Securing Password Storage

Analyzing past failure & secure design

-jOHN
Internal Chief Technology Officer
Principal
@m1splacedsoul

cigital

History: /etc/password

- Circa 1973
- ‘one-way’ password encryption
- chmod a+r etc/password
- DES takes 1 sec. per password

etc/password

```
root:0:0:EC90xWpTKCo
hjackman:100:100:KMEzyulaQQ2
bgoldthwa:101:101:Po2gweIEPZ2
jsteven:102:500:EC90xWpTKCo
msoul:103:500:NTB4S.iQhwk
nminaj:104:500:a2N/98VTt2c
```

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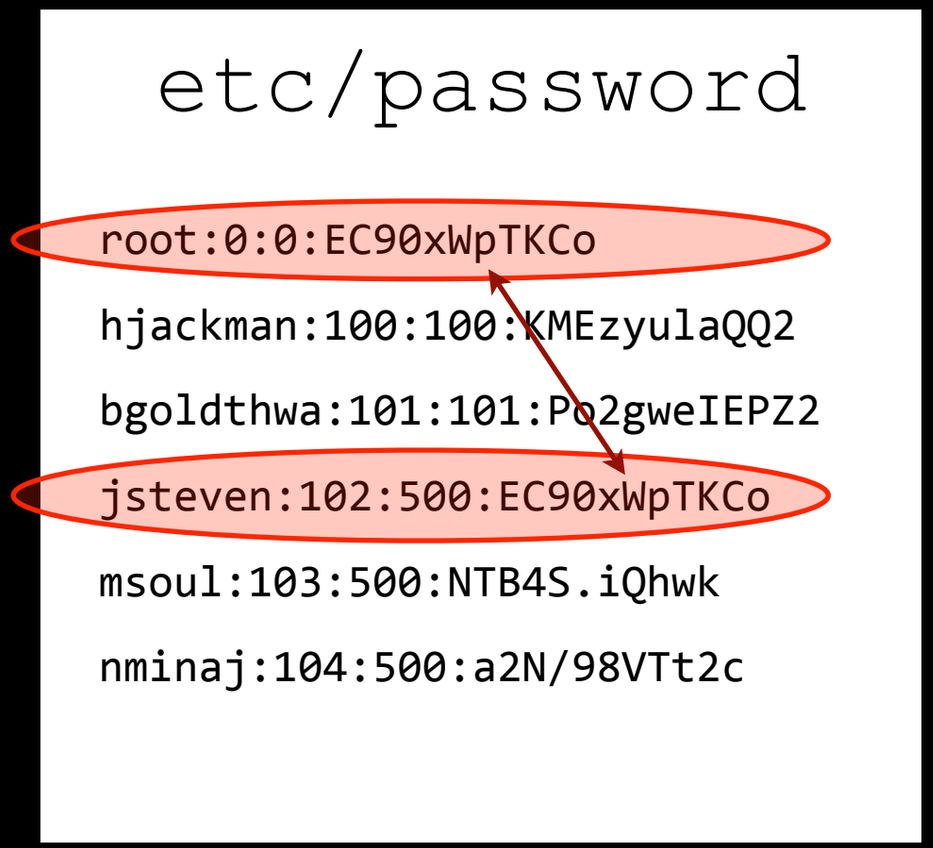


Salt Control

Fixing /etc/password

I<3NickyMin@j!

Fixing /etc/password

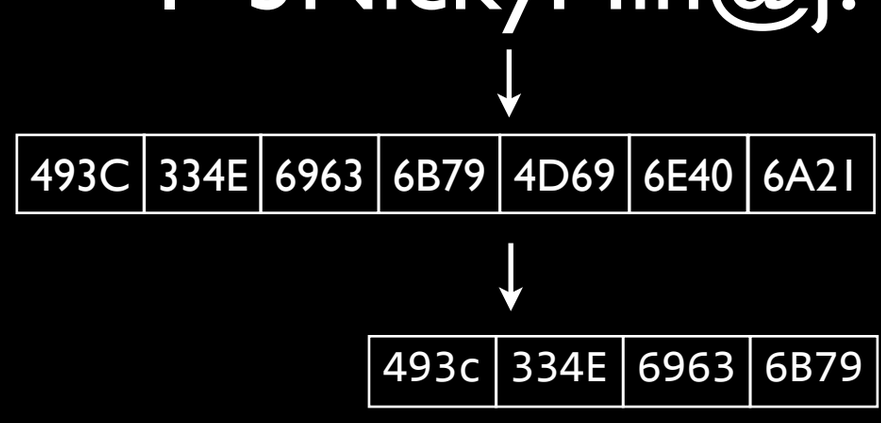
- ‘Good’ Password

I<3NickyMin@j!

112b

Fixing /etc/password

- ‘Good’ Password



- truncate (8-chars)

Fixing /etc/password

- ‘Good’ Password

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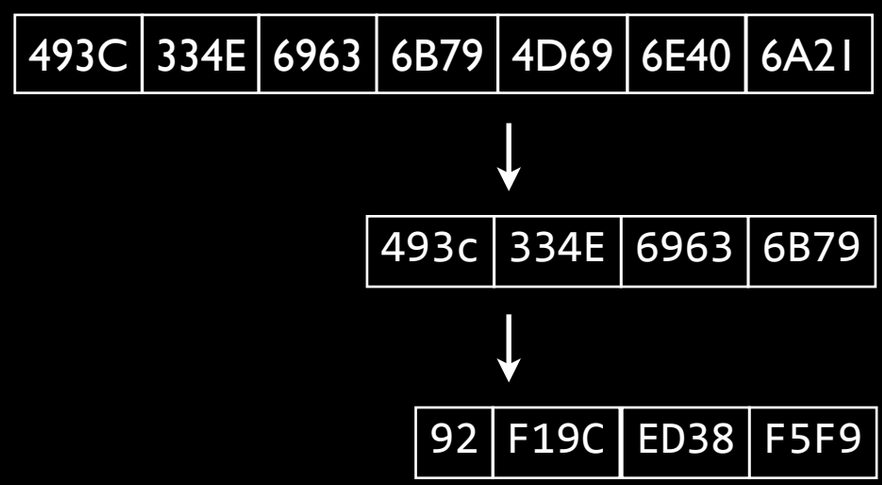

