http://wwmsite.wpengine.com/wp-content/uploads/2011/12/Integrity-lion-300x222.jpg

Symmetric Encryption 2: Integrity

w/ material from Michelle Mazurek, Dave Levin, Jon Katz, David Brumley

Summing up (so far)

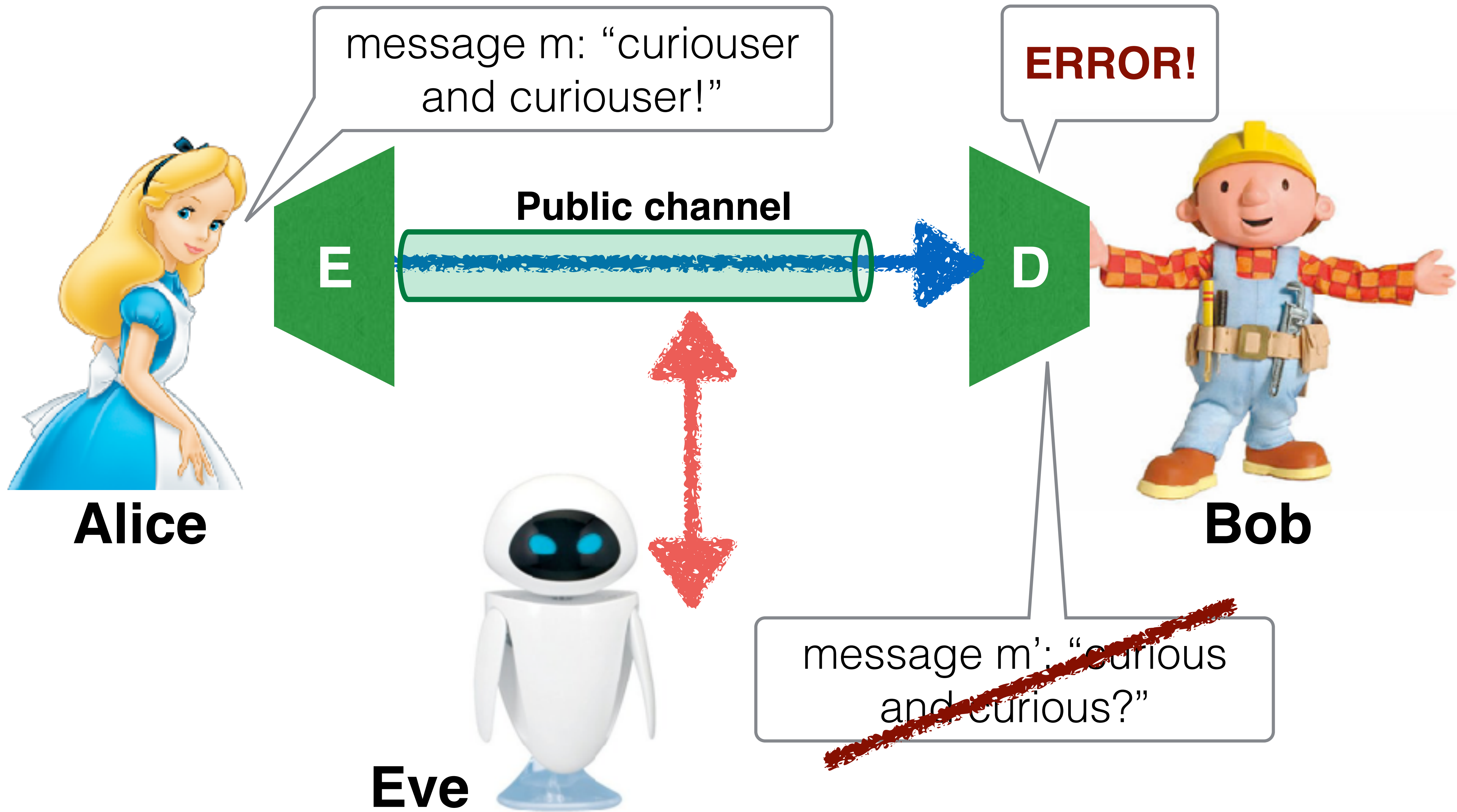
- Computational security
  - Adversary receives encryption of either m_0 or m_1
  - Can’t do better than guess which it is
- Secure PRF: Adversary can’t distinguish between PRF and actual random function
- Block ciphers: Secure when used properly (IVs!)
  - Multiple encryption modes

