Basics of Cryptography, Cryptoprotocols, and Steganography

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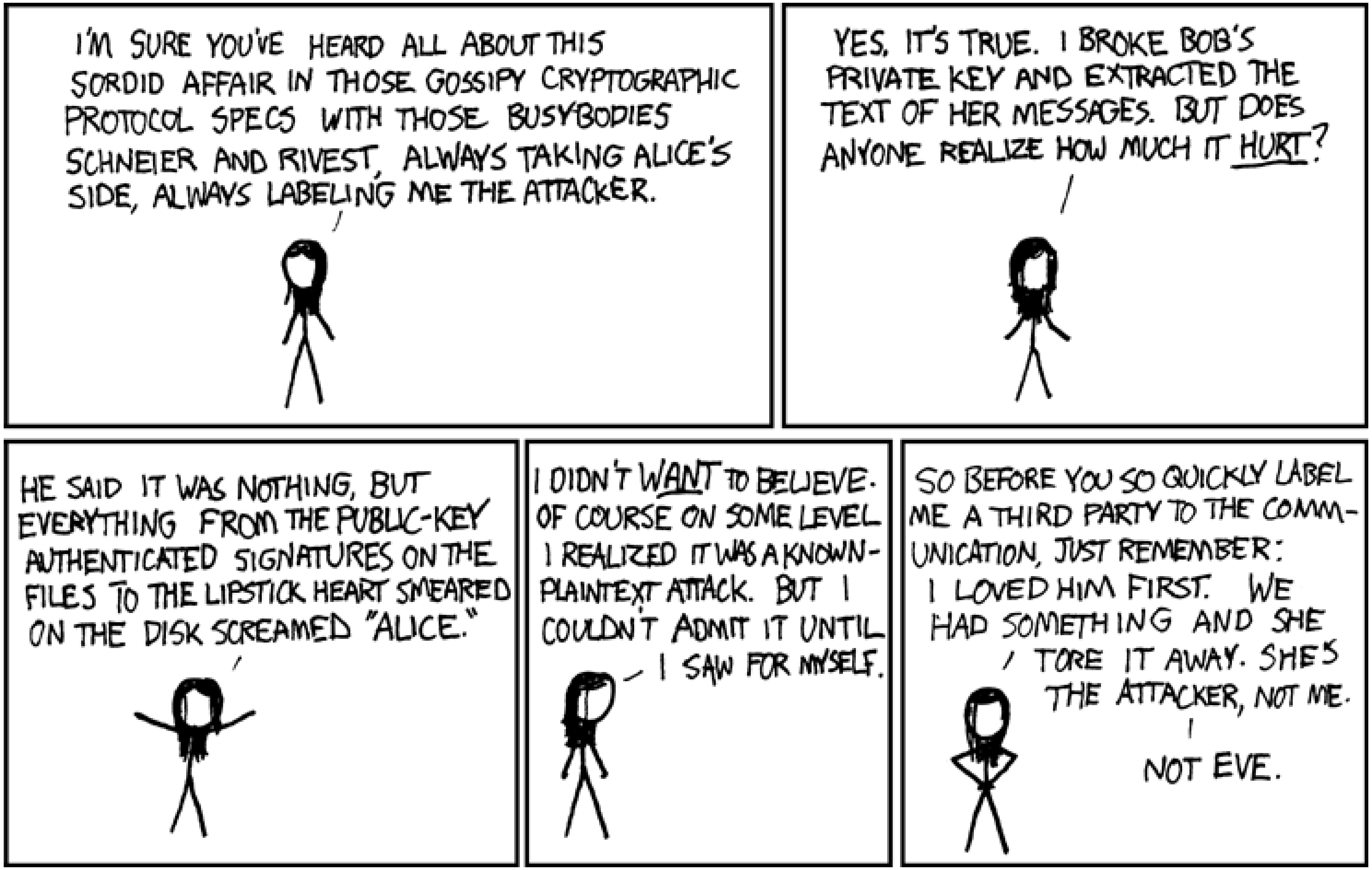
Security Requirements

- Alice wants to send a message to Bob. Moreover, Alice wants to send the message securely: Alice wants to make sure Eve cannot read the message."
  - [Adapted from Schneier, *Applied Cryptography*, 2nd edition, 1996]
- Exercise 1. Draw a picture of this scenario.
- Exercise 2. Discuss Alice's security requirements, using the terminology developed to date in CompSci 725.
- Exercise 3. In this scenario, Alice is the sender, Bob is the receiver, and Eve is the eavesdropper. Name another actor with an important role in communication security.
  - Sample answers are widely available on the internet, see e.g. http://en.wikipedia.org/wiki/Alice_and_Bob.



