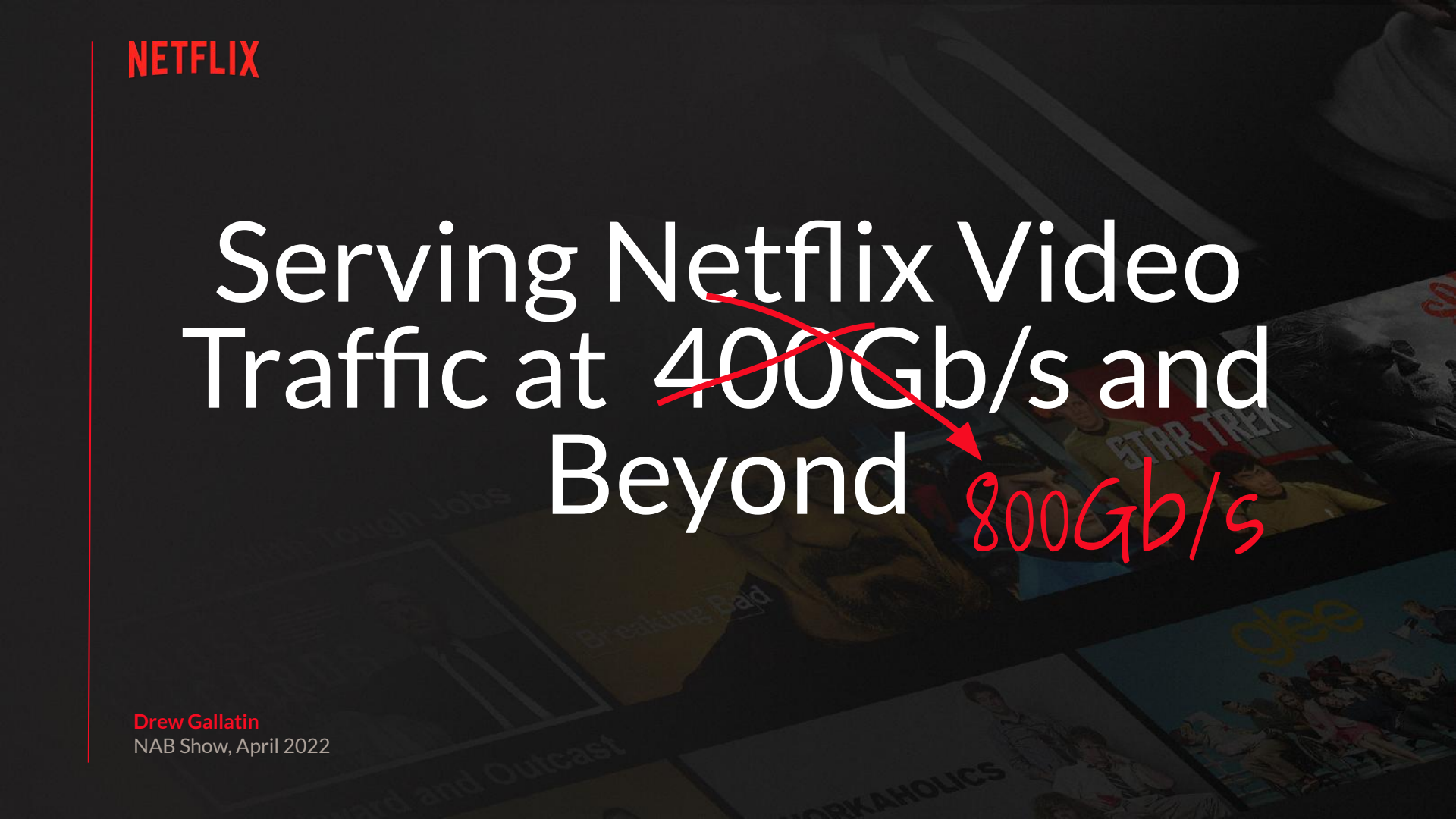
NETFLIX

Serving Netflix Video Traffic at 400Gb/s and Beyond

Drew Gallatin
NAB Show, April 2022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Serving Netflix Video Traffic at 400Gb/s and Beyond
800Gb/s
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Netflix Workload:

- Serve only static media files
- Pre-encoded for all codecs/bitrates
  - Video quality is of the utmost importance, so we don’t transcode on the server
- Greatly simplifies server workload

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Netflix Video Serving Stack

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

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Timeline:

- ***Asynchronous Sendfile (2014)***
- Kernel TLS (2016)
- Network-centric NUMA (2019)
- Inline Hardware (NIC) kTLS (2022)
- 800G initial results

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Sendfile

- Since we are serving static files, we can use sendfile(2)
- Sendfile directs the kernel to send data from a file descriptor to a TCP socket
- This eliminates the need to copy data into or out of the kernel

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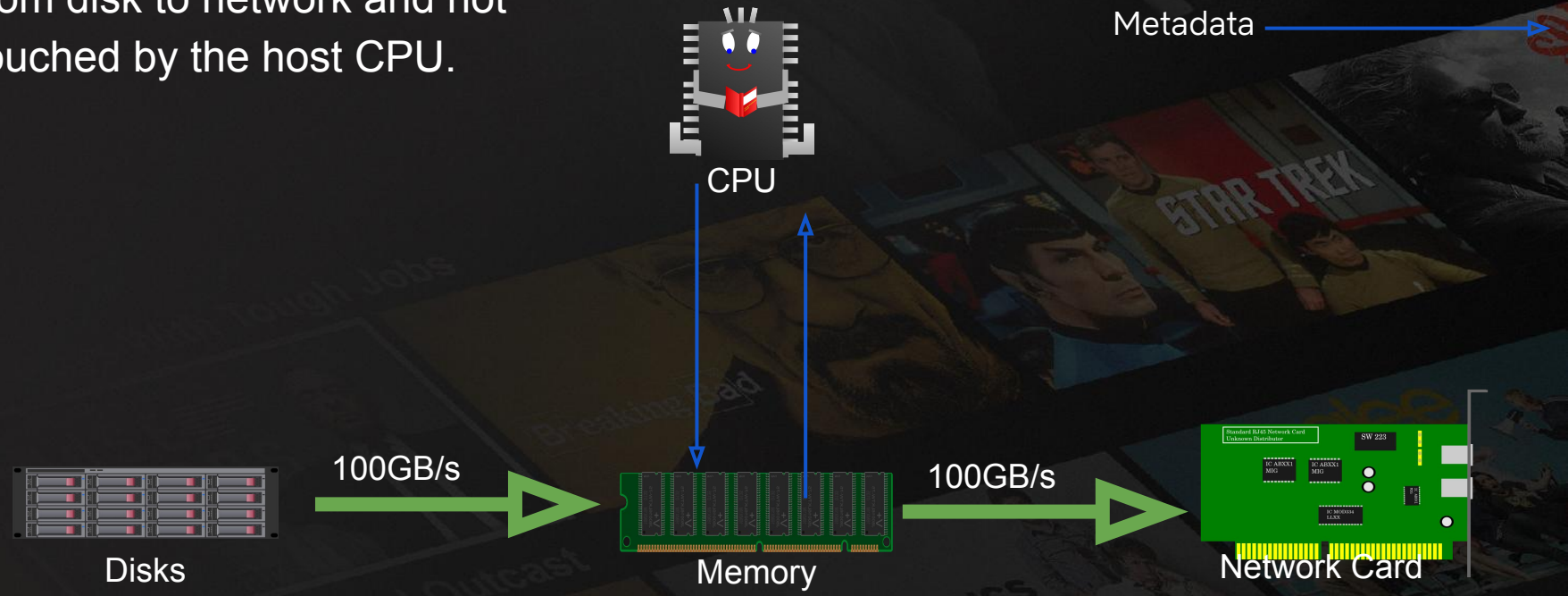
Netflix Video Serving Data Flow

Using sendfile, data is sent directly from disk to network and not touched by the host CPU.



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Problem: Disk reads can block sendfile

- When an nginx worker is blocked, it cannot service other requests
- Solutions to prevent nginx from blocking like aio or thread pools scale poorly

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Solution: Asynchronous sendfile

- sendfile() becomes “fire and forget”
- Empty buffers are appended to the TCP socket buffer. TCP stops when it sees an empty buffer.
- When disk read completes, disk interrupt handler informs TCP it is ready to send

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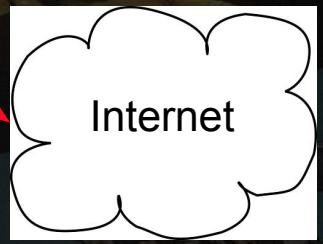
Asynchronous sendfile

Socket Buffer

Disks



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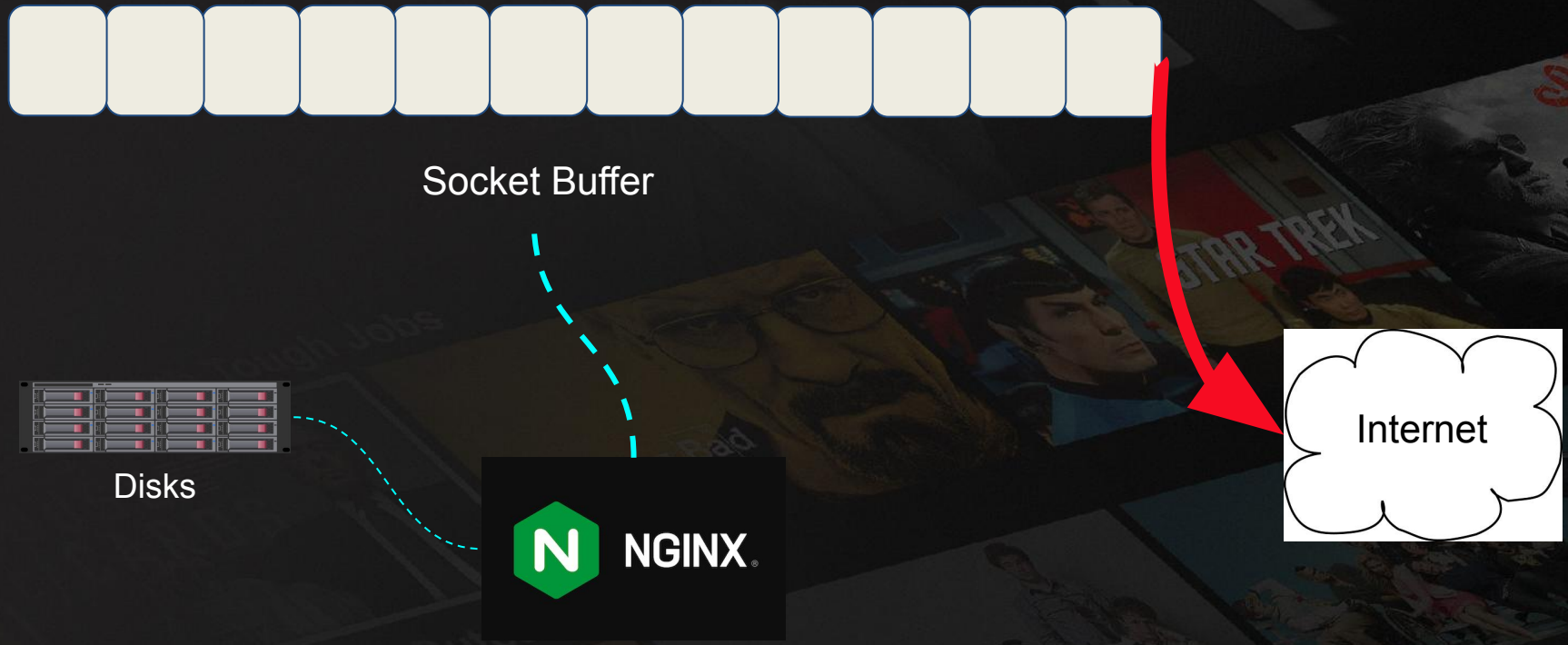
Asynchronous sendfile



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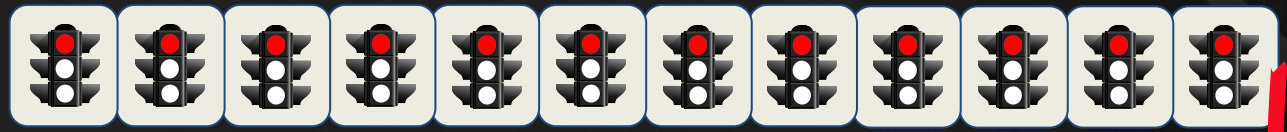
Asynchronous sendfile



Socket Buffer

Disks

NGINX.

Internet

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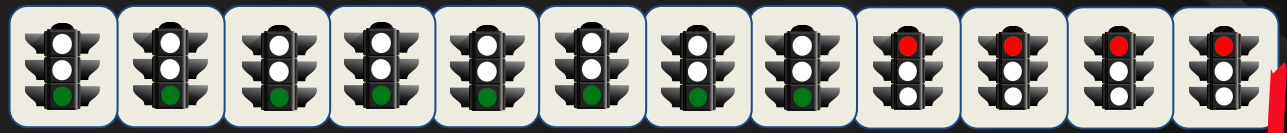
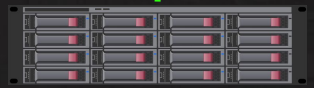
Asynchronous sendfile



Socket Buffer



Disks

Internet

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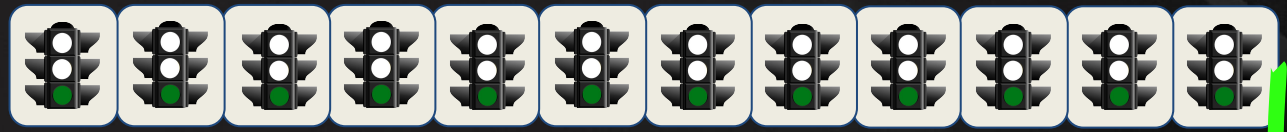
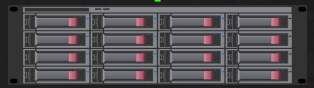
Asynchronous sendfile



Socket Buffer



Disks

Internet

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Asynchronous sendfile

Socket Buffer

Internet

Disks

NGINX.

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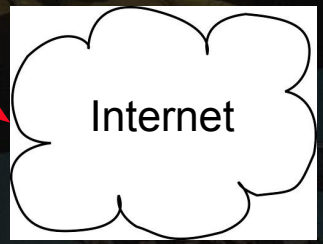
Asynchronous sendfile

Socket Buffer

Disks



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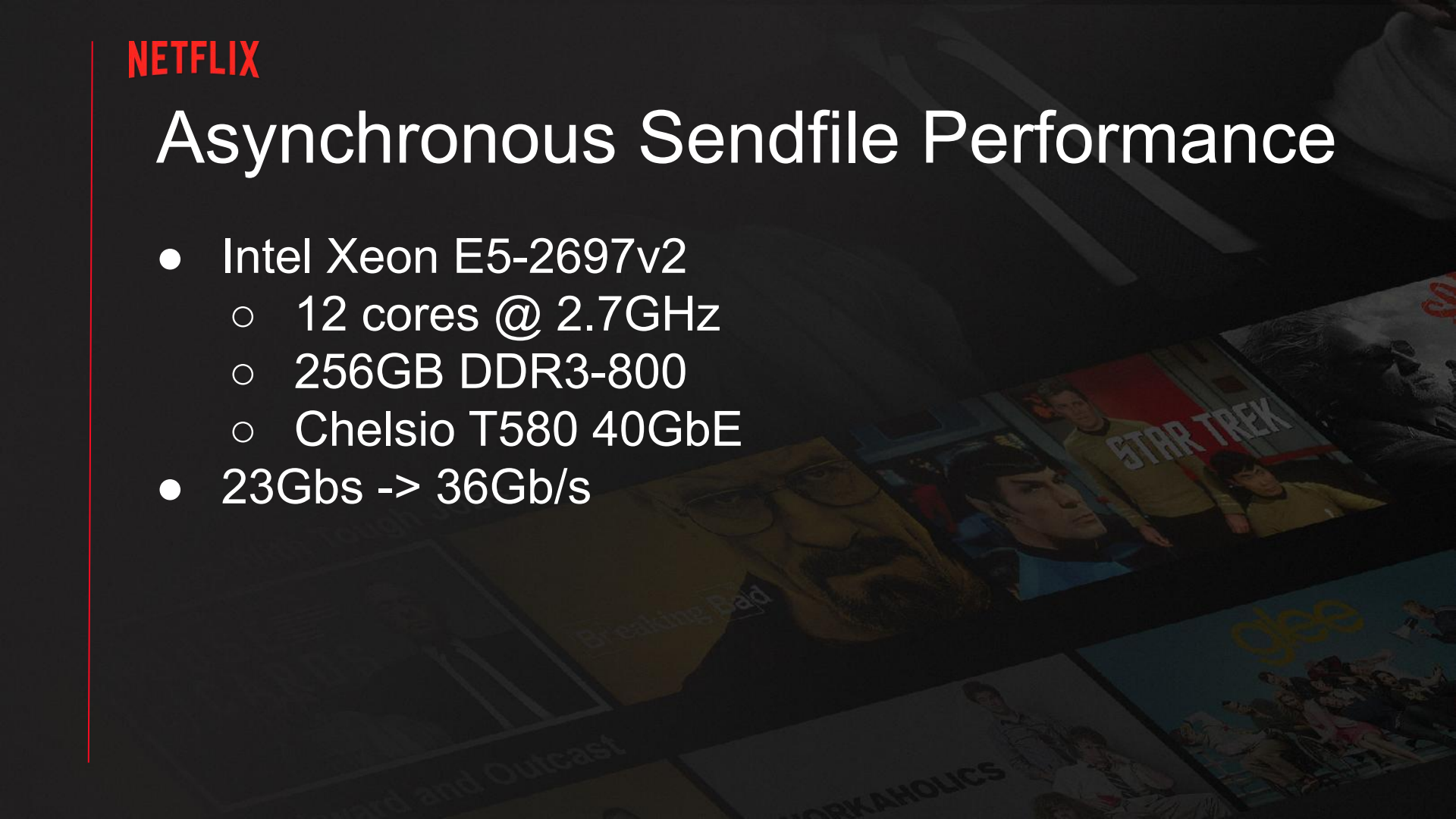
Asynchronous Sendfile Performance

- Intel Xeon E5-2697v2
  - 12 cores @ 2.7GHz
  - 256GB DDR3-800
  - Chelsio T580 40GbE
- 23Gbs -> 36Gb/s



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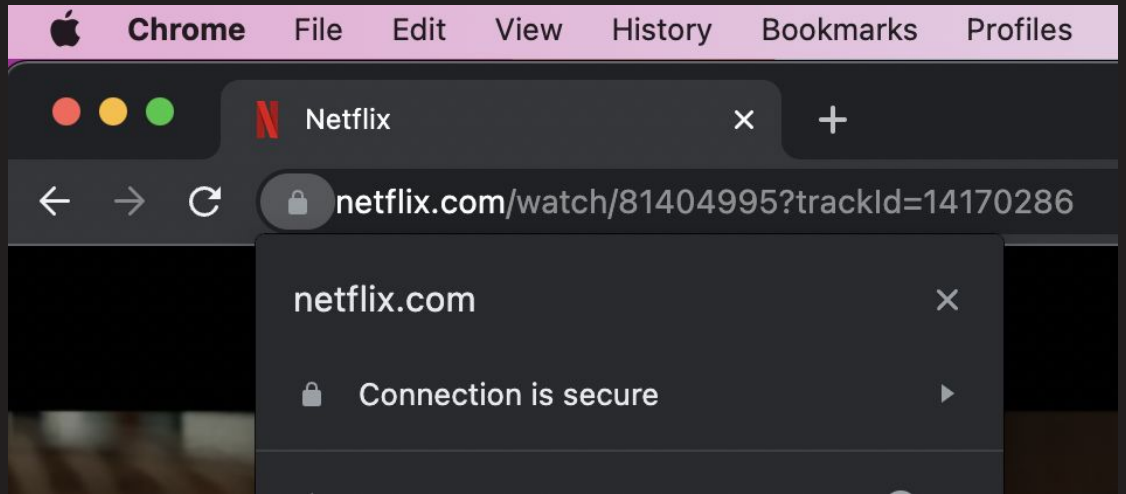
Timeline:

- Asynchronous Sendfile (2014)
- ***Kernel TLS (2016)***
- Network-centric NUMA (2019)
- Inline Hardware (NIC) kTLS (2022)
- 800G initial results

What's TLS?

- ***T**ransport **L**ayer **S**ecurity*
- **TLS** encrypts traffic between clients and the OCA



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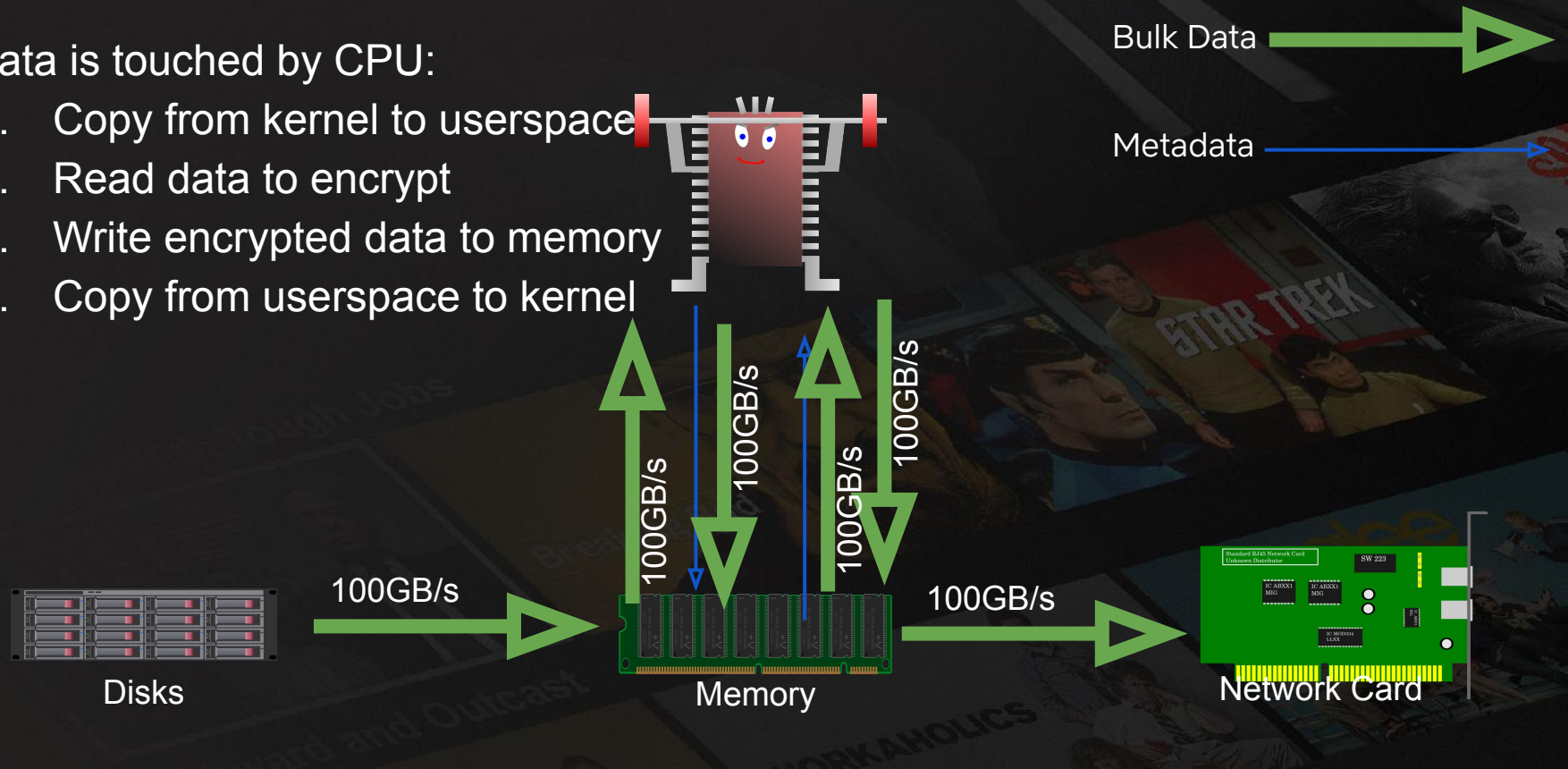
TLS Prevents Sendfile & Triples Memory BW

Data is touched by CPU:

1. Copy from kernel to userspace
2. Read data to encrypt
3. Write encrypted data to memory
4. Copy from userspace to kernel



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Solution: Move TLS into the kernel

- Eliminates copies between userspace and kernel
- Restores sendfile dataflow
- TLS handshakes (eg, session setup, session resumption) handled in userspace.
- TLS state handed to the kernel
- Kernel does bulk crypto as part of sendfile pipeline

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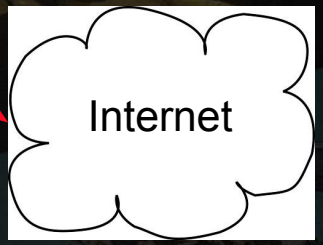
Asynchronous sendfile + kTLS

