Containers Do Not Need Network Stacks

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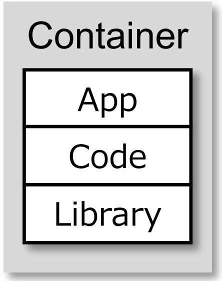
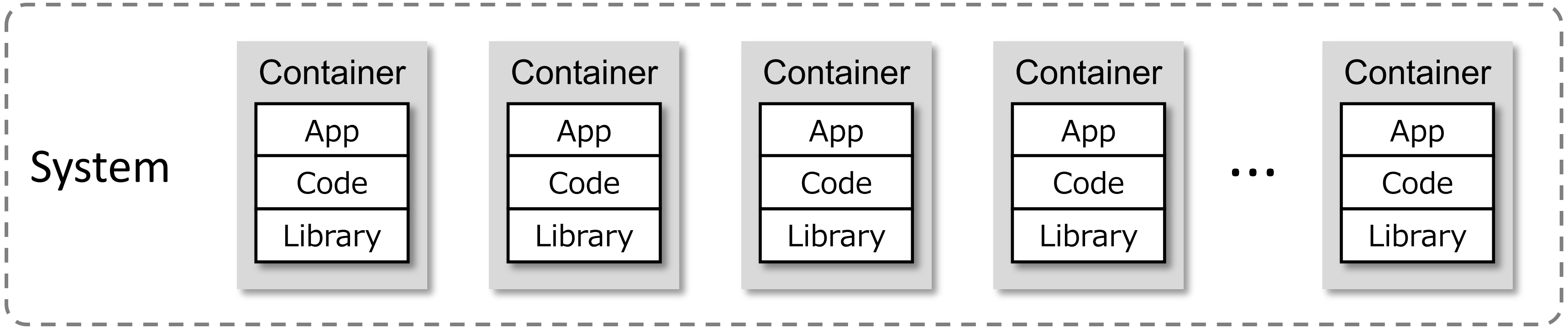
iijlab seminar 2018/10/16

Based on *Ryo Nakamura, Yuji Sekiya, and Hajime Tazaki. 2018. "Grafting Sockets for Fast Container Networking". In ANCS '18: Symposium on Architectures for Networking and Communications Systems, July 23–24, 2018, Ithaca, NY, USA.*

Containers

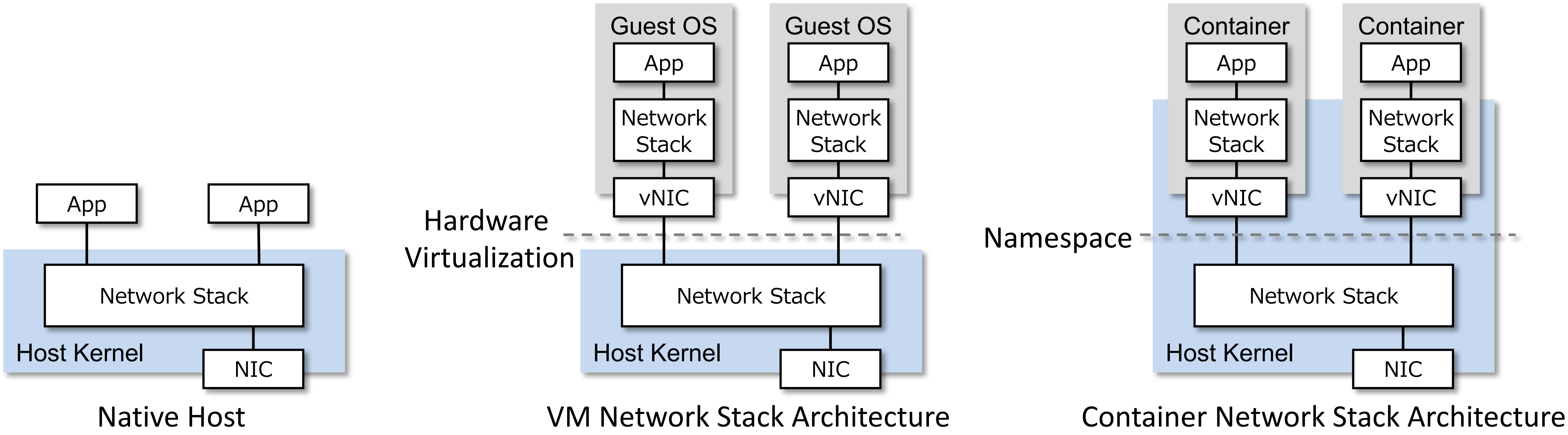
- A package of an application execution environment
  - version-controllable
  - portable
  - lightweight
- Microservice architecture
  - An application (service) runs on a container
  - Multiple containers comprise a system





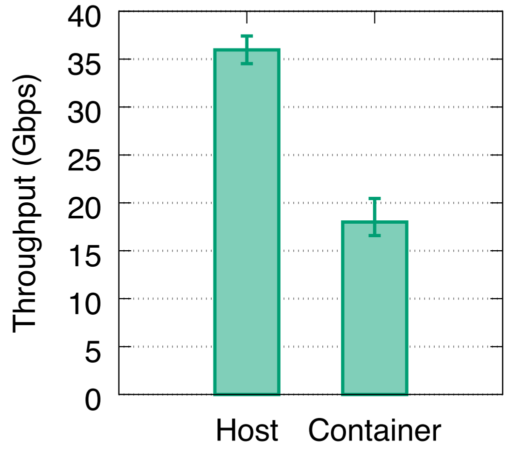
The beginning of container networking

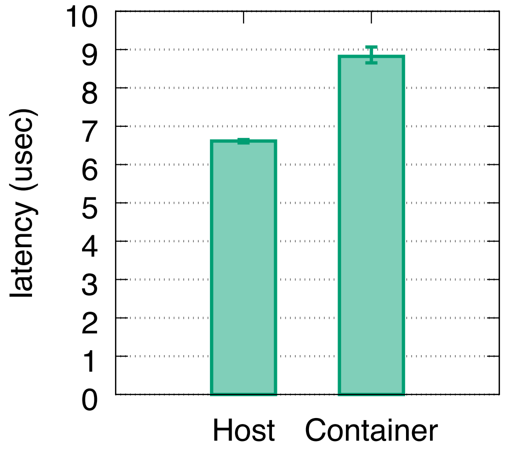
- A container is a separated namespace in a host OS
  - Containers need to connect to other containers, host, and external networks
- The conventional approach: Adapters and Links
  - *Virtual NICs* (veth interface in Linux)

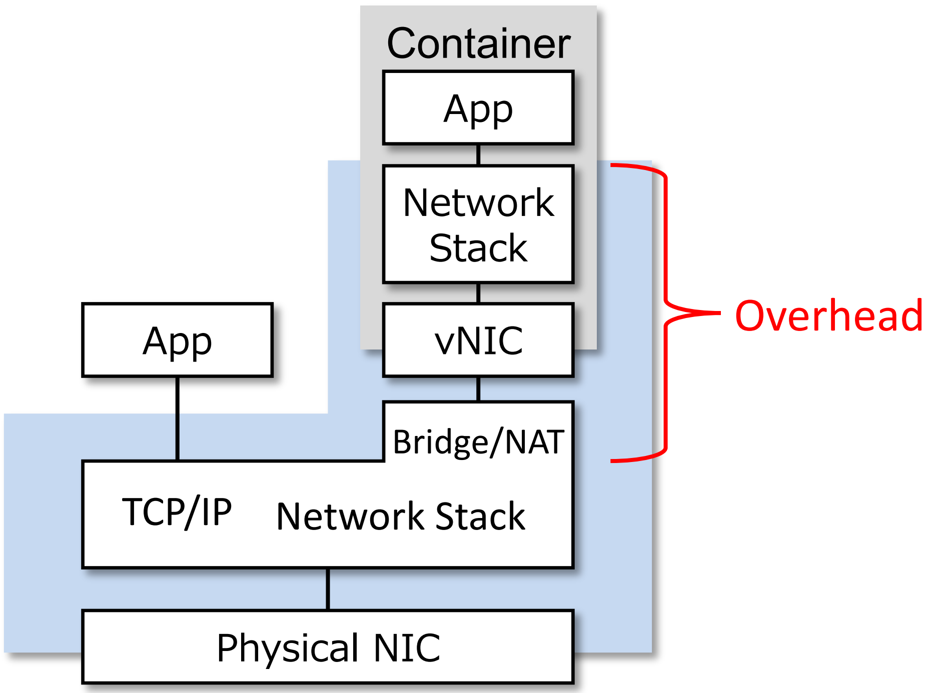


Overhead of container networking

- Container involves
  - virtual NIC (veth)
  - virtual bridge and NAT (docker0) in the host network stack
- Network performance degradation
  - degrade throughput by 50%
  - increase latency by 25%

