Security and Privacy in IoT
CSE 708 Fall 2021

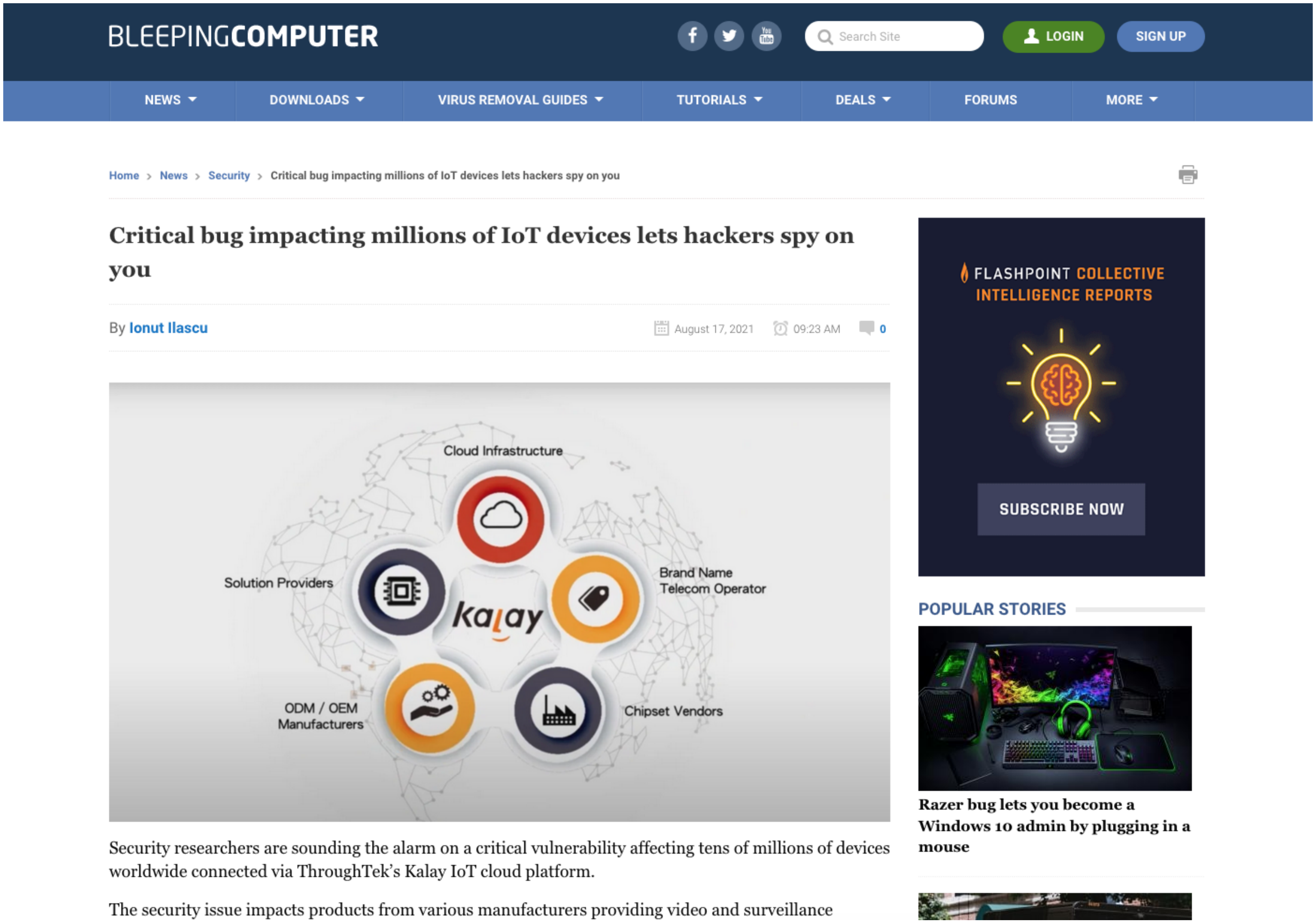
Fundamental Security and Cryptography Concepts

Department of Computer Science and Engineering
University at Buffalo

IoT and Security

- Why do we talk about Internet of Things and security?

IoT Security Breaches



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Critical bug impacting millions of IoT devices lets hackers spy on you

By Ionut Ilascu August 17, 2021 09:23 AM 0

Security researchers are sounding the alarm on a critical vulnerability affecting tens of millions of devices worldwide connected via ThroughTek's Kalay IoT cloud platform.

