CSE107: Intro to Modern Cryptography

https://cseweb.ucsd.edu/classes/sp22/cse107-a/

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Lecture 6a

Hash functions

Hash functions

Collision resistance

Compression functions and the Merkle-Damgård (MD) transform

Hash functions from block ciphers: the Davies-Meyer method

Cryptanalytic attacks
Plan

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Cryptanalytic attacks
New Topic: Hash functions

- MD: MD4, MD5, MD6
- SHA2: SHA1, SHA224, SHA256, SHA384, SHA512
- SHA3: SHA3-224, SHA3-256, SHA3-384, SHA3-512

Their primary purpose is collision-resistant data compression, but they have many other purposes and properties as well ... A hash function is often treated like a magic wand ...

Some uses:
- Certificates: How you know www.snapchat.com really is Snapchat
- Bitcoin
- Data authentication with HMAC: TLS, ...
New Topic: Hash functions

- MD: MD4, MD5, MD6
- SHA2: SHA1, SHA224, SHA256, SHA384, SHA512
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Their primary purpose is collision-resistant data compression, but they have many other purposes and properties as well ... A hash function is often treated like a magic wand ...

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- Data authentication with HMAC: TLS, ...

SHA = “Secure Hash Algorithm”
SHA1 is dead ...

At death's door for years, widely used SHA1 function is now dead

Algorithm underpinning Internet security falls to first-known collision attack.

DAN GOODIN - 2/23/2017, 5:01 AM
Definition of a hash function

**Definition**

A *hash function* is just a family of functions $H : \text{Keys} \times D \rightarrow R$ of functions, meaning for each $K \in \text{Keys}$ we have a function $H_K : D \rightarrow R$ defined by $H_K(x) = H(K, x)$. The hash function may be:

- keyless if Keys only contains the empty string: $\text{Keys} = \{\varepsilon\}$.
- keyed if Keys is a non-trivial set.

The domain $D$ is typically all arbitrary length strings, and the range is typically a set of fixed-length bit strings.
“Hash” is a common word

WARNING: a cryptographic hash function has nothing (or very little) to do with a hash table.

- a hash table does use a Key → Value function, sometimes even called a hash function...
- but a **cryptographic** hash function has to meet much stronger criteria!

A cryptographic hash function would be good (albeit slow) for a hash table, but not the converse!
Let \( h : D \rightarrow \{0, 1\}^n \) be some hash function (keyed or not).

- **Preimage:** Given a random \( y \in \{0, 1\}^n \), can we find \( x \in D \) such that \( h(x) = y \)?
- **Second preimage:** Given a random \( x \in D \), can we find \( x' \in D \) such that \( h(x) = h(x') \)?
- **Collisions:** Can we find two elements \( x, x' \in D \) such that \( h(x) = h(x') \)?

These goals are increasingly harder to reach for an adversary.

On the other hand, when we want to define security, it is a stricter requirement to ask for even collision resistance to be infeasible in practice.
Plan

Hash functions

Collision resistance

Compression functions and the Merkle-Damgård (MD) transform

Hash functions from block ciphers: the Davies-Meyer method

Cryptanalytic attacks
A **collision** for a function \( h : D \rightarrow \{0, 1\}^n \) is a pair \( x_1, x_2 \in D \) of points such that

- \( h(x_1) = h(x_2) \), and
- \( x_1 \neq x_2 \).

If \( |D| > 2^n \) then the pigeonhole principle tells us that there must exist a collision for \( h \).
Collisions

Definition: collision

A collision for a function $h : D \rightarrow \{0, 1\}^n$ is a pair $x_1, x_2 \in D$ of points such that

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![Diagram showing a function with collisions]
Collisions

**Definition: collision**

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- \( h(x_1) = h(x_2) \), and
- \( x_1 \neq x_2 \).

If \( |D| > 2^n \) then the pigeonhole principle tells us that there must exist a collision for \( h \).

We want that even though collisions exist, they are hard to find.
Collision-resistance of a function family

The formalism considers a family $H : \text{Keys} \times D \rightarrow R$ of functions, meaning for each $K \in \text{Keys}$ we have a function $H_K : D \rightarrow R$ defined by $H_K(x) = H(K, x)$.

