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Let SDN Be Your Eyes: Secure Forensics in Data Center Networks

Adam Bates
University of Oregon

Kevin Butler
University of Oregon

Andreas Haeberlen
University of Pennsylvania

Micah Sherr
Georgetown University

Wenchao Zhou
Georgetown University

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Secure Forensics

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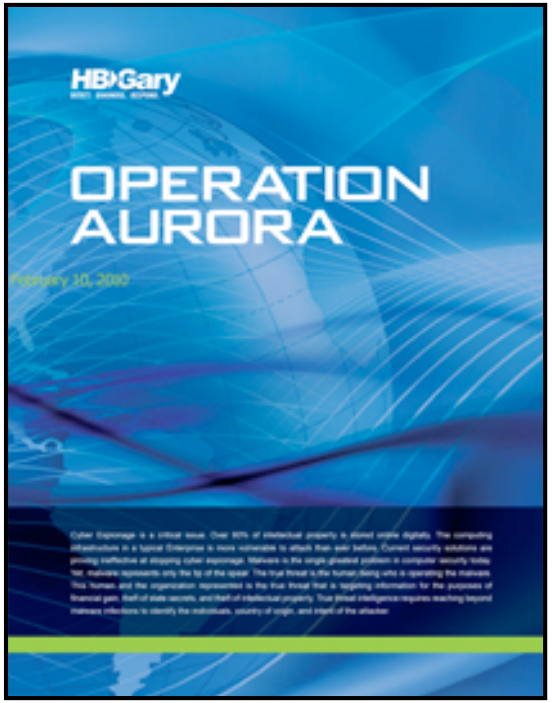
- Investigating the possibility of a security breach is extremely difficult.
- When suspicious events may be malicious or benign, finding an explanation for the event can be a tedious, manual task.
- Due to the possibility of advanced persistent threats, fast detection and investigation of anomalies is essential.



Secure Forensics

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When parts of your network have been compromised, who can you trust to provide answers about the attack??

Let SDN Be Your Eyes

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- We propose that Software Defined Networking (SDN) can be used to bootstrap trust in network forensics for data centers.
- We present an SDN-based *network provenance* system that extends into the network itself, creating a secure monitoring layer for all network activity.
- Our system possesses the ability to:
  - **Detect Covert Communication**
  - **Detect Equivocation**
  - **Detect Missing Forensic Records**

Unexpected Behavior?

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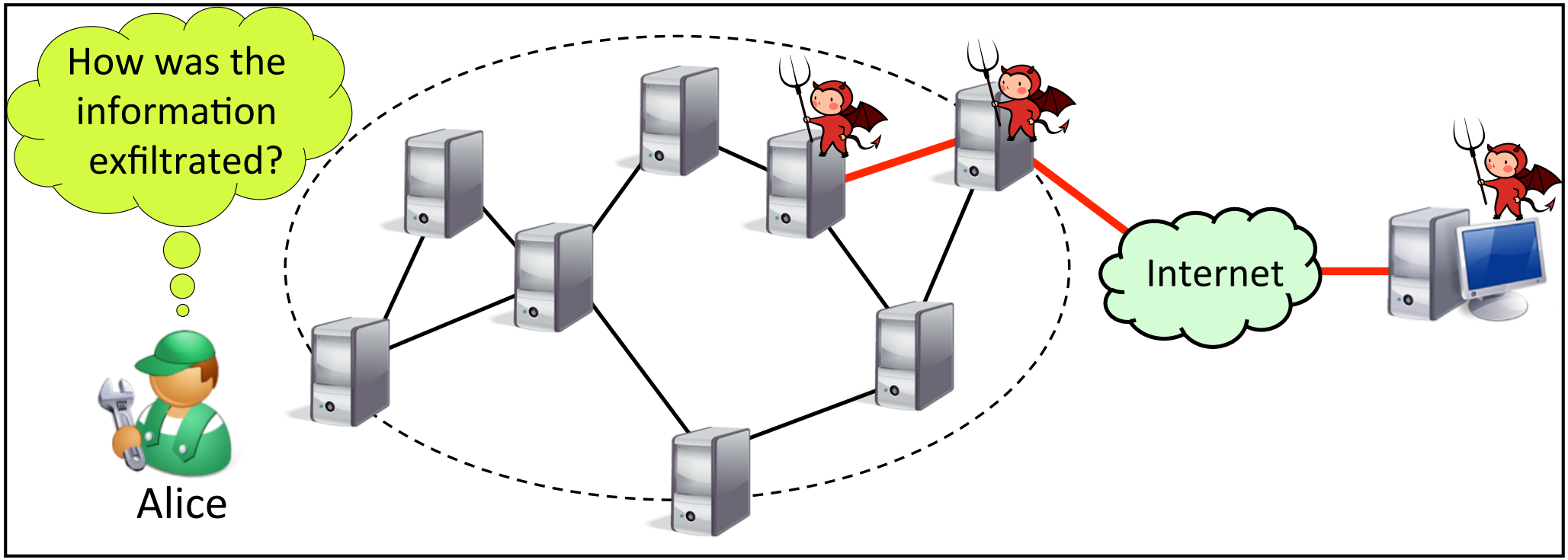
Question: *Who can Alice trust for answers about the network?*



Unexpected Behavior?

