CSci 5271
Introduction to Computer Security
Day 15: Cryptography part 1: symmetric key

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Outline

Crypto basics

Announcements intermission

Stream ciphers

Block ciphers and modes of operation

Hash functions and MACs

Building a secure channel

-ography, -ology, -analysis

- Cryptography (narrow sense): designing encryption
- Cryptanalysis: breaking encryption
- Cryptology: both of the above
- Code (narrow sense): word-for-concept substitution
- Cipher: the "codes" we actually care about

Caesar cipher

- Advance three letters in alphabet: $A \to D, B \to E, \ldots$
- Decrypt by going back three letters
- Internet-era variant: rot-13
- Easy to break if you know the principle

Keys and Kerckhoffs's principle

- The only secret part of the cipher is a *key*
- Security does not depend on anything else being secret
- Modern (esp. civilian, academic) crypto embraces openness quite strongly

Symmetric vs. public key

- Symmetric key (today's lecture): one key used by all participants
- Public key: one key kept secret, another published
  - Techniques invented in 1970s
  - Makes key distribution easier
  - Depends on fancier math

Goal: secure channel

- Leaks no content information
  - Not protected: size, timing
- Messages delivered intact and in order
  - Or not at all
- Even if an adversary can read, insert, and delete traffic

One-time pad

- Secret key is truly random data as long as message
- Encrypt by XOR (more generally addition mod alphabet size)
- Provides perfect, "information-theoretic" secrecy
- No way to get around key size requirement

Computational security

- More realistic: assume adversary has a limit on computing power
- Secure if breaking encryption is computationally infeasible
  - E.g., exponential-time brute-force search
- Ties cryptography to complexity theory

Key sizes and security levels

- Difficulty measured in powers of two, ignore small constant factors
- Power of attack measured by number of steps, aim for better than brute force
- 2^{32} definitely too easy, probably 2^{64} too
- Modern symmetric key size: at least 2^{128}

Crypto primitives

- Base complicated systems on a minimal number of simple operations
- Designed to be fast, secure in wide variety of uses
- Study those primitives very intensely

Attacks on encryption

- Known ciphertext
  - Weakest attack
- Known plaintext (and corresponding ciphertext)
- Chosen plaintext
- Chosen ciphertext (and plaintext)
  - Strongest version: adaptive

Certificational attacks

- Good primitive claims no attack more effective than brute force
- Any break is news, even if it's not yet practical
  - Canary in the coal mine
- E.g., $2^{126.1}$ attack against AES-128
- Also watched: attacks against simplified variants

Fundamental ignorance

- We don't really know that any computational cryptosystem is secure
- Security proof would be tantamount to proving $\mathrm{P} \neq \mathrm{NP}$
- Crypto is fundamentally more uncertain than other parts of security

Relative proofs

- Prove security under an unproved assumption
- In symmetric crypto, prove a construction is secure if the primitive is
  - Often the proof looks like: if the construction is insecure, so is the primitive
- Can also prove immunity against a particular kind of attack

Random oracle paradigm

- Assume ideal model of primitives: functions selected uniformly from a large space
  - Anderson: elves in boxes
- Not theoretically sound; assumption cannot be satisfied
- But seems to be safe in practice

Pseudorandomness and distinguishers

- Claim: primitive cannot be distinguished from a truly random counterpart
  - In polynomial time with non-negligible probability
- We can build a distinguisher algorithm to exploit any weakness
- Slightly too strong for most practical primitives, but a good goal

Open standards

- How can we get good primitives?
- Open-world best practice: run competition, invite experts to propose then attack
- Run by neutral experts, e.g. US NIST
- Recent good examples: AES, SHA-3

A certain three-letter agency

- National Security Agency (NSA): has primary responsibility for "signals intelligence"
- Dual-mission tension:
  - Break the encryption of everyone in the world
  - Help US encryption not be broken by foreign powers

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Note to early readers

- This is the section of the slides most likely to change in the final version
- If class has already happened, make sure you have the latest slides for announcements

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Stream ciphers

- Closest computational version of one-time pad
- Key (or seed) used to generate a long pseudorandom bitstream
- Closely related: cryptographic RNG

Shift register stream ciphers

- Linear-feedback shift register (LFSR): easy way to generate long pseudorandom sequence
  - But linearity allows for attack
- Several ways to add non-linearity
- Common in constrained hardware, poor security record

RC4

- Fast, simple, widely used software stream cipher
  - Previously a trade secret, also "ARCFOUR"
- Many attacks, none yet fatal to careful users (e.g. TLS)
  - Famous non-careful user: WEP
- Now deprecated, not recommended for new uses

