Bar Mitzvah Attack: Breaking SSL with 13-Year Old RC4 Weakness

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Why Bar Mitzvah?

- בר מיצווה (Hebrew)
- According to Jewish tradition, when Jewish boys become 13 years old, they become accountable for their actions and become a ***Bar Mitzvah***.
- The attack is based on a vulnerability in RC4 that was “born” (discovered) 13 years ago and recently (August 2014) “celebrated” it’s Bar-Mitzvah.
- The Invariance Weakness
  - Weaknesses in the key scheduling algorithm of RC4. Fluhrer, Mantin, and Shamir (SAC 2001)
  - Analysis of the stream cipher RC4. Mantin (My M. Sc. Thesis, 2001)

On TLS

- **On TLS**
- On RC4
- The Invariance Weakness
- The Attacks
- Conclusion

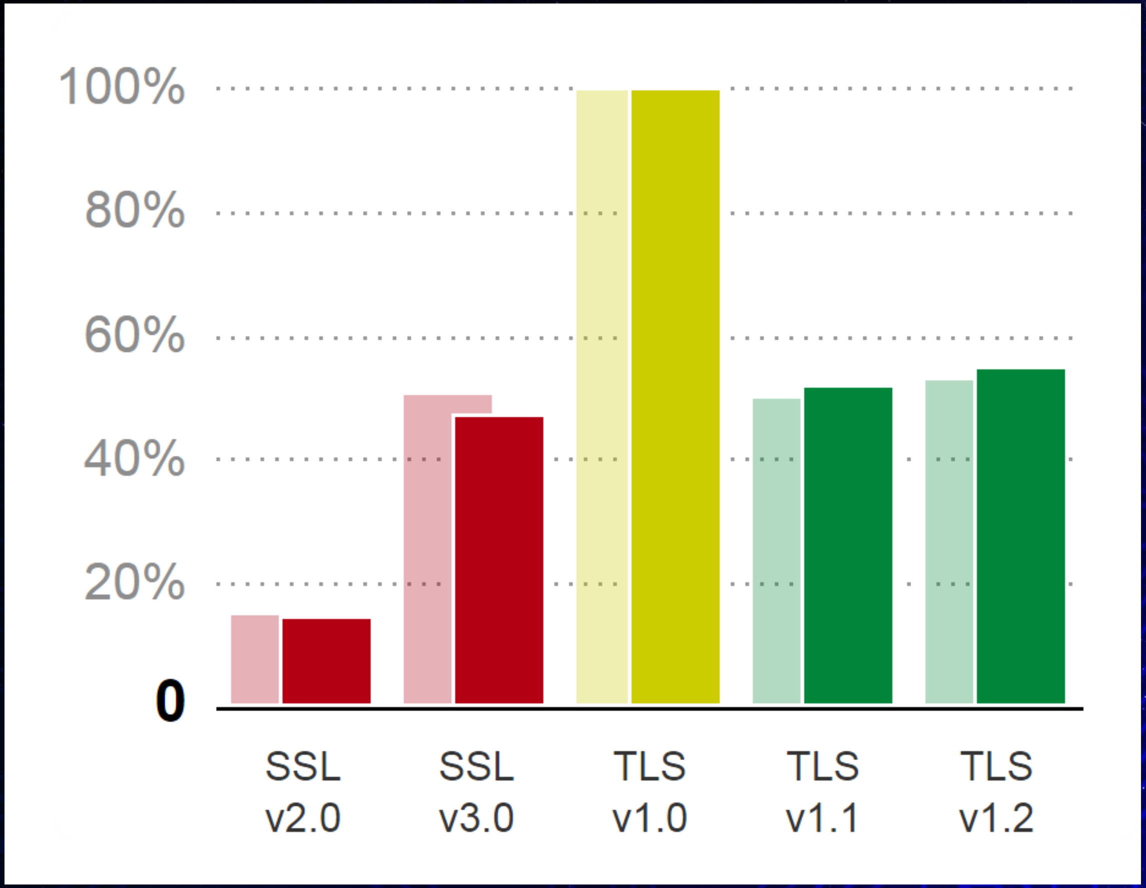
From SSL to TLS

- The Secure Socket Layer
  - Developed by Netscape for https communication
  - SSL 3.0 (RFC 6101) released in 1996

- Renamed to Transport Layer Security in 1999
  - TLS 1.0 (RFC 2246, 1999)
  - TLS 1.1 (RFC 4346, 2006)
  - TLS 1.2 (RFC 5246, 2008)
  - TLS1.3: work in progress

TLS Protocol Support

- SSL-Pulse (March 9, 2015)



TLS Objectives

- Mutual Authentication
  - Usually only Server authentication is used
- Data Protection
  - Data Integrity
  - Data Confidentiality

Passive Attacker (Sniffing)

alice.wonder@gmail.com

Alice123!

Man-in-the-Middle Attacker (MitM)

alice.wonder@gmail.com
Alice123!

alice.wonder@gmail.com
Alice123!