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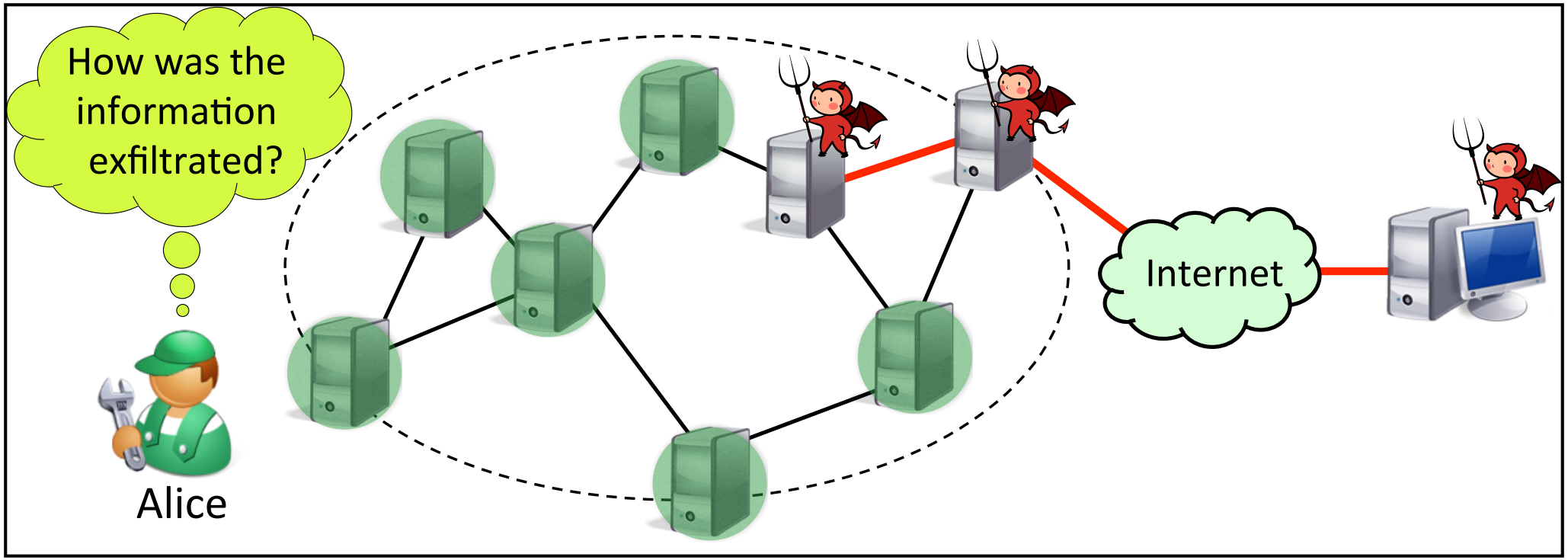
Question: *Who can Alice trust for answers about the network?*



Answer: *Trust the available correct nodes in the network.*

(Secure Network Provenance [ZFN+2011])

Secure Network Provenance [ZFN+2011]

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- Secure Network Provenance (SNP) constructs a *provenance graph* based on system execution.
- Each node manages its own tamper evident log and follows an inter-node message commitment protocol.
- An administrator queries nodes' logs to reconstruct a provenance graph, detecting faulty nodes through finding inconsistencies and omissions.
- **Limitation**: SNP anchors trust in a critical mass of *correct* nodes; its view of the network shrinks as more nodes fail or are compromised.

Secure Network Provenance [ZFN+2011]

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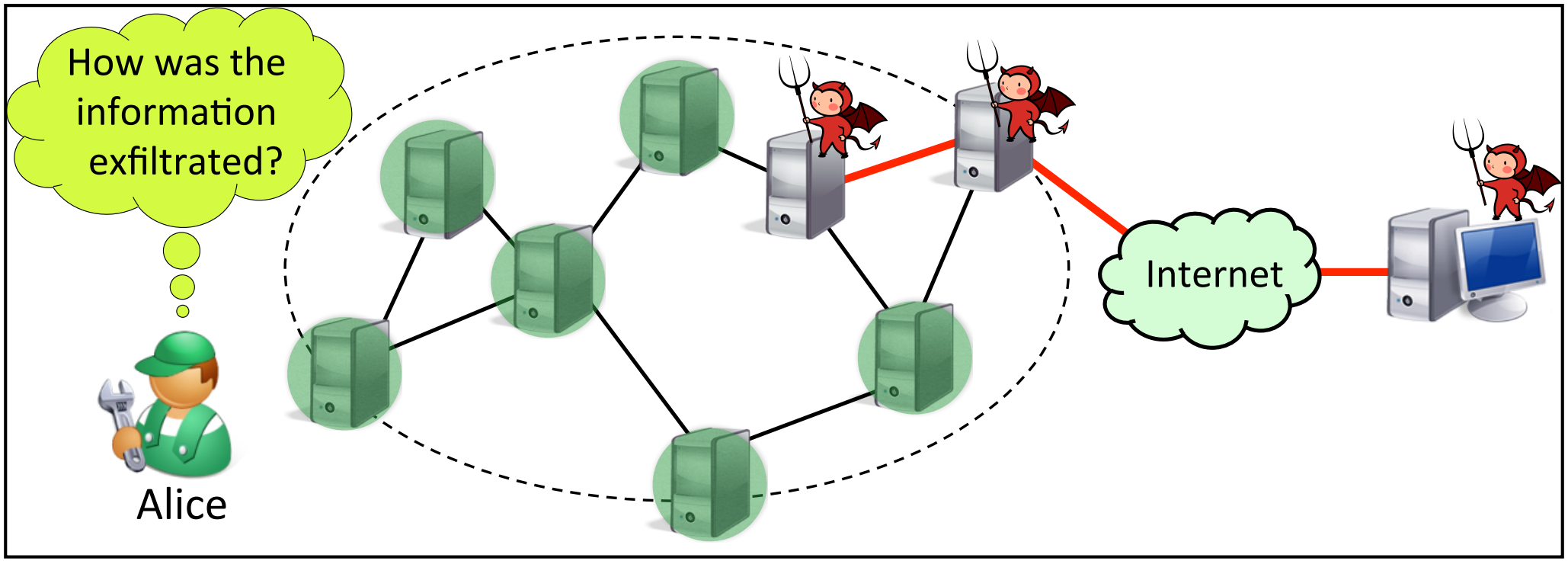

- **Limitation**: SNP anchors trust in a critical mass of *correct* nodes; its view of the network shrinks as more nodes fail or are compromised.

Secure Network Provenance [ZFN+11]

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Our Key Insight: Instead of anchoring trust at the host, we can use SDN to bootstrap trust in provenance-based network forensics.

- **Limitation**: SNP anchors trust in a critical mass of *correct* nodes; its view of the network shrinks as more nodes fail or are compromised.

Software-Defined Networking

- Programmable switches that facilitate decoupling of network's *data plane* from an abstract *control plane*.
- A Network Controller can instruct switches to handle flows in different ways. This is accomplished by pattern matching on network packet headers.
- SDN switches offer modest on-board functionality for packet processing, such as forwarding, dropping, flooding, header modification, etc.
- Higher-level network functionality is achieved by forwarding packets to "Middleboxes", which can actually now be placed anywhere in the network.

Security Goals

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Our system sets the following security goals:

- **Prevent Covert Communication**: eliminate all unmonitored paths for explicit communication between nodes within the network.
- **Detect Equivocation**: catch nodes that attempt to make inconsistent claims about their activities.
- **Response Availability**: In the event that message transcripts are missing, this should always be detectable by the system and the administrator.

