

NETFLIX

Serving Netflix Video at 400Gb/s on FreeBSD

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EuroBSDCon 2021

Outline:

- Motivation
- Description of production platform
- Description of workload
- To NUMA or not to NUMA?
- Inline Hardware (NIC) kTLS
- Alternate platforms

Motivation:

- Since 2020, Netflix has been able to serve 200Gb/s of TLS encrypted video traffic from a single server.
- How can we serve ~400Gb/s of video from the same servers?

Netflix Video Serving Workload

- FreeBSD-current
- NGINX web server
- Video served via sendfile(2) and encrypted using software kTLS

Netflix Video Serving Hardware

- AMD EPYC 7502P (“Rome”)
 - 32 cores @ 2.5GHz
 - 256GB DDR4-3200
 - 8 channels
 - ~150GB/s mem bw
 - Or ~1.2Tb/s in networking units
 - 128 lanes PCIe Gen4
 - ~250GB/s of IO bandwidth
 - Or ~2Tb/s in networking units

Netflix Video Serving Hardware

- 2x Mellanox ConnectX-6 Dx
 - Gen4 x16, 2 full speed 100GbE ports per NIC
 - 4 x 100GbE in total
 - Support for NIC kTLS offload
- 18x WD SN720 NVME
 - 2TB
 - PCIe Gen3 x4

Performance Results:

- 240Gb/s
- Limited by memory BW
 - Determined empirically by using AMDuProfPCM

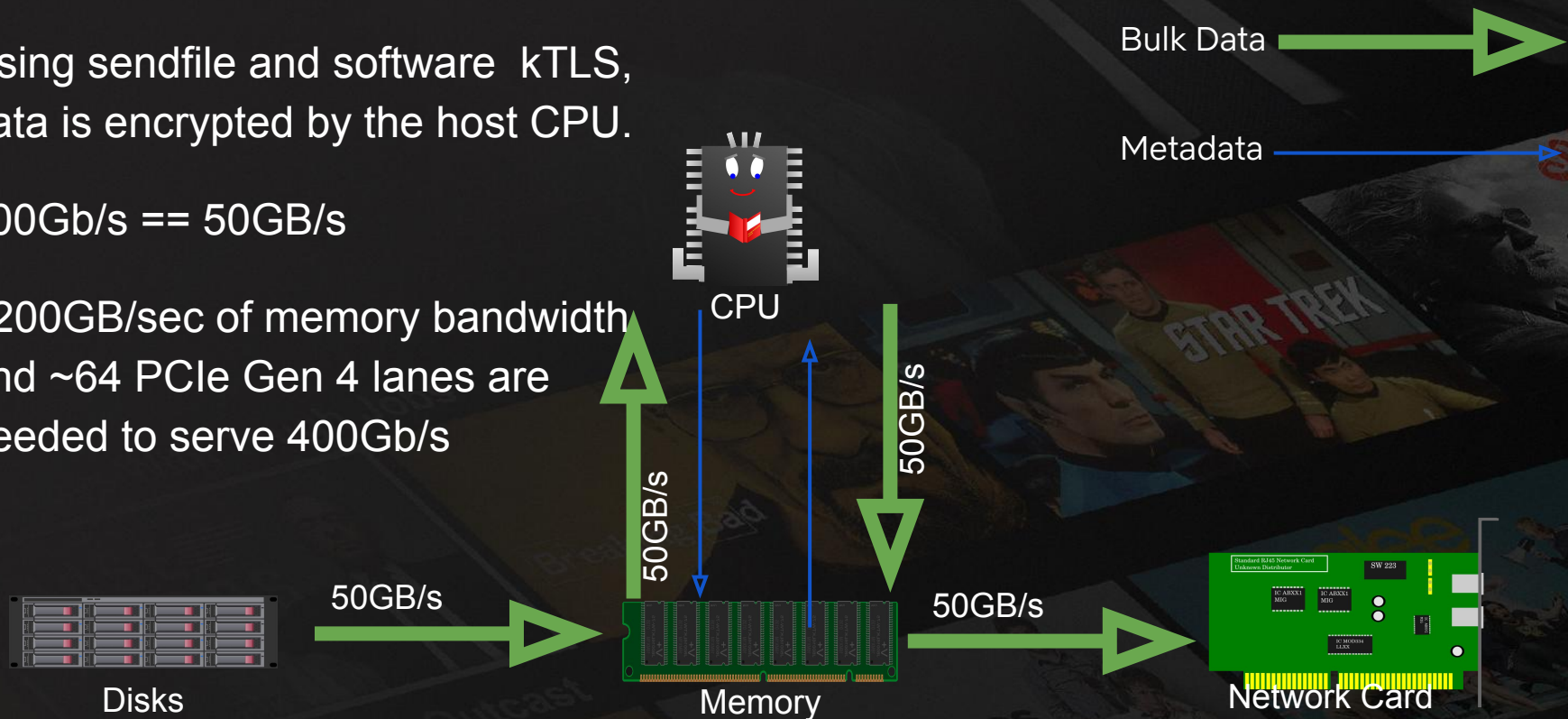
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Netflix 400Gb/s Video Serving Data Flow

Using sendfile and software kTLS, data is encrypted by the host CPU.

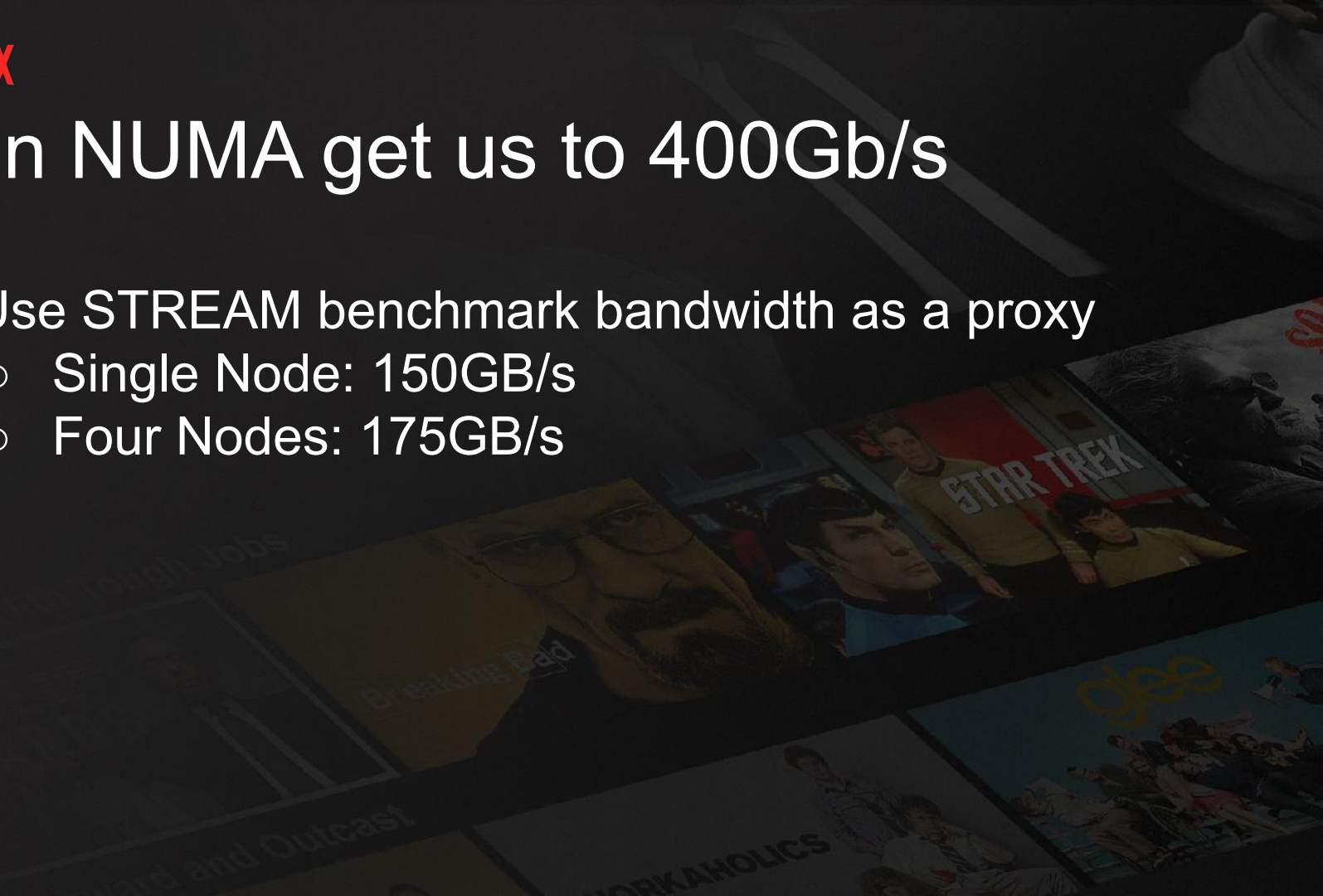
400Gb/s == 50GB/s

~200GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s



Can NUMA get us to 400Gb/s

- Use STREAM benchmark bandwidth as a proxy
 - Single Node: 150GB/s
 - Four Nodes: 175GB/s



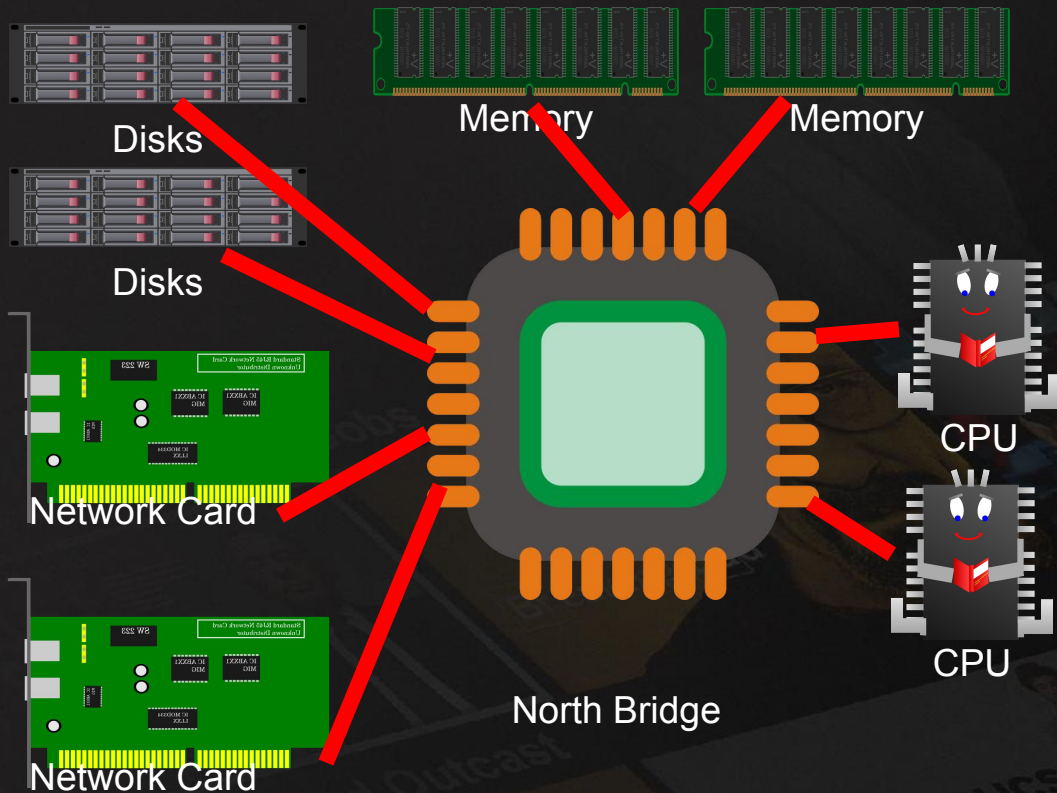
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What is NUMA?

Non Uniform Memory Architecture

That means memory and/or devices can be “closer” to some CPU cores

Multi CPU Before NUMA



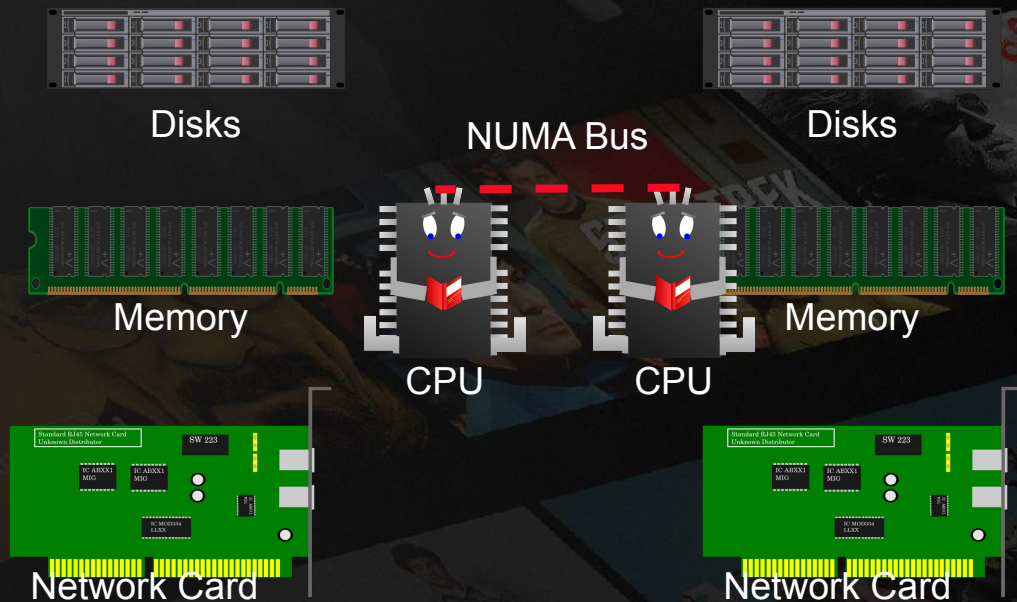
Memory access was *UNIFORM*:

Each core had equal and direct access to all memory and IO devices.

Multi Socket system with NUMA:

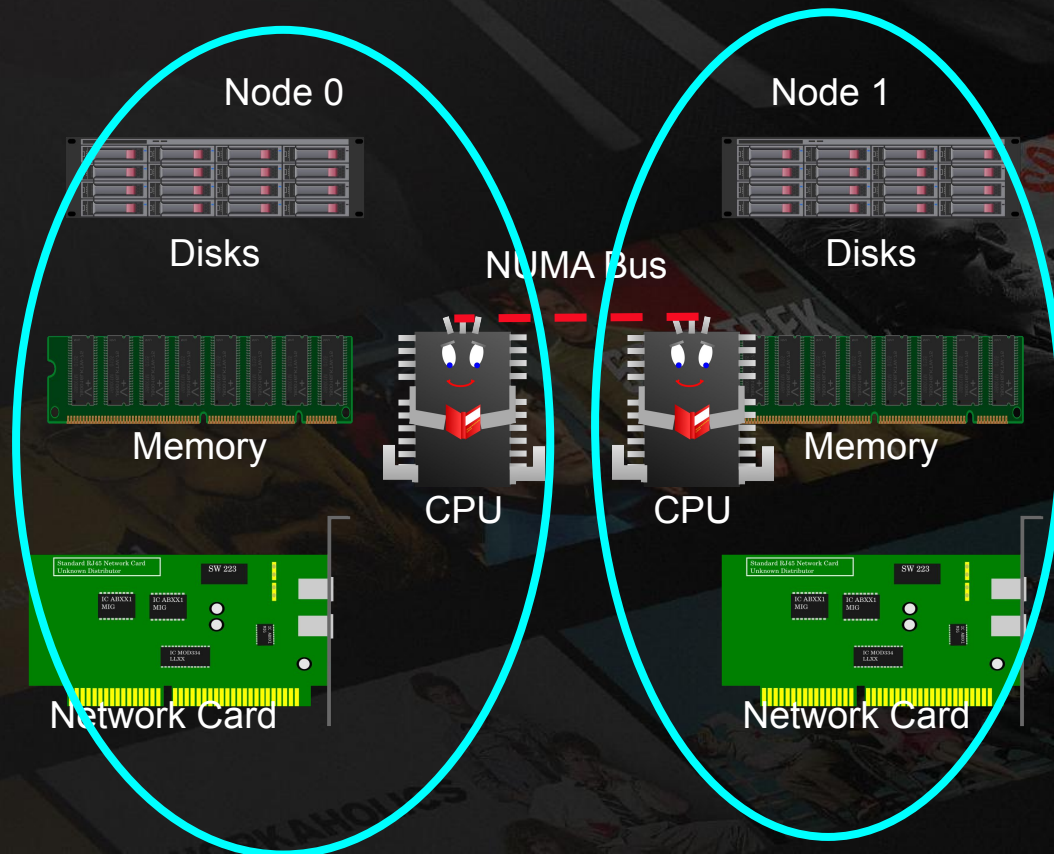
Memory access can be **NON-UNIFORM**

- Each core has unequal access to memory
- Each core has unequal access to I/O devices