TLS Security

- Cipher attacks (BEAST, RC4 (Royal Holloway)
- Compression attacks (CRIME, TIME, BREACH)
- Downgrade attacks (POODLE)
- Padding Oracle attacks (Lucky13)
- Implementation attacks (Heartbleed)

On RC4

- On TLS
- On RC4
- The Invariance Weakness
- The Attacks
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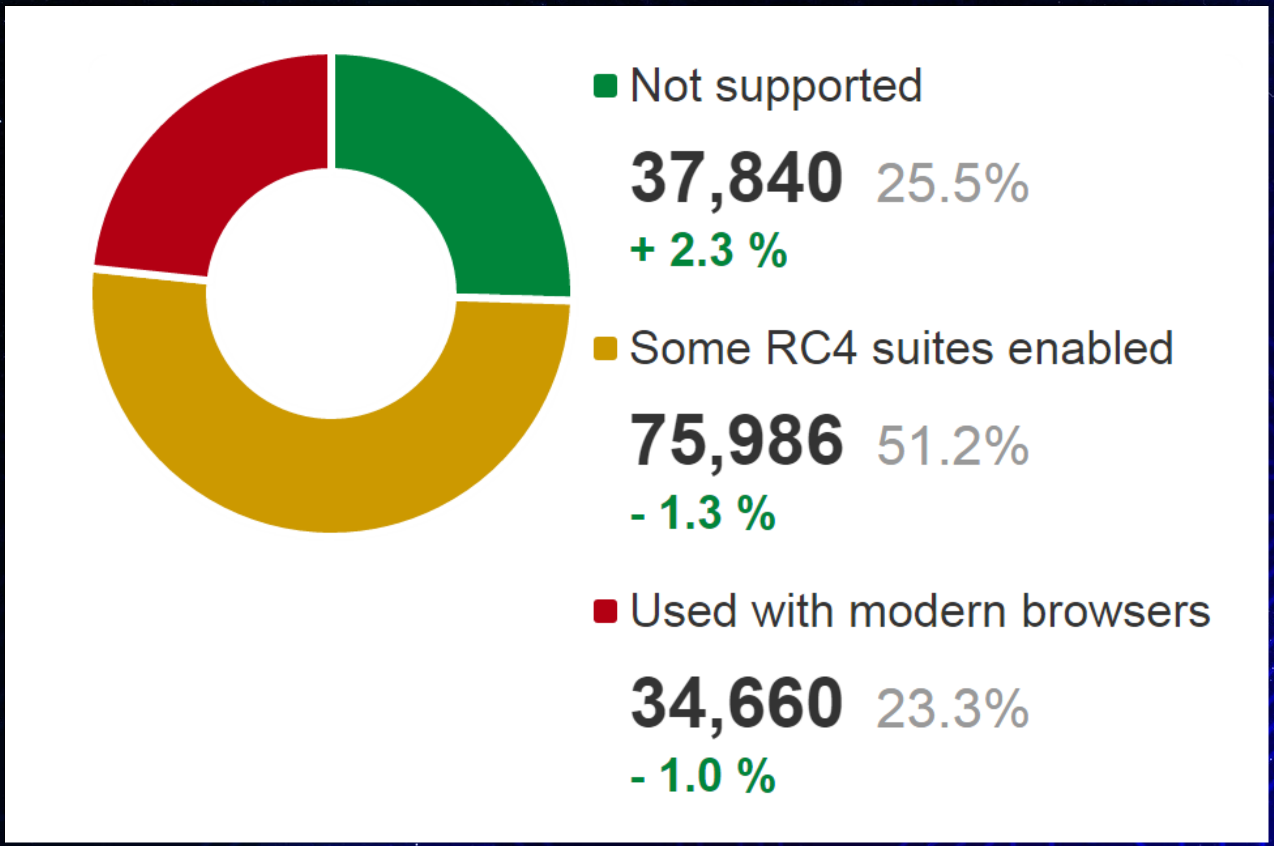
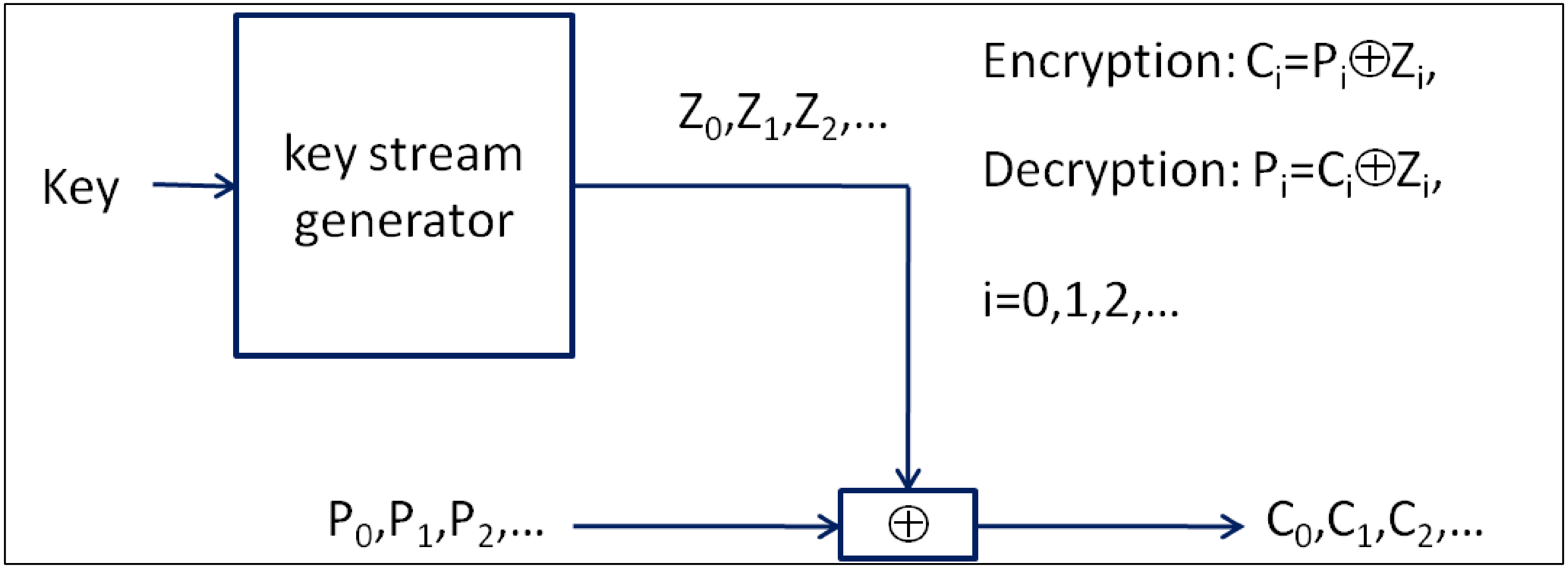
RC4 Usage in TLS