Threat Model & Assumptions

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- Nodes are subject to Byzantine Faults due to compromise or system failure.
- Faulty nodes may take actions collectively or individually to hide their presence from administrators.
- ALL communication in the network takes place over a network of SDN switches.
- SDN switch security, while important, is also not considered here. Switches are trusted.

SDN Building Blocks

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What do we need from SDN?

- We are looking for a trustworthy *global observer* of network events.
- Since SDN switches offer constrained functionality, we introduce **Provenance Verification Points (PVP),** a middlebox for forensic analysis of network packets.
- Switches force all flows through a PVP.
- Switches perform access control of network resources through communication with the PVP/Controller.

Provenance Verification Points

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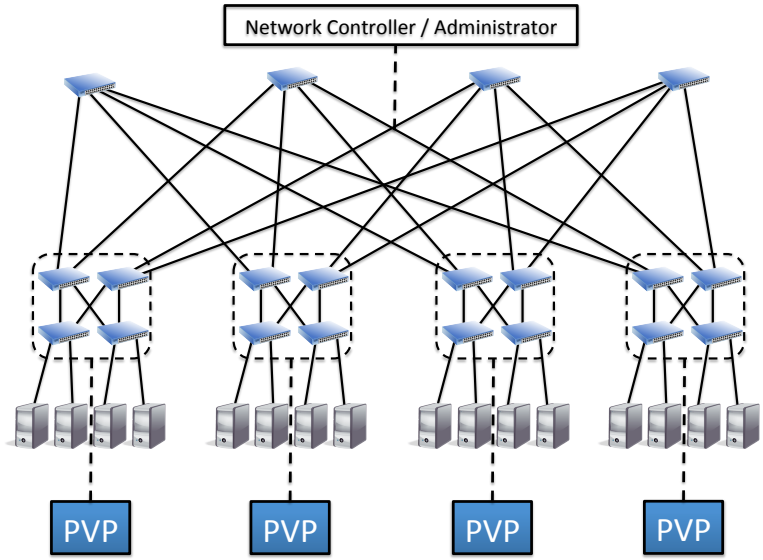
- Provide a verification layer to a host-level message commitment protocol [HKD07].
- *All* network traffic is duplicated at the switch and forwarded to both the recipient and a PVP.
- During forensic investigation, the administrator queries both the nodes and the PVP in order to get an accurate explanation for network activity.



PVPs are a distributed set of middleboxes that observe and record node-to-node communications.

Design Consideration #1

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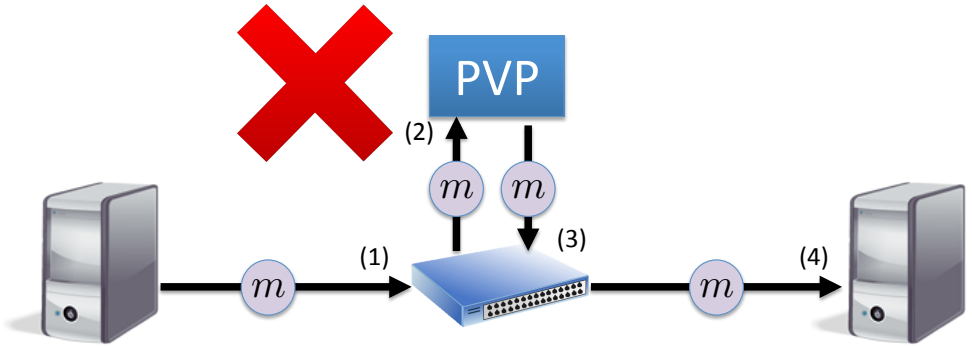
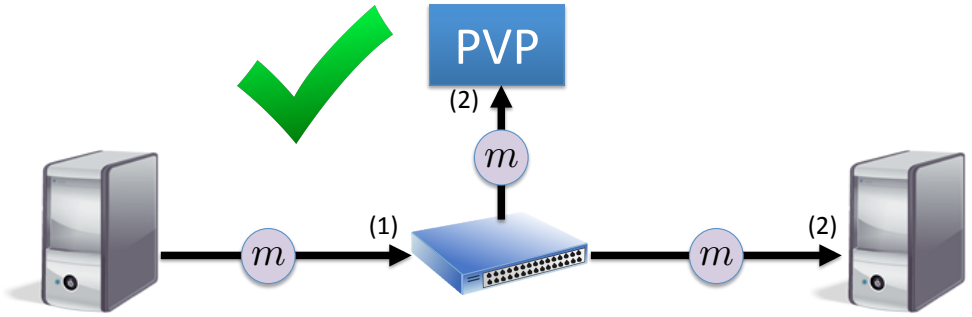
Should the PVPs interpose on traffic, or receive mirrored traffic?

- Interposition imposes additional latency.
- Mirroring means that PVPs cannot actively detect or prevent exfiltration, but…
- If a protocol violation is detected, the PVP notifies the Network Controller to isolate the culprit.



Option 1: PVPs intercept all messages.



Option 2: PVPs receive copies of all messages.

Design Consideration #2

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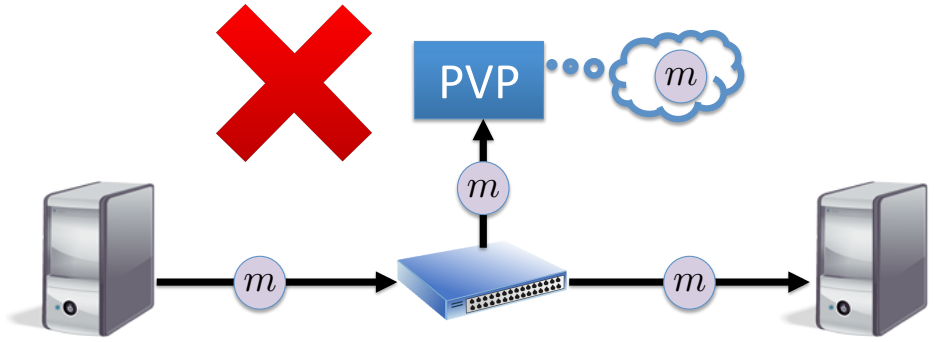
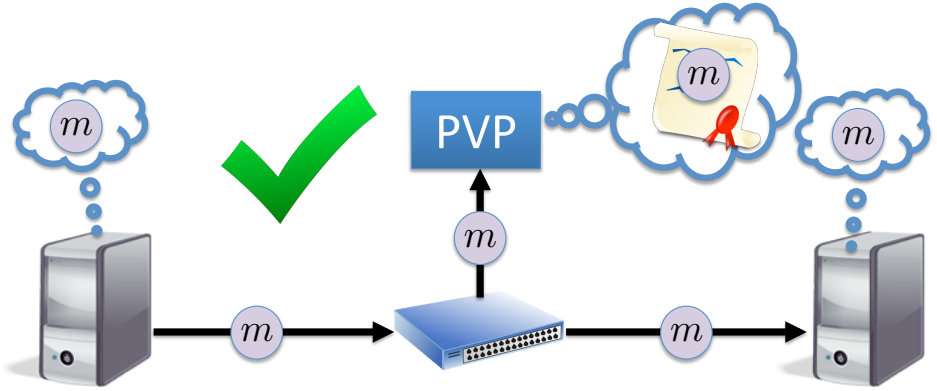
Should nodes participate in the network provenance protocol?

