DNS Data Exfiltration Prevention: Kernel-Enforced Endpoint Security

Scalable Framework to Disrupt DNS C2 and Tunneling

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What is Data Exfiltration

Definition: Unauthorized extraction or transmission of sensitive data from a system

Impact: Reputation, Financial Losses to Enterprises

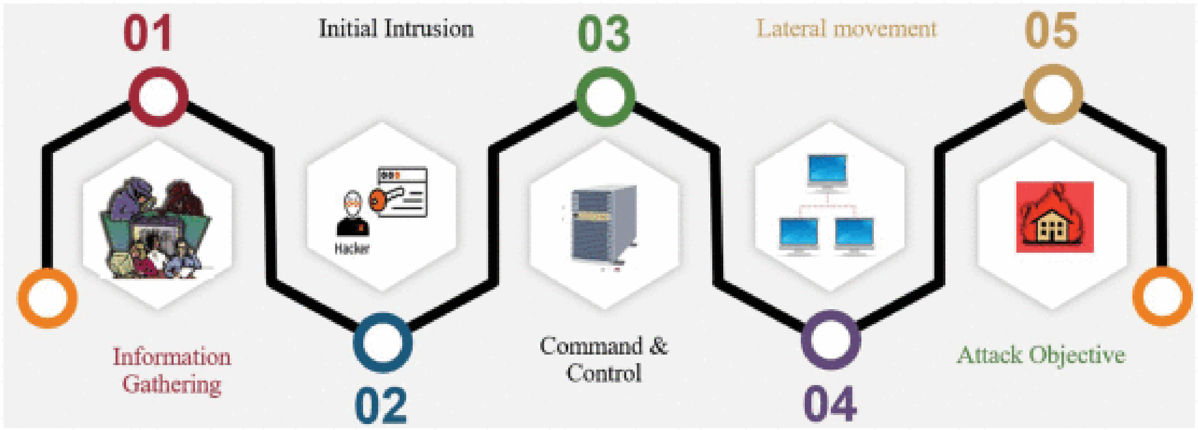
Attack Lifecycle

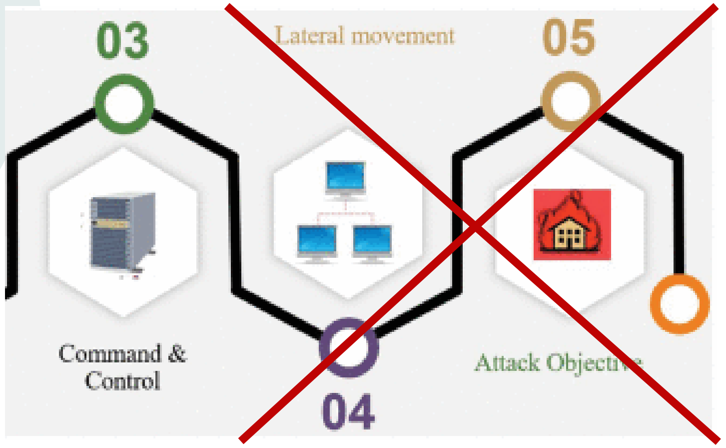
- 🕵️ Information Reconnaissance
- 🔒 Initial Intrusion / Infiltration
- 📡 **Command and Control**
- 🔄 Lateral Movement
- 💣 Command Execution and Data Breaches

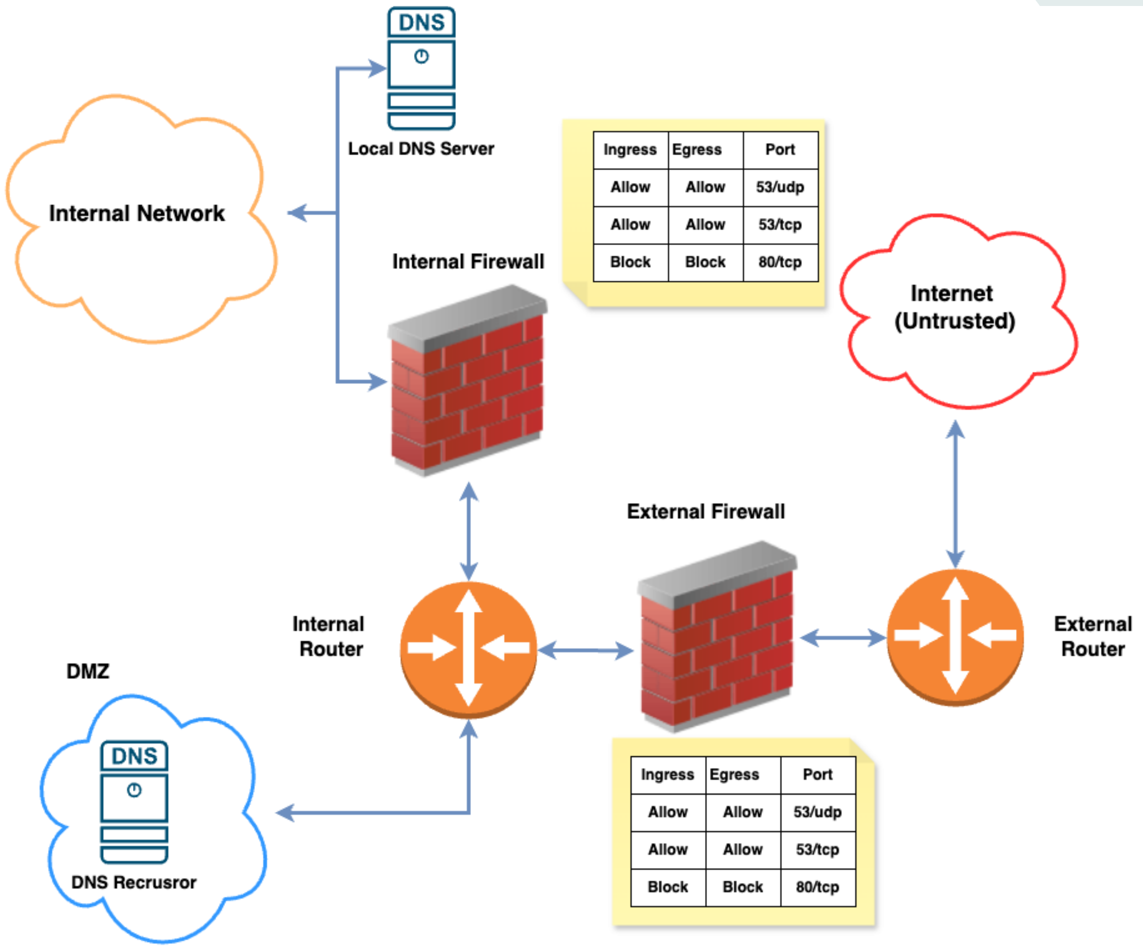
Core Defense Strategy

- 🛡️ Endpoint Security (EDR / XDR)

[Singamaneni et al.]







Why DNS is a Blind Spot

Unencrypted by default – Allows attackers to hide malicious payloads in plain sight.

Rarely monitored deeply – DNS logs are often ignored, giving adversaries a free channel.

Firewall blindspot – DNS ports (53 UDP/TCP) stay open, bypassing most traditional defenses.

DNS Data Exfiltration

DNS C2 – Uses DNS queries and responses to maintain covert communication with attacker infrastructure.

DNS Tunneling – Encapsulates arbitrary data within DNS packets to bypass network restrictions.

DNS Raw Exfiltration – Leaks sensitive data directly in DNS queries (e.g., encoded in subdomains), avoiding traditional detection.