The game $\text{CR}_H$:

- **Initialize**
  
  - $K \leftarrow$ Keys
  - Return $K$

- **Fn**($x$)
  
  - Return $H_K(x)$

- **Finalize**($x_1, x_2$)
  
  - If $(x_1 = x_2)$ then return false
  - If $(x_1 \not\in D$ or $x_2 \not\in D)$ then return false
  - Return $(H_K(x_1) = H_K(x_2))$

Let

$$\text{Adv}_{H}^{\text{cr}}(A) = \Pr \left[ \text{CR}_H^A \Rightarrow \text{true} \right].$$
Collision-resistance

Game $CR_H$

procedure Initialize
$K \leftarrow$ Keys
Return $K$

procedure $Fn(x)$
Return $H_K(x)$

procedure Finalize$(x_1, x_2)$
If $(x_1 = x_2)$ then return false
If $(x_1 \notin D$ or $x_2 \notin D)$ then return false
Return $(H_K(x_1) = H_K(x_2))$

Here, the adversary can see inside the box!

- The Return statement in Initialize means that the adversary $A$ gets $K$ as input. The key $K$ here is not secret!
- The $Fn$ oracle uses nothing that the adversary doesn’t know, so it’s public.

Adversary $A$ takes $K$ and tries to output a collision $x_1, x_2$ for $H_K$. $A$’s output is the input to Finalize, and the game returns true if the collision is valid.
Let $N = 2^{256}$ and define

$$H: \{1, \ldots, N\} \times \{0, 1, 2, \ldots\} \rightarrow \{0, 1, \ldots, N - 1\}$$

by

$$H(K, x) = (x \mod K).$$

**Q:** Is $H$ collision resistant?
Let \( N = 2^{256} \) and define

\[
H: \quad \{1, \ldots, N\} \times \{0, 1, 2, \ldots\} \to \{0, 1, \ldots, N - 1\}
\]

by

\[
H(K, x) = (x \mod K).
\]

Q: Is \( H \) collision resistant?
A: NO!

Why? \((x + K) \mod K = x \mod K\)

**adversary** \( A(K) \)

\[
x_1 \leftarrow 0; \quad x_2 \leftarrow K; \quad \text{Return } x_1, x_2
\]

\[
\text{Adv}_{H}^{\text{cr}}(A) = 1
\]
Let $E: \{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a block cipher.  
Let $H: \{0, 1\}^k \times \{0, 1\}^{2n} \rightarrow \{0, 1\}^n$ be defined by 

\[\text{Alg } H(K, x[1]x[2])\]

\[y \leftarrow E_K(E_K(x[1]) \oplus x[2]); \text{ Return } y\]

Let’s show that $H$ is not collision-resistant by giving an efficient adversary $A$ such that $\textbf{Adv}^c_H(A) = 1$. 

Example

Let $E: \{0,1\}^k \times \{0,1\}^n \to \{0,1\}^n$ be a block cipher.
Let $H: \{0,1\}^k \times \{0,1\}^{2n} \to \{0,1\}^n$ be defined by

**Alg** $H(K, x[1]x[2])$

$y \leftarrow E_K(E_K(x[1]) \oplus x[2])$; Return $y$

Let’s show that $H$ is not collision-resistant by giving an efficient adversary $A$ such that $\text{Adv}_H^{\text{cr}}(A) = 1$.

**Idea:** Pick $x_1 = x_1[1]x_1[2]$ and $x_2 = x_2[1]x_2[2]$ so that

$E_K(x_1[1]) \oplus x_1[2] = E_K(x_2[1]) \oplus x_2[2]$
**Example**

**Alg** $H(K, x[1]x[2])$

$y \leftarrow E_K(E_K(x[1]) \oplus x[2])$; Return $y$

**Idea:** Pick $x_1 = x_1[1]x_1[2]$ and $x_2 = x_2[1]x_2[2]$ so that

$$E_K(x_1[1]) \oplus x_1[2] = E_K(x_2[1]) \oplus x_2[2]$$

Many possible answers:
Example

**Alg** \( H(K, x[1]x[2]) \)

\[ y \leftarrow E_K(E_K(x[1]) \oplus x[2]); \text{ Return } y \]

