computer security and cryptography are distinct subjects.

Threats and attacks

- Some threats are obvious – e.g., reading traffic on a shared network to gain information like a password or other personal information.
- Some threats are unobvious – e.g., pretending to be an official server.
- Some threats attack the mechanism – e.g., the attacker purchases something with their credit card and later denies that they actually did the purchase.
- Security threats fall into three broad classes:
  - *Leakage* – the acquisition of information by unauthorized recipients;
  - *Tampering* – the unauthorized alteration of information;
  - *Vandalism* – interference with the proper operation of a system without gain to the perpetrator.

Attacks on distributed systems depend on access to an existing communication channel. A communication channel can be misused in different ways:

- *Eavesdropping* – obtaining copies of messages without authority.
- *Masquerading* – sending or receiving messages using the identity of another principal without their authority.
- *Message tampering* – intercepting messages and altering their contents before passing them on (or substituting a different message in their place); e.g. the *man-in-the-middle* attack.
- *Replaying* – storing intercepted messages and sending them at a later date.
- *Denial of service* – flooding a channel or other resource with messages in order to deny access for others.

Some attacks can be arguable, e.g. to what extent is spam email considered a denial of service attack?

Threats from mobile code

- Some distributed systems allow code, called mobile code, to be communicated to a remote host, to be executed by that host. In this case it is necessary to ensure that the host, including all processes and resources available at the host, is secure from any operations that the mobile code undertakes; while of course still allowing legitimate operations.

- Similar to this is the case where code is delivered in an email or via the web browser. The operating system will typically ask the user whether the code should be trusted or not, e.g. to access files and the Internet.
- The Java VM has undergone revisions to ensure that mobile code does not pose a security risk.

- Construction of environments for running mobile code in a secure way is generally more difficult than providing secure channels. A different approach is to validate that the mobile code is not harmful. Trusted Network Computing works along these lines.

Information leakage

- Information leakage can be particularly difficult to prevent. E.g. a flood of messages to a dealer in a particular market can be a meaningful and useful piece of information; even though the messages are themselves secure.
- When the operation of a system and/or its outputs can be observed then there is the potential for information leakage.
- E.g. there are many forms of anonymizing networks, where a client can communicate anonymously with a server. However if the client always makes requests on a Thursday afternoon, then the behavior may be observed and the clients' identity may be inferred.
- Basically, the system must appear to be random in order for no information to be leaked.

Securing electronic transactions

- There are a number of uses of the Internet that require secure transactions:
  - Email – personal information is often transmitted via email, including e.g. credit card details, and in some cases emails are used to authenticate a user, e.g. when a user is signing up to a mailing list.
  - Purchase of goods and services – payments for goods and services commonly happen via a web interface. Digital products are delivered via the Internet.
  - Banking transactions – money can be directly transferred between bank accounts and different kinds of payment services can be used, e.g BPAY for paying bills.
  - Micro transactions – many digital goods and services, such as per page reading of a book, usage of a CPU, a single music title, 10 minutes of an Internet radio station, etc, require very low transaction costs since the price for such services may amount to fractions of a cent.
- Some example security policies for securing web purchases include:
  - Authenticate the vendor to the buyer, so that the buyer is confident that the server is operated by the vendor.
  - Ensure that credit card and personal details are transmitted, unaltered and privately, from the buyer to the vendor and that the details are kept private at all times.
  - Responses from the vendor, including digital goods and services, should be received by the buyer without alteration or disclosure during transmission. In this case, authenticating the buyer is not usually required since the vendor is happy so long as the money is made available.
  - It should be possible for a buyer to complete a secure transaction with a vendor even if there has been no previous contact between buyer and vendor and without the involvement of a third party.

Designing secure systems

- Building a completely secure system is akin to building a completely bug-free system.
- Known threats can be listed and the designer can show how the distributed system offers security against such threats.
- Logs of sensitive system actions can be used to audit and determine if security violations have or are taking place. E.g. a log file can contain whether attempts to use supervisor resources have failed, due to incorrect password.
- Costs of implementing a policy mechanism must be balanced against the threat. Costs of attack can be traded, i.e. how much does it cost the attacker in terms of time and resources.
- Security should not needlessly inhibit legitimate uses.

