PROTOCOL STATE FUZZING OF TLS IMPLEMENTATIONS

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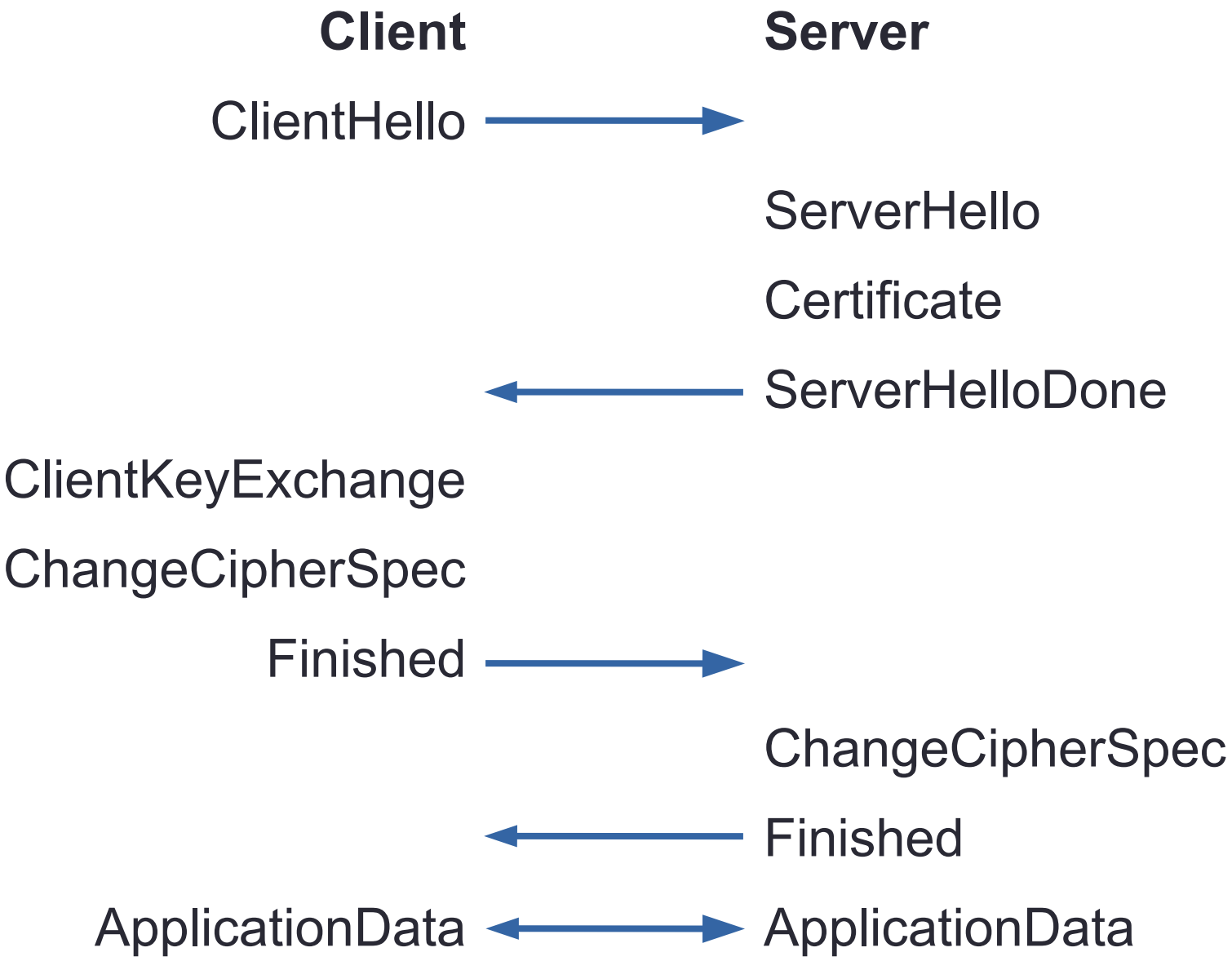
Short introduction to TLS



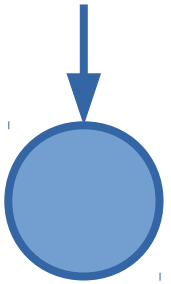
State machines

- Every application that implements a protocol has to implement the corresponding state machine
- Mealy machines
  - Set of states
  - Input alphabet
  - Output alphabet
- Specify in all states for each input
  - Returned output
  - Next state
- It is unambiguous