- truncate (8-chars)
- 7bit encoding

Fixing /etc/password

- ‘Good’ Password

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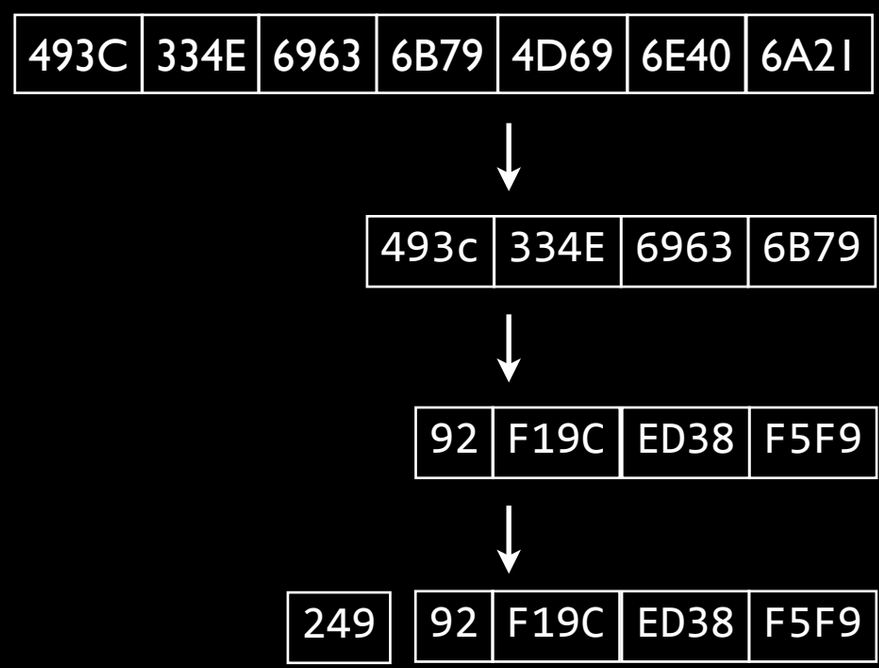
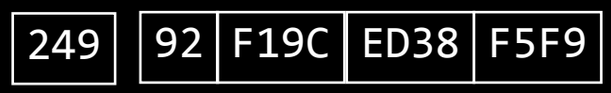


- truncate (8-chars)
- 7bit encoding
- Add 12b SALT

Fixing: /etc/password

- salt + derived key (dK)



68b

Fixing: /etc/password

- salt + derived key (dK)
- plaintext (pT) for encryption

Fixing: /etc/password

- salt + derived key (dK)
- plaintext (pT) for encryption
- crypt(DES, salt, dKey, pT)
  - 25 Iterations
- which is...


```
c_txt = des(s, dK, pT)

for (i=0; i<25; i++)

     c_txt = des(s, dK, c_txt)
```

Brute-forcing Nicki

I<3NickyMin@j!

Brute-forcing Nicki

I<3NickyMin@j! ⟶ ac | EC9 | 0xWp | TKCo 104b

How much work do I have to do?

