Stateful Greybox Fuzzing

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- Introduction
- Related works
- Automatic state identification
- Stateful greybox fuzzer
- State fuzzing algorithm
- Evaluation
- Conclusion

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- Stateful programs
  - require input messages to be sent in a certain expected order
  - e.g., protocol implementations

- Stateful bugs
  - triggered when a sequence of messages, events, or actions are given as an input

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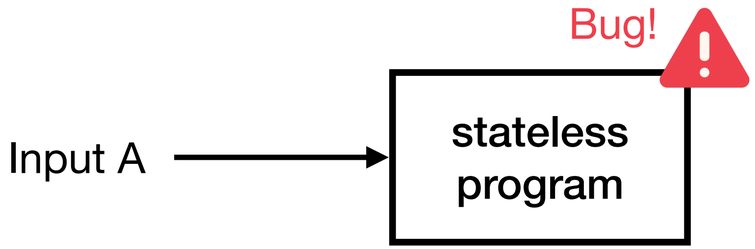

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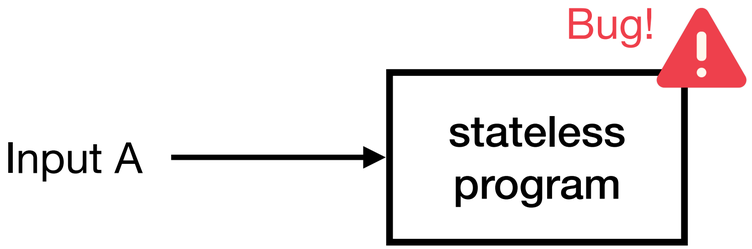

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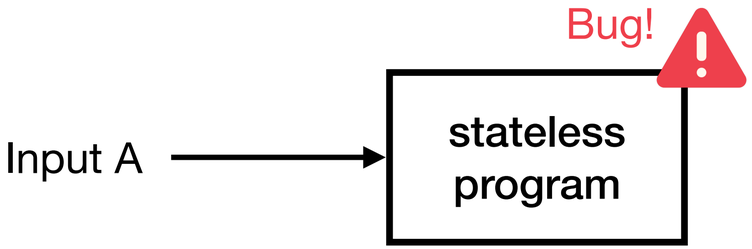

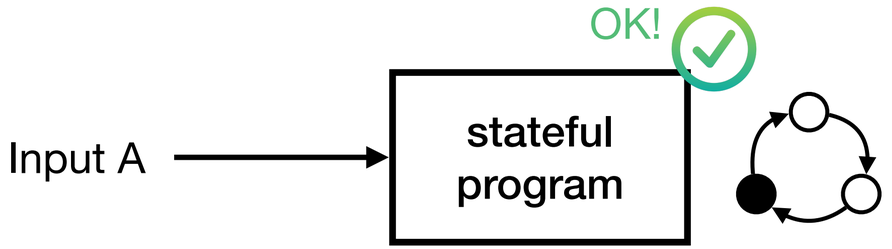

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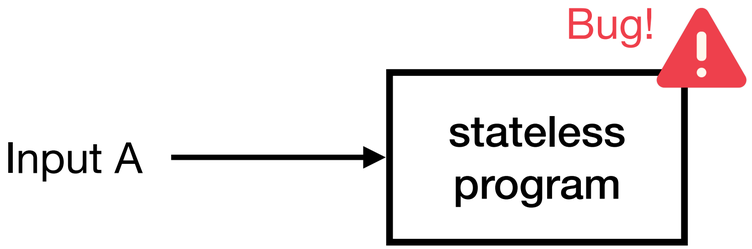

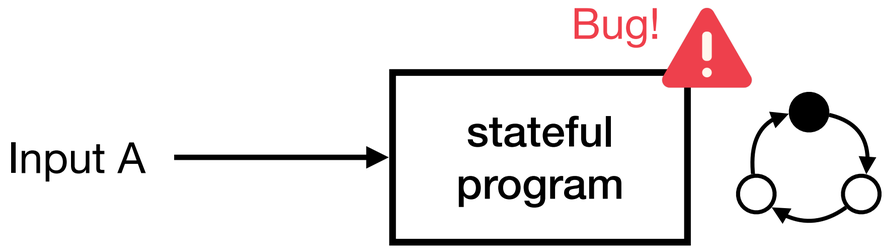

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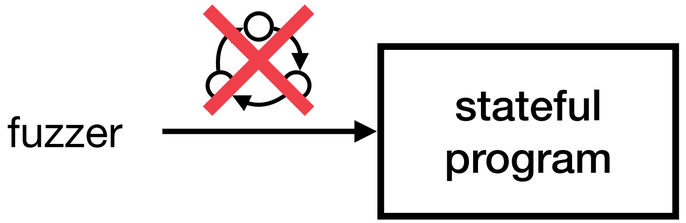
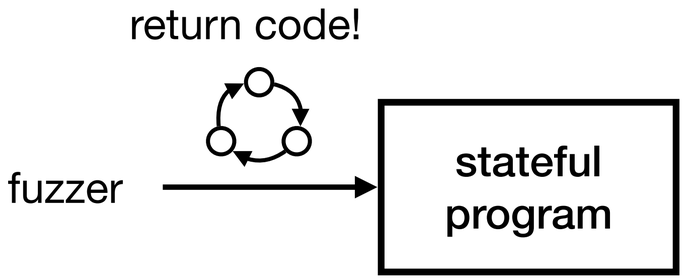
- How to efficiently find stateful bugs?
  - How to **cover the state space without a specification** of the required event sequences

Limitations of Related works

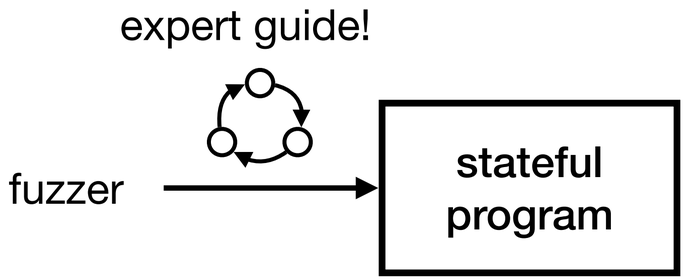
- AFL, Libfuzzer
  - stateless fuzzers
  - cannot generate a sequence of inputs



- AFLNet
  - exploit return code to infer states



- IJON
  - requires manual effort,
    i.e., knowledge of state specification



Automatic state identification

- Most of stateful softwares use named constants to represent internal states
  - e.g., enumeration type or #define macro