Alice and Bob

http://xkcd.com/177/ (Creative Commons 2.5 licence)

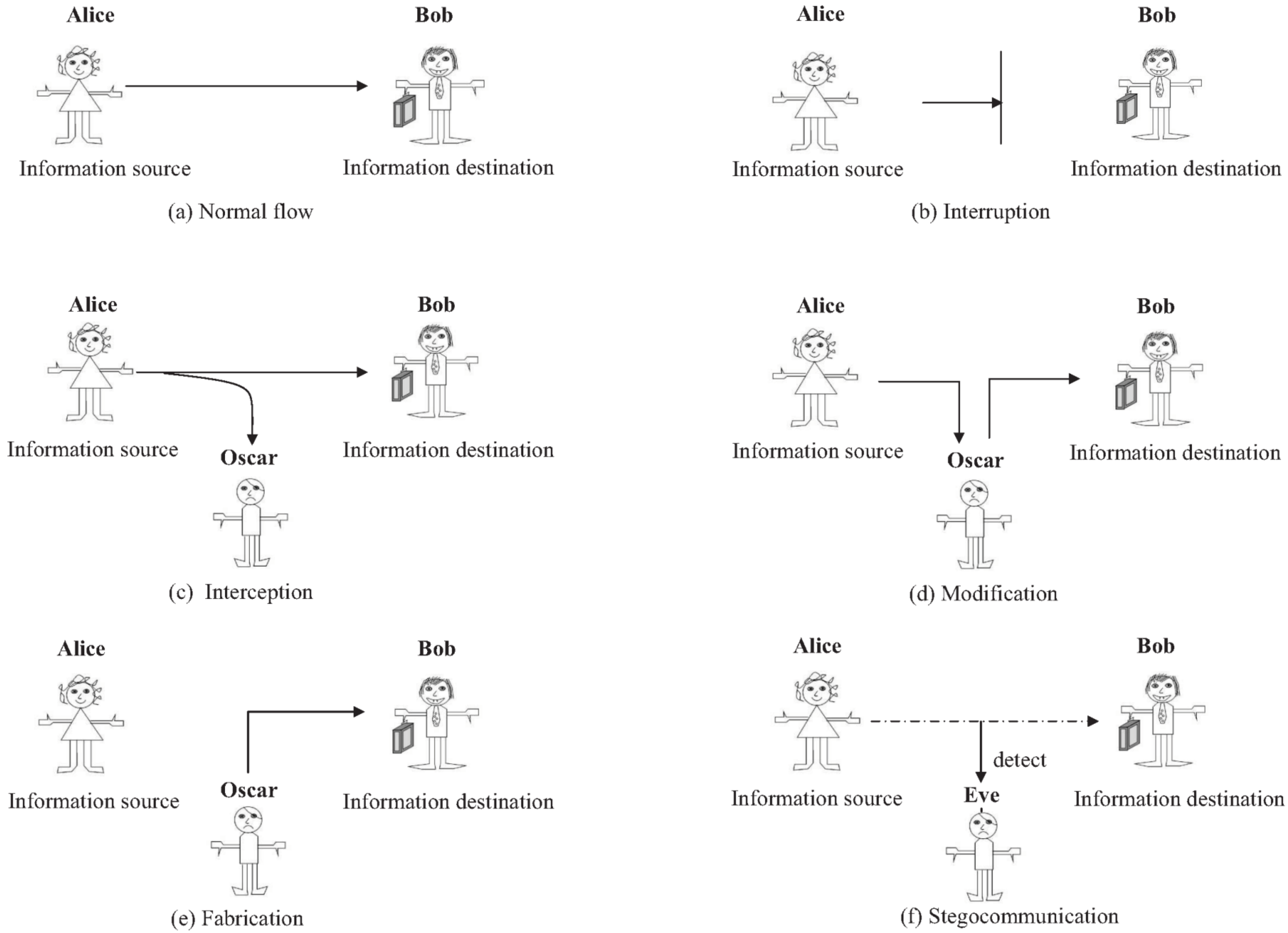


Fig. 1. Normal message flow, and five fundamental threats to this flow.