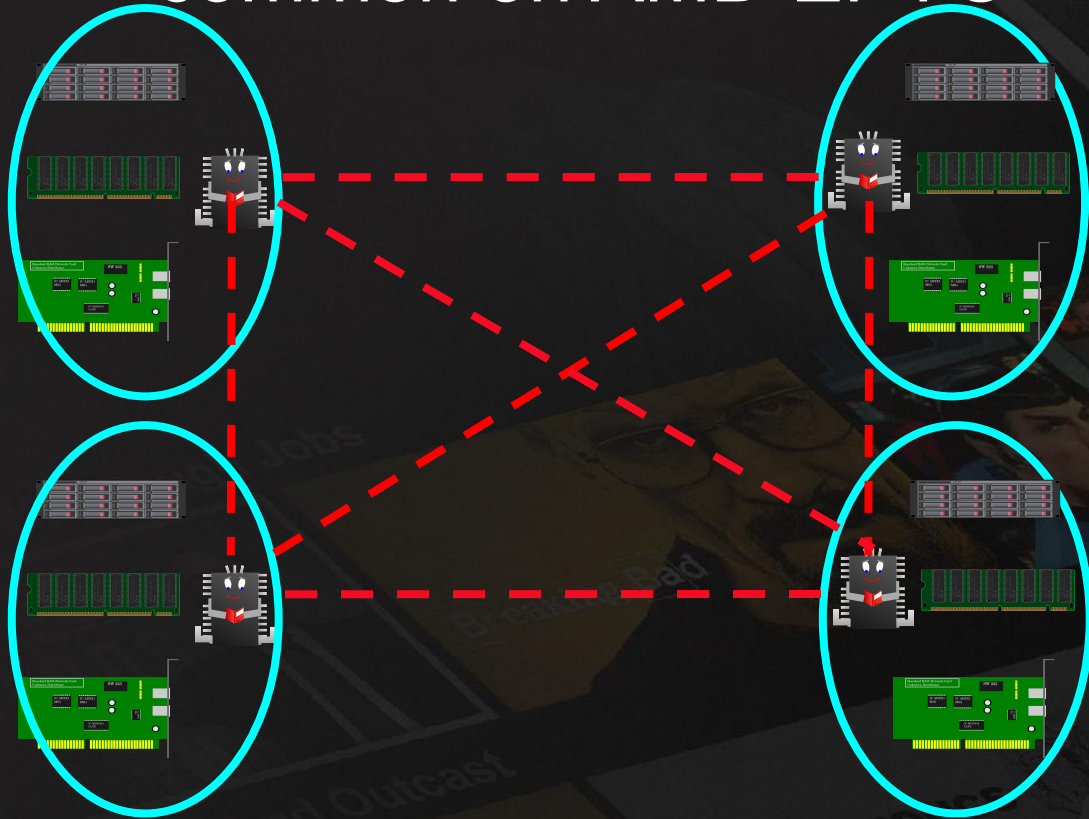
Present day NUMA:

Each locality zone called a “NUMA Domain” or “NUMA Node”



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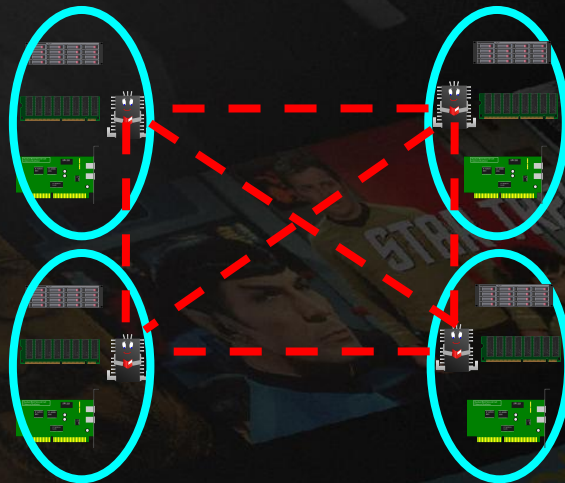
4 Node configurations are common on AMD EPYC



Cross-Domain costs

Latency Penalties:

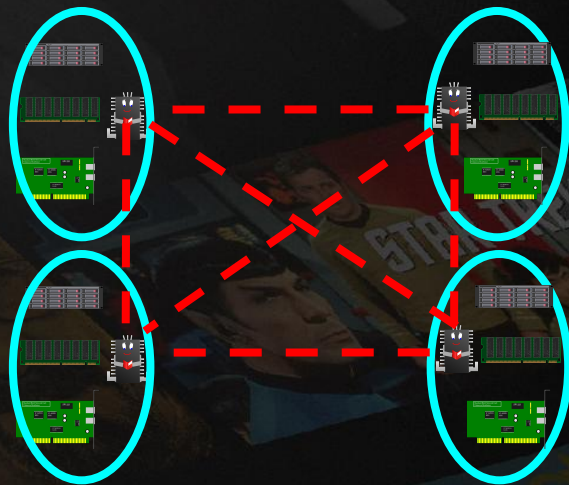
- 12-28ns



Cross-Domain costs

Bandwidth Limit:

- AMD Infinity Fabric
 - ~47GB/s per link
 - ~280GB/s total



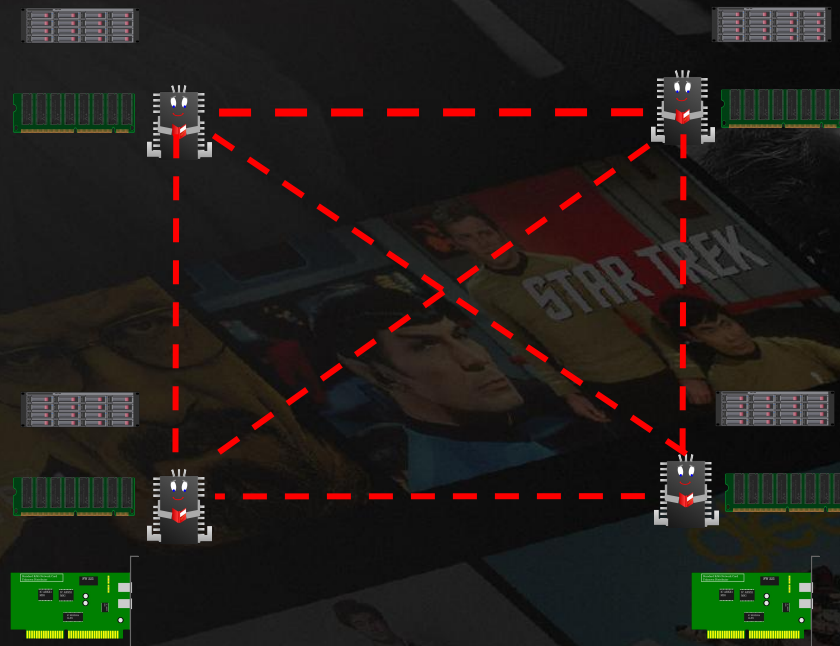
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Strategy: Keep as much of our 200GB/sec of bulk data off the NUMA fabric is possible

- Bulk data congests NUMA fabric and leads to CPU stalls when competing with normal memory accesses.

4 Nodes, worst case

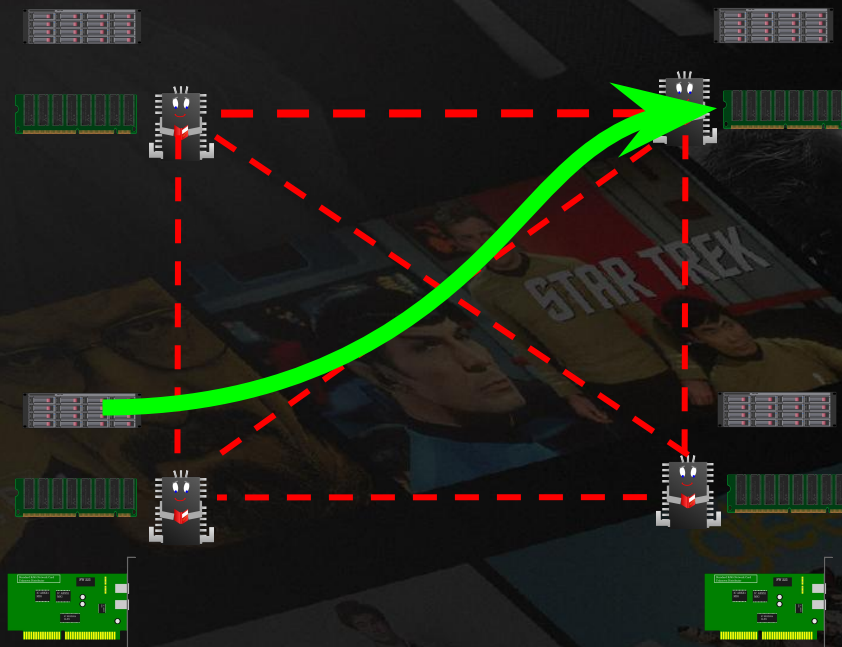
Steps to send data:



4 Nodes, worst case

Steps to send data:

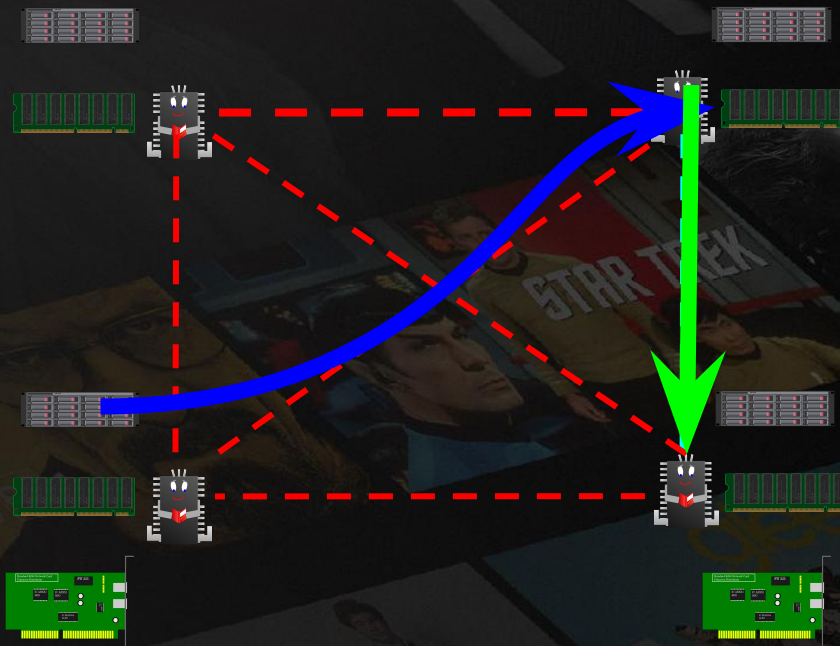
- DMA data from disk to memory
 - First NUMA bus crossing



4 Nodes, worst case

Steps to send data:

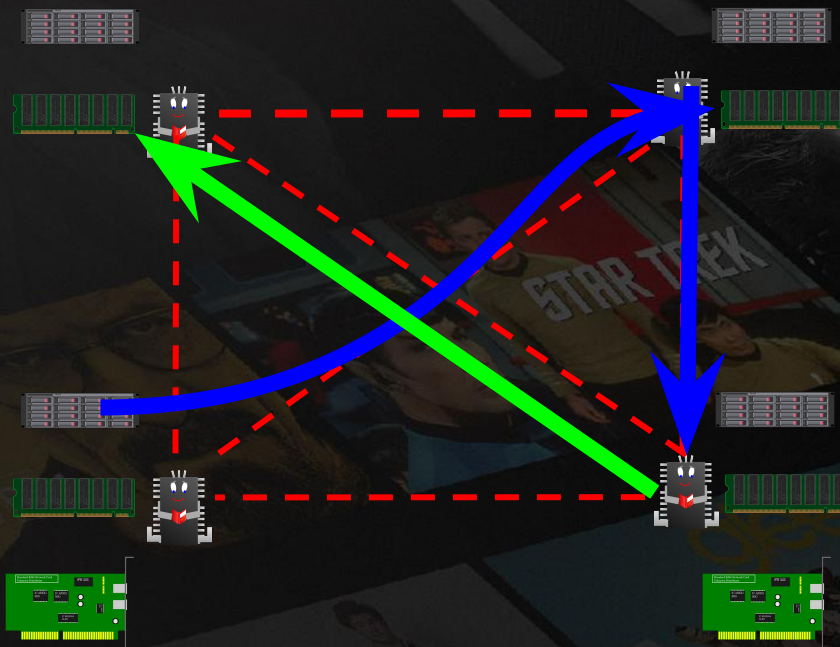
- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
 - Second NUMA crossing



4 Nodes, worst case

Steps to send data:

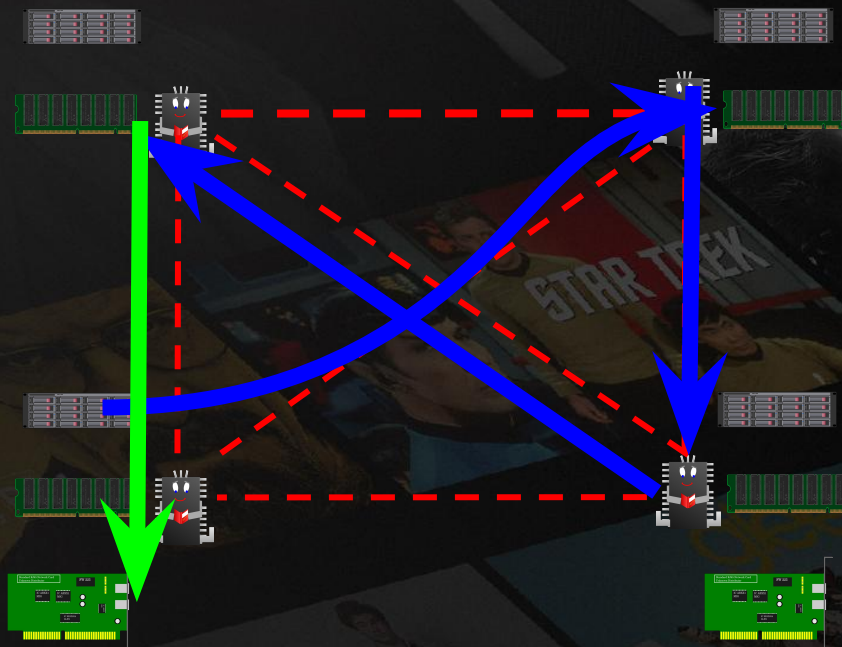
- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
 - Second NUMA crossing
- CPU writes data for encryption
 - Third NUMA crossing



4 Nodes, worst case

Steps to send data:

- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
 - Second NUMA crossing
- CPU writes data for encryption
 - Third NUMA crossing
- DMA data from memory to network
 - Fourth NUMA crossing



Worst Case Summary:

- 4 NUMA crossings
- 200GB/s of data on the NUMA fabric
 - Fabric saturates, cannot handle the load.
 - CPU Stalls, saturates early

Best Case Summary:

- 0 NUMA crossings
- 0GB/s of data on the NUMA fabric

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How can we get as close as possible to the best case?

- Constrained to use 1 IP address per host
- Must use lagg(4) LACP network bonding

Impose order on the chaos.. *somehow:*

- Disk centric siloing
 - Try to do everything on the NUMA node where the content is stored
- Network centric siloing
 - Try to do as much as we can on the NUMA node that the LACP partner chose for us

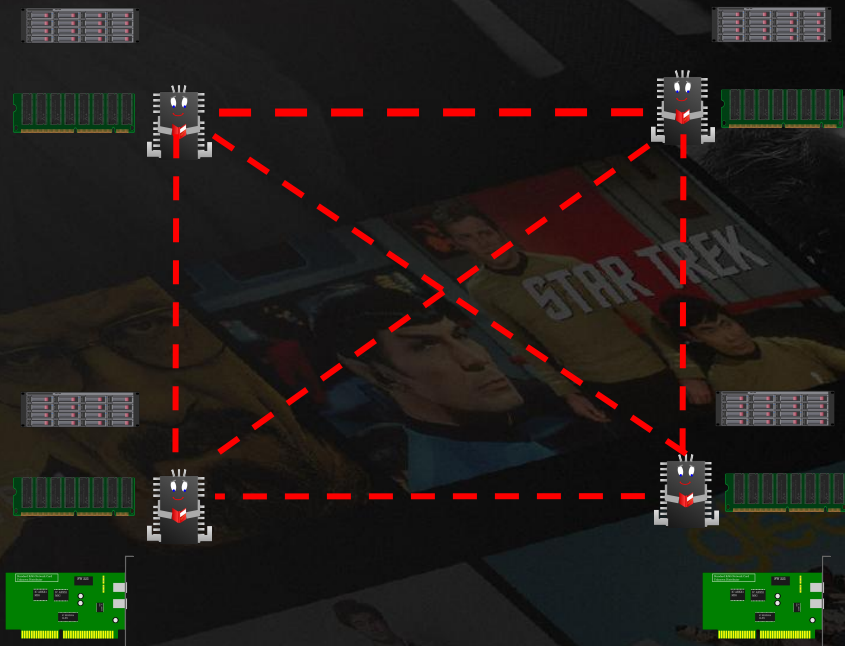
Network centric siloing

- Associate network connections with NUMA nodes
- Allocate local memory to back media files when they are DMA'ed from disk
- Allocate local memory for TLS crypto destination buffers & do SW crypto locally
- Run kTLS workers, RACK / BBR TCP pacers with domain affinity
- Choose local lagg(4) egress port

All of this is upstream!

