Foundations of Network and Computer Security

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Lecture #8
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Announcements

- Quiz #2, Tuesday, Sept 28th
- Project #0 due Tuesday, Oct 5th
- Midterm, Thursday, Oct 14th
- Exams are closed notes, calculators allowed
- Remember to consult the class calendar

Key Generation

- Bob generates his keys as follows
  - Choose two large distinct random primes p, q
  - Set n = pq (in Z… no finite groups yet)
  - Compute $\phi(n) = \phi(pq) = \phi(p)\phi(q) = (p-1)(q-1)$
  - Choose some $e \in Z_{\phi(n)}^*$
  - Compute $d = e^{-1}$ in $Z_{\phi(n)}^*$
  - Set pk = (e,n) and sk = (d,n)
    - Here (e,n) is the ordered pair (e,n) and does not mean gcd

RSA Encryption

- For any message $M \in Z_n^*$
  - Alice has pk = (e,n)
  - Alice computes $C = M^e \bmod n$
  - That's it

- To decrypt
  - Bob has sk = (d,n)
  - He computes $C^d \bmod n = M$
    - We need to prove this

RSA Proof

- Need to show that for any $M \in Z_n^*$, $M^{ed} = M \bmod n$
  - $ed = 1 \bmod \phi(n)$ [by def of d]
  - So $ed = k\phi(n) + 1$ [by def of modulus]
  - So working in Z_n^*, $M^{ed} = M^{k\phi(n) + 1} = M^{k\phi(n)} M^1 = (M^{\phi(n)})^k M = 1^k M = M$
    - Do you see LaGrange's Theorem there?
- This doesn't say anything about the security of RSA, just that we can decrypt

Security of RSA

- Clearly if we can factor efficiently, RSA breaks
  - It's unknown if breaking RSA implies we can factor
- *Basic* RSA is not good encryption
  - There are problems with using RSA as I've just described; don't do it
  - Use a method like OAEP
    - We won't go into this

Factoring Technology

- Factoring Algorithms
  - Try everything up to sqrt(n)
    - Good if n is small
  - Sieving
    - Ditto
  - Quadratic Sieve, Elliptic Curves, Pollard’s Rho Algorithm
    - Good up to about 40 bits
  - Number Field Sieve
    - State of the Art for large composites

The Number Field Sieve

- Running time is estimated as

$$e^{(1.526+o(1))(\log n)^{1/3}(\log \log n)^{2/3}}$$

- This is super-polynomial, but sub-exponential
  - It's unknown what the complexity of this problem is, but it's thought that it lies between P and NPC, assuming P $\neq$ NP

NFS (cont)

- How it works (sort of)
  - The first step is called “sieving” and it can be widely distributed
  - The second step builds and solves a system of equations in a large matrix and must be done on a large computer
    - Massive memory requirements
    - Usually done on a large supercomputer

The Record

- In Dec, 2003, RSA-576 was factored
  - That’s 576 bits, 174 decimal digits
  - The next number is RSA-640 which is

    310741824049004372135075003588856793003734602284271
27545720161948823206440518081504556346829671723286
78243791627283803341547107310850191954852900733772
4822783525742386454014691736602477652346609

  - Anyone delivering the two factors gets an immediate A in the class (and 10,000 USD)

On the Forefront

- Other methods in the offing
  - Bernstein’s Integer Factoring Circuits
  - TWIRL and TWINKLE
    - Using lights and mirrors
  - Shamir and Tromer’s methods
    - They estimate that factoring a 1024 bit RSA modulus would take 10M USD to build and one year to run
      - Some skepticism has been expressed
  - And the beat goes on…
    - I wonder what the NSA knows

Implementation Notes

- We didn't say anything about how to *implement* RSA
  - What were the hard steps?!
    - Key generation:
      - Two large primes
      - Finding inverses mode $\phi(n)$
    - Encryption
      - Computing M^e mod n for large M, e, n
  - All this can be done reasonably efficiently

Implementation Notes (cont)

- Finding inverses
  - Linear time with Euclid's Extended Algorithm
- Modular exponentiation
  - Use repeated squaring and reduce by the modulus to keep things manageable
- Primality Testing
  - Sieve first, use pseudo-prime test, then Rabin-Miller if you want to be sure
    - Primality testing is the slowest part of all this
    - Ever generate keys for PGP, GPG, OpenSSL, etc?

