A SYSTEM TO VERIFY NETWORK BEHAVIOR OF KNOWN CRYPTOGRAPHIC CLIENTS

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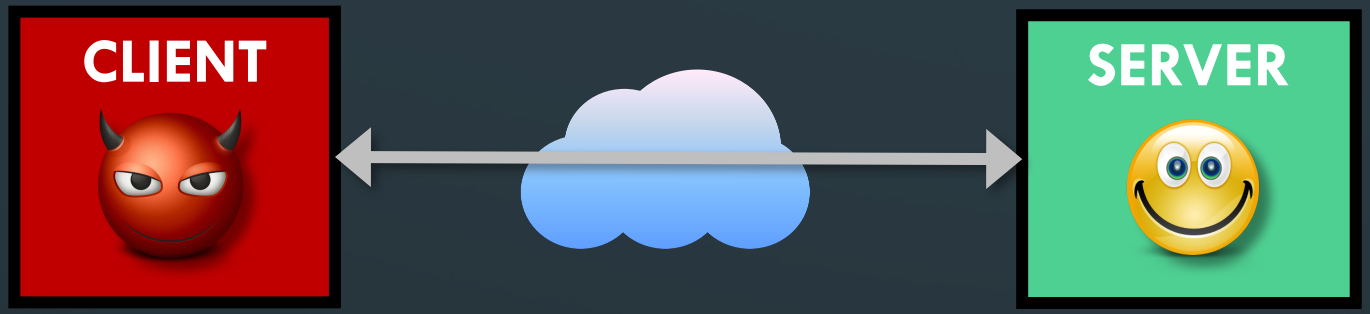
INVALID COMMAND ATTACKS

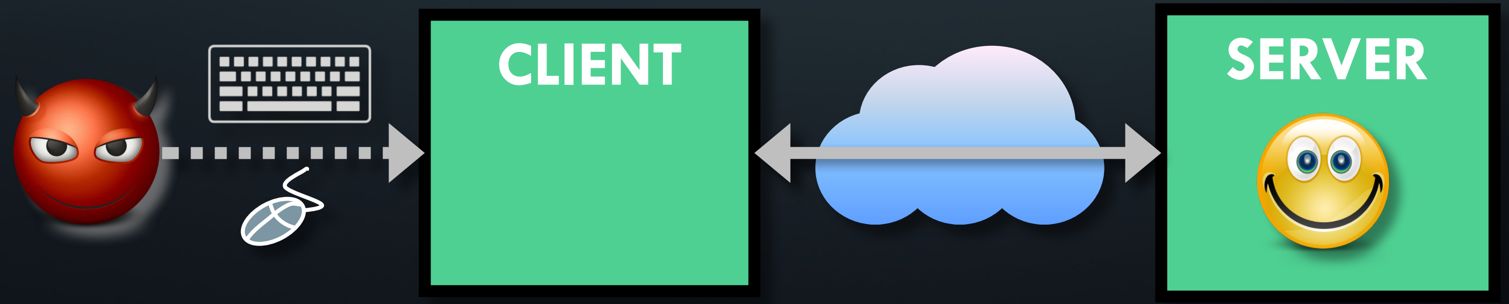


INVALID COMMAND

Client exhibits behavior, as seen by the server, that is inconsistent with the sanctioned client software.

Forms of Exploit:

1. **Maliciously crafted packet**
2. **Valid packets; illegal sequence**



Constrained attacker
(valid commands only)

Goal: constrain *all attackers* to this limited behavior.

TRANSPORT LAYER SECURITY (TLS) - RFC 5246

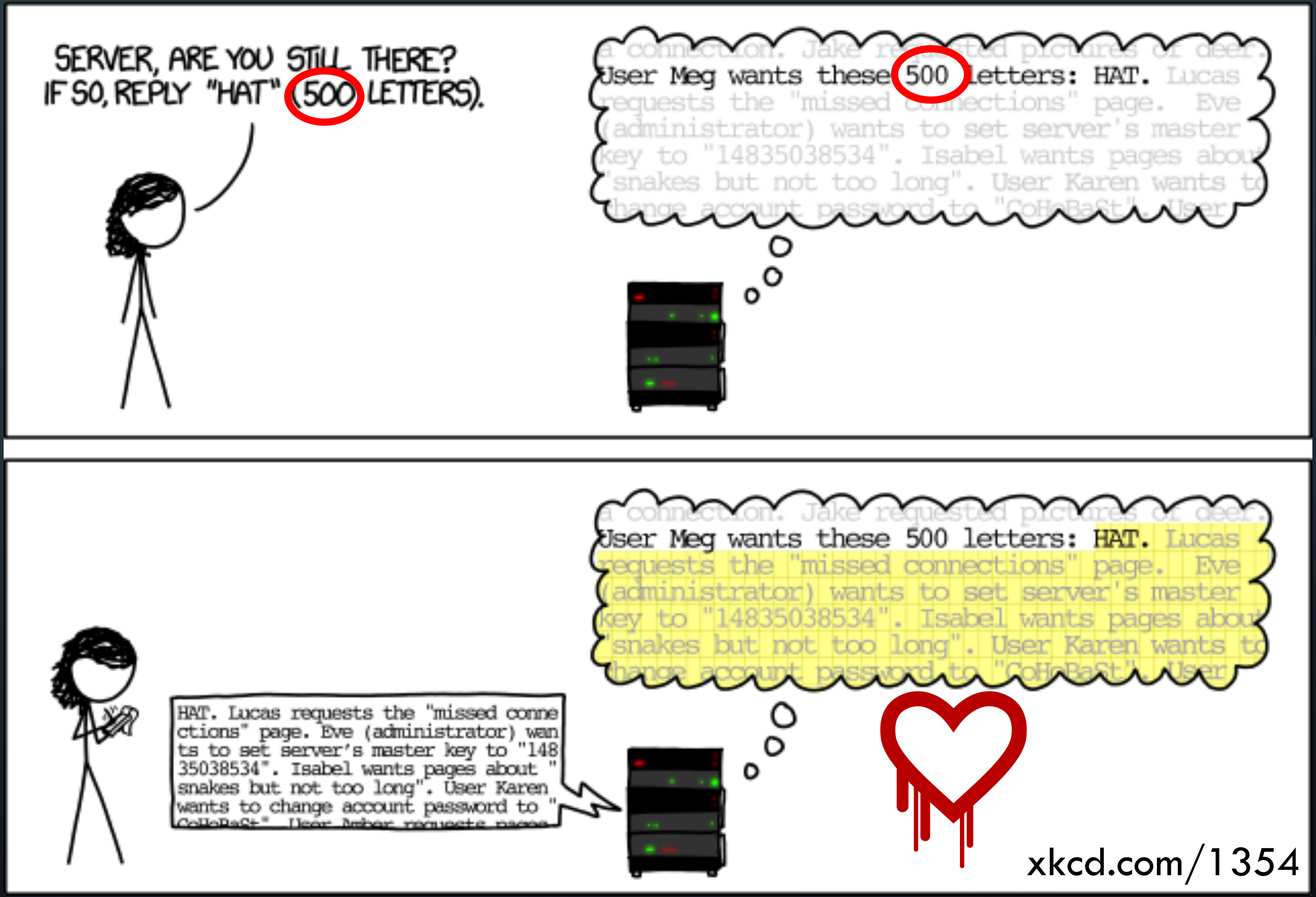
- Handshake Protocol
  - Select cipher, authentication, key exchange
- Record Layer
  - Provides confidentiality and integrity
  - Encapsulates other protocols
- Alerts and Heartbeats

From Jan 2014 to Aug 2016, most of the server-side vulnerabilities in OpenSSL involved invalid commands (23 of 37 required tampering with client behavior).

