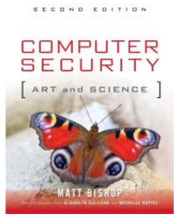
Key Management

Chapter 11

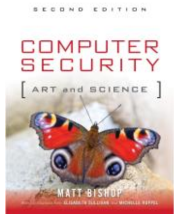
Overview

- Key exchange
  - Session vs. interchange keys
  - Classical, public key methods
  - Key generation
- Cryptographic key infrastructure
  - Certificates
- Key storage
  - Key escrow
  - Key revocation



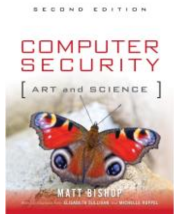
Notation

- $X \rightarrow Y : \{ Z \,||\, W \}\, k_{X,Y}$
  - X sends Y the message produced by concatenating Z and W enciphered by key $k_{X,Y}$, which is shared by users X and Y
- $A \rightarrow T : \{ Z \}\, k_A \,||\, \{ W \}\, k_{A,T}$
  - A sends T a message consisting of the concatenation of Z enciphered using k_A, A's key, and W enciphered using $k_{A,T}$, the key shared by A and T
- r_1, r_2 nonces (nonrepeating random numbers)



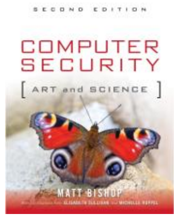
Session, Interchange Keys

- Alice wants to send a message *m* to Bob
  - Assume public key encryption
  - Alice generates a random cryptographic key k_s and uses it to encipher *m*
    - To be used for this message *only*
    - Called a *session key*
  - She enciphers k_s with Bob;s public key k_B
    - k_B enciphers all session keys Alice uses to communicate with Bob
    - Called an interchange *key*
  - Alice sends $\{ m \} k_s \{ k_s \} k_B$



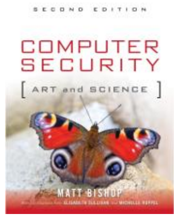
Benefits

- Limits amount of traffic enciphered with single key
  - Standard practice, to decrease the amount of traffic an attacker can obtain
- Prevents some attacks
  - Example: Alice will send Bob message that is either “BUY” or “SELL”. Eve computes possible ciphertexts { “BUY” } k_B and { “SELL” } k_B. Eve intercepts enciphered message, compares, and gets plaintext at once



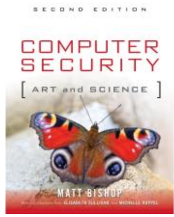
Key Exchange Algorithms

- Goal: Alice, Bob get shared key
  - Key cannot be sent in clear
    - Attacker can listen in
    - Key can be sent enciphered, or derived from exchanged data plus data not known to an eavesdropper
  - Alice, Bob may trust third party
  - All cryptosystems, protocols publicly known
    - Only secret data is the keys, ancillary information known only to Alice and Bob needed to derive keys
    - Anything transmitted is assumed known to attacker



Symmetric Key Exchange

- Bootstrap problem: how do Alice, Bob begin?
  - Alice can't send it to Bob in the clear!
- Assume trusted third party, Cathy
  - Alice and Cathy share secret key k_A
  - Bob and Cathy share secret key k_B
- Use this to exchange shared key k_s



Simple Protocol

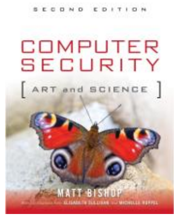
$$\text{Alice} \xrightarrow{\{\text{ request for session key to Bob }\}\ k_A} \text{Cathy}$$

$$\text{Alice} \xleftarrow{\{\ k_s\ \}\ k_A\ ||\ \{\ k_s\ \}\ k_B} \text{Cathy}$$

$$\text{Alice} \xrightarrow{\{\ k_s\ \}\ k_B} \text{Bob}$$

Problems

- How does Bob know he is talking to Alice?
  - Replay attack: Eve records message from Alice to Bob, later replays it; Bob may think he's talking to Alice, but he isn't
  - Session key reuse: Eve replays message from Alice to Bob, so Bob re-uses session key
- Protocols must provide authentication and defense against replay



Needham-Schroeder

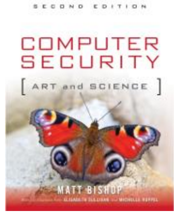
Alice $\xrightarrow{\text{Alice} \mid\mid \text{Bob} \mid\mid r_1}$ Cathy

Alice $\xleftarrow{\{ \text{Alice} \mid\mid \text{Bob} \mid\mid r_1 \mid\mid k_s \mid\mid \{ \text{Alice} \mid\mid k_s \} k_B \} k_A}$ Cathy

Alice $\xrightarrow{\{ \text{Alice} \mid\mid k_s \} k_B}$ Bob

Alice $\xleftarrow{\{ r_2 \} k_s}$ Bob

Alice $\xrightarrow{\{ r_2 - 1 \} k_s}$ Bob

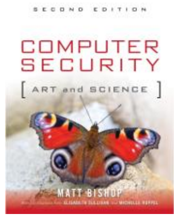


Argument: Alice talking to Bob

- Second message
  - Enciphered using key only she, Cathy knows
    - So Cathy enciphered it
  - Response to first message
    - As r_1 in it matches r_1 in first message
- Third message
  - Alice knows only Bob can read it
    - As only Bob can derive session key from message
  - Any messages enciphered with that key are from Bob

Argument: Bob talking to Alice

- Third message
  - Enciphered using key only he, Cathy know
    - So Cathy enciphered it
  - Names Alice, session key
    - Cathy provided session key, says Alice is other party
- Fourth message
  - Uses session key to determine if it is replay from Eve
    - If not, Alice will respond correctly in fifth message
    - If so, Eve can’t decipher r_2 and so can’t respond, or responds incorrectly



Denning-Sacco Modification

- Assumption: all keys are secret
- Question: suppose Eve can obtain session key. How does that affect protocol?
    - In what follows, Eve knows k_s