Note on Primality Testing

- Primality testing is *different* from factoring
  - Kind of interesting that we can tell something is composite without being able to actually factor it
- Recent result from IIT trio
  - Recently it was shown that deterministic primality testing could be done in polynomial time
    - Complexity was like $O(n^{12})$, though it's been slightly reduced since then
  - One of our faculty thought this meant RSA was broken!
- Randomized algorithms like Rabin-Miller are far more efficient than the IIT algorithm, so we'll keep using those

Digital Signatures

- Digital Signatures are authentication in the asymmetric key model
  - MAC was in the symmetric key model
- Once again, Alice wants to send an authenticated message to Bob
  - This time they don't share a key
  - The security definition is the same
    - ACMA model

We Can Use RSA to Sign

- RSA gives us a signing primitive as well
  - Alice generates her RSA keys
    - Signing key sk = (d,n)
    - Verification key vk = (e,n)
    - Distributes verification key to the world
    - Keeps signing key private
  - To sign message $M \in Z_n^*$
    - Alice computes sig = M^d mod n
    - Alice sends (M, sig) to Bob
  - To verify (M', sig')
    - Bob checks to ensure M' = sig'^e mod n
    - If not, he rejects
- Once again, don't do this; use PSS or similar

Efficiency

- Why is this inefficient?
  - Signature is same size as message!
  - For MACs, our tag was small… that was good
- Hash-then-sign
  - We normally use a cryptographic hash function on the message, then sign the hash
  - This produces a much smaller signature
  - 2nd-preimage resistance is key here
    - Without 2nd-preimage resistance, forgeries would be possible by attacking the hash function

Let’s Sum Up

- Symmetric Key Model
  - Encryption
    - ECB (bad), CBC, CTR
      - All these are modes of operation built on a blockcipher
  - Authentication (MACs)
    - CBC MAC, XCBC, UMAC, HMAC
- Asymmetric Key Model
  - Encryption
    - RSA-OAEP
      - Assumes factoring product of large primes is hard
  - Authentication
    - RSA signatures
      - Usually hash-then-sign

Next Up: SSL

- Next we'll look at how to put all this together to form a network security protocol
- We will use SSL/TLS as our model since it's ubiquitous
- But first, we'll digress to talk about OpenSSL, and our first part of the project (a warm-up)

OpenSSL

- Was SSLeay
- Open Source
- Has everything we’ve talked about and a lot more
- Most everything can be done on the command line
- Ungainly, awkward, inconsistent
  - Mostly because of history
  - Have fun, it’s the only game in town
- http://www.openssl.org/

Brief Tutorial

- This is a grad class; you can figure it out from the man page, but…
  - Syntax is

  % openssl <cmd> <parms>

  - cmd can be ‘enc’, ‘rsautl’, ‘x509’, and more
  - We’ll start with the ‘enc’ command (symmetric encryption)
  - Let’s look at the enc command in more detail

OpenSSL enc command

- openssl enc -ciphername [-in filename] [-out filename] [-pass arg] [-e] [-d] [-a] [-K key] [-iv IV] [-p] [-P]
- -ciphername can be
  - des-ecb (yuk!), des-cbc (hmm), des (same as des-cbc), des-ede3-cbc, des3 (same), aes-128-cbc, bf, cast, idea, rc5
  - Can omit the ‘enc’ command if specifying these… kind of hokey
- If you don’t specify filenames, reads from and writes to stdin/stdout
  - Looks like garbage, of course
- If you don’t specify a password on the command line, it prompts you for one
  - Why are command-line passwords bad?
  - You can use environment variables but this is bad too
  - You can point to a file on disk… less bad
- What does the password do?
  - Password is converted to produce IV and blockcipher key

enc (cont)

% openssl aes-128-cbc –P

```
salt=39A9CF66C733597E
key=FB7D6E2490318E5CFC113751C10402A4
iv =6ED946AD35158A2BD3E7B5BAFC9A83EA
```

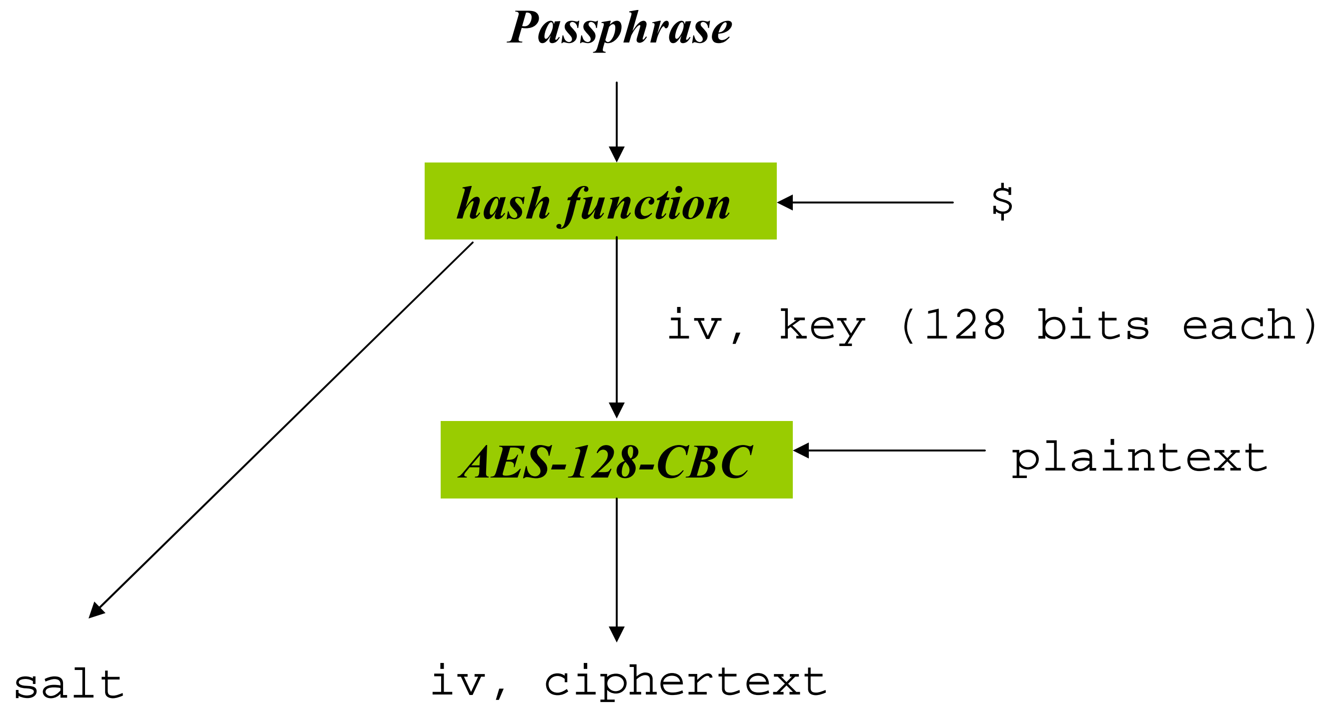
- salt is a random number generated for each encryption in order to make the key and iv different even with the same password
  - Begins to get confusing… didn't we just change the IV before?
  - Use this mode only when deriving a new key for each encryption
    - Eg, when encrypting a file on disk for our own use
  - If key is fixed, we specify it and the iv explicitly