State machine inference

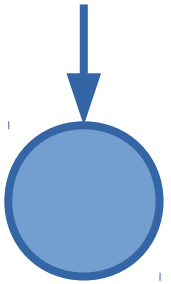
- Extract state machines from implementations by communicating with them
- Fuzzing of message order
- Discover bugs
- Provides interesting insights in the code
- Will not find carefully hidden backdoors

State machine inference



State machine inference

→ ClientHello
← ServerHello



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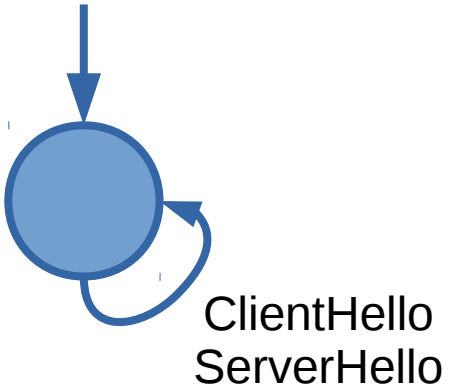

State machine inference

→ ClientHello
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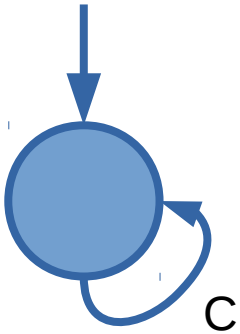
→ Other messages
← Fatal alert / Connection close



ClientHello
ServerHello

State machine inference

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State machine inference

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→ ClientHello, ClientHello
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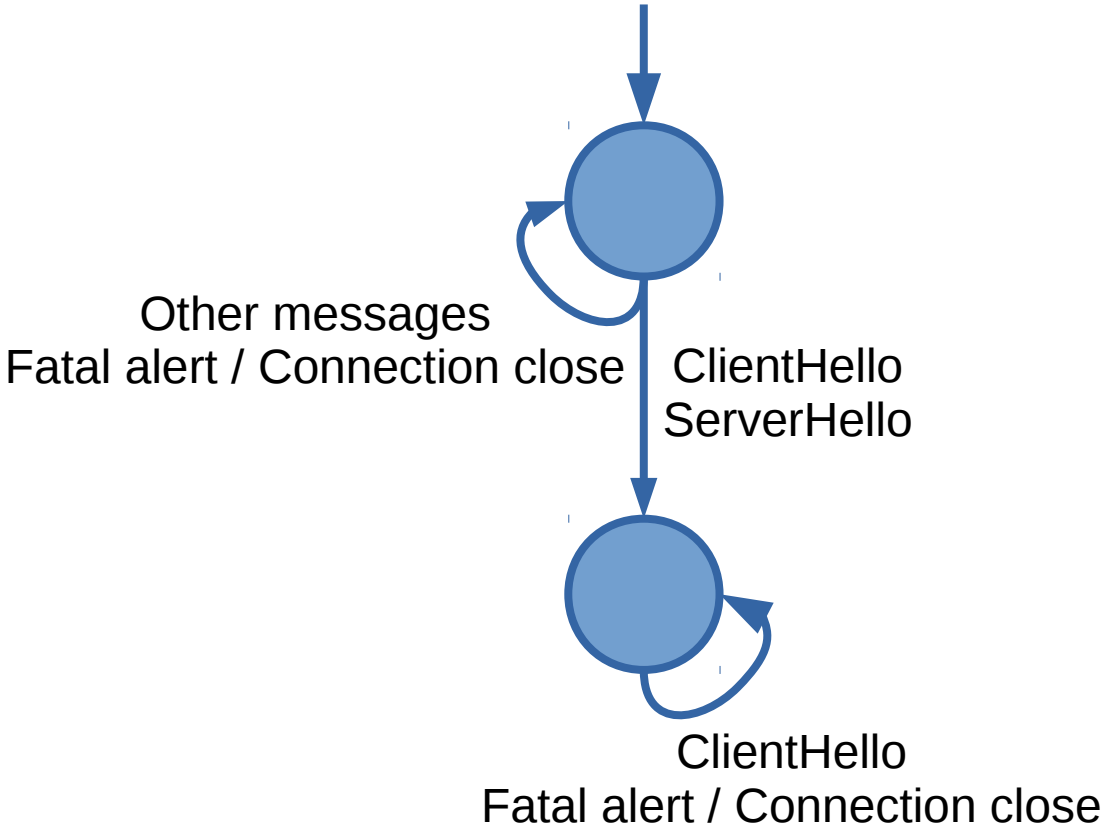
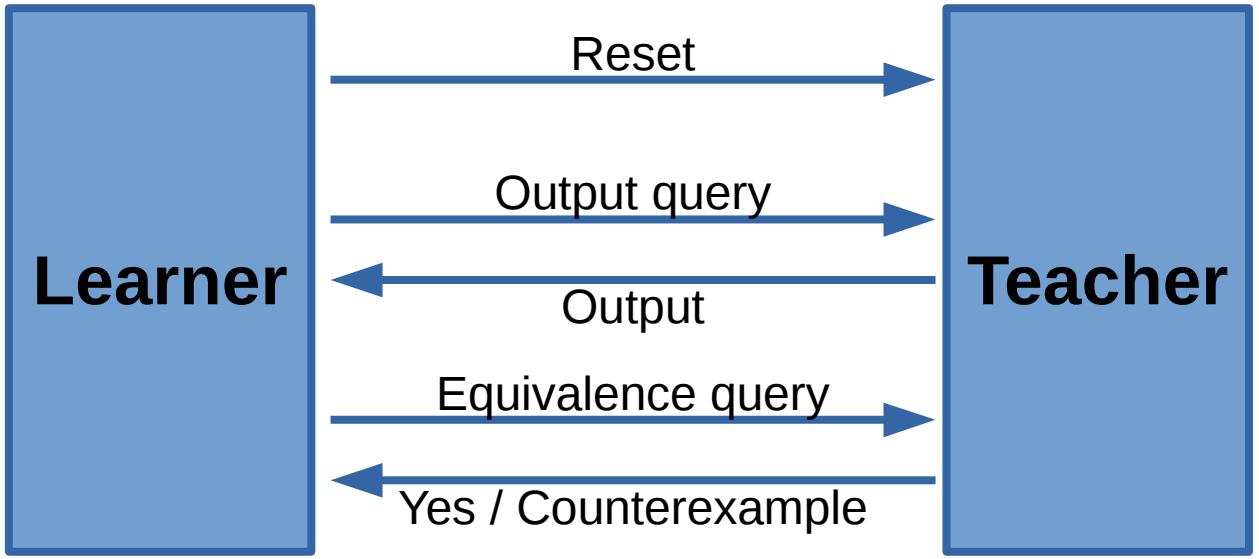