- SSL-Pulse (March 9, 2015)



Stream Ciphers



Keystream randomness = plaintext security

RC4

- Rivest Code 4
- The most popular Stream Cipher for almost 30 years
- Details kept secret until the WEP attack in 2001

RC4 Algorithm

Key Scheduling Algorithm (KSA)

Pseudo-Random Generation Algorithm (PRGA)

All operations are mod 256

```
KSA(K):
    j = 0
    S = [0, 1, 2, …, 255]
    for i = 0..255
        j = (j + S[i] + K[i mode L])
        S[i] <-> S[j]
```

```
PRGA(S_0):
    i = 0
    j = 0
    S = S_0
    While bytes are needed:
        i = i + 1
        j = j + S[i]
        S[i] <-> S[j]
        Emit S[S[i]+S[j]]
```

RC4 Algorithm

KSA(K):
- j = 0
- S = [0, 1, 2, …, 255]
- for i = 0..255
  - j = (j + S[i] + K[i mode L])
  - S[i] $\leftrightarrow$ S[j]

PRGA(S_0):
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  - Emit S[S[i]+S[j]]

RC4 (In)Randomness

- RC4 in **NOT** pseudo-random
  - 2^{30} distinguisher (Fluhrer-McGrew, 2000) (patterns used in the RH attack)
  - 2^{26} byte distinguishing algorithm (Mantin, 2005)
  - 2^{45} Prediction algorithm (Mantin, 2005)

RC4 Initialization

- The weakest link of RC4 since 2001
- Keystream biases
  - The second-byte bias (Mantin-Shamir, 2001)
  - Many others
- Key-keystream correlations
  - The IV Weakness and the WEP Attack (Fluhrer-Mantin-Shamir, 2001)
  - Enhanced WEP Attack I (Mantin, 2005)
  - Enhanced WEP Attack II (Tews-Weinmann-Pyshkin, 2007)
  - More Key-keystream correlations (Klein, 2005)
- Initial permutation biases (my thesis 2001, Mironov 2002)

- The Invariance Weakness (Fluhrer-Mantin-Shamir, 2001)

The Invariance Weakness

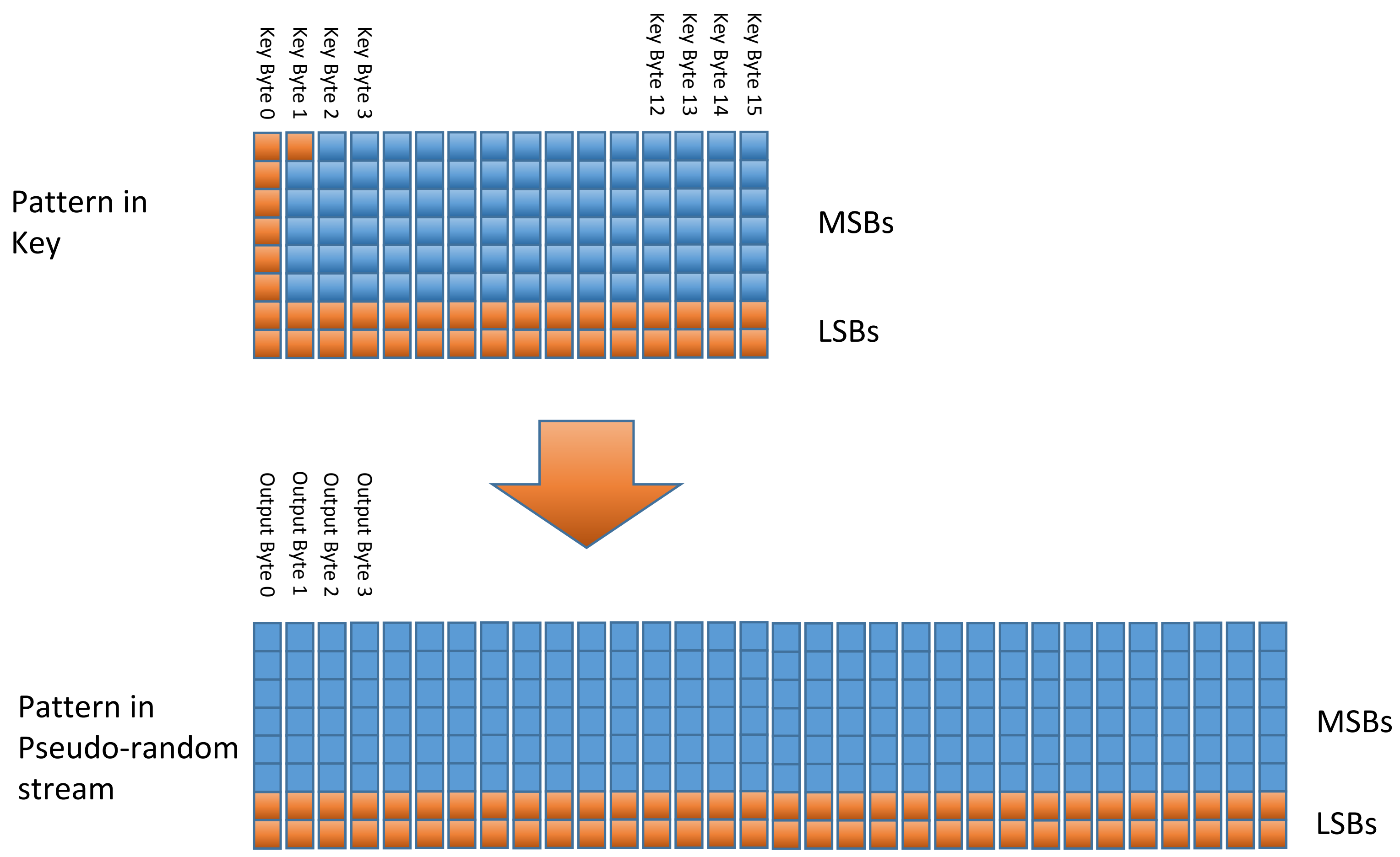
- On TLS
- On RC4
- The Invariance Weakness
- The Attacks
- Conclusion