4 Nodes, worst case with siloing

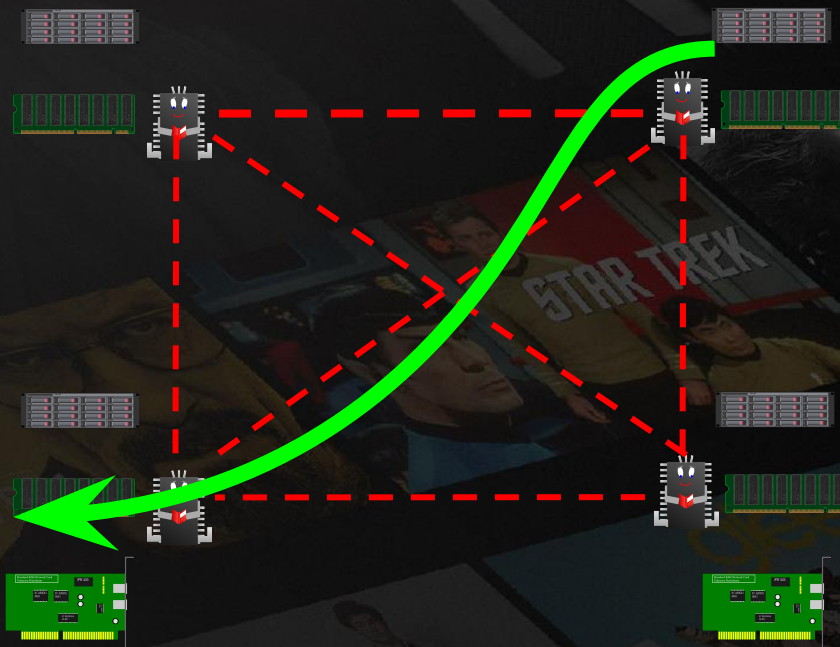
Steps to send data:



4 Nodes, worst case with siloing

Steps to send data:

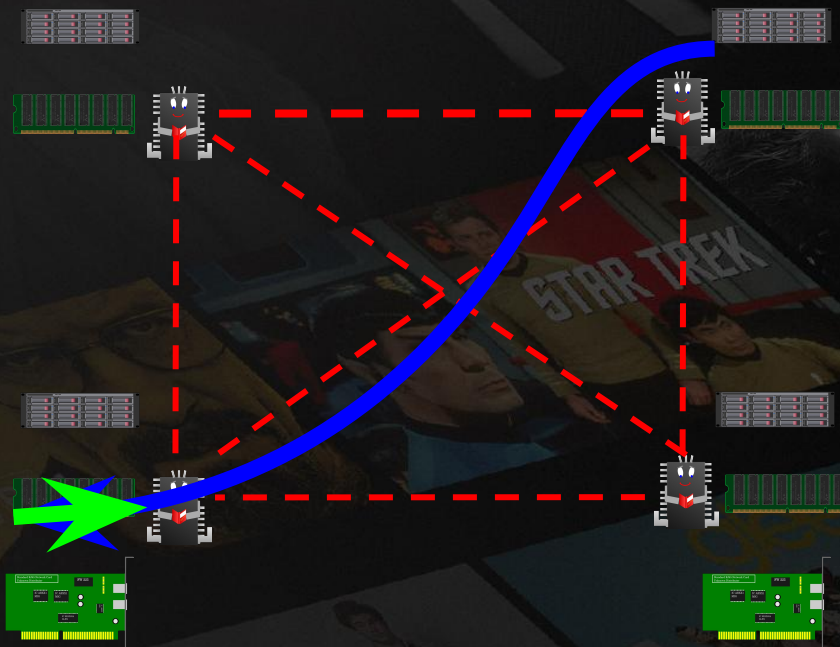
- DMA data from disk to memory
 - First NUMA bus crossing



4 Nodes, worst case with siloing

Steps to send data:

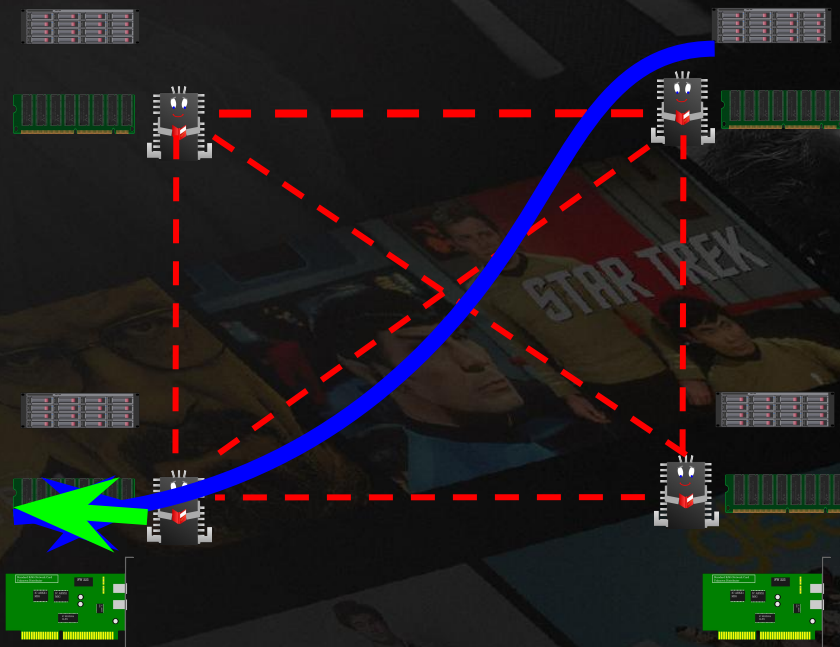
- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption



4 Nodes, worst case with siloing

Steps to send data:

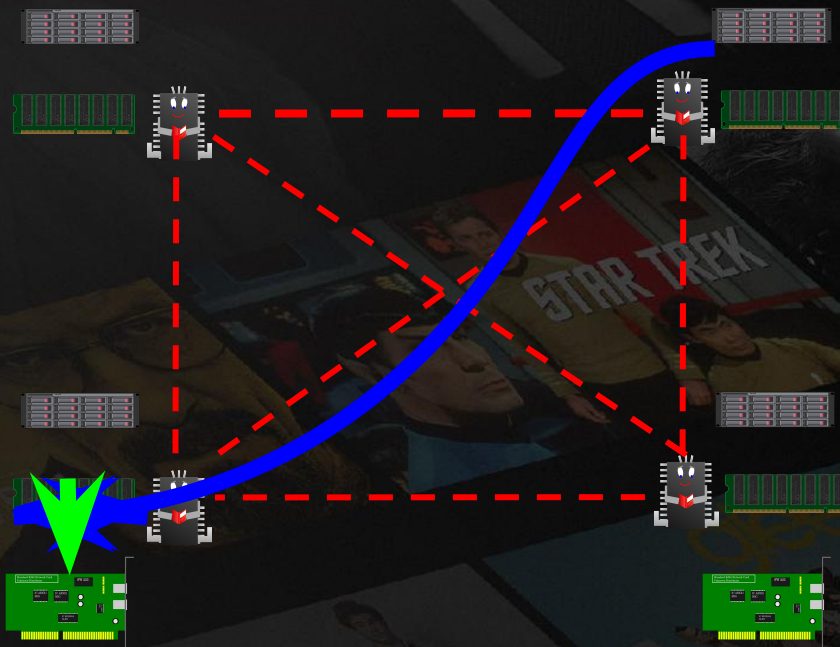
- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
- CPU writes data for encryption



4 Nodes, worst case with siloing

Steps to send data:

- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
- CPU writes data for encryption
- DMA data from memory to network



Worst Case Summary:

- 1 NUMA crossing on average
 - 100% of disk reads across NUMA
- 50GB/s of data on each NUMA fabric link
 - Much less than the 280GB/sec of Infinity fabric bandwidth

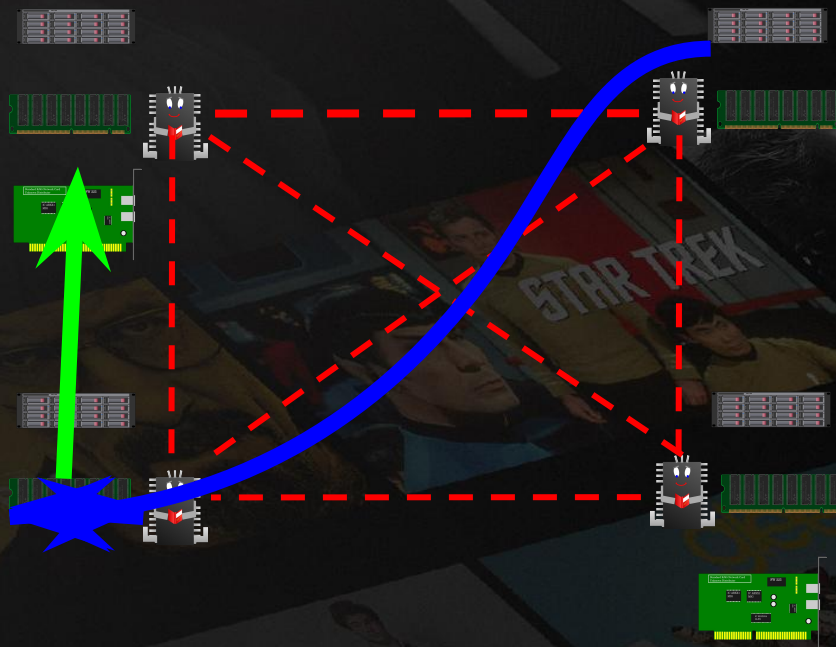
Real Life is *Messy*

- NICs on only 2 of the 4 NUMA nodes
- Differing number of NVME on each node
- Hacks to “pretend” we have NICs in all 4 domains
- Impacts worst and average cases

4 Nodes, worst case with siloing: messy

Steps to send data:

- DMA data from disk to memory
 - First NUMA bus crossing
- CPU reads data for encryption
- CPU writes data for encryption
- DMA data from memory to network



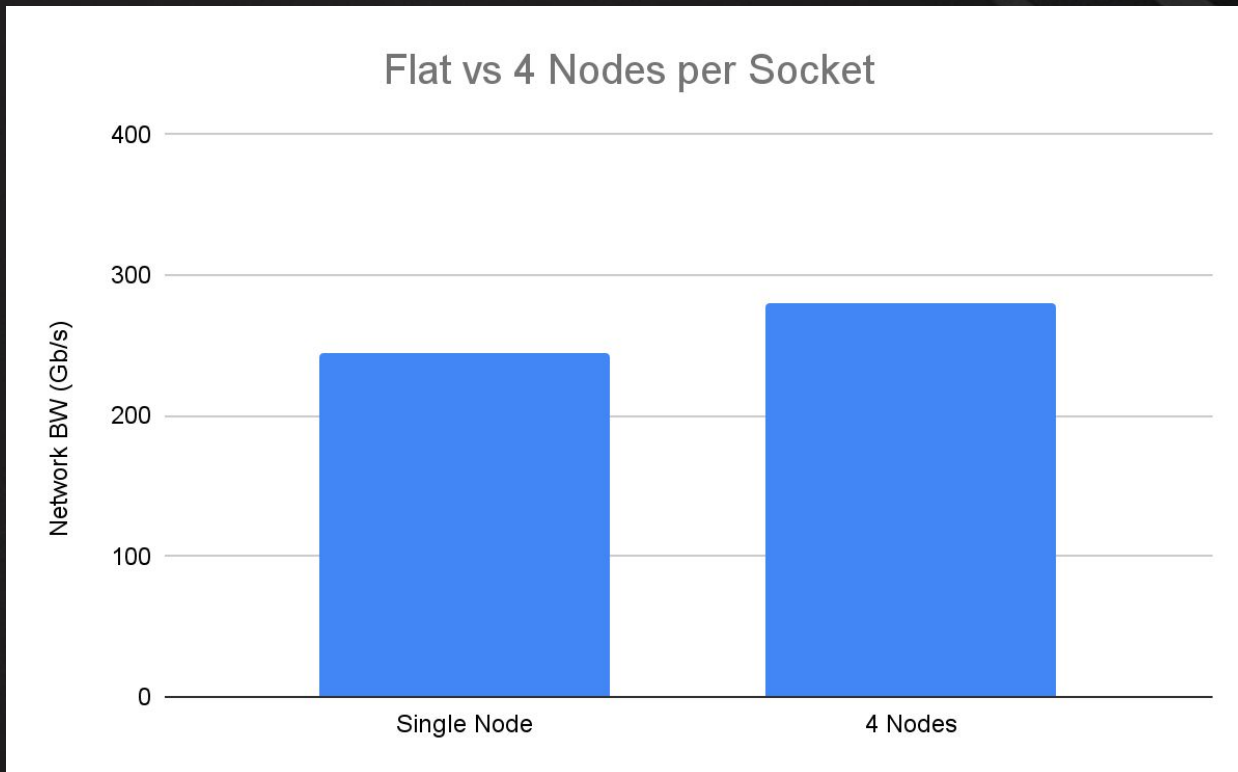
Worst Case Summary:

- 2 NUMA crossing on average
 - 100% of disk reads across NUMA
 - 100% of network writes across NUMA
- 100GB/s of data on the NUMA fabric
 - Less than the 280GB/s of Infinity fabric bandwidth

Average Case Summary:

- 1.25 NUMA crossings on average
 - 75% of disk reads across NUMA
 - 50% of NIC transmits across NUMA due to unbalanced setup
- 62.5 GB/sec of data on NUMA fabric

Performance: 1 vs 4 nodes



Would NIC based kTLS
offload help for 400Gb/s ?

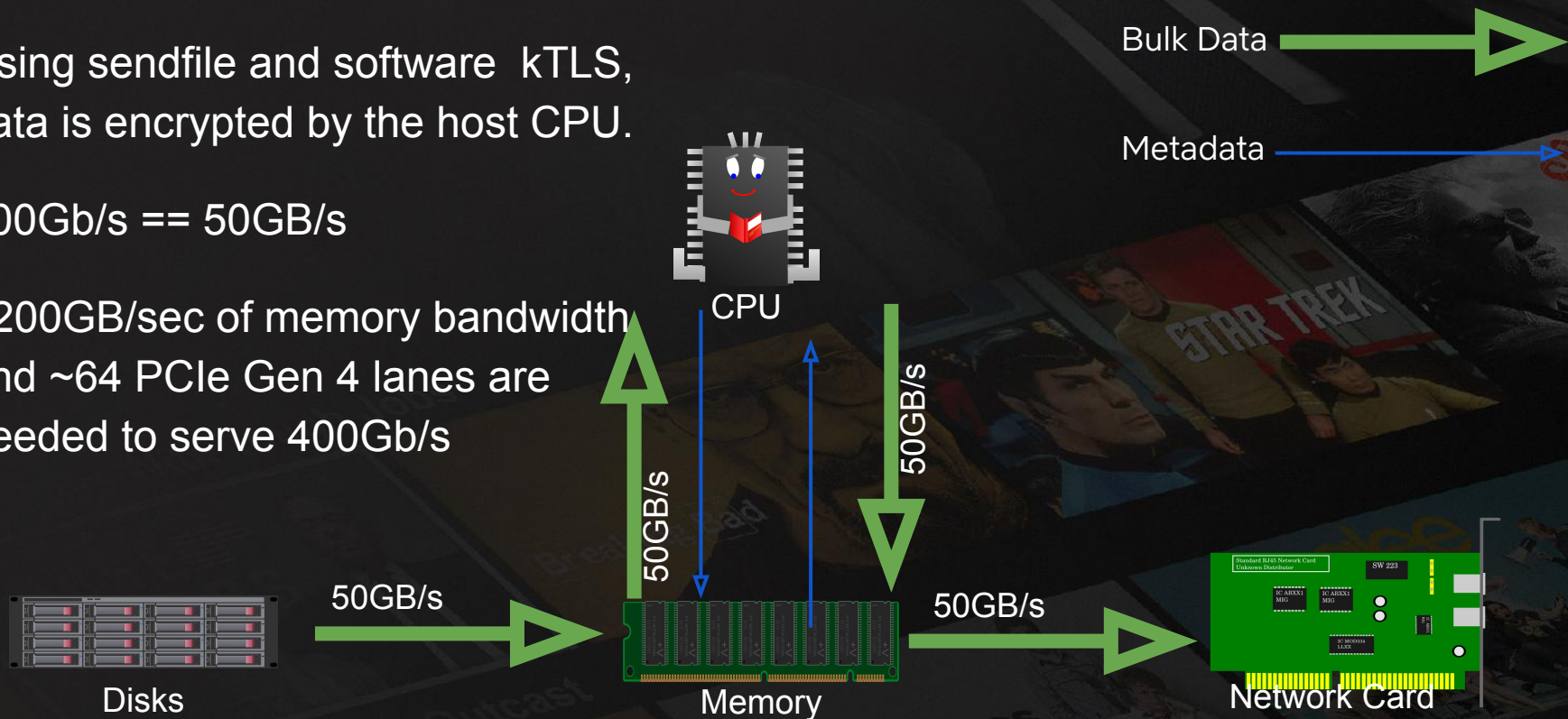
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Netflix 400Gb/s Video Serving Data Flow

Using sendfile and software kTLS, data is encrypted by the host CPU.