Message integrity and authentication

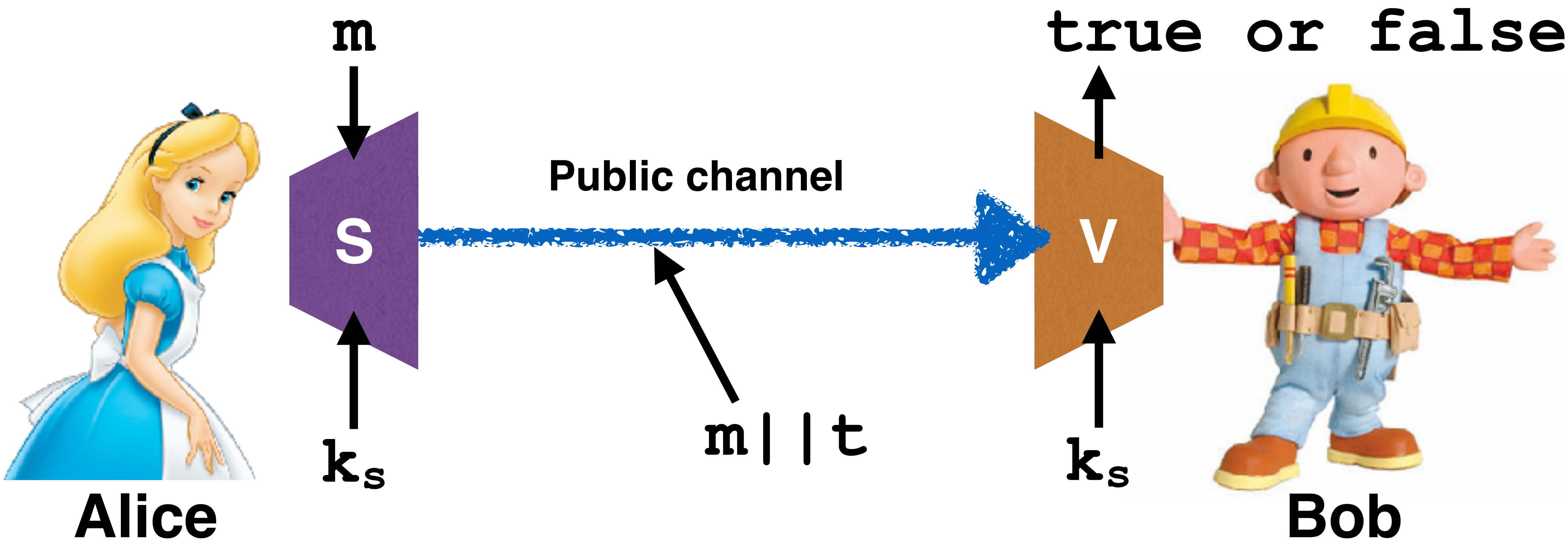
- Privacy and integrity are ***orthogonal***
    - Up to now we've had privacy without integrity
    - Now we will do integrity without privacy
    - And later, both at once
- Reminder: Goal is to ***detect*** tampering
    - Not to prevent it!

Goal: Integrity

Eve should not be able to alter *m* without detection.



Message authentication (MAC)



$t = \mathbf{S}ign(m, k_S)$ $\mathbf{V}erify(m,t,k_S)$?= true

Only someone who knows k_S could have sent the message!

Non-repudiation

- A special case of authentication
- Only Alice can have sent the message
  - Bob could not have made it up
  - Alice cannot effectively deny having sent it
- Why would you want this?

MAC definition

- $t{:}T = S(k,m)$
- $V(k,m,t)$ = yes or no
- $V(k, m, S(k,m))$ = yes

Straw example #1: CRC

- CRC = cyclic redundancy check
  - Binary division gives short, deterministic “summary” of data
- S(k,m) = CRC(m)
- What’s wrong with this plan?

MAC security

- Alice sends message m with tag t
- Attacker's power: Chosen plaintext
  - Can observe correct (m_i, t_i) pairs
  - Can use MAC oracle to get t_x for chosen m_x
- Attacker's goal: Generate some valid m', t' for m' not previously seen
  - m' does not have to make sense!
- Secure if: Pr[V(k, m', t') == yes] is very small

Called: Existential forgery

Replay attacks

- Does a MAC prevent a replay attack?

- NO — Must be prevented at a higher level
  - Application-dependent scenario
  - Nonce, timestamp, etc. (more later)