From "A Security Model for VoIP Steganography", by Yu, Thomborson et al., DOI 10.1109/MINES.2009.227, 2009.

An Attack Taxonomy for Communication Systems

1. *Interception* (attacker reads the message)
2. *Interruption* (attacker prevents delivery)
3. *Modification* (attacker changes the message)
4. *Fabrication* (attacker injects a message)
   a) *Impersonation* (attacker pretends to be a legitimate sender or receiver, e.g. this is either a fabrication or an interruption)
5. *Stegocommunication* (Alice and Bob make surreptitious use of a communication system; Eve wears a "white hat")
6. *Repudiation* (a black-hat Alice falsely asserts she did not send a message to Bob, or a black-hat Bob falsely asserts that he didn't receive a message from Alice); white-hat Judy is the judge.

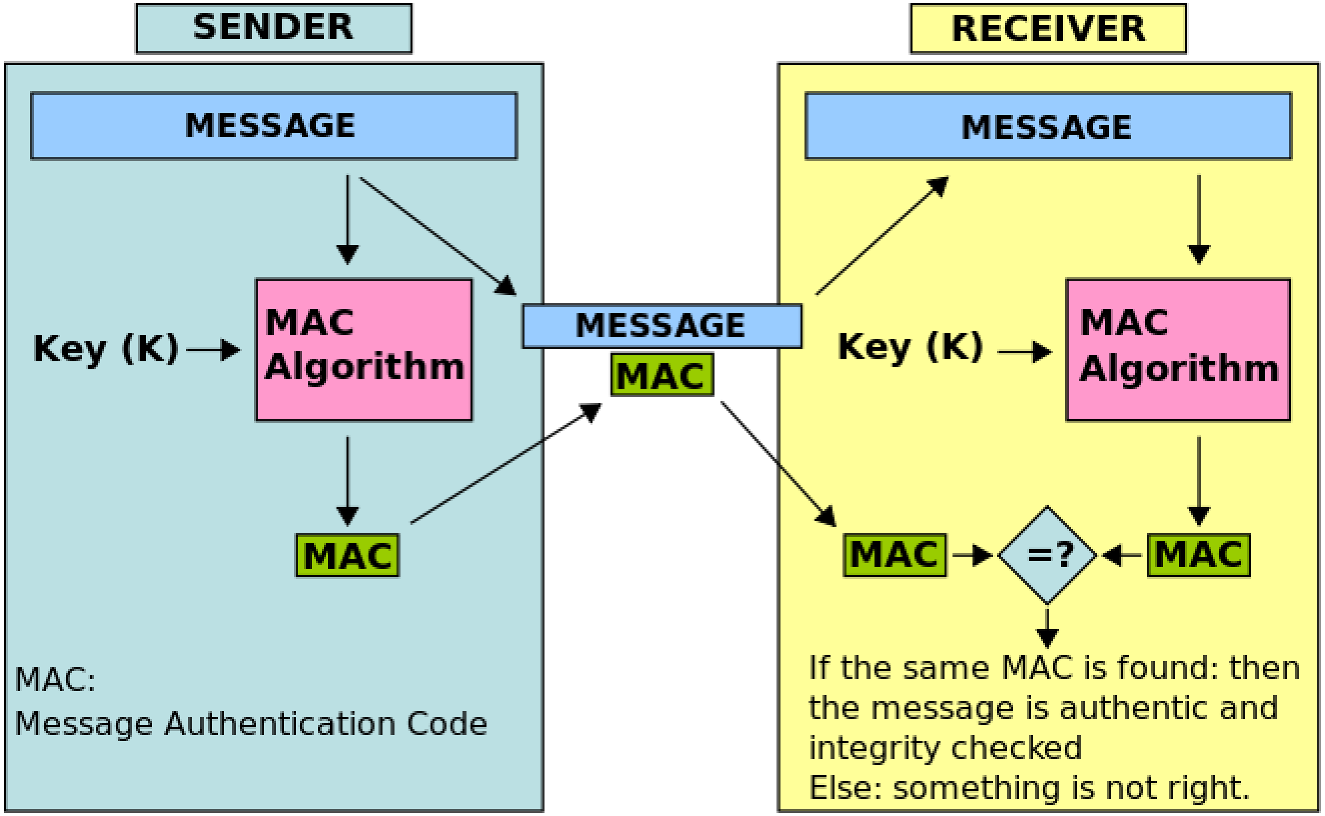
Symmetric and Public-Key Encryption

- If the decryption key `d` can be computed from the encryption key `e`, then the algorithm is called *symmetric*.
  - Example: `E(p) = (p + e) mod 256` is a symmetric (and very weak) encryption of a char `p`, because `D(x) = (x + d) mod 256` is a decryptor when `d = 256 - e`.
- If the decryption key cannot be feasibly computed from the encryption key, then the algorithm is called *asymmetric* or *public-key*.

Message Integrity

- Encryption assures confidentiality
  - Assume: the attacker can't discover the key or "crack" the cypher.
- Integrity can also be assured by message codes.
- Sending a plaintext message, plus its Message Authentication Code (MAC), will ensure message integrity to anyone who knows the (shared) secret key.
  - The CBC-MAC is the last ciphertext block from a CBC-mode block cipher.
  - Changing any message bit will change the MAC – this defends against modification.