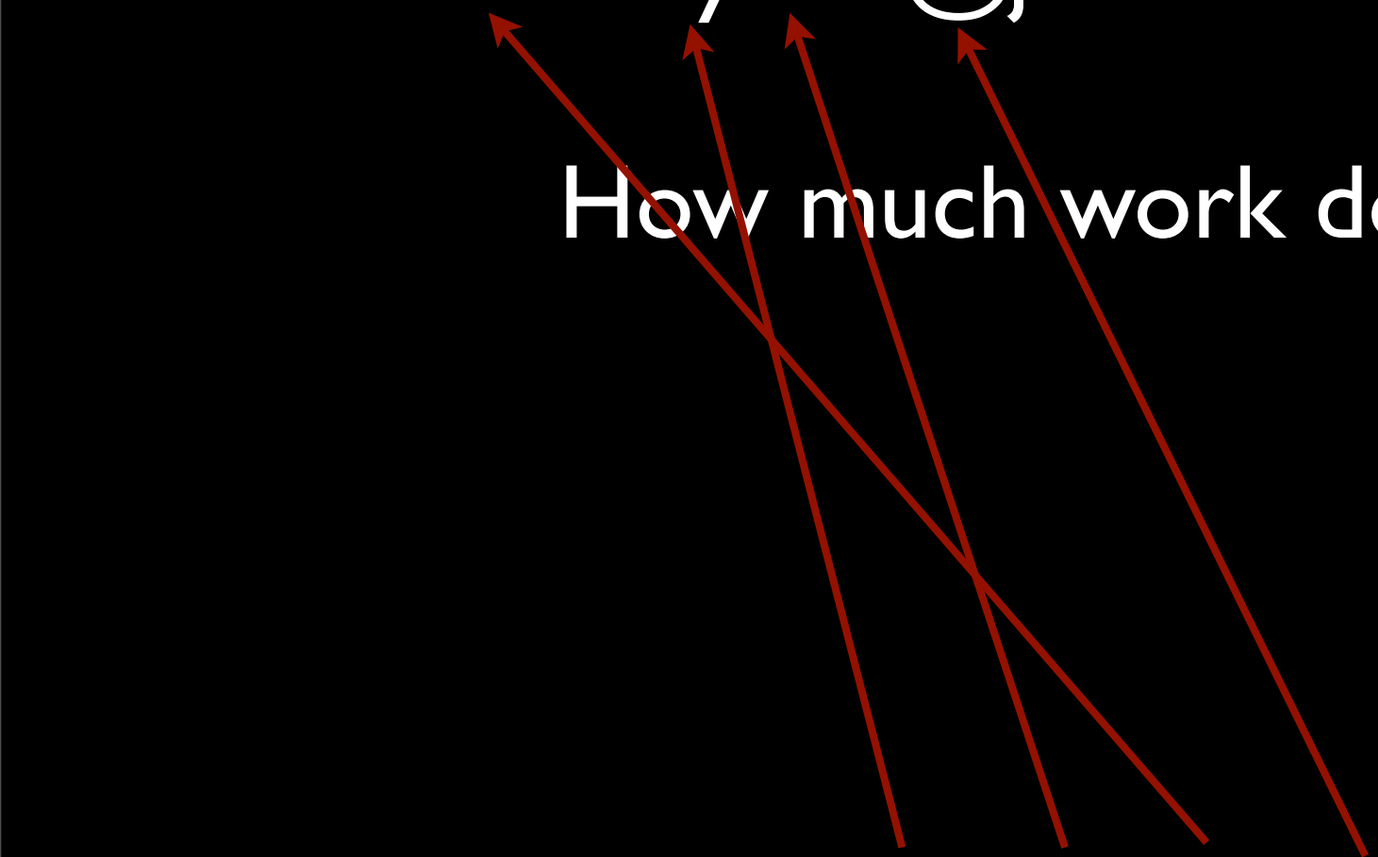
2^{11} 16^{11} 2^{112}

2^{13} 16^{13} 2^{99}

Brute-forcing Nicki

I<3NickyMin@j! ⟶ `ac` `EC9` `0xWp` `TKCo` `104b`

How much work do I have to do?



26+26+10+33 = 95

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95^{15} 2^{99}

...Bringing us to 2012

What do we have here?

00000fac2ec84586f9f5221a05c0e9acc3d2e670
0000022c7caab3ac515777b611af73afc3d2ee50
deb46f052152cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
b3344eaec4585720ca23b338e58449e4c3d2f628
674db9e37ace89b77401fa2bfe456144c3d2f708
37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
000005891870 1830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
d178cbe8d2a38a1575d3feed73d3f033c3d304d8
00000273b52ee943ab763d2bb3d83f5dc3d30904

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0000022c7caab3ac515777b611af73afc3d2ee50
deb46f052152cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
b3344eaec4585720ca23b338e58449e4c3d2f628
674db9e37ace89b77401fa2bfe456144c3d2f708
37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
000005891870 1830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
d178cbe8d2a38a1575d3feed73d3f033c3d304d8
00000273b52ee943ab763d2bb3d83f5dc3d30904

