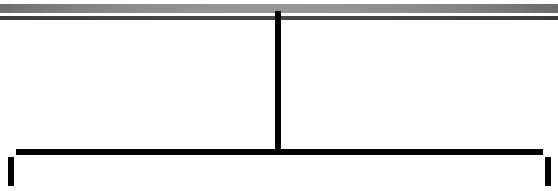
INFS 766/INFT 865
Internet Security Protocols

Lectures 3 and 4
Cryptography in network protocols

Prof. Ravi Sandhu

CRYPTOGRAPHY

CRYPTOGRAPHIC TECHNOLOGY



SECRET KEY

Symmetric Key
Single Key
Conventional

PUBLIC KEY

Asymmetric Key
Two Key

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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**

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CRYPTOGRAPHIC SERVICES

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

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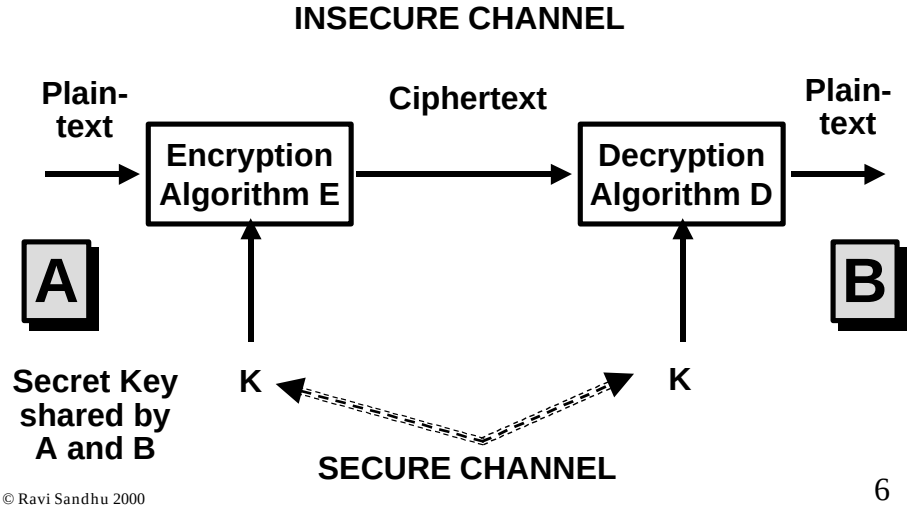
SECRET KEY CRYPTOSYSTEM



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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

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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

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CRYPTANALYSIS

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

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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

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KNOWN PLAINTEXT ATTACK

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

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

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KNOWN PLAINTEXT ATTACK

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

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

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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

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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**

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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**

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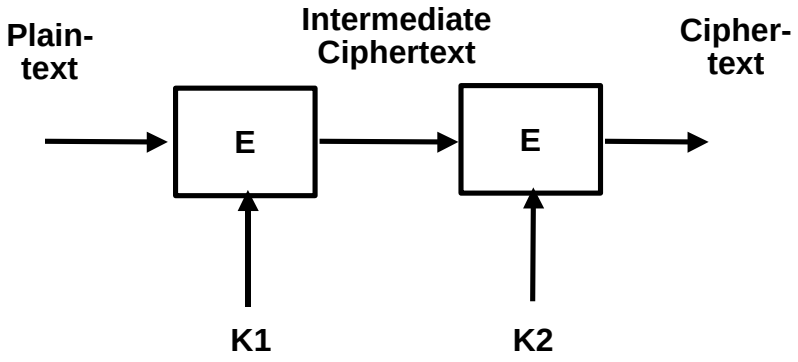
DOUBLE DES



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

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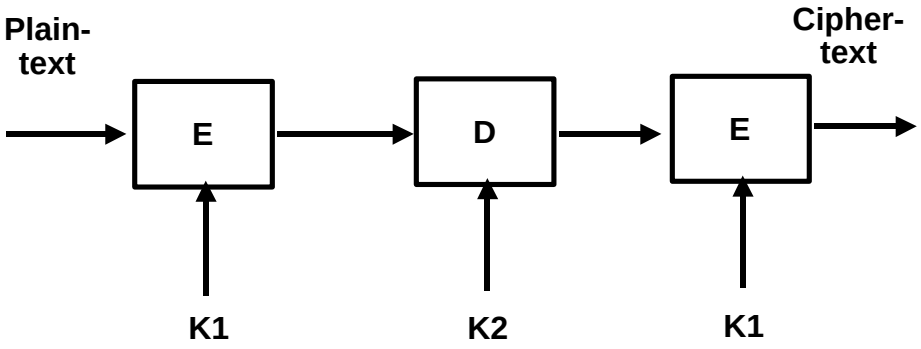
TRIPLE DES



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

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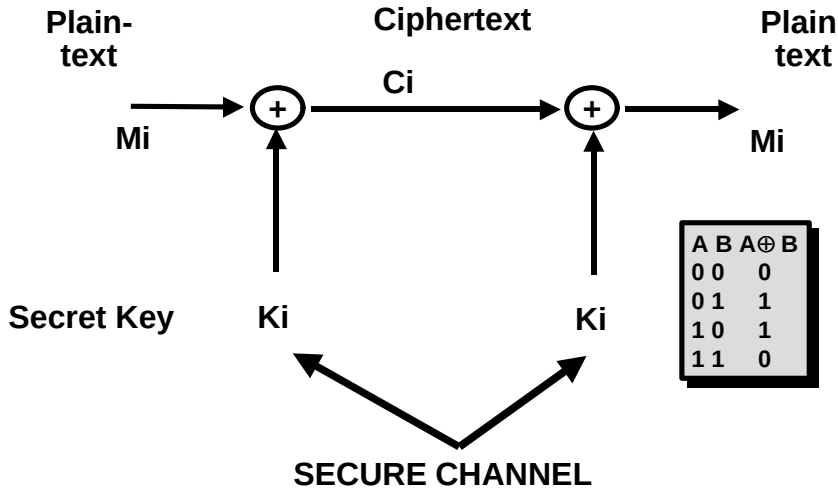
PERFECT SECRECY
VERNAM ONE-TIME PAD



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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

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NEXT GENERATION SECRET KEY CRYPTOSYSTEMS

- new Advanced Encryption Standard under development by NIST
  - must support key-block combinations of 128-128, 192-128, 256-128
  - may support other combinations
- ongoing international competition
- will be in place in a couple of years

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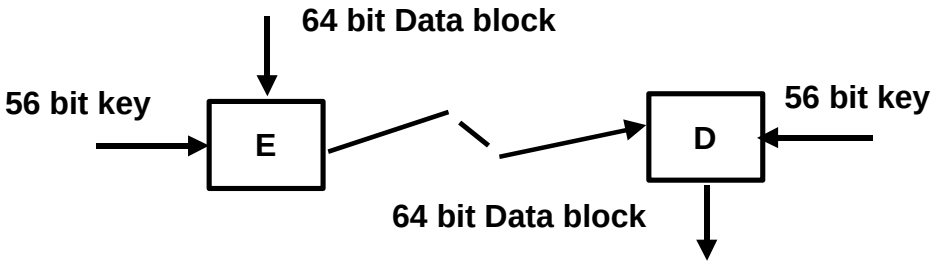
ELECTRONIC CODE BOOK (ECB) MODE



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

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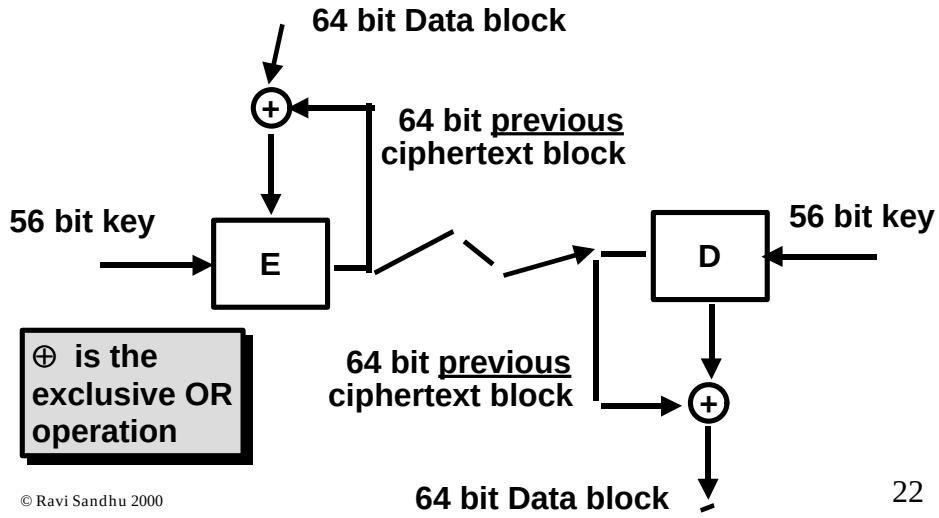
CIPHER BLOCK CHAINING (CBC) MODE



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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

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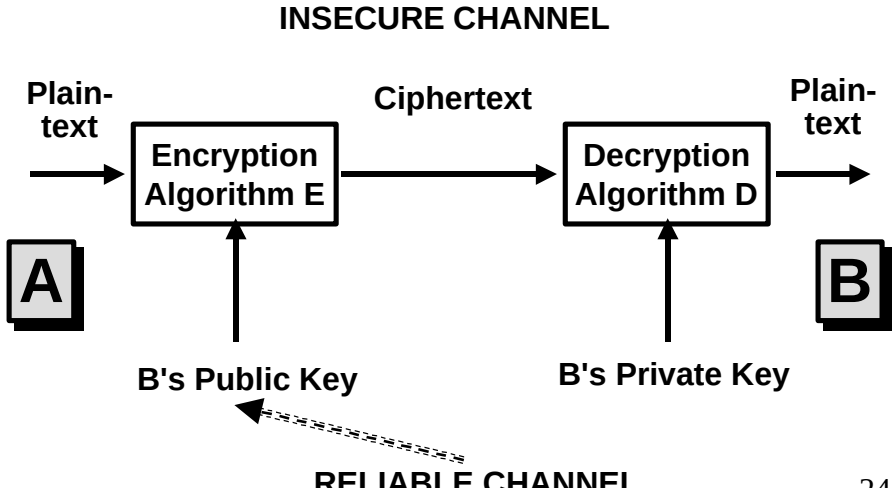
PUBLIC KEY ENCRYPTION



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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

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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

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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**

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RSA

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

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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)

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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

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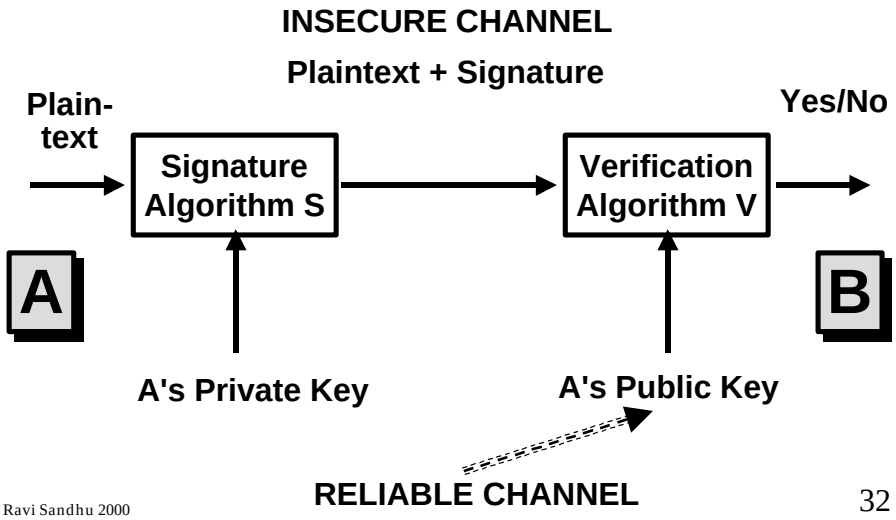
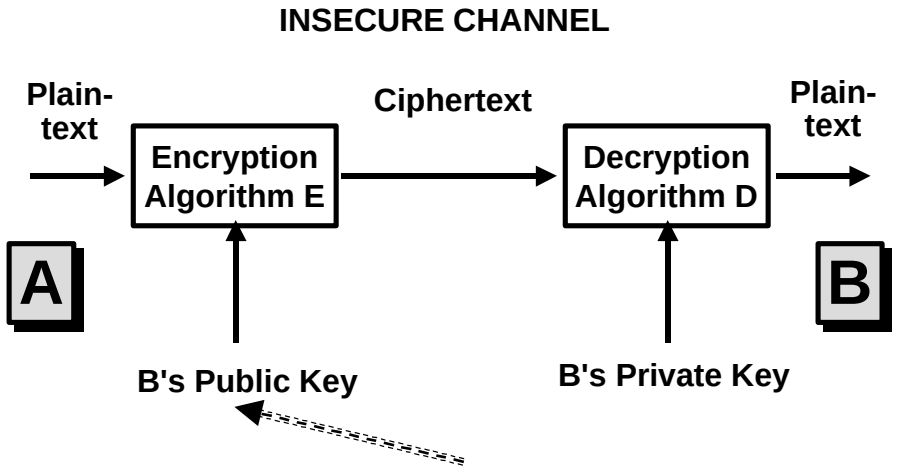
RSA KEY SIZE

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

DIGITAL SIGNATURES



COMPARE PUBLIC KEY ENCRYPTION



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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**

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EL GAMAL AND VARIANTS

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

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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

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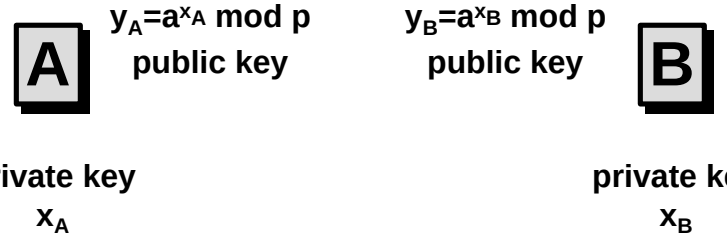
NIST DIGITAL SIGNATURE STANDARD

- 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 ESTABLISHMENT



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

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

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**

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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**

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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**

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PKCS STANDARDS

- **de facto standards initiated by RSA Data Inc.**

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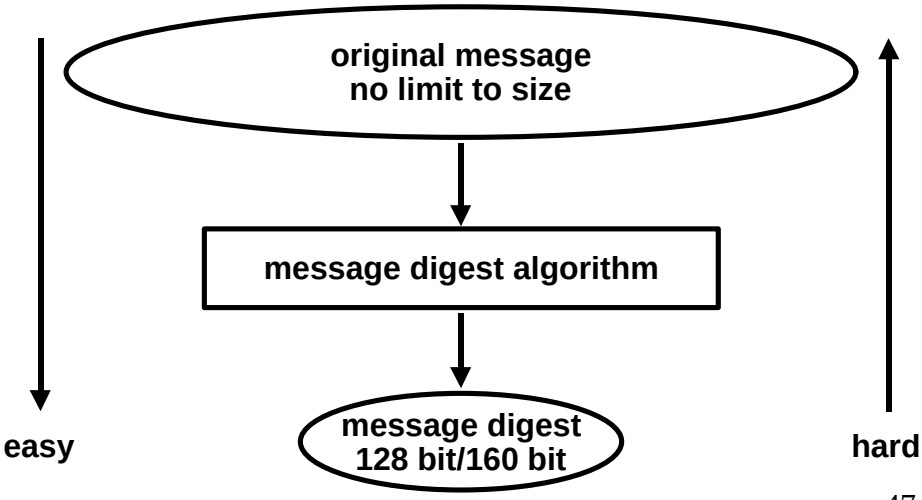
MESSAGE DIGEST



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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**

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DESIRED CHARACTERISTICS

- **weak hash 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**

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DESIRED CHARACTERISTICS

- **strong hash function**
  - **difficult to find any 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**

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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**

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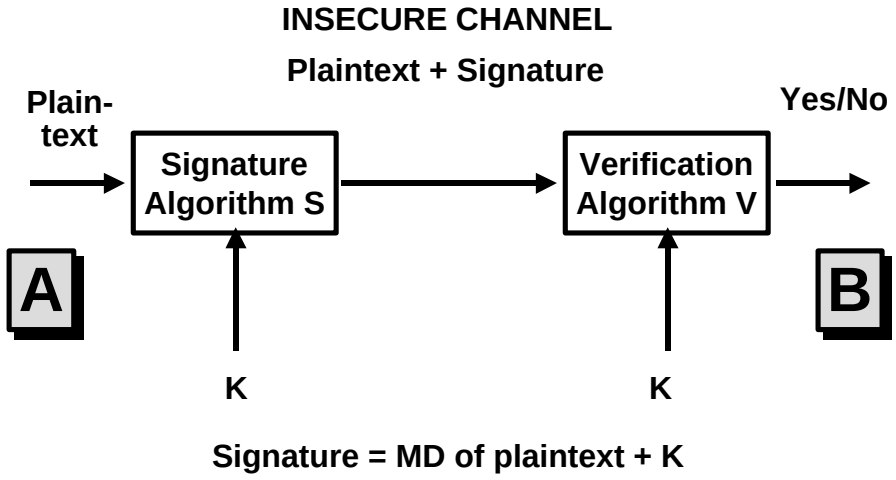
MESSAGE AUTHENTICATION CODES



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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**

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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**

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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

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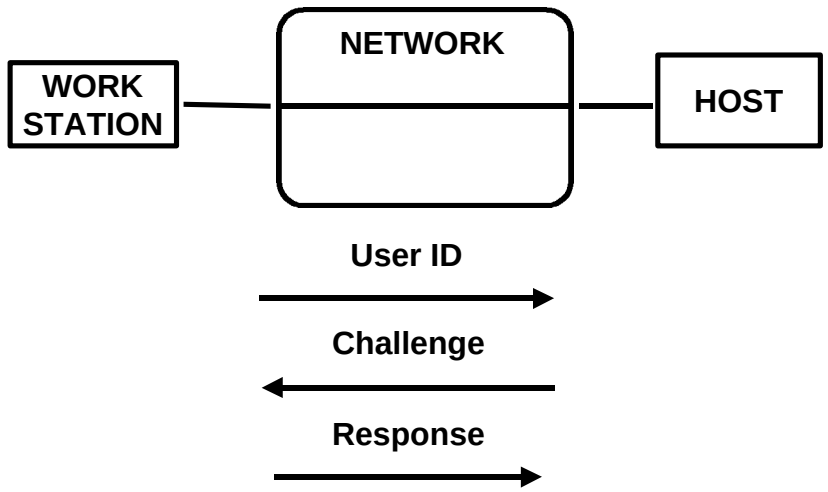
STRONG AUTHENTICATION CHALLENGE RESPONSE



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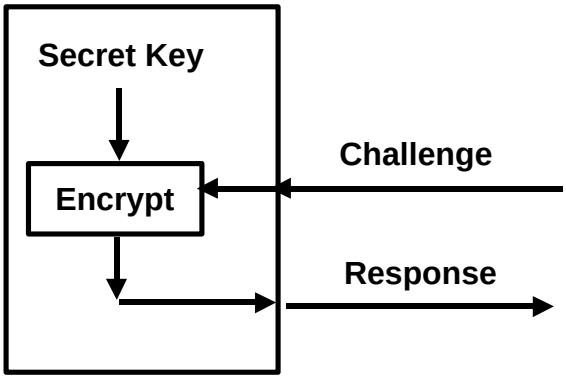
CHALLENGE RESPONSE



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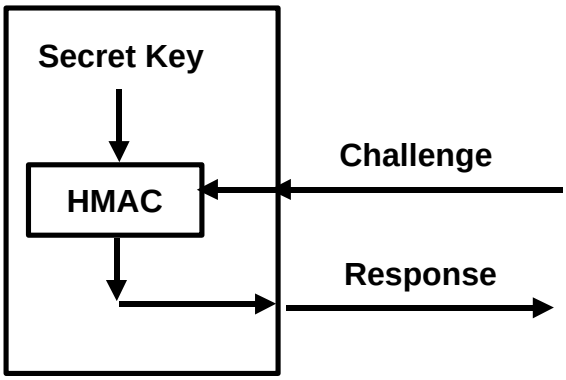
CHALLENGE RESPONSE



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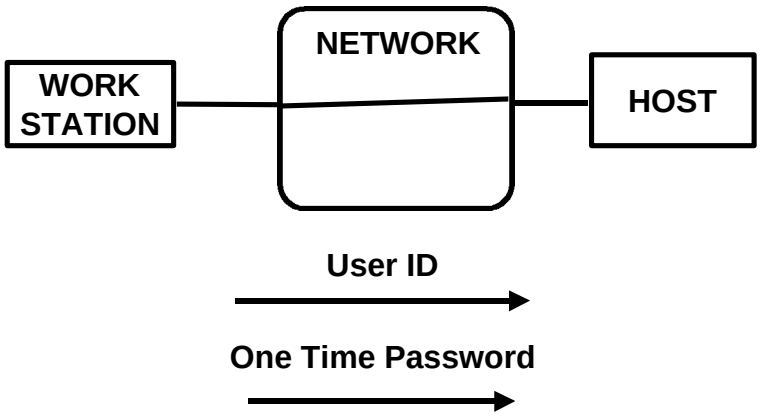
TIME SYNCHRONIZED



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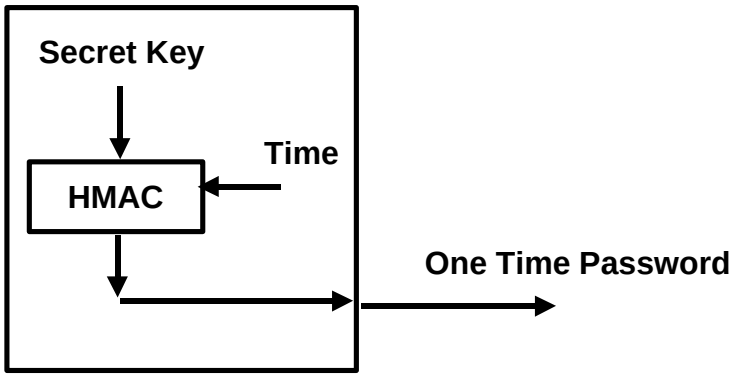
TIME SYNCHRONIZED



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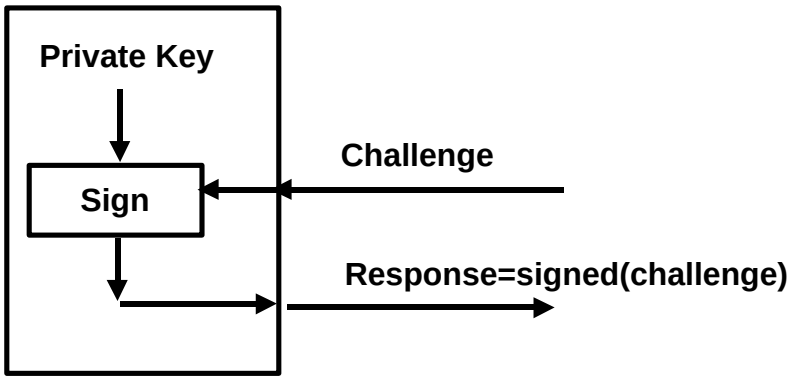
PUBLIC KEY BASED



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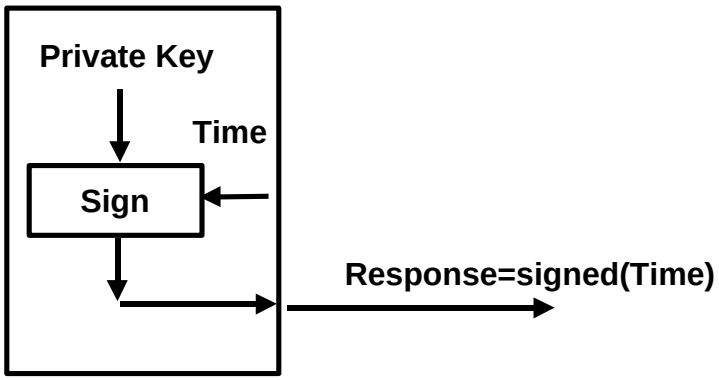
PUBLIC KEY BASED



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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

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X.509 CERTIFICATE

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

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X.509 CERTIFICATE

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

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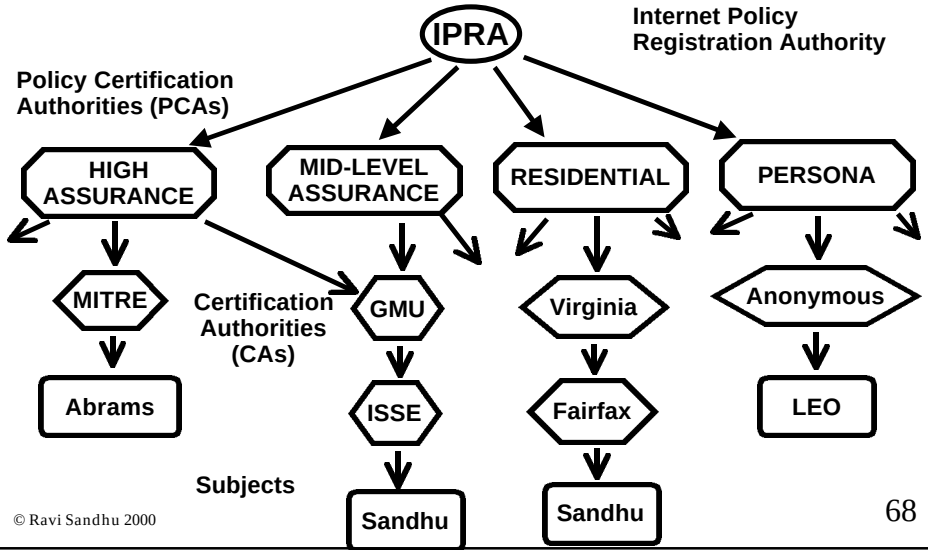
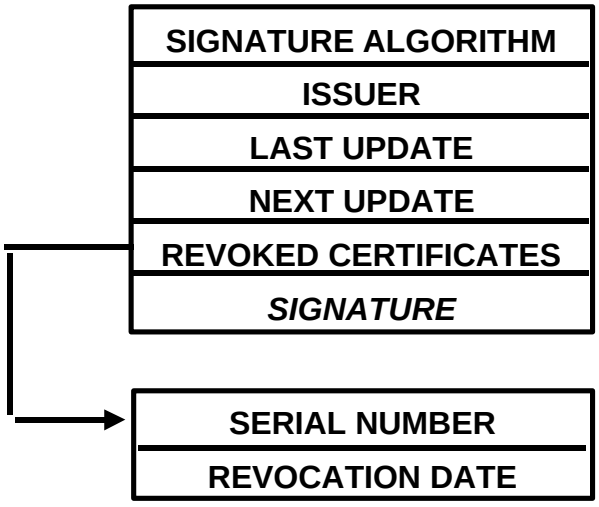
CERTIFICATE TRUST

- 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



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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**

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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

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X.509v2 CRL INNOVATIONS

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

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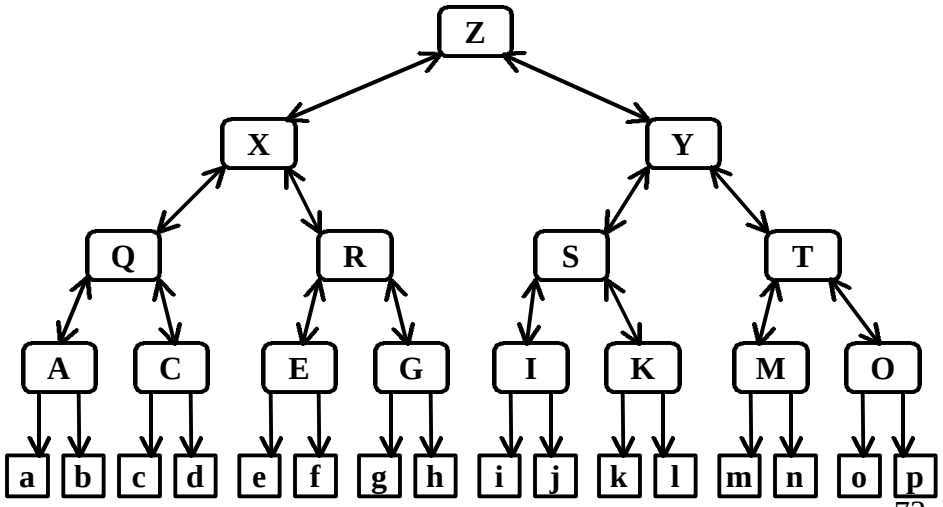
GENERAL HIERARCHICAL STRUCTURE



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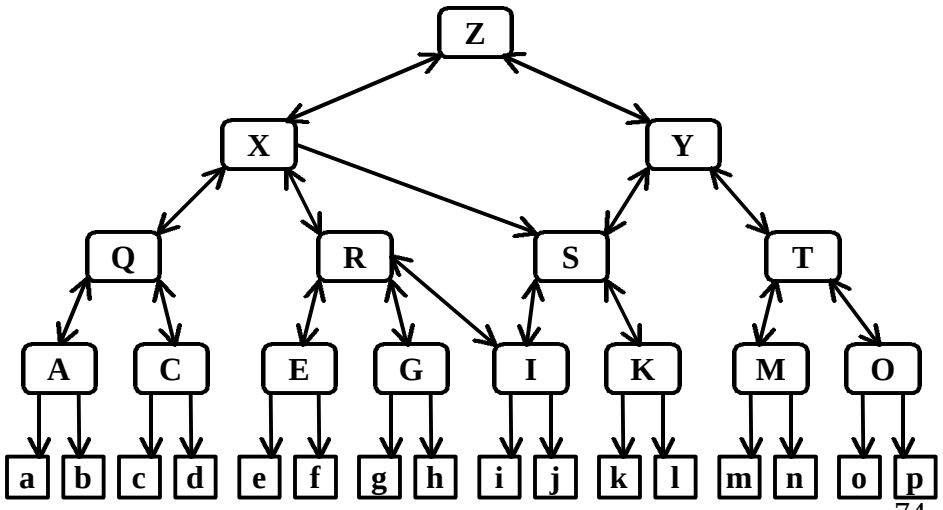
GENERAL HIERARCHICAL STRUCTURE WITH ADDED LINKS



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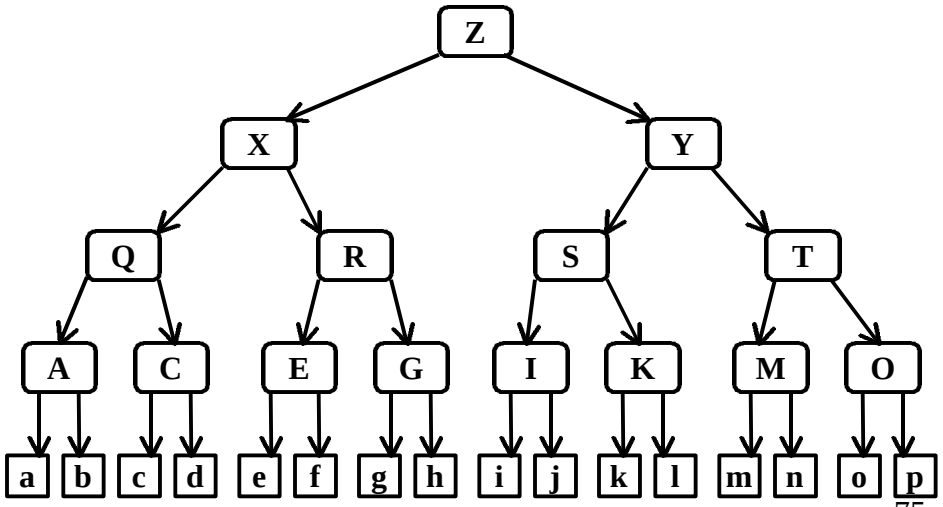
TOP-DOWN HIERARCHICAL STRUCTURE



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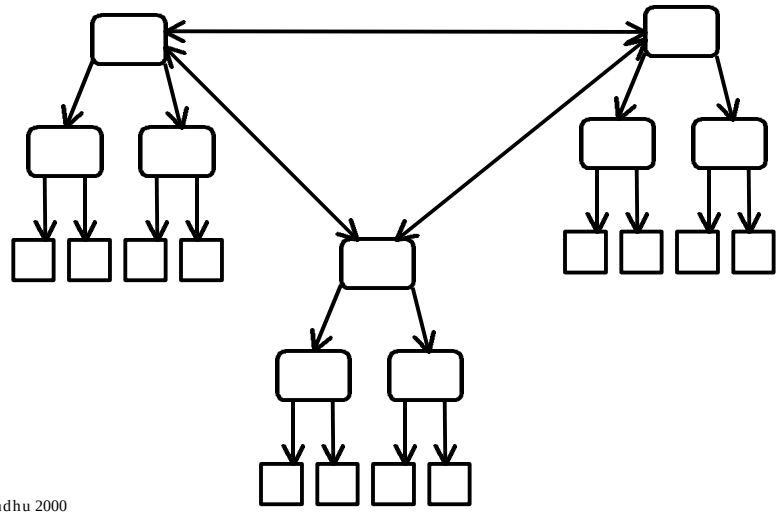
FOREST OF HIERARCHIES



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