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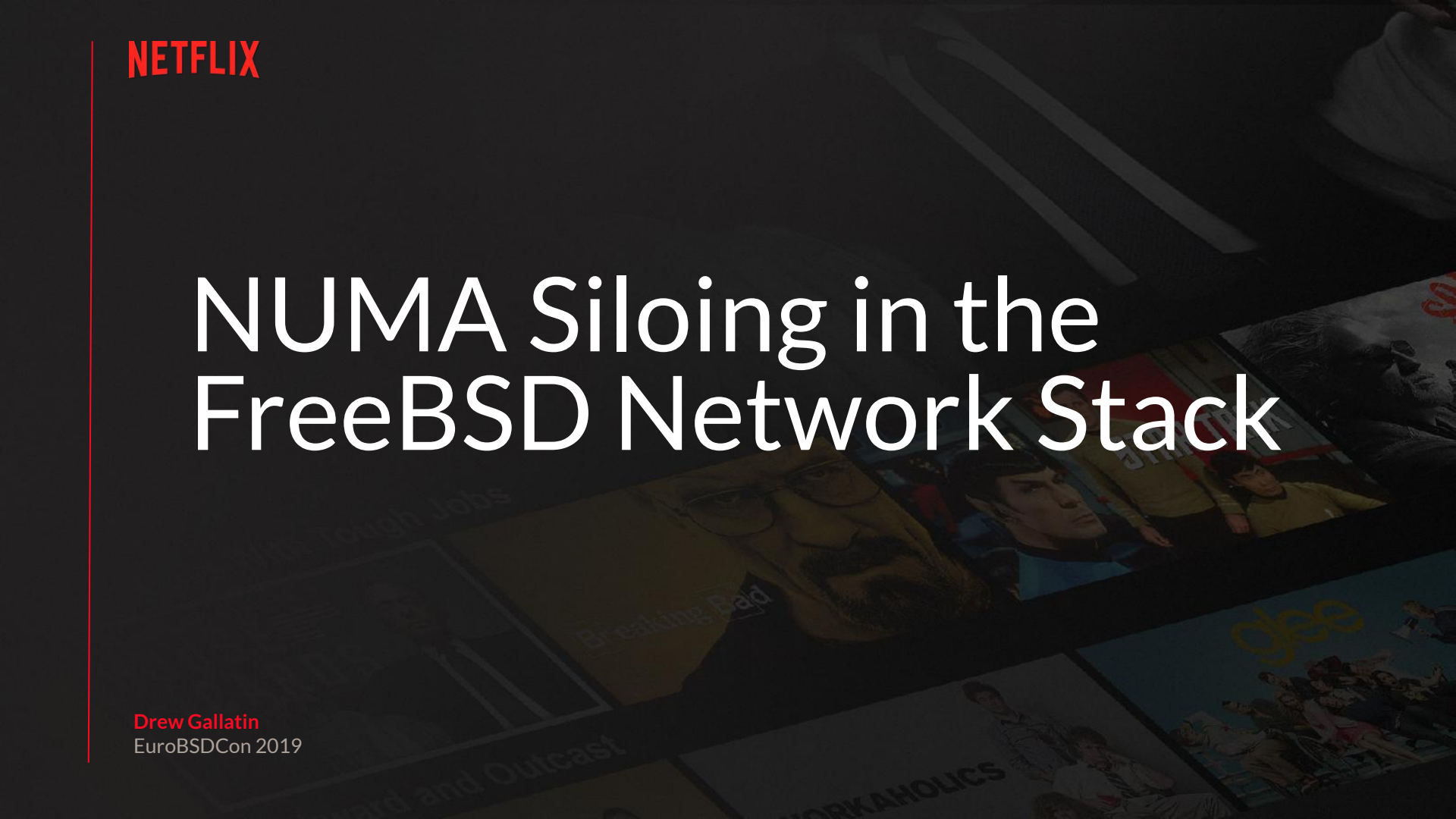
NUMA Siloing in the FreeBSD Network Stack



Drew Gallatin

EuroBSDCon 2019

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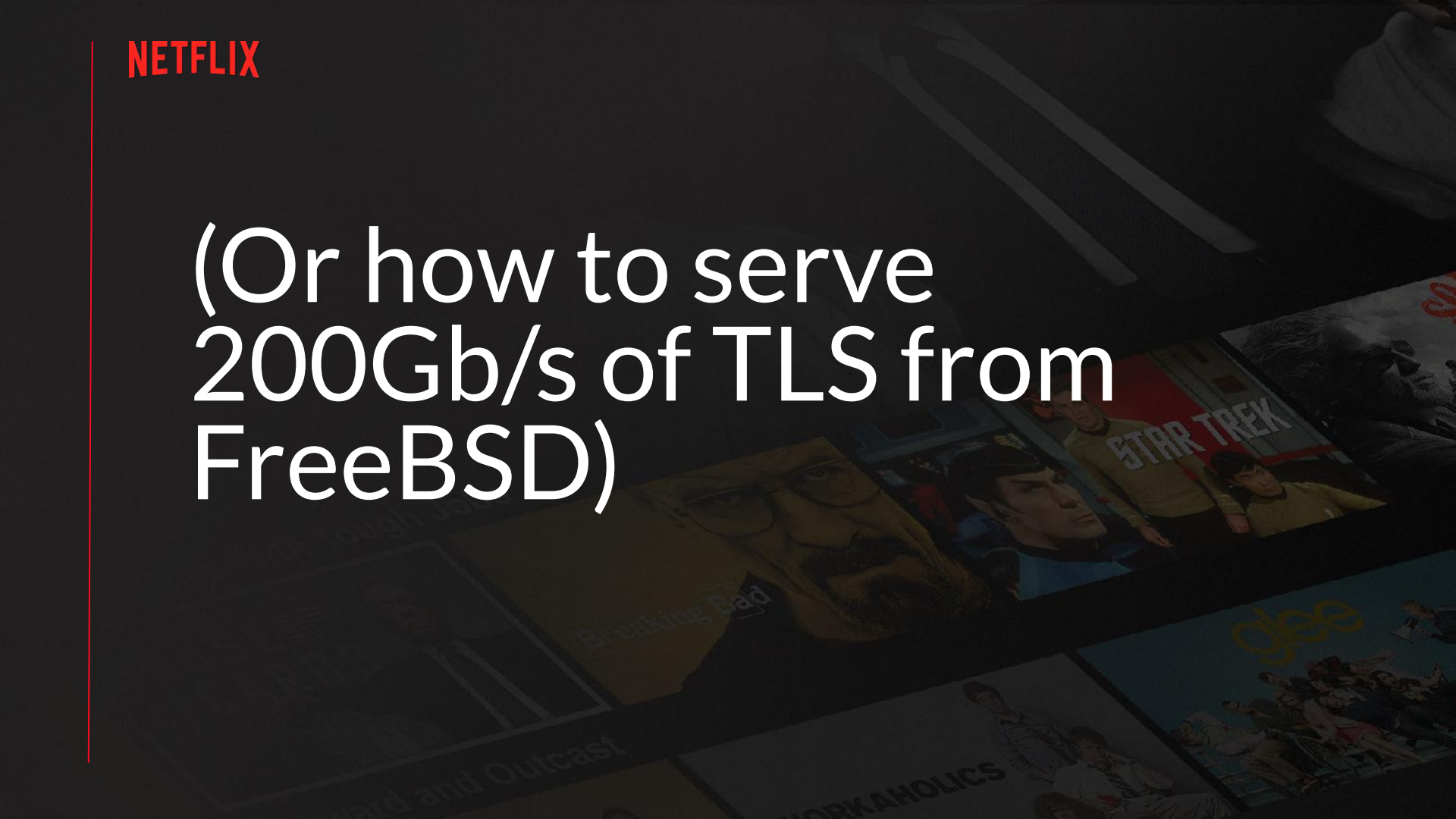
(Or how to serve 200Gb/s of TLS from FreeBSD)



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Motivation:

- Since 2016, Netflix has been able to serve 100Gb/s of TLS encrypted video traffic from a single server.
- How can we serve ~200Gb/s of video from a single server?

