

CSE 3400 - Introduction to Computer & Network Security
(aka: Introduction to Cybersecurity)

Lecture 10

Public Key Cryptography – Part I

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Outline

- ❑ Number theory review.
- ❑ Intro to public key cryptography.
- ❑ Key exchange.
- ❑ Hardness assumptions: DL, CDH, DDH.



Number Theory Review

Our Focus

- A brief overview of mainly modular arithmetic.
- The minimalist set we need in topics covered in this course.

The Modulo Operation

Definition 1.2 (The modulo operation). *Let $a, m \in \mathbb{Z}$ be integers such that $m > 0$. We say that an integer r is a residue of a modulo m if $0 \leq r < m$ and $(\exists i \in \mathbb{Z})(a = r + i \cdot m)$. For any given $a, m \in \mathbb{Z}$, there is exactly one such residue of a modulo m ; we denote it by $a \pmod{m}$.*

Properties (make it easier to compute complex modular arithmetic expressions):

$$(a + b) \pmod{m} = [(a \pmod{m}) + (b \pmod{m})] \pmod{m} \quad (1.2)$$

$$(a - b) \pmod{m} = [(a \pmod{m}) - (b \pmod{m})] \pmod{m} \quad (1.3)$$

$$a \cdot b \pmod{m} = [(a \pmod{m}) \cdot (b \pmod{m})] \pmod{m} \quad (1.4)$$

$$a^b \pmod{m} = (a \pmod{m})^b \pmod{m} \quad (1.5)$$

The Modulo Operation

Properties (extends also to polynomials):

Similar properties hold for any polynomial $p(x)$ with integer coefficients and input ($x \in \mathbb{Z}$), as well as for a polynomial $p(x_1, x_2, \dots)$ with integer coefficients and multiple integer parameters ($x_1, x_2, \dots \in \mathbb{Z}$):

$$[p(x)] \bmod m = [p(x \bmod m)] \bmod m \quad (1.6)$$

$$[p(x_1, x_2, \dots)] \bmod m = p(x_1 \bmod m, x_2, \dots) \bmod m = \quad (1.7)$$

$$= p(x_1 \bmod m, \dots) \bmod m \quad (1.8)$$

Examples

- $7 \bmod 9 = ?$
- $13 \bmod 8 = ?$
- $0 \bmod 11 = ?$
- $4 \bmod 4 = ?$
- $(30 + 66) \bmod 11 = ?$
- How about: $445 \cdot (81 \cdot 34^{13} + 83 \cdot 33^{345}) \bmod 4$?

Denote $445 \cdot (81 \cdot 34^{13} + 83 \cdot 33^{345}) \bmod 4$ by x . Then we find x as follows:

$$\begin{aligned}x &= 445 \cdot (81 \cdot 34^{13} + 83 \cdot 33^{345}) \bmod 4 \\&= (445 \bmod 4) \cdot ((81 \bmod 4) \cdot (34 \bmod 4)^{13} + \\&\quad + (83 \bmod 4) \cdot (33 \bmod 4)^{345}) \bmod 4 \\&= 1 \cdot (1 \cdot 2^{13} + 3 \cdot 1^{345}) \bmod 4 \\&= (2 \cdot 4^6 + 3) \bmod 4 \\&= 3 \bmod 4 = 3\end{aligned}$$

Multiplicative Inverse

- Needed to support division in modular arithmetic.
 - Division not always produce integers.
 - Modular arithmetic requires integers to work with!!
- To compute $a/b \bmod m$, multiply a by the multiplicative inverse of b .
 - That is compute $ab \bmod m = ab^{-1} \bmod m$.
 - Where b^{-1} is the multiplicative inverse such that $bb^{-1} \bmod m = 1$
- Not all integers have multiplicative inverses with respect to a specific modulus m.

Multiplicative Inverse

Definition 1.3. Let $x, m \in \mathbb{Z}$ be integers such that $m > 0$ and $x \bmod m \neq 0$. Then there is a unique integer x^{-1} such that $x \cdot x^{-1} \bmod m = 1$ and $m > x^{-1} > 0$. We say that x^{-1} is the multiplicative inverse of x modulo m .

□ Examples:

- $3/5 \bmod 4 = 3 \cdot 5^{-1} \bmod 4 = ?$
- $3/5 \bmod 6 = 3 \cdot 5^{-1} \bmod 6 = ?$

Fact 1.2. Let $x, m \in \mathbb{Z}$ be integers such that $m > 0$ and $x \bmod m \neq 0$. Then there is an efficient algorithm that finds $x^{-1} \bmod m$.

- Such an algorithm is called the Extended Euclidean algorithm (out of scope for this course).

Modular Exponentiation

- Will be encountered a lot; discrete log based scheme, RSA, etc.
- We have seen a property to reduce the base, but how about the exponent?
 - Its reduction will be with respect to a different modulus than the one in the original operation.
- Fermat's Little Theorem:

Theorem 1.1. *For any integers $a, b, p \in \mathbb{Z}$, if p is a prime and $p > 0$, then*

$$\begin{aligned} a^b \mod p &= a^{b \mod (p-1)} \mod p \\ &= (a \mod p)^{b \mod (p-1)} \mod p \end{aligned} \tag{1.9}$$

Modular Exponentiation

- Examples; Use Fermat's Little theorem (if applicable) to solve the following:
 - $13^{32} \bmod 31 = ?$
 - $19^{930} \bmod 4 = ?$
 - $19^{60} \bmod 7 = ?$
- Can we reduce the exponent for non prime (composite) modulus?
 - We can use Euler's Theorem.

Euler's Function

- Called also Euler's Totient function. For every integer $n > 1$, this function computes the number of positive integers that are less than n and co-prime to n .

$$\phi(n) \equiv |\{i \in \mathbb{N} | i < n \wedge \gcd(i, n) = 1\}| \quad (1.10)$$

Examples:

n	1	2	3	4	5	6	7	8	9	10
$\phi(n)$	1	1	2	2	4	2	6	4	6	4
factors?	none	none	none	$2 \cdot 2$	none	$2 \cdot 3$	none	2^3	$3 \cdot 3$	$2 \cdot 5$

Euler's Function Properties

Lemma 1.1. *For any prime $p > 1$ holds $\phi(p) = p - 1$. For prime $q > 1$ s.t. $q \neq p$ holds $\phi(p \cdot q) = (p - 1)(q - 1)$.*

Lemma 1.2 (Euler function multiplicative property). *If a and b are co-prime positive integers, then $\phi(a \cdot b) = \phi(a) \cdot \phi(b)$.*

Lemma 1.3. *For any prime p and integer $l > 0$ holds $\phi(p^l) = p^l - p^{l-1}$.*

Lemma 1.4. *Let $n = \prod_{i=1}^n (p_i^{l_i})$, where $\{p_i\}$ is a set of distinct primes (all different), and l_i is a set of positive integers (exponents of the different primes). Then:*

$$\phi(n) = \phi\left(\prod_{i=1}^n (p_i^{l_i})\right) = \prod_{i=1}^n \left(p_i^{l_i} - p_i^{l_i-1}\right) \quad (1.12)$$

Euler's Theorem

Theorem 1.2 (Euler's theorem). *For any co-prime integers m, n holds $m^{\phi(n)} = 1 \pmod{n}$. Furthermore, for any integer l holds:*

$$m^l \pmod{n} = m^{l \pmod{\phi(n)}} \pmod{n} \quad (1.19)$$

□ Examples:

- $13^{31} \pmod{31} = ?$
- $27^{26} \pmod{10} = ?$

Last Stop

- **Congruence:** $a \equiv b \pmod{m}$
 - Used when two expressions have the same residue with respect to some modulus.
 - It is an equivalence relation, so it satisfies:
 - Reflexivity:** $a \equiv a \pmod{m}$.
 - Symmetry:** $a \equiv b \pmod{m}$ if $b \equiv a \pmod{m}$.
 - Transitivity:** if $a \equiv b \pmod{m}$ and $b \equiv c \pmod{m}$ then $a \equiv c \pmod{m}$.
- Lastly, we have the fundamental theorem of arithmetic.