Worst-case assumptions and design guidelines

- Interfaces are exposed – e.g. a socket interface is open to the public, in much the same way as the front door of a house.
- Networks are insecure – messages can be looked at, copied and falsified.
- Limit the lifetime and scope of each secret – keys and passwords can be broken, given enough time and resources.
- Algorithms and program code are available to attackers – the bigger and more widely distributed a secret is, the greater the risk of its disclosure. Open source code is scrutinized by many more programmers than closed source code and this helps to find potential security problems before they are taken advantage of.
- Attackers may have access to large resources – available computing power needs to be predicted into the life time of the system and systems need to be secure against some orders of magnitude beyond this.
- Minimize the trusted base – parts of the system that are responsible for enforcing security are trusted, the greater the number of trusted parts the greater the complexity and so the greater risk of errors and misuse.

Cryptography

Familiar names for the protagonists in security protocols:

- *Alice* – First participant.
- *Bob* – Second participant.
- *Carol* – Participant in three- and four-party protocols.
- *Dave* – Participant in four-party protocols.
- *Eve* – Eavesdropper.
- *Mallory* – Malicious attacker.
- *Sara* – A server.

Encryption keys

There are two main classes of encryption algorithms: *shared secret key* algorithms and *public/private key* algorithms.
Some common cryptographic notation includes:

- k_A – Alice's secret key.
- k_B – Bob's secret key.
- k_{AB} – Secret key shared between Alice and Bob.
- k_A^{priv} – Alice's private key (known only to Alice).
- k_A^{pub} – Alice's public key (published by Alice for everyone to read).
- $\{M\}_k$ – Message M encrypted with key k.
- $[M]_k$ – Message M signed with key k.

Basic properties

- Given an encryption algorithm, E, a decryption algorithm, D, a key, k, and a message, M, $\{M\}_k = E(M, k)$ and $M = D(\{M\}_k, k)$.
- If $k = k_A$ is Alice's secret key then $\{M\}_k$ can only be decrypted by Alice using k.
- If $k = k_{AB}$ is a secret key shared between Alice and Bob then $\{M\}_k$ can only be decrypted by Alice or Bob using k.
- If $k = k_A^{priv}$ is Alice's private key, from a public/private key pair, then $\{M\}_k$ can be decrypted by anyone who has k_A^{pub}.
- If $k = k_A^{pub}$ is Alice's public key, from a public/private key pair, then $\{M\}_k$ can only be decrypted by Alice using k_A^{priv}.
- Private/secret keys should be securely maintained since their use is compromised if an attacker obtains a copy of them.
- Public/private key encryption algorithms typically require *100 to 1000 times more processing power* than secret-key algorithms.

Secrecy and integrity

A fundamental policy is one of ensuring secrecy of a message. If Alice and Bob have agreed to a shared key and encryption/decryption algorithm then for a sequence of messages $M_1, M_2, \ldots$:

1. Alice uses k_{AB} and E to encrypt message M_i and sends $\{M_i\}_{k_{AB}}$ to Bob.
2. Bob uses k_{AB} and D to decrypt message $\{M_i\}_{k_{AB}}$.

If the message makes sense when it is decrypted, or better if it contains some agreed upon value such as a checksum, then Bob can be confident that the message is from Alice and that it has not been tampered with. Some problems:

- How can Alice communicate a shared key k_{AB} to Bob securely?
- How does Bob know that a received message is a not a copy of some previous meessage $\{M_i\}_{k_{AB}}$ captured by an attacker Mallory and resent to Bob?

Authentication using a trusted third party

Consider the case when Alice wants to access a resource held by Bob. Sara is an authentication server that is securely managed. Sara issues passwords to all users including Alice and Bob. Sara knows k_A and k_B because they are derived from the passwords.