- **Remote Code Execution (RCE)**
  - Shell code exploits
  - Script executions, File corruptions
  - Process Side channeling exploits
  - Example: **Sliver C2, Hexane, APT29 (Cozy Bear).**
- **Persistent Backdoors**
  - Deployment rootkits, ransomwares
  - Example: **Turla** group
- **Network Pivoting (Port Forwarding)**
  - Compromised machines act as proxies to reach deeper into private infrastructure
  - Example: **Cobalt Strike, Hexane, DNSSystem**

Existing Approaches

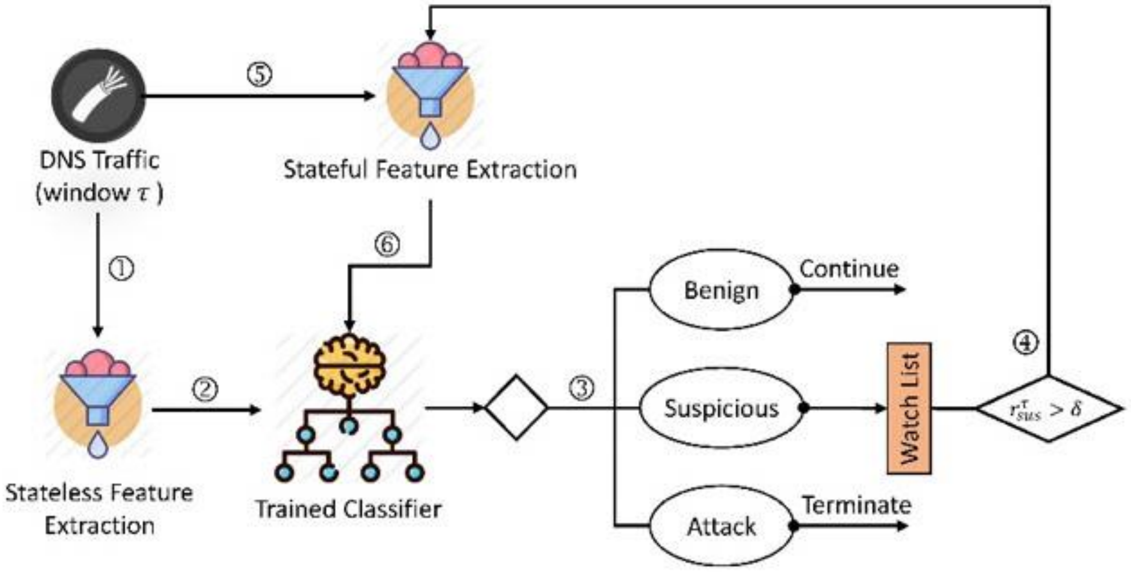
- **Semi-Passive Analysis**
  - **DNS Exfiltration Security as Middleware**
    - Palo Alto Precision Guard AI Security
    - Infoblox DNS exfiltration security
- **Passive Analysis**
  - Anomaly Detection *[Bilge et al.]*
  - Threat Signatures, Domain Reputation scoring [*Antonakakis et al.]*

Existing Approaches – Passive Analysis

- **Anomaly Detection:**
  - **Traffic Behavior Analysis**
    - DNS Passive Traffic Volume Analysis
    - DNS Passive Traffic timing Statistical Analysis
  - **Machine Learning-based Threat Intelligence**
    - Uses machine learning models to identify traffic anomalies.
- **Threat Signatures:**
  - DNS Domain Scoring
  - Malicious domain signature

Stateless Features – Lexical Analysis

Stateful Features – Statistical Analysis



[Samaneh et al., Jawad et al.]

Issues with current approaches

- **Slow Detection → High Dwell Time → More Damage**
- **Extremely slow to Advanced C2 Attacks**
- **Dynamic Threat Patterns**:
  - Varying Throughput
  - Slow and Stealthy Rate
  - Kernel Encapsulated Traffic
  - Port Obfuscation
- **Centralized monitoring and analysis systems don't scale**
- **Ineffective over IP Masquerading & Domain Generation Algorithms**

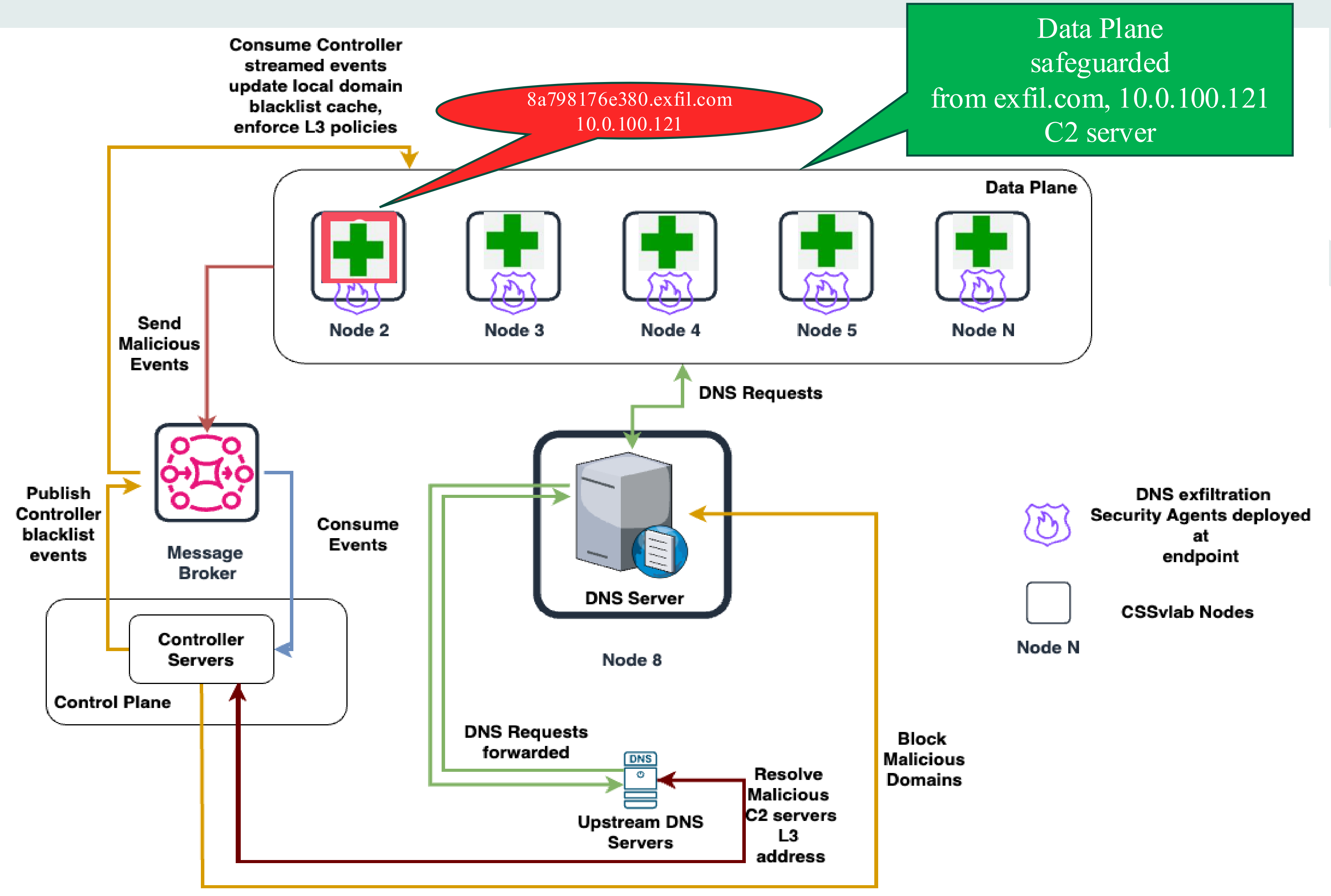
Solution:

Real-time, proactive enforcement at Ring 0 — inside the kernel, where no userland evasion can hide.