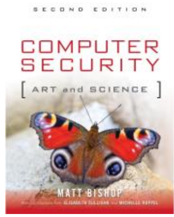
$$\text{Eve} \xrightarrow{\{\text{ Alice } || \ k_s \}\, k_B} \text{Bob}$$

$$\text{Eve} \xleftarrow{\{ r_2 \}\, k_s} \text{Bob}$$

$$\text{Eve} \xrightarrow{\{ r_2 - 1 \}\, k_s} \text{Bob}$$

Problem and Solution

- In protocol above, Eve impersonates Alice
- Problem: replay in third step
  - First in previous slide
- Solution: use time stamp *T* to detect replay
- Weakness: if clocks not synchronized, may either reject valid messages or accept replays
  - Parties with either slow or fast clocks vulnerable to replay
  - Resetting clock does *not* eliminate vulnerability



Needham-Schroeder with Denning-Sacco Modification

Alice $\xrightarrow{\text{Alice} \,||\, \text{Bob} \,||\, r_1}$ Cathy

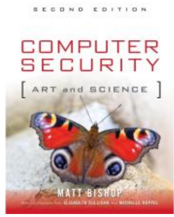
Alice $\xleftarrow{\{\,\text{Alice} \,||\, \text{Bob} \,||\, r_1 \,||\, k_s \,||\, \{\,\text{Alice} \,||\, T \,||\, k_s\,\}\, k_B\,\}\, k_A}$ Cathy

Alice $\xrightarrow{\{\,\text{Alice} \,||\, T \,||\, k_s\,\}\, k_B}$ Bob

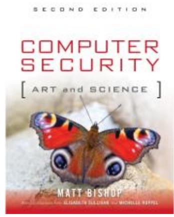
Alice $\xleftarrow{\{\,r_2\,\}\, k_s}$ Bob

Alice $\xrightarrow{\{\,r_2 - 1\,\}\, k_s}$ Bob

Otway-Rees Protocol



- Corrects problem
  - That is, Eve replaying the third message in the protocol
- Does not use timestamps
  - Not vulnerable to the problems that Denning-Sacco modification has
- Uses integer *n* to associate all messages with particular exchange



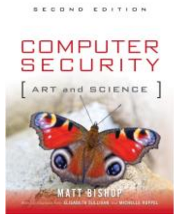
The Protocol

$$\text{Alice} \xrightarrow{n \,||\, \text{Alice} \,||\, \text{Bob} \,||\, \{ r_1 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_A} \text{Bob}$$

$$\text{Cathy} \xleftarrow[\{ r_2 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_B]{n \,||\, \text{Alice} \,||\, \text{Bob} \,||\, \{ r_1 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_A \,||} \text{Bob}$$

$$\text{Cathy} \xrightarrow{n \,||\, \{ r_1 \,||\, k_s \}\, k_A \,||\, \{ r_2 \,||\, k_s \}\, k_B} \text{Bob}$$

$$\text{Alice} \xleftarrow{n \,||\, \{ r_1 \,||\, k_s \}\, k_A} \text{Bob}$$



Argument: Alice talking to Bob

- Fourth message
  - If *n* matches first message, Alice knows it is part of this protocol exchange
  - Cathy generated k_s because only she, Alice know k_A
  - Enciphered part belongs to exchange as r_1 matches r_1 in encrypted part of first message

Argument: Bob talking to Alice

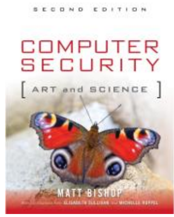
- Third message
  - If n matches second message, Bob knows it is part of this protocol exchange
  - Cathy generated k_s because only she, Bob know k_B
  - Enciphered part belongs to exchange as r_2 matches r_2 in encrypted part of second message

Replay Attack

- Eve acquires old k_s, message in third step
  - $n \mid\mid \{ r_1 \mid\mid k_s \} k_A \mid\mid \{ r_2 \mid\mid k_s \} k_B$
- Eve forwards appropriate part to Alice
  - Alice has no ongoing key exchange with Bob: *n* matches nothing, so is rejected
  - Alice has ongoing key exchange with Bob: *n* does not match, so is again rejected
    - If replay is for the current key exchange, *and* Eve sent the relevant part *before* Bob did, Eve could simply listen to traffic; no replay involved

Bellare-Rogaway Protocol

- Note that authentication, symmetric key exchange are really different problems
  - So they focus only on symmetric key exchange
- In what follows, h_{Alice} and h_{Bob} are keyed hash functions using Alice's and Bob's secret keys, respectively



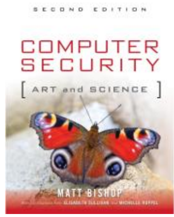
The Protocol

Alice $\xrightarrow{\text{Alice} \,||\, \text{Bob} \,||\, r_1}$ Bob

Bob $\xleftarrow{\text{Alice} \,||\, \text{Bob} \,||\, r_1 \,||\, r_2}$ Cathy

Cathy $\xrightarrow{\{ k_{session} \} k_{\text{Bob}} \,||\, h_{\text{Bob}}(\text{Alice} \,||\, \text{Bob} \,||\, r_2 \,||\, \{k_{session} \} k_{\text{Bob}})}$ Bob

Cathy $\xrightarrow{\{ k_{session} \} k_{\text{Alice}} \,||\, h_{\text{Alice}}(\text{Alice} \,||\, \text{Bob} \,||\, r_2 \,||\, \{k_{session} \} k_{\text{Alice}})}$ Alice



Argument: Alice, Bob, and Cathy

- Bob knows the nonce r_2
- When he receives the message from Cathy, he uses his secret key k_{Bob} to compute $h_{\text{Bob}}(\text{Alice} \mid\mid \text{Bob} \mid\mid r_2 \mid\mid \{ k_{session} \}k_{\text{Bob}})$
  - Note $\{ k_{session} \}k_{\text{Bob}}$ is first part of message, so Bob need not decipher it
- Compare result with what he received from Cathy
- If equal, decipher $\{ k_{session} \}k_{\text{Bob}}$ to get the session key

Argument: Eve is Stymied

Eve intercepts message in steps 3 and 4

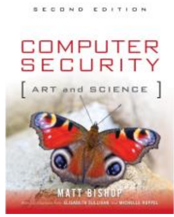
- To get session key, Eve needs Alice’s and Bob’s secret keys
  - By assumption, she does not
- Eve has a previously used session key, recorded corresponding message from steps 3 and 4, and replays it
- Case 1: new protocol exchange has begun
  - Nonces r_1, r_2 are different than r_1, r_2 in replayed message, so Alice, Bob reject message
- Case 2: new protocol exchange has not begum
  - As Eve is sending message for step 3 and 4, and Alice and Bob never did steps 1 and 2, they discard the replayed message