SHA1('password'): 1e4c9b93f3f0682250b6cf8331b7ee68fd8

What's wrong?

```
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```

00000fac2ec84586f9f5221a05c0e9acc3d2e670
0000022c7caab3ac515777b611af73afc3d2ee50
deb46f05215 2cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
b3344eaec4585720ca23b338e58449e4c3d2f628
674db9e37ace89b77401fa2bfe45614 4c3d2f708
37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
0000058918701830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
d178cbe8d2a38a1575d3feed73d3f033c3d304d8
00000273b52ee943ab763d2bb3d83f5dc3d30904

What's wrong?

`SHA1('password'): 1e4c9b93f3f0682250b6cf8331b7ee68fd8`

- If they'd salted, how would I have found *my password*?

00000fac2ec84586f9f5221a05c0e9acc3d2e670
0000022c7caab3ac515777b611af73afc3d2ee50
deb46f05215 2cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
b3344eaec4585720ca23b338e58449e4c3d2f628
674db9e37ace89b77401fa2bfe45614 4c3d2f708
37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
0000058918701830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
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- If they'd salted, how would I have found *my password*?
- How do I build an attack to reverse *all the passwords?*

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0000022c7caab3ac515777b611af73afc3d2ee50
deb46f052152cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
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37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
000005891870 1830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
d178cbe8d2a38a1575d3feed73d3f033c3d304d8
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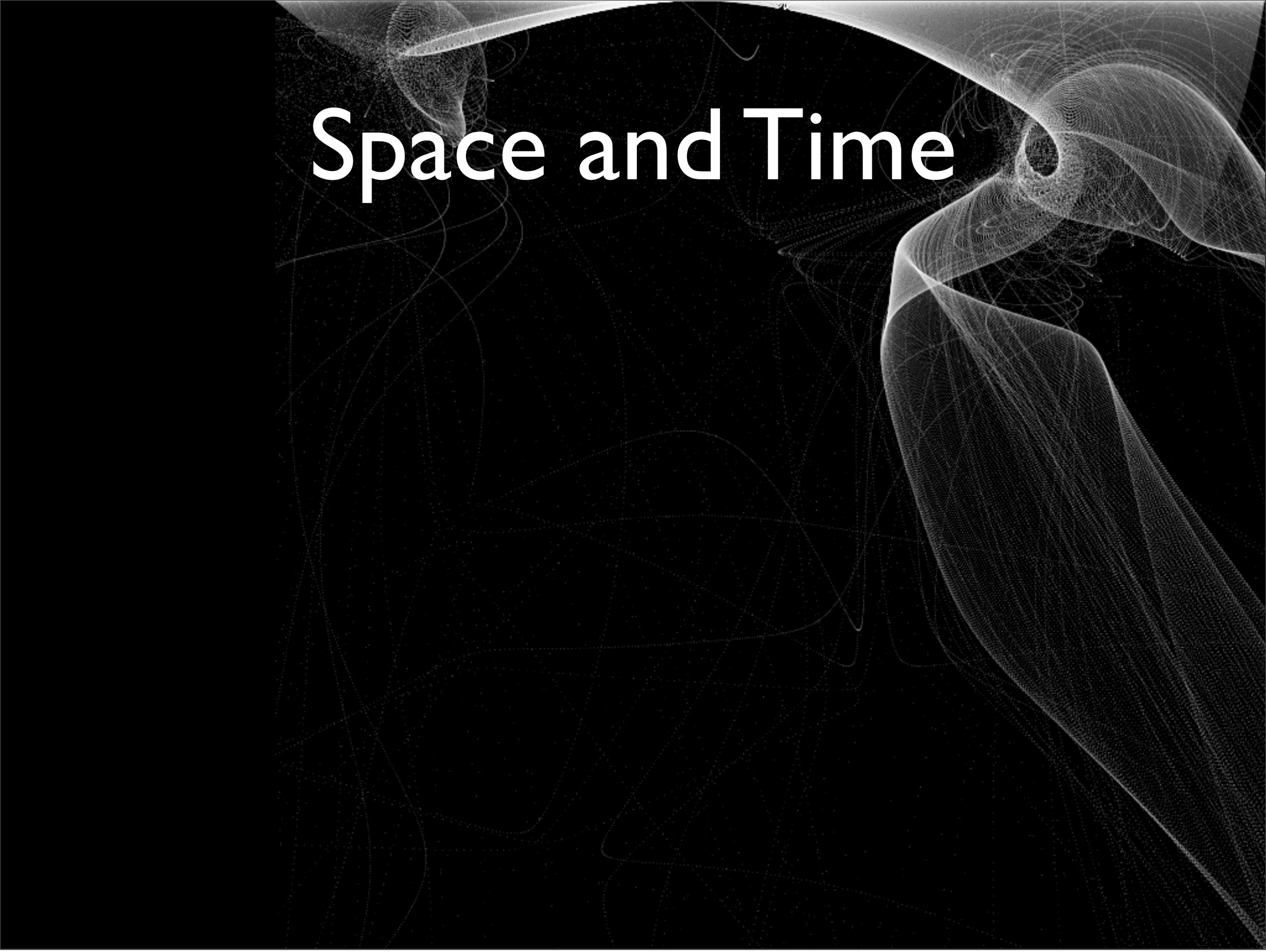
What's wrong?

`SHA1('password'): 1e4c9b93f3f0682250b6cf8331b7ee68fd8`

- If they'd salted, how would I have found *my password*?
- How do I build an attack to reverse *all the passwords?*
- How long *would that take?*

00000fac2ec84586f9f5221a05c0e9acc3d2e670
0000022c7caab3ac515777b611af73afc3d2ee50
deb46f052152cfed79e3b96f51e52b82c3d2ee8e
00000dc7cc04ea056cc8162a4cbd65aec3d2f0eb
00000a2c4f4b579fc778e4910518a48ec3d2f111