Theorem 1.3 (The fundamental theorem of arithmetic). *Every number $n > 1$ has a unique representation as a product of powers of distinct primes.*

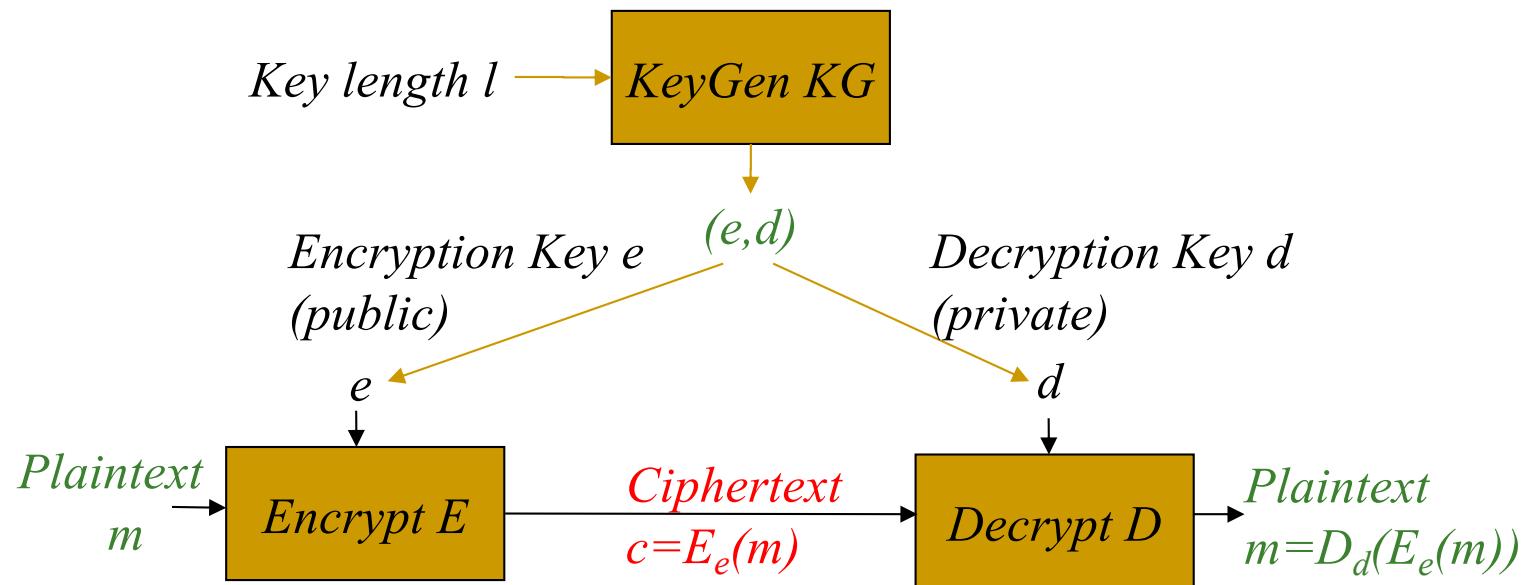
Intro to Public Key Cryptography

Public Key Cryptology

- Kerckhoff: cryptosystem (algorithm) is public
- What we learned until now:
 - Only the key is secret (unknown to attacker)
 - Same key for encryption, decryption
→ if you can encrypt, you can also decrypt!
- But can we give encryption capability without a decryption capability?
 - Yes, using public key cryptography!

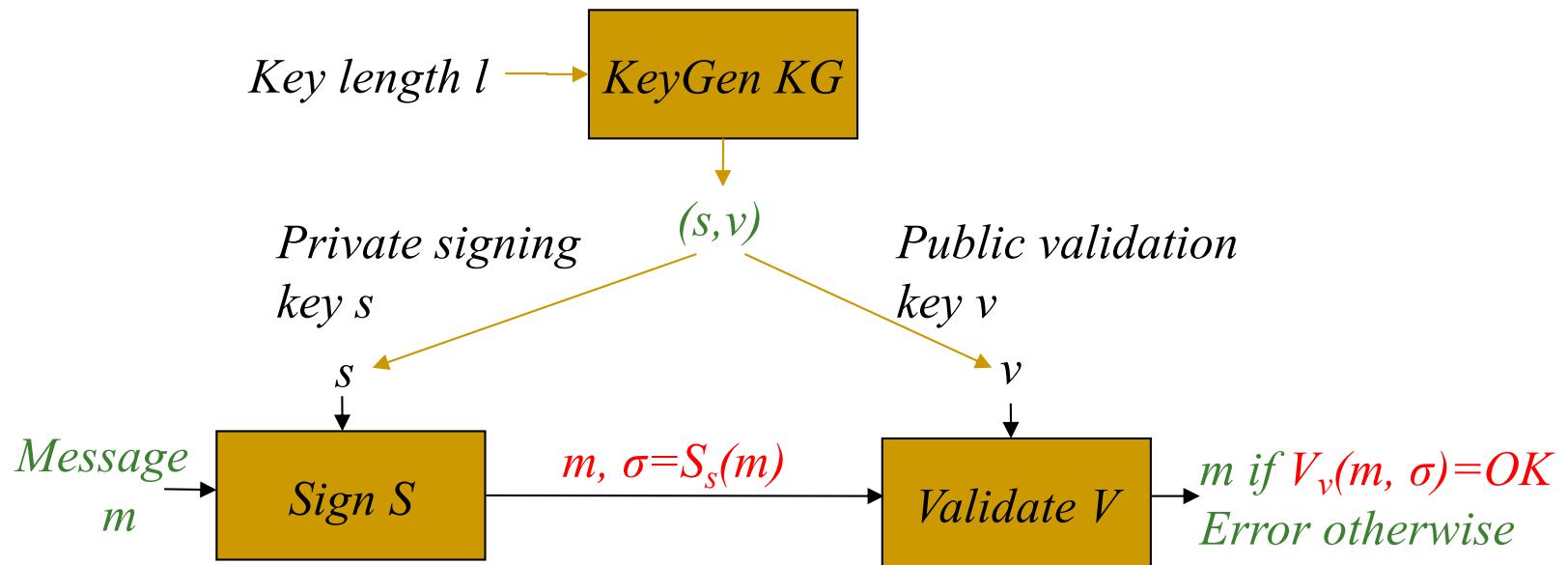
Public Key Cryptosystem (PKC)

- Kerckhoff: cryptosystem (algorithm) is public
- [DH76]: can encryption key be public, too??
 - Decryption key will be different (and private)
 - Everybody can send me mail, only I can read it.



Is it Only About Encryption?

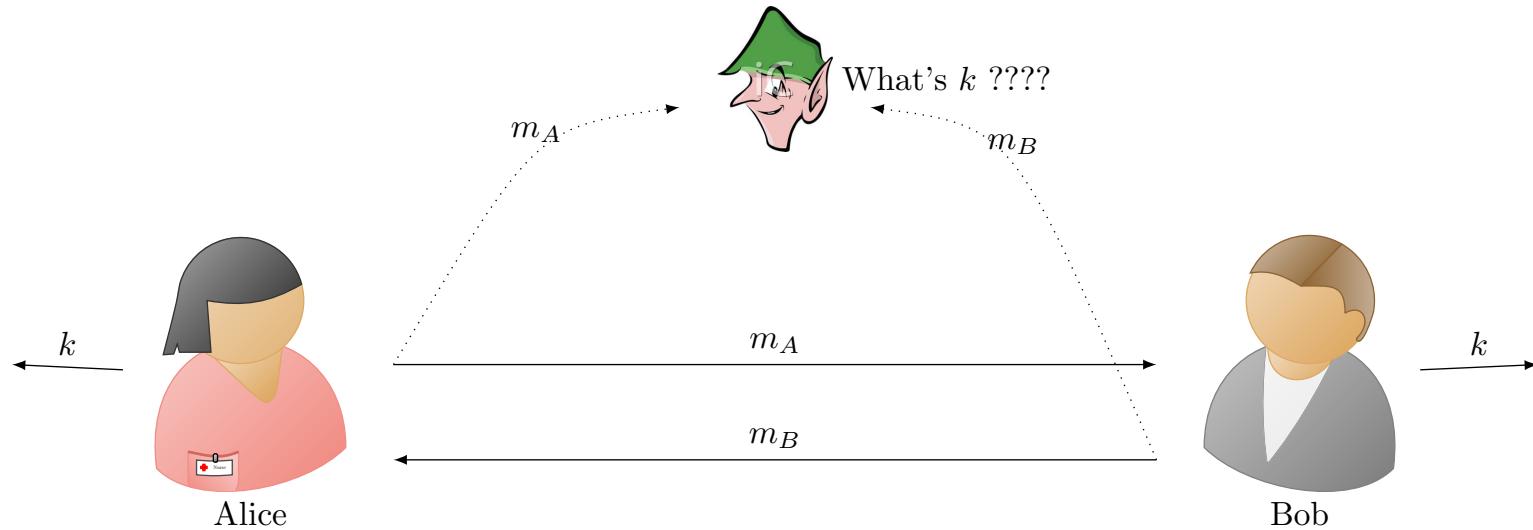
- Also: Digital signatures (RSA, DSA, ...)
 - Sign with private key s , verify with public key v
 - (Recall MACs; a shared key cryptosystem for message authentication).



More: Key-Exchange Protocol

■ Key Exchange Protocols

- ❑ Establish shared key between Alice and Bob **without** assuming an existing shared ('master') key !!
- ❑ Use public information from A and B to setup shared secret key k .
- ❑ Eavesdropper cannot learn the key k .



Public keys solve more problems...

- Signatures provide **evidences**
 - Everyone can validate, only ‘owner’ can sign
- Establish shared secret keys
 - Use authenticated public keys
 - Signed by trusted certificate authority (CA)
 - Or: use DH key exchange
- Stronger resiliency to key exposure
 - Perfect forward secrecy and recover security
 - Protect confidentiality from possible key exposures
 - Threshold (and proactive) security
 - Resilient to exposure of k out of n parties (every period)

Public keys are easier...

- To distribute:
 - From directory or from incoming message (still need to be authenticated)
 - Less keys to distribute (same public key to all)
- To maintain:
 - Can keep in non-secure storage as long as being validated (e.g. using MAC) before using
 - Less keys: $O(|parties|)$, not $O(|parties|^2)$
- So: why not **always** use public key crypto?