Automated learning

- Deterministic Mealy machine
- Learner
  - Adapted L* algorithm by Niese
- Teacher
  - Equivalence queries approximated
    - Random traces
    - Chow's W-method



Automated learning

- LearnLib by TU Dortmund
  - Implementation of adapted L* and equivalence algorithms
- Equivalence checking using modified W-method
  - Given an upper bound it is guaranteed to find the correct state machine
  - Depth specified to search for counter-examples
  - After a socket is closed no data will be received
- Custom test harness for TLS
- Manual analysis if we see unexpected behavior

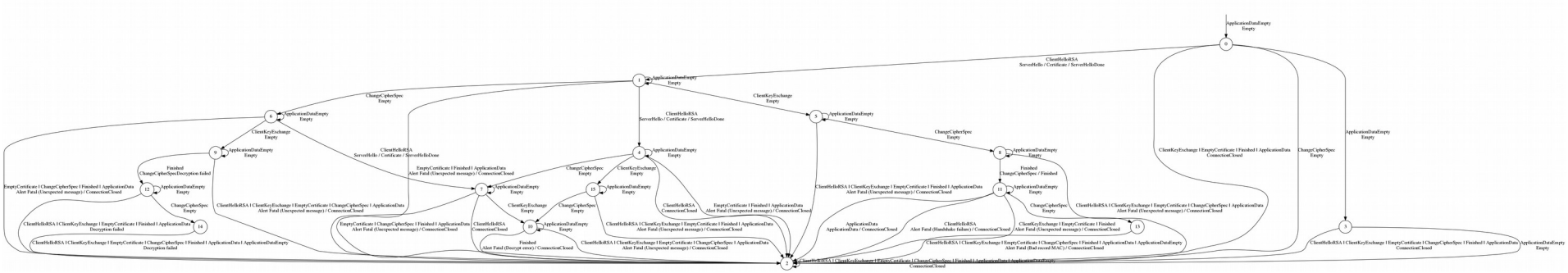
Test harness

- (Almost) stateless TLS implementation
- Minimal state in test harness to handle encryption
- Support to test clients and servers
- All regular TLS messages and Heartbeat extensions
  - RSA and DH key exchange
  - Client authentication
  - Some special symbols that correspond to exceptions in the test harness

