Cryptographic Hash Functions
Part I

Cryptography 1

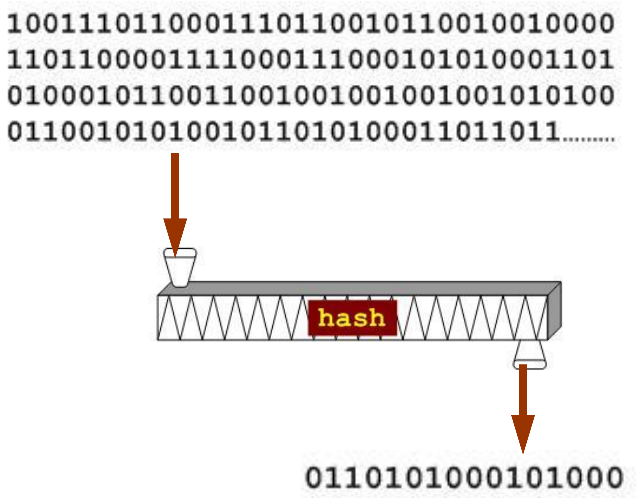
Andreas Hülsing, TU/e
Based on slides by Sebastiaan de Hoogh, TU/e

how are hash functions used?

- integrity protection
  - strong checksum
  - for file system integrity (Bit-torrent) or software downloads
- password hashing
  - “one-way encryption” (≠ encryption !!!)
  - dedicated algorithms like scrypt / argon2 use HF as building block
- digital signature (asymmetric)
- MAC – message authentication code (symmetric)
  - Efficient symmetric ‘digital signature’
- key derivation
- pseudo-random number generation
- …

what is a hash function?

- $\mathrm{h}: \{0,1\}^* \rightarrow \{0,1\}^n$
  (general: $\mathrm{h}: S \rightarrow \{0,1\}^n$ for some set S)
- **input**: bit string *m* of arbitrary length
  - length may be 0
  - in practice a very large bound on the length is imposed, such as 2^{64} (≈ 2.1 million TB)
  - input often called the *message*
- **output**: bit string *h*(*m*) of fixed length *n*
  - e.g. *n* = 128, 160, 224, 256, 384, 512
  - *compression*
  - output often called *hash value*, *message digest*, *fingerprint*
- *h*(*m*) is easy to compute from *m*
- no secret information, no secret key