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Netflix Video Serving Workload

- FreeBSD-current
- NGINX web server
- Video served via sendfile(2) and encrypted using software kTLS
  - TCP_TXTLS_ENABLE from tcp(4)

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Why do we need NUMA for 200Gb/s ?

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Netflix Video Serving Hardware for 100Gb/s

- Intel “Broadwell” Xeon (original 100g)
  - 60GB/s mem bw
  - 40 lanes PCIe Gen3
    - ~32GB/s of IO bandwidth
- Intel “Skylake” & “Cascade Lake” Xeon (new 100g)
  - 90GB/s mem bw
  - 48 lanes PCIe Gen 3
    - ~38GB/s of IO bandwidth

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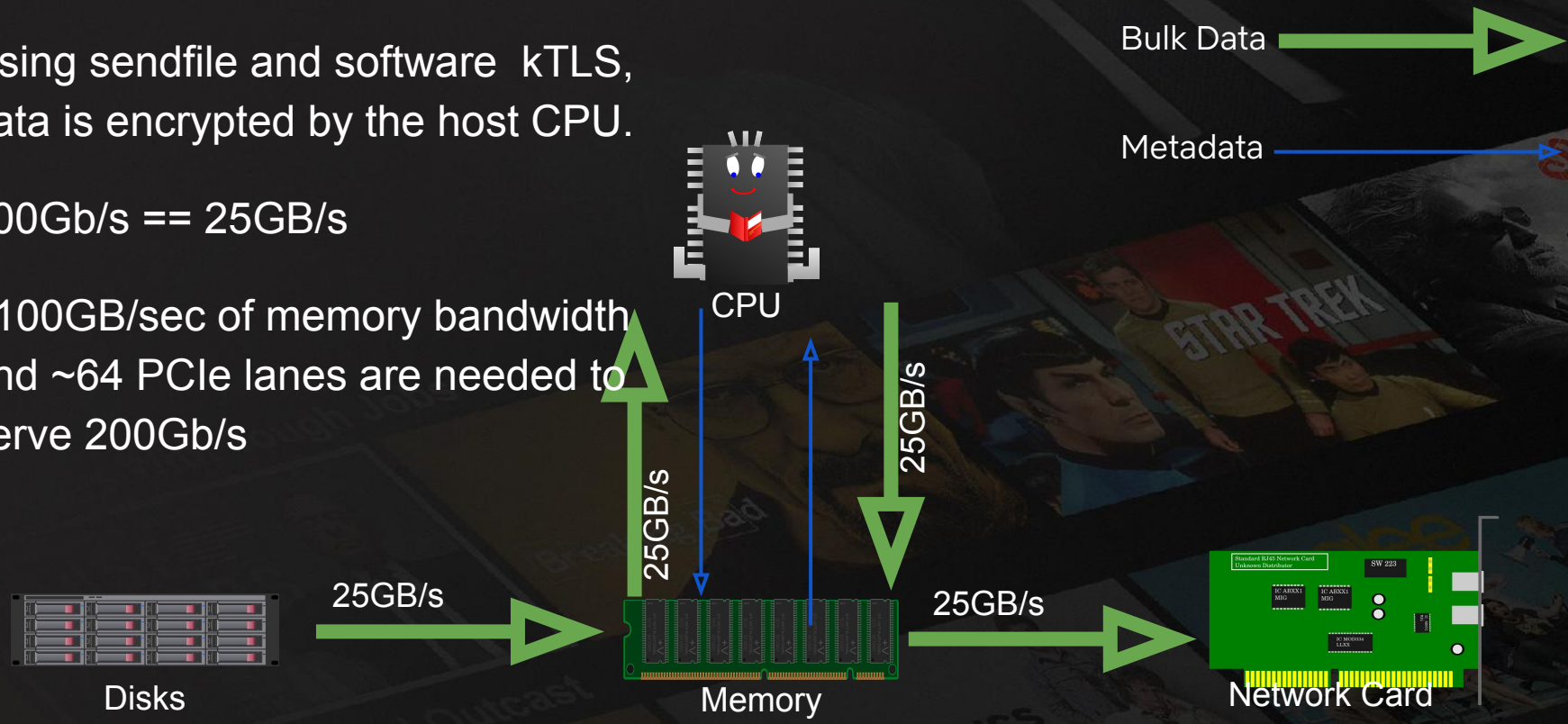
Netflix 200Gb/s Video Serving Data Flow

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

200Gb/s == 25GB/s

~100GB/sec of memory bandwidth and ~64 PCIe lanes are needed to serve 200Gb/s



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Netflix Video Serving Hardware for 200Gb/s (Intel) "Throw another CPU socket at it"

- 2x Intel "Skylake" / "Cascade Lake" Xeon
  - Dual Xeon(R) Silver 4116 / 4216
  - 2 UPI links connecting Xeons
  - 180GB/s (2 x 90GB/s) mem bw
  - 96 (2 x 48) lanes PCIe Gen 3
    - ~75GB/s IO bandwidth

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Netflix Video Serving Hardware for 200Gb/s (Intel)

- 8x PCIe Gen3 x4 NVME
  - 4 per NUMA node
- 2x PCIe Gen3 x16 100GbE NIC
  - 1 per NUMA node

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Netflix Video Serving Hardware for 200Gb/s (AMD) “4 chips in 1 socket”

- AMD EPYC “Naples” / “Rome”
  - 7551 & 7502P
  - Single socket, quad “Chiplet”
  - Infinity Fabric connecting chiplets
  - 120-150GB/s mem bw
  - 128 lanes PCIe Gen 3 (Gen 4 for 7502P)
    - 100GB/sec IO BW (200GB/s Gen 4)

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Netflix Video Serving Hardware for 200Gb/s (AMD) “4 chips in 1 socket”

- 8x PCIe Gen3 x4 NVME
  - 2 per NUMA node
- 4x PCIe Gen3 x16 100GbE NIC
  - 1 per NUMA node

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Initial 200G prototype performance:

- 85Gb/s (AMD)
- 130Gb/s (Intel)
- 80% CPU
- ~40% QPI saturation
  - Measured by Intel's pcm.x tool from the intel-pcm port
- Unknown Infinity Fabric saturation
  - AMD's tools are lacking (even on Linux)