- *IF PVPs are more trustworthy,* cutting out nodes would be more secure…
- But if PVPs do ALL of the work, it will be difficult to keep up with the network in real time…
- Instead, the PVP performs the minimum work needed to assure security goals.



Option 1: PVP is solely responsible for message tracking.



Option 2: Nodes track messages sent and received, PVP maintains minimal proof of transmissions.

Message Commitment Protocol

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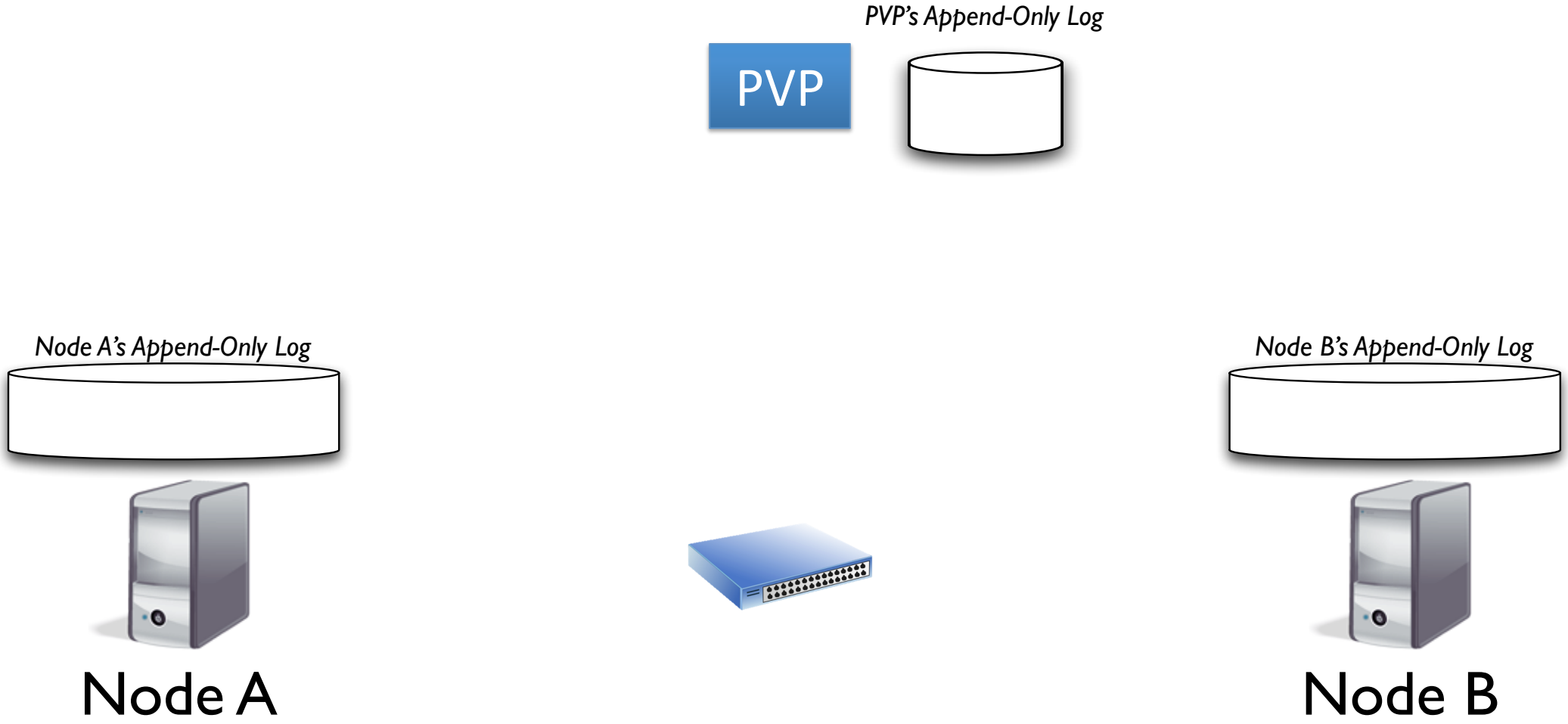
Node *A* wishes to send a message *m* to Node *B*…



Message Commitment Protocol

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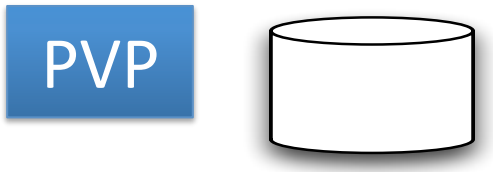
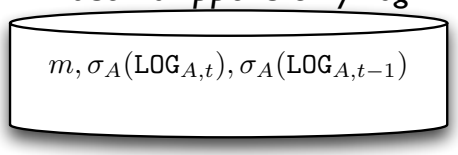
Node *A* wishes to send a message *m* to Node *B*…

Node A records *m*, a signature of his log at the current time, and a signature of his log at the immediate previous time.

PVP's Append-Only Log



Node A's Append-Only Log



Node A

Node B's Append-Only Log

Node B

Message Commitment Protocol

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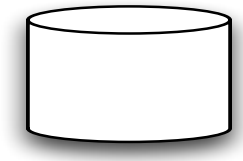
Node *A* wishes to send a message *m* to Node *B*…

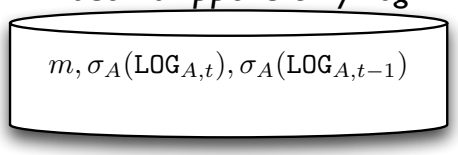
Node A then sends the message and log commitments to Node B.

