CSE 484 / CSE M 584: Computer Security and Privacy

Cryptography:
Hash Functions, MACs (finish)
Asymmetric Cryptography (start)

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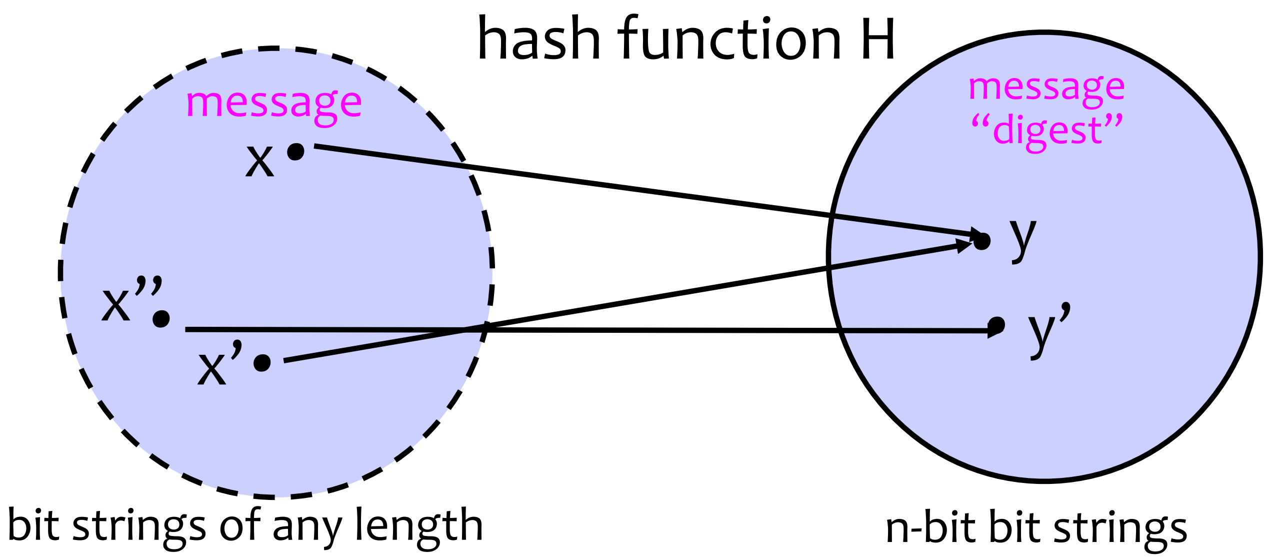
Hash Functions

Hash Functions: Main Idea



- Hash function H is a lossy compression function
  - Collision: h(x)=h(x') for distinct inputs x, x'
- H(x) should look "random"
  - Every bit (almost) equally likely to be 0 or 1
- <u>Cryptographic</u> hash function needs a few properties…

Property 1: One-Way

- Intuition: hash should be hard to invert
  - "Preimage resistance"
  - Let $h(x') = y \in \{0,1\}^n$ for a random x'
  - Given y, it should be hard to find any x such that h(x)=y
- How hard?
  - Brute-force: try every possible x, see if h(x)=y
  - SHA-1 (common hash function) has 160-bit output
    - Expect to try 2^{159} inputs before finding one that hashes to y.

Property 2: Collision Resistance

- Should be hard to find $x \neq x'$ such that $h(x)=h(x')$
- Birthday paradox means that brute-force collision search is only $O(2^{n/2})$, *not* $O(2^n)$
  - For SHA-1, this means $O(2^{80})$ vs. $O(2^{160})$

