University of Stuttgart
Institute of
Information Security

Carnegie Mellon University

Inria

Indian Institute of Technology Gandhinagar

DY*: A Modular Symbolic Verification Framework for Executable Cryptographic Protocol Code [EuroS&P 21]

GDR'21 | sec.uni-stuttgart.de

SEC

Bhargavan, Bichhawat, Do, Hosseyni, Küsters, Schmitz, Würtele

Cryptographic Protcols are Everywhere: Golden Era of Crypto

- Ubiquitous HTTPS: TLS 1.3, QUIC, ACME/Let's Encrypt, ...
- Secure Messaging: Signal, MLS, ...
- Single-Sign On: OAuth, OIDC, SAML, ...
- Wireless: Wifi/WPA, 4G, 5G, Zigbee, ...
- Payment: EMV, W3C Web Payments, ...
- Post-Quantum Crypto: NIST KEMs, Signature, ...
- Lightweight Crypto: IETF LAKE, NIST LWC

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COMPUTERWORLD UNITED STATES INSIDER

NEWS

EMV flaw allows 'pre-play' attacks on chip-enabled payment cards

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QUIC

Wi Fi™

SAML v2.0 Security Assertion Markup Language

Let's Encrypt

Signal

zigbee

OAUTH 2

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ZDNet CENTRAL EUROPE MIDDLE EAST SCANDINAVIA AFRICA UK ITALY SPAIN MORE NEWSLETTERS

'Triple handshake' bug another big problem for TLS/SSL

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Logjam: the latest TLS vulnerability explained

21/05/2015

UIC

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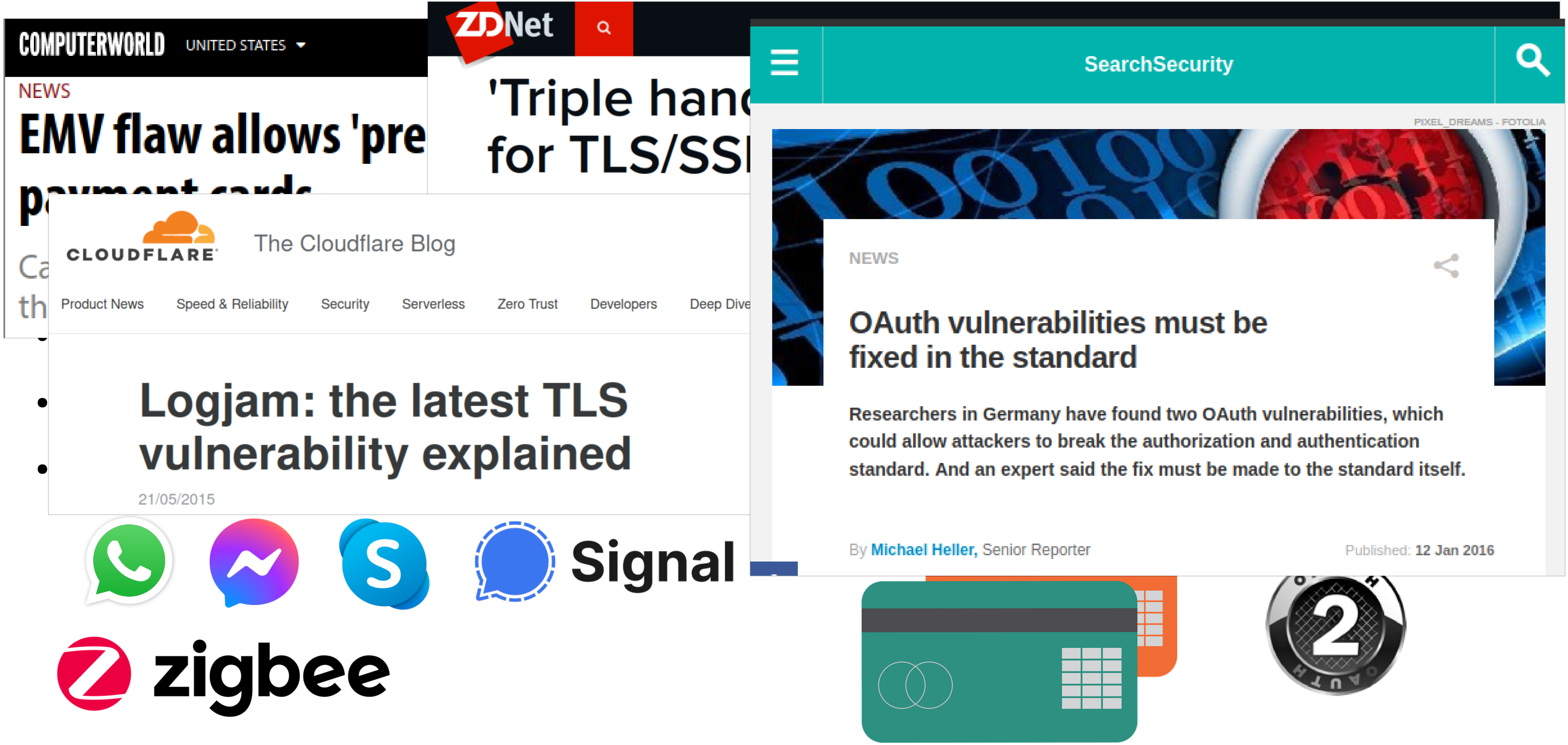

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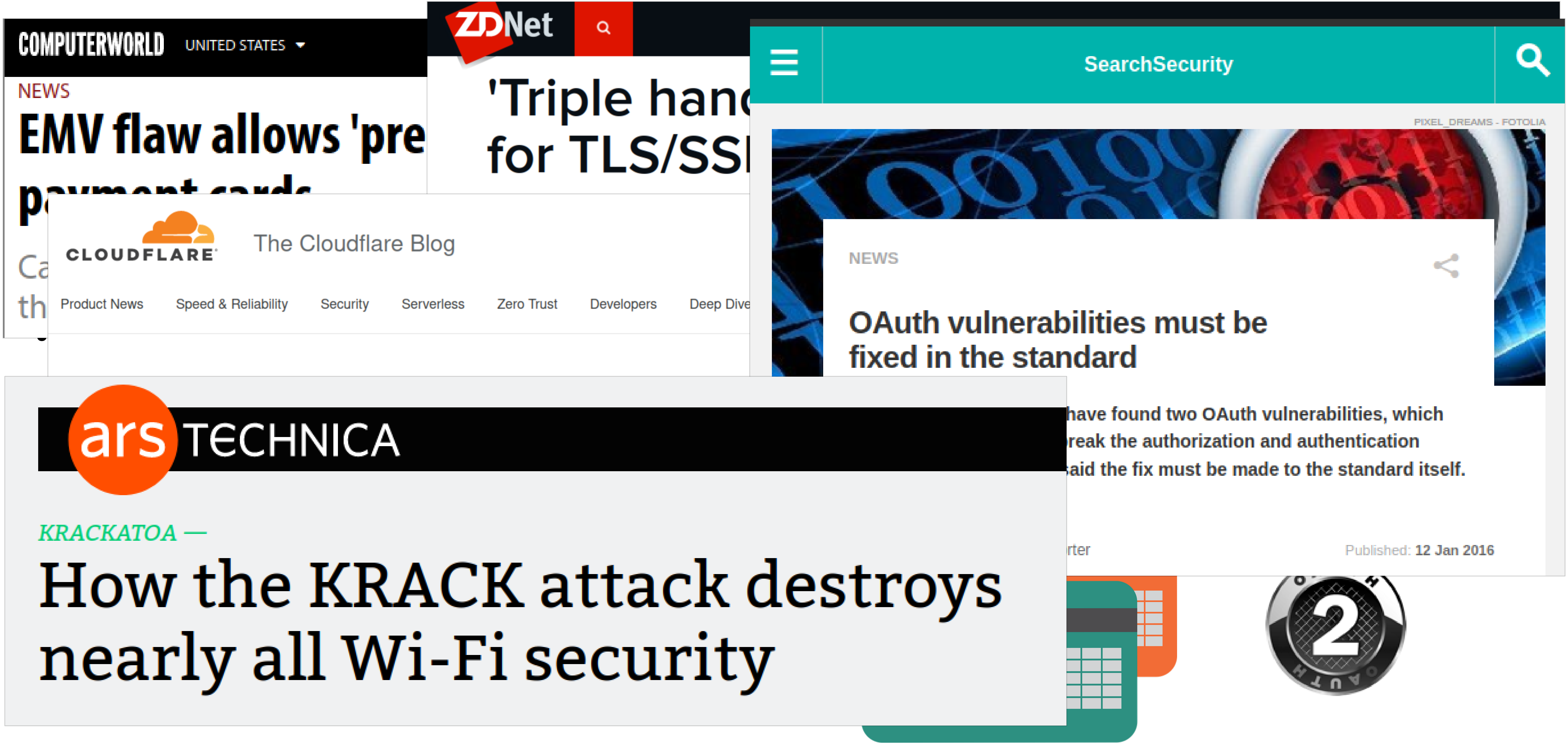
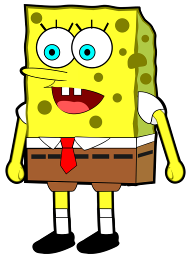


Signal Messaging Protocol

- Asynchronous continuous key exchange protocol

Signal

$G = \langle g \rangle$



x random $\xrightarrow{g^x}$

$(g^y)^x = g^{xy} \xleftarrow{g^y}$ y random

$(g^x)^y = g^{xy}$

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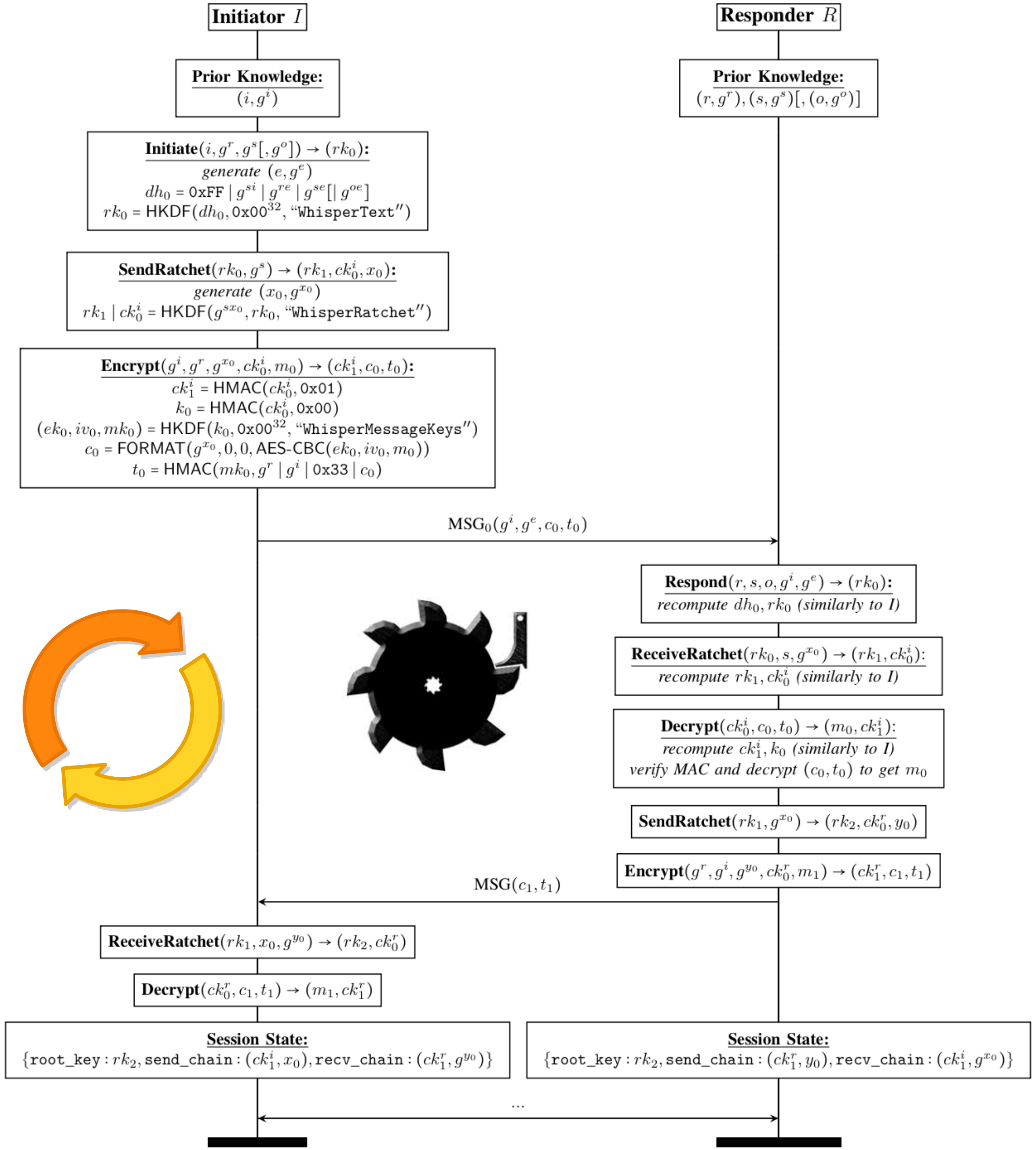
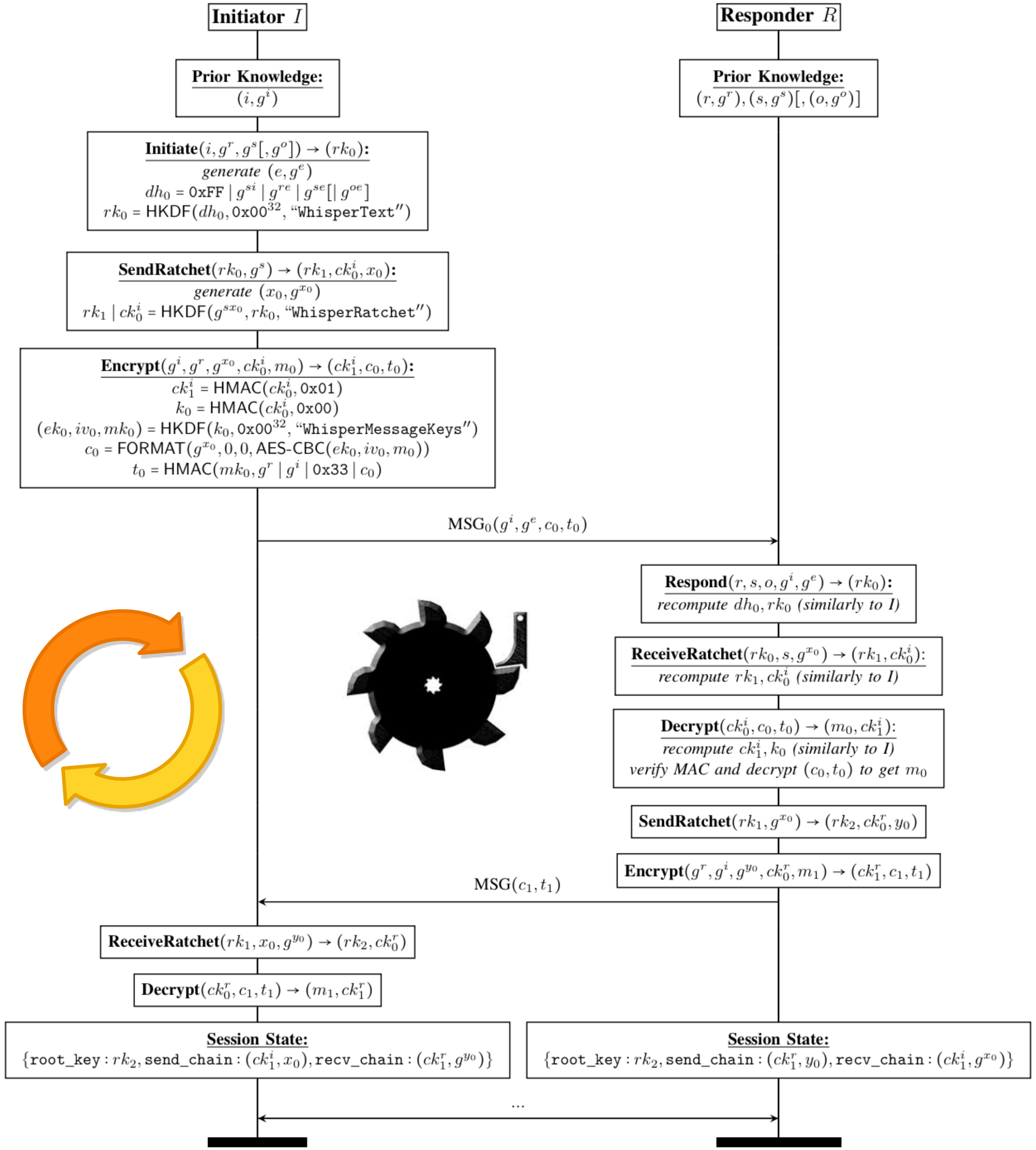


Signal Messaging Protocol

- Asynchronous continuous key exchange protocol
- Multiple subprotocols
  - X3DH (initial key exchange)
  - DH Ratchet (post-compromise security)
  - Hash Ratchet (forward security)
  - Authenticated Encryption (message security)