400Gb/s == 50GB/s

~200GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s



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Netflix 400Gb/s Video Serving Data Flow

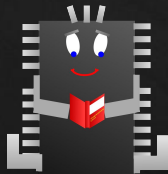
Using sendfile and software kTLS, data is encrypted by the host CPU.

400Gb/s == 50GB/s

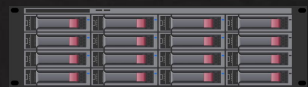
~~~200GB/sec of memory bandwidth~~  
~~and ~64 PCIe Gen 4 lanes are~~  
needed to serve 400Gb/s

Bulk Data 

Metadata 

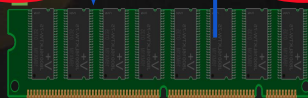


CPU



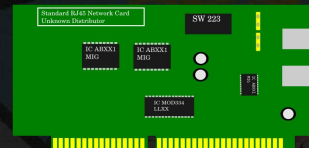
Disks

50GB/s

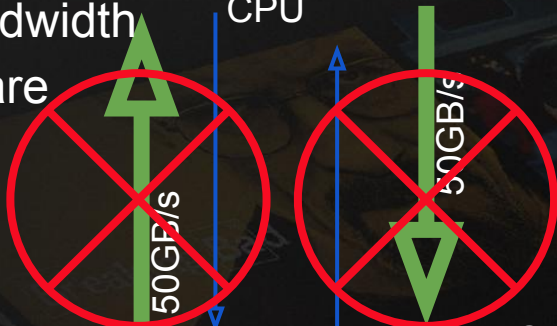


Memory

50GB/s



Network Card



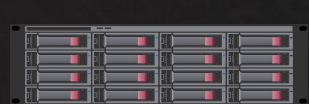
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Using sendfile and NIC kTLS, data is encrypted by the NIC.

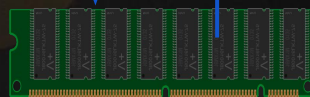
400Gb/s == 50GB/s

~100GB/sec of memory bandwidth and ~64 PCIe Gen 4 lanes are needed to serve 400Gb/s

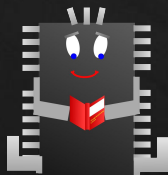


Disks

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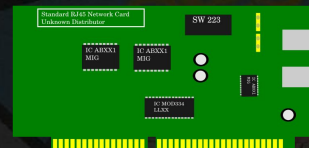
Memory



CPU



50GB/s



Network Card

Bulk Data



Metadata



# What is NIC kTLS?:

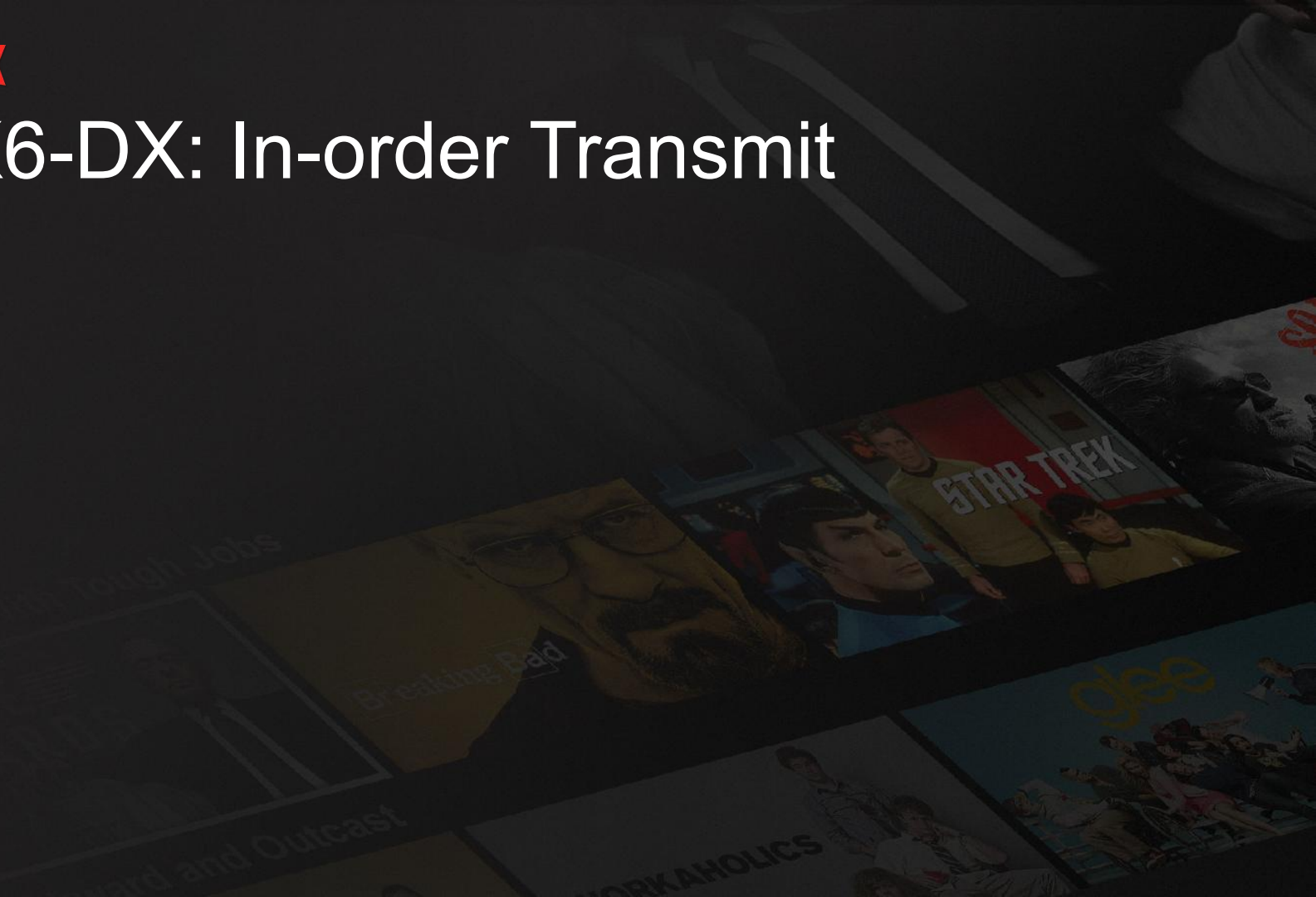
- Hardware Inline TLS
- TLS session is established in userspace.
- When crypto is moved to the kernel, the kernel passes crypto keys to the NIC
- TLS records are encrypted by NIC as the data flows through it on transmit
  - No more detour through the CPU for crypto
  - This cuts memory BW requirements in half!

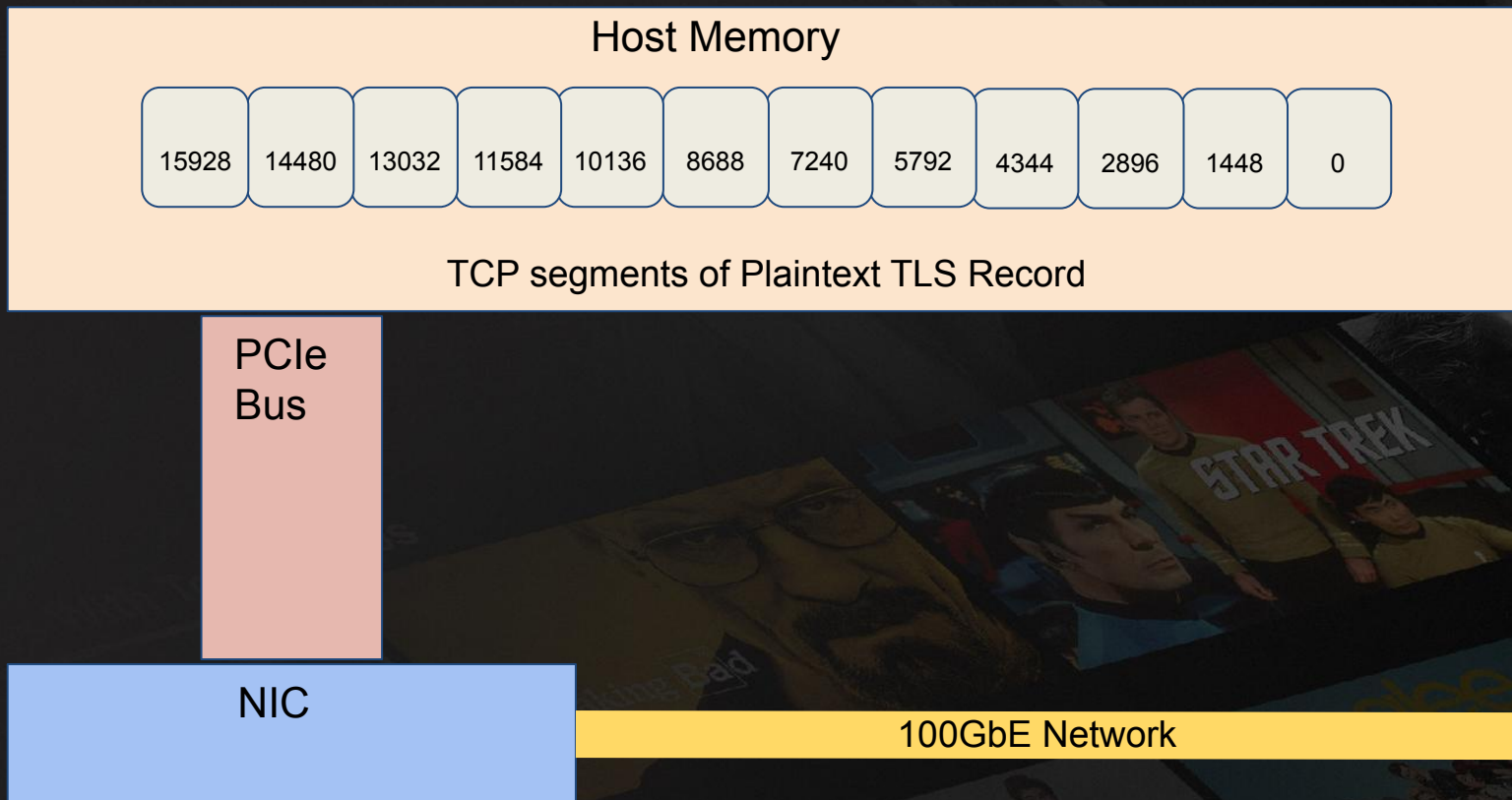
# Mellanox ConnectX-6 Dx

- Offloads TLS 1.2 and 1.3 for AES GCM cipher
- Retains crypto state within a TLS record
  - Means that the TCP stack can send partial TLS records without performance loss
- If a packet is sent out of order (eg, a TCP retransmit), it must re-DMA the record containing the out of order packet

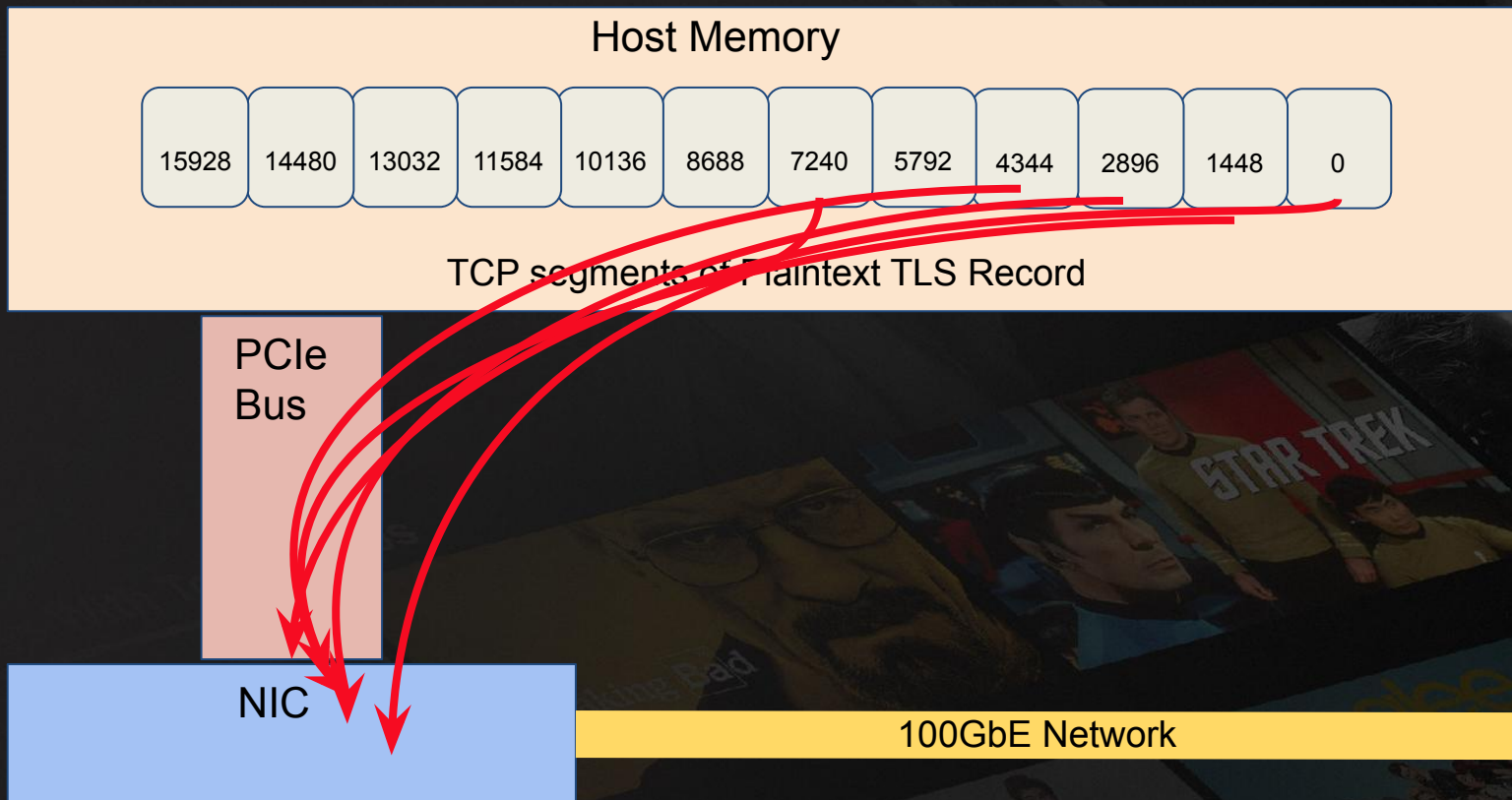
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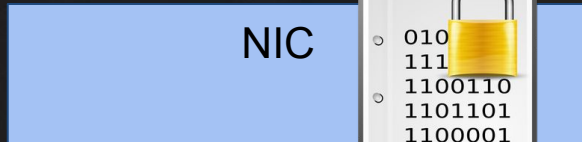
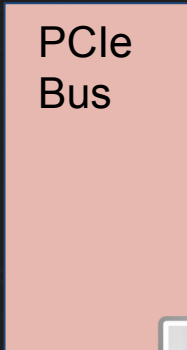
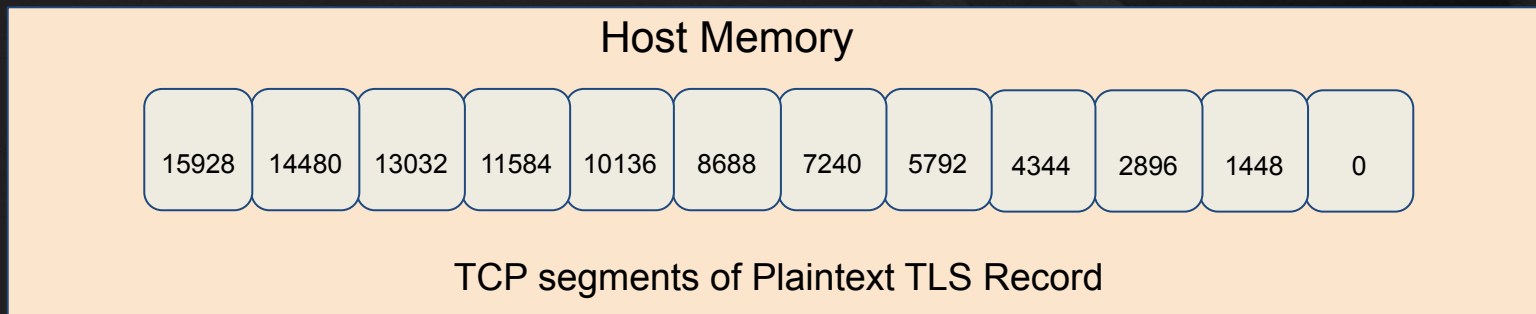
# CX6-DX: In-order Transmit





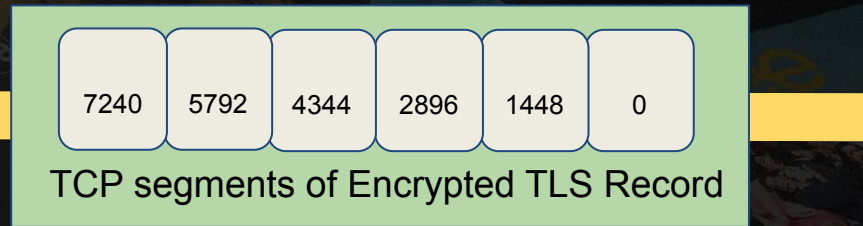
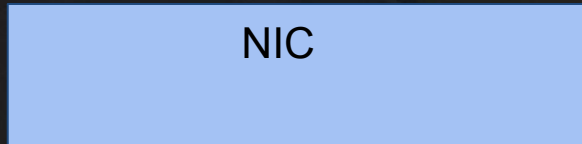
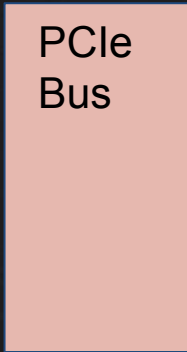
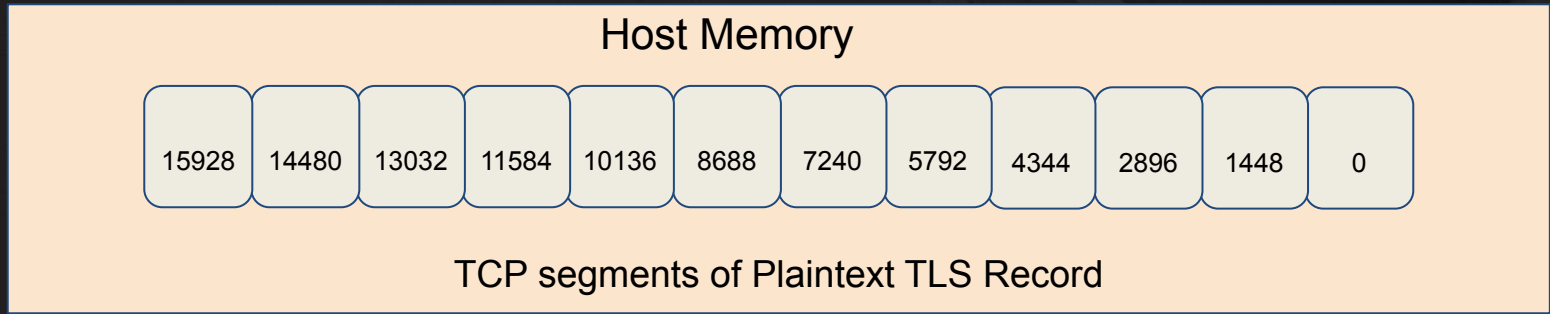
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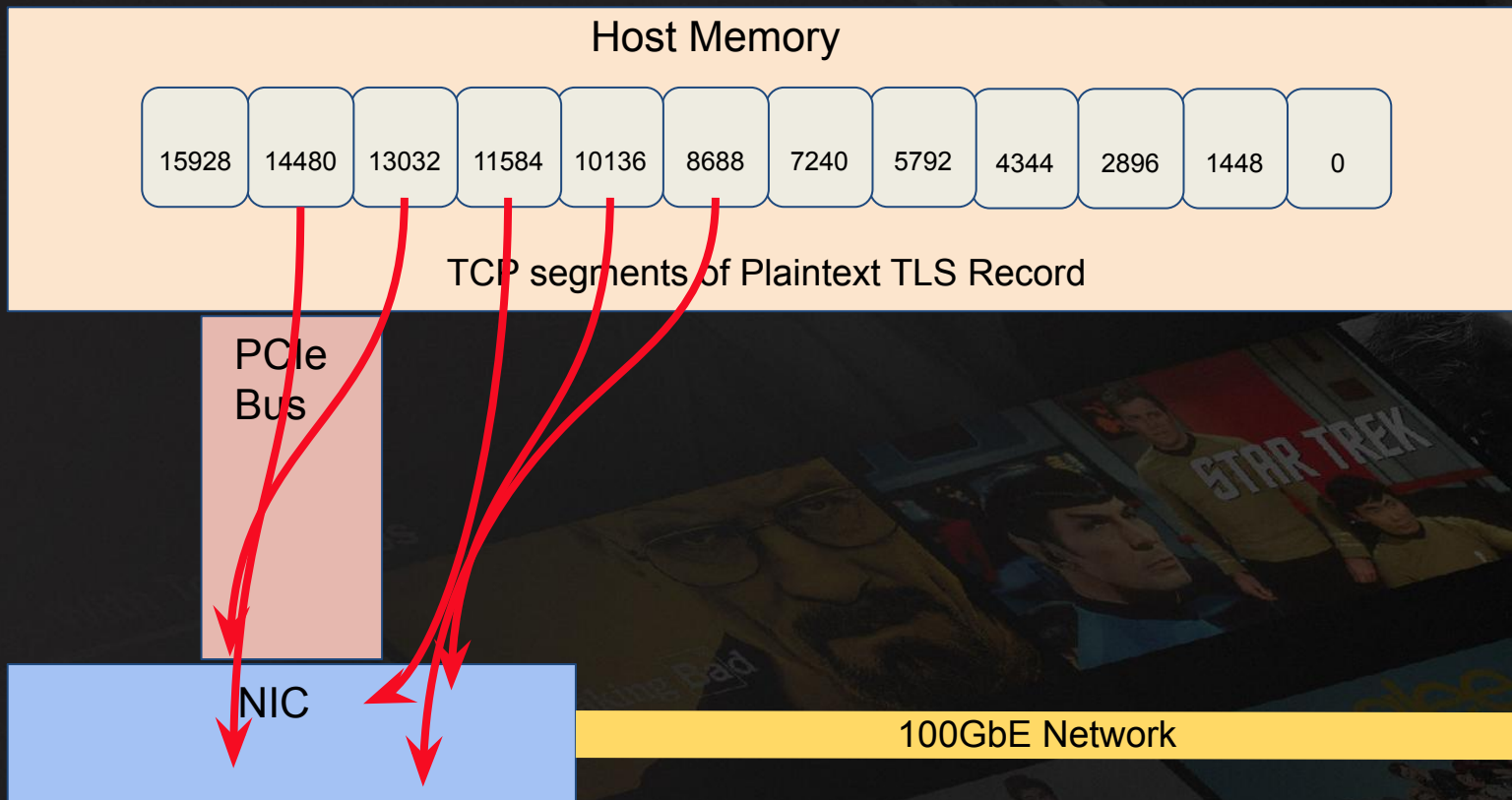


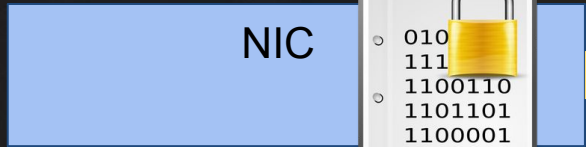
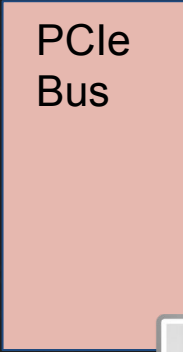
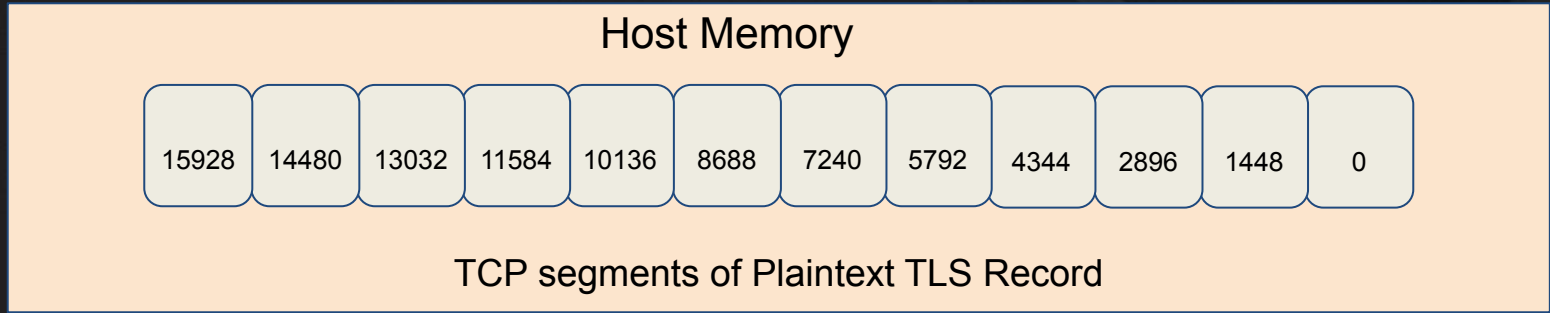
TCP segments of Encrypted TLS Record