One-Way vs. Collision Resistance

- One-wayness does <u>not</u> imply collision resistance
  - Suppose g is one-way
  - Define h(x) as g(x’) where x’ is x except the last bit
    - h is one-way (to invert h, must invert g)
    - Collisions for h are easy to find: for any x, h(x0)=h(x1)
- Collision resistance does <u>not</u> imply one-wayness
  - Suppose g is collision-resistant
  - Define y=h(x) to be 0x if x is n-bit long, 1g(x) otherwise
    - Collisions for h are hard to find: if y starts with 0, then there are no collisions, if y starts with 1, then must find collisions in g
    - h is not one way: half of all y’s (those whose first bit is 0) are easy to invert (how?); random y is invertible with probab. ½

Property 3: Weak Collision Resistance

- Given randomly chosen x, hard to find x' such that h(x)=h(x')
  - Attacker must find collision for a specific x. By contrast, to break collision resistance it is enough to find any collision.
  - Brute-force attack requires $O(2^n)$ time
- Weak collision resistance does not imply collision resistance.

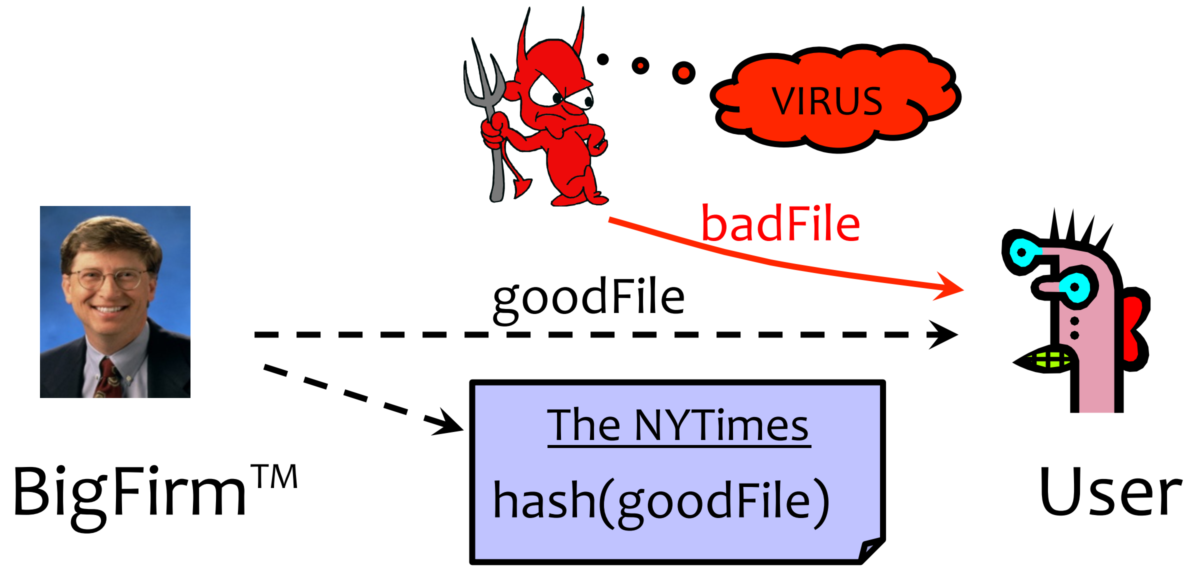
Hashing vs. Encryption

- Hashing is one-way. There is no "un-hashing"
  - A ciphertext can be decrypted with a decryption key… hashes have no equivalent of "decryption"
- Hash(x) looks "random" but can be compared for equality with Hash(x')
  - Hash the same input twice → same hash value
  - Encrypt the same input twice → different ciphertexts
- Crytographic hashes are also known as "cryptographic checksums" or "message digests"

Application: Password Hashing

- Instead of user password, store hash(password)
- When user enters a password, compute its hash and compare with the entry in the password file
  - System does not store actual passwords!
  - Cannot go from hash to password!
- Why is hashing better than encryption here?
- Does hashing protect weak, easily guessable passwords?

Application: Software Integrity



Goal: Software manufacturer wants to ensure file is received by users without modification.

Idea: given goodFile and hash(goodFile), very hard to find badFile such that hash(goodFile)=hash(badFile)

Which Property Do We Need?