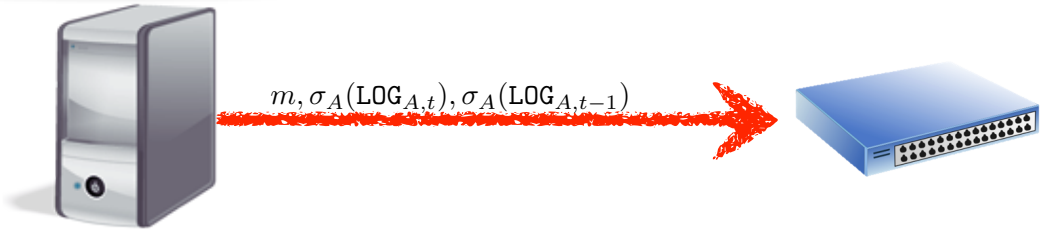
PVP's Append-Only Log

PVP



Node A's Append-Only Log





Node A

Node B's Append-Only Log

Node B

Message Commitment Protocol

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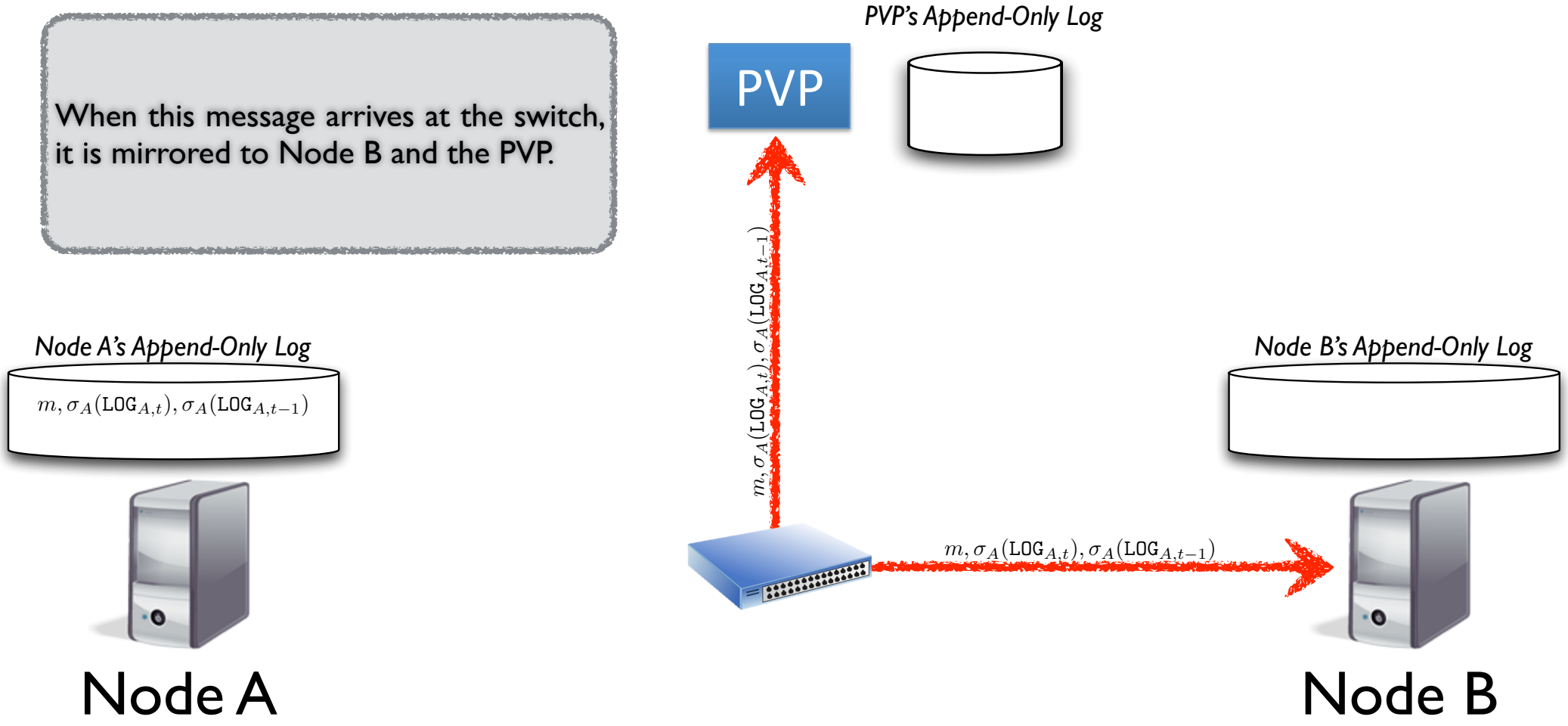
Node *A* wishes to send a message *m* to Node *B*…

When this message arrives at the switch, it is mirrored to Node B and the PVP.



Message Commitment Protocol

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Node *A* wishes to send a message *m* to Node *B*…

After verifying the signatures, Node B logs the entire message from Node A. However, the PVP logs just the current signature (or "authenticator").

PVP's Append-Only Log

PVP

$\sigma_A(\texttt{LOG}_{A,t})$

Node A's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$

Node B's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$

Node A

Node B

Message Commitment Protocol

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Node *A* wishes to send a message *m* to Node *B*…

Node B ACK's message *m* by following the same procedure, logging the message and then sending an ACK of *m* and log signatures back to Node A.