The Invariance Weakness

- The neglected counterpart of the IV Weakness
- Left in the shadows for 13 years

- RC4 weak keys
  - Huge class of keys (2^{-24} fraction for 128bit keys)
  - Bad mixing of the key with the permutation
  - Permutation parts remain **intact**

Key Patterns



The Weak Keys

- The keys (q-class)
  - — K[i] = (1 - i) mode q
  - — K[0] = 1

```
KSA(K):
    j = 0
    S = [0, 1, 2, …, 255]
    for i = 0..255
        j = (j + S[i] + K[i mode L])
        S[i] ↔ S[j]
```

- How does it work?
  - — Swaps preserve least significant bits
  - — Initial permutation has S[i] = i (mod 2^q)
  - — Final permutation has S[i] = i (mod 2^q)

Plaintext Leakage

- Initial permutation has LSB pattern
- LSB patterns leak to the keystream
  - But bad swaps ruin them
- Plaintext LSB leak

```
PRGA(S0):
    i = 0
    j = 0
    S = S0
    While bytes are needed:
        i = i + 1
        j = j + S[i]
        S[i] <-> S[j]
        Emit S[S[i]+S[j]]
```

Keystream randomness = plaintext security

Weak Key Classes

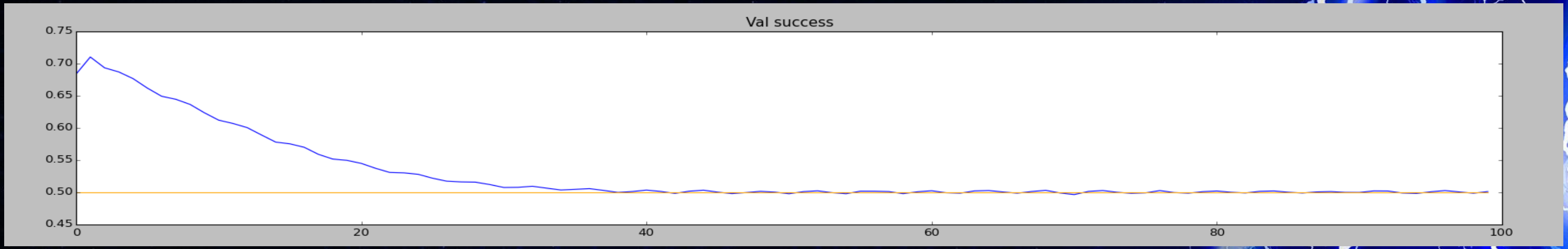
# LSBs	Applicability	Class Fraction (8-byte key)	Class Fraction (16-byte key)
1	Keys with even number of bytes	2^{-16}	2^{-24}
2	Keys with number of bytes that is a multiple of 4	2^{-23}	2^{-39}
3	Keys with number of bytes that is a multiple of 8	2^{-30}	2^{-54}
4	Keys with number of bytes that is a multiple of 16	2^{-37}	2^{-69}

Plaintext Leakage

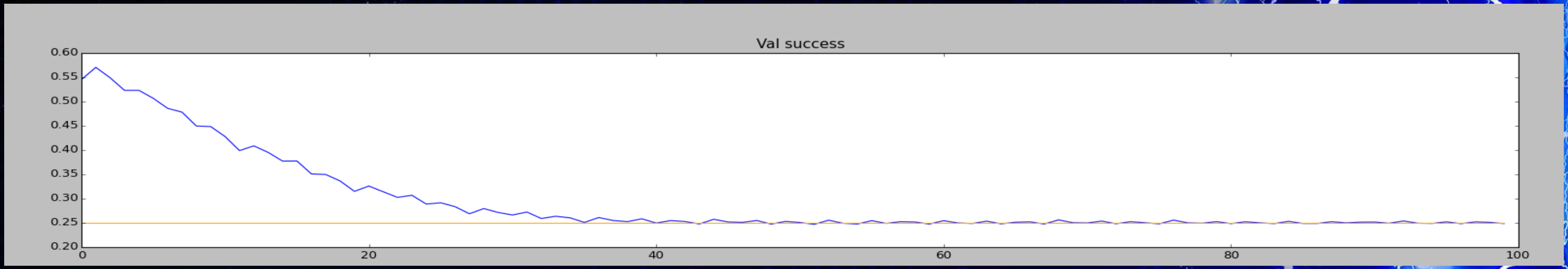
- When a weak key is used, “many” plaintext bit leak
- Q1: Can we tell when that happens?
  — Yes, when plaintext patterns exist
- Q2: How many bits?