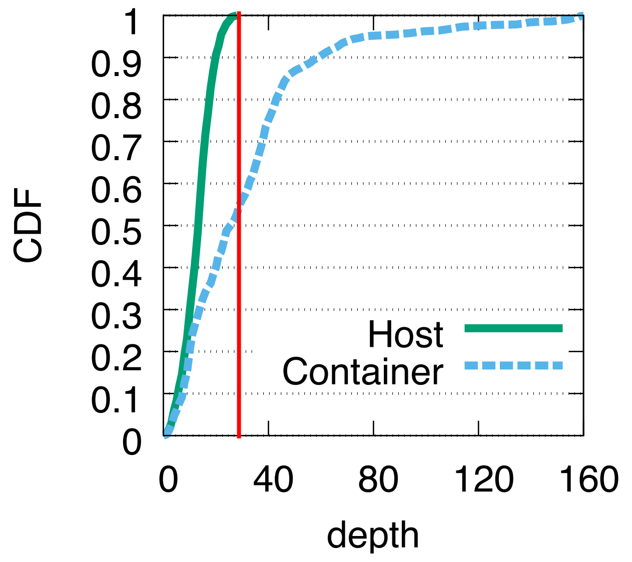




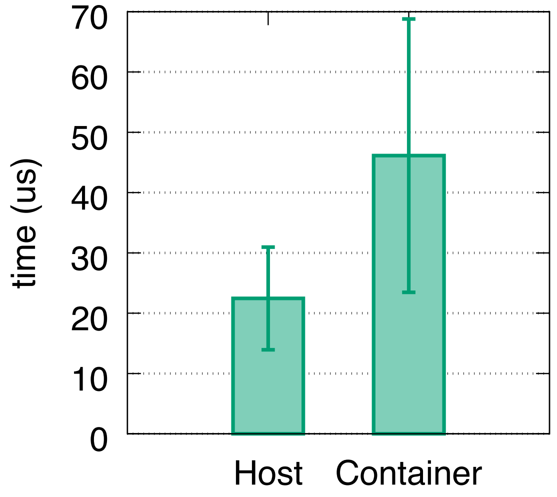


The long data path

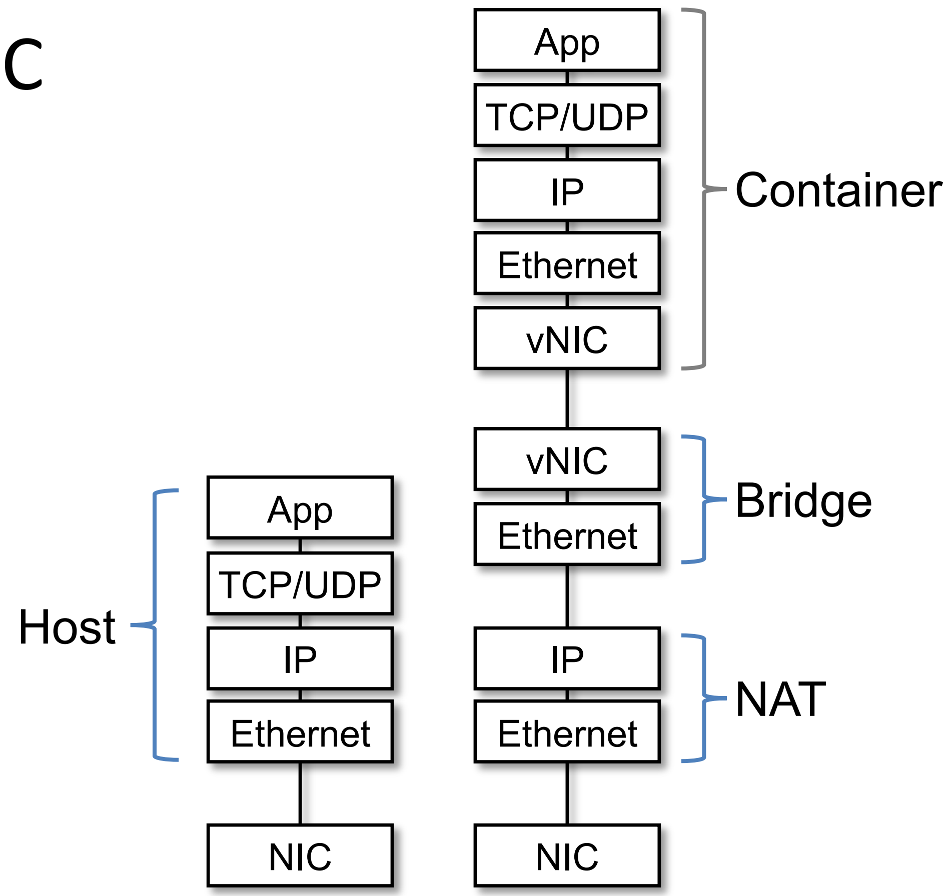
- from an application in container to NIC
  - Time to transmit a packet increases
  - ➢Throughput and latency are degraded



Depth of called functions from `udp_sendmsg()`



Elapsed time in `udp_sendmsg()`



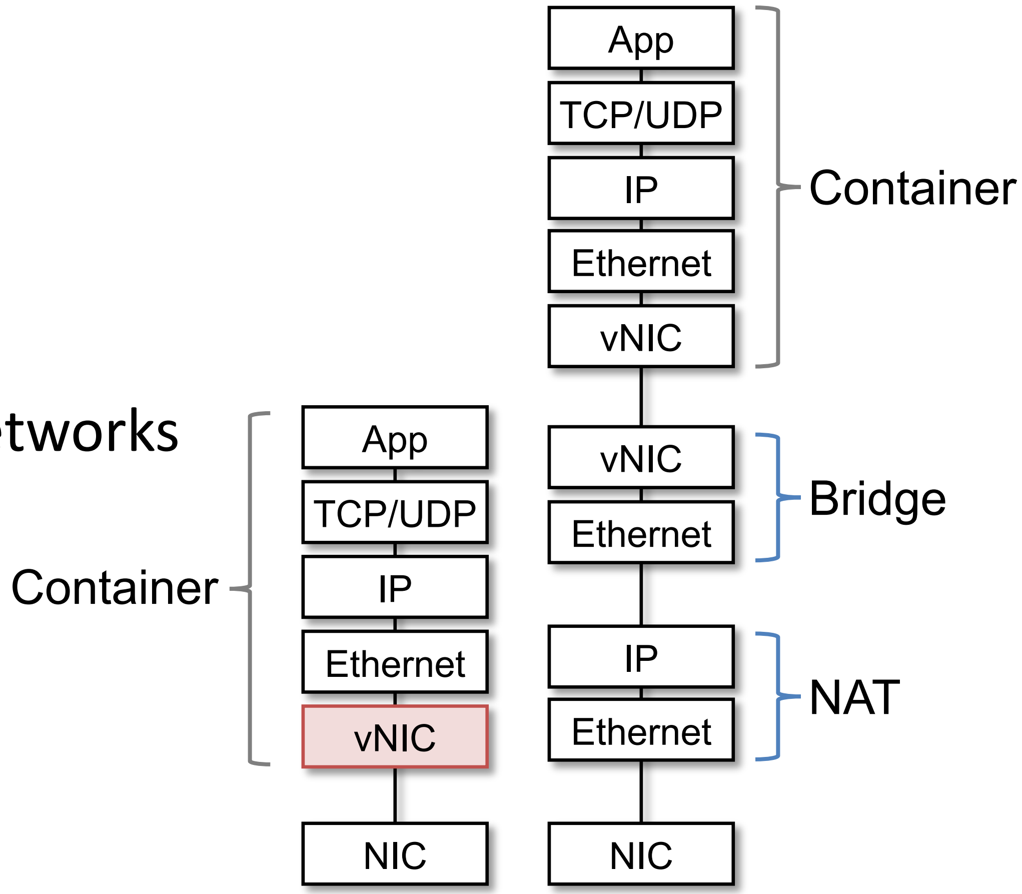
State-of-the-art container networking

1. Interface Virtualization
    - Directly attaching interfaces to containers (bypassing host network stack)
    - macvlan, SR-IOV
2. Optimized Network Stacks
    - Reinventing the entire or a part of network stacks
    - FreeFlow[1], Cilium[2]

[1] Tianlong Yu, et al., "FreeFlow: High Performance Container Networking". HotNets'16
[2] Cilium, https://cilium.io/

State-of-the-art: Interface Virtualization

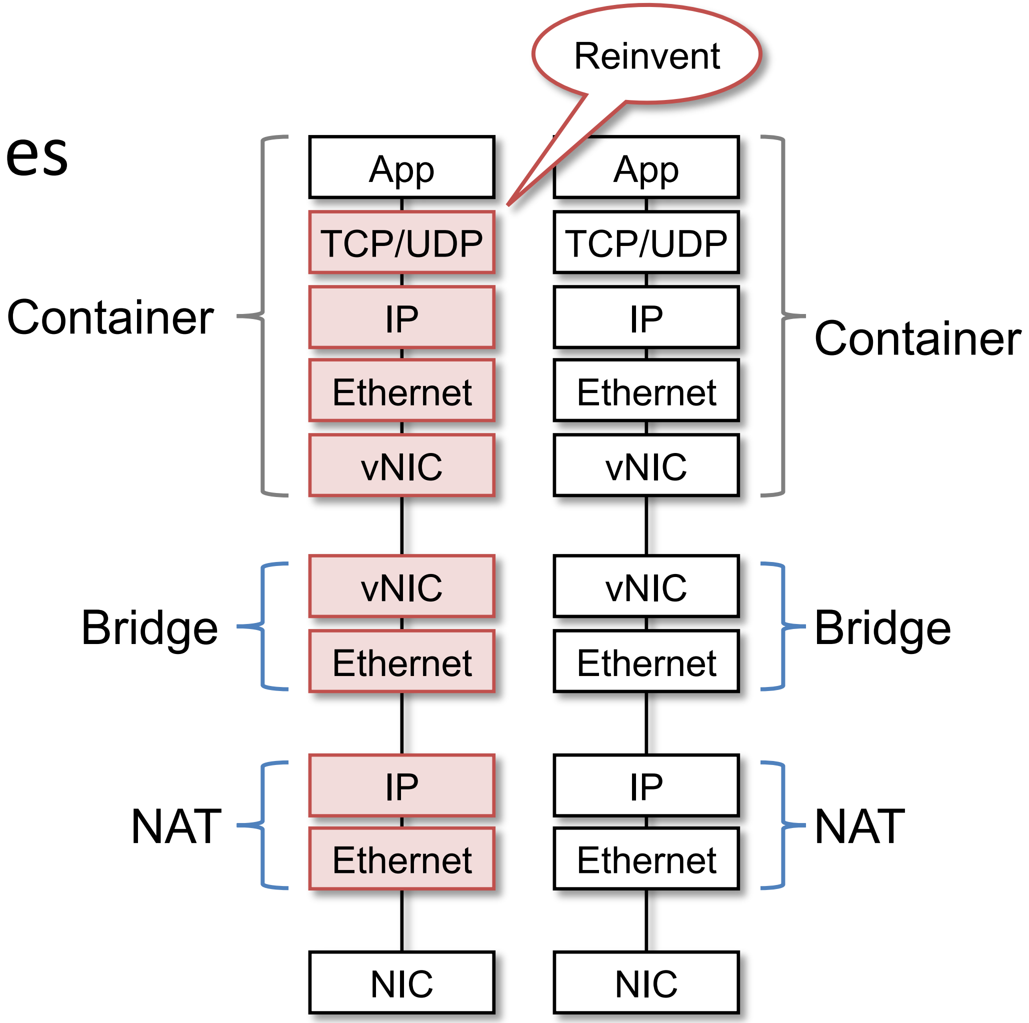
- Bypassing the host network stack
  - macvlan achieves comparable network performance with native host[3]
- Complicating management
  - Outer networks must manage container networks
    - addressing, tenant separation, access control, etc
  - NAT conceals container networks from outer networks and infrastructures



[3] Yang, et al, "Performance of Container Networking Technologies", HotConNet'17