**Idea:** Pick \( x_1 = x_1[1]x_1[2] \) and \( x_2 = x_2[1]x_2[2] \) so that

\[ E_K(x_1[1]) \oplus x_1[2] = E_K(x_2[1]) \oplus x_2[2] \]

Many possible answers:

**adversary** \( A_1(K) \)

\[
\begin{align*}
    x_1[1] & \leftarrow 0^n; \quad x_2[1] \leftarrow 1^n; \\
    x_1[2] & \leftarrow E_K(x_1[1]); \quad x_2[2] \leftarrow E_K(x_2[1])
\end{align*}
\]

Return \( x_1, x_2 \)

Then \( \text{Adv}_{H}^{\text{CR}}(A_1) = 1 \) and \( A_1 \) is efficient, so \( H \) is not CR.
Example

**Alg** $H(K, x[1]x[2])$

$y \leftarrow E_K(E_K(x[1]) \oplus x[2])$; Return $y$

**Idea:** Pick $x_1 = x_1[1]x_1[2]$ and $x_2 = x_2[1]x_2[2]$ so that

$$E_K(x_1[1]) \oplus x_1[2] = E_K(x_2[1]) \oplus x_2[2]$$

Many possible answers:

**adversary** $A_2(K)$

$x_1 \leftarrow 0^n1^n$; $x_2[2] \leftarrow 0^n$; $x_2[1] \leftarrow E_K^{-1}(E_K(x_1[1]) \oplus x_1[2] \oplus x_2[2])$

return $x_1, x_2$

Then $\text{Adv}_{H}^{cr}(A_2) = 1$ and $A_2$ is efficient, so $H$ is not CR.

Note how we used the fact that $A_2$ knows $K$ and the fact that $E$ is a block cipher!
Exercise

Let $E: \{0, 1\}^k \times \{0, 1\}^\ell \to \{0, 1\}^\ell$ be a block cipher. Let $D$ be the set of all strings whose length is a positive multiple of $\ell$.

Define the hash function $H: \{0, 1\}^k \times D \to \{0, 1\}^\ell$ as follows:

**Alg** $H(K, M)$


$C[0] \leftarrow 0^\ell$

For $i = 1, \ldots, n$ do

\[
B[i] \leftarrow E(K, C[i - 1] \oplus M[i]); \\
C[i] \leftarrow E(K, B[i] \oplus M[i])
\]

Return $C[n]$

Show that $H$ is not CR by giving an efficient adversary $A$ such that $\text{Adv}^\text{cr}_H(A) = 1$. 

UCSD CSE107: Intro to Modern Cryptography; Hash functions
Keyless hash functions

We say that $H$: $\text{Keys} \times D \rightarrow R$ is **keyless** if $\text{Keys} = \{\varepsilon\}$ consists of just one key, the empty string.

In this case we write $H(x)$ in place of $H(\varepsilon, x)$ or $H_\varepsilon(x)$.

Practical hash functions like the MD, SHA2 and SHA3 series are keyless.
Plan

Collision resistance
  An example: SHA256
  Applications of hash functions
  Inherent limitations: birthday attacks
SHA256

The hash function SHA256: \(\{0, 1\}^{<2^{64}} \rightarrow \{0, 1\}^{256}\) is **keyless**, with

- Inputs being strings \(X\) of any length strictly less than \(2^{64}\)
- Outputs always having length 256.