Socket Buffer

Disks



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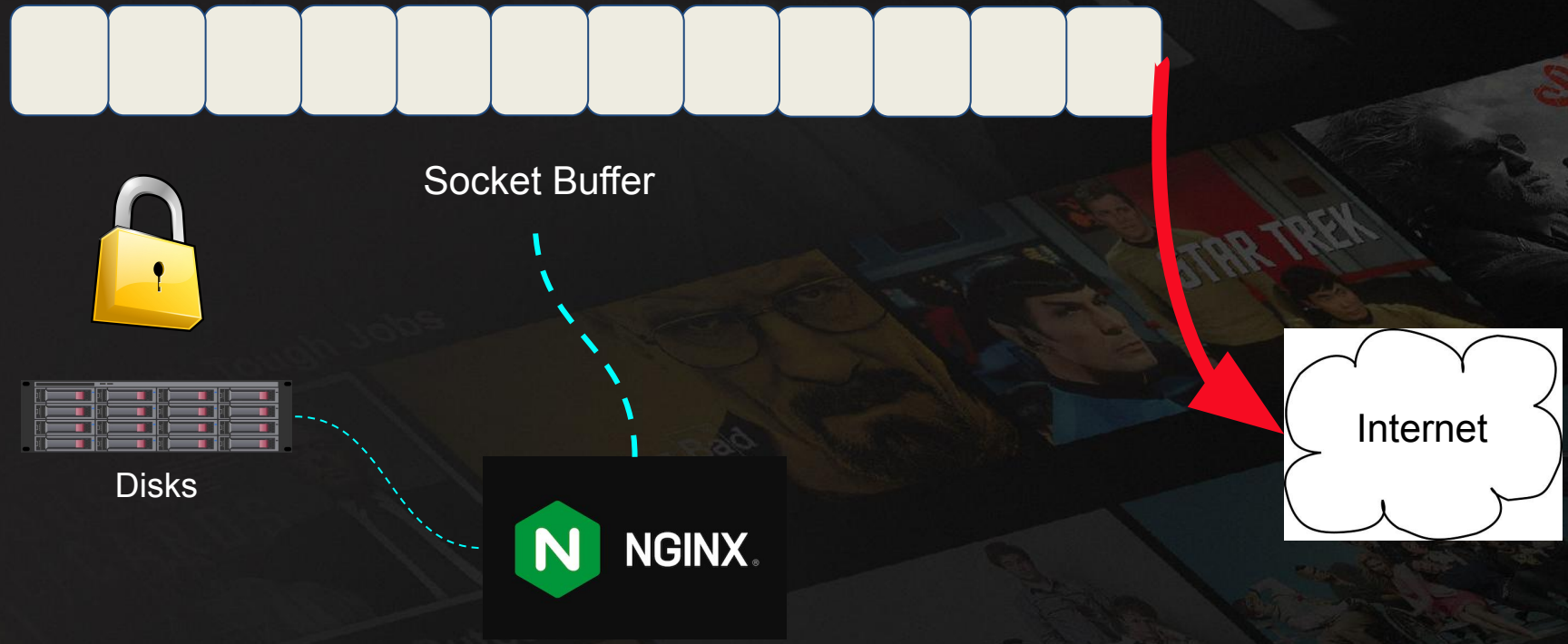
Asynchronous sendfile



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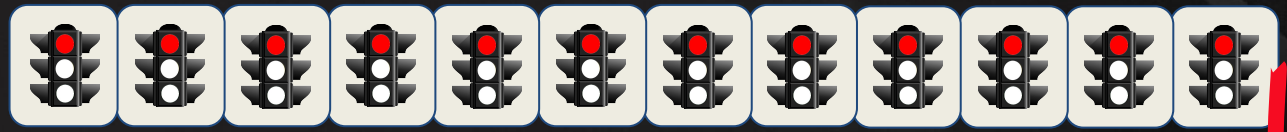
Asynchronous sendfile + kTLS



Socket Buffer

Disks

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Internet

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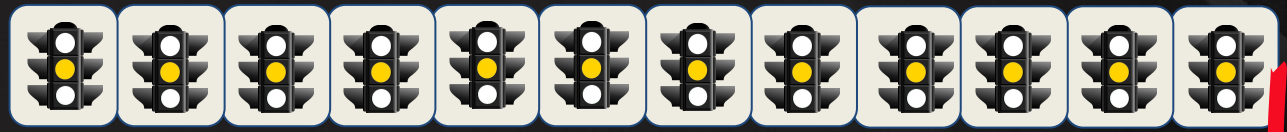
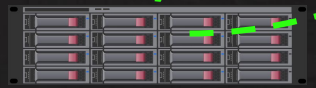
Asynchronous sendfile + kTLS



Socket Buffer



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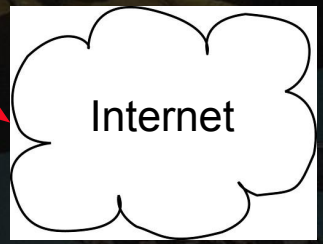

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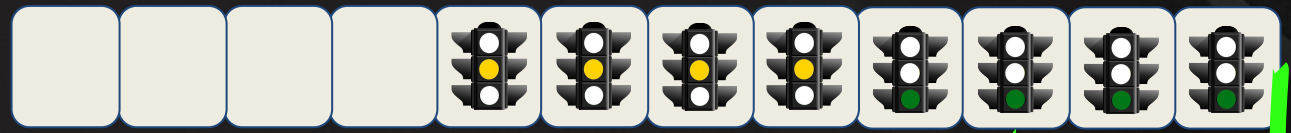
Asynchronous sendfile + kTLS



Socket Buffer

Disks

Internet

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Asynchronous sendfile + kTLS

Socket Buffer

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Asynchronous sendfile + kTLS

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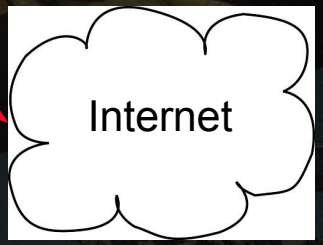

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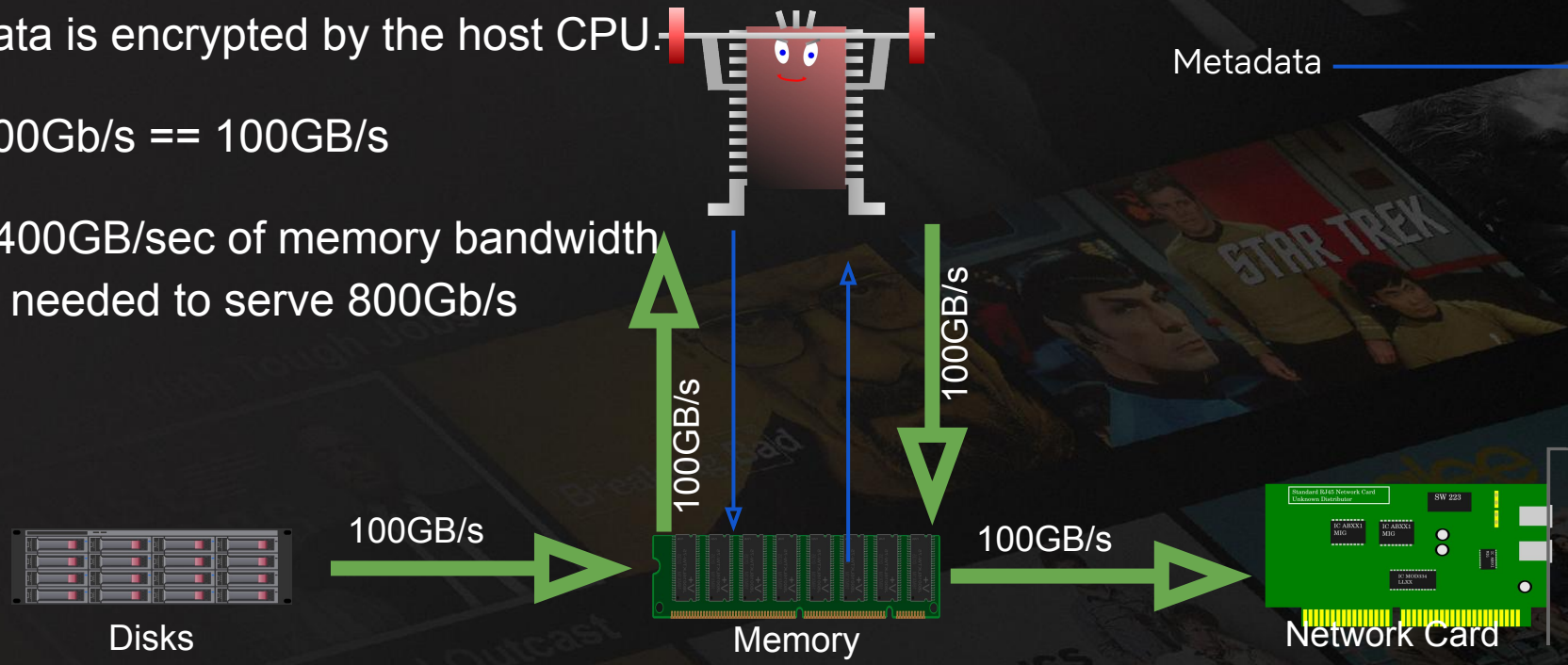
Netflix 800Gb/s Video Serving Data Flow

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

800Gb/s == 100GB/s

~400GB/sec of memory bandwidth is needed to serve 800Gb/s



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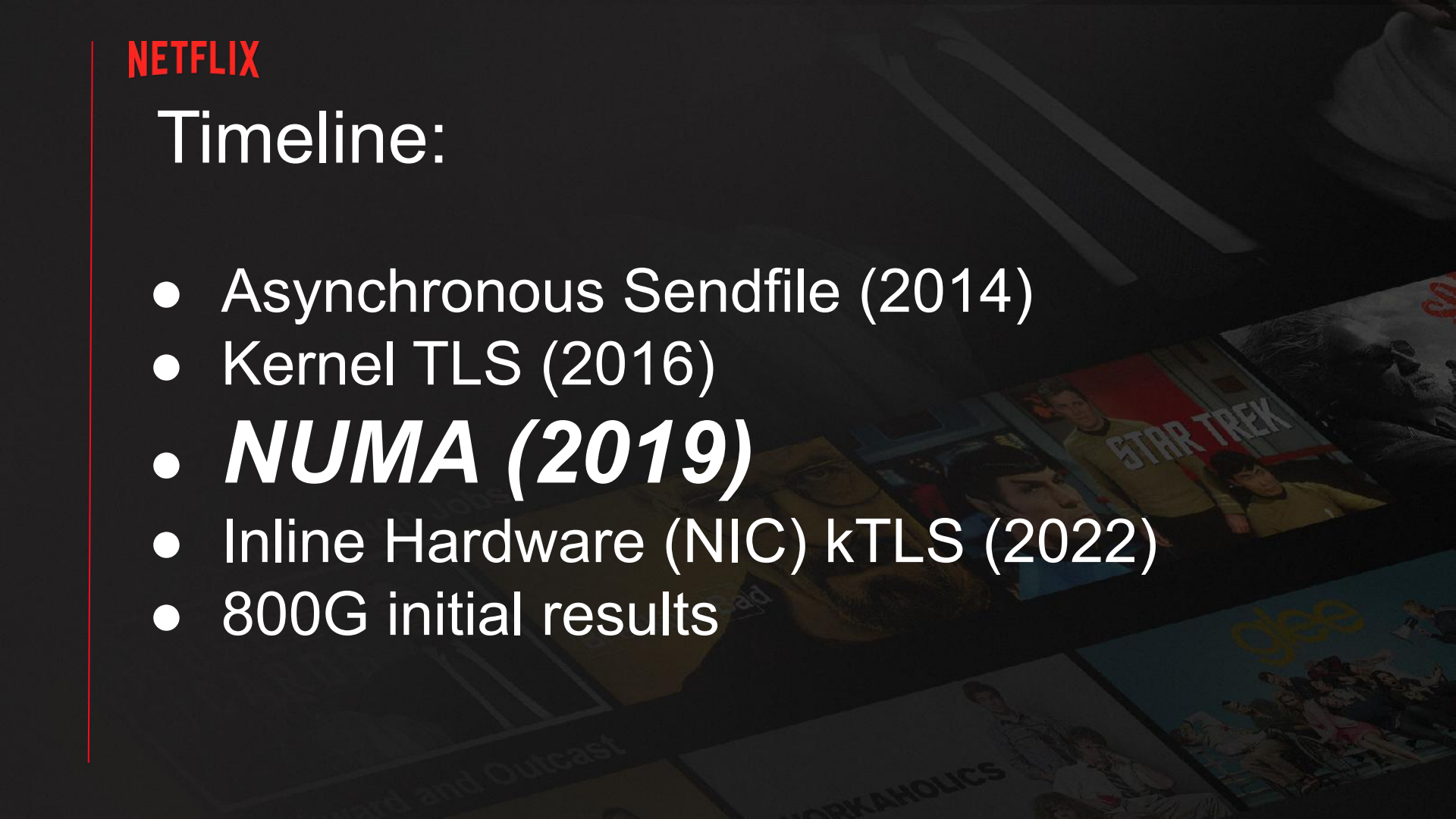
- Inline Hardware (NIC) kTLS (2022)
- 800G initial results



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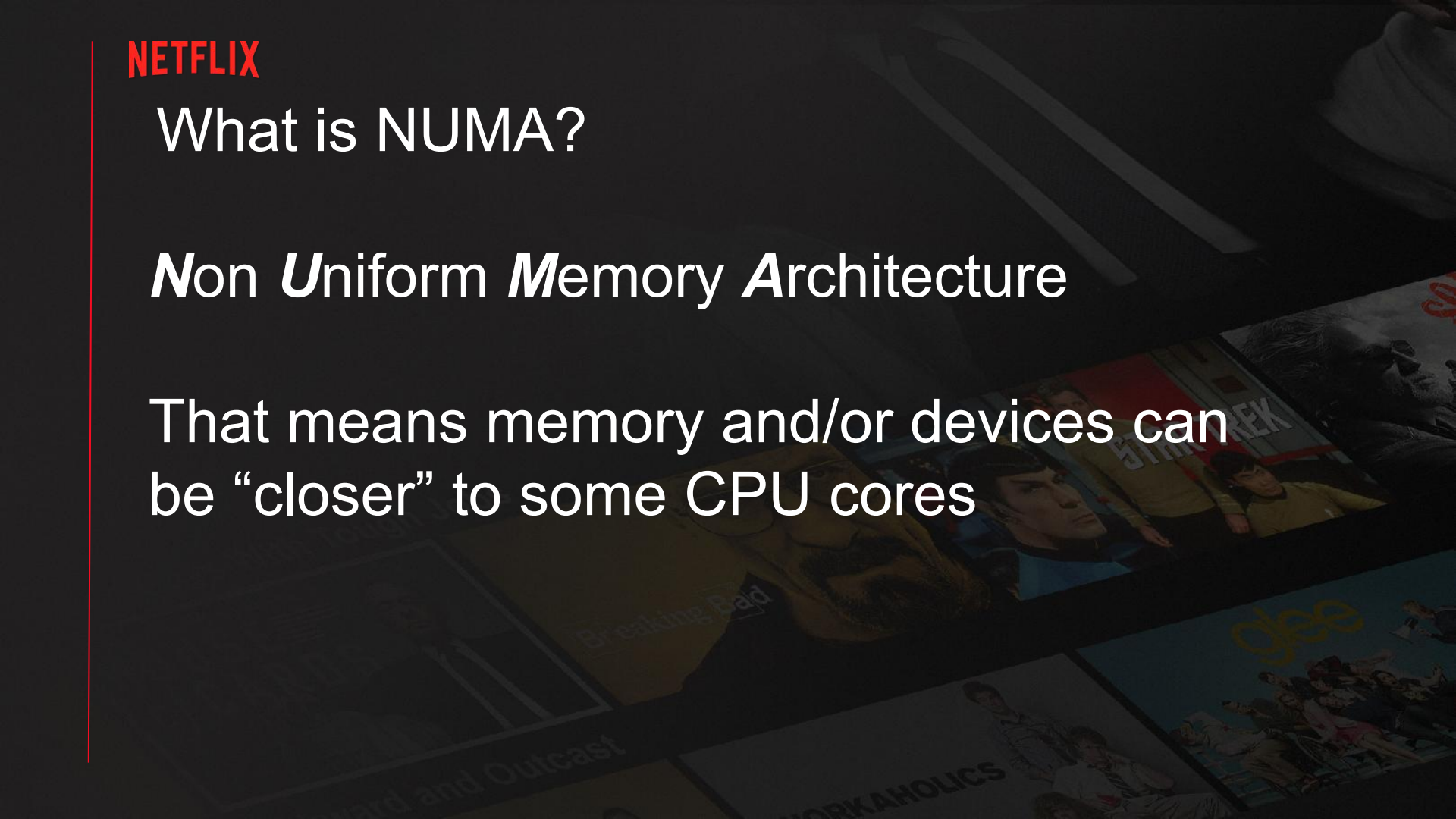
What is NUMA?

Non ***U***niform ***M***emory ***A***rchitecture

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



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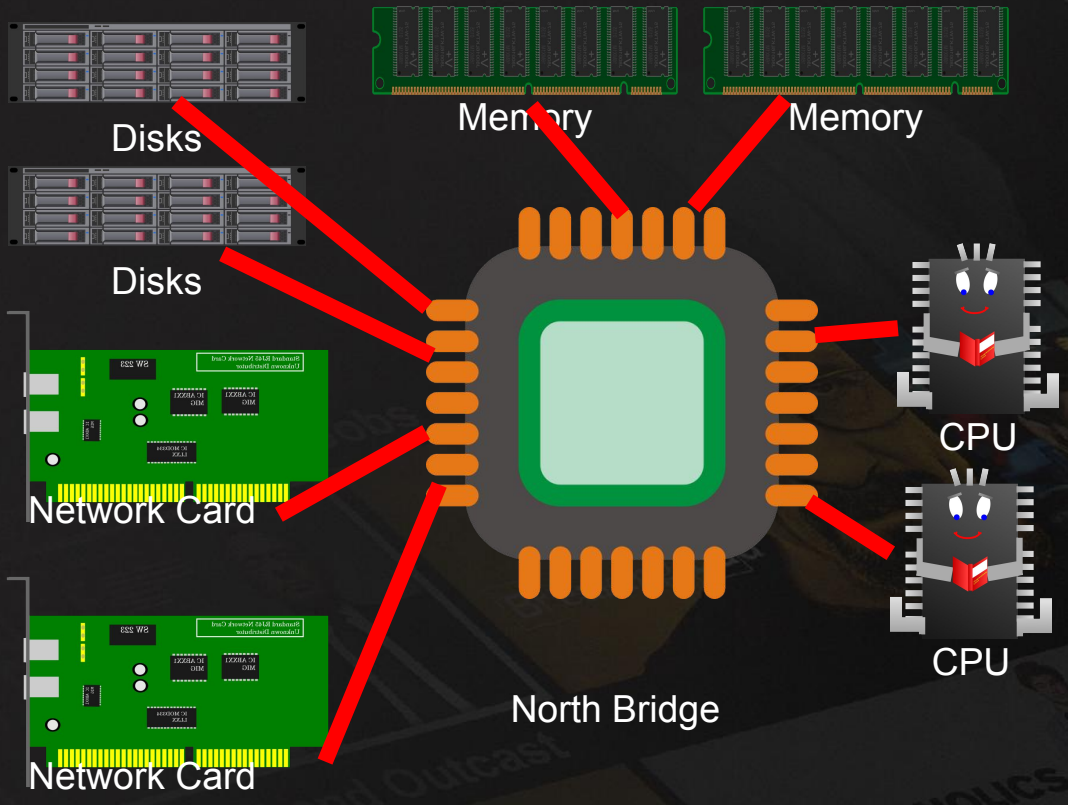
Multi CPU Before NUMA



Memory access was *UNIFORM:*

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

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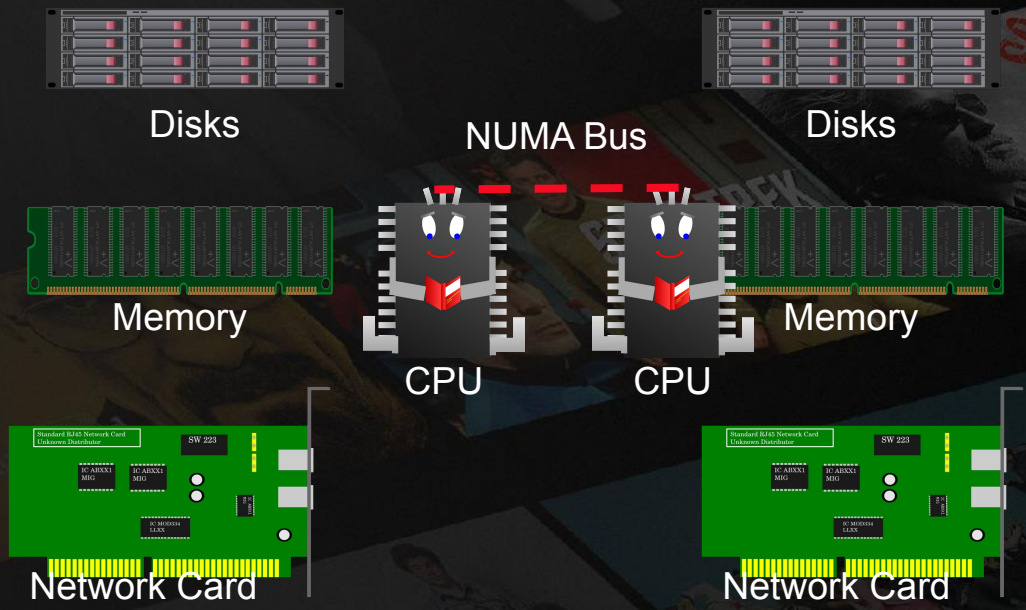
Multi Socket system with NUMA:

Memory access can be ***NON-UNIFORM***

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



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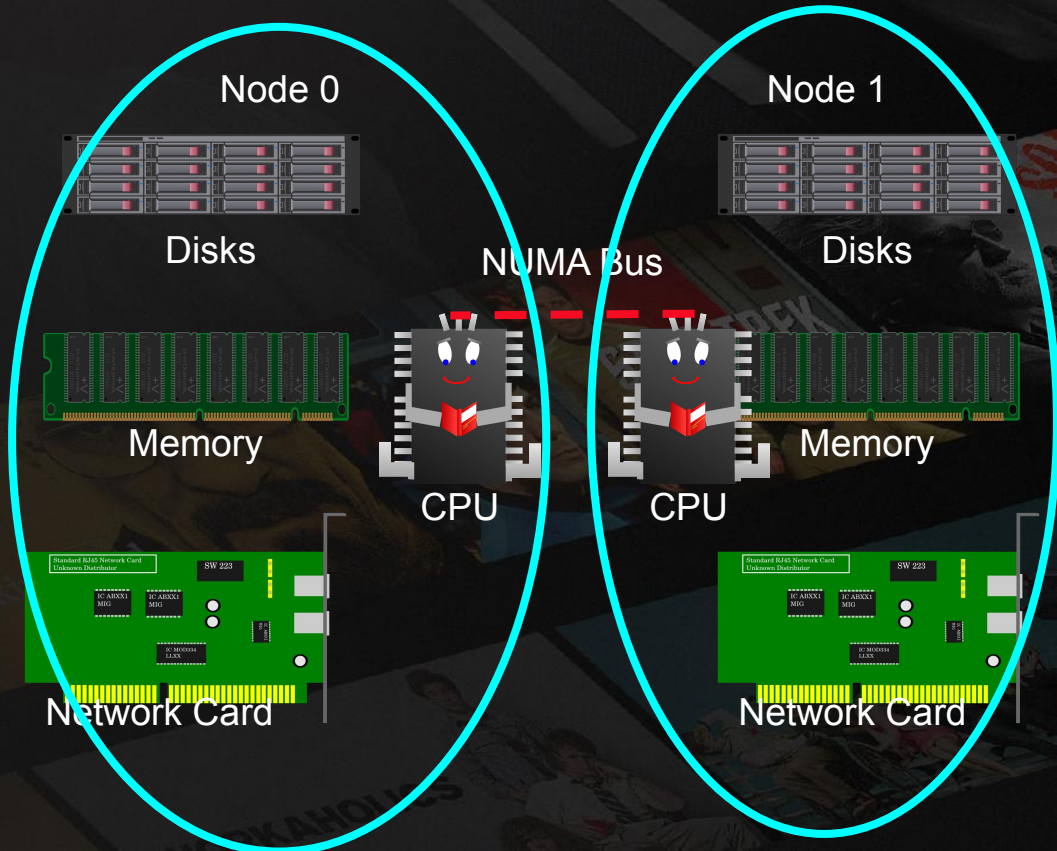
Present day NUMA:

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



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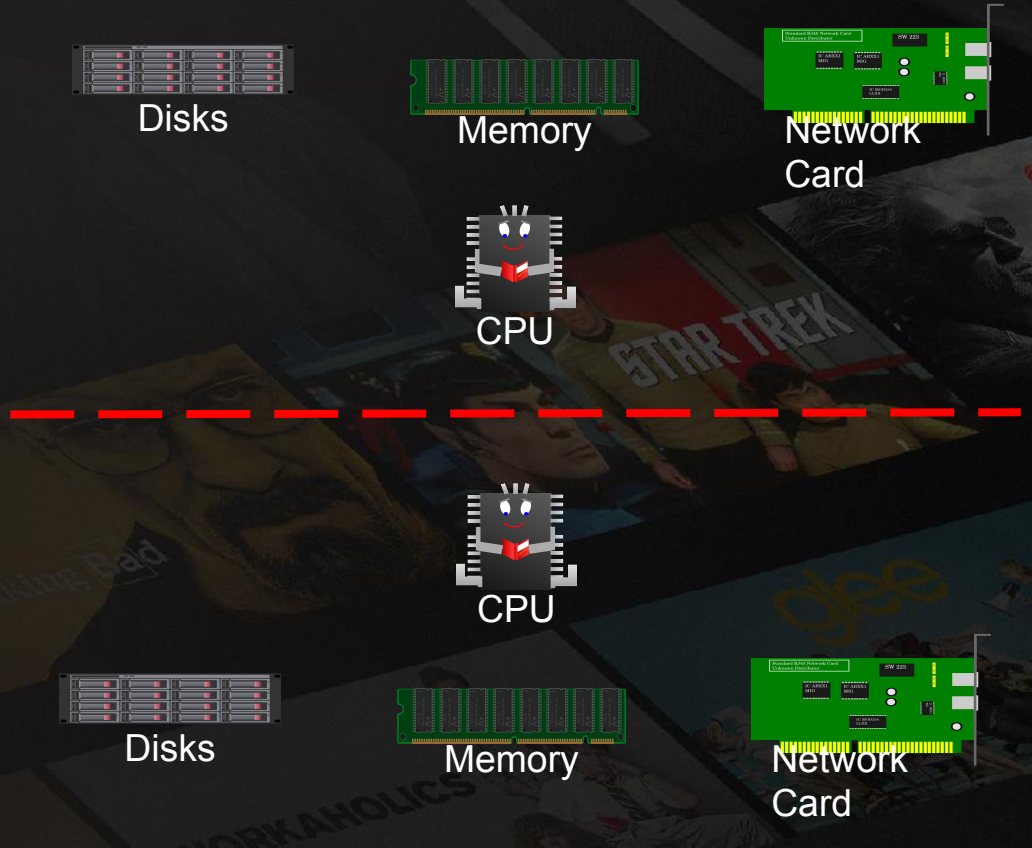
Strategy: Keep as much of our 400GB/sec of bulk data off the NUMA fabric as possible

- Bulk data congests NUMA fabric and leads to CPU stalls.