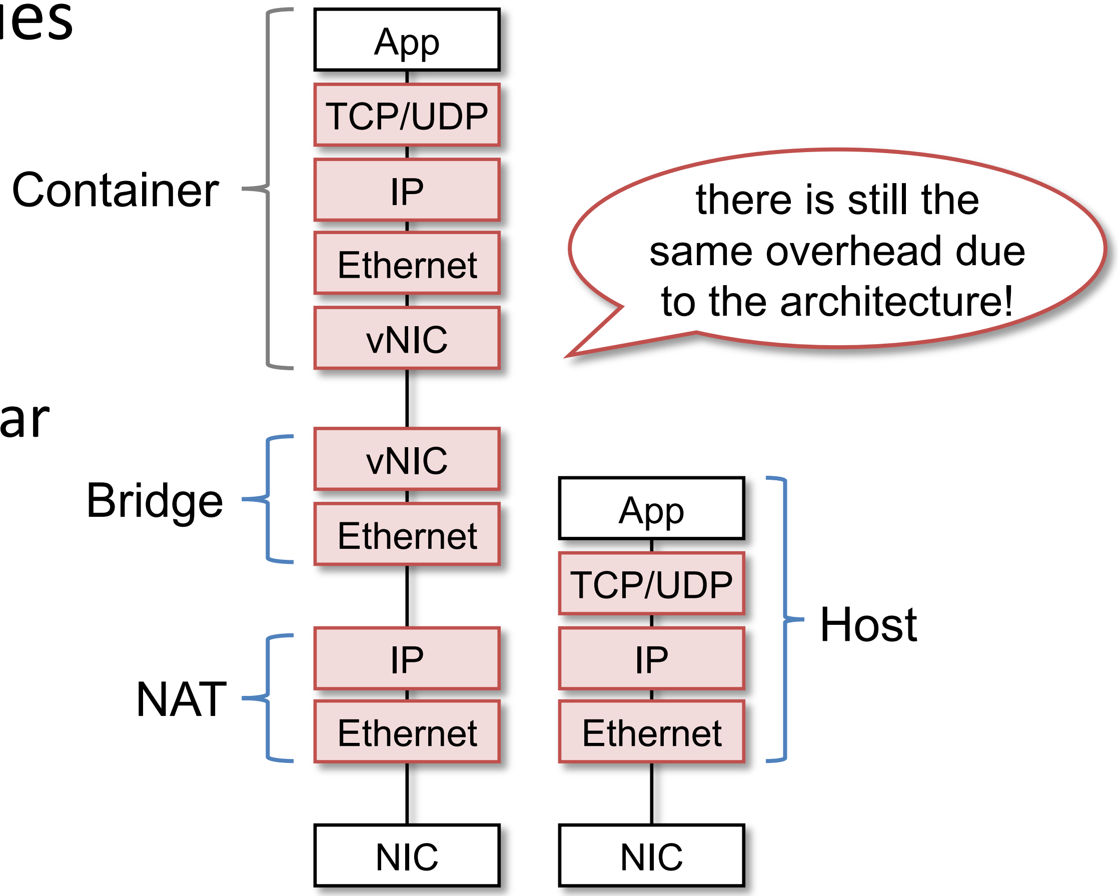
State-of-the-art: Optimized network stacks

- Using high-speed packet I/O techniques
  - FreeFlow uses DPDK and RDMA
  - Cilium uses XDP (eBPF)



State-of-the-art: Optimized network stacks

- Using high-speed packet I/O techniques
  - FreeFlow uses DPDK and RDMA
  - Cilium uses XDP (eBPF)
- The long data path will be the next bottleneck
  - Protocol processing cost do not disappear
    - In Arrakis OS[4], network protocol processing occupies 100% of processing cost on a simple UDP echo server
  - It will be more significant bottleneck in comparison with native hosts

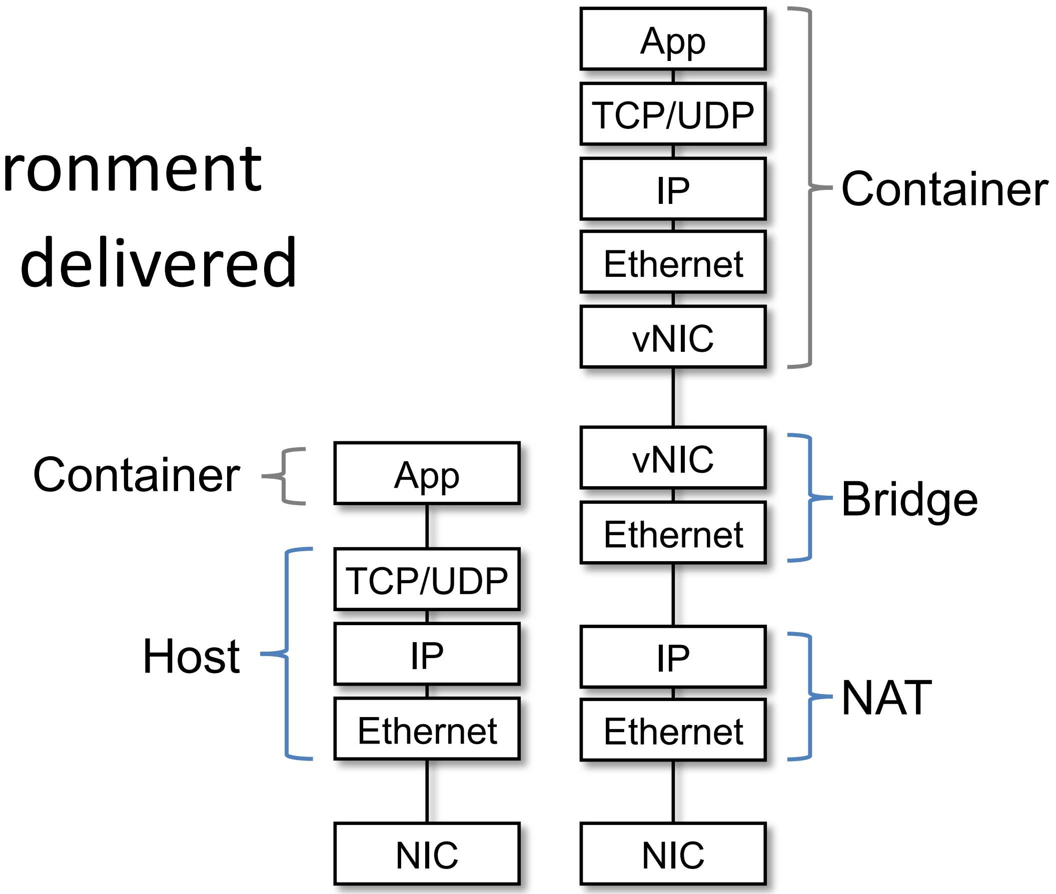


[4] Simon, et al, "Arrakis: The Operating System is the Control Plane", OSDI'14

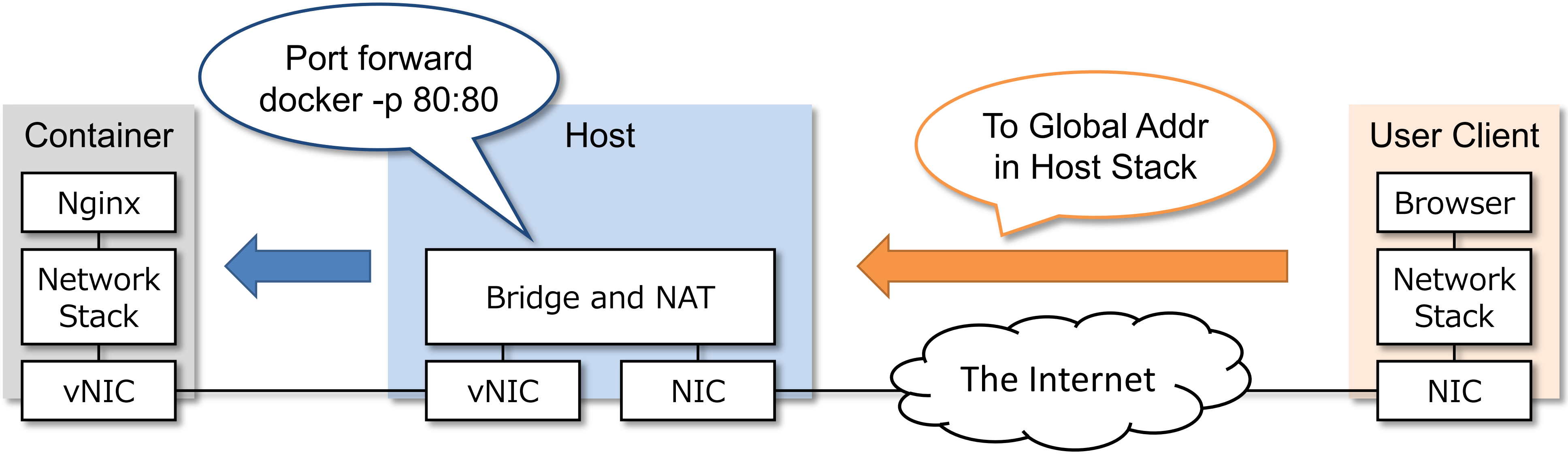
The third approach: Bypassing container network stacks

- A container is
  - just an application execution environment
  - not interested in how packets are delivered

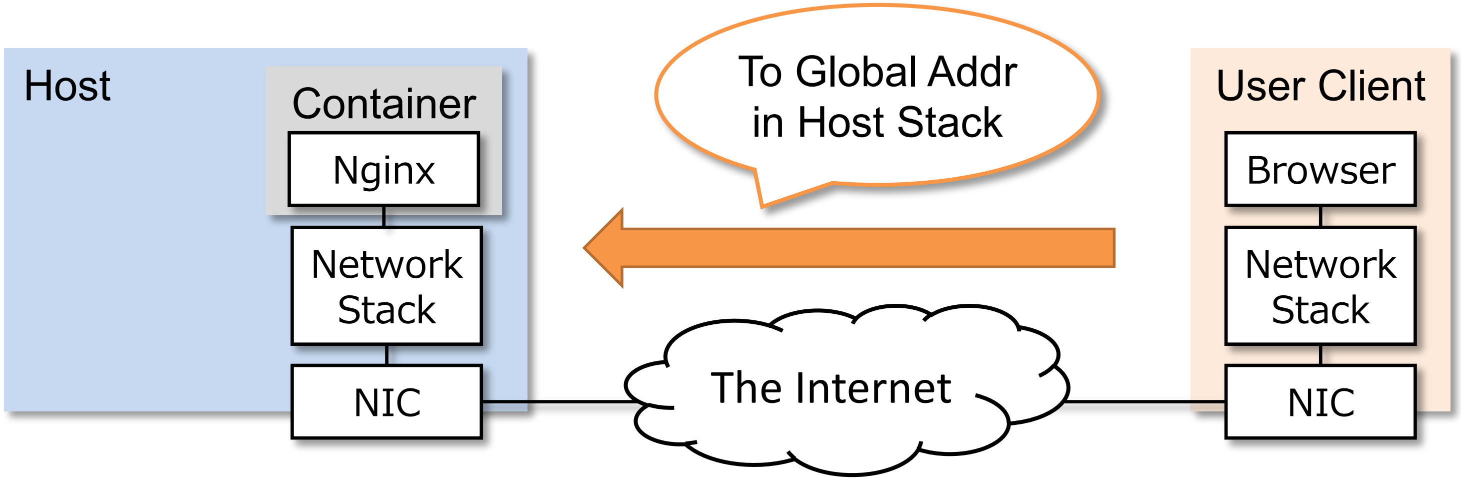
Then, we can bypass container network stacks to mitigate the overhead?