  - Unless you know the secret key, you can't compute a MAC from the plaintext – this defends against fabrication.
- Keyed hashes (HMACs) are another popular type of MAC.
  - SHA-1 and MD5 are used in SSL
  - To learn more, read Stamp's *Information Security*, 2nd Edition, Wiley, 2011, at pp. 136-7.

MAC



http://en.wikipedia.org/wiki/Message_authentication_code

Public Key Cryptography

Encryption E: $Plaintext \times EncryptionKey \rightarrow Cyphertext$

Decryption D: $Cyphertext \times DecryptionKey \rightarrow Plaintext$

- The sender must know the encryption key.
- The receiver can decrypt, if they know the decryption key.
- In *public-key cryptography*, we use key-pairs (***s***, ***p***), where our secret key ***s*** cannot be computed efficiently (as far as anyone knows) from our public key ***p*** and our encrypted messages.
  - The algorithms (E, D) are standardized.
  - We let everyone know our public key ***p***.
  - We don't let anyone else know our corresponding secret key ***s***.
  - Anybody can send us encrypted messages using E(*, ***p***).
  - Convenient notation: $\{P\}_{\mathbf{Alice}}$ is plaintext P that has been encrypted by a secret key named "Alice". [Stamp, pp. 89-91, 323]

Authentication in PK Cryptography

- We can use a secret key ***s*** to encrypt a message which everyone can decrypt using our corresponding public key ***p***.
  - $E(P, \mathbf{s})$ is a "signed message". Simpler notation: $[P]_{\mathbf{Alice}}$
  - Only people who know the secret key named "Alice" can create this signature.
  - Anyone who knows the public key for "Alice" can validate this signature.
  - This defends against impersonation and repudiation attacks.
- If you use a key-pair (***s***, ***p***) for encryption, then you can't use it safely for signing!
  - Do you understand why?