Straw example #2: Block cipher

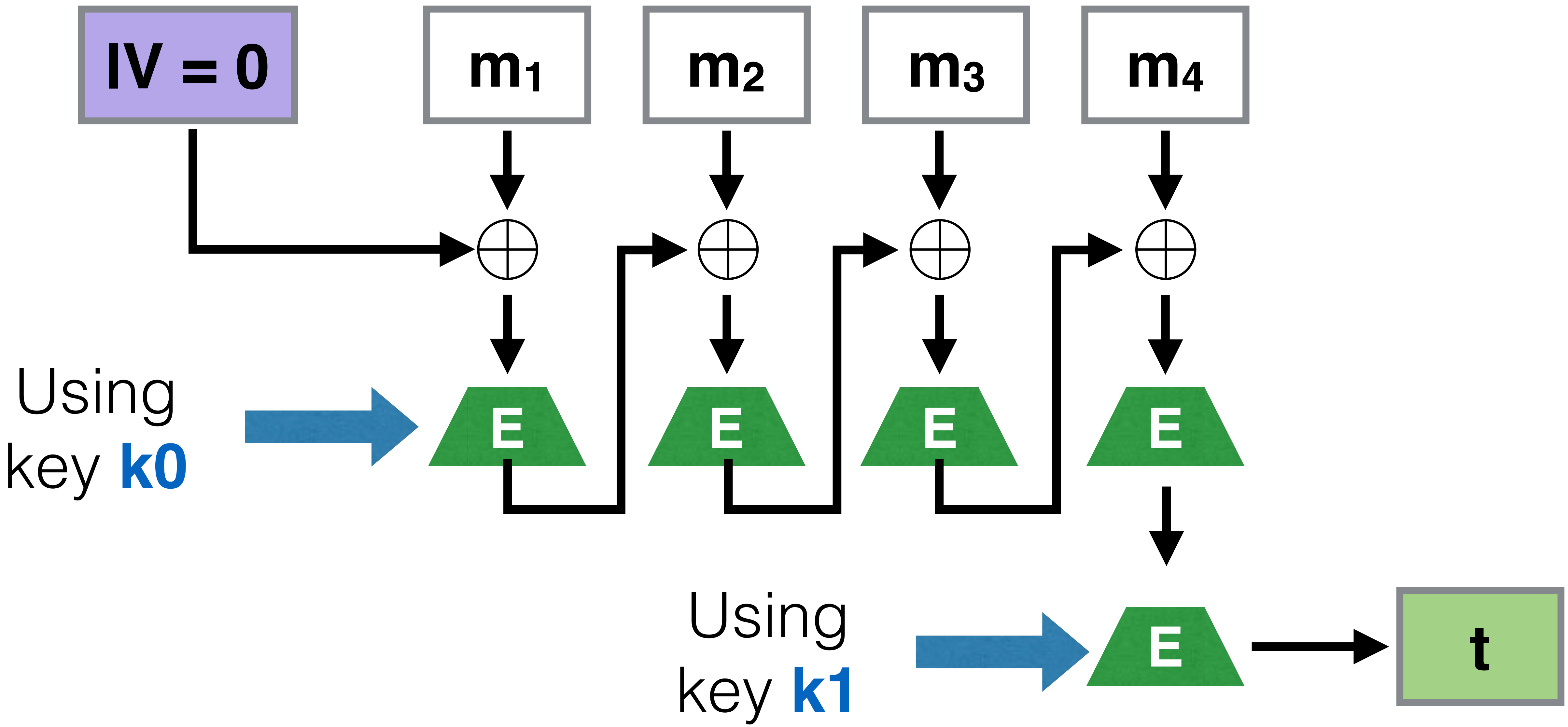
- Suppose message is exactly one block
- $t = S(k,m) = E(k,m)$
  - t is 128 bits long under AES
- Is this secure? Why?

Security sketch

- Since E(k,m) is a secure block cipher, can conceptually replace E(k,m) with a random permutation.
- Seeing $E(k,m_1)$ … $E(k,m_n)$ doesn't help predict unseen m_{n+1}
- Probability of a random guess is $1/2^L$
  - L = length of output tag (in bits)
  - Need to make sure L is long enough!

But this only works for tiny messages!

Encrypted CBC (ECBC)



Verify: Same algorithm as signing

ECBC vs. CBC

- Output only one block instead of many
  - Don’t need to recover the plaintext
  - AES => 2^{-128} chance of guessing
- We used two keys
  - Necessary to prevent existential forgery
- Both require serial computation

Why two keys?

- Attacker requests tag for message m (m_1 .. m_n)
  - Get corresponding tag t = c[n]
- Attacker creates message m' (one block long)
  - Request tag t' for (t XOR m')
- Resulting t' is valid for m || m'

Uh oh.

MACs with Hashes

Hash functions

- A pseudorandom, one-way function
    - ***Does not*** require a key
- H(m) = h
    - Input m = ***pre-image***, can be arbitrary length
    - Output h = ***digest*** or ***hash***, fixed small length
- Generally very fast to compute

Cryptographic hash

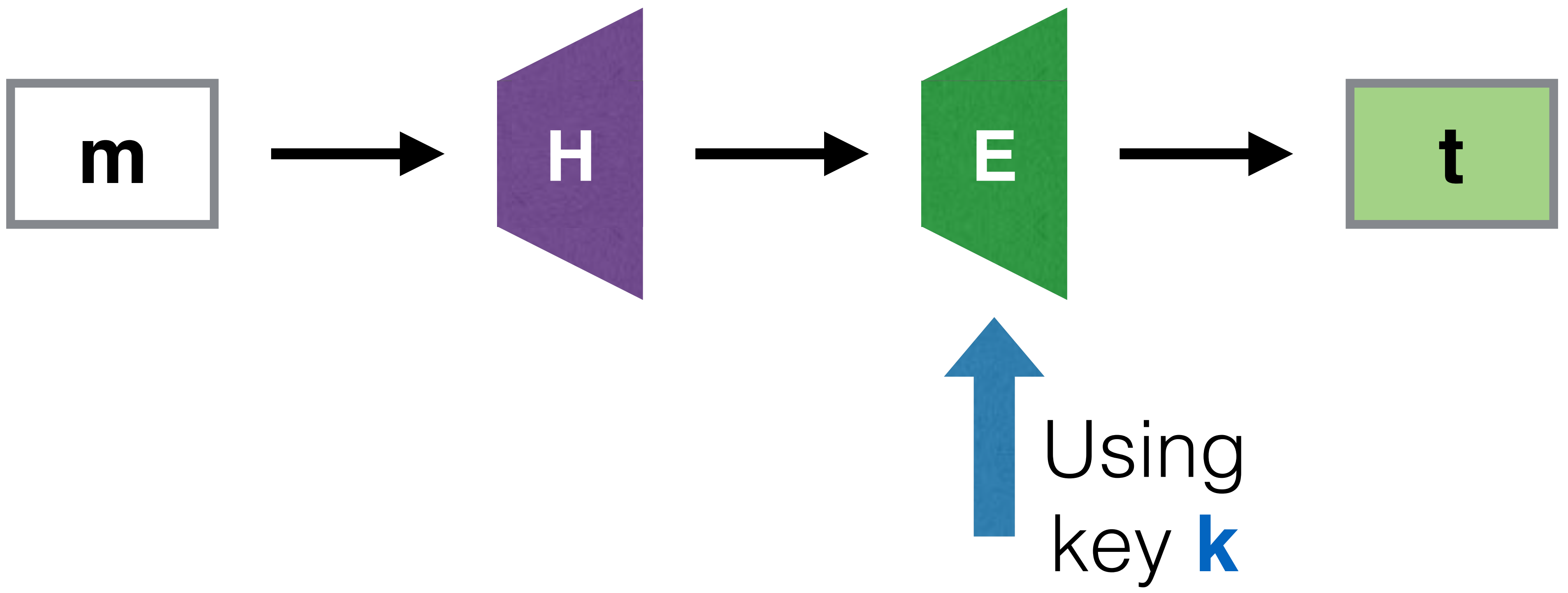
- ***Pre-image resistance***:
  - Given H(m), it's hard to find m
- ***Collision resistant***:
  - Given H(m), it's hard to find m' s.t.
    - m' != m
    - H(m') = H(m)
  - ***Even more***: Pr[any bit matching] = 1/2