A question: Do containers *really* need network stacks?



Container has network stack



Container does not have network stack

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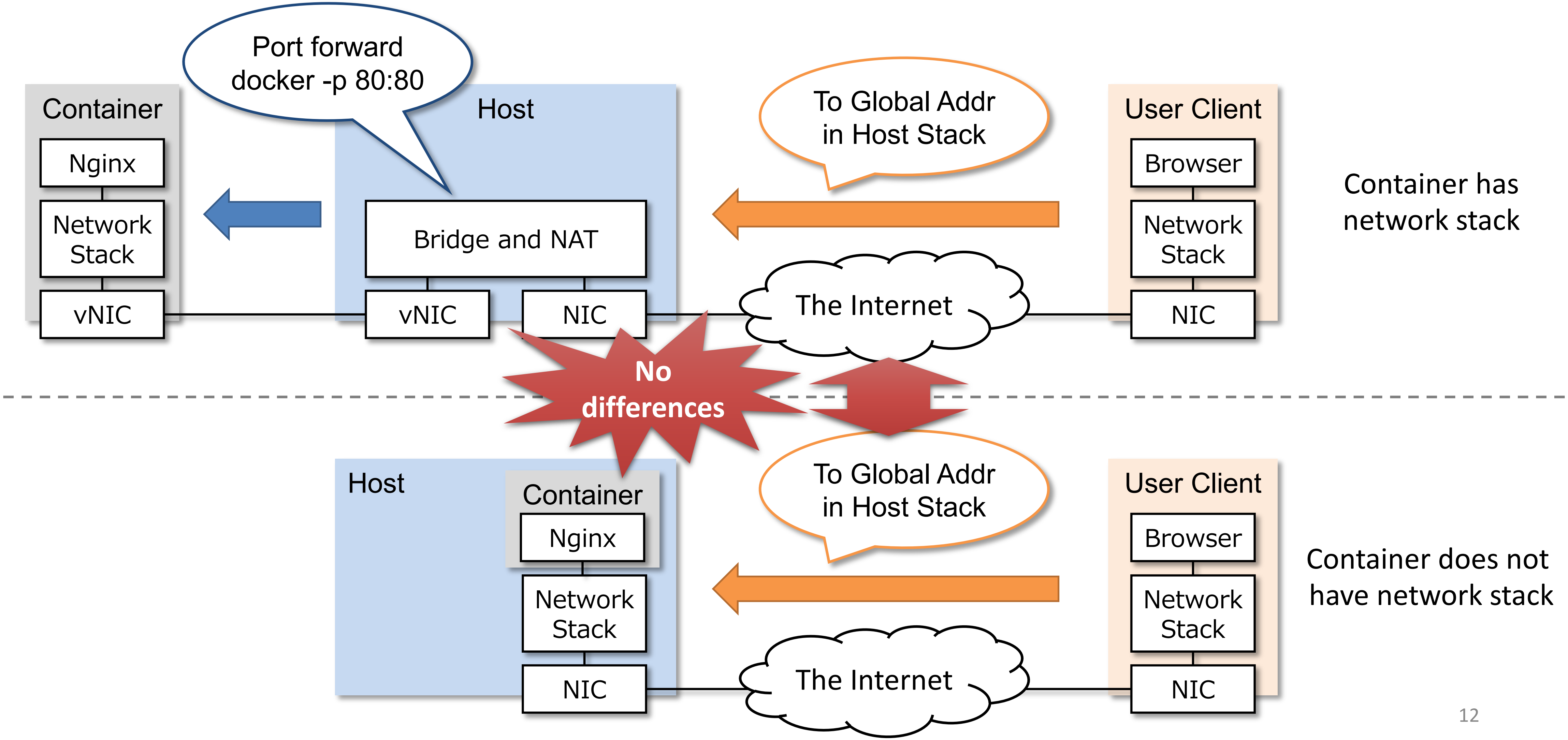
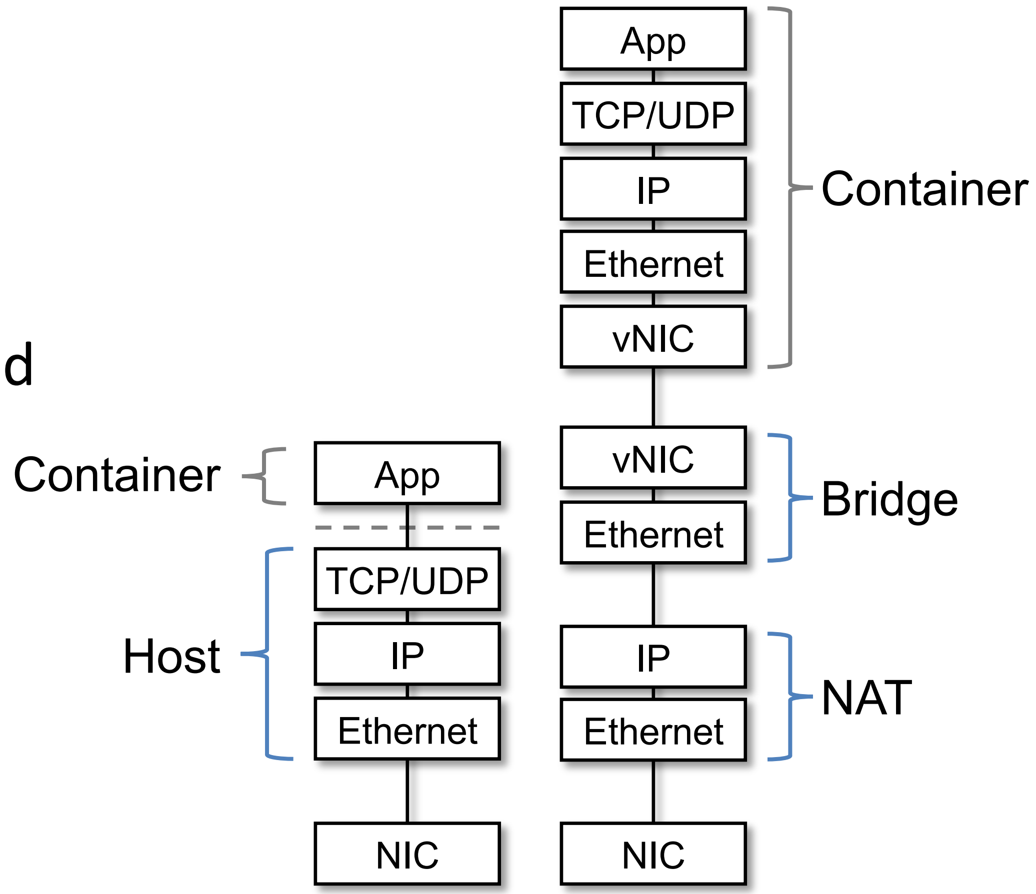


Container has network stack

Container does not have network stack

The third approach: Bypassing container network stacks, cont'd

- A container is
  - just an application execution environment
  - not interested in how packets are delivered
  - Then, ***we can bypass container network stacks***
- Network stack separation should be retained
  - `docker run --net=host` can cause unintended or malicious resource uses
    - address, port, protocol, etc
- **A new mechanism is needed**
  - connecting App on a container to the host
  - with proper access control