b3344eaec4585720ca23b338e58449e4c3d2f628
674db9e37ace89b77401fa2bfe456144c3d2f708
37b5b1edf4f84a85d79d04d75fd8f8a1c3d2fbde
00000e56fae33ab04c81e727bf24bedbc3d2fc5a
000005891870 1830b2cca174758f7af4c3d30432
000002e09ee4e5a8fcdae7e3082c9d8ec3d304a5
d178cbe8d2a38a1575d3feed73d3f033c3d304d8
00000273b52ee943ab763d2bb3d83f5dc3d30904

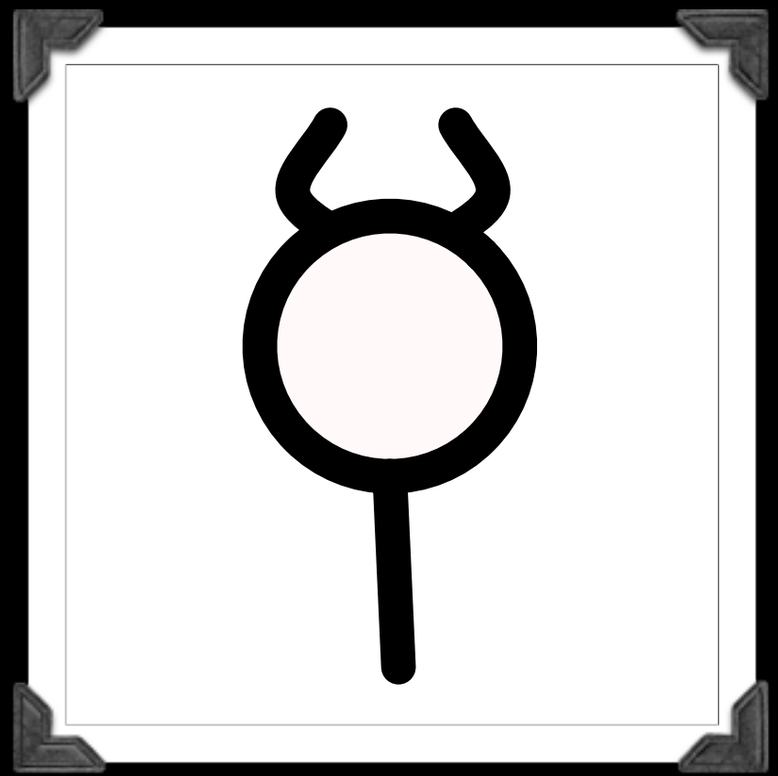
Space and Time



How long does this take?

- Depends on the threat...
  - Some guy
  - Well-equipped Attacker
  - Nation-state

- Is the algorithm supported by your *script-kiddie tool*?



Sir G. Threat IV

circa 2004

Thyme

		(z-z | A-Z | 0-9)^4	(z-z | A-Z | 0-9)^5	(z-z | A-Z | 0-9)^6	(z-z | A-Z | 0-9)^7	(z-z | A-Z | 0-9)^8	(z-z | A-Z | 0-9)^9	(z-z | A-Z | 0-9)^{10}	(z-z | A-Z | 0-9)^{11}
Attacking 2 million hashes (25M/sec)	**NVS 4200M GPU**	1 second	37 seconds	38 minutes	39 hours	101 days	17 years	1,064 years	
	!@#$%^&*()`~-_=+|[]{};:'",.<>/?	4 seconds	5 minutes	8 hours	30 days	7 years	726 years	68,317 years	
Attacking a single hash (32M/sec)	**NVS 4200M GPU**	0.5 seconds	29 seconds	30 minutes	31 hours	80 days	13 years	832 years	
	!@#$%^&*()`~-_=+|[]{};:'",.<>/?	2.5 seconds	4 minutes	6 hours	23 days	6 years	567 years	53,373 years	
Attacking a single salted hash (30M/sec)	**NVS 4200M GPU**	0.5 seconds	31 seconds	32 minutes	33 hours	84 days	14 years	887 years	
6.25% performace loss	!@#$%^&*()`~-_=+|[]{};:'",.<>/?	2.6 seconds	4.1 minutes	6.4 hours	25 days	6.4 years	606 years	56,931 years	
Attacking a single hash (85M/sec)	**$100 Nvidia GTS 250**	0.2 seconds	11 seconds	11 minutes	12 hours	30 days	5 years	313 years	19,413 years
	!@#$%^&*()`~-_=+|[]{};:'",.<>/?	1 second	1.4 minutes	2 hours	9 days	2 years	214 years	20,093 years	1,889,000 years
Attacking a single hash (2.3B/sec)	**$500 ATI Radeon HD 5970**							11.5 years	717 years
	!@#$%^&*()`~-_=+|[]{};:'",.<>/?						7.9 years	743 years	69,803 years

espace

Search Space	Pre-calculated Size
307,000 word dictionary	16 MB
(z-z | A-Z | 0-9)^4	338 MB
(z-z | A-Z | 0-9)6^5	21 GB
(z-z | A-Z | 0-9)^6	1.3 TB
(z-z | A-Z | 0-9)^7	87 TB
(z-z | A-Z | 0-9)^8	5,560 TB
(z-z | A-Z | 0-9)^9	357,000 TB
(z-z | A-Z | 0-9)^{10}	22,900,149 TB