PVP's Append-Only Log

PVP

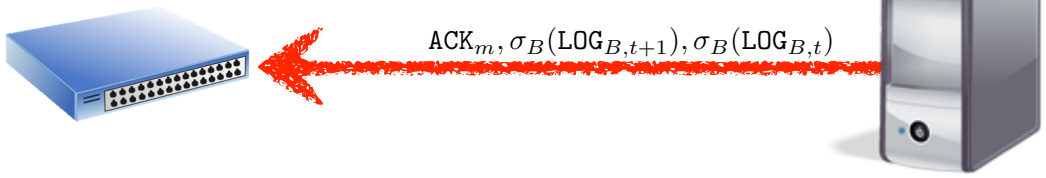
$\sigma_A(\texttt{LOG}_{A,t})$

Node A's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$

Node B's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$
$\texttt{ACK}_m, \sigma_B(\texttt{LOG}_{B,t+1}), \sigma_B(\texttt{LOG}_{B,t})$



Node A

Node B

Message Commitment Protocol

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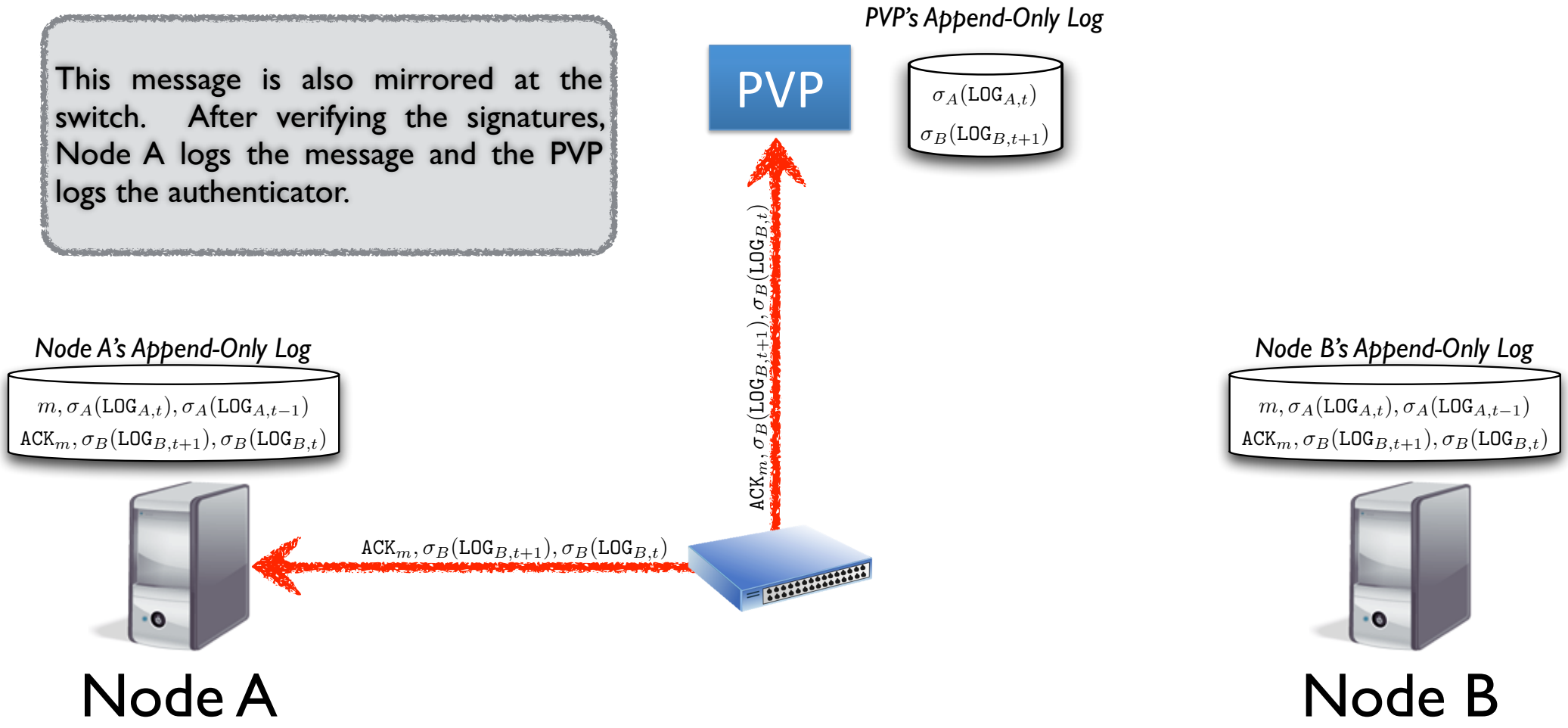
Node *A* wishes to send a message *m* to Node *B*…

This message is also mirrored at the switch. After verifying the signatures, Node A logs the message and the PVP logs the authenticator.



Querying

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Administrator asks "*Why did m exist at time t?*"

Node A's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$
$\texttt{ACK}_m, \sigma_B(\texttt{LOG}_{B,t+1}), \sigma_B(\texttt{LOG}_{B,t})$

Node A

PVP's Append-Only Log

$\sigma_A(\texttt{LOG}_{A,t})$
$\sigma_B(\texttt{LOG}_{B,t+1})$

PVP

Node B's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$
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Node B

