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Exploring Composable Network Stacks from Isolated Components with WebAssembly and QUIC

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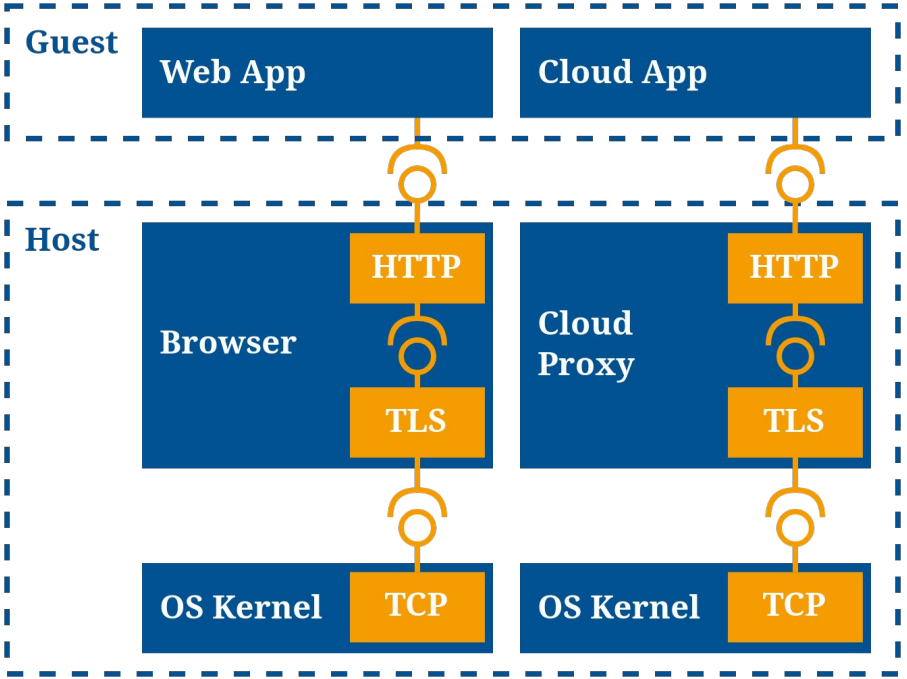
State of the Art

- Modern web apps demand tailored network protocols
  - Real-time & Multimedia
- Apps use generic protocol implementations provided by the underlying platform
  - Browser & Cloud Host
- Host runs many guests
  - Browser tabs
  - Containers
  - Isolated guests
  - Efficient host protocols

