UniBPF: Safe and Verifiable Unikernels Extensions

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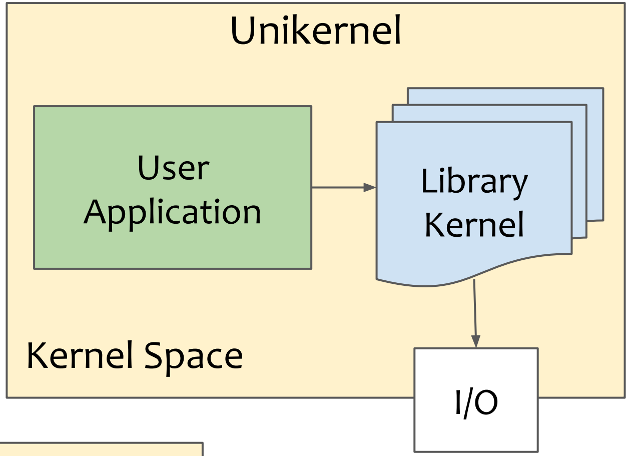
Motivation

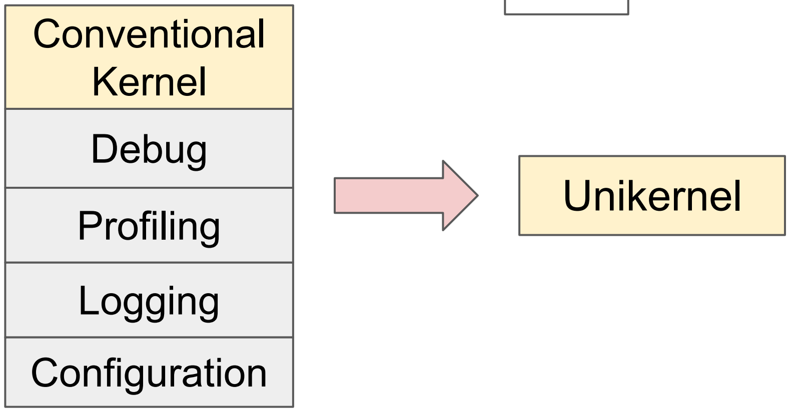
Unikernels

- Kernel as a library
- Eliminate unneeded components.
- Optimize system procedures, e.g., system calls
- Compact, efficient, secure

But…

- Lack of **debuggability**
- Lack of **observability**
- Lack of **runtime-extensibility**



