INFS 766
Internet Security Protocols

Lectures 3 and 4
Cryptography in network protocols

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CRYPTOGRAPHY

CRYPTOGRAPHIC TECHNOLOGY

SECRET KEY

Symmetric Key
Single Key
Conventional

PUBLIC KEY

Asymmetric Key
Two Key

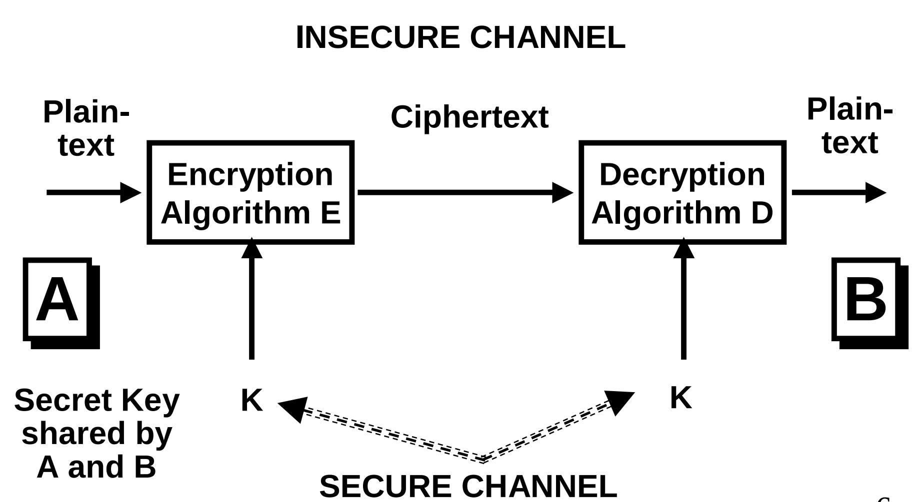
CRYPTOGRAPHIC TECHNOLOGY

- **Secret-key encryption**
- **Public-key encryption**
- **Public-key digital signatures**
- **Public-key key agreement**
- **Message digests**
- **Message authentication codes**
- **Challenge-response authentication**
- **Public-key certificates**

CRYPTOGRAPHIC SERVICES

- confidentiality
  - traffic flow confidentiality
- integrity
- authentication
- non-repudiation

SECRET KEY CRYPTOSYSTEM



SECRET KEY CRYPTOSYSTEM

- confidentiality depends only on secrecy of the key
  - size of key is critical
- secret key systems do not scale well
  - with N parties we need to generate and distribute N*(N-1)/2 keys
- A and B can be people or computers

MASTER KEYS AND SESSION KEYS

- long-term or master keys
  - prolonged use increases exposure
- session keys
  - short-term keys communicated by means of
    - long-term secret keys
    - public key technology

CRYPTANALYSIS

- ciphertext only
  - cryptanalyst only knows ciphertext
- known plaintext
  - cryptanalyst knows some plaintext-ciphertext pairs
- chosen plaintext
- chosen ciphertext

KNOWN PLAINTEXT ATTACK

- 40 bit key requires $2^{39} \approx 5 * 10^{11}$ trials on average (exportable from USA)
- trials/second time required

trials/second	time required
1	20,000 years
10^3	20 years
10^6	6 days
10^9	9 minutes
10^{12}	0.5 seconds

KNOWN PLAINTEXT ATTACK

- **56 bit key requires $2^{55} \approx 3.6 * 10^{16}$ trials on average (DES)**
- **trials/second time required**

1	**10^9 years**
10^3	**10^6 years**
10^6	**10^3 years**
10^9	**1 year**
10^{12}	**10 hours**

KNOWN PLAINTEXT ATTACK

- **80 bit key requires $2^{79} \approx 6 * 10^{23}$ trials on average (SKIPJACK)**
- **trials/second time required**

1	**10^{16} years**
10^3	**10^{13} years**
10^6	**10^{10} years**
10^9	**10^7 years**
10^{12}	**10^4 years**

KNOWN PLAINTEXT ATTACK

- **128 bit key requires $2^{127} \approx 2 * 10^{38}$ trials on average (IDEA)**
- **trials/second time required**

trials/second	time required
1	**10^{30} years**
10^{3}	**10^{27} years**
10^{6}	**10^{24} years**
10^{9}	**10^{21} years**
10^{12}	**10^{18} years**

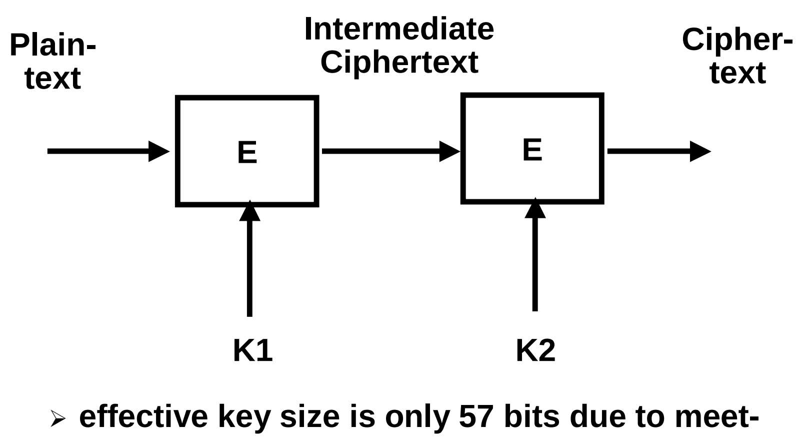
DICTIONARY ATTACKS

- **if keys are poorly chosen known plaintext attacks can be very simple**
- **often the user's password is the key**
  - **in a dictionary attack the cryptanalyst tries passwords from a dictionary, rather than all possible keys**
  - **for a 20,000 word dictionary, 1 trial/second will crack a poor password in less than 3 hours**