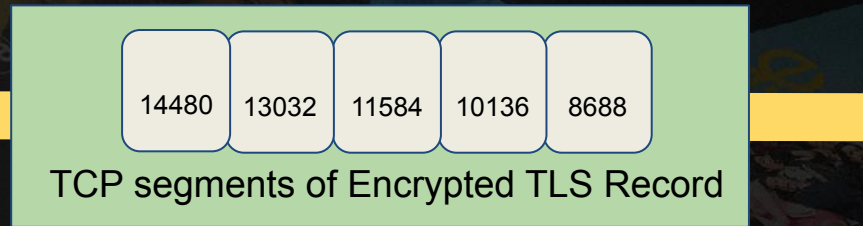
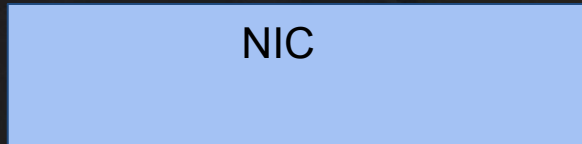
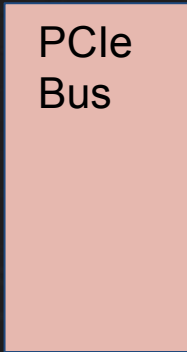
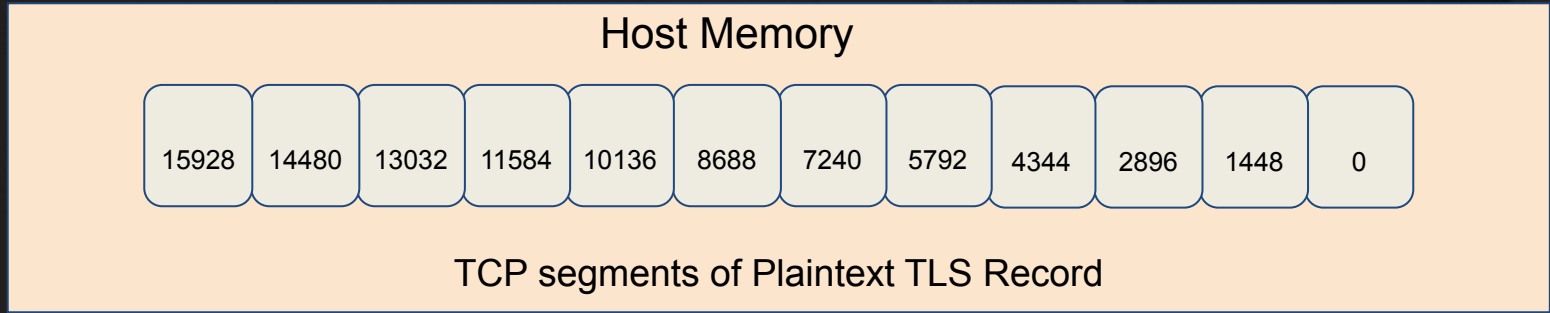


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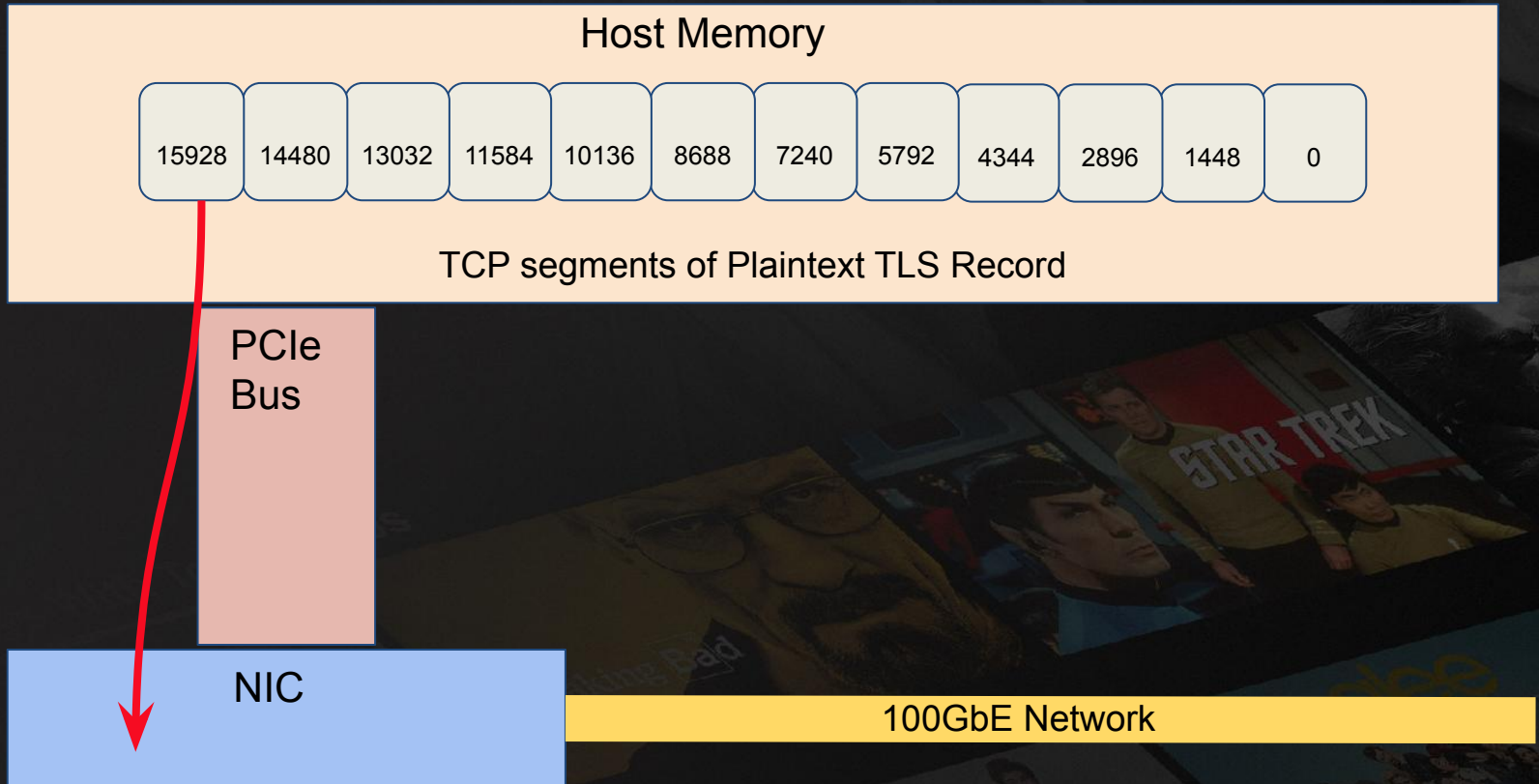


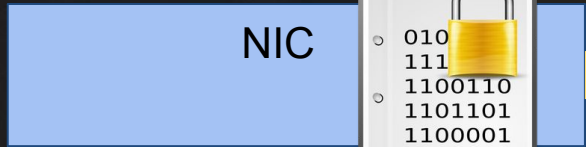
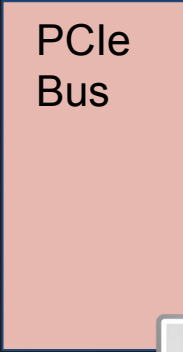
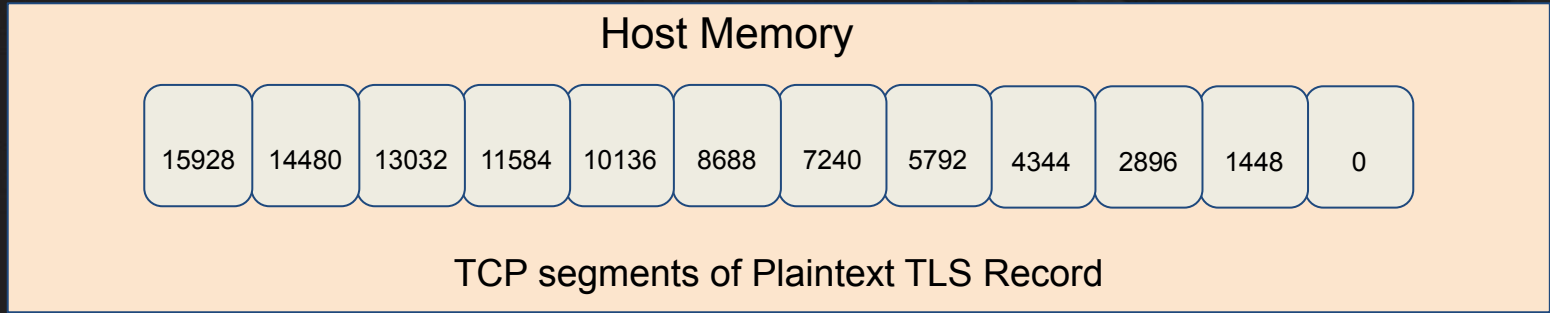


TCP segments of Encrypted TLS Record



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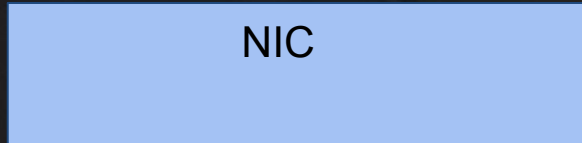
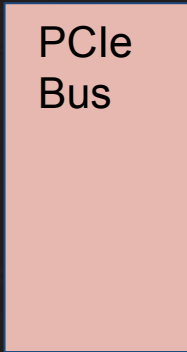
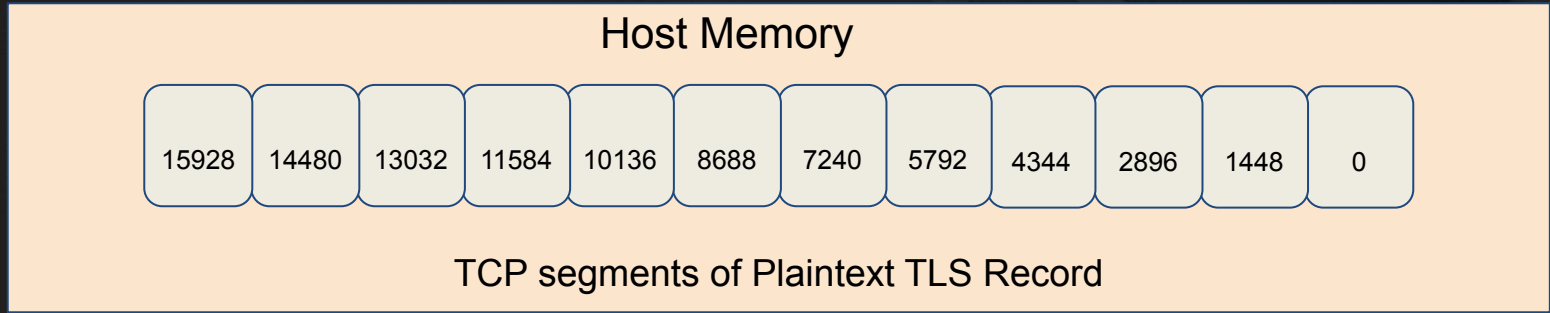




- o 010
- o 111
- o 1100110
- o 1101101
- o 1100001



TCP segments of Encrypted TLS Record

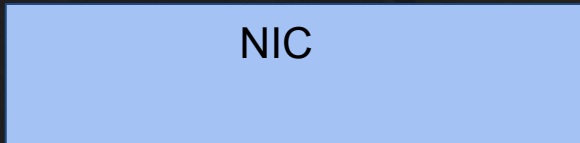
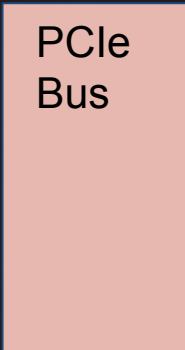
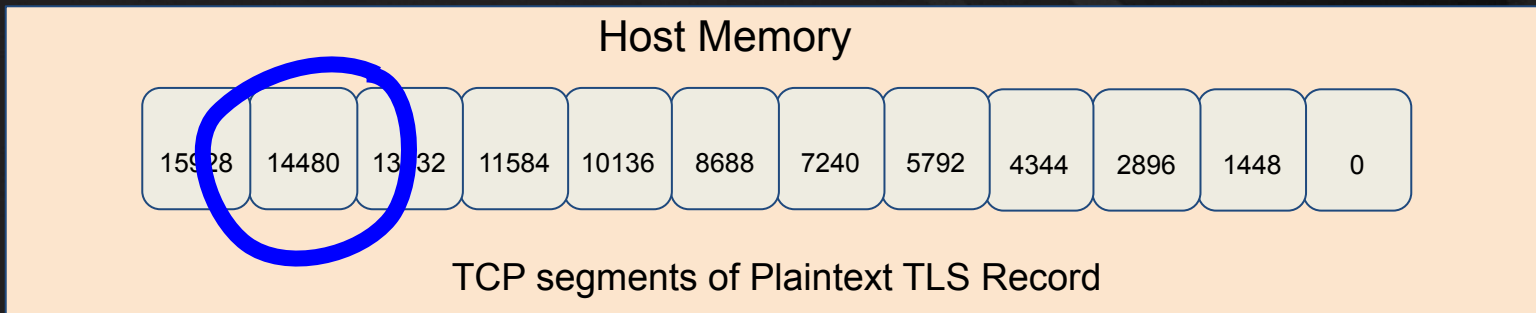


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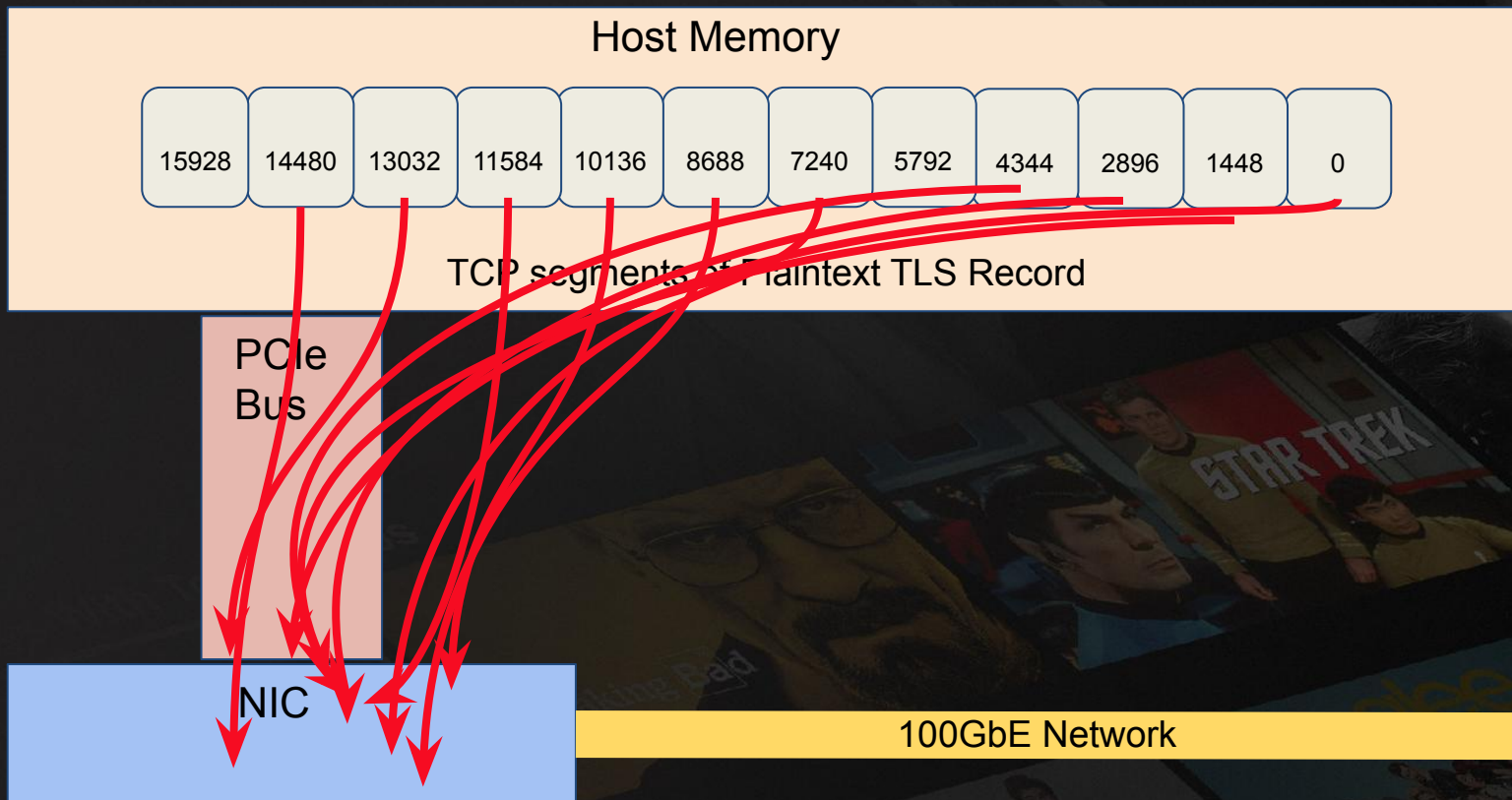
# CX6-DX: TCP Retransmit

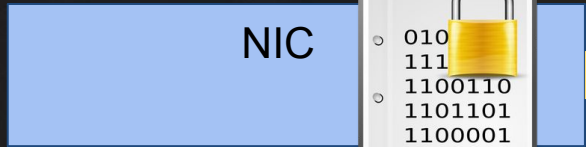
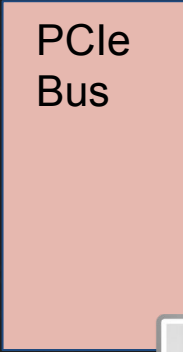
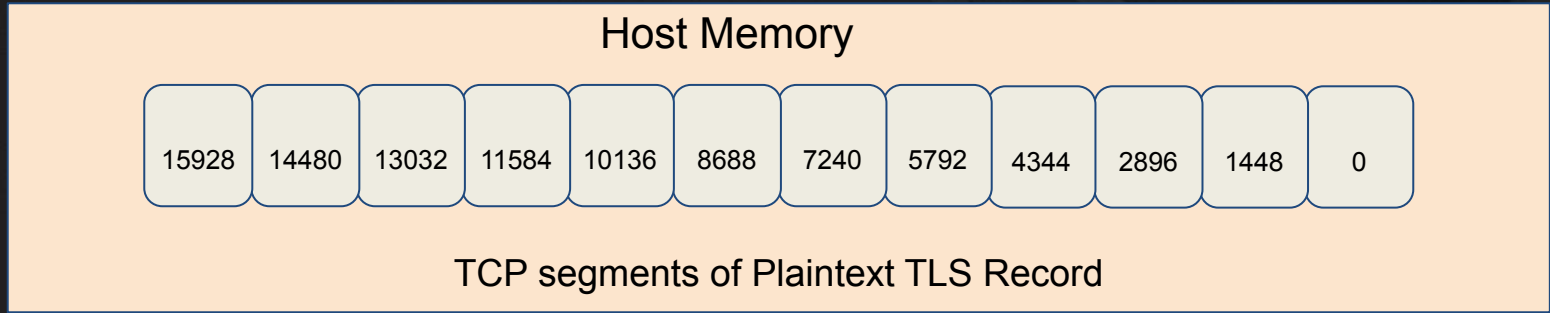




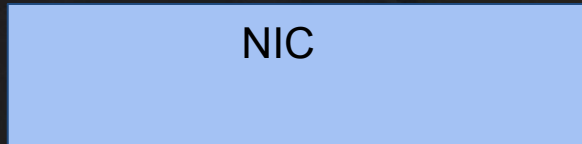
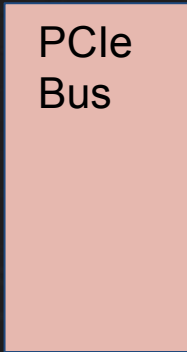
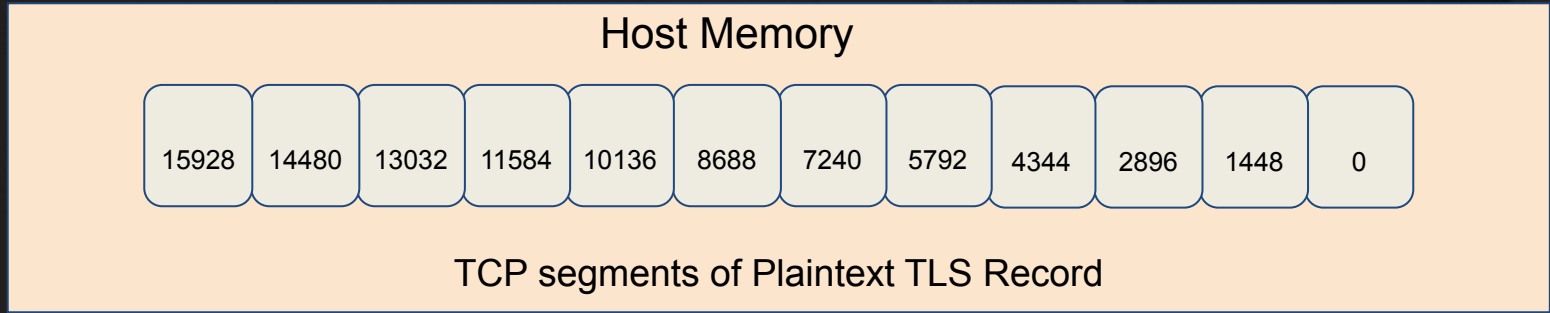


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TCP segments of Encrypted TLS Record



# CX6-DX: Initial Results

Peak: 125Gb/s per NIC, (~250Gb/s total)

Sustained: 75Gb/s per NIC, (~150Gb/s total)

- Pre-release Firmware

# CX6-DX: Initial performance

- NIC stores TLS state per-session
- We have a lot of sessions active
  - (~400k sessions for 400Gb/s)
  - Performance gets worse the more sessions we add
- Limited memory on-board NIC
  - NIC pages in and out to buffers in host RAM
  - Buffers managed by NIC

# PCIe Relaxed Ordering

- Allows PCIe transactions to pass each other
  - Should eliminate pipeline bubbles due to “slow” reads delaying fast ones.
  - May help with “paging in” TLS connection state
- Enabled Relaxed Ordering
  - Didn't help
  - Turns out CX6-DX pre-release firmware hardcoded Relaxed Ordering to disabled

# CX6-DX: Results from next firmware

- Firmware update enabled Relaxed Ordering on NIC
- Peak results improved:

160Gb/s per NIC (~320Gb/s total)

- Note that peak and sustained were effectively identical from this fw update forward.
- This is a new record!
- Nearly as fast as SW TLS (per NIC): 160Gb/s vs 190Gb/s, much faster overall



# CX6-DX: Results from production fw

- Firmware update added “TLS\_OPTIMIZE” setting
- Peak & sustained results improved:

190Gb/s per NIC (~380Gb/s total)!