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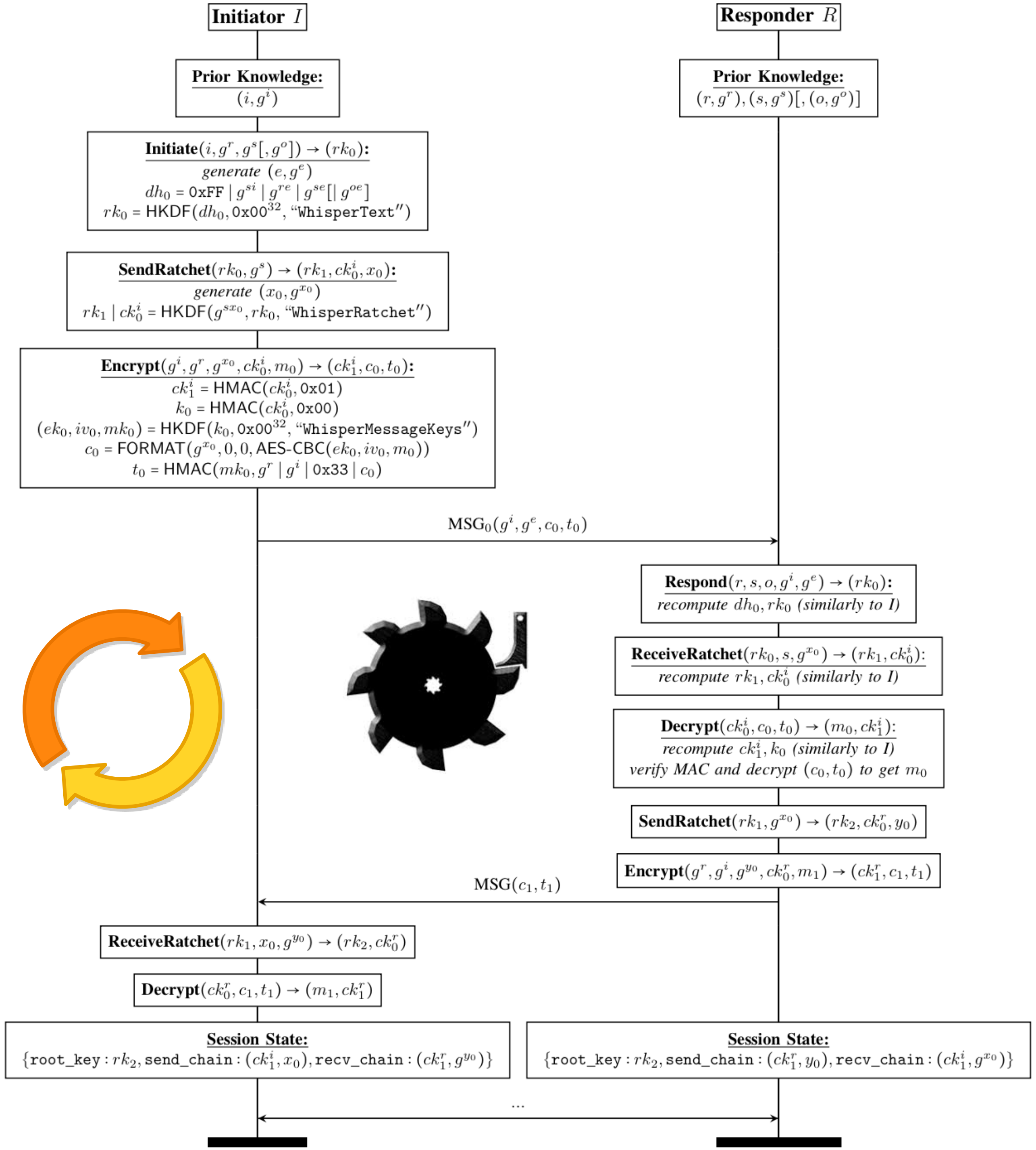

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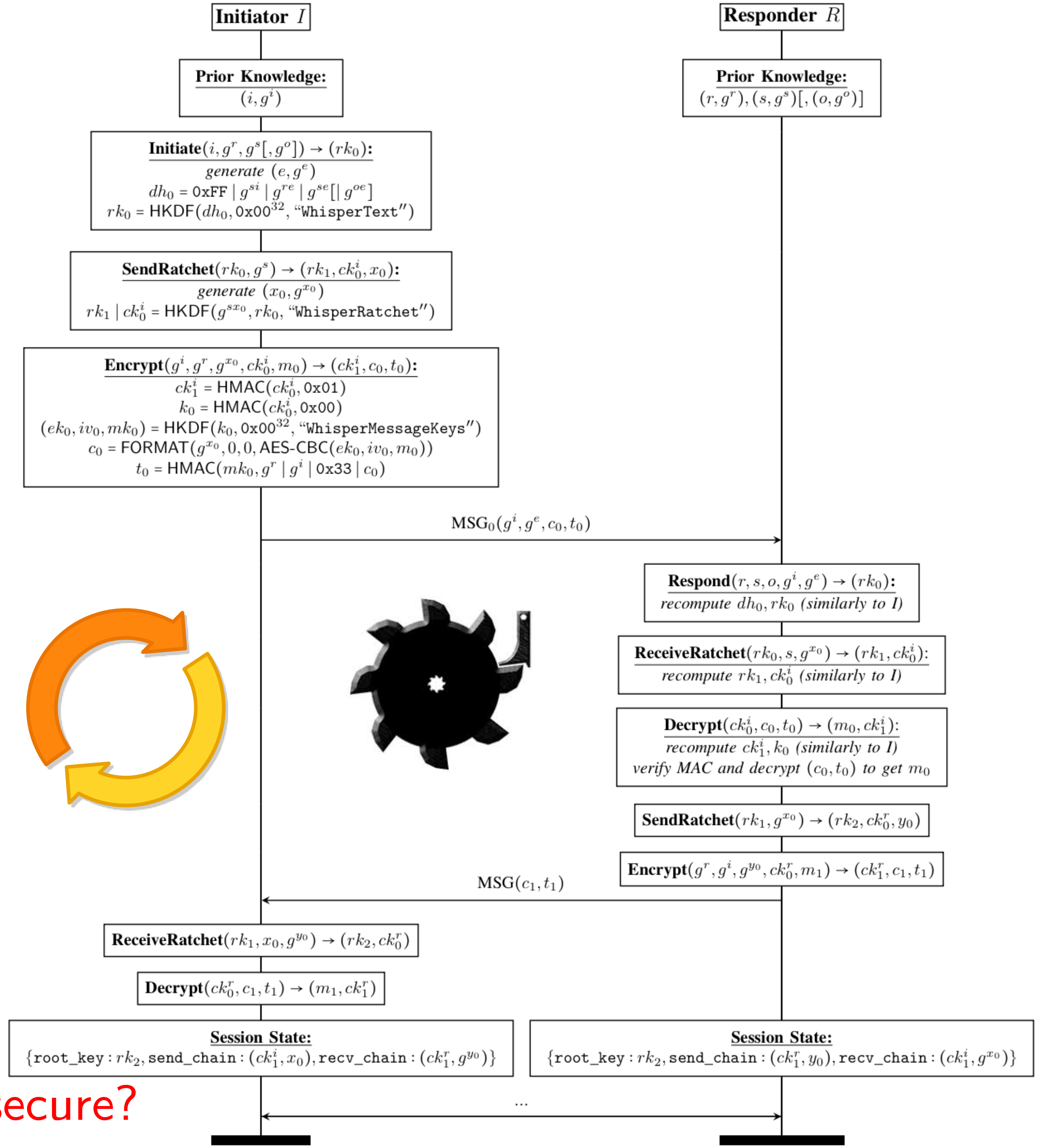
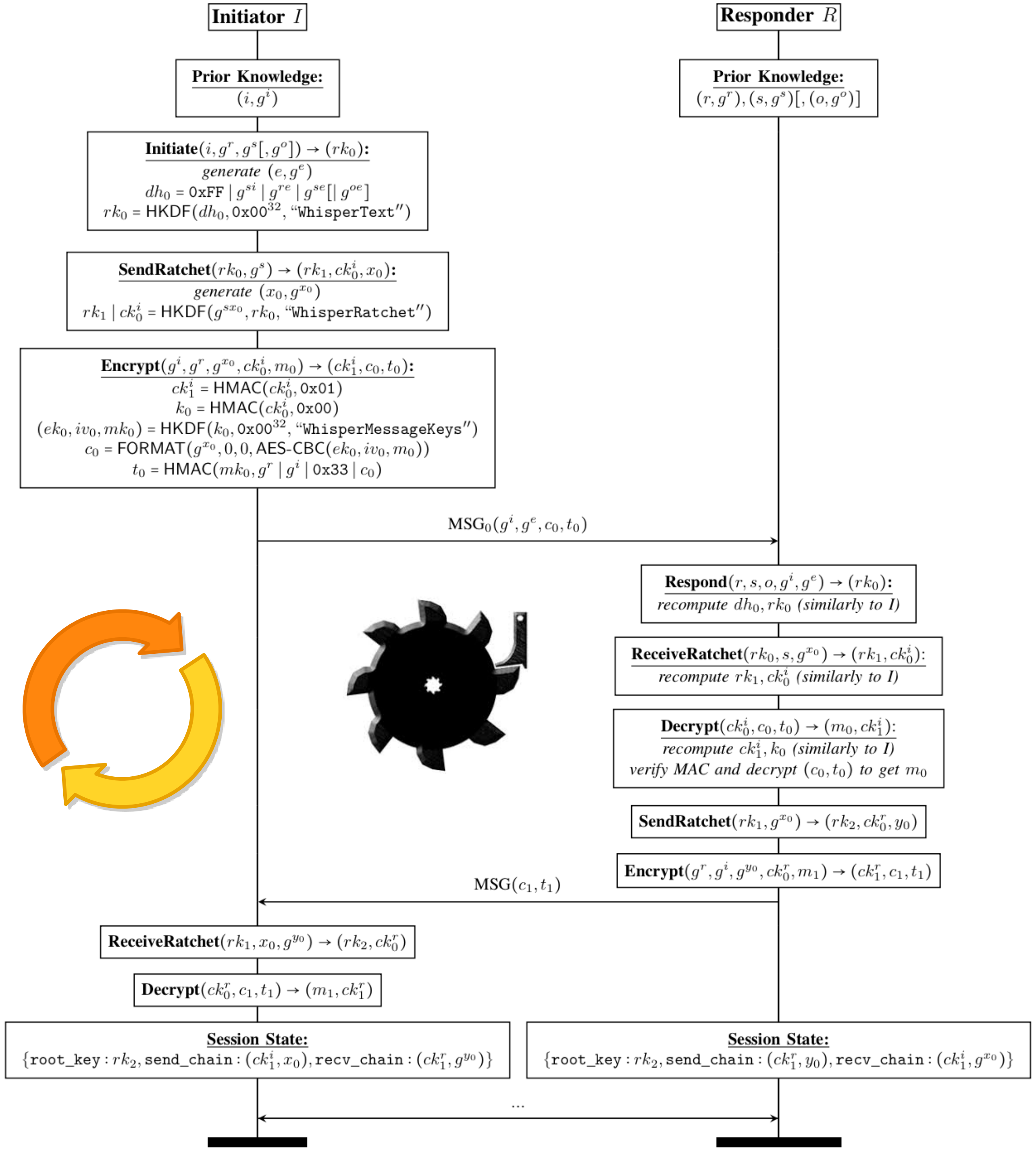
  - Security of each message depends on a chain of derived keys
- Can we mechanically verify that the protocol is secure?

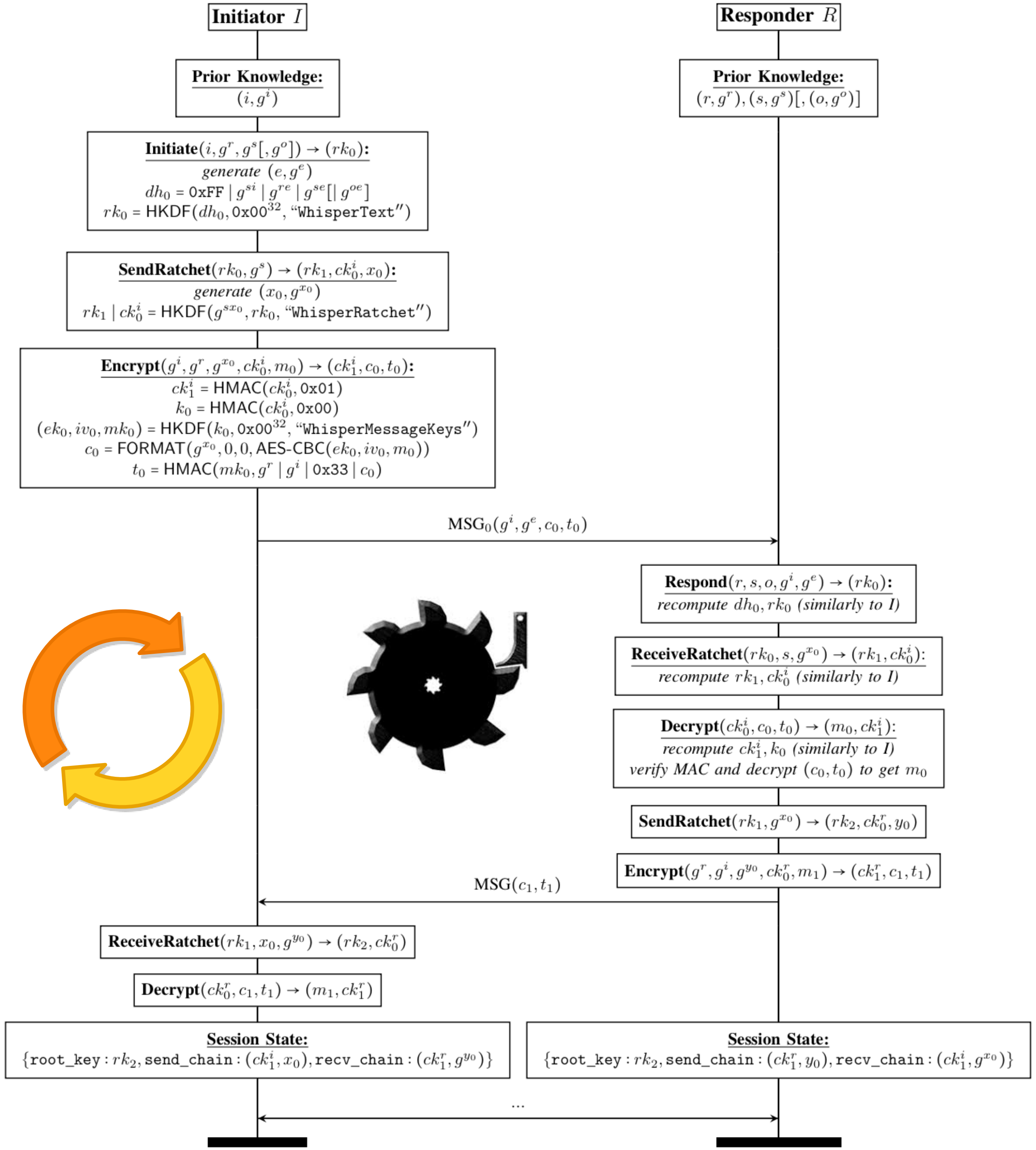


Formalizing Signal



Formalizing Signal

- Existing Analyses
  - Using ProVerif and CryptoVerif
  - Model X3DH, Double Ratchet
  - Few hundred lines written in applied pi calculus



Formalizing Signal

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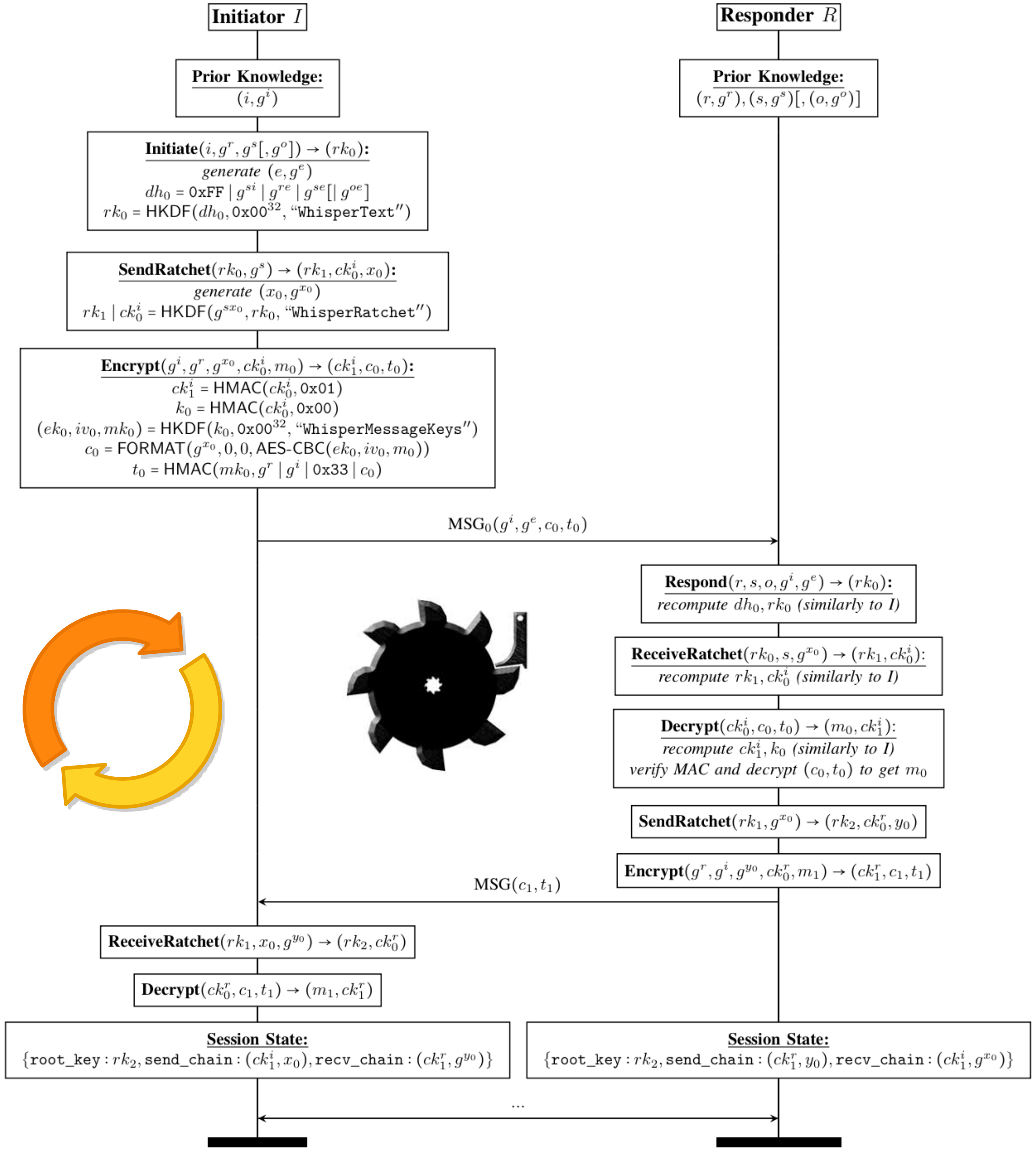
  - Few hundred lines written in applied pi calculus
- One major limitation of existing analyses: Proofs for only 3 message rounds due to recursion