\[
\begin{align*}
\textbf{Alg } \text{SHA256}(X) \quad &\text{// } |X| < 2^{64} \\
M &\leftarrow \text{shapad}(X) \quad \text{// } |M| \mod 512 = 0 \\
M^{(1)} M^{(2)} \ldots M^{(n)} &\leftarrow M \quad \text{// Break } M \text{ into 512 bit blocks} \\
H_0^{(0)} &\leftarrow 6a09e667 \ ; H_1^{(0)} \leftarrow \text{bb67ae85} \ ; \cdots \ ; H_7^{(0)} \leftarrow \text{5be0cd19} \\
H^{(0)} &\leftarrow H_0^{(0)} H_1^{(0)} \cdots H_7^{(0)} \quad \text{// } |H_i^{(0)}| = 32, |H^{(0)}| = 256 \\
\text{For } i = 1, \ldots, n \text{ do } H^{(i)} &\leftarrow \text{sha256}(M^{(i)} \parallel H^{(i-1)}) \\
\text{Return } H^{(n)}
\end{align*}
\]

\(\text{sha256}: \{0, 1\}^{512+256} \rightarrow \{0, 1\}^{256}\) is the **compression function**.
Padding, and initialization vector $H^{(0)}$

**Algorithm** \( \text{shapad}(X) \)  

\[
\text{// } |X| < 2^{64}
\]

\[
d \leftarrow (447 - |X|) \mod 512 \quad \text{// Chosen to make } |M| \text{ a multiple of 512}
\]

Let \( \ell \) be the 64-bit binary representation of \( |X| \)

\[
M \leftarrow X \parallel 1 \parallel 0^d \parallel \ell \quad \text{// } |M| \text{ is a multiple of 512}
\]

return \( M \)

The 32-bit word \( H^{(0)}_j \) was obtained by taking the first 32 bits of the fractional part of the square root of the \( j \)-th prime number \( (0 \leq j \leq 7) \).
Padding, and initialization vector $H^{(0)}$

**Alg** \( \text{shapad}(X) \)  \hspace{1cm} // \hspace{1cm} |X| < 2^{64} \\
\( d \leftarrow (447 - |X|) \) mod 512  \hspace{1cm} // \hspace{1cm} \text{Chosen to make } |M| \text{ a multiple of 512} \\
Let \( \ell \) be the 64-bit binary representation of \( |X| \) \\
\( M \leftarrow X \parallel 1 \parallel 0^d \parallel \ell \)  \hspace{1cm} // \hspace{1cm} |M| \text{ is a multiple of 512} \\
return \( M \)

The 32-bit word \( H_j^{(0)} \) was obtained by taking the first 32 bits of the fractional part of the square root of the \( j \)-th prime number \( (0 \leq j \leq 7) \).

**Question:** Why square roots as opposed to simply picking the words at random and embedding them in the code?

**Speculation:** Perhaps to prevent suspicion of subversion (planting of a backdoor)?
Compression function sha256

Compression function sha256: \( \{0, 1\}^{512+256} \rightarrow \{0, 1\}^{256} \) takes a 512 + 256 = 768 bit input and returns a 256-bit output.

**Alg** sha256\((x \parallel v)\)  // \( |x|=512, |v|=256 \)

\[
w \leftarrow E^\text{sha256}(x, v)
\]

\[
w_0 \cdots w_7 \leftarrow w \quad // \text{ Break } w \text{ into 32-bit words}
\]

\[
v_0 \ldots v_7 \leftarrow v \quad // \text{ Break } v \text{ into 32-bit words}
\]

For \( j = 0, \ldots, 7 \) do \( h_j \leftarrow w_j + v_j \)

\[
h \leftarrow h_0 \ldots h_7 \quad // \ |h| = 256
\]

Return \( h \)

Here and on next slide, “+” denotes addition modulo \( 2^{32} \).

\( E^\text{sha256} : \{0, 1\}^{512} \times \{0, 1\}^{256} \rightarrow \{0, 1\}^{256} \) is a block cipher with 512-bit keys and 256-bit blocks.
**Block cipher \( E^{\text{sha256}} \)**

\[
\text{Alg } E^{\text{sha256}}(x, v) \quad \text{// } x \text{ is a 512-bit key, } v \text{ is a 256-bit input}
\]

\[
x_0 \cdots x_{15} \leftarrow x \quad \text{// Break } x \text{ into 32-bit words}
\]

For \( t = 0, \ldots, 15 \) do \( W_t \leftarrow x_t \)