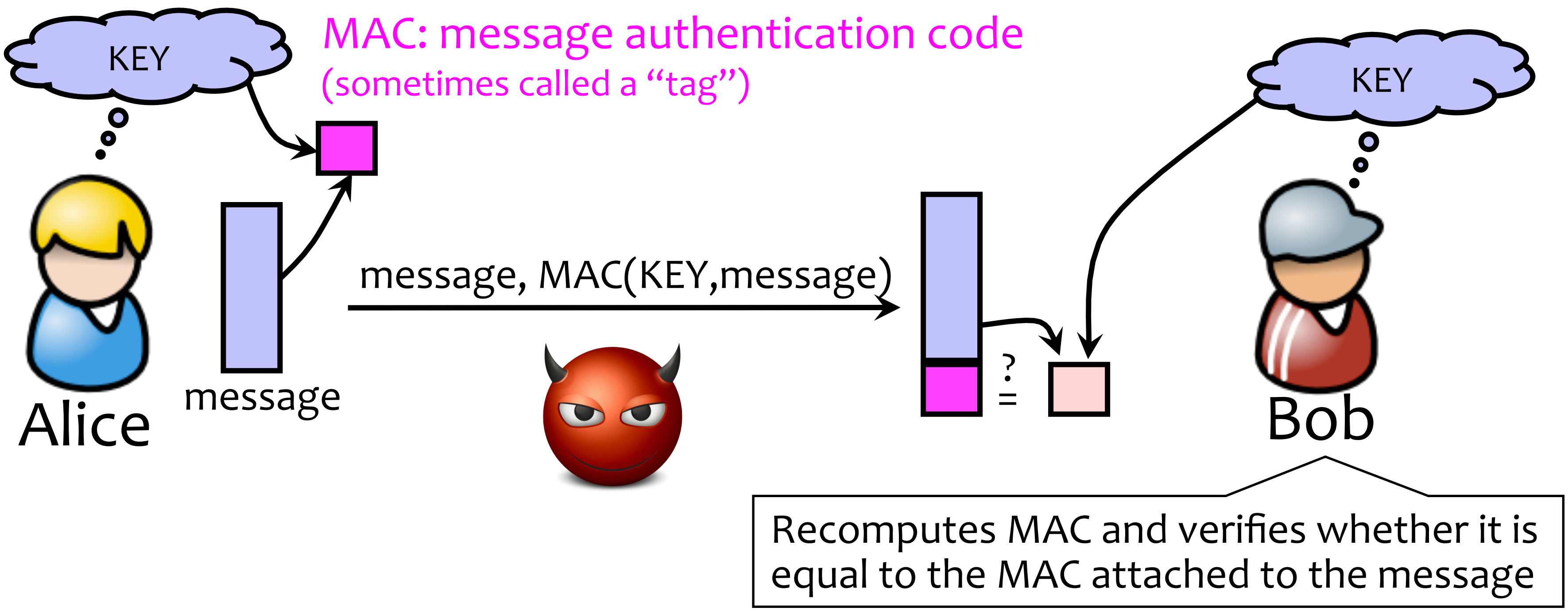
- UNIX passwords stored as hash(password)
  - One-wayness: hard to recover the/a valid password
- Integrity of software distribution
  - Weak collision resistance
  - But software images are not really random… may need full collision resistance if considering malicious developers
- Auction bidding
  - Alice wants to bid B, sends H(B), later reveals B
  - One-wayness: rival bidders should not recover B (this may mean that she needs to hash some randomness with B too)
  - Collision resistance: Alice should not be able to change her mind to bid B' such that H(B)=H(B')

Common Hash Functions

- MD5
  - 128-bit output
  - Designed by Ron Rivest, used very widely
  - Collision-resistance broken (summer of 2004)
- RIPEMD-160
  - 160-bit variant of MD5
- SHA-1 (Secure Hash Algorithm)
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Also recently broken! (Theoretically -- not practical.)
- SHA-256, SHA-512, SHA-224, SHA-384
- SHA-3: standard released by NIST in August 2015

Recall: Achieving Integrity

Message authentication schemes: A tool for protecting integrity.



