Filling in the Gaps:

Modelling Negotiation in the TLS Protocol

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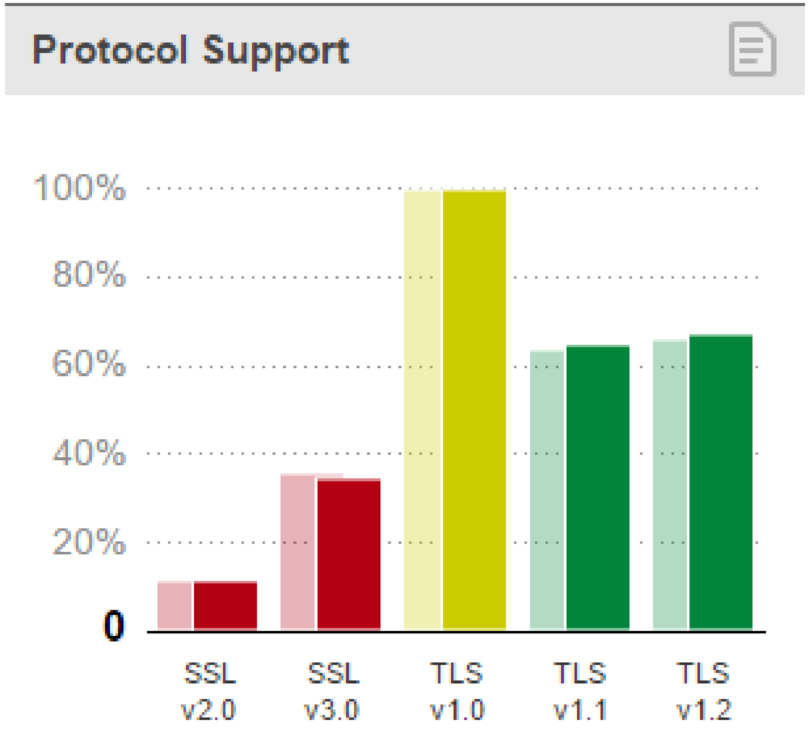
Outline

1. Motivation
2. Negotiation in the TLS Protocol
3. Modelling negotiation in a provable security framework
4. Analysis of TLS ciphersuite and version negotiation
5. Conclusions

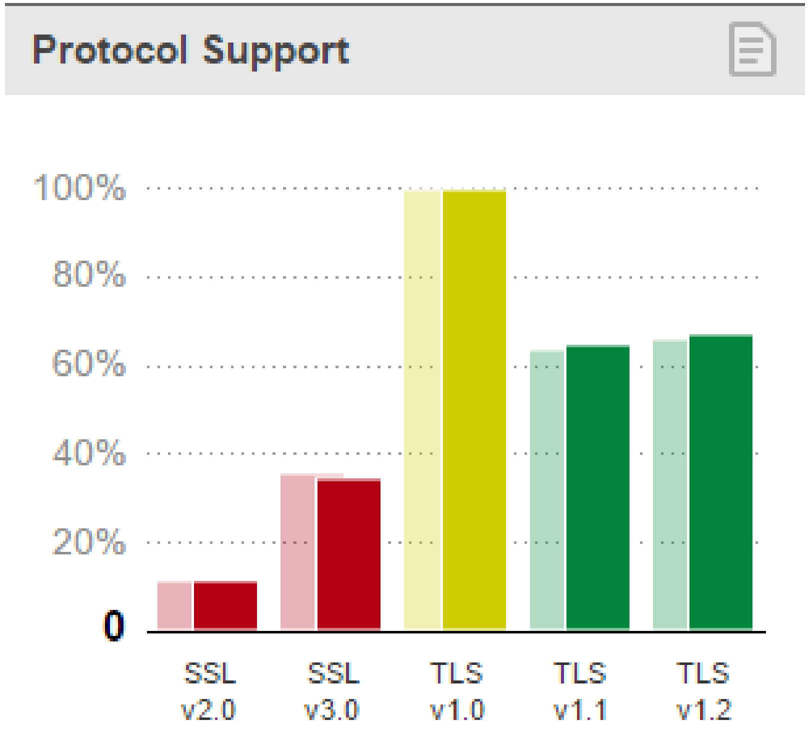
Motivation

- TLS implementations have complex functionality
- Current analyses' of TLS protocol do not cover all aspects
- Algorithmic agility is desired to increase interoperability
- However, interoperability can affect security

Motivation


Protocol Support
100%
80%
60%
40%
20%
0
SSL v2.0
SSL v3.0
TLS v1.0
TLS v1.1
TLS v1.2

Motivation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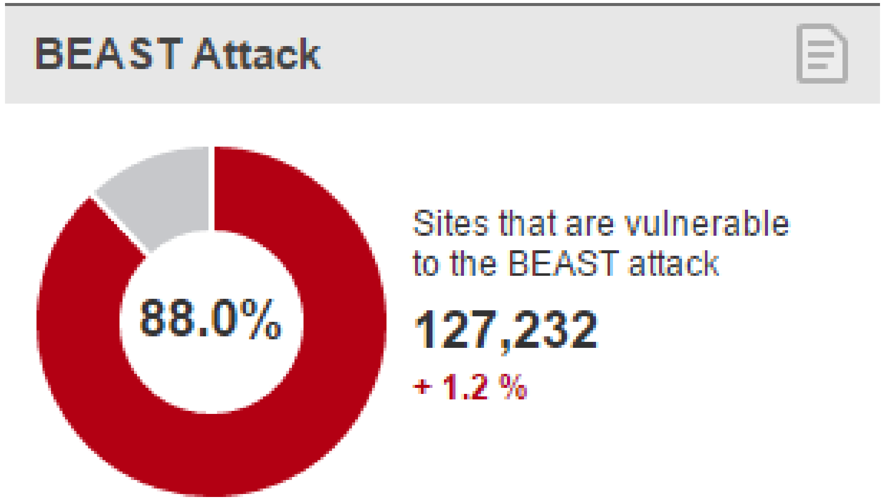
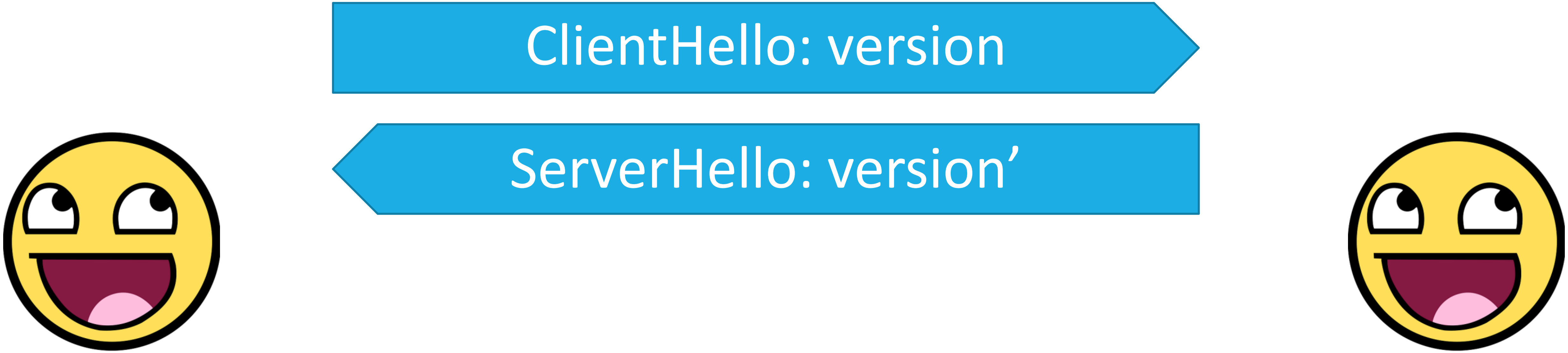