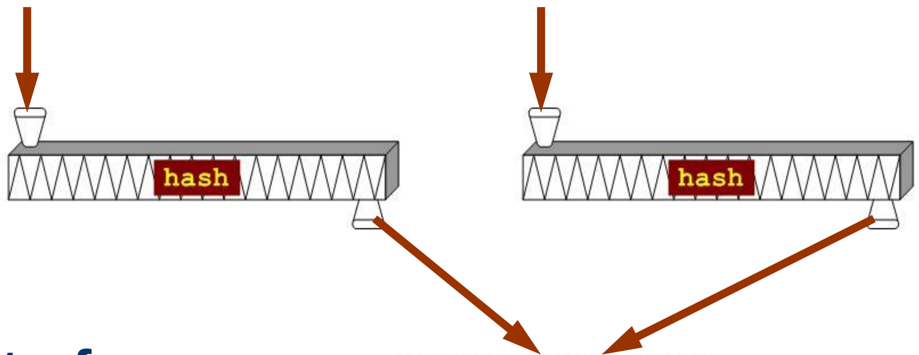
hash collision

- m_1, m_2 are a *collision* for h if

  $h(m_1) = h(m_2)$ while $m_1 \neq m_2$

I owe you € 100 I owe you € 5000

different documents



0110101000101000

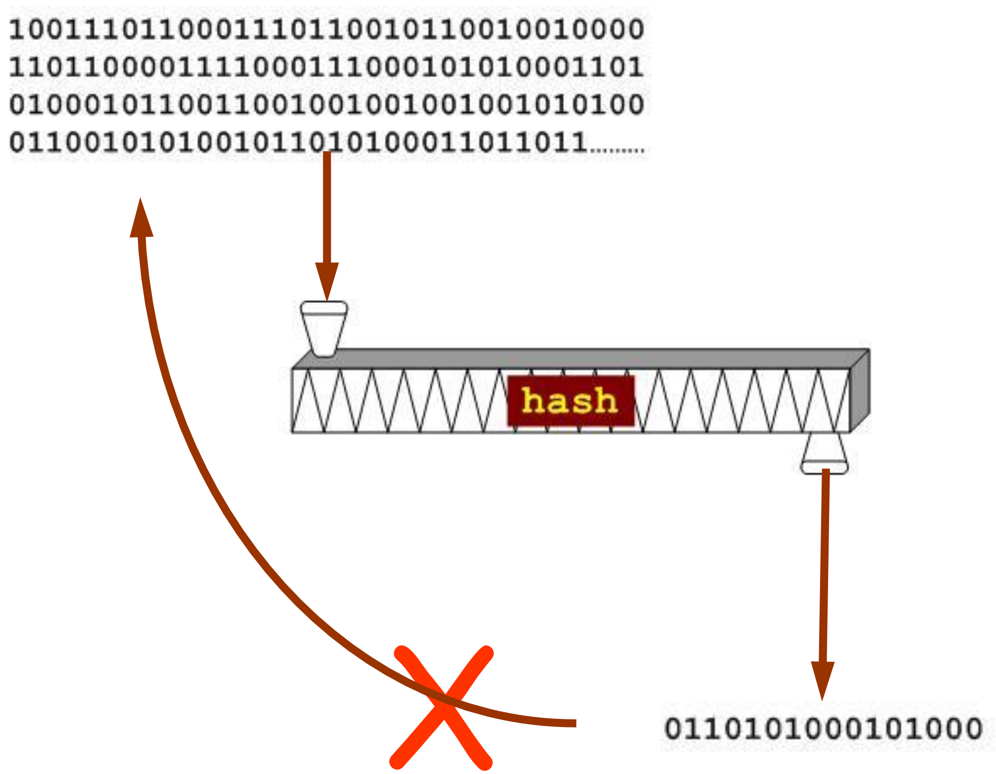
identical hash = collision

- there exist a lot of collisions
  - pigeonhole principle (a.k.a. Schubladensatz)

preimage

- given h_0, then m is a *preimage* of h_0 if

  $h(m) = h_0$



Note:
h_0 might have many preimages!

cryptographic hash function requirements

- ***collision resistance***: it should be computationally infeasible to find a collision m_1, m_2 for h
  - i.e. $h(m_1) = h(m_2)$
- ***preimage resistance***: given h_0 it should be computationally infeasible to find a preimage m for h_0 under h
  - i.e. $h(m) = h_0$
- ***second preimage resistance***: given m_0 it should be computationally infeasible to find a colliding m for m_0 under h
  - i.e. $h(m) = h(m_0)$

Other terminology (don’t use)

- *one-way* function = preimage resistant
- *weak collision resistant* = second preimage resistant
- *strong collison resistant* = collision resistant
- OWHF – one-way hash function
  - preimage resistant
- CRHF – collision resistant hash function
  - second preimage resistant and collision resistant

Don‘t use these. Be more specific!

Formal treatment

- **Efficient Algorithm**
  - Runs in **polynomial time**,
    i.e. for input of length **n**, $t_A \leq n^k = poly(n)$ for some **constant k**
- **Probabilistic Polynomial Time (PPT) Algorithm:**
  - Randomized Algorithm
  - Runs in **polynomial time**
  - Outputs the right solution with some **probability**
- **Negligible:**
  We call $\varepsilon(n)$ negligible if

$$(\exists n_c > 0)(\forall n > n_c)\colon \varepsilon(n) < \frac{1}{poly(n)}$$

Formal treatment

For security parameter n, key space K, message space M and range R, a family of hash functions $F_n=(I,H)$ is a pair of efficient algorithms:

- $I(1^n)$: The key generation algorithm that outputs a (public) function key $k \in K$
- $H(k,m)$: Takes a key $k \in K$ and a message m $\in M$ and outputs outputs the hash value $H(k,m) \in R$

Formal security properties: CR

$\mathcal{C}$

$\mathcal{A}$

$k \leftarrow I(1^n)$

$\xrightarrow{\quad k \quad}$

$\xleftarrow{\quad (m_1, m_2) \quad}$

$$H(k, m_1) = H(k, m_2)$$
$$\wedge\ (m_1 \neq m_2)?$$

Formal security properties: CR

Collision resistance: **For any PPT adversary A, the following probability is negligible in n:**

$$Pr[k \leftarrow I(1^n), (m_1, m_2) \leftarrow A(1^n, k): H(k, m_1) = H(k, m_2) \wedge (m_1 \neq m_2)]$$