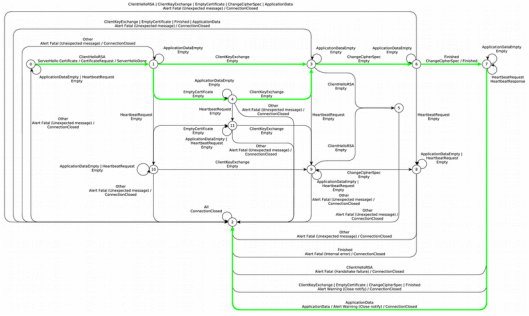
Analysis of TLS servers

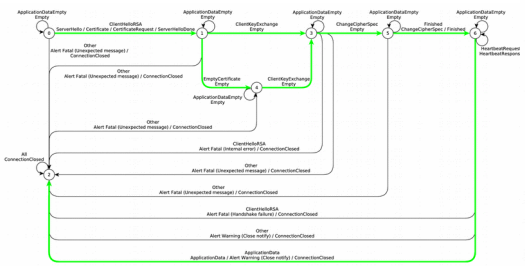
- 9 TLS implementations
  - OpenSSL
  - GnuTLS
  - Java Secure Socket Extension
  - mbed TLS (previously PolarSSL)
  - NSS
  - RSA BSAFE for C
  - RSA BSAFE for Java
  - miTLS
  - nqsb-TLS
- Every learned model different