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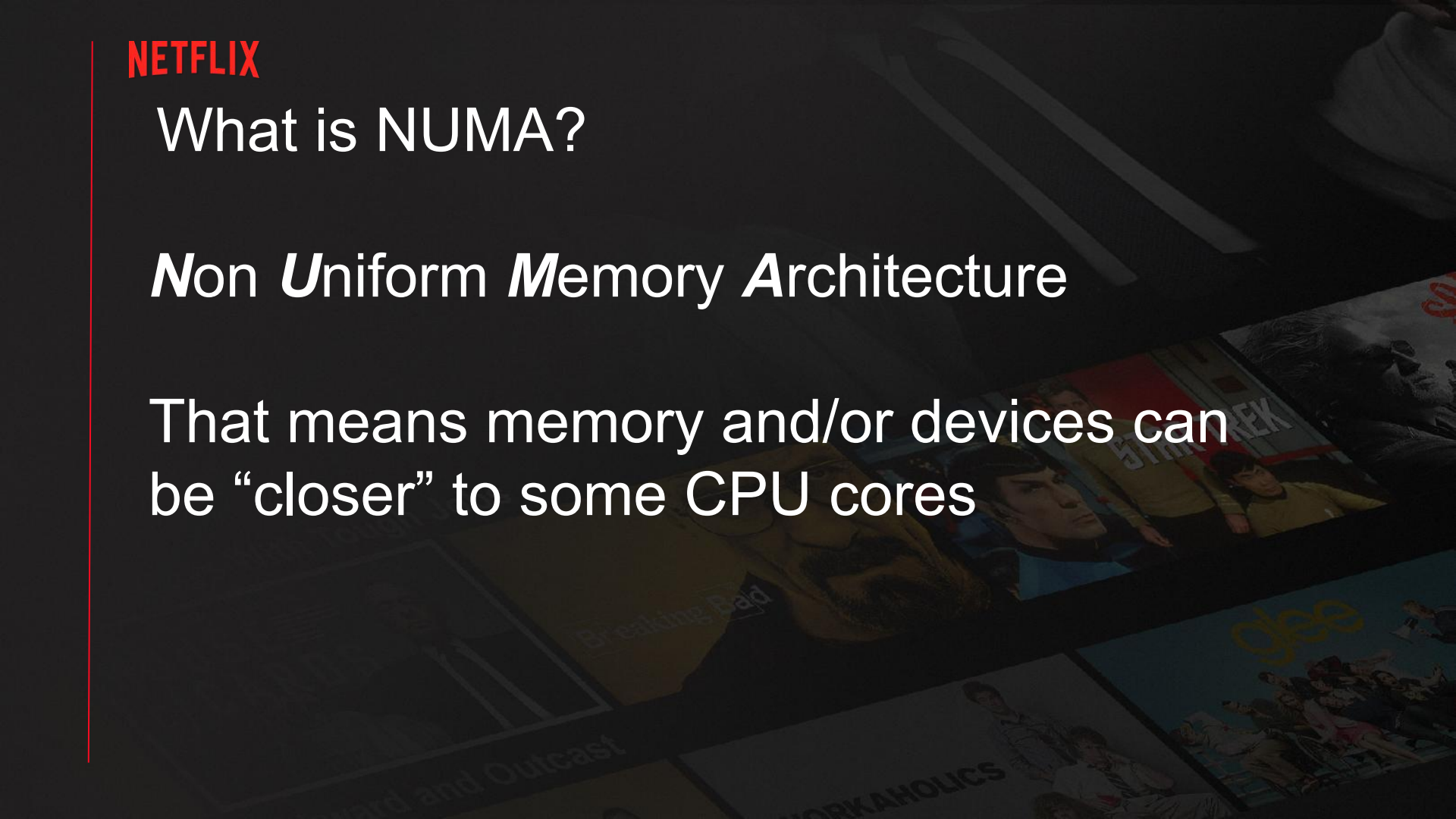
What is NUMA?

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

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



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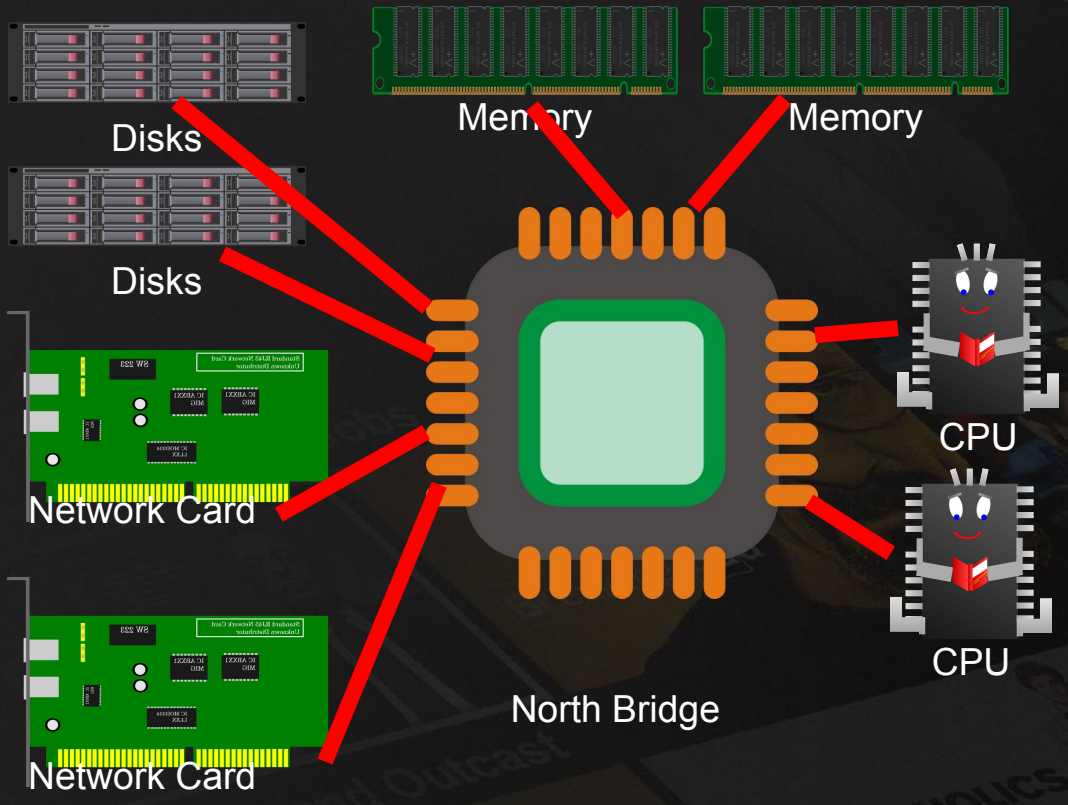
Multi Socket Before NUMA