Security Framework Architecture

Architecture Components

- **Data Plane**
  - eBPF endpoint agents
- **Control Plane**
  - Controller Servers
- **Infrastructure**
  - DNS Server
  - Apache Kafka



Security Framework Goals

Real-Time DNS Exfiltration Prevention

Implement in-kernel deep packet inspection and enforcement to block all forms of DNS exfiltration channels.

AI-Assisted Threat Detection

Use deep learning in userspace to detect advanced obfuscated exfiltration payloads with high accuracy aiding kernel enforcements.

Dynamic Cross-Layer Policy Enforcement

Enforce in-kernel L3 network policies adaptively and domain blacklisting on DNS server to combat DGA.

Malicious Process Aware Active Response

Instantly detect and kill implants, preventing lateral movement and further damage.

Scalable Multi-Cloud Deployment

Ensure framework's horizontal scales for real-world production cloud environments.

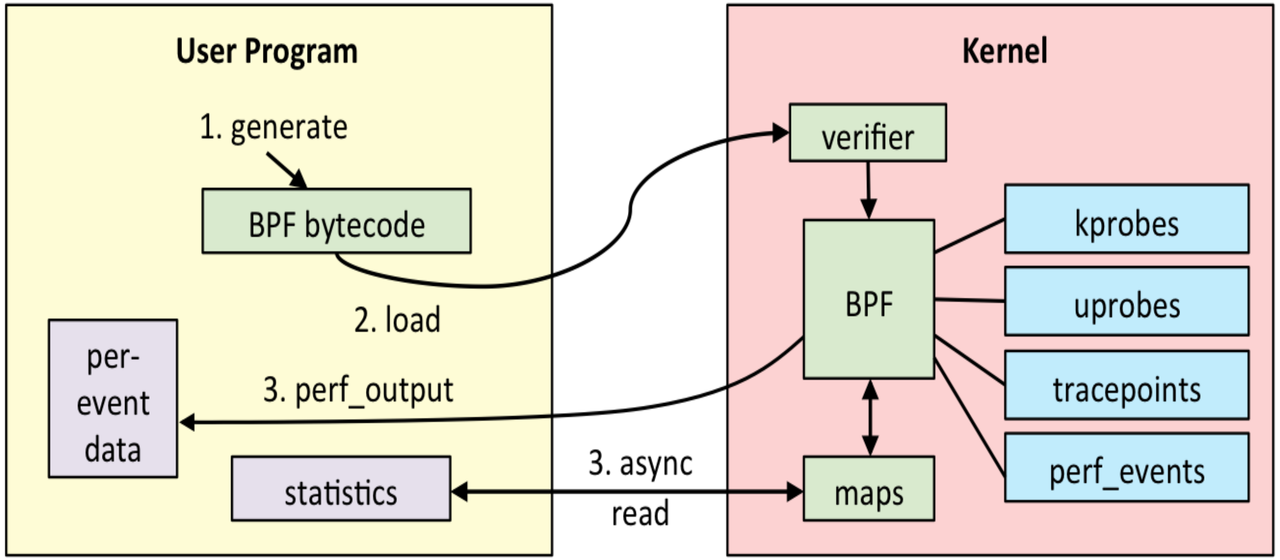
Broader Impact and Applicability

- **Cloud Providers & HyperScalers**
  - Strengthens DNS-layer security in managed services.
  - Examples: AWS Route 53, Google Cloud DNS, Azure DNS.
- **National Security & Defense**
  - Disrupts advanced malware APT groups alive using DNS-based C2 channels.
  - Examples: Turla Venom, Skitnet, Lazarus, OilRig, Hexane.
- **Regulated Enterprises (Finance, Healthcare)**
  - Augments DLP capabilities over DNS for private cloud and on-premise environments.
  - Examples: Financial institutions, healthcare networks.
- **Security Vendors (EDR/XDR/DNS Security)**
  - Integrates as a modular addon to extend EDR/XDR threat prevention at the DNS level.
  - Examples: CrowdStrike Falcon, Cisco HyperShield, Palo Alto Precision AI, Broadcom Carbon Black.

eBPF – Extended Berkley Packet Filter

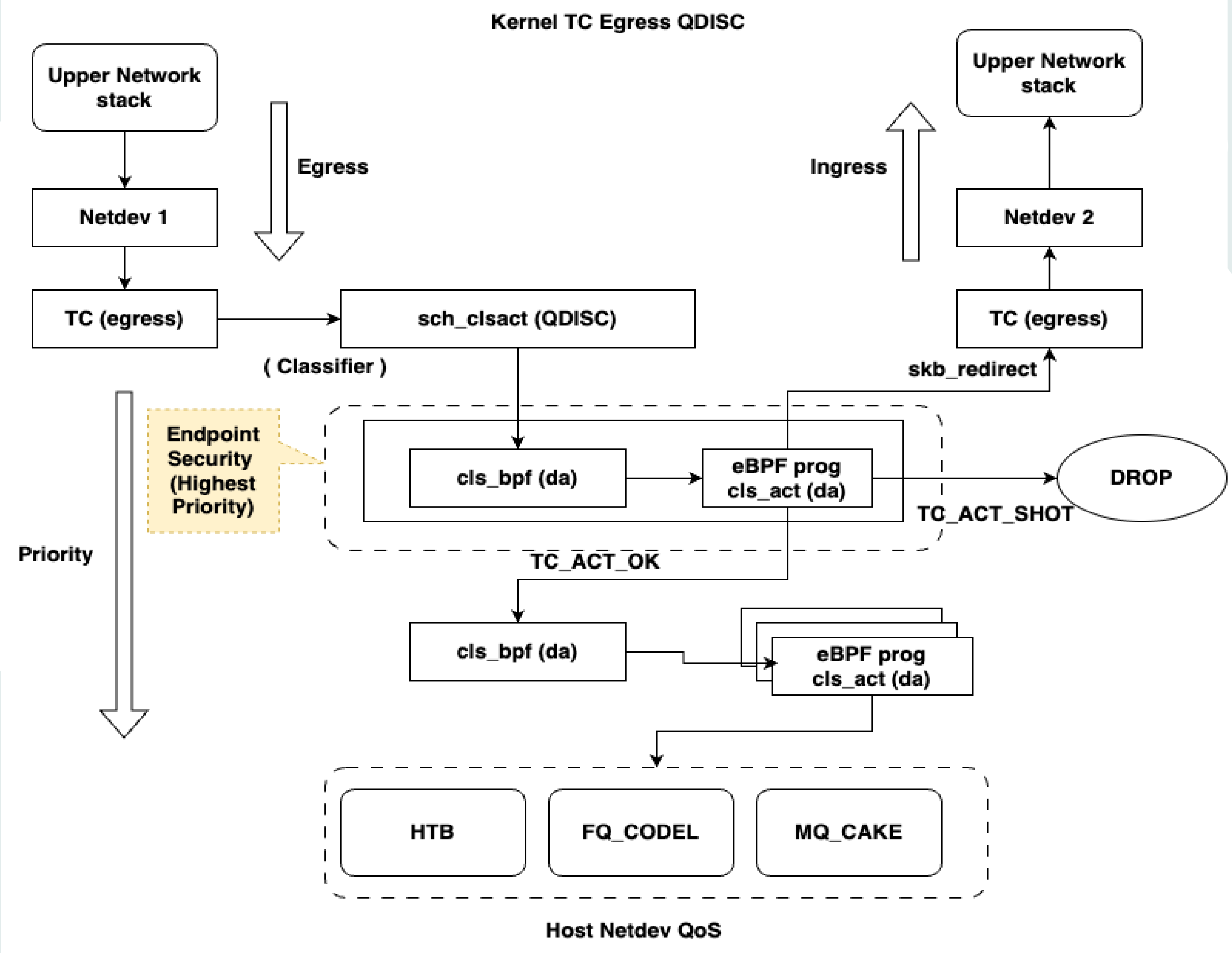
- Reprogram the Linux kernel in safe way
- Modern way to write kernel modules

1. Runs BPF virtual machine inside kernel
2. Custom BPF bytecode
3. Uses 512 bytes of stack
4. eBPF Maps as heap
5. CPU architecture agnostic



Linux Kernel Network Stack

- Sockets
- TCP/IP Stack
- Netfilter
- Traffic Control (QoS)
- Network Drivers



[Jamal Salim et al., Daniel Borkmann et al.]