The security issue impacts products from various manufacturers providing video and surveillance

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SECURITY & PRIVACY

Warning: Bug allows complete takeover of dozens of popular routers

BY JAMES GELINAS, KOMANDO.COM • JUNE 20, 2020 SHARE:

Your router plays multiple roles in keeping your home network together. Not only does it connect all of your

Security Objectives

- Fundamental security objectives
  - Confidentiality (C): confidential or private information is not disclosed or made available to unauthorized parties
  - Integrity (I) : unauthorized modification of data is not permitted
  - Availability (A): resources are promptly available to authorized parties
- Confidentiality covers data confidentiality and privacy
- Integrity covers data integrity and system integrity

More on Security Objectives

- Other security concepts
  - Authenticity: the property of being genuine and being able to be verified and trusted
    - entity authentication: the entity is who it claims it is
    - data authentication: the data is coming from a trusted source
  - Access control: only authorized parties can use specific resources in compliance with their privileges
  - Non-repudiability (repudiability): inability (ability) to deny communication or actions
  - Accountability: the requirement that all actions of an entity are traced uniquely to that entity
    - covers non-repudiability, intrusion detection, fault isolation, etc.

Symmetric Encryption

- A computationally secure symmetric key encryption scheme is defined as:
  - a private-key encryption scheme consists of polynomial-time algorithms (Gen, Enc, Dec) such that
    1. Gen: on input the security parameter 1^n, outputs key k
    2. Enc: on input a key k and a message $m \in \{0,1\}^*$, outputs ciphertext c
    3. Dec: on input a key k and ciphertext c, outputs plaintext m (or fails)
  - we write $k \leftarrow \mathsf{Gen}(1^n)$, $c \leftarrow \mathsf{Enc}_k(m)$, and $m := \mathsf{Dec}_k(c)$
    - this notation means that Gen and Enc are probabilistic and Dec is deterministic

Symmetric Encryption

- Types of attacks
  - ciphertext only attack: adversary knows a number of ciphertexts
  - known plaintext attack: adversary knows some pairs of ciphertexts and corresponding plaintexts
  - chosen plaintext attack: adversary knows ciphertexts for messages of its choice
  - chosen ciphertext attack: adversary knows plaintexts for ciphertexts of its choice
- A standard minimum expected security is indistinguishable encryption under a chosen plaintext attack

Symmetric Encryption

- Symmetric encryption today would be instantiated with AES (Advanced Encryption Standard)
  - must use one of the secure encryption modes
  - a secure authenticated encryption mode can be used if confidentiality and integrity are simultaneously desired

Message Authentication Codes

- A MAC scheme is defined by three algorithms:
  - key generation: a randomized algorithm, which on input a security parameter 1^n, produces key a k
  - MAC generation: a possibly randomized algorithm, which on input a message m and key k, produces a tag t
  - MAC verification: a deterministic algorithm, which on input a message m, tag t, and key k, outputs a bit b

Message Authentication Codes

- We desire for a MAC to be existentially unforgeable under an adaptive chosen-message attack
  - an adversary is allowed to query tags on messages of its choice
  - at some point it outputs a pair (m, t)
  - the forgery is considered successful if m hasn't been queried before and t is a valid tag for it
  - as with encryption, security guarantees depend on the security parameter
- The most popular MAC instantiation is HMAC

Hash Functions

- A hash function h is an efficiently-computable function that maps an input x of an arbitrary length to a (short) fixed-length output $h(x)$

- h must satisfy the following security properties:

  – Preimage resistance (one-way): given $h(x)$, it is difficult to find x

  – Second preimage resistance (weak collision resistance): given x, it is difficult to find x' such that $x' \neq x$ and $h(x') = h(x)$

  – Collision resistance (strong collision resistance): it is difficult to find any x, x' such that $x' \neq x$ and $h(x') = h(x)$