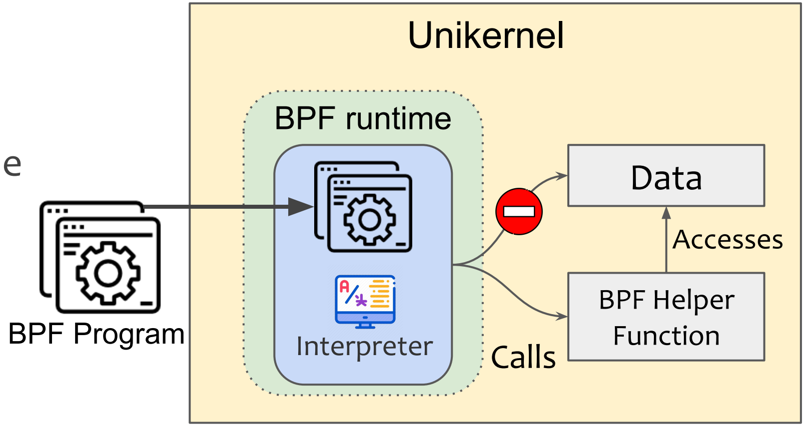


State-of-the-art

Extensible Unikernels with **BPF:**

- e**BPF Runtime** + kernel tracing with **interpreters.** But…

❌ **Lack of verifier:**
  - Use an interpreter to provide sandboxed runtime



❌ **Insufficient security guarantee:**
  - Cannot resist runtime errors

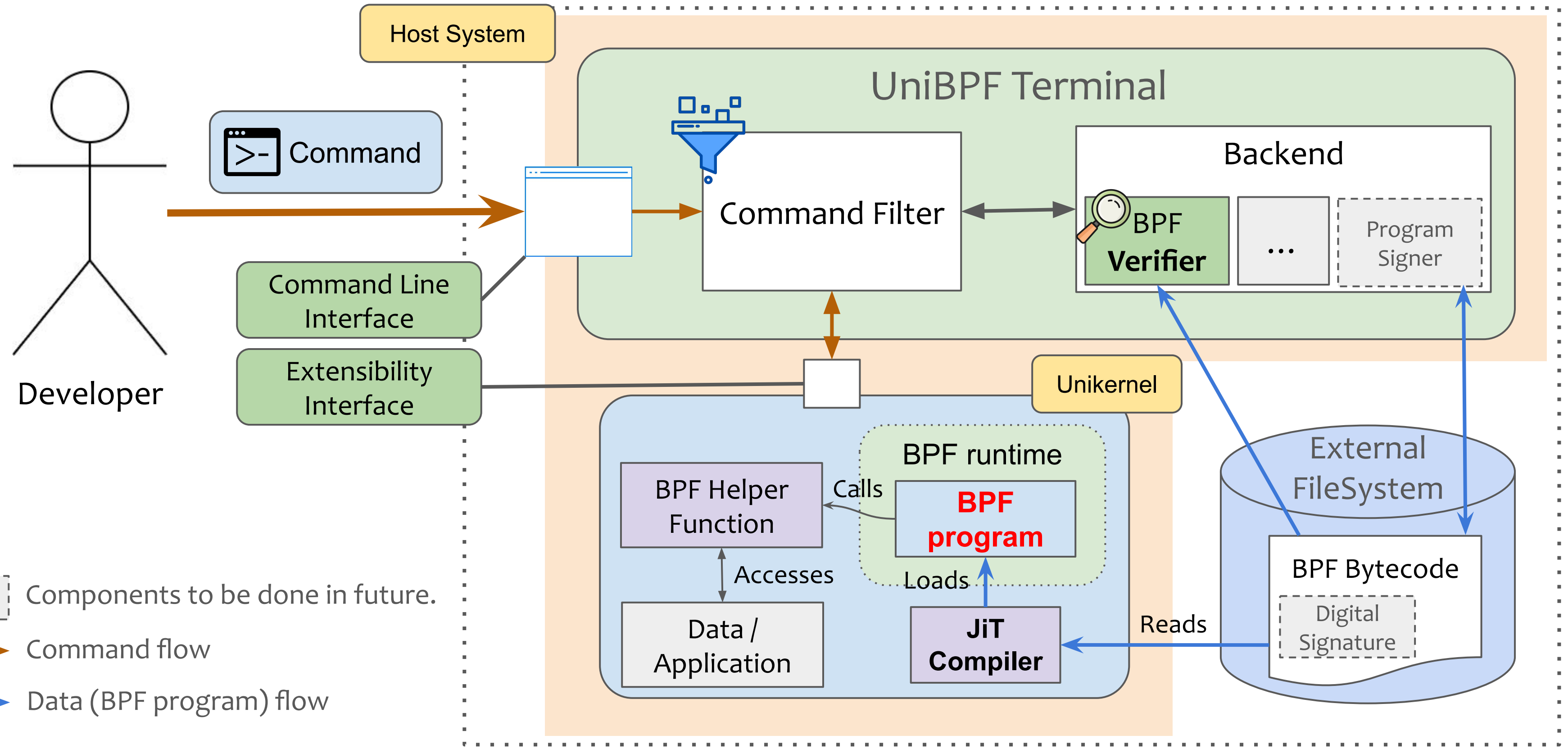
❌ **Inefficient runtime:**
  - Our work: ≤ 600% **slowdown** in instruction level v.s. JiT compiled

Research Question

How can we have a safe and verifiable extension for Unikernels?

- Design Goal
  - **Safety:** Ensure safety of executing extension binaries
  - **Sustainable Design:** Easy to use, easy to maintain
  - **Performance:** Acceptable overhead and improve BPF runtime efficiency

System Overview



Components to be done in future.