Kerberos

- Authentication system
  - Based on Needham-Schroeder with Denning-Sacco modification
  - Central server plays role of trusted third party (“Cathy”)
- Ticket
  - Issuer vouches for identity of requester of service
- Authenticator
  - Identifies sender

Idea

- User u authenticates to Kerberos server
  - Obtains ticket $T_{u,TGS}$ for ticket granting service (TGS)
- User u wants to use service s:
  - User sends authenticator A_u, ticket $T_{u,TGS}$ to TGS asking for ticket for service
  - TGS sends ticket $T_{u,s}$ to user
  - User sends A_u, $T_{u,s}$ to server as request to use s
- Details follow



Ticket

- Credential saying issuer has identified ticket requester
- Example ticket issued to user *u* for service *s*

$$T_{u,s} = s \,||\, \{ u \,||\, u\text{'s address} \,||\, \text{valid time} \,||\, k_{u,s} \}\, k_s$$

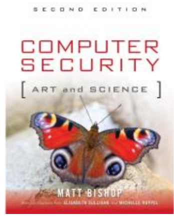
  where:
  - $k_{u,s}$ is session key for user and service
  - Valid time is interval for which ticket valid
  - *u*'s address may be IP address or something else
    - Note: more fields, but not relevant here

Authenticator

- Credential containing identity of sender of ticket
  - Used to confirm sender is entity to which ticket was issued
- Example: authenticator user *u* generates for service *s*

$$A_{u,s} = \{ u \,||\, \text{generation time} \,||\, k_t \}\, k_{u,s}$$

  where:
  - k_t is alternate session key
  - Generation time is when authenticator generated
    - Note: more fields, not relevant here



Protocol

$$user \xrightarrow{\;user \,||\, TGS\;} AS$$

$$AS \xleftarrow{\;\{ k_{u,TGS} \} k_u \,||\, T_{u,TGS}\;} user$$

$$user \xrightarrow{\;service \,||\, A_{u,TGS} \,||\, T_{u,TGS}\;} TGS$$

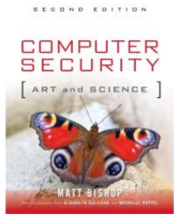
$$user \xleftarrow{\;user \,||\, \{ k_{u,s} \} k_{u,TGS} \,||\, T_{u,s}\;} TGS$$

$$user \xrightarrow{\;A_{u,s} \,||\, T_{u,s}\;} service$$

$$user \xleftarrow{\;\{ t + 1 \} k_{u,s}\;} service$$

Analysis

- First two steps get user ticket to use TGS
  - User *u* can obtain session key only if *u* knows key shared with AS
- Next four steps show how *u* gets and uses ticket for service *s*
  - Service *s* validates request by checking sender (using $A_{u,s}$) is same as entity ticket issued to
  - Step 6 optional; used when *u* requests confirmation



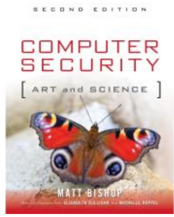
Problems

- Relies on synchronized clocks
  - If not synchronized and old tickets, authenticators not cached, replay is possible
- Tickets have some fixed fields
  - Dictionary attacks possible
  - Kerberos 4 session keys weak (had much less than 56 bits of randomness); researchers at Purdue found them from tickets in minutes

Public Key Key Exchange

- Here interchange keys known
  - e_A, e_B Alice and Bob's public keys known to all
  - d_A, d_B Alice and Bob's private keys known only to owner
- Simple protocol
  - k_s is desired session key

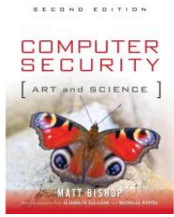
$$\text{Alice} \xrightarrow{\{ k_s \}\, e_B} \text{Bob}$$



Problem and Solution

- Vulnerable to forgery or replay
  - Because e_B known to anyone, Bob has no assurance that Alice sent message
- Simple fix uses Alice's private key
  - k_s is desired session key