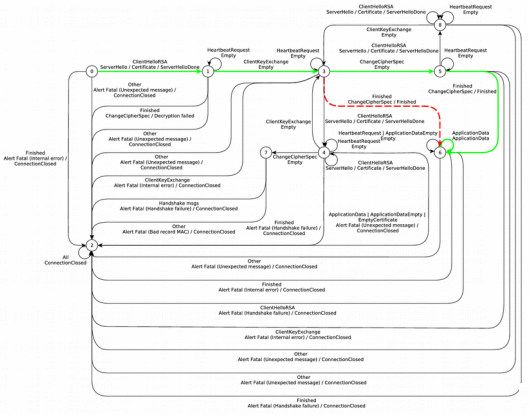
Learned models

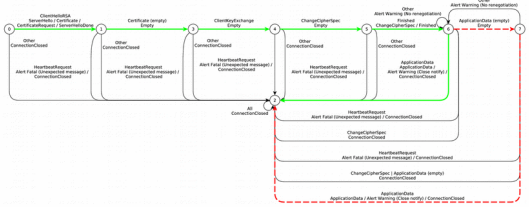


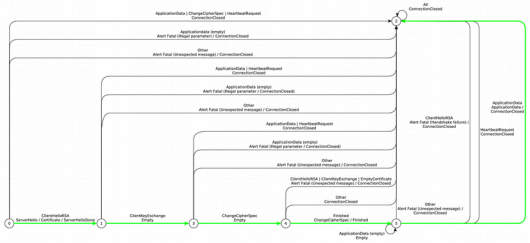
Learned models

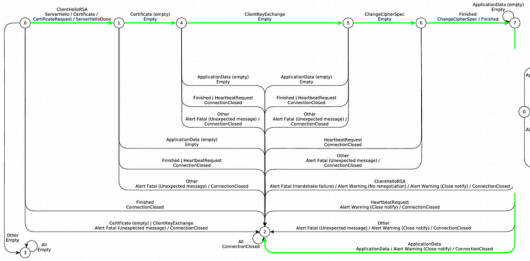


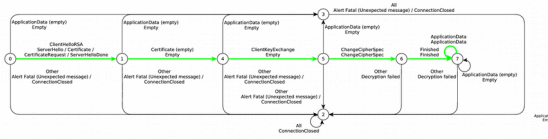


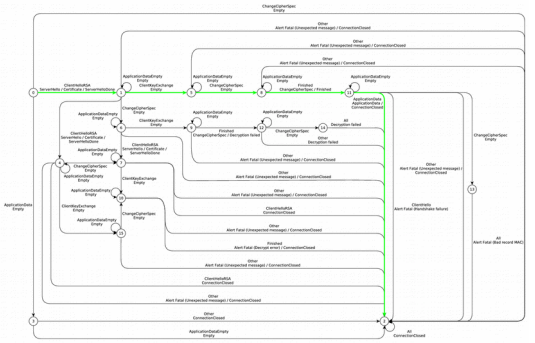


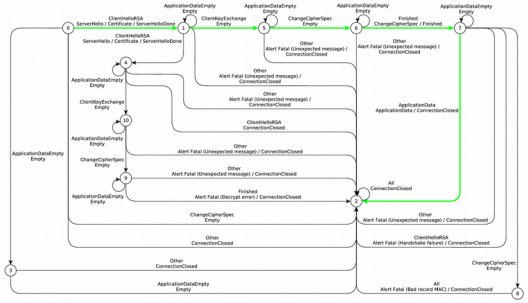


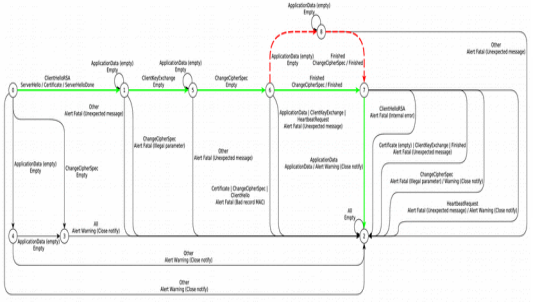


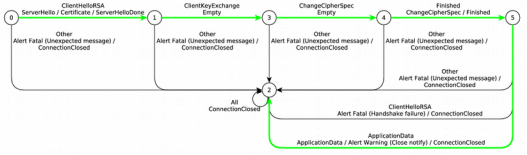










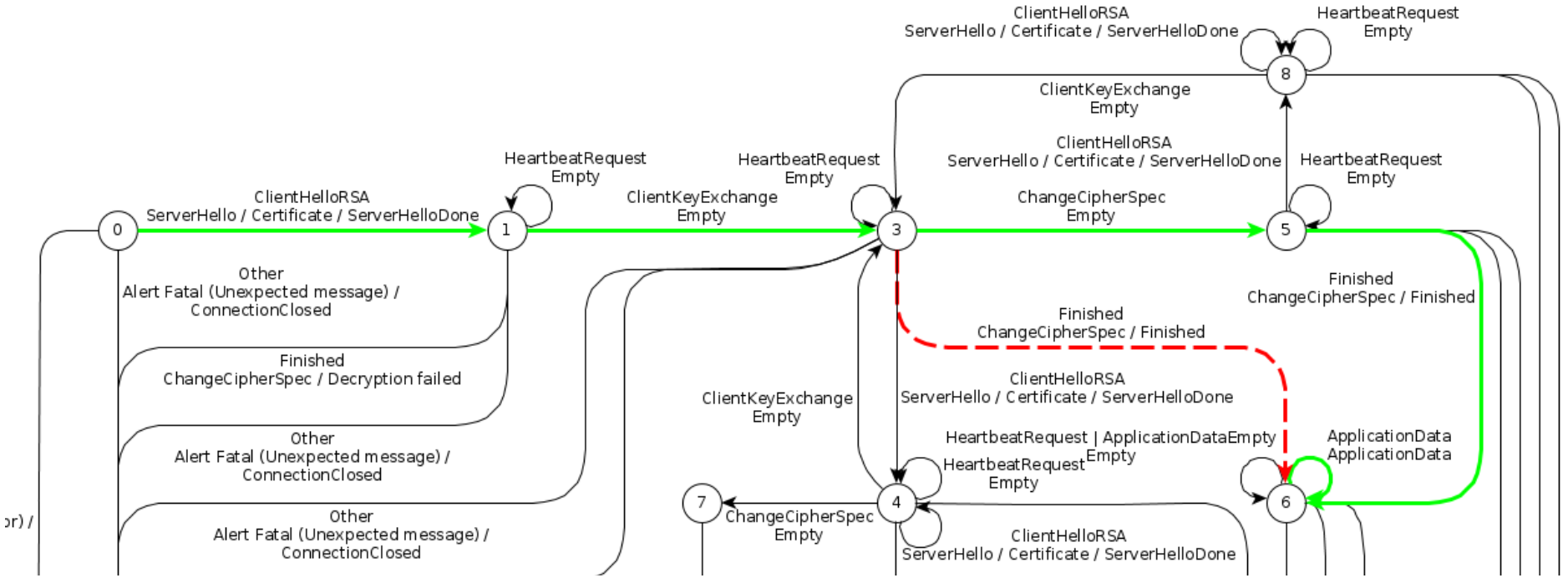


Results

- Used demo applications when provided
- 6 to 16 states
- 6 minutes to over 8 hours
  - Under 1 hour if connections are properly closed
  - Dependent on implementation specific time-outs (100ms to 1,5s)
- Several new flaws in different implementations