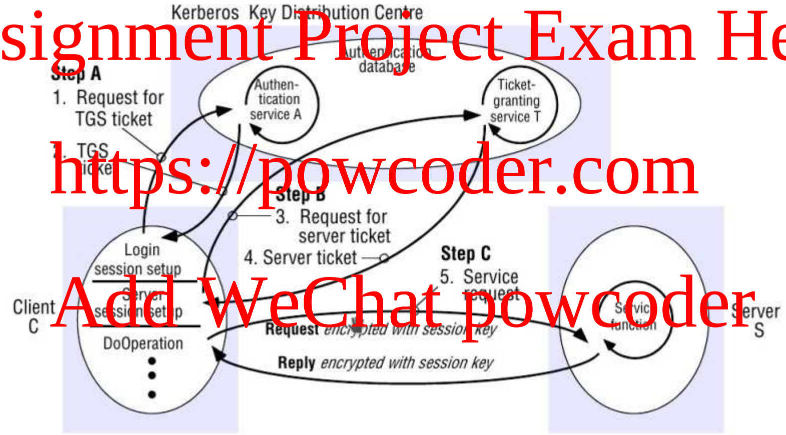
1. Alice sends an (unencrypted) message to Sara stating her identity and requesting a ticket for access to Bob.
2. Sara sends a response to Alice encrypted using k_A consisting of a ticket encrypted in k_B and a new secret key k_{AB} for use when communicating with Bob: $\{\{Ticket\}_{k_B}, k_{AB}\}_{k_A}$.

3. Alice decrypts the response using k_A. Alice cannot tamper with the ticket before sending it, because it is encrypted with k_B.
4. Alice sends a request R to Bob: $\{Ticket\}_{k_B}, Alice, R$.

5. Bob receives the encrypted ticket and decrypts it using his key k_B, where the ticket is actually $Ticket = \{k_{AB}, Alice\}$. Alice and Bob can now communicate using the shared key or *session key*, k_{AB}.

The previous algorithm is a simplified version of the authentication protocol originally developed by Roger Needham and Michael Schroeder.

Kerberos overview



Challenge Response

- The use of an authentication server is practical in situations where all users are part of a single organization. It is not practical when access is required between parties that are not supervised by a single organization.

- Simple systems like Telnet send passwords from client to server "in the clear". Such passwords are easily compromised by eavesdroppers.
- The *challenge-response* technique is now widely used to avoid sending passwords in the clear. The identity of a client is established by sending the client an encrypted message that only the client should be able to decrypt, this is called a challenge message. If the client cannot decrypt the challenge message then the client cannot properly respond.

Authenticated communication with public keys

1. Alice accesses a *key distribution service*, Sara, to obtain a *public-key certificate* giving Bob's public key. The public-key certificate, *Cert*, is a message signed by Sara using k_S^{priv}. The key k_S^{pub} is widely known by Alice and others and is used to check the signature. Among other things the the certificate contains $Bob, keyname, k_B^{pub}$.
2. Alice creates k_{AB} and encrypts it using k_B^{pub} with a public-key algorithm. She sends the result to Bob, along with a name that identifies the public/private key pair (since Bob may have several public/private keys). Alice sends $\{keyname, \{k_{AB}\}_{k_B^{pub}}\}$.
3. Bob selects the appropriate private key k_B^{priv} and decrypts the message to obtain k_{AB}. Alice and Bob can now securely communicate.

If the message from Alice to Bob was tampered with then the decrypted k_{AB} will not match and messages back from Bob will not make sense. Having said this, Alice can also encrypt some additional identification in the original message, e.g. a checksum or Alice's email address, etc.

Digital signature

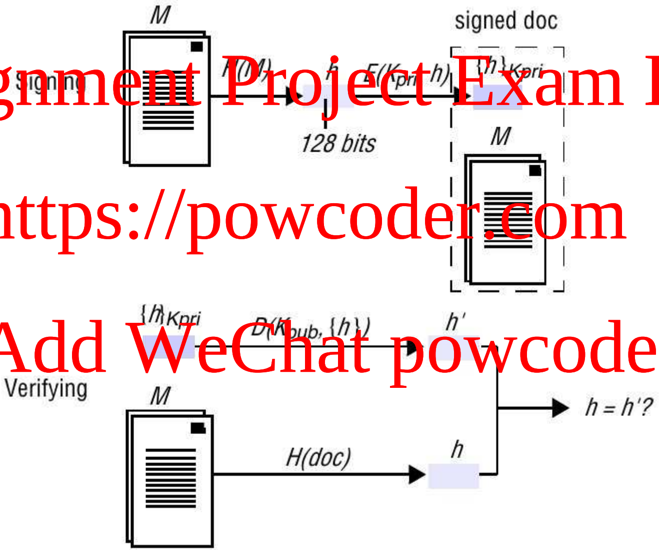
- A *digital signature* serves the same role as a signature, binding an identity to a message.