Leakage Statistics

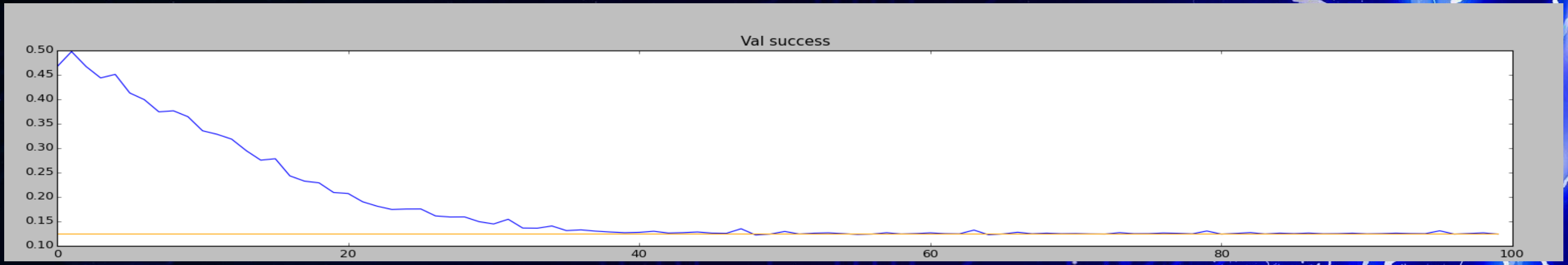
Q=1



Q=2



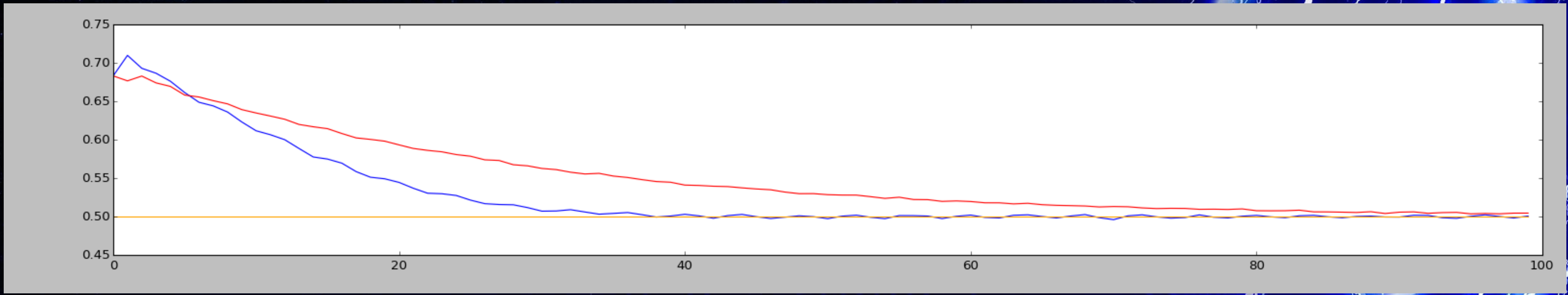
Q=3



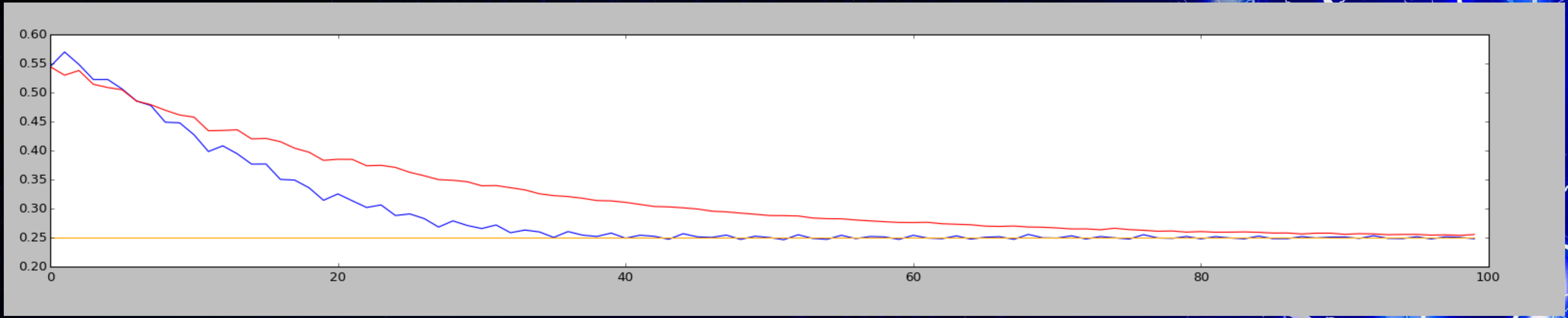
Diff-Based Leakage

- The permutation is ruined with the keystream generation
- Bit prediction gets out of sync when j hits a "ruined" part
- Switch to diff

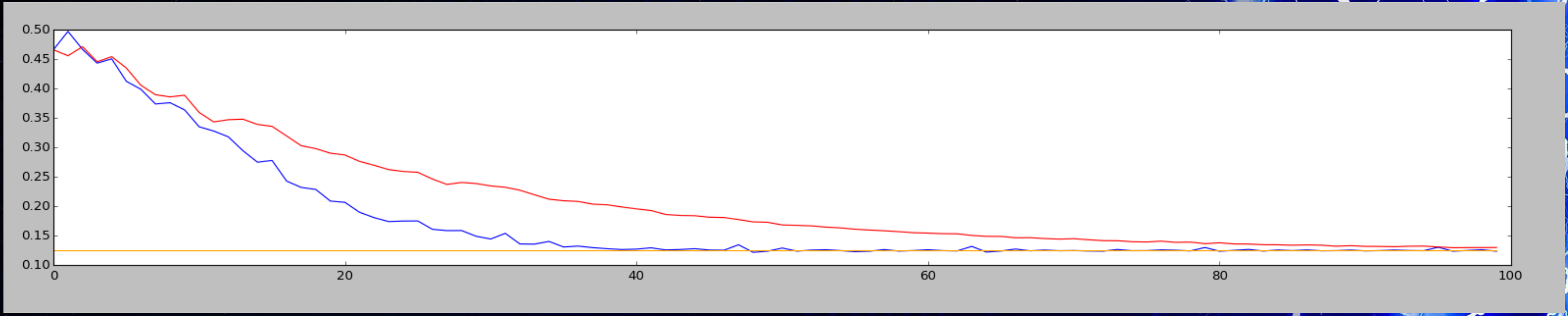
Diff-Based Leakage (q=1)