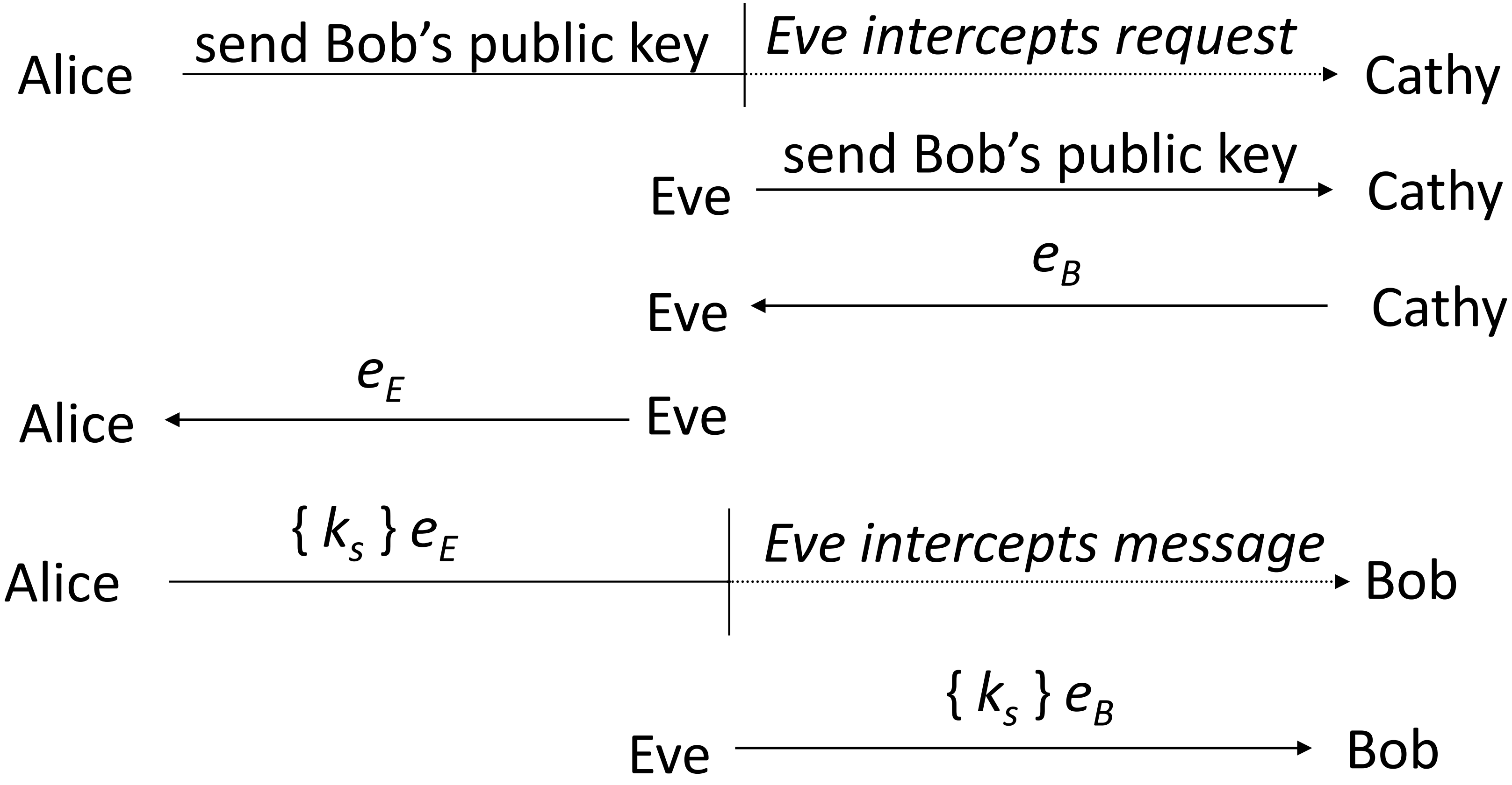
$$\text{Alice} \xrightarrow{\{\,\{\,k_s\,\}\,d_A\,\}\,e_B} \text{Bob}$$

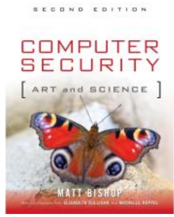


Notes

- Can include message enciphered with k_s
- Assumes Bob has Alice's public key, and *vice versa*
  - If not, each must get it from public server
  - If keys not bound to identity of owner, attacker Eve can launch a *man-in-the-middle* attack (next slide; Cathy is public server providing public keys)
    - Solution to this (binding identity to keys) discussed later as public key infrastructure (PKI)

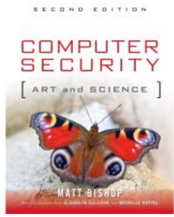
Man-in-the-Middle Attack





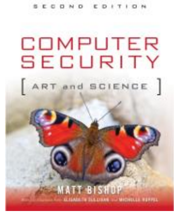
Diffie-Hellman

- Compute a common, shared key
  - Called a *symmetric key exchange protocol*
- Based on discrete logarithm problem
  - Given integers n, g and prime number p, compute k such that $n = g^k \bmod p$
  - Solutions known for small p
  - Solutions computationally infeasible as p grows large



Algorithm

- Constants: prime p, integer $g \neq 0, 1, p-1$
  - Known to all participants
- Alice chooses private key k_{Alice}, computes public key $K_{\text{Alice}} = g^{k_{\text{Alice}}} \bmod p$
- Bob chooses private key k_{Bob}, computes public key $K_{\text{Bob}} = g^{k_{\text{Bob}}} \bmod p$
- To communicate with Bob, Anne computes $K_{\text{Alice,Bob}} = K_{\text{Bob}}{}^{k_{\text{Alice}}} \bmod p$
- To communicate with Anne, Bob computes $K_{\text{Bob,Alice}} = K_{\text{Alice}}{}^{k_{\text{Bob}}} \bmod p$
- It can be shown $K_{\text{Alice,Bob}} = K_{\text{Bob,Alice}}$



Example

- Assume p = 121001 and g = 6981
- Alice chooses k_{Alice} = 526784
  - Then $K_{\text{Alice}} = 6981^{26874} \bmod 121001 = 22258$
- Bob chooses k_{Bob} = 5596
  - Then $K_{\text{Bob}} = 6981^{5596} \bmod 121001 = 112706$
- Shared key:
  - $K_{\text{Bob}}{}^{k_{\text{Alice}}} \bmod p = 112706^{26874} \bmod 121001 = 78618$
  - $K_{\text{Alice}}{}^{k_{Bob}} \bmod p = 22258^{5596} \bmod 121001 = 78618$

Example (Elliptic Curve Version)

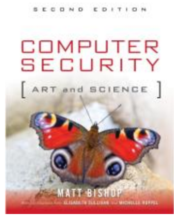
- Alice, Bob agree to use the curve $y^2 = x^3 + 4x + 14 \bmod 2503$ and the point $P = (1002, 493)$; curve has $n = 2428$ integer points
- Alice chooses $k_{\text{Alice}} = 1379$
  - Then $K_{\text{Alice}} = k_{\text{Alice}} P \bmod p = 1379(1002,493) \bmod 2503 = (1041,1659)$
- Bob chooses $k_{\text{Bob}} = 2011$
  - Then $K_{\text{Bob}} = k_{\text{Bob}} P \bmod p = 2011(1002,493) \bmod 2503 = (629,548)$
- Shared key:
  - $K_{\text{Bob}} k_{\text{Alice}} \bmod p = 2011(1041,1659) \bmod 2503 = (2075,2458)$
  - $K_{\text{Alice}} k_{\text{Bob}} \bmod p = 1379(629,548) \bmod 2503 = (2075,2458)$

Key Generation

- Goal: generate keys that are difficult to guess
- Problem statement: given a set of *k* potential keys, choose one randomly
  - Equivalent to selecting a random number between 0 and *k*–1 inclusive
- Why is this hard: generating random numbers
  - Actually, numbers are usually *pseudorandom*, that is, generated by an algorithm

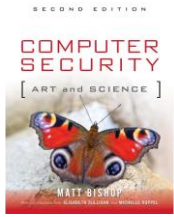
What is “Random”?