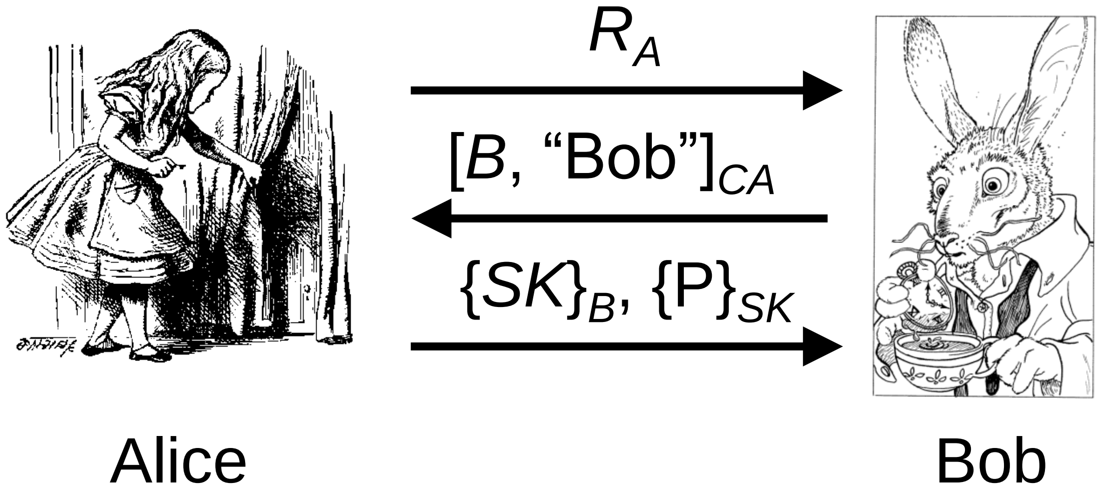
Key Management & Distribution

- We should use many different public/private key pairs:
  - For our email,
  - For our bank account (our partner knows this private key too),
  - For our workgroup (shared with other members), …
- A "public key infrastructure" (PKI) will help us create, publicise, and discover public keys ($\boldsymbol{p_1}$, $\boldsymbol{p_2}$, …).
- A "certificate authority" (CA) is a registry for public keys – this is an important part of a PKI..
  - The CA uses one of its signing keys to sign a "certificate" of the form $[name, p]_{\mathrm{CA}}$.
  - Anyone who knows the CA's corresponding public key can verify that *p* was registered by someone who convinced the CA that they are identified by *name*.
  - Note: we also need some way to discover CAs and their keys… our web browsers help with this…

Some Security Issues with CAs

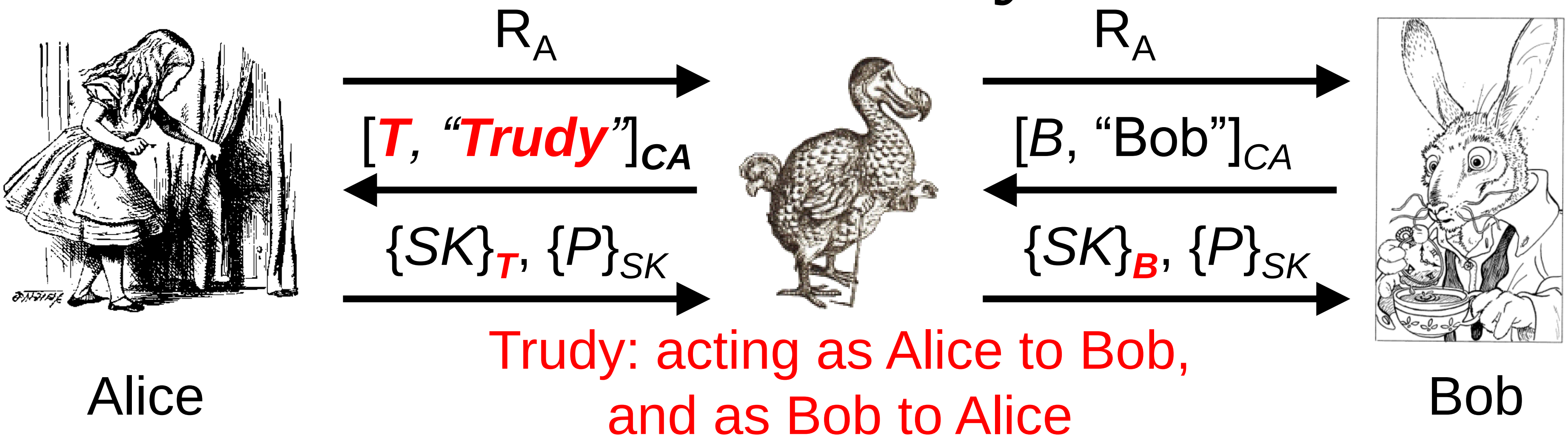
- The *name* in a certificate might not be a unique identifier for a person or an organisation – there are many people named “John Doe”.
- A CA might register a key to an impersonator.
- The end-user might not inspect the certificate to confirm that
  - *name* is a (reasonably) unique identifier for the person or organisation they are trying to communicate with.

A Simple Cryptographic Protocol



1. Alice sends a service request R_A to Bob.
2. Bob replies with his digital certificate.
   - Bob's certificate contains Bob's public key *B* and Bob's name.
   - This certificate was signed by a Certificate Authority, using a public key *CA* which Alice already knows.
3. Alice creates a symmetric key *SK*. This is a "session key".
   - Alice sends *SK* to Bob, encrypted with public key *B*.
   - Alice and Bob will use *SK* to encrypt their plaintext messages.