- In the case of public/private keys, the identity is the public/private key pair itself.
- A digital signature requires the use of a *digest*. A digest is a function, $Digest(M)$, that maps an arbitrary message, M, to a fixed length datum. The digest function must be such that a given datum is very unlikely to be mapped to from two different messages. The SHA-2 hash function is a good example of this.

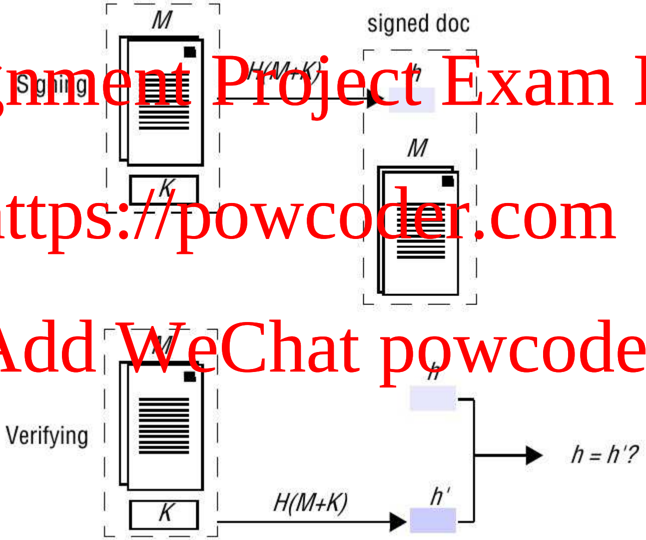
- If Alice wants to sign a message, M, then Alice constructs $\{M, Digest(M)_{k_A^{priv}}\}$.
- A receiver, Bob, decrypts the digest using k_A^{pub}. Bob also computes the digest of M locally. If the message or the encrypted digest were tampered with then the results will not match.

- This is effectively a signature based on the identity k_A^{priv} since no other private key would produce that encrypted digest and no other message is likely to produce that digest. Alice cannot deny that she signed the message.

Digital Signature with pub/priv keys



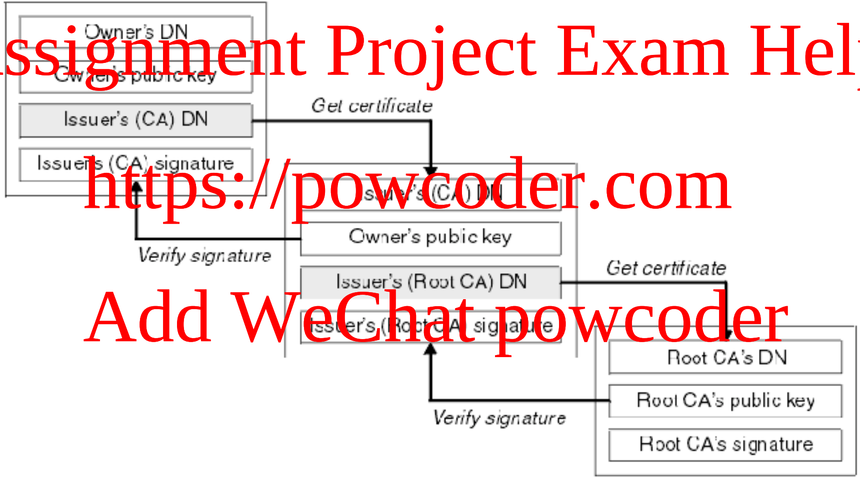
Digital Signature with shared key



Certificate chains

- For Alice to authenticate a certificate from Sara concerning Bob's public key, Alice must first have Sara's public key. This poses a recursive problem.
- In the simplest case, Sara creates a *self-signed* certificate, which is attesting to her own public key. The self-signed certificate is widely publicized (e.g. by distributing with operating system or browser installation). This certificate is *trusted*. The private key must be closely guarded in order to maintain the integrity of all certificates that are signed with it.
- However, assume that Carol has signed a certificate attesting to Bob's public key and that Sara has signed a certificate attesting to Carol's public key. This is an example of a *certificate chain*. If Alice trusts Carol's certificate then she can authenticate Bob's identity. Otherwise Alice must first authenticate Carol's identity using Sara's certificate.
- *Revoking* a certificate is usually by using predefined expiry dates. Otherwise anyone who may make use of the certificate must be told that the certificate is to be revoked.