Diff-Based Leakage (q=2)



Diff-Based Leakage (q=3)



The Leakage

- Using the 1-Class
  - 1st diff LSB is guessed correctly with probability 0.68
  - 37th diff LSB is guessed correctly with probability of 0.546
  - 100th diff LSB is guessed correctly with probability of 0.503
- Pattern tracking is possible for
  - 37 bytes with 1/22 probability
  - 68 bytes with 1/64 probability
  - 100 bytes with 1/330 probability
- First 100 LSBs are exposed to leakage

The Attacks

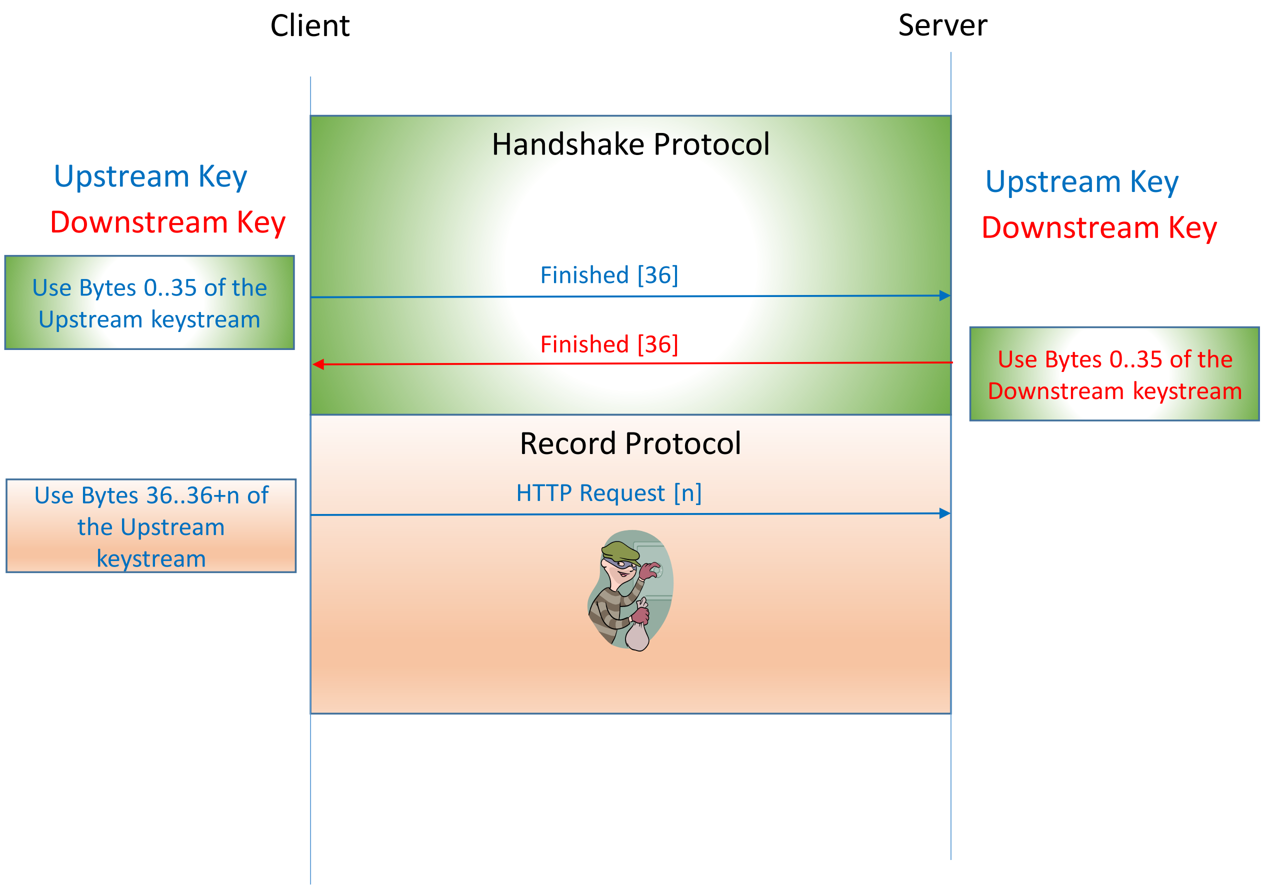
- On TLS
- On RC4
- The Invariance Weakness
- **The Attacks**
- Conclusion

The Attacks

The Attack Scenario

- The Attack Scenario
- Using LSBs
- Man-in-the-Middle Attack
- Sniffing-Only Attack
- One-Time Encryption

RC4 @ TLS


Client
Server
Handshake Protocol
Upstream Key
Downstream Key
Upstream Key
Downstream Key
Finished [36]
Use Bytes 0..35 of the Upstream keystream
Finished [36]
Use Bytes 0..35 of the Downstream keystream
Record Protocol
HTTP Request [n]
Use Bytes 36..36+n of the Upstream keystream

The Attack Basic Scenario

- Attacker waits for a “hit” - weak key occurrence
  - Attacker identifies the hit using plaintext patterns
  - 2^{24} keys until hitting a weak key
  - Several dozen/hundred hits to get successful tracking (target length dependent)

- Attacker predicts keystream LSB diffs
- Attacker recovers plaintext LSB values (after byte 36)

The Attacks

The Attack Scenario

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LSB Leakage

- Acceleration of Trial and Error attacks
  - Sneak below threshold-based detectors

- Dictionary attack on weak passwords

LSB for Weak Passwords

	Web Accounts	LSB Groups	Brute Force Worst Case	Brute Force Avg Case
Top 100	4.4%	68	6	1.5
Top 1000	13.2%	252	24	4
Top 10,000	30%	557	201	18

LSB for Credit Card Numbers

- CCN entropy:
  - — 6-prefix: known
  - — 4-suffix: not guarded
  - — 1-byte: checksum