CURRENT GENERATION SECRET KEY CRYPTOSYSTEMS

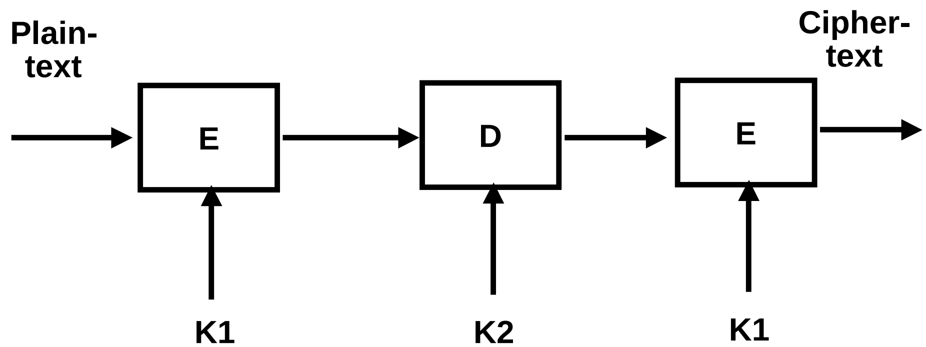
- **64 bit data block size**
  - **DES: 56 bit key**
  - **Triple DES: 112 bit key**
  - **Triple DES: 168 bit key**
  - **Skipjack: 80 bit key**
  - **IDEA: 128 bit key**
  - **RC2: variable size key: 1 byte to 128 bytes**
  - **many others**

DOUBLE DES



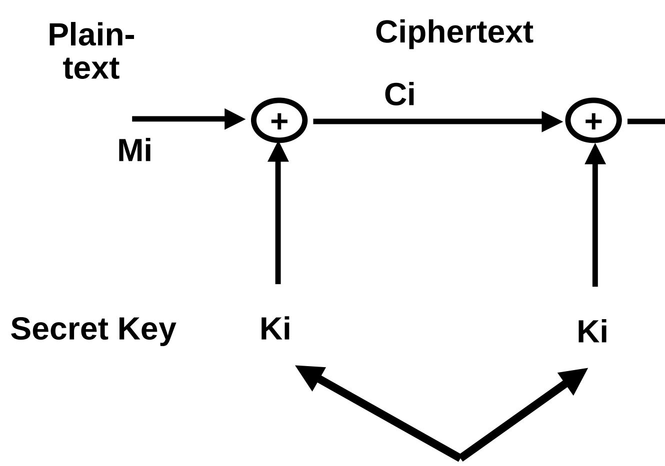
- **effective key size is only 57 bits due to meet-in-the-middle attack**

TRIPLE DES



- **effective key size is 112 bits due to meet-in-the-middle attack**

PERFECT SECRECY
VERNAM ONE-TIME PAD



A	B	A⊕B
0	0	0
0	1	1
1	0	1
1	1	0

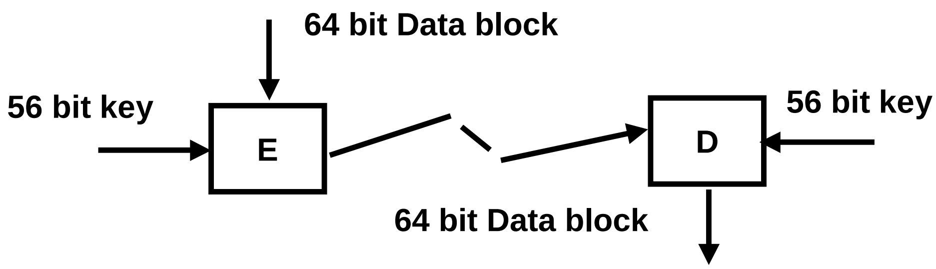
PERFECT SECRECY VERNAM ONE-TIME PAD

- known plaintext reveals the portion of the key that has been used, but does not reveal anything about the future bits of the key
- has been used
- can be approximated

ADVANCED ENCRYPTION STANDARD

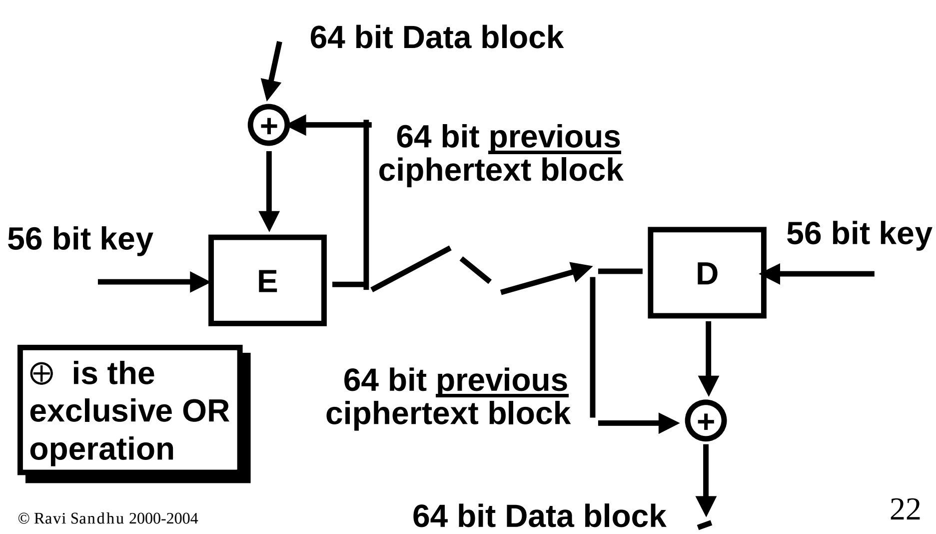
- New Advanced Encryption Standard under development by NIST
  - must support key-block combinations of 128-128, 192-128, 256-128
  - may support other combinations
- selection of Rijndaehl algorithm announced in 2000
- will be in place in a couple of years