Dual AMD: Worst Case Data Flow

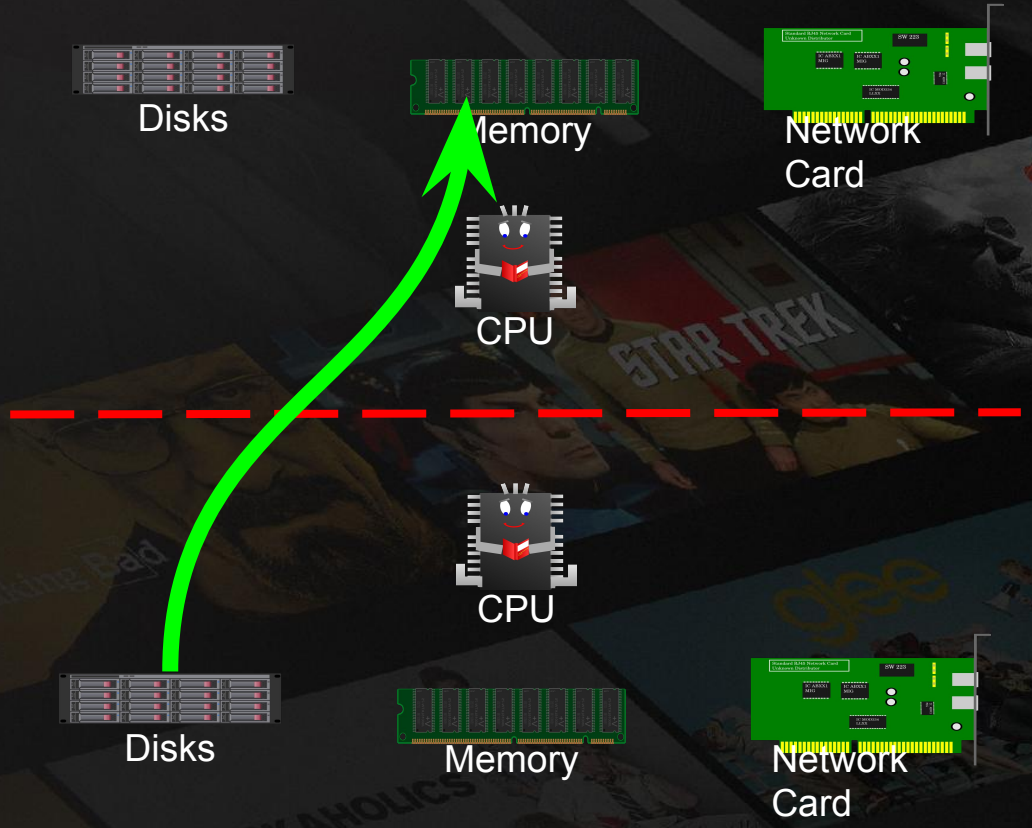
Steps to send data:



Dual AMD: Worst Case Data Flow

Steps to send data:

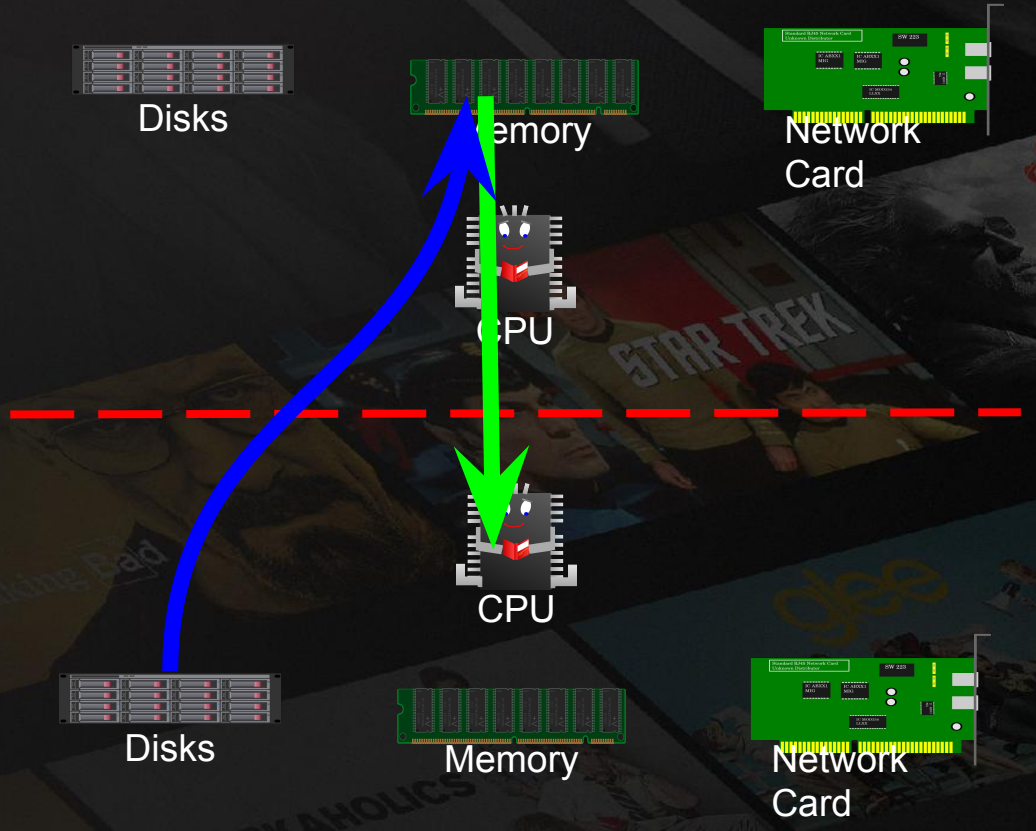
- DMA data from disk to memory
  - First NUMA bus crossing



Dual AMD: Worst Case Data Flow

Steps to send data:

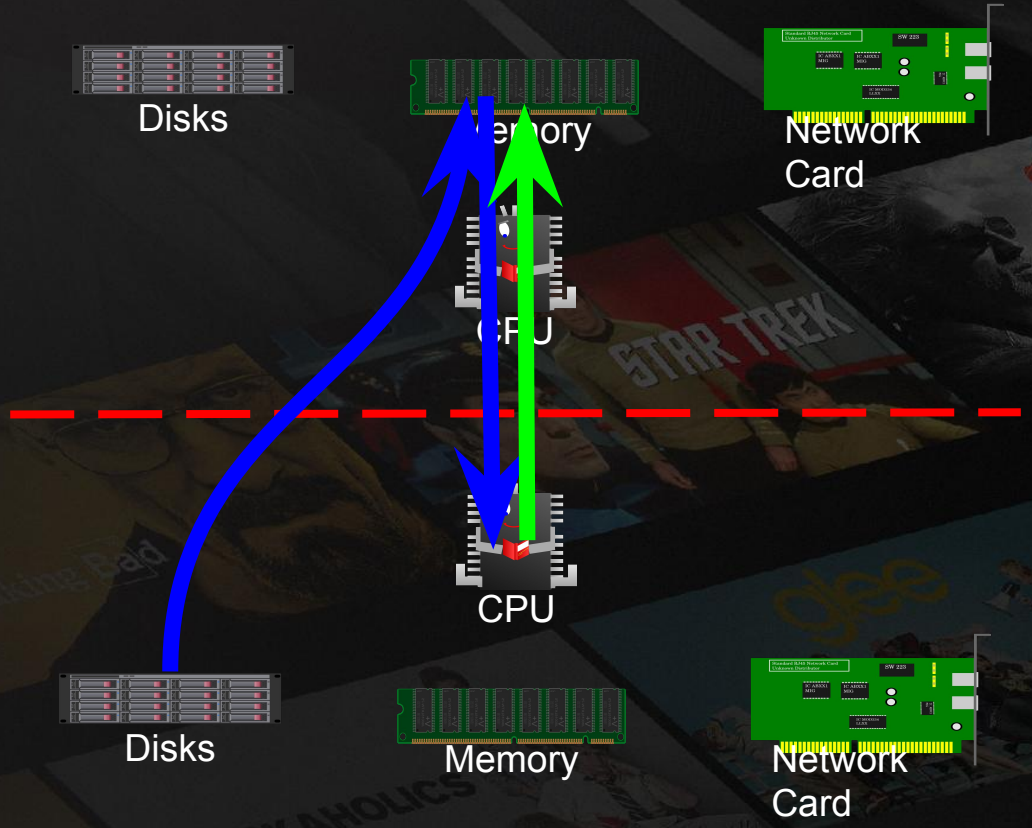
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
  - Second NUMA crossing



Dual AMD: Worst Case Data Flow

Steps to send data:

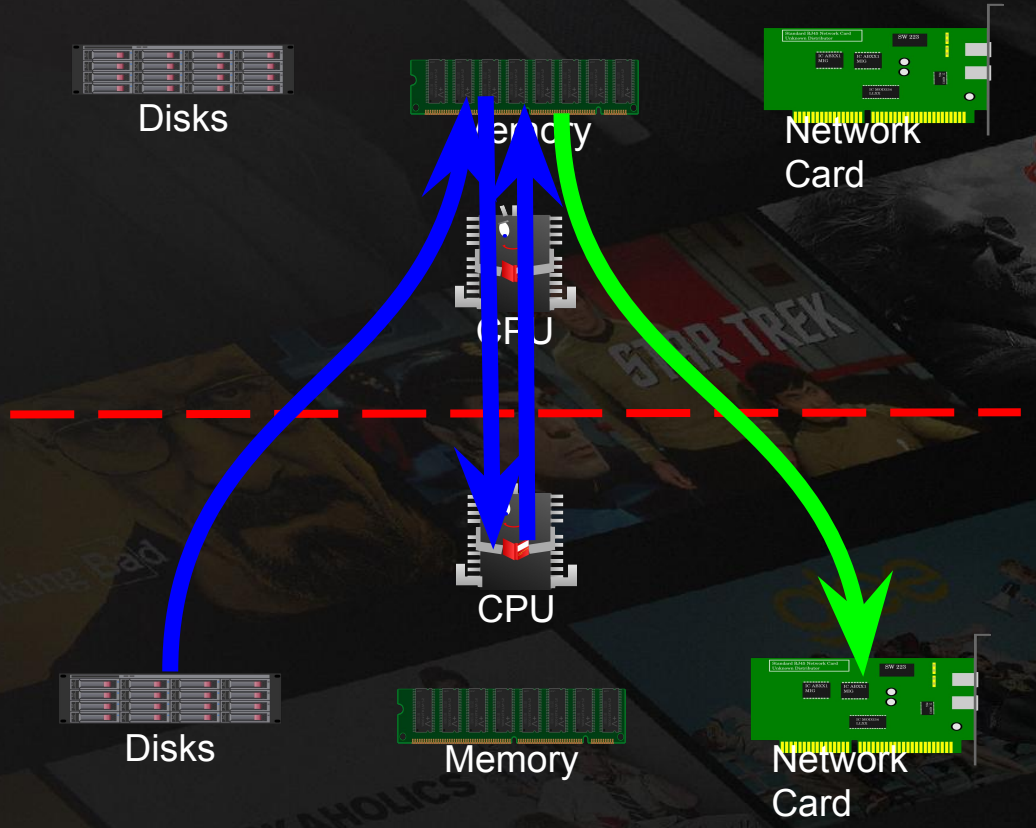
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
  - Second NUMA crossing
- CPU writes encrypted data
  - Third NUMA crossing



Dual AMD: Worst Case Data Flow

Steps to send data:

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



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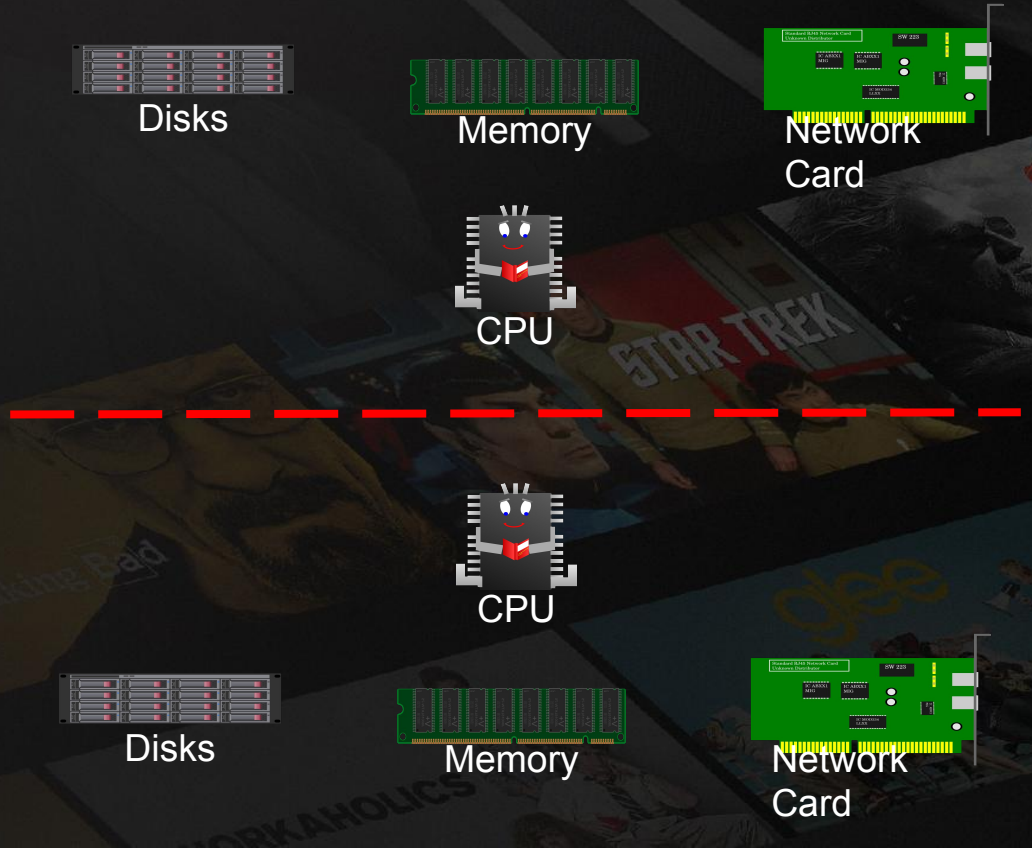
Worst Case Summary:

- 4 NUMA crossings
- 400GB/s of data on the NUMA fabric
  - Fabric saturates, cannot handle the load.
  - CPU Stalls, saturates early

NETFLIX Dual AMD: Best Case Data Flow

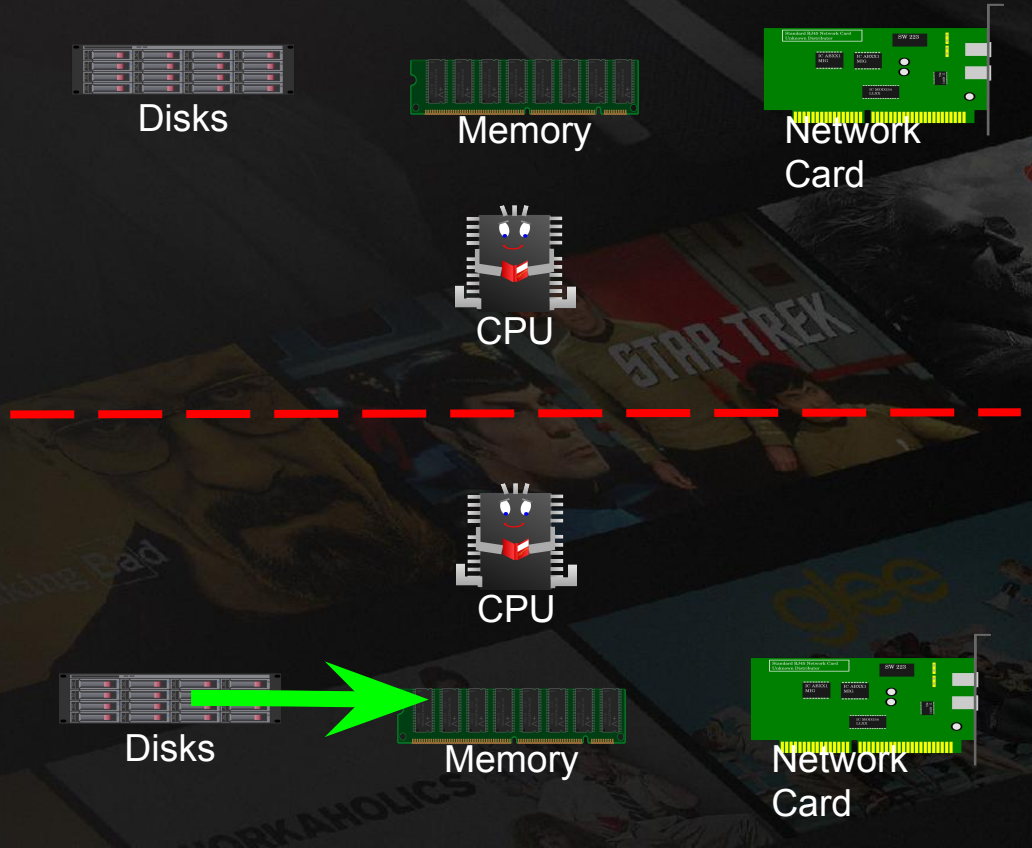
Steps to send data:



NETFLIX Dual AMD: Best Case Data Flow

Steps to send data:

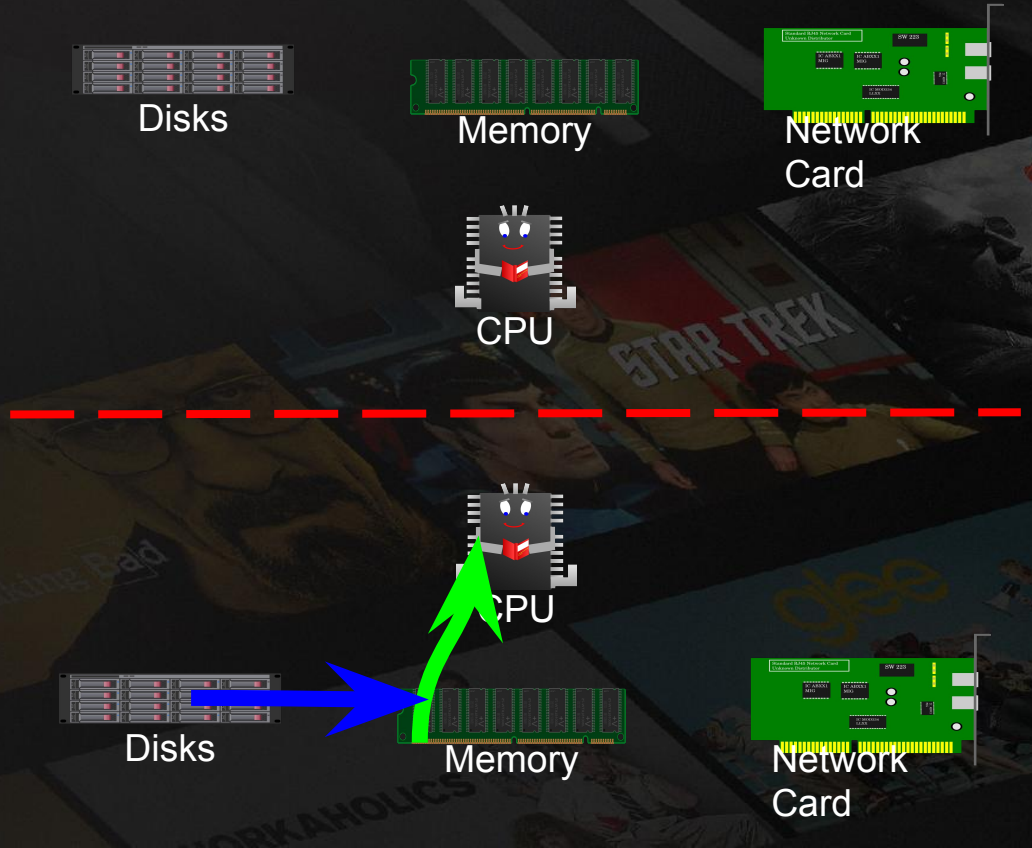
- DMA data from disk to memory



NETFLIX Dual AMD: Best Case Data Flow

Steps to send data:

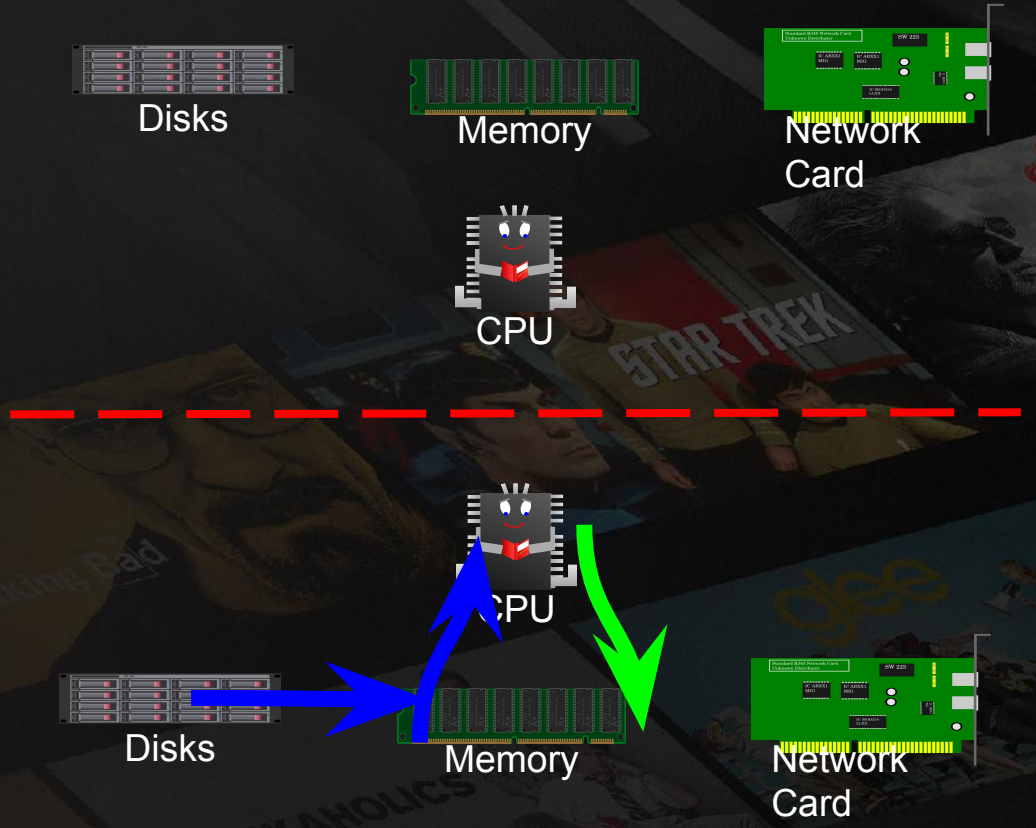
- DMA data from disk to memory
- CPU Reads data for encryption



NETFLIX Dual AMD: Best Case Data Flow

Steps to send data:

- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data

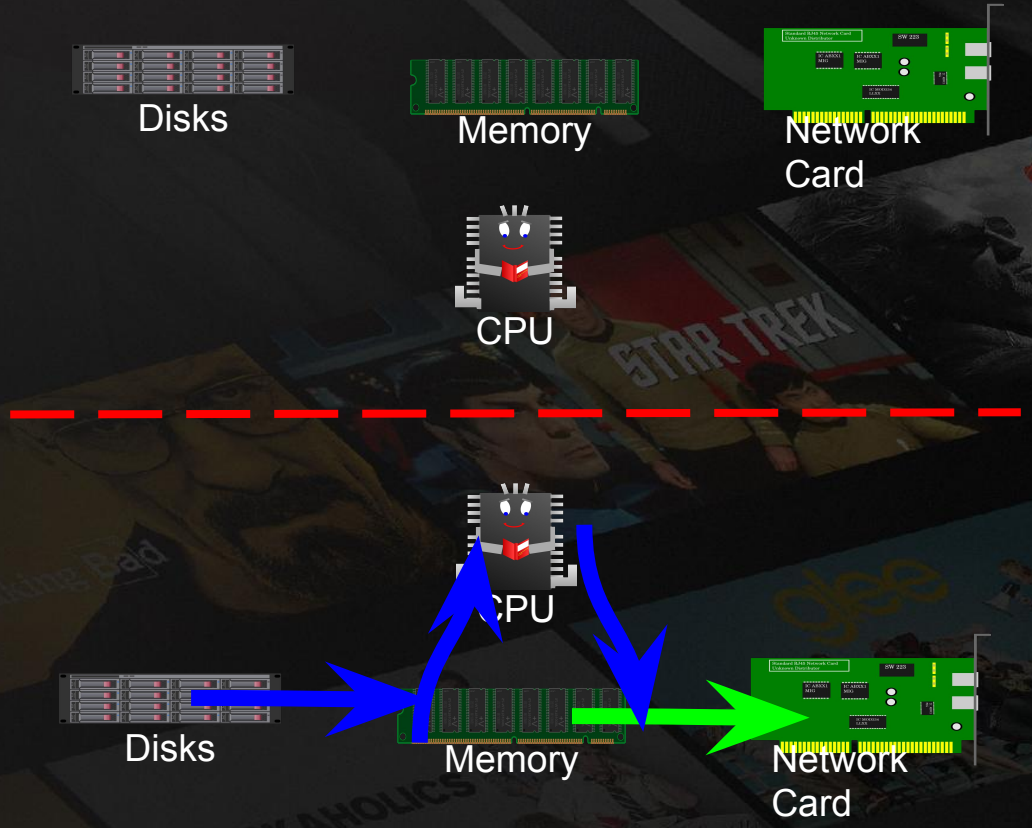


Dual AMD: Best Case Data Flow

Steps to send data:

- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data
- DMA from memory to Network