Formal security properties: PRE

$\mathcal{C}$ $\mathcal{A}$

$k \leftarrow I(1^n)$

$x \leftarrow D$

$h \leftarrow H(k, x)$

$\xrightarrow{k,\, h}$

$\xleftarrow{m}$

$H(k, m) = h?$

Formal security properties: PRE

Preimage resistance: For any PPT adversary A, the following probability is negligible in n:

$$Pr[k \leftarrow I(1^n), x \leftarrow D, h \leftarrow H(k,x), \\ m \leftarrow A(1^n, k, h) : H(k, m) = h]$$

Formal security properties: SPR

$\mathcal{C}$

$k \leftarrow I(1^n)$

$m \leftarrow M$ —— m, k ——→

←—— m' ——

$$H(k, m) = H(k, m') \wedge (m \neq m')?$$

Formal security properties: SPR

***Second-preimage resistance*: For any PPT adversary $\mathcal{A}$, the following probability is negligible in n:**

$$Pr[k \leftarrow I(1^n), m \leftarrow M, m' \leftarrow A(1^n, k, m): H(k, m) = H(k, m') \wedge (m \neq m')]$$

Reductions

- Transform an algorithm for problem 1 into an algorithm for problem 2.
- „Reduces problem 2 to problem 1“
- Allows to relate the hardness of problems:

  If there exists an efficient reduction that reduces problem 2 to problem 1 then an efficient algorithm solving problem 1 can be used to efficiently solve problem 2.

Reductions II

Use in cryptography:

- **Relate security properties**
- **„Provable Security“: Reduce an assumed to be hard problem to breaking the security of your scheme.**
- **Actually this does not proof security! Only shows that scheme is secure IF the problem is hard.**

Relations between hash function security properties

Easy start: CR -> SPR

Theorem (informal): If F is collision resistant then it is second preimage resistant.

Proof:

- By contradiction: Assume A breaks SPR of F then we can build an oracle machine M^A that breaks CR.
- Given key k, M^A first samples random $m \leftarrow M$
- M^A runs $m' \leftarrow A(1^n, k, m)$ and outputs (m', m)
- M^A runs in approx. same time as A and has same success probability. -> Tight reduction

Reduction: CR -> SPR

$\mathcal{C}$ $\quad\quad M^{A}$

$k \leftarrow I(1^n)$

$\xrightarrow{\;k\;}$ (from $\mathcal{C}$ to M^A)

$m_1 \leftarrow M$

$\xrightarrow{\;m_1, k\;}$ (from M^A to $\mathcal{A}$)

$\xleftarrow{\;m_2\;}$ (from $\mathcal{A}$ to M^A)

$\xleftarrow{\;(m_1, m_2)\;}$ (from M^A to $\mathcal{C}$)

$H(k, m_1) = H(k, m_2)$
$\wedge\ (m_1 \neq m_2)$?

Easy start: CR -> SPR

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Proof:

- By contradiction: Assume A breaks SPR of F then we can build an oracle machine M^A that breaks CR.
- Given key k, M^A first samples random $m \leftarrow M$
- M^A runs $m' \leftarrow A(1^n, k, m)$ and outputs (m', m)
- M^A runs in approx. same time as A and has same success probability. -> Tight reduction

SPR -> PRE ?

Theorem (informal): If F is second-preimage resistant then it is also preimage resistant.

Proof:

- By contradiction: Assume A breaks PRE of F then we can build an oracle machine M^A that breaks SPR.
- Given key k, m, M^A runs $m' \leftarrow A(1^n, k, H(k,m))$ and outputs (m', m)
- M^A runs in same time as A and has same success probability.

Do you find the mistake?

SPR -> PRE ?

Theorem (informal): If *F* is second-preimage resistant then it is also preimage resistant.

Counter example:

- **the *identity function* *id* : $\{0,1\}^n \rightarrow \{0,1\}^n$ is second-preimage resistant but not preimage resistant**

SPR -> PRE ?

Theorem (informal): If F is second-preimage resistant then it is also preimage resistant.

Proof:

- By contradiction: Assume A breaks PRE of F then we can build an oracle machine M^A that breaks SPR.
- Given key k, m, M [illegible] and outputs (m',m)
- M^A runs in same time as A and has same success probability.

We are not guaranteed that $m \neq m'$!

Do you find the mistake?

SPR -> PRE ?