- With 16 LSBs, the search domain drops from 100,000 possibilities to only 1500

LSB for Session Cookies

- PHP Session Cookie: up-to 2^{32} brute-force reduction
- ASP Session Cookie: 2^{16} brute-force reduction

The Attacks

The Attack Scenario

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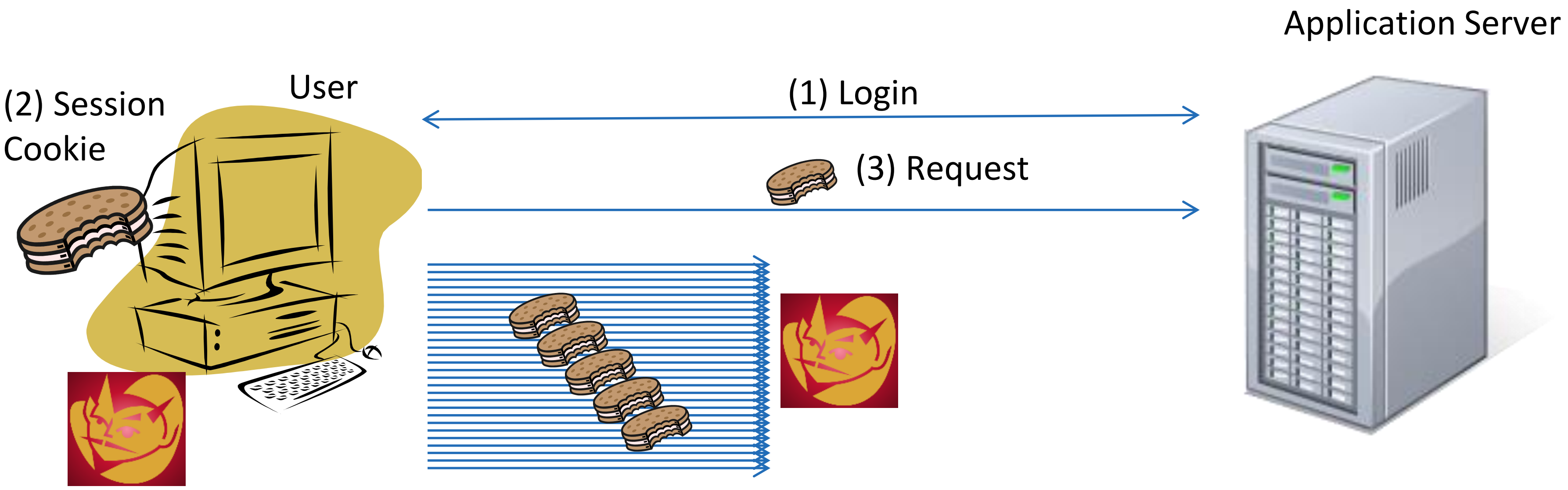
Differences from BEAST/RH

- Attack requires a single “hit”
- 100 first bytes are at risk

- Extract only partial info

BEAST-like Attack

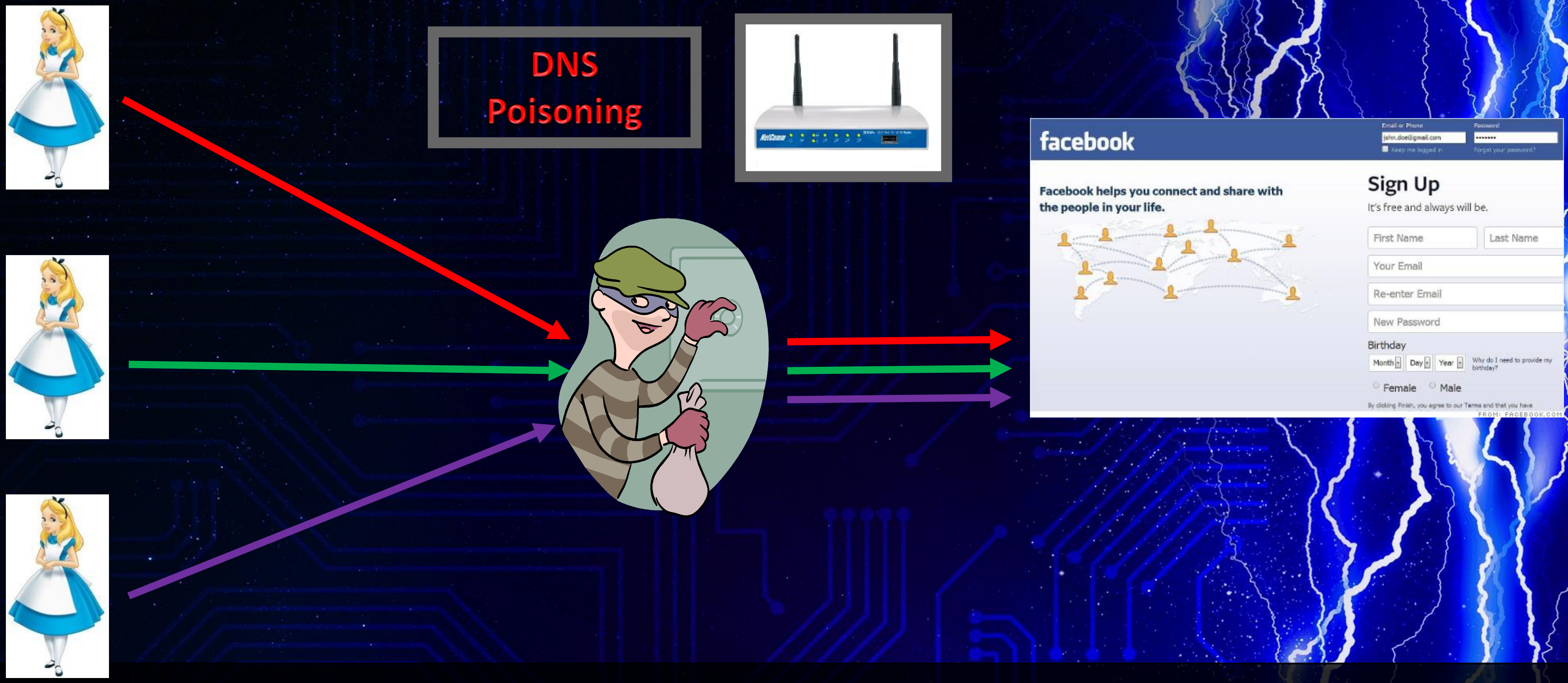


- 1 billion connections required
- Insensitive to Resets

Group Attack

Attack requires a single “hit”