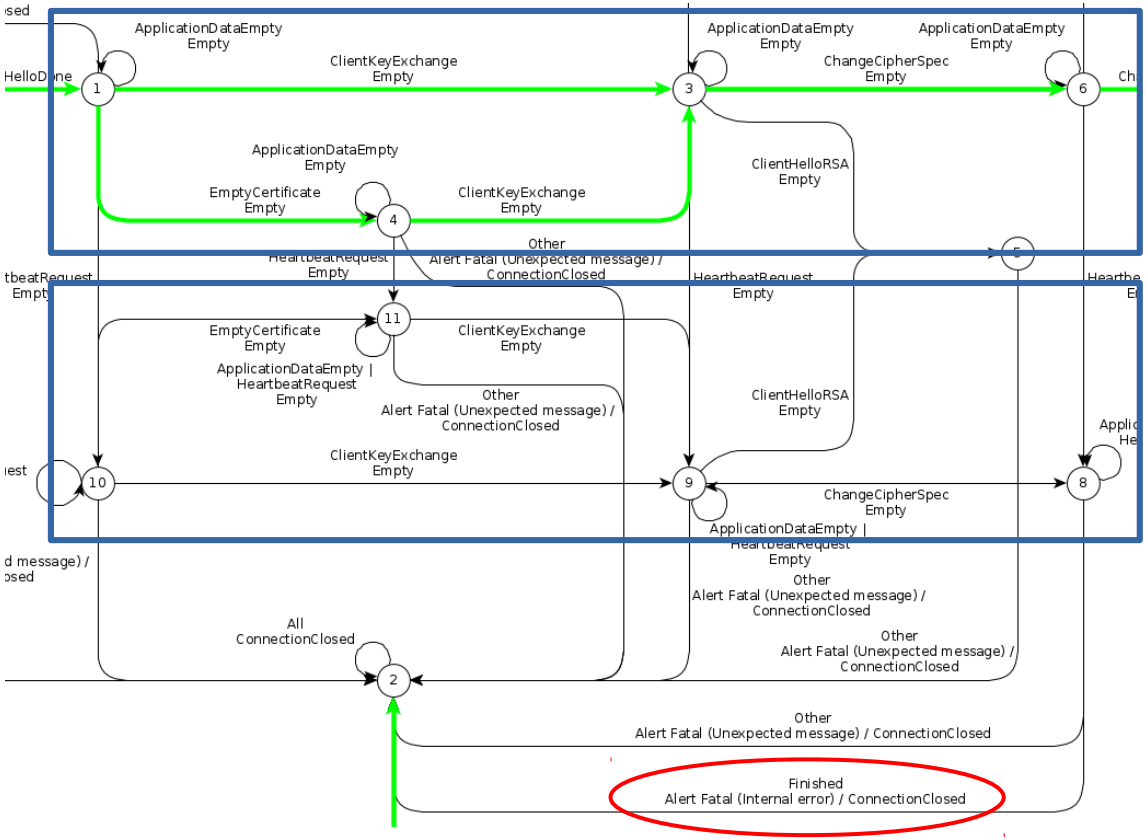
Java Secure Socket Extension

- Possible to skip ChangeCipherSpec message
- Server will accept plaintext data
- Problem also present in client
- Also found by the Prosecco group at INRIA
- Fixed in January 2015