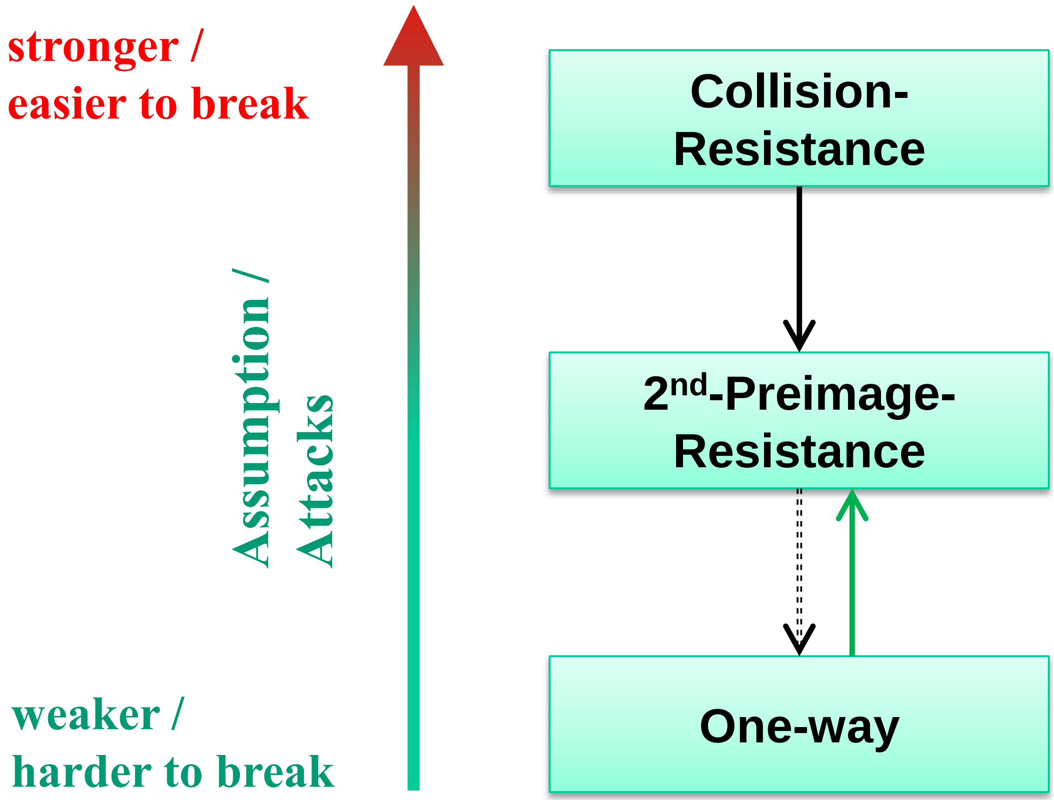
Theorem (informal, corrected): If F is second-preimage resistant, $|M| \geq 2|R|$, and $H(k,m)$ is regular for every k, then it is also preimage resistant.

Proof:

- **By contradiction: Assume A breaks PRE of F then we can build an oracle machine M^A that breaks SPR.**
- **Given key k, m, M^A runs $m' \leftarrow A(1^n, k, H(k,m))$ and outputs (m',m)**
- **M^A runs in same time as A and has at least half the success probability.**

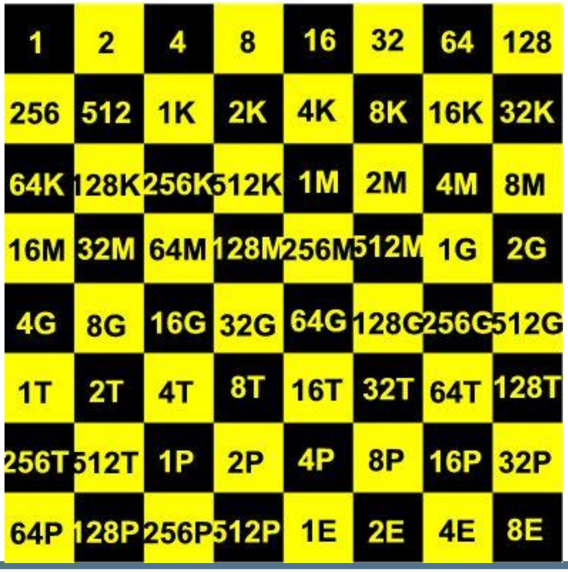
Same corrections have to be applied for CR -> PRE