Security Protocols: SSO

Single Sign-On allows users to authenticate to service A using an account at service B

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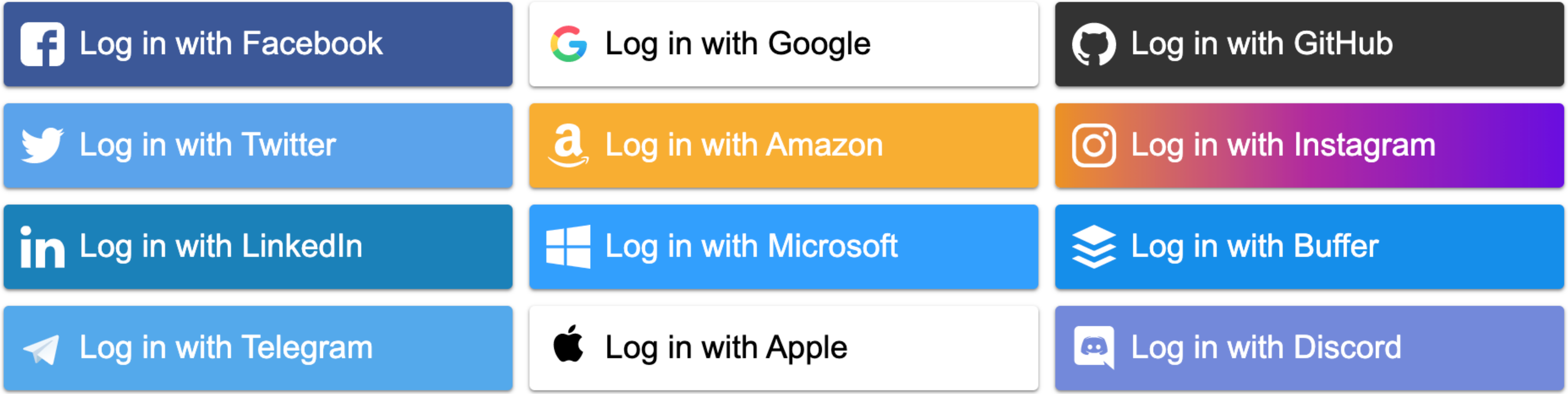

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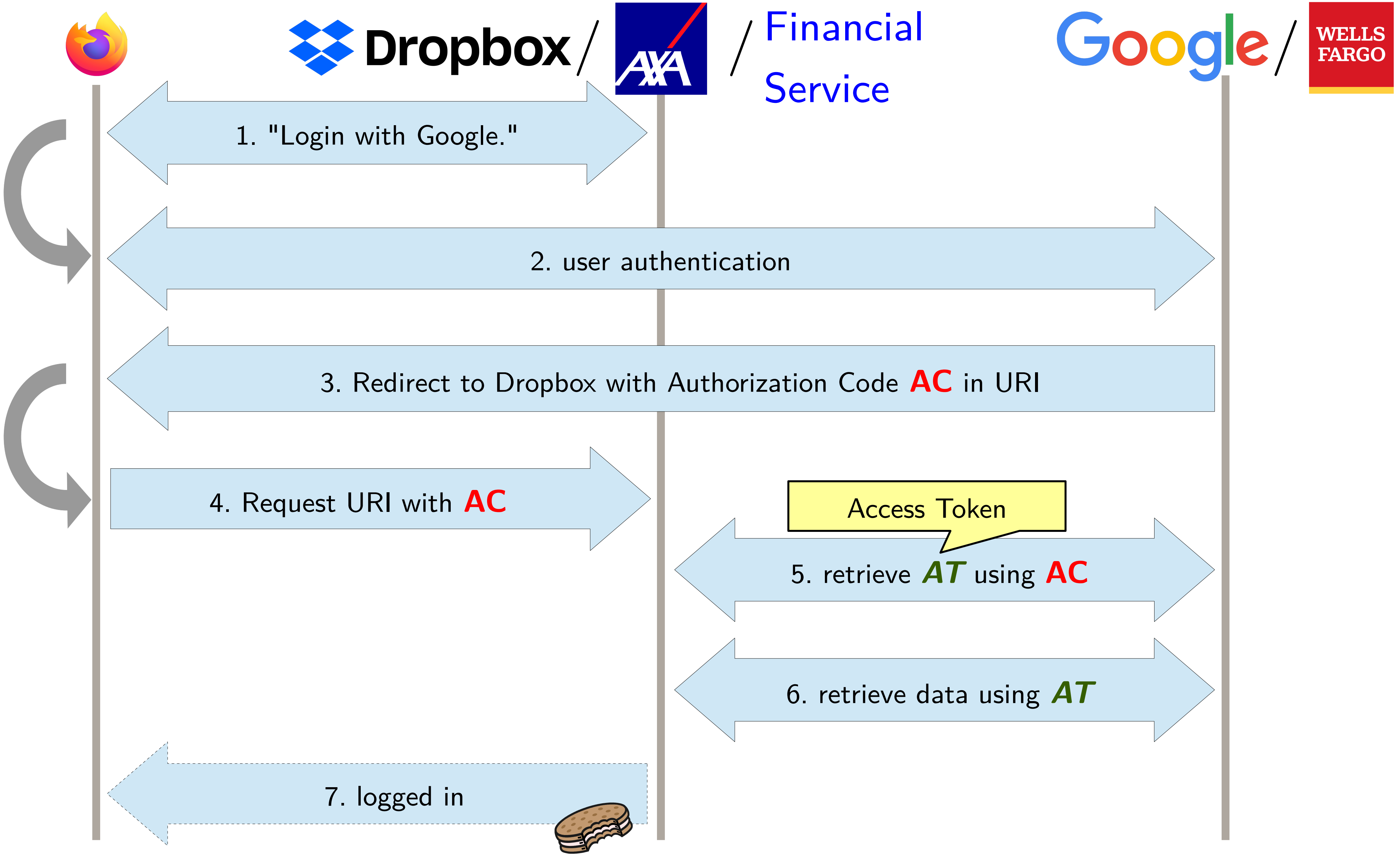
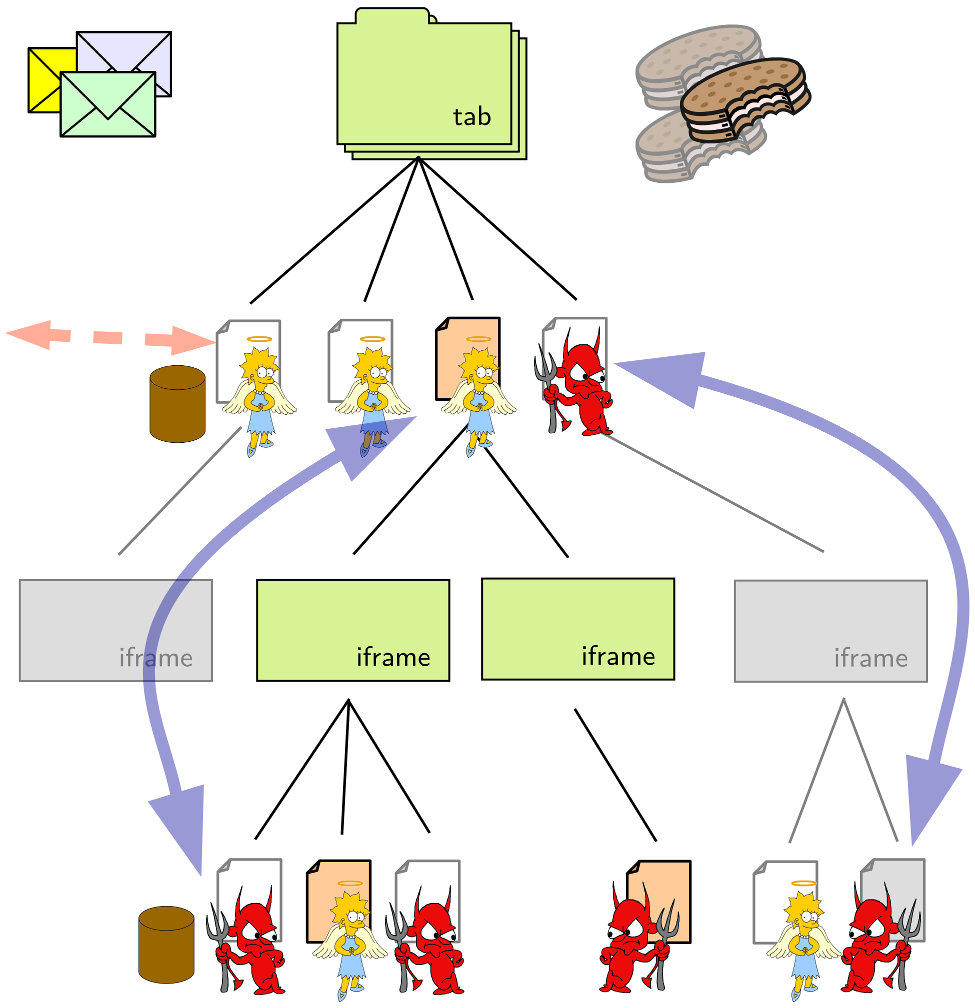
OAuth2.0

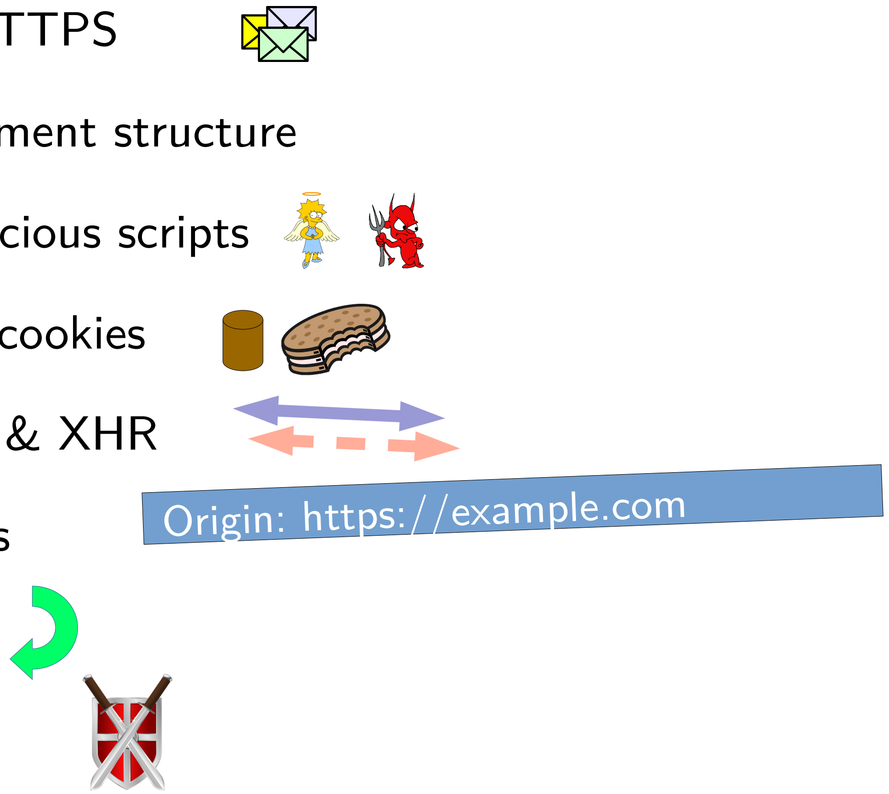
Authorization Code Mode



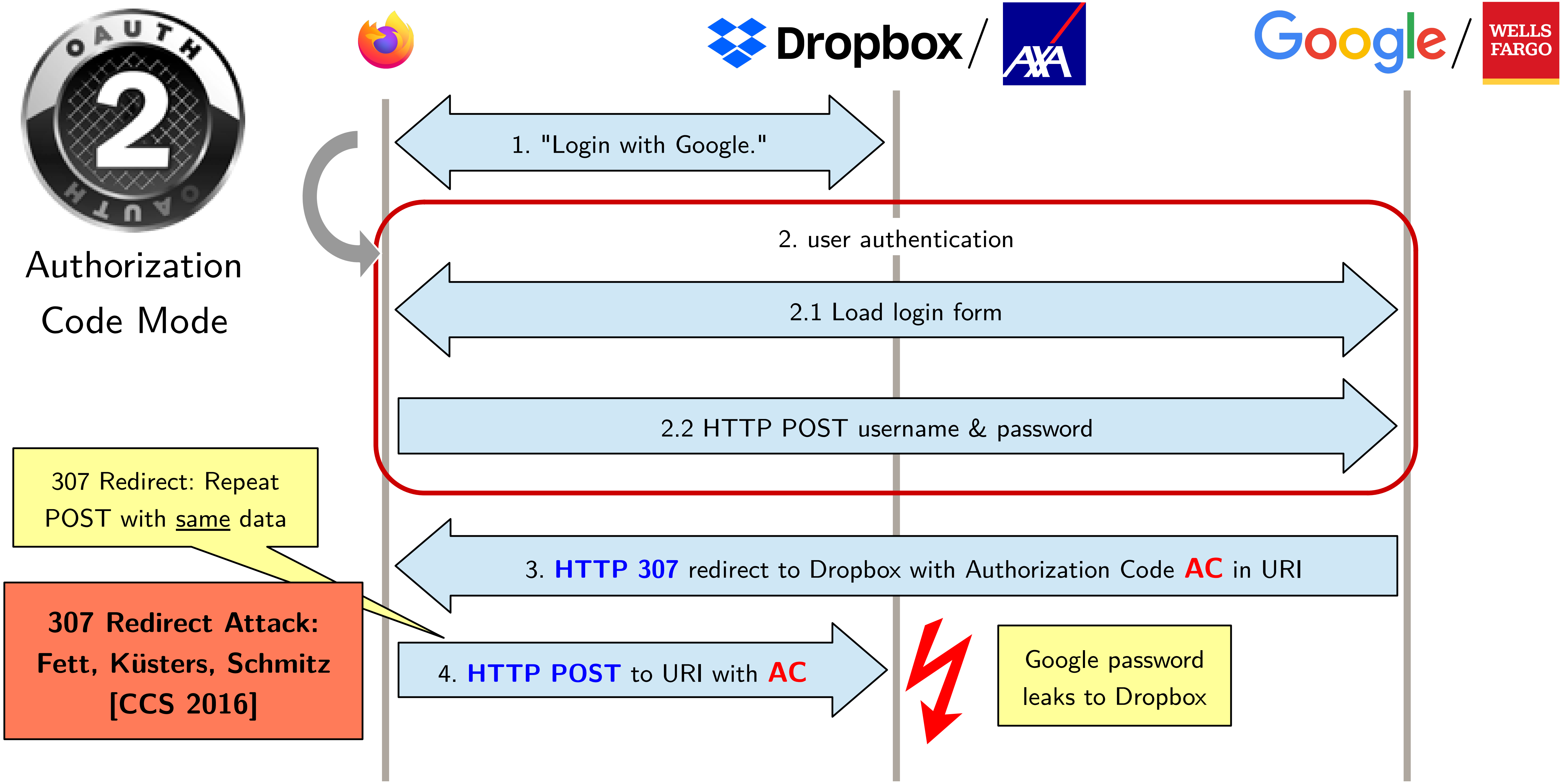
The Web is a Complex Environment



- DNS, HTTP, HTTPS
- window & document structure
- honest and malicious scripts
- Web storage & cookies
- Web messaging & XHR
- message headers
- redirections
- security policies
- ...