- *Sequence of cryptographically random numbers*: a sequence of numbers n_1, n_2, … such that for any integer $k > 0$, an observer cannot predict n_k even if all of n_1, …, n_{k-1} are known
- Best: physical source of randomness
  - Random pulses
  - Electromagnetic phenomena
  - Characteristics of computing environment such as disk latency
  - Ambient background noise



What is “Pseudorandom”?

- *Sequence of cryptographically pseudorandom numbers*: sequence of numbers intended to simulate a sequence of cryptographically random numbers but generated by an algorithm
- Very difficult to do this well
  - Linear congruential generators [$x_k = (ax_{k-1} + b) \bmod n$] broken
  - Polynomial congruential generators [$x_k = (a_j x_{k-1}^j + \ldots + a_1 x_{k-1}\ a_0) \bmod n$] broken too
  - Here, “broken” means next number in sequence can be determined



Best Pseudorandom Numbers

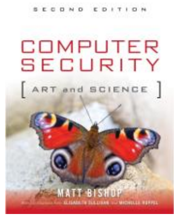
- *Strong mixing function*: function of 2 or more inputs with each bit of output depending on some nonlinear function of all input bits
  - Examples: AES, SHA-512, SHA-3
  - Use on UNIX-based systems:

    ```
    (date; ps gaux) | sha512
    ```

    where "`ps gaux`" lists all information about all processes on system

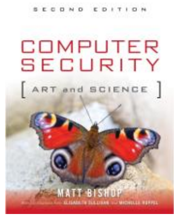
Biometrics

- Physical variations cause slight differences in successive biometric readings and so is good source of randomness
  - This causes randomness in the least significant bits of the data
- Biometrics for generating keys tied to individuals
  - Requires: adversary unlikely to determine them, but must be regenerated consistently
- Represent data as bit string (*feature descriptor*)
  - Transform it in some way
  - Generate cryptographic key from this
  - Add some randomness so if key compromised, a new and different one can be created



Cryptographic Key Infrastructure

- Goal: bind identity to key
- Symmetric: not possible as all keys are shared
  - Use protocols to agree on a shared key (see earlier)
- Public key: bind identity to public key
  - Crucial as people will use key to communicate with principal whose identity is bound to key
  - Erroneous binding means no secrecy between principals
  - Assume principal identified by an acceptable name



Certificates

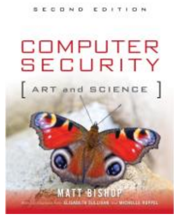
- Create token (message) containing
  - Identity of principal (here, Alice)
  - Corresponding public key e_{Alice}
  - Timestamp (when issued)
  - Other information (perhaps identity of signer)

  signed by trusted authority (here, Cathy)

$$C_{\text{Alice}} = \{e_{\text{Alice}} \mid\mid \text{Alice} \mid\mid T\}\, d_{\text{Cathy}}$$

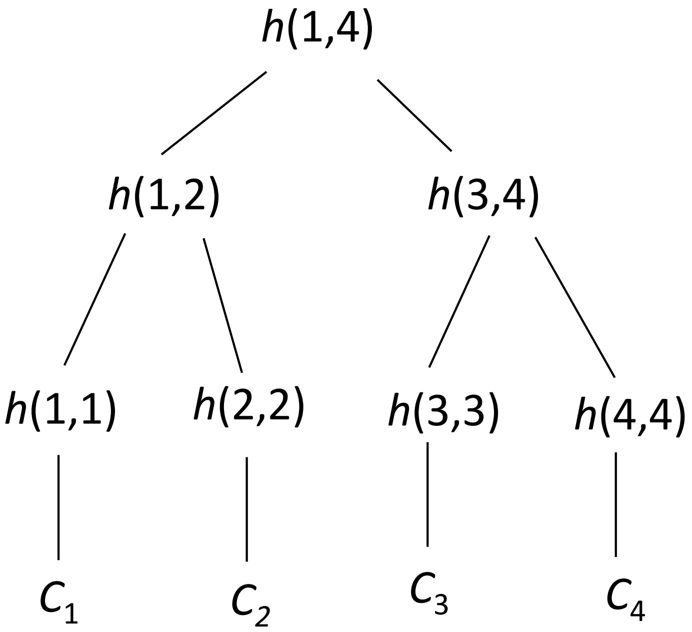
Use

- Bob gets Alice’s certificate
  - If he knows Cathy’s public key, he can decipher the certificate
    - When was certificate issued?
    - Is the principal Alice?
  - Now Bob has Alice’s public key
- Problem: Bob needs Cathy’s public key to validate certificate
  - Problem pushed “up” a level
  - Two approaches: Merkle’s tree, signature chains

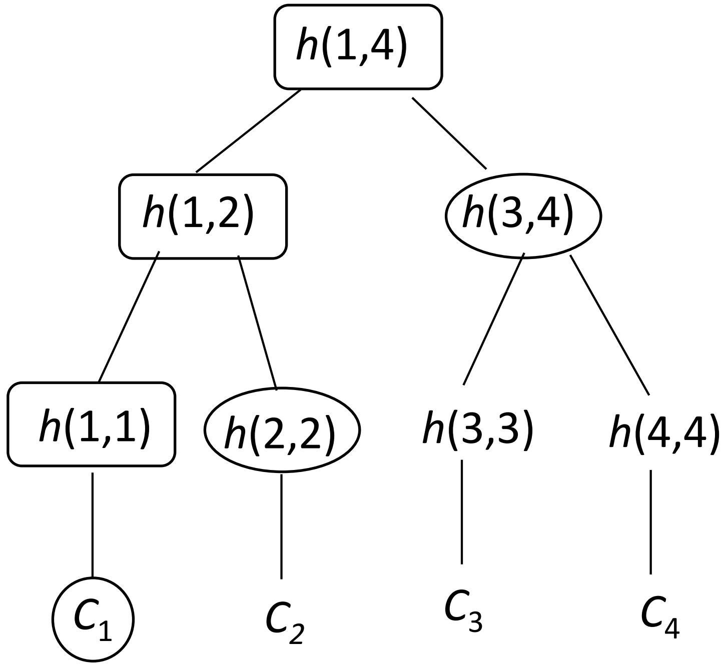


Merkle's Tree Scheme

- Keep certificates in a file
  - Changing any certificate changes the file
  - Use crypto hash functions to detect this
- Define hashes recursively
  - *h* is hash function
  - C_i is certificate *i*
- Hash of file (*h*(1,4) in example) known to all