Hash Functions

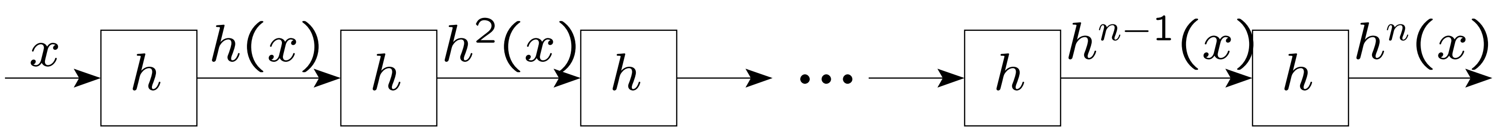
- Generic brute force attacks on hash functions with n-bit output have the following complexity
  - difficulty of finding a preimage is 2^n
  - difficulty of finding a second preimage is 2^n
  - difficulty of finding a collision with at least 50% probability is about $2^{n/2}$
  - all properties are desired for a general-use hash function
- Today a hash function is instantiated with SHA-2 (SHA-256 or higher) or SHA-3

Other Uses of Hash Functions

- Hash Chains
  - a method for authenticating multiple user logins or packet streams
  - consists of successive application of a hash function to a string
  - n applications of the hash function on x is denoted by $h^n(x)$
  - this produces a hash chain of length n
- Example:
  - $h^4(x) = h(h(h(h(x))))$ produces a hash chain of length 4

Hash Chains

- Authentication using hash chains
  - user generates a hash chain of length n
  - at time 1, the user sends $auth_1 = h^n(x)$ (and possibly authenticates it through other means)
  - the recipient stores $auth = auth_1$
  - at time 2, the user sends $auth_2 = h^{n-1}(x)$
  - the recipient checks whether $h(auth_2) = auth_1$ and, if so, accepts
  - the recipient updated $auth = auth_2$
  - etc.

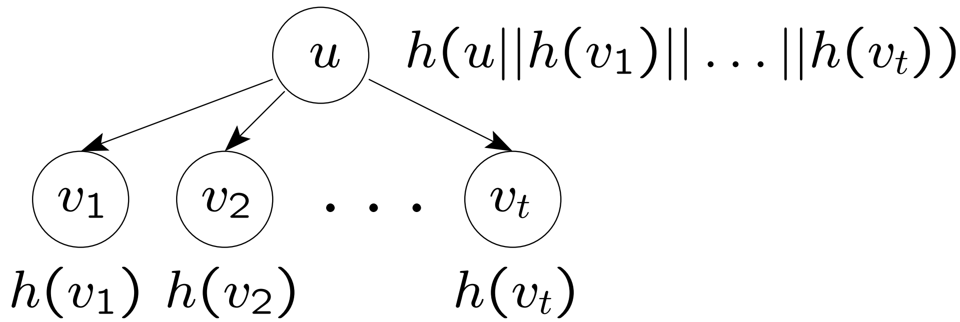


Merkle Hash Trees

- Merkle Hash Tree
  - integrity verification mechanism for hierarchically structured documents or databases
  - the technique works on trees only
  - the hash of the tree is computed in the bottom-up fashion
- Generation of a Merkle hash tree
  - for a leaf node v, simply compute its hash $h(v)$
  - for a non-leaf node u with children $v_1, \ldots, v_t$, compute its hash as $h(u||h(v_1)||\ldots||h(v_t))$