The Price of PKC

■ Assumptions

- Applied PKC algorithms are based on a small number of specific computational assumptions
 - Mainly: hardness of factoring and discrete-log
- Both may fail against quantum computers

■ Overhead

- Computational
- Key length
- Output length (ciphertext/signature)

Public key crypto is harder...

- Requires related public, private keys
 - Private key 'reverses' public key
 - Public key does not expose private key
- Substantial overhead
 - Successful cryptanalytic shortcuts → need long keys
 - Elliptic Curves (EC) may allow shorter key (almost no shortcuts found)
 - Complex computations
 - RSA: very complex (slow) key generation
- Most: based on hard modular math problems

[LV02]	Required key size		
Year	AES	RSA, DH	EC
2010	78	1369	160
2020	86	1881	161
2030	93	2493	176
2040	101	3214	191

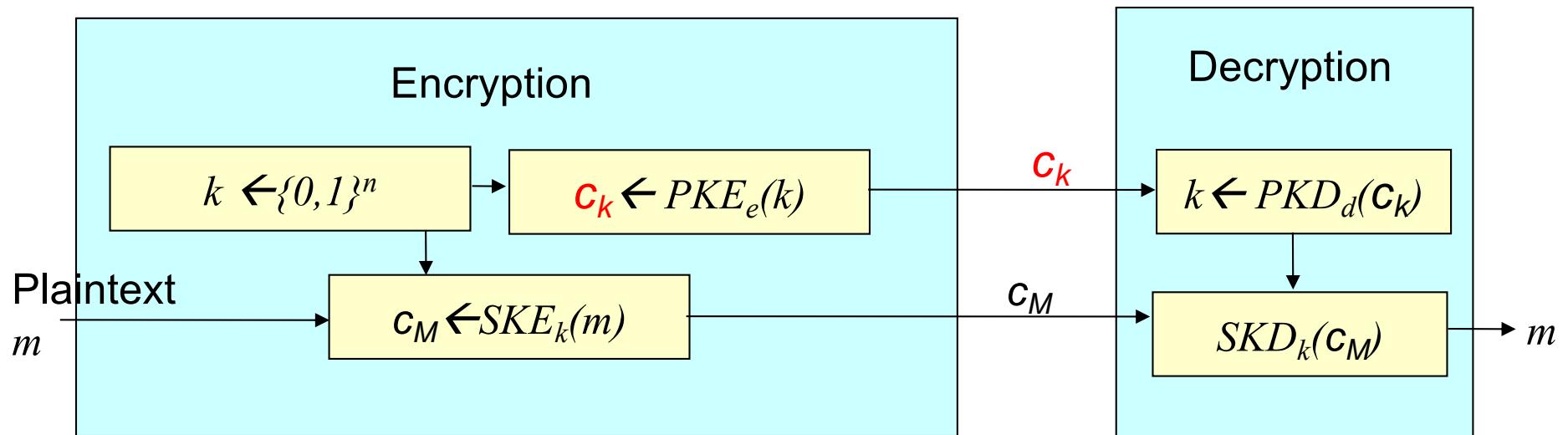
Commercial-grade security
Lenstra & Verheul [LV02]

In Sum

- Minimize the use of PKC
- In particular: apply PKC only to **short inputs**
- How ??
 - For signatures:
 - **Hash-then-sign**
 - For public-key encryption:
 - **Hybrid encryption**

Hybrid Encryption ('enveloping')

- Challenge: public key cryptosystems are slow
- Hybrid encryption:
 - Use a shared key encryption scheme to encrypt all messages.
 - But use a public key encryption system to exchange the shared key (Alice generates the k , encrypt it under Bob's public key and send it to Bob, Bob can then recover this key).



Hard Modular Math Problems

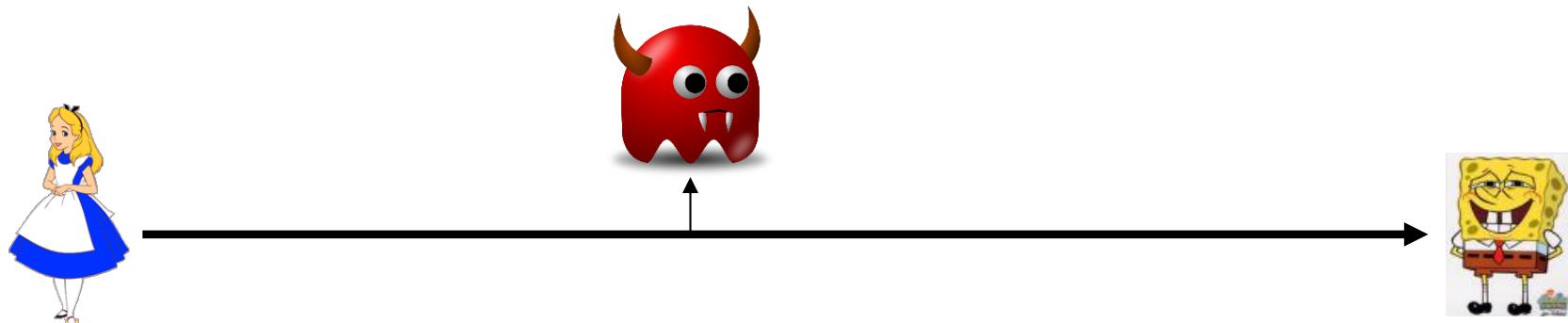
- No efficient solution, in spite of extensive efforts
 - But: **verification** of solutions is easy ('one-way' hardness)
 - Discrete log: exponentiation
- **Problem 1: Factoring**
 - Choose randomly $p, q \in_R \text{LargePrimes}$
 - Given $n = pq$, it is infeasible to find p, q
 - Verification? Easy, just multiply factors
 - Basis for the RSA cryptosystem and many other tools
- **Problem 2: Discrete logarithm in cyclic group \mathbb{Z}_p^***
 - Where p is a safe prime [details in textbook]
 - Given random number, find its (discrete) logarithm
 - Verification is efficient by exponentiation: $O((\lg n)^3)$
 - Basis for the Diffie-Hellman Key Exchange and many other tools
 - We first discuss key-Exchange problem, then [DH] and disc-log

Key Exchange

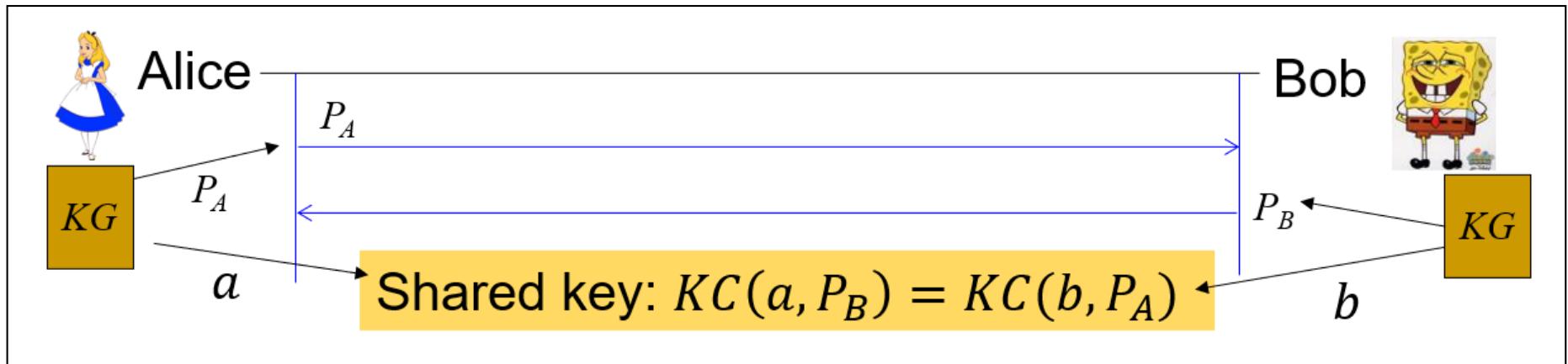
The Key Exchange Problem

Aka key agreement

- Alice and Bob want to agree on secret (key)
 - Secure against **eavesdropper** adversary
 - Assume no prior shared secrets (key)
 - Otherwise seems trivial
 - Actually, we'll later show it's also useful in this case...



