Foundations of Network and Computer Security

John Black

Lecture #2
Aug 26th 2004

CSCI 6268/TLEN 5831, Fall 2004

Economist Survey

- Please read it
- Main points
  - Security is a MUCH broader topic than just SSL and viruses
  - Firewalls don’t always work
  - Economics are a factor
  - And more...

What *IS* Computer Security?

- Cryptography
  - Mostly based in mathematics
- Network Services
  - Offense: Overflows, SQL injection, format strings, etc
  - Defense: Firewalls, IDSes, Sandboxing, Honeypots
- Software Engineering
  - You have to find all flaws, they only have to find one
- Policy
  - Laws affect profoundly our security and privacy, as we have already seen

What *IS* Computer Security?

- Soft Science
  - Trust Models (Bell-LaPadula, Insider Threat, etc)
  - Economics, Game Theory
  - Social Engineering
- Education
  - Students become our programmers
    - Insufficient training in security issues
- Various
  - Credit Card Scanners
    - Should you trust your CC# on the Internet?
  - ATM story

Cryptography

- Introduction to cryptography
  - Why?
    - We’re doing things bottom-up
    - Crypto is a fundamental building block for securing networks, but by NO MEANS a panacea
  - Often done well
    - Breaking the crypto is often not the easiest way in
      - Instead exploit some of those other holes!
  - Long history
  - Based on lots of math

In the Beginning…

- “Classical” cryptography
  - Caesar cipher aka shift cipher
    - A → Z, B → A, C → B, etc…
    - We are shifting by -1 or, equivalently, by 25
    - Here the “domain” is A…Z and shifts are done modulo 26
      - Ex: What happens to “IBM” with a shift of 25?

Kerckhoff

- Kerckhoff's principal
  - Assume algorithm is public and all security rests with the "key"
  - The opposite philosophy is sometimes called "security thru obscurity"
    - Often dubious
      - Experts say you *want* people to see the algorithm… the more analysis it sees, the better!
    - Used in military settings however
      - Why give them *any* information??
      - Skipjack was this way

What is a “key”?

- We have a basic enciphering mechanism
  - We just saw the Caesar cipher
- The “key” is the “variable” part of the algorithm
  - What was our key with the Caesar cipher?
  - How many keys were possible?
  - Why is this cipher insecure?

Digression on Blocksize

- The “blocksize” of a cipher is the size, in bits, of its domain
  - Caesar took 26 inputs, so about 4.7 bit blocksize
  - We take lg(|D|) to compute blocksize
    - Often it’s already specified in bits
  - Keysize is analogous
    - What was the keysize of the Caesar cipher?
- A “blockcipher” always outputs the same number of bits as it takes in
  - Ciphers induce a “permutation” on their domain
    - This means they are 1-to-1
    - Without this, we couldn’t decipher!

Improving Caesar

- Substitution Cipher
  - We allow each {A,…, Z} to map to any other character in this set
    - Ex: A → Q, B → S, C → A, etc…
    - We must still ensure a 1-to-1 mapping!
    - How many mappings are possible?
    - What is the key here?
    - What is the keysize?
  - Is exhaustive key-search feasible here?

Exhaustive Key-search

- We had 403291461126605635584000000 possible keys
  - Keysize is lg of this, or about 88.4 bits
  - Infeasible even with a lot of money and resources!
- Rule of Thumb
  - 2^{30} quite easily
  - 2^{40} takes a while, but doable (exportable keysize!)
  - 2^{50} special hardware, parallelism important
  - 2^{60} only large government organizations
  - 2^{70} approaching the (current) limits of imagination

So Substitution Cipher is Secure?

- Nope
  - Ever do the Sunday Cryptograms?
  - Attacks:
    - Frequency analysis
      - etaoinshrdlu…
    - Diphthongs, triphthongs
      - ST, TH, not QX
    - Word lengths
      - A and I are only 1-letter words
    - Other statistical measures
      - Index of Coincidence

What did we just Implicitly Assume?

- What assumption was made in these attacks?
- What was a central feature of the Substitution Cipher which permitted these attacks? (hard)
- How can we repair these problems?

Small Blocksizes are Bad

- Ok, we had a blocksize of < 5 bits
  - So fix it!
  - Try 64 bits instead
  - All is well?
    - How many permutations are there now?
      - $2^{64}! \approx 2^{2^{70}}$
      - Stirling's formula: $n! \approx (n/e)^n \sqrt{2\pi n}$
    - What is the keysize (in bits)?
      - About 2^{70} bits! Yow!
      - 64 GB is $2^6 * 2^{30} * 2^3 = 2^{39}$

Key is too Large

- We can't store 2^{70} bit keys
  - What can we do then?
  - Idea: instead of representing ALL 2^{64}! permutations we select a "random looking" subset of them!
    - We will implement the map via an algorithm
    - Our subset will be MUCH smaller than the set of all permutations

Example Blockcipher

- Suppose we have 64-bit blocksize
- Suppose we have 64-bit keys
  - Notice this is **FAR** smaller than 2^{70}-bit keys, so we will be representing a *vastly* smaller set of permutations
  - Select a key K at random from $\{0,1\}^{64}$
    - $\{0,1\}^{64}$ is the set of all length-64 binary strings
- Let $C = P \oplus K$
  - Here $\oplus$ means XOR

Digression on Terminology

- Note that we used specific letters in our formula $C = P \oplus K$
  - P is the “plaintext”
  - C is the “ciphertext”
  - K is usually used for “key”
- Call this blockcipher X
  - $X : \{0,1\}^{64} \times \{0,1\}^{64} \rightarrow \{0,1\}^{64}$
  - This means E takes two 64-bit strings and produces a 64-bit output

Looking at Blockcipher X

- First, is it even a valid cipher?
  - Is it 1-to-1?
    - Basic facts on xor's:
      - $A \oplus A = 0$ $A \oplus B = B \oplus A$
      - $A \oplus 0 = A$ $A \oplus (B \oplus C) = (A \oplus B) \oplus C$
    - So prove 1-to-1:
      - Suppose $P \neq P'$ but $C = C$
      - Then $P \oplus K = P' \oplus K$
      - so $P \oplus P' = K \oplus K$
      - and $P \oplus P' = 0$
      - so $P = P'$, contradiction

So it's *Syntactically* Valid

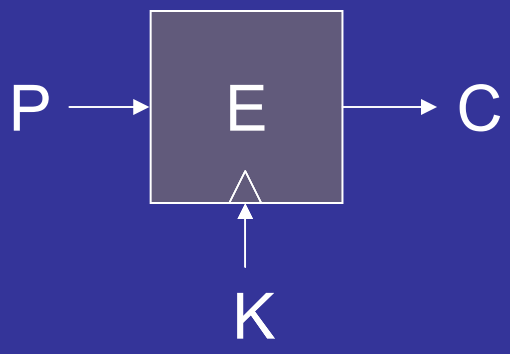
- What about its security?
  - It's terrible, but before we can really look more closely at it we need to learn more about what "secure" means
  - A second problem is that we still haven't said how to "encrypt," only to "encipher"
    - Encryption handles a bunch of variable-length messages
    - Enciphering handles inputs of one fixed size; ergo the term "blockcipher"

Background

- So really we've been talking about things like encryption and security with proper definitions!
  - Although it may be a pain, definitions are a central (and often ignored) part of doing "science"
  - You will see textbooks teach cryptography without defining the terms they use
  - We have an intuitive sense of these things, but we can't do <u>science</u> without writing down precise meanings for the terms we're using
  - The network security part of the course won't be much like this

Blockciphers

- One of the most basic components
  - Used EVERYWHERE in cryptography
  - Blockcipher E maps a k-bit key K and an n-bit plaintext P to an n-bit ciphertext C
  - Requirement: for any fixed K, E(K, ·) is a permutation (ie, is 1-to-1)



Security

- Intuition:
  - A “secure” blockcipher under a (uniformly-chosen) random key should “look random”
- More precisely (but still informal):
  - Suppose you are given a black-box which contains blockcipher E with a secret, random, fixed key K embedded within it
  - Suppose you are also given another black-box (looks identical) which has a permutation π from n-bits to n-bits embedded within it, and π was chosen uniformly at random from the set of all $2^n!$ possible permutations
  - You are allowed to submit arbitrary plaintexts and ciphertexts of your choice to either box
  - Could you tell which was which using a “reasonable” amount of computation?

Blockcipher Security (cont.)

- A “good” blockcipher requires that, on average, you must use a TON of computational resources to distinguish these two black-boxes from one another
  - A good blockcipher is therefore called “computationally indistinguishable” from a random permutation
  - If we had 2^{70}-bit keys, we could have *perfect* 64-bit blockciphers
  - Since we are implementing only a small fraction, we had better try and ensure there is no computationally-simple way to recognize this subset

Blockcipher Security (cont.)

- If we can distinguish between black-boxes quickly, we say there is a "distinguishing attack"
  - Practical uses?
  - Notice that we might succeed here even without getting the key!
    - Certainly getting the key is sufficient since we assume we know the underlying algorithm
    - What is the attack if we know the key?

Theme to Note

- Note that our notion of security asks for MORE than we often need in practice
  - This is a common theme in cryptography: if it is reasonable and seemingly achievable to efficiently get more than you might need in practice, then require that your algorithms meet these higher requirements.

Our Blockcipher X

- So is X secure under this definition?
  - No, simple distinguishing attack:
    - Select one black-box arbitrarily (doesn't matter which one)
    - Submit plaintext $P=0^{64}$ receiving ciphertext C
    - Submit plaintext $P'=1^{64}$ receiving ciphertext C'
    - If black-box is our friend X (under key K) then we will have
      - $C = K$ and $C' = K \oplus 1^{64}$
      - So if $C \oplus C' = 1^{64}$ we guess that this box is blockcipher X
      - If not, we guess that this box is the random permutation

Analysis of X (cont.)

- What is the probability that we guess wrong?
  - Ie, what is the chance that two random distinct 64-bit strings are 1's complements of each other?
  - $1/(2^{64}-1)$ … about 1 in 10^{20}
- Note that this method does not depend on the key K