Kernel Enforced Endpoint Security

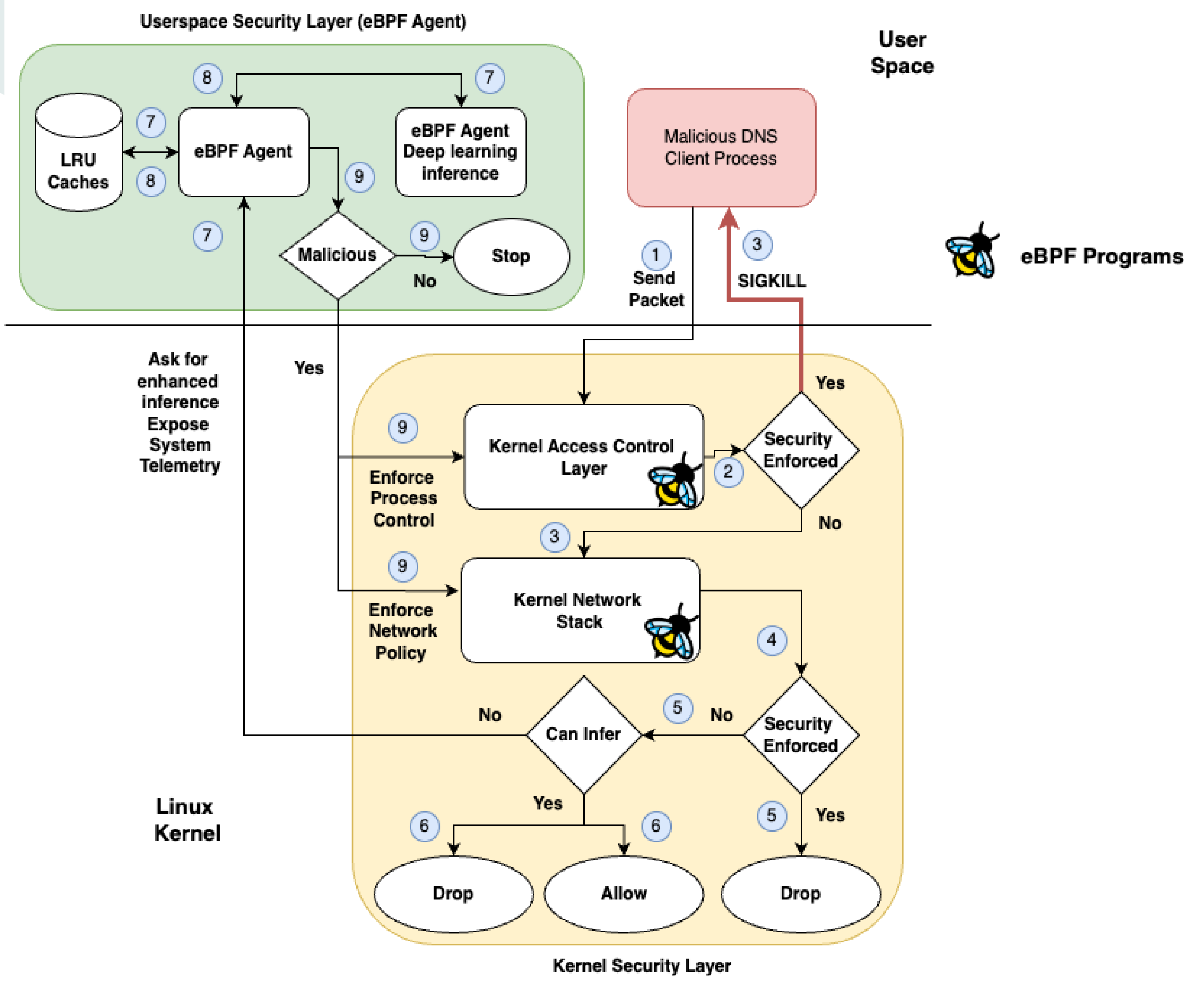
Agent based Endpoint Security

Userspace

- eBPF Agent
- eBPF Agent LRU Caches
- ONNX Quantized Deep Learning Model

Linux Kernel

- **Inference Unix Domain Sockets**
- **Kernel Network Stack (eBPF)**
  - Socket Layer
  - Traffic Control
- **Kernel Security Layer (eBPF)**
  - Kernel Security Modules
  - Kernel Syscall



eBPF Agent Operations Modes

eBPF Agents in Data Plane handle DNS exfiltration over UDP

Mode	Goal	Requirement	Security Enforcement Process
Strict Enforcement Active Mode	Kill C2 Implants, ensure zero data loss and C2 command execution.	DNS Traffic over UDP ports (53, 5353,5355), for encapsulated and non-encapsulated traffic.	• **Kernel**: Live Redirects suspicious DNS packets to userspace. • **Userspace** Trace malicious process exfiltration count and terminates it, resend benign packets.
Process-Aware Adaptive Passive Mode	Kill C2 Implants, ensure negligible data loss and minimal C2 command execution.	DNS Traffic over random UDP ports.	• **Kernel:** Allow suspicious traffic passthrough. In Kernel start threat hunting process tied to malicious DNS packets. • **Userspace:** Trace malicious process and terminates it.