Example hash functions

- MD5: Known collision attacks, still frequently used
- SHA-1, SHA-256, SHA-512, etc.
  - SHA1 is theoretically broken
- New SHA-3 (224, 256, 385, 512)
  - Public contest 2007-2012
  - Officially standardized August 2015

Hash-MAC

- Most widely used MAC on internet
- General idea: hash then PRF (short MAC)
  - Translate arbitrary message into one block
  - Works if H and E are both secure



Aside: Birthday paradox

- How likely 2 people in a room share a birthday?
  - Pr > 50% with 23 people!
  - Why? There are n^2 different pairs
- With X possibility space and n samples:
  - $Pr[x_i = x_j] \sim 50\%$ when $n = X^{1/2}$
- Upshot: May need to change keys frequently

Integrity vs. Authentication

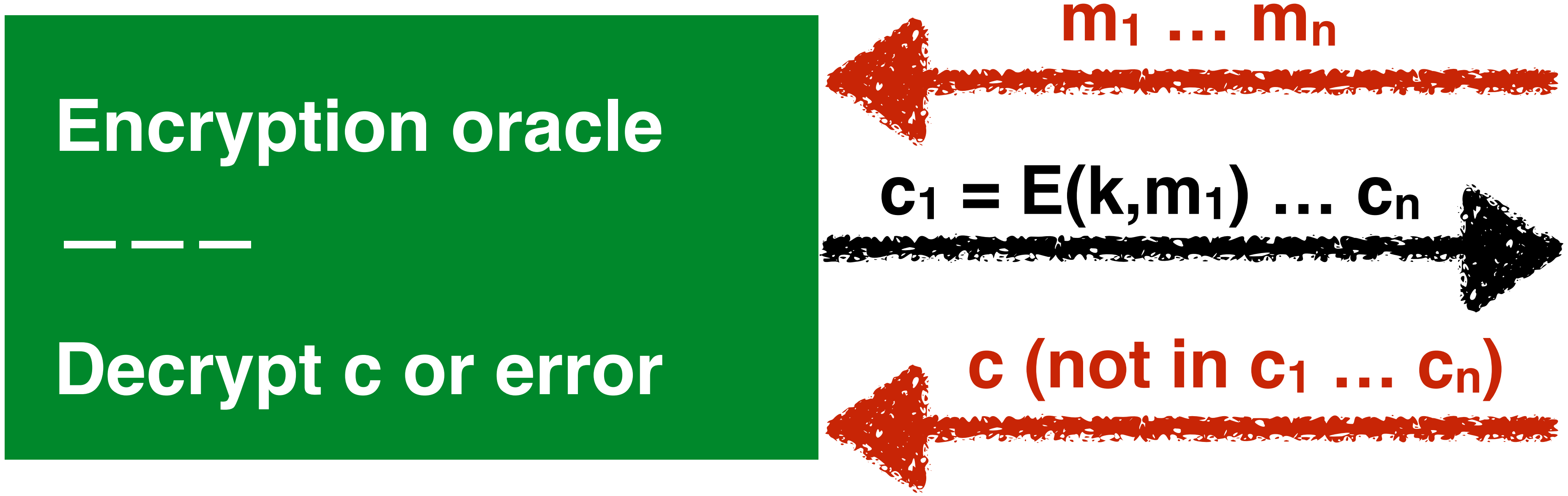
- Recall: What is the difference?
  - Don’t forget non-repudiation
- Do symmetric MACs like ECBC and Hash-Mac give one, or both? Which?
- Problem: ***More than one person*** knows the key