Encryption $\neq$ integrity

- Encryption protects secrecy, not message integrity
- For constant-size encryption, changing the ciphertext just creates a different plaintext
- How will your system handle that?
- Always need to take care of integrity separately

Stream cipher mutability

- Strong example of encryption vs. integrity
- In stream cipher, flipping a ciphertext bit flips the corresponding plaintext bit, only
- Very convenient for targeted changes

Stream cipher assessment

- Currently out of fashion as a primitive in software
- Not inherently insecure
  - Other common pitfall: must not reuse key(stream)
- Currently no widely vetted primitives

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Basic idea

- Encryption/decryption for a fixed sized block
- Insecure if block size is too small
  - Barely enough: 64 bits; current standard: 128
- Reversible, so must be one-to-one and onto function

Pseudorandom permutation

- Ideal model: key selects a random invertible function
- I.e., permutation (PRP) on block space
  - Note: not permutation on bits
- "Strong" PRP: distinguisher can decrypt as well as encrypt

Confusion and diffusion

- Basic design principles articulated by Shannon
- Confusion: combine elements so none can be analyzed individually
- Diffusion: spread the effect of one symbol around to others
- Iterate multiple *rounds* of transformation

Substitution/permutation network

- Parallel structure combining reversible elements:
- Substitution: invertible lookup table ("S-box")
- Permutation: shuffle bits

AES

- Advanced Encryption Standard: NIST contest 2001
  - Developed under the name Rijndael
- 128-bit block, 128/192/256-bit key
- Fast software implementation with lookup tables (or dedicated insns)
- Allowed by US government up to Top Secret

Feistel cipher

- Split block in half, operate in turn: $(L_{i+1}, R_{i+1}) = (R_i, L_i \oplus F(R_i, K_i))$
- Key advantage: F need not be invertible
  - Also saves space in hardware
- Luby-Rackoff: if F is pseudo-random, 4 or more rounds gives a strong PRP

DES

- Data Encryption Standard: AES predecessor 1977-2005
- 64-bit block, 56-bit key
- Implementable in 70s hardware, not terribly fast in software
- Triple DES variant still used in places

Some DES history

- Developed primarily at IBM, based on an earlier cipher named "Lucifer"
- Final spec helped and "helped" by the NSA
  - Argued for smaller key size
  - S-boxes tweaked to avoid a then-secret attack
- Eventually victim to brute-force attack

DES brute force history

1977	est. \$20m cost custom hardware
1993	est. \$1m cost custom hardware
1997	distributed software break
1998	\$250k built ASIC hardware
2006	\$10k FPGAs
2012	as-a-service against MS-CHAPv2

Double encryption?

- Combine two different block ciphers?
  - Belt and suspenders
- Anderson: don't do it
- FS&K: could do it, not a recommendation
- Maurer and Massey (J.Crypt'93): might only be as strong as first cipher

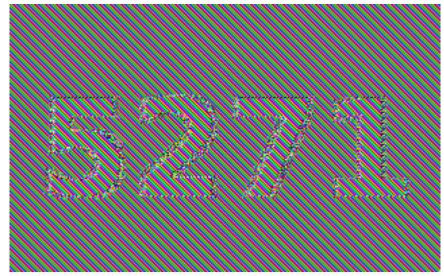
Modes of operation

- How to build a cipher for arbitrary-length data from a block cipher
- Many approaches considered
  - For some reason, most have three-letter acronyms
- More recently: properties susceptible to relative proof

ECB

- Electronic CodeBook
- Split into blocks, apply cipher to each one individually
- Leaks equalities between plaintext blocks
- Almost never suitable for general use

Do not use ECB



CBC

- Cipher Block Chaining
- $C_i = E_K(P_i \oplus C_{i-1})$
- Probably most popular in current systems
- Plaintext changes propagate forever, ciphertext changes only one block

CBC: getting an IV

- C_0 is called the initialization vector (IV)
  - Must be known for decryption
- IV should be random-looking
  - To prevent first-block equalities from leaking (lesser version of ECB problem)
- Common approaches
  - Generate at random
  - Encrypt a nonce

Stream modes: OFB, CTR

- Output FeedBack: produce keystream by repeatedly encrypting the IV
  - Danger: collisions lead to repeated keystream
- Counter: produce from encryptions of an incrementing value
  - Recently becoming more popular: allows parallelization and random access

Outline

Ideal model

- Ideal crypto hash function: pseudorandom function
  - Arbitrary input, fixed-size output
- Simplest kind of elf in box, theoretically very convenient
- But large gap with real systems: better practice is to target particular properties

Kinds of attacks

- Pre-image, "inversion": given y, find x such that $H(x) = y$
- Second preimage, targeted collision: given x, $H(x)$, find $x' \neq x$ such that $H(x') = H(x)$
- (Free) collision: find x_1, x_2 such that $H(x_1) = H(x_2)$

Birthday paradox and attack

- There are almost certainly two people in this classroom with the same birthday
- n people have $\binom{n}{2} = \Theta(n^2)$ pairs
- So only about $\sqrt{n}$ expected for collision
- "Birthday attack" finds collisions in any function

Security levels

- For function with k-bit output:
- Preimage and second preimage should have complexity 2^k
- Collision has complexity $2^{k/2}$
- Conservative: use hash function twice as big as block cipher key
  - Though if you're paranoid, cipher blocks can repeat too

Non-cryptographic hash functions

- The ones you probably use for hash tables
- CRCs, checksums
- Output too small, but also not resistant to attack
- E.g., CRC is linear and algebraically nice

Short hash function history

- On the way out: MD5 (128 bit)
  - Flaws known, collision-finding now routine
- SHA(-0): first from NIST/NSA, quickly withdrawn
  - Likely flaw discovered 3 years later
- SHA-1: fixed SHA-0, 160-bit output.
- 2^{60} collision attack described in 2013
  - First public collision found (using 6.5 kCPU yr) in 2017

Length extension problem

- MD5, SHA1, etc., computed left to right over blocks
- Can sometimes compute $H(a \parallel b)$ in terms of $H(a)$
  - $\parallel$ means bit string concatenation
- Makes many PRF-style constructions insecure

SHA-2 and SHA-3

- SHA-2: evolutionary, larger, improvement of SHA-1
  - Exists as SHA-$\{224, 256, 384, 512\}$
  - But still has length-extension problem
- SHA-3: chosen recently in open competition like AES
  - Formerly known as Keccak, official standard Aug. 2015
  - New design, fixes length extension
  - Not yet very widely used

MAC: basic idea

- Message authentication code: similar to hash function, but with a key
- Adversary without key cannot forge MACs
- Strong definition: adversary cannot forge anything, even given chosen-message MACs on other messages

CBC-MAC construction

- Same process as CBC encryption, but:
  - Start with IV of 0
  - Return only the last ciphertext block
- Both these conditions needed for security
- For fixed-length messages (only), as secure as the block cipher

HMAC construction

- $H(K \parallel M)$: insecure due to length extension
  - Still not recommended: $H(M \parallel K)$, $H(K \parallel M \parallel K)$
- HMAC: $H(K \oplus a \parallel H(K \oplus b \parallel M))$
- Standard $a = \mathtt{0x5c}^*$, $b = \mathtt{0x36}^*$
- Probably the most widely used MAC

Outline

Session keys

- Don't use your long term password, etc., directly as a key
- Instead, *session key* used for just one channel
- In modern practice, usually obtained with public-key crypto
- Separate keys for encryption and MACing

Order of operations

- Encrypt and MAC ("in parallel")
  - Safe only under extra assumptions on the MAC
- Encrypt then MAC
  - Has cleanest formal safety proof
- MAC then Encrypt
  - Preferred by FS&K for some practical reasons
  - Can also be secure

Authenticated encryption modes

- Encrypting and MACing as separate steps is about twice as expensive as just encrypting
- "Authenticated encryption" modes do both at once
  - Newer (circa 2000) innovation, many variants
- NIST-standardized and unpatented: Galois Counter Mode (GCM)

Ordering and message numbers

- Also don't want attacker to be able to replay or reorder messages
- Simple approach: prefix each message with counter
- Discard duplicate/out-of-order messages

Padding

- Adjust message size to match multiple of block size
- To be reversible, must sometimes make message longer
- E.g.: for 16-byte block, append either 1, or $2\ 2$, or $3\ 3\ 3$, up to 16 "16" bytes

Padding oracle attack

- Have to be careful that decoding of padding does not leak information
- E.g., spend same amount of time MACing and checking padding whether or not padding is right
- Remote timing attack against CBC TLS published 2013

Don't actually reinvent the wheel

- This is all implemented carefully in OpenSSL, SSH, etc.
- Good to understand it, but rarely sensible to reimplement it
- You'll probably miss at least one of decades' worth of attacks

Next time

- Public-key encryption protocols
- More about provable security and appropriate paranoia