The third approach: Bypassing container network stacks, cont'd

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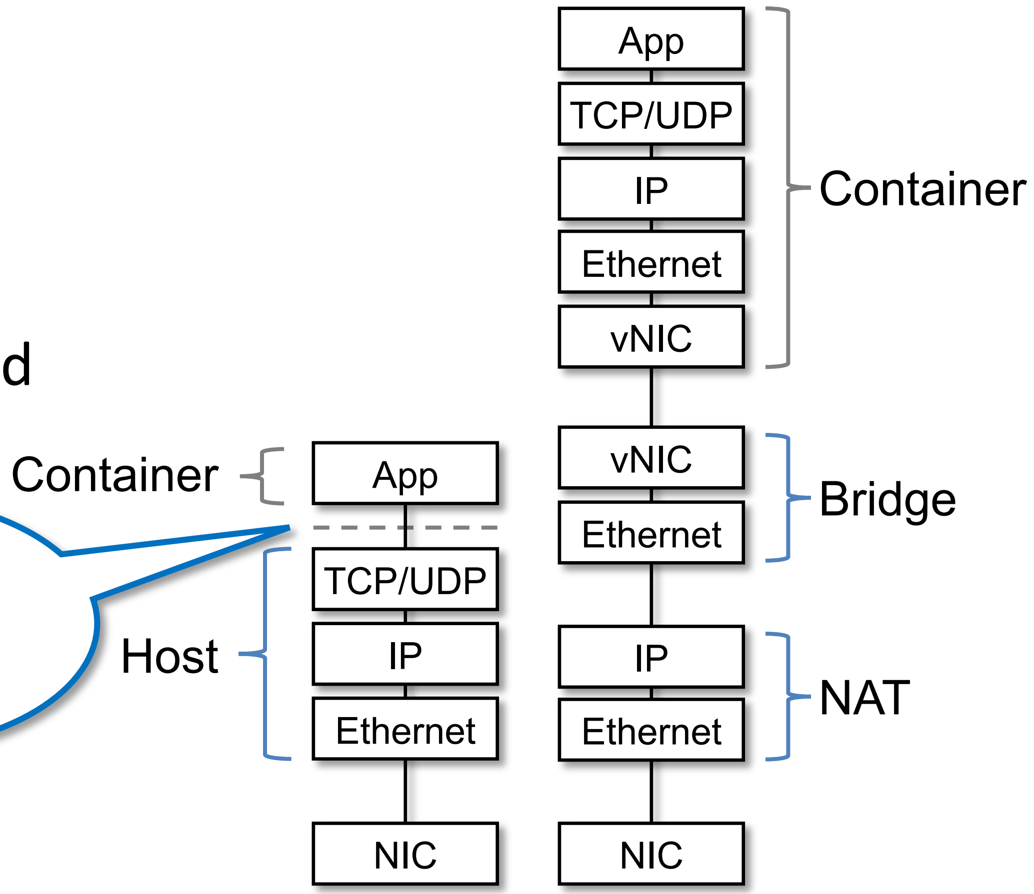
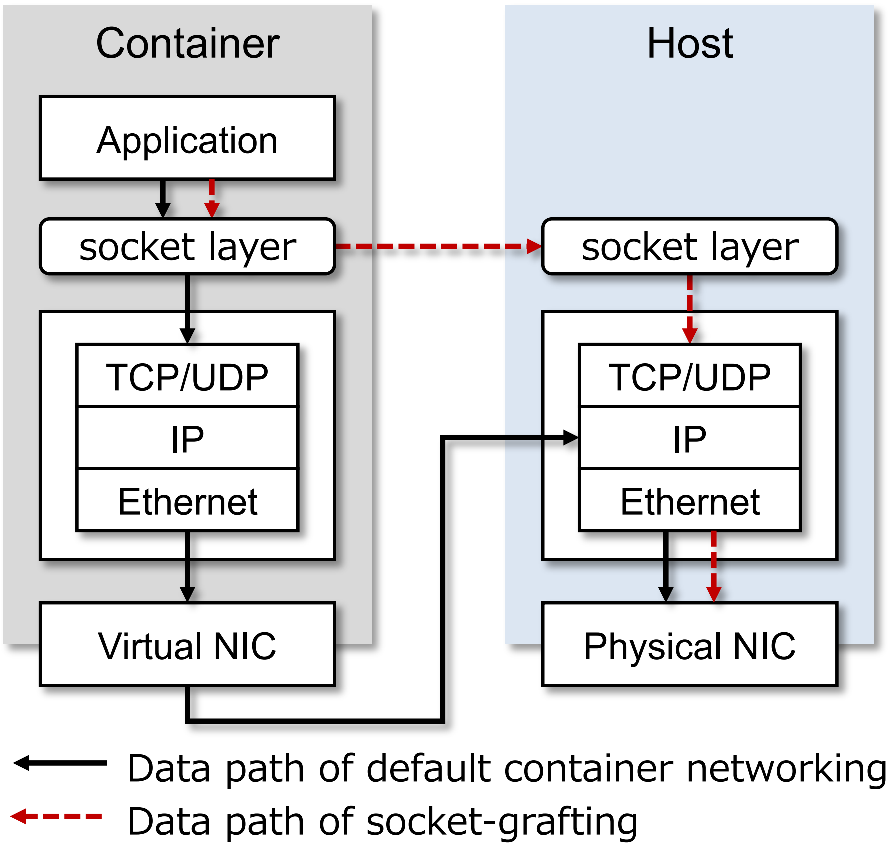


Approach: Socket-Grafting

- Grafting sockets in containers onto sockets in hosts
  - A socket-layer communication channel design
  - graft = 接ぎ木する、移植する

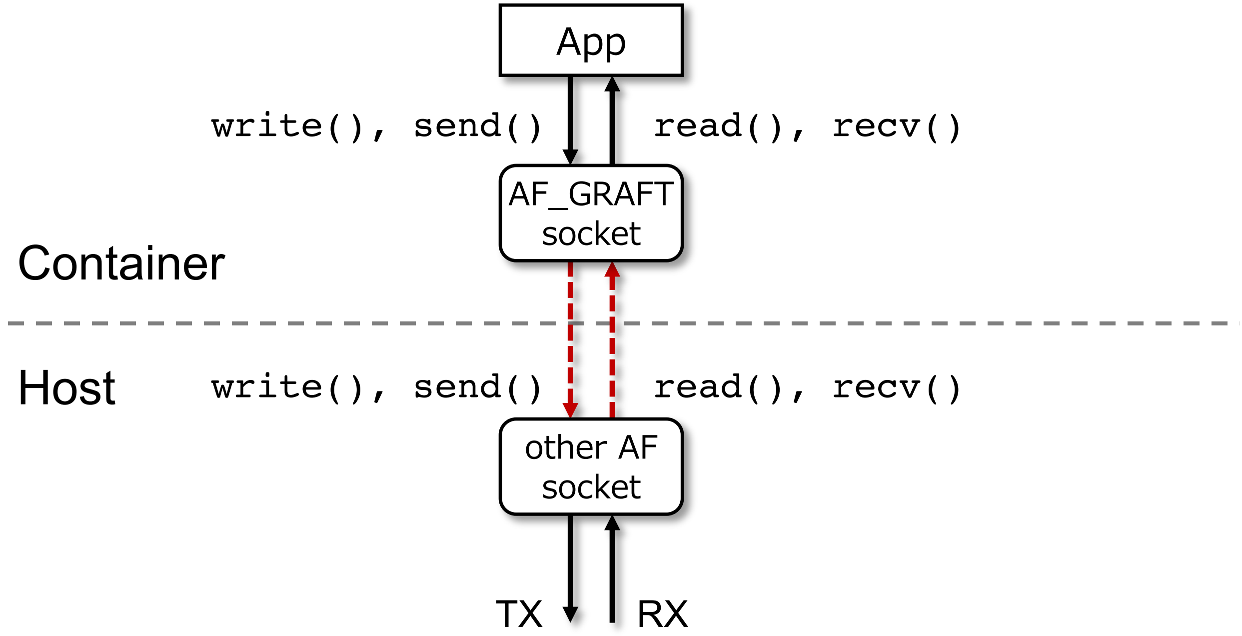
✓One Network stack on the data path

✓Independent from network stack implementations



Mechanism: AF_GRAFT

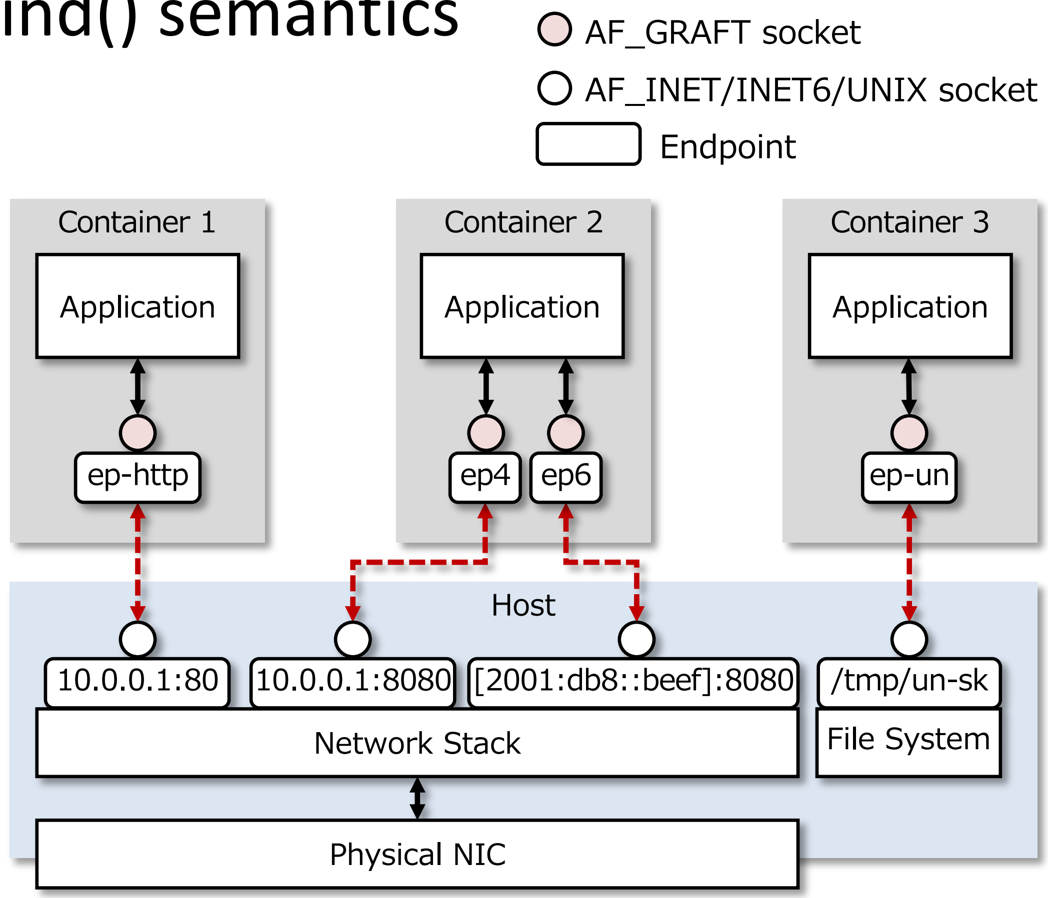
- A new address family for grafting sockets
  - Applications in containers create AF_GRAFT sockets
  - AF_GRAFT sockets are grafted onto other AF sockets across the network namespace boundary



Graft endpoint

- *Names* for AF_GRAFT sockets in the bind() semantics
  - Arbitrary strings
- GRAFT <-> Host endpoint mapping
  - AF_GRAFT manages the mapping table per container
  - preventing misuse of the host namespace

Graft endpoint	Host endpoint
ep-http	10.0.0.1:80
ep4	10.0.0.1:8080
ep6	[2001:db8::beef]:8080
ep-un	/tmp/un-sk



AF_GRAFT Socket API

```
/* Structure describing a graft socket address (endpoint) */
struct sockaddr_gr {
        __kernel_sa_family_t sgr_family;
        char sgr_epname[AF_GRAFT_EPNAME_MAX];
};
```

```
int sock;
struct sockaddr_gr saddr_gr;

sock = socket(AF_GRAFT, SOCK_STREAM, IPPROTO_TCP);

saddr_gr.sgr_family = AF_GRAFT;
strncpy(saddr_gr.sgr_epname, “ep-http”, 7);

bind(sock, (struct sockaddr *)&saddr_gr, sizeof(saddr_gr));
/* Then, you can use sock as usual TCP sockets */
```