Protocol Analysis



- How can Alice detect that Trudy is "in the middle"?
- What does your web-browser do, when it receives a digital certificate that says "Trudy" instead of "Bob"?
- Trudy's certificate might be [T, "Bob"]$_{CA'}$
  - If you follow a URL to "https://www.bankofamerica.org", your browser might form an SSL connection with a Nigerian website which spoofs the website of a legitimate bank, or a <u>website controlled by a disgruntled BoA customer</u>.
- Have you ever inspected an SSL certificate?

Attacks on Cryptographic Protocols

- A ciphertext may be broken by…
  - Discovering the “restricted” algorithm (if the algorithm doesn’t require a key).
  - Discovering the key by non-cryptographic means (bribery, theft, ‘just asking’).
  - Discovering the key by “brute-force search” (through all possible keys).
  - Discovering the key by cryptanalysis based on other information, such as known pairs of (plaintext, ciphertext).
- The weakest point in the system may not be its cryptography!
  - See Ferguson & Schneier, *Practical Cryptography*, 2003.
  - For example: you should consider what identification was required, when a CA accepted a key, before you accept any public key from that CA as a “proof of identity”.

Limitations and Usage of PKI

- If a Certificate Authority is offline, or if you can’t be bothered to wait for a response, you will use the public keys stored in your local computer.
  - Warning: a public key may be revoked at any time, e.g. if someone reports their key was stolen.
- Key Continuity Management is an alternative to CAs.
  - The first time someone presents a key, *you* decide whether or not to accept it.
  - When someone presents a key that you have accepted previously, it’s ok to accept it again if you haven’t had any bad experiences with that key,
  - If someone presents a changed key, you should think carefully before accepting!
  - This idea was introduced in SSH, in 1996. It was named, and identified as a general design principle, by Peter Gutmann (http://www.cs.auckland.ac.nz/~pgut001/).
  - Reference: Simson Garfinkel, in http://www.simson.net/thesis/pki3.pdf

Identification and Authentication

- You can authenticate your identity to a local machine by
  - what you have (e.g. a smart card),
  - what you know (e.g. a password),
  - what you "are" (e.g. your thumbprint or handwriting)
- After you have authenticated yourself locally, then you can use cryptographic protocols to…
  - … authenticate your outgoing messages (if others know your public key);
  - … verify the integrity of your incoming messages (if you know your correspondents' public keys);
  - … send confidential messages to other people (if you know their public keys).
  - Warning: you (and others) must trust the operations of your local machine! We'll return to this subject…

Steganography

- The art of sending undetectable messages.
  - The primary goal of the wardens is detection of stegocommunication.
  - The primary goal of the prisoners is availability.
  - It's up to the analyst to decide the colours of the hats!
    - Steganography, like cryptography, may be used by black-hats or white-hats.
- Steganography is *complementary* to cryptography.
  - Using strong cryptography, Alice and Bob achieve confidentiality and integrity.
  - Alice and Bob should use steganography if they're worried about availability or traffic analysis.
    - Cryptographic communications are "obviously" encrypted.
  - If warden Walter can't understand what Alice is saying…
    - Should he punish Alice for sending an encrypted message?
    - Should he prevent Alice's encrypted message from reaching Bob?
    - Should he carefully watch Bob, after allowing him to read the message?

Wardens and Prisoners

- "On July 17 [1965], a prisoner [in Mt Eden Prison] asked a guard to pass a newspaper to another prisoner in another cell.
- "The guard found a coded note in its pages.
  - Unable to decipher the message he simply copied it for the file.
- "Inexplicably, he then delivered the newspaper and its mysterious contents.
  - If that note had been successfully read, what occurred next would have been avoided.
  - … The prisoners began smashing up the central office and set it on fire at the same time other prisoners were being unlocked.
  - What the *Herald* would later call a 'wild orgy of destruction' ensured firefighters entering the jail were forced to retreat. …"

["The night all hell broke loose at Mt Eden Prison", NZ Herald, 28 July 2015]

Watermarking, Tamper-Proofing and Obfuscation – Tools for Software Protection

Christian Collberg & Clark Thomborson

IEEE Transactions on Software Engineering 28:8, 735-746, August 2002.

DOI: 10.1109/TSE.2002.1027797

Watermarking and Fingerprinting

Watermark: an additional message, embedded into a cover message.