ELECTRONIC CODE BOOK (ECB) MODE



- OK for small messages
- identical data blocks will be identically encrypted

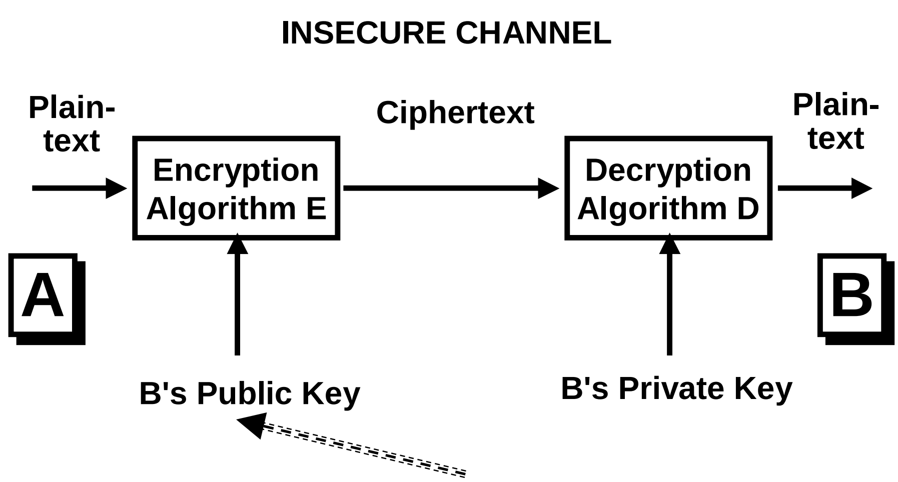
CIPHER BLOCK CHAINING (CBC) MODE



CIPHER BLOCK CHAINING (CBC) MODE

- **Needs an Initialization Vector (IV) to serve as the first feedback block**
- **IV need not be secret or random**
- **Integrity of the IV is important, otherwise first data block can be arbitrarily changed.**
- **IV should be changed from message to message, or first block of every message should be distinct**

PUBLIC KEY ENCRYPTION



PUBLIC KEY CRYPTOSYSTEM

- **solves the key distribution problem provided there is a reliable channel for communication of public keys**
- **requires reliable dissemination of 1 public key/party**
- **scales well for large-scale systems**

PUBLIC KEY ENCRYPTION

- **confidentiality based on infeasibility of computing B's private key from B's public key**
- **key sizes are large (512 bits and above) to make this computation infeasible**

SPEED OF PUBLIC KEY VERSUS SECRET KEY

- **Public key runs at kilobits/second**
  - **think modem connection**
- **Secret key runs at megabits/second and even gigabits/second**
  - **think LAN or disk connection**
- **This large difference in speed is likely to remain independent of technology advances**

RSA

- **public key is (n,e)**
- **private key is d**
- **encrypt: $C = M^e \bmod n$**
- **decrypt: $M = C^d \bmod n$**

GENERATION OF RSA KEYS

- **choose 2 large (100 digit) prime numbers p and q**
- **compute n = p * q**
- **pick e relatively prime to (p-1)*(q-1)**
- **compute d, e*d = 1 mod (p-1)*(q-1)**
- **publish (n,e)**
- **keep d secret (and discard p, q)**

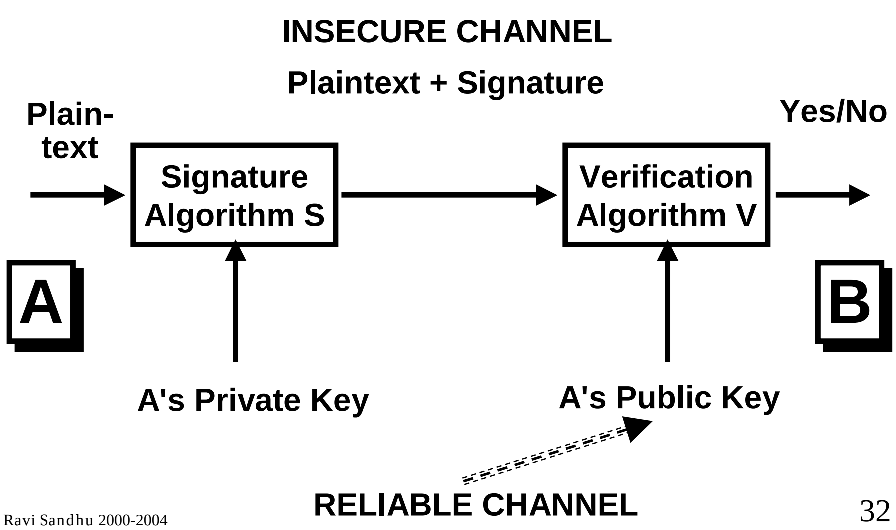
PROTECTION OF RSA KEYS

- **compute d, e*d = 1 mod (p-1)*(q-1)**
  - **if factorization of n into p*q is known, this is easy to do**
- **security of RSA is no better than the difficulty of factoring n into p, q**