BEAST Attack
88.0%
Sites that are vulnerable to the BEAST attack
127,232
+ 1.2 %

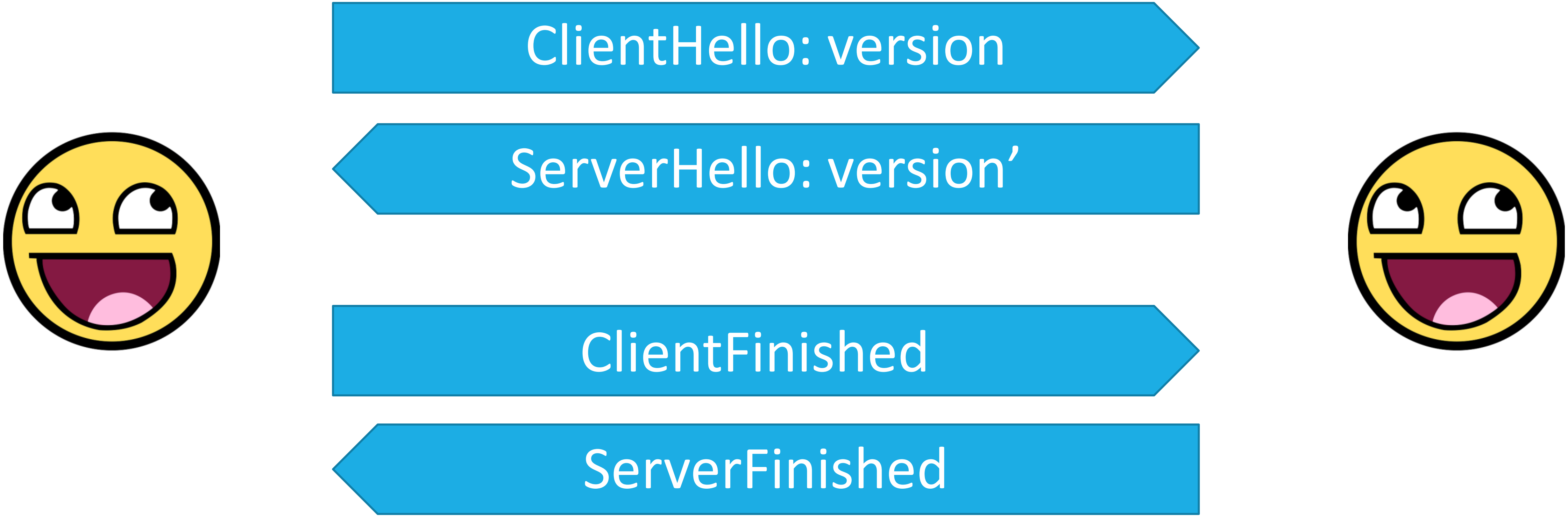
Version Negotiation



ClientHello: version

ServerHello: version’

Version Negotiation



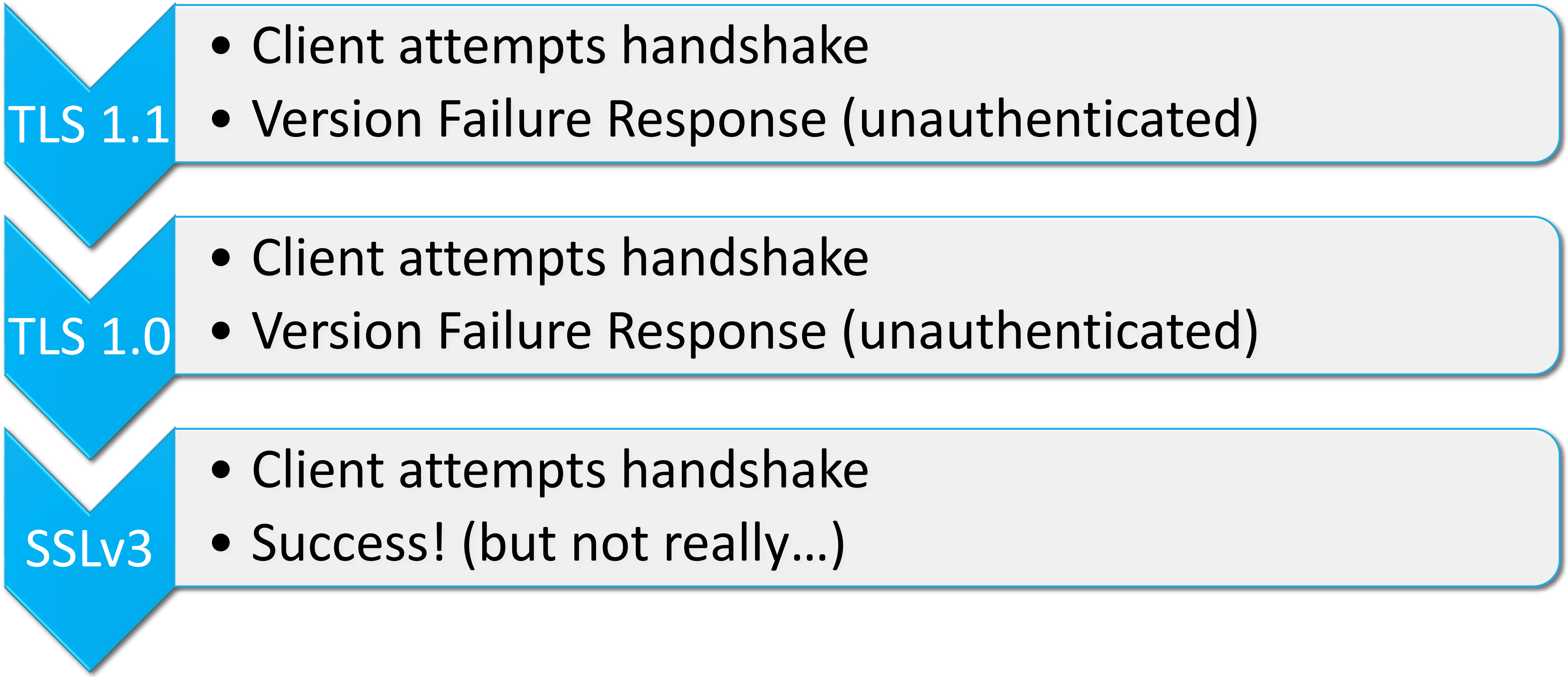
ClientHello: version

ServerHello: version’

ClientFinished

ServerFinished

Version Downgrade Dance



TLS 1.1

- Client attempts handshake
- Version Failure Response (unauthenticated)

TLS 1.0

- Client attempts handshake
- Version Failure Response (unauthenticated)