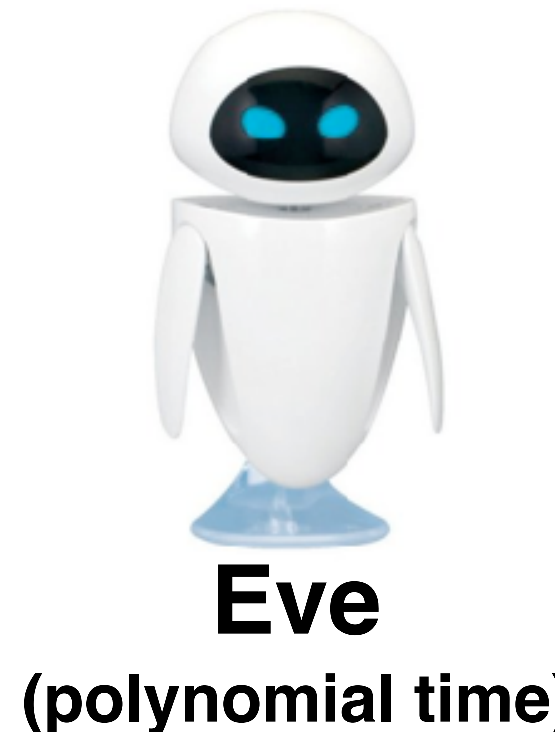
Authenticated Encryption

- Previously:
    - Privacy / secrecy
    - Integrity
- Now: Both at once

Ciphertext integrity

- Maintain semantic secrecy under CPA attack
- Attacker ***cannot create a new ciphertext*** that decrypts properly!