ONNX DNN Model

- Model Architecture ONNX Graph
- Sample Malicious Data
- Features

Feature	Description

Malicious Exfiltrated data DNS queries
381c018e3f5d05b78e3f6a026381e0f3476c066e8017be6ba9f5a9d758ef.d04bc3e0fc58e5a2401da590f3ee268a6af637eaafd210e58060a41082dc.92d594840bcb32a6500f39248db646e4e602f8547294692d83a4b4680223.b4d0ce0ec94abc9b6821cea90561aac558a6ba30b53e6b.bleed.io
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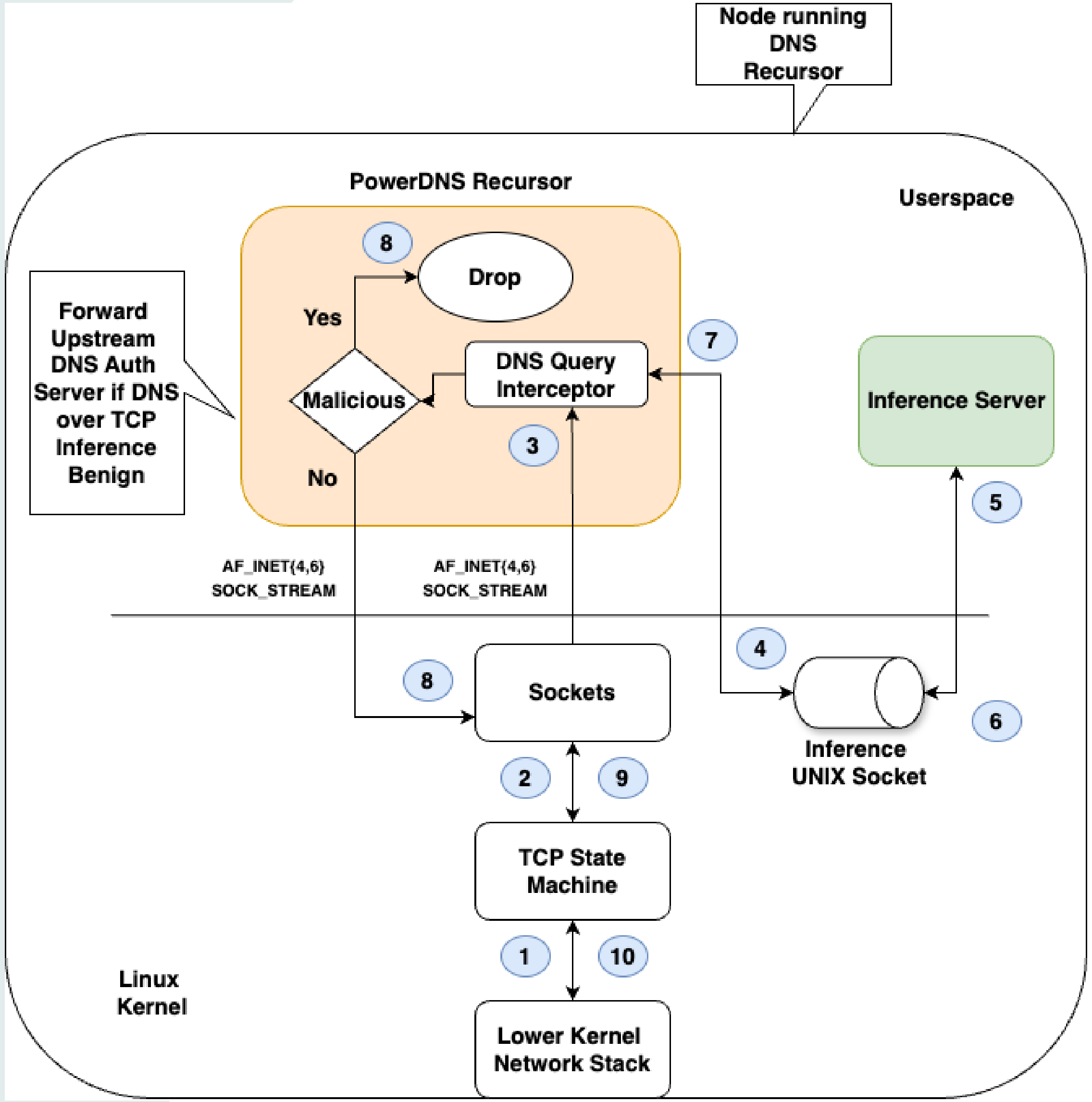
Datasets

Dataset Type	Source / Characteristics	Size	Primary Goal
Trusted Benign Cache	Top 1M Cisco Second-Level Domains (SLDs)	1 Million	Reduce inference on known-good traffic.
ISP-Captured DNS	Live-sniffed ISP DNS traffic [Ziza et al.]	50 Million	Provide real-world benign & malicious baseline.
Synthetic Exfiltration	Custom-generated (DET, DNSCat2, Sliver, Nuages, Custom Scripts, etc.);	2.4 Million	Malicious samples use varied obfuscation across file formats
Final Combined Dataset	Synthetically formed	3.8 millions	Balanced dataset w/ obfuscated payloads across file formats

Design Adjustment

Prevent DNS Exfiltration over TCP

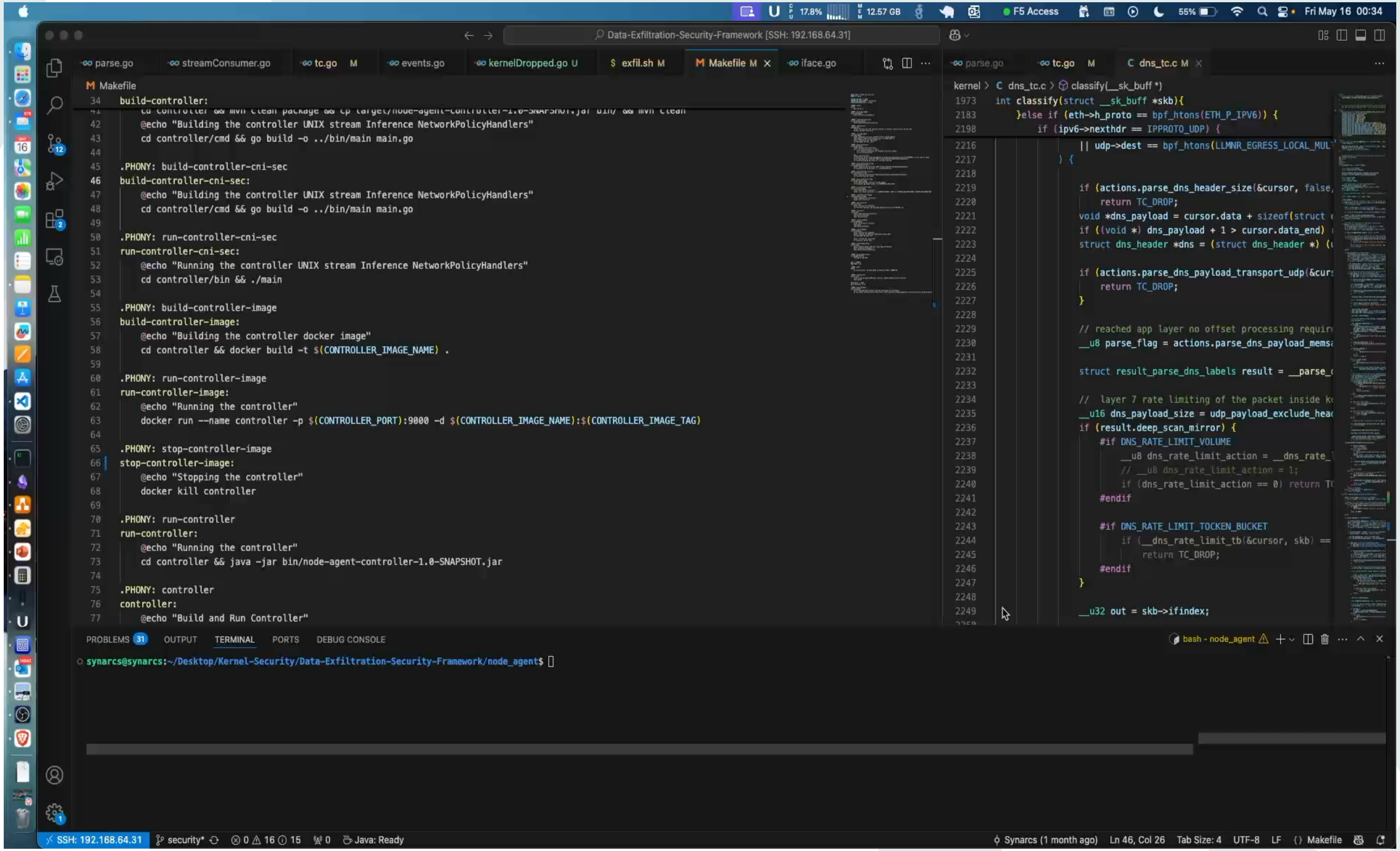
- Runs on
  - PowerDNS Recursor
- Relies on
  - PowerDNS recursor Query Interceptors
  - Inference UNIX domain sockets



Success Measure

- Response Speed
- Detection Accuracy
  - High Precision and Low False positives
- Volume of Data loss prior removal
- Scalability in distributed environments
- System Performance Impact
  - Kernel
  - Userspace

Framework Security Strength



Results and Evaluation

- Model Metrics
- Throughput comparisons (Active mode)
- Resources
  - Memory Usage
    - Security Agent memory usage at endpoints in data plane
  - CPU Flame Graph
    - eBPF Agent CPU Flame Graph

