# TLSkex: Harnessing virtual machine introspection for decrypting TLS communication

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31.03.2016


# Motivation

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- Encrypted communication (especially TLS) became ubiquitous in the Internet (https, voip, mail, etc.)
- **Why do we need to decrypt encrypted communication?**
  - Adversaries use encryption to hide attacks
  - Network intrusion detection systems can not decrypt network traffic (especially Infrastructure-as-a-service based Clouds)
  - Distinction between legitimate and malicious traffic is hard
  - Malware analysis

# Active Approaches

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- **Man-in-the-middle attack (MITM)**
  - Force client not to encrypt: proxy replaces `https` with `http` in URLs of websites (sslstrip [4])
  - TLS Proxy that uses a fake certificate (sslsniff [3], sslsplit [1])
- **Disadvantages:**
  - can be detected
  - does not work with certificate pinning
  - (may) reduce the security level

# Passive Approaches

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- Decryption of the traffic with the private **RSA key** (ssldump [2])
  - Key acquisition from hard disk or main memory
  - Extraction of the RSA keys from main memory (simple pattern matching for the ASN.1 structure);
- **Disadvantages:**
  - Only applicable when the hard disk or main memory can be accessed
  - not feasible for malware analysis
  - Fails when DH or ECDH session keys are used

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**Approach**

- Monitor the network traffic of virtual machines (passively)
- Extract the *TLS session keys* from main memory of virtual machines
- Disadvantage: Works only when access to main memory is given (virtual machines, Firewire, . . . )

# TLSkex Architecture

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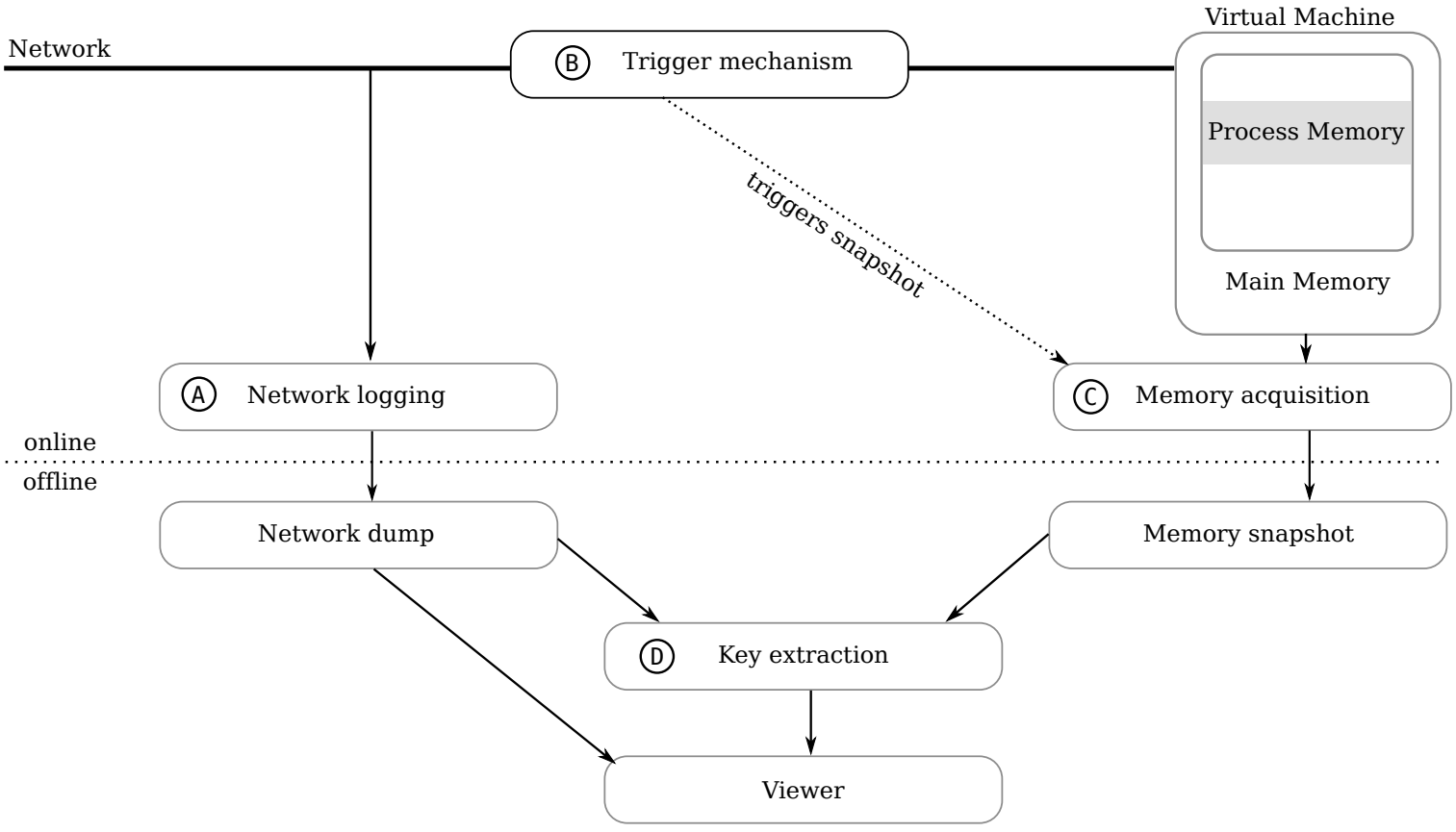

# Background: TLS Key Exchange

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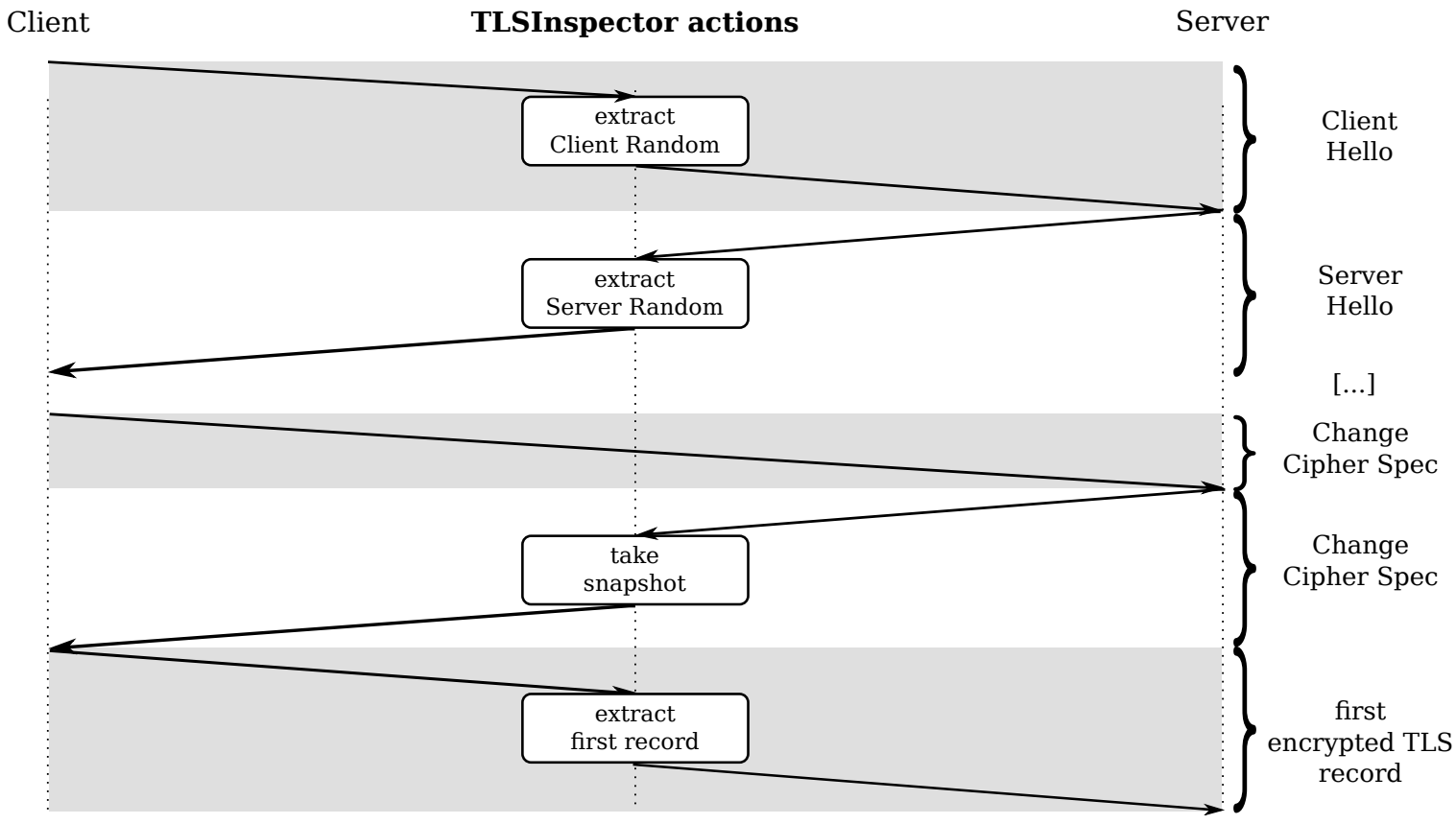

# (B) Network Monitoring

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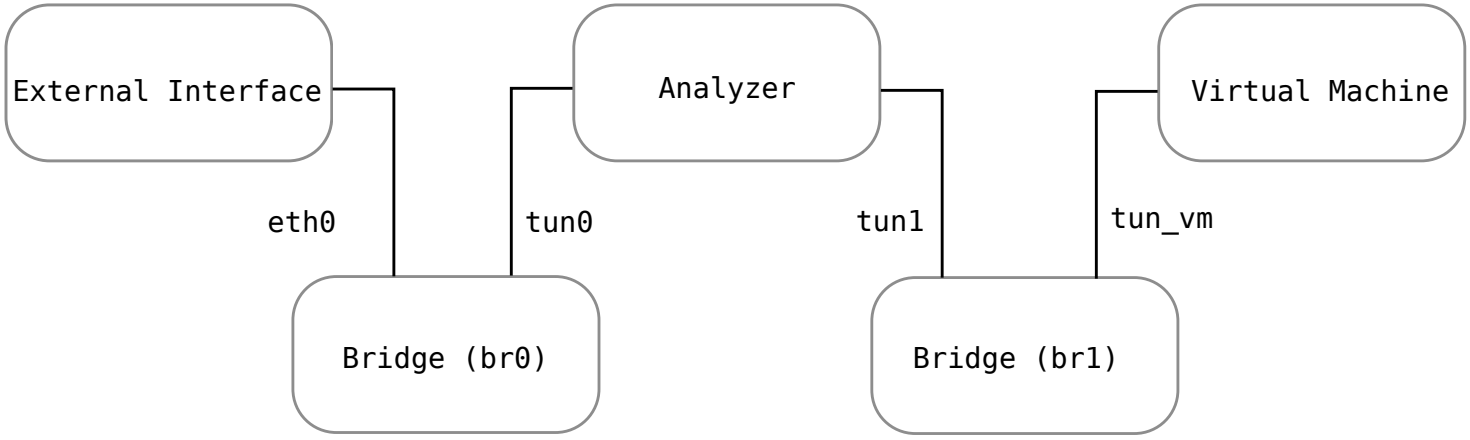


**Timing**

- Snapshot must be taken when the key material is exchanged and before the connection is terminated
- When a communication partner has computed the key material it sends a *ChangeCipherSpec* message
- TLSInspector monitors the network traffic and triggers the snapshot when a *ChangeCipherSpec* message is sent

# TLSInspector Architecture

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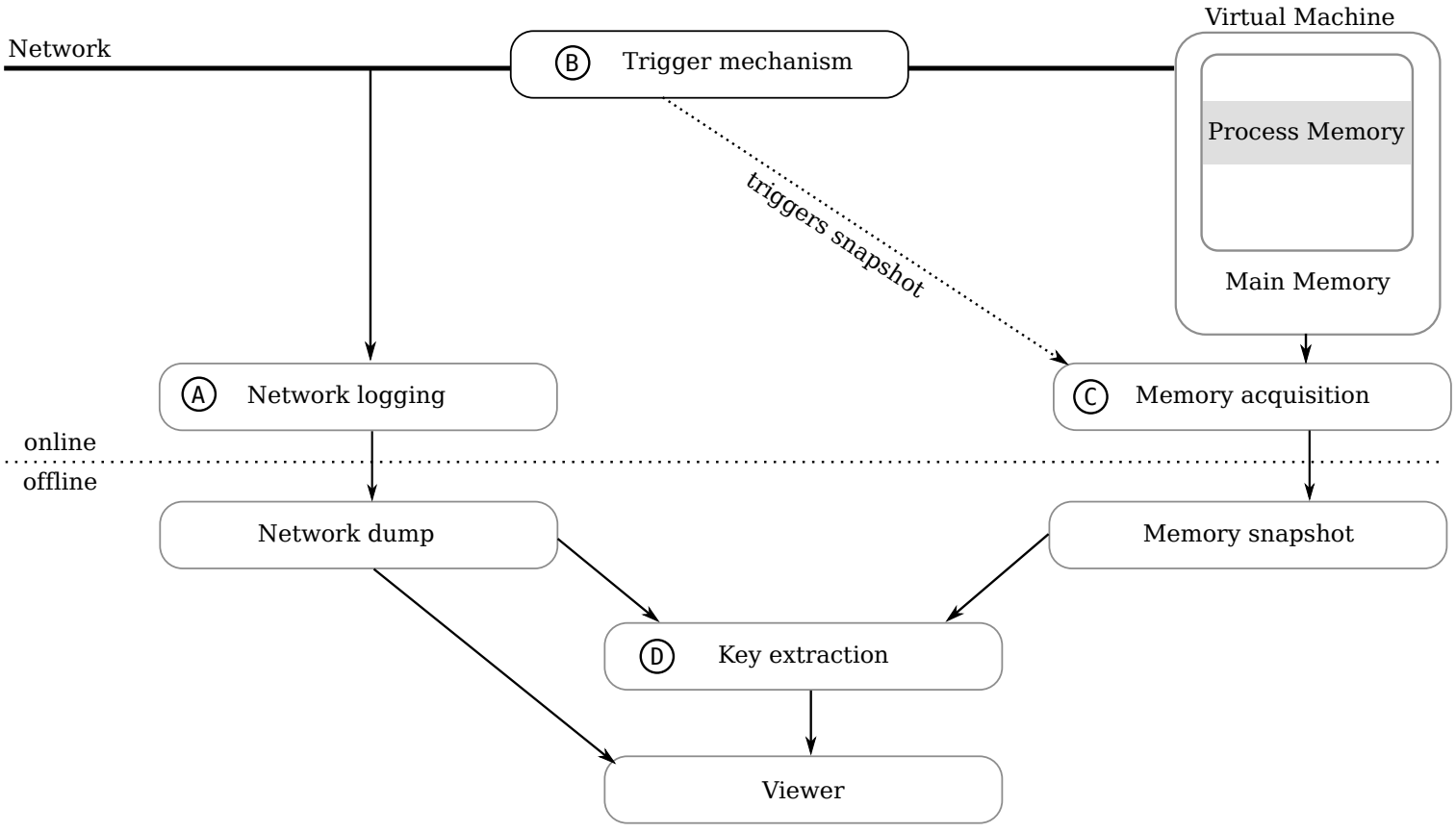

# (C) Memory Acquisition

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**Snapshot**

- The memory of a virtual machine is accessed via libVMI
- Only the memory of the process that handles the connection
- Only *write-able* and *anonymous* pages
- Extract information from kernel memory (task_struct)

# (C) Memory Acquisition - Improved

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**Save only modified pages**

- Set memory event on every page of a process when TCP connections is established
- Save dirty pages
- When hand shake is done, take snapshot of
  - dirty pages
  - newly allocated pages

# Background: TLS Key Exchange

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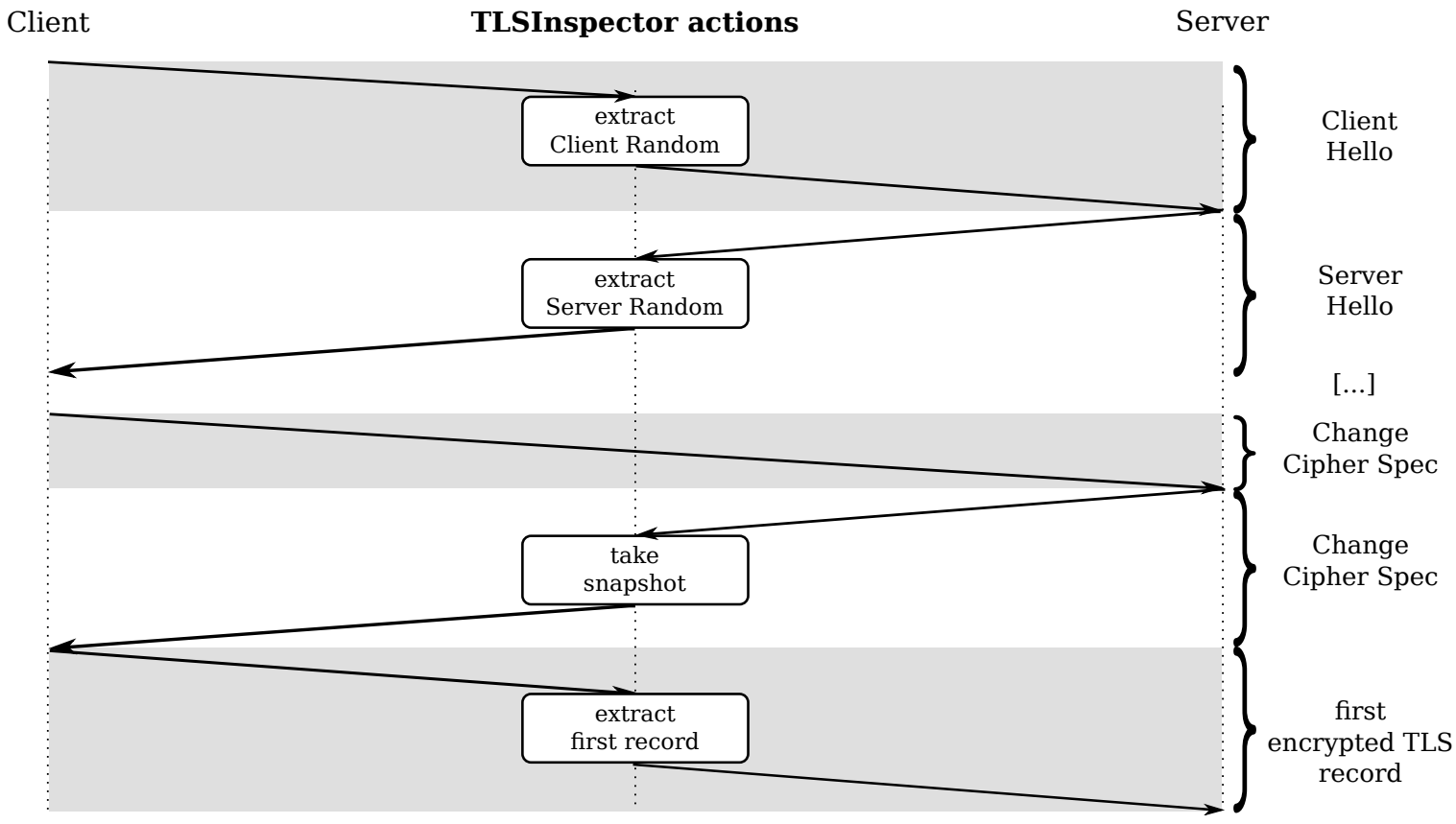

# Evaluation - Snapshot time

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| Process | total | anon&writeable | new | modified | dumped | $t_{snap\_start}$ | $t_{snap\_stop}$ | $t_{search}$ |
|---|---|---|---|---|---|---|---|---|
| Apache2 | 72090 | 3715 | 0 | 26 | 26 | 4.3 ms | 4.4 ms | 30 ms |
| Curl | 38264 | 3438 | 15 | 19 | 34 | 3.3 ms | 4.0 ms | 2 ms |
| Wget | 22813 | 1378 | 16 | 13 | 29 | 4.0 ms | 3.5 ms | 2 ms |
| s_client | 6114 | 152 | 9 | 22 | 31 | 0.4 ms | 0.6 ms | 8 ms |

Table: Amount of mapped and changed memory pages (4096 bytes) of different processes during the key negotiation procedure and the time to prepare ($t_{snap\_start}$) and take ($t_{snap\_stop}$) a differential snapshot; $t_{search}$ denotes the time to extract a key from a snapshot

# TLSInspector Architecture

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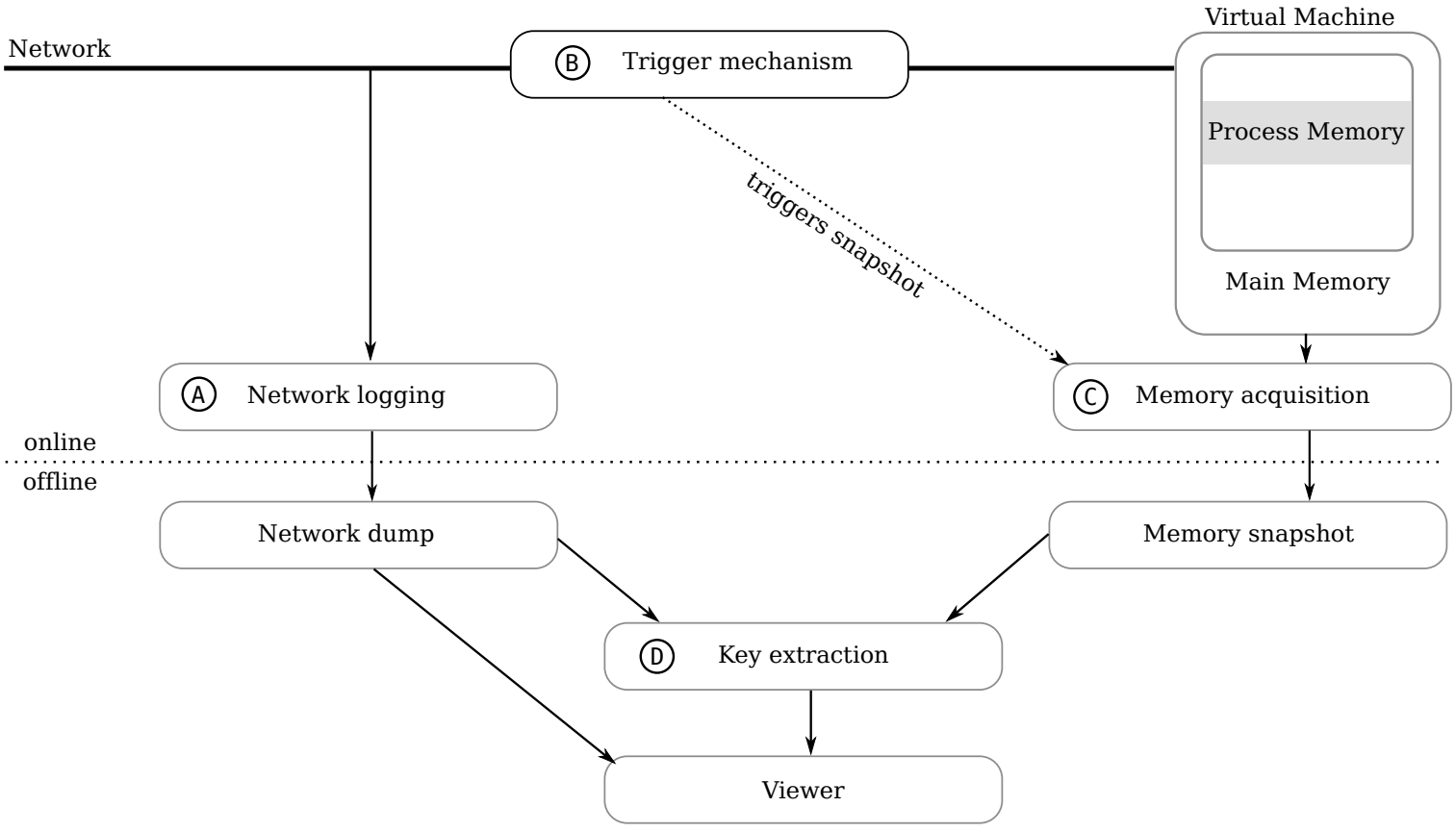

# (D) Key Extraction

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**Problem**

- There is no standardized way to store TLS session keys in memory

**Brute force approach**

- Test every byte sequence as a key for the TLS connection
- Use message authentication code in TLS record to verify if key is corrected and data has been decrypted correctly
- **Advantage:** Implementation independent
- **Problem:** Attacker can fool monitoring tool, e.g., split key

# (D) Key Extraction Improvements

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- Test only 4 byte aligned sequences
- Skip null byte areas
- Heuristics - Pretest keys
  - check if it is ASCII string
  - compare amount of zeroes and ones, should be uniformly distributed (k: deviation from expected mean)

$$\sum_{\mu-k}^{\mu+k} \binom{n}{k} p^k * (1-p)^{n-k} >= 0.89$$

$$k = 16, \mu = 192, p = 0.5$$

# Evaluation - Heuristics

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| | a | | | | | | b | c | d |
|---|---|---|---|---|---|---|---|---|---|
| **Process** | **k=1** | **k=2** | **k=4** | **k=8** | **k=16** | **k=32** | **no string** | **not all 0 / 1** | **combined (k=16)** |
| key included | 8.12 | 16.2 | 31.6 | 58.5 | 89.7 | 99.9 | $1 - 10^{-15}$ | $1 - 10^{-19}$ | 87.7 |
| Apache2 | 0.10 | 0.28 | 0.64 | 1.27 | 2.33 | 4.26 | 85.49 | 43.54 | 1.69 |
| Curl | 0.15 | 0.45 | 1.04 | 2.11 | 3.50 | 4.75 | 77.53 | 10.55 | 3.32 |
| Wget | 0.15 | 0.46 | 1.06 | 2.15 | 3.60 | 4.91 | 78.10 | 10.68 | 3.38 |
| s_client | 0.054 | 0.18 | 0.49 | 0.96 | 1.89 | 3.40 | 56.52 | 37.35 | 1.63 |

Table: First row: probability that a key is not eliminated by the heuristic. Other rows: percentage of a memory snapshot that contains a 48 byte long and four byte aligned sequence with: a) $192 \pm k$ one bits, b) the byte sequence is not an ASCII string c) no 8 byte sequence with only zero or only one bits d) a to c combined

# Discussion

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- Easy to circumvent:
  - Start dedicated crypto process
  - Store key not in a 48 byte sequence
  - Mix byte order
  - Use different protocol or change TLS slightly
- Are kernel structures still trustworty?
- Potential DoS vector?
- Ethical considerations

# Conclusion

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**Non Intrusive**

- No active manipulation of communication
- No modification of application

**Universal:**

- Independence of specific key exchange
- Independence of encryption algorithm
- Independence of client/server role
- Independence of the implementation

# Questions

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