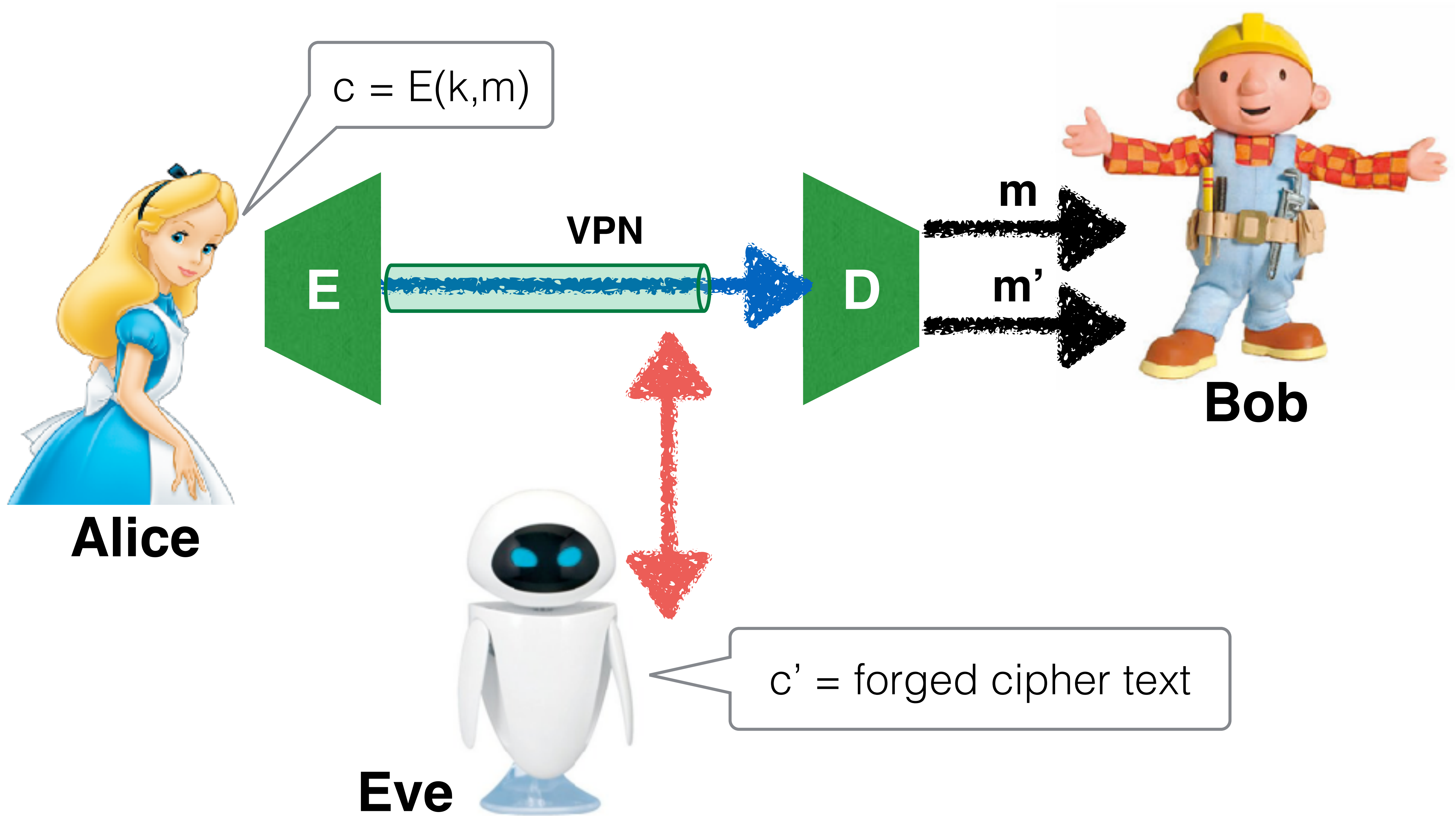




Ciphertext integrity IFF prob. of decryption without error is very small

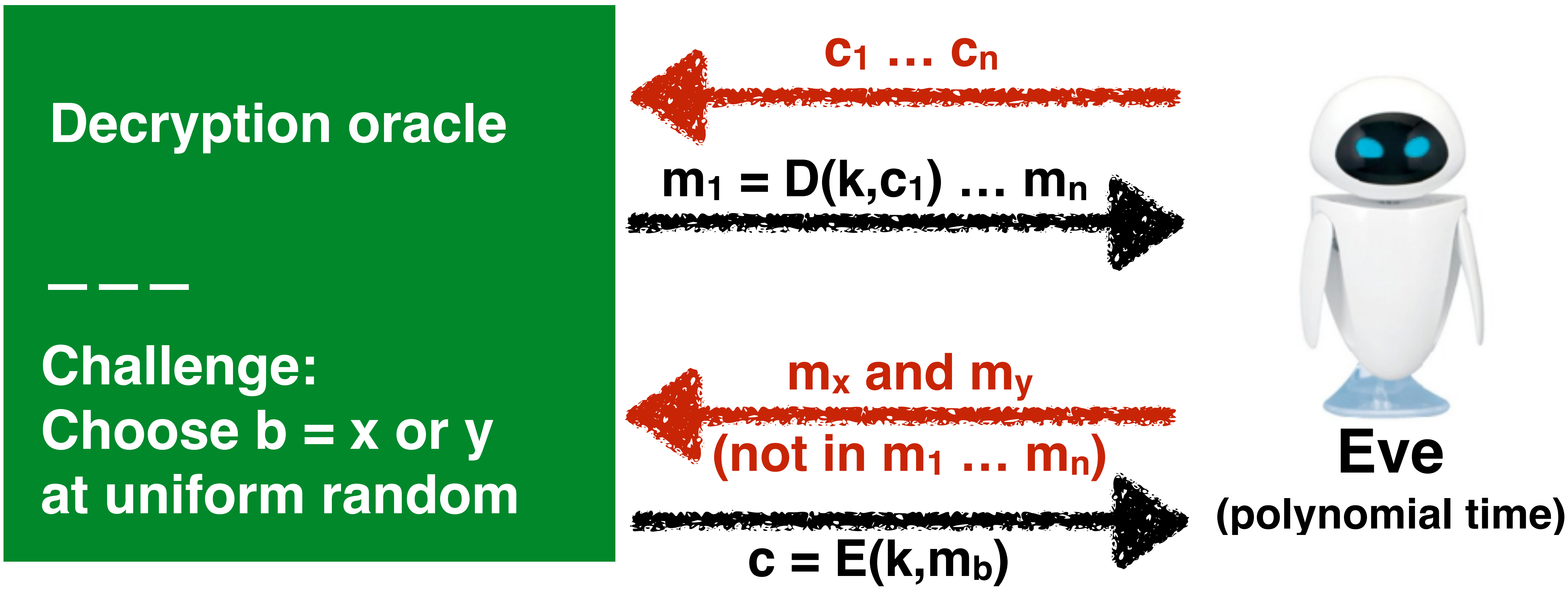
CCA revisited

Eve can get a cipher text decrypted



CCA game

- Attacker gets encryption oracle + decryption oracle
  - (Encryption oracle not shown)



Eve's job: Guess whether x or y was picked. CCA-secure IFF no better than guessing

CBC is not CCA-secure

Challenge:
Choose b = x or y at uniform random
— — —

Decryption oracle

m_x and m_y

$|m_x| = |m_y| = 1$ blk

$c = E(k,m_b) = IV \,||\, c[0]$

$c' = (IV \text{ xor } 1) \,||\, c[0]$

$m' = D(k,c') = m_b \text{ xor } 1$

Eve
(polynomial time)

Uh oh.

Ciphertext integrity (aka authenticated encryption) ***can protect*** against CCA!

Because only someone who knows *k* can send a message that will decrypt properly.