Many Attacks based on Web Features (Examples)



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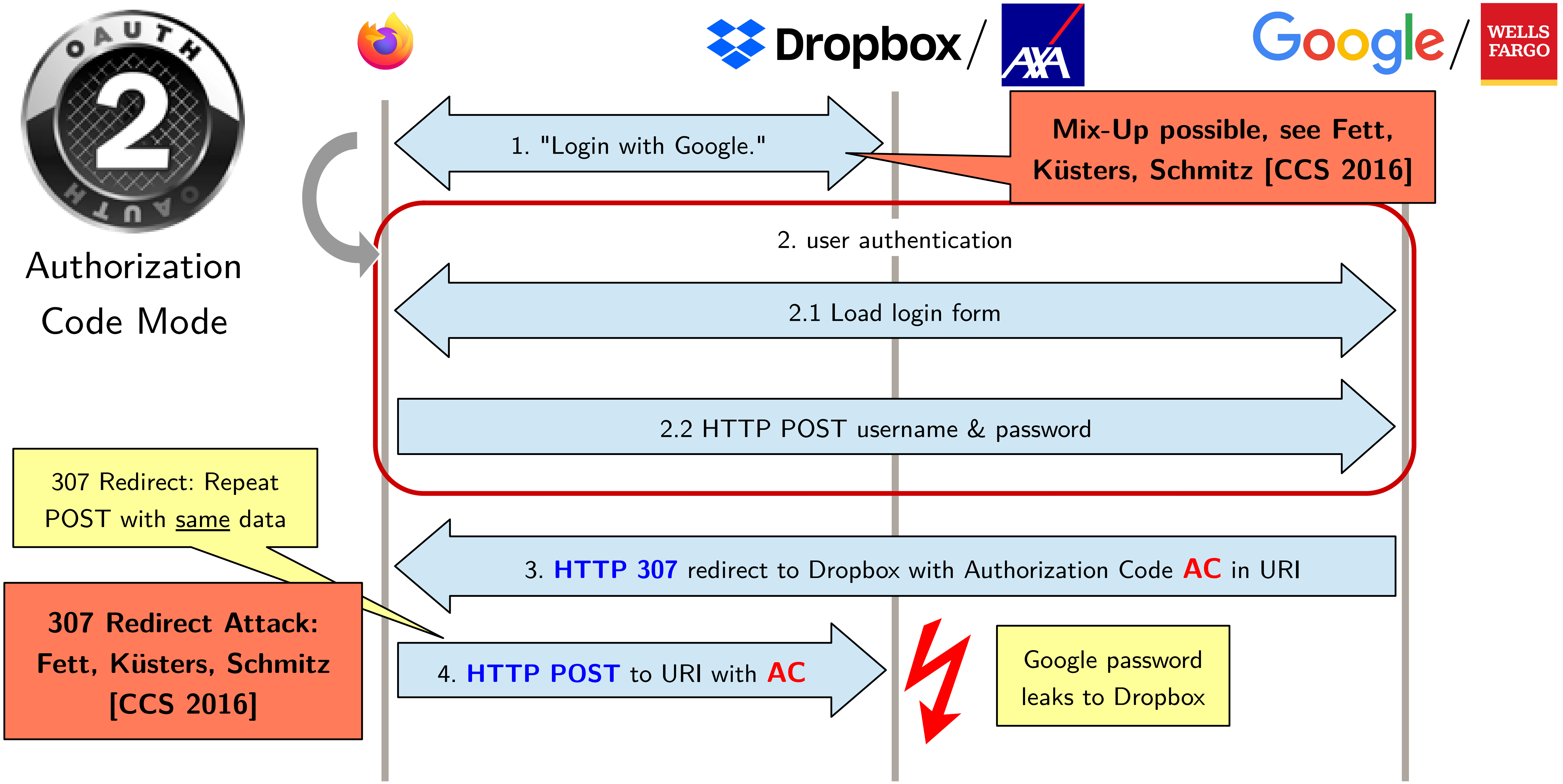

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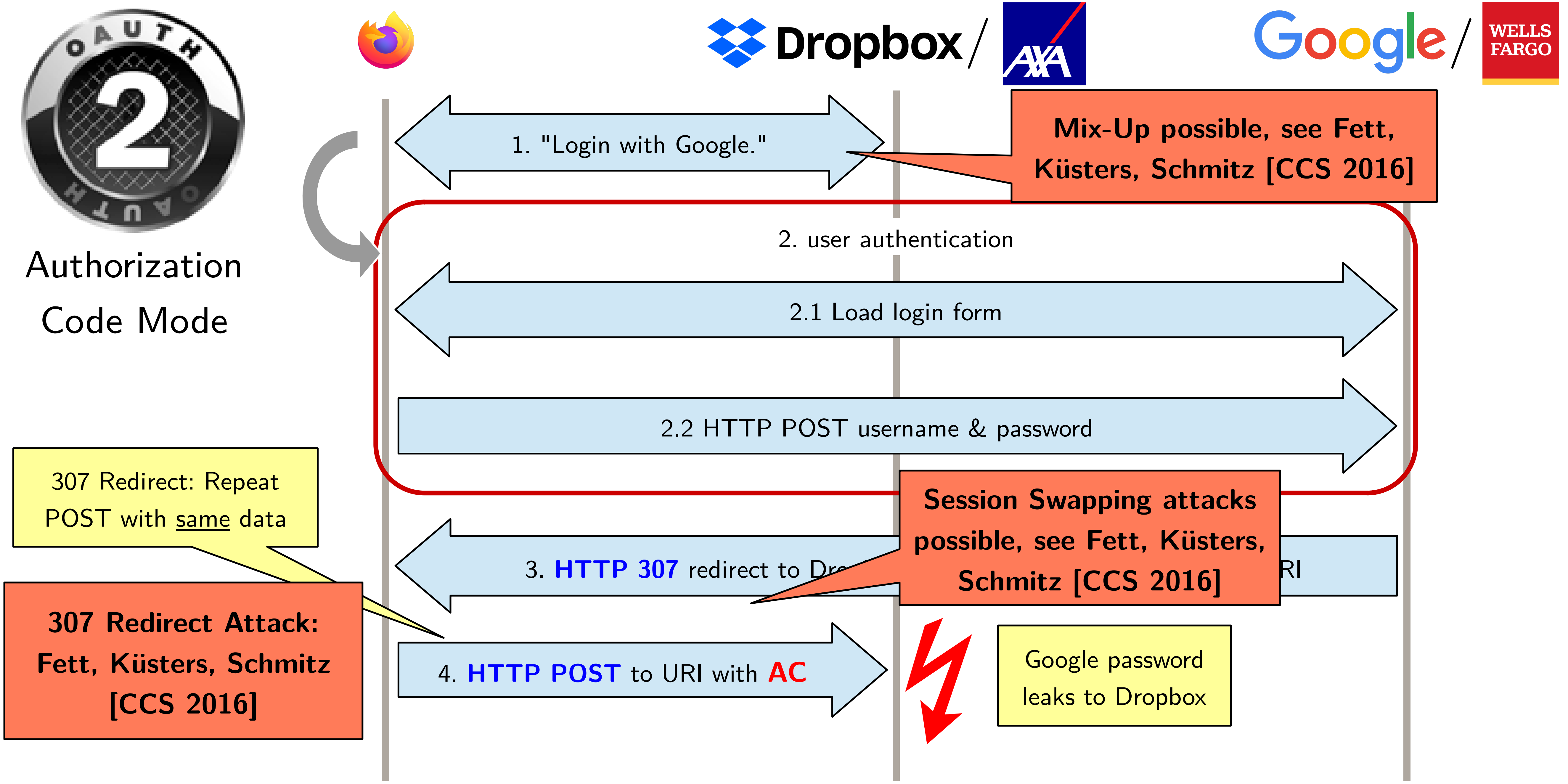

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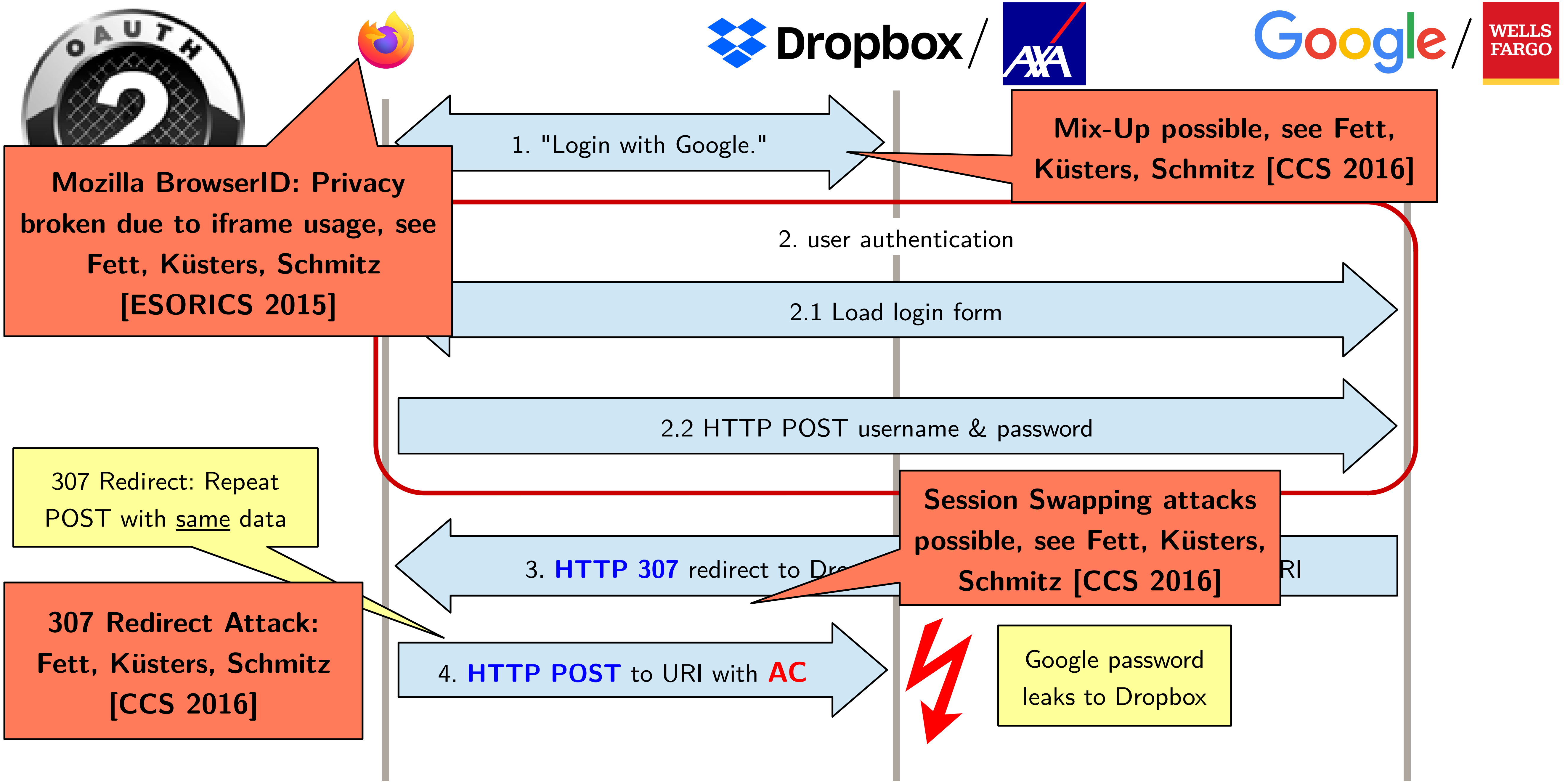

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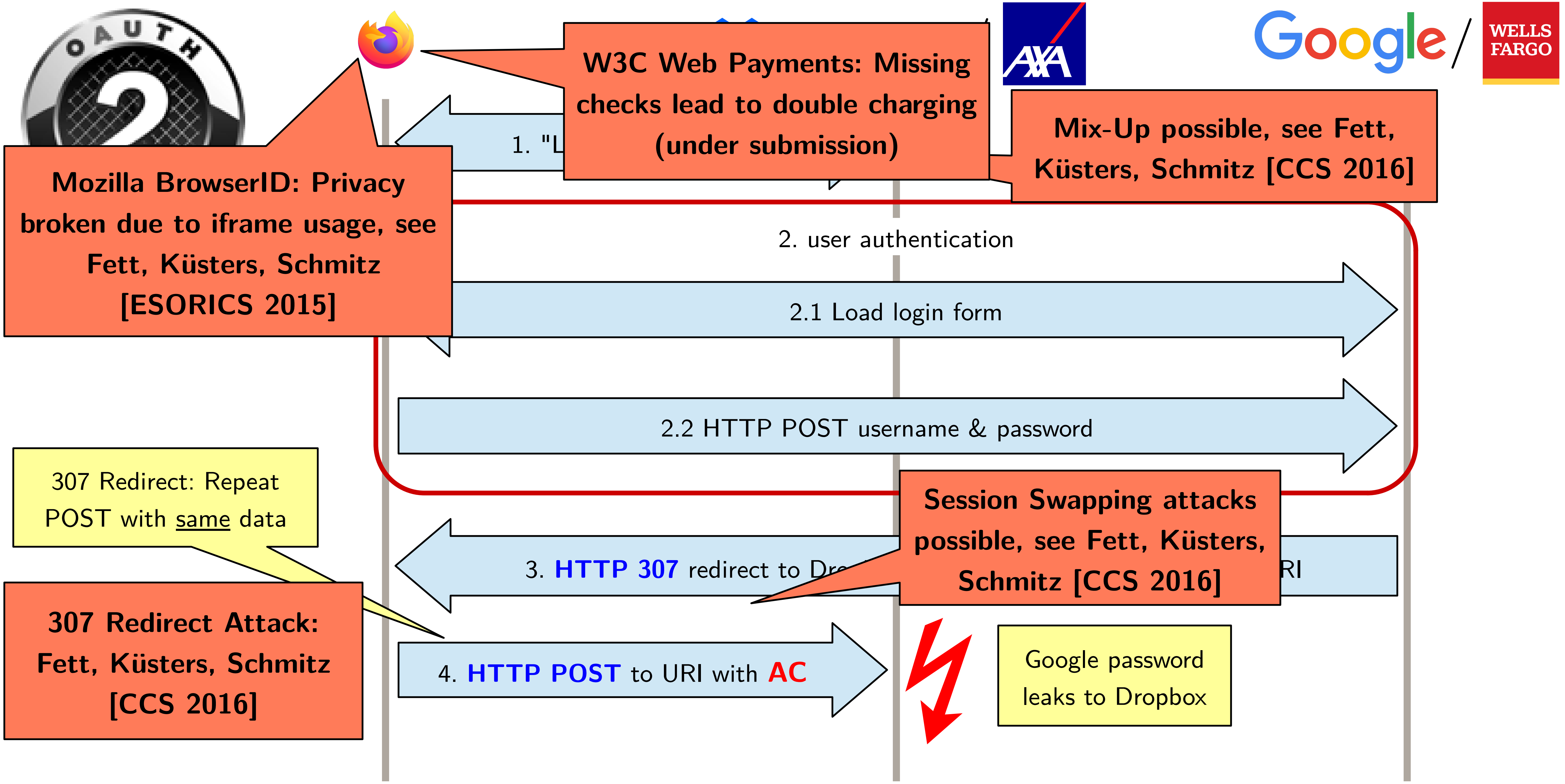

Analysis of Security Protocols on the Web: Main Research Lines

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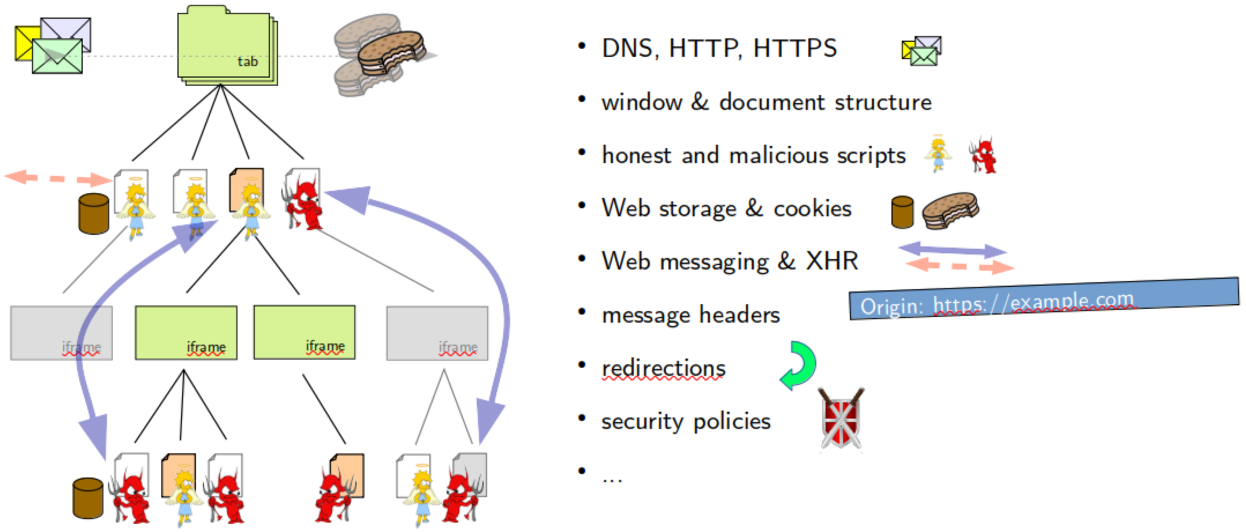
  - Simplified and abstract models of the web
- Web Infrastructure Model (WIM)
  - Fett, Küsters, Schmitz [S&P 2014]
  - Detailed model
  - Used for many case studies (OAuth, OIDC, BrowserID, FAPI, W3C Web Payments)
  - Manual pen-and-paper analyses



Analysis of Security Protocols: Tools

Computational Tools:
CryptoVerif, EasyCrypt, ...