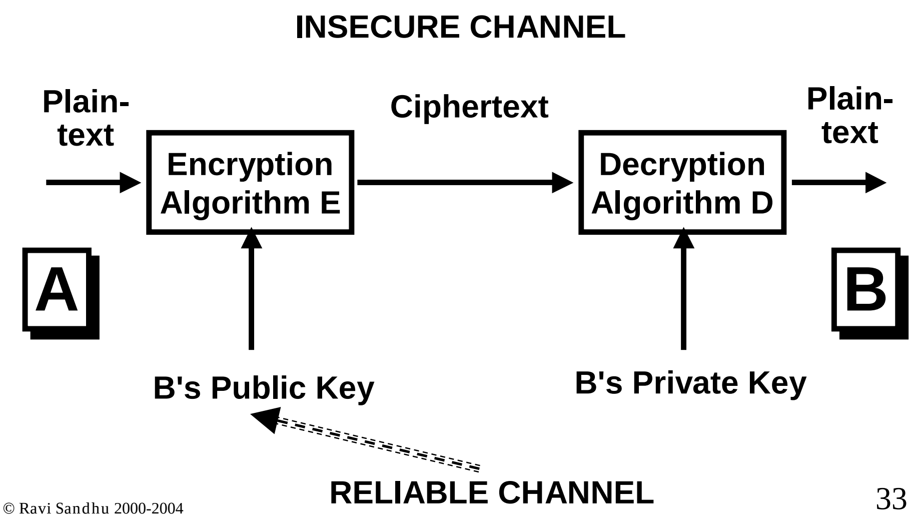
RSA KEY SIZE

- key size of RSA is selected by the user
  - casual 384 bits
  - “commercial” 512 bits
  - “military” 1024 bits

DIGITAL SIGNATURES



COMPARE PUBLIC KEY ENCRYPTION



DIGITAL SIGNATURES IN RSA

- **RSA has a unique property, not shared by other public key systems**
- **Encryption and decryption commute**
  - **$(M^e \bmod n)^d \bmod n = M$ encryption**
  - **$(M^d \bmod n)^e \bmod n = M$ signature**
- **Same public key can be use for encryption and signature**

EL GAMAL AND VARIANTS

- encryption only
- signature only
  - 1000's of variants
  - including NIST's DSA

NIST DIGITAL SIGNATURE STANDARD

- System-wide constants
  - p 512-1024 bit prime
  - q 160 bit prime divisor of p-1
  - g $g = h^{((p-1)/q)} \bmod p$, $1<h<p-1$
- El-Gamal variant
  - separate algorithms for digital signature and public-key encryption

NIST DIGITAL SIGNATURE STANDARD

- to sign message m: private key x
  - choose random r
  - compute v = (g^r mod p) mod q
  - compute s = (m+xv)/k mod q
  - signature is (s,v,m)
- to verify signature: public key y
  - compute u1 = m/s mod q
  - compute u2 = v/s mod q
  - verify that v = (g^{u1}*y^{u2} mod p) mod q

NIST DIGITAL SIGNATURE STANDARD

- signature does not repeat, since r will be different on each occasion
- if same random number r is used for two messages, the system is broken
- message expands by a factor of 2
- RSA signatures do repeat, and there is no message expansion

DIFFIE-HELLMAN KEY AGREEMENT

A $y_A = a^{x_A} \bmod p$ **public key**

$y_B = a^{x_B} \bmod p$ **public key** **B**

private key x_A

private key x_B

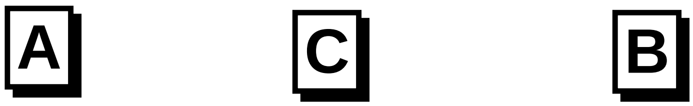
$$k = y_B^{x_A} \bmod p = y_A^{x_B} \bmod p = a^{x_A * x_B} \bmod p$$

system constants: p: prime number, a: integer

DIFFIE-HELLMAN KEY ESTABLISHMENT

- **security depends on difficulty of computing x given $y=a^x \bmod p$**
  called the discrete logarithm problem

MAN IN THE MIDDLE ATTACK



CURRENT GENERATION PUBLIC KEY SYSTEMS

- **RSA (Rivest, Shamir and Adelman)**
  - **the only one to provide digital signature and encryption using the same public-private key pair**
  - **security based on factoring**
- **ElGamal Encryption**
  - **public-key encryption only**
  - **security based on digital logarithm**
- **DSA signatures**
  - **public-key signature only**
  - **one of many variants of ElGamal signature**
  - **security based on digital logarithm**

CURRENT GENERATION PUBLIC KEY SYSTEMS

- DH (Diffie-Hellman)
  - secret key agreement only
  - security based on digital logarithm
- ECC (Elliptic curve cryptography)
  - security based on digital logarithm in elliptic curve field
  - uses analogs of
    - ElGamal encryption
    - DH key agreement
    - DSA digital signature

ELLIPTIC CURVE CRYPTOGRAPHY

- mathematics is more complicated than RSA or Diffie-Hellman
- elliptic curves have been studied for over one hundred years
- computation is done in a group defined by an elliptic curve

ELLIPTIC CURVE CRYPTOGRAPHY

- **160 bit ECC public key is claimed to be as secure as 1024 bit RSA or Diffie-Hellman key**
- **good for small hardware implementations such as smart cards**

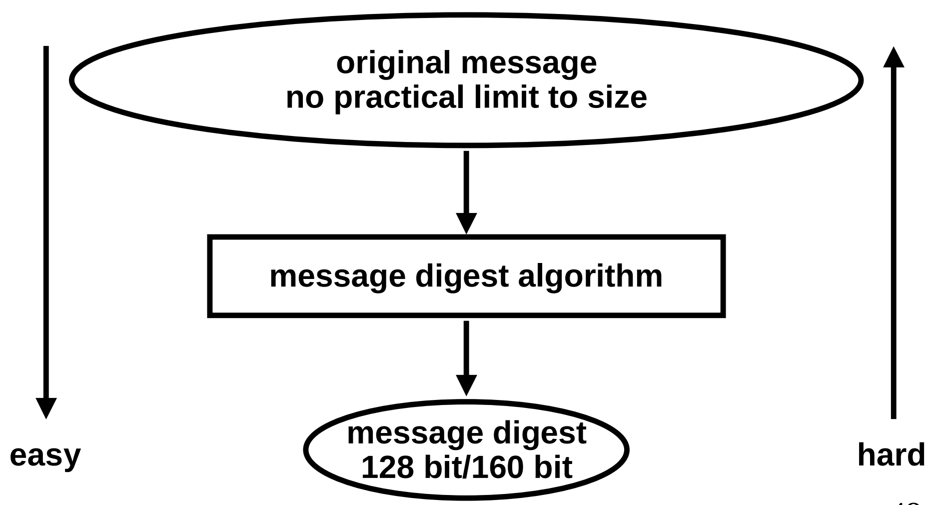
ELLIPTIC CURVE CRYPTOGRAPHY

- **ECDSA: Elliptic Curve digital signature algorithm based on NIST Digital Signature Standard**
- **ECSVA: Elliptic Curve key agreement algorithm based on Diffie-Hellman**
- **ECES: Elliptic Curve encryption algorithm based on El-Gamal**