Defining a Key Exchange Protocol



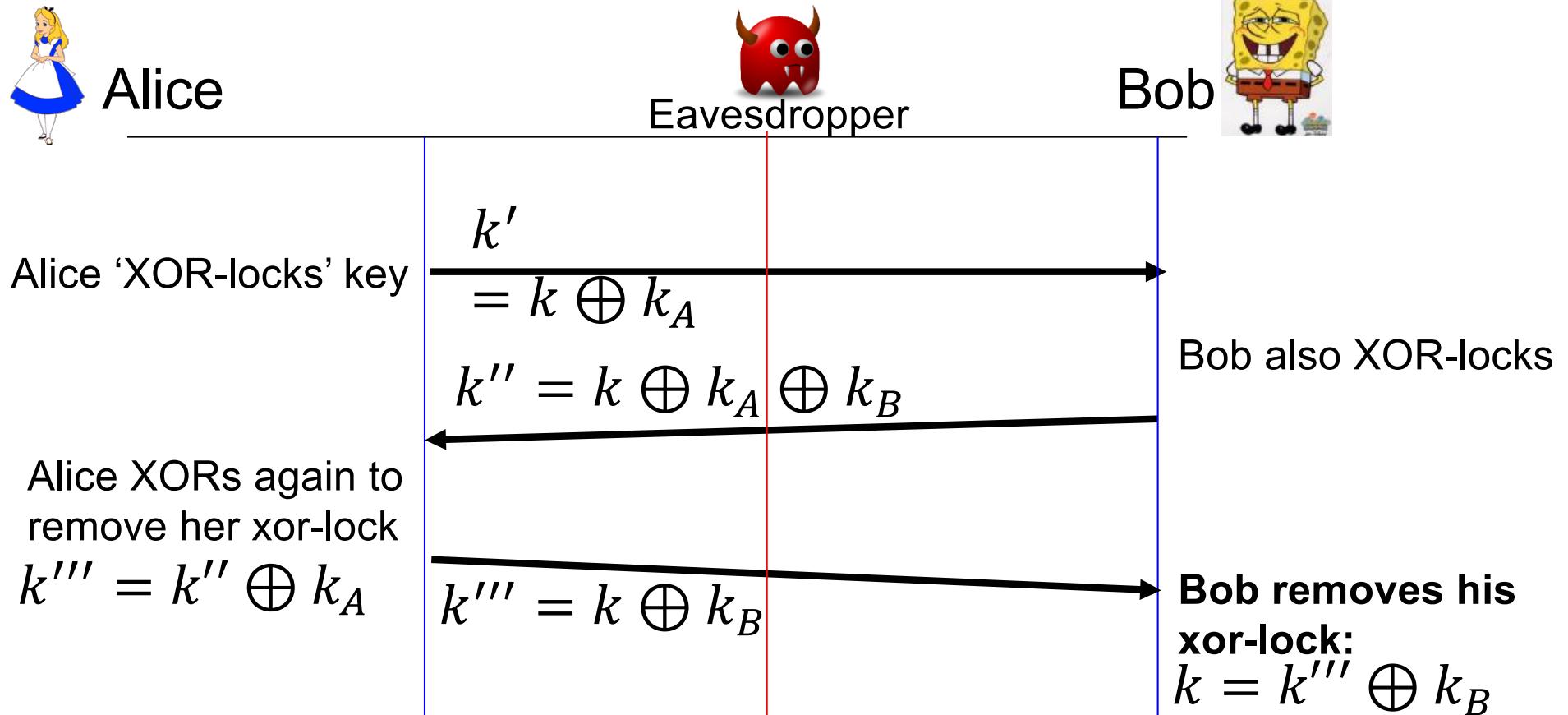
Must satisfy correctness; both parties compute the same shared key, and key indistinguishability (see next slide).

Security a Key Exchange Protocol

Definition 6.5 (The key indistinguishability requirement). *Let (KG, KC) be a key-exchange protocol, and \mathcal{A} be an efficient (PPT) adversary. We say that (KG, KC) ensures key-indistinguishability if for every PPT adversary \mathcal{A} and for sufficiently-large security parameter 1^l , holds:*

$$\Pr \left[\begin{array}{c} \mathcal{A}(P_A, P_B, KC(a, P_A)) = 1 \\ \text{where} \\ (a, P_A) \xleftarrow{\$} KG(1^l), \\ (b, P_B) \xleftarrow{\$} KG(1^l) \end{array} \right] - \Pr \left[\begin{array}{c} \mathcal{A}(P_A, P_B, r) = 1 \\ \text{where} \\ (a, P_A) \xleftarrow{\$} KG(1^l), \\ (b, P_B) \xleftarrow{\$} KG(1^l), \\ r \xleftarrow{\$} \{0, 1\}^{|KC(a, P_A)|} \end{array} \right] \in NEGL(1^l)$$

XOR (One Time Pad) Key Exchange?



Is this secure?

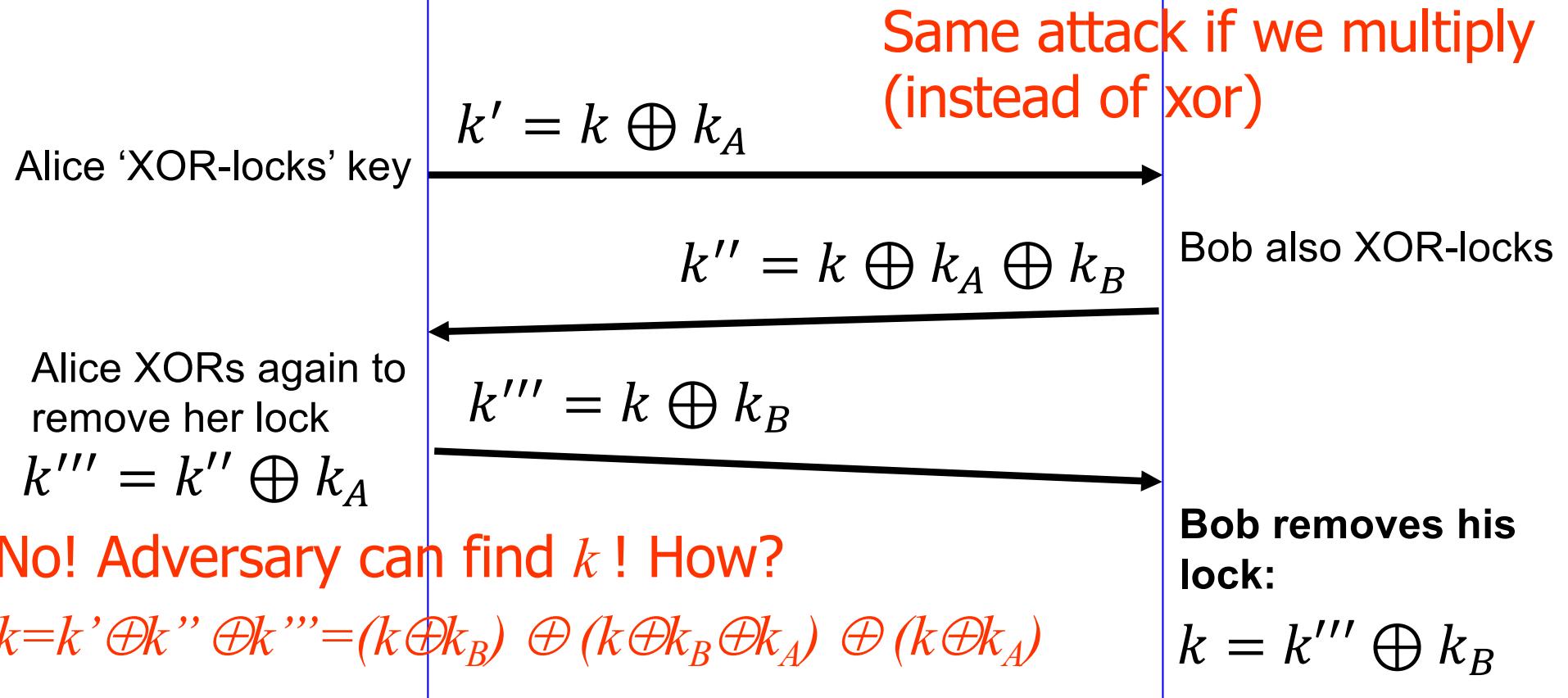
Can we use XOR (One Time Pad) as lock?