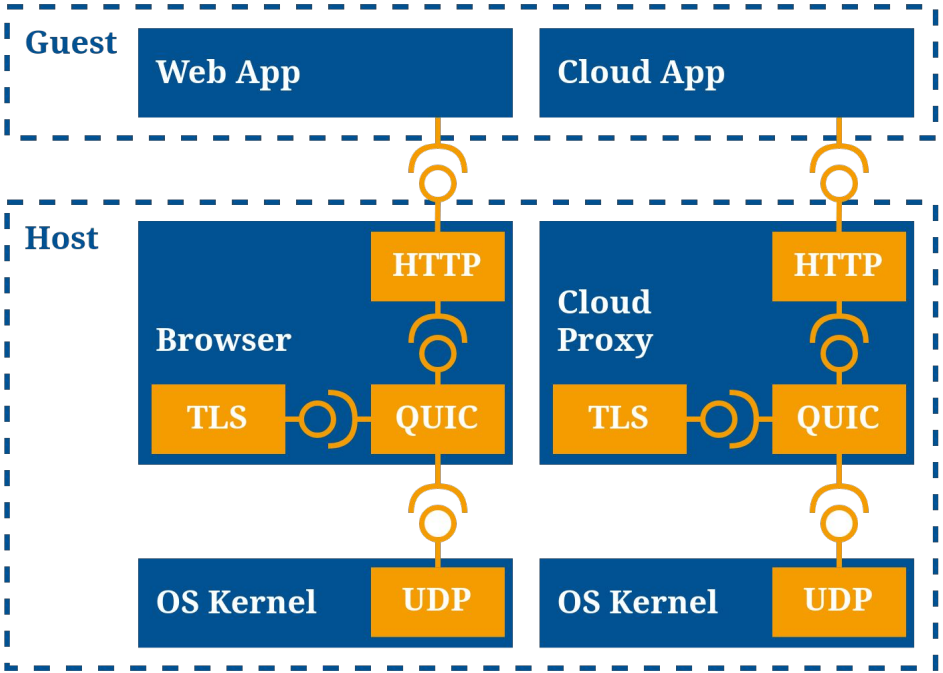


☐ **Lack of protocol adaptability by guest**

QUIC

- Standardized by the IETF in 2021
- General purpose
- Extensible
- Foundation for HTTP/3, RoQ, MoQ
- Userspace implementation maintains rapid development

☐ **Lack of protocol adaptability by guest**



Related Work

2019 De Coninck et al. - Pluginizing QUIC
adapt QUIC via eBPF

2020 Tran et al. - Beyond socket options: Towards fully extensible Linux transport stacks
adapt Linux MPTCP with eBPF

2024 De Coninck - Core QUIC: Enabling Dynamic, Implementation-Agnostic Protocol Extensions
adapt QUIC via WASM

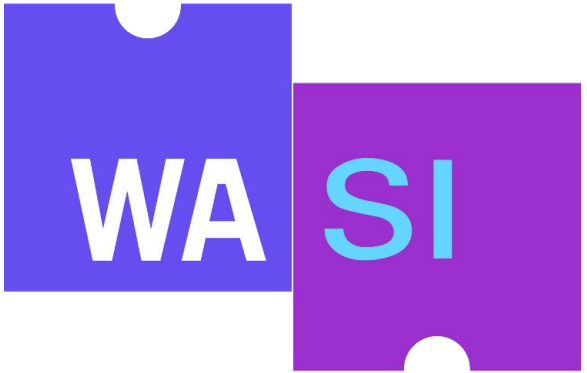
- **Hooks into provided implementation**
- **No extensive performance analysis**

WebAssembly (WASM)

- W3C standard since 2019
- Low-level bytecode format
- Compilation target
- Secure
  - Designed to run untrusted code
- No system calls
- Portable
  - Runs anywhere
  - Requires runtime environment (similar to JVM)

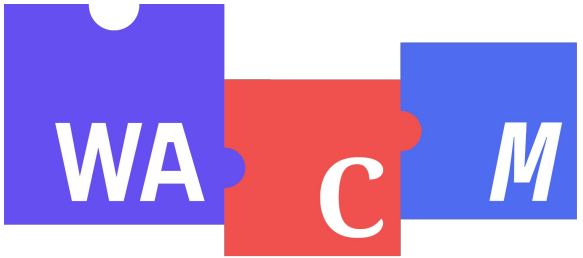
WebAssembly System Interface (WASI)

- In development; Preview 2 in 2024
- Collection of common APIs for system interaction
- Secure & Portable
- Import of required functions into WASM module



WebAssembly Component Model

- In development
- Secure composition of separately compiled WASM modules
- host-to-WASM and WASM-to-WASM linking
- shared-nothing-linking
  - each WASM module runs in isolated memory