so...

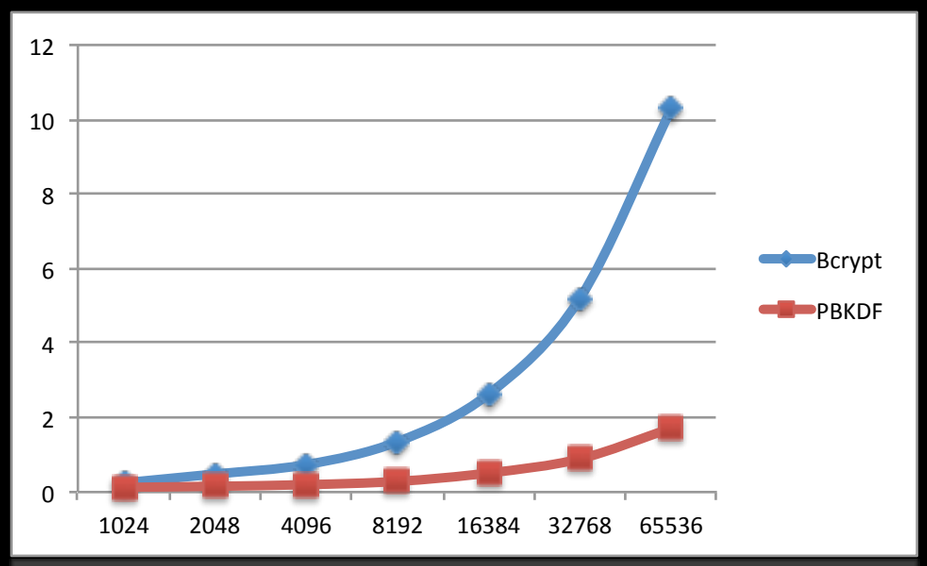
We’re gonna have to brute-force it...

Storing a pre-computed table seems intractable

...OK, how long will this take?

Algorithms scale *linearly* with iterations

Rounds	PBKDF2	Bcrypt
1024	0.125	0.25
2048	0.155	0.483
4096	0.198	0.735
8192	0.286	1.35
16384	0.511	2.632
32768	0.891	5.201
65536	1.715	10.284
(Iteration Count)	(Seconds)	(Seconds)



$$$ vs. Iteration Count

	NVS 4200M	GTX 550TI	GTX 670	GTX 690
Cores	48	192	1,344	3,072
Cost	-	$125	$400	$1,000

Can we fix it?

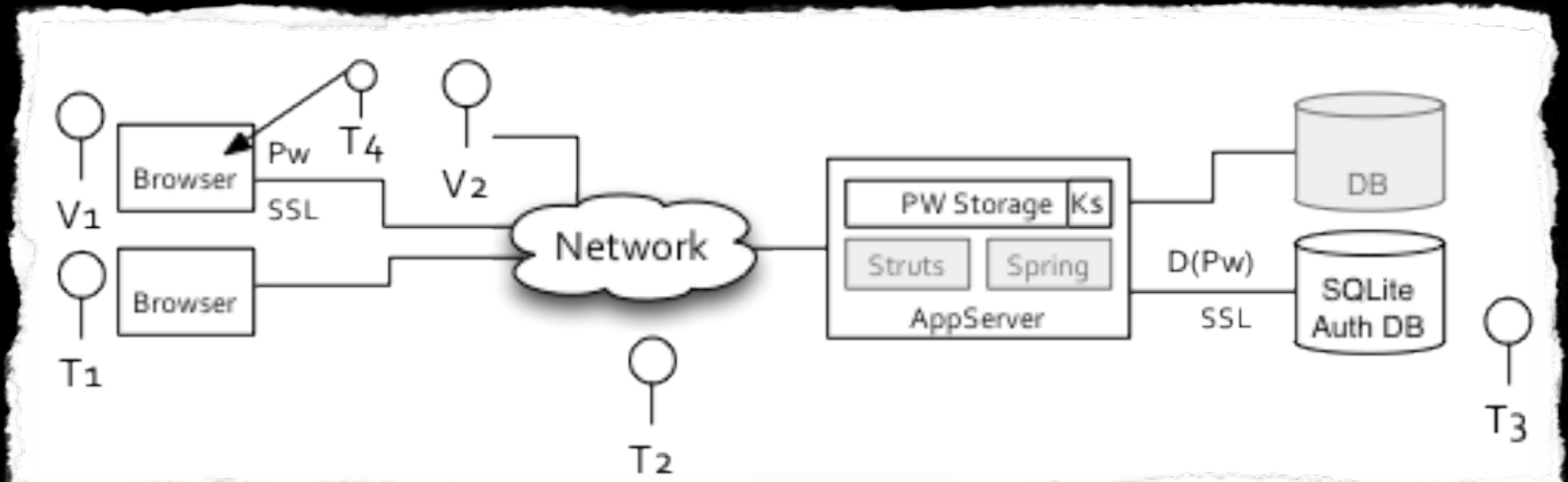
What about those iterations?

c = ?

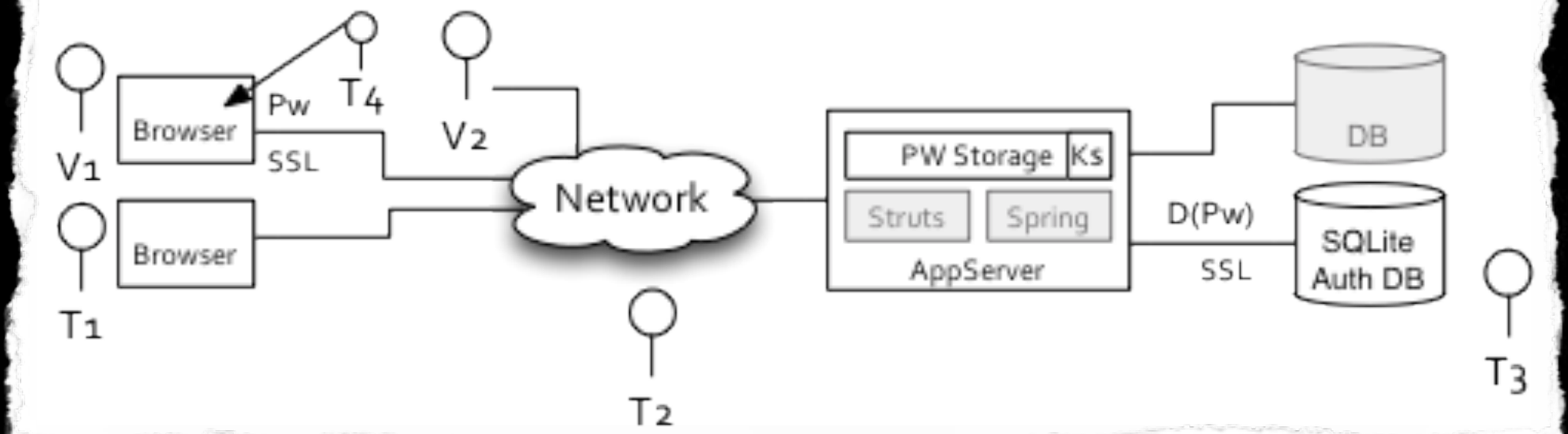
What about those iterations?

OK so look....

Threat Model



Threat Model



1. [V1] - *Active System User* : Compromises one's self through use of the system
    a. Accesses the system normally through a browser
    b. May access the system through a compromised network (exposing them to [T2])

2. [V2] - Offline *System User* : Suffers compromise without use of system
    a. Accesses the system normally through a browser
    b. May suffer compromise due to by duplicate password detection or by bulk export and reversal of stored passwords, for instance.

1. [T1] – *Internet-based Threat* : Access to the app
   - Possesses [1+] valid login to system;
   - Interacts w/ system through browser or AppSec tools;
   - Capable of discovering/executing all AppSec attacks;
   - Capable of acting as MiM [T2] in addition to T1 capabilities;
   - Data show that if [T1] can lift PW, they are likely to also be able to lift/correlate UNs;
   - Capable of rainbow table generation & amateur cryptanalysis;
   - Can NOT conduct state-of-art (accelerated/optimized) cryptanalytic, statistical, or rainbow-table attacks;
   - Can NOT conduct effective bulk phishing, malware installation, or botnet campaigns beyond individual AppSec attacks (i.e. CSRF, etc.).

2. [T2] - *Man-in-the-Middle* : Ability to interpose in communications between victim [V1] and the application server serving it content.
   - May passively observe HTTP traffic;
   - May actively observe and modify HTTP traffic, as a proxy;