- Focus on cryptographic core
- Messages are bitstrings
- Probabilistic

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Dependent Types:

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- ✗ abstract models
- ✗ bounded data structures
- ✗ no modularity
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- ✗ interoperability

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- ✔ global trace & properties
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focus on implementation aspects

- ✔ modular proofs
- ✔ implementation level analysis
- ✔ unbounded structures
- ✔ inductive reasoning
- ✔ executable models
- ✔ interoperability

- ✗ missing global view
- ✗ limited expressivity w.r.t. security prop.
- ✗ limited support for mutable state
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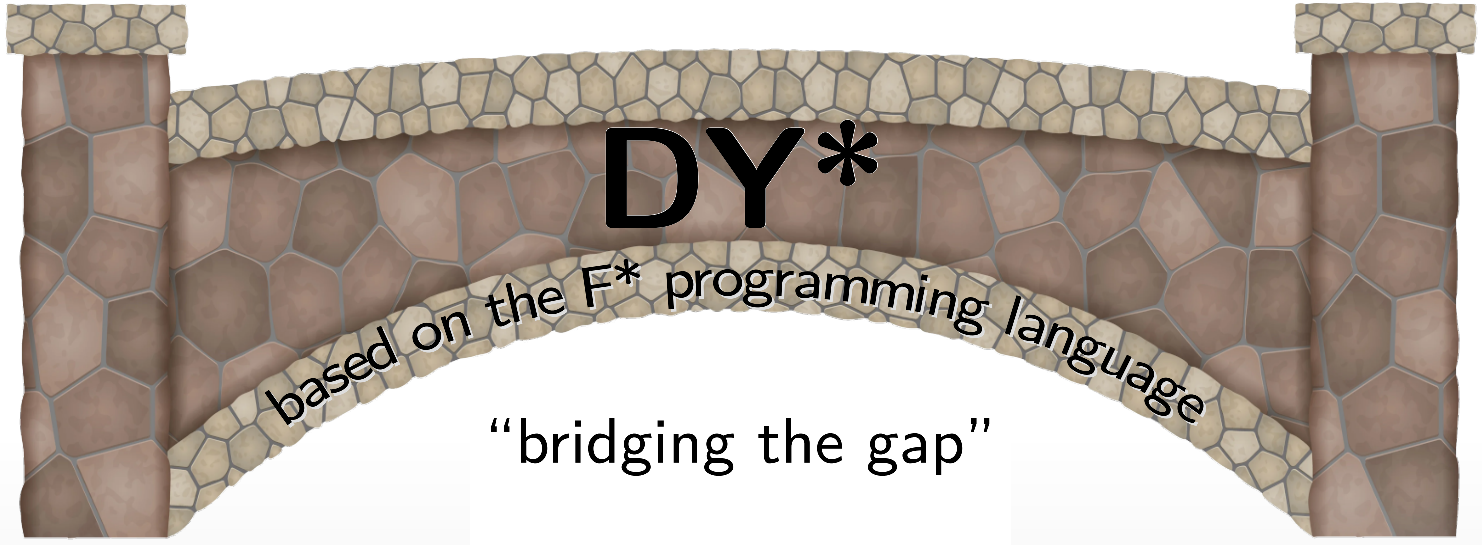

"bridging the gap"

- ✔ (mostly) automated analysis
- ✔ global trace & properties
- ✔ equational theories

- ✔ modular proofs
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What is F*?

- Functional programming language aimed at program verification
- Developed and actively supported by Microsoft Research, INRIA, and others
- Already used to prove security of, for example, parts of TLS 1.3
- Rich, versatile type system
  - Dependent types
  - Refinement types
  - Pre/post conditions
  - Backed by SMT-Solver Z3
  - Can be used to precisely express strong (security) properties
- F* program can be translated to OCaml, F#, C, or JavaScript

F* - Simple Example

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val factorial: nat -> nat

let rec factorial n =

    if n<=1 then 1 else n * (factorial (n-1))
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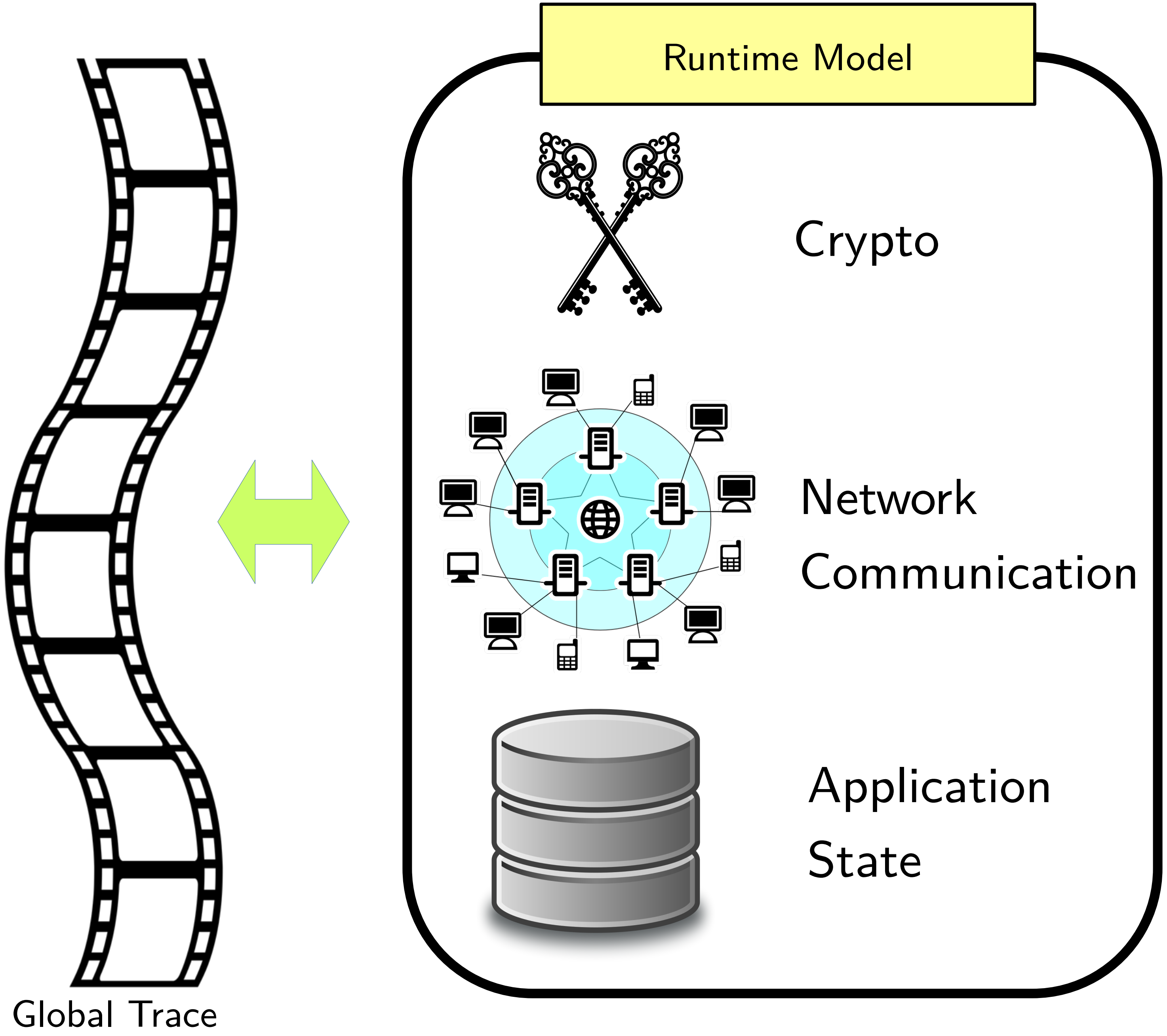
Induction Start

Induction Step

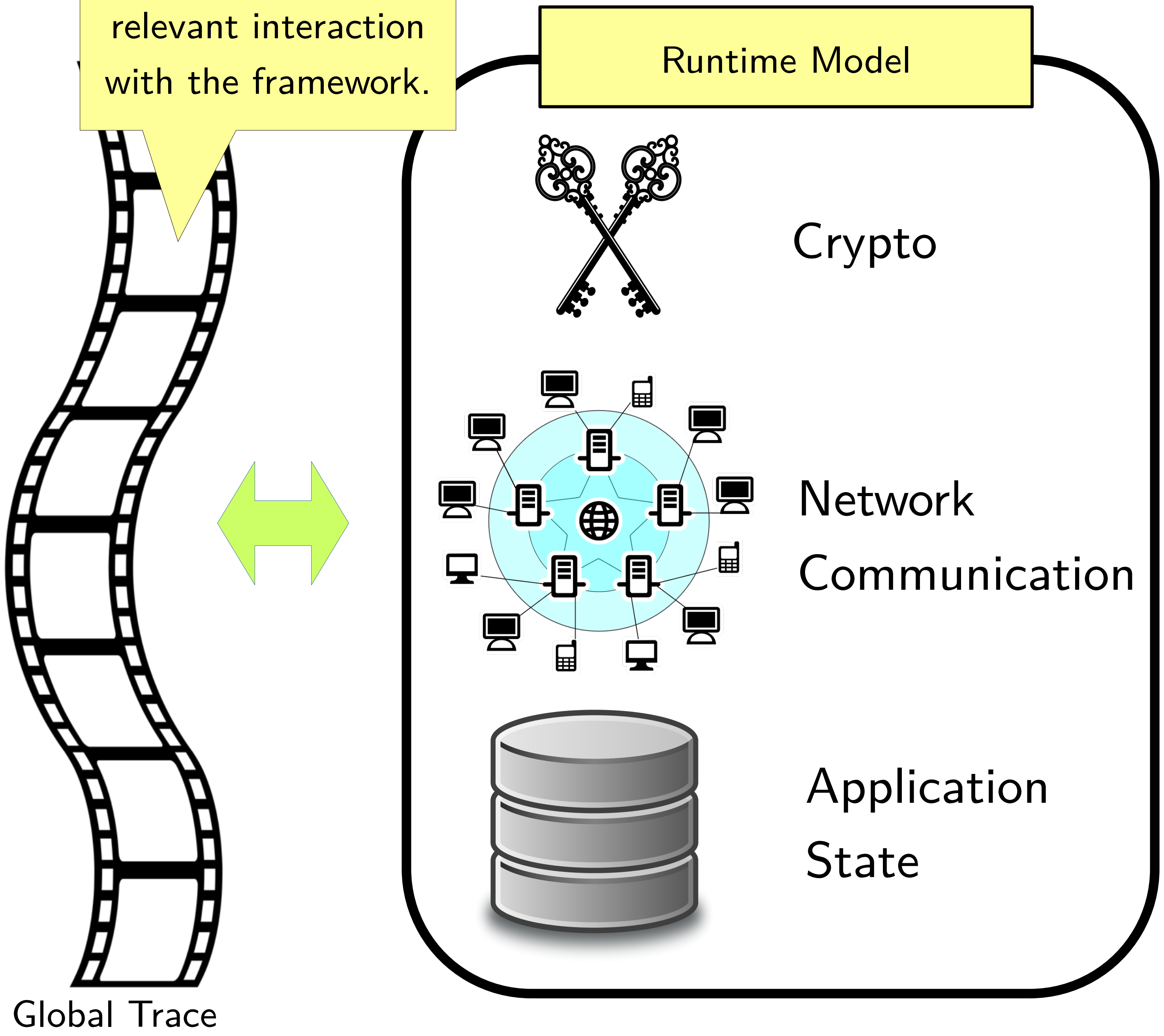
verified

Dolev-Yao* (DY*): Architecture



Dolev-Yao* (DY*): Architecture

Append-only log that captures relevant interaction with the framework.



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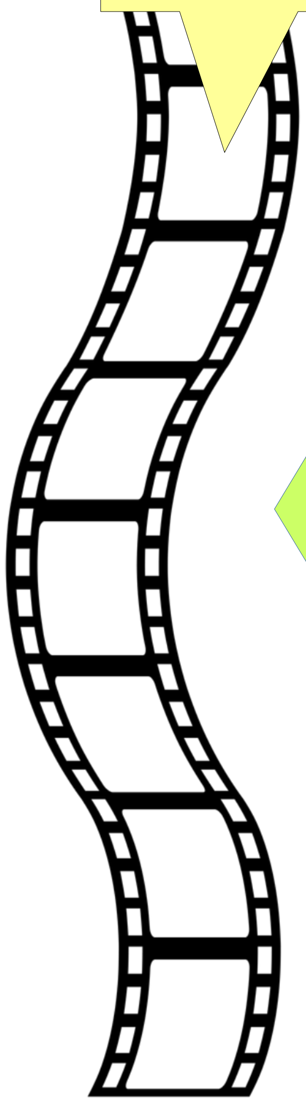
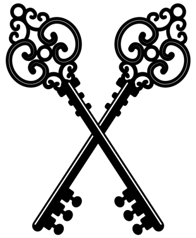
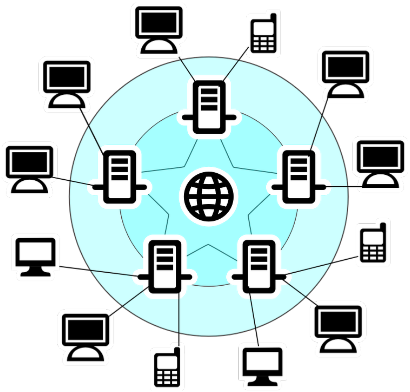


Global Trace

Runtime Model



Crypto



Network Communication

Application State

Protocol Implementation

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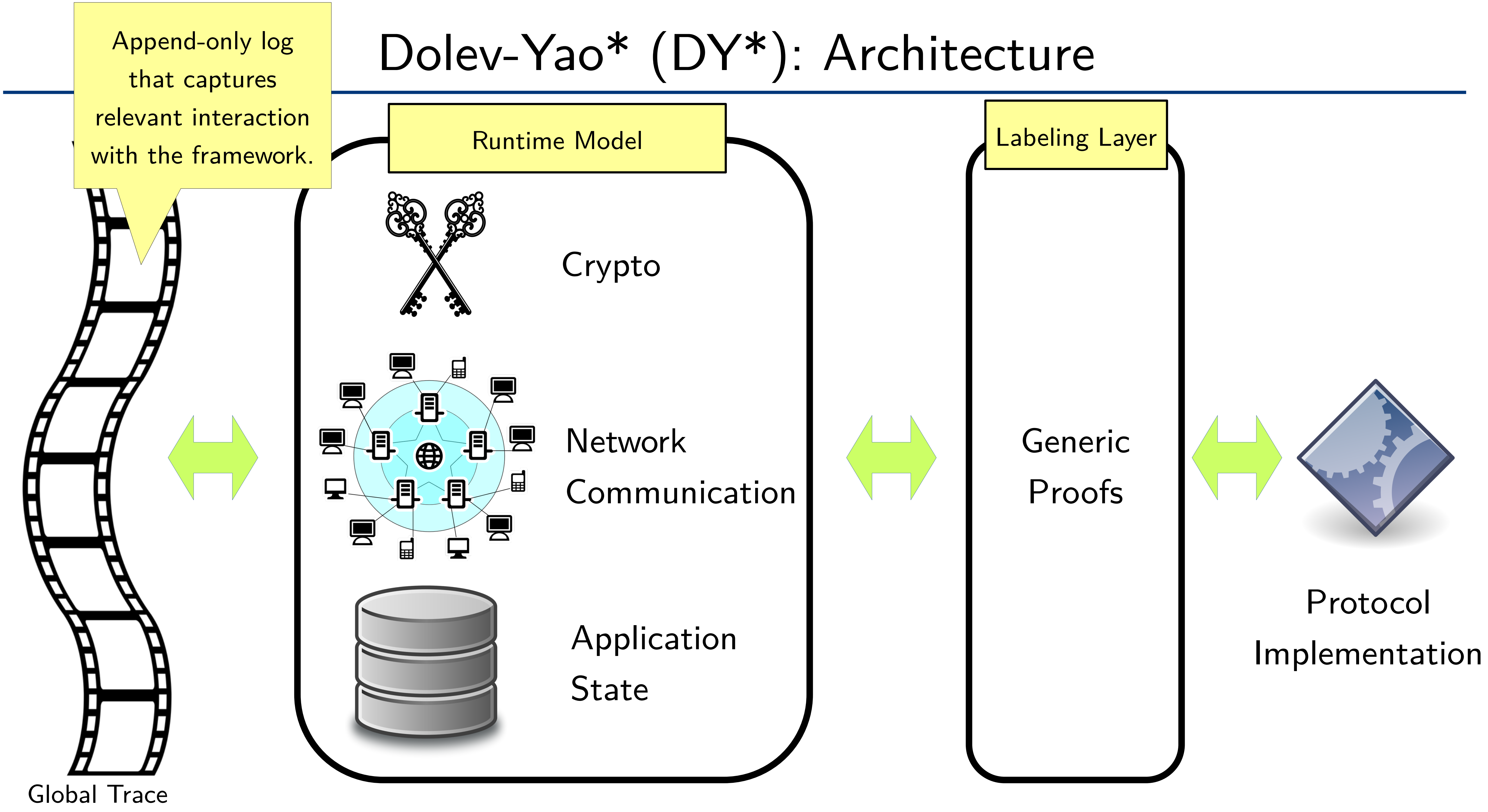