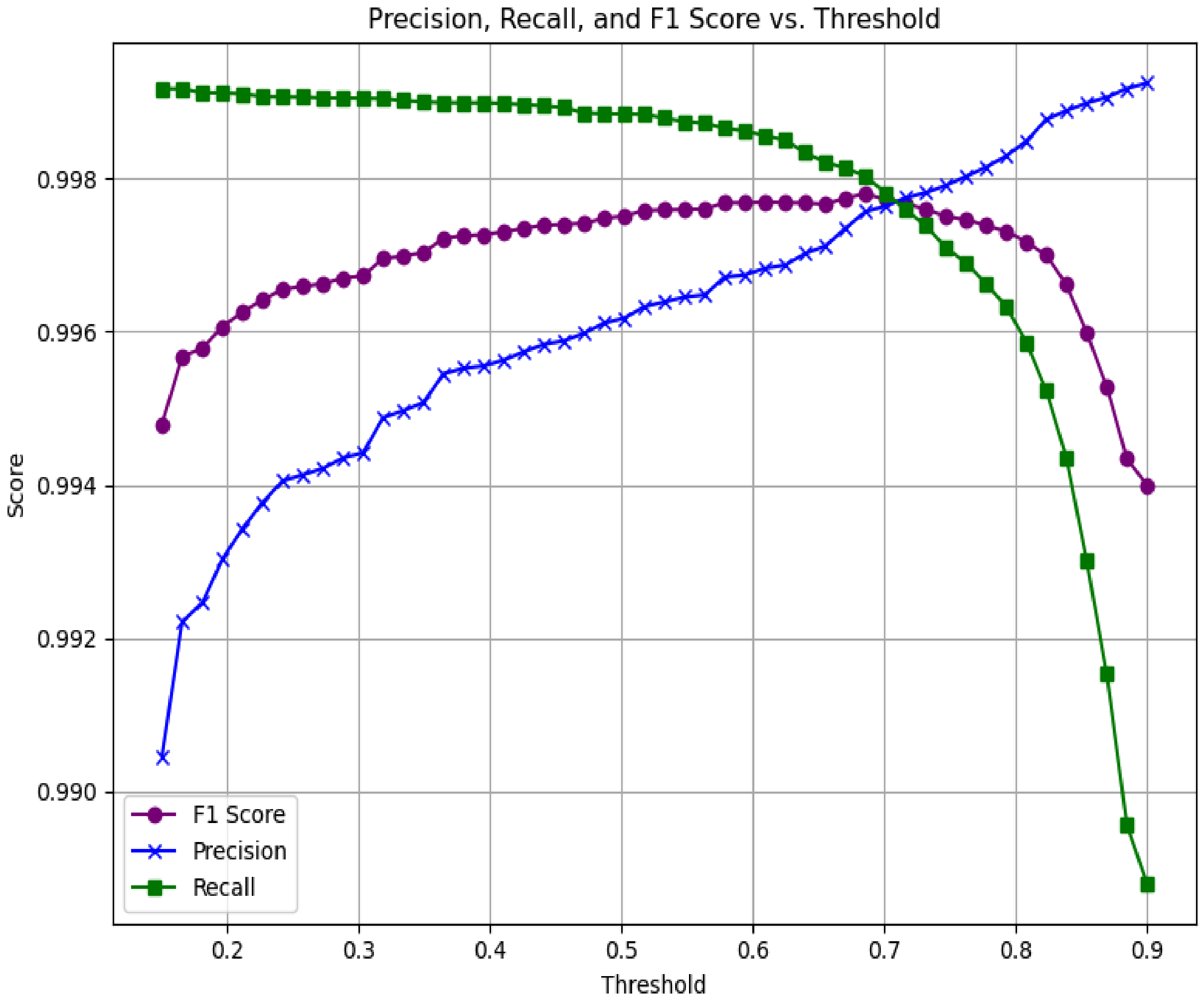
Test Bench
CPU: Intel Xeon 6130
Memory: 8 GB
Linux Kernel: 6.12.4
Network Driver: netvsc
Bandwidth: 100 Gb/sec
Root QDISC: Fq_Codel
Queues: 8 RX / TX

DNN Model Metrics

Metric	Training	Validation
Accuracy	0.9973	0.9997
AUC	0.9997	0.9997
Loss	0.0099	0.0091
Precision	0.9959	0.9959
Recall	0.9987	0.9988