Command flow

Data (BPF program) flow

Background: extended Berkeley Packet Filter (eBPF)

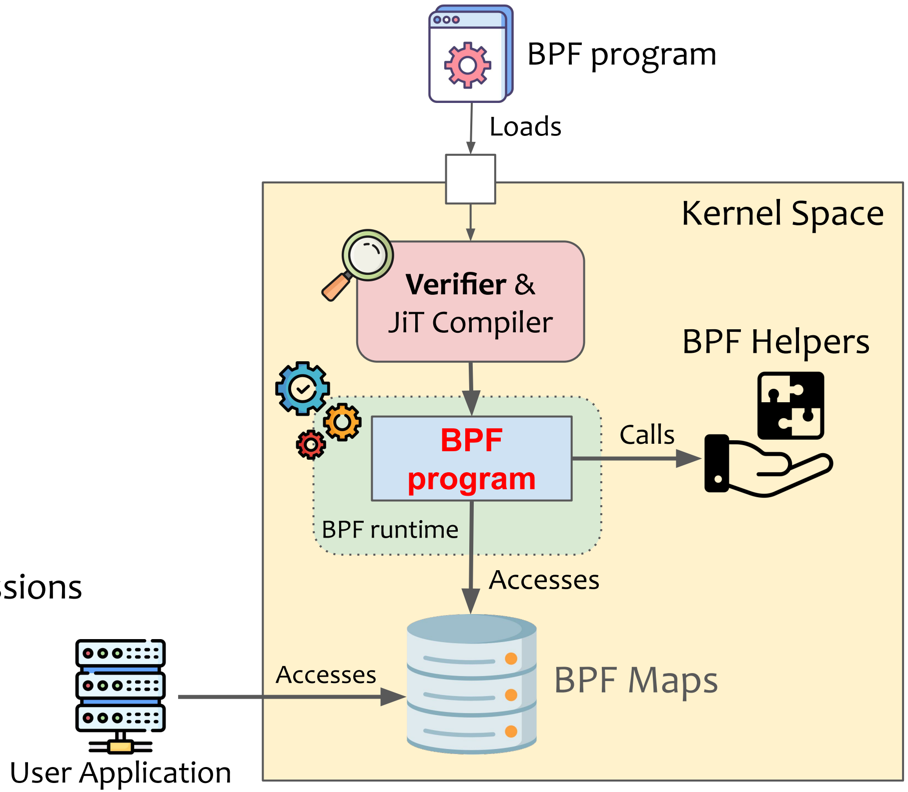
Lightweight in-kernel language VM

Sandbox property can be ensured by:

- Using **interpreters** (weaker)
- Using **verifiers** to verify in advance (stronger)
  - Detects potential sandbox escalation
  - Forbid undefined behaviors

Useful features:

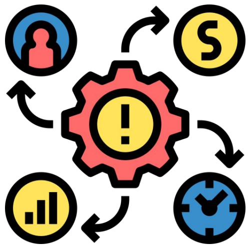
- Maps (kv-store)
- Helper functions
- Program Types: Runtime context & helper permissions



Outline

- ~~Motivation & Background~~
- Design Challenges
- Evaluation
- Further Ideas

Design Challenges



1. Impact of Verification Processes on Unikernel Applications’ Runtime

2. Feasibility of Integrating Verifier into Unikernel Application

3. Usability and Maintainability: Configuring Shared Verifier for Different Unikernels

① Verification can block Unikernel applications

❌ Lack of **multi-processing** support:
- Application is the only process

❌ Lack of comprehensive schedulers:
- CPU resource is released by voluntary *“yields”*

Verification is time-consuming!
- Our example BPF program: **12.05 ms** to verify 26 instructions.
- Lower-Bound: **8.82 ms**