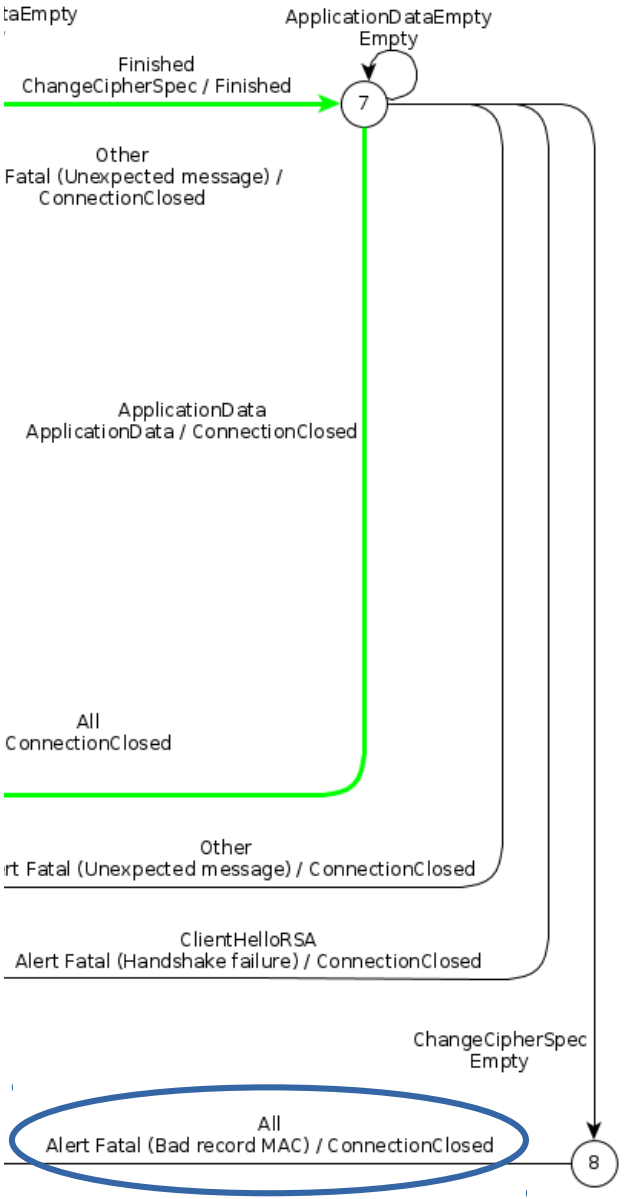
GnuTLS

- Shadow path after sending HeartbeatRequest during handshake
- Buffer handshake messages for hash in Finished reset
- Same problem present in the client



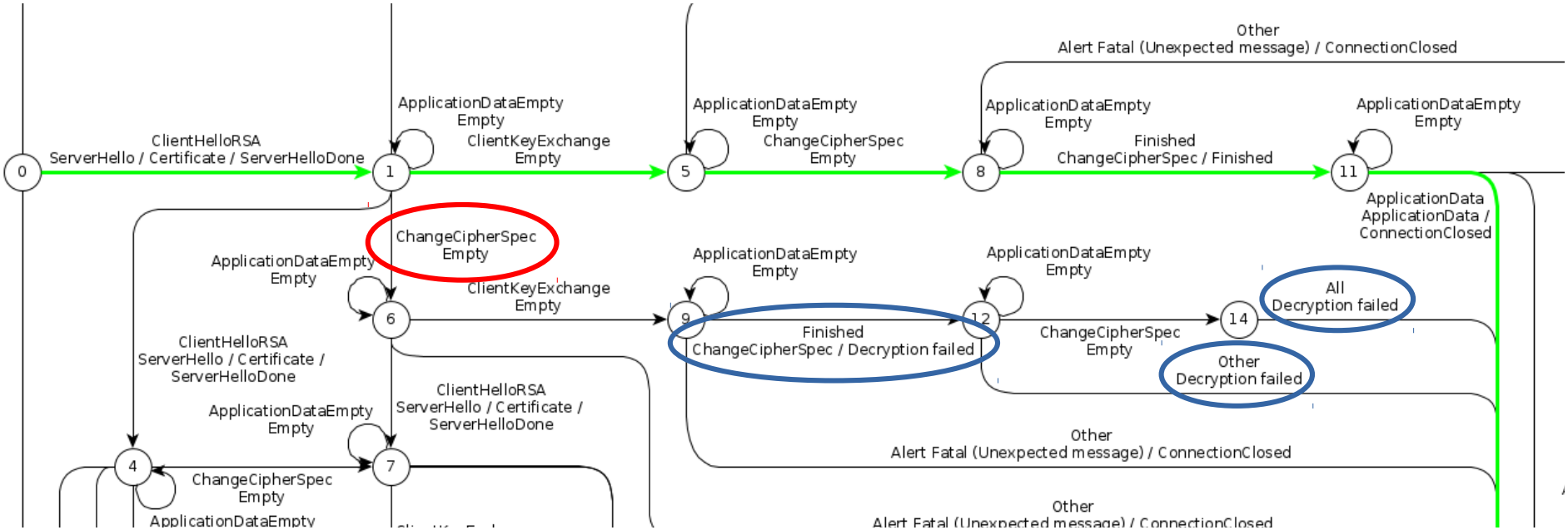
OpenSSL

- Sending a ChangeCipherSpec after successful handshake gets server in invalid state
- Client key set to server key
- Same keys used for both directions
- Fixed in 1.0.1k
- Same issue present in LibreSSL