Outbound connections

- Dynamic-port graft endpoint
  - It uses randomly selected port numbers == typical client sockets
  - For example, mapping `ep-out` on `X.X.X.X:random`

```
sock = socket(AF_GRAFT, SOCK_STREAM, IPPROTO_TCP);

saddr_gr.sgr_family = AF_GRAFT;
strncpy(saddr_gr.sgr_epname, “ep-out”, 7);
bind(sock, (struct sockaddr *)&saddr_gr, sizeof(saddr_gr));

/* Then sock is grafted onto source IP:RandomPort socket*/

connect(sock, (struct sockaddr *)&dst, sizeof(dst));
```

Implementation

- https://github.com/upa/af-graft, AF_GRAFT kernel module
  - no kernel patches (but overwriting an existing AF number, AF_IPX)
  - Grafting is implemented as function call
    - no buffering, queueing, messaging => minimal overhead!
  - A few socket options for practical uses
  - A modified iproute2 for configuring the mapping table

```
$ ip graft add ep-http type ipv4 addr 10.0.0.1 port 80
$ ip graft add ep-out type ipv4 addr 10.0.0.2 port dynamic
$ ip graft del ep-un
$ ip graft show
```

Existing application with AF_GRAFT

- AF_GRAFT is a new address family
  - Applications need source code modifications
  - It is easy because of the familiar socket API, but difficult to deploy

➢ Overriding system calls by the LD_PRELOAD trick
  - `$ LD_PRELOAD libgraft-hijack.so app`
    - hijacking functions in shared library
  - Hijacking:
    1. getaddrinfo()
    2. socket(), bind(), and connect()
  - to convert address family-dependent socket operations into AF_GRAFT-capable ones

getaddrinfo()

- It was carefully designed to achieve AF-independent codes
  - Our modified getaddrinfo() can return AF_GRAFT and sockaddr_gr
- However, unfortunately, this is not the case in practical applications...

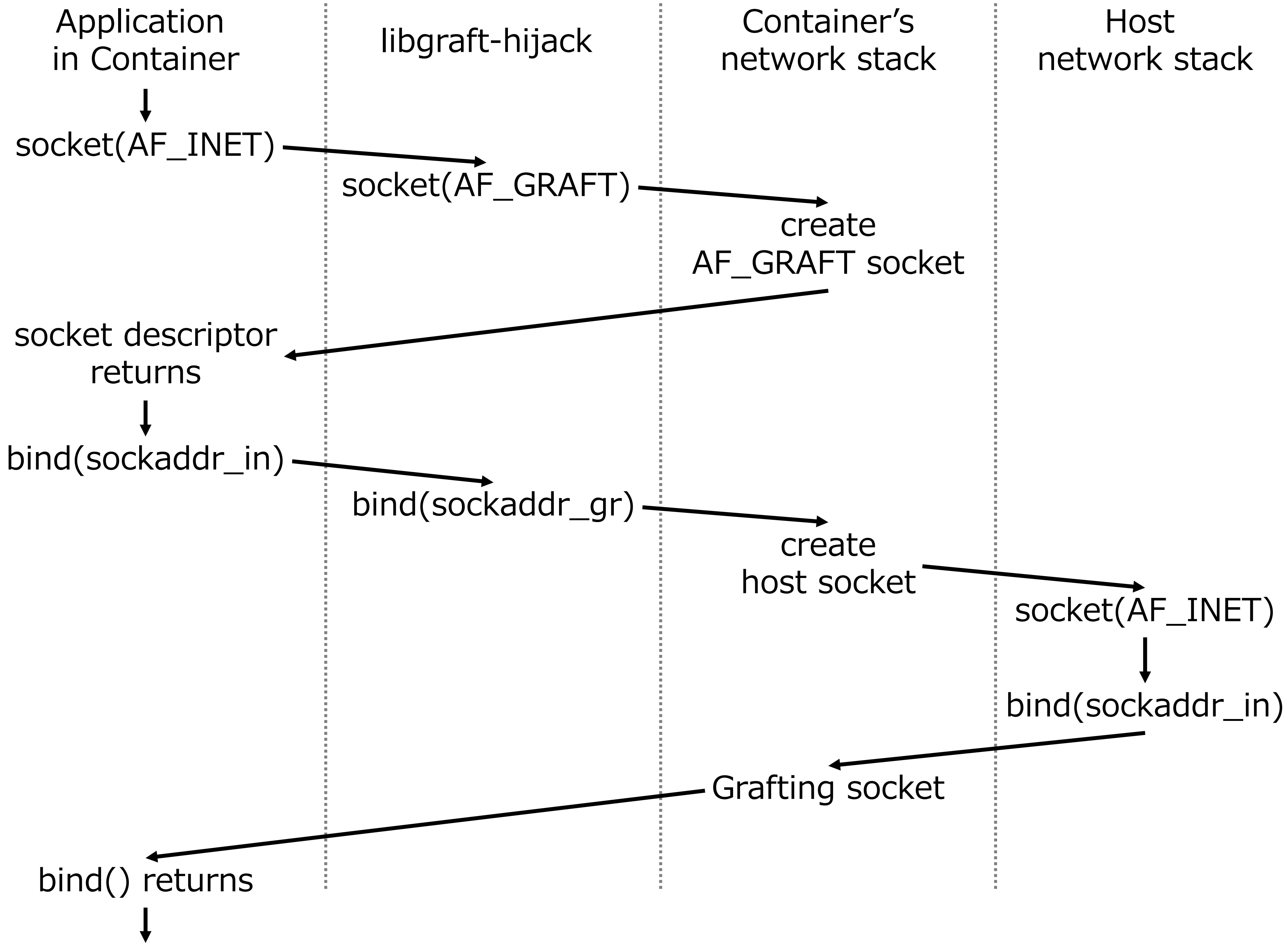
```
/* IPv4 */
if (server_res->ai_family == AF_INET) {
        ... make ipv4 socket ...
}
/* IPv6 */
else if (server_res->ai_family == AF_INET6) {
        ... make ipv6 socket ...
}
/* Unknown protocol */
else {
        errno = EAFNOSUPPORT;
        return -1;
}
```

from iperf3

[5] Jun-ichiro itojun Itoh, KAME Project, “Implementing AF-independent application”, http://www.kame.net/newsletter/19980604/

Hijacking socket() and bind()

- Hijacked socket()
  - returns AF_GRAFT sockets instead of AF_INET/INET6
- Hijacked bind()
  - uses sockaddr_gr instead of sockaddr_in/in6
- An env variable specifies which sockaddr convert to which sockaddr_gr
  - GRAFT_CONV_PAIRS="0.0.0.0:80=ep-http"



Application in Container
libgraft-hijack
Container's network stack
Host network stack
socket(AF_INET)
socket(AF_GRAFT)
create AF_GRAFT socket
socket descriptor returns
bind(sockaddr_in)
bind(sockaddr_gr)
create host socket
socket(AF_INET)
bind(sockaddr_in)
Grafting socket
bind() returns

bind() before connect() for outbound connections

1. connect() does not need to call bind()
2. But, AF_GRAFT requires bind() to determine host sockets

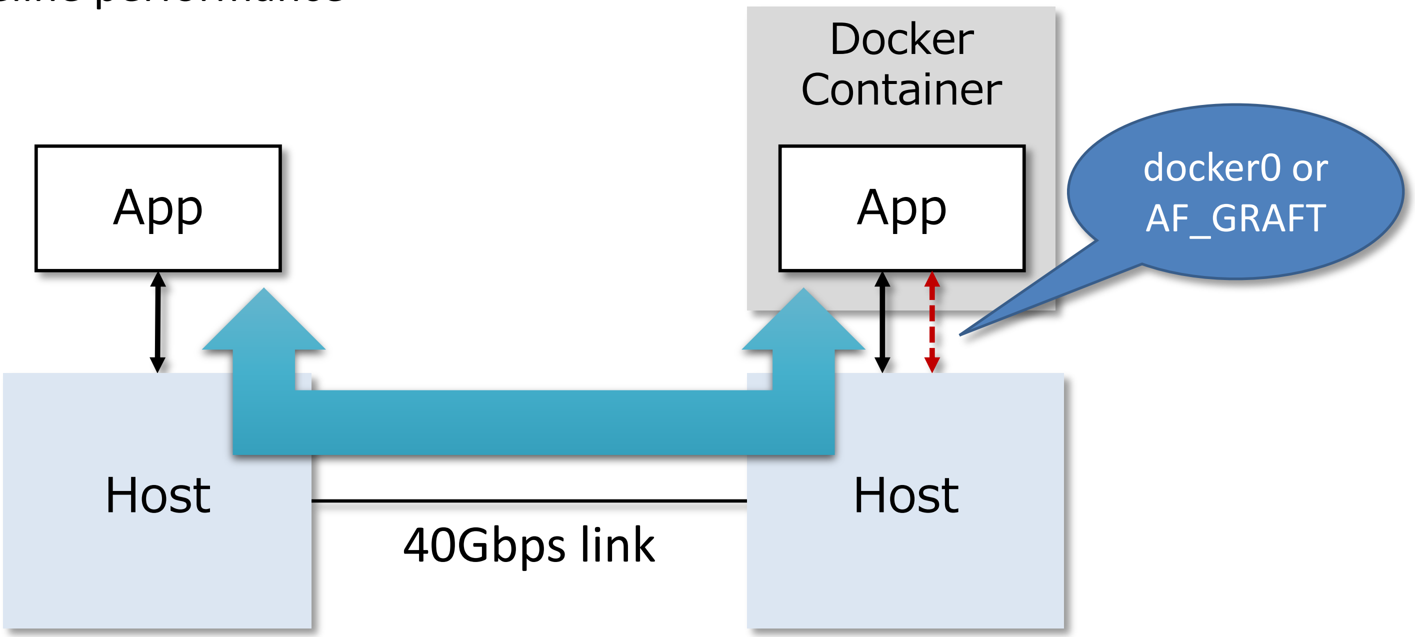
✓ The hijacked connect() calls bind before connect()
  - sendto() and sendmsg() are also hijacked in the same manner

Evaluation

- Throughput and latency
  - iperf3 and sockperf
- HTTP server
  - NGINX and siege
- Message Queue
  - Zero MQ
- Networking
  - native host
  - docker0 (NAT)
  - AF_GRAFT
    - with libgraft-hijack.so