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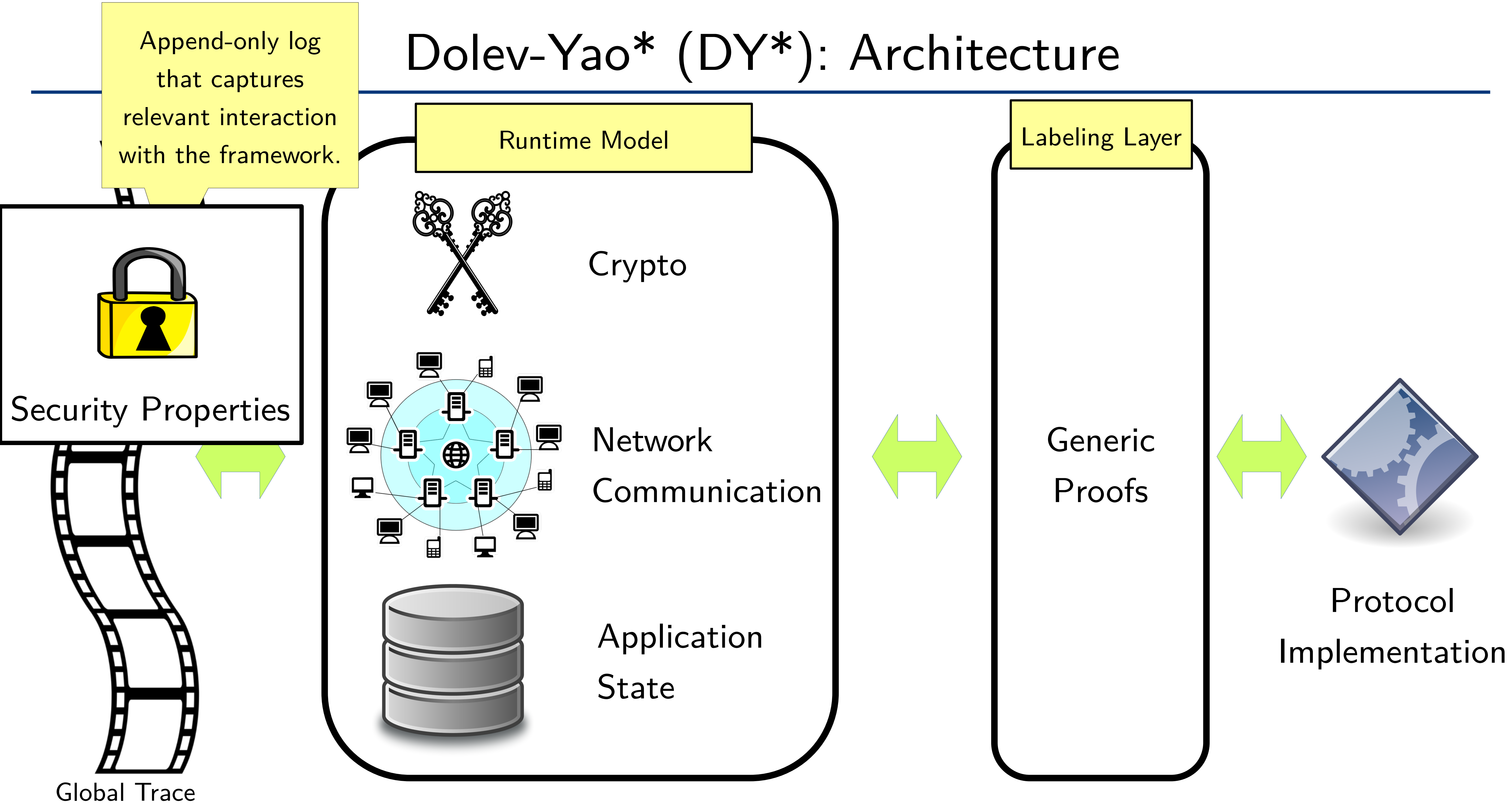

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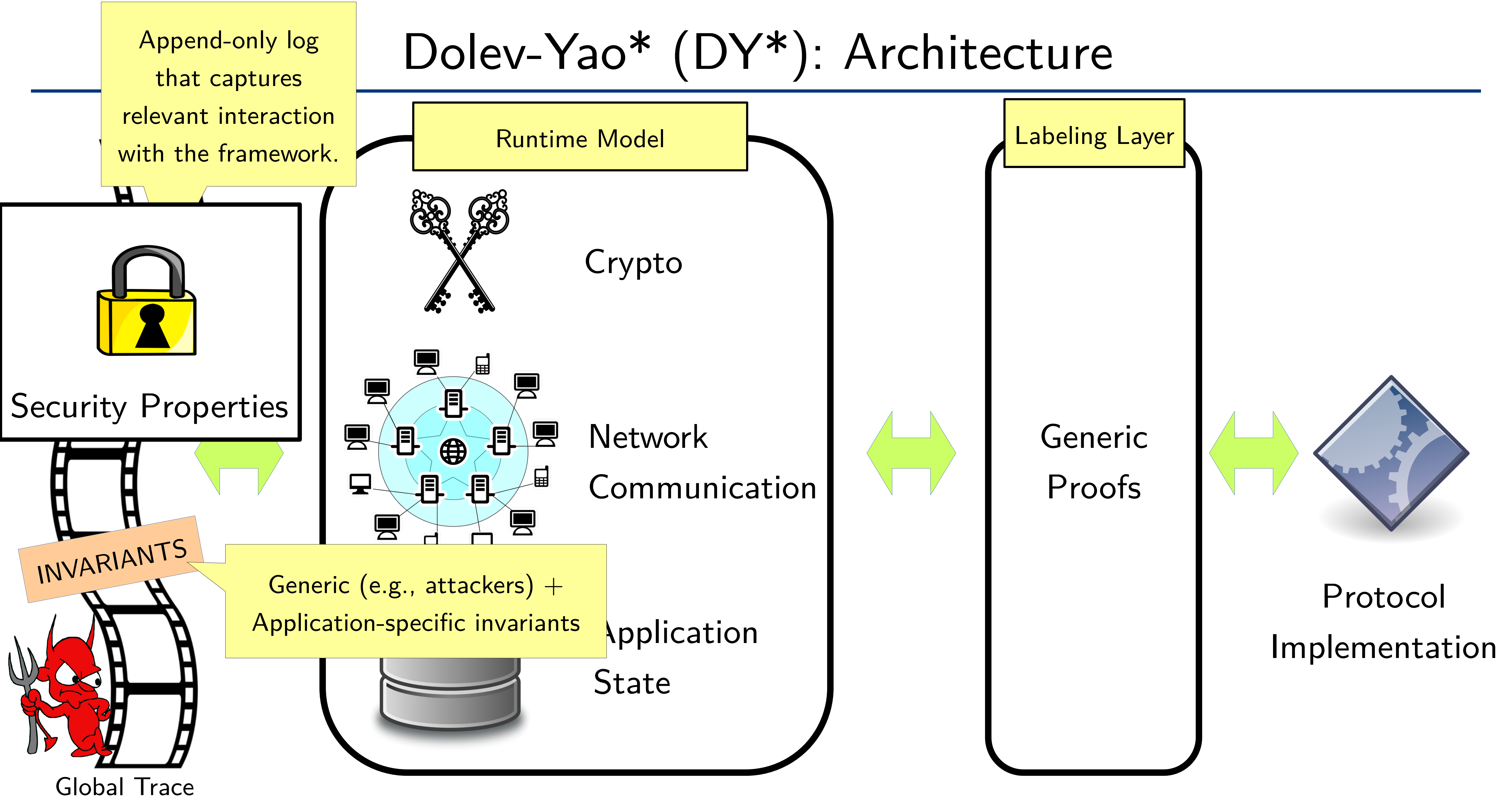

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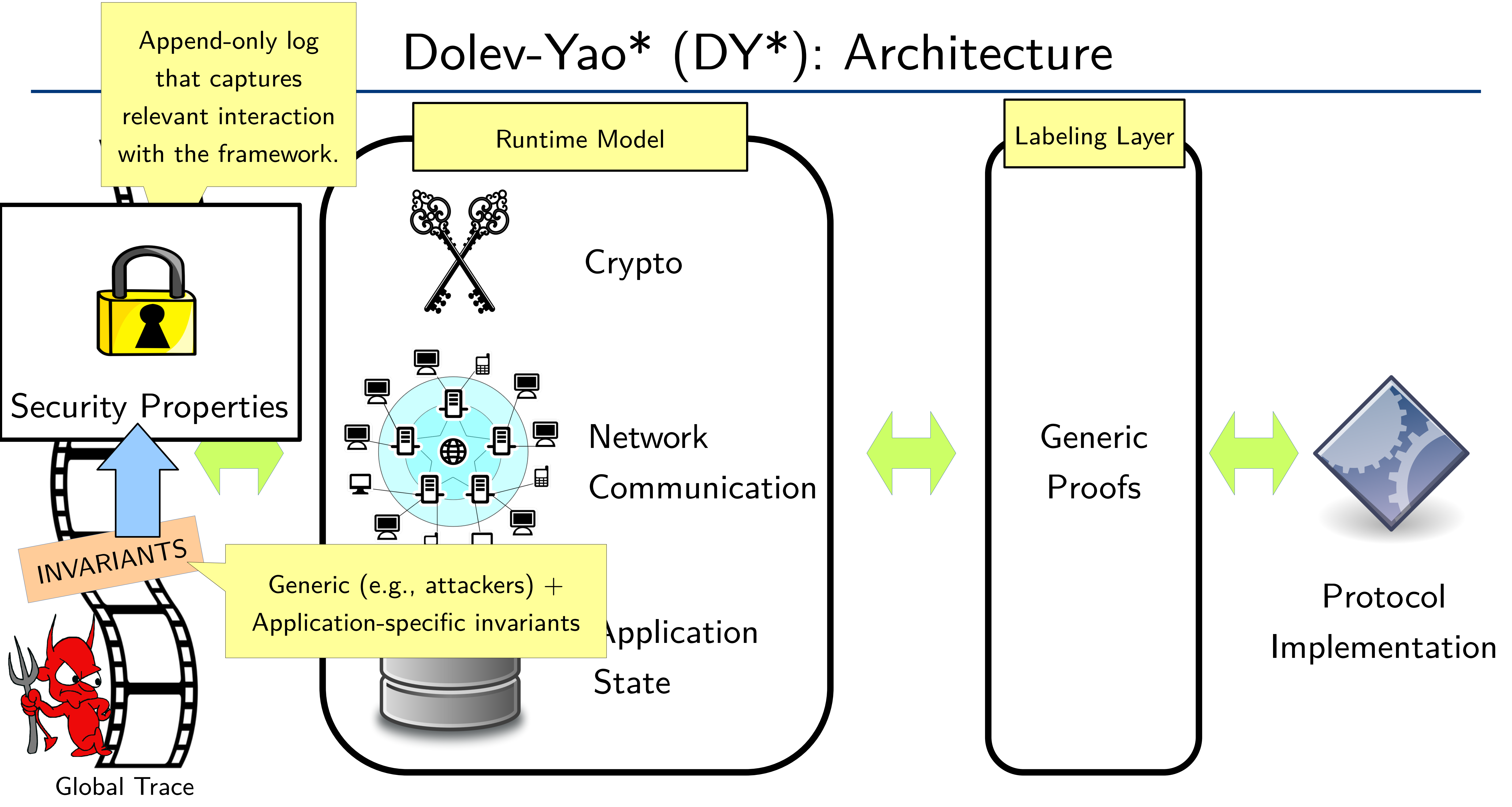

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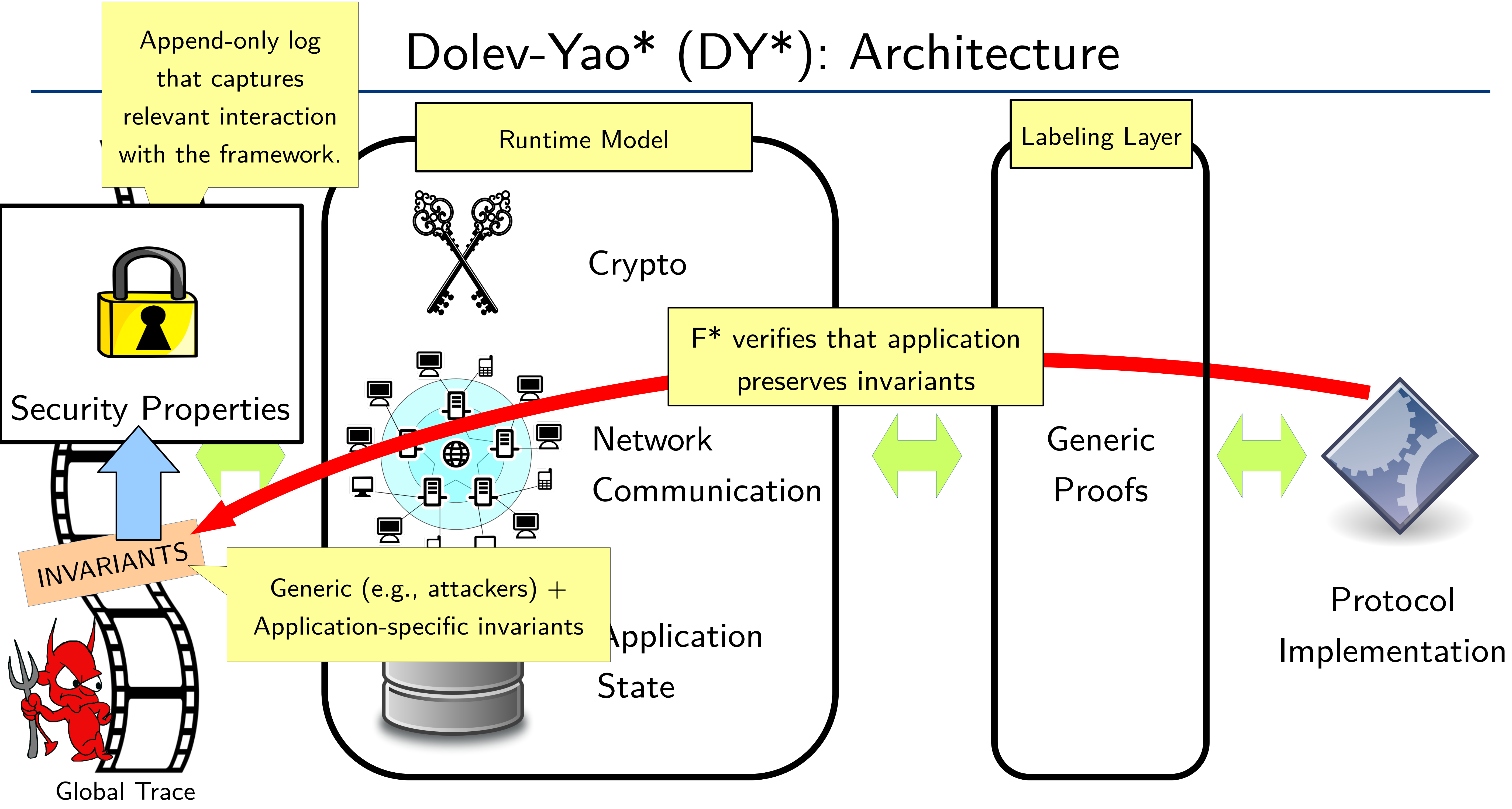

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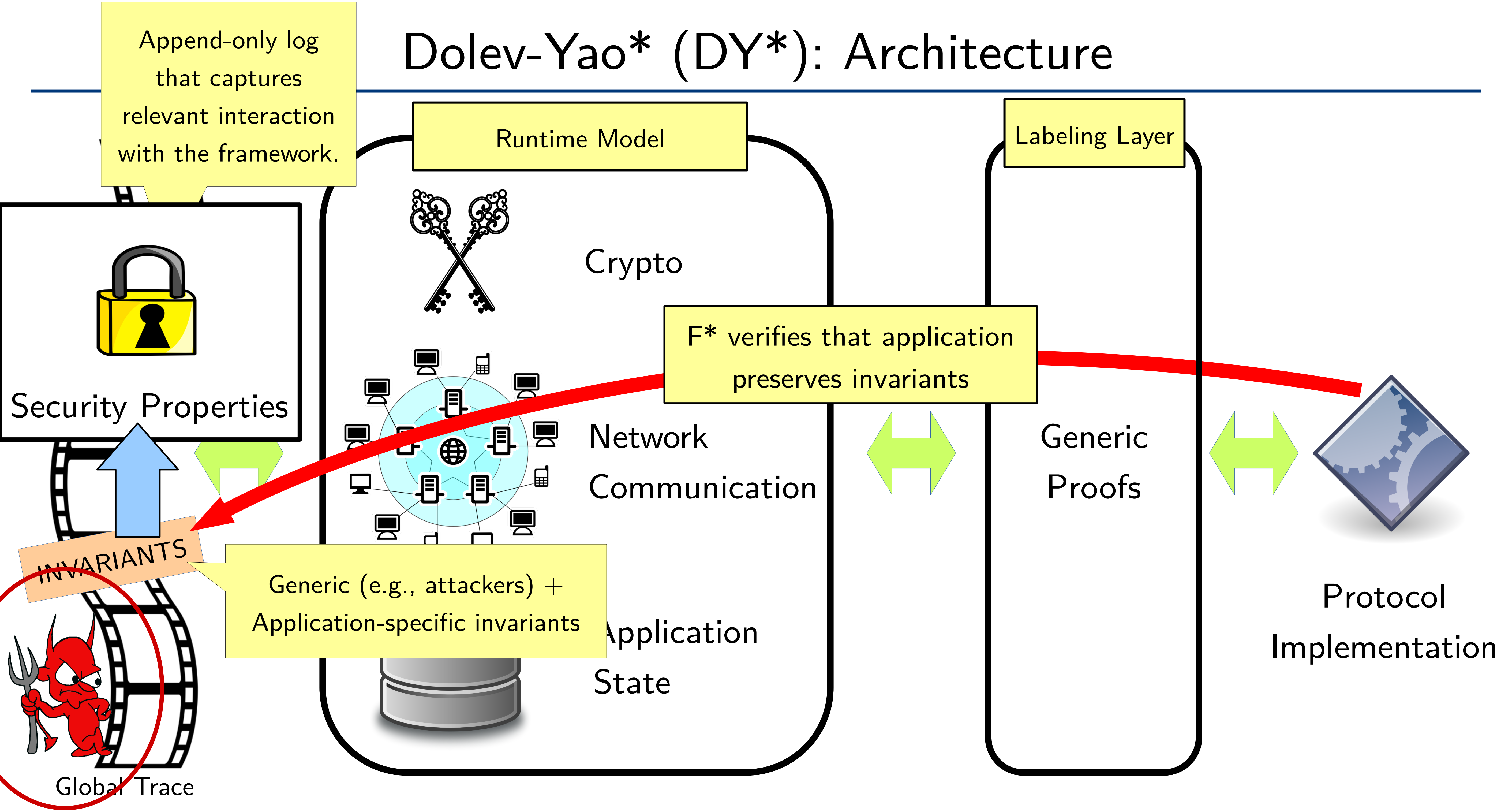
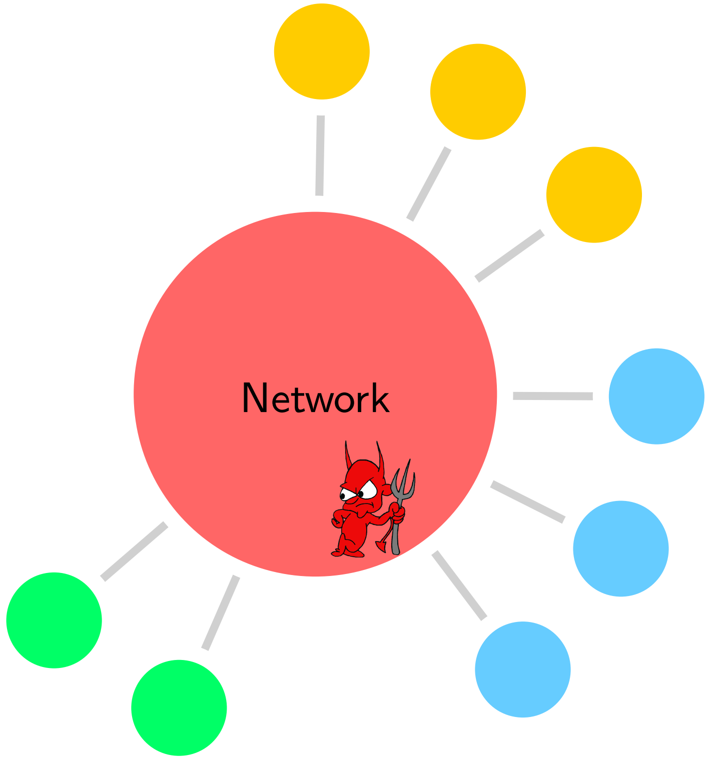