Summary: Relations



generic (brute force) attacks

- assume: hash function behaves like random function
- **preimages** and **second preimages** can be found by **random guessing search**
  - search space: ≈ n bits, ≈ 2^n hash function calls
- **collisions** can be found by **birthdaying**
  - search space: ≈ ½n bits,
    ≈ $2^{½n}$ hash function calls
- this is a big difference
  - MD5 is a 128 bit hash function
  - (second) preimage random search:
    ≈ 2^{128} ≈ 3×10^{38} MD5 calls
  - collision birthday search: only
    ≈ 2^{64} ≈ 2×10^{19} MD5 calls



birthday paradox

- **birthday paradox**

  given a set of *t* (≥ 10) elements

  take a sample of size *k* (drawn with repetition)

  in order to get a probability ≥ ½ on a collision

  (i.e. an element drawn at least twice)

  k has to be $> 1.2 \sqrt{t}$

- **consequence**

  if $F : A \rightarrow B$ is a surjective random function

  and $|A| >> |B|$

  then one can expect a collision after about $\sqrt{(|B|)}$ random function calls

meaningful birthdaying

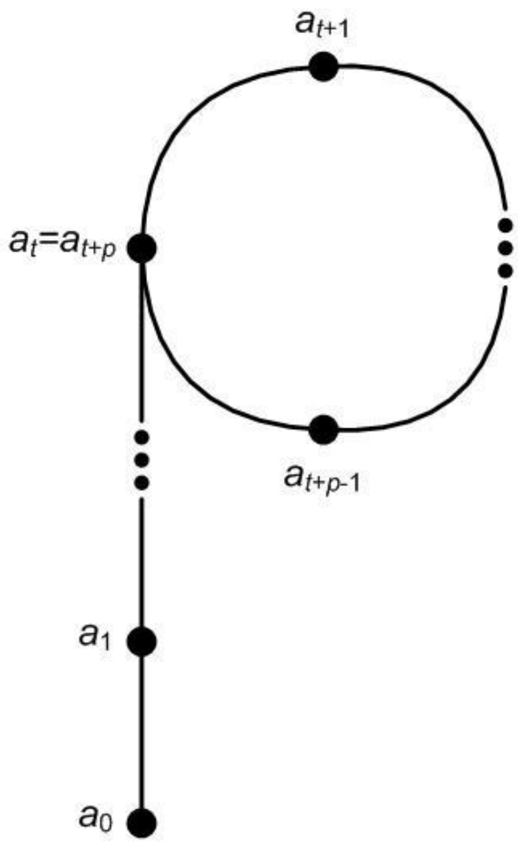
- **random birthdaying**
  - do exhaustive search on *n/2* bits
  - messages will be 'random'
  - messages will not be 'meaningful'
- **Yuval (1979)**
  - start with two meaningful messages m_1, m_2 for which you want to find a collision
  - identify *n/2* independent positions where the messages can be changed at bitlevel without changing the meaning
    - e.g. tab ←→ space, space ←→ newline, etc.
  - do random search on those positions

implementing birthdaying

- **naïve**
  - store $2^{n/2}$ possible messages for m_1 and $2^{n/2}$ possible messages for m_2 and check all 2^n pairs
- **less naïve**
  - store $2^{n/2}$ possible messages for m_1 and for each possible m_2 check whether its hash is in the list
- **smart: Pollard-ρ with Floyd's cycle finding algorithm**
  - computational complexity still $O(2^{n/2})$
  - but only constant small storage required

Pollard-ρ and Floyd cycle finding

- **Pollard-ρ**
  - iterate the hash function:
    a_0, $a_1 = h(a_0)$, $a_2 = h(a_1)$, $a_3 = h(a_2)$, …
  - this is ultimately periodic:
    - there are minimal t, p such that $a_{t+p} = a_t$
    - theory of random functions: both t, p are of size $2^{n/2}$
- **Floyd's cycle finding algorithm**
  - Floyd: start with (a_1,a_2) and compute (a_2,a_4), (a_3,a_6), (a_4,a_8), …, (a_q,a_{2q}) until $a_{2q} = a_q$; this happens for some $q < t + p$



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security parameter

- *security parameter* n: resistant against (brute force / random guessing) attack with search space of size 2^n
  - complexity of an n-bit exhaustive search
  - n-bit *security level*
- nowadays 2^{80} computations deemed impractical
- but 2^{64} computations are possible
  - security parameter 64 now seen as insufficient
- to have some security margin:
  security parameter 128 is required

- for collision resistance hash length should be $2n$ to reach security with parameter n
- *-> Use at least 256 bit hash functions like SHA2-256*