   - May passively observe SSL traffic (HTTPS);
   - May be able to interpose, observe, and modify SSL as a proxy;
   - Capable of network-based attacks but not able to 'break' SSL in new or innovative ways;
   - Capable of replaying observed traffic;
   - *** If [T2] conducts [T1.AV3] and modifies code/script bound for [V1], they 'promote' to [T4]. See [T4].

3. [T3] – *LAN-based Threat* : Threat actors within equivalence-class to DB admin
   - May acts as [T2] within the network segment AppServer ← → DB;
   - Has console/network access to AppServer database;
   - May have access (ACLs) to AuthN credentials unless otherwise specified;
   - Presumed to be 'root' on database;
   - May index, sort, and conduct other operations on bulk <protected>(pw) store 'invisibly'.

4. [T4] - *MiB Threat* : [T1] with access to victims' browsers
   - See [T1];
   - Capable of conducting [T1.AV3] (replace code-in-browser);
   - Capable of adding persistent code/data to victims' [V1] browser.

5. [T5] - *Concerted Threat* : [T1]-like threat with capabilities of [T1], [T3], and [T4]. LAN access obtained through means of compromise of other or related systems.
   - Well-funded, patient threat has unlimited time/money
   - Capable of cryptanalytic attack, in addition to more coarse means (such as Rainbow tables)

Threat	Attack Vector	In-Bounds?
[T1] AppSec	AV0 - Observe client operations	Yes
	AV1 - Inject DB, bulk credentials lift	Yes
	AV2 - Brute force PW w/ AuthN API	Yes
	AV3 - AppSec attack (XSS, CSRF, SQLI)	Yes
	AV4 - Register 2 users, compare	Yes
[T2] MiM	AV1 - Interposition, Proxy	No
	AV2 - Interposition, Proxy, SSL	No
	AV3 - Timing attacks	Yes
[T3] Admin	AV1 - Bulk credential export	Yes
	AV2 - [T1] style attack	Yes
	AV3 - Direct action w/ DB	Yes
[T4] MiB	AV1 - Keylogger	No
	AV2 - Other persistent script/data	No
[T5] Concerted	AV1 - PRNG	Yes
	AV2 - DOS	Yes

...Simply it

- Reverse it...
- Chosen plaintext attack
- Dictionary attack
- Brute-force attack
- rainbow table creation
- Length-extension attack
- Oracle Padding attack
- Crypt-analytic attack
- Side-channel attack (such as timing or DPA)

Hash properties