Memory access was *UNIFORM:*

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

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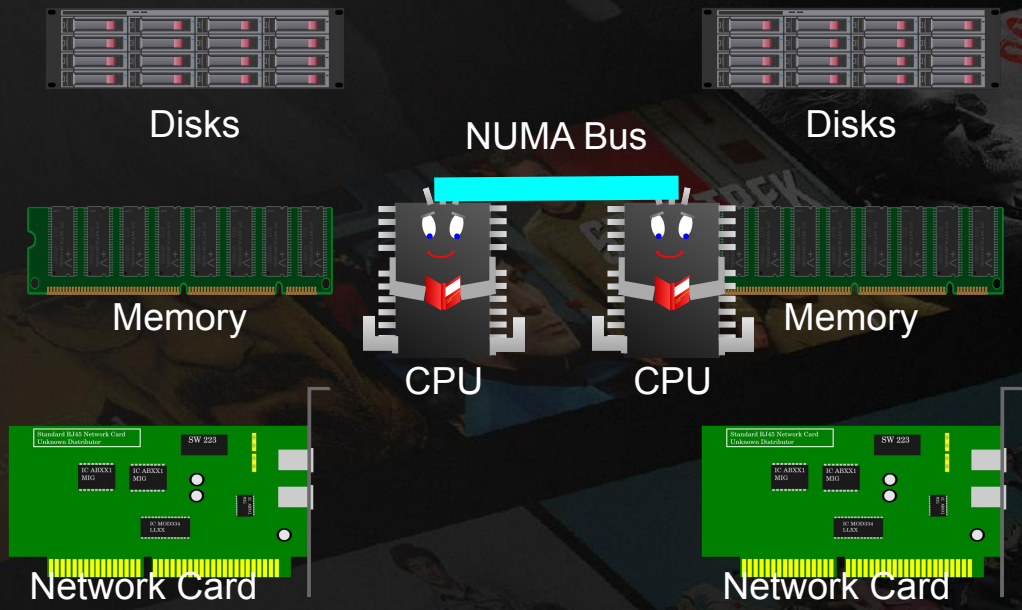
Multi Socket system with NUMA:

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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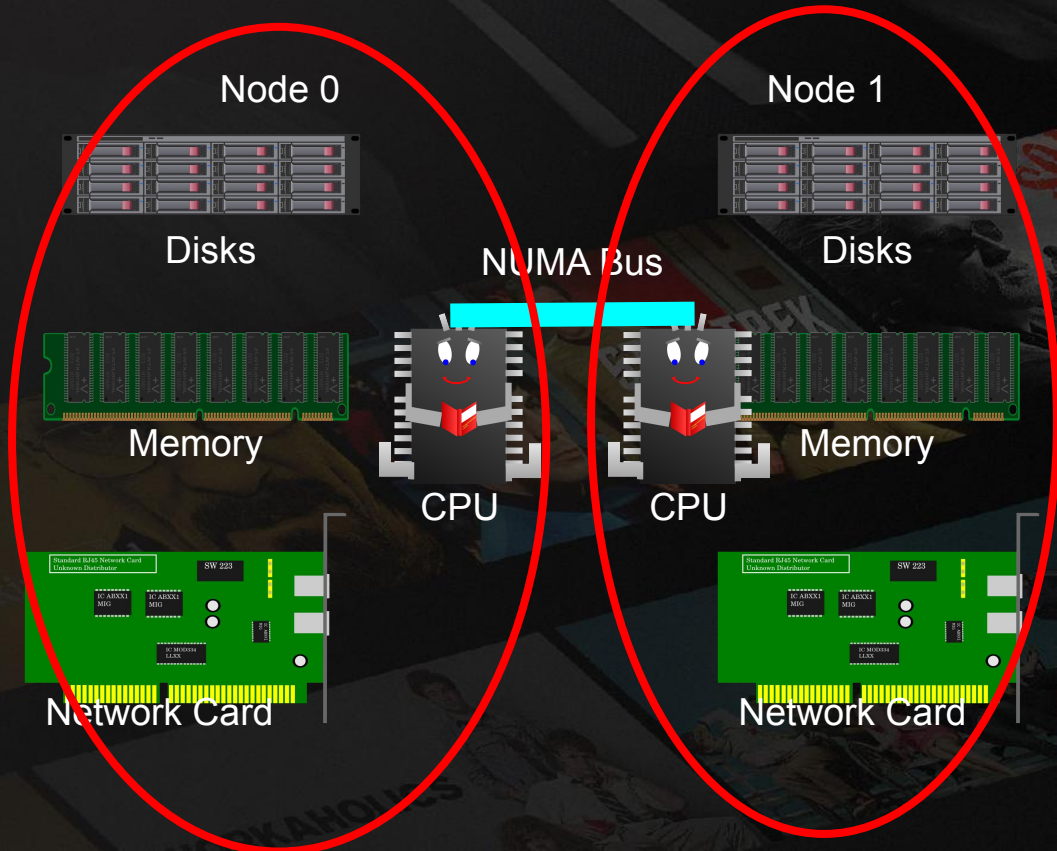
Present day NUMA:

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



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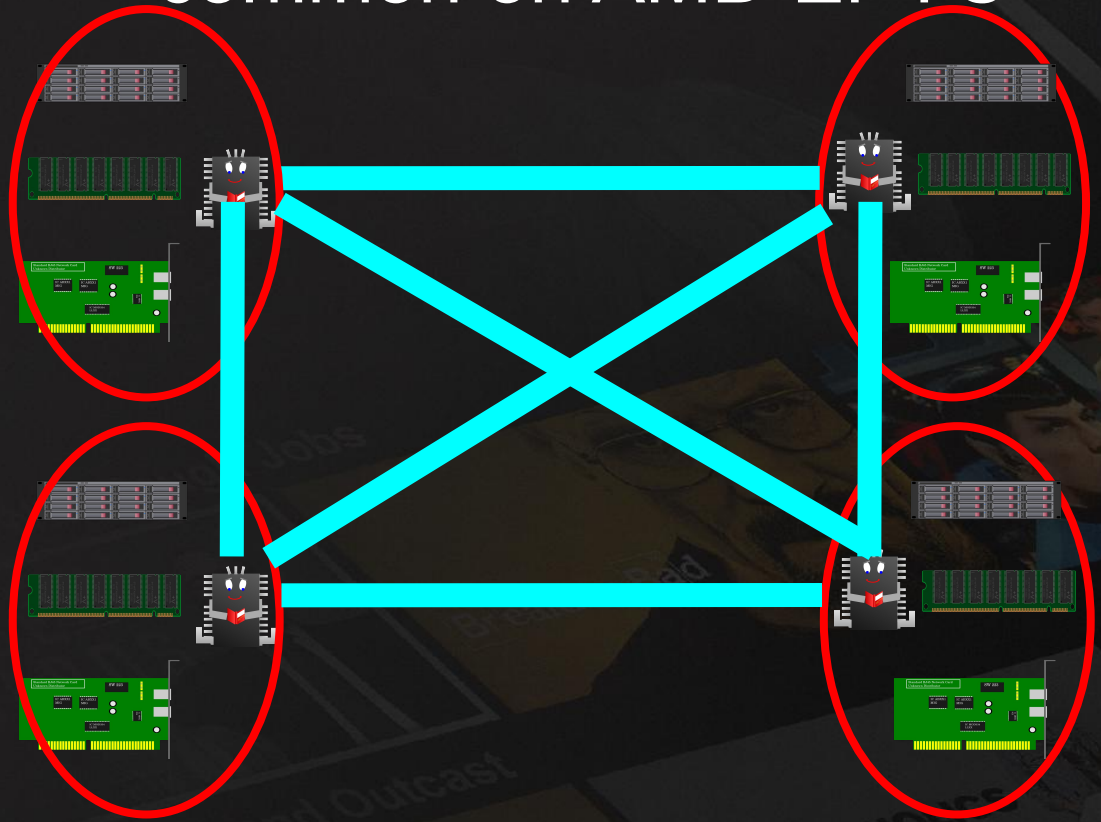
4 Node configurations are common on AMD EPYC