For \( t = 16, \ldots, 63 \) do \( W_t \leftarrow \sigma_1(W_{t-2}) + W_{t-7} + \sigma_0(W_{t-15}) + W_{t-16} \)

\[
v_0 \cdots v_7 \leftarrow v \quad \text{// Break } v \text{ into 32-bit words}
\]

For \( j = 0, \ldots, 7 \) do \( S_j \leftarrow v_j \quad \text{// Initialize 256-bit state } S \)

For \( t = 0, \ldots, 63 \) do \quad \text{// 64 rounds}

\[
T_1 \leftarrow S_7 + \gamma_1(S_4) + \text{Ch}(S_4, S_5, S_6) + C_t + W_t \\
T_2 \leftarrow \gamma_0(S_0) + \text{Maj}(S_0, S_1, S_2) \\
S_7 \leftarrow S_6; S_6 \leftarrow S_5; S_5 \leftarrow S_4; S_4 \leftarrow S_3 + T_1 \\
S_3 \leftarrow S_2; S_2 \leftarrow S_1; S_1 \leftarrow S_0; S_0 \leftarrow T_1 + T_2
\]

\( S \leftarrow S_0 \cdots S_7 \)

Return \( S \quad \text{// 256-bit output} \)
Internals of block cipher $E^{sha256}$

On the previous slide:

- $\sigma_0, \sigma_1, \gamma_0, \gamma_1, Ch, Maj$ are functions not detailed here.
- $C_1 = 428a2f98, C_2 = 71374491, \ldots, C_{63} = c67178f2$ are constants, where $C_i$ is the first 32 bits of the fractional part of the cube root of the $i$-th prime.
Try it on the course web page!

- Over the years, SHA256 has become commonplace. It is (most probably) supported by your web browser, which executes the example above in Javascript.

- However, it takes time for such goodies to percolate. No SHA-3 in there yet (check the documentation for possible updates)
Plan

Collision resistance
  An example: SHA256

Applications of hash functions

Inherent limitations: birthday attacks
Usage of hash functions

Uses include hashing the data before signing in creation of certificates, data authentication with HMAC, key-derivation, Bitcoin, ...

These will have to wait, so we illustrate another use, the hashing of passwords.
Client $A$ has a password $PW$ that is also stored by server $B$

- $A$ authenticates itself by sending $PW$ to $B$ over a secure channel (TLS)

$A^{PW} \xrightarrow{PW} B^{PW}$

**Problem:** The password will be found by an attacker who compromises the server.

These types of server compromises are common and often in the news: Yahoo, Equifax, ...
Hashed passwords

- Client $A$ has a password $PW$ and server stores $\overline{PW} = H(PW)$.
- $A$ sends $PW$ to $B$ (over a secure channel) and $B$ checks that $H(PW) = \overline{PW}$

$$A^{PW} \xrightarrow{PW} B^{\overline{PW}}$$

Server compromise results in attacker getting $\overline{PW}$ which should not reveal $PW$ as long as $H$ is one-way, which is a consequence of collision-resistance.

But we will revisit this when we consider dictionary attacks!

This is (part of) how client authentication is done on the Internet, for example login to gmail.com.
Plan

Collision resistance
  An example: SHA256
  Applications of hash functions
  Inherent limitations: birthday attacks
Birthday collision-finding attack

Let $H : \{0, 1\}^k \times D \rightarrow \{0, 1\}^n$ be a family of functions with $|D| > 2^n$. The $q$-trial birthday attack is the following adversary $A_q$ for game $\text{CR}_H$:

**adversary** $A_q(K)$

for $i = 1, \ldots, q$ do $x_i \leftarrow D$; $y_i \leftarrow H_K(x_i)$
if $\exists i, j \ (i \neq j \text{ and } y_i = y_j \text{ and } x_i \neq x_j)$ then return $x_i, x_j$
else return $\bot$

We can analyze this via the birthday problem, and show that

$$\text{Adv}^\text{cr}_{H}(A_q) \geq 0.3 \cdot \frac{q(q-1)}{2^n}.$$ 

So a collision can usually be found in about $q = \sqrt{2^n}$ trials.
Cost of birthday attacks

**adversary** $A_q(K)$

for $i = 1, \ldots, q$ do $x_i \xleftarrow{\$} D$; $y_i \leftarrow H_K(x_i)$

if $\exists i, j$ ($i \neq j$ and $y_i = y_j$ and $x_i \neq x_j$) then return $x_i, x_j$

else return ⊥

If $q \approx 2^{n/2}$, this is expected to succeed.