```
digest = hash(plaintext);
```

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- Uniqueness

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- Determinism

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- Non-predictability

Hash properties

```
digest = hash(plaintext);
```

- Uniqueness
- Determinism
- Collision resistance
- Non-reversibility
- Non-predictability
- Diffusion

Use a better hash?

SHA-2!

- SHA-224
- SHA-256
- SHA-384
- SHA-512

Use a better hash?

SHA-2!

- SHA-224
- SHA-256
- SHA-384
- SHA-512

What property of hashes do these ‘work on’?

hmac properties

```
digest = hash(key, plaintext);
```

hmac properties

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```

- `extends hash` (inherits hash properties)

hmac properties

```
digest = hash(key, plaintext);
```

- `extends hash` (inherits hash properties)
- ‘signature’ : digest/verify by key-holder only

What's the Salt do again?

```
salt || digest = hash(key, salt || plaintext);
```

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```
salt || digest = hash(key, salt || plaintext);
```

- De-duplicates digest texts
- Adds entropy to input space
  - ...raising brute force time
  - ...increasing rainbow table size

Adaptive Hashes

```
salt || digest = PBKDF(hmac, salt, pw, c=);
```

Adaptive Hashes

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salt || digest = PBKDF(hmac, salt, pw, c=);
```

```
prev_round = sha1(key, salt, pw);
for (int i=0; i < c; i++){
    prev_round = sha1(key, salt, prev_round);
}
return prev_round;
```

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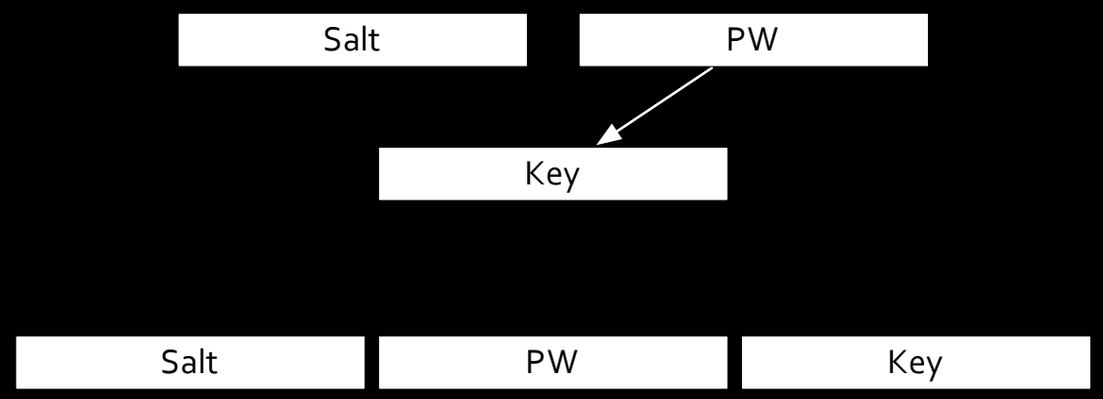
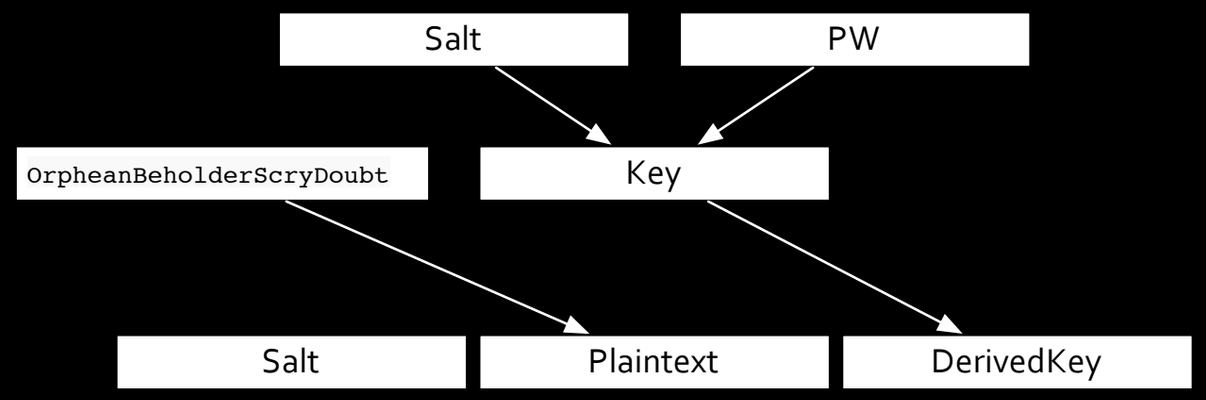


bcrypt!

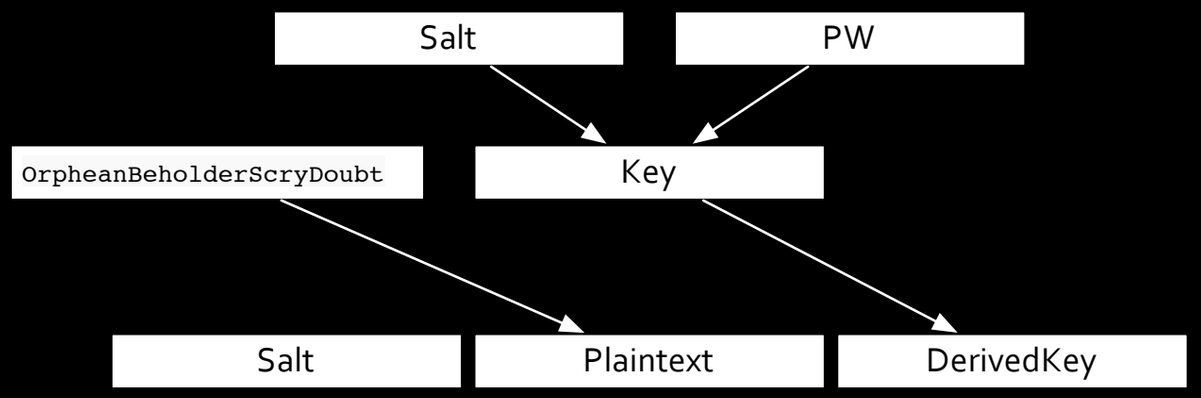
```
salt || digest = bcrypt(salt, pw, c=);
```



bcrypt!

```
salt || digest = bcrypt(salt, pw, c=);
```

```
key = eks(salt, pw);
prev_round = “OrpheanBeholderScryDoubt”;
for (int i=0; i < c; i++){
   prev_round = encryptECB(key, prev_round);
}
return salt||prev_round;
```



Compatible fix

COMPAT, FIPS

<version$_{scheme}$>||<salt$_{user}$>||<digest> := HMAC(<key$_{site}$>, <mixed construct>)

<mixed construct> := <version$_{scheme}$>||<salt$_{user}$>||<pw$_{user}$>

- HMAC := hmac-sha256
- key$_{site}$:= PSMKeyTool(SHA256()):32B;
- salt$_{user}$:= SHA1PRNG() | FIPS186-2():32B;
- pw$_{user}$:= <governed by password fitness>

Fix

Supported (Reversible)

<ciphertext> := ENC(<wrapper key_{site}>, <$version_{scheme}$>||<$salt_{user}$>||<round 1>)

<round 1> := HMAC-2(<key_{site}>, <mixed construct>)

<mixed construct> := <$version_{scheme}$>||<$salt_{user}$>||<pw_{user}>

<key_{site}>:= PSMKeyTool(HMAC-1, <$salt_{site}$>, <pw_{site}>, <c_{inters}>, DkL)

<wrapper key_{site}> := PSMKeyTool(HMAC-1, <$salt_{wrapper}$>, <$pw_{wrapper}$>, <c_{inters}>, DkL)

- ENC := AES
- HMAC-1 := hmac-sha1
- HMAC-2 := hmac-sha512
- PSMKeyTool := rfc2898 PBKDF2(HMAC-1, <$salt_{site}$>, c=10000000, DkL=32B): 32B;
- $salt_{user}$:= SHA1PRNG():32B;
- $salt_{site}$:= SHA1PRNG():32B;
- $salt_{wrapper}$:= SHA1PRNG():32B;
- pw_{user} := <governed by password fitness>

Why? (God why!?)

- Irreversible
- Resists padding / length extension
- Versioned

- No impact to user experience (speed)
- Recovery from stolen key w/o User interaction
- Stolen key AND database still demands brute force
- *Version MAC'd*