SSLv3

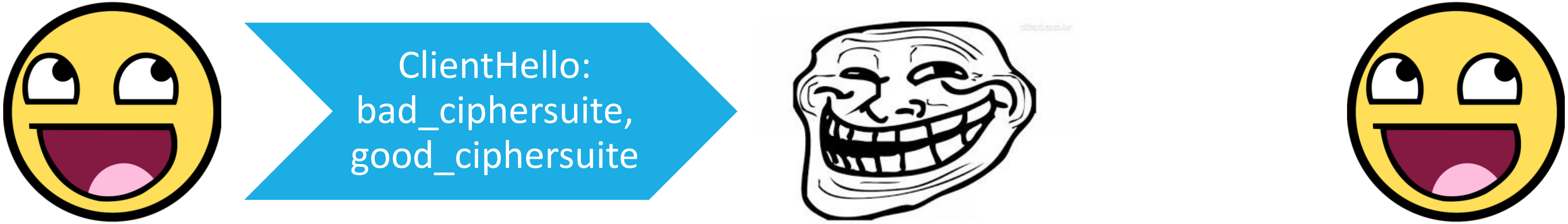
- Client attempts handshake
- Success! (but not really…)

Version Downgrade Attacks

- POODLE attack (Möller, Duong and Kotowicz, 2014)
  - Utilizes downgrade to SSLv3

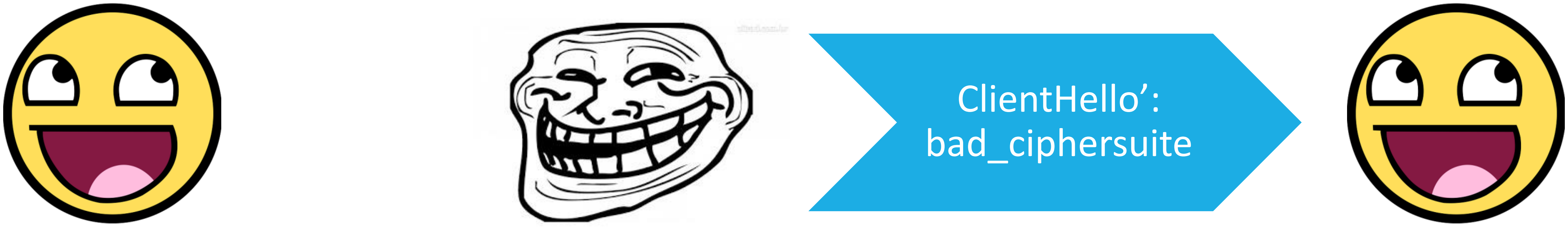
- Signalling Cipher Suite Value (Möller and Langley, 2015)
  - TLS extension to prevent downgrade attacks

Ciphersuite Downgrade Attacks



ClientHello:
bad_ciphersuite,
good_ciphersuite

Ciphersuite Downgrade Attacks

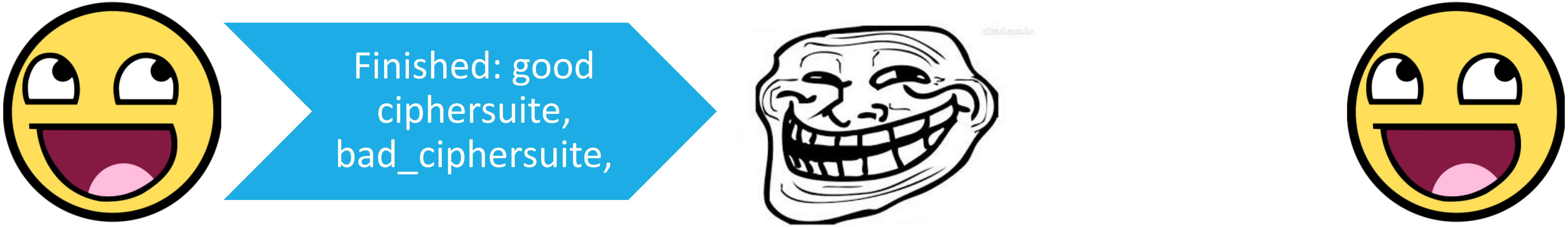


ClientHello’:
bad_ciphersuite

Ciphersuite Downgrade Attacks

ServerHello:
bad_ciphersuite

Ciphersuite Downgrade Attacks

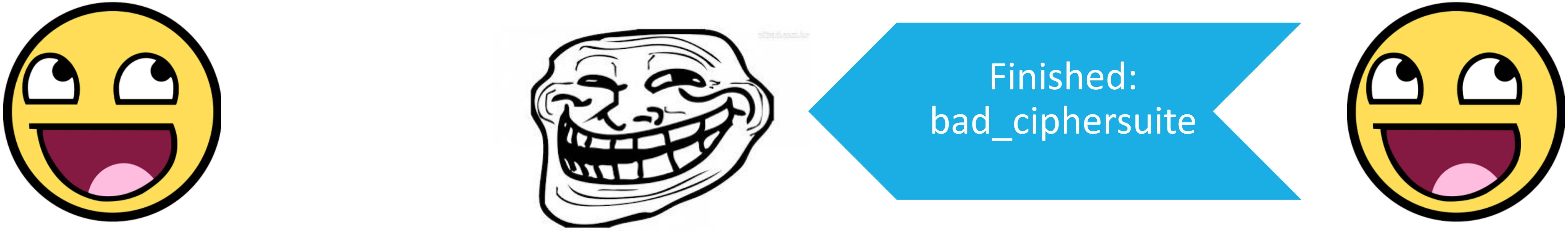


Finished: good ciphersuite, bad_ciphersuite,

Ciphersuite Downgrade Attacks

Finished’:
bad_ciphersuite

Ciphersuite Downgrade Attacks



Finished:
bad_ciphersuite

Ciphersuite Downgrade Attacks

Finished’: good ciphersuite, bad_ciphersuite

Ciphersuite Downgrade Attacks

- FREAK attack – (Beurdouche, Bhargavan, Delignat-Lavaud, Fournet, Kohlweiss, Pironti, Strub, Zinzindohoue, Zanella-Béguelin; 2015)
  - Implementation errors allow the negotiation of Export-RSA despite no indicated support

- Logjam Attack – (Adrian, Bhargavan, Durumeric, Gaudry, Green, Halderman, Heninger, Springall, Thomé, Valenta, VanderSloot, Wustrow, Zanella-Beguelin, and Zimmermann; 2015)
  - Protocol logic misinterprets export-DHE shares as “normal” DHE shares

Observations

- Clearly negotiation from a family of protocols can affect security of the protocol as a whole