Merkle Hash Trees

- Merkle Hash Tree



  – this computation continues until the hash of the root is computed

  – the hash of the root corresponds to the hash of the entire tree

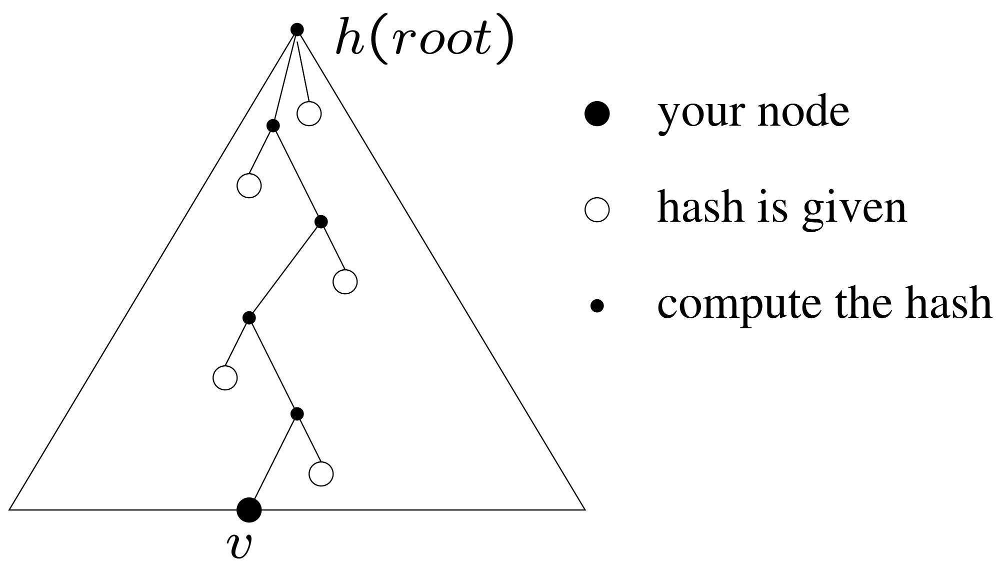
- Integrity verification

  – node integrity verification is much faster than hashing the entire tree

  – to check node v, obtain hashes of the nodes on the path from v to the root

Merkle Hash Trees

- Integrity verification in Merkle Hash Tree



  - compute the hash of v and combine it with other hashes on the path to the root
  - compare your hash of the root with what you are given
  - the node you are authenticating doesn't have to be a leaf

Pseudorandom Generator

- Let G be a (deterministic) algorithm that on input n-bit string s outputs a string of length $\ell(n)$
- G is a pseudorandom generator if the following is true:
  1. (expansion) for any n, output is longer than input: $\ell(n) > n$
  2. (pseudorandomness) any PPT distinguisher D can't tell the difference with non-negligible probability:

     $$|\mathsf{Pr}[D(r) = 1] - \mathsf{Pr}[D(G(s)) = 1]| \leq \mathsf{negl}(n)$$

     where r and s are random strings of size $\ell(n)$ and n
- The seed s must be treated similar to a key

Pseudorandom Function

- An efficient function $F : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}^n$ is a pseudorandom function if any PPT distinguisher D cannot tell apart outputs of F_k and f, i.e.,

$$|\Pr[D^{F_k(\cdot)}(1^n) = 1] - \Pr[D^{f(\cdot)}(1^n) = 1]| \leq \mathsf{negl}(n)$$

  for a uniformly chosen function $f : \{0,1\}^n \to \{0,1\}^n$ and uniformly chosen key $k \leftarrow \{0,1\}^n$

- A typical instantiation of a PRF is AES

- A PRF can also be used to build a PRG
  - define $\mathsf{PRG}(k) := \mathsf{PRF}_k(0)||\mathsf{PRF}_k(1)||\ldots$

Public Key Encryption

- A public-key encryption scheme consists of three algorithms (Gen, Enc, Dec) such that:

  1. key generation Gen, on input security parameter 1^n, outputs a public-private key pair (pk, sk)
  2. encryption Enc, on input public key pk and messages m from the message space, outputs ciphertext $c \leftarrow \mathsf{Enc}_{pk}(m)$
     - message space often depends on pk
  3. decryption Dec, on input private key sk and ciphertext c, outputs a message $m := \mathsf{Dec}_{sk}(c)$ or a special failure symbol $\perp$.

- As before, the minimum security expectation is indistinguishability under a chosen-plaintext attack

Digital Signatures

- A signature scheme is defined by three algorithms $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ such that:

  1. key generation algorithm Gen, on input a security parameter 1^n, outputs a key pair (pk, sk), where pk is the public key and sk is the private key.

  2. signing algorithm Sign, on input a private key sk and message $m \in \{0, 1\}^*$, outputs a signature σ, i.e., $\sigma \leftarrow \mathsf{Sign}_{sk}(m)$

  3. verification algorithm Vrfy, on input a public key pk, a message m, and a signature σ, outputs a bit b, where $b = 1$ means the signature is valid and $b = 0$ means it is invalid, i.e., $b := \mathsf{Vrfy}_{pk}(m, \sigma)$

- We'll want to achieve the same level of security as for MACs: existential unforgeability under an adaptive chosen-message attack

Groups

- A group G is a set of elements together with a binary operation $\circ$ such that
  - the set is closed under the operation $\circ$, i.e., for every $a, b \in G$, $a \circ b$ is a unique element of G
  - the associative law holds, i.e., for all $a, b, c \in G$, $a \circ (b \circ c) = (a \circ b) \circ c$
  - the set has a unique identity element e such that $a \circ e = e \circ a = a$ for every $a \in G$
  - every element has a unique inverse a^{-1} in G such that $a \circ a^{-1} = a^{-1} \circ a = e$