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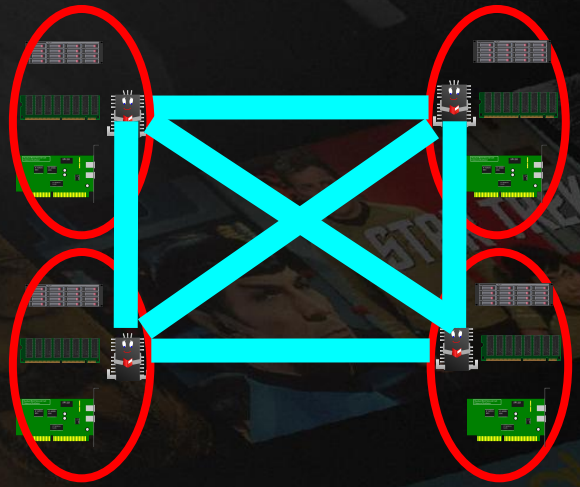
Cross-Domain costs

Latency Penalty:

- ~50ns unloaded
- Much, much, much more than 50ns loaded



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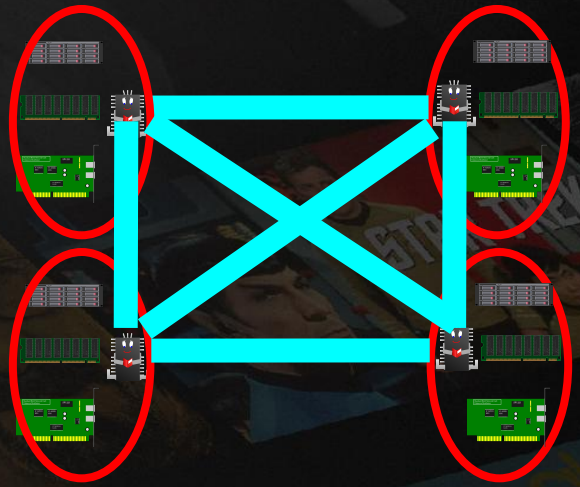
Cross-Domain costs

Bandwidth Limit:

- Intel UPI
  - ~20GB/sec per link
  - Normally 2 or 3 links
- AMD Infinity Fabric
  - ~40GB/s



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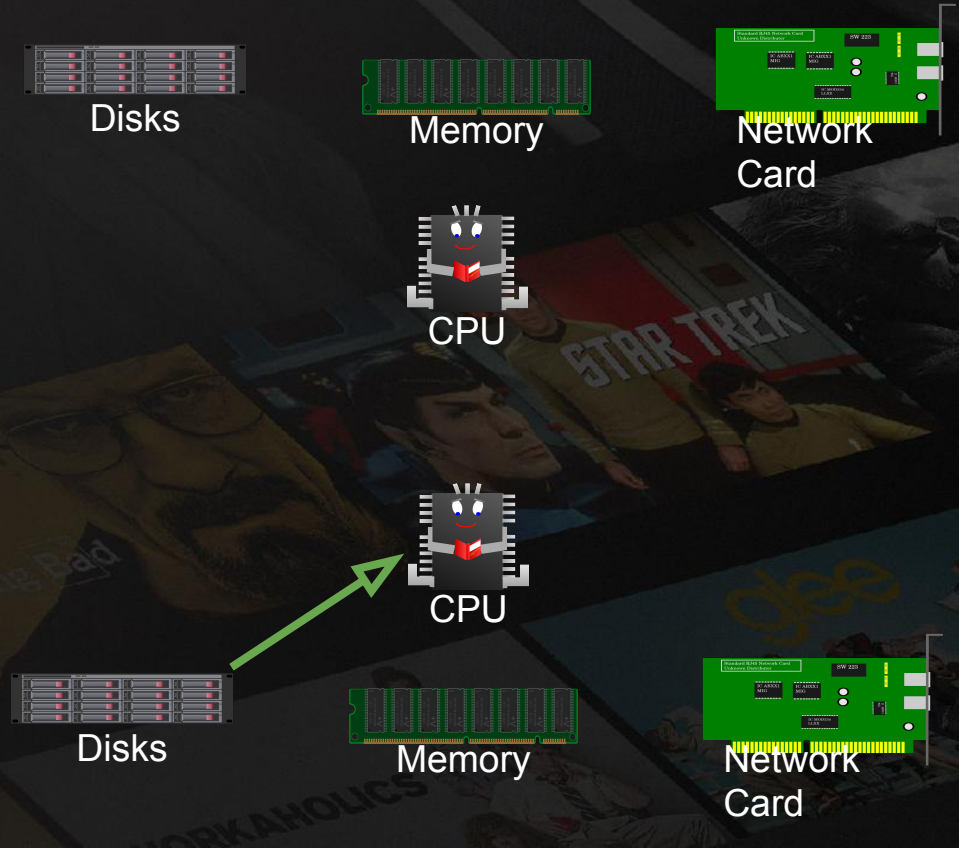
Strategy: Keep as much of our 100GB/sec of bulk data off the NUMA fabric is possible

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

NETFLIX Dual Xeon: Worst Case Data Flow

Steps to send data:

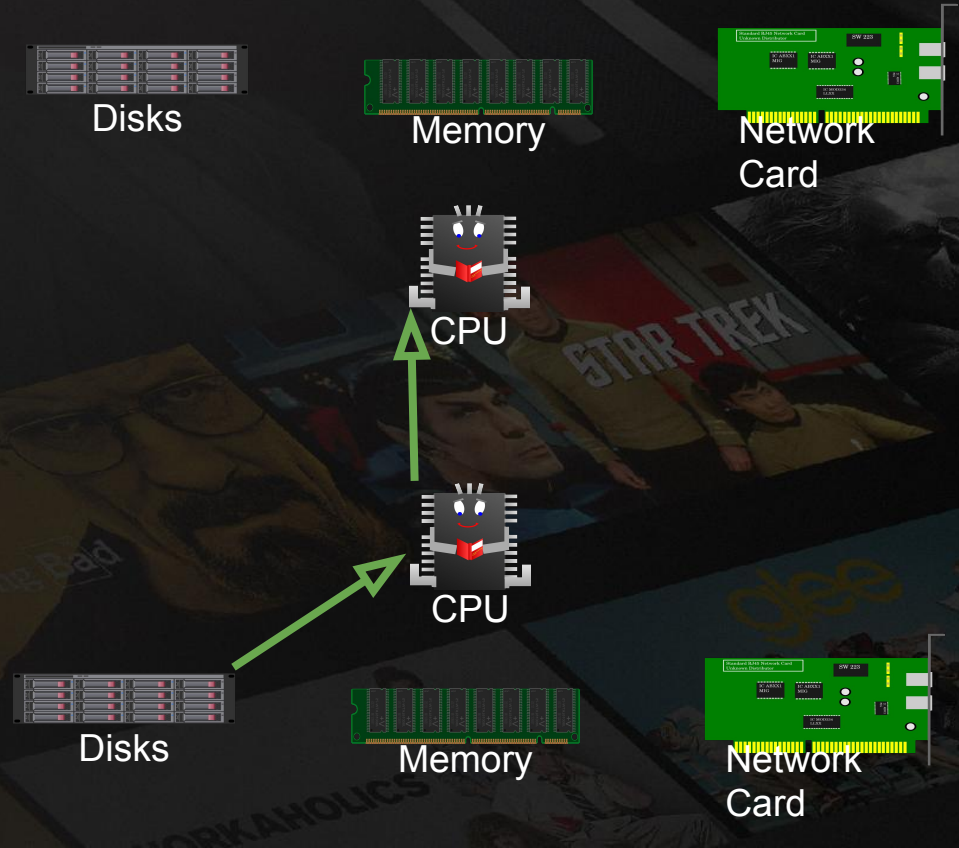
- DMA data from disk to memory



Dual Xeon: Worst Case Data Flow

Steps to send data:

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



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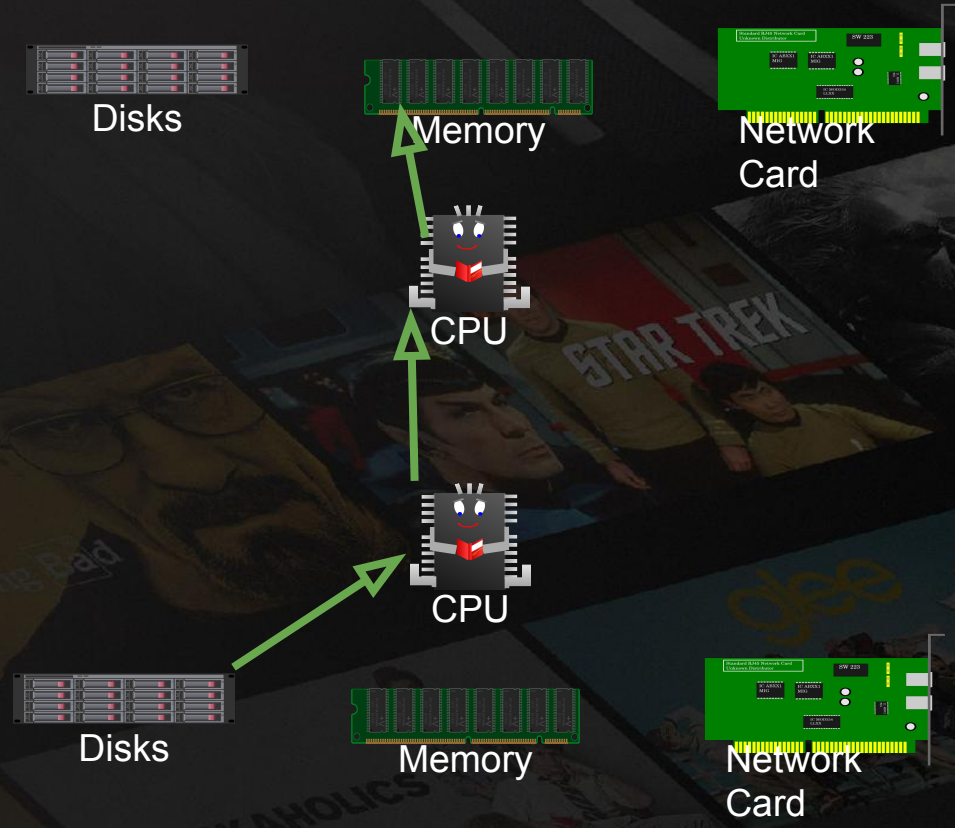
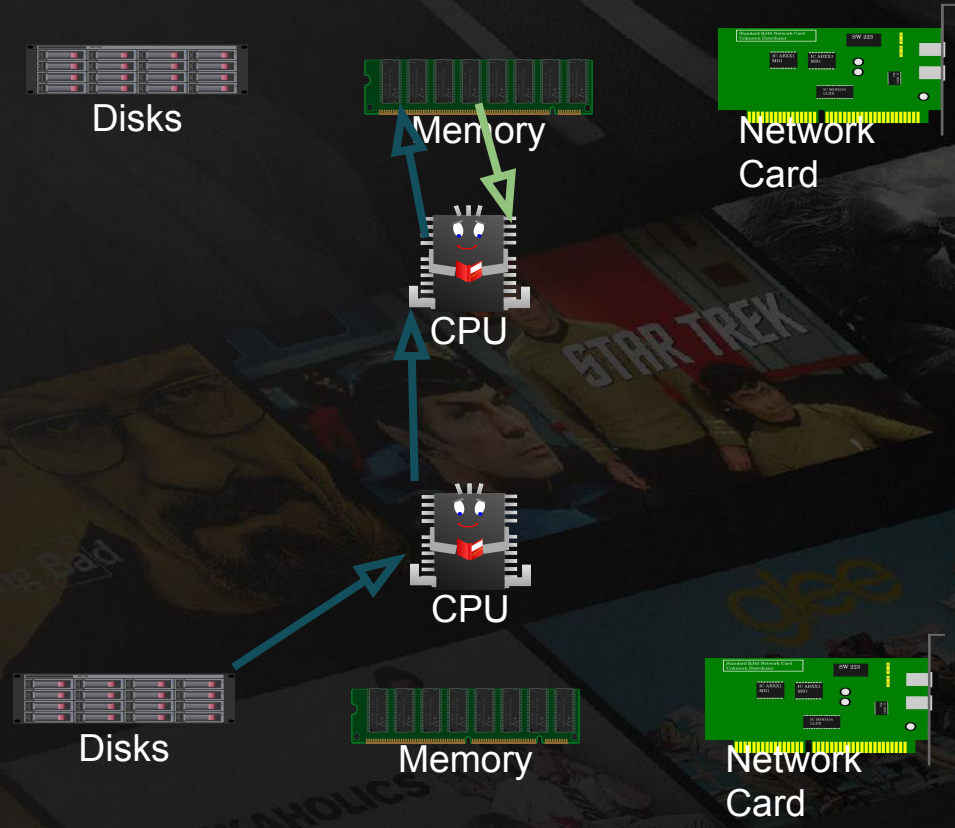


Dual Xeon: Worst Case Data Flow

Steps to send data:

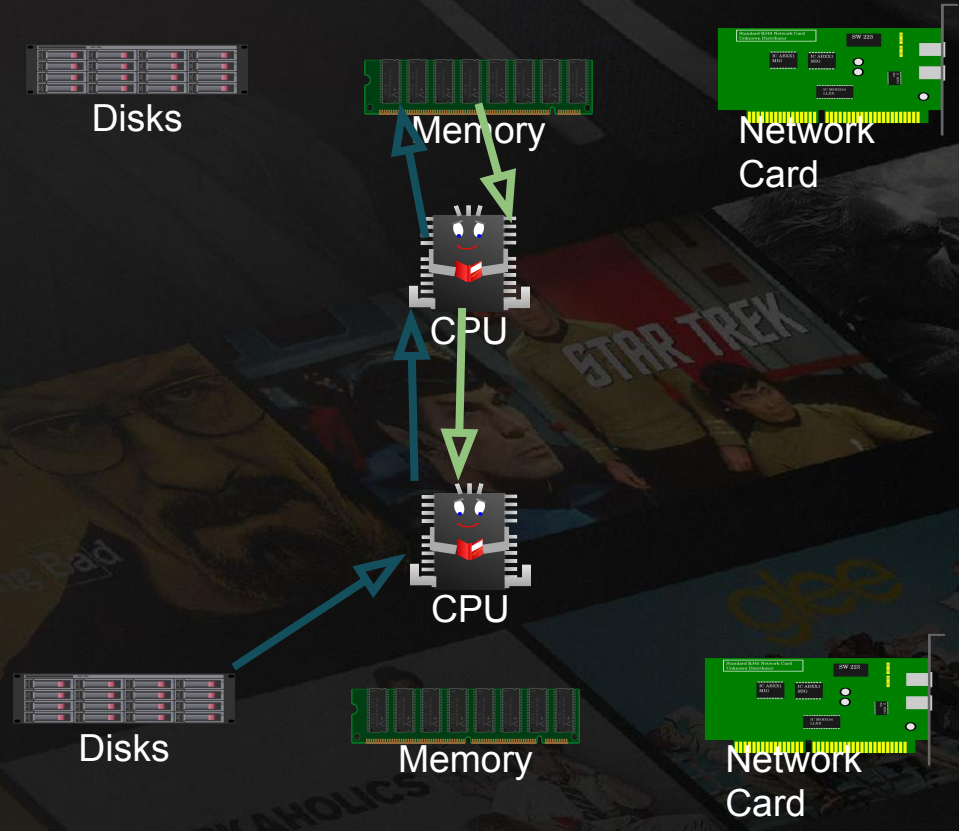
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption



Dual Xeon: Worst Case Data Flow

Steps to send data:

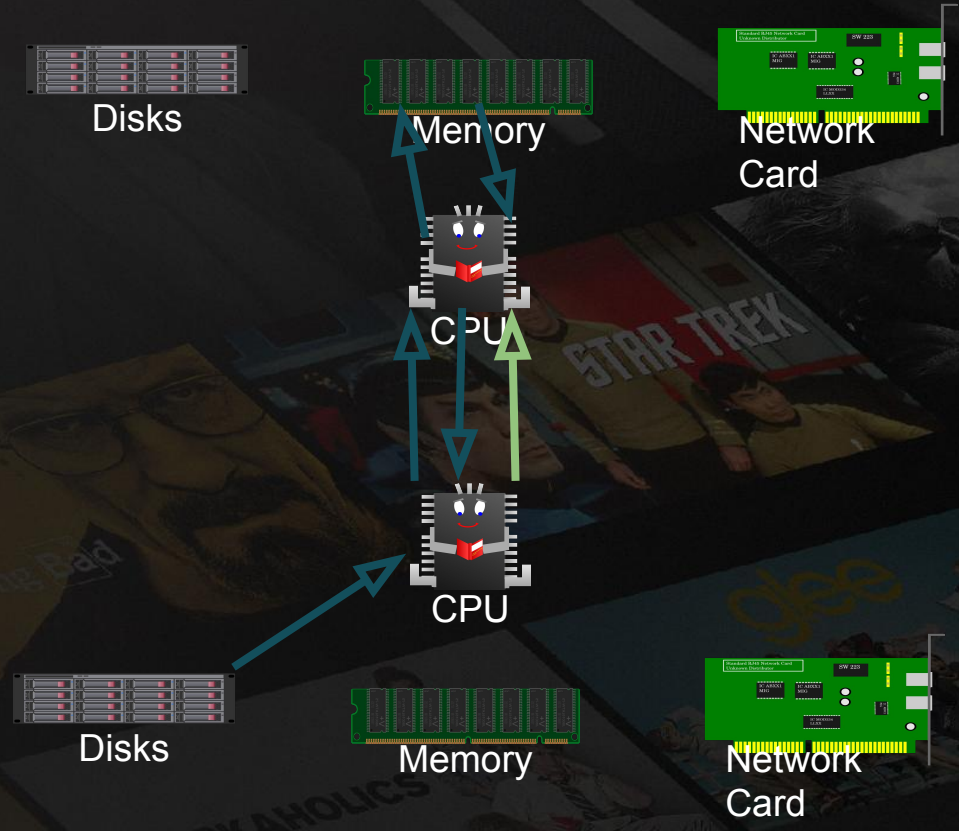
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
  - Second NUMA crossing



Dual Xeon: 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 Xeon: Worst Case Data Flow

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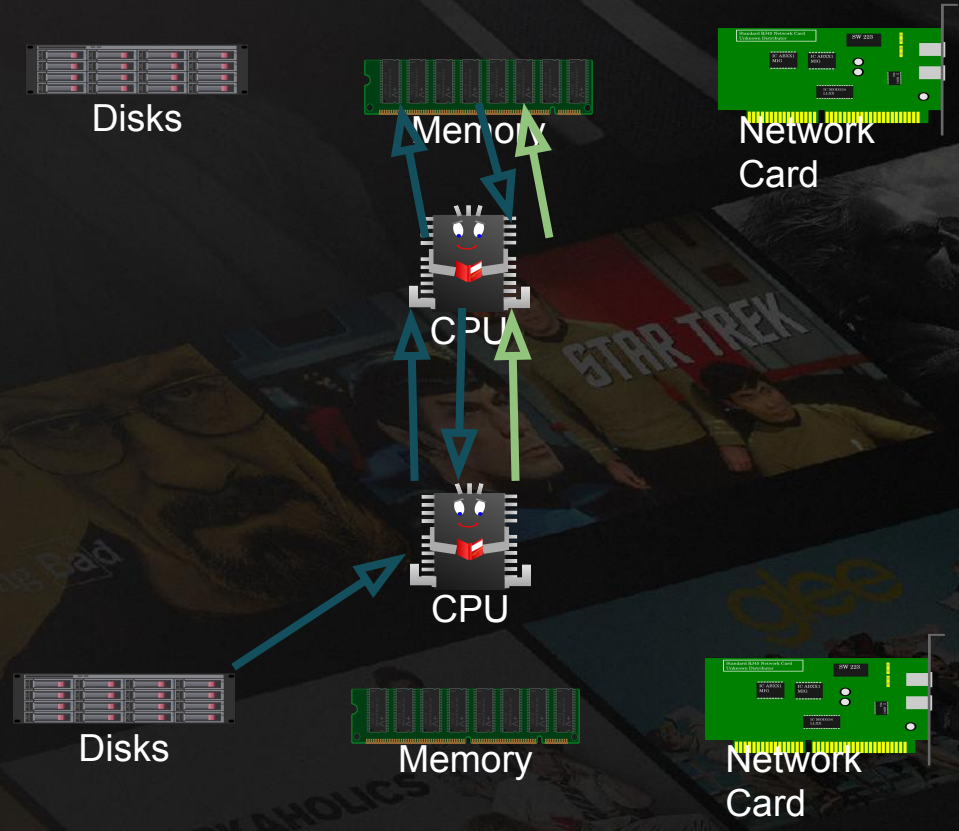
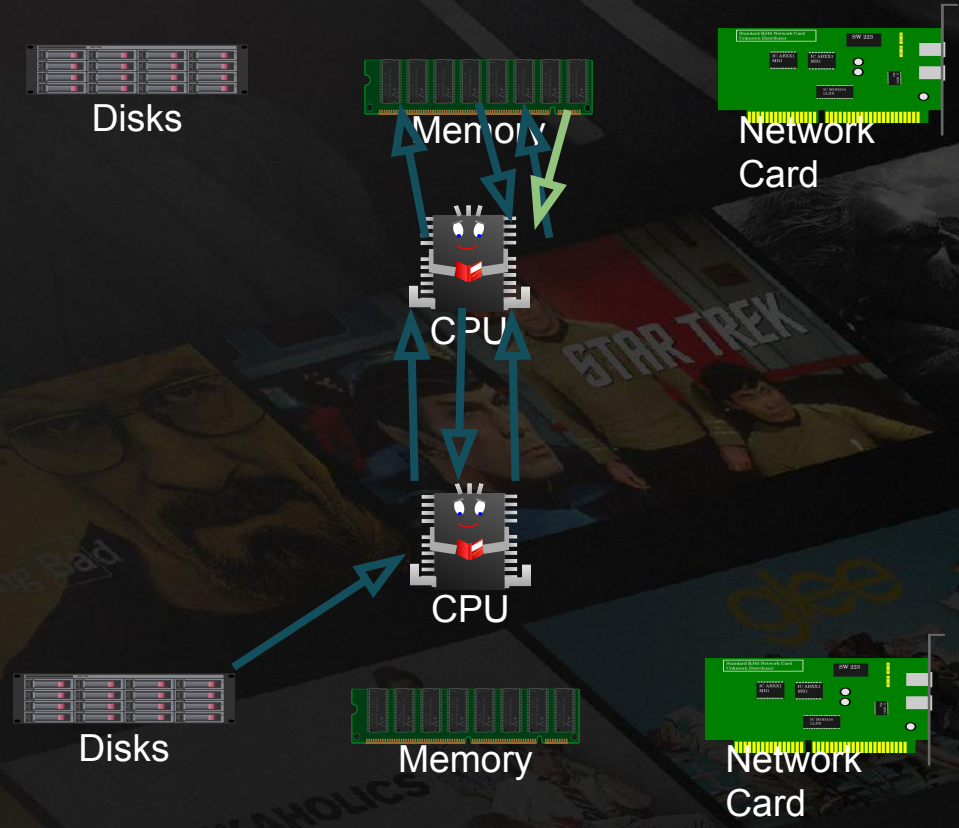