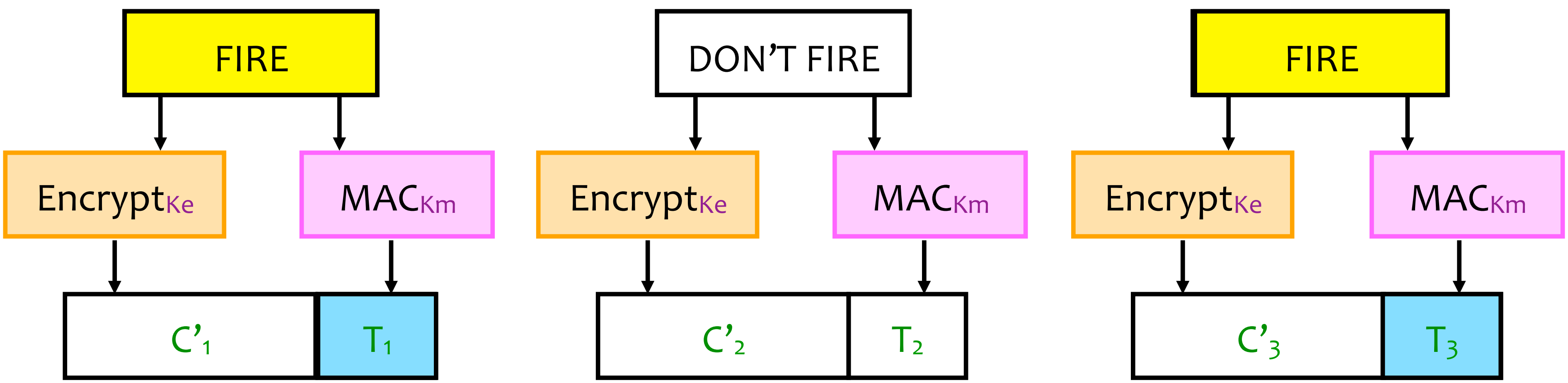
Integrity and authentication: only someone who knows KEY can compute correct MAC for a given message.

HMAC

- Construct MAC from a cryptographic hash function
  - Invented by Bellare, Canetti, and Krawczyk (1996)
  - Used in SSL/TLS, mandatory for IPsec
- Why not encryption?
  - Hashing is faster than block ciphers in software
  - Can easily replace one hash function with another
  - There used to be US export restrictions on encryption

Authenticated Encryption

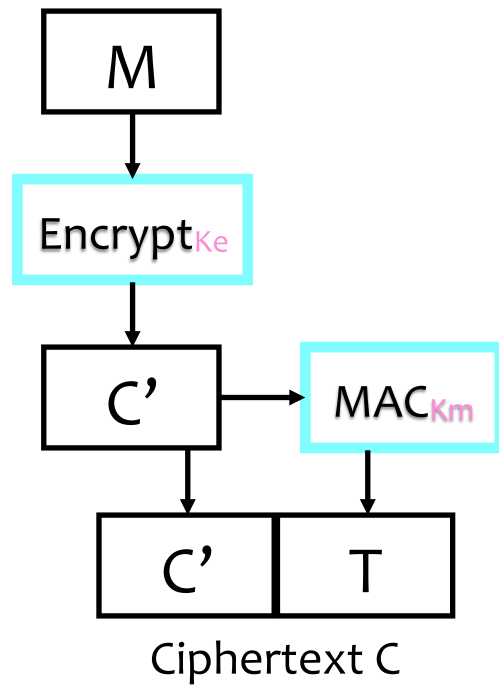
- What if we want both privacy and integrity?
- Natural approach: combine encryption scheme and a MAC.
- But be careful!
  - Obvious approach: Encrypt-and-MAC
  - Problem: MAC is deterministic! same plaintext → same MAC



Authenticated Encryption

- Instead:
  Encrypt *then* MAC.