- H2O HTTP server

```
35  typedef enum enum_h2o_http2_stream_state_t {
36      /**
37       * stream in idle state (but registered; i.e. priority stream)
38       */
39      H2O_HTTP2_STREAM_STATE_IDLE,
40      /**
41       * receiving headers
42       */
43      H2O_HTTP2_STREAM_STATE_RECV_HEADERS,
44      /**
45       * receiving body (or trailers), waiting for the arrival of END_STREAM
46       */
47      H2O_HTTP2_STREAM_STATE_RECV_BODY,
48      /**
49       * received request but haven't been assigned a handler
50       */
51      H2O_HTTP2_STREAM_STATE_REQ_PENDING,
```

- openssl

```
1007  typedef enum {
1008      TLS_ST_BEFORE,
1009      TLS_ST_OK,
1010      DTLS_ST_CR_HELLO_VERIFY_REQUEST,
1011      TLS_ST_CR_SRVR_HELLO,
1012      TLS_ST_CR_CERT,
1013      TLS_ST_CR_COMP_CERT,
1014      TLS_ST_CR_CERT_STATUS,
1015      TLS_ST_CR_KEY_EXCH,
1016      TLS_ST_CR_CERT_REQ,
1017      TLS_ST_CR_SRVR_DONE,
1018      TLS_ST_CR_SESSION_TICKET,
1019      TLS_ST_CR_CHANGE,
1020      TLS_ST_CR_FINISHED,
1021      TLS_ST_CW_CLNT_HELLO,
```

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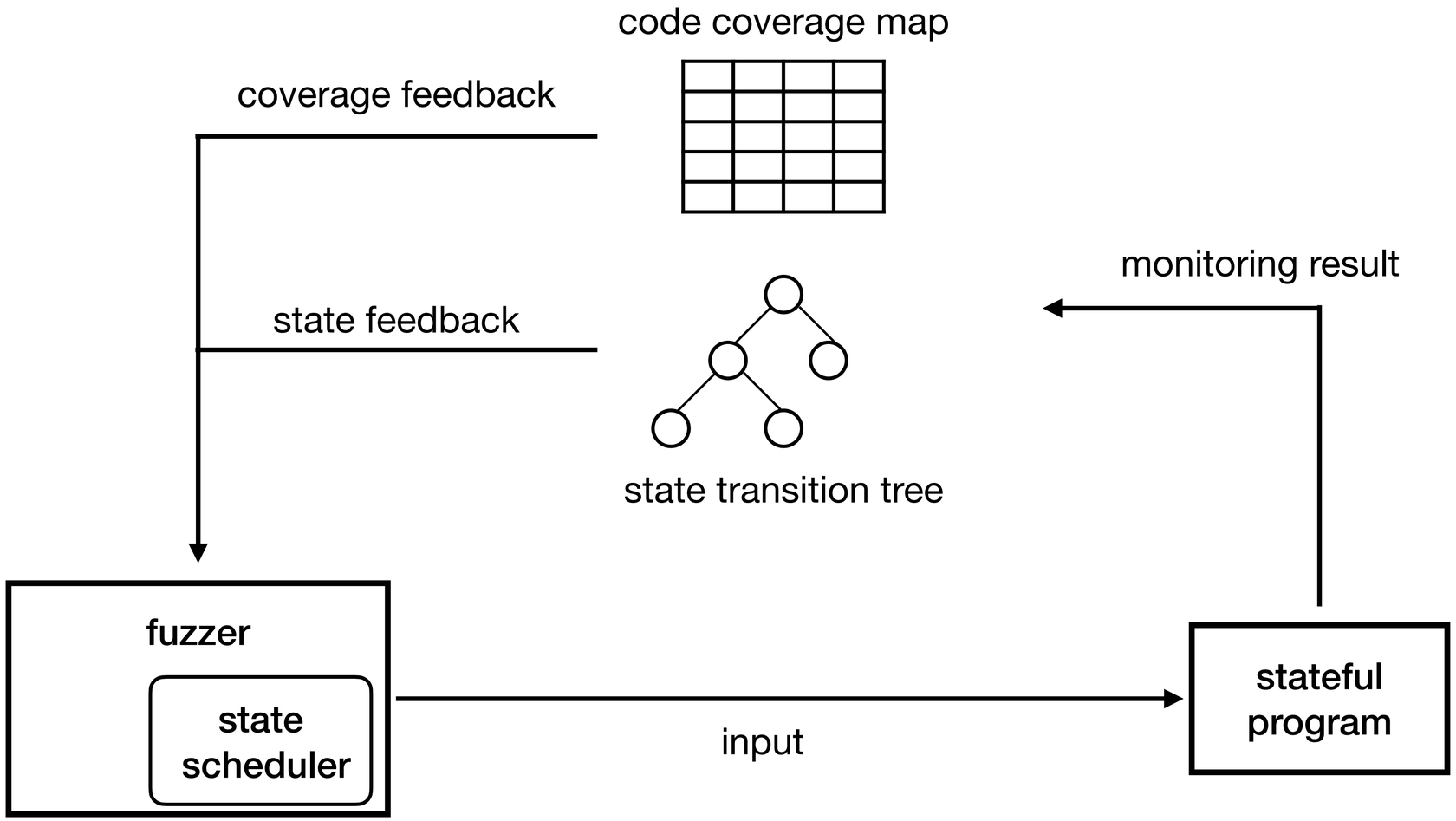
- State representation using named constants can be seen in Top-50 most widely used protocol implementations
  - e.g., FTP, SFTP, TLS, SMTP, HTTP2, RDP, NTP, IMAP, IRC, SMB, DAAP, SIP, DICOM, VNC, RTSP, MQTT
  - 44 use enumeration type and 6 use #define macro

Automatic state identification

- Idea
  - Approximate state variables
    (variables used to represent state in stateful programs)
    by the variables with named constants!

- False positives?
  - other variables such as configuration variables or error code variables sometimes take named constants
  - authors show that over 99% of extracted variables are true state variables!