Cost in memory: $\approx 2^{n/2}$ as well.
Cost of birthday attacks

**adversary** $A_q(K)$

for $i = 1, \ldots, q$ do $x_i \leftarrow D$; $y_i \leftarrow H_K(x_i)$

if $\exists i, j$ ($i \neq j$ and $y_i = y_j$ and $x_i \neq x_j$) then return $x_i, x_j$

else return $\perp$

If $q \approx 2^{n/2}$, this is expected to succeed.

Cost in memory: $\approx 2^{n/2}$ as well.

BUT there are multiple ways to optimize this and obtain (almost) the same cost with memory $O(1)$. One approach is to look for cycles in the graph

$x \rightarrow H(x) \rightarrow H(H(x)) \rightarrow \ldots$

It takes time $O(2^{n/2})$ and memory $O(1)$ to find collisions on a hash function with $n$-bit output.
Birthday attack times

<table>
<thead>
<tr>
<th>Function</th>
<th>$n$</th>
<th>$T_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD4</td>
<td>128</td>
<td>$2^{64}$</td>
</tr>
<tr>
<td>MD5</td>
<td>128</td>
<td>$2^{64}$</td>
</tr>
<tr>
<td>SHA1</td>
<td>160</td>
<td>$2^{80}$</td>
</tr>
<tr>
<td>SHA256</td>
<td>256</td>
<td>$2^{128}$</td>
</tr>
<tr>
<td>SHA512</td>
<td>512</td>
<td>$2^{256}$</td>
</tr>
<tr>
<td>SHA3-256</td>
<td>256</td>
<td>$2^{128}$</td>
</tr>
<tr>
<td>SHA3-512</td>
<td>512</td>
<td>$2^{256}$</td>
</tr>
</tbody>
</table>

$T_B$ is the number of trials to find collisions via a birthday attack.

Design of hash functions aims to make the birthday attack the best collision-finding attack, meaning it is desired that there be no attack succeeding in time much less than $T_B$. 
Collision resistance security of a hash function that outputs $n$ bits cannot exceed $n/2$-bit security, because of the birthday paradox attack.

($x$-bit security means: breaking purportedly takes time $\geq 2^x$)

Preimage and second preimage security are a different story, but these are weaker notions.
Plan

Hash functions

Collision resistance

Compression functions and the Merkle-Damgård (MD) transform

Hash functions from block ciphers: the Davies-Meyer method

Cryptanalytic attacks
A compression function is a family $h : \{0, 1\}^k \times \{0, 1\}^{b+n} \rightarrow \{0, 1\}^n$ of functions whose inputs are of a fixed size $b + n$, where $b$ is called the block size.

E.g. $b = 512$ and $n = 256$, in which case

$$h : \{0, 1\}^k \times \{0, 1\}^{768} \rightarrow \{0, 1\}^{256}$$
Let $h : \{0, 1\}^k \times \{0, 1\}^{b+n} \rightarrow \{0, 1\}^n$ be a compression function with block length $b$. Let $D$ be the set of all strings of at most $2^b - 1$ blocks.

The MD transform builds from $h$ a family of functions

$$H : \{0, 1\}^k \times D \rightarrow \{0, 1\}^n.$$

Coming next:

- How the MD transform works
- The nice properties of MD
MD setup

Given: Compression function $h : \{0, 1\}^k \times \{0, 1\}^{b+n} \to \{0, 1\}^n$.

Build: Hash function $H : \{0, 1\}^k \times D \to \{0, 1\}^n$.

Since $M \in D$, its length $|M|$ is a multiple of the block length $b$.

Definition: length in number of blocks

We let $|M|_b = |M|/b$ be the number of $b$-bit blocks in $M$.