Dual Xeon: Worst Case Data Flow

Steps to send data:

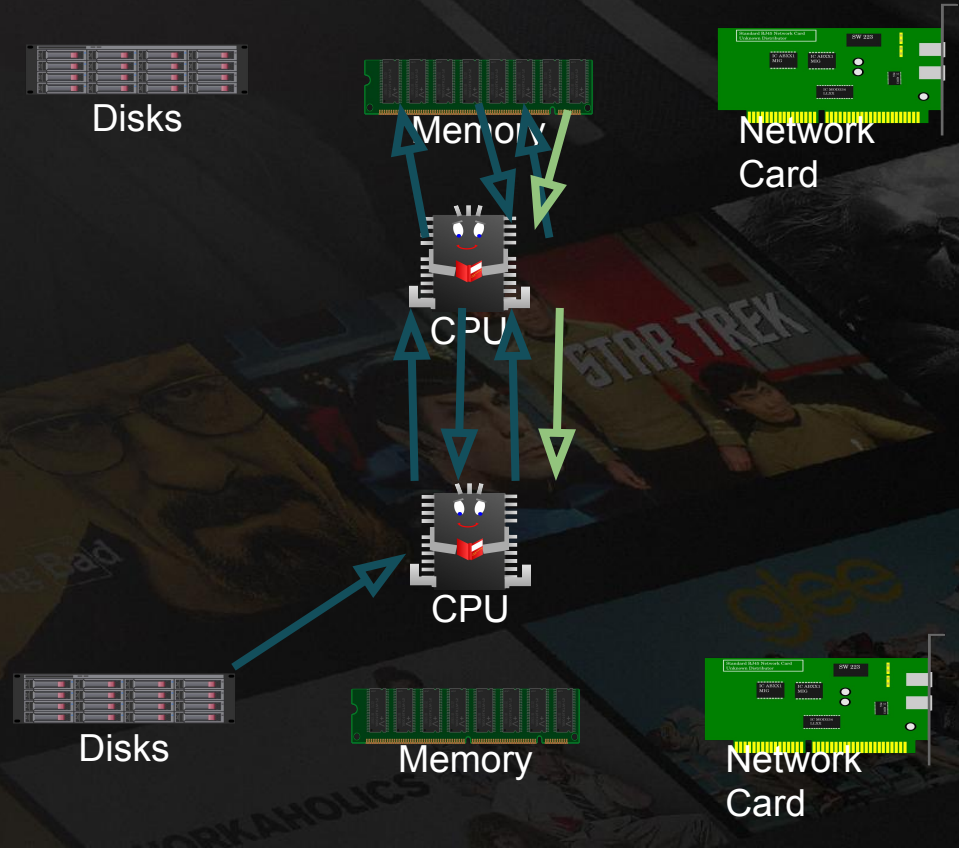
- DMA data from disk to memory
  - First NUMA bus crossing
- CPU reads data for encryption
  - Second NUMA crossing
- CPU writes encrypted data
  - Third NUMA crossing
- DMA from memory to Network



Dual Xeon: 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



Dual Xeon: Worst Case Data Flow

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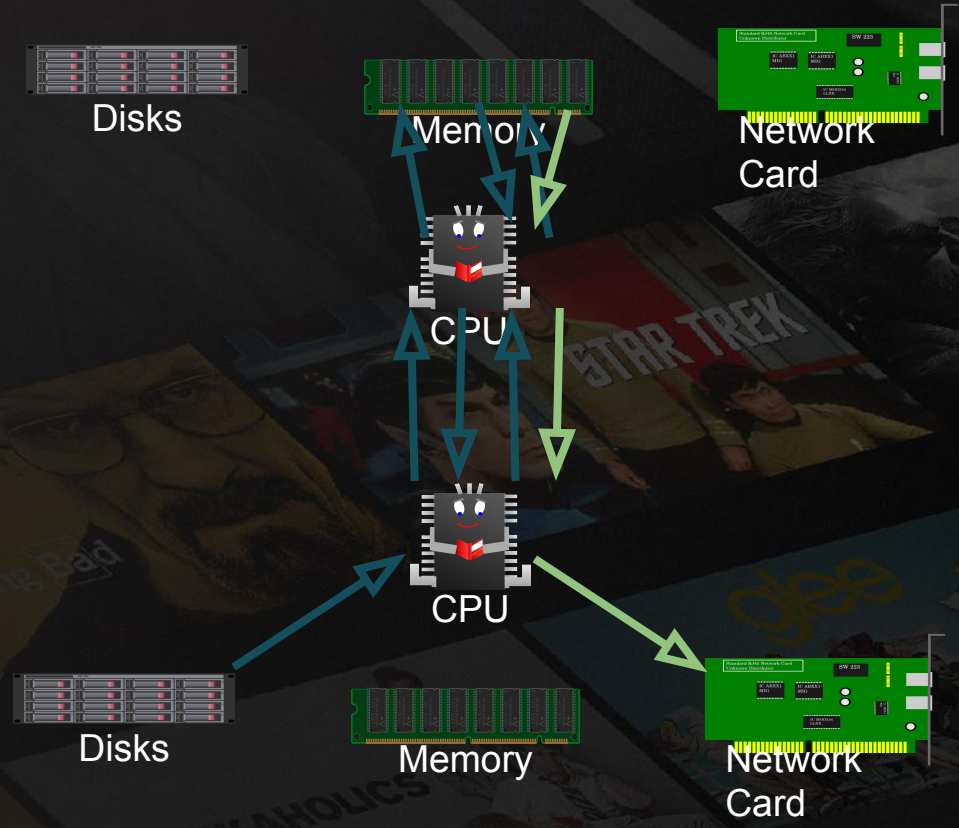
- CPU writes encrypted data
  - Third NUMA crossing
- DMA from memory to Network
  - Fourth NUMA crossing



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