PKCS STANDARDS

- de facto standards initiated by RSA Data Inc.

MESSAGE DIGEST



MESSAGE DIGEST

- for performance reasons
  - sign the message digest
  - not the message
- <u>one way</u> function
  - m=H(M) is easy to compute
  - M=H^{-1}(m) is hard to compute

DESIRED CHARACTERISTICS

- <u>weak hash</u> function
  - difficult to find M' such that H(M')=H(M)
- given M, m=H(M) try messages at random to find M' with H(M')=m
  - 2^k trials on average, k=64 to be safe

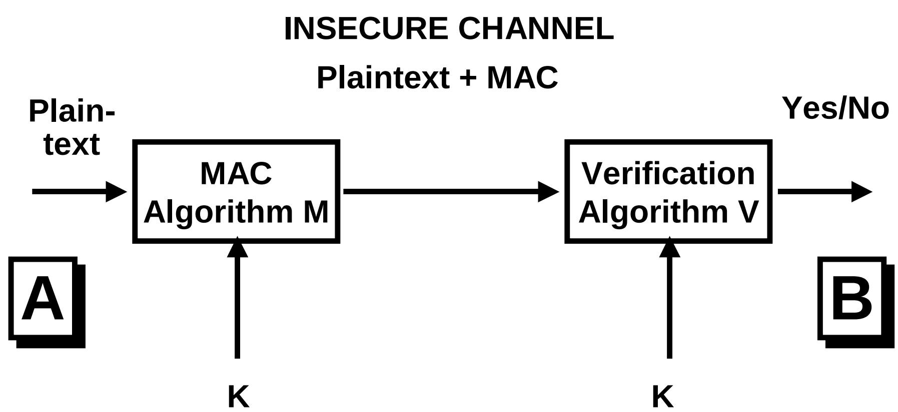
DESIRED CHARACTERISTICS

- **<u>strong hash</u> function**
  - **difficult to find <u>any</u> two M and M' such that H(M')=H(M)**
- **try pairs of messages at random to find M and M' such that H(M')=H(M)**
  - **$2^{k/2}$ trials on average, k=128 to be safe**
  - **k=160 is better**

CURRENTT GENERATION MESSAGE DIGEST ALGORITHMS

- **MD5 (Message Digest 5)**
  - **128 bit message digest**
  - **falling out of favor**
- **SHA (Secure Hash Algorithm)**
  - **160 bit message digest**
  - **slightly slower than MD5 but more secure**

MESSAGE AUTHENTICATION CODES



MAC = MD of plaintext + K

CURRENT GENERATION MAC ALGORITHMS

- **HMAC-MD5, HMAC-SHA**
  - **IETF standard**
  - **general technique for constructing a MAC from a message digest algorithm**
- **Older MACs are based on secret key encryption algorithms (notably DES) and are still in use**
  - **DES based MACs are 64 bit and not considered strong anymore**

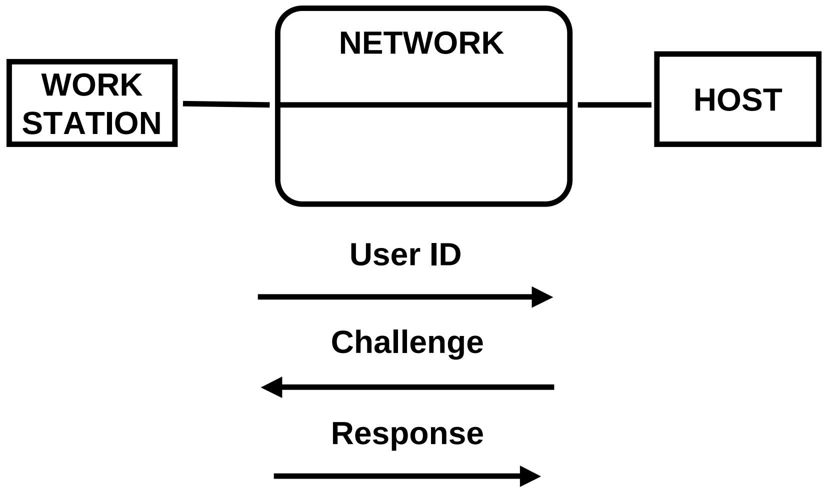
HMAC

- **HMAC computation**
- **$HMAC_K(M) = h(K \oplus opad \,||\, h(K \oplus ipad \,||\, M))$**
  - **h is any message digest function**
  - **M message**
  - **K secret key**
  - **opad, ipad: fixed outer and inner padding**
- **HMAC-MD5, HMAC-SHA**