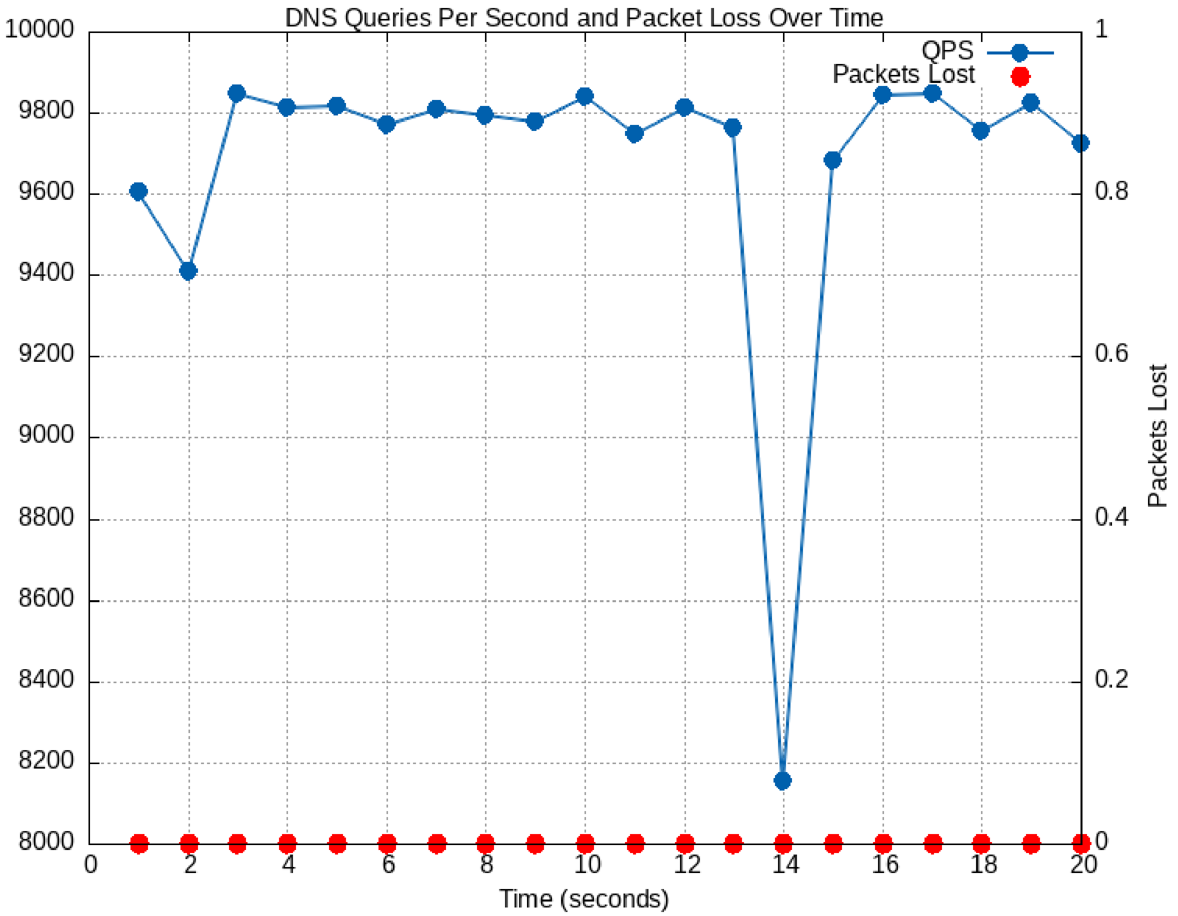
Table 5.1: Model Evaluation Metrics

Model Performance

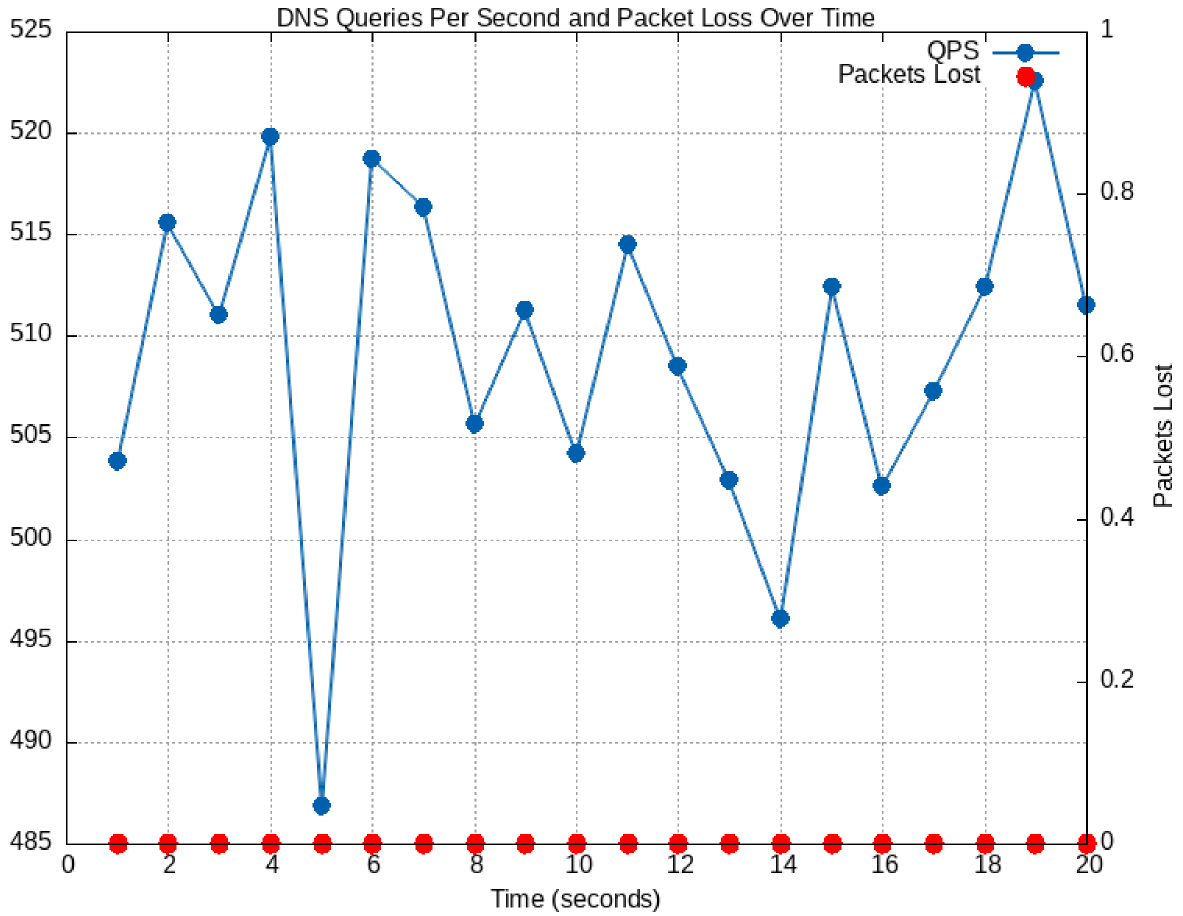


Model Scores

Throughput comparisons – Active Mode



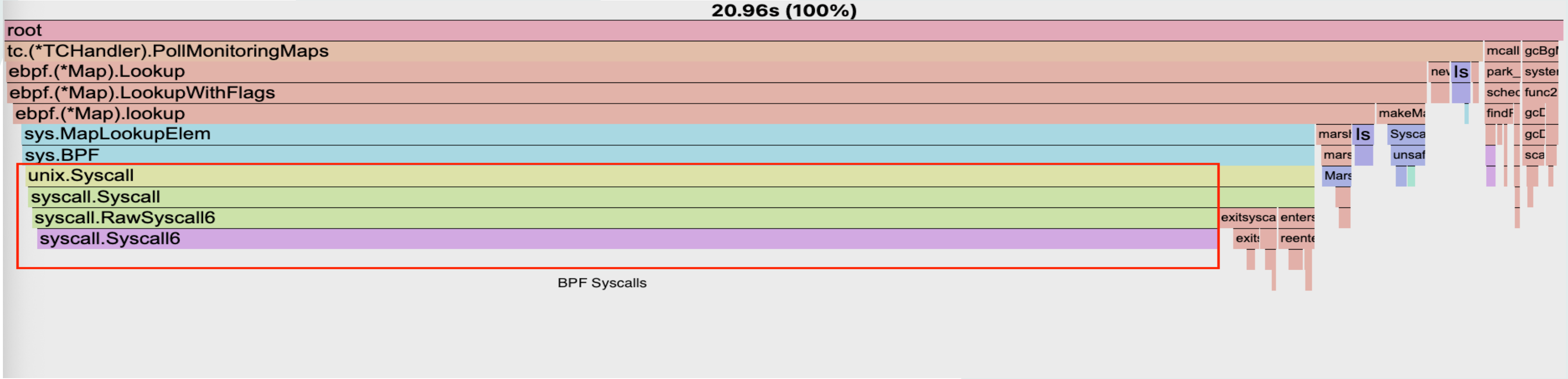
Agent LRU Cache Read-Through Hit



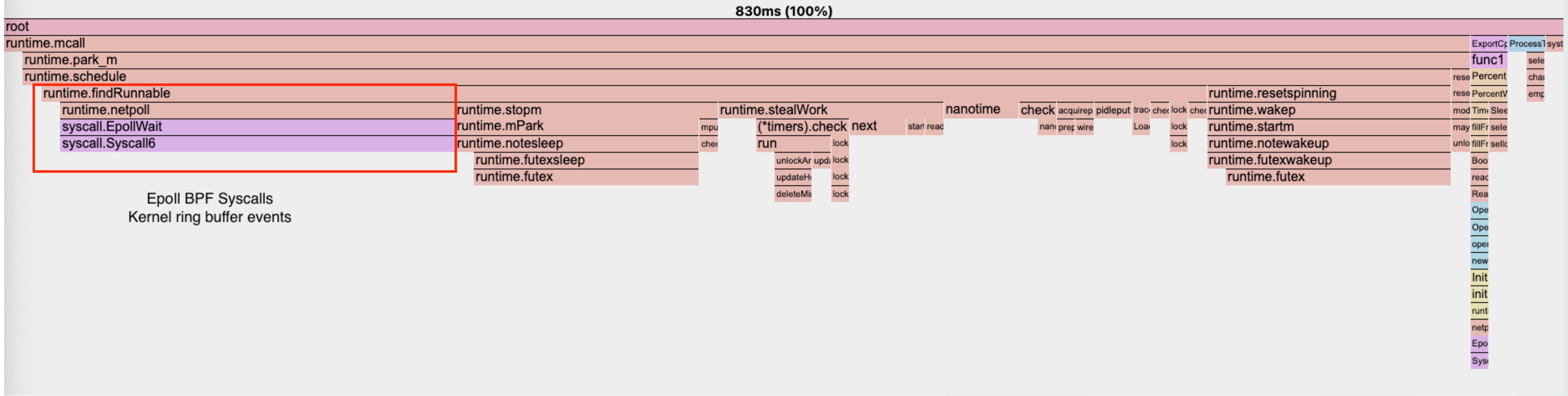
ONNX Live Inferencing

Resource Usage – eBPF Agent Flame Graph

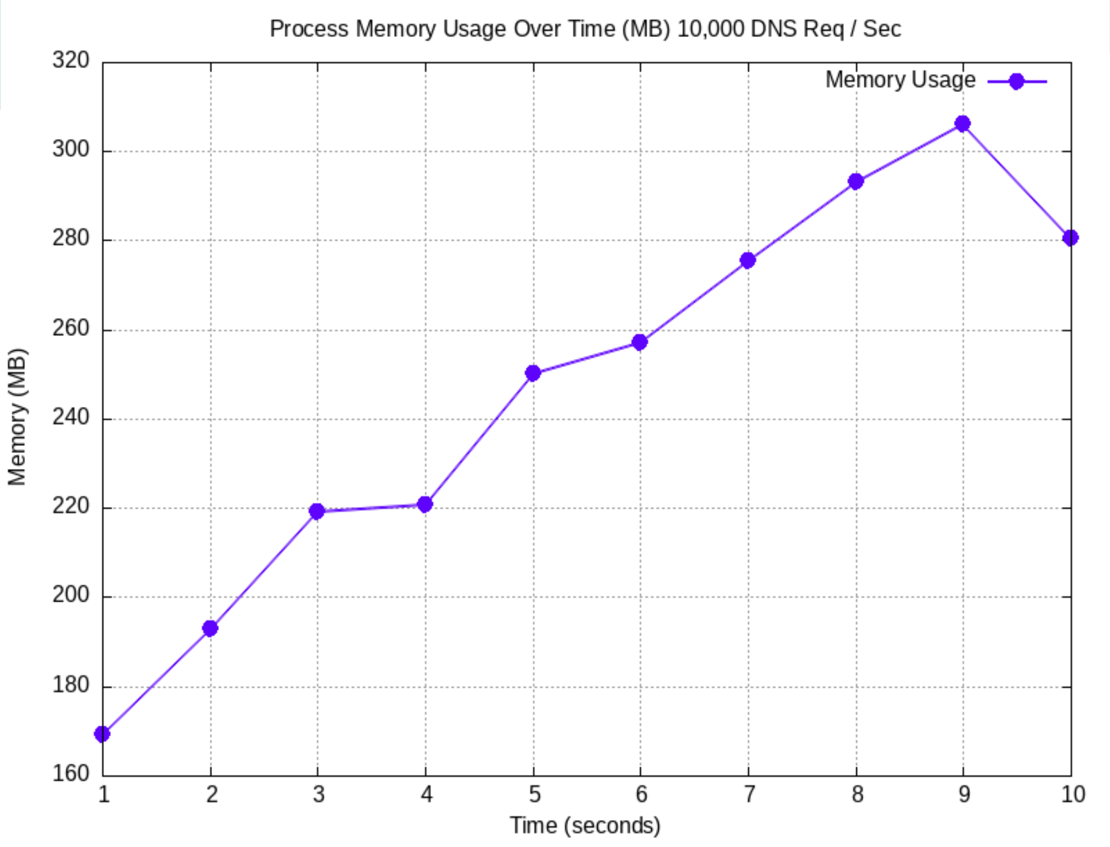
Userspace Busy-Polling overhead monitoring maps

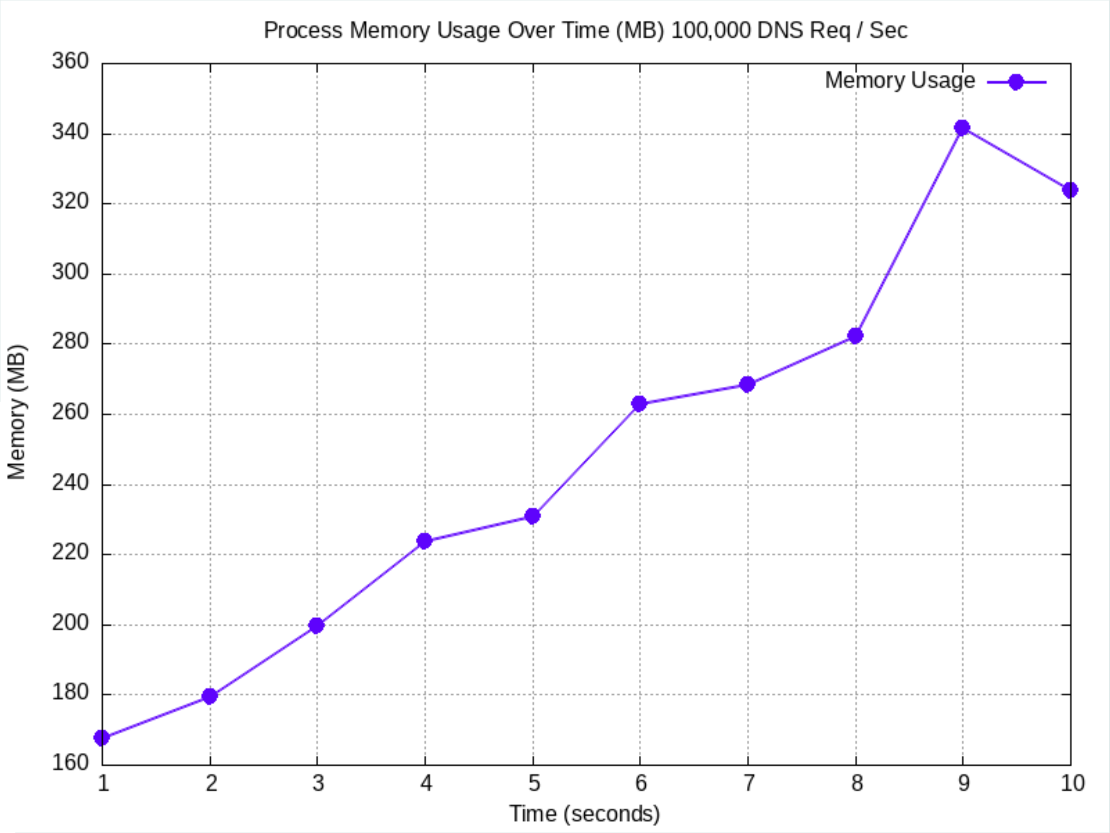


Kernel Epoll asynchronous I/O agent performance boost



Resource Usage - Memory





10,000 DNS Req / Sec

100,000 DNS Req / Sec

Knowledge Gained

- Kernel DataPath
- Kernel TCP Congestion control (rene, cubic, BBR)
- Userspace-kernel synchronization (kernel spin locks, RCU, userspace mutex, atomic ref_counters), kernel asynchronous I/O
- Kernel Security Layer (LSM, seccomp)
- Distributed Systems concepts intersection with system performance
  - Caching Write / Read-through policies
  - Caching Eviction Policies
  - Data Streaming
  - NUMA cache coherence → NetFlow Steering

Future Work

- **Extend Support for DNS-over-TCP and Encrypted Tunnels:** Implement in-kernel eBPF-based detection for DNS-over-TCP replicating TCP state machine over kernel socket layer, paired with userspace DPI via Envoy proxy.
- **Add In-Kernel TLS Fingerprinting**: Use eBPF for TLS fingerprinting (e.g., JA3/JA4) to detect DNS exfiltration over TLS (DOH), DNS over mTLS, WireGuard.
- **Rate-Limiting Based on Volume and Throughput:** Integrate egress CSLACT-based dynamic rate limiting for DNS mass data breaches integrating EDT_BPF, FQ_CODEL and HTB QDISC's.
- **XDP-Based Flood Prevention:** Introduce XDP ingress filtering inside kernel to mitigate NXDOMAIN-based DNS water torture and DNS amplification attacks on the endpoint.

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