Auth. Encr. limitations

- Does not protect against replay
- Does not protect against e.g. timing attacks

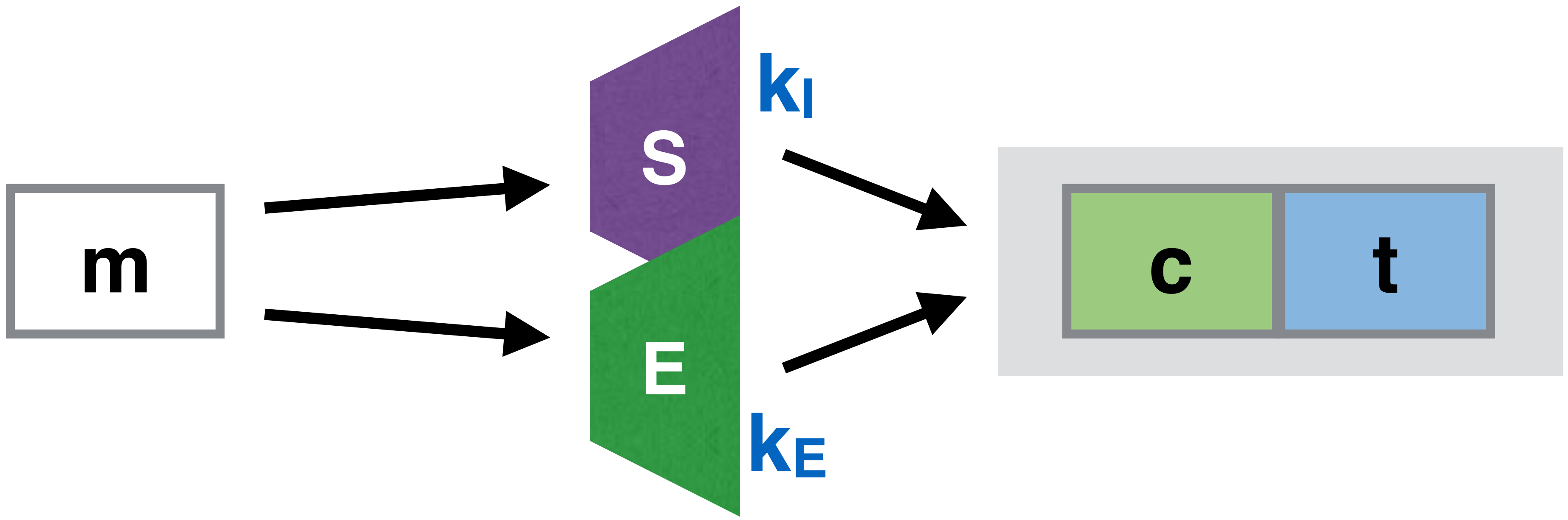
Constructing authenticated encryption

Three basic options

Can you guess?

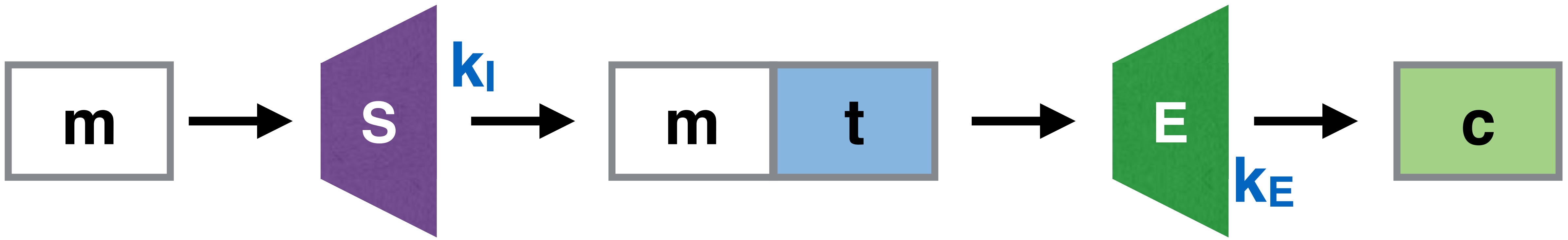
- Encrypt and MAC
- MAC **then** encrypt
- Encrypt **then** MAC

Encrypt and MAC



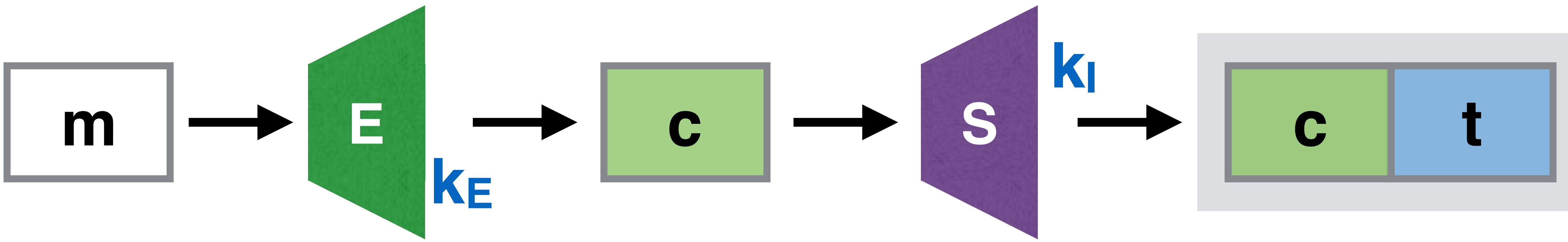
- Send E(m) || MAC(m)
- This is not secure b/c MAC may leak information about the message
  - Secrecy is not a MAC property

MAC then encrypt



- Send E(m || MAC(m))
- This can be insecure in some combinations
  - Always follow standards!