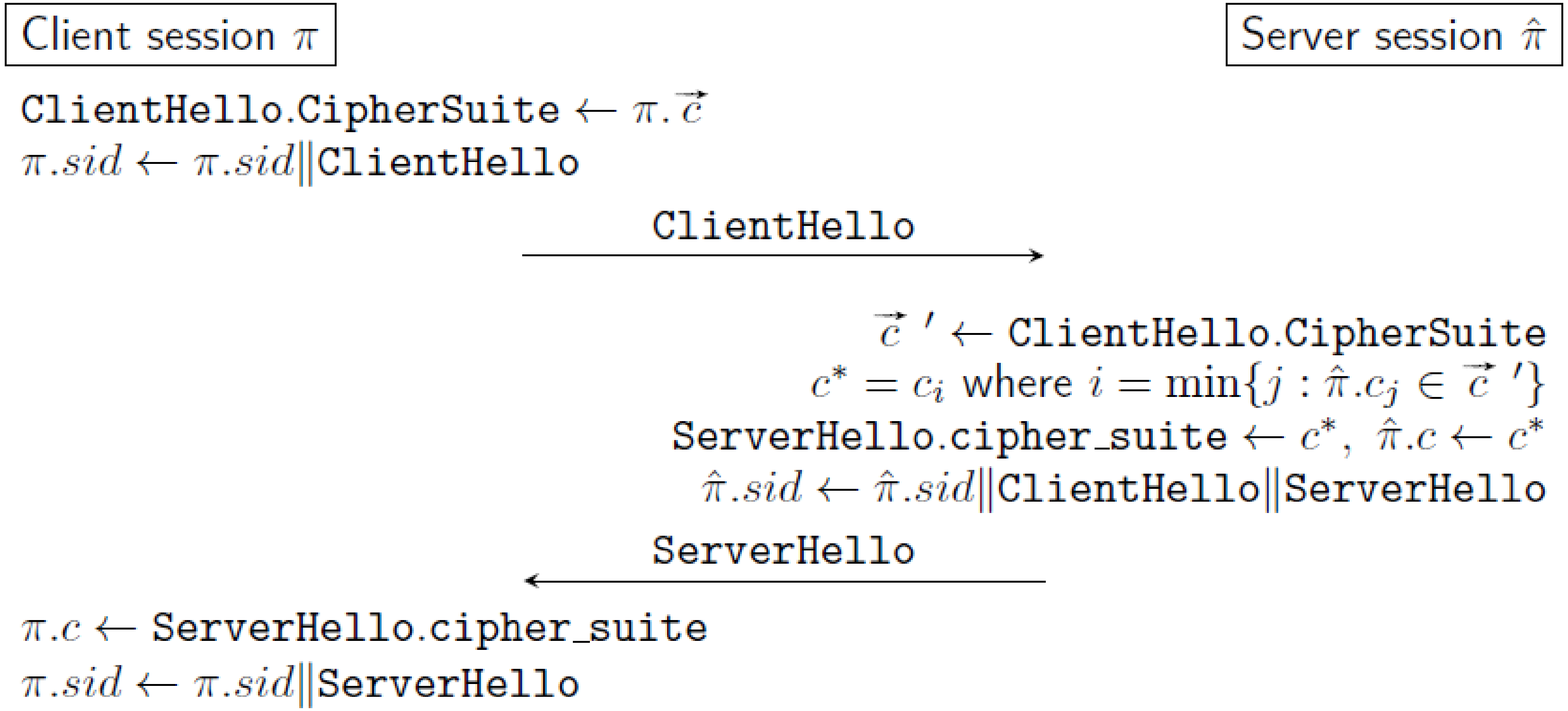
- What can we say about the security of the collection of protocols?

Talking ‘bout negotiation

- Treat the handshake as two phases:
  - A negotiation phase: common to all handshake runs
  - A sub-protocol phase: uses negotiated values to execute key-exchange/authentication, etc.

- “Optimal” negotiation:
  - Both parties have ordered list of elements/preferences
  - Also have an “optimality function”
  - Negotiation is optimal if they output same value and it’s the output of *opt(list, list’)*

Ciphersuite Negotiation Phase



Client session π

Server session $\hat{\pi}$

$\texttt{ClientHello.CipherSuite} \leftarrow \pi.\vec{c}$

$\pi.sid \leftarrow \pi.sid \| \texttt{ClientHello}$

$\xrightarrow{\texttt{ClientHello}}$

$\vec{c}\,' \leftarrow \texttt{ClientHello.CipherSuite}$

$c^* = c_i$ where $i = \min\{j : \hat{\pi}.c_j \in \vec{c}\,'\}$

$\texttt{ServerHello.cipher\_suite} \leftarrow c^*, \ \hat{\pi}.c \leftarrow c^*$

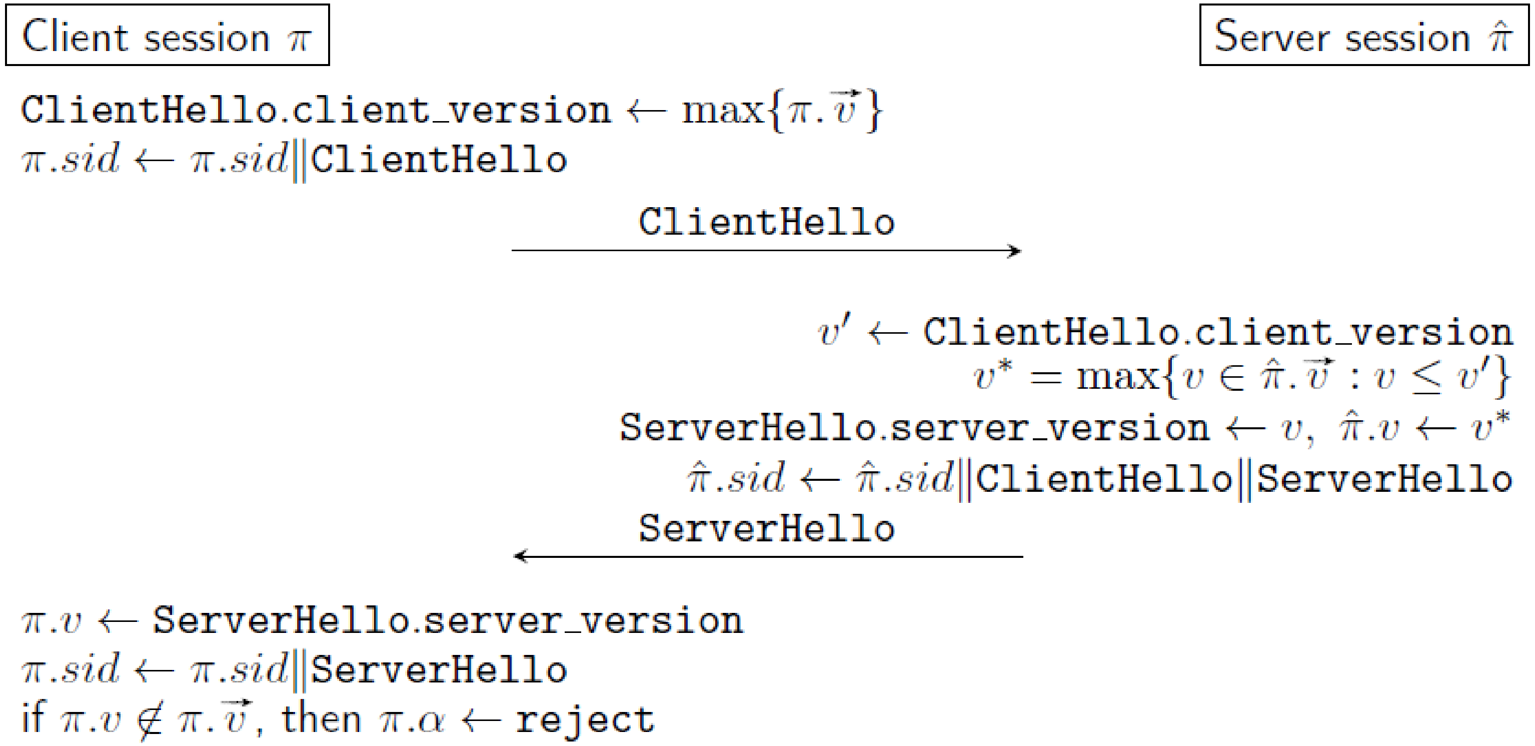
$\hat{\pi}.sid \leftarrow \hat{\pi}.sid \| \texttt{ClientHello} \| \texttt{ServerHello}$