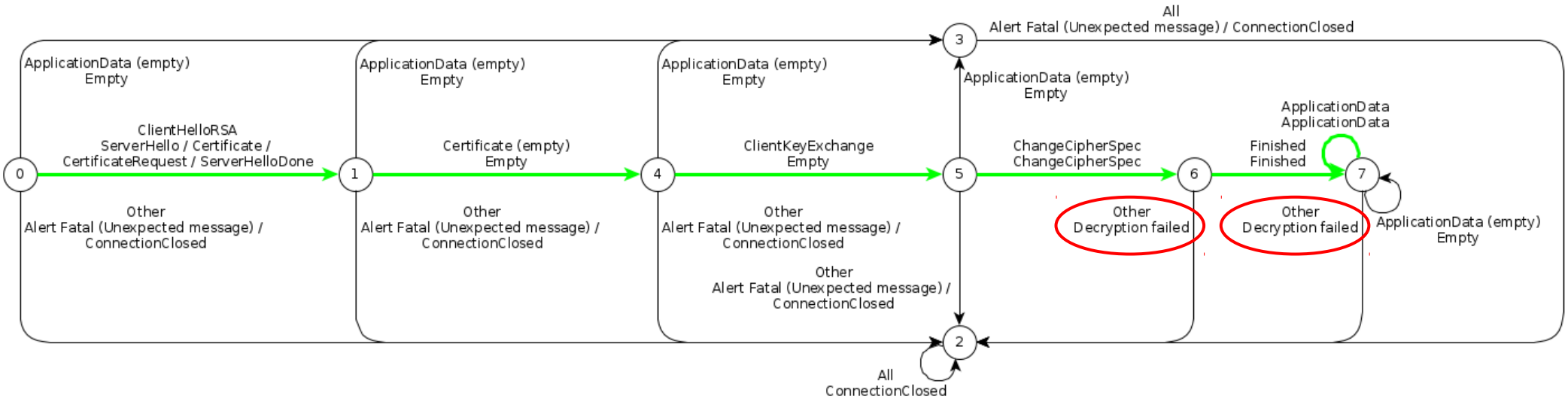
OpenSSL

- Able to detect EarlyCCS bug by Kikuchi
- By modifying the test harness we can successfully exploit this flaw



nqsb-TLS

- Plaintext alerts returned after ChangeCipherSpec
- No security flaw
- Quickly fixed
- Shows it is a useful technique during development
- Different interpretation of the specification



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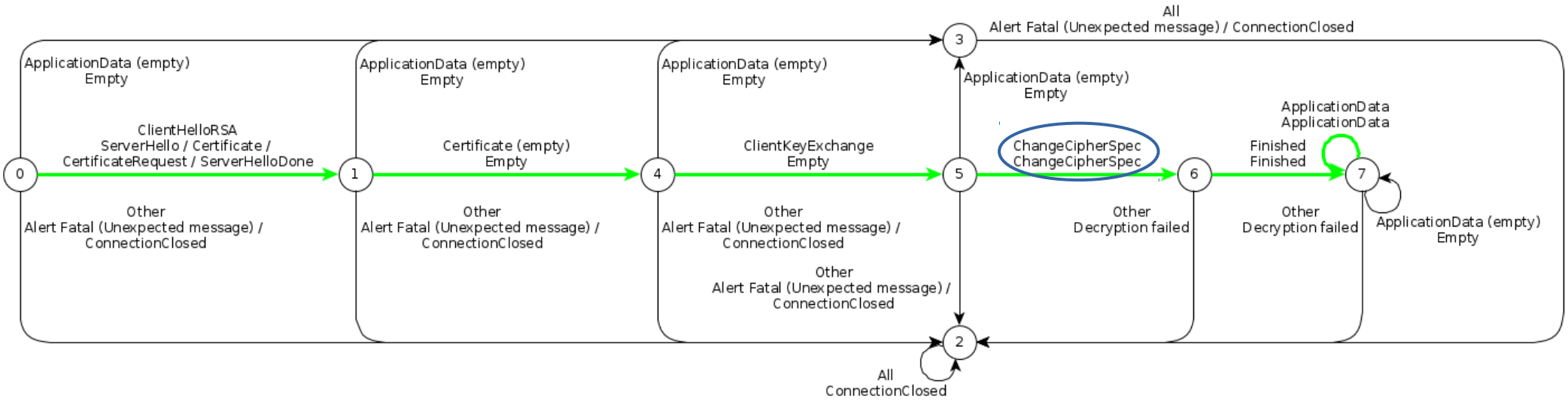

Conclusions

- Protocol state fuzzing is a useful technique to find security flaws and other bugs related to the implementation of state machines
- Everybody interprets specifications differently and makes different design decisions
- It would be good to include state machines in specifications

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Thank you for your attention!