- (Not as good:
  MAC-then-Encrypt)



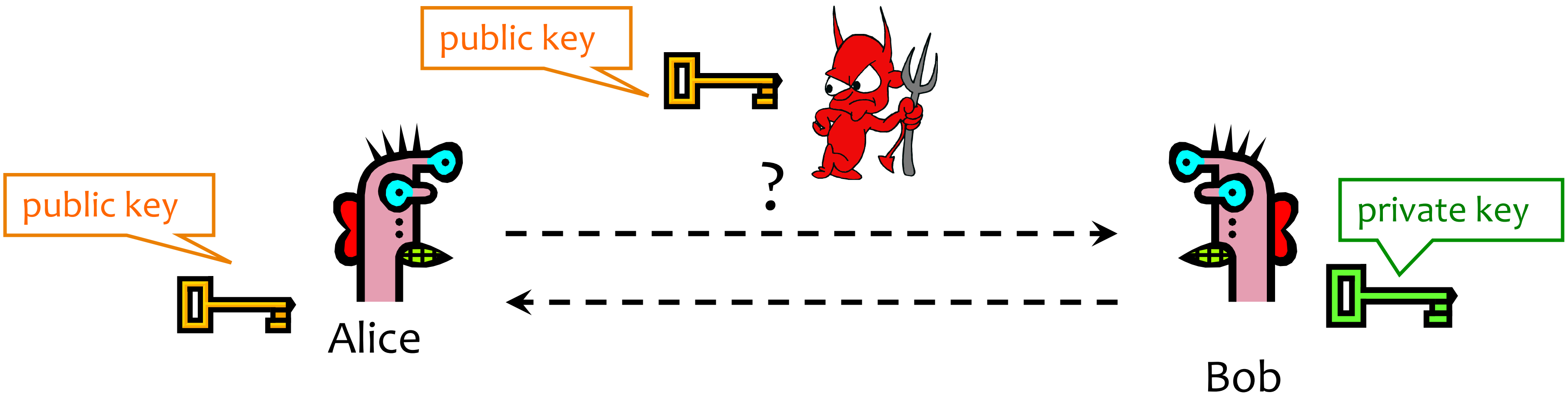
Encrypt-then-MAC

Asymmetric (Public Key) Cryptography

Reminder: Symmetric Cryptography

- **1 secret key (or 2 or …)**, shared between sender/receiver
- Repeat fast and simple operations lots of times (rounds) to mix up key and ciphertext
- **Why do we think it is secure?** (simplistic)
  - Lots of heuristic arguments
    - If we do lots and lots and lots of mixing, no simple formula (and reversible) describing the whole process (cryptographic weakness).
    - Mix in ways we think it's hard to short-circuit all the rounds. Especially non-linear mixing, e.g., S-boxes.
  - Some math gives us confidence in these assumptions

Public Key Crypto: Basic Problem



<u>Given</u>: Everybody knows Bob's public key
Only Bob knows the corresponding private key

<u>Goals</u>: 1. Alice wants to send a secret message to Bob
2. Bob wants to authenticate himself