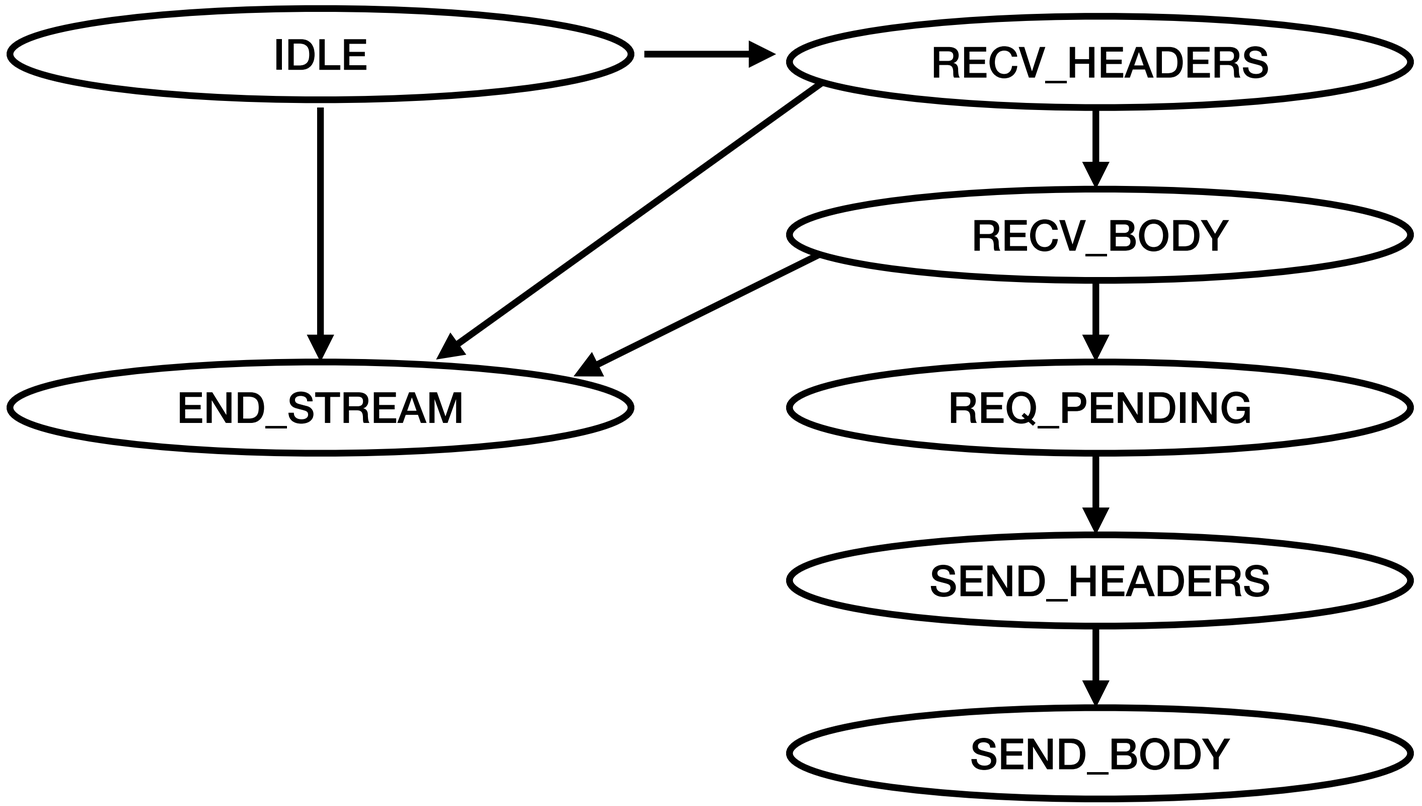
Stateful greybox fuzzer (SGFuzz)



State transition tree construction

- To construct state transition tree, SGFuzz monitors the changes of values of enumeration variables

  - monitor ‘stream-state’ variable in h2o



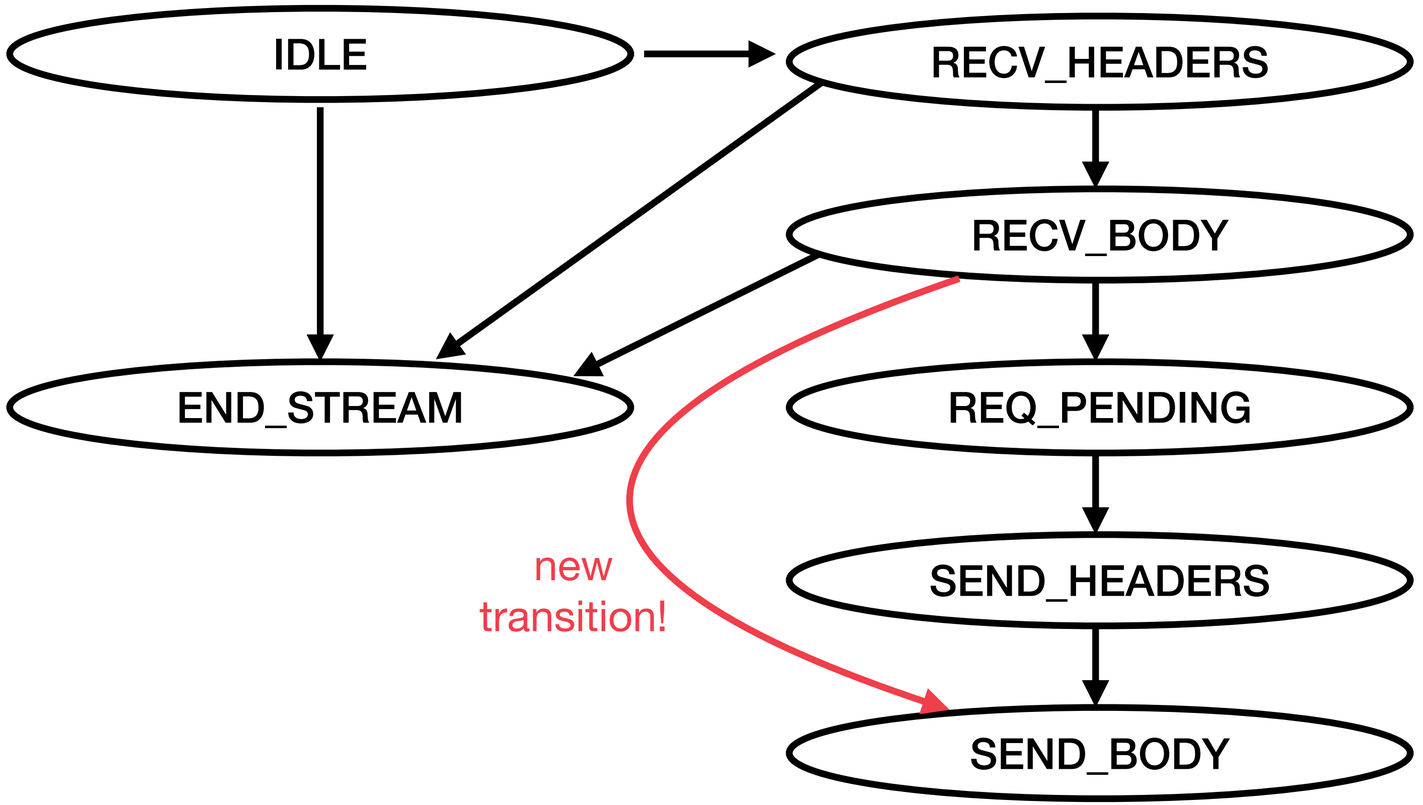
State fuzzing algorithm

- Procedure

  1. save the inputs that trigger new state transition

  2. assign more energy on the “core-logic” state sequences

  3. correlate input bytes and state transitions, giving more opportunities on mutating these bytes