HEARTBLEED (CVE-2014-0160)

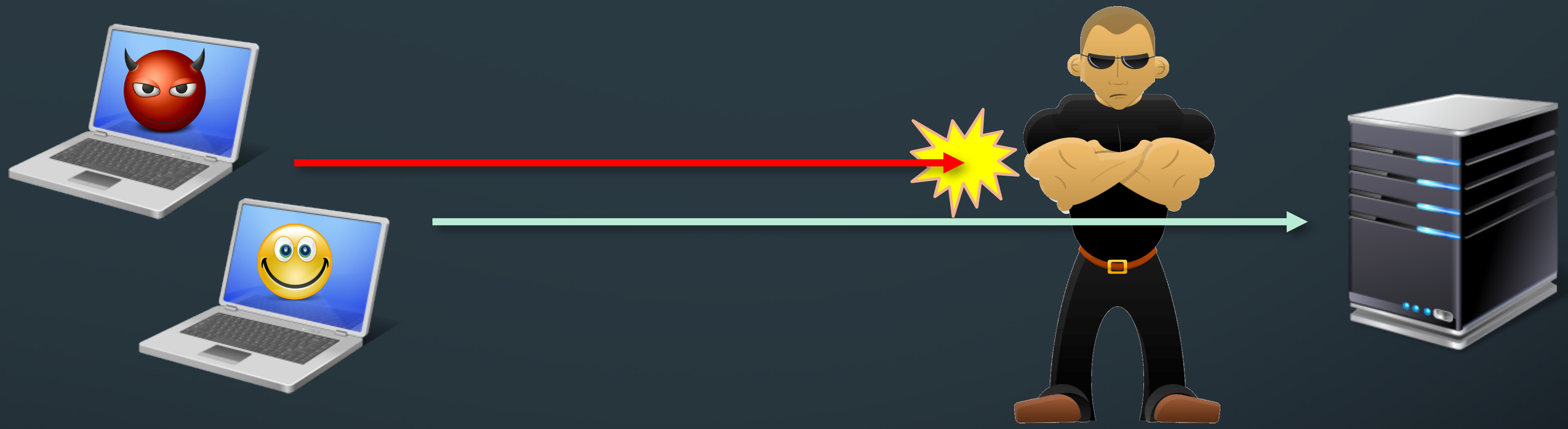
- Implementation bug in OpenSSL TLS Heartbeat handler
- Nearly all OpenSSL applications vulnerable for 2 years
- 17% (~500,000) of the Internet's web servers

HEARTBLEED



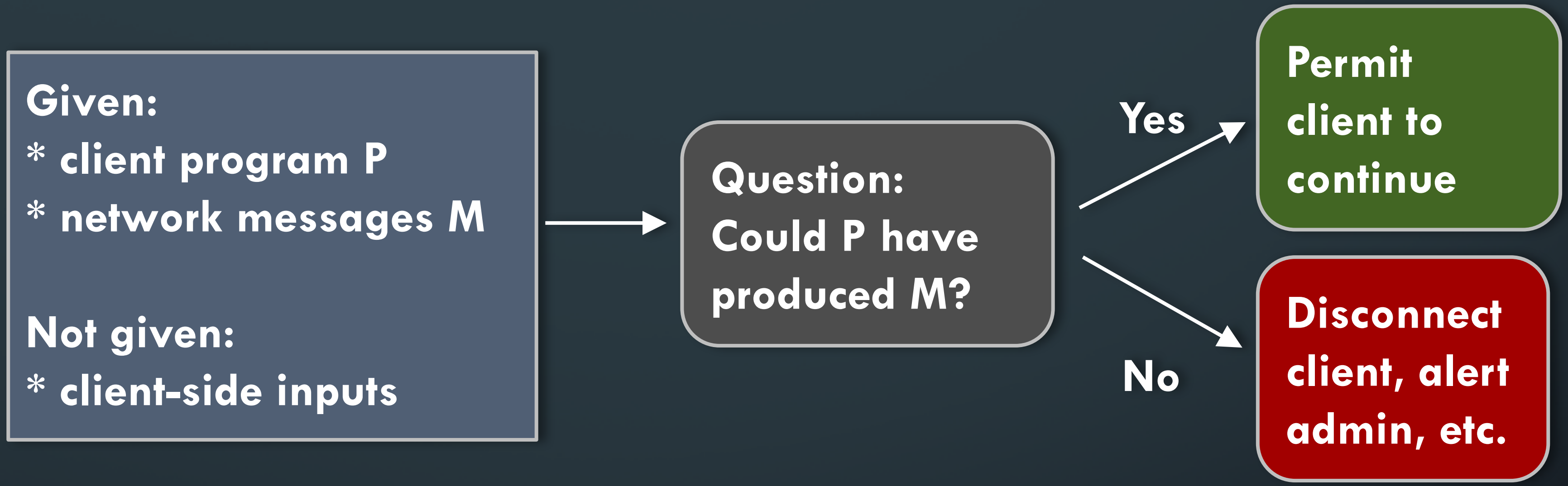
xkcd.com/1354

HOW CAN WE DEFEND THE SERVER?