Public Key Cryptography

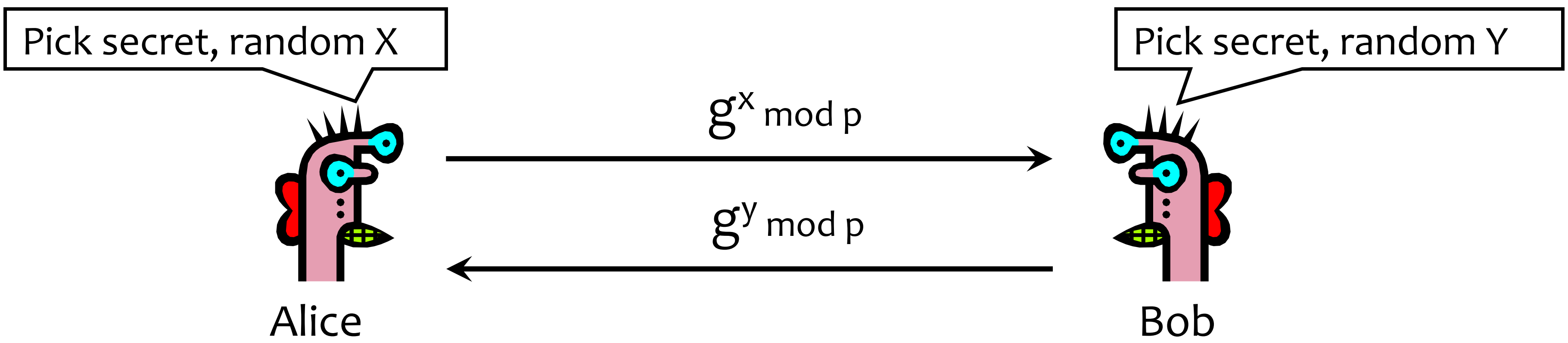
- Everyone has **1 private key and 1 public key**
  - Or 2 private and 2 public, when considering both encryption and authentication
- Mathematical relationship between private and public keys
- **Why do we think it is secure?** (simplistic)
  - Relies entirely on **problems we believe are "hard"**

Applications of Public Key Crypto

- Encryption for confidentiality
  - Anyone can encrypt a message
    - With symmetric crypto, must know secret key to encrypt
  - Only someone who knows private key can decrypt
  - Key management is simpler (or at least different)
    - Secret is stored only at one site: good for open environments
- Digital signatures for authentication
  - Can "sign" a message with your private key
- Session key establishment
  - Exchange messages to create a secret session key
  - Then switch to symmetric cryptography (why?)

Diffie-Hellman Protocol (1976)

- Alice and Bob never met and share no secrets
- Public info: p and g
  - p is a large prime number, g is a generator of Z_p^*
    - $Z_p^*=\{1, 2 \ldots p-1\}$; $\forall a \in Z_p^*$ $\exists i$ such that $a=g^i \bmod p$
    - Modular arithmetic: numbers "wrap around" after they reach p



Compute $k=(g^y)^x=g^{xy} \bmod p$

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Why is Diffie-Hellman Secure?

- Discrete Logarithm (DL) problem:
  given g^x *mod p*, it's hard to extract x
  - There is no known <u>efficient</u> algorithm for doing this
  - This is <u>not</u> enough for Diffie-Hellman to be secure!
- Computational Diffie-Hellman (CDH) problem:
  given g^x and g^y, it's hard to compute g^{xy} *mod p*
  - … unless you know x or y, in which case it's easy
- Decisional Diffie-Hellman (DDH) problem:

  given g^x and g^y, it's hard to tell the difference between g^{xy} *mod p* and g^r *mod p* where r is random

Properties of Diffie-Hellman

- Assuming DDH problem is hard (depends on choice of parameters!), Diffie-Hellman protocol is a secure key establishment protocol against passive attackers
  - Eavesdropper can't tell the difference between the established key and a random value
  - Can use the new key for symmetric cryptography
- Diffie-Hellman protocol (by itself) does not provide authentication

Requirements for Public Key Encryption

- Key generation: computationally easy to generate a pair (public key PK, private key SK)
- Encryption: given plaintext M and public key PK, easy to compute ciphertext $C=E_{PK}(M)$
- Decryption: given ciphertext $C=E_{PK}(M)$ and private key SK, easy to compute plaintext M
  - Infeasible to learn anything about M from C without SK
  - Trapdoor function: Decrypt(SK,Encrypt(PK,M))=M