0 NUMA crossings!



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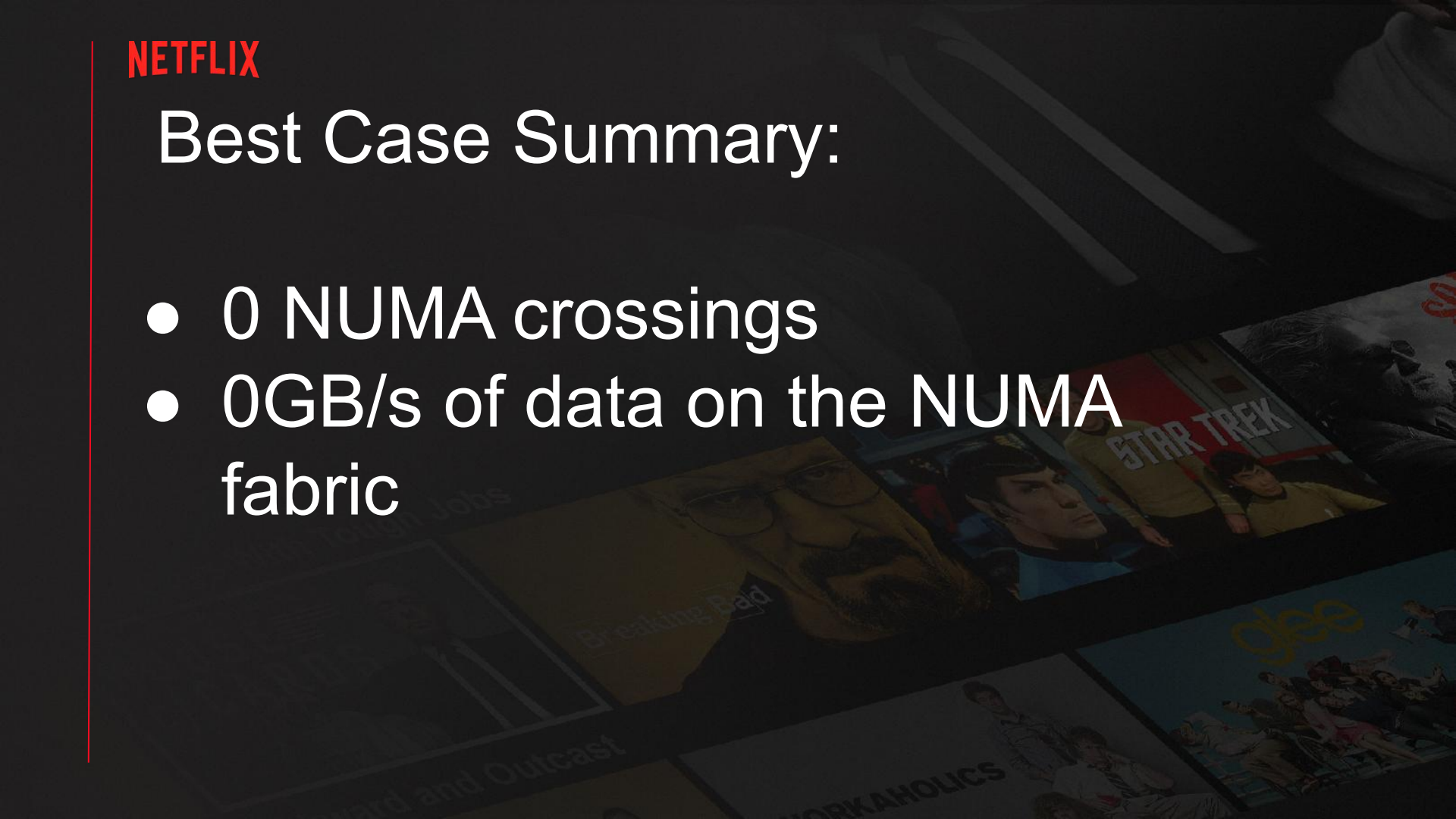
Best Case Summary:

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



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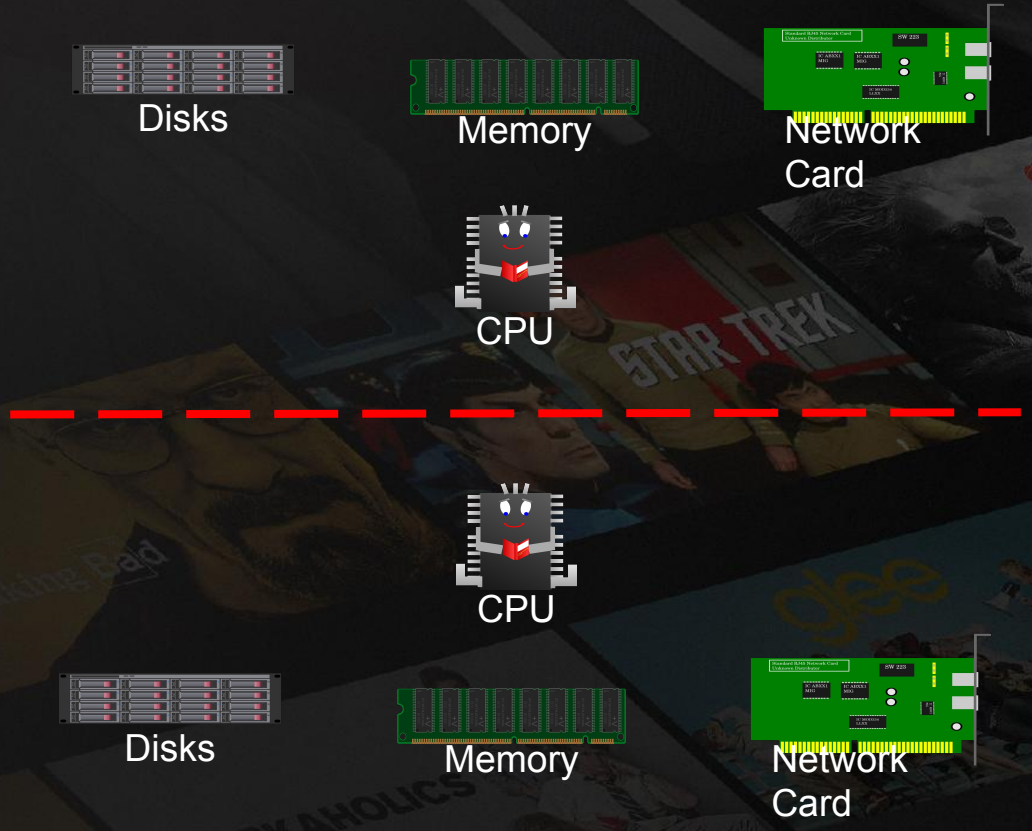
Impose order on the chaos.. *somehow*:

- 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

Dual AMD: Worst Case Data Flow With Network Centric NUMA Siloing

Steps to send data:



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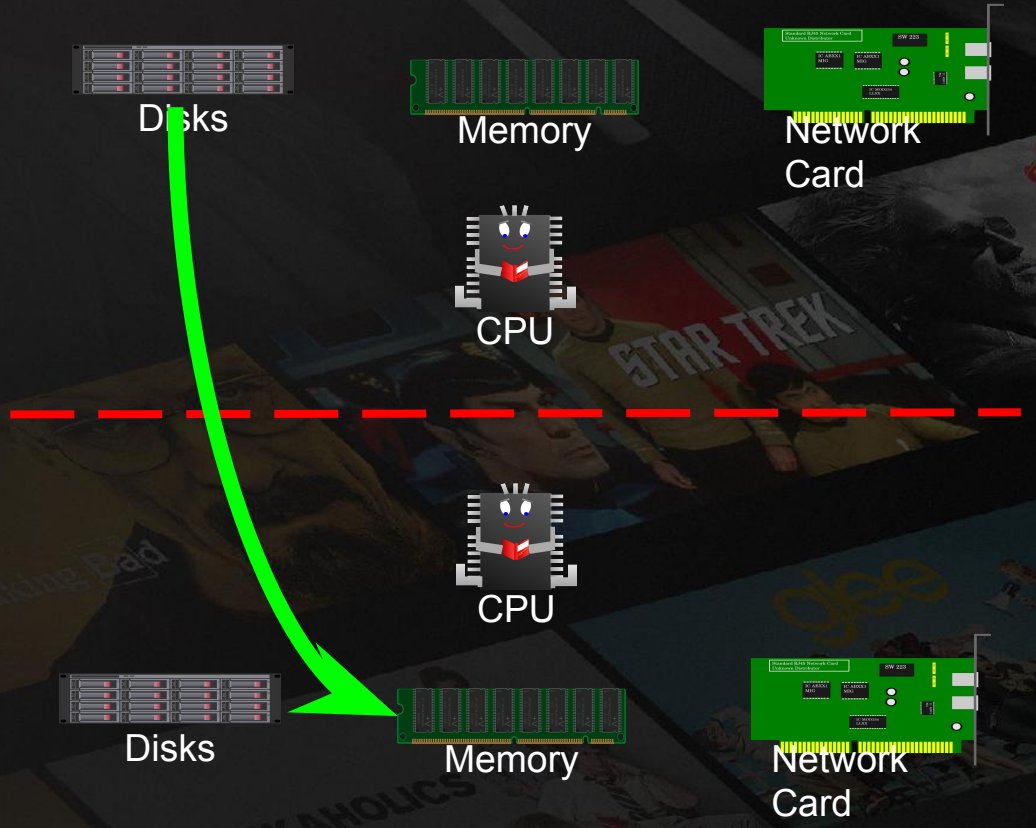
Dual AMD: Worst Case Data Flow With Network Centric NUMA Siloing

Steps to send data:

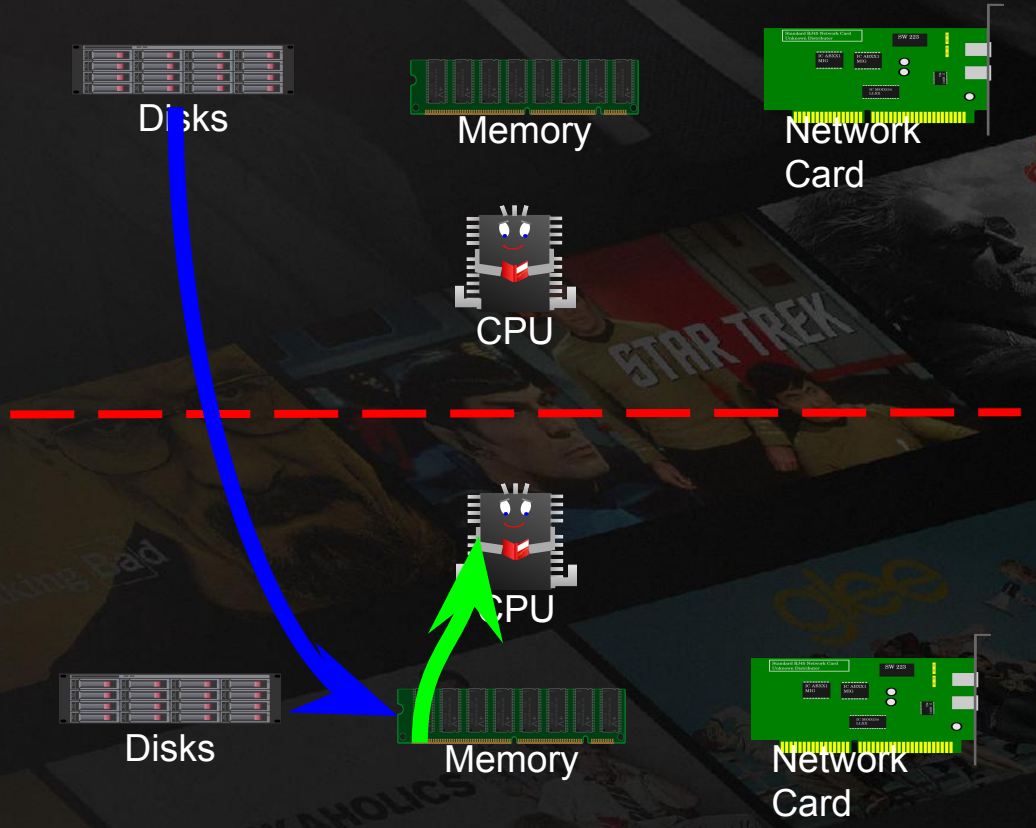
- DMA data from disk to memory
  - First NUMA bus crossing



Dual AMD: Worst Case Data Flow With Network Centric NUMA Siloing

Steps to send data:

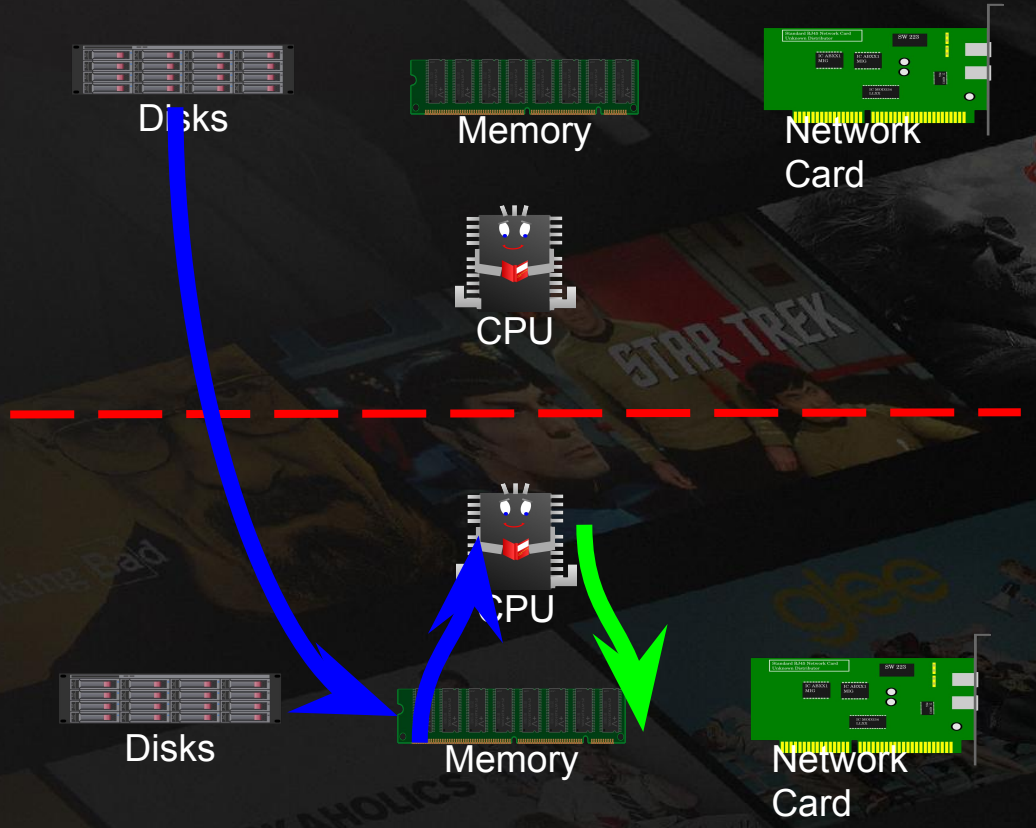
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU Reads data for encryption



Dual AMD: Worst Case Data Flow With Network Centric NUMA Siloing

Steps to send data:

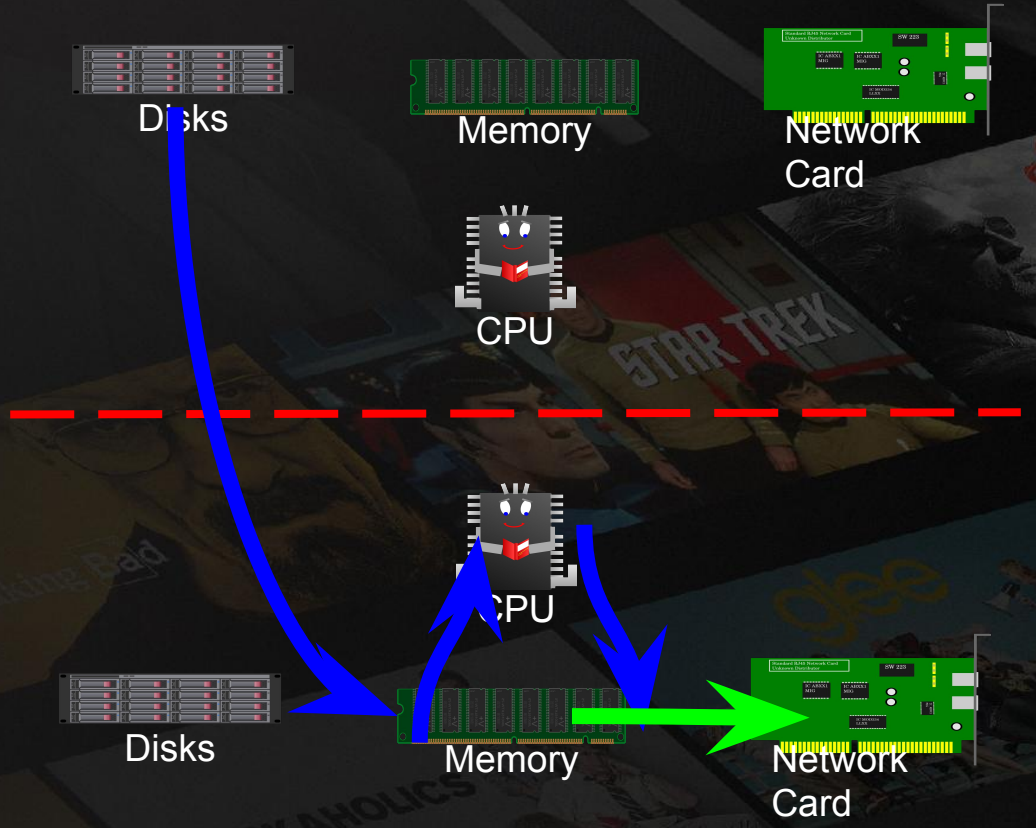
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU Reads data for encryption
- CPU Writes encrypted data



Dual AMD: Worst Case Data Flow With Network Centric NUMA Siloing

Steps to send data:

- DMA data from disk to memory
  - First NUMA bus crossing
- CPU Reads data for encryption
- CPU Writes encrypted data
- DMA from memory to Network



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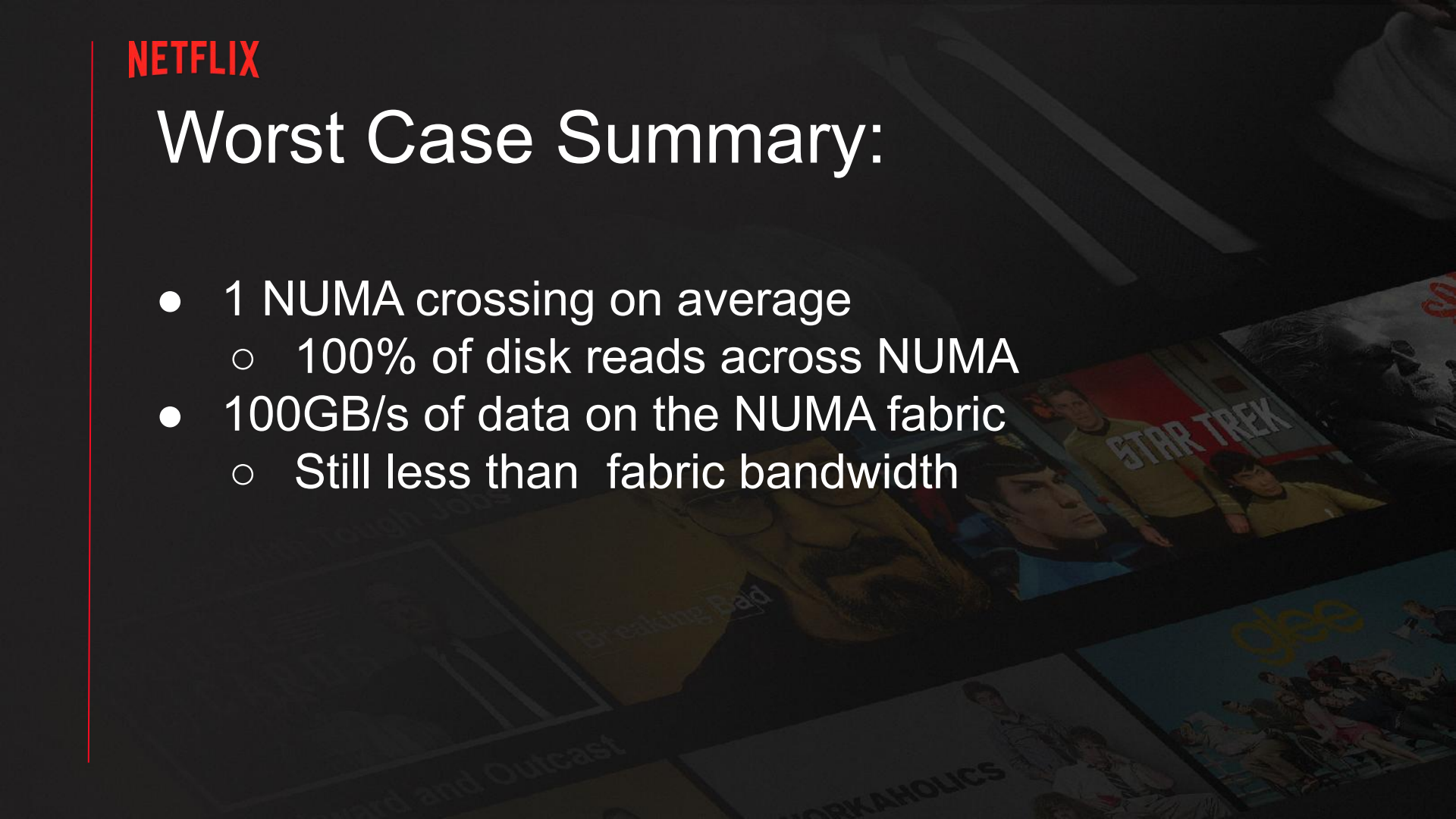
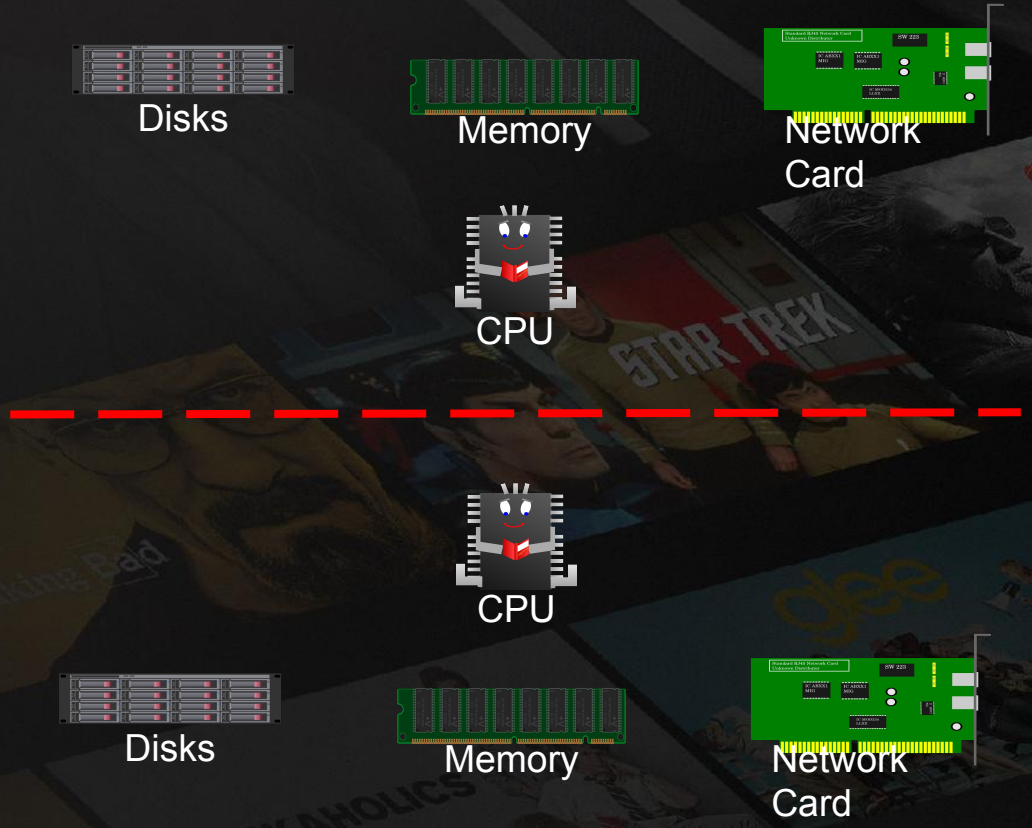
Worst Case Summary:

- 1 NUMA crossing on average
  - 100% of disk reads across NUMA
- 100GB/s of data on the NUMA fabric
  - Still less than fabric bandwidth



Dual AMD: Worst Case Data Flow With Disk Centric NUMA Siloing

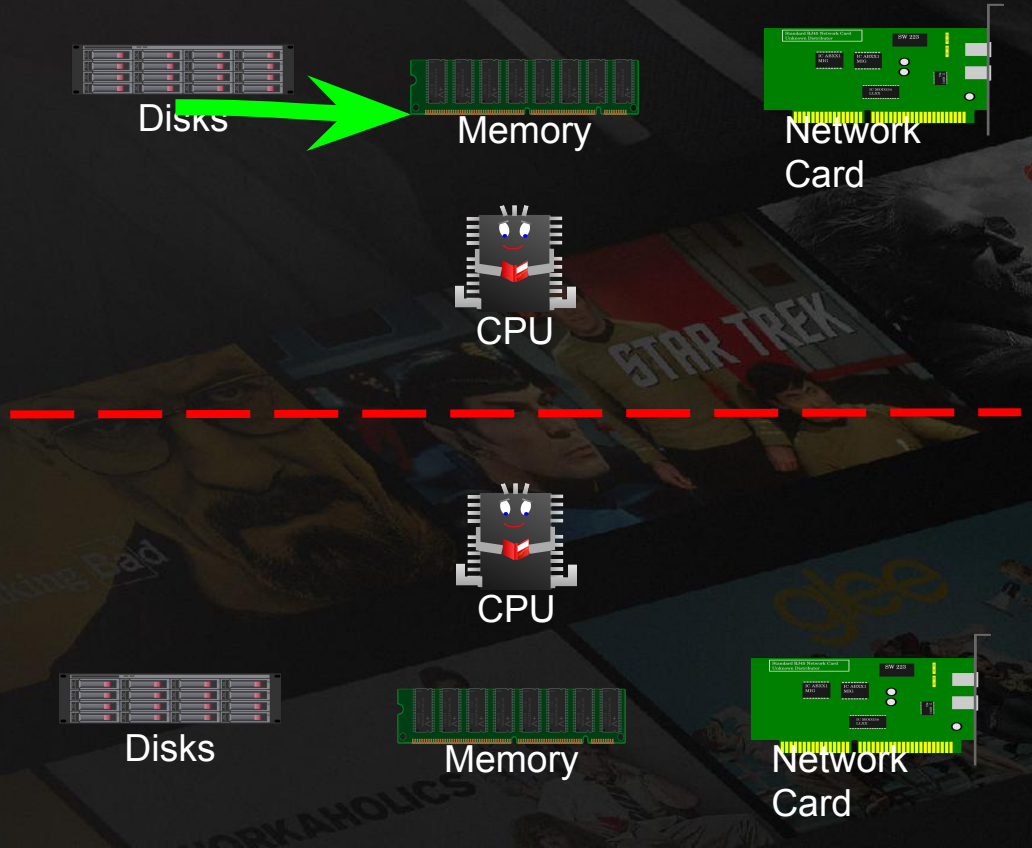
Steps to send data:



Dual AMD: Worst Case Data Flow With Disk Centric NUMA Siloing

Steps to send data:

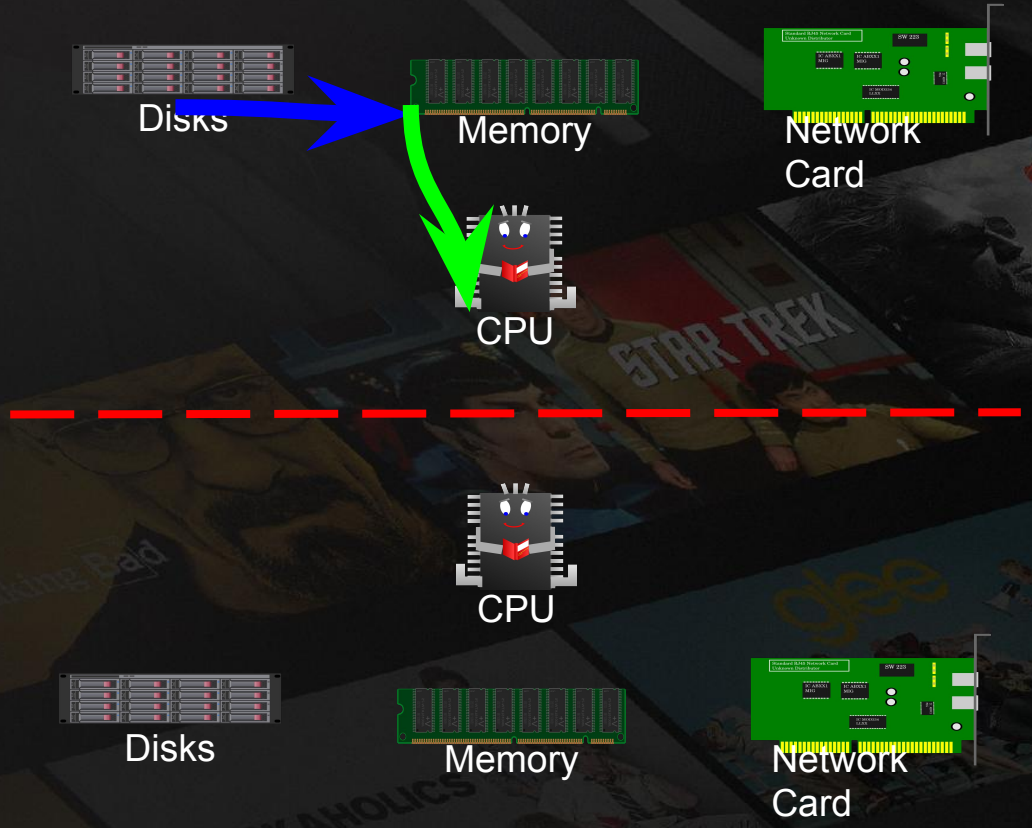
- DMA data from disk to memory



Dual AMD: Worst Case Data Flow With Disk Centric NUMA Siloing

Steps to send data:

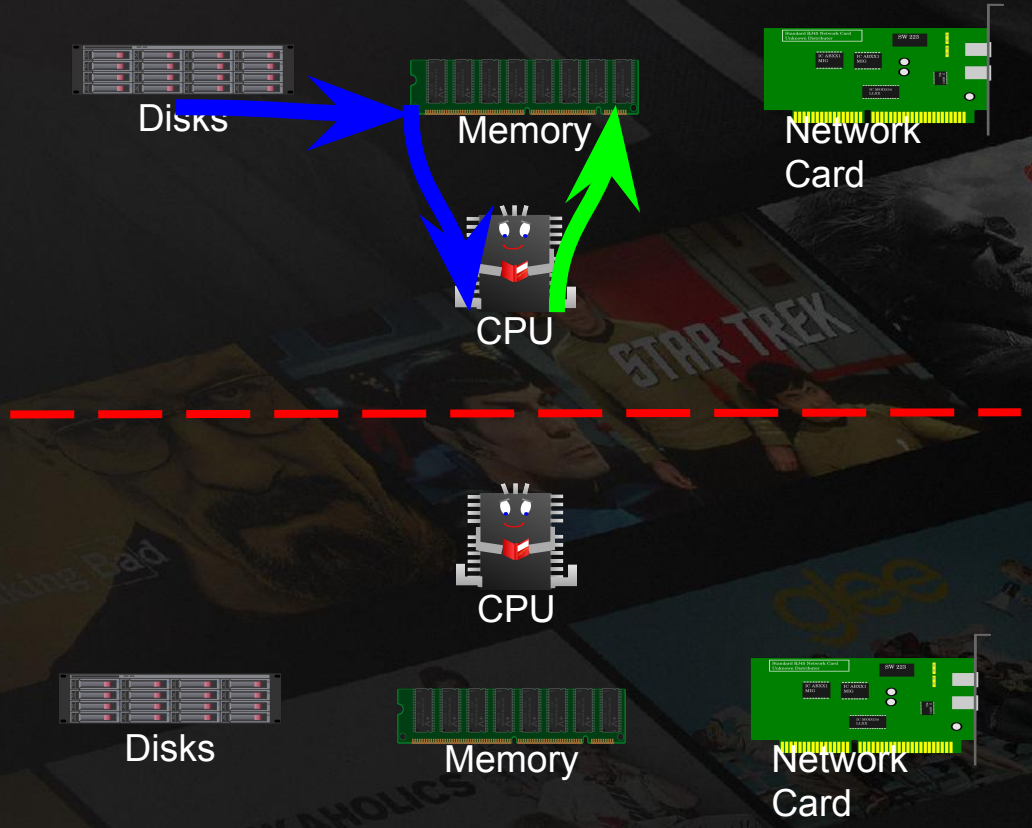
- DMA data from disk to memory
- CPU Reads data for encryption



Dual AMD: Worst Case Data Flow With Disk Centric NUMA Siloing

Steps to send data:

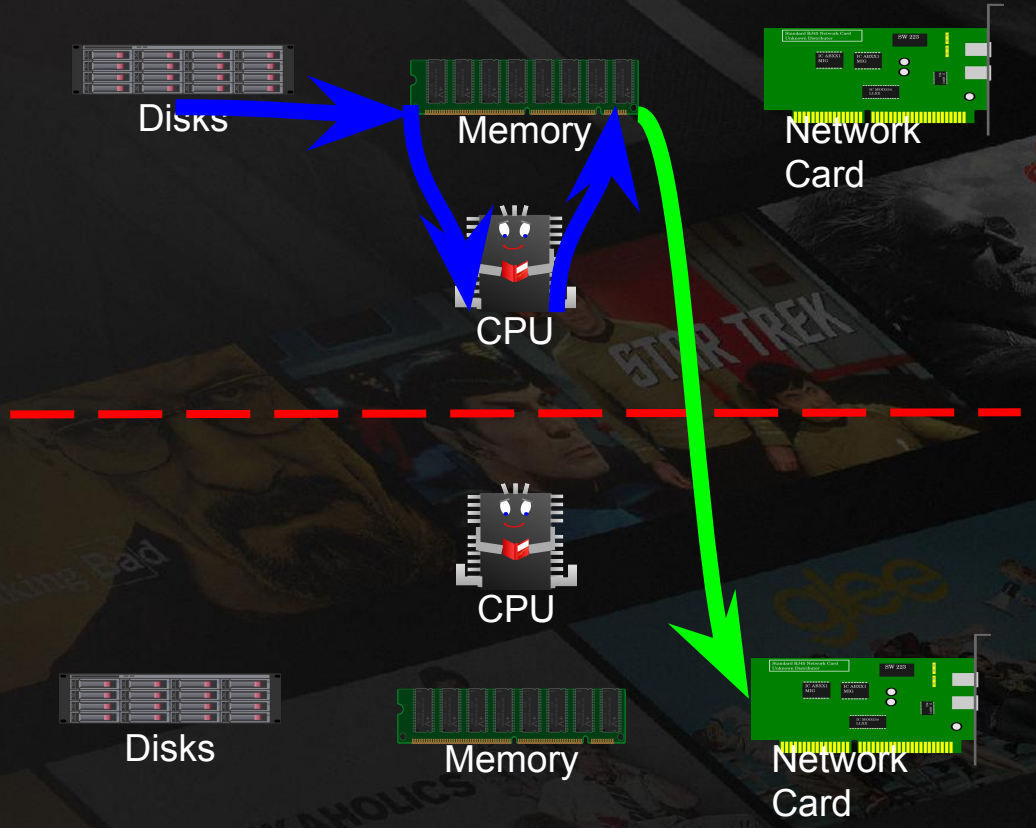
- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data



Dual AMD: Worst Case Data Flow With Disk Centric NUMA Siloing

Steps to send data:

- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data
- NIC Reads data for transmit
  - First NUMA bus crossing



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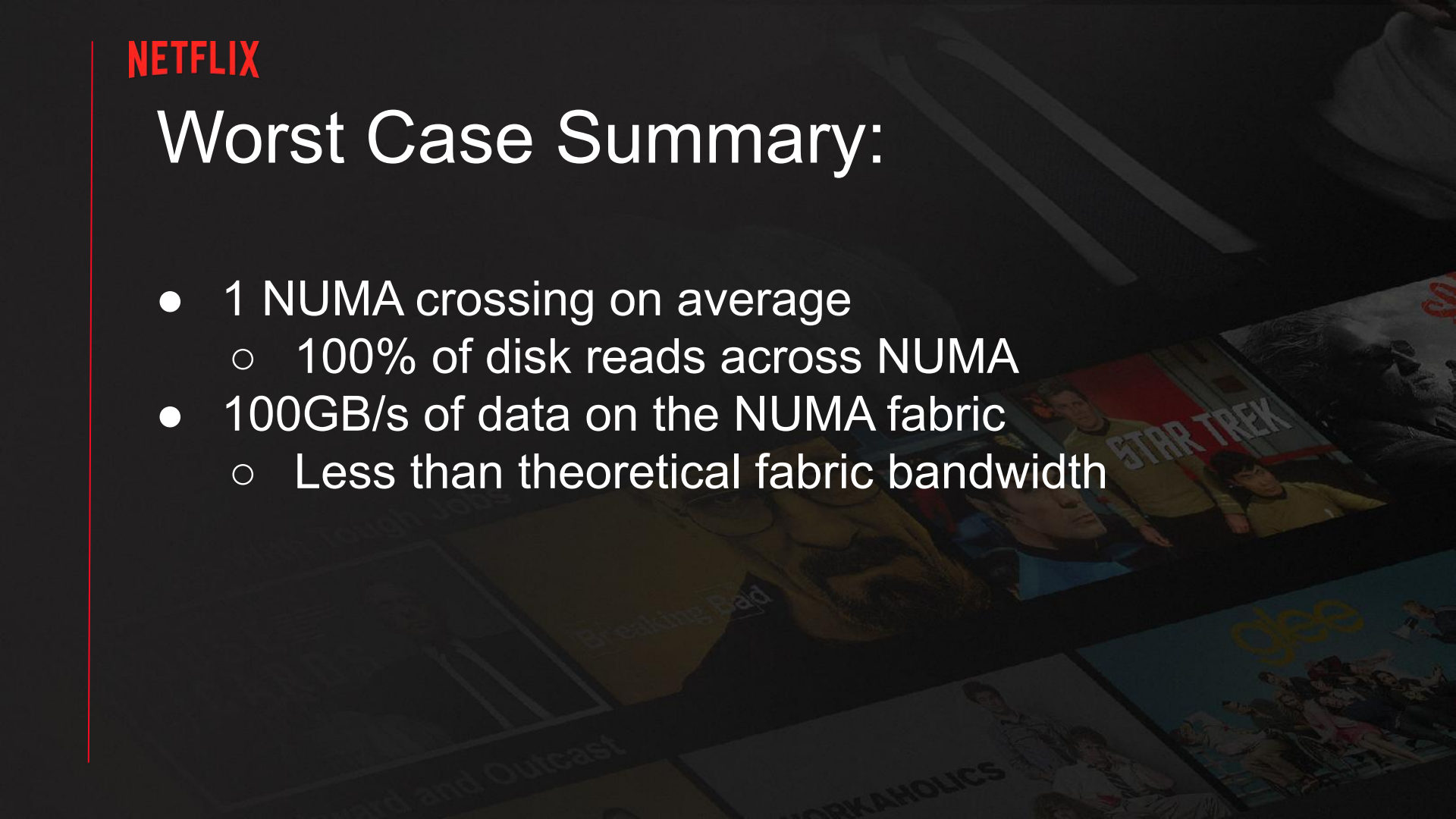
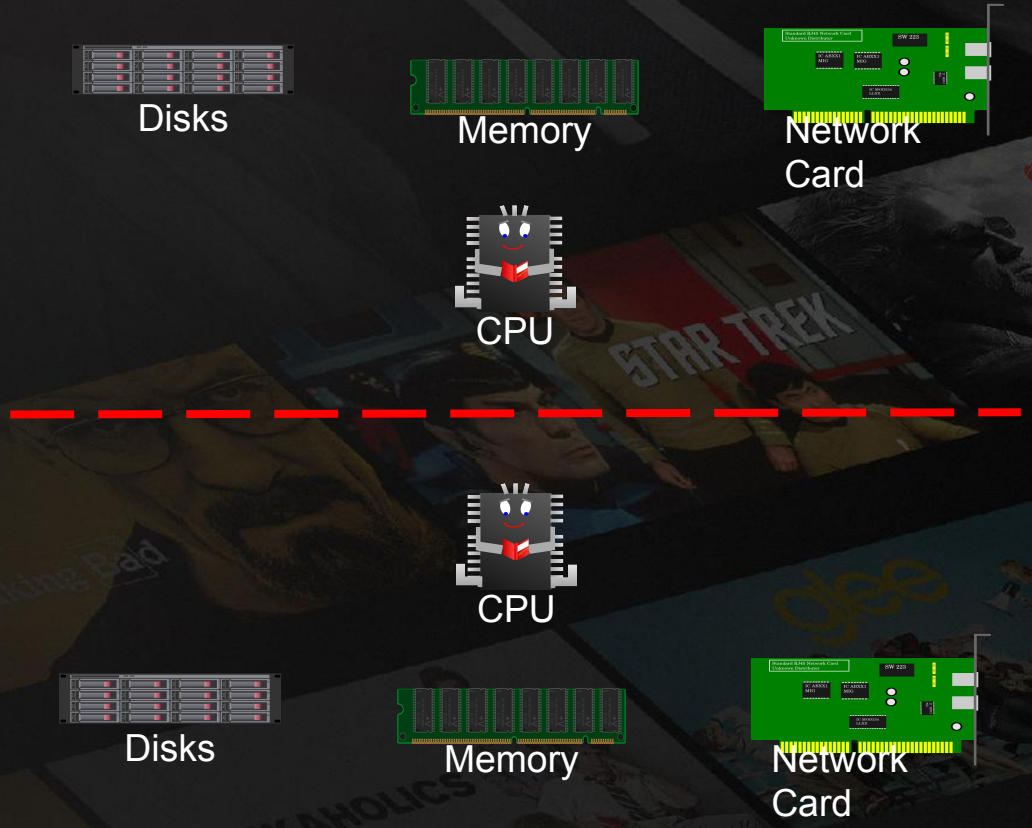
Worst Case Summary:

- 1 NUMA crossing on average
  - 100% of disk reads across NUMA
- 100GB/s of data on the NUMA fabric
  - Less than theoretical fabric bandwidth



Dual AMD: Worst Case Data Flow With Strict Disk Centric NUMA Siloing

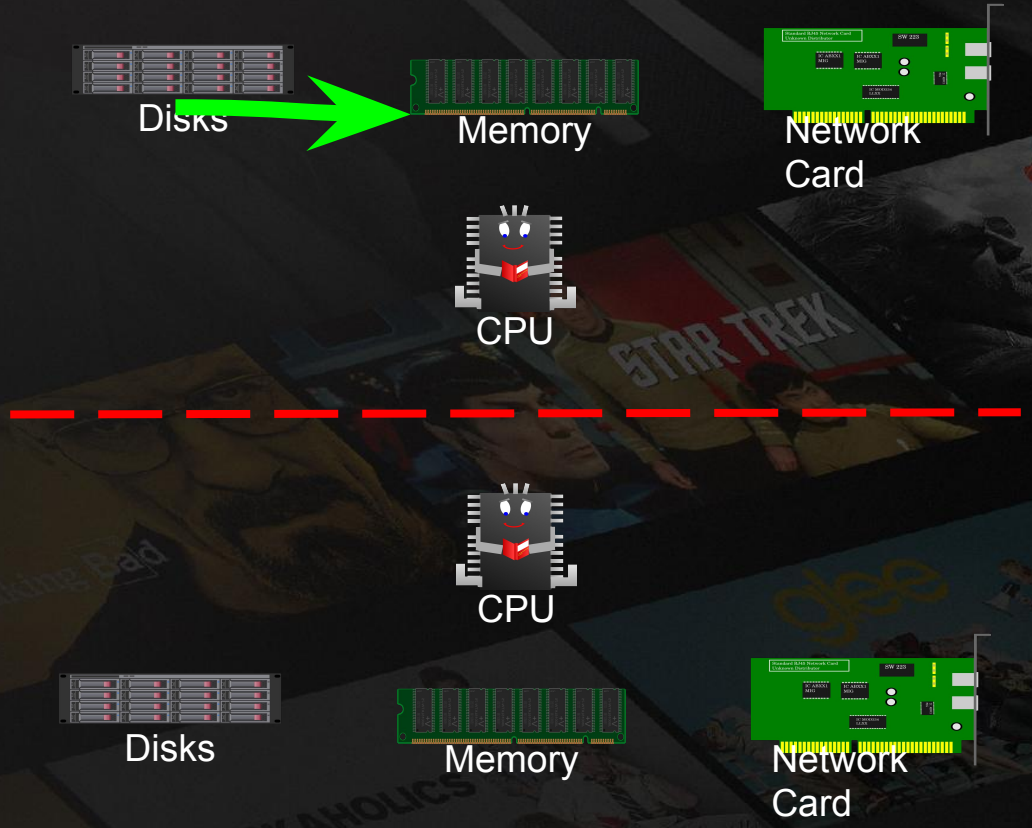
Steps to send data:



Dual AMD: Worst Case Data Flow With Strict Disk Centric NUMA Siloing

Steps to send data:

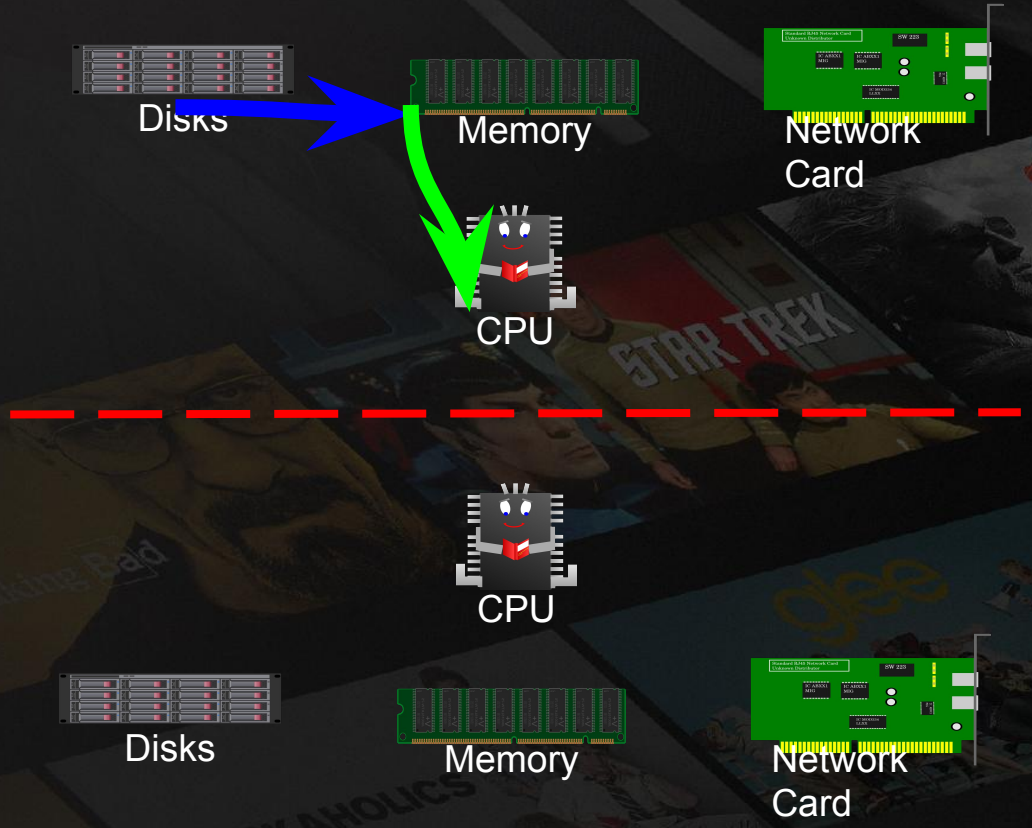
- DMA data from disk to memory



Dual AMD: Worst Case Data Flow With Strict Disk Centric NUMA Siloing

Steps to send data:

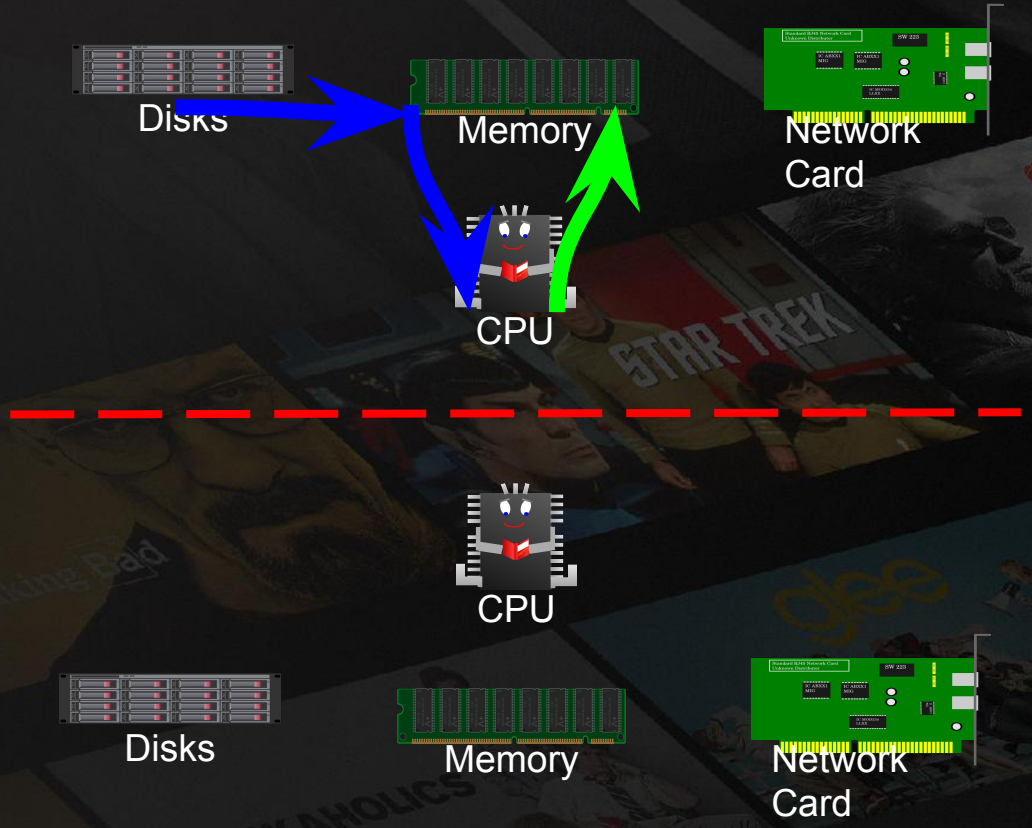
- DMA data from disk to memory
- CPU Reads data for encryption



Dual AMD: Worst Case Data Flow With Strict Disk Centric NUMA Siloing

Steps to send data:

- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data

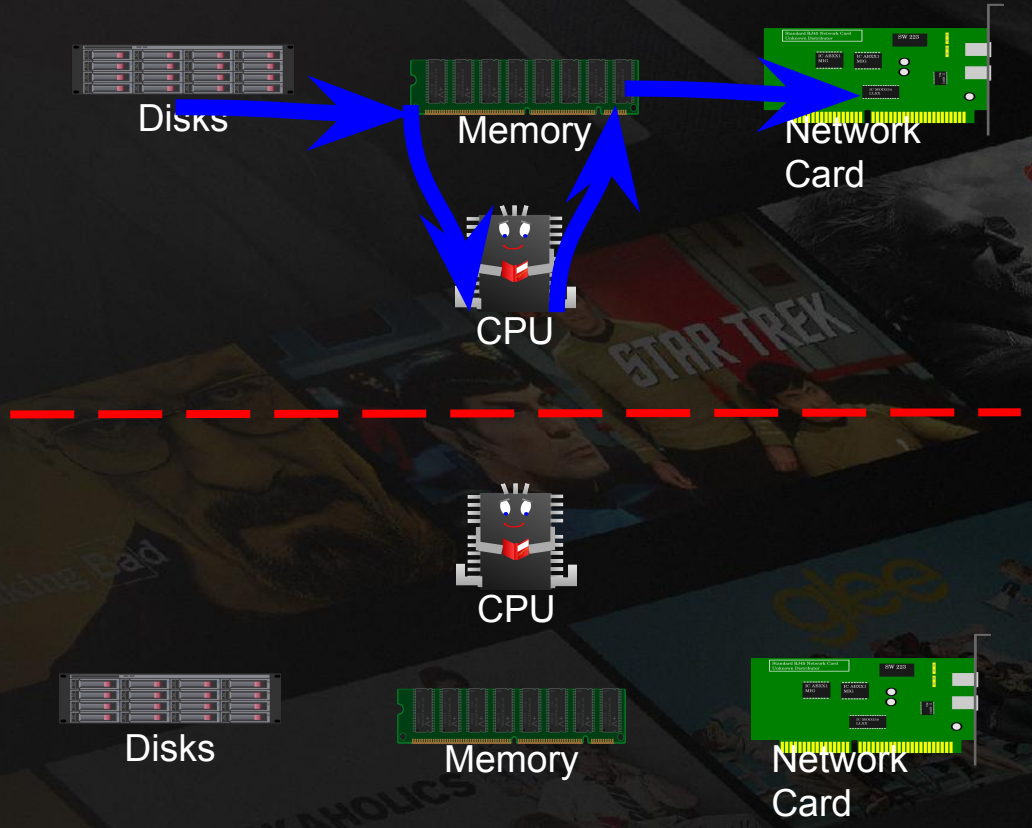


NETFLIX

Dual AMD: Worst Case Data Flow With Strict Disk Centric NUMA Siloing

Steps to send data:

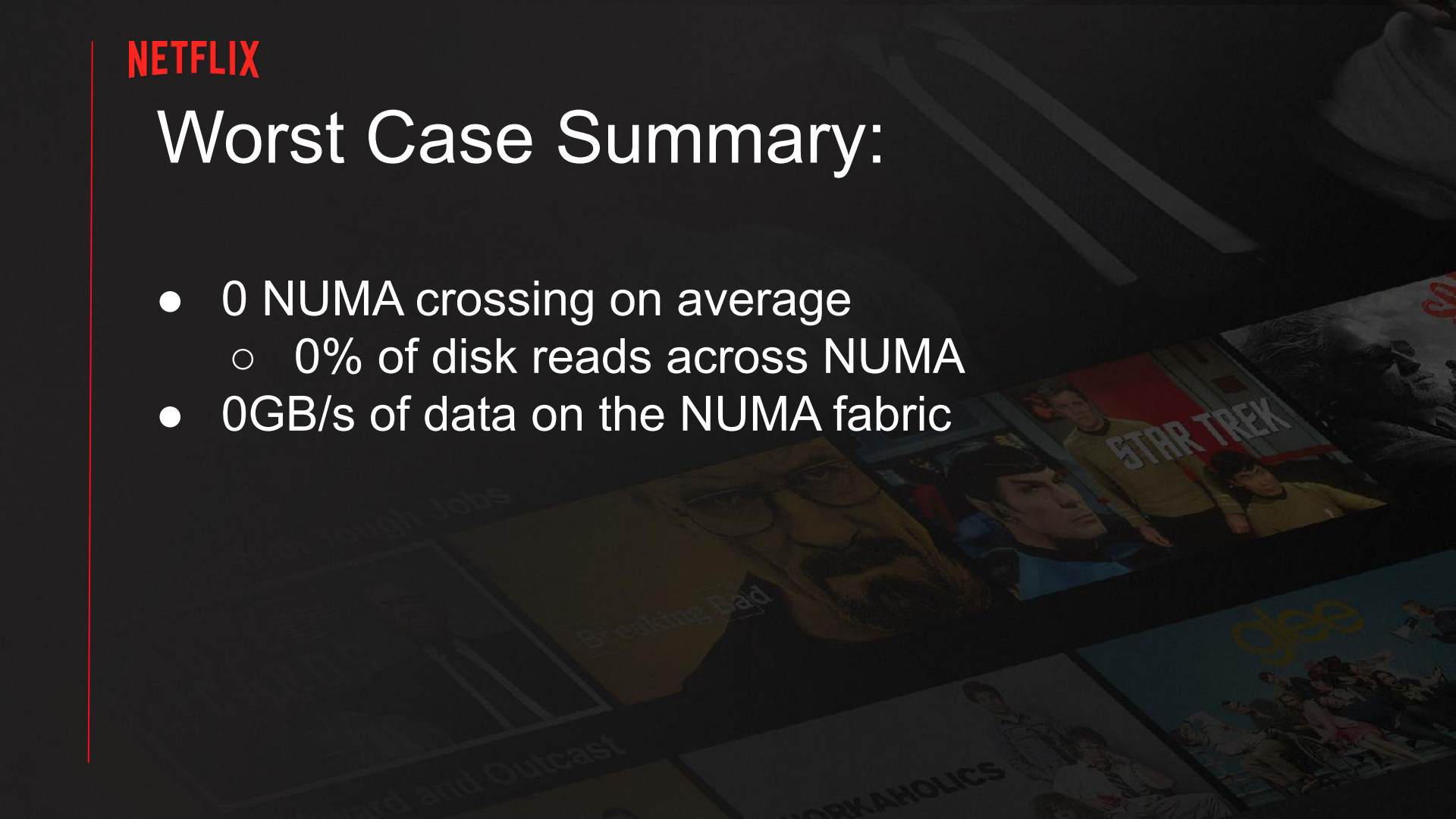
- DMA data from disk to memory
- CPU Reads data for encryption
- CPU Writes encrypted data
- NIC Reads data for transmit



NETFLIX

Worst Case Summary:

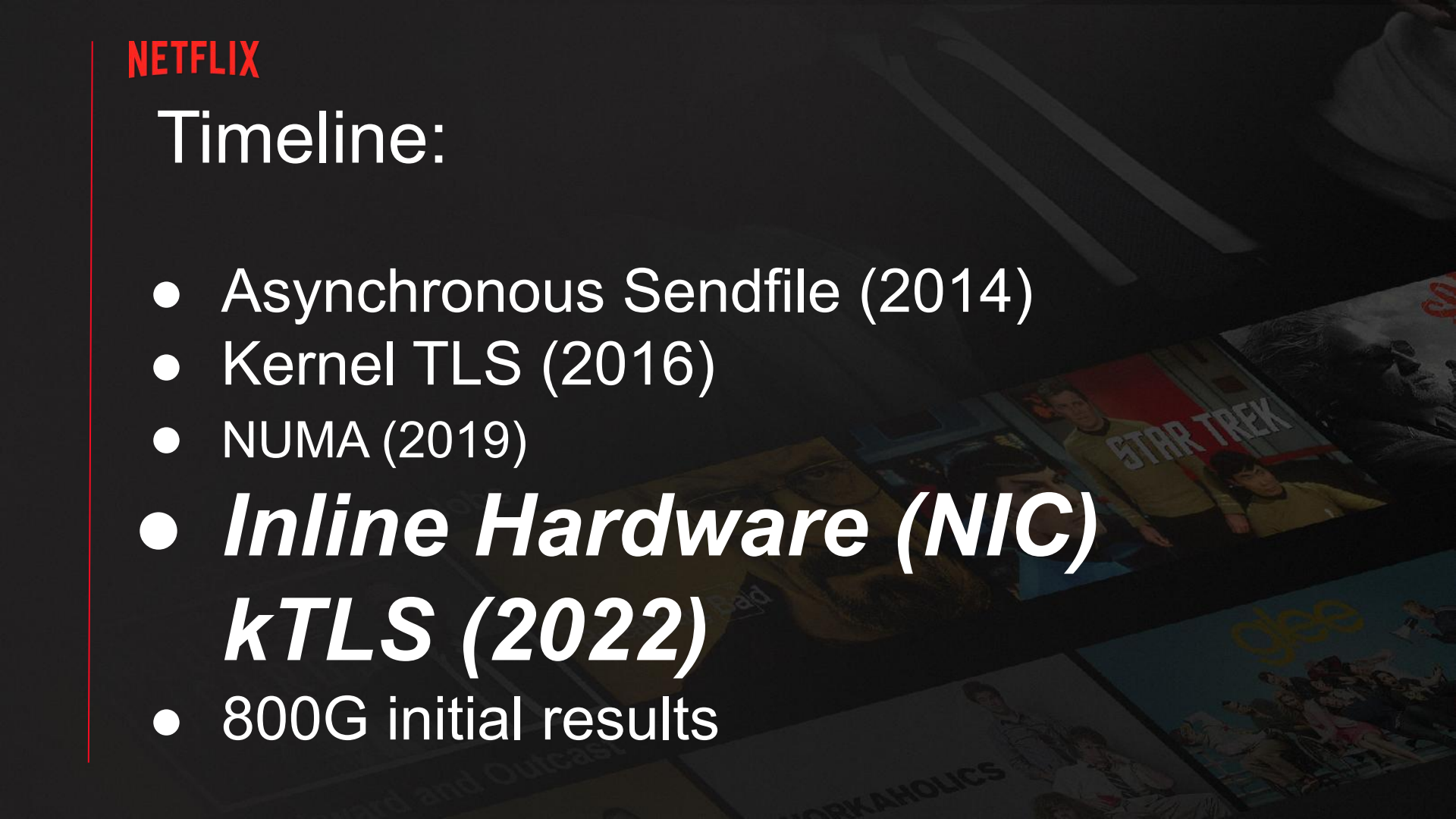
- 0 NUMA crossing on average
  - 0% of disk reads across NUMA
- 0GB/s of data on the NUMA fabric



NETFLIX

Timeline:

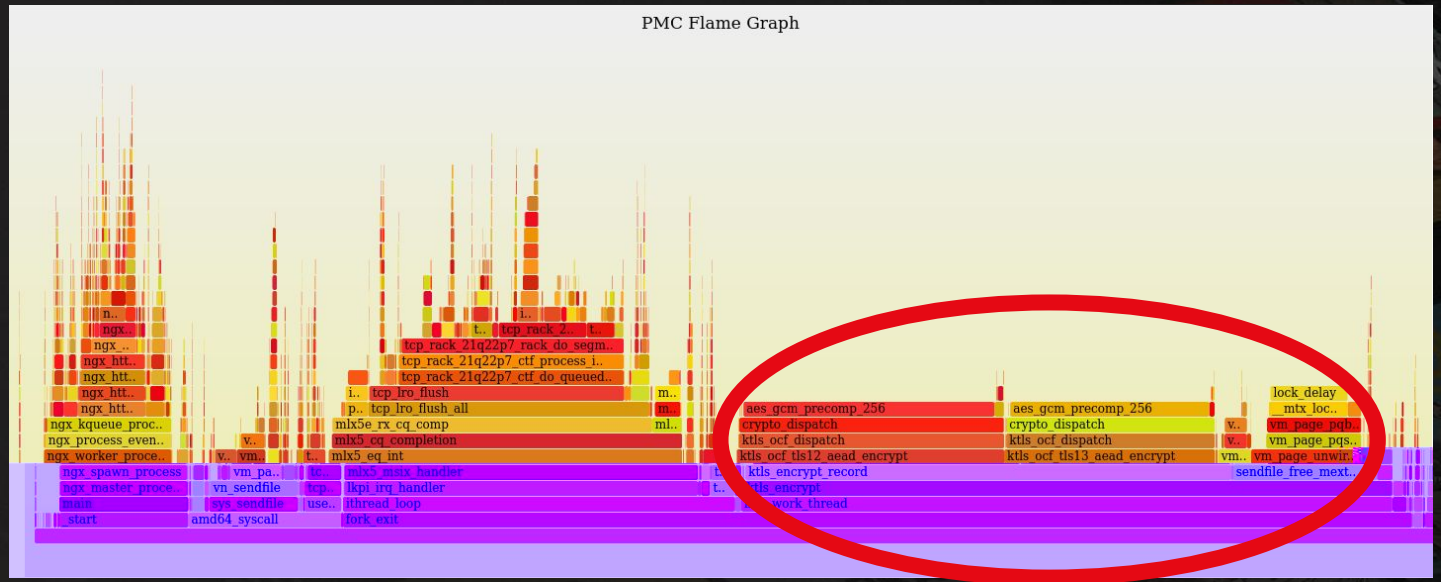
- Asynchronous Sendfile (2014)
- Kernel TLS (2016)
- NUMA (2019)
- ***Inline Hardware (NIC) kTLS (2022)***
- 800G initial results



NETFLIX

Why offload kTLS?

- kTLS uses almost half of our CPU cycles



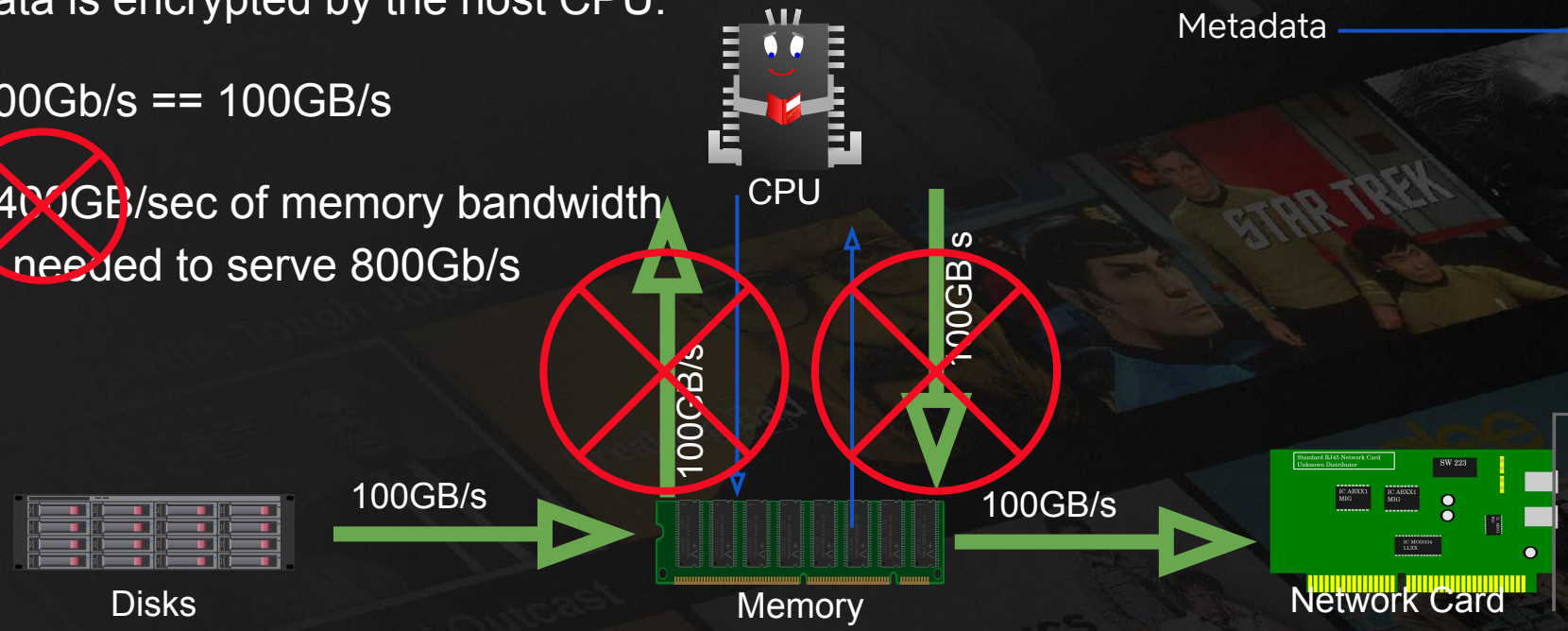
NETFLIX

Netflix 800Gb/s Video Serving Data Flow

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

800Gb/s == 100GB/s

~400GB/sec of memory bandwidth is needed to serve 800Gb/s



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Mellanox (NVIDIA) NIC kTLS

- Discussed with Mellanox starting in 2016
- First prototypes of CX6-DX in early 2020
- Iterated for 2+ years to make it production ready
- kTLS offload enabled in production last quarter

NETFLIX

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 & CPU use in half!

NETFLIX

Netflix 800Gb/s Video Serving Data Flow

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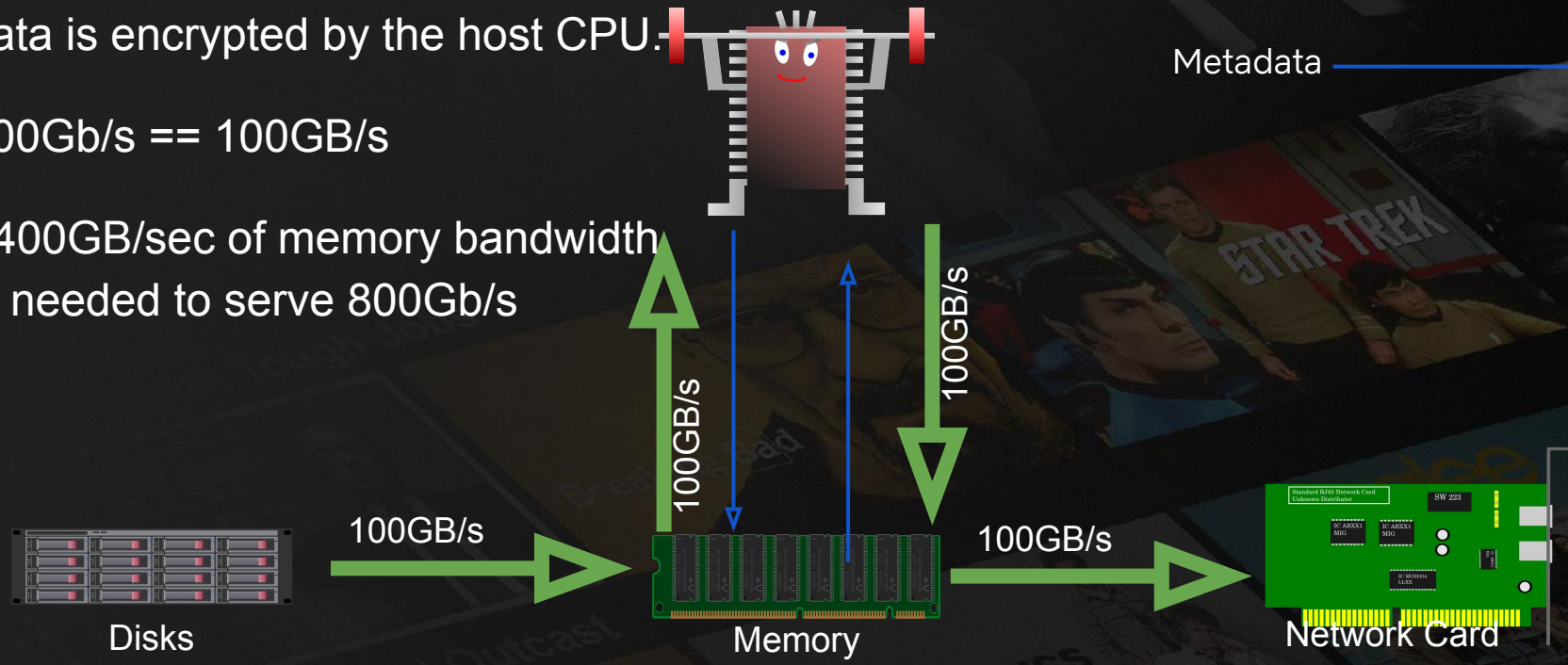

NETFLIX

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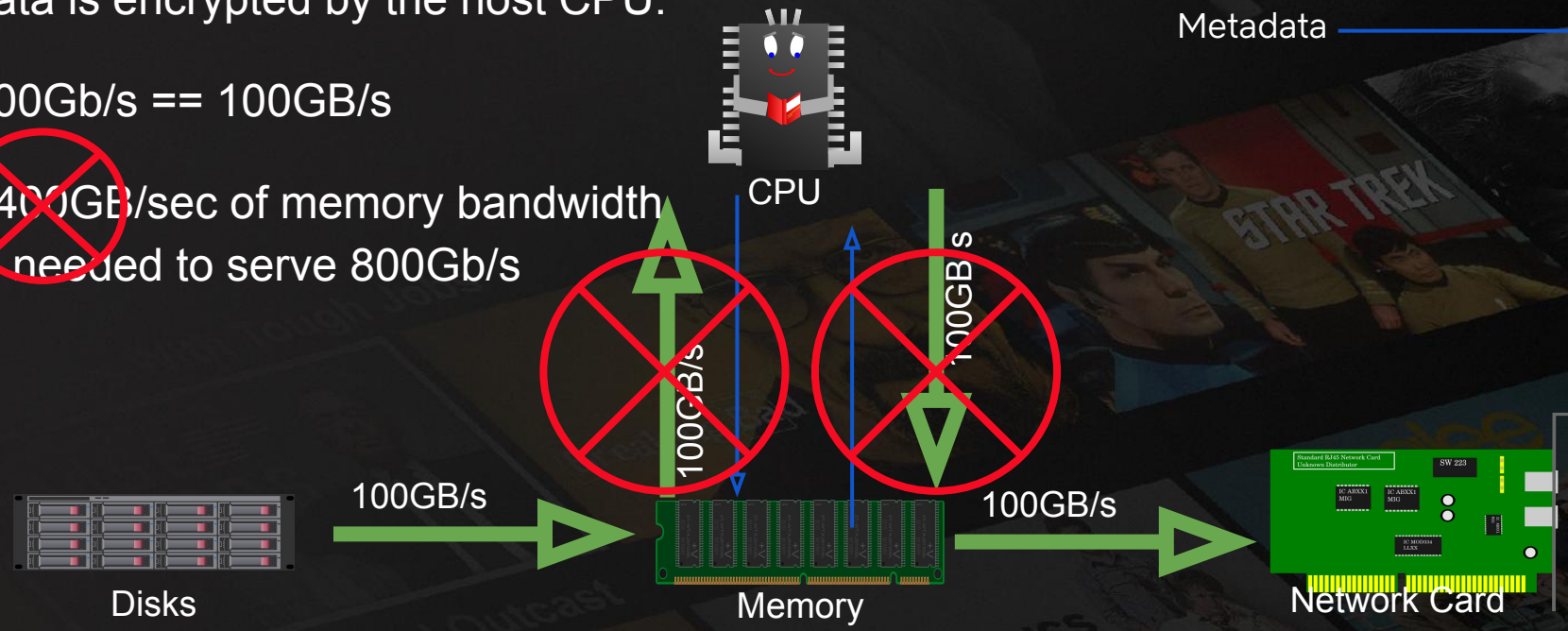
~400GB/sec of memory bandwidth is needed to serve 800Gb/s



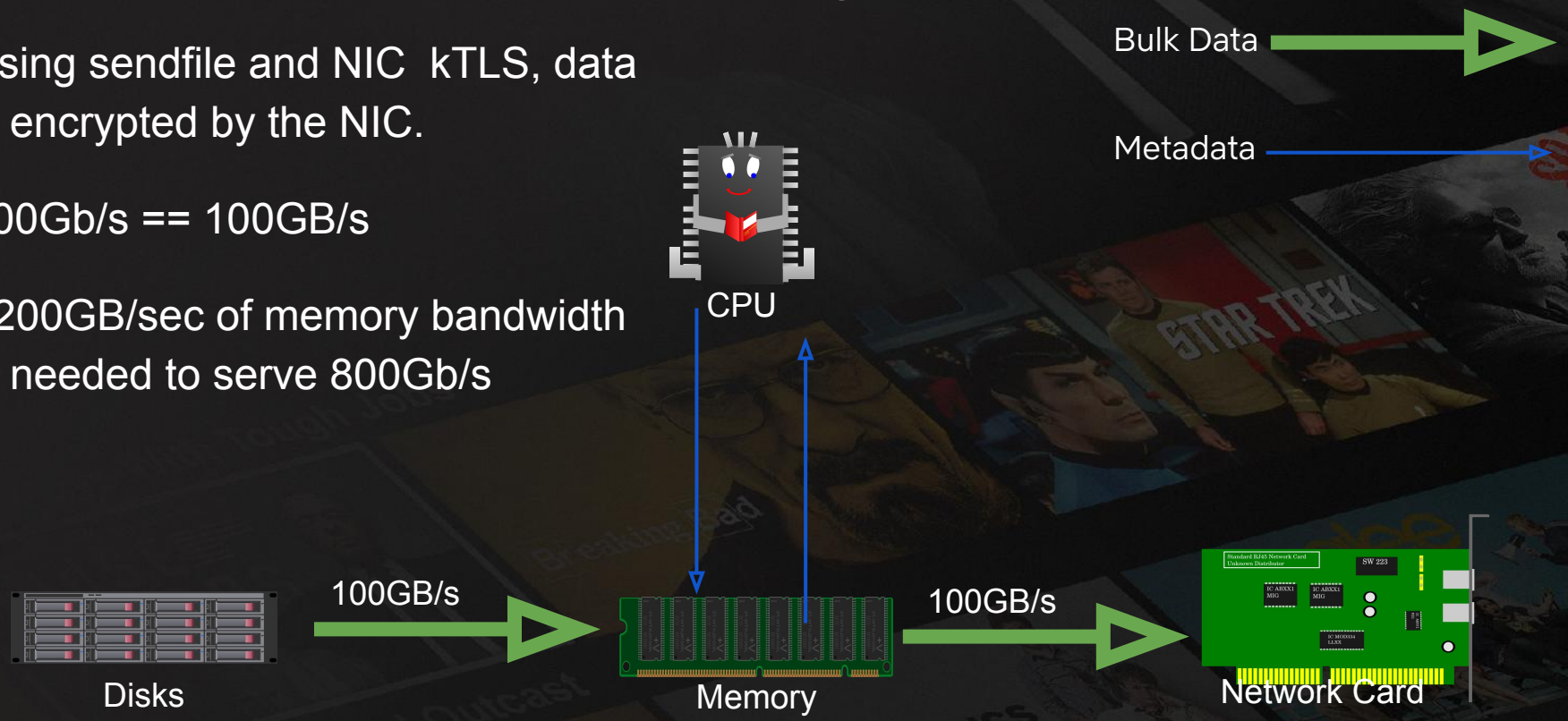
NETFLIX

Netflix 800Gb/s Video Serving Data Flow

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

800Gb/s == 100GB/s

~200GB/sec of memory bandwidth is needed to serve 800Gb/s



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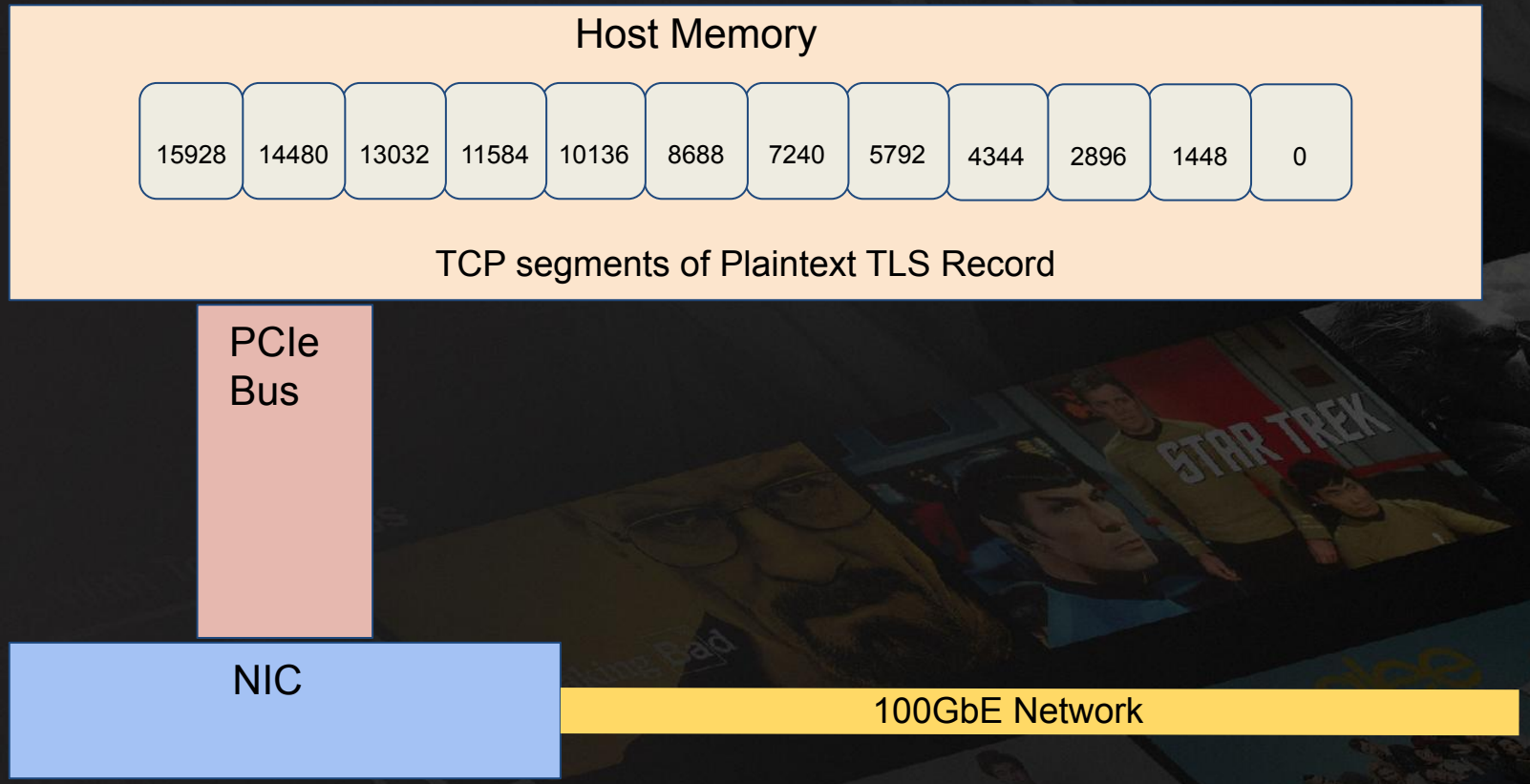
Mellanox ConnectX-6 Dx