Encrypt then MAC

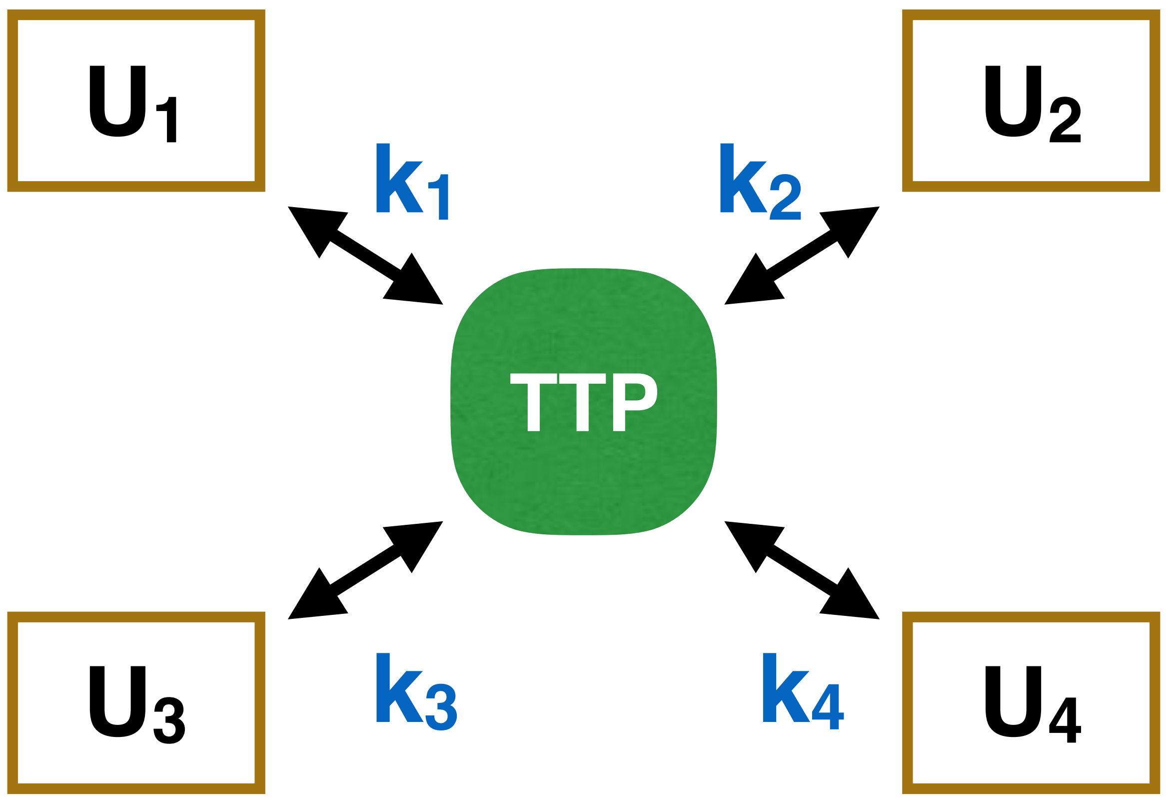


- Send E(m) || Mac(E(m))
- This is **always secure**! Intuition:
  - MAC reveals only info about ciphertext (OK)
  - MAC ensures ciphertext has not been tampered

Key exchange

- Up to now, we have assumed Alice and Bob share a secret key
- How did that happen?
- How does this scale to many users?

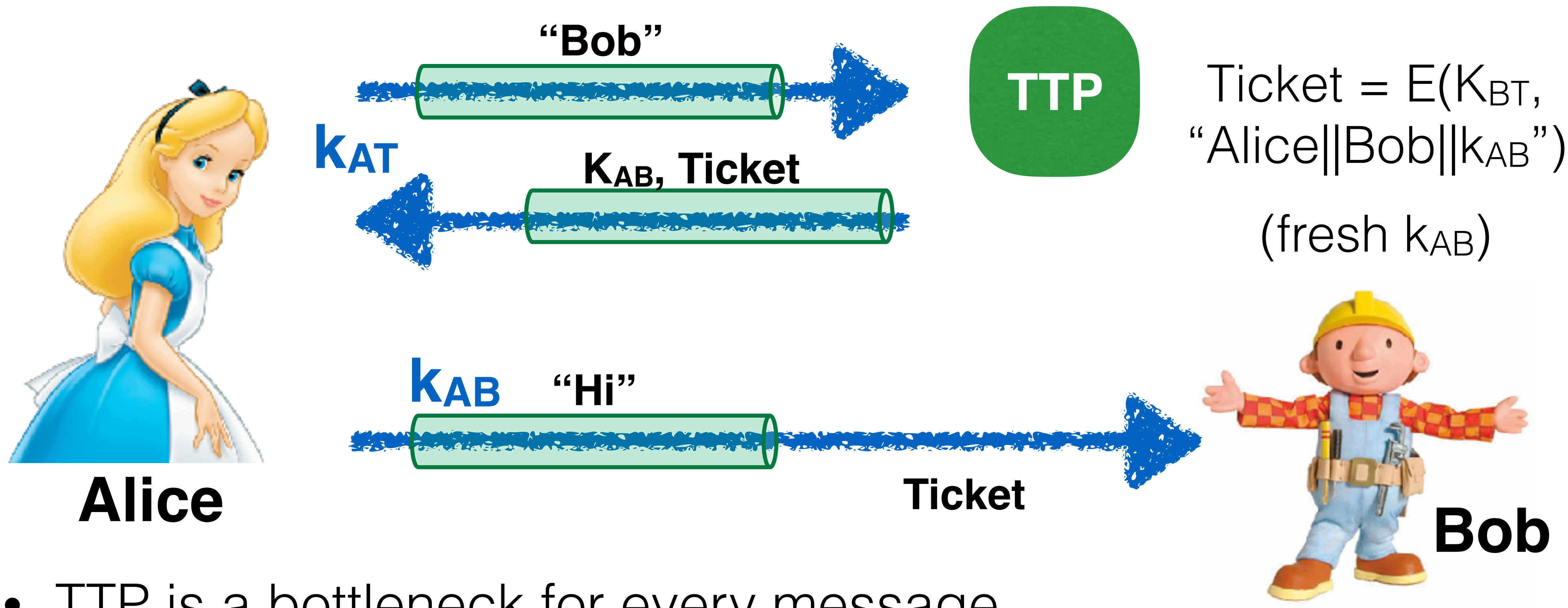
One solution: Trusted third party (TTP)



- TTP is a bottleneck for every message
- TTP must be online at all times
- TTP can read every message
- Does not solve bootstrapping problem

Session keys and tickets

Used for Kerberos



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