INFS 766
Internet Security Protocols

Lectures 3 and 4
Cryptography in network protocols

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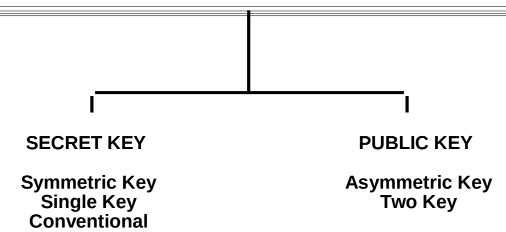
CRYPTOGRAPHY

CRYPTOGRAPHIC TECHNOLOGY



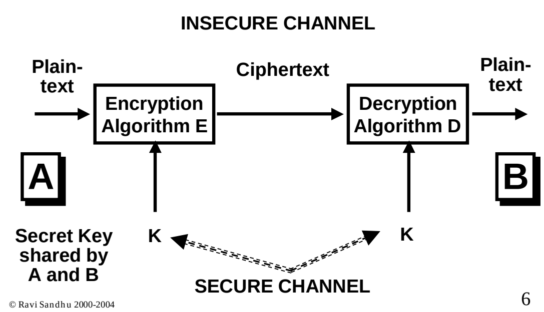
CRYPTOGRAPHIC TECHNOLOGY

- 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 $2^{55} \approx 3.6 * 10^{\wedge 16}$ 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

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

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

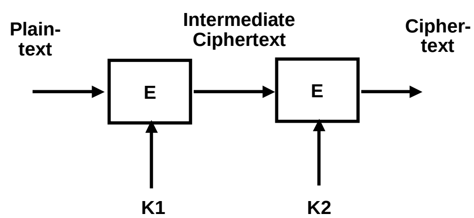
DICTIONARY ATTACKS

- 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

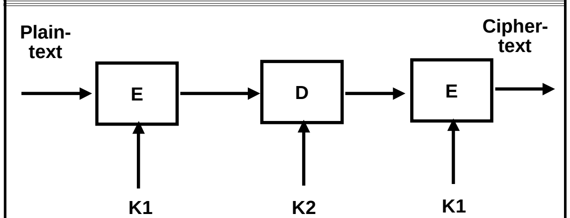
- 64 bit data block size
  - DES: 56 bit key
  - Triple DES: 112 bit key
  - Triple DES: 168 bit key
  - Skipjack: 80 bit key
  - IDEA: 128 bit key
  - RC2: variable size key: 1 byte to 128 bytes
  - many others

DOUBLE DES



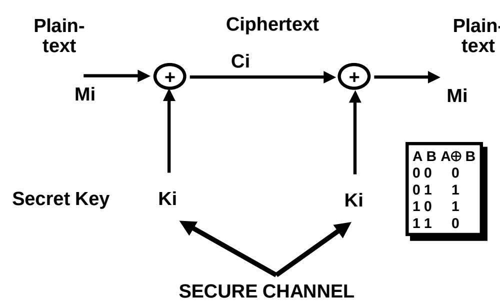
- effective key size is only 57 bits due to meet-in-the-middle attack

TRIPLE DES



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

PERFECT SECRECY VERNAM ONE-TIME PAD



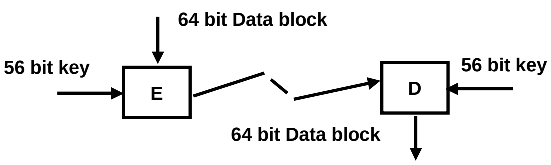
PERFECT SECRECY VERNAM ONE-TIME PAD

- 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

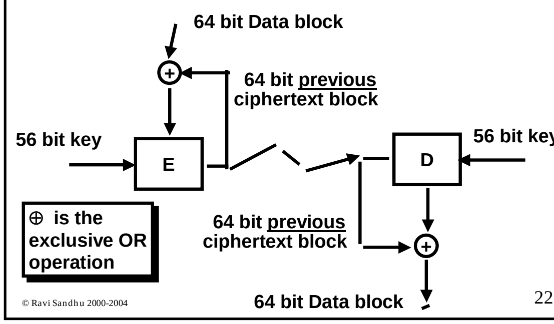
- New Advanced Encryption Standard under development by NIST
  - must support key-block combinations of 128-128, 192-128, 256-128
  - may support other combinations
- selection of Rijndaehl algorithm announced in 2000
- will be in place in a couple of years

ELECTRONIC CODE BOOK (ECB) MODE



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

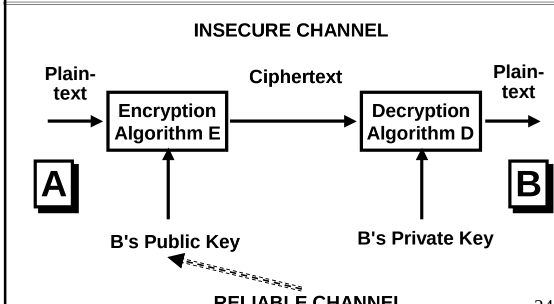
CIPHER BLOCK CHAINING (CBC) MODE



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)

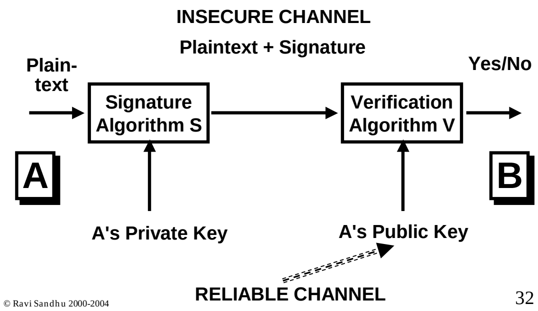
PROTECTION OF RSA KEYS

- 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

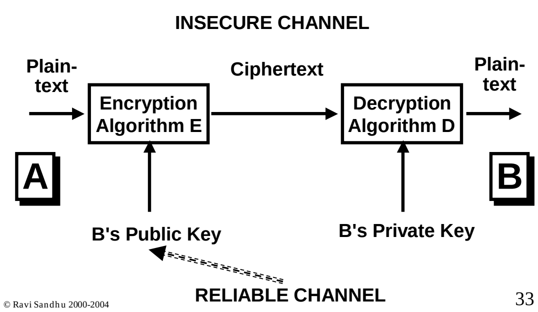
RSA KEY SIZE

- 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 $v = (g^r \bmod p) \bmod q$
  - compute $s = (m+xv)/k \bmod q$
  - signature is (s,v,m)
- to verify signature: public key y
  - compute $u1 = m/s \bmod q$
  - compute $u2 = v/s \bmod q$
  - verify that $v = (g^{u1} * y^{u2} \bmod p) \bmod q$

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

A C B

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

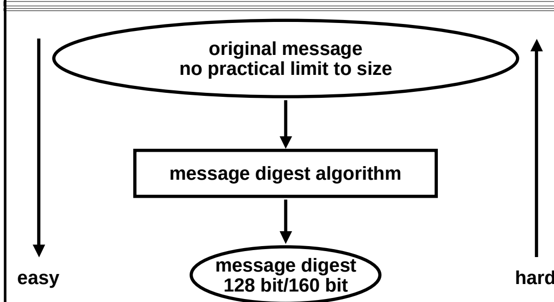
ELLIPTIC CURVE CRYPTOGRAPHY

- 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**

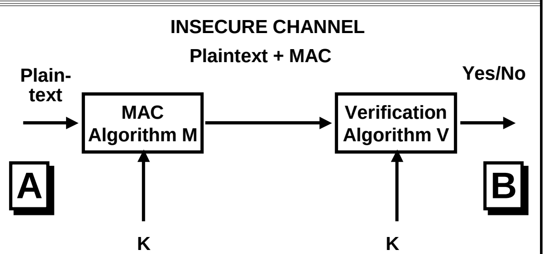
DESIRED CHARACTERISTICS

- **<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**

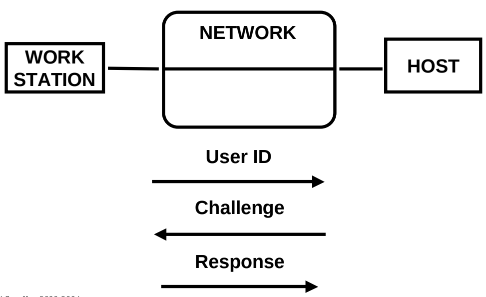
HMAC

- **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**

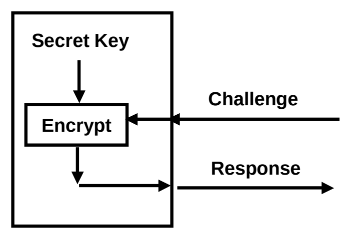
SAFE CRYPTOGRAPHY

- **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**

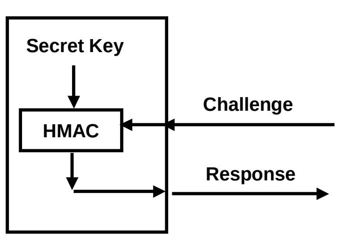
STRONG AUTHENTICATION CHALLENGE RESPONSE



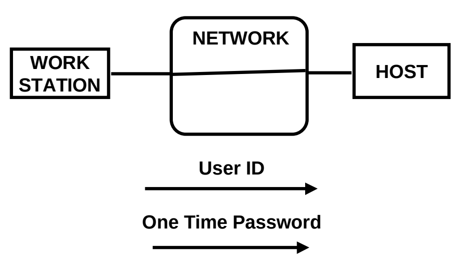
CHALLENGE RESPONSE



CHALLENGE RESPONSE



TIME SYNCHRONIZED



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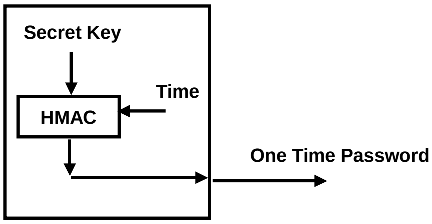
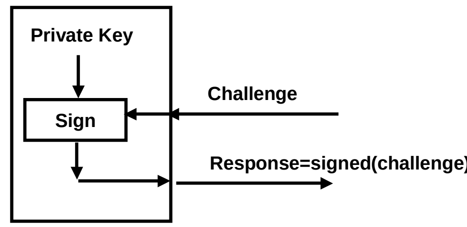


PUBLIC KEY SIGNATURE BASED



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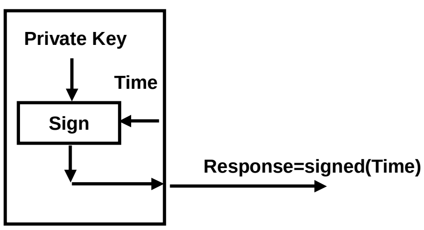
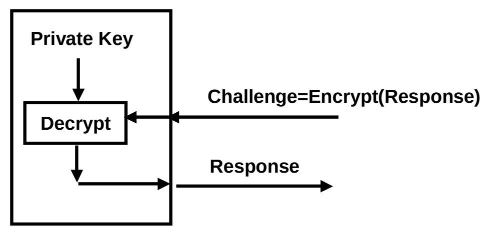
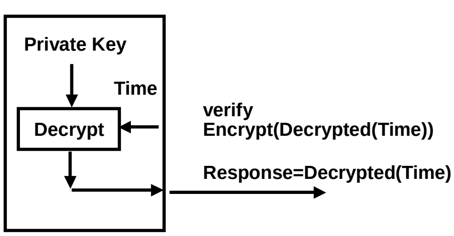


PUBLIC KEY ENCRYPTION BASED



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

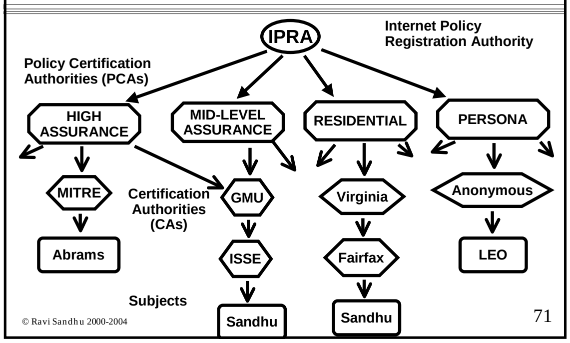
X.509v1 CERTIFICATE

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

SIGNATURE ALGORITHM
ISSUER
LAST UPDATE
NEXT UPDATE
REVOKED CERTIFICATES
SIGNATURE

SERIAL NUMBER
REVOCATION DATE

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**

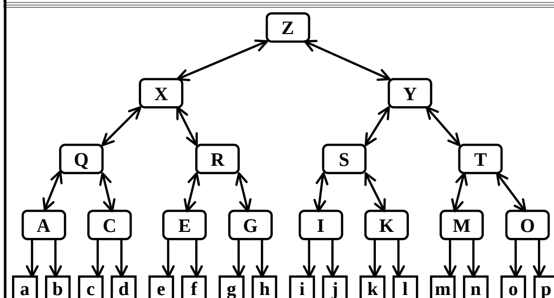
X.509v3 CERTIFICATE INNOVATIONS

- **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**

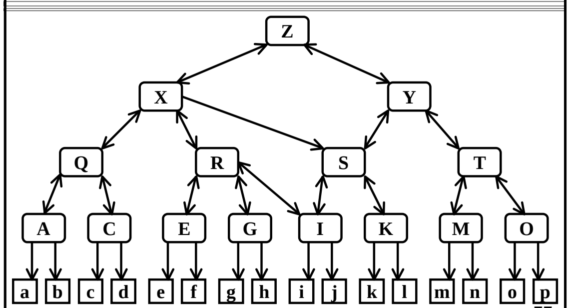
X.509v2 CRL INNOVATIONS

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

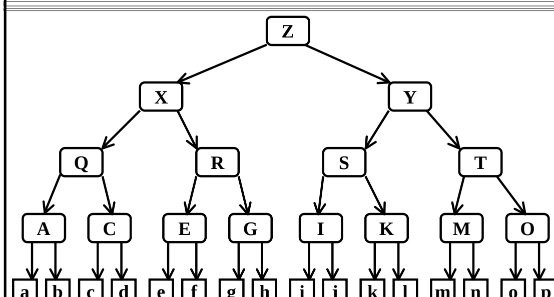
GENERAL HIERARCHICAL STRUCTURE



GENERAL HIERARCHICAL STRUCTURE WITH ADDED LINKS



TOP-DOWN HIERARCHICAL STRUCTURE



FOREST OF HIERARCHIES