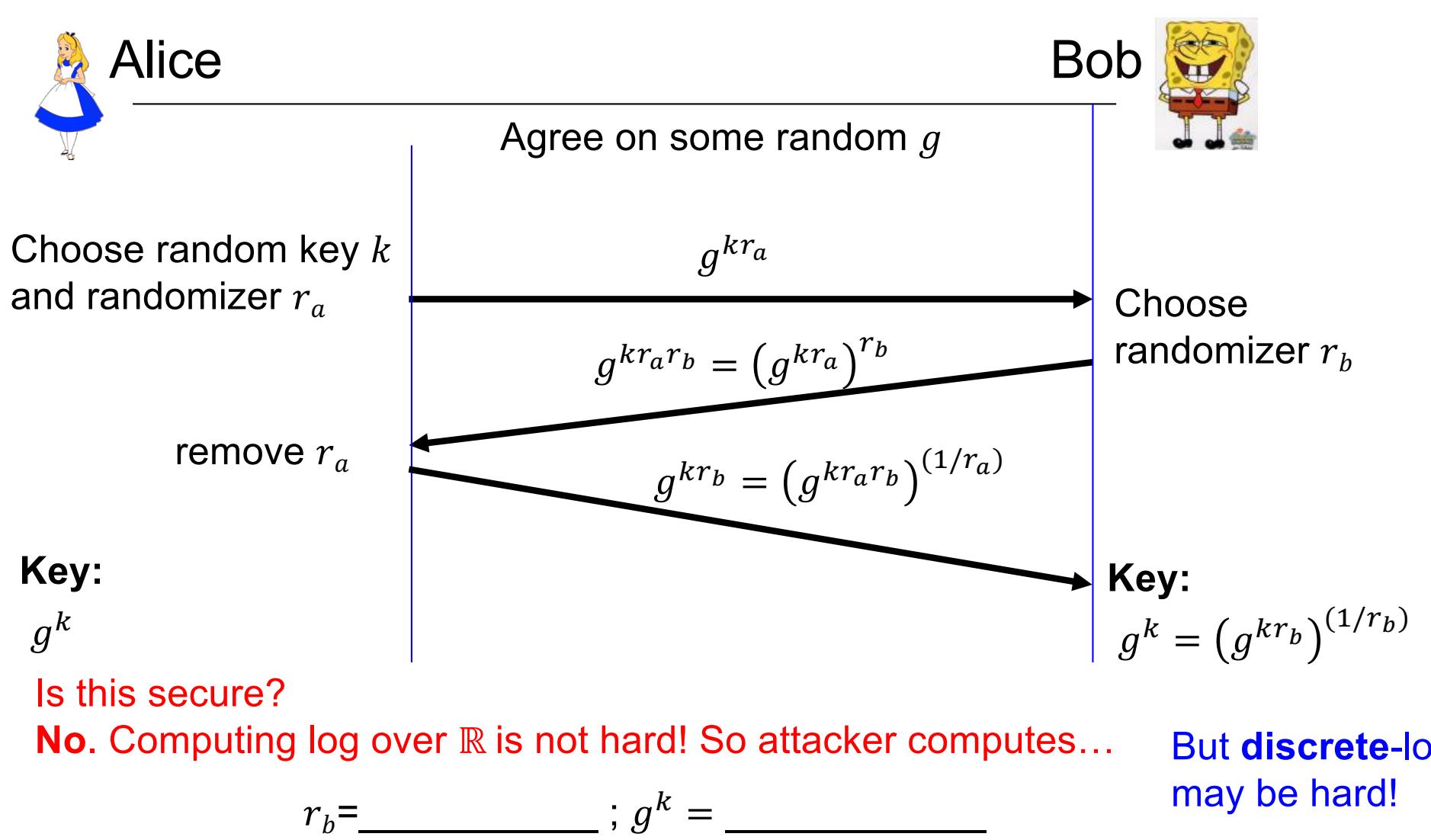
Alice



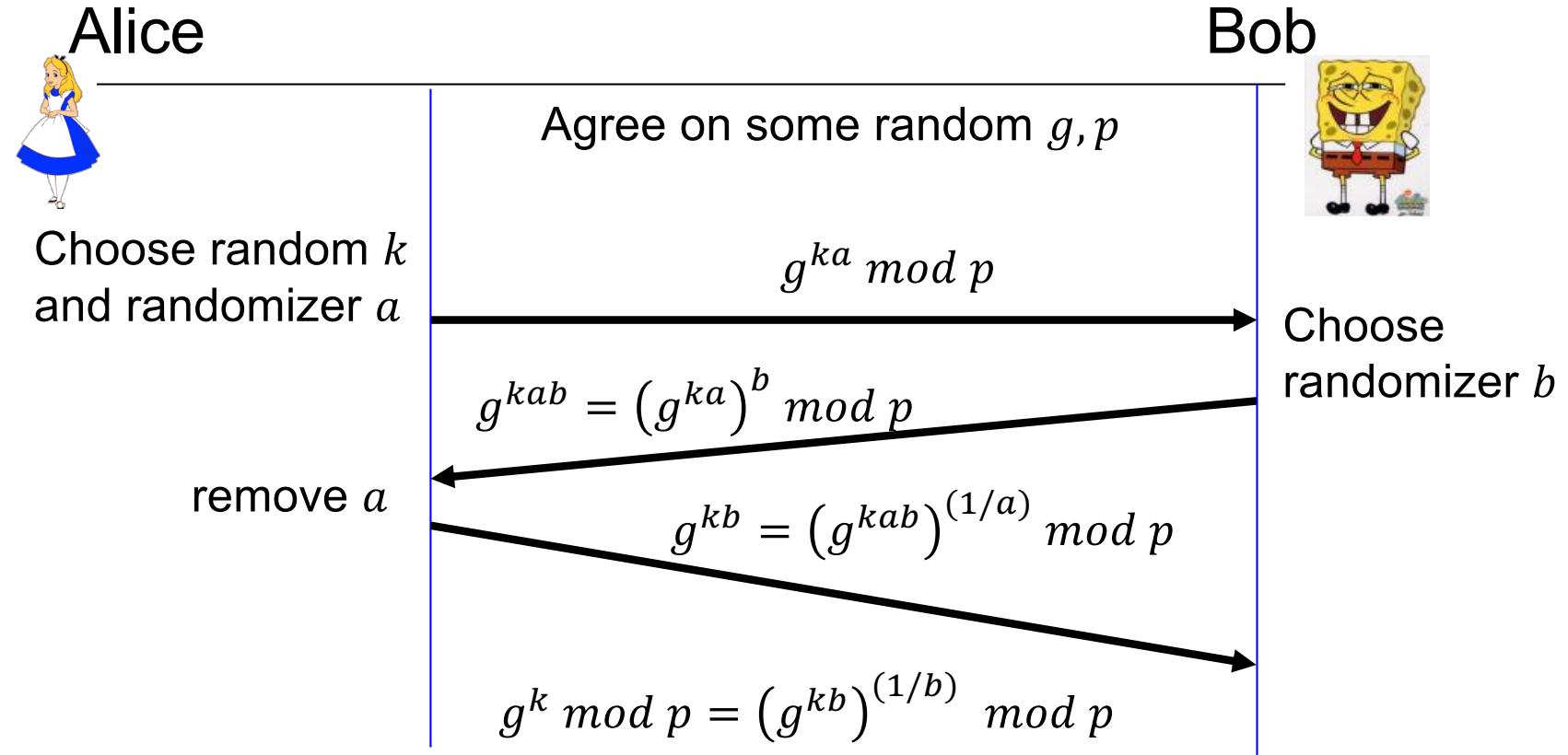
Bob



Exponentiation Key Exchange Protocol ?



Discrete Exponentiation Key Exchange



Is this secure???

Not for 'bad' p , e.g., $p = 2^t + 1$ for some integer t

'Yes' [assumption...] for 'safe prime' $p = 2q + 1$ (for prime q)

Discrete Log (DL) Assumption
and
The Computational/Decisional Diffie-
Hellman Assumptions (CDH/DDH)
and
The DH Key Exchange Protocol

The Discrete Log Problem

- Computing logarithm is quite efficient over the reals
- Consider a cyclic multiplicative group G
 - Cyclic group: exists generator g s.t. $(\forall a \in G)(\exists i)(a = g^i)$
 - Discrete log problem: given generator g and $a \in G$, find i s.t. $a = g^i$
 - Verification: exponentiation (efficient algorithm)
 - For prime p , the group $\mathbb{Z}_p^* = \{1, \dots, p-1\}$ is cyclic [multiplications mod p]
- Is discrete-log hard?
 - Some ‘weak’ groups, i.e., where disc-log is **not** hard:
 - \mathbb{Z}_p^* for prime p , where $(p - 1)$ has only ‘small’ prime factors
 - Using the Pohlig-Hellman algorithm
 - Check!! Mistakes/trapdoors found, e.g., in OpenSSL’16
 - Other groups studied, considered Ok (‘hard’)
 - **Safe-prime** groups: \mathbb{Z}_p^* for **safe prime**: $p = 2q + 1$ for prime q

Discrete Log Assumption

[for safe prime group: $p = 2q + 1$ for prime q]

Given PPT adversary A , and n -bit safe prime p :

$$\Pr \left[\begin{array}{l} g \leftarrow \text{Generator}(Z_p^*); \\ x \stackrel{\$}{\leftarrow} Z_p^* \\ A(x) = a \mid x = g^a \text{ mod } p \end{array} \right] \approx \text{negl}(n)$$

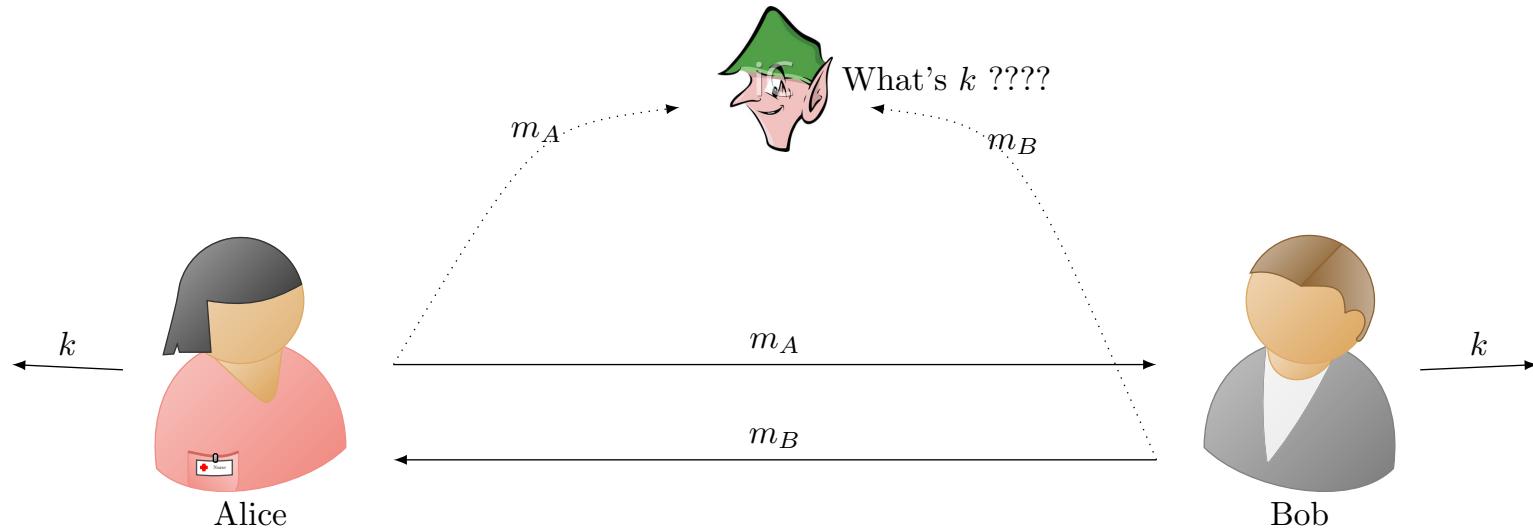
Comments:

1. Similar assumptions for (some) other groups
2. Knowing q , it is easy to find a generator g
3. Any generator (primitive element) will do

[DH76]: DH Key-Exchange Protocol

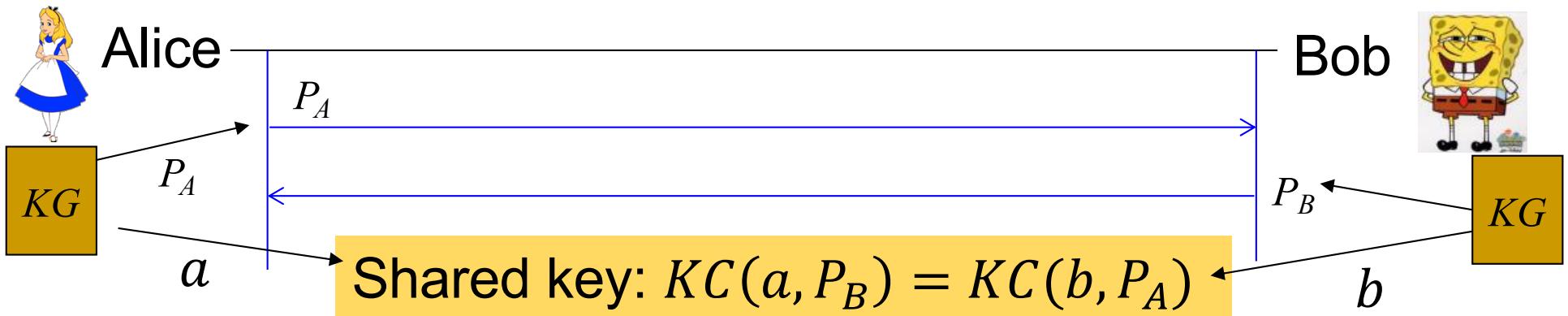
■ Key Exchange Protocols

- ❑ Establish shared key between Alice and Bob
- ❑ **Without** assuming an existing shared ('master') key !!
- ❑ Use public information from A, B to setup shared secret key k .
- ❑ Eavesdropper cannot learn the key k .



One-Round Key-Exchange Protocol

- Establish shared key between Alice and Bob **Without** assuming an existing shared ('master') key !!
- Use public information from A, B to setup shared secret key k .
- Eavesdropper cannot learn the key k .
- Typical protocols: only one round, two functions:
 - Key-generation (KG) , Key-combining (KC)

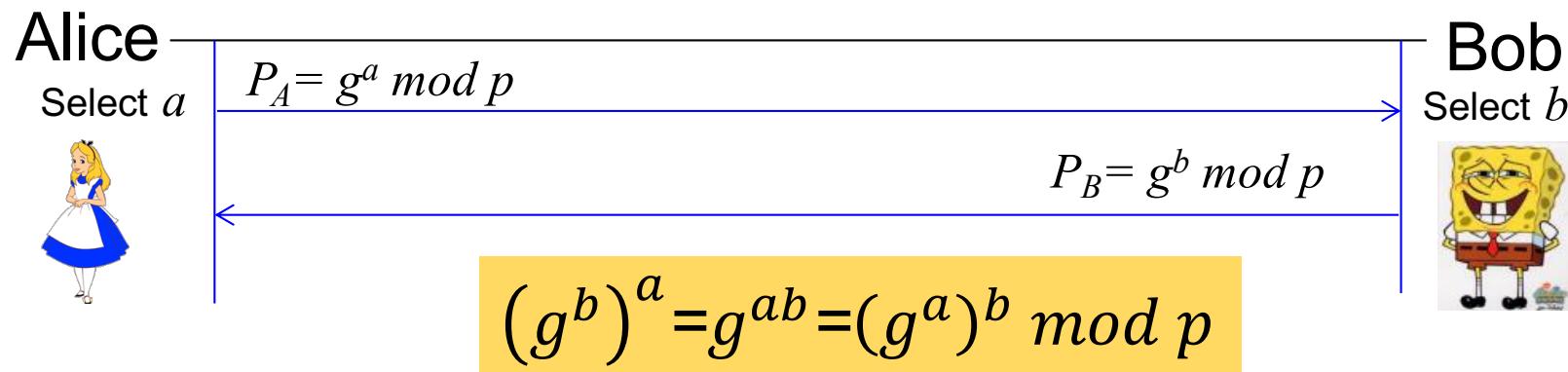


Goals: Correctness (above) and key-indistinguishability (in textbook)

Diffie-Hellman [DH] Key Exchange

Using cyclic group \mathbb{Z}_p^*

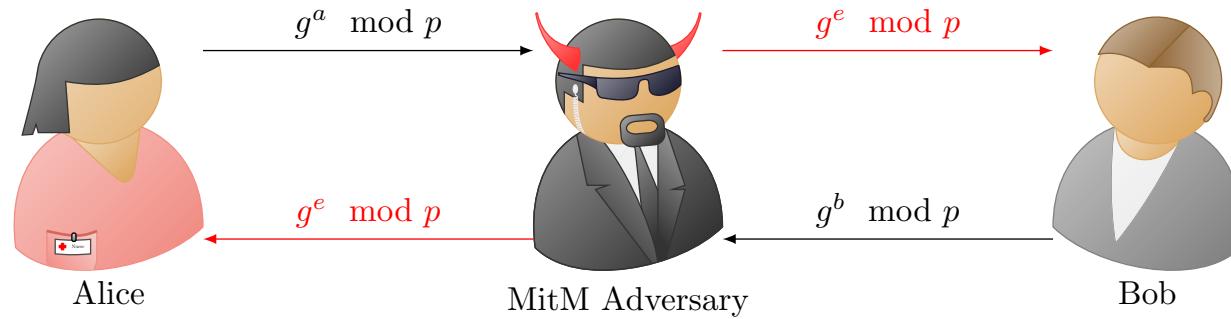
- Simplified Discrete Exponentiation Key Exchange
- Agree on a random safe prime p
 - And generator g for the cyclic group \mathbb{Z}_p^*
- Alice: secret key a , public key $P_A = g^a \text{ mod } p$
- Bob: secret key b , public key $P_B = g^b \text{ mod } p$
- To set up a shared key :



Caution: Authenticate Public Keys!

- Diffie-Hellman key exchange is only secure using the authentic public keys
 - Or (equivalently): against eavesdropper
- If Bob simply receives Alice's public key, [DH] is vulnerable to 'Man in the Middle' attack

$$a \xleftarrow{\$} \{1, \dots, p\} \quad e \xleftarrow{\$} \{1, \dots, p\} \quad b \xleftarrow{\$} \{1, \dots, p\}$$



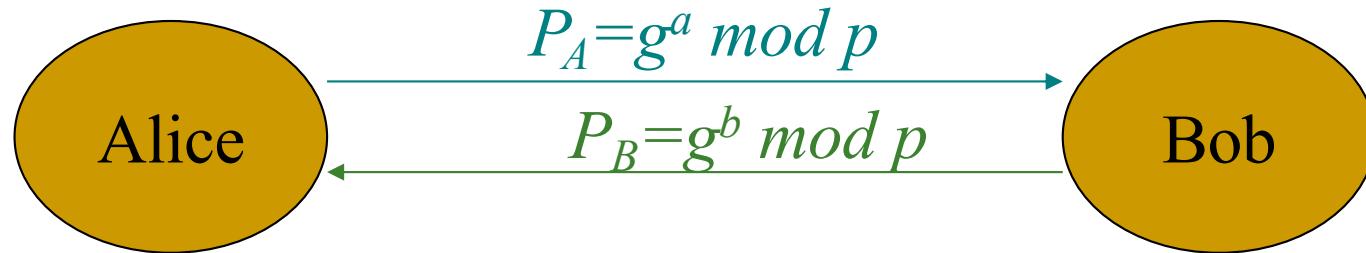
$$(g^e)^a = g^{a \cdot e} \bmod p$$

$$(g^a)^e = g^{a \cdot e} \bmod p, \quad (g^b)^e = g^{b \cdot e} \bmod p$$

$$(g^e)^b = g^{b \cdot e} \bmod p$$

Security of [DH] Key Exchange

- Assume authenticated communication
- Based on Computational Discrete Log Assumption
- But DH requires stronger assumption than Disc-Log:
 - Maybe from $g^b \bmod p$ and $g^a \bmod p$, adversary can compute $g^{ab} \bmod p$ (without knowing/learning a, b or ab)?