- Messages may be images, audio, video, text, executables, …
- Visible or invisible (steganographic) embeddings
- Robust (difficult to remove) or fragile (guaranteed to be removed) if cover is distorted.
- Watermarking (only one extra message per cover) or fingerprinting (different versions of the cover carry different messages).

Our Desiderata for (Robust, Invisible) SW Watermarks

- Watermarks should be stealthy -- difficult for an adversary to locate.
- Watermarks should be resilient to attack -- resisting attempts at removal even if they are located.
- Watermarks should have a high data-rate -- so that we can store a meaningful message without significantly increasing the size of the object.

Attacks on Watermarks

- **Subtractive** attacks: remove the watermark (WM) without damaging the cover.
- **Additive** attacks: add a new WM without revealing “which WM was added first”.
- **Distortive** attacks: modify the WM without damaging the cover.
- **Collusive** attacks: examine two fingerprinted objects, or a watermarked object and its unwatermarked cover; find the differences; construct a new object without a recognisable mark.

Defenses for Robust Software Watermarks

- **Obfuscation**: we can modify the software, so that a reverse engineer will have great difficulty figuring out how to reproduce the cover without also reproducing the WM.
- **Tamperproofing**: we can add integrity-checking code that (almost always) renders it unusable if the object is modified.

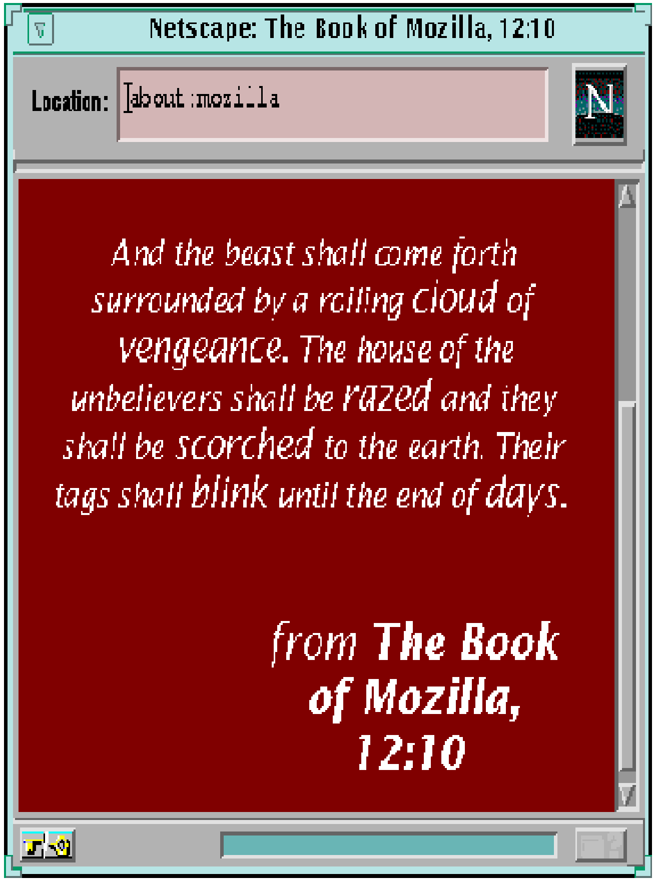
Classification of Software Watermarks

- Static code watermarks are stored in the section of the executable that contains instructions.
- Static data watermarks are stored in other sections of the executable.
- ☞ Dynamic data watermarks are stored in a program's execution state. Such watermarks are resilient to distortive (obfuscation) attacks.

Dynamic Watermarks

- **Easter Eggs** are revealed to any end-user who types a special input sequence.
- **Execution Trace Watermarks** are carried (steganographically) in the instruction execution sequence of a program, when it is given a special input.
- ☞ **Data Structure Watermarks** are built (steganographically) by a program, when it is given a special input sequence (possibly null).