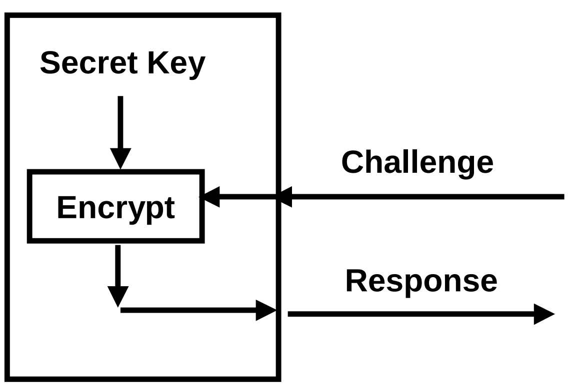
SAFE CRYPTOGRAPHY

- **Secret-key encryption**
  - **128 bit or higher**
- **Public-key**
  - **1024 bit or higher**
- **Message digests**
  - **160 bit or higher**
- **A large portion of what is deployed is much weaker**

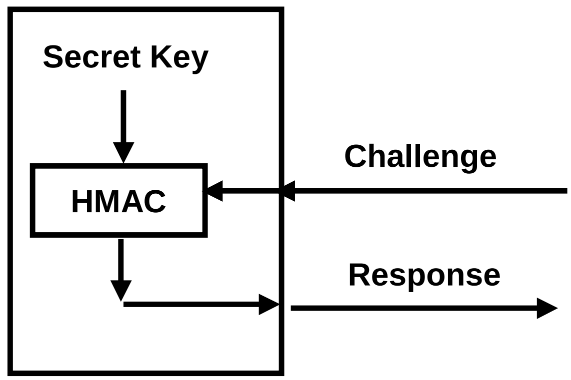
STRONG AUTHENTICATION CHALLENGE RESPONSE



