# The HMAC construction: A decade later

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# What is HMAC?

- HMAC: A Message Authentication Code based on Cryptographic Hash functions [Bellare-C-Krawczyk96].
- Developed for the IPSec standard of the Internet Engineering Task Force (IETF).
- Currently:

  - incorporated in IPSec, SSL/TLS, SSH, Kerberos, SHTTP, HTTPS, SRTP, MSEC, ...
  - ANSI and NIST standards
  - Used daily by all of us.

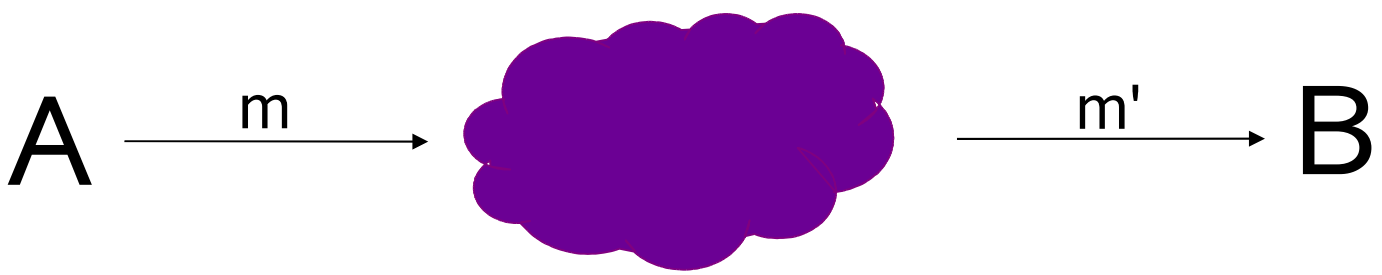
# Why is HMAC interesting?

- "Theoretical" security analysis impacts the security of real systems.
- Demonstrates the importance of modelling and abstraction in practical cryptography.
- The recent attacks on hash functions highlight the properties of the HMAC design and analysis.
- Use the HMAC lesson to propose requirements for the next cryptographic hash function.

# Organization

- Authentication, MACs, Hash-based MACs
- HMAC construction and analysis
- Other uses of HMAC:
  - Pseudo-Random Functions
  - Extractors
- What properties do we want from a "cryptographic hash function"?

# Authentication




The goal: Any tampering with messages should be detected.

*"If B accepts message m from A then A has sent m to B."*

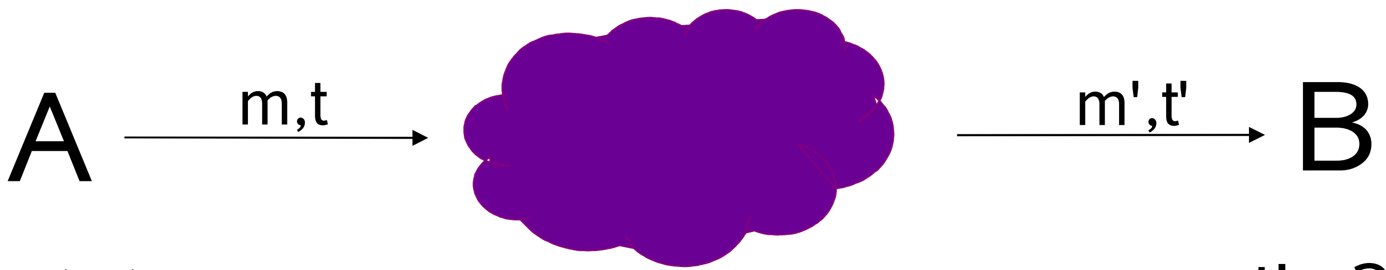
- One of the most basic cryptographic tasks
- The basis for any security-conscious interaction over an open network

# Elements of authentication

**The structure of typical cryptographic solutions:**

- Initial entity authentication:
  The parties perform an initial exchange, bootstrapping from initial trusted information on each other. The result is a secret key that binds the parties to each other.
- Message authentication:
  The parties use the key to authenticate exchanged messages via message authentication codes.

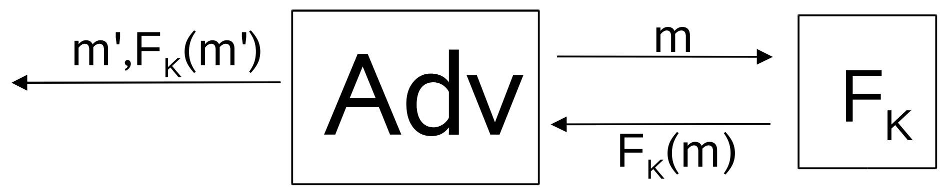
# Message Authentication Codes




$t=F_K(m)$ $t' =? F_K(m')$

- A and B obtain a common secret key K
- A and B agree on a keyed function F
- A sends $t=F_K(m)$ together with m
- B gets (m',t') and accepts m' if $t'=F_K(m')$.

# Message Authentication Codes: A definition




## The MAC game:

- Key K chosen at random
- An attacker can adaptively ask queries m and get $F_K$(m).
- F is a good MAC function if the attacker is unable to “predict” F, i.e. generate (m',$F_K$(m')) for an unqueried m'.

Definition can be quantified, counting:

- Number and length of queries
- Local computation
- Probability of success.

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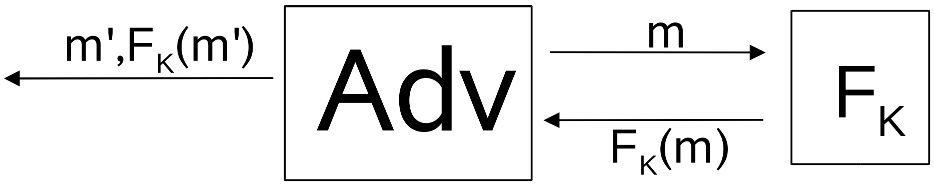


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Note: this is a weaker requirement than pseudorandom functions.

# IPSec

# The IP Security effort (1993-)

- An initiative of the Internet Engineering Task Force (IETF)
- Goal: provide a ubiquitous mechanism for securing internet traffic:
  - Common to all Internet traffic
  - Sits in the OS kernel, thus always available (but also hard to deploy and modify)
  - Can be easily used by network components (routers, NAT boxes, firewalls, etc.)

# A central challenge in 1995: Find a good Message Authentication Code

Requirements:

- Very fast on a variety of platforms
- Ubiquitously available
- Not susceptible to US export controls
- Secure…

# MACs for IPSec: Available options

- DES in CBC-MAC mode:
  - Relatively slow in software
  - Only 64-bit MACs
  - Export controls limit to 40-bit keys
- MACs based on “cryptographic hash functions (CHF)” such as MD5, SHA1, RIPEMD.
  - CHFs  are anyway incorporated in most libraries
  - Very fast in software
  - Not susceptible to export controls
  - “Nice” security properties

The choice was clear. But, how to do it securely?

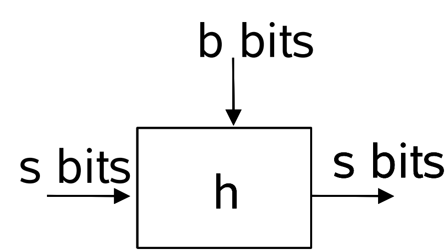
# Cryptographic Hash Functions

# Basics: The common structure of CHFs

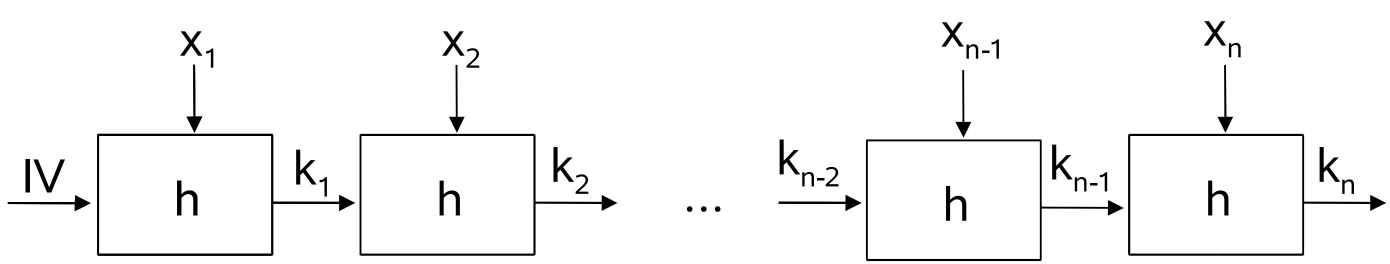
- Iterated applications of a basic element, the “compression function” h, using  the Merkle-Damgard (“cascade”) structure.
- Initialize via a fixed s-bit value IV.

b = 512
MD5: s=128
SHA1,RIPEMD: s=160

$$H_k(x_1 \ldots x_n) = \begin{cases} h_{H_k(x_1 \ldots x_{n-1})}(x_n) & n>1 \\ h_k(x_1) & n=1 \end{cases}$$




$$H(x) = H_{IV}(x)$$



# Security properties of CHFs

Main design goal was collision resistance:

Infeasible to find x,y with H(x)=H(y).

*Theorem [Damgard89]:*

*If $h_k$ is collision resistant on b-bit inputs, then $H_k$ is collision resistant for any input length.*

But:

- Used in many situations that require different, "ad-hoc" security properties.
- Treated like "magic functions": Output is assumed to be random and completely uncorrelated with the input.

# MACs from CHFs

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- Proposal 1- Prepend the key: $Prep_k(m) = H(k|m)$
  - If H is a “random function” then Prep is a secure MAC.
  - But, Prep is susceptible to “extension attacks”: let $|m_1|=|m_2|=b$. Then obtain $t=Prep_k(m_1)$, and compute $Prep_k(m_1|m_2)=h_t(m_2)$.
  - Still, the proposal was quite popular. (“Packet headers always include the length, thus the attack is not practical.”)

# MACs from CHFs

- Proposal 2 - Append the key:

$$App_k(m) = H(m|k)$$

- Prevents extension attacks.
- if h is a "random function" then App is secure MAC.
- But, strongly depends on collisions resistance of H.
  (k enters the computation only at the very end.)
  Can we do better?

# MACs from CHFs

- Proposal 3 - Prepend and append the key:

  $Env_k(m)=H(k|m|k)$ [RFC 1828, Aug95]

  -To align or not to align? [Preneel-VanOorschot95]

  -What are the assumptions on H/h?

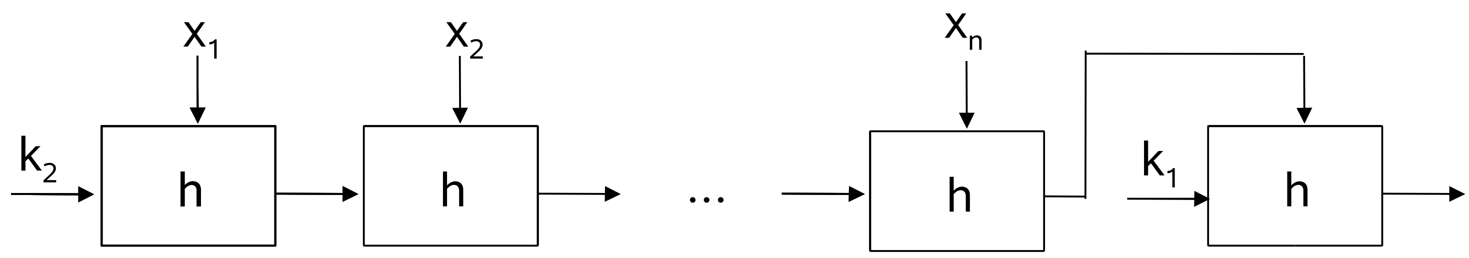
- Proposal 4: Start with Env, and add key-related operations to h [Preneel-VanOorschot95]

None of the above had sound security analysis...

# HMAC

# Towards HMAC: The NMAC construction

$$NMAC_{k1,k2}(m) = H_{k1}(H_{k2}(m))$$




- Idea 1: Incorporate the key via the IV.
  Better for modeling and analysis. Follows the design of the underlying CHF.
- Idea 2: Use two independent keys. Indeed, each key has a different role in the analysis.

# Performance of NMAC

- Internal application of H: Same as plain hashing of the message
- Extrnal application of H: Single run of h.

The overhead of the external application is negligible for long messages (packets), and tolerable even for small packets.

# Security of NMAC (I)

Approach: reduce to weak properties of h.

Assume an attacker A that breaks NMAC. That is:

- A asks sees $NMAC_{k1,k2}(m_1)$, $NMAC_{k1,k2}(m_2)$,… for adaptively chosen $m_1, m_2$,… .
- A generates $m'$, $NMAC_{k1,k2}(m')$ for a new $m'$.

Then:

- If $H_{k2}(m')=H_{k2}(m_i)$ for some i, then A has found a collision in $H_{k2}$, with an unknown $k_2$.
- Else, A managed to "predict" $h_{k1}$, without either knowing $k_1$ nor directly seeing the input.

More precisely…

# Weak collision resistance

- H is weak collision resistant (WCR) if, given oracle access to $H_k$ for a random k, it is infeasible to find x,y such that $H_k(x)=H_k(y)$.

By itself, equivalent to finding collisions with a *known* random key.
(First get $k'=H_k(m)$ for a random m, and then find a collision in $H_{k'}()$.)

- H is very WCR if, given oracle access to $H_{k1}(H_{k2}())$ for a random $k_1,k_2$, it is infeasible to find x,y such that $H_{k2}(x)=H_{k2}(y)$.

# Security of NMAC (II)

NMAC is a secure MAC as long as:

- $h_k$ is a secure MAC on b-bit messages.
- $H_k$ is very weak collision resistant.

Note: Analysis is quantitatively tight.

- No increase in # queries or running time,
- Adversarial success probability is at most the sum of the assumed success probabilities.

# Downsides of NMAC:

- Need to change the IV, thus change existing libraries that include CHFs.
- Key is long (256 or 320 bits).

HMAC gets around these, at the price of an additional mild assumption on h.

# The HMAC construction

$$HMAC_k(m)=H(\ k\oplus opad \mid H(k\oplus ipad \mid m)\ )$$

$|k|=s$ (128 or 160)

opad = 0x36 repeated to make b bits

ipad = 0x5c repeated to make b bits

$\oplus$ is bitwise exclusive or

Note:

-key is short

-keying is only via the input, so no change in existing code.

-Performance: 2 additional applications of h.

# Security of HMAC

By reduction to the security of NMAC.

Recall: $HMAC_k(m)=H(k\oplus opad \mid H(k\oplus ipad \mid m))$

$NMAC_{k1,k2}(m)= H_{k1}(H_{k2}(m))$

Notice: $HMAC_k(m)=NMAC_{k1,k2}(m)$,

where $k_{k1}=H(k\oplus opad)$, $k_{k2}=H(k\oplus ipad)$.

Thus, assuming that:

$$G(k)=H(k\oplus opad),H(k\oplus ipad)$$

is a pseudorandom generator from s bits to 2s bits, we have that HMAC is a MAC function if NMAC is.

# Looking back: HMAC as a tradeoff

HMAC is a tradeoff between "theoretical elegance" and practical needs:

- The underlying assumptions on the CHF are not the most "elegant" possible.
- Construction is not the most efficient possible.

But:

- Provides convincing and sound arguments that breaking HMAC would mean a complete break of the CHF.
- Design is simple and does not require change of existing code.

# Other uses of HMAC

Once HMAC became readily available, people started to use it in different ways… e.g.:

- Pseudorandom function (PRF):
  for "key expansion": generate multiple PR keys from a single short key. In IPSec, TLS, SSH, KERBEROS…

- "Collision-resistant PRF": In TESLA (stream authentication for the MSEC secure multicast standard).

- "Computational randomness extractor": For deriving pseudo-random keys from somewhat random keying material.

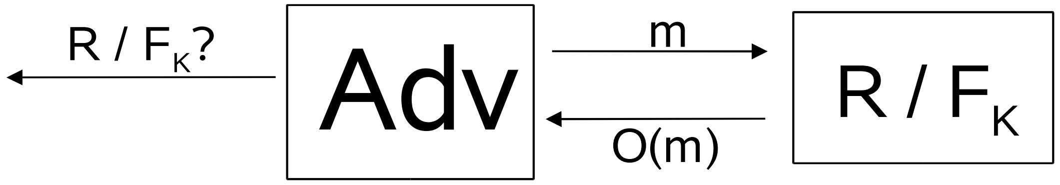
Will talk on the uses as a PRF and an Extractor.

# Pseudo-random functions

PRFs are keyed functions that behave like random functions as long as the key is random and secret.

More formally, PRFs are defined via a game:

- Oracle O is fixed to either $F_K$ for a random key K, or a random function R with the same domain and range.
- An attacker can adaptively ask queries m and get O(m).
- F is a good PRF if the attacker is unable to tell whether it interacts with R or with $F_K$.



# HMAC as a PRF

Fact 1: If the compression function $h_K$ is a PRF on b-bit inputs then the cascade $H_K$ is a PRF on variable size inputs, *as long as no query is a prefix of another* [Bellare-C-Krawczyk97].

Fact 2: If $h_K$ is a PRF on b-bit inputs and $H_K$ is Almost Universal (AU) on v-size inputs, then $NMAC_K$ is a PRF on v-size inputs [Bellare05]. *($H_K$ is AU if for any x,y $Prob_K(H_K(x)=H_K(y))$ is negl.)*

Fact 3: If $h_K$ is a PRF on b-bit inputs then $NMAC_K$ is AU [Bellare05].

→ **If $h_K$ is a PRF on b-bit inputs then $NMAC_K$ is a PRF on v-size inputs.**

→ **If in addition $G(k)=H(k\oplus opad),H(k\oplus ipad)$ is a PRG then $HMAC_K$ is a PRF on v-size inputs.**

# The extraction problem

Some key exchange protocols generate "defective keys":

- Have much "computational entropy", but
- Are not pseudorandom.

Goal: Extract a pseudorandom key.

# Main example: Diffie-Hellman exchanges

Public: Algebraic group G, generator g

| A | | B |
|---|---|---|
| Choose x in [1..\|G\|] | $\xrightarrow{g^x}$ | |
| | $\xleftarrow{g^y}$ | Choose y in [1..\|G\|] |
| output $(g^y)^x = g^{xy}$ | | Output $(g^x)^y = g^{xy}$ |

# Properties of the generated key ($g^{xy}$)

The Decisional Diffie-Hellman (DDH) assumption implies:

$$(g, g^x, g^y, g^{xy}) \sim (g, g^x, g^y, g^r)$$

But:

- DDH is a strong assumption.
- Even under DDH, $g^{xy}$ is pseudorandom only in the group G, which is often embedded in a much larger group (eg, $Z_p$)
- Even in best case, when $|G|=q$, $p=2q+1$, we only have that $g^{xy}$ is pseudorandom in a small subset of $\{0,1\}^k$.
- When the exchange is not authenticated by external mechanisms (e.g., in the MQV or HMQV protocols) the guarantees are even weaker.

# Common practice

Hash using a CHF and hope for the best…

If the CHF is modeled as a random oracle then everything is ok.

But, can we do better?

# Randomness extractors

Input:

- A “defective random source”, namely a value drawn from a distribution with substantial entropy,
- A short truly random value.

Output:

- A value that is statistically close to random.

A computational variant [Dodis-Gennaro-Hastad-Krawczyk-Rabin05]:

Input:

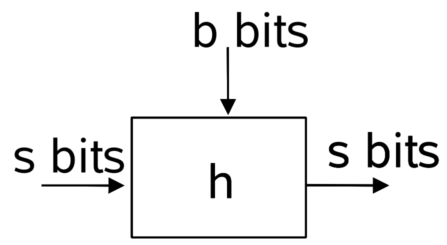
- A (secret) value drawn from a distribution with substantial “computational entropy”,
- A (public) truly random value.

Output:

- A (secret) pseudorandom value

# HMAC as an extractor

Assume the compression function $h_k$ is a c-extractor from b-bit inputs to s-bit outputs, with an s-bit public random input.




Then:

- The cascade $H_k$ is a c-extractor from v-length input to s-bit outputs, as long as each input block has sufficient c-entropy given all subsequent blocks [DGHKR05,CG88].
- NMAC and HMAC behave similarly, when assuming in addition that h is a PRF from s-bits to s-bits with b-bit key.

# Using HMAC as an extractor

Applicable when the parties have some trusted public randomness (e.g., the protocol involves exchanging public authenticated random nonces).

Here do: $k = \mathrm{HMAC}_r(g^{xy})$

where r is the public randomness (eg, concatenation of nonces).

K is guaranteed to be pseudorandom as long as $g^{xy}$ has enough c-entropy.

- Indeed, HMAC is used this way in IPSec's IKE.

# Open question:

What to do when there is no trusted public randomness?

Here the best we know today is to model the CHF as a random oracle.

Can we do better?

# HMAC as a Random Oracle

HMAC was designed to get away from unnecessary random oracle modeling.

Still, it turns out that the HMAC/NMAC constructions can be used to extend Random Oracles [Coron-Dodis-Malinaud-Punya05]:

- If h is a random oracle on b-bit inputs, then:
  - The cascade H of h is a random oracle on variable-length inputs, as long as queries are prefix-free.
  - The HMAC/NMAC constructions are Random Oracles on variable-length inputs.

# Recent attacks on CHFs

The [Wang-Yu-Yin05] collision attacks againt MD5 and SHA1 imply:

- Can find collisions in current functions in time $2^{O(60)}$.
- Same approach seems to work for a random, public IV (but needs a “human in the loop” for each new IV).

# Implications on HMAC:

- Another reminder that H is not a Random Oracle (and not even h).
- Weak collision resistance (with secret IV) is somewhat affected, due to the extension attack.
- Very weak collision resistance does not seem to be affected.
- Neither the PRF nor the MAC assumptions on h seem to be affected.
- The c-extraction assumption on h seems unaffected.

In contrast, other suggestions of hash-based MACs are seriously affected.

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Perhaps we want different functions for different applications?

# Summary: Why is HMAC interesting?

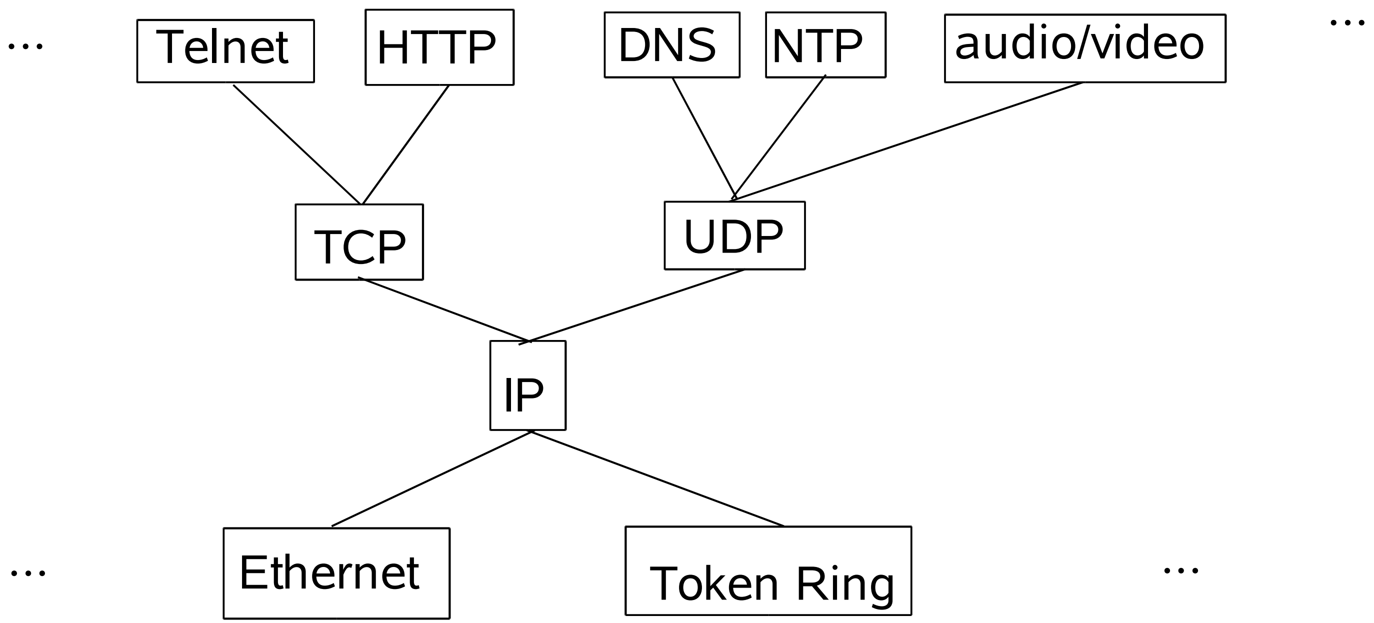
- An example where “theoretical” security analysis has impact on acceptability and practical security.
- Demonstrates the importance of modeling and abstraction in practical cryptography: Different models of the same construction bring different results, all useful.
- The recent attacks on hash functions highlight the properties of the HMAC design and analysis.
- Can use the HMAC lesson to propose requirements for the next cryptographic hash function.

# Basic structure of the IPSec protocol:

- Key exchange: Two peers obtain a common secret key in an authenticated way. (Application layer protocol)
- Data protection: Encryption and authentication. (IP layer protocol: Each packet encoded and decoded individually.)
- Per-packet transforms:
  - Authentication header (AH): Authentication only
  - ESP: Authentication and/or encryption

Seems simple enough. But turns out to be far from that...

# IP: the common denominator of the Internet



# HMAC as a standard

After much discussion and debate, HMAC was accepted as the mandatory-to-implement MAC function for IPSec (RFC 2104).

- Rare example of a security standard where "theoretical" modeling and analysis has helped acceptance as standard.

Other IETF standards that incorporate HMAC:
TLS, SHTTP, SSH, HTTPS, KERBEROS, SRTP,...

NIST standard: FIPS 198
ANSI standard: X9.71

Incorporated in practically any browser and OS today.