$\xleftarrow{\texttt{ServerHello}}$

$\pi.c \leftarrow \texttt{ServerHello.cipher\_suite}$

$\pi.sid \leftarrow \pi.sid \| \texttt{ServerHello}$

Version Negotiation Phase



Client session π

Server session $\hat{\pi}$

$\texttt{ClientHello.client\_version} \leftarrow \max\{\pi.\vec{v}\}$

$\pi.sid \leftarrow \pi.sid \| \texttt{ClientHello}$

$\xrightarrow{\texttt{ClientHello}}$

$v' \leftarrow \texttt{ClientHello.client\_version}$

$v^* = \max\{v \in \hat{\pi}.\vec{v} : v \leq v'\}$

$\texttt{ServerHello.server\_version} \leftarrow v,\ \hat{\pi}.v \leftarrow v^*$

$\hat{\pi}.sid \leftarrow \hat{\pi}.sid \| \texttt{ClientHello} \| \texttt{ServerHello}$

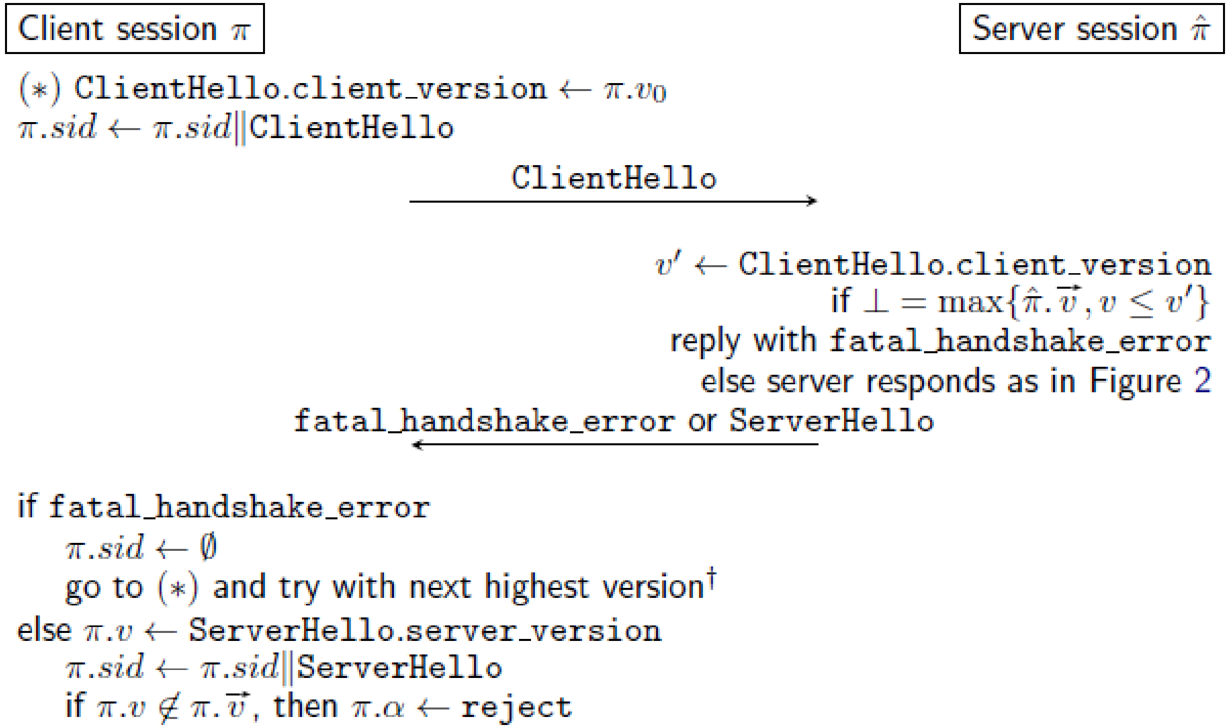
$\xleftarrow{\texttt{ServerHello}}$

$\pi.v \leftarrow \texttt{ServerHello.server\_version}$

$\pi.sid \leftarrow \pi.sid \| \texttt{ServerHello}$

if $\pi.v \notin \pi.\vec{v}$, then $\pi.\alpha \leftarrow \texttt{reject}$

Version Negotiation Phase - Fallback



Client session π

Server session $\hat{\pi}$

```
(∗) ClientHello.client_version ← $\pi.v_0$
$\pi.sid \leftarrow \pi.sid \|$ClientHello
```

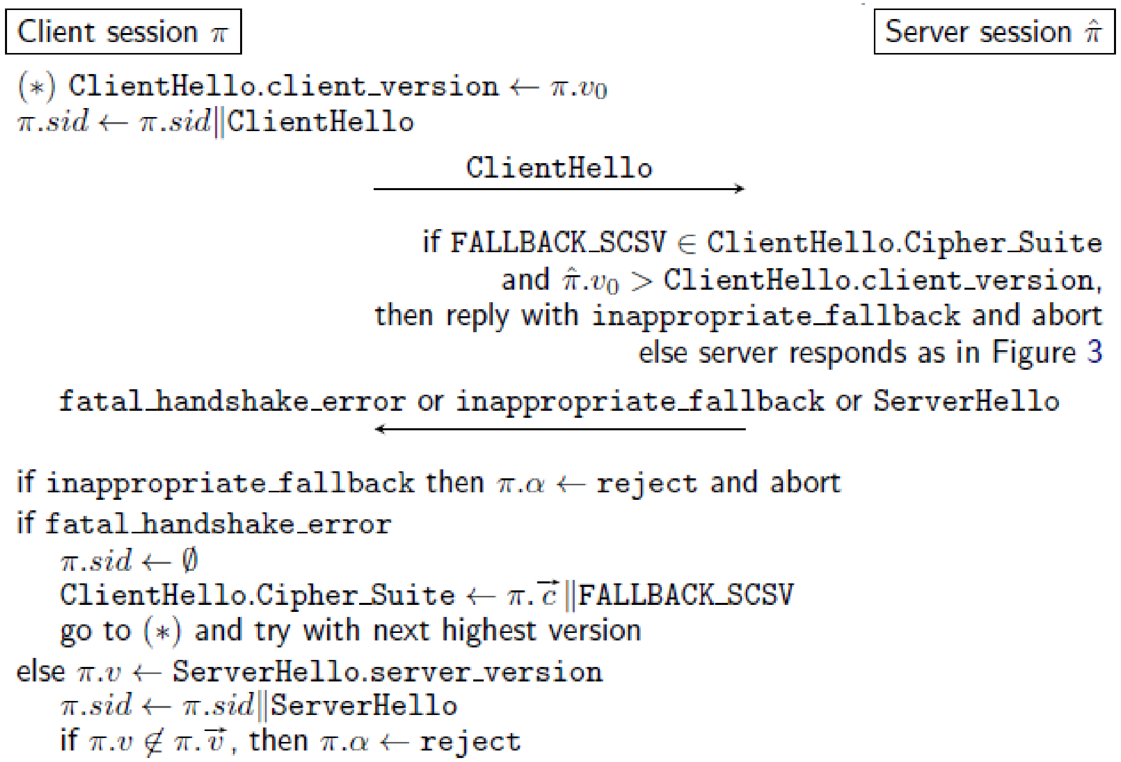
ClientHello $\longrightarrow$

```
$v' \leftarrow$ ClientHello.client_version
if $\bot = \max\{\hat{\pi}.\vec{v}, v \le v'\}$
reply with fatal_handshake_error
else server responds as in Figure 2
```