With common approaches:
- Clients may experience huge **latencies**

```c
__attribute__((section("executable"), used))
__u64 hash(uk_bpf_type_executable_t* context) {

    __u64 sum = 0;

    for(int index = 0; index < 256; index++) {
        char* input = context->data + index;
        if(input >= context->data_end) {
            break;
        }

        char to_add = *input;

        if(to_add >= ’A’ && to_add <= ’Z’) {
            to_add += ’A’ - ’a’;
        } else if(to_add >= ’0’ && to_add <= ’9’) {
            to_add -= ’0’;
        }

        sum += to_add;
    }

    return sum;
}
```

Put BPF verifiers as processes on the host system where schedulers are more flexible

② BPF Verifiers Are Too Complicated to Integrate

- Common BPF verifiers are **complicated:**
  - PREVAIL (PLDI'19): 27,000 Lines of code
  - KLINT (NSDI'22): 13,000 Lines of code

- Common BPF verifiers need **complicated runtime:**
  - PREVAIL: C++ runtime library
  - KLINT: Python Interpreter
  - Linux BPF verifier: GPL License, Depends on Linux

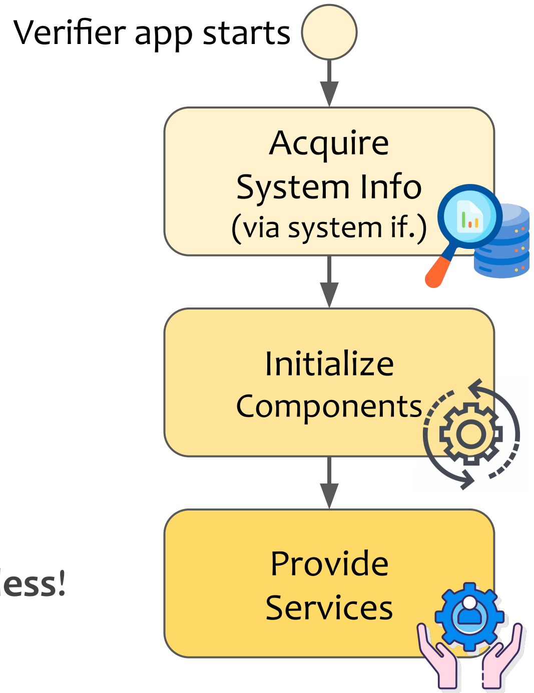
💡 Put BPF Verifiers on the host system utilizing the host system's runtime environment

③ Customizability Impedes Building a Unified Solution

Our Goal: Maintain customizability for BPF runtime

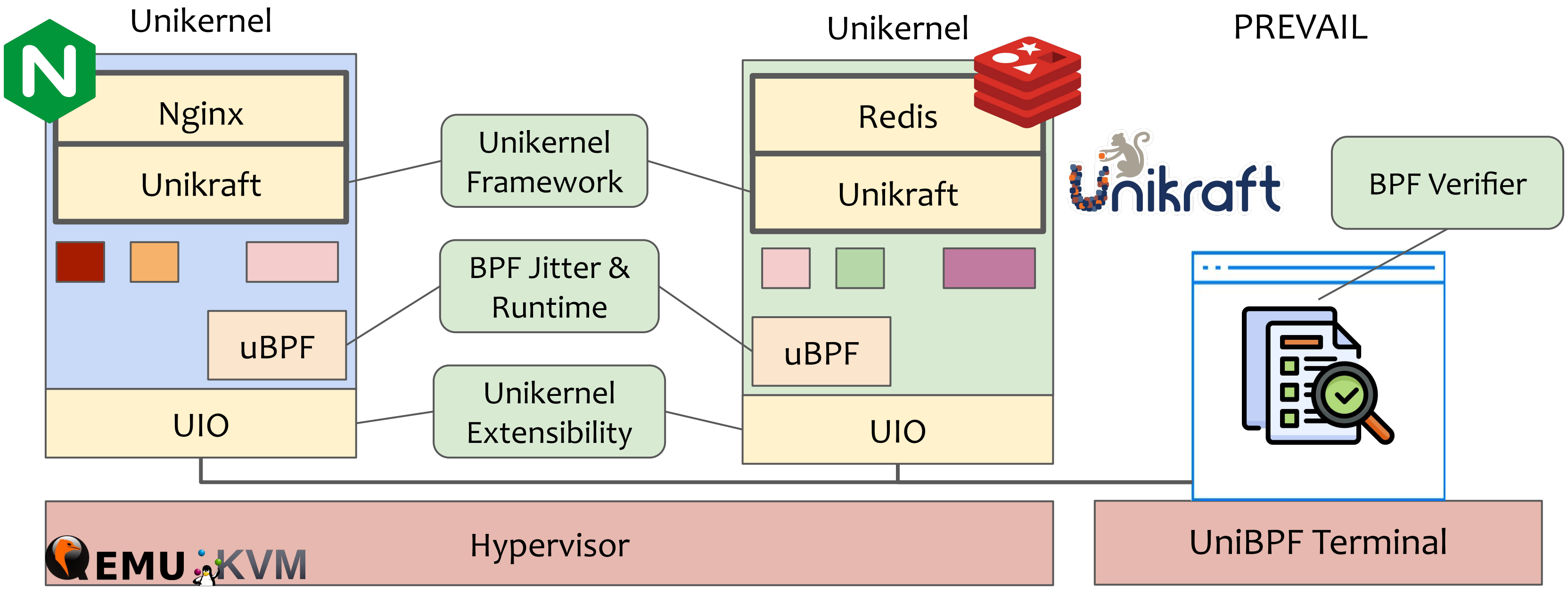
- BPF Helper functions & program types
- Keep compactness
- Increase our system's usability