# CX6-DX: What's needed to use of NIC TLS in production at Netflix?

- QoE testing
  - Measure various factors, such as rebuffer rate, play delay, time to quality, etc.
  - Initial results are great
  - Larger, more complete study scheduled soon.

# CX6-DX: What's needed to use of NIC TLS in production at Netflix?

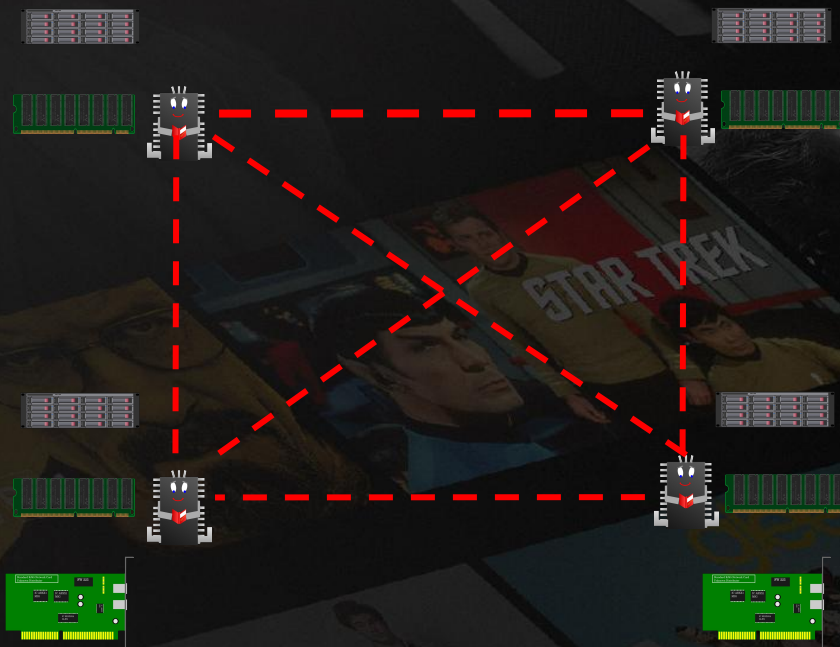
- Track retransmits & move sessions to software
  - Monitor bytes retransmitted for lossy networks
  - Monitor segments retransmitted to protect against attacks

# CX6-DX: Mixed HW/SW session perf?

- Moving a non-trivial percentage of conns to SW has unanticipated BW cost.
- Setting SW switch threshold to 1% bytes retransmitted moves  $\frac{1}{3}$  of conns to SW
- Max stable BW moves from 380Gb/s to 350Gb/s with roughly  $\frac{1}{3}$  of connections in SW
  - Performance impact is more than expected

# 4 Nodes, worst case with siloing + NIC kTLS

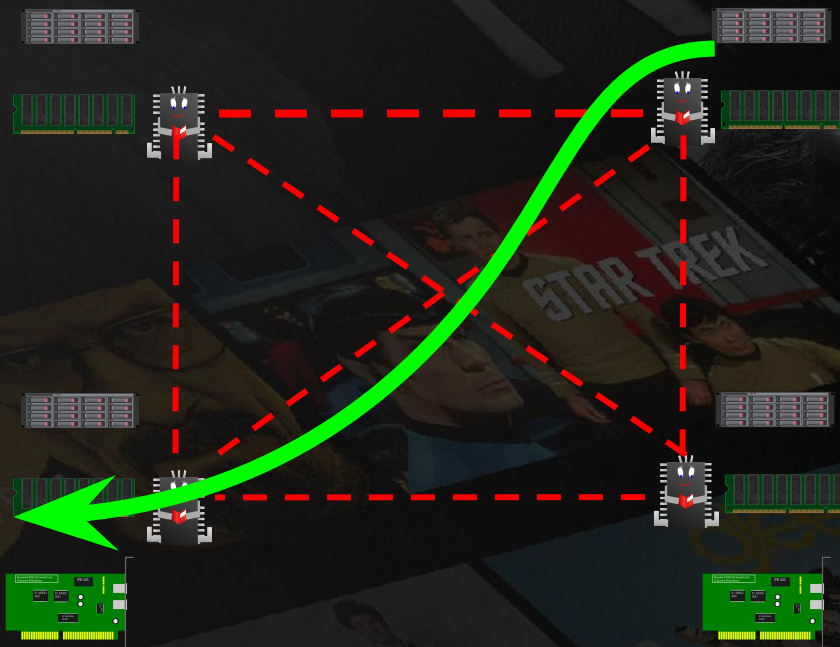
Steps to send data:



# 4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

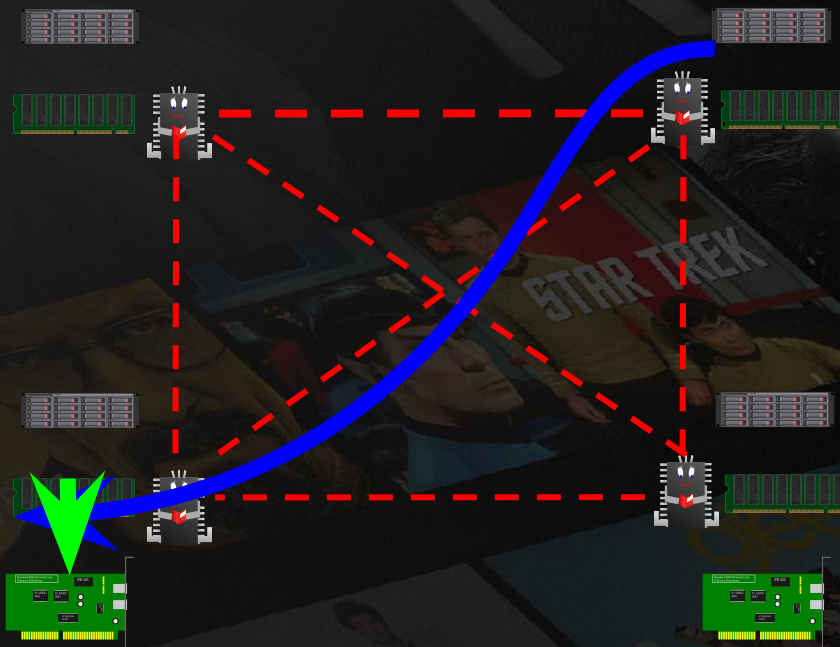
- DMA data from disk to memory
  - First NUMA bus crossing



## 4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

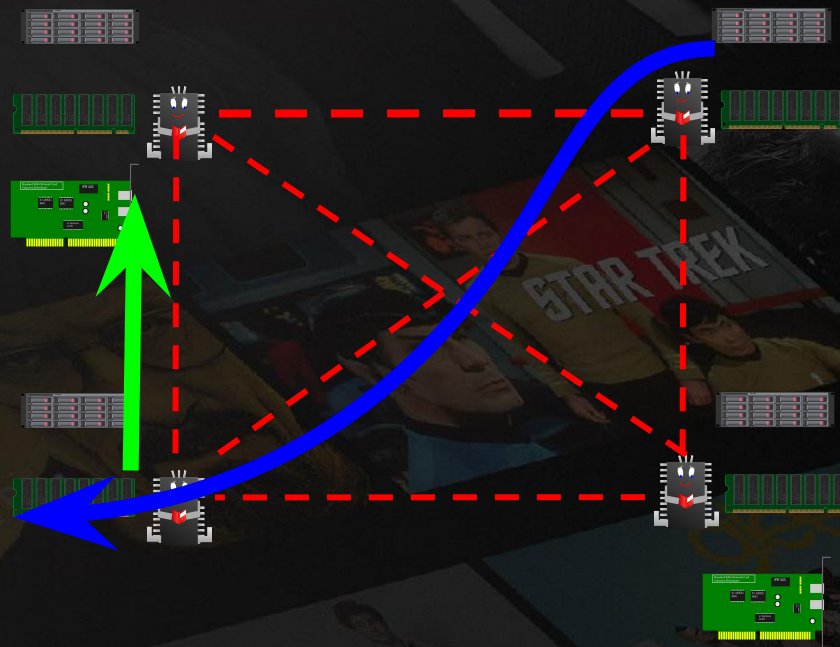
- DMA data from disk to memory
  - First NUMA bus crossing
- DMA data from memory to network



## 4 Nodes, worst case with siloing + NIC kTLS

Steps to send data:

- DMA data from disk to memory
  - First NUMA bus crossing
- DMA data from memory to network





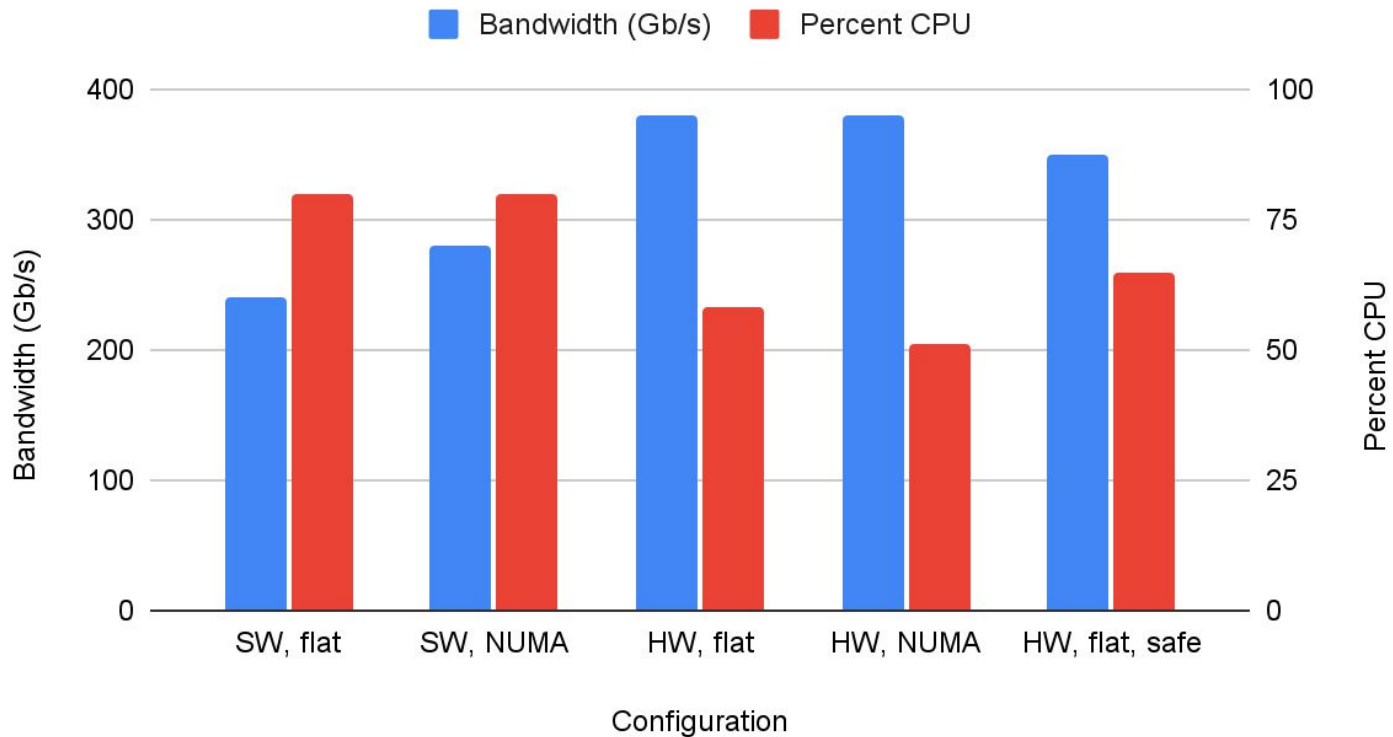
# Worst Case Summary:

- 2 NUMA crossing on average
  - 100% of disk reads across NUMA
  - 100% of network writes across NUMA
- 100GB/s of data on the NUMA fabric
  - Less than the 280GB/s of Infinity fabric bandwidth

# Average Case Summary:

- 1.25 NUMA crossings on average
  - 75% of disk reads across NUMA
  - 50% of NIC transmits across NUMA due to unbalanced setup
- 62.5 GB/sec of data on NUMA fabric

## AMD Rome Performance



# Other platforms? Ampere Altra

- “Mt. Snow”
  - Q80-30: 80 3.0GHz Arm Neoverse-N1 cores
  - 8 channels of 256GB DDR4-3200
  - 128 Lanes Gen4 PCIe
  - 16x WD SN720 2TB NVMe
  - 2 Mellanox CX6-DX NICs

# Other platforms? Ampere Altra

- Minimal access to system counters
  - No way to see memory BW usage
  - No way to see IO bandwidth or latency
  - Leads to feeling like you're driving blind

# Other platforms? Ampere Altra

- Poor performance with SW kTLS:
  - CPU limited at 180Gb/s
- Poor initial performance with NIC TLS
  - PCIe limited at 240Gb/s
    - Very low CPU utilization
    - NICs saturated, and we see lots of output drops