- 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

NETFLIX

CX6-DX: In-order Transmit

NETFLIX


Host Memory
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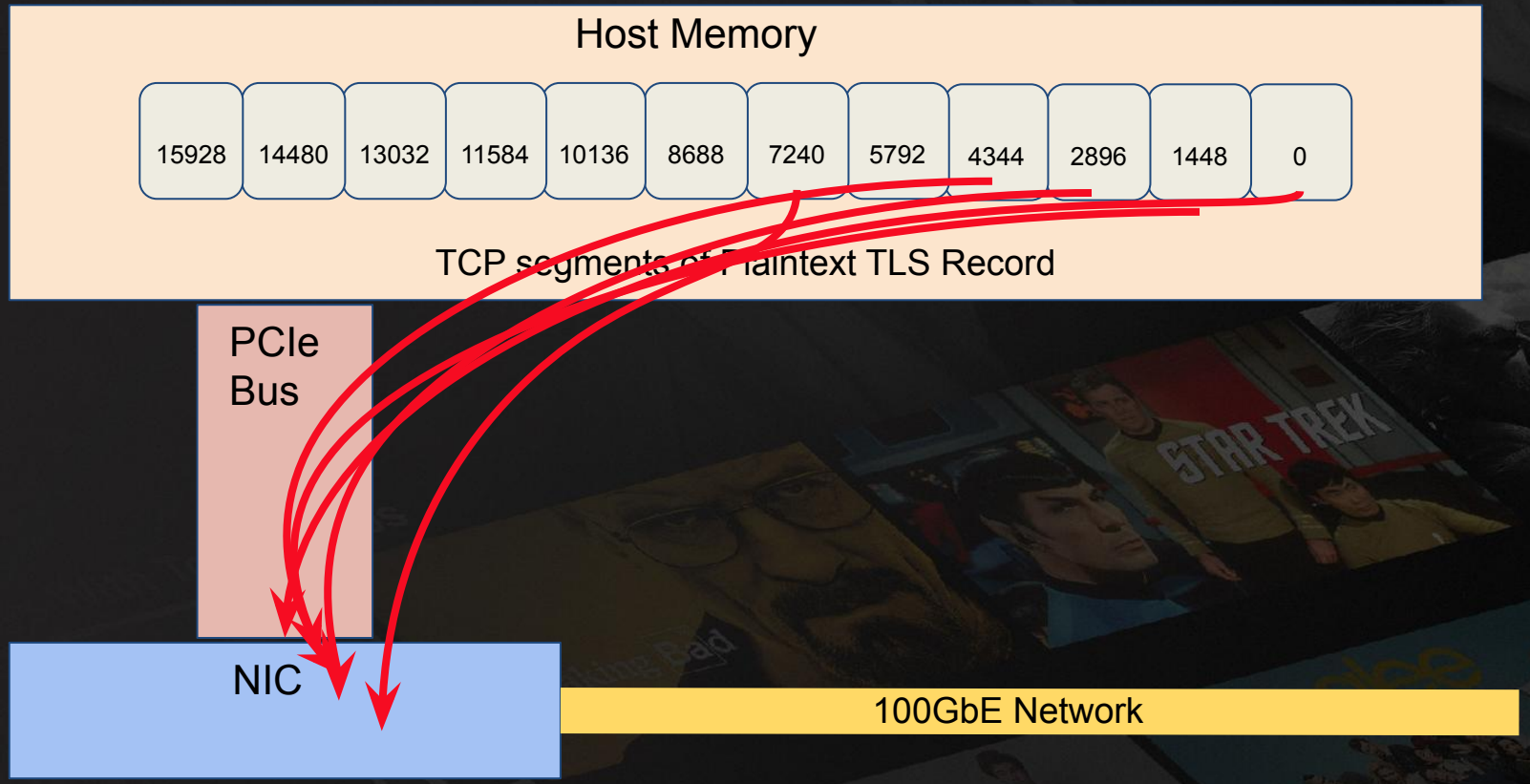
TCP segments of Plaintext TLS Record
PCIe Bus
NIC
100GbE Network

NETFLIX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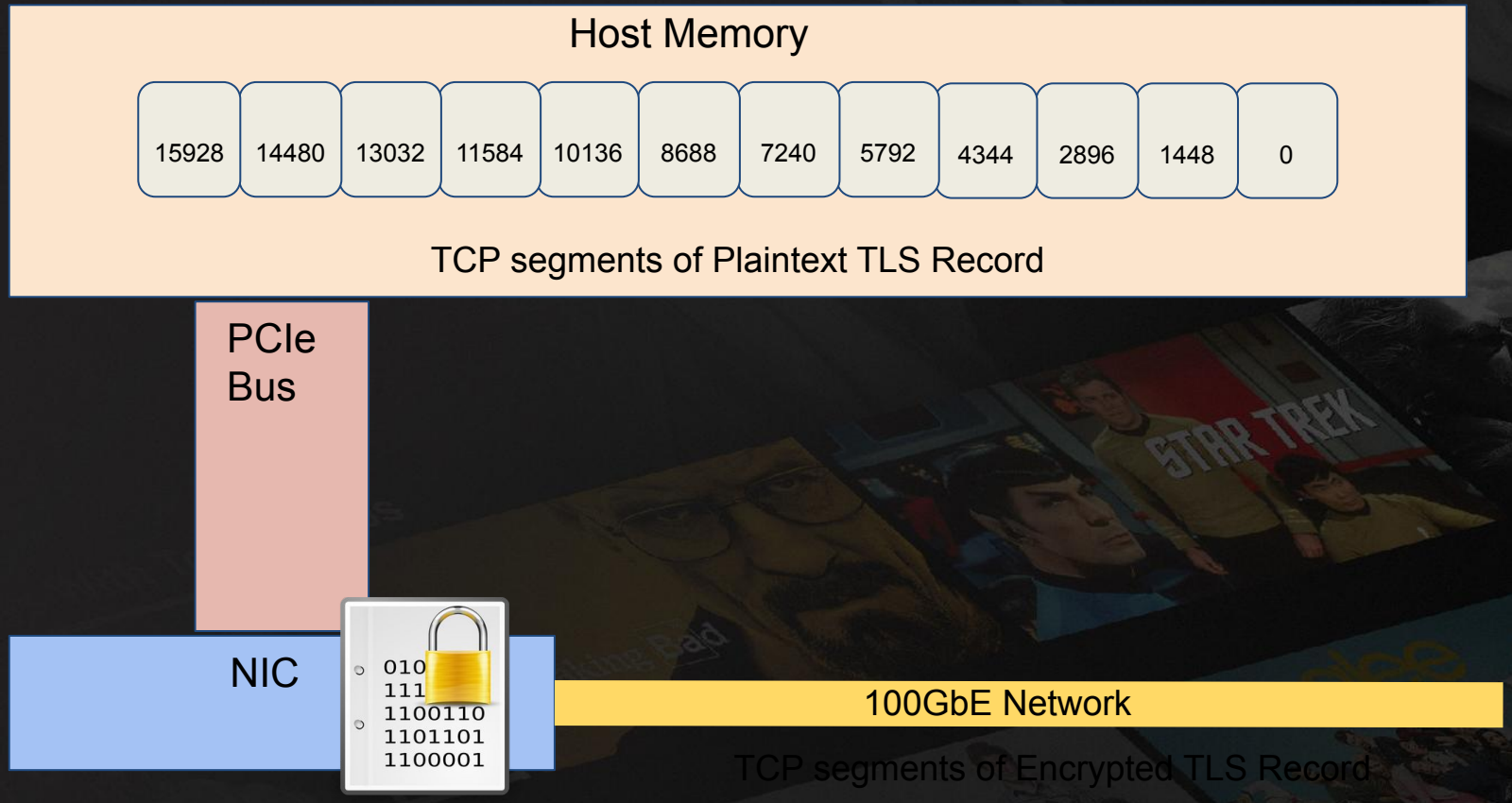
NETFLIX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TCP segments of Plaintext TLS Record
PCIe Bus
NIC
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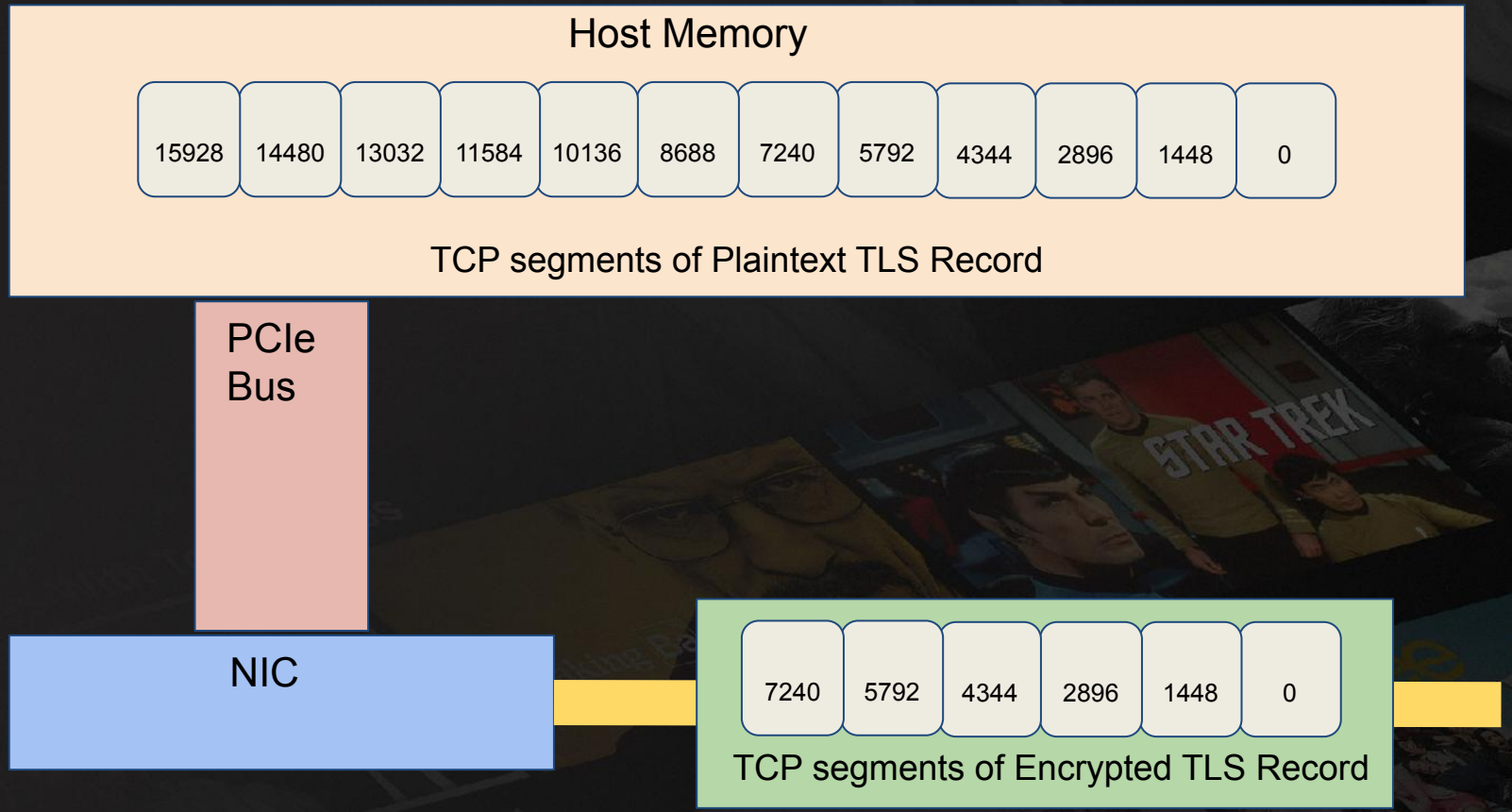
1100001
100GbE Network
TCP segments of Encrypted TLS Record

NETFLIX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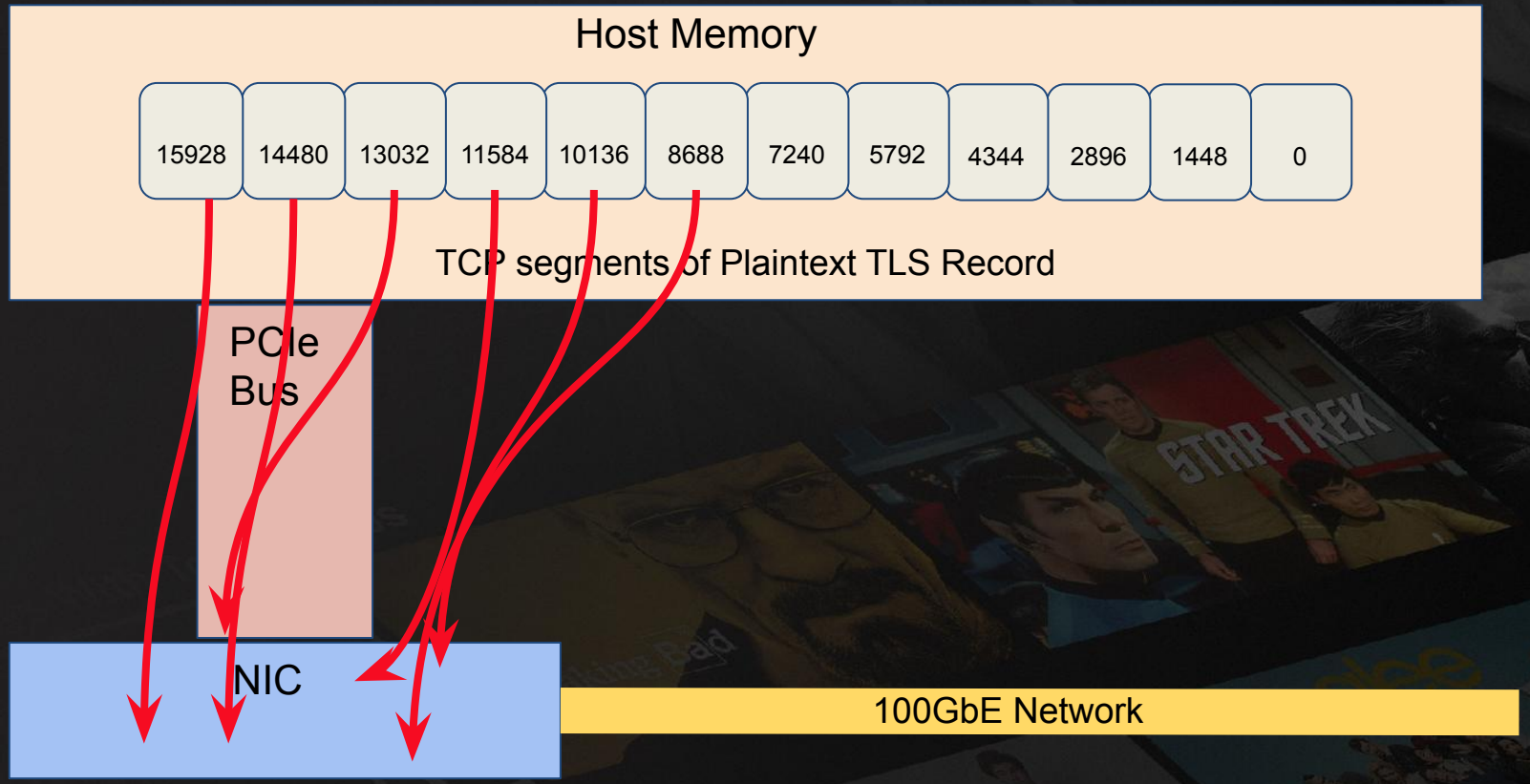
NETFLIX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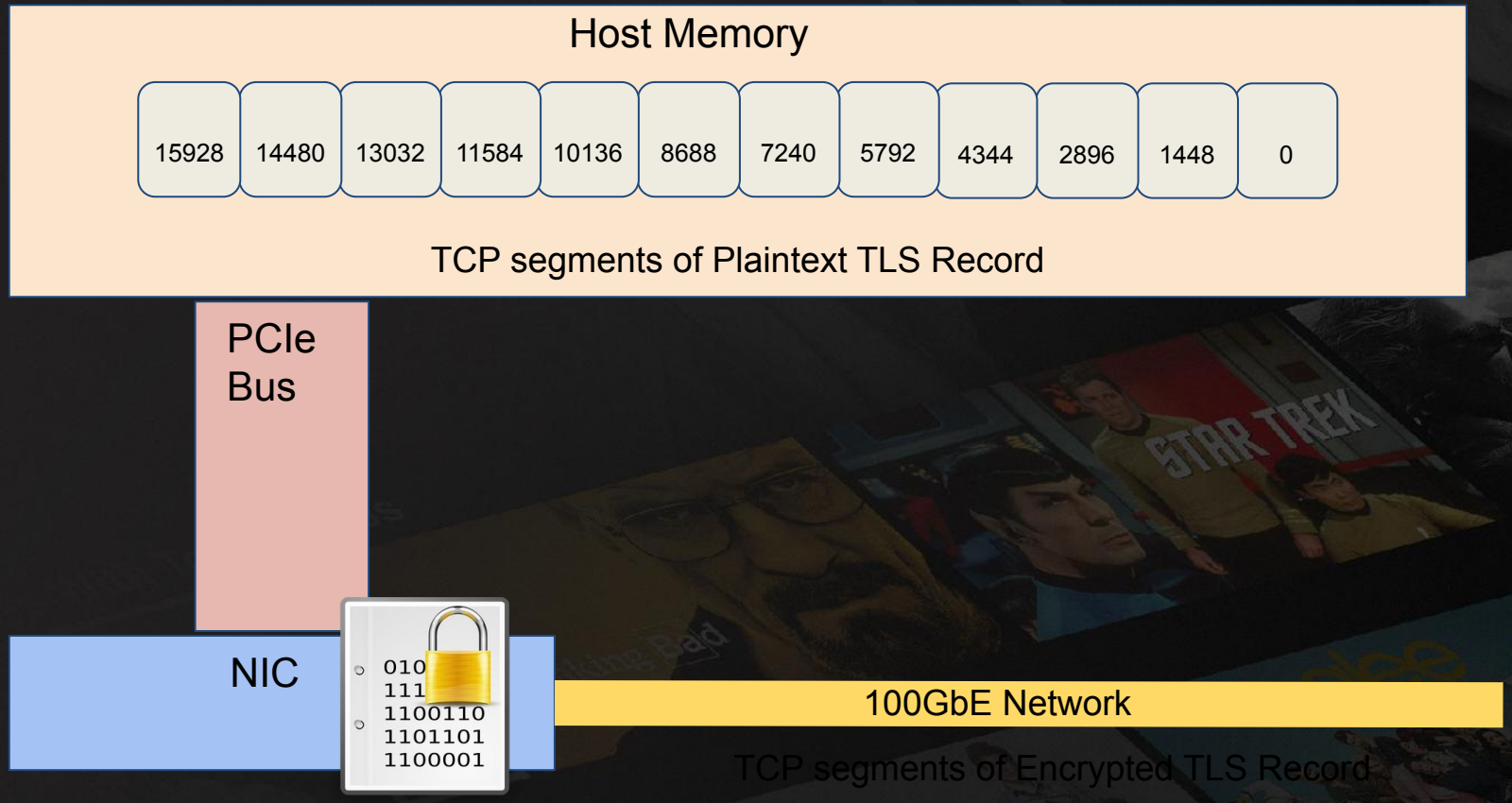
NETFLIX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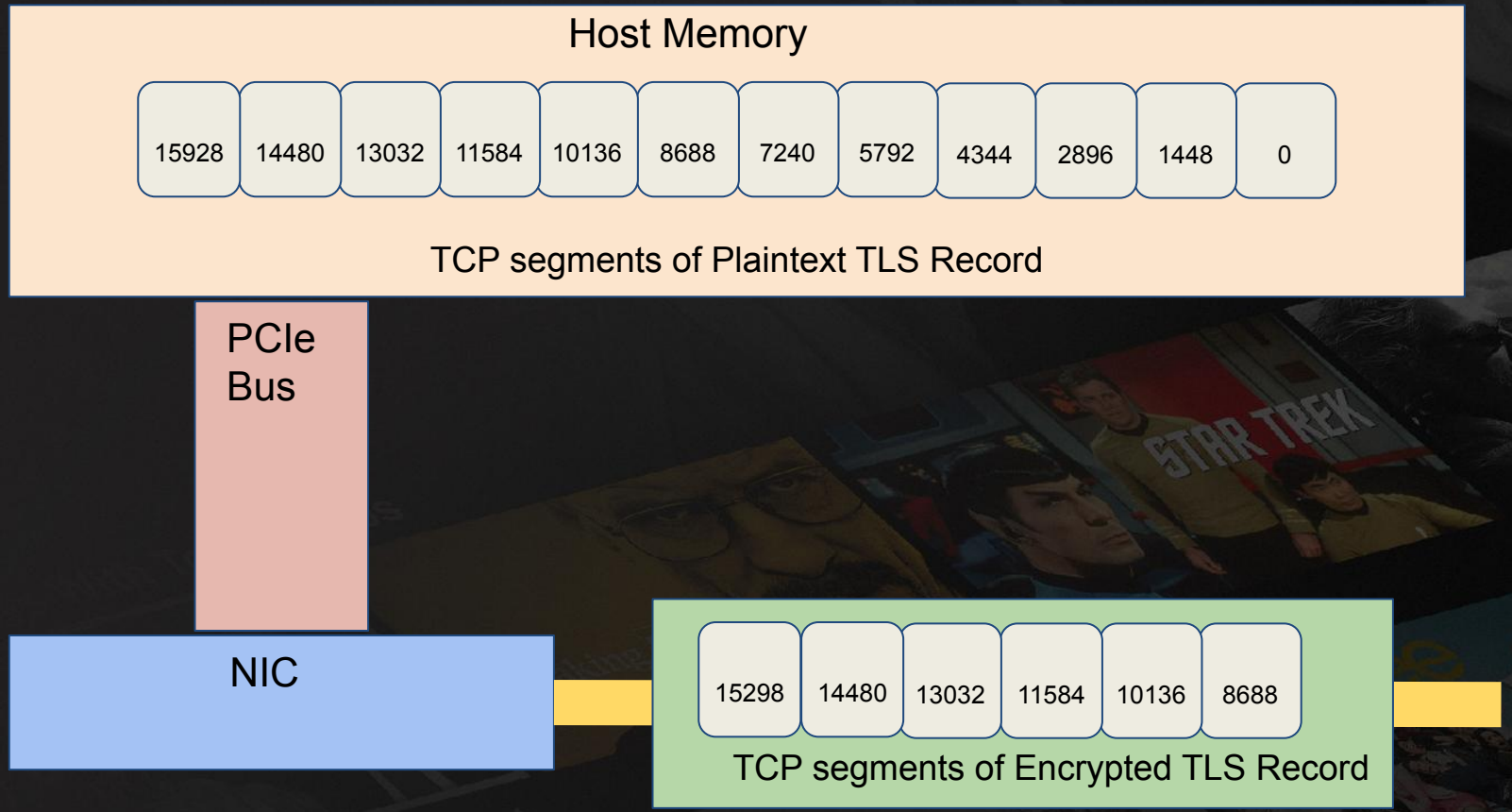
NETFLIX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TCP segments of Plaintext TLS Record
PCIe Bus
NIC
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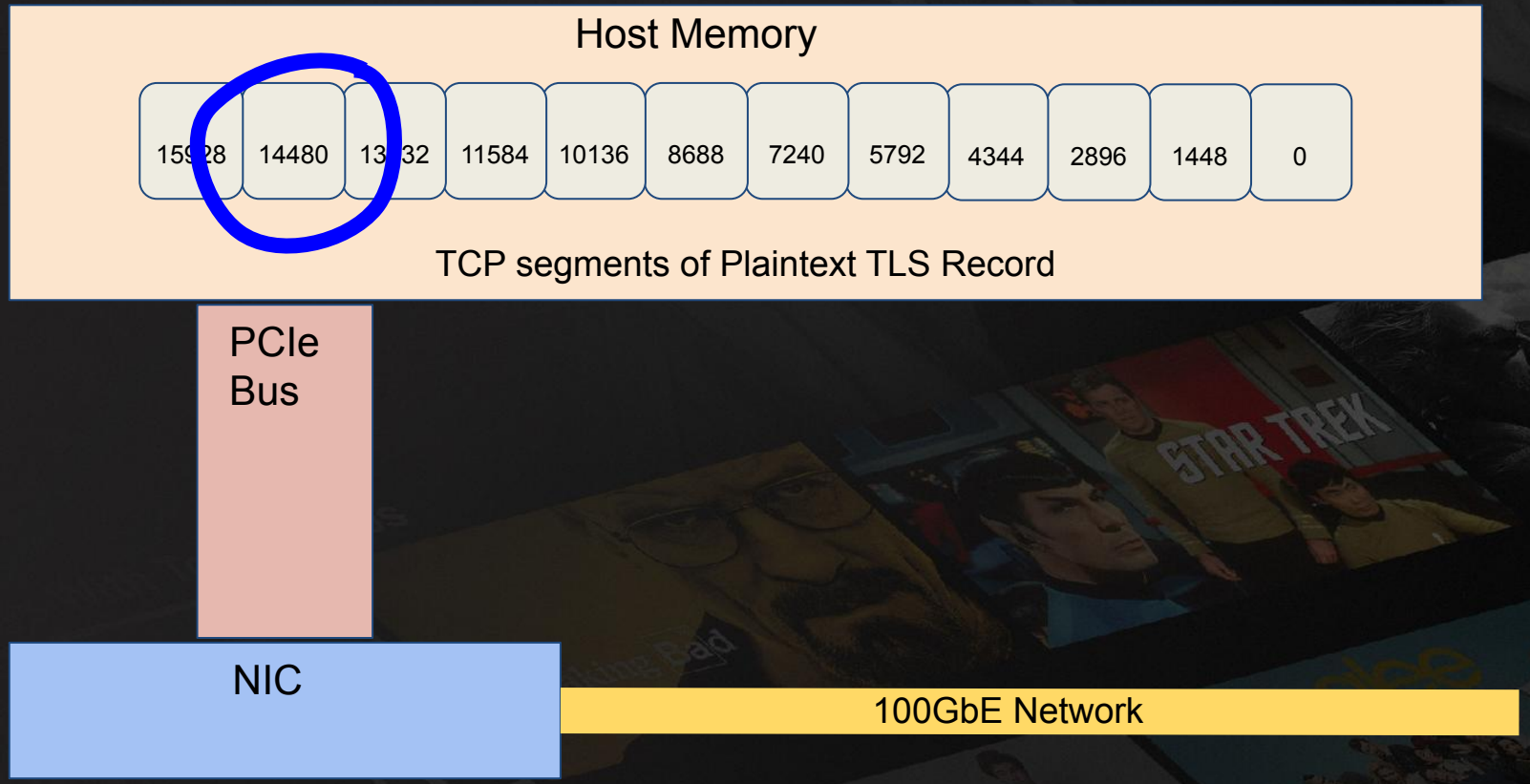
8688
TCP segments of Encrypted TLS Record