Querying

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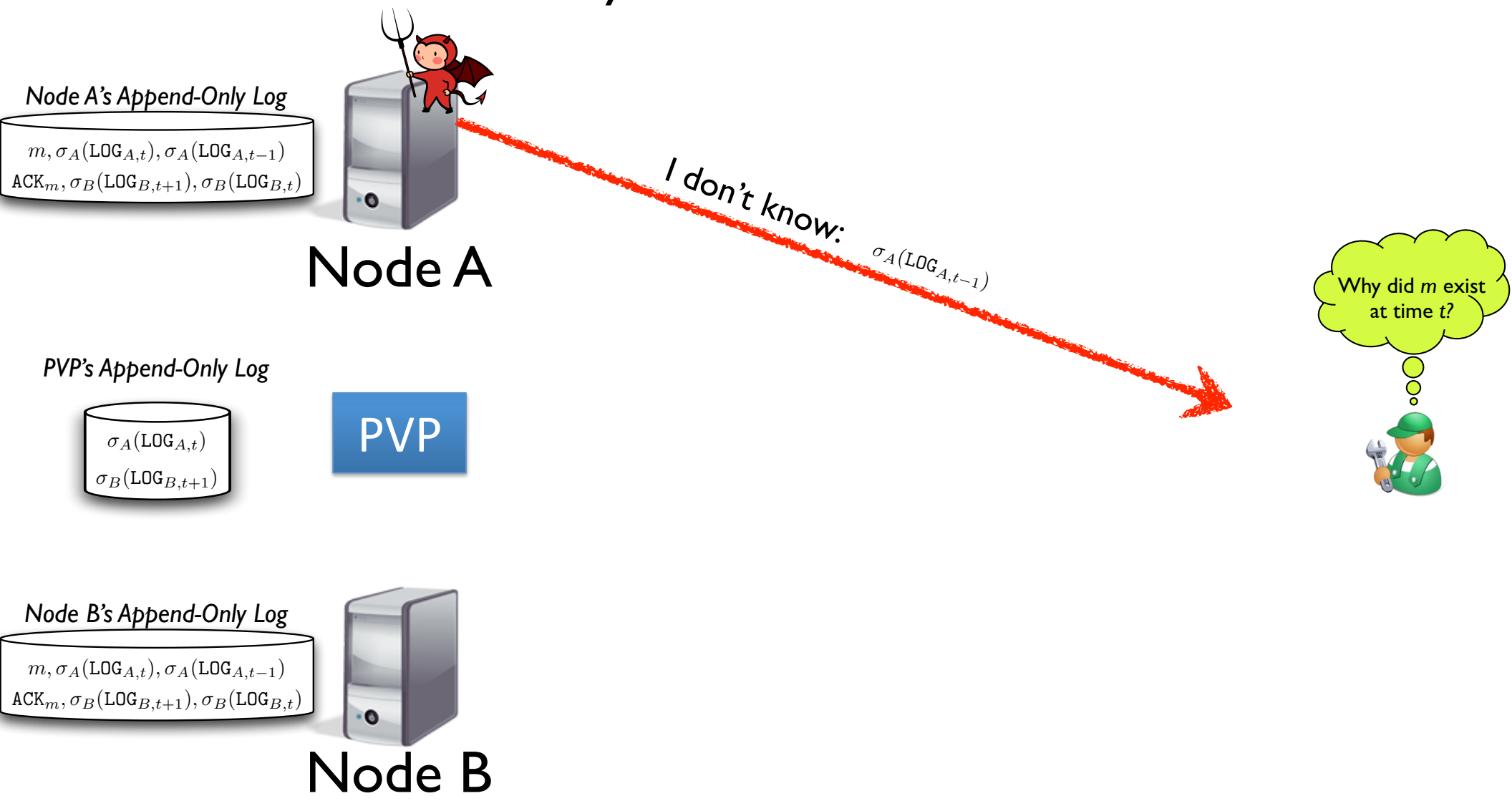

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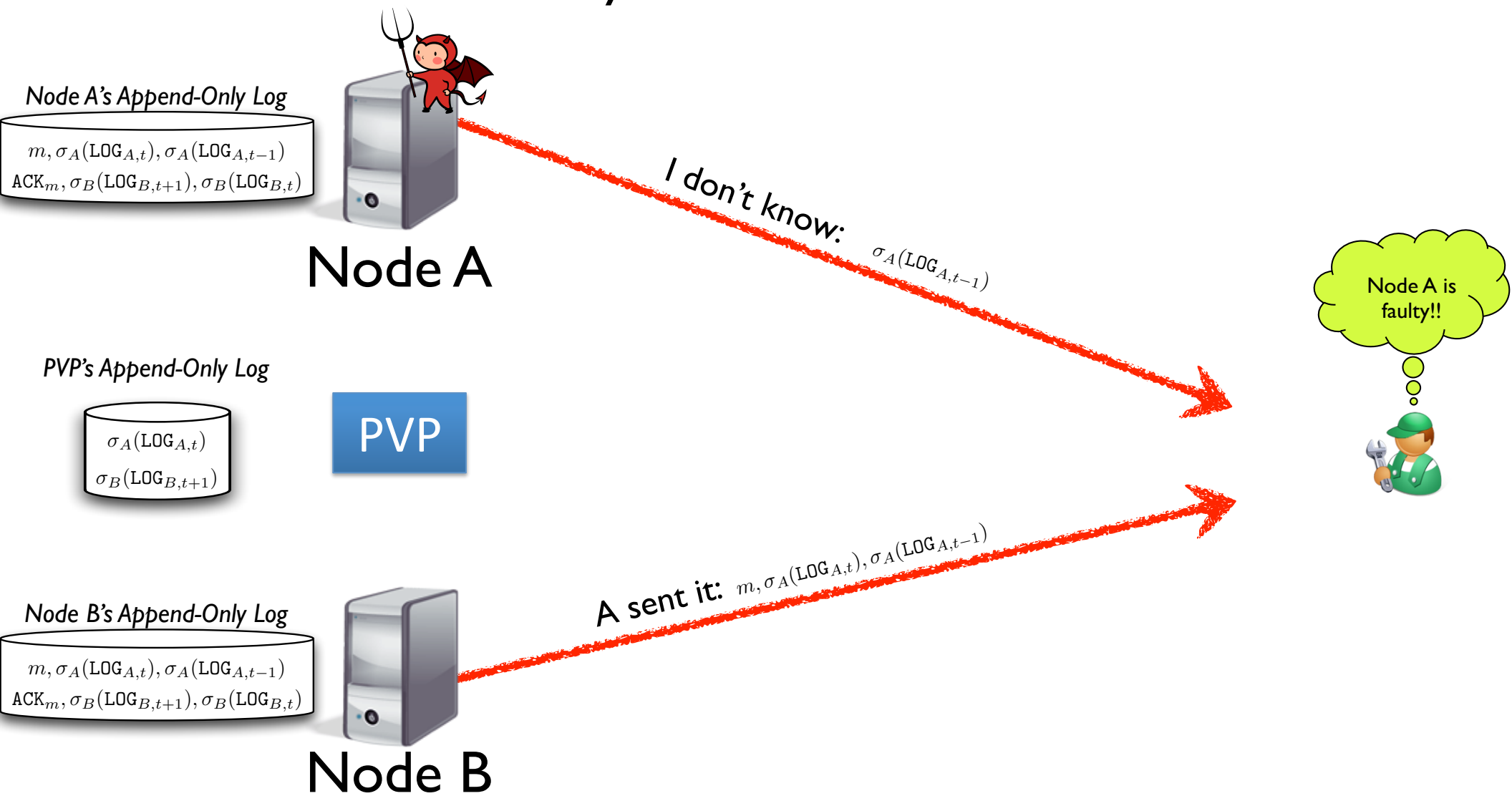