Easter Eggs

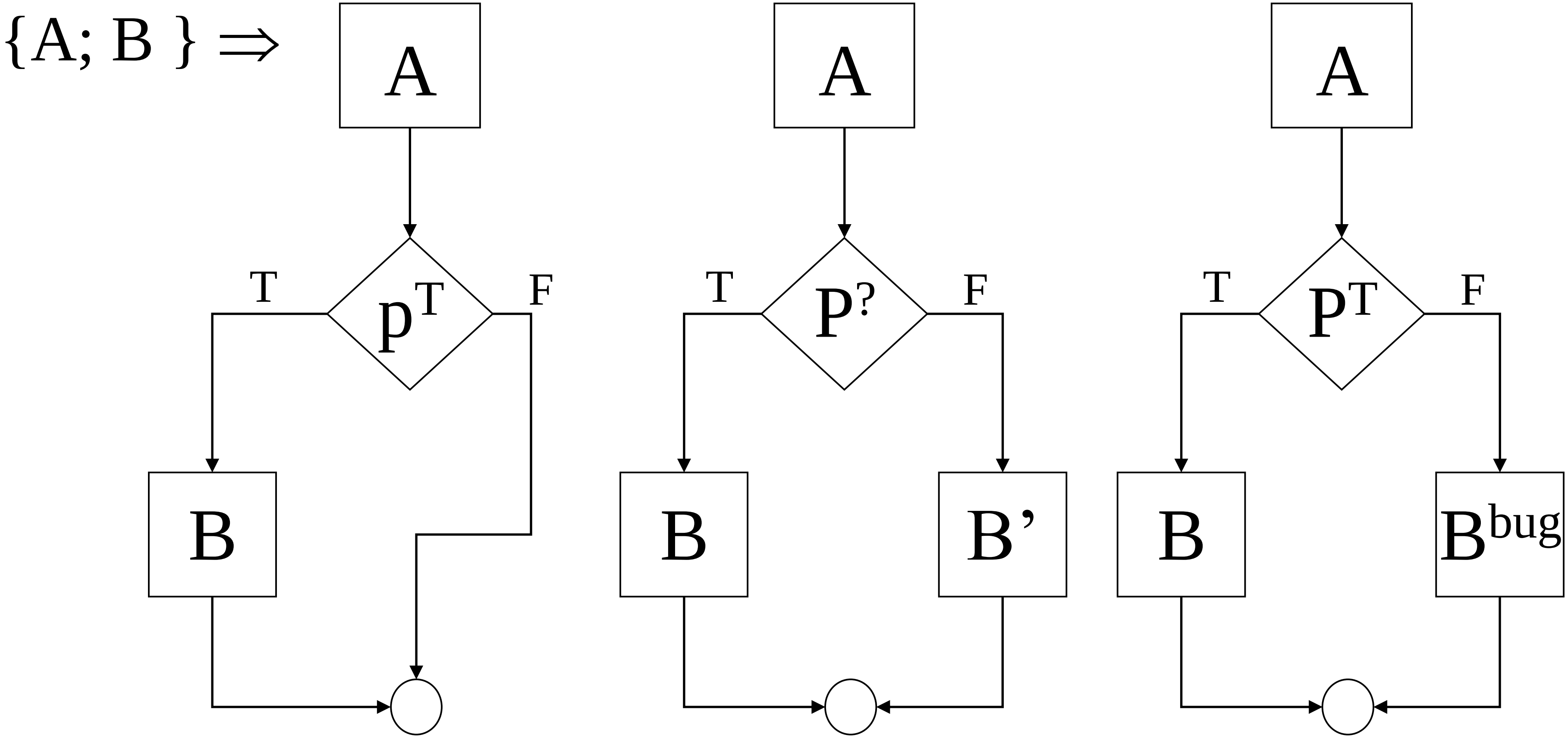


- The watermark is visible -- if you know where to look!
- Not resilient, once the secret is out.
- See www.eeggs.com

Software Obfuscation

- Many authors, websites and even a few commercial products offer "automatic obfuscation" as a defense against reverse engineering.
- Existing products generally operate at the lexical level of software, for example by removing or scrambling the names of identifiers.
- We were the first (in 1997) to use "opaque predicates" to obfuscate the control structure of software.

Opaque Predicates



"always true" "indeterminate" "tamperproof"

("always false" is not shown)

Conclusion

- Software obfuscation can make it more difficult for pirates to defeat standard tamperproofing mechanisms, or to engage in other forms of reverse engineering.
- Software watermarking can embed "ownership marks" in software, making it difficult for anyone to be sure that they have "removed all the marks".
- Software steganography is immature:
  - More R&D is required before robust obfuscating and watermarking tools will be easy to use.