We parse $M$ as

$$M[1] \ldots M[\ell] \leftarrow M.$$  

Note: in PlayCrypt, this is done with $M = \text{split}(M,b\text{\_bytes})$.

Let $\langle \ell \rangle$ denote the $b$-bit binary representation of $\ell \in \{0, \ldots, 2^b - 1\}$.
MD transform

Given: Compression function \( h : \{0, 1\}^k \times \{0, 1\}^{b+n} \rightarrow \{0, 1\}^n \).

Build: Hash function \( H : \{0, 1\}^k \times D \rightarrow \{0, 1\}^n \).

**Alg** \( H(K, M) \)

\[
m \leftarrow |M|_b ; M[m + 1] \leftarrow \langle m \rangle ; V[0] \leftarrow 0^n
\]

For \( i = 1, \ldots, m + 1 \) do

\[
V[i] \leftarrow h_K(M[i] \parallel V[i - 1])
\]

Return \( V[m + 1] \)
Theorem: MD preserves CR

Let \( h : \{0, 1\}^k \times \{0, 1\}^{b+n} \rightarrow \{0, 1\}^n \) be a family of functions and let \( H : \{0, 1\}^k \times D \rightarrow \{0, 1\}^n \) be obtained from \( h \) via the MD transform. Given a cr-adversary \( A_H \) we can build a cr-adversary \( A_h \) such that

\[
\text{Adv}^\text{cr}_{H}(A_H) \leq \text{Adv}^\text{cr}_{h}(A_h)
\]

and the running time of \( A_h \) is that of \( A_H \) plus the time for computing \( H \) on the outputs of \( A_H \).

Implications:

\[
h \text{ CR } \Rightarrow \text{Adv}^\text{cr}_{h}(A_h) \text{ small }
\]

\[
\Rightarrow \text{Adv}^\text{cr}_{H}(A_H) \text{ small }
\]

\[
\Rightarrow H \text{ CR}
\]
Theorem: MD preserves collision resistance

If $h$ is CR, then so is $H$.

- The problem of hashing long inputs has been reduced to the problem of hashing fixed-length inputs.
- There is no need to try to attack $H$. You won’t find a weakness in it unless $h$ has one. That is, $H$ is guaranteed to be secure assuming $h$ is secure.
MD is great

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- For this reason, MD is the design used in many hash functions, including the MD and SHA2 series. SHA3 uses a different paradigm.
- However, MD is no silver bullet, especially for uses of hash functions that we will learn about later!
Hash functions

Collision resistance

Compression functions and the Merkle-Damgård (MD) transform

Hash functions from block ciphers: the Davies-Meyer method

Cryptanalytic attacks
A candidate compression function

Let $E : \{0, 1\}^b \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a block cipher. Let us define the keyless compression function $h : \{0, 1\}^{b+n} \rightarrow \{0, 1\}^n$ by

$$h(x \parallel v) = E_x(v).$$

**Question:** Is $h$ collision resistant?
A candidate compression function

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**Answer:** NO, $h$ is NOT collision-resistant, because the following adversary $A$ has $\text{Adv}^\text{cr}_h(A) = 1$:

**adversary $A$**

$x_1 \leftarrow 0^b ; x_2 \leftarrow 1^b ;$
$v_1 \leftarrow 0^n ; y \leftarrow E_{x_1}(v_1) ; v_2 \leftarrow E_{x_2}^{-1}(y)$
Return $x_1 \parallel v_1, x_2 \parallel v_2$
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$$h(x \parallel v) = E_x(v) \oplus v.$$ 

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The Davies-Meyer compression function

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We seek an adversary that outputs distinct $x_1 \ || \ v_1$, $x_2 \ || \ v_2$ satisfying

$$E_{x_1}(v_1) \oplus v_1 = E_{x_2}(v_2) \oplus v_2.$$  

**Answer:** Unclear how to solve this equation, even though we can pick all four variables.
Let $E : \{0, 1\}^b \times \{0, 1\}^n \to \{0, 1\}^n$ be a block cipher. Let us define keyless compression function $h : \{0, 1\}^{b+n} \to \{0, 1\}^n$ by

$$h(x \parallel v) = E_x(v) \oplus v.$$ 

This is called the Davies-Meyer method and is used in the MD and SHA2 series of hash functions, modulo that $\oplus$ may be replaced by addition.