Attacker Model

Active Network Attacker

- Can derive arbitrary messages from its knowledge
- Cannot "break" crypto, i.e., no decryption w/o key, no forging of signatures, ...
- Can (dynamically) corrupt principals and sessions

Goal: Show that protocol is secure given such an attacker



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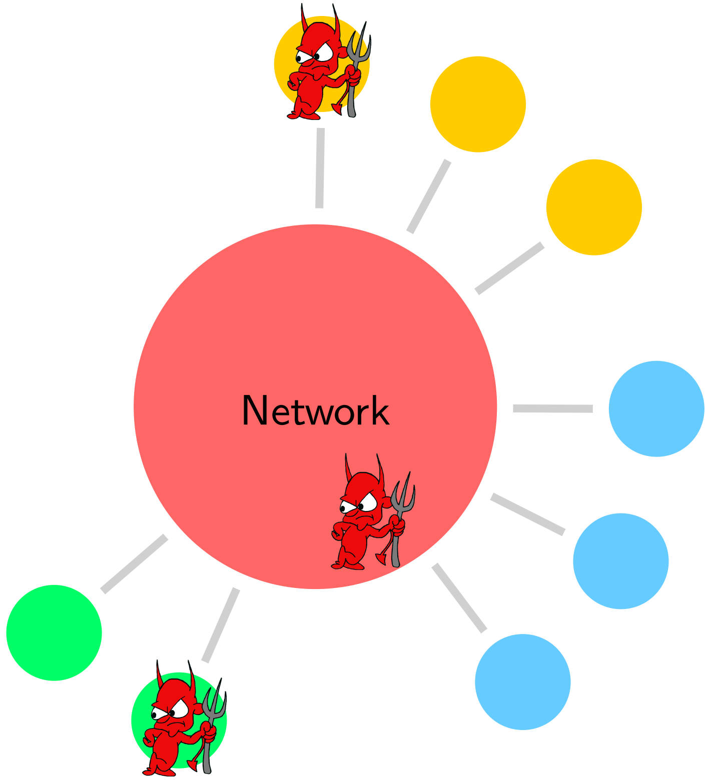

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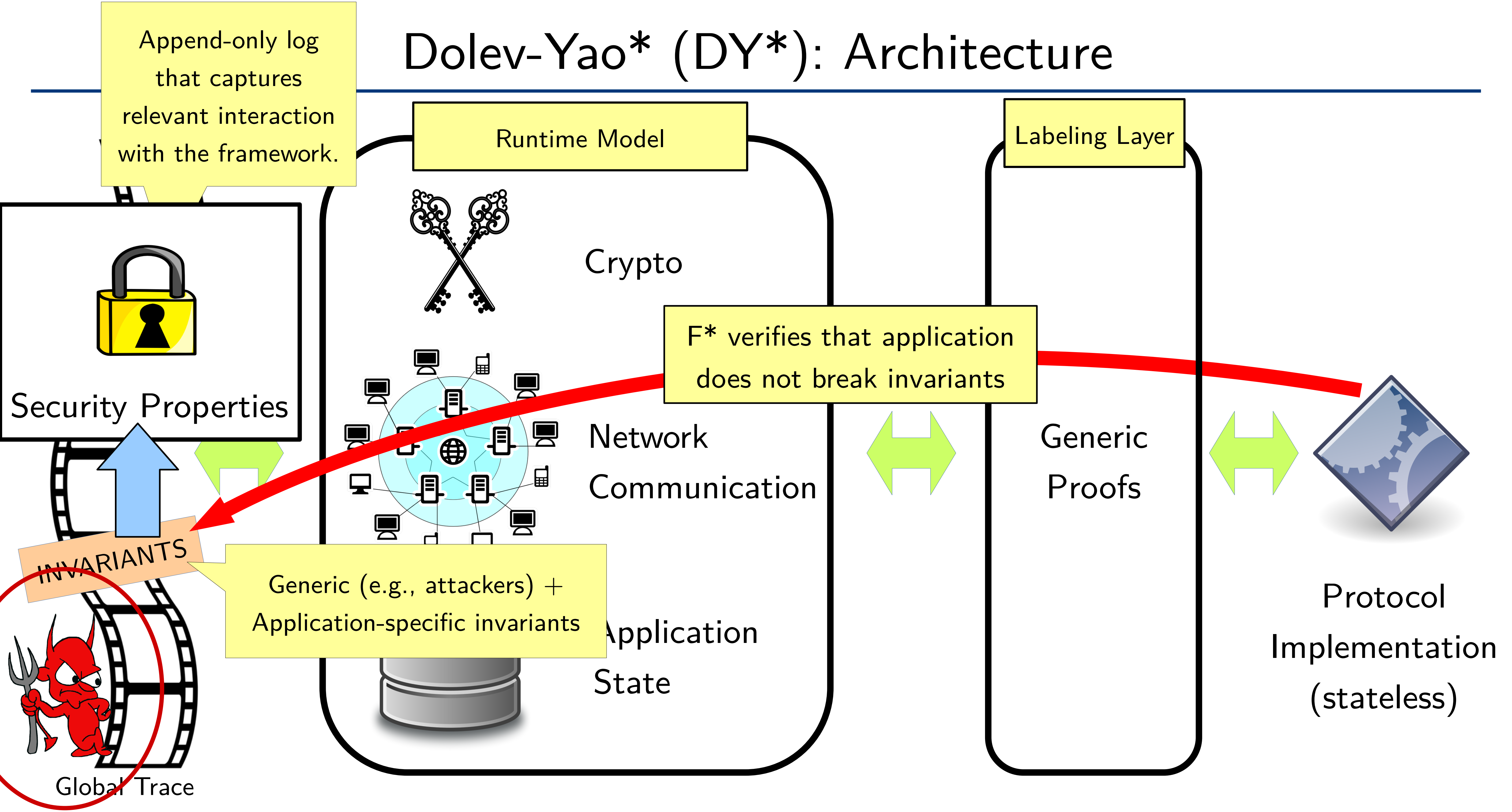

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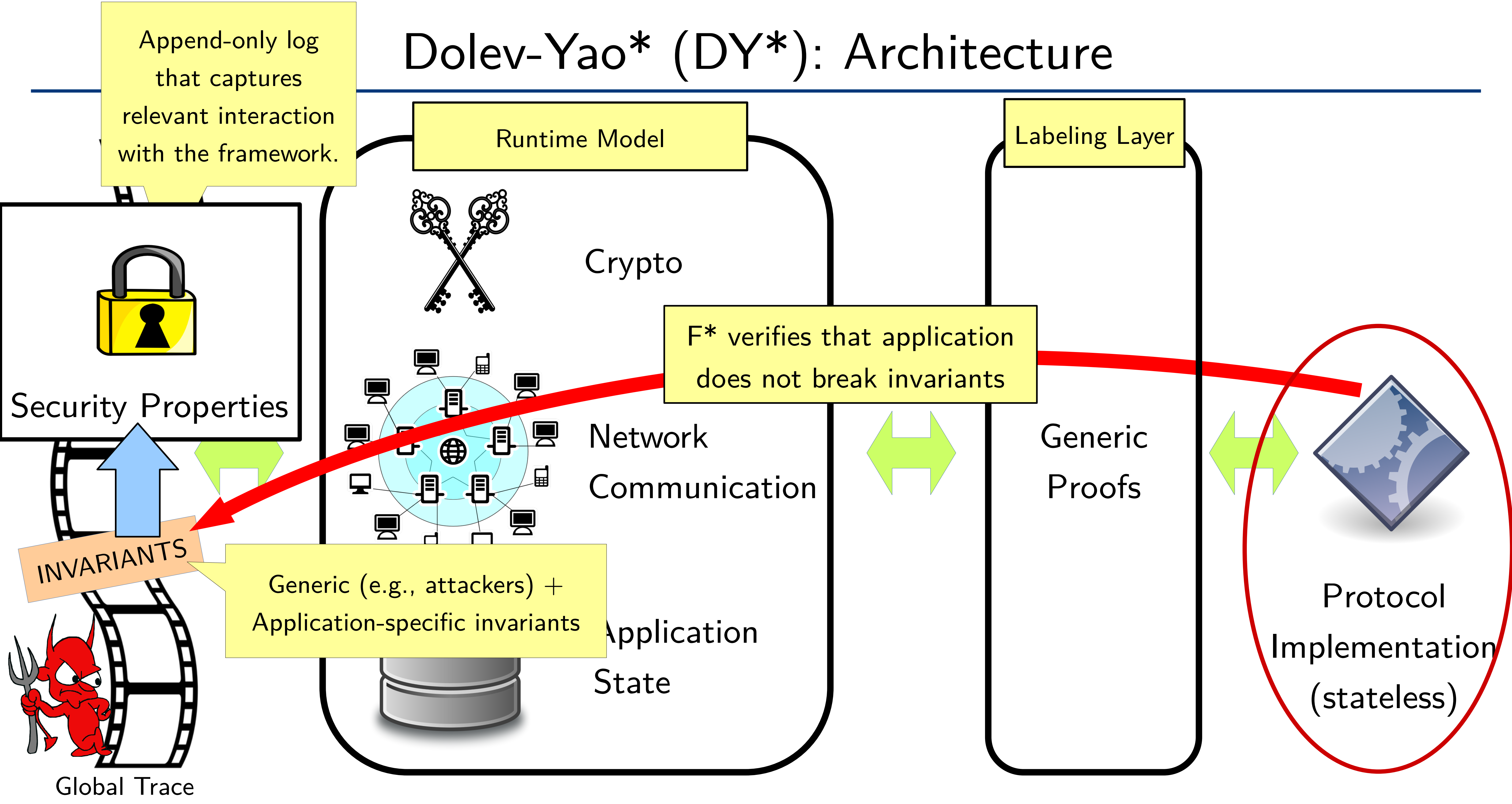

DY* Example: Protocol Code ISO-DH

```
let initiator_send_msg_1 a b =
  let si = new_session_number a in
  let (|t0,x|) = rand_gen (readers [V a si 0]) (dh_usage "ISODH.dh_key") in
  let gx = dh_pk x in

  let ev = initiate a b gx in
  trigger_event a ev;

  let t1 = global_timestamp () in
  let new_ss_st = InitiatorSentMsg1 b x in
  let new_ss = serialize_valid_session_st t1 a si 0 new_ss_st in
  new_session a si 0 new_ss;

  let t2 = global_timestamp () in
  let msg1 = Msg1 a gx in
  let w_msg1 = serialize_msg t2 msg1 in
  let i = send a b w_msg1 in
  i, si
```

DY* Example: Protocol Code ISO-DH

```
let initiator_send_msg_1 a b =
  let si = new_session_number a in
  let (|t0,x|) = rand_gen (readers [V a si 0]) (dh_usage "ISODH.dh_key") in
  let gx = dh_pk x in

  let ev = initiate a b gx in
  trigger_event a ev;

  let t1 = global_timestamp () in
  let new_ss_st = InitiatorSentMsg1 b x in
  let new_ss = serialize_valid_session_st t1 a si 0 new_ss_st in
  new_session a si 0 new_ss;

  let t2 = global_timestamp () in
  let msg1 = Msg1 a gx in
  let w_msg1 = serialize_msg t2 msg1 in
  let i = send a b w_msg1 in
  i, si
```