$\longleftarrow$ fatal_handshake_error or ServerHello

```
if fatal_handshake_error
    $\pi.sid \leftarrow \emptyset$
    go to (∗) and try with next highest version$^\dagger$
else $\pi.v \leftarrow$ ServerHello.server_version
    $\pi.sid \leftarrow \pi.sid \|$ServerHello
    if $\pi.v \notin \pi.\vec{v}$, then $\pi.\alpha \leftarrow$ reject
```

Version Negotiation Phase - SCSV



Client session π

Server session $\hat{\pi}$

$(*)$ ClientHello.client_version $\leftarrow \pi.v_0$

$\pi.sid \leftarrow \pi.sid \| $ ClientHello

$\xrightarrow{\text{ClientHello}}$

if FALLBACK_SCSV $\in$ ClientHello.Cipher_Suite

and $\hat{\pi}.v_0 >$ ClientHello.client_version,

then reply with inappropriate_fallback and abort

else server responds as in Figure 3

$\xleftarrow{\text{fatal\_handshake\_error or inappropriate\_fallback or ServerHello}}$

```
if inappropriate_fallback then $\pi.\alpha \leftarrow$ reject and abort
if fatal_handshake_error
    $\pi.sid \leftarrow \emptyset$
    ClientHello.Cipher_Suite $\leftarrow \pi.\vec{c} \|$FALLBACK_SCSV
    go to $(*)$ and try with next highest version
else $\pi.v \leftarrow$ ServerHello.server_version
    $\pi.sid \leftarrow \pi.sid \|$ServerHello
    if $\pi.v \notin \pi.\vec{v}$, then $\pi.\alpha \leftarrow$ reject
```

Using previous results

- Can see from downgrade attacks that security of the negotiation relates to the authentication of transcript

- Negotiation-Authentication Theorem:
  - Condition 1: All Negotiation Phase messages are in the session identifier
  - Condition 2: If no modification of messages, negotiation always “optimal”
    - Then:

$$\mathrm{Adv}^{\mathsf{neg},\omega}_{\mathrm{NP}\|\overrightarrow{\mathrm{SP}},n}(\mathcal{A}) = \mathrm{Adv}^{\mathsf{acce\text{-}auth}}_{\mathrm{NP}\|\mathrm{SP}_n}(\mathcal{A})$$

Ciphersuite Negotiation “secure”

- 1. All negotiation messages contained in transcript
- 2. Ciphersuite negotiation optimal without active adversary

- If all ciphersuites result in secure authentication properties
  then negotiating to any given ciphersuite is secure

Version Negotiation (no fallback) “secure”

- 1. All negotiation messages contained in transcript
- 2. Version negotiation optimal without active adversary

- If all versions result in secure authentication properties

  then negotiating to any given version is secure

Version Negotiation (w/ fallback) “secure”

- 1. All negotiation messages contained in transcript?

Version Negotiation (w/ fallback) insecure

- 1. All negotiation messages contained in transcript?

NOOOOOOOOOOOOOOOOOOOOOOOOO

Version Negotiation (w/ fallback) insecure

- 1. All negotiation messages contained in transcript?

NOOOOOOOOOOOOOOOOOOOOOOOOO

- Negotiation occurs across multiple handshakes, session identifier is only the transcript of the most recent handshake

Version Negotiation (w/ SCSV) “secure”

- 1. All negotiation messages contained in transcript?

Version Negotiation (w/ SCSV) “secure”

- 1. All negotiation messages contained in transcript?

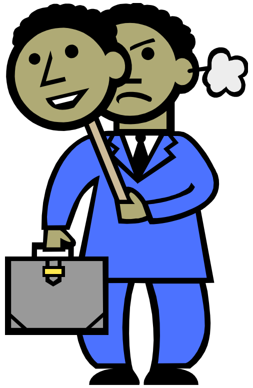
  Nope!

- Can prove security more directly

Version Negotiation (w/ SCSV) “secure”

Adversary

Version-SCSV

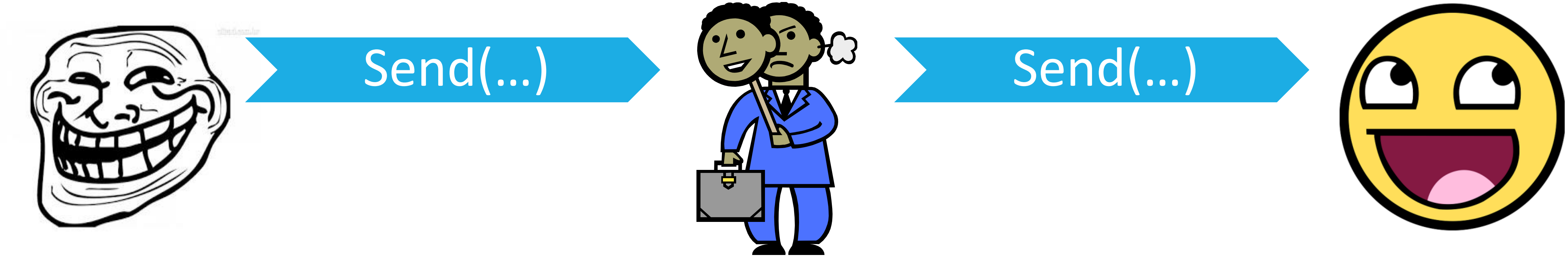


Simulator

Challenger

Version-No-Fallback

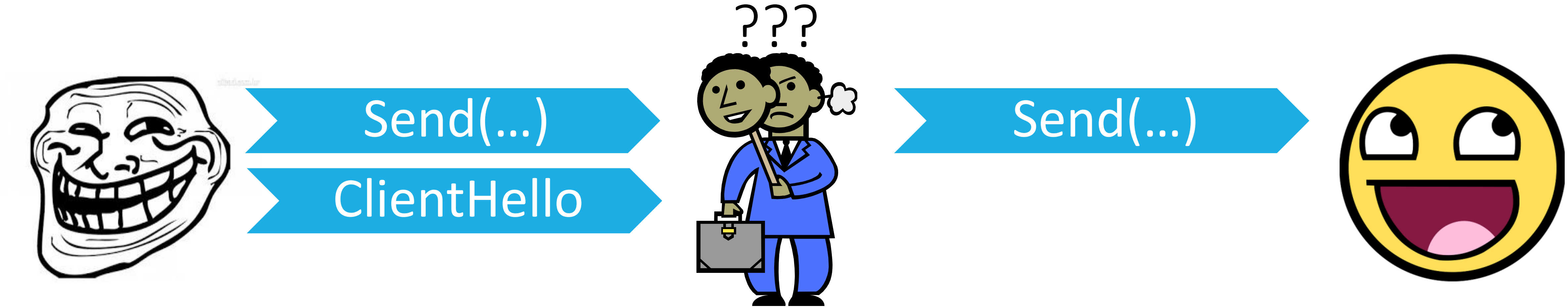
Version Negotiation (w/ SCSV) “secure”



Send(…)

Send(…)

Version Negotiation (w/ SCSV) “secure”