- But, without a standard framework:
  - Each Unikernel needs one BPF verifier: **Unmaintable**!
  - Waived support for customizable parts: Our work is **Meaningless**!



We provide libraries that allow developers to easily export their BPF runtime specifications

Implementation



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Evaluation - Safety

Evaluation Program	Result - Interpreter	Result - JiT Compiled	Result - UniBPF
OOB*	Terminated	Exploited	**Denied**
OOB* with Nullptr	Terminated	System crashed	**Denied**
Infinity Loop	System freezes	System freezes	**Denied**
Division by Zero	Error Ignored	Error Ignored	Partially **Denied**
Instruction Type Safety	Error Ignored	Error Ignored	**Denied**
Program Type Safety	Error Ignored	Error Ignored	**Denied**
Helper Function Type Safety	Error Ignored	Error Ignored	**Denied**

: Memory Safety
: Termination
: Runtime Errors
: Type Safety

UniBPF provide a safer BPF runtime extension for Unikernel

*) OOB: Out of bound memory access

Evaluation - Verification and JiT Overhead

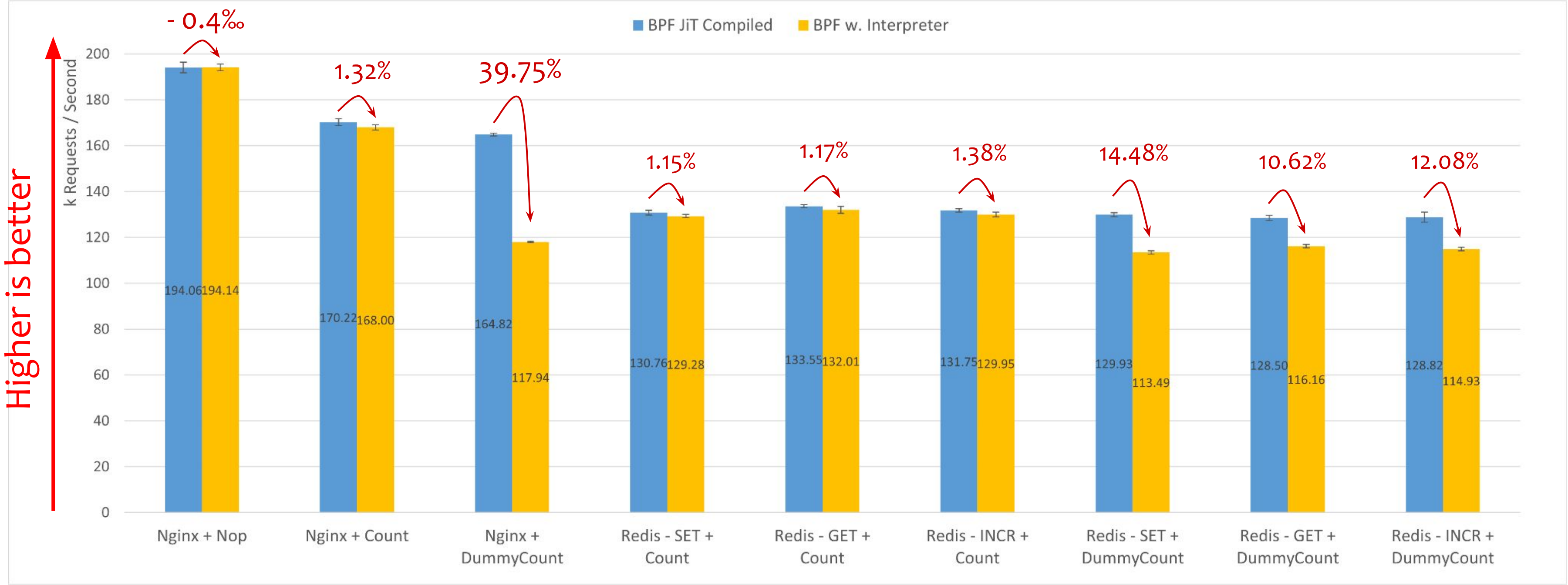
	Instructions	Verification Time Overhead*	Verification Memory Overhead*	JiT Time Overhead
Nop	2	8.82 ms	3328 kb	9.74 ms