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seeds that have triggered core logic transitions are more likely to be chosen

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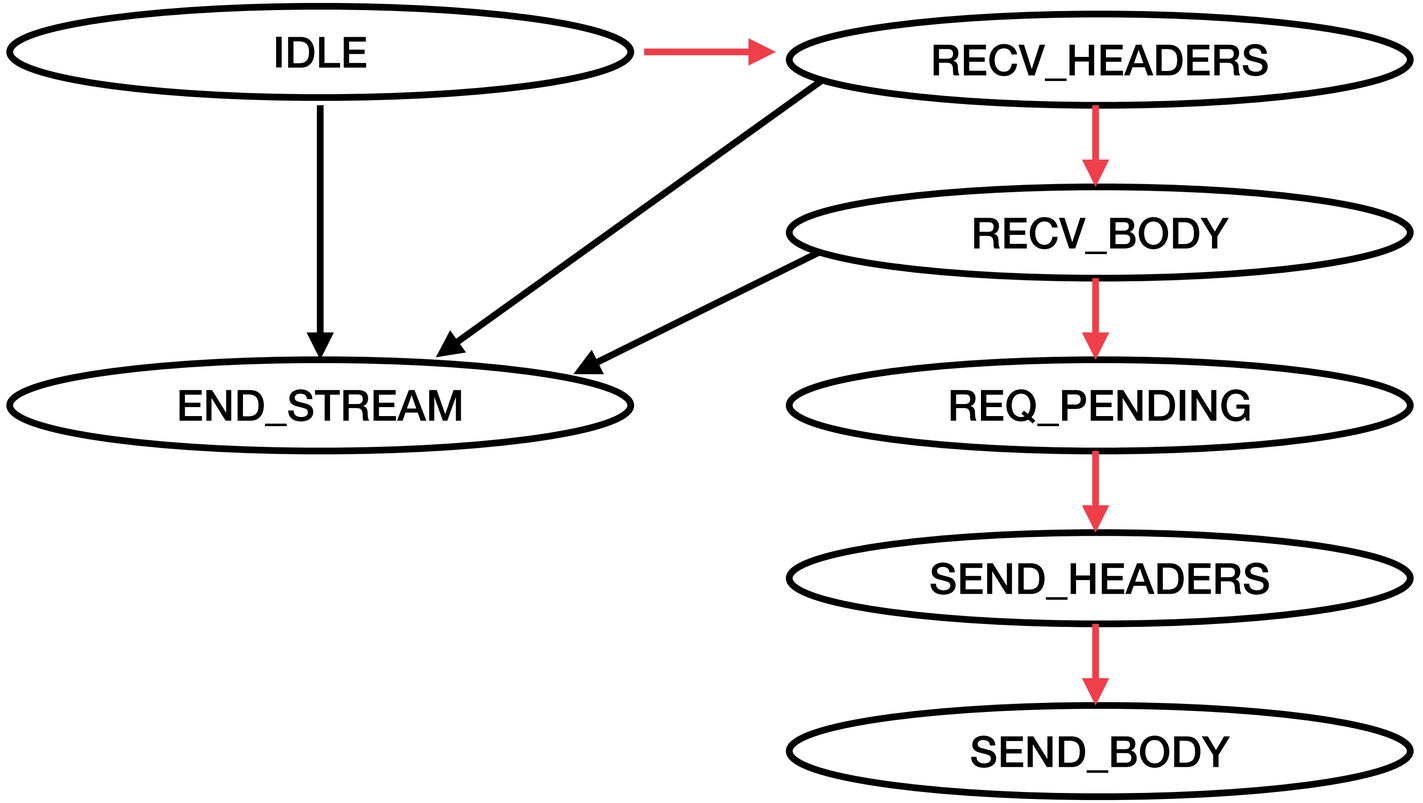

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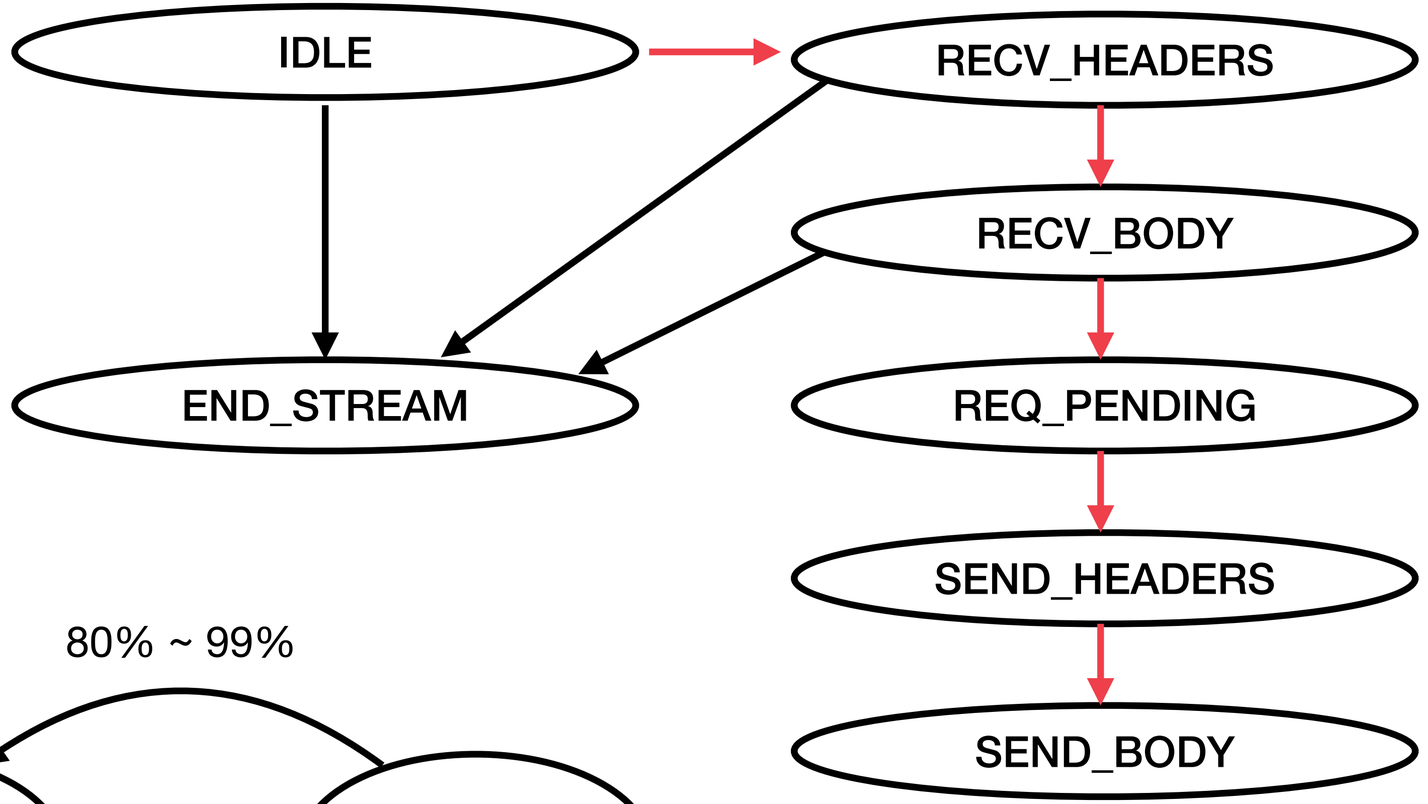