Pool of Potential Victims



The Attacks

The Attack Scenario

- The Attack Scenario
- Using LSBs
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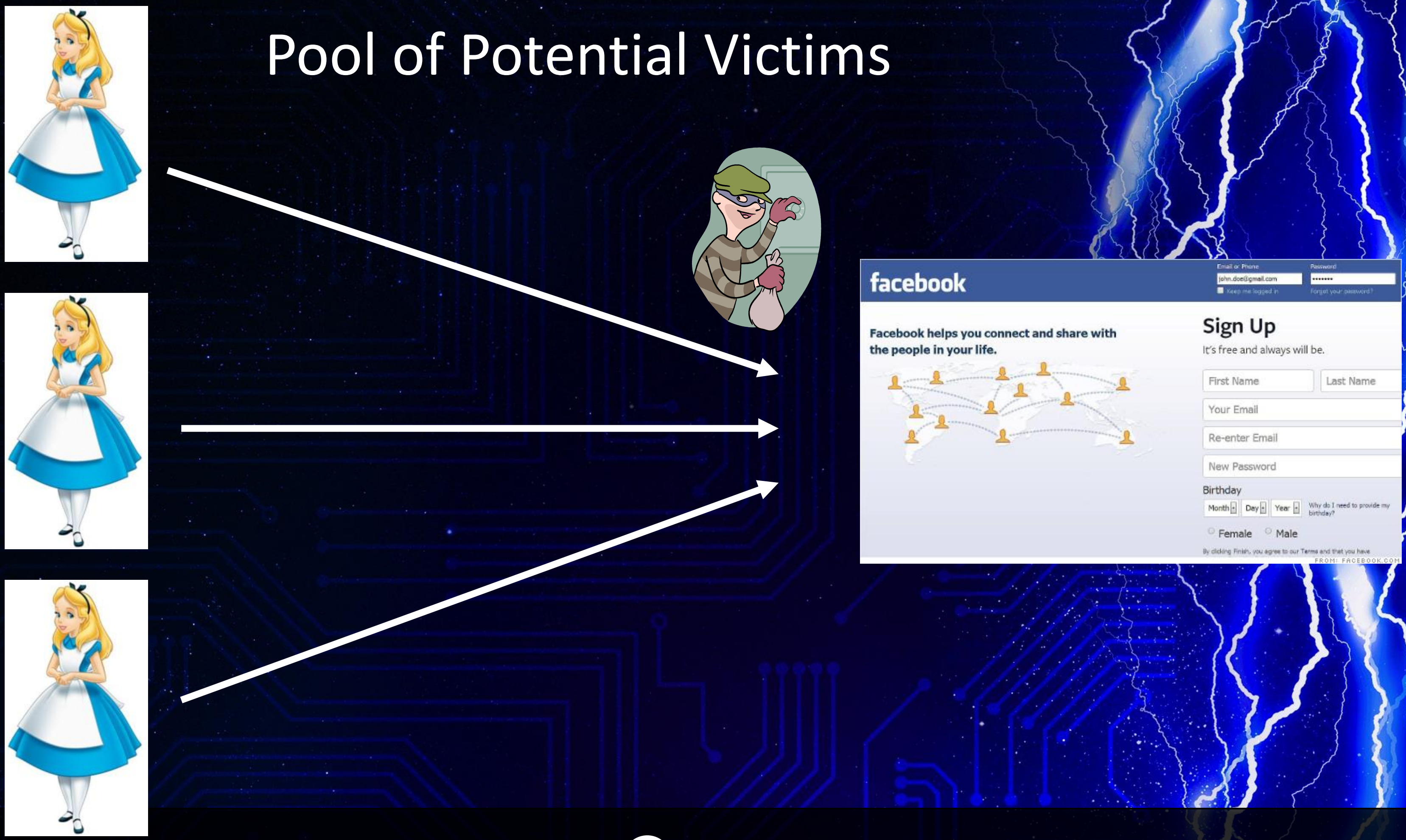
Non-Targeted Passive Attack

Attack requires a single "hit"

Pool of Potential Victims



1 Billion Connections?

- Facebook has 890 million DAU (Daily Active Users)

- Most login more than once a day

The Attacks

The Attack Scenario

- The Attack Scenario
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- Man-in-the-Middle Attack
- Sniffing-Only Attack
- One-Time Encryption

One-time Usage

- Every time you send a secret over TLS/RC4 connection
  - You have a 1:16 million chance to get a bad key
  - You have a 1 in a billion chance to get unlucky and leak a significant portion of your secret

- Small numbers, but definitely not negligible
- RC4 stats: 30% of Internet TLS connections

Conclusion

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- On RC4
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Summary

- The Invariance Weakness of RC4 can be used to mount new attacks on TLS
- The Reset Insensitivity nature of the attack opens the door to new attack scenarios
- First passive attack on TLS

Conclusions

- RC4 is a not a secure cipher (old news)
- The initialization mechanism of RC4 is very weak (old news)
- The impact of these facts on the (In)Security of systems using RC4 is underestimated

Q & A