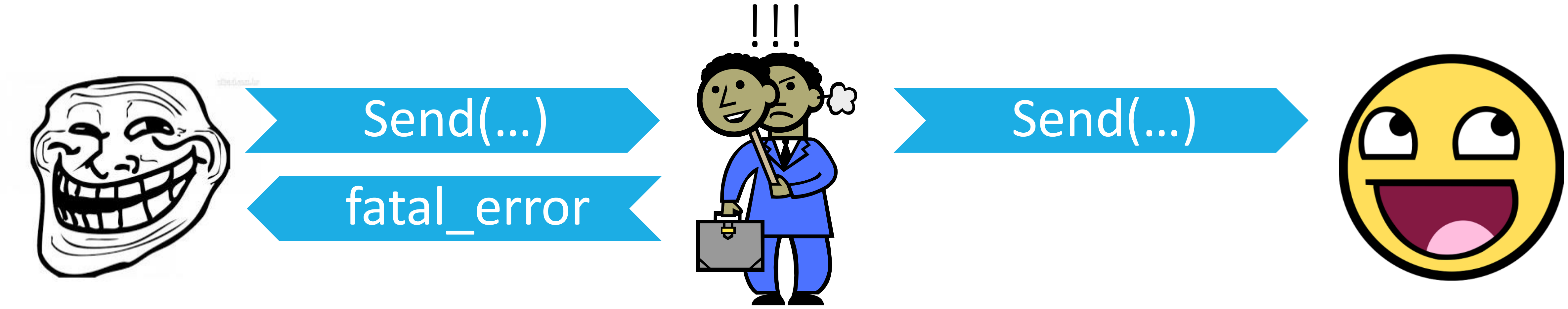
Send(…)

ClientHello

???

Send(…)

Version Negotiation (w/ SCSV) “secure”

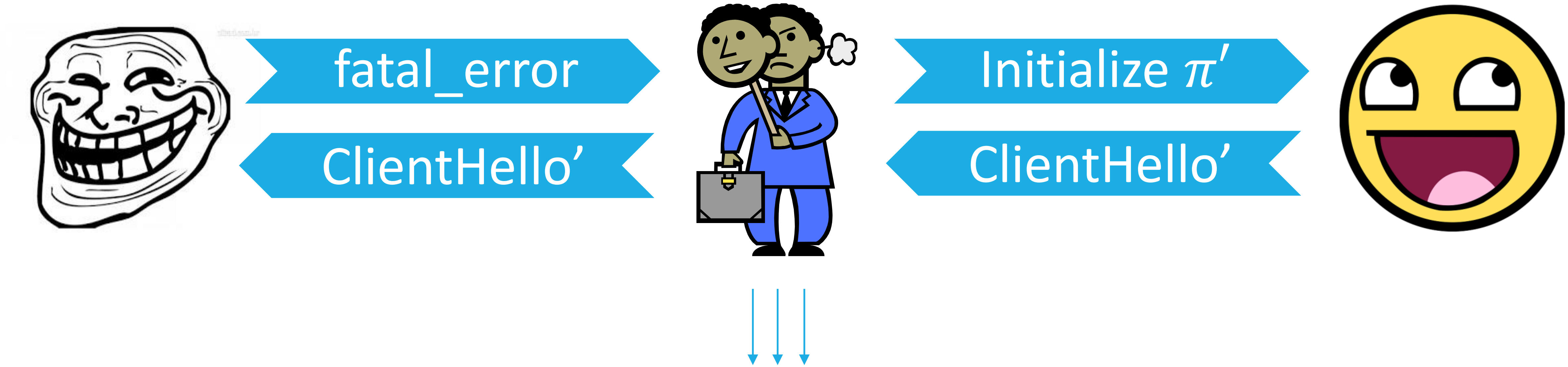


Send(…)

fatal_error

Send(…)

Version Negotiation (w/ SCSV) “secure”



fatal_error

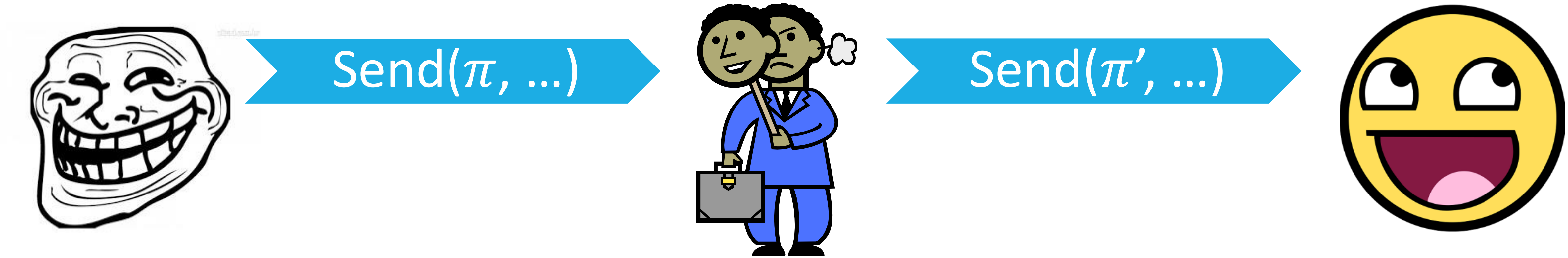
ClientHello’

Initialize π'

ClientHello’

Fallback List: Session π : π'

Version Negotiation (w/ SCSV) “secure”

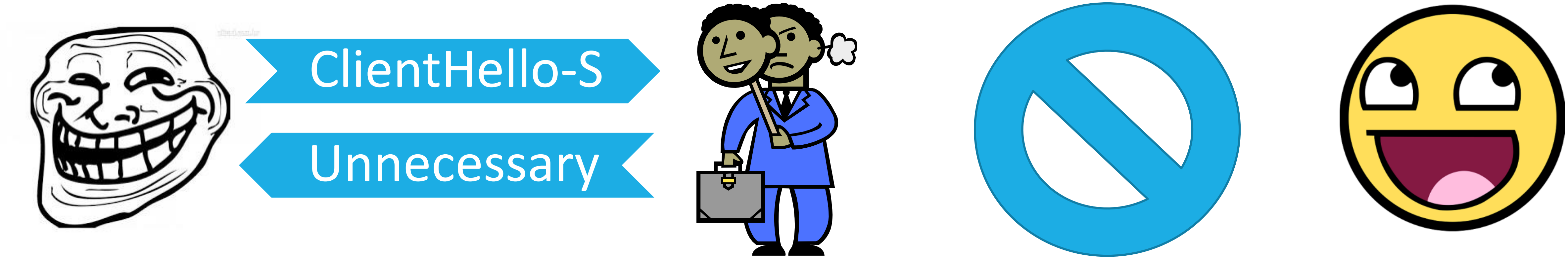


Send(π, …)

Send(π’, …)

Fallback List: Session π : π’

Version Negotiation (w/ SCSV) “secure”



ClientHello-S

Unnecessary

Fallback List: Session π : π'

Version Negotiation (w/ SCSV) “secure”

- 2 cases exist if successful adversary:
  - Breaking a session on the Fallback-List
  - Breaking a session not on the Fallback List

- Each case bounds the success of the adversary with the success of breaking ACCE authentication

Version Negotiation (w/ SCSV) “secure”

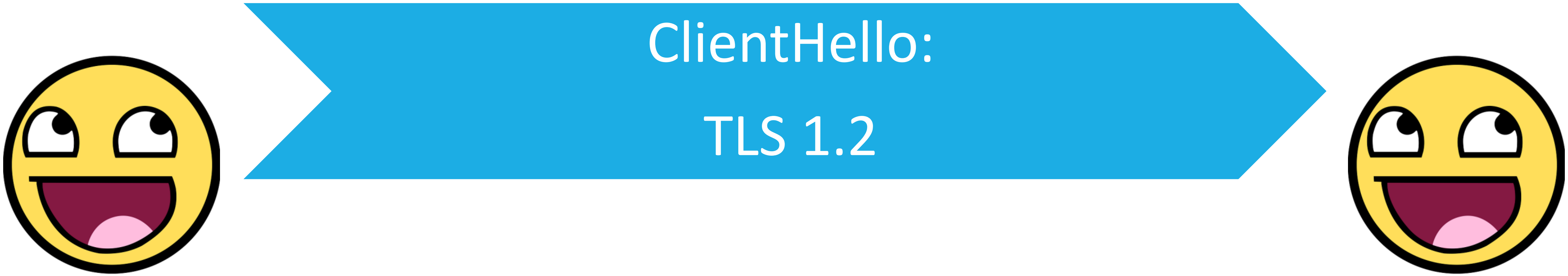
- 1. All negotiation messages contained in transcript?