NETFLIX

CX6-DX: TCP Retransmit

NETFLIX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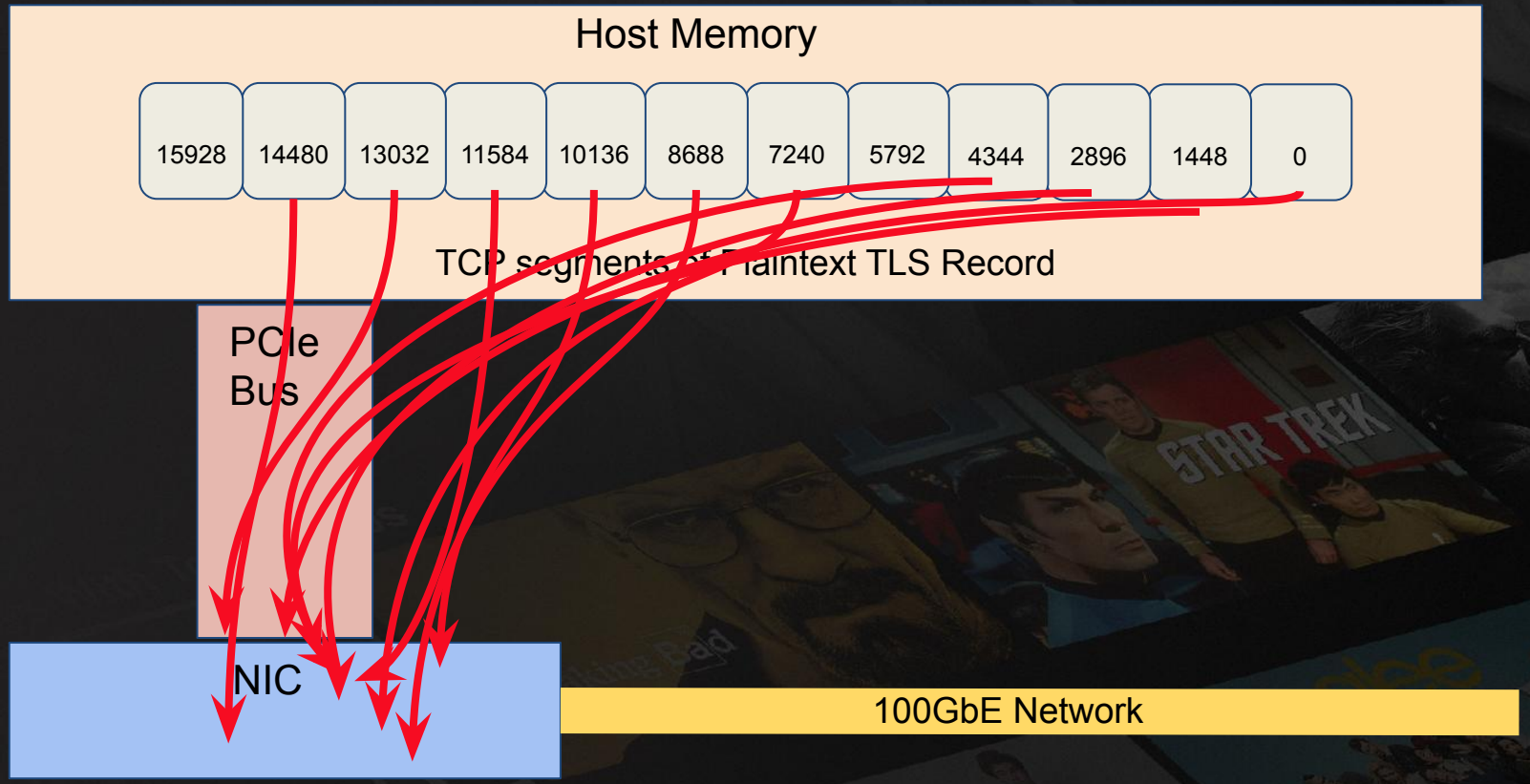
NETFLIX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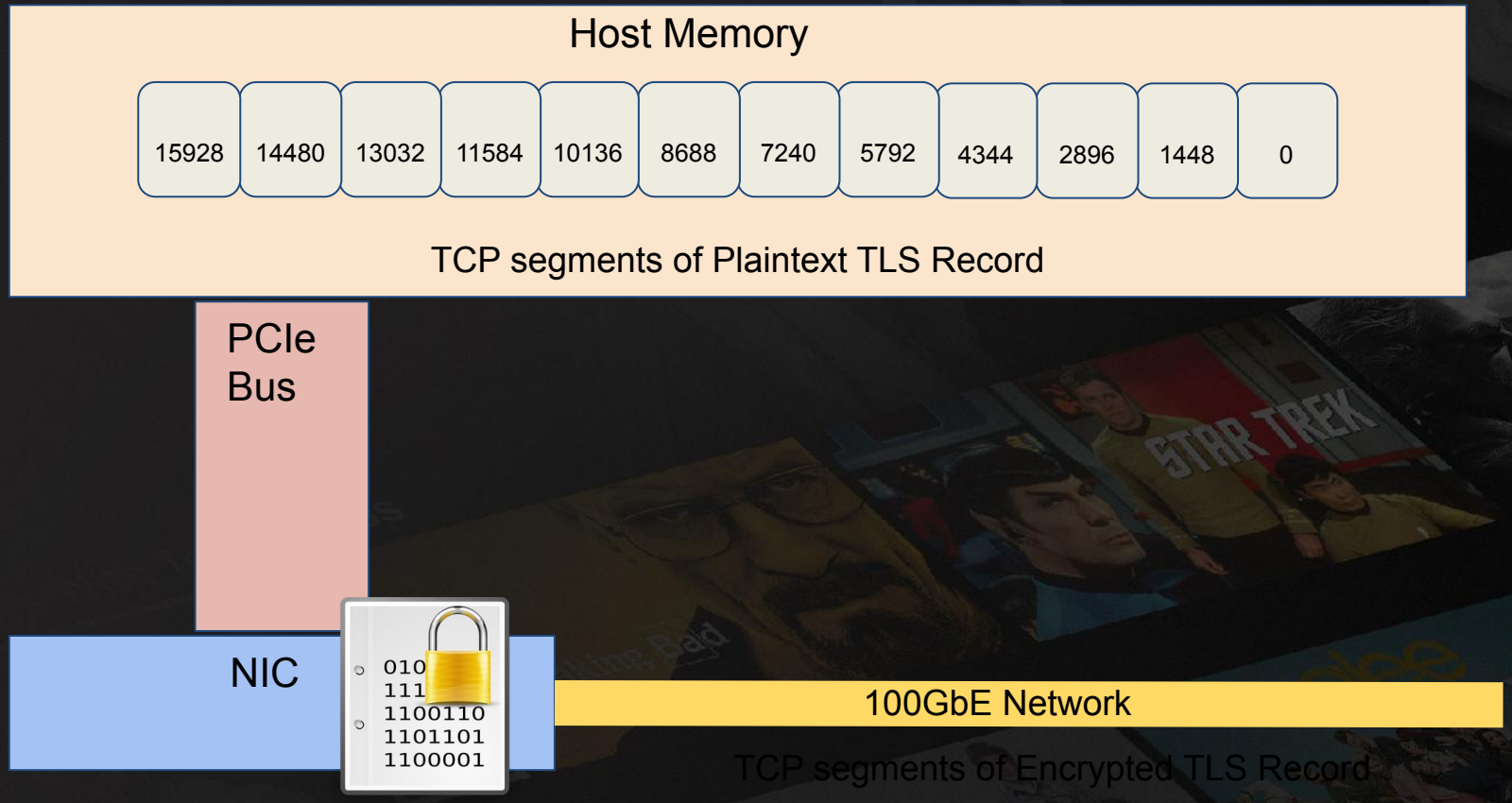
NETFLIX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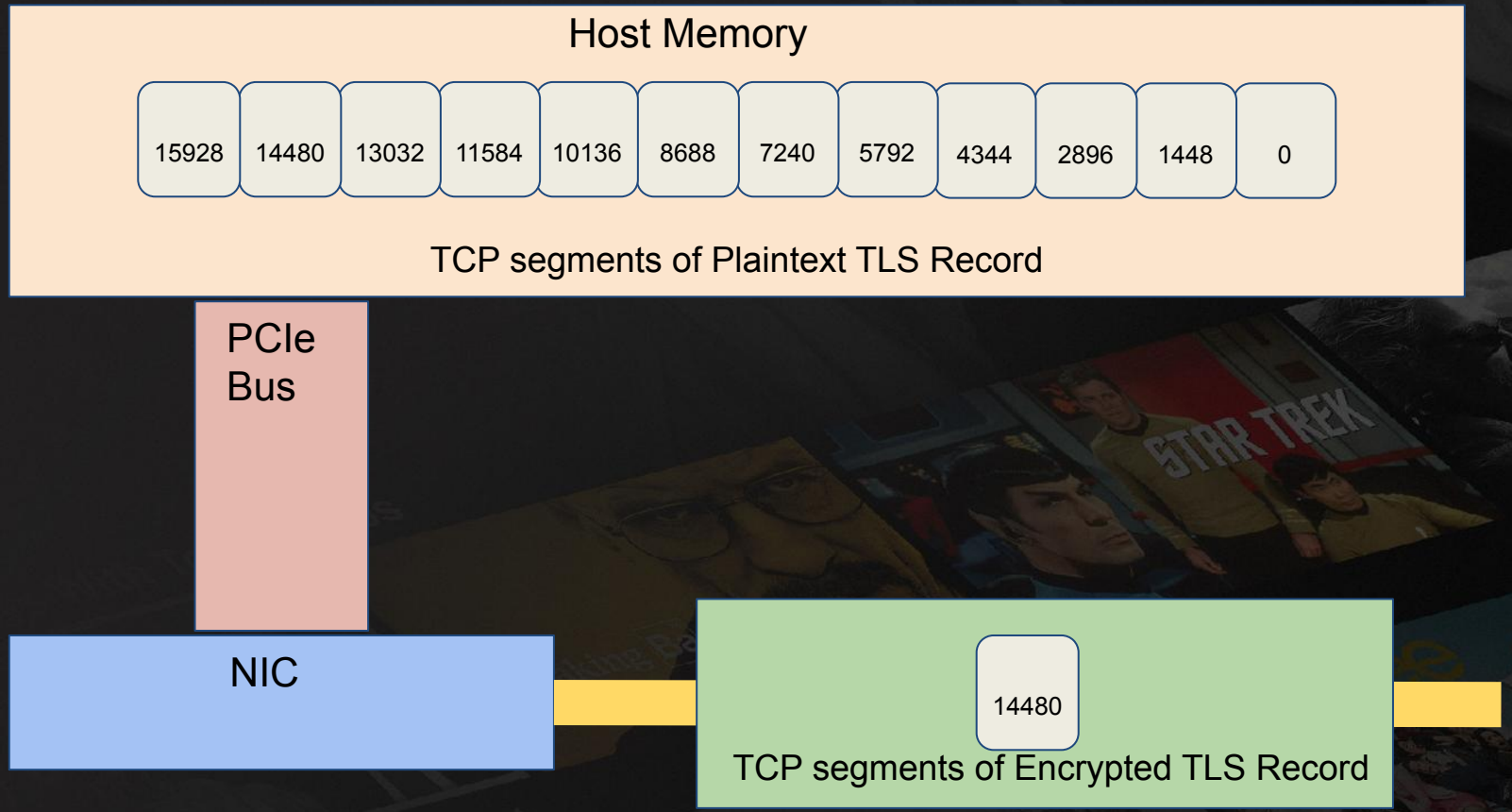
NETFLIX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14480
TCP segments of Encrypted TLS Record

NETFLIX

Timeline:

- Asynchronous Sendfile (2014)
- Kernel TLS (2016)
- NUMA (2019)
- Inline Hardware (NIC) kTLS (2022)
- ***800G initial results***

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800G Prototype Details

- Dell R7525
- 2x AMD EPYC 7713 64c / 128t (128c / 256t total)
- 3x xGMI links between sockets
- 512 GB RAM
- 4x Mellanox ConnectX-6 Dx (8x 100GbE ports)
- 16x Intel Gen4 x4 14TB NVME

NETFLIX

Initial Results: 420Gb/s

- Ran in 1NPS mode
- Network Siloing mode
- CPUs mostly idle
  - AMD guessed that xGMI was down-linking to x2
  - Set xGMI speed to 18GT/s and forced link width to x16, and disabled dynamic link width management

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Results with DLWM forced: 500Gb/s

- Ran in 1NPS mode
- Network Siloing mode
  - NVME data DMA'ed to NIC's NUMA Node
- xGMI link usage very uneven:
  - 15GB/s, 4GB/s and 2GB/s
  - Turns out that NVME is not evenly distributed by IO Quadrants
  - Even hashing of cross-socket to xGMI depends on evenly distributed IO

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How to Improve xGMI Hashing

- Hashing based on device doing DMA
  - NVME is very uneven
  - NICs are much less uneven
  - “Network Siloing” normally does DMA from NVME to remote node, local to NIC
- Flip things, and do DMA from NVME to local buffers
  - “Disk centric siloing”
- The NICs are now doing DMA across xGMI

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Results with Disk Centric Siloing: 670Gb/s

- Much more even xGMI hashing:
  - 10/10/7 GB/s
- Problematic because:
  - Daemon that “locks” content into memory is not NUMA aware & can lead to page daemon thrashing.
  - Still pressure on xGMI links

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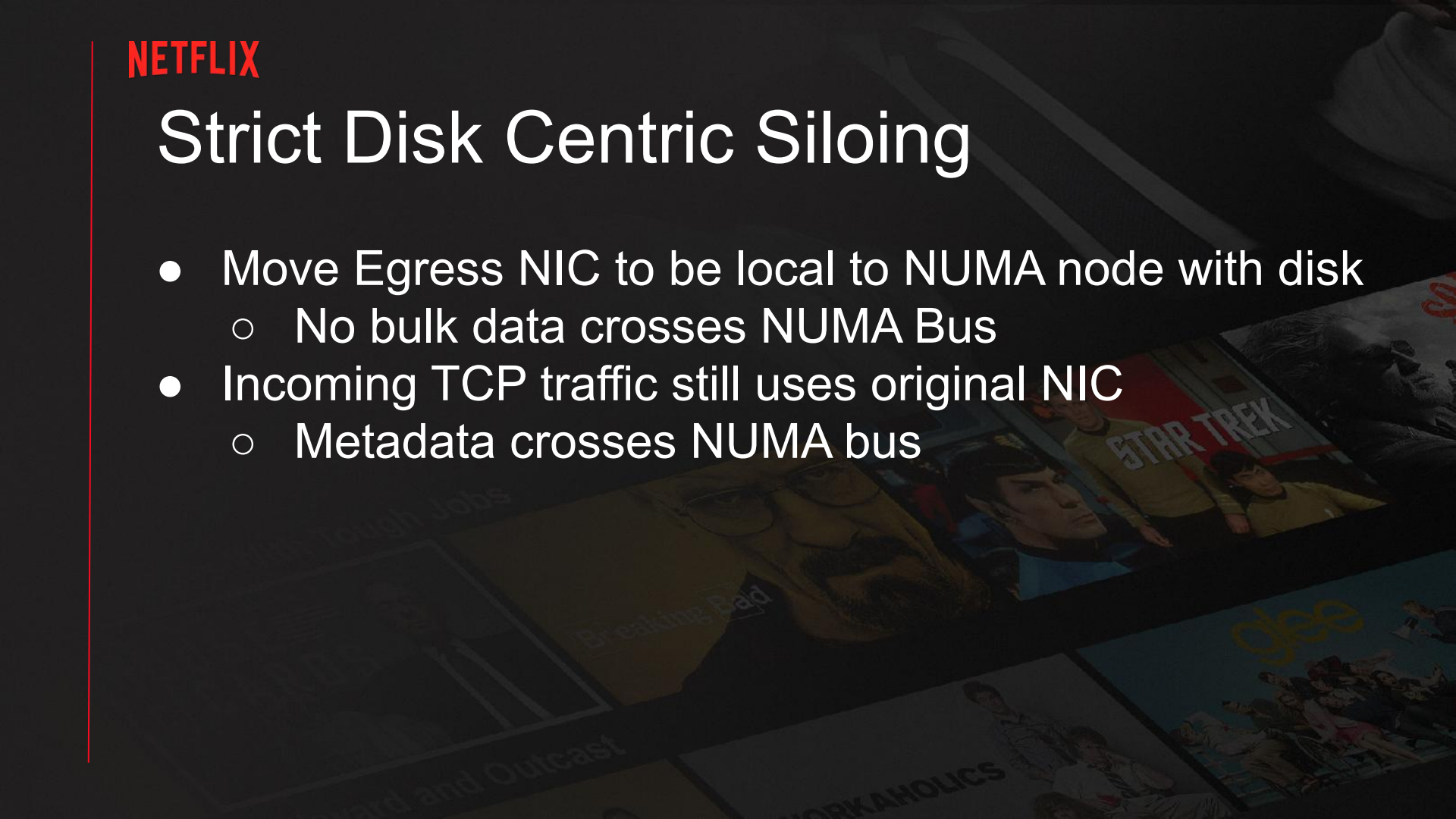
Strict Disk Centric Siloing

- Move Egress NIC to be local to NUMA node with disk
  - No bulk data crosses NUMA Bus
- Incoming TCP traffic still uses original NIC
  - Metadata crosses NUMA bus



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“Strict Disk Centric Siloing” Results: 720Gb/s

- Much less xGMI traffic
- Limited by NIC output drops, not CPU.
- Cause of drops is now largely due to:
  - Page daemon interfering with nginx on popular node
  - Uneven loading on NICs due to content popularity differences. (NICs on popular node doing 94Gb/s, others doing 84Gb/s)

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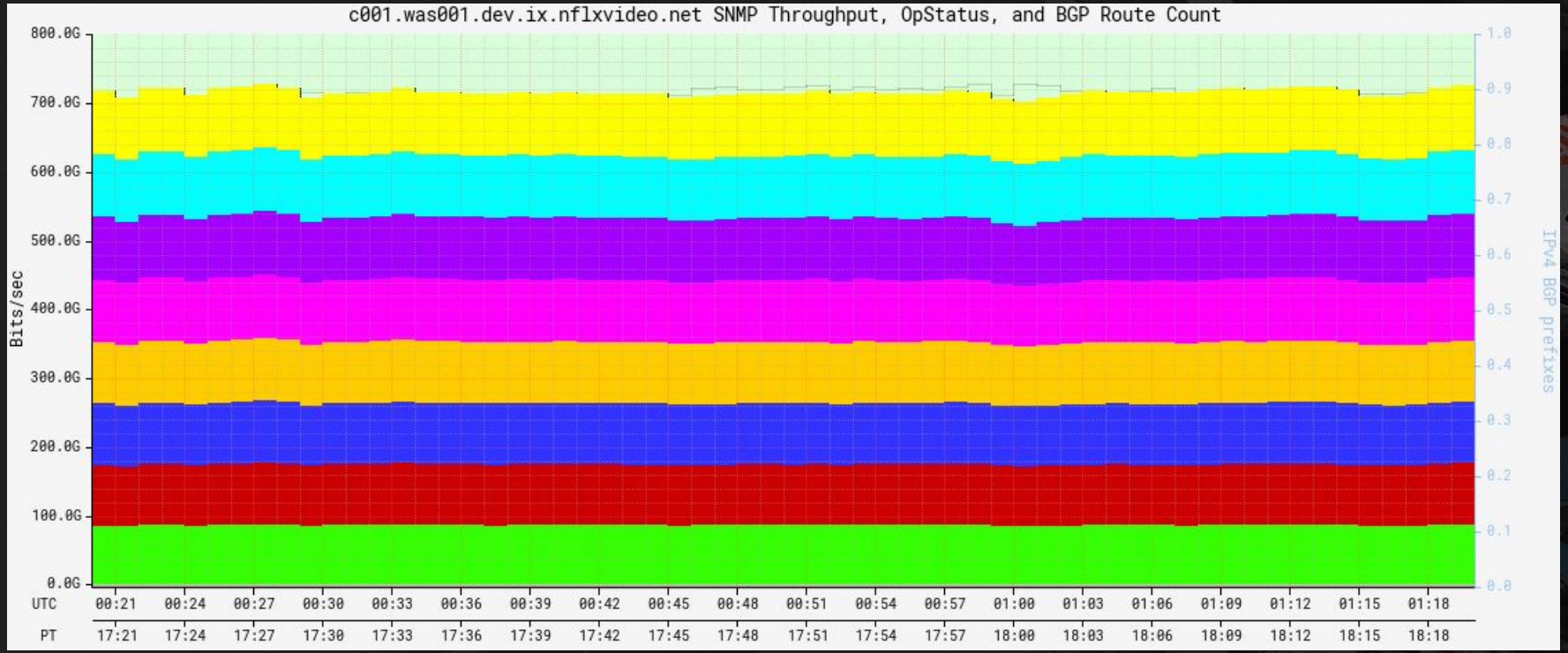
c001.was001.dev.ix.nflxvideo.net SNMP Throughput, OpStatus, and BGP Route Count
Bits/sec
800.0G
700.0G
600.0G
500.0G
400.0G
300.0G
200.0G
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0.0G
IPv4 BGP prefixes
1.0
0.9
0.8
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PT 17:21 17:24 17:27 17:30 17:33 17:36 17:39 17:42 17:45 17:48 17:51 17:54 17:57 18:00 18:03 18:06 18:09 18:12 18:15 18:18

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Credits

- Async Sendfile
  - Gleb Smirnoff, Konstantin Belousov, Igor Sysoev, Jeff Roberson, Scott Long
- kTLS
  - Scott Long, Randall Stewart, Drew Gallatin, John Mark Gurney, John Baldwin
- NUMA
  - Drew Gallatin, Jeff Roberson, Mark Johnston
- Inline Hardware (NIC) kTLS
  - John Baldwin, Drew Gallatin, Hans Petter Seleaski, Boris Pismenny, Navdeep Parhar

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Credits

- Experimental 800GbE Host
  - Warren Harrop and the Netflix hardware team
  - MBX (integrator)
  - AMD (EPYC 7713 CPUs)
  - Dell (PowerEdge R7525)
  - Mellanox/NVIDIA (ConnectX-6 Dx NICS)
  - Intel (P5316 NVME)

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Thank you!