Validation



- To validate C_1:
  - Compute $h(1, 1)$
  - Obtain $h(2, 2)$
  - Compute $h(1, 2)$
  - Obtain $h(3, 4)$
  - Compute $h(1,4)$
  - Compare to known $h(1, 4)$
- Need to know hashes of children of nodes on path that are not computed
- In drawing at left:
  - Circle contains what is to be validated
  - Ovals are what are to be obtained
  - Curved rectangles are what are to be computed

Details

- f: $D \times D \rightarrow D$ maps bit strings to bit strings
- h: $N \times N \rightarrow D$ maps integers to bit strings
  - if $i \geq j$, $h(i, j) = f(C_i, C_j)$
  - if $i < j$, $h(i, j) = f(h(i, \lfloor (i+j)/2 \rfloor), h(\lfloor (i+j)/2 \rfloor + 1, j))$

Problem

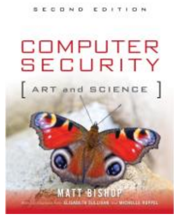
- File must be available for validation
  - Otherwise, can't recompute hash at root of tree
  - Intermediate hashes would do
- Not practical in most circumstances
  - If any public key changed, validation fails unless tree is updated
  - This includes compromised certificates as well as legitimate public key changes
  - If copies of tree are widely distributed, a change to one must be reflected by all

Certificate Signature Chains

- Create certificate
  - Generate hash of certificate
  - Encipher hash with issuer's private key
- Validate
  - Obtain issuer's public key
  - Decipher enciphered hash
  - Recompute hash from certificate and compare
- Problem: getting issuer's public key

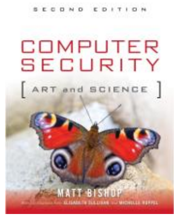
X.509 Chains

- Some certificate components in X.509v3:
  - Version
  - Serial number
  - Signature algorithm identifier: hash algorithm
  - Issuer’s name; uniquely identifies issuer
  - Interval of validity
  - Subject’s name; uniquely identifies subject
  - Subject’s public key
  - Signature: enciphered hash



X.509 Certificate Validation

- Obtain issuer’s public key
  - The one for the particular signature algorithm
- Decipher signature
  - Gives hash of certificate
- Recompute hash from certificate and compare
  - If they differ, there’s a problem
- Check interval of validity
  - This confirms that certificate is current



Issuers

- *Certification Authority* (*CA*): entity that issues certificates
  - Multiple issuers pose validation problem
  - Alice's CA is Cathy; Bob's CA is Don; how can Alice validate Bob's certificate?
  - Have Cathy and Don cross-certify by issuing certificates for each other

Validation and Cross-Certifying

- Notation: *X*<<*Y*>> means *X* issues certificate for *Y*
- Certificates:
  - Cathy<<Alice>>
  - Dan<<Bob>
  - Cathy<<Dan>>
  - Dan<<Cathy>>
- Alice validates Bob's certificate
  - Alice obtains Cathy<<Dan>>
  - Alice uses (known) public key of Cathy to validate Cathy<<Dan>>
  - Alice uses Cathy<<Dan>> to validate Dan<<Bob>>

PGP Chains

- OpenPGP certificates structured into packets
  - One public key packet
  - Zero or more signature packets
- Public key packet:
  - Version (3 or 4; 3 compatible with all versions of PGP, 4 not compatible with older versions of PGP)
  - Creation time
  - Validity period (present in version 3 only)
  - Public key algorithm, associated parameters
  - Public key

OpenPGP Signature Packet

- Version 3 signature packet
  - Version (3)
  - Signature type (level of trust)
  - Creation time (when next fields hashed)
  - Signer’s key identifier (identifies key to encipher hash)
  - Public key algorithm (used to encipher hash)
  - Hash algorithm
  - Part of signed hash (used for quick check)
  - Signature (enciphered hash)
- Version 4 packet more complex

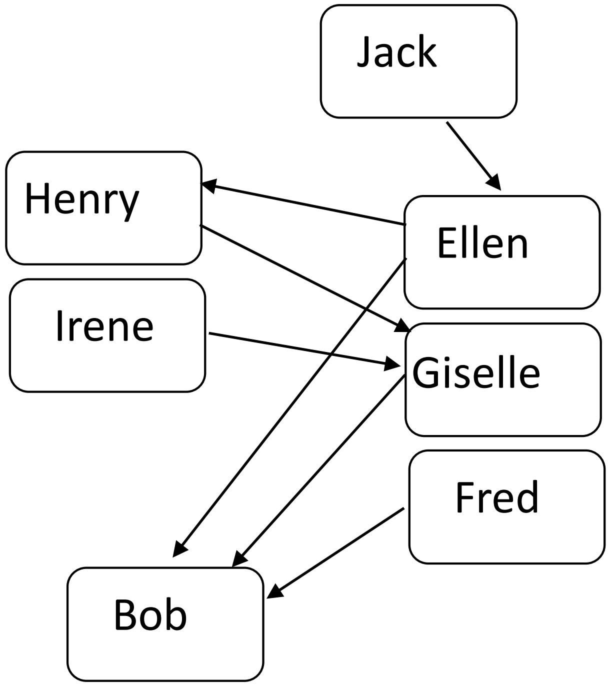
Signing

- Single certificate may have multiple signatures
- Notion of “trust” embedded in each signature
  - Range from “untrusted” to “ultimate trust”
  - Signer defines meaning of trust level (no standards!)
- All version 4 keys signed by the subject of the certificate
  - Called “self-signing”
  - Version 3 certificates can be too

Validating Certificates

- Alice needs to validate Bob's OpenPGP cert
    - Does not know Fred, Giselle, or Ellen
- Alice gets Giselle's cert
    - Knows Henry slightly, but his signature is at "casual" level of trust
- Alice gets Ellen's cert
    - Knows Jack, so uses his cert to validate Ellen's, then hers to validate Bob's