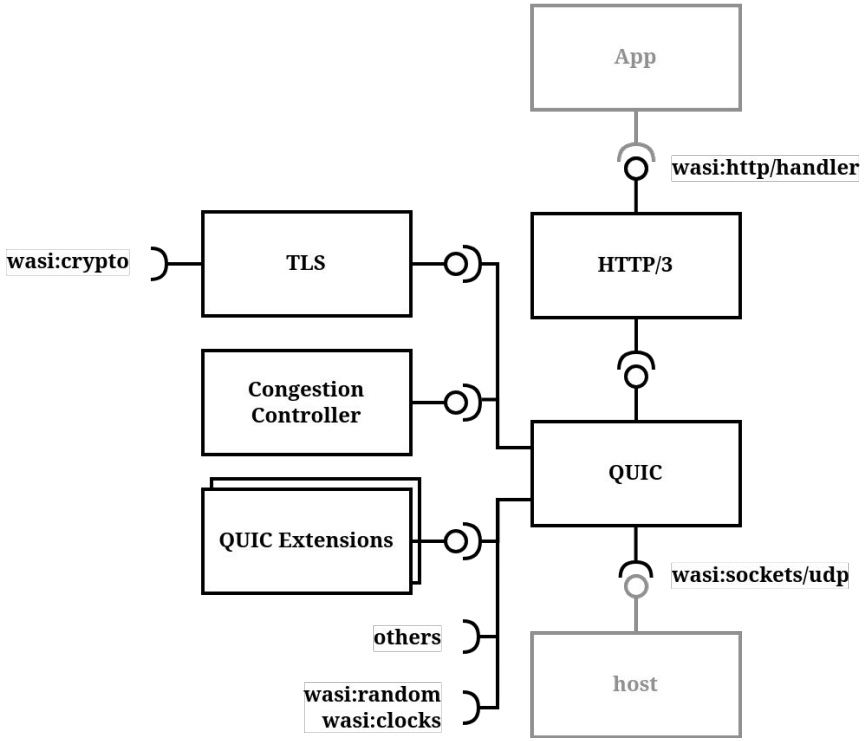
non-official logo

Design - QUIC Components

- QUIC stacks consist of functional units
  - demuxer, tls, stream frame sorter, cc, flow controller, frame scheduler, h3
- tight-coupling & in same memory region

⇒

- define interfaces by WIT IDL
- call-by-value
- resource handles

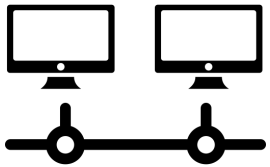


Component Sources

- Host system
  - OS, browser, or cloud runtime

- Third-party repository
  - warg

- Guest application
  - e.g. cloud tenant



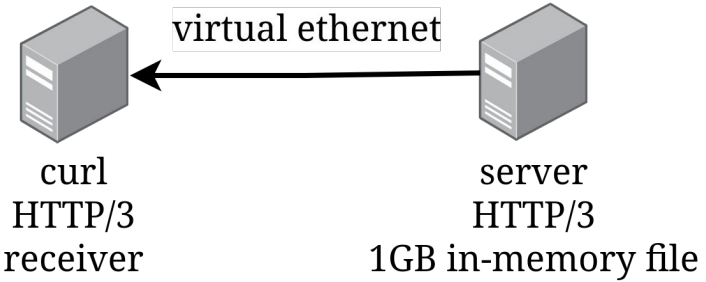
- Peer
  - during handshake or connection

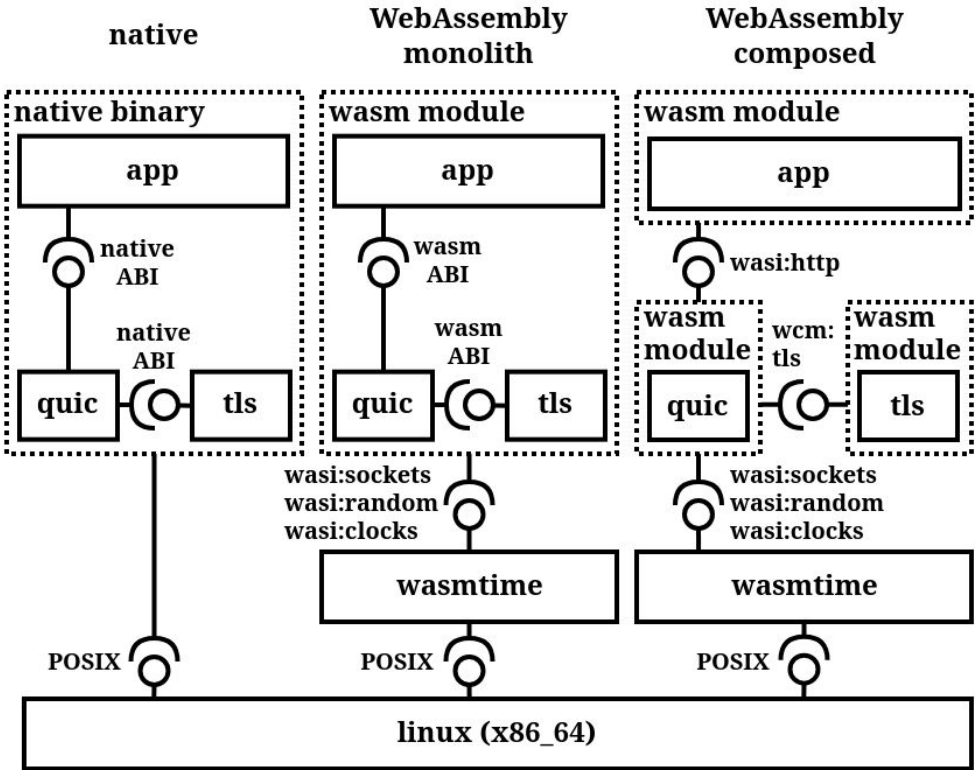
⇒ **strong isolation is key when running untrusted network components**