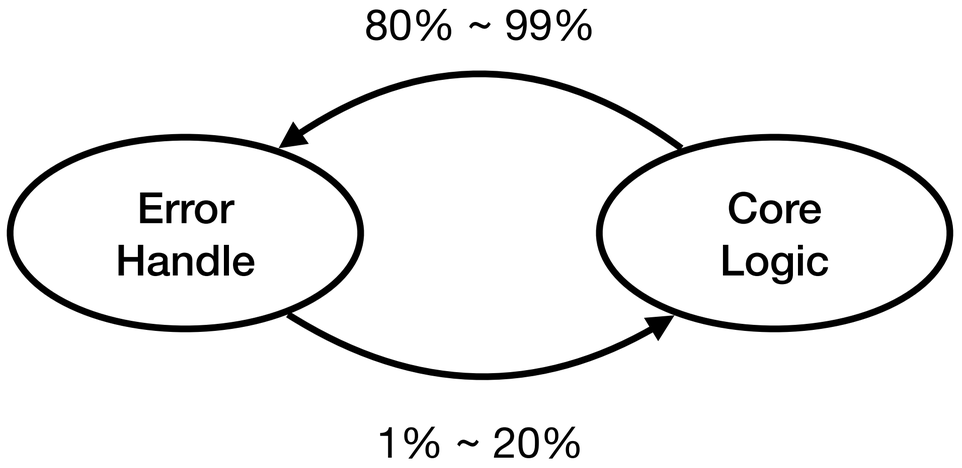

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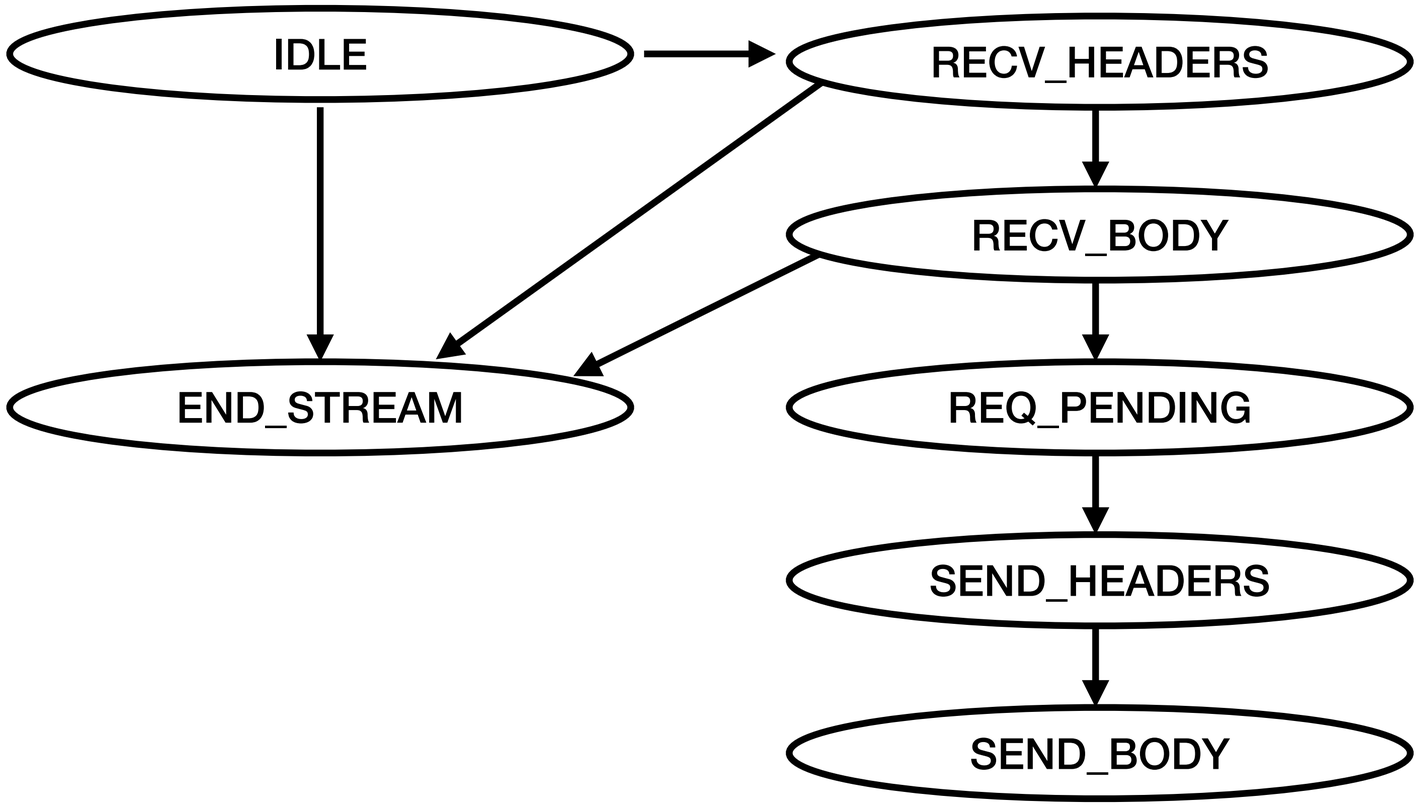