In particular the compression function sha256 of SHA256 is underlain in this way by the block cipher $E^{sha256} : \{0, 1\}^{512} \times \{0, 1\}^{256} \to \{0, 1\}^{256}$ that we saw earlier, with $\oplus$ being replaced by component-wise addition modulo $2^{32}$. 
Plan

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Cryptanalytic attacks
Cryptanalytic attacks

So far we have looked at attacks that do not attempt to exploit the structure of $h$.

Can we get better attacks if we do exploit the structure?

Ideally not, but hash functions have fallen short!
Cryptanalytic attacks against hash functions

<table>
<thead>
<tr>
<th>When</th>
<th>Against</th>
<th>Time</th>
<th>Who</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993, 1996</td>
<td>md5</td>
<td>$2^{16}$</td>
<td>[dBBo, Do]</td>
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<tr>
<td>2004</td>
<td>MD5</td>
<td>1 hour</td>
<td>[WaFeLaYu]</td>
</tr>
<tr>
<td>2005, 2006</td>
<td>MD5</td>
<td>1 minute</td>
<td>[LeWadW, Kl]</td>
</tr>
<tr>
<td>2005</td>
<td>SHA1</td>
<td>$2^{69}$</td>
<td>[WaYiYu]</td>
</tr>
<tr>
<td>2017</td>
<td>SHA1</td>
<td>$2^{63.1}$</td>
<td>[SBKAM]</td>
</tr>
</tbody>
</table>

Collisions found in compression function md5 of MD5 did not yield collisions for MD5, but collisions for MD5 are now easy.

2017: Google, Microsoft and Mozilla browsers stop accepting SHA1-based certificates.

The SHA256 and SHA512 hash functions are still viewed as secure, meaning the best known attack is the birthday attack.
Flame exploited an MD5 attack

Crypto breakthrough shows Flame was designed by world-class scientists

The spy malware achieved an attack unlike any cryptographers have seen before.

DAN GOODIN - 6/7/2012, 11:20 AM

The Flame espionage malware that infected computers in Iran achieved mathematically sophisticated attacks that could only have been accomplished by world-class cryptographers, two of the world's foremost cryptography experts said.

"We have confirmed that Flame uses a yet unknown MD5 chosen-prefix collision attack," Marc Stevens wrote in an email posted to a cryptography discussion group earlier this week. "The collision attack itself is very interesting from a scientific viewpoint, and there are already some practical implications." Benne de Weger, a Stevens colleague and another expert in cryptographic collision

Flame

- Revealed: Stuxnet "beta's" devious alternate attack on Iran nuke program
- Massive espionage malware targeting governments undetected for 5 years
- Iranian computers targeted by new malicious data wiper program
- New in-the-wild malware
SHA1 collision: https://shattered.io/

Here are two PDF files that display different content, yet have the same SHA-1 digest.
MD5 was known to have weaknesses in the 1990s. A full collision was computed in 2004. People are still using MD5 now.

SHA-1’s flaws have been known since 2005. A full collision was computed in 2017. Deprecation of SHA-1 has been slowed by intense resistance.

Linus Torvalds on Git’s use of SHA-1: (2020: timid move towards SHA2-256)

I doubt the sky is falling for git as a source control management tool. Do we want to migrate to another hash? Yes. Is it "game over" for SHA1 like people want to say? Probably not.

I haven’t seen the attack details, but I bet

(a) the fact that we have a separate size encoding makes it much harder to do on git objects in the first place

(b) we can probably easily add some extra sanity checks to the opaque data we do have, to make it much harder to do the hiding of random data that these attacks pretty much always depend on.
Problem: Deprecating weak algorithms or parameters breaks backwards compatibility.

Problem: Many people think they understand cryptography and can make their own security choices.

Problem: Cryptography is hard.

General Principle: Attacks get better. An “academic” break violating a theoretical definition of security may lead later on to a “real-world” vulnerability.