  Nope!

- Can prove security more directly

- HOWEVER: Non-contiguous support of TLS version (i.e. supporting 1.2 and 1.0 but not 1.1) can break version negotiation with SCSV

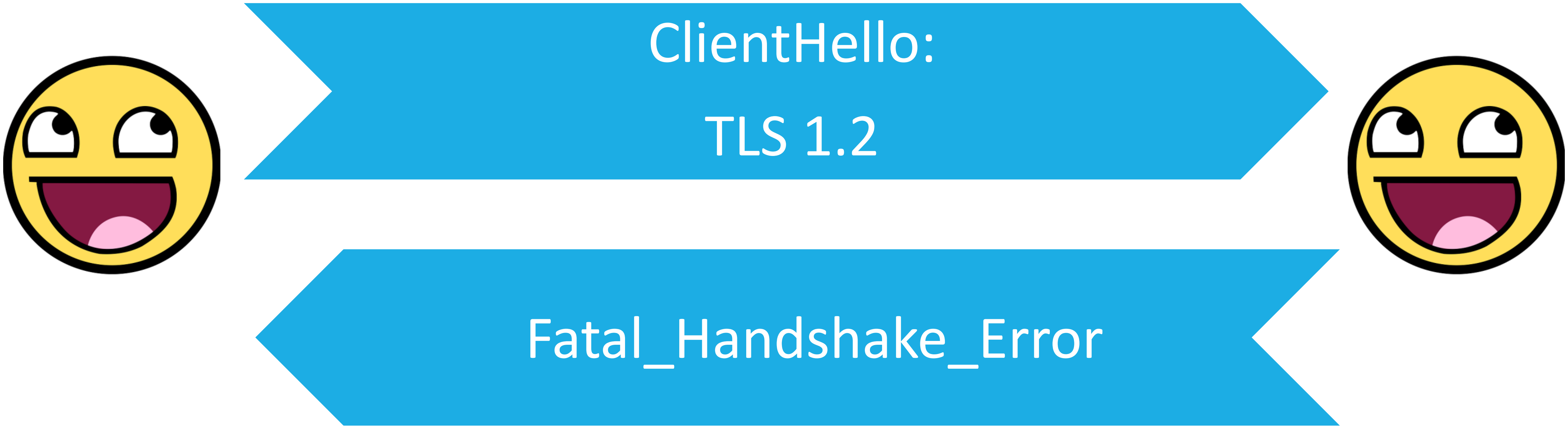
SCSV Non-Contiguous Example



ClientHello:

TLS 1.2

SCSV Non-Contiguous Example

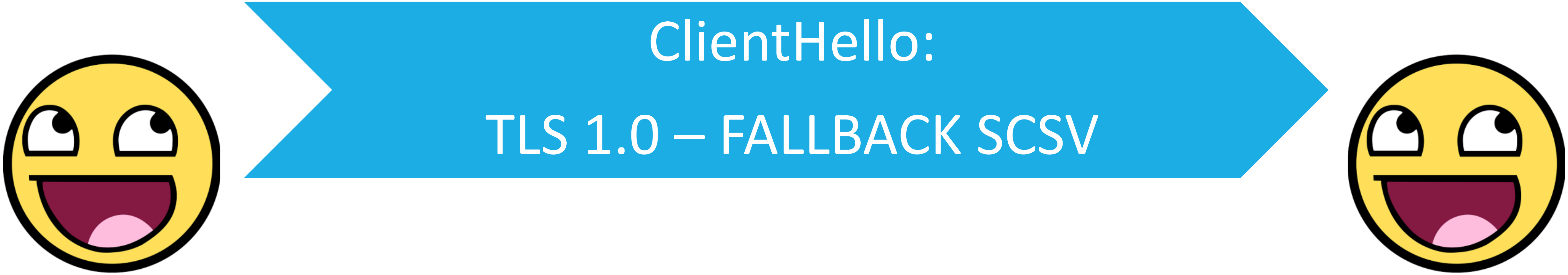


ClientHello:

TLS 1.2

Fatal_Handshake_Error

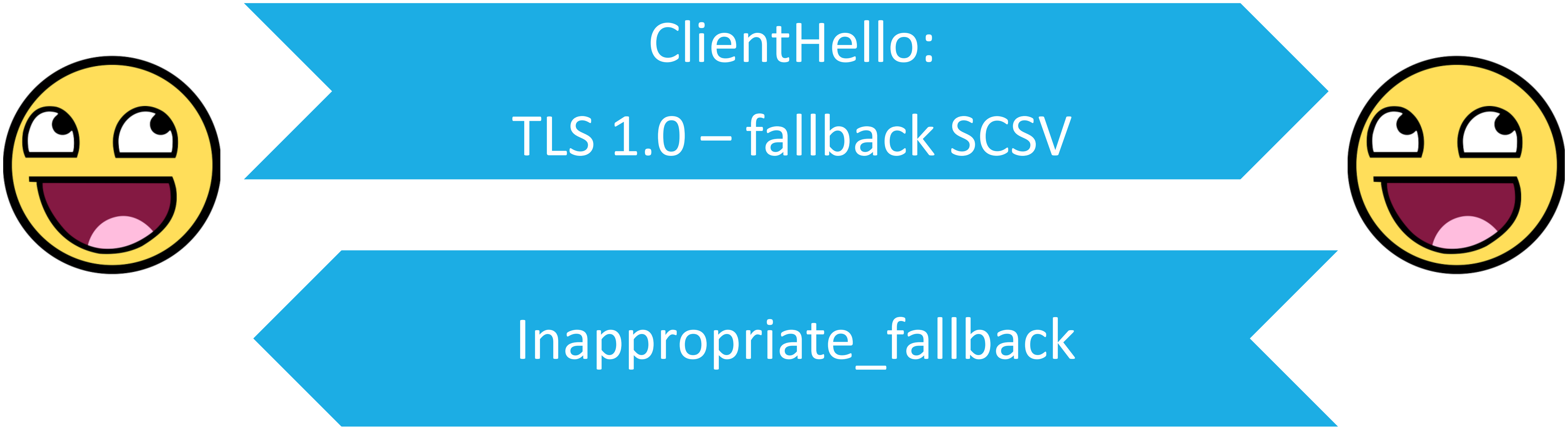
SCSV Non-Contiguous Example



ClientHello:

TLS 1.0 – FALLBACK SCSV

SCSV Non-Contiguous Example



ClientHello:

TLS 1.0 – fallback SCSV

Inappropriate_fallback

Conclusions

- When considering negotiation security, think:

Weakest Link Security

- Additionally:

Always authenticate everything

Thanks!

Questions?