SymTCP: Eluding Stateful Deep Packet Inspection with Automated Discrepancy Discovery

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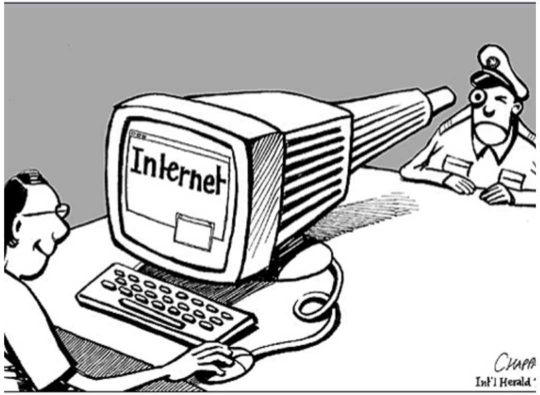
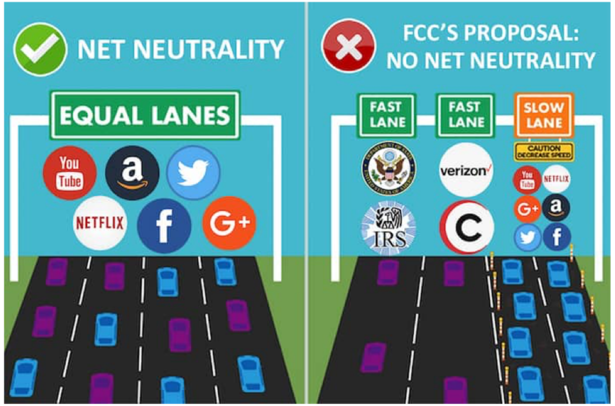
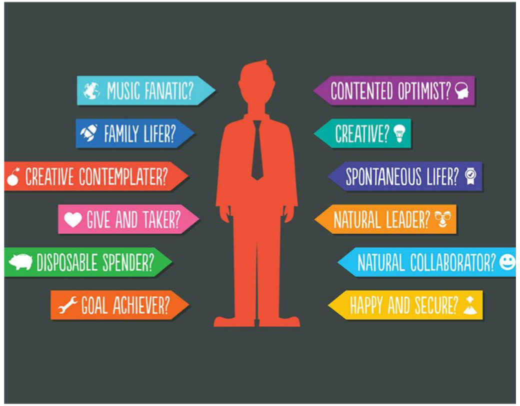
What is DPI (Deep Packet Inspection)?



Censorship and Surveillance

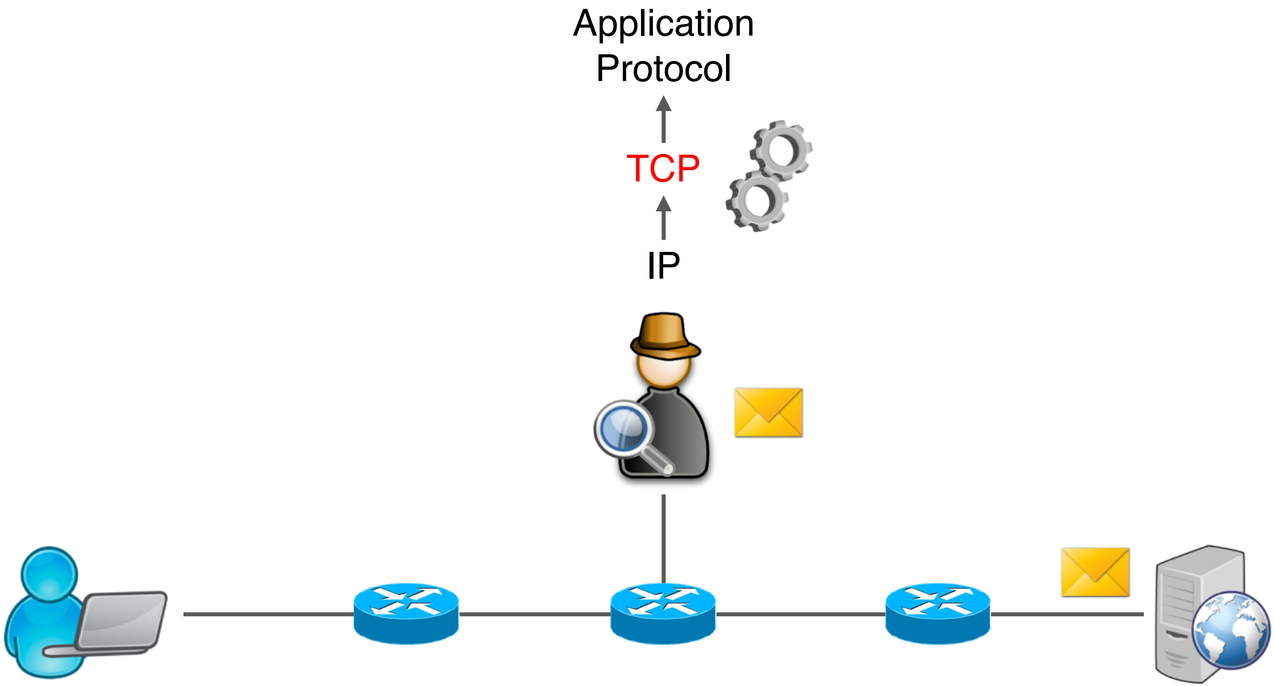


ISP Traffic Differentiation

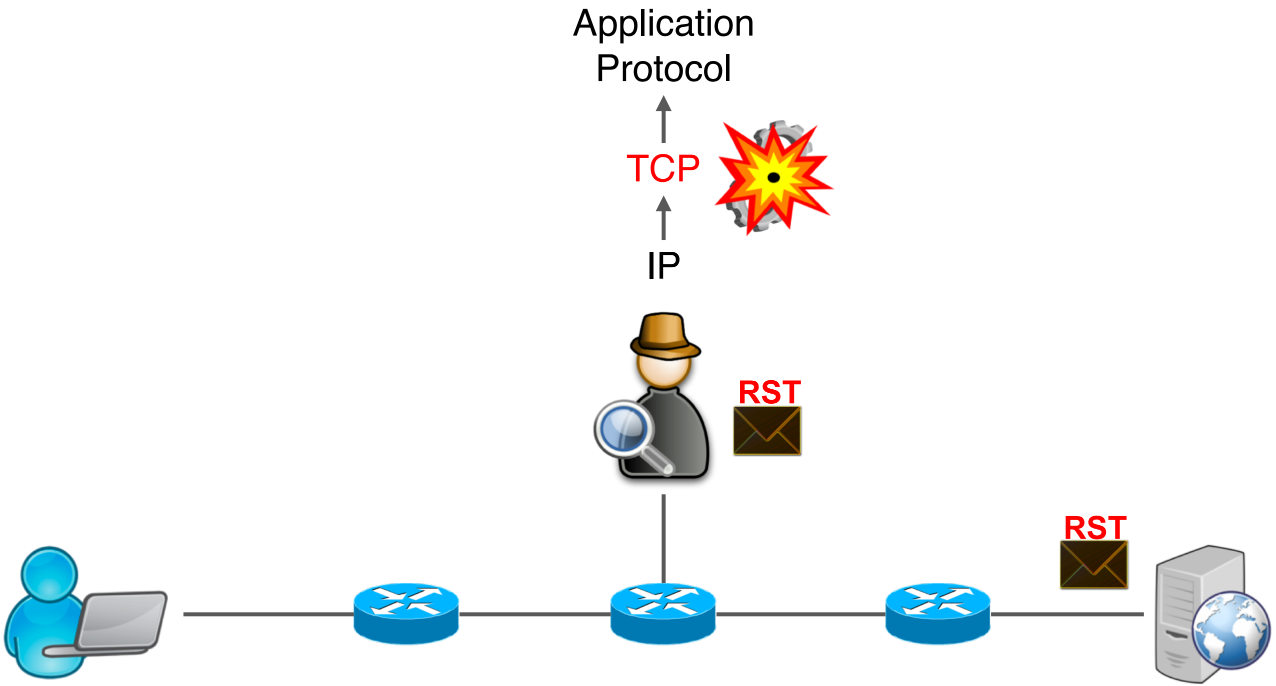


Modeling Users for Online Ads

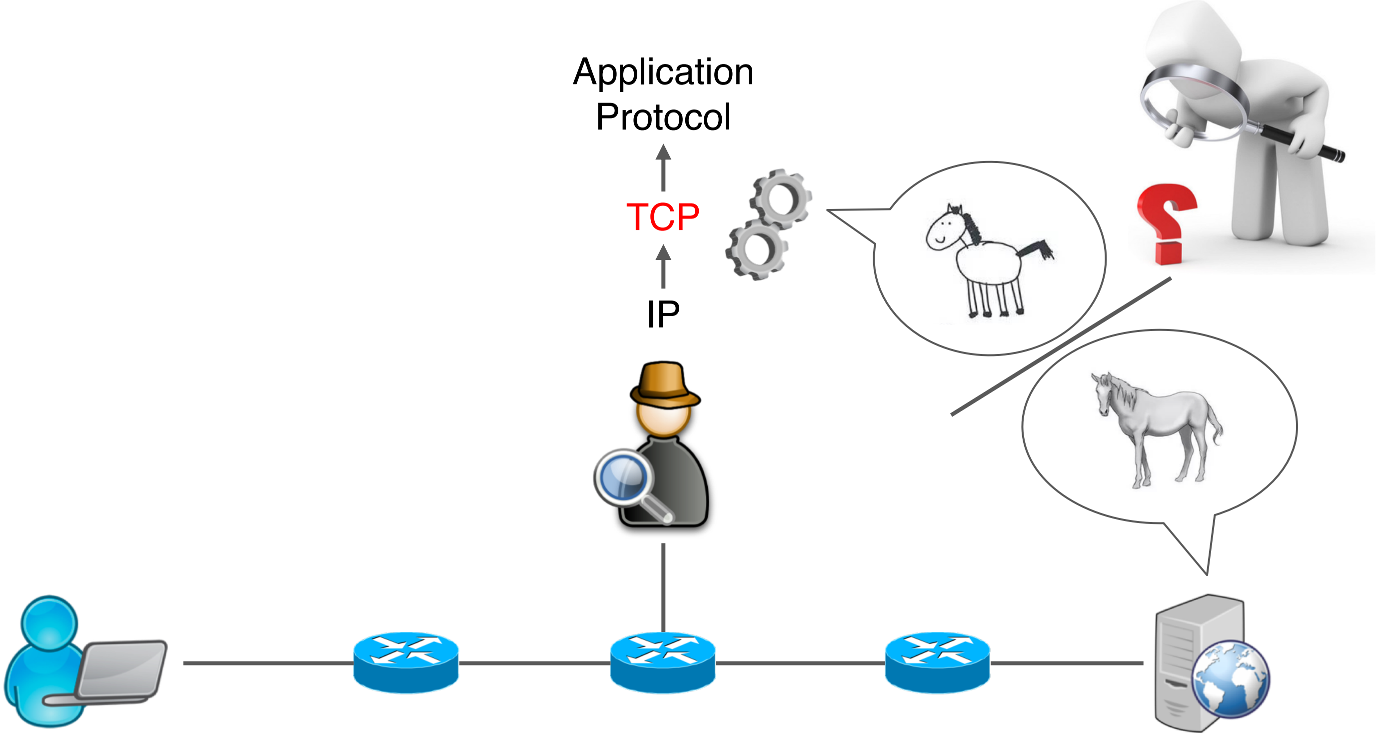
How does DPI work?



How does DPI work?



How does DPI work?



Implementation-level discrepancy

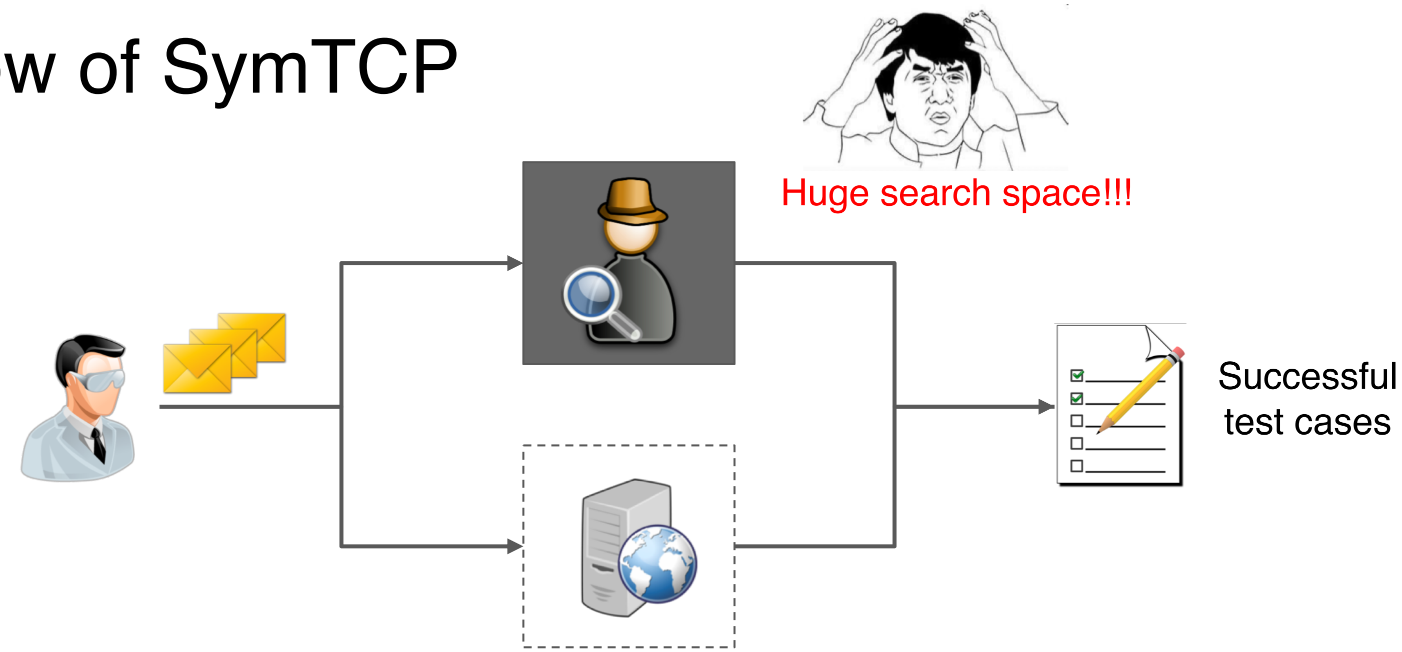
```
// Linux TCP timestamp validation
if ((signed int)(last_tsval - current_tsval) <= 1) {
    // succeed
} else {
    // fail
}
```

$\text{last\_tsval} - 1 \le \text{current\_tsval} \le \text{last\_tsval} + 2^{31}$

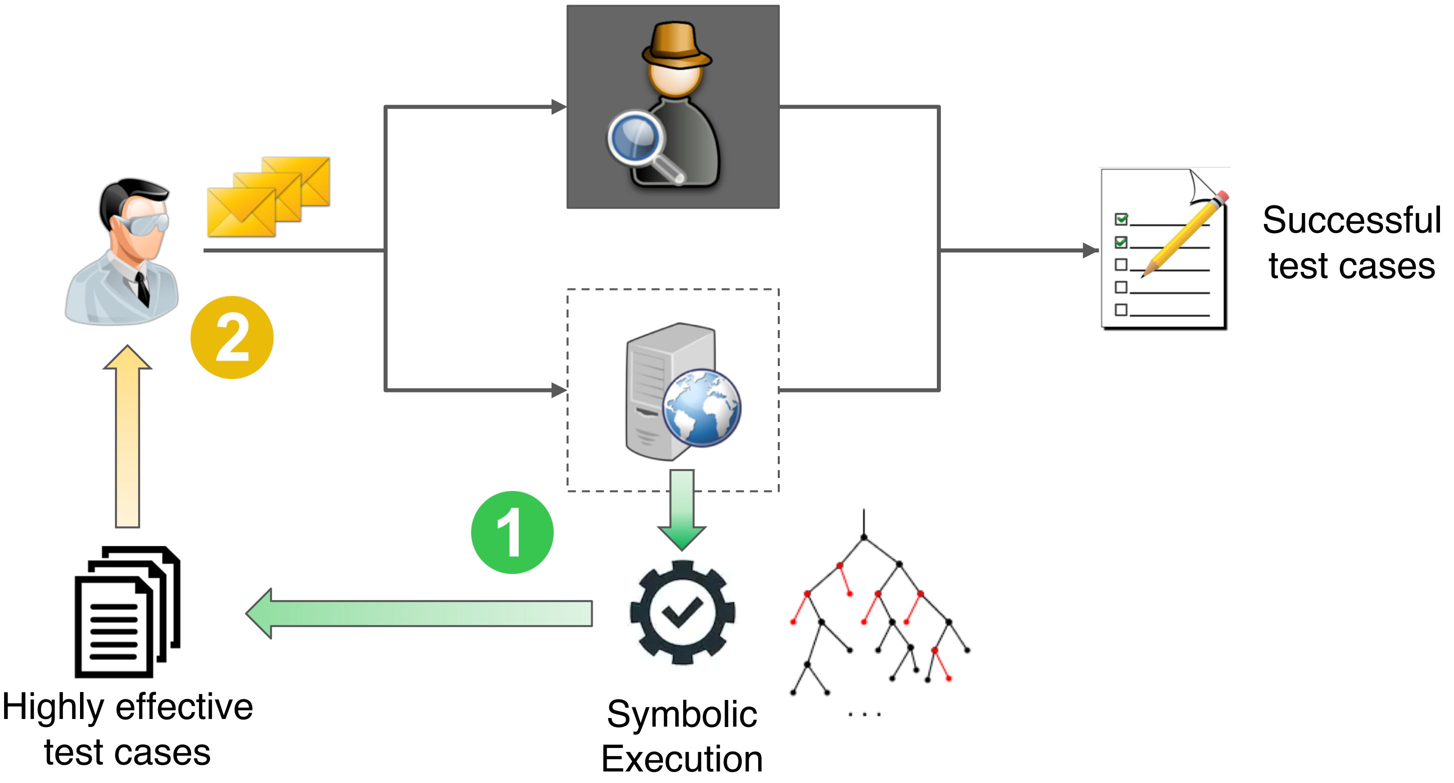
```
// Snort TCP timestamp validation
if ((signed int)((current_tsval - last_tsval) + 1) < 0) {
    // fail
} else {
    // succeed
}
```

$\text{last\_tsval} - 1 \le \text{current\_tsval} \le \text{last\_tsval} + 2^{31} \mathbf{- 2}$

Workflow of SymTCP



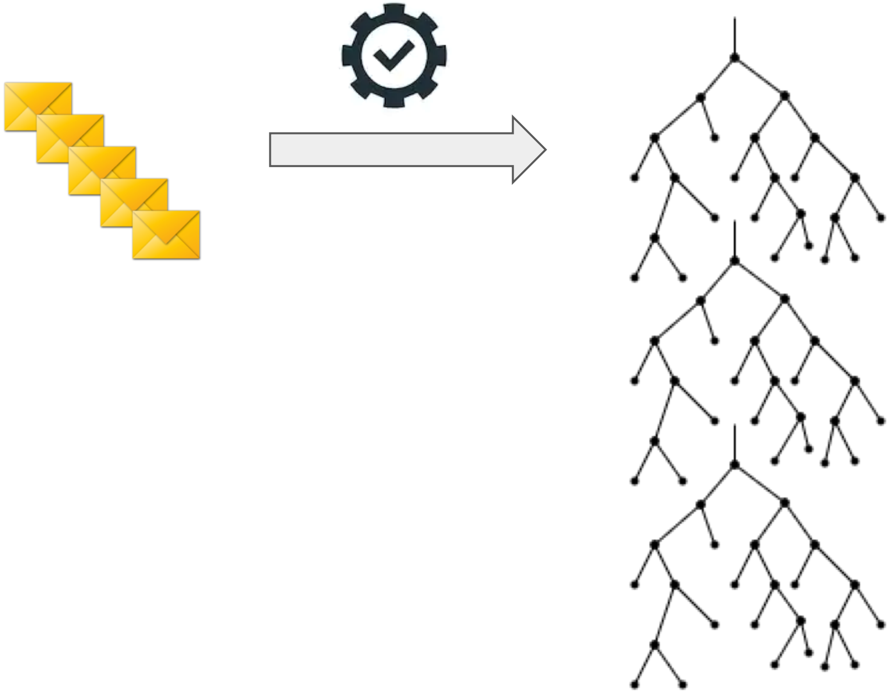
Workflow of SymTCP

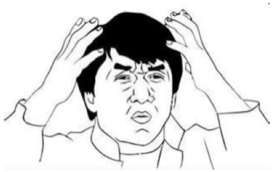


Problem with symbolic execution

All possible packets

All possible execution paths





Path explosion!!!

Pruning decisions

Labeling “drop” / “accept” points

In the program, we label where a packet gets dropped or accepted (i.e. TCP state changed). We try to cover these accept/drop points.

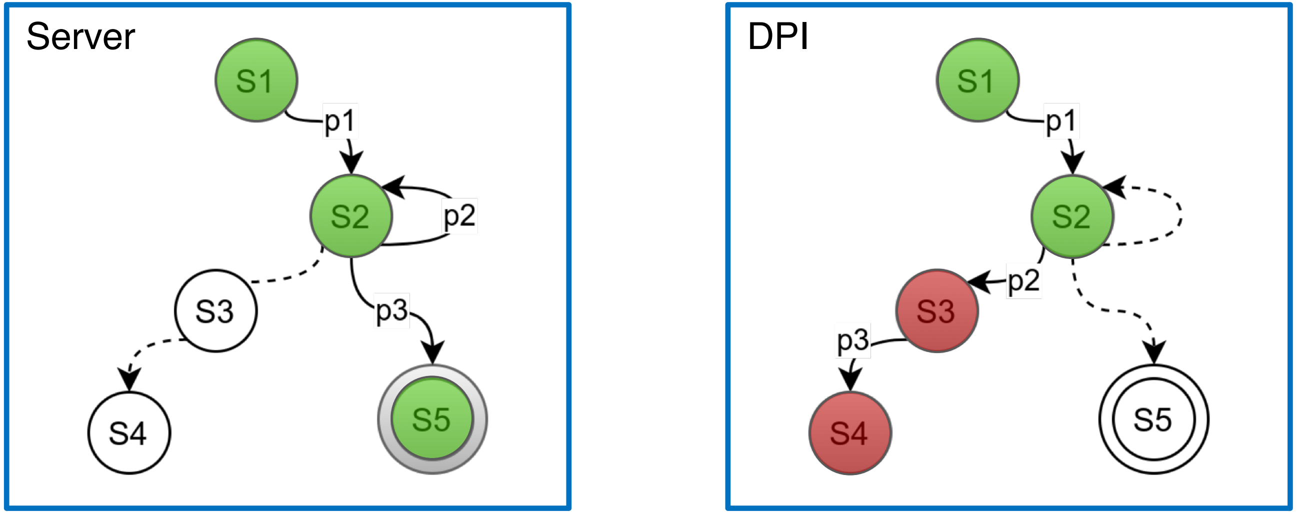
Bounding TCP options

We allow each TCP option to occur only once, and at most 5 different TCP options in a packet.

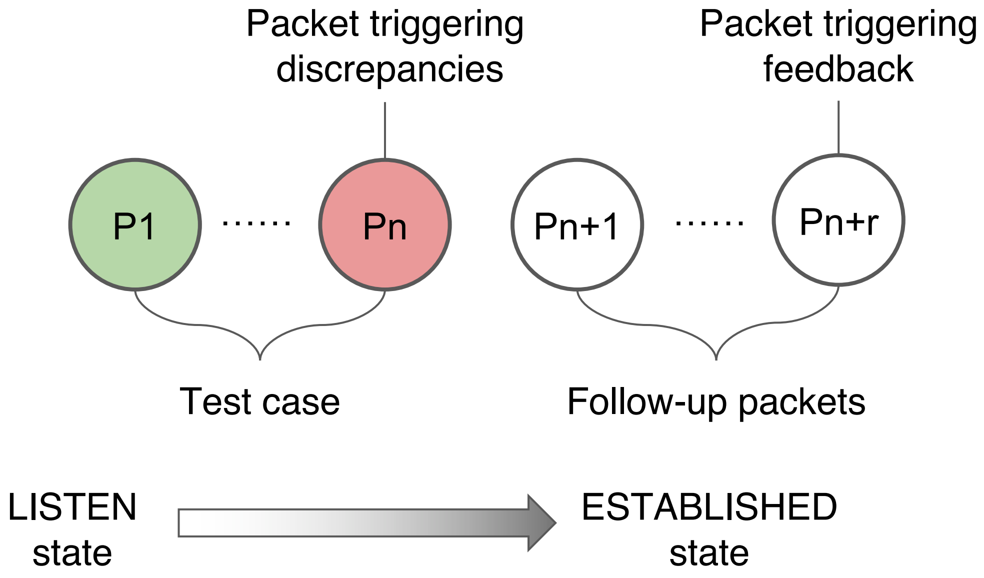
Pruning uninteresting TCP states

We terminate an execution path once it reaches any uninteresting TCP state (e.g., TIME_WAIT, CLOSED)

Differential testing DPI



Complete packet sequence



Symbolic execution performance

- Linux kernel v4.9.3
- 72 core Intel Xeon CPU and 256GB memory
- 1/2/3 symbolic packets
- 20/40/60 byte length packet

No TCP options

# of pkts	20-byte TCP pkts		40-byte TCP pkts		[illegible]	
	Time to cover	Covered drop points	Time to cover	Covered drop points	[illegible]	[illegible]
1	5s	8	5s	9	[illegible]	[illegible]
2	20s	16	20m	19	18m	18
3	50s	31	1h2m	39	40m	38

Time cost could vary due to randomness in path selection of symbolic execution.

56,787 test cases
Sampled 10,000 test cases

Zeek (formerly Bro)

- 6082 successful test cases, 9 strategies, 2 novel strategies

TABLE IV. SUCCESSFUL STRATEGIES ON ZEEK V2.6

Strategy	TCP state	Insertion/Evasion packet	Linux	Zeek
† SYN with data	L/SR/E	(I) SYN packet with data	Ignore data	Accept data
† Multiple SYN	SR/E	(I) SYN packet with out-of-window SEQ num	Discard and send ACK	Reset TCB
† Pure FIN	E	(I) Pure FIN packet without ACK flag	Discard (may send ACK)	Flush and reset receive buffer
† Bad RST/FIN	SR/E	(I) RST or FIN packet with out-of-window SEQ num	Discard (may send ACK)	Flush and reset receive buffer
† Data overlapping	SR/E	(I) Out-of-order data packet, then overlapping in-order data packet	Accept in-order data	Accept first data
† Data without ACK	SR/E	(I) Data packet without ACK flag	Discard	Accept
† Data bad ACK	E	(I) Data packet with ACK > snd_nxt or < snd_una - window_size	Discard	Accept
∗ Big gap	SR/E	(I) Data packet with SEQ > rcv_nxt + max_gap_size (16384)	Accept	Ignore later data
∗ SEQ < ISN	SR/E	(E) Data packet with SEQ num < client ISN and in-window data	Accept in-window data	Ignore

* TCP State: L - Listen, SR - SYN_RECV, E - ESTABLISHED. (I) - Insertion, (E) - Evasion. † - Old strategy, ∗ - New strategy.

Snort

- 652 successful test cases, 11 strategies, 3 novel

TABLE V. SUCCESSFUL STRATEGIES ON SNORT V2.9.13

Strategy	TCP state	Insertion/Evasion packet	Linux	Snort
† Multiple SYN	E	(I) SYN packet with in-window SEQ num	Discard and send ACK	Teardown TCB
† In-window FIN	E	(I) FIN packet with SEQ num in window but $\neq$ rcv_nxt	Ignore FIN (may accept data)	Cut off later data
† FIN/ACK bad ACK	E	(I) FIN/ACK packet with ACK num $>$ snd_nxt or $<$ snd_una - window_size	Discard (may send ACK)	Cut off later data
† FIN/ACK MD5	SR/E	(I) FIN/ACK packet with TCP MD5 option	Discard	Cut off later data
† In-window RST	E	(I) RST packet with SEQ num $\neq$ rcv_nxt but still in window	Discard and send ACK	Teardown TCB
† RST bad timestamp	SR	(I) RST packet with bad timestamp	Discard	Teardown TCB
† RST MD5	SR/E	(I) RST packet with TCP MD5 option	Discard	Teardown TCB
† RST/ACK bad ACK num	SR	(I) RST/ACK packet with ACK num $\neq$ server ISN + 1	Discard	Teardown TCB
∗ Partial in-window RST	E	(I) RST packet with SEQ num $<$ rcv_nxt but partial data in window	Discard	Teardown TCB
∗ Urgent data	SR/E	(E) Data packet with URG flag and urgent pointer set	Consume 1 byte urgent data	Ignore all data before urgent pointer
∗ Time gap	SR/E	(E) Data packet timestamp = last timestamp + 0x7fffffff/0x80000000	Accept	Ignore

* TCP State: L - Listen, SR - SYN_RECV, E - ESTABLISHED. (I) - Insertion, (E) - Evasion. † - Old strategy, ∗ - New strategy.

Great Firewall of China (GFW)

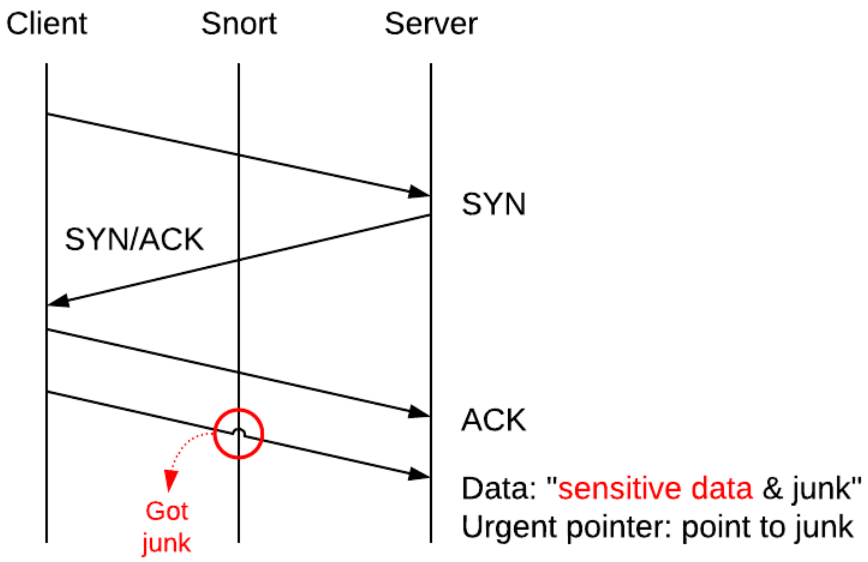
- 4587 successful test cases, 12 strategies, 9 novel

TABLE VI. SUCCESSFUL STRATEGIES ON THE GFW

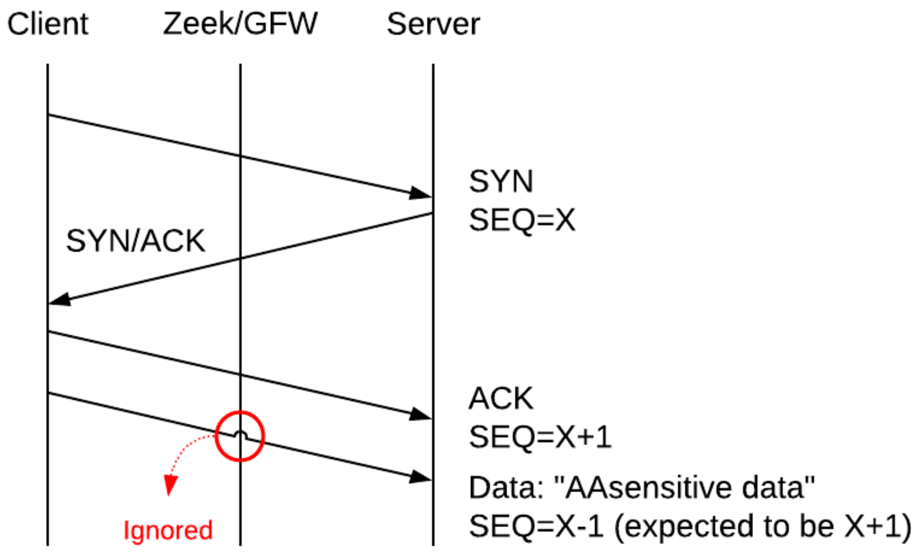
Strategy	TCP state	Insertion/Evasion packet	Linux	GFW
† Bad RST	SR/E	(I) RST packet with bad checksum or TCP MD5 option	Discard	Teardown TCB
† Bad data	SR/E	(I) Data packet with bad checksum or TCP MD5 option or bad timestamp	Discard	Accept
† Data without ACK	SR/E	(I) Data packet without ACK flag	Discard	Accept
$*$ SEQ $\leq$ ISN	SR/E	(E) Data packet with SEQ num $\leq$ client ISN and in-window data	Accept in-window data	Ignore
$*$ Small segments	SR	(E) Data packet with payload size $\leq$ 8 bytes	Accept	Ignore
$*$ FIN with data	SR/E	(I) FIN packet with data and without ACK flag	Discard	Teardown TCB
$*$ Bad FIN/ACK data	E	(I) FIN/ACK packet with data and bad checksum or TCP MD5 option or bad timestamp	Discard	Teardown TCB
$*$ FIN/ACK data bad ACK	E	(I) FIN/ACK packet with data and ACK num $>$ snd_nxt or $<$ snd_una - window_size	Discard	Teardown TCB
$*$ Out-of-window SYN data	SR	(I) SYN packet with SEQ num out of window and data	Discard and send ACK	Desynchronized
$*$ Retransmitted SYN data	SR	(I) SYN packet with SEQ num = client ISN and data	Discard	Desynchronized
$*$ RST bad timestamp	SR	(I) RST packet with bad timestamp	Discard	Teardown TCB
$*$ RST/ACK bad ACK num	SR	(I) RST/ACK packet with SEQ num $\neq$ server ISN + 1	Discard	Teardown TCB

* TCP State: L - Listen, SR - SYN_RECV, E - ESTABLISHED. (I) - Insertion, (E) - Evasion. † - Old strategy, $*$ - New strategy.

Case study



1. Urgent Pointer (Snort)



2. Underflow SEQ (Zeek & GFW)

Key contributions

- A novel approach that **combines whitebox and blackbox testing**
  - Whitebox: Extract a reference model from server with symbolic execution
  - Blackbox: Infer internal states of DPI with follow-up packets
- First to run symbolic execution on **full-fledged TCP implementation** and send **multiple symbolic packets**
- Highly **efficient** and **effective automated tool** to unearth discrepancies between different TCP implementations
  - Facilitate DPI elusion
  - Help developers fix implementation bugs

Conclusion

- A novel approach combines whitebox and blackbox testing to automatically discover TCP implementation-level discrepancies
- Evaluated against 3 well-known DPI systems, Zeek (Bro), Snort, and the GFW, and found 14 novel strategies
- A significant step in testing and eluding DPI systems

Thank You!

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GitHub Repo