Arrows show signatures
Self signatures not shown



Public Key Infrastructures (PKIs)

- An infrastructure that manages public keys and certificate authorities
  - This includes registration authorities and other entities involved in creating and issuing certificates

Internet X.509 PKI

- *End entity certificate*: a certificate issued to entities not authorized to issue certificates
- *Certificate authority certificate*: a certificate issued to a CA
  - *Self-issued*: issuer, subject are the same entity
  - *Self-signed*: self-issued certificate in which public key in certificate can be used to validate that certificate's digital signature
- *Trust anchor*: CA that begins a certificate signature chain
- *Cross-certificate*: certificate for one CA issued by another CA
- *Registration authority*: entity delegated the registration task by a CA
  - CA trusts RA to properly identify, authenticate, validate entity

Certificate Extensions

- Critical: mandatory accept or reject, depending on content
  - If application can’t recognize or process it, certificate rejected
- Non-critical: can be ignored if unrecognized
- All conforming CAs must support the following:
  - Authority key identifier: identifies public key used to validate certificate’s digital signature
    - Must not be marked critical
  - Subject key identifier: same value of authority key field, but if subject is CA, this must be present
    - Must not be marked critical

CA Certificate Extension Support

- All conforming CAs must support the following:
  - Key usage: describes purposes for which public key can be used
    - If certificate used to validate digital signatures on certificates, must be present
    - Should be marked critical
  - Basic constraints: identifies whether subject is CA if the certificate can be used to validate another certificate’s digital signature, number of intermediate certificates that may follow this one in a chain and that are not self-signed
    - Must be critical if certificate used to validate digital signatures of certificates
    - May be critical or non-critical otherwise
  - Certificate policies: describes policy under which certificate is issued and what it can be used for
    - Should be marked critical

CA Certificate Extensions

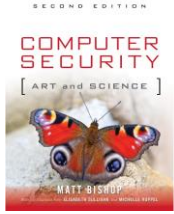
- Authority key identifier eliminates need to try different keys of issuing CA to determine whether certificate valid
  - In earlier versions of Internet PKI, this also indicated applicable policy
  - Key usage, certificate policy extensions now do this explicitly
- Key usage makes clear what public key is to be used for
  - Before, assumed valid for any purpose, or embedded in issuer's policy
- Basic constraints limits length of certificate chain beginning here
  - Doesn't include self-signed certificates

Conforming Applications Certificate Extensions

- Conforming applications that process certificates must recognize:
  - *Key usage*, *certificate policies*, *basic constraints* extensions
  - *Subject alternative name*: another name for subject; must be verified by CA or RA
    - Must be critical
  - *Name constraints*: constrains names in subject, subject alternative name of non-self-signed certificates following it in certificate chain
  - *Policy constraints*: controls when policy for chain containing this certificate must be explicit or when policy of issuer need not be same as that of subject
    - Must be critical

Conforming Applications Certificate Extensions

- Conforming applications that process certificates must recognize:
    - Extended key usage: issuer uses this to specify uses of public key beyond those in the key usage extension
    - Inhibit anyPolicy: wildcard (anyPolicy) matches policies only if it occurs in intermediate self-signed certificate in certificate chain
        - Must be critical
- Subject alternative name allows multiple subject names in certificate
    - Previous versions allowed only one subject name per certificate
- Extended key usage allows public key to be used in ways not identified in key usage



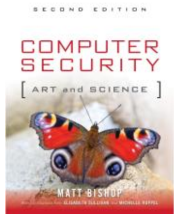
PKI Problems

Basis for any PKI is trust

- Trust that the binding of identity to public key is correct
  - Degree of confidence depends on CA or RA
- Trust that appropriate CA issued the certificate
  - Also that issuance policies are understood
  - Also that implementation of signing, and PKI mechanisms,
- Certificate does not embody authorization
  - Identity may, but that is external to PKI
- Trust that no 2 certificates will have same public (and hence private) key

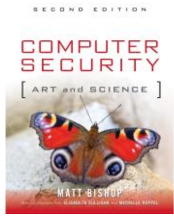
Storing Keys

- Multi-user or networked systems: attackers may defeat access control mechanisms
  - Encipher file containing key
    - Attacker can monitor keystrokes to decipher files
    - Key will be resident in memory that attacker may be able to read
  - Use physical devices like “smart card”
    - Key never enters system
    - Card can be stolen, so have 2 devices combine bits to make single key



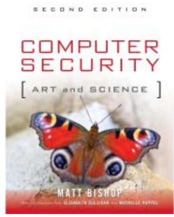
Key Escrow

- *Key escrow system* allows authorized third party to recover key
  - Useful when keys belong to roles, such as system operator, rather than individuals
  - Business: recovery of backup keys
  - Law enforcement: recovery of keys that authorized parties require access to
- Goal: provide this without weakening cryptosystem
- Very controversial



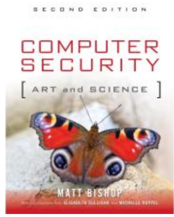
Desirable Properties

- Escrow system should not depend on encipherment algorithm
- Privacy protection mechanisms must work from end to end and be part of user interface
- Requirements must map to key exchange protocol
- System supporting key escrow must require all parties to authenticate themselves
- If message to be observable for limited time, key escrow system must ensure keys valid for that period of time only



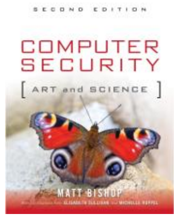
Components

- User security component
  - Does the encipherment, decipherment
  - Supports the key escrow component
- Key escrow component
  - Manages storage, use of data recovery keys
- Data recovery component
  - Does key recovery



Example: ESS, Clipper Chip

- Escrow Encryption Standard
  - Set of interlocking components
  - Designed to balance need for law enforcement access to enciphered traffic with citizens’ right to privacy
- Clipper chip prepares per-message escrow information
  - Each chip numbered uniquely by UID
  - Special facility programs chip
- Key Escrow Decrypt Processor (KEDP)
  - Available to agencies authorized to read messages