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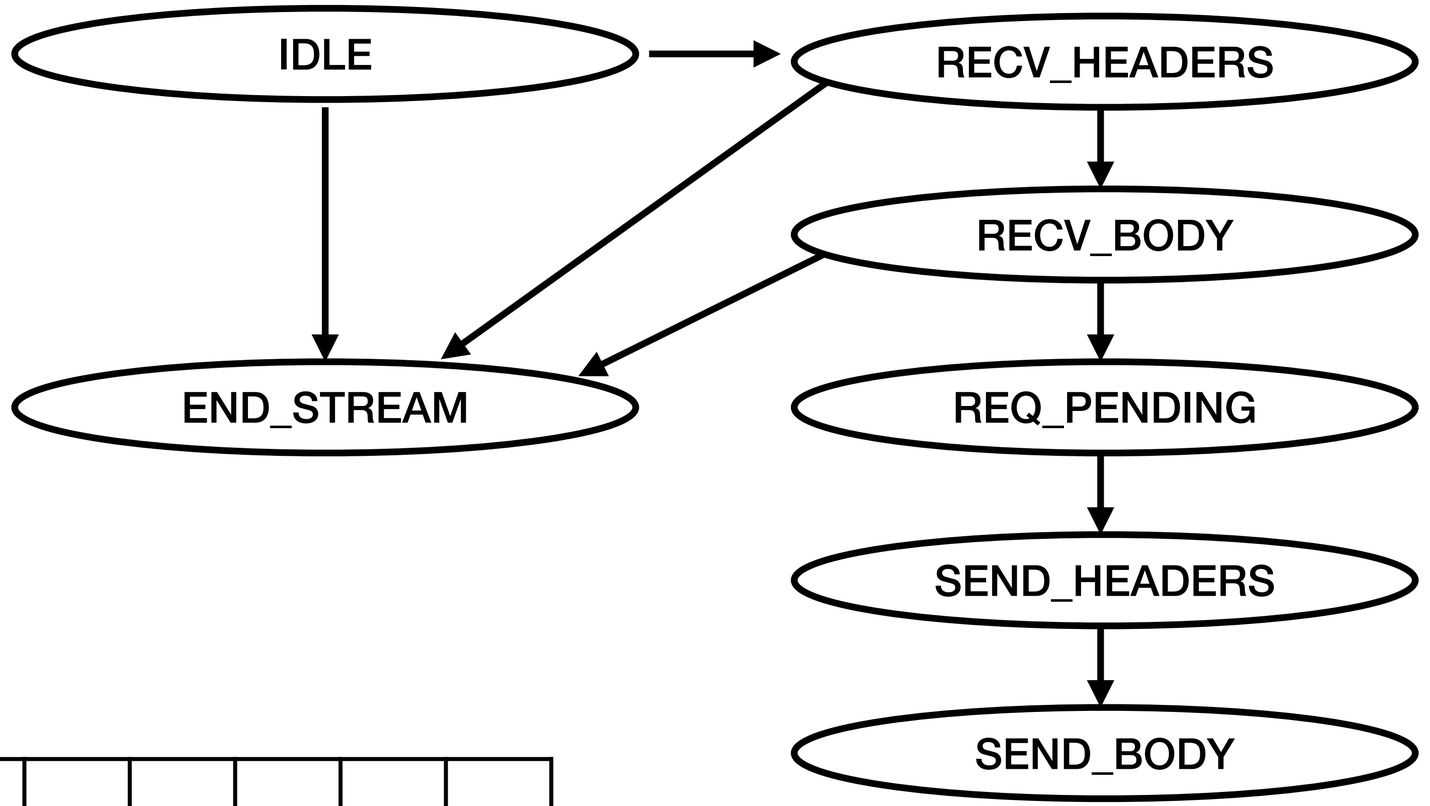

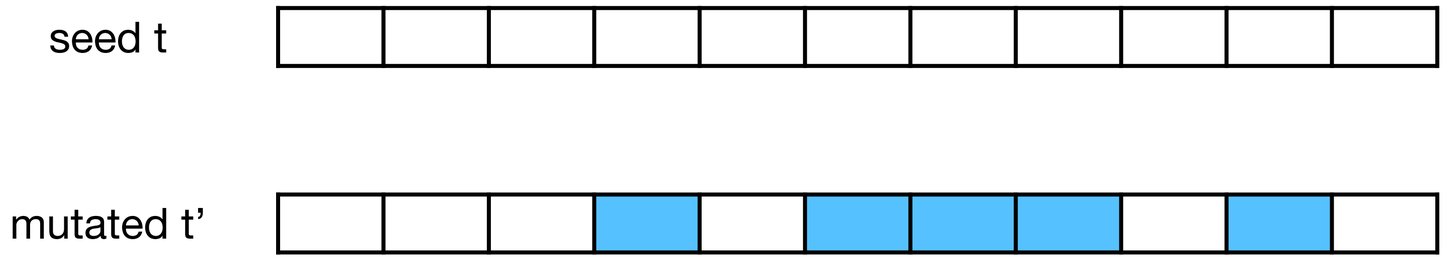

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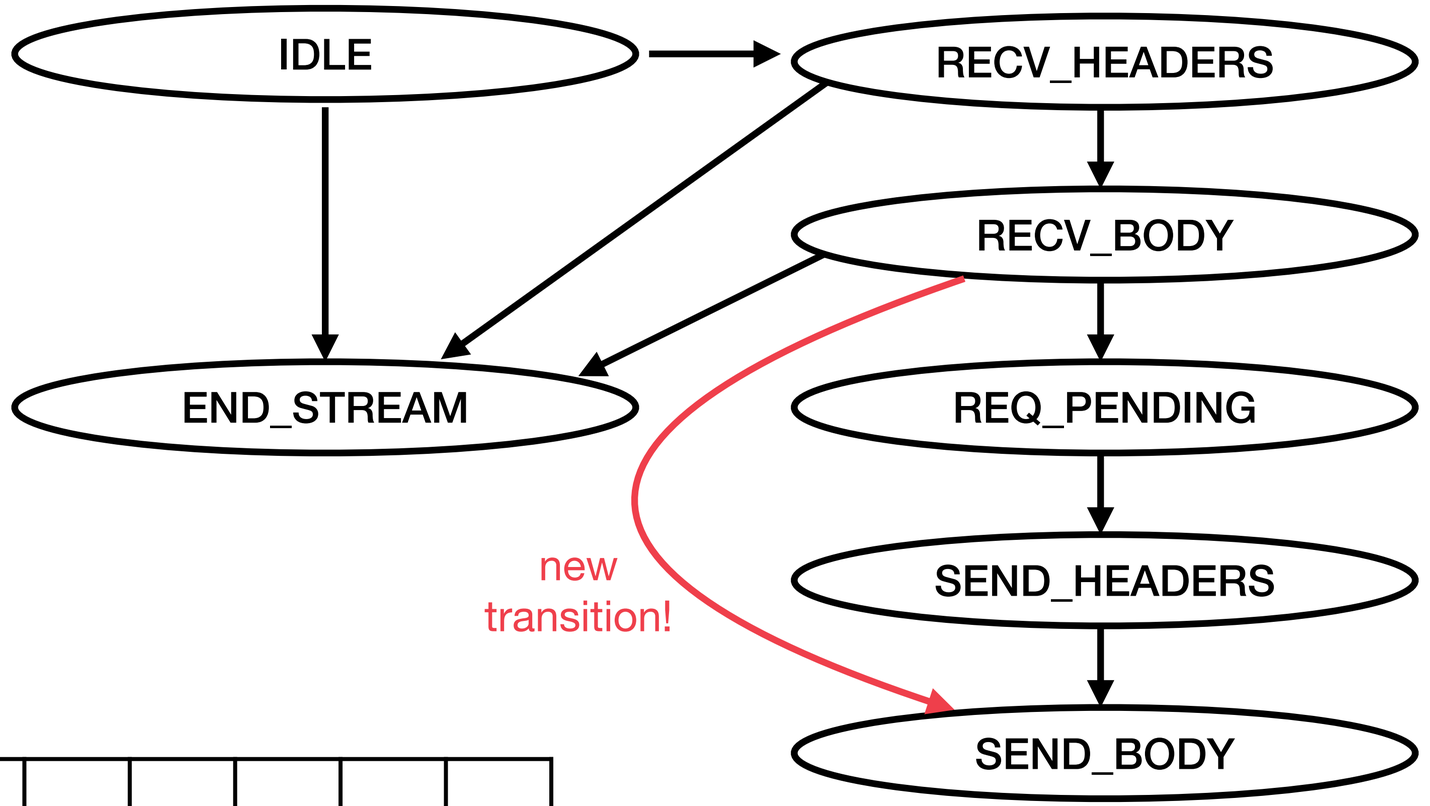

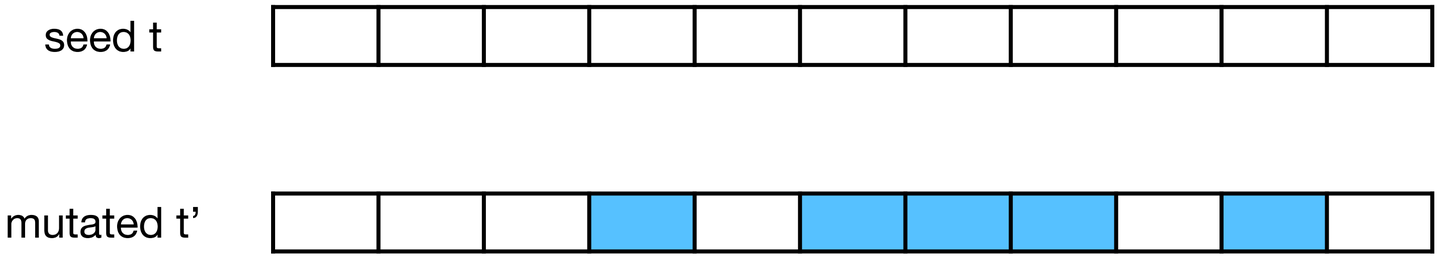

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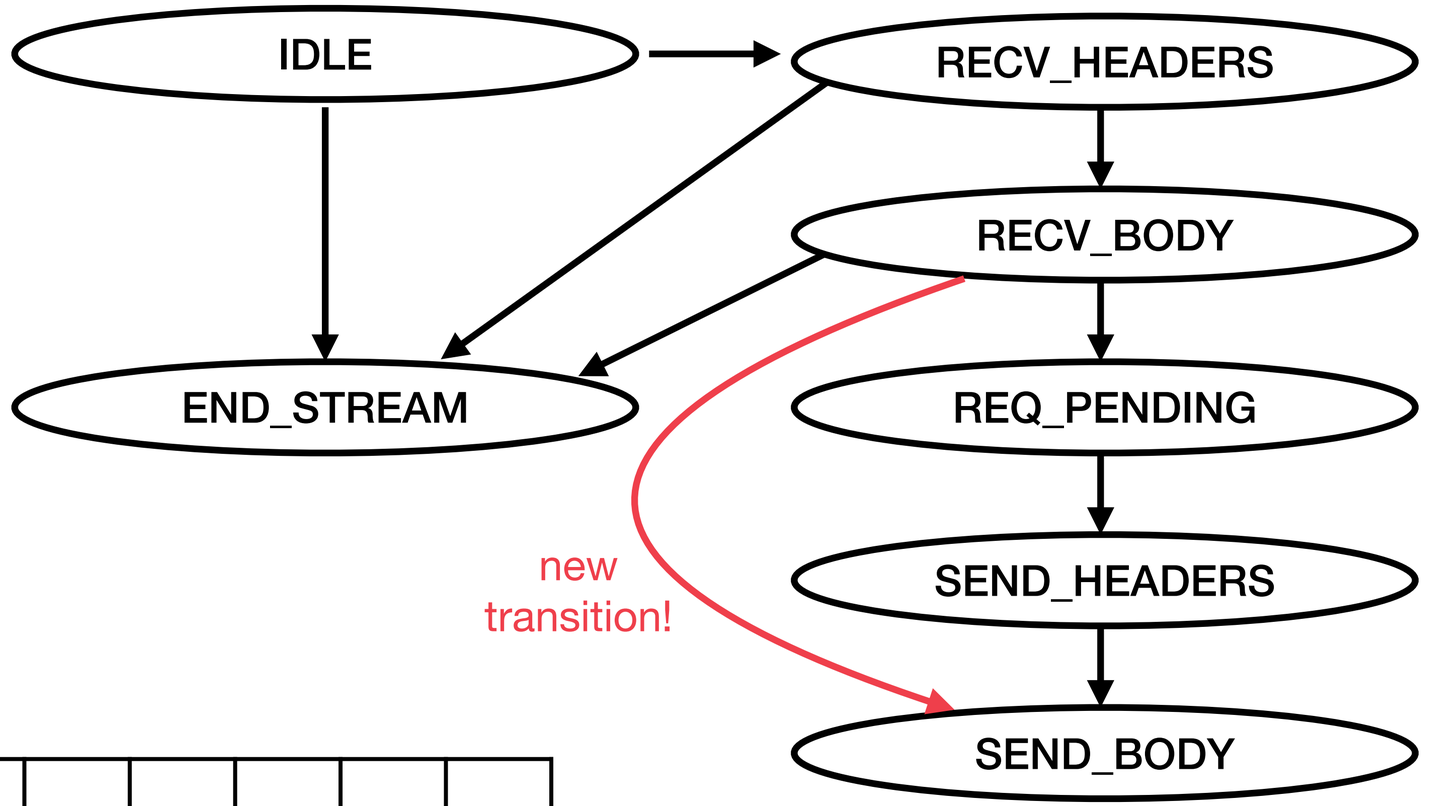

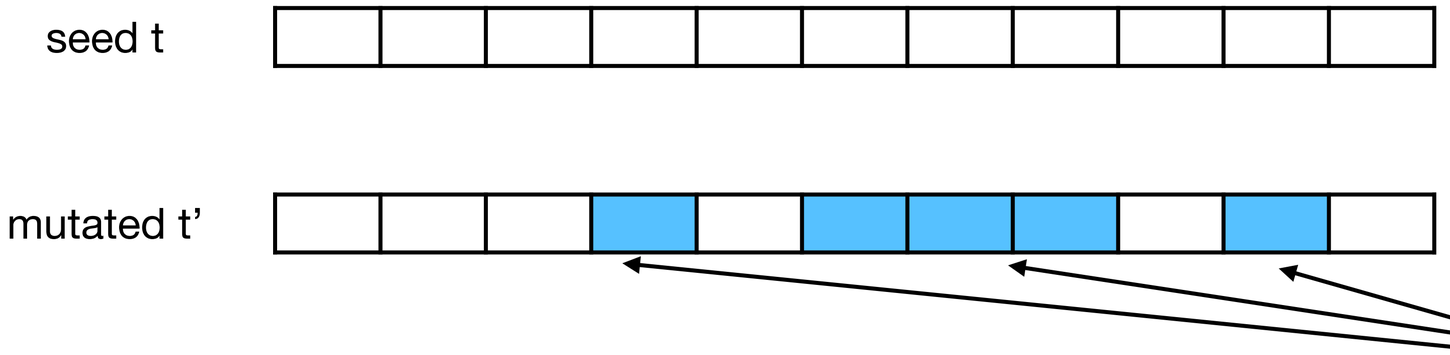

Evaluation setup

- Target programs
  - run 20 times for each target program
  - fuzz 23 hours for each run

Program	Protocol
H2O	HTTP
MbedTLS	SSL/TLS
OpenSSL	SSL/TLS
Curl	Several
Gstreamer	Custom
Live555	RTSP
Owntone	DAAP
DCMTK	DICOM

Evaluation: state transition coverage

- Measure the number of state transition sequences in the State Transition Tree

Subject	AFLNet	LibFuzzer	IJON	SGFuzz	Factor
H2O	-	70.80	91.85	1849.30	26.1
MbedTLS	-	22.80	32.45	50.80	2.2
Curl	-	150.25	375.75	14630.80	97.3
Gstreamer	-	49.40	134.20	4067.30	82.3
OpenSSL	13.25	23.95	29.60	33.10	1.4
Live555	138.27	184.15	405.3	1162.30	6.3
OwnTone	1.00	46.40	426.00	930.15	20.0
DCMTK	68.10	189.25	267.50	6737.05	35.6

Avg: 33.9x

- On average, SGFuzz covers state transition sequences 30 times more than the baseline LibFuzzer.

Evaluation: state identification effectiveness

- 99.5% nodes are related to the true states.

Subject	State Transition Tree		
	All Nodes	State	Percentage
H2O	6418	6417	99.98%
MbedTLS	167	167	100.00%
Curl	35690	35629	99.83%
Gstreamer	11240	11224	99.86%
OpenSSL	817	789	96.57%
Live555	17446	17446	100.00%
OwnTone	3671	3671	100.00%
DCMTK	27178	27109	99.75%

Avg: 99.50%

Evaluation: new bugs

- Found 12 previously unknown bugs in 23 hours, and 10 of 12 are stateful bugs

Subject	Version	Type	Stateful	CVE
Live555	1.08	Stack-based overflow in liveMedia/MP3FileSource.cpp	✓	CVE-2021-38380
Live555	1.08	Heap use after free in liveMedia/MatroskaFile.cpp	✓	CVE-2021-38381
Live555	1.08	Heap use after free in liveMedia/MPEG1or2Demux.cpp	✓	CVE-2021-38382
Live555	1.08	Memory leak in liveMedia/AC3AudioStreamFramer.cpp	✓	CVE-2021-39282
Live555	1.08	Assertion in UsageEnvironment/UsageEnvironment.cpp	✓	CVE-2021-39283
Live555	1.08	Heap-based overflow in BasicUsageEnvironment/BasicTaskScheduler.cpp	✓	CVE-2021-41396
Live555	1.08	Memory leak in liveMedia/MPEG1or2Demux.cpp	✓	CVE-2021-41397
OwnTone	28.2	Heap use after free in src/misc.c	✗	CVE-2021-38383
DCMTK	3.6.6	Memory leak in dcmnet/libsrc/dulparse.cc	✗	CVE-2021-41687
DCMTK	3.6.6	Memory leak in dcmnet/libsrc/dulparse.cc	✓	CVE-2021-41688
DCMTK	3.6.6	Heap use after free in dcmqrdb/libsrc/dcmqrsrv.cc	✓	CVE-2021-41689
DCMTK	3.6.6	Heap-based overflow in dcmnet/libsrc/diutil.cc	✓	CVE-2021-41690

Conclusion

- Present Stateful greybox fuzzer (SGFuzz)
  - automatically identify and monitor state of target program
- Show SGFuzz outperforms baseline fuzzers in terms of state transition coverage
  - covers 30 times more than the baseline LibFuzzer
- Show the effectiveness of state identification
  - on average, 99.5% nodes are related to the true states