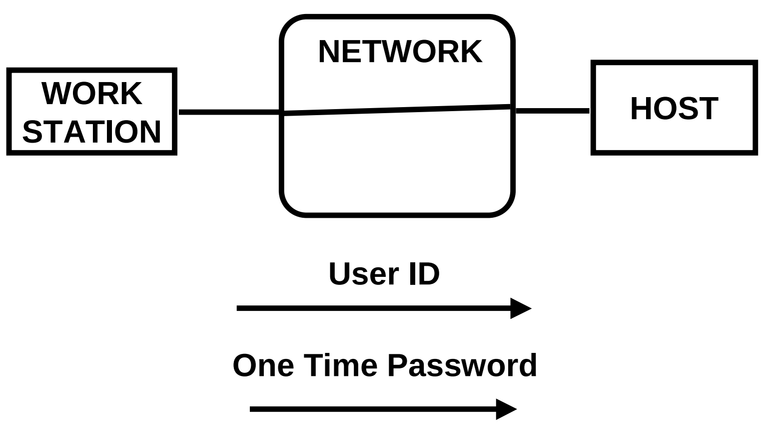
CHALLENGE RESPONSE



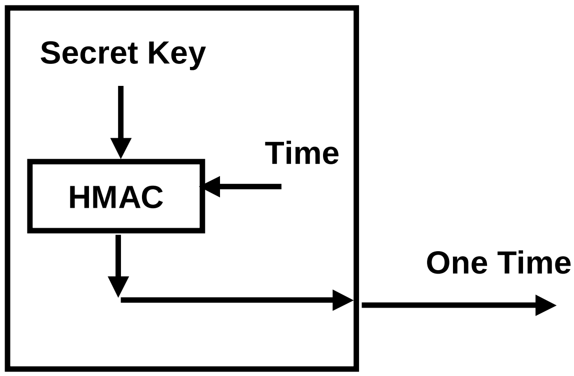
CHALLENGE RESPONSE



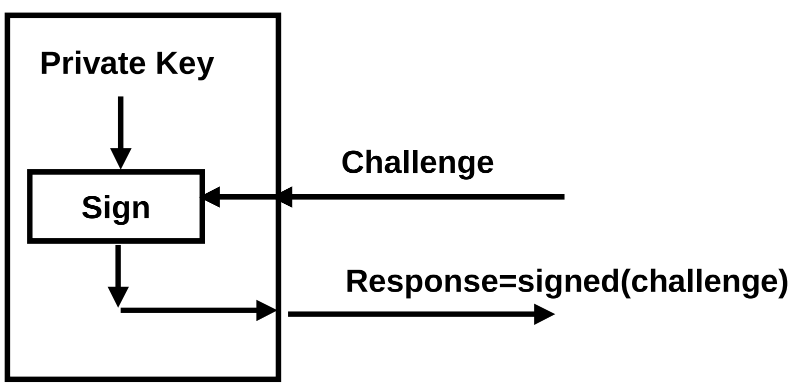
TIME SYNCHRONIZED



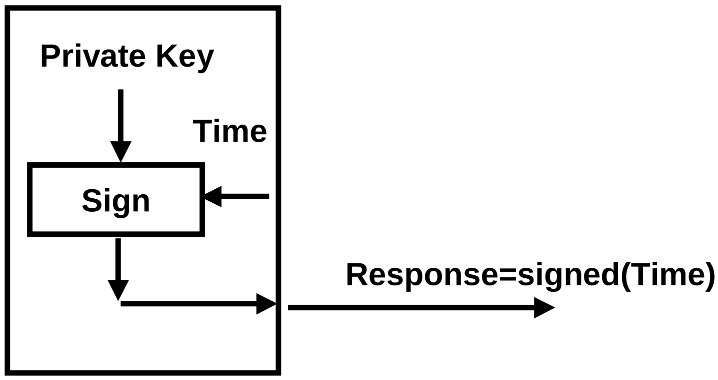
TIME SYNCHRONIZED



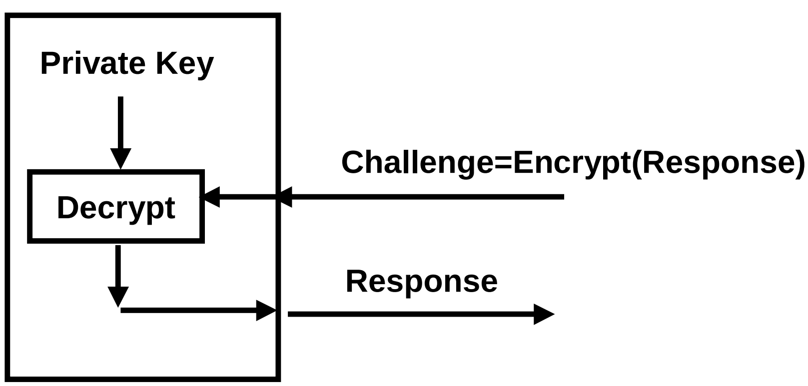
PUBLIC KEY SIGNATURE BASED



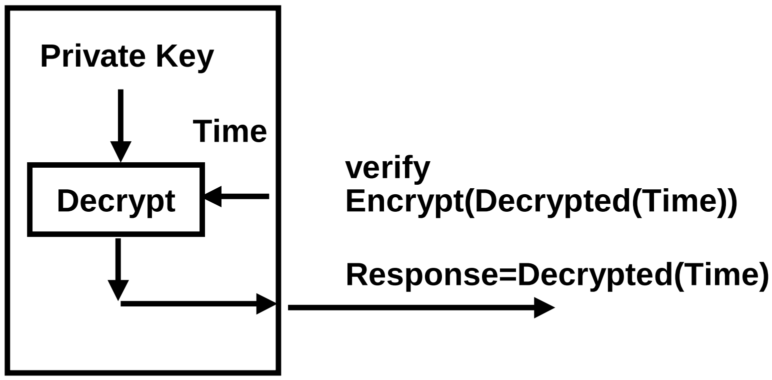
PUBLIC KEY SIGNATURE BASED



PUBLIC KEY ENCRYPTION BASED



PUBLIC KEY ENCRYPT BASED



PUBLIC-KEY INFRASTRUCTURE

PUBLIC-KEY CERTIFICATES

- ❖ **reliable distribution of public-keys**
- ❖ **public-key encryption**
  - ➢ **sender needs public key of receiver**
- ❖ **public-key digital signatures**
  - ➢ **receiver needs public key of sender**
- ❖ **public-key key agreement**
  - ➢ **both need each other's public keys**

X.509v1 CERTIFICATE

VERSION
SERIAL NUMBER
SIGNATURE ALGORITHM
ISSUER
VALIDITY
SUBJECT
SUBJECT PUBLIC KEY INFO
SIGNATURE

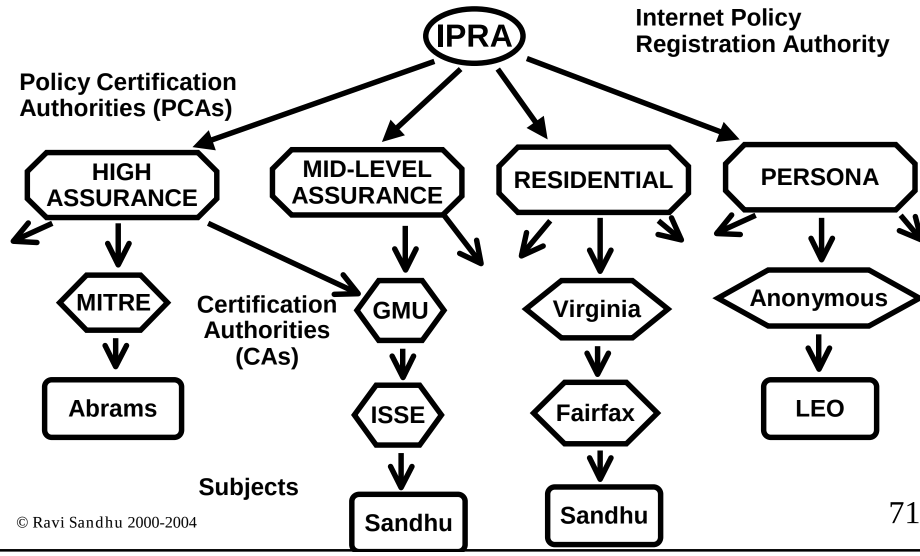
X.509v1 CERTIFICATE

1
1234567891011121314
RSA+MD5, 512
C=US, S=VA, O=GMU, OU=ISE
9/9/99-1/1/1
C=US, S=VA, O=GMU, OU=ISE, CN=Ravi Sandhu
RSA, 1024, xxxxxxxxxxxxxxxxxxxxxxxxx
SIGNATURE

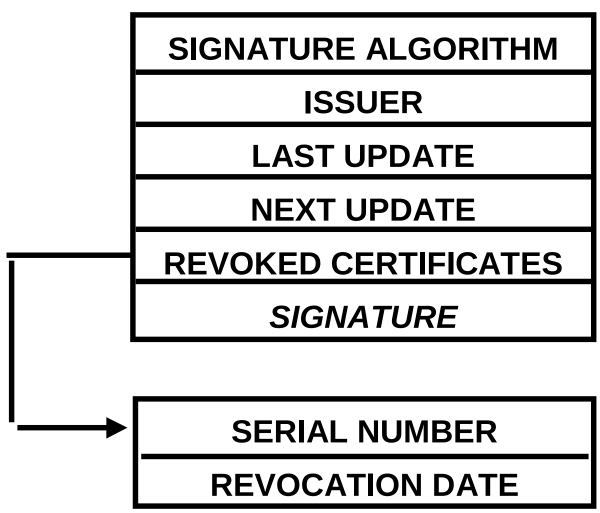
CERTIFICATE TRUST

- **how to acquire public key of the issuer to verify signature**
- **whether or not to trust certificates signed by the issuer for this subject**

PEM CERTIFICATION GRAPH



CRL FORMAT



X.509 CERTIFICATES

- **X.509v1**
  - **very basic**
- **X.509v2**
  - **adds unique identifiers to prevent against reuse of X.500 names**
- **X.509v3**
  - **adds many extensions**
  - **can be further extended**