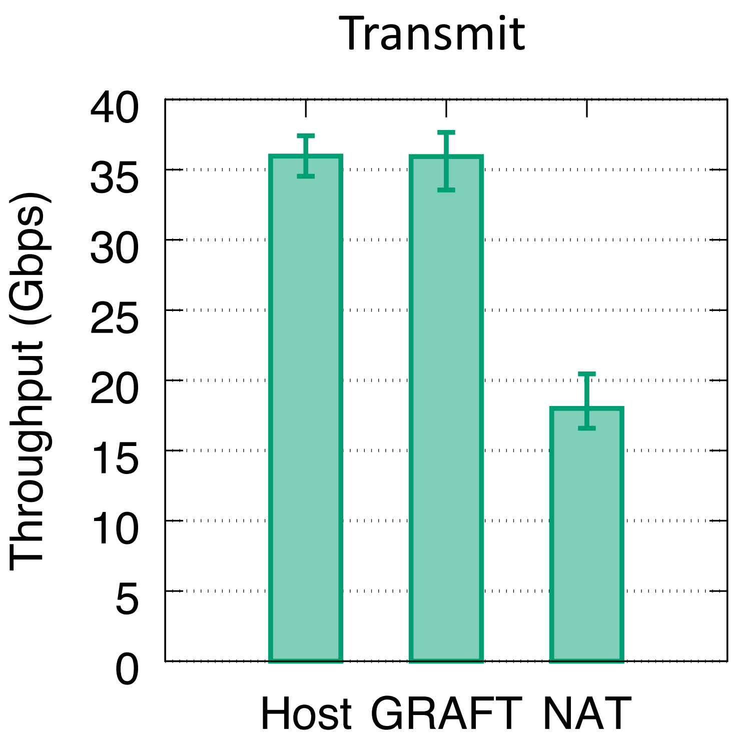
Baseline performance (Throughput and latency)

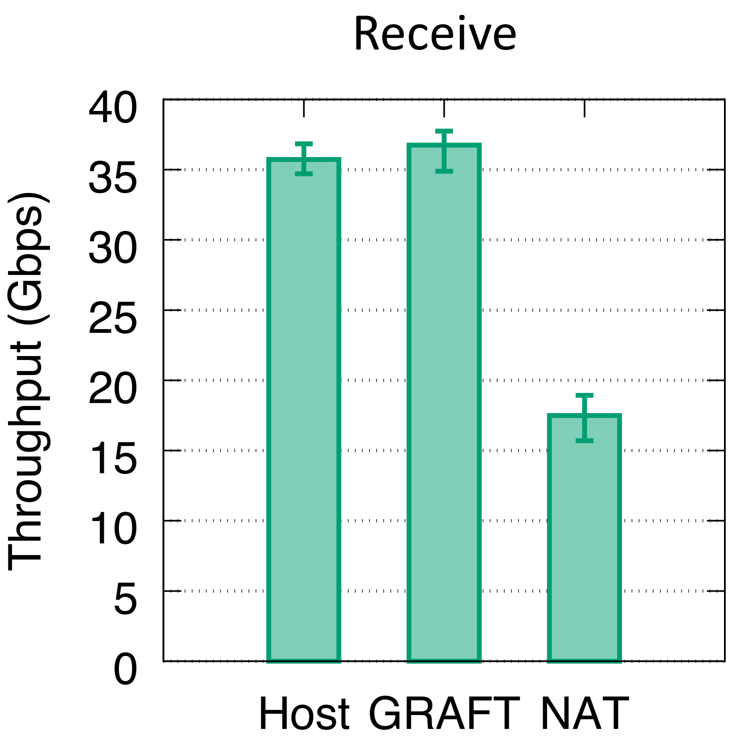
Microservice Architecture (HTTP server, Message Queue)

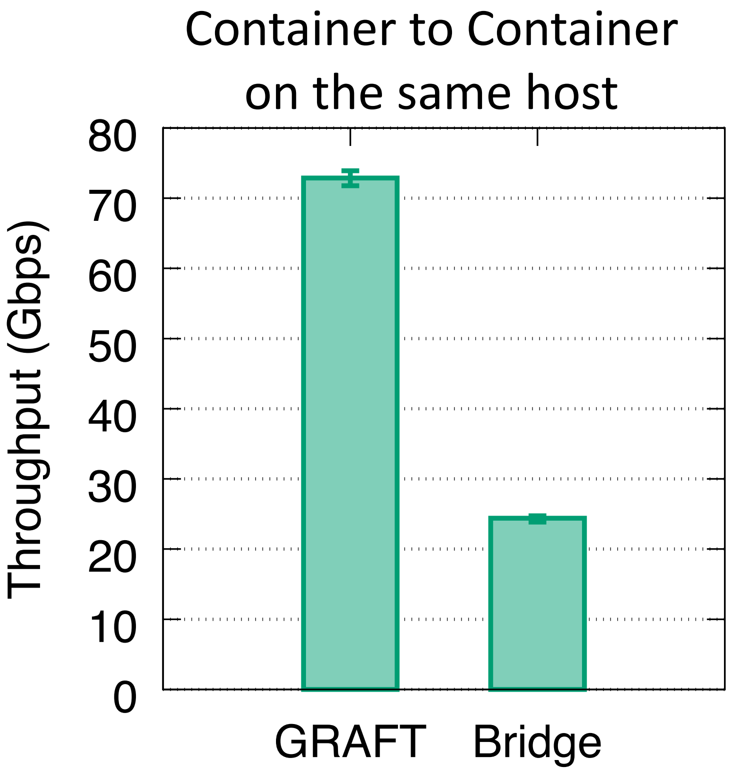


Host:
Linux 4.4.0, Intel Core i7-3770K 3.5GHz CPU,
32GB memory, Mellanox ConnectX-4 LX 40Gbps NIC

Throughput

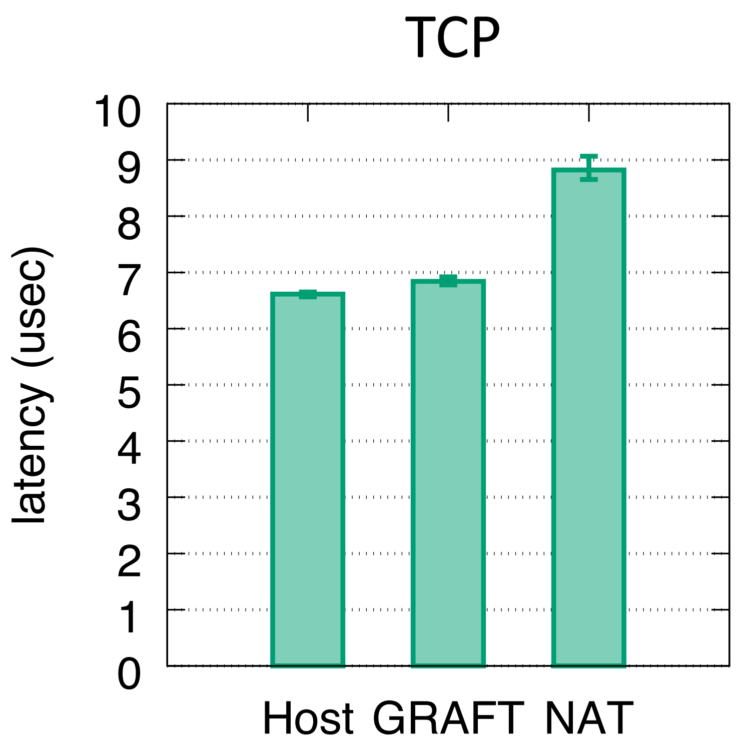


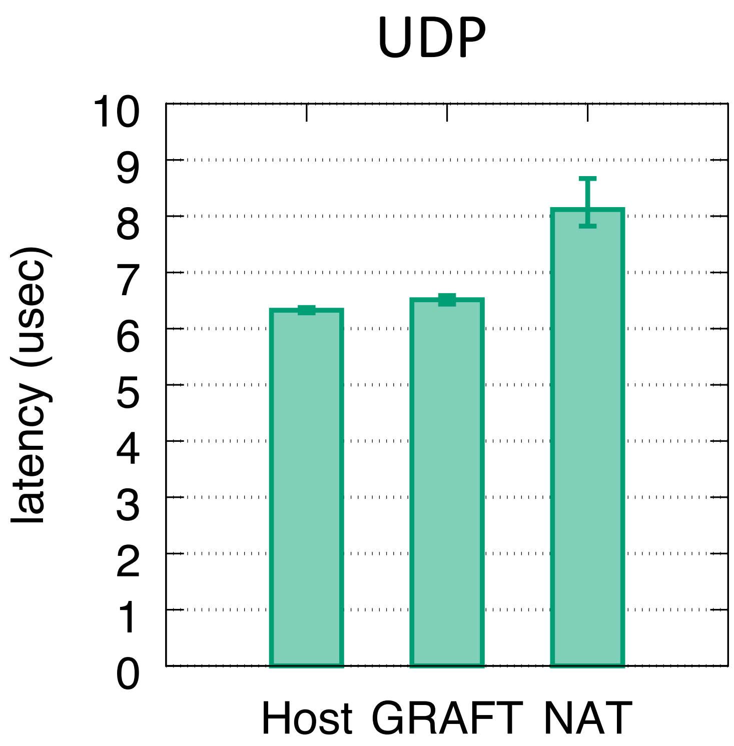




- AF_GRAFT successfully mitigates the degradation
- Container to container communication via AF_GRAFT is the same as the communication via the loopback interface