- Behavioral verification: permit authorized client software's behavior only
  - Eliminates entire classes of attack *without knowing about them*
  - Usually requires client modification or sending of client inputs
- Goal: rapid detection of exploit attempts

BEHAVIORAL VERIFICATION OF A CLIENT

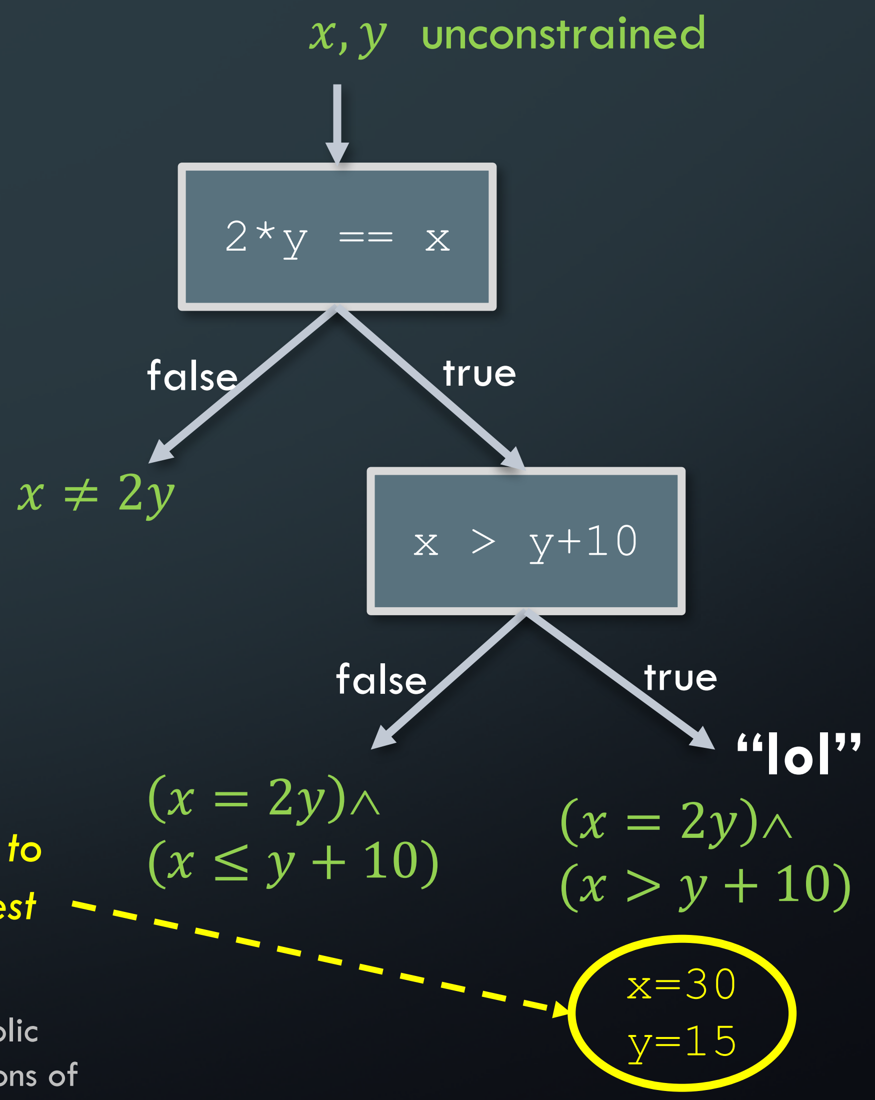


- General case: undecidable
- Specific instances: may be practical
- E.g., detect cheating in online games (Cochran & Reiter 2013)

SYMBOLIC EXECUTION

```
x = sym_input();
y = sym_input();
testme(x,y);

void testme(int x, int y)
{
    int z = 2*y;
    if (z == x) {
        if (x > y+10)
            printf("lol");
    }
}
```



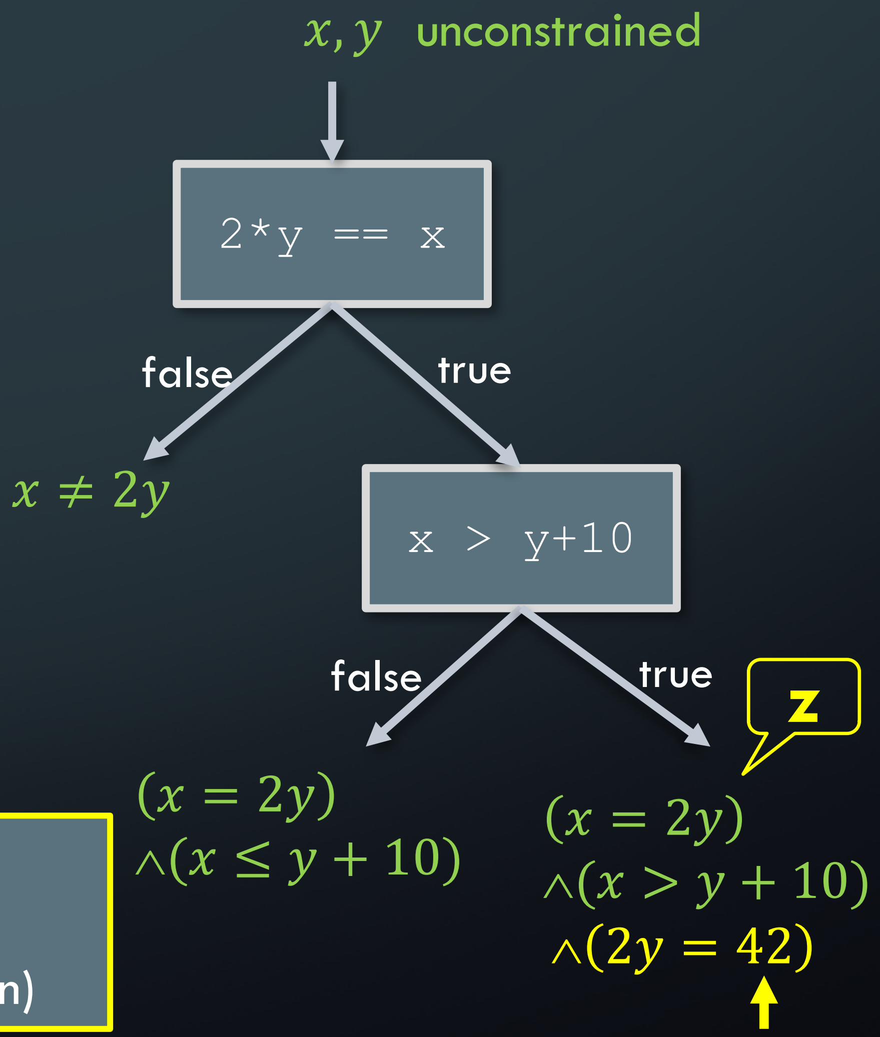
Apply SAT solver to obtain concrete test case.

Example adapted from: Cristian Cadar, and Koushik Sen. "Symbolic execution for software testing: three decades later." Communications of the ACM 56.2 (2013): 82-90.