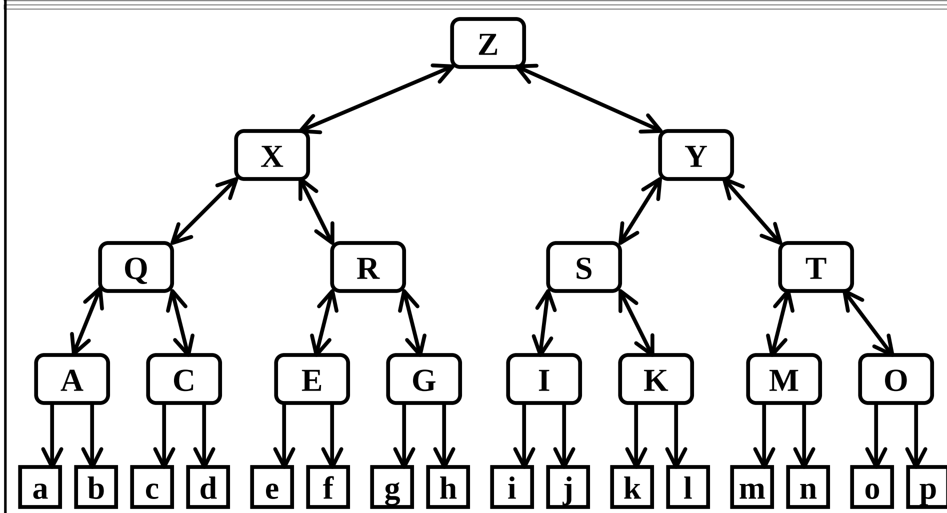
X.509v3 CERTIFICATE INNOVATIONS

- **distinguish various certificates**
  - **signature, encryption, key-agreement**
- **identification info in addition to X.500 name**
  - **internet names: email addresses, host names, URLs**
- **issuer can state policy and usage**
  - **good enough for casual email but not for signing checks**
- **limits on use of signature keys for further certification**
- **extensible**
  - **proprietary extensions can be defined and registered**
- **attribute certificates**
  - **ongoing work**

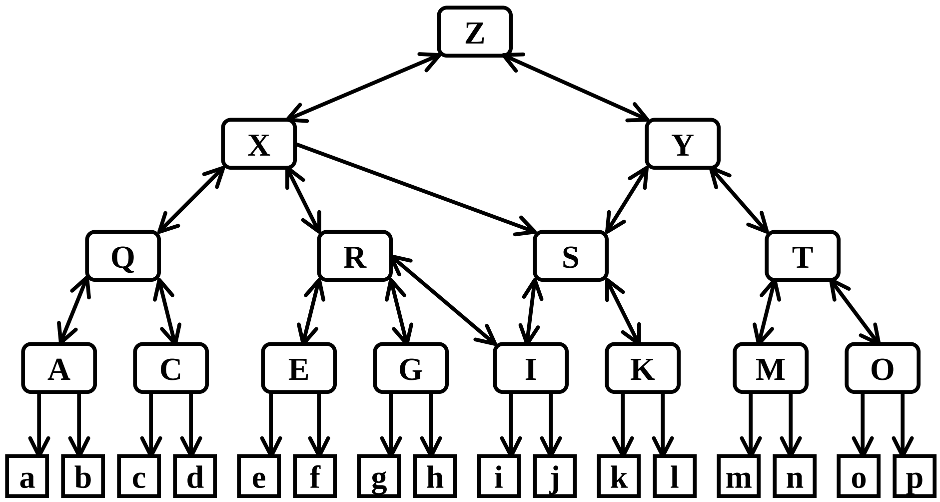
X.509v2 CRL INNOVATIONS

- ❖ CRL distribution points
- ❖ indirect CRLs
- ❖ delta CRLs
- ❖ revocation reason
- ❖ push CRLs

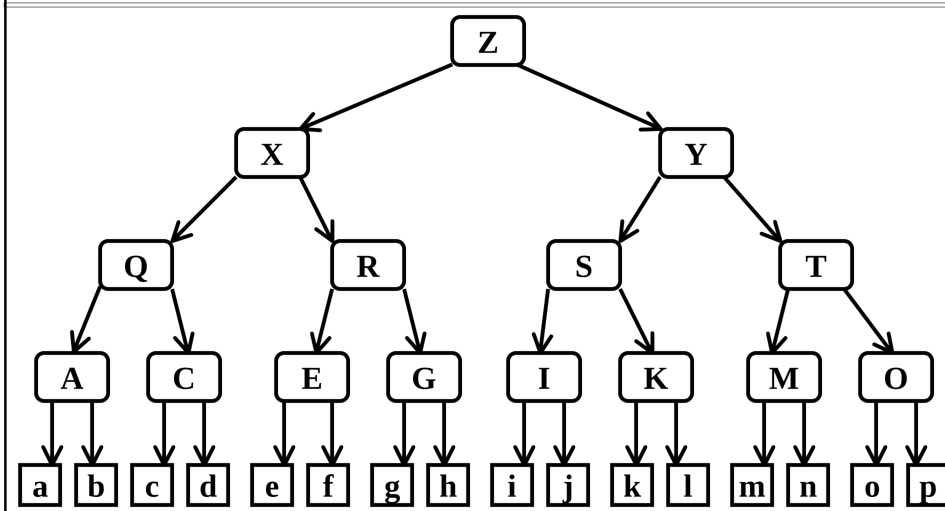
GENERAL HIERARCHICAL STRUCTURE



GENERAL HIERARCHICAL STRUCTURE WITH ADDED LINKS



TOP-DOWN HIERARCHICAL STRUCTURE



FOREST OF HIERARCHIES