Groups

- Size of a group
  - a group is finite if it has only a finite number of elements
  - the number of elements of a finite group is called the order of the group
- The multiplicative group modulo m is denoted by $\mathbb{Z}_m^*$
- A cyclic group is one that contains an element a whose powers (using multiplicative notation of group operation) a^i and a^{-i} make up the entire group
- An element a with such property is called a generator of the group

Discrete Logarithm Problem

- Discrete logarithms
  - we are given a cyclic group G of order q
  - then there exists an element $g \in G$ such that $G = \langle g \rangle = \{g^i : 0 \leq i \leq q - 1\}$
  - for each $h \in G$ there is a unique x such that $g^x = h$
  - such x is called the discrete logarithm of h with respect to g and we use $x = \log_g h$
- The discrete logarithm problem
  - in a cyclic group G with given generator g, compute unique $\log_g h$ for a random element $h \in G$

Discrete Logarithm Problem

- Groups in which the discrete logarithm problem is hard
  - multiplicative group over $\mathbb{Z}_p^*$ with prime p with certain constraints on the order of the group
  - a subgroup of the above
    - this will allow us to produce a group of prime order q
  - an elliptic curve group modulo a prime p

Diffie-Hellman Key Exchange

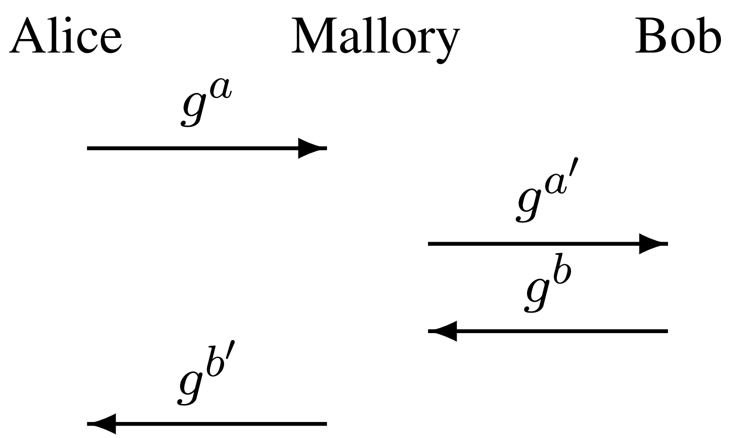
- Diffie-Hellman key exchange protocol
  - Alice and Bob want to compute a shared key unknown to eavesdroppers
  - Alice and Bob share public parameters: a group G of order q and a generator g
  - Alice randomly chooses $x \in \mathbb{Z}_q$ and sends g^x to Bob: $A \xrightarrow{g^x} B$
  - Bob randomly chooses $y \in \mathbb{Z}_q$ and sends g^y to Alice: $A \xleftarrow{g^y} B$
  - the shared secret is set to g^{xy}
    - Alice computes it as $(g^y)^x = g^{xy}$
    - Bob computes it as $(g^x)^y = g^{xy}$
  - it is believed to be infeasible for an eavesdropper to compute g^{xy} given g^x and g^y

Diffie-Hellman Key Exchange

- Diffie-Hellman key exchange protocol
  - Alice and Bob are able to establish a shared secret with no prior relationship
  - it is believed to be infeasible for an eavesdropper to compute g^{xy} given g^x and g^y
- Diffie-Hellman problem
  - Computational Diffie-Hellman (CDH) problem
    - given g, g^x and g^y, compute g^{xy}
  - Decision Diffie-Hellman (DDH) problem
    - given g, g^x, g^y, and g^z, determine whether $xy = z$ (modulo q)

Diffie-Hellman Key Exchange

- Man-in-the-middle attack on Diffie-Hellman key exchange



  - Alice shares the key $g^{ab'}$ with Mallory
  - Bob shares the key $g^{a'b}$ with Mallory
  - Alice and Bob do not share any key