Generate a fresh nonce

DY* Example: Protocol Code ISO-DH

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Generate a fresh nonce

Protocol event

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Generate a fresh nonce

Protocol event

Update state

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```

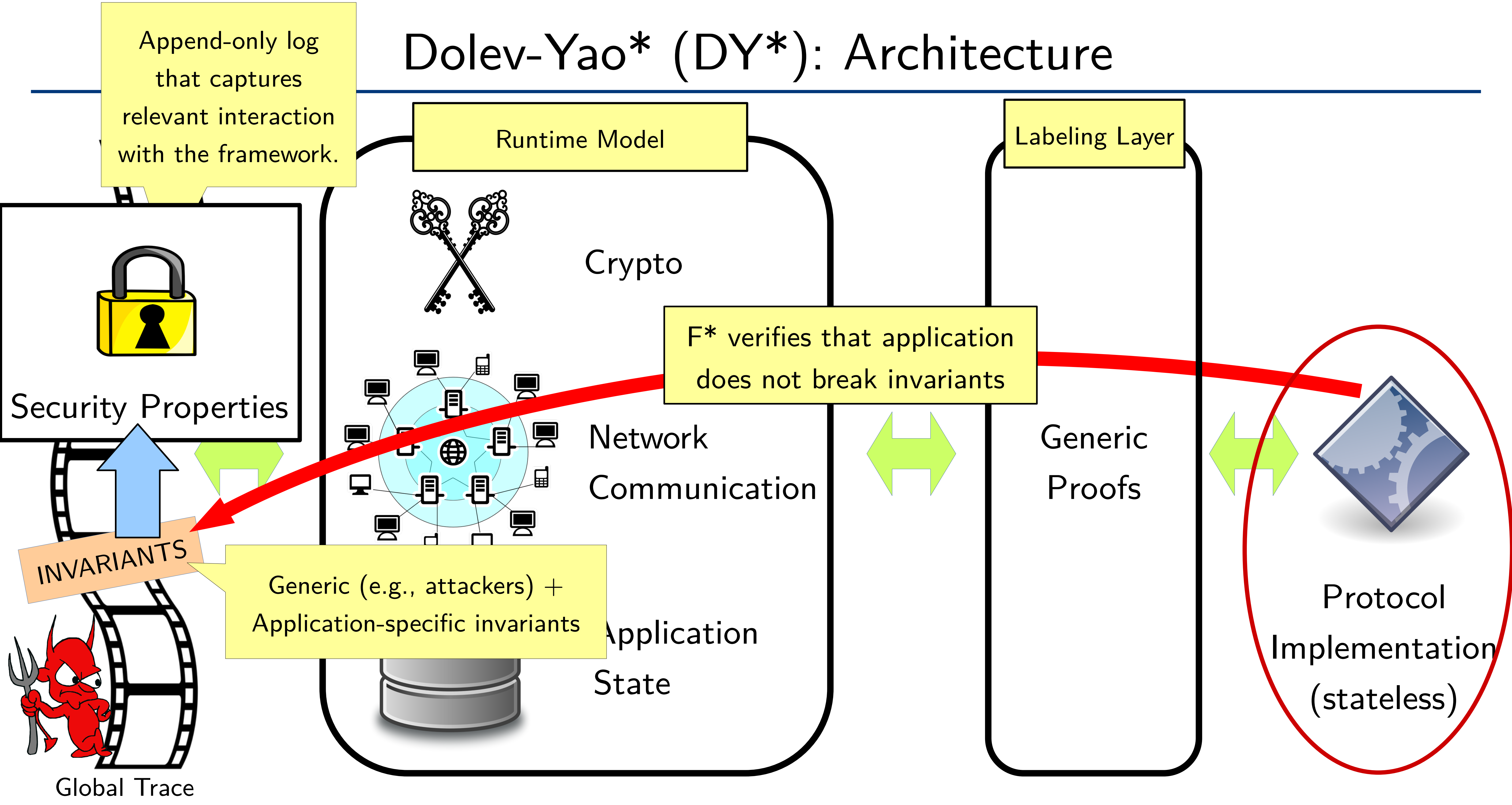
Generate a fresh nonce

Protocol event

Update state

Send message

Dolev-Yao* (DY*): Architecture



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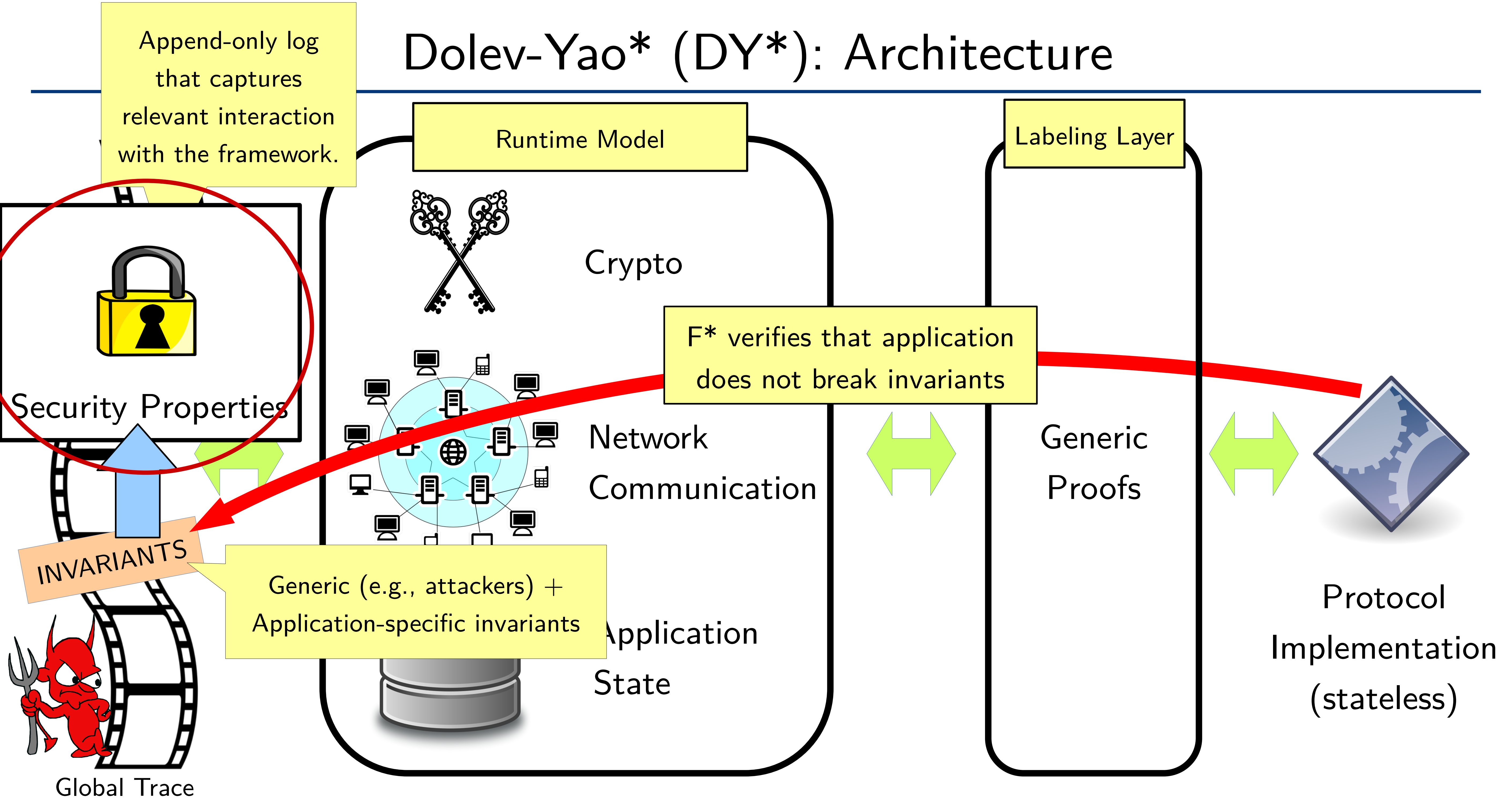

DY* Example: Security Property

Forward secrecy for an authenticated key exchange protocol (ISO-DH):

```
val initiator_forward_secrecy_lemma: i:timestamp -> a:principal -> b:principal ->
    gx:bytes -> gy:bytes -> k:bytes -> LCrypto unit (pki isodh)

  (requires (fun t0 -> i < trace_len t0 /\
                      did_event_occur_at i a (finishI a b gx gy k)))

  (ensures (fun t0 _ t1 -> t0 == t1 /\ (
            corrupt_at i (P b) \/
            (exists si sj vi vj . is_labeled isodh_global_usage i k
                                  (join (readers [V a si vi]) (readers [V b sj vj])) /\
                                  ( corrupt_at (trace_len t0) (V a si vi) \/
                                    corrupt_at (trace_len t0) (V b sj vj) \/
                                    is_unknown_to_attacker_at (trace_len t0) k)
  ))))
```

DY* Example: Security Property

Forward secrecy for an authenticated key exchange protocol (ISO-DH):

```
val initiator_forward_secrecy_lemma: i:timestamp -> a:principal -> b:pr
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Whenever Alice finishes the protocol s.t. Alice assumes that she talked to Bob and exchanged a key k ...

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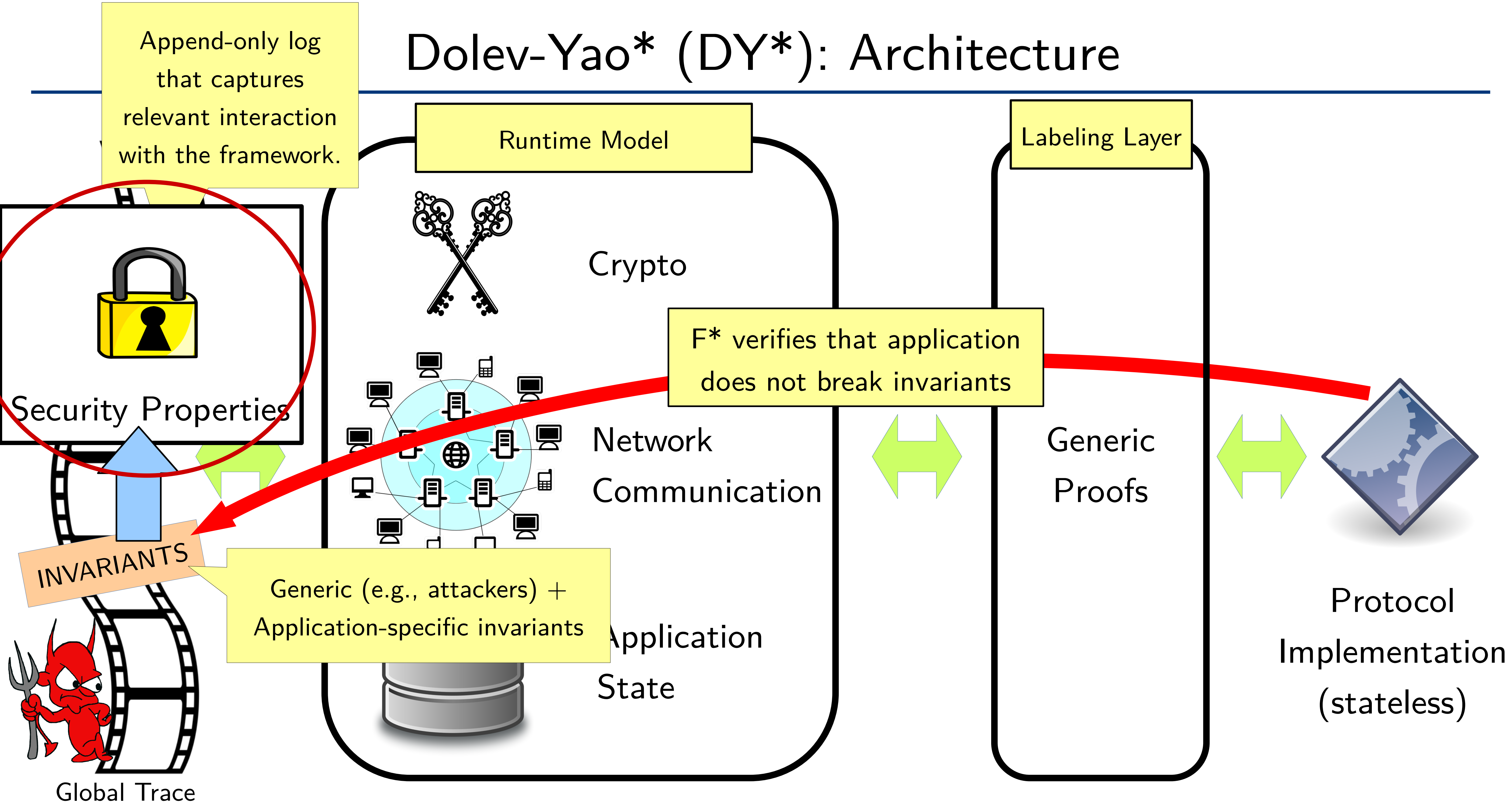
  ))))
```

Whenever Alice finishes the protocol s.t. Alice assumes that she talked to Bob and exchanged a key k …

… then Bob was compromised during the protocol run OR …

… the exchanged key k is unknown to the attacker (even if long-term key is later compromised).

Dolev-Yao* (DY*): Architecture



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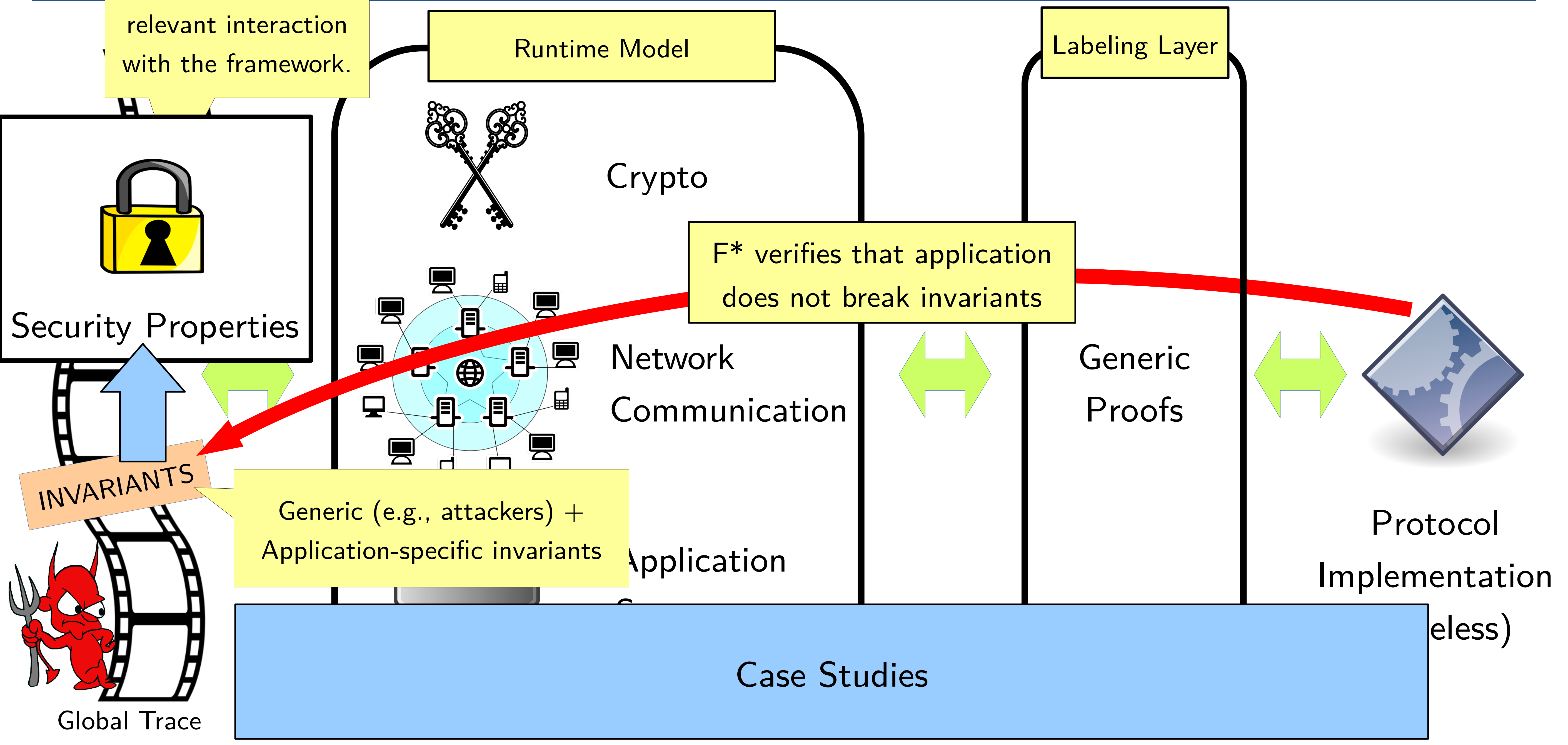

Case Studies So Far

- Signal Messaging Protocol

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- Automatic Certificate Management Environment (ACME)

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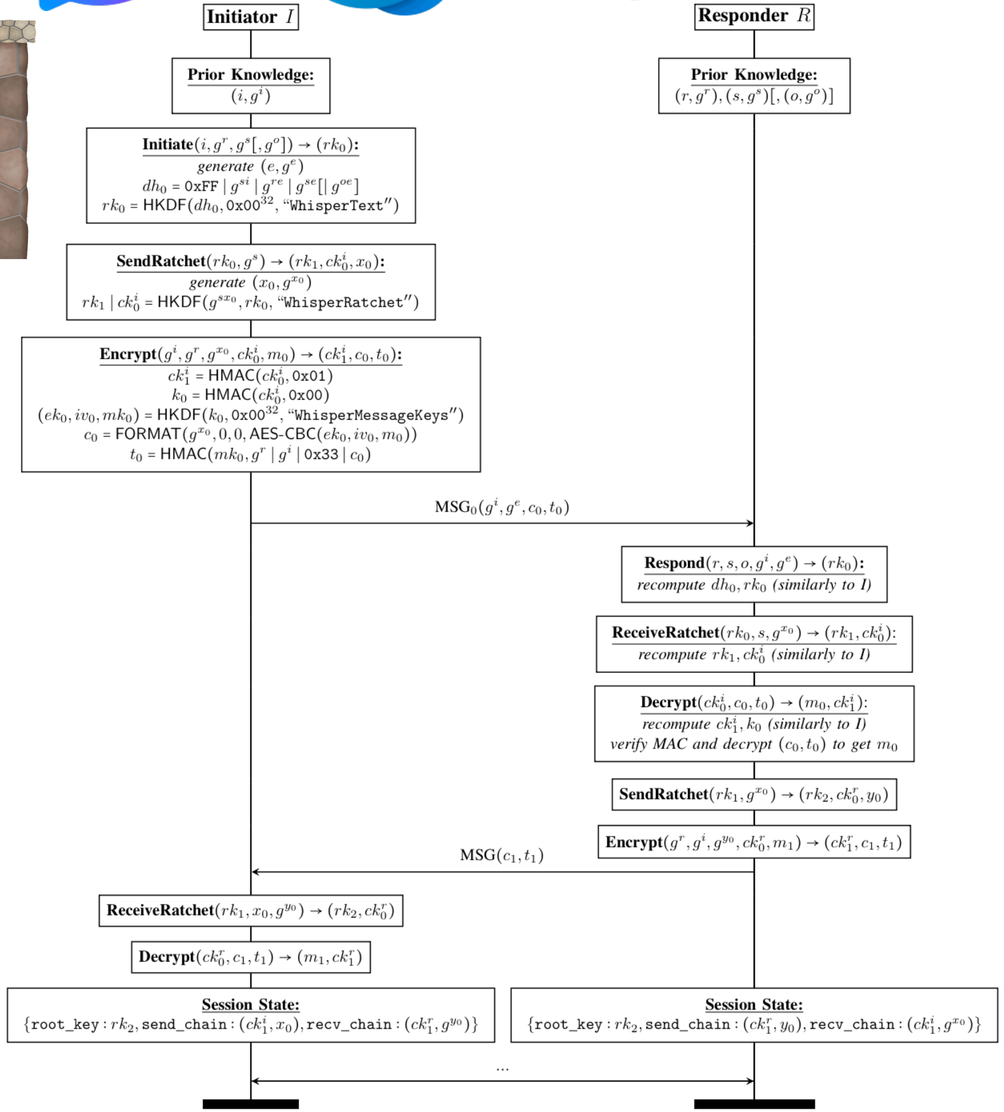
Signal Messaging Protocol

- First mechanized proof accounting for
  - Forward Secrecy
  - Post-compromise Security
  - Unbounded number of protocol rounds

  at the same time



- First type-based formulation and proof of post-compromise security for any protocol
- First analysis of Signal based on dependent types

Case Studies So Far

- Signal Messaging Protocol
  - Unbounded number of rounds (racheting)
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Automatic Certificate Management Environment (ACME)

- Main User: Let's Encrypt
  - Over 250M active domains with LE certificates
  - Currently issuing ∼ 2M certificates/day
  - Issued more than 1B certificates so far
- ACME is supported by many other certification authorities (e.g., Buypass, DigiCert, GlobalSign, ZeroSSL)

Statistics from `https://letsencrypt.org/stats/`

Automatic Certificate Management Environment (ACME)

ACME is extremely security critical

- Two previous formal analyses (ProVerif, Tamarin)
  - Very abstract models
  - Only consider certificates for a single domain
  - No loops of subprotocols
  - No precise state management
  - No details of message formats

Limited by the used tools – DY* analysis overcomes these limitations

- Our analysis is one of the largest & most in-depth formal security analyses in the literature (16,000 LoC)
- ACME client model can interoperate with real-world server

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Conclusion & Future Work

- Golden era of cryptographic protocols
- We recently proposed DY*, a new mechanized symbolic verification framework for protocols and their code
  - Overcomes many limitations of existing tools
  - Precise reasoning on global properties
  - Account for low-level protocol details
  - Protocol models can even be interoperable

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  - WIM*: mechanize the **Web Infrastructure Model**
  - Concrete DY*: fully verified implementations
  - Equivalence properties
  - Computational analysis

Conclusion & Future Work

See [S&P ‘14, ESORICS ‘15, CCS ‘15, CCS ‘16, CSF ‘17, S&P ‘19]

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Postdoc position in Stuttgart

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