Computational DH (CDH) Assumption [for safe prime group]

Given PPT adversary A:

$$\Pr \left[\begin{array}{l} (p, q) \leftarrow \text{primes s.t. } p = 2q + 1; \\ g \leftarrow \text{Generator}(\mathbb{Z}_p^*); \\ a, b \leftarrow \{1 \dots p - 1\}; \\ A(g^a, g^b \bmod p) = g^{ab} \bmod p \end{array} \right] \approx \text{negl}(n)$$

Assume CDH holds. Can we use g^{ab} as key?

Not necessarily; maybe finding some bits of g^{ab} is easy?

Using DH securely?

- Consider \mathbb{Z}_p^* (multiplicative group for (safe) prime p)
- Can g^a, g^b expose *something* about $g^{ba} \bmod p$?
- Bad news:
 - Finding (at least) **one bit** about $g^{ba} \bmod p$ is easy!
 - Specifically: if it is quadratic-residue: $x=g^{ba} \bmod p = y^2 \bmod p$
 - Euler showed this holds if $x^{(p-1)/2} = 1 \bmod p$
 - Details in textbook
- Good news:
 - Many of the bits were shown to be as secure as the whole
 - Also, there are other groups (e.g., Schnorr's), where testing for QR appears to be a hard problem
- So...how to use DH 'securely'?

Using DH securely?

- Adversary may compute *some* bits over $g^{ba} \bmod p$
- So...how to use DH ‘securely’? Two options!
- Option 1: Use DH but with a ‘stronger’ group, e.g., Schnorr’s - **not** \mathbb{Z}_p^* (mod safe-prime p)
 - The (stronger) **Decisional DH (DDH) Assumption**: adversary can’t **distinguish** between $[g^a, g^b, g^{ab}]$ and $[g^a, g^b, g^c]$, for random a, b, c .
- Option 2: use DH with safe prime p ... (*where only CDH holds*) but use a **key derivation function (KDF)** to derive a secure shared key
- Applied crypto mostly uses KDF... and we too ☺

Using DH ‘securely’: CDH+KDF

- With CDH, adversary may be able to compute some *partial* information about $g^{ba} \bmod p$...
 - But ‘most bits are random’
- **Solution: Key Derivation Function (KDF)**
 - Two variants: random-keyed and unkeyed (deterministic)
- Randomized - KDF: $k = KDF_s(g^{ab} \bmod p)$ where KDF is a key derivation function and s is public random (‘salt’)
- Deterministic - crypto-hash: $k = h(g^{ab} \bmod p)$ where h is randomness-extracting crypto-hash
 - No need in salt, but **not** provably-secure
- **Question:** isn’t (every) PRF a KDF? [not that easy ☺]
- **Note:** definition of KDF isn’t trivial

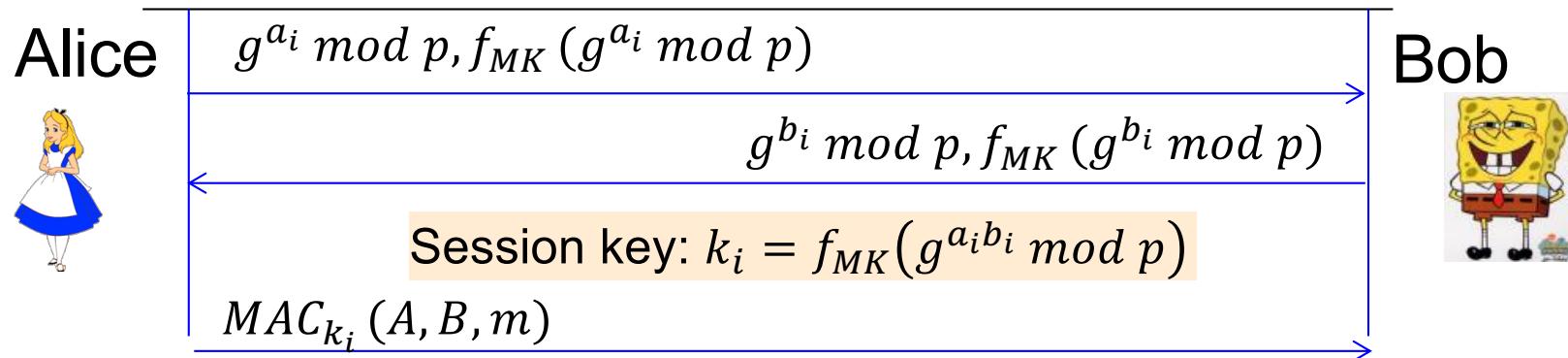
Resilience to Key Exposure

Authenticated DH

- Recall: DH not secure against MitM attacker
 - We assumed authenticated channel [shared key?]
 - If we have shared key, why not just use it??
- Use DH for **resiliency to key exposure**
 - Do authenticated DH periodically
 - Use derived key for confidentiality, authentication
 - Some protocols use key to authenticate next exchange
 - → Perfect Forward Secrecy (PFS):
 - Confidentiality of session i is resilient to exposure of all keys, except i -th session key, after session i ended

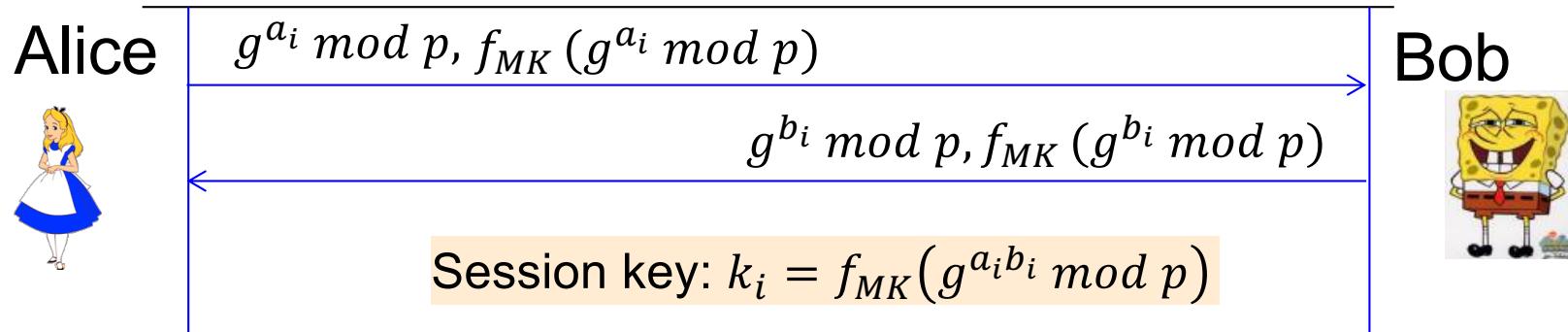
Authenticated DH: using KDF/PRF _[TLS]

- Assume f which is both a PRF and a KDF
- MK is secret + f is PRF (& MAC) \rightarrow authentication
 - And, assuming MK is secret, session keys are secure – even if disclosure would be easy (quantum computers or math breakthrough)
- Assuming CDH and that f is **KDF**: secure if MK exposed
 - Since most bits of $g^{a_i b_i}$ are secret
 - Against eavesdropping adv. or if MK-exposed only after session ends.
 - Perfect forward secrecy (PFS) !



Using DH for Exposure-Resiliency

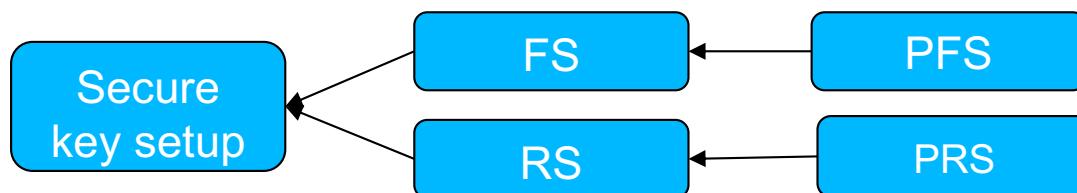
- What is the resiliency of authenticated DH protocol to key exposures?



- Until MK is exposed: secure against to MitM
- Once MK is exposed: vulnerable to MitM
 - But still secure against eavesdropper
- Hence: Perfect Forward Secrecy!