- A solution is to build an authenticated Diffie-Hellman key exchange

Diffie-Hellman Key Exchange

- Certificates can be used to aid authentication
  - each user U has a private signing key sk_U and the corresponding public verification key pk_U
  - there is a trusted authority TA that signs keys
  - user U holds a certificate $\mathsf{cert}(U)$ issued by the TA

$$\mathsf{cert}(U) = (U, pk_U, \sigma_{TA}(U, pk_U))$$

- Signatures and certificates can be used to strengthen Diffie-Hellman key exchange
  - different versions of authenticated Diffie-Hellman key exchange are used including in TLS

Bilinear Maps

- A one-way function $e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}_T$ is a bilinear map if the following conditions hold:
  - (Efficient) $\mathbb{G}_1$, $\mathbb{G}_2$, and $\mathbb{G}_T$ are groups of the same prime order p, and there exists an efficient algorithm for computing e.
  - (Bilinear) For all $g \in \mathbb{G}_1$, $\tilde{g} \in \mathbb{G}_2$, and $a, b \in \mathbb{Z}_p$, $e(g^a, \tilde{g}^b) = e(g, \tilde{g})^{ab}$.
  - (Non-degenerate) If g generates $\mathbb{G}_1$ and $\tilde{g}$ generates $\mathbb{G}_2$, then $e(g, \tilde{g})$ generates $\mathbb{G}_T$.
- Bilinear maps are also called groups with pairings

Commitments

- Commitment schemes
  - a commitment scheme allows one to "commit" to a message m by computing a committed value com
  - it can later be opened to reveal m
  - the following properties are required to hold:
    - hiding property: commitment com reveals nothing about message m
    - binding property: it is infeasible to find another message $m' \neq m$ such that com can be opened to m'

Commitments

- A commitment scheme is defined by three algorithms
  - Gen: randomized algorithm that takes a security parameter 1^n and outputs public parameters params
  - Com: randomized algorithm that takes params and a message $m \in \{0,1\}^n$ and outputs commitment com
    - we make the randomness that Com uses explicit, denote it by r, and use $\mathsf{com} = \mathsf{Com}(\mathsf{param}, m, r)$
  - Open: a deterministic algorithm that decommits to m by typically disclosing m and r
    - the verifier that check whether com is in fact equal to $\mathsf{Com}(\mathsf{params}, m, r)$

Commitments

- We can use hash functions to create a commitment scheme (in the random oracle model):
  - Gen takes a security prameter 1^n and chooses an appropriate hash funcion h
  - to commit to m, choose uniform $r \in \{0,1\}^n$ and output $\mathsf{Com}(m,r) := h(m||r)$
  - hiding follows because adversary can query $h(*||r)$ with only a negligible probability
  - binding follows from the collision resistance property of h
- A popular number-theoretic commitment is Pedersen commitment of the form $\mathsf{Com}(m,r) = g^m h^r$ in a DDH group

Homomorphic Encryption

- Homomorphic encryption allows for computing on encrypted data without access to the underlying plaintexts
  - it is a special type of encryption that, given ciphertexts, permits computation on the underlying plaintexts

$$\mathsf{Enc}_k(m_1) \otimes \mathsf{Enc}_k(m_2) = \mathsf{Enc}_k(m_1 \oplus m_2)$$

  - homomorphic encryption enables computation on encrypted data and results in efficient protocols for certain problems
  - besides Gen, Enc, and Dec, additional algorithm(s) specify how to use homomorphic properties

Homomorphic Encryption

- We'll look at two types of public-key homomorphic encryption
- The first type is called partially homomorphic encryption (or just HE for short) and comes with one homomorphic operation
  - of most significant importance to us is the ability to add (integer) values inside ciphertexts
  - we have $\mathsf{Enc}_{pk}(m_1) \cdot \mathsf{Enc}_{pk}(m_2) = \mathsf{Enc}_{pk}(m_1 + m_2)$
  - which in turn implies $\mathsf{Enc}_{pk}(m)^c = \mathsf{Enc}_{pk}(m \cdot c)$
  - Paillier encryption scheme (1999) is a popular cryptosystem of this type

Homomorphic Encryption

- The second type is called fully homomorphic encryption (FHE)
  - it supports two types of operations on ciphertexts: addition and multiplication
  - this type enables any function to be evaluated on encrypted data
  - this is suitable for secure computation outsourcing to a single server
- The drawback of FHE is its speed
  - it is not always suitable for moderate or large functions or amounts of data

Summary

- There are many different types of tools which can be used to build secure solutions
- We'll explore them as part of this course