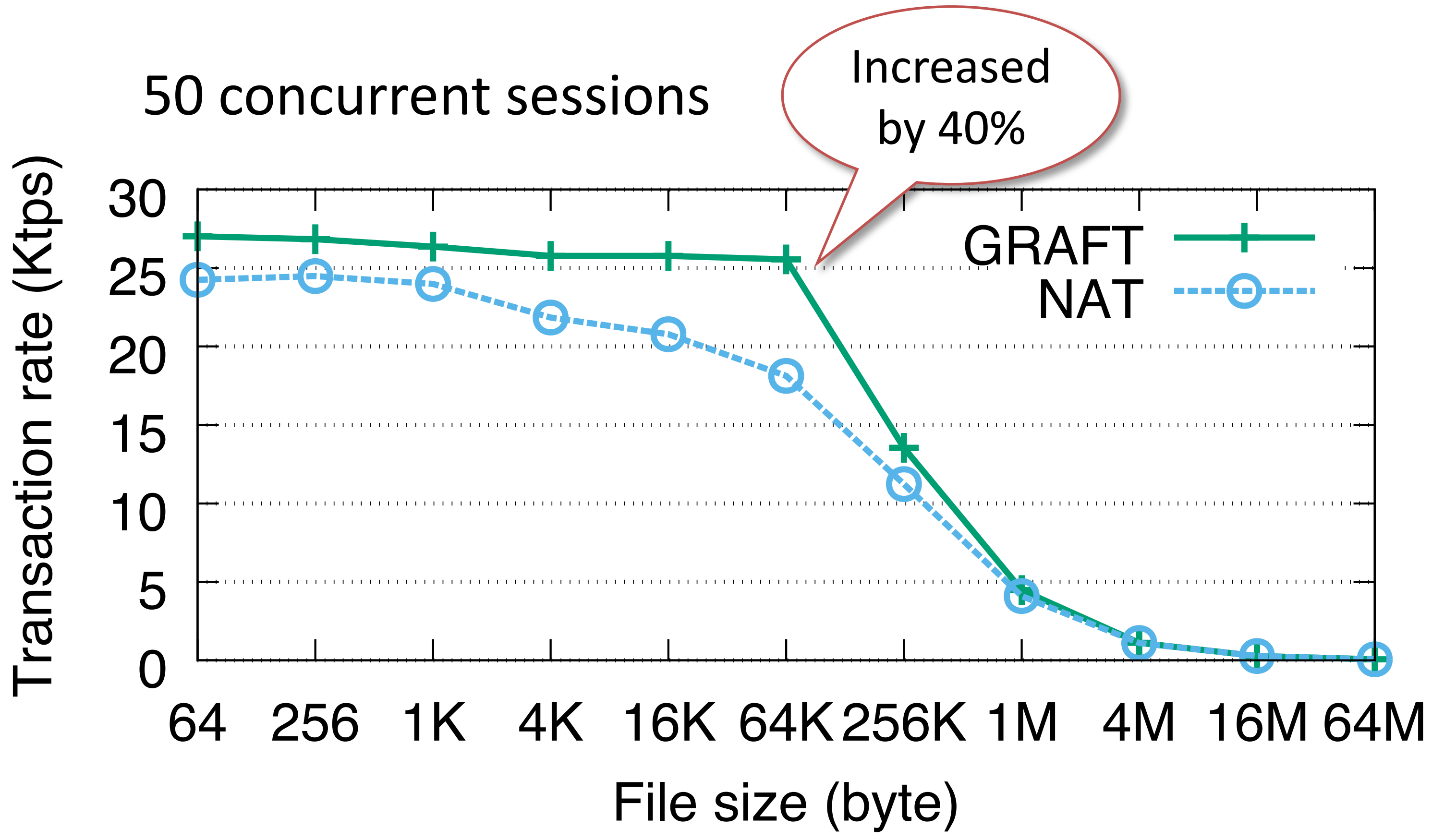
Latency

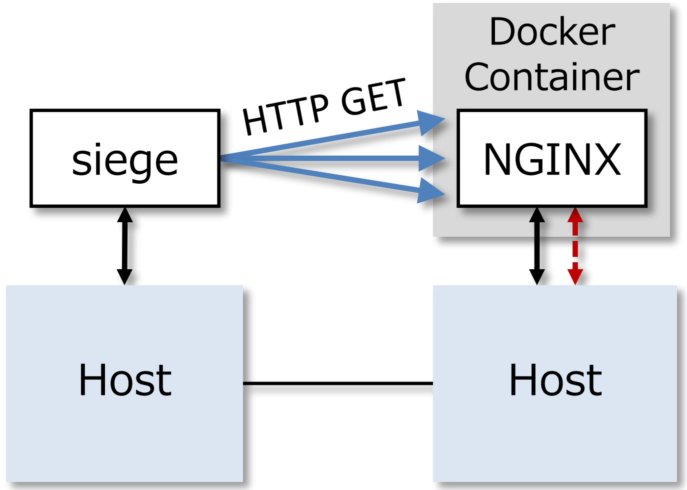




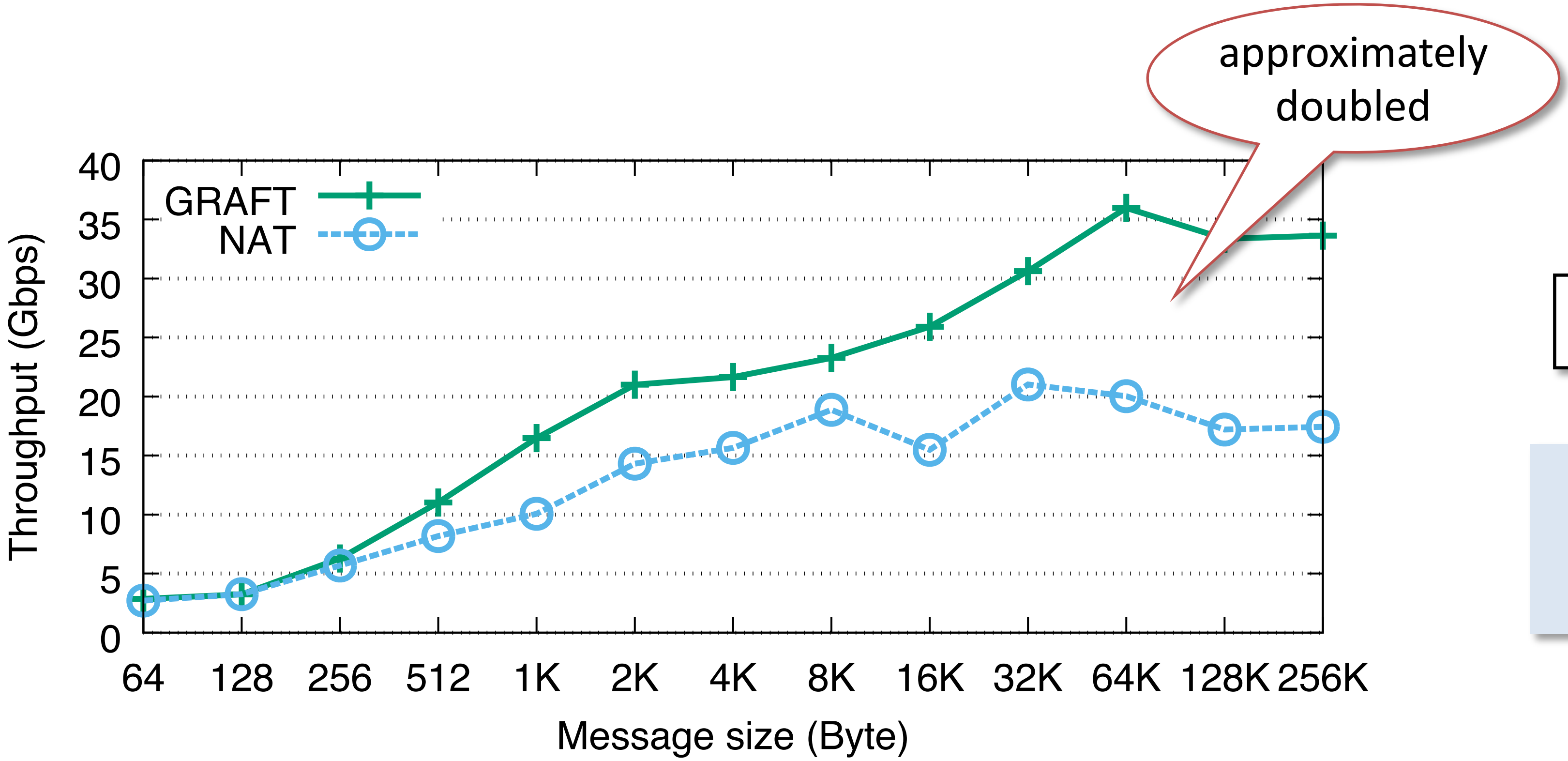
- As well as the throughput test, AF_GRAFT also mitigates degradation from the latency perspective

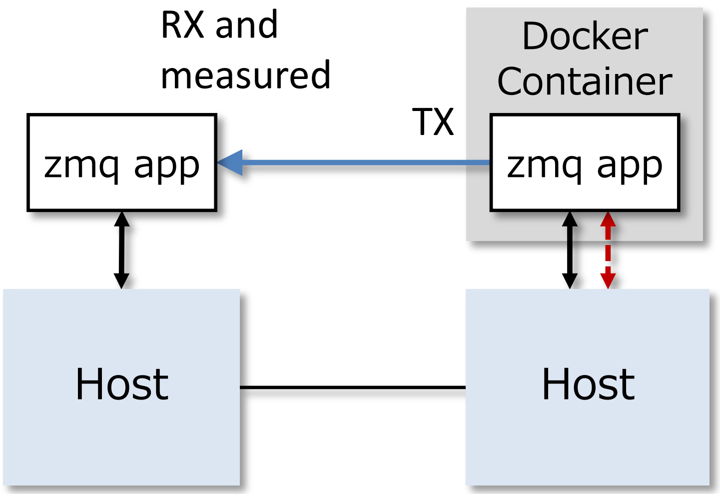
HTTP server benchmark





Message Queue benchmark





Limitations

- The LD_PRELOAD trick is not applicable to
  - Statically linked libraries
  - Golang that implements syscall without libc
- AF_GRAFT does not improve network stack performance
  - It never outperforms the performance of native hosts
- Network-***sensitive*** applications
  - e.g., Container-based NFV

Conclusion

- Socket-Grafting
  - Containers with network-*insensitive* applications do not need network stacks
  - Bypassing container's network stack by exploiting the socket layer
  - A new address family, called AF_GRAFT, as a practical mechanism for grafting
- The evaluation results demonstrated
  - Mitigating the network performance degradation due to the long data path
  - HTTP: 10-40% throughput improvement
  - ZeroMQ: up to doubled the throughput and 30% shorter latenct

ToDo

- Integrating AF_GRAFT into Docker
  - Docker network driver plugin?
  - Option like -p?
  - We need comments or partners implementing such plugins ;)
- Integrating AF_GRAFT into Kubernetes
  - More complicated due to the service IP abstraction and load balancing
  - The Container Network Interface (CNI) focuses on the traditional abstraction (?)
- Go Go Netdev 0x13!