USING SYMBOLIC EXECUTION TO DETECT INVALID COMMAND ATTACKS

```
x = sym_input();
y = sym_input();
testme(x,y);

void testme(int x, int y)
{
    int z = 2*y;
    if (z == x) {
        if (x > y+10)
            send(z);
    }
}
```

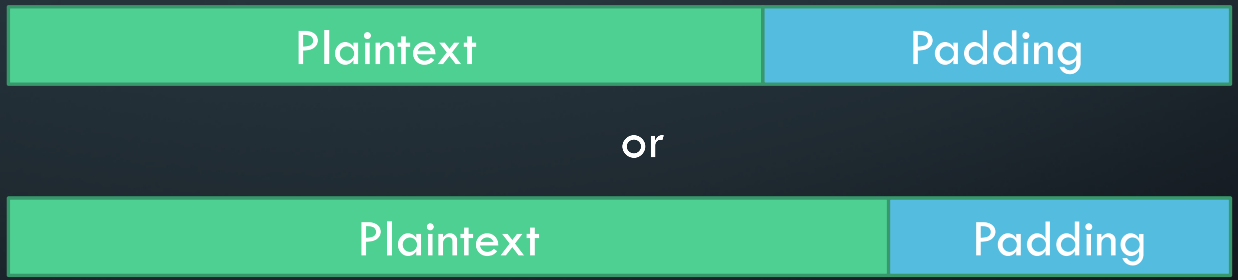


Can this program produce…

- $z = 42$**?** **Yes** $(x = 42, y = 21)$
- $z = 41$**?** **No** ($z = 2y$ so it must be even)

CHALLENGES IN VALIDATING CLIENTS IN CRYPTOGRAPHIC PROTOCOLS (1)

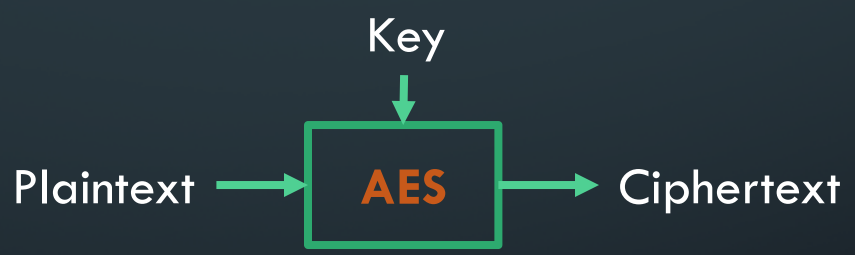
- Symbolic execution generally accommodates program variables with unknown values, but their *sizes* must be known
- Crypto protocols that hide sizes of client-side inputs (e.g., using padding) dramatically grow the search space



- Solution: Explore inputs of different sizes *in parallel*

CHALLENGES IN VALIDATING CLIENTS IN CRYPTOGRAPHIC PROTOCOLS (2)

- Some functions are too costly to execute on symbolic inputs
- Example: cryptographic functions
  - AES block cipher is a very complex formula of key and plaintext

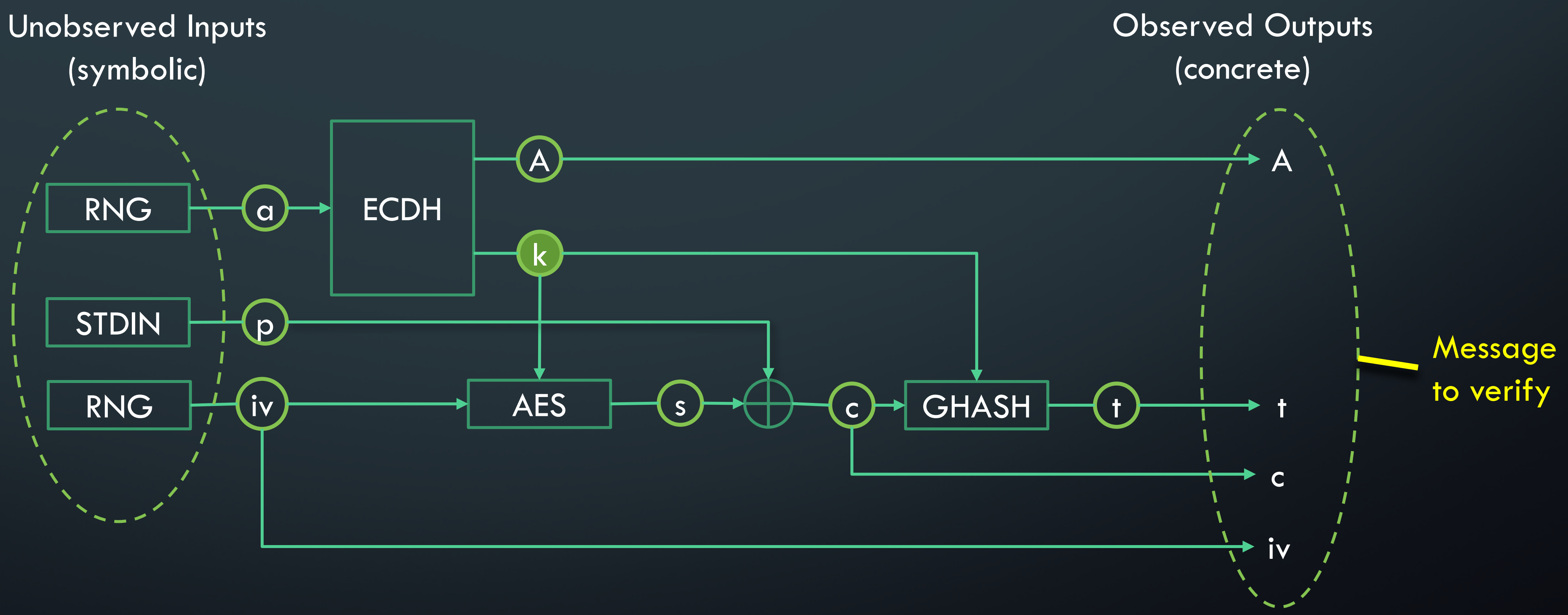


- Solution:
  - Give the verifier the session key
  - Defer executing prohibitive functions until inputs can be inferred
    - Any functions not executed then amount to assumptions

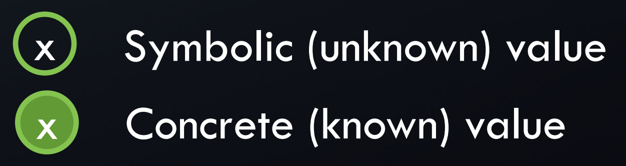
MULTIPASS SYMBOLIC EXECUTION

- Input: user specifies prohibitive functions, using an API
- Algorithm:
  1. Run symbolic execution.
     a) For each prohibitive function check if any inputs are symbolic
     b) If so, "skip" the function: return unconstrained symbolic output
     c) Otherwise, execute the function normally (all inputs are concrete)
  2. Concretize any variables with unique solution
  3. Repeat steps 1-2 until fixed point

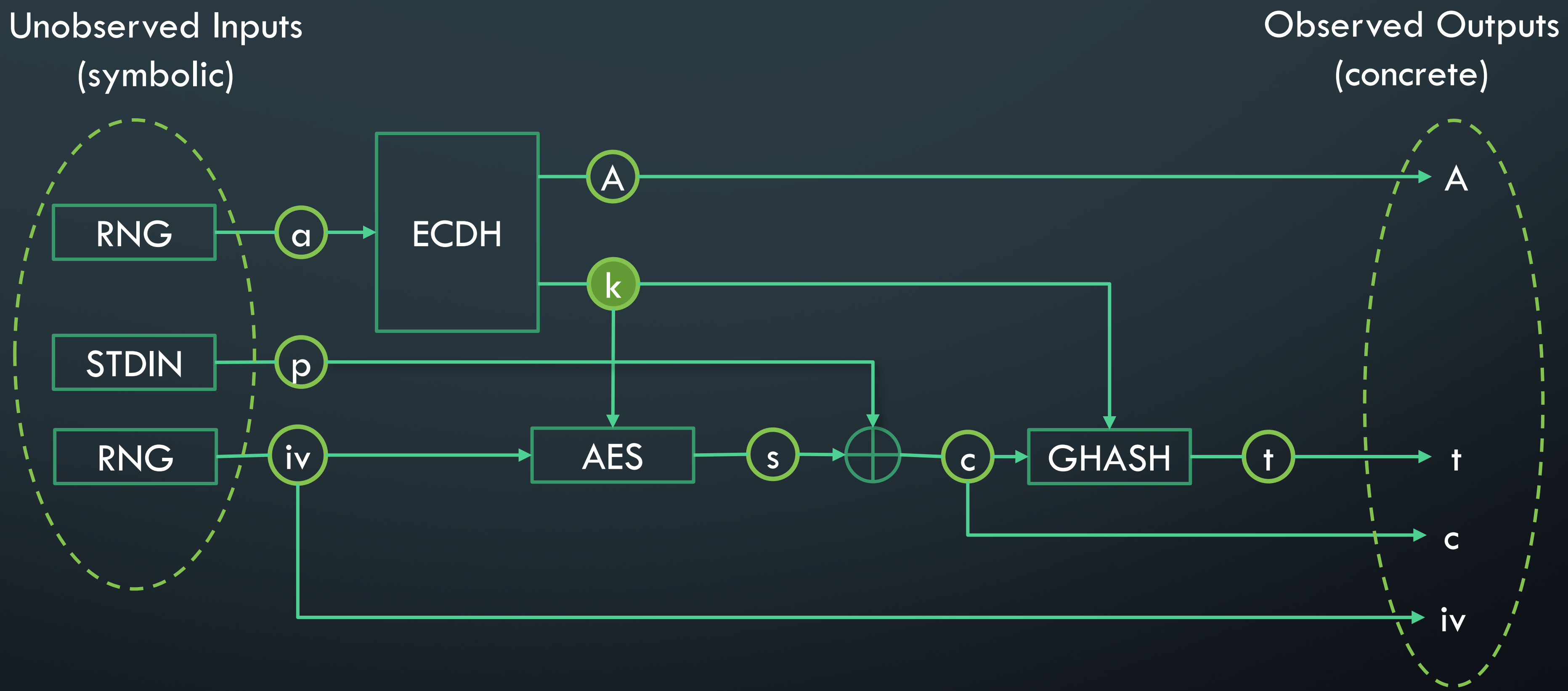
EXAMPLE: TLS CLIENT VALIDATION

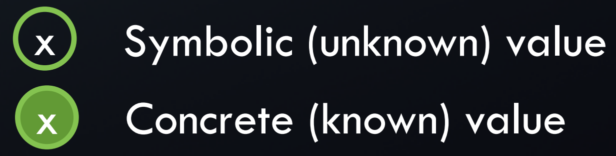


We assume knowledge of AES symmetric key, k, which is part of server state.

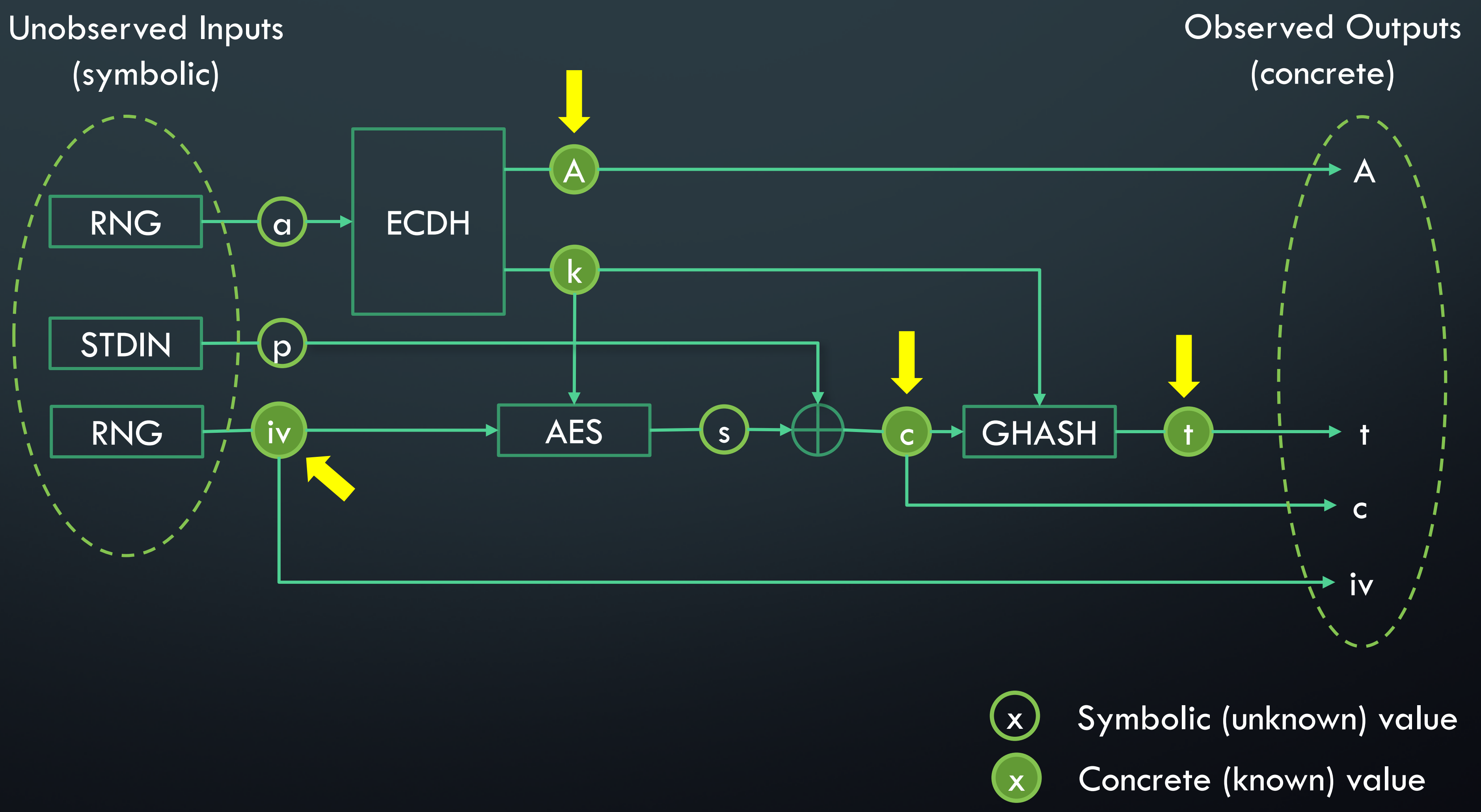


TLS CLIENT VALIDATION
PASS 1(A): SYMBOLIC EXECUTION

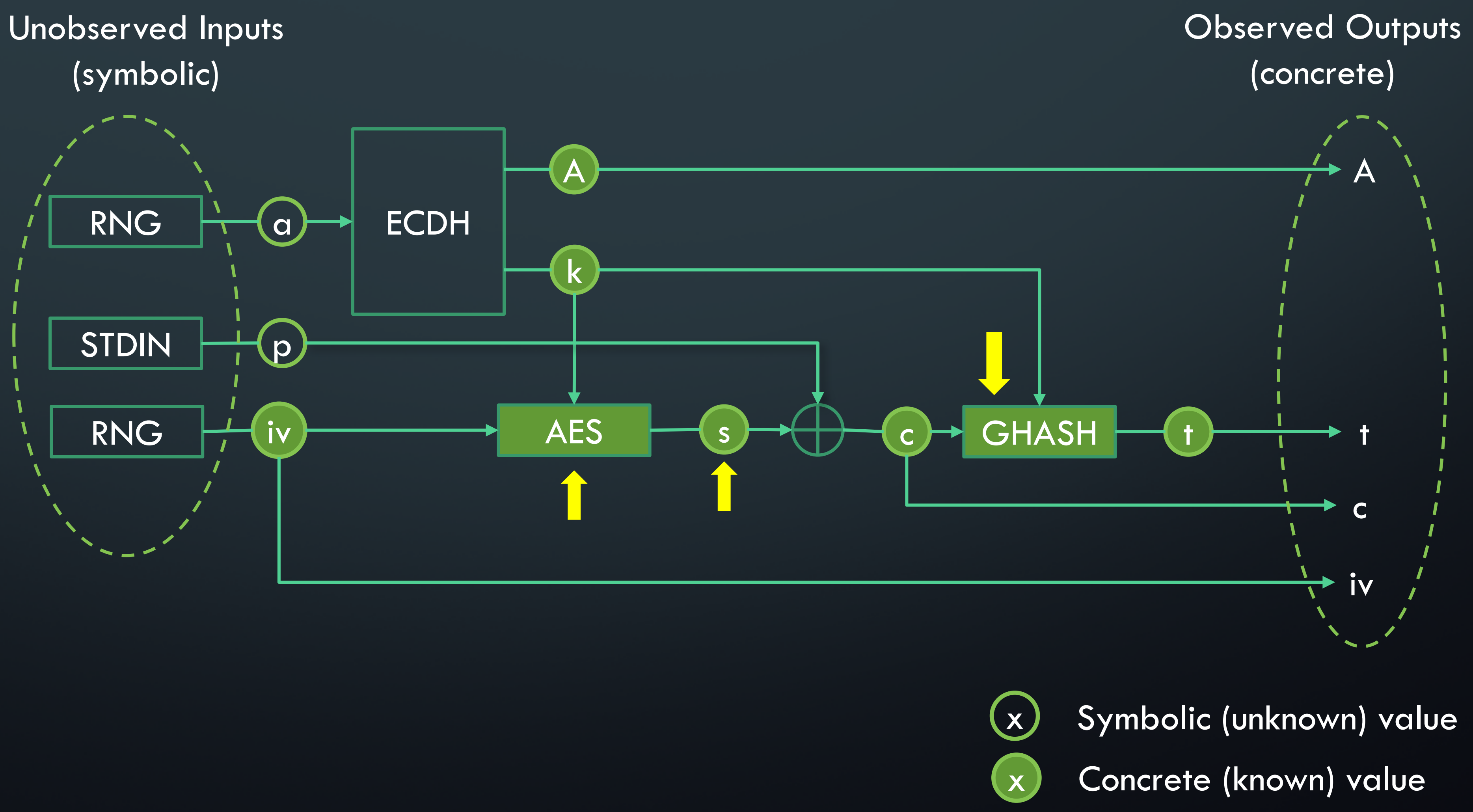




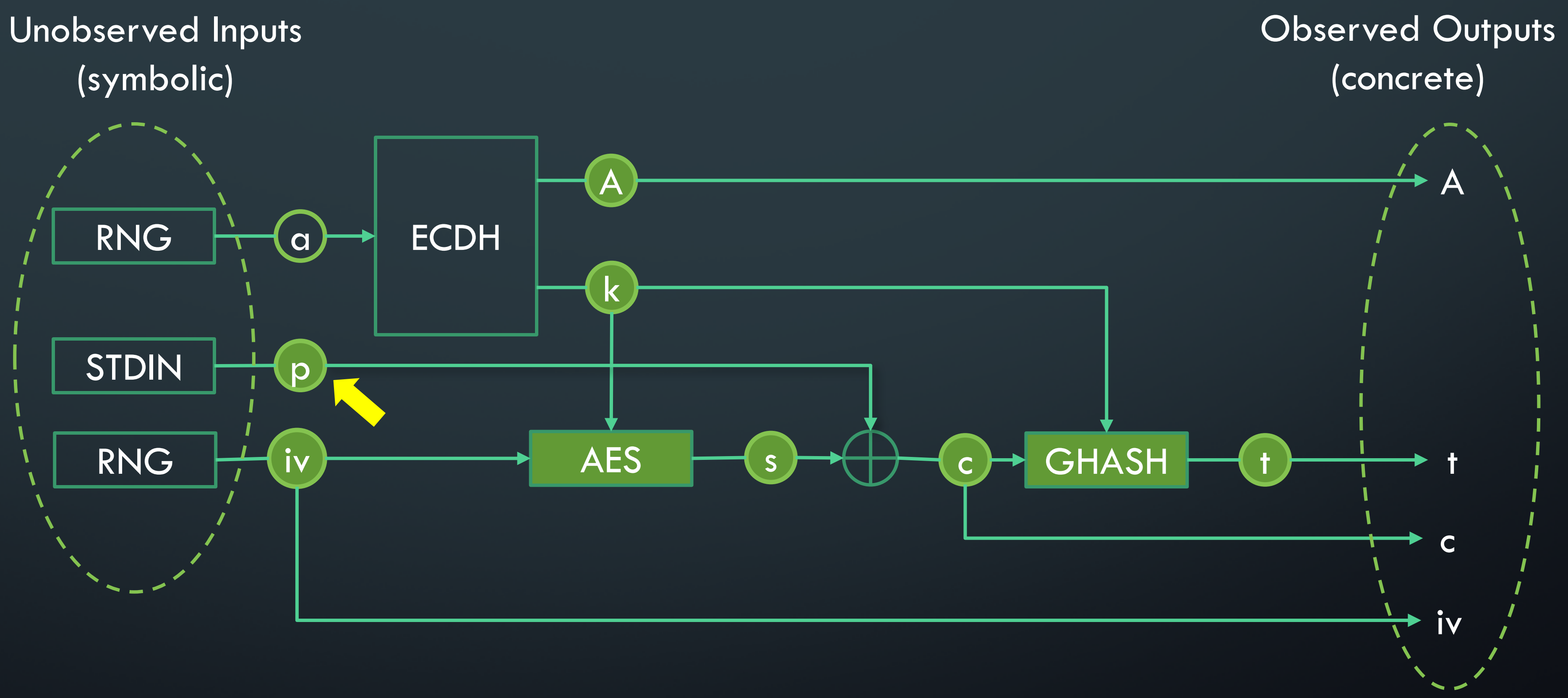
TLS CLIENT VALIDATION
PASS 1(B): CONCRETIZATION



TLS CLIENT VALIDATION
PASS 2(A): SYMBOLIC EXECUTION



TLS CLIENT VALIDATION
PASS 2(B): CONCRETIZATION

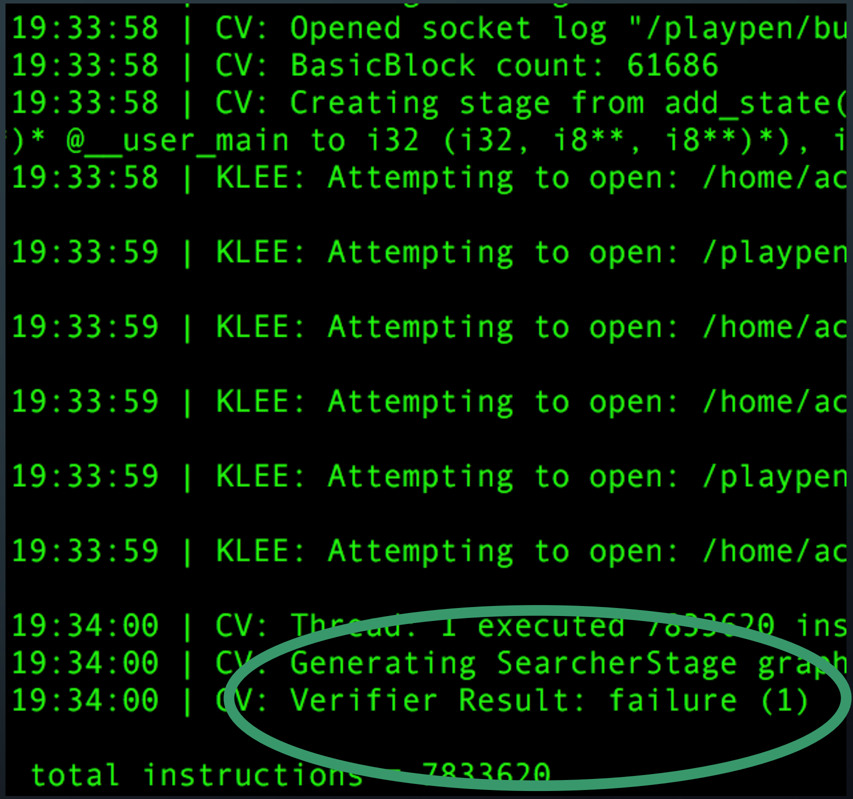


x Symbolic (unknown) value

x Concrete (known) value

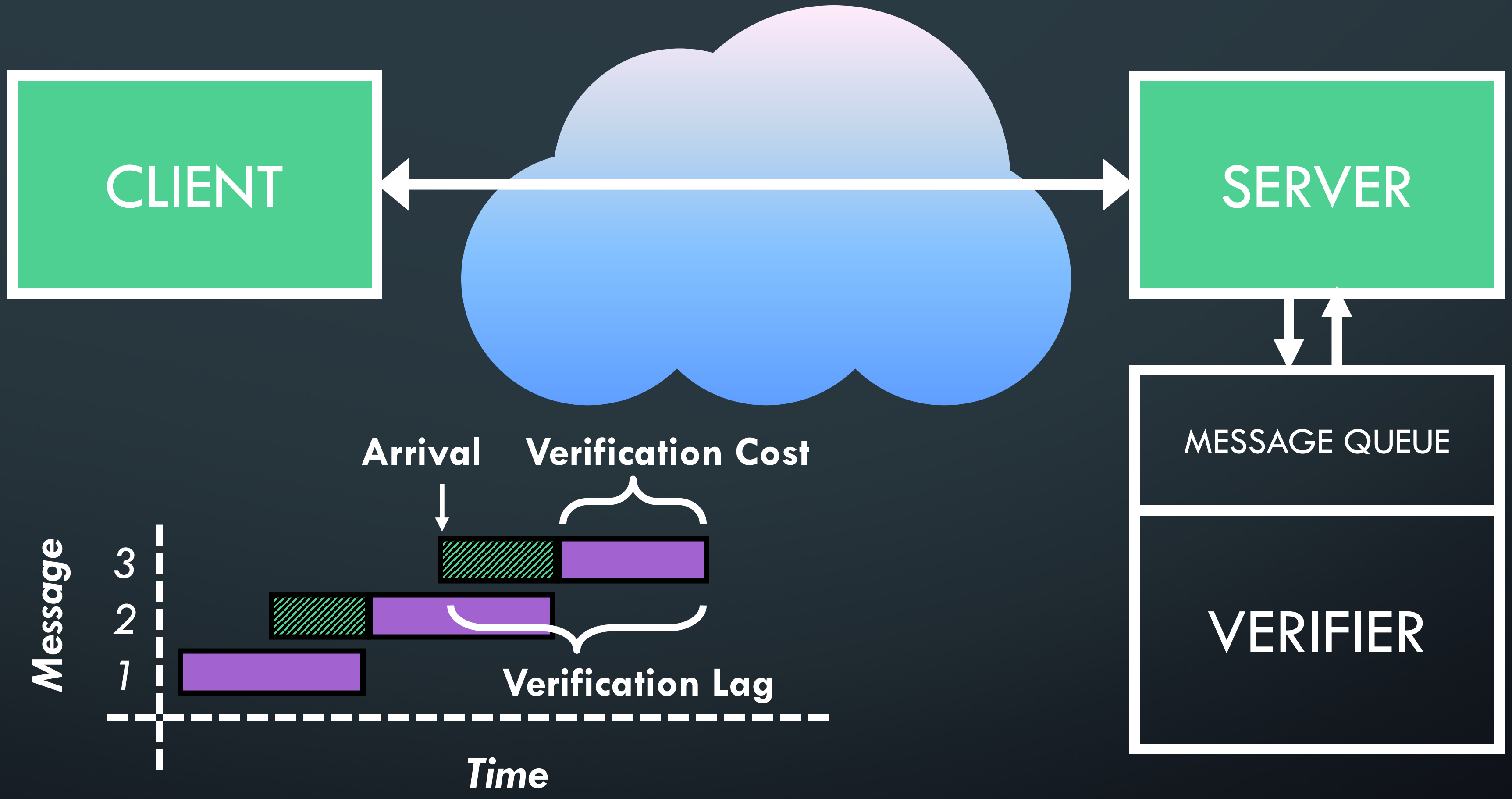
ASSESSMENT: DETECTING HEARTBLEED (WITHOUT LOOKING FOR IT)

- Malicious s_client
  - performs handshake
  - sends Heartbleed exploit
- Validation
  - Handshake is verified
  - No explanation found for malicious Heartbeat



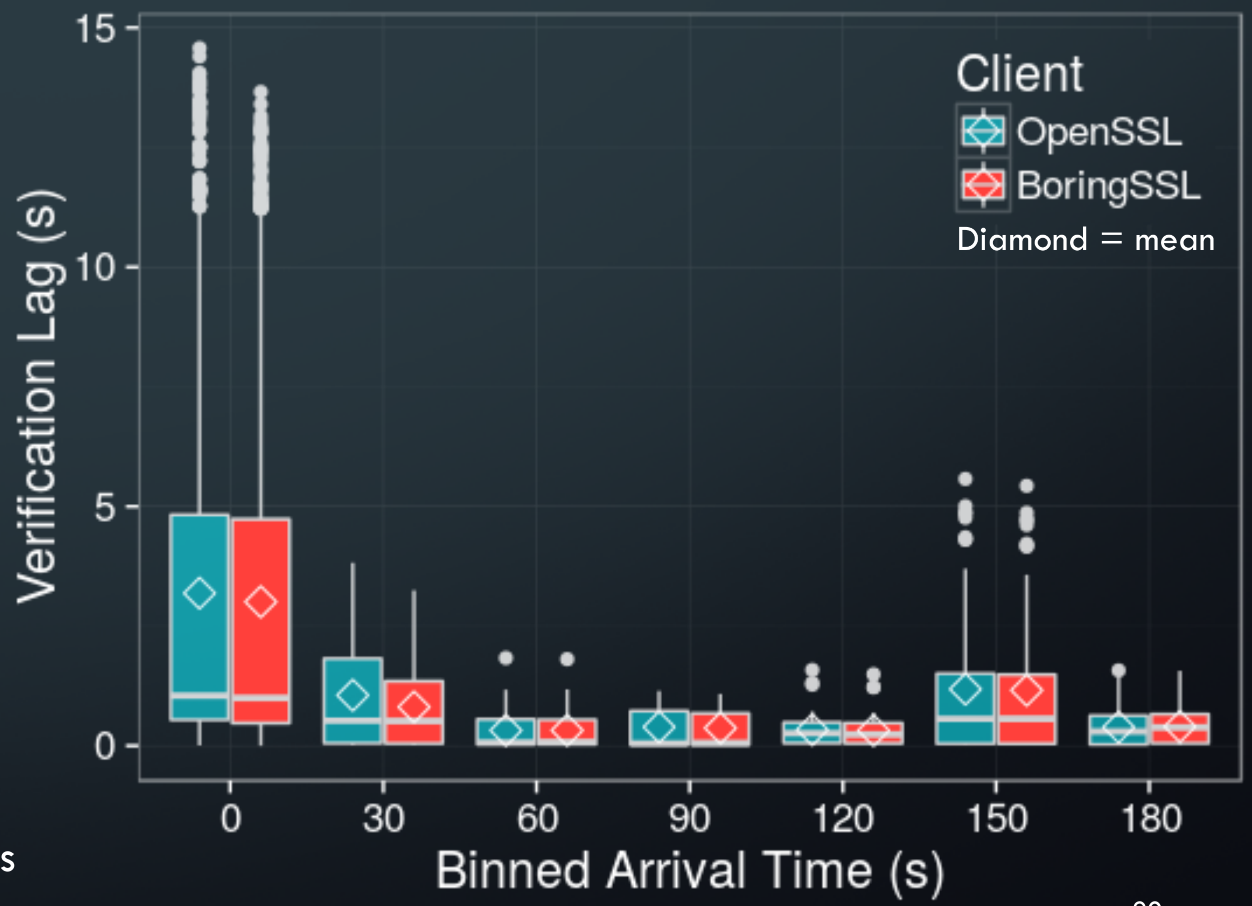
Detection in ~2s

MEASURING PERFORMANCE



PERFORMANCE EVALUATION

- 21 TLS 1.2 sessions from 3 min. of Gmail activity
- OpenSSL & BoringSSL command line clients
- Single-core verifier (3.2 GHz)
- Cost: 49ms per TLS record
- Lag: median 0.85s, max 15s



NOTE: without server-to-client appdata packets

OTHER EVALUATION MEASURES

- Parallelization / Stress Test
  - TLS 1.2 + up to 128 bytes of padding (from draft TLS 1.3)
  - 16-thread verifier keeps pace
- Invalid command attack: valid packets, illegal sequence
  - CVE-2015-0205 client authentication vulnerability
  - Verifier rejects attack traffic
- Confirm appropriateness of command line client
  - Unmodified Chrome browser interacting with Apache server
  - Verified using BoringSSL command line client

SUMMARY

- Behavioral verification for cryptographic clients
  - Multipass symbolic execution handles cryptographic functions
  - Parallelization optimizes search of large state spaces
- Detection of previously unknown client misbehavior
  - E.g., a Heartbleed exploit with no Heartbleed-specific configuration
- Performance roughly keeps pace with real workload
  - Behavioral verification on Gmail TLS sessions