# Ampere: PCIe Extended Tags

- Poor initial performance with NIC TLS: 240Gb/s
- Very low CPU utilization
- NICs saturated, and we see lots of output drops
- Seems like a PCIe problem

# Ampere: PCIe Extended Tags

- PCIe is more of a network than a bus
- Number of outstanding DMA reads is limited by the number of PCIe “tags”
- PCIe tag space is 5-bits by default, allowing for 32 DMAs to be in-flight at the same time
- PCIe extended tags increase the tag space to 8 bits, allowing 256 DMA reads in flight at the same time
- Like increasing TCP window size.



# Ampere: PCIe Extended Tags

- After enabling extended tags, we see a bandwidth improvement:

240Gb/s -> 320Gb/s

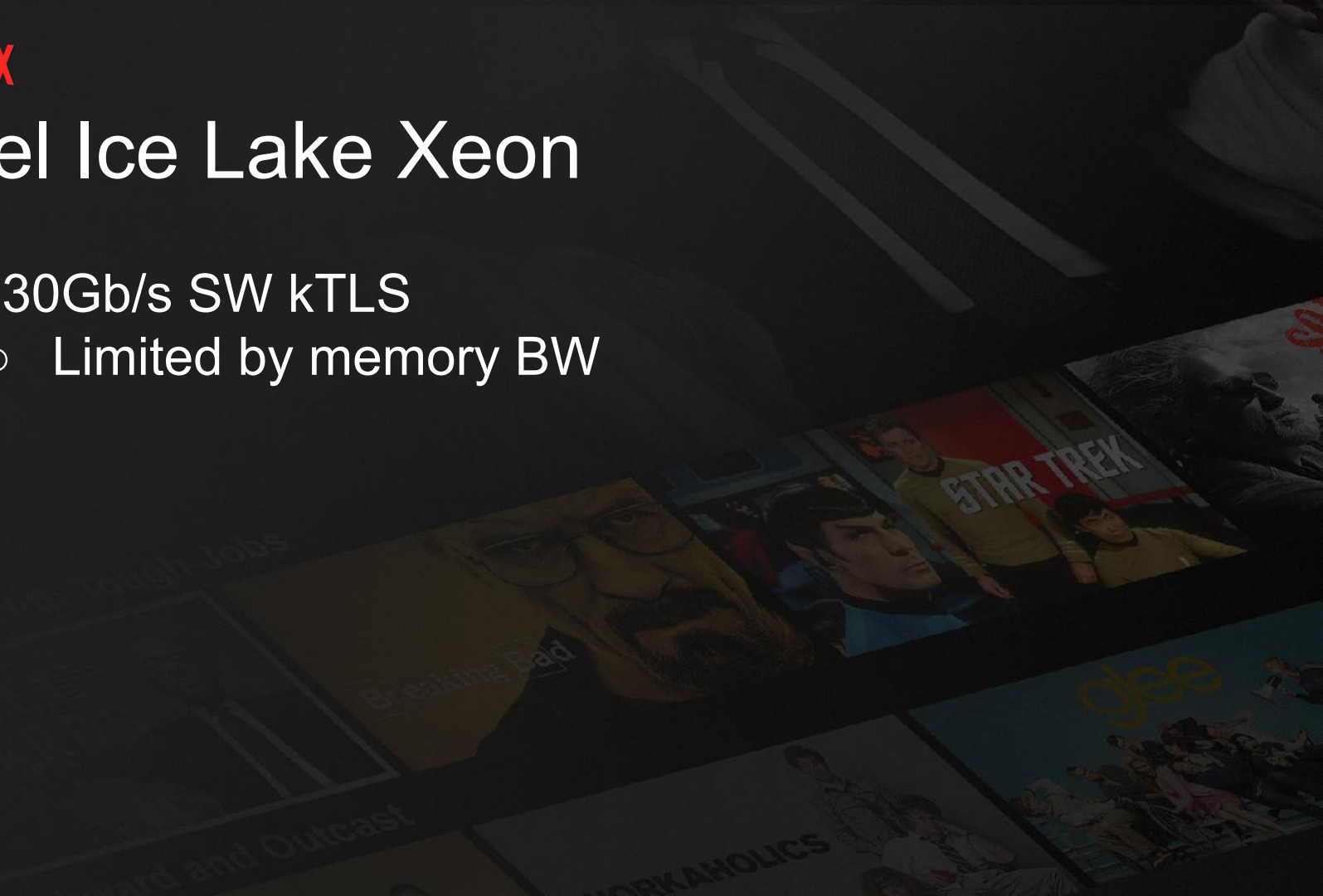
# Other platforms? Intel Ice Lake Xeon

- 8352V CPU
  - 36 cores, 2.1GHz
  - 8 channels 256GB DDR4-3200 (running at 2933)
  - 64 Lanes Gen4 PCIe
  - 20x Kioxia 4TB NVMe (PCIe Gen4)
  - 2 Mellanox CX6-DX NICs

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# Intel Ice Lake Xeon

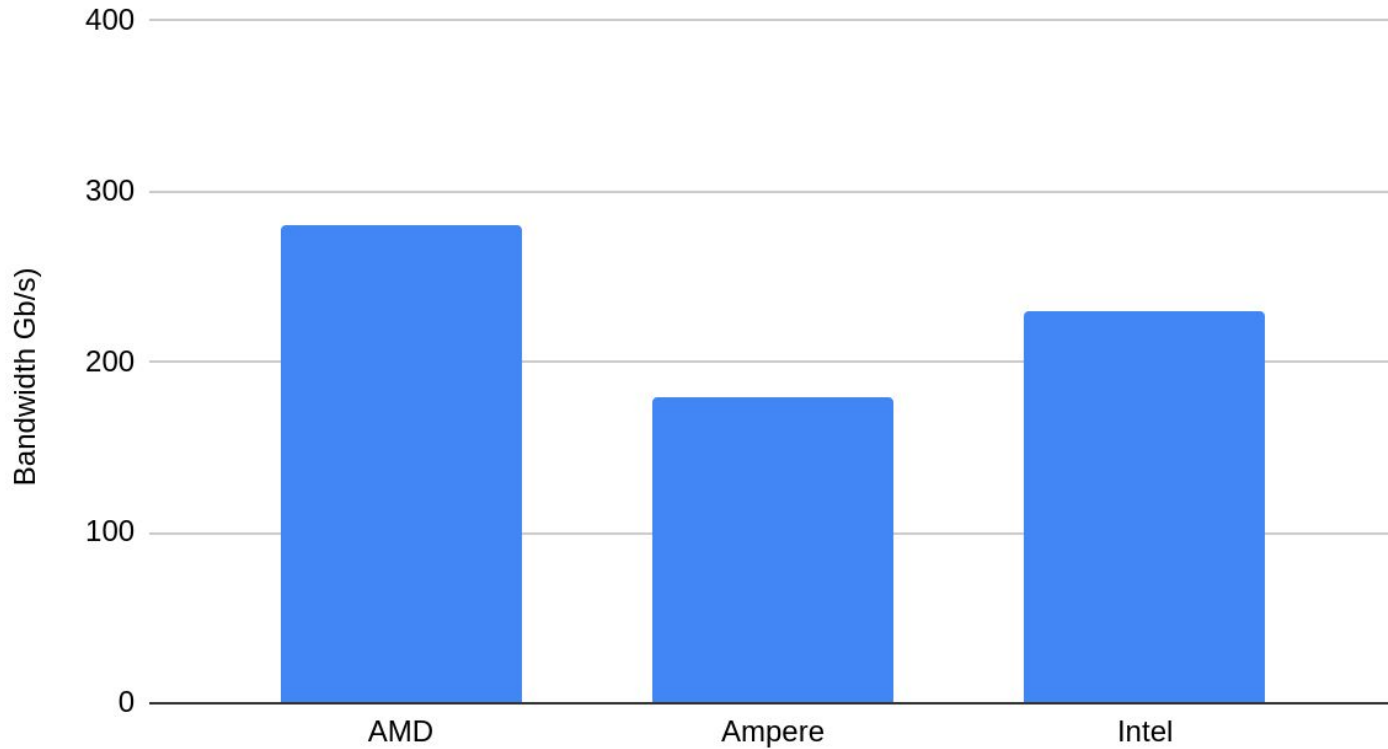
- 230Gb/s SW kTLS
  - Limited by memory BW



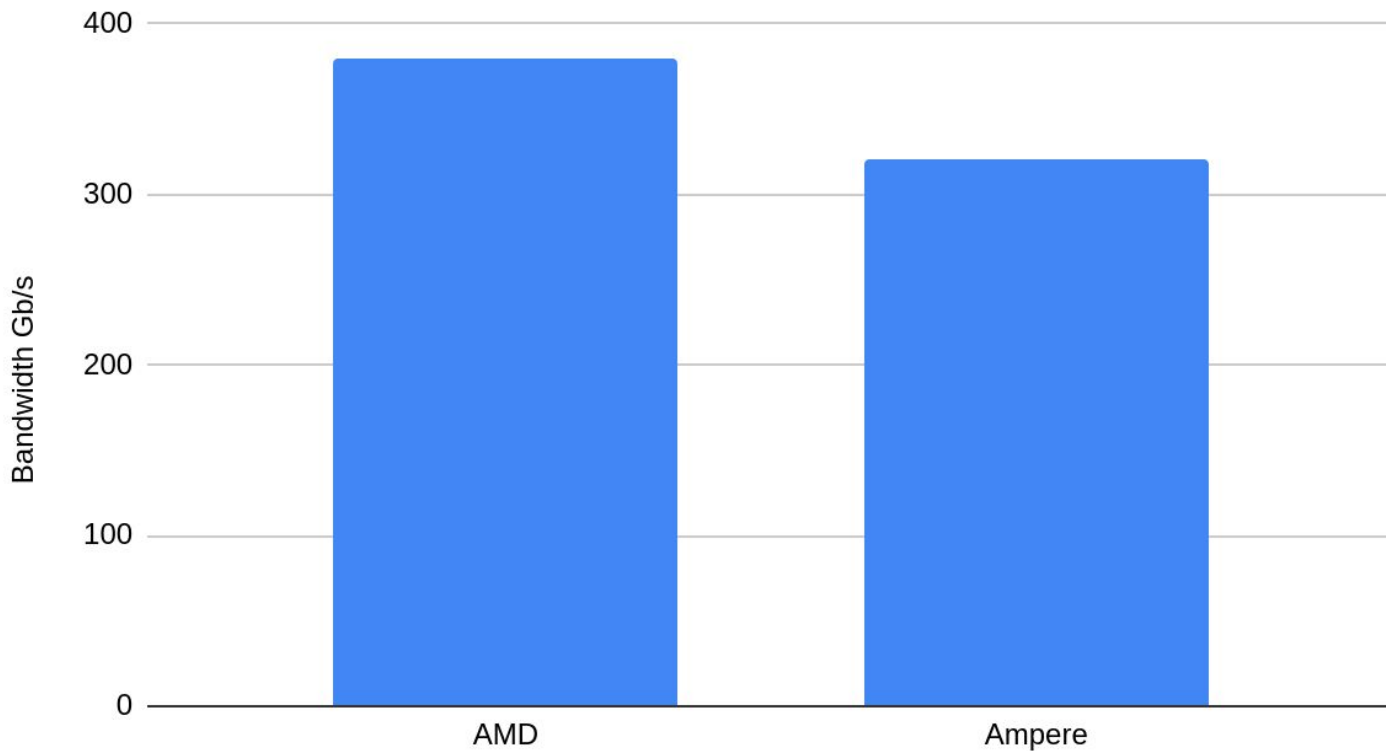
# Intel Ice Lake Xeon (WIP)

- 230Gb/s SW kTLS
  - Limited by memory BW
    - 8352V runs memory at 2993, others SKUs run at 3200
      - Would expect the same performance as AMD from that
- BIOS locked out PCIe Relaxed ordering, so no NIC kTLS results yet

## Max SW kTLS Bandwidth



## NIC (Hardware Inline) kTLS Bandwidth



## But wait, there's .... not ... more..

- 800Gb prototype sitting on datacenter floor due to shipping exception 😞
- Something to talk about next year?

A screenshot of a shipping tracking notification. At the top, it says "ADD NICKNAME" and "DELETED" (in a red box). Below that, it says "Updated delivery: Thursday, September 16, 2021 by end of day". Underneath, it says "Initially expected: Thursday, 9/16/2021". A progress bar shows a red line with a red exclamation mark icon, indicating a delay. Below the bar, it says "DELAY HERNDON, VA" and "GET STATUS UPDATES". At the bottom, it says "Direct signature required" and shows the origin "FROM Libertyville, IL US" and destination "TO ASHBURN, VA US" with a "MANAGE DELIVERY" link.

ADD NICKNAME

DELETED

Updated delivery:  
Thursday, September 16, 2021 by end of day

Initially expected: Thursday, 9/16/2021

DELAY  
HERNDON, VA

GET STATUS UPDATES

Direct signature required

FROM  
Libertyville, IL US

TO  
ASHBURN, VA US

MANAGE DELIVERY

# Many thanks to:

- **Warren Harrop & the Netflix Open Connect hardware team for putting together the testbed.**