Evaluation

- 3 server variants
- Cloudflare quiche: replace mio
- BoringSSL: remove ASM; WASI randomness
- Dotted boxes show isolated memory

Testbed:

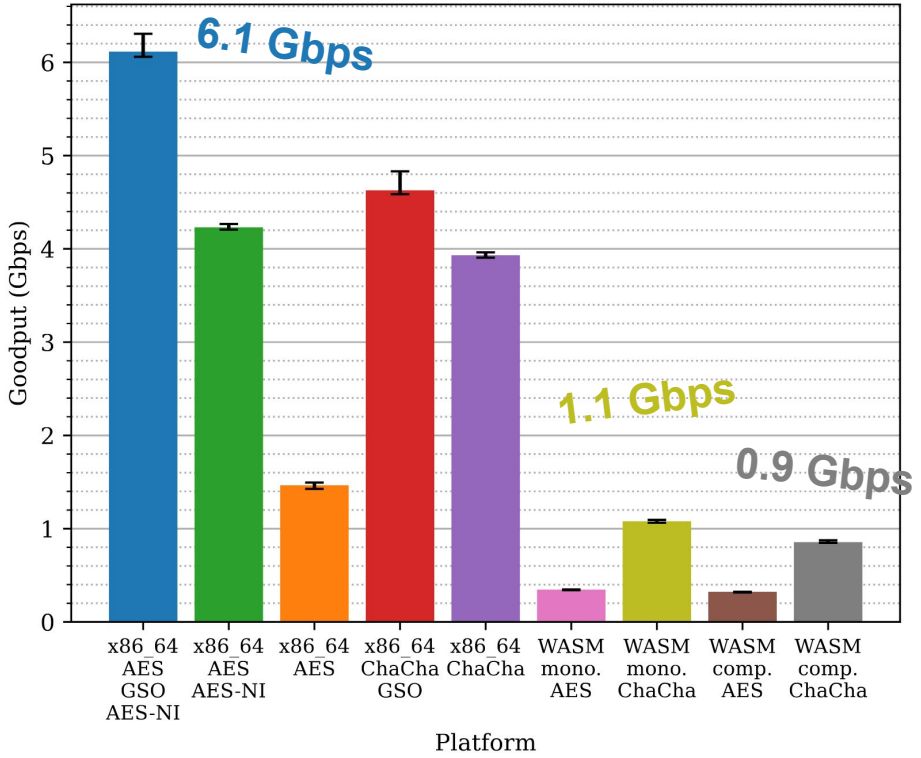




Evaluation - Goodput

- understand cost of isolation
- meet application demands
  - high bandwidth
  - low power consumption
- optimizations
  - GSO
  - AES-NI

? what causes the reduced performance



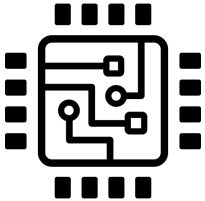
Evaluation - Call Stack Analysis

- Sample and categorize call stacks
- **100x** AES slowdown
- **20x** crypto slowdown using ChaCha
- **17x** cycles spent on memory copies
- **5x** socket IO slowdown