Resiliency Notions: Shared + Public Key

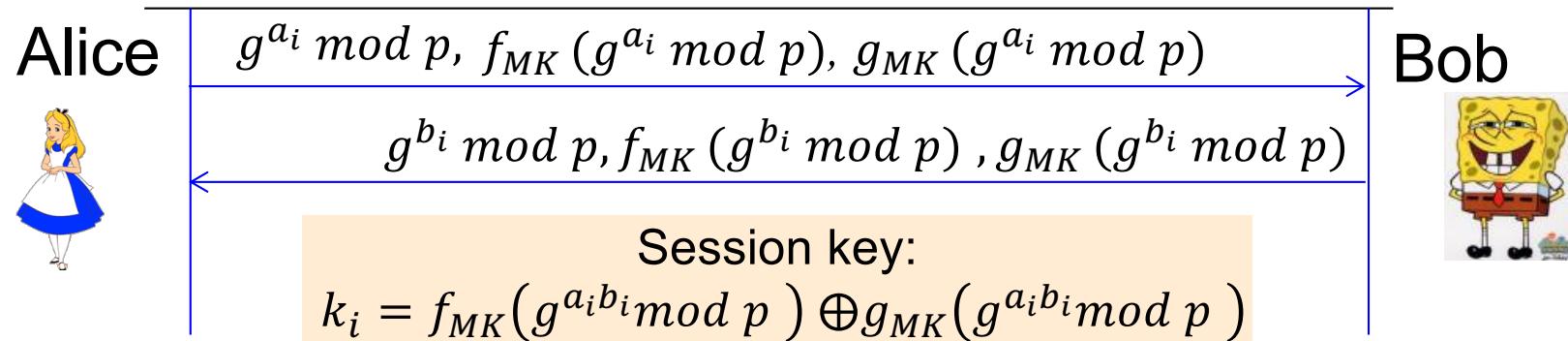
Notion	Session i is secure if keys not exposed, and...	Crypto
Secure key-setup	... attacker is given <u>session key</u> k_j ($j \neq i$). Master key never exposed !	 ey
Forward secrecy	... attacker is given all keys of sessions $> i$	 ey
Perfect Forward Secrecy (PFS)	... is also given all keys of sessions $< i$, <u>but only after session i ended</u>	 ey
Recover Security	... if no attack during session i , or if previous session, $i - 1$, is secure	No!
Perfect Recover Security (PRS)	... if no MitM attack during session i , or if previous session, $i - 1$, is secure	Why?



Exposing master key makes all future session vulnerable to MitM

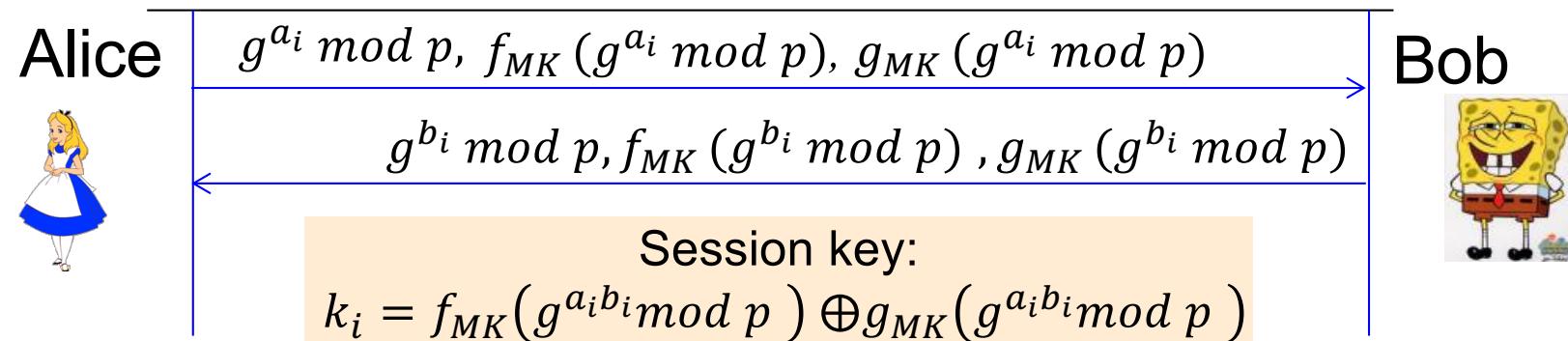
Exercise: what about this variant?

- Use two functions, f, g :



Exercise: what about this variant?

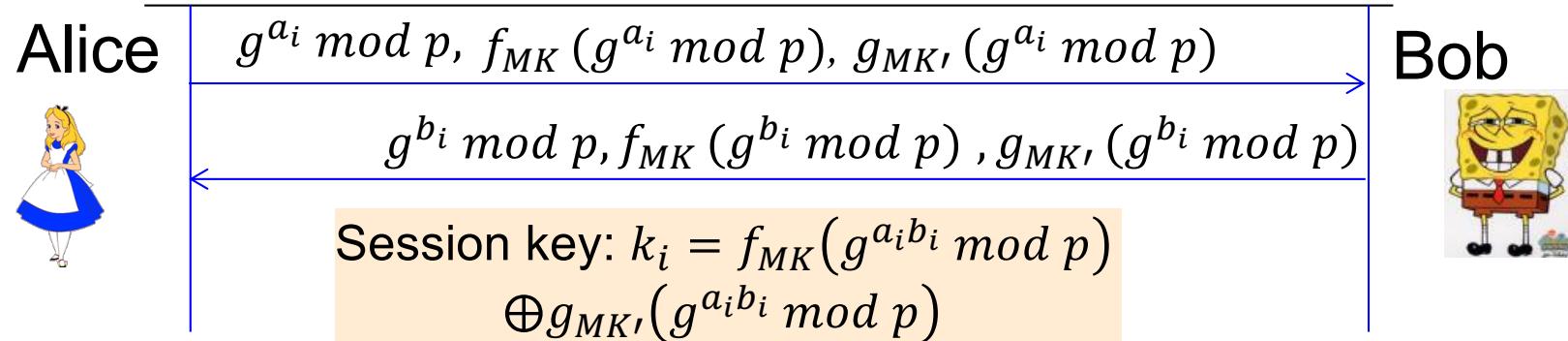
- Use two functions, f, g :



- Not secure !!
- Why?
 - Counterexample using secure f, g
- How to fix?

Exercise: what about this variant?

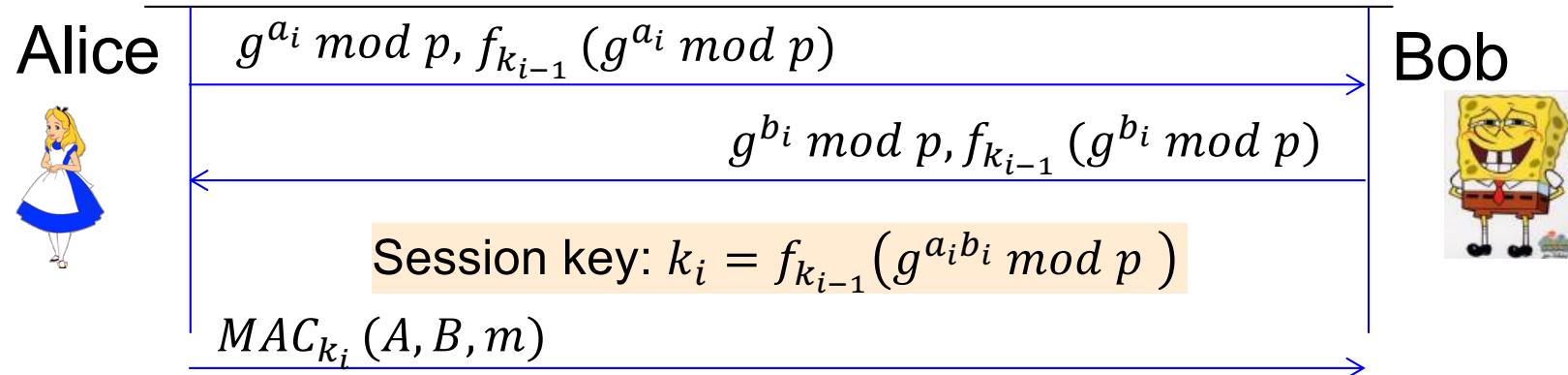
- Two master keys MK, MK' and functions, f, g :



- Secure
- Authentication is secure if either f, g is a MAC
- Key is pseudorandom if either:
 - MK, MK' are secret, random and f/g is PRF, or
 - MK, MK' are random and f / g is KDF and DH is hard

Perfect Recover Secrecy: Ratchet DH

- Extend Auth-DH to perfect recover secrecy (PRS)
 - Idea: avoid fixed master key; use 'ratchet' of keys



- PRS: session i secure, if previous session $(i - 1)$ secure, or if no MitM during session i
- Previous key k_{i-1} was secret \rightarrow session i was authenticated \rightarrow k_i is secret
 - Or: no MitM \rightarrow security due to DH

Ratchet-DH's Exposure-Resiliency

Notion	Session i is secure if keys not exposed, and...	Ratchet-DH
Secure key-setup	... attacker is given <u>session key</u> k_j ($j \neq i$). Master key never exposed !	
Forward secrecy	... attacker is given all keys of sessions $> i$	
Perfect Forward Secrecy (PFS)	... is also given all keys of sessions $< i$, <u>but only after session i ended</u>	
Recover Secrecy	... if no attack during session i , or if previous session, $i - 1$, is secure	
Perfect Recover Secrecy (PRS)	... if no MitM attack during session i , or if previous session, $i - 1$, is secure	

Covered Material From the Textbook

- Chapter 1: section 1.2
- Chapter 6: sections 6.1, 6.2, 6.3, and 6.4

Thank You!