- **FreeBSD developers for making such an awesome OS**

**Slides at:**

**<https://people.freebsd.org/~gallatin/talks/euro2021.pdf>**



# Disk centric siloing

- Associate disk controllers with NUMA nodes
- Associate NUMA affinity with files
- Associate network connections with NUMA nodes
- Move connections to be “close” to the disk where the contents file is stored.
- After the connection is moved, there will be 0 NUMA crossings!

# Disk centric siloing problems

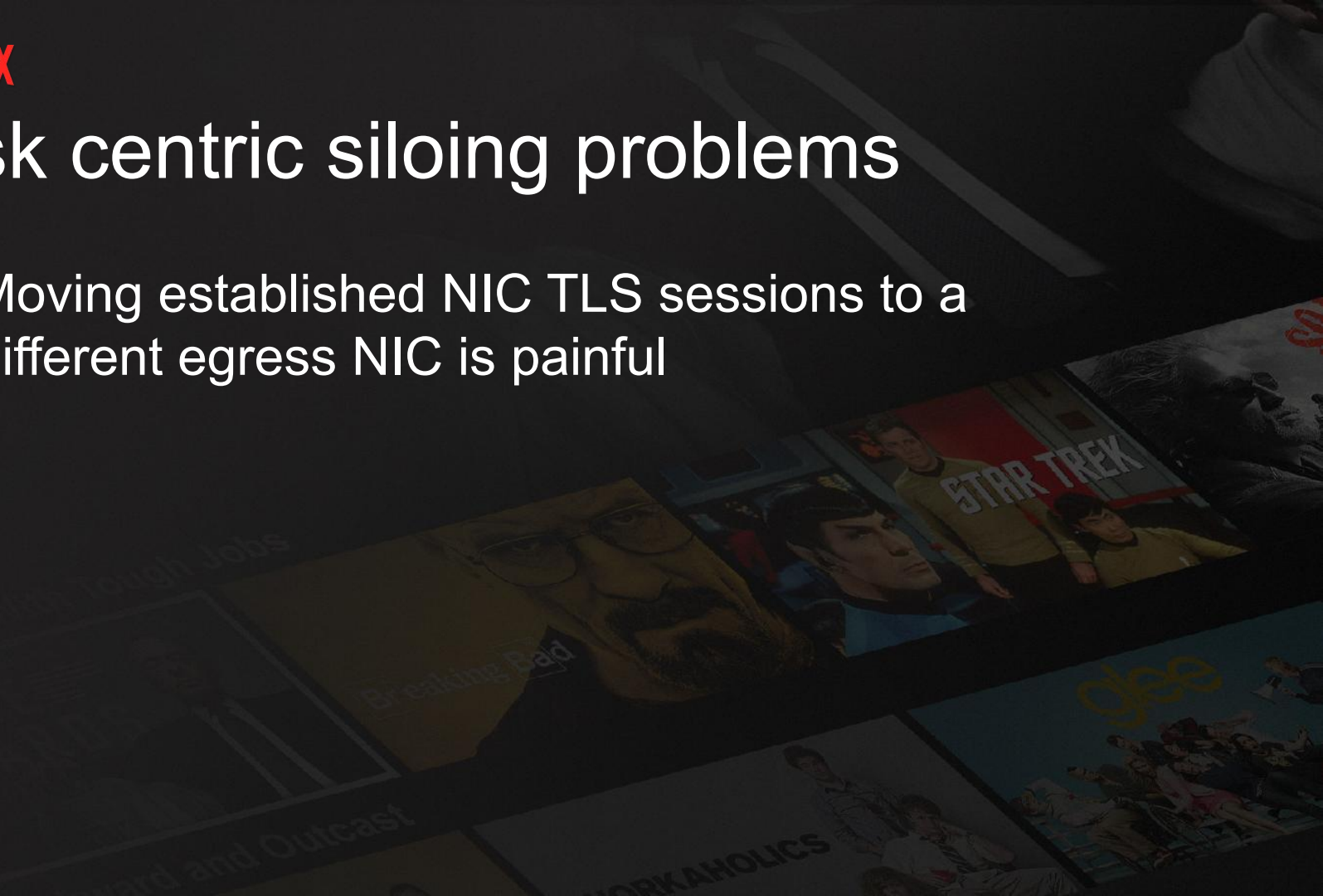
- No way to tell link partner that we want LACP to direct traffic to a different switch/router port
  - So TCP acks and http requests will come in on the “wrong” port
- Moving connections can lead to TCP re-ordering due to using multiple egress NICs
- Some clients issue http GET requests for different content on the same TCP connection
  - **Content may be on different NUMA domains!**

# Disk centric siloing problems

- Different numbers of NVME drives on each domain
  - Node 3 has 3x the number of NVME drives as Node 0
- Content popularity differences can lead to hot and cold disks
- All of this adds up to uneven use of each Numa Node.
  - Output limited by hottest Numa node

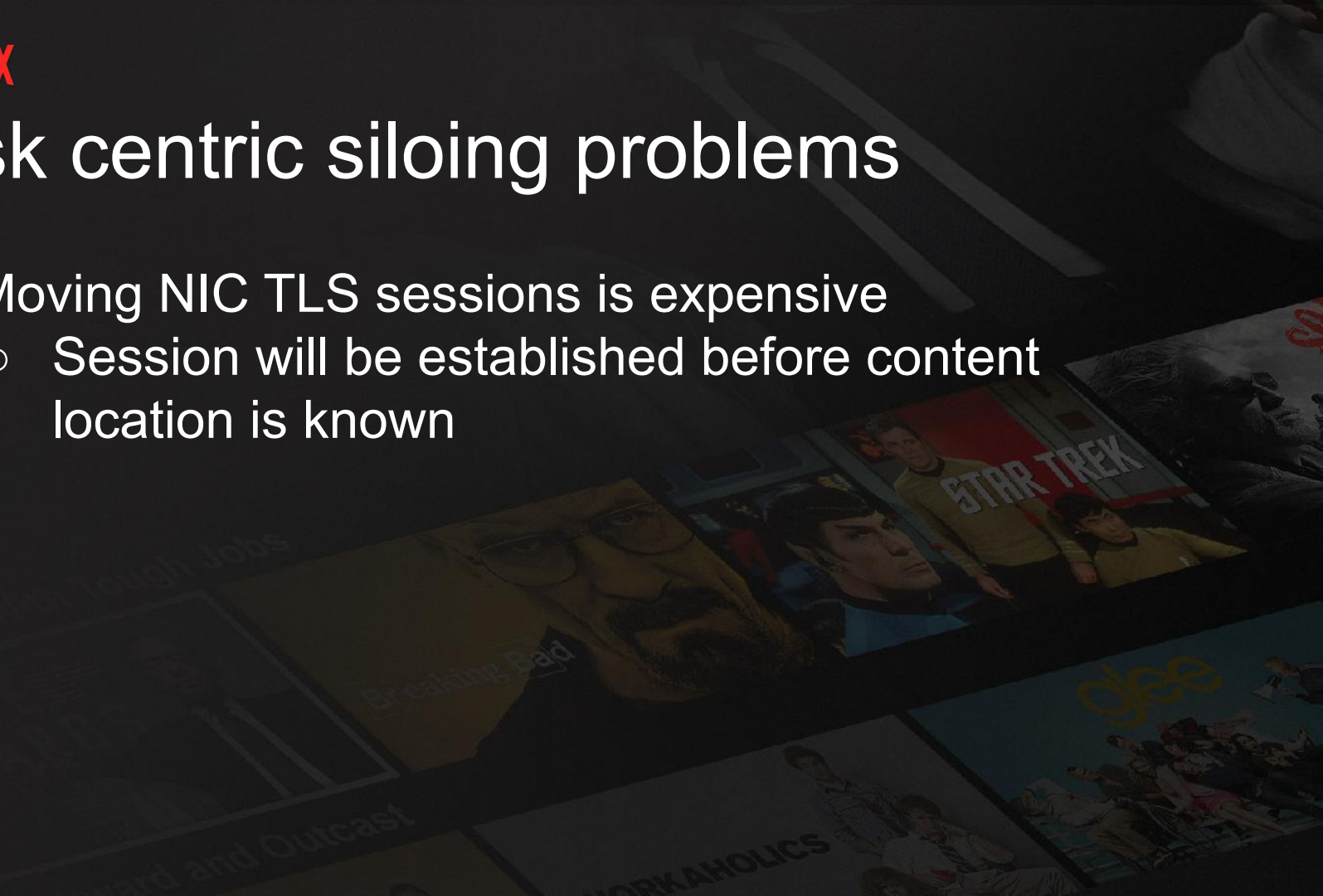
# Disk centric siloing problems

- Moving established NIC TLS sessions to a different egress NIC is painful



# Disk centric siloing problems

- Moving NIC TLS sessions is expensive
  - Session will be established before content location is known



# AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Allocate host pages to back files on NUMA node close to NVME, not NIC
  - Eliminates the 0.75 crossings for 4 domains with NVME
  - Still have the 0.5 crossings on average for remapped NICs

# AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Assumes equal number of NVME on each node
  - Actual machine has:
    - Node 0: 2 NVME
    - Node 1: 6 NVME
    - Node 2: 4 NVME
    - Node 3: 6 NVME

# AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Peak of ~300Gb/s
  - Traffic unequal due to more NVME on Node 3
  - Output drops on mce3 (NIC port on Node 3) at 98Gb/s, while mce0 (NIC port on Node 1) is mostly idle at 40Gb/s
  - Tried “remapping” NVME and pretending some drives in different domains



# AMD: NUMA w/NIC kTLS Offload

- Disk Siloing
  - Pretended some of Node 3's NVME drives were in Node 1
    - Reached a peak of ~350Gb/s
    - Output still uneven between domains because of uneven popularity of content on different NVME drives
  - Sharding based on network (LACP) far more even