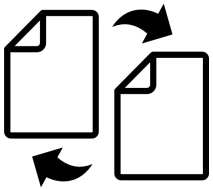
	crypto	copy	socket io	total
x86_64 AES128 GSO AES-NI	1.05 ± 0.21	0.43 ± 0.07	2.05 ± 0.33	7.68 ± 0.16
x86_64 AES128 AES-NI	1.28 ± 0.09	0.51 ± 0.04	7.28 ± 0.08	11.47 ± 0.13
x86_64 ChaCha20 GSO	1.81 ± 0.06	0.44 ± 0.04	2.69 ± 0.11	9.97 ± 0.17
x86_64 ChaCha20	2.00 ± 0.05	0.49 ± 0.05	7.02 ± 0.07	12.16 ± 0.08
x86_64 AES128	11.19 ± 0.09	0.57 ± 0.05	8.79 ± 0.10	32.93 ± 0.08
WASM AES128 monolith	111.83 ± 0.40	2.73 ± 0.08	11.68 ± 0.13	150.31 ± 0.48
WASM ChaCha20 monolith	20.63 ± 0.21	2.92 ± 0.15	11.23 ± 0.17	53.64 ± 0.31
WASM AES128 composed	111.42 ± 0.55	8.79 ± 0.21	11.74 ± 0.22	157.00 ± 0.48
WASM ChaCha20 composed	20.47 ± 0.10	8.66 ± 0.15	11.24 ± 0.24	59.57 ± 0.25

10^9 CPU cycles per transferred GiB. 4000 Hz sample rate. Mean of 20 repetitions.

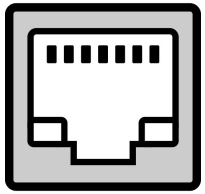
Open Challenges



- Accelerating cryptography
  - ISA specific ASM
  - wasi-crypto



- Reduce memory copies
  - inter-component communication with safe memory sharing



- Access efficient host network APIs
  - batched or asynchronous OS socket APIs

Use Cases

- Serverless and browser plugins
  - e.g. host provides API for guest to register custom multipath schedulers
- TLS isolation
  - cryptographic material stays in TLS component
- Kernel deployment
  - augment high-efficient QUIC implementation in kernel
- Simulation and test environments
  - easy to integrate in existing tools and environments

Conclusion

- Modularizing network stacks is technically feasible
- Overhead limits use for high-performance applications
  - from 6.1 Gbps to 0.9 Gbps
- Comprehensive analysis of WASM component isolation
  - Throughput, and call stack
- Identified major open challenges and possible solutions
  - cryptography, memory-copy, and network IO

⇒ **on the best way to an efficient and modular network stack**

Q&A

Crypto WIT Interface

```
package cm:quichewasm;

interface crypto {
    type c-int = s32;
    type usize = u32;

    resource evp-aead;
    resource evp-aead-ctx { constructor(); }

    resource buffer {
        constructor(buffer: list<u8>);
        take-back-copy: func() → option<list<u8>>;
    }
    resource usize-ptr {
        constructor(number: usize);
        back: func() → usize;
    }

    evp-aead-aes-one28-gcm: func() → evp-aead;
    evp-aead-aes-two56-gcm: func() → evp-aead;
    evp-aead-aes-chacha20-poly1305: func() → evp-aead;

    evp-aead-ctx-init: func(ctx: borrow<evp-aead-ctx>, aead: borrow<evp-aead>, key: borrow<buffer>, key-len: usi
    evp-aead-ctx-open: func(ctx: borrow<evp-aead-ctx>, out: borrow<buffer>, out-len: borrow<usize-ptr>, max-out-
    evp-aead-ctx-seal-scatter: func( ctx: borrow<evp-aead-ctx>, out: borrow<buffer>, out-tag: borrow<buffer>, ou
}

NOR   interface.wit                                                    1 sel  1:23
```