Hash	26	12.05 ms (7.43 instr./ ms)	4096 kb	9.79 ms
Adds	1002	43.60 ms (28.75 instr./ms)	5056 kb	9.85 ms

: The lower bound overhead of the entire system.

* : Overhead made to the host system.

The JiT compilation overhead and the corresponding verification overhead are negligible

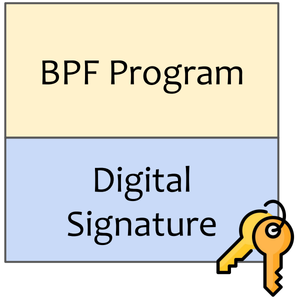
Evaluation - BPF Kernel Tracing **Nginx** and **Redis**



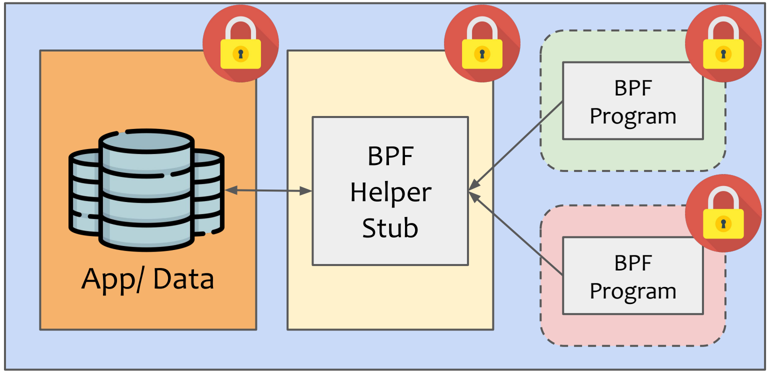
The improvement in jitted BPF runtime is more significant as the program size increases

Further Ideas

- Ensure verification integrity with **digital signature**



- More robust BPF runtime isolation:
    - Intel **MPK**
    - BPF helper function stub



- Support verification with BPF maps
- BPF program as configurations
- Secure verification process from malicious cloud provider: **Confidential VM**

Conclusion

- UniBPF provides **safer** BPF runtime
  - Resist runtime errors interpreters cannot
  - Protect jitted runtime from malicious codes

- Only brings **negligible overhead**

- Enables **more efficient runtime** through JiT compilation
  - Instruction level: Up to 600%
  - Kernel-Tracing:
    - Nginx: 40% ~
    - Redis: 14.48% ~

Try it out!

https://github.com/TUM-DSE/ushell/