http://publib.boulder.ibm.com



A standard for digital certificates is X.509. From Wikipedia, the structure of an X.509 version 3 certificate is:

```
* Certificate
    * Version
    * Serial Number
    * Algorithm ID
    * Issuer
    * Validity
        * Not Before
        * Not After
    * Subject
    * Subject Public Key Info
        * Public Key Algorithm
        * Subject Public Key
    * Issuer Unique Identifier (Optional)
    * Subject Unique Identifier (Optional)
    * Extensions (Optional)
* Certificate Signature Algorithm
* Certificate Signature
```

```
Certificate:
  Data:
   Version: 3 (0x2)
   Serial Number: 1 (0x1)
   Signature Algorithm: md5WithRSAEncryption
   Issuer: C=ZA, ST=Western Cape, L=Cape Town, O=Thawte Consulting cc,
           OU=Certification Services Division,
           CN=Thawte Server CA/Email=server-certs@thawte.com
   Validity
       Not Before: Aug  1 00:00:00 1996 GMT
       Not After : Dec 31 23:59:59 2020 GMT
   Subject: C=ZA, ST=Western Cape, L=Cape Town, O=Thawte Consulting cc,
            OU=Certification Services Division,
            CN=Thawte Server CA/Email=server-certs@thawte.com
   Subject Public Key Info:
       Public Key Algorithm: rsaEncryption
       RSA Public Key: (1024 bit)
           Modulus (1024 bit):
               00:d3:a4:50:6e:c8:ff:56:6b:e6:cf:5d:b6:ea:0c:
               68:75:47:a2:aa:c2:da:84:25:fc:a8:f4:47:51:da:
               85:b5:20:74:94:86:1e:0f:75:c9:e9:08:61:f5:06:
               6d:30:6e:15:19:02:e9:52:c0:62:db:4d:99:9e:e2:
               6a:0c:44:38:cd:fe:be:e3:64:09:70:c5:fe:b1:6b:
               29:b6:2f:49:c8:3b:d4:27:04:25:10:97:2f:e7:90:
               6d:c0:28:42:99:d7:4c:43:de:c3:f5:21:6d:54:9f:
               5d:c3:58:e1:c0:e4:d9:5b:b0:b8:dc:b4:7b:df:36:
               3a:c2:b5:66:22:12:d6:87:0d
           Exponent: 65537 (0x10001)
   X509v3 extensions:
       X509v3 Basic Constraints: critical
           CA:TRUE
Signature Algorithm: md5WithRSAEncryption
```

```
07:fa:4c:69:5c:fb:95:cc:46:ee:85:83:4d:21:30:8e:ca:d9:
a8:6f:49:1a:e6:da:51:e3:60:70:6c:84:61:11:a1:1a:c8:48:
3e:59:43:7d:4f:95:3d:a1:8b:b7:0b:62:98:7a:75:8a:dd:88:
4e:4e:9e:40:db:a8:cc:32:74:b9:6f:0d:c6:e3:b3:44:0b:d9:
8a:6f:9a:29:9b:99:18:28:3b:d1:e3:40:28:9a:5a:3c:d5:b5:
e7:20:1b:3b:c1:a4:ab:8d:e9:51:d9:e2:4c:2c:[illegible]:a9:da:b9:
b2:75:1b:f6:42:f2:ef:c7:f2:18:f9:39:bc:a3:f1:8a:23:2e:
70:47
```

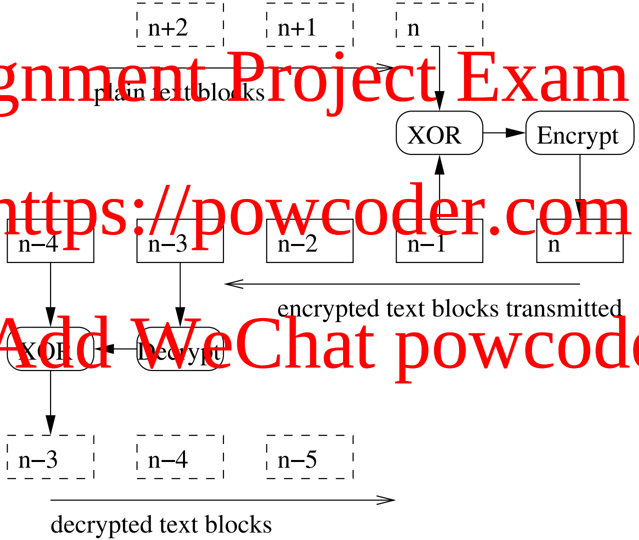
Cryptographic algorithms

- Secret key cryptography is often referred to as *symmetric* cryptography. Public/private key cryptography is often referred to as *asymmetric*.
- *Block ciphers* operate on fixed-size blocks of data; 64 bits is a popular size for the blocks. A message is subdivided into blocks and the last block is padded to the standard length. Each block is encrypted independently. A block is transmitted as soon as it is encrypted.

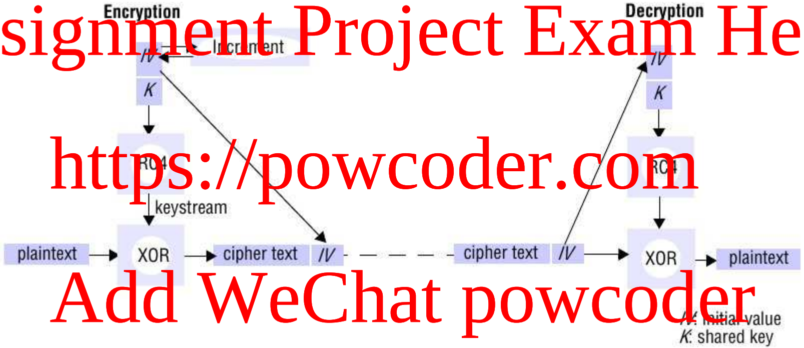
- *Cipher block chaining* avoids the problem of identical plain text blocks encrypted to identical encrypted blocks. However, if the same message is send to do different recipients then it will still look the same and this poses an information leakage weakness. To guard against this a block called an *initialization vector* is used to start each message in a different way.

- *Stream ciphers* are used when the data cannot be easily divided into blocks. In this case, an agreed upon *key stream* (such as from a random number generator with known seed) is encrypted and the output is XOR'ed with the data stream.

Cipher Block chaining



Streaming Cipher in IEEE 802.11 WEP



WEP (Wired Equivalent Privacy) security is seriously flawed and everyone should now be using at least WPA2 (WiFi Protected Access version 2).

Some symmetric algorithms include:

- *TEA*: Tiny Encryption Algorithm, and subsequently the Extended (XTEA) version that guards against some minor weaknesses. The algorithm uses 128 bit keys to encrypt 64 bit blocks. The algorithm consists of only a few lines of code (hence the name), is secure and reasonably fast.
- *DES*: Data Encryption Standard uses a 56 bit key to encrypt a 64 bit block. This algorithm is now considered obsolete because it is too weak. The triple DES version, 3DES, is stronger but takes a long time to encrypt.
- *IDEA*: International Data Encryption Algorithm uses a 128 bit key to encrypt 64 bit blocks. It is a faster and more secure successor to DES.
- *RC4*: A stream cipher that uses keys of any length up to 256 bytes. About 10 times as fast as DES and was widely used in WiFi networks until a weakness was exposed.
- *AES*: Advanced Encryption Standard has variable block length and key length with specifications for keys with a length of 128, 192 or 256 bits to encrypt blocks with length of 128, 192 or 256 bits. Block and key lengths can be extended by multiples of 32 bits.

- The most widely known asymmetric algorithm is *RSA* or the Rivest, Shamir and Adelman algorithm.
- RSA is based on the use of the product of two very large prime numbers (greater than 10e100). Its strength comes from the fact that the determination of the prime factors of such large numbers is very computationally expensive.
- There are no known flaws in RSA.
- One potential weakness of all public-key algorithms is that an attacker, having the public key, can try to decrypt a message by encrypting all possible messages and finding the one that matches the target message. Such an attack can be defended against by only encrypting messages that have at least as many bits as the key, hence the attack is no better than trying all possible keys.
  - One analysis done in 2014 (`https://www.di-mgt.com.au/cryptokeys.html`) reports that "to crack some ciphertext encrypted with a 64-bit key by the brute-force method of trying every combination of keys possible means you have 2^{64} possible combinations or 1.8×10^{19}. If you have a computer that can carry out one encryption operation every millisecond, it will take about 292 million years to find the correct value. Speed up your computer by a million times and it will still take about 3 centuries to solve. In practice, a set of supercomputers operating in parallel can crack a 64-bit key in a relatively short time. If an attacker has access to a large selection of messages all encrypted with the same key, there are other techniques that can be used to reduce the time to derive the key."

Secure socket layer

The *Secure Socket Layer* and its successor the *Transport Layer Security* (TLS) protocol are intended to provide a flexible means for clients and server to communicate using a secure channel.

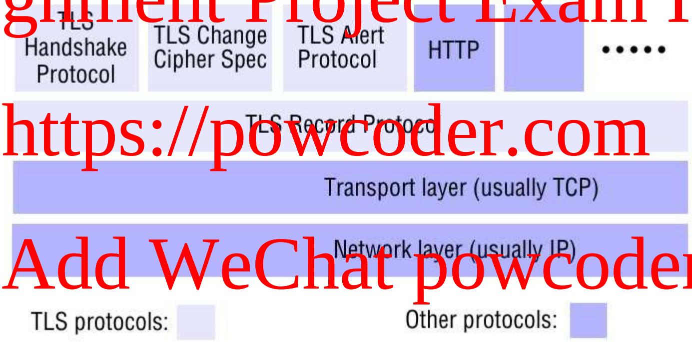
In typical use the server is authenticated while the client remains unauthenticated. The protocols allow client/server applications to communicate in a way designed to prevent eavesdropping, tampering and message forgery.

There are three basic phases:

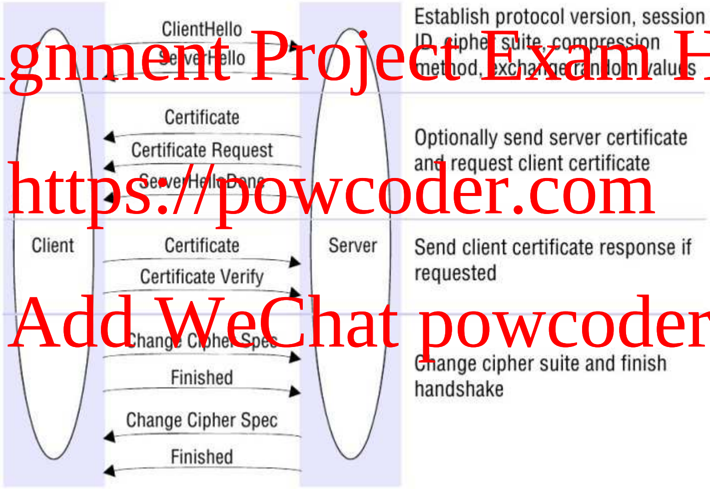
- Peer negotiation for algorithm support.
- Public key encryption-based key exchange and certificate-based authentication.
- Symmetric cipher-based traffic encryption.

Generally the protocol uses a Record Protocol layer that exchanges records; each record can be optionally compressed, encrypted and packed with a message authentication code (a signature that uses a shared secret key). Each record has a type that specifies an upper level protocol including Handshake, Change Cipher Spec and Alert Protocol.

TLS protocol stack



TLS handshake



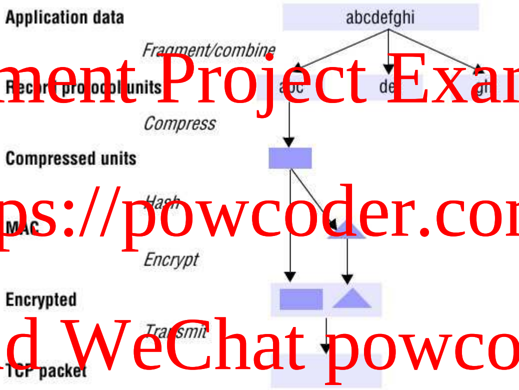
The first phase allows the client and server to establish which cipher, compression method and other connection parameters are to be used.

The second phase exchanges certificates. A *master secret* or common secret is negotiated and this is used to generate all other key data for the purpose of encryption.

Security measures include:

- Numbering all records and including the sequence numbers in the signatures.
- The message that ends the handshake sends a hash of all the exchanged data seen by both parties.
- Hashing is done by combining (XORing) the results of both MD5 and SHA, in case one is found to be vulnerable.

TLS record protocol



Optional compression is included because the computations can share work with the encryption and thereby save work overall; i.e. it is faster than compressing separately and then securely transmitting the compressed data.