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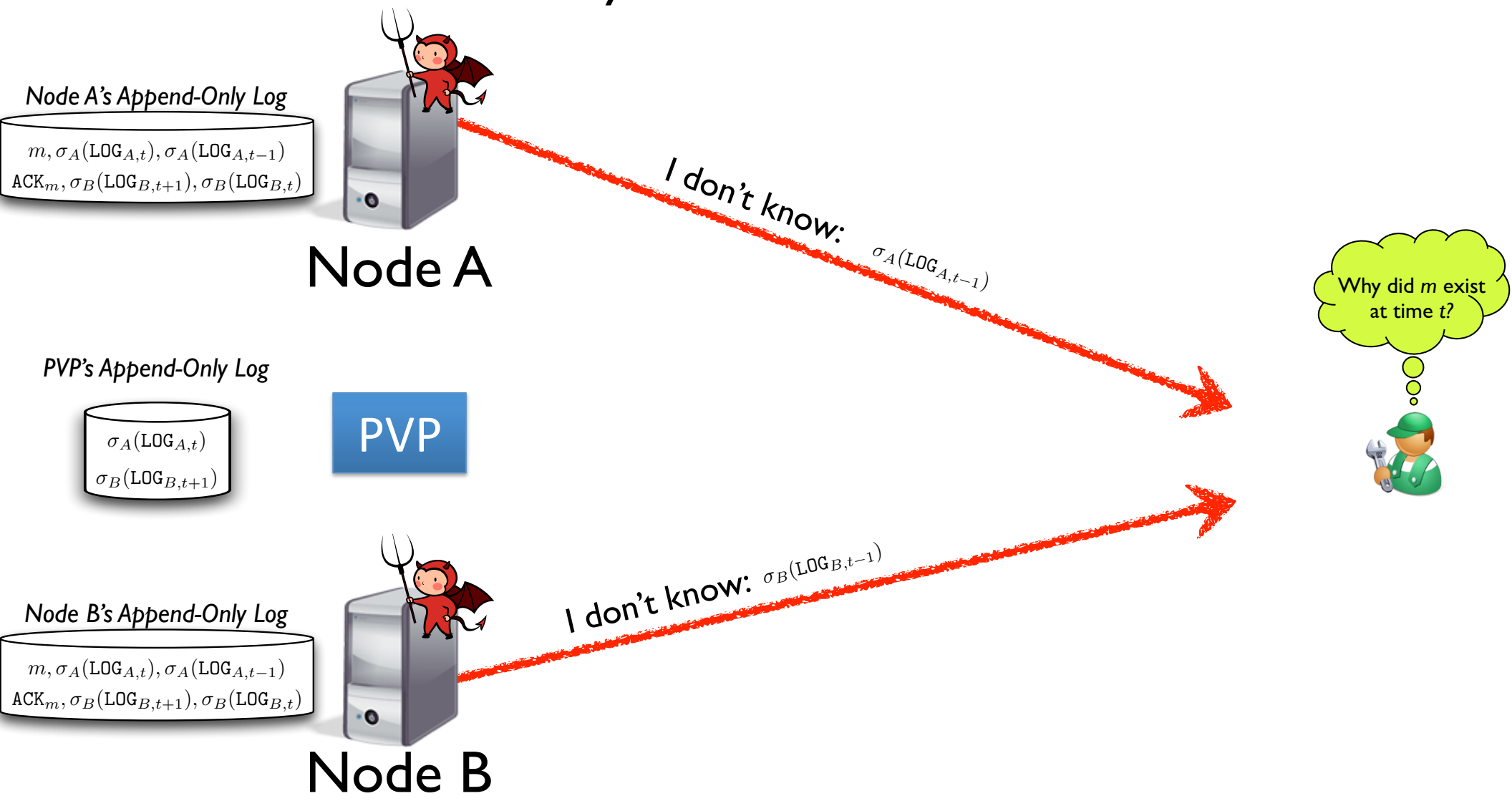

Querying

UNIVERSITY OF OREGON

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Node A's Append-Only Log

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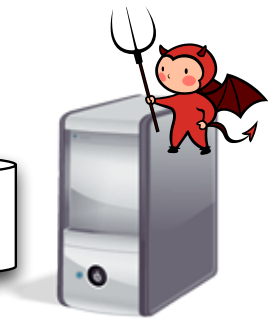


Node A

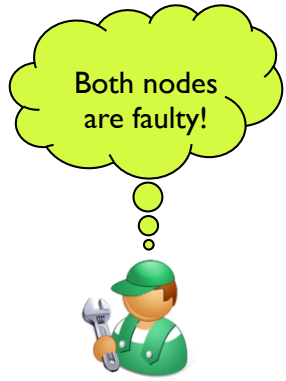
PVP's Append-Only Log

$\sigma_A(\texttt{LOG}_{A,t})$
$\sigma_B(\texttt{LOG}_{B,t+1})$

PVP

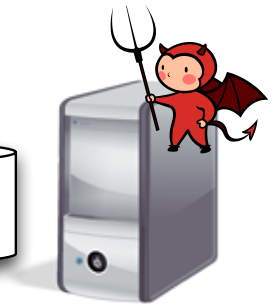
Here is proof of A and B's activity at time *t:*

$\sigma_A(\texttt{LOG}_{A,t})$ $\sigma_B(\texttt{LOG}_{B,t+1})$



Node B's Append-Only Log

$m, \sigma_A(\texttt{LOG}_{A,t}), \sigma_A(\texttt{LOG}_{A,t-1})$
$\texttt{ACK}_m, \sigma_B(\texttt{LOG}_{B,t+1}), \sigma_B(\texttt{LOG}_{B,t})$



Node B

Are PVPs Trustworthy?

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- We do not have to explicitly trust the PVP. Because nodes keep a local log, they have proof to defend themselves with against a faulty PVP.
- If the PVP claims that a node sent an unauthenticated message, the node cannot defend itself. At this point, an administrator will need to resolve the conflict.
  - *We now know that either the PVP or the node is faulty!*
- In the presence of faulty PVPs, our security guarantees gracefully degrade to those of [ZFN+11].

Future Work

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- **Message Loss**. PVPs can recover by identifying retransmissions and polling the switch for flow statistics (This is an OpenFlow feature).
- **Timing Side Channels**. Incorporating timing information into our commitment protocol *may* permit Alice to later test for side channels.
- **Automated Forensics**. We believe that a policy-driven approach to network provenance would obviate the need for instrumenting applications to follow the message commitment protocol.

Conclusion

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- We have shown that SDN can be used as a trust anchor to overcome limitations on previous network forensic systems.
- Using SDN, we have shown for the first time that reliable detection of covert communication between compromised hosts is possible.
- There are a variety of exciting opportunities and challenges in this area. We look forward to exploring them in future work.

Thank you

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Any Questions?

Adam Bates
amb@cs.uoregon.edu