    % openssl aes-128-cbc –K FB7D6E2490318E5CFC113751C10402A4 –iv 6ED946AD35158A2BD3E7B5BAFC9A83EA

Understanding Passwords vs. a Specified IV and Key

- So there are two modes you can use with enc
  - 1) Specify the key and IV yourself
    - This means YOU are in charge of ensuring the IV doesn't repeat
      - Use a good random number source or
      - Use a counter (which you have to maintain… headache!)
  - 2) Use a passphrase
    - OpenSSL uses randomness for you by generating a salt along with the IV and AES key
    - Passphrases are less secure (more guessable) in general
- Either way, we get non-deterministic encryption

Passphrase-Based enc



Things to think about:

- How to decrypt?
- Is the passphrase safe even though the salt and iv are known?

So How to Encrypt

- Let's encrypt the file 'test'

```
% cat test
hi there
% openssl aes-128-cbc -in test
enter aes-128-cbc encryption password:
Verifying - enter aes-128-cbc encryption password:
Salted__mTR&Qi¦¹K¯¿Ó̀àg&5&kE
```

- What's up with the garbage?
  – Of course the AES outputs aren't ASCII!
  – Use –base64 option

base64

- This is an encoding scheme (not cryptographic)
  - Translates each set of 6 bits into a subset of ASCII which is printable
  - Makes ‘garbage’ binary into printable ASCII
    - Kind of like uuencode
  - Of course this mapping is invertible
  - For encryption we want to do this after we encrypt
  - For decryption, we undo this before we decrypt
  - This is the –a flag for ‘enc’ but –base64 works as well and is preferable

Example: base64

- Let’s encrypt file ‘test’ again, but output readable ciphertext

```
% openssl aes-128-cbc -in test -base64
enter aes-128-cbc encryption password:
Verifying - enter aes-128-cbc encryption password:
U2FsdGVkX1/tdjfZnPrD+mSjBBO7InU8Mo4ttzTk8eY=
```

- We’ll always use this option when dealing with portability issues
  - Like sending ciphertext over email

Decrypting

- The command to decrypt is once again ‘enc’
  - This makes no sense; get used to it
  - Use the –d flag to tell enc to decrypt
  - Let’s decrypt the string

  `U2FsdGVkX1/tdjfZnPrD+mSjBBO7InU8Mo4ttzTk8eY=`

  which I’ve placed into a file called ‘test.enc’

```
% openssl enc -d -in test.enc
U2FsdGVkX18FZENOZFZdYvLoqPdpRTgZw2CZIQs6bMQ=
```

Hunh?

- It just gave back the ciphertext?!
  – We didn't specify an encryption algorithm
  – Default is the identity map (get used to it)
  – Let's try again

```
% openssl aes-128-cbc -d -in test.enc
enter aes-128-cbc decryption password:
bad magic number
```

- Ok, now what's wrong?

Error messages not useful

- We forgot to undo the –base64
  - The error msg didn’t tell us that (get used to it)
  - One more try:

```
% openssl aes-128-cbc -d -in test.enc -base64
enter aes-128-cbc decryption password:
hi there
```

  - It was all worth it, right?
  - Now it’s your turn

Project #0

- I'll give you a ciphertext, you find the password
  - Password is a three-letter lowercase alpha string
  - Main purpose is to get you to figure out where openssl lives on your computer(s)
  - Don't do it by hand
  - Full description on our web page
    - Due Oct 5th, in class