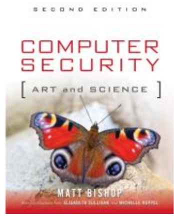


User Security Component

- Unique device key k_{unique}
- Non-unique family key k_{family}
- Cipher is Skipjack
  - Classical cipher: 80 bit key, 64 bit input, output blocks
- Generates Law Enforcement Access Field (LEAF) of 128 bits:
  - $\{ \text{UID} \mid\mid \{ k_{session} \} k_{unique} \mid\mid \mathit{hash} \} k_{family}$
  - *hash*: 16 bit authenticator from session key and initialization vector

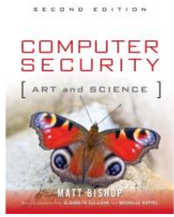
Programming User Components

- Done in a secure facility
- Two escrow agencies needed
  - Agents from each present
  - Each supplies a random seed and key number
  - Family key components combined to get k_{family}
  - Key numbers combined to make key component enciphering key k_{comp}
  - Random seeds mixed with other data to produce sequence of unique keys k_{unique}
- Each chip imprinted with UID, k_{unique}, k_{family}



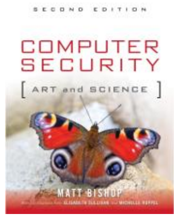
The Escrow Components

- During initialization of user security component, process creates k_{u1} and k_{u2} where $k_{unique} = k_{u1} \oplus k_{u2}$
  - First escrow agency gets $\{ k_{u1} \} k_{comp}$
  - Second escrow agency gets $\{ k_{u2} \} k_{comp}$



Obtaining Access

- Alice obtains legal authorization to read message
- She runs message LEAF through KEDP
  - LEAF is { UID || { $k_{session}$ } k_{unique} || *hash* } k_{family}
- KEDP uses (known) k_{family} to validate LEAF, obtain sending device's UID
- Authorization, LEAF taken to escrow agencies



Agencies’ Role

- Each validates authorization
- Each supplies $\{ k_{ui} \} k_{comp}$, corresponding key number
- KEDP takes these and LEAF:
  - Key numbers produce k_{comp}
  - k_{comp} produces k_{u1} and k_{u2}
  - k_{u1} and k_{u2} produce k_{unique}
  - k_{unique} and LEAF produce $k_{session}$

Problems

- *hash* too short; LEAF 128 bits, so given a hash:
  - 2^{112} LEAFs show this as a valid hash
  - 1 has actual session key, UID
  - Easy to generate a LEAF with a valid hash but meaningless session key and UID
    - Turns out deployed devices would prevent this attack
- Scheme does not meet temporal requirement
  - As k_{unique} fixed for each unit, once message is read, any future messages can be read

Yaksha Security System

- Key escrow system meeting all 5 criteria
- Based on RSA, central server
  - Central server (Yaksha server) generates session key
- Each user has 2 private keys
  - Alice's modulus n_A, public key e_A
  - First private key d_{AA} known only to Alice
  - Second private key d_{AY} known only to Yaksha central server
  - $d_{AA}\, d_{AY} \bmod \phi(n_A) = d_A$

Alice and Bob

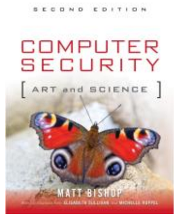
- Alice wants to send message to Bob
  - Alice asks Yaksha server for session key
  - Yaksha server generates $k_{session}$
  - Yaksha server sends Alice the key as:

    $C_A = (k_{session})^{d_{AY} e_A} \bmod n_A$
  - Alice computes

    $(C_A)^{d_{AA}} \bmod n_A = k_{session}$

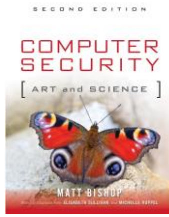
Analysis

- Authority can read only one message per escrowed key
  - Meets requirement 5 (temporal one), because “time” interpreted as “session”
- Independent of message enciphering key
  - Meets requirement 1
  - Interchange algorithm, keys fixed
- Others met by supporting infrastructure



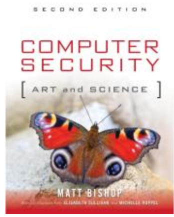
Alternate Approaches

- Tie to time
  - Session key not given as escrow key, but related key is
  - To derive session key, must solve instance of discrete log problem
- Tie to probability
  - Oblivious transfer: message received with specified probability
  - Idea: *translucent cryptography* allows fraction *f* of messages to be read by third party
  - Not key escrow, but similar in spirit



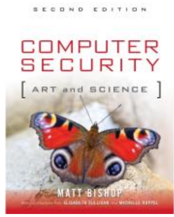
Identity-Based Encryption

- Party has a publicly known identifier as public key
- Trusted third party uses (or provides) a secret to use with public key to derive private key
  - Trusted third party can derive private key as it knows secret, public key
  - Others cannot as they do not know secret
  - Can be used as escrow system, with third party as escrow agent



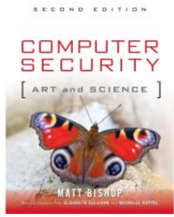
Identity-Based Encryption

- Properties public key cryptosystems must meet (Shamir):
  - Private keys can be easily computed from public key and secret *s*
  - Computationally infeasible to compute private key from public key without knowing *s*
- Shamir showed RSA cannot satisfy both conditions simultaneously
- Boneh and Franklin’s method meets these conditions
  - Can be augmented to provide “global escrow” keys to decrypt any ciphertext encrypted using public keys of their system



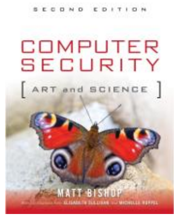
Key Revocation

- Certificates invalidated *before* expiration
  - Usually due to compromised key
  - May be due to change in circumstance (*e.g.,* someone leaving company)
- Problems
  - Entity revoking certificate authorized to do so
  - Revocation information circulates to everyone fast enough
    - Network delays, infrastructure problems may delay information



CRLs

- *Certificate revocation list* lists certificates that are revoked
- X.509: only certificate issuer can revoke certificate
  - Added to CRL
- PGP: signers can revoke signatures; owners can revoke certificates, or allow others to do so
  - Revocation message placed in PGP packet and signed
  - Flag marks it as revocation message



Key Points

- Key management critical to effective use of cryptosystems
  - Different levels of keys (session *vs*. interchange)
- Keys need infrastructure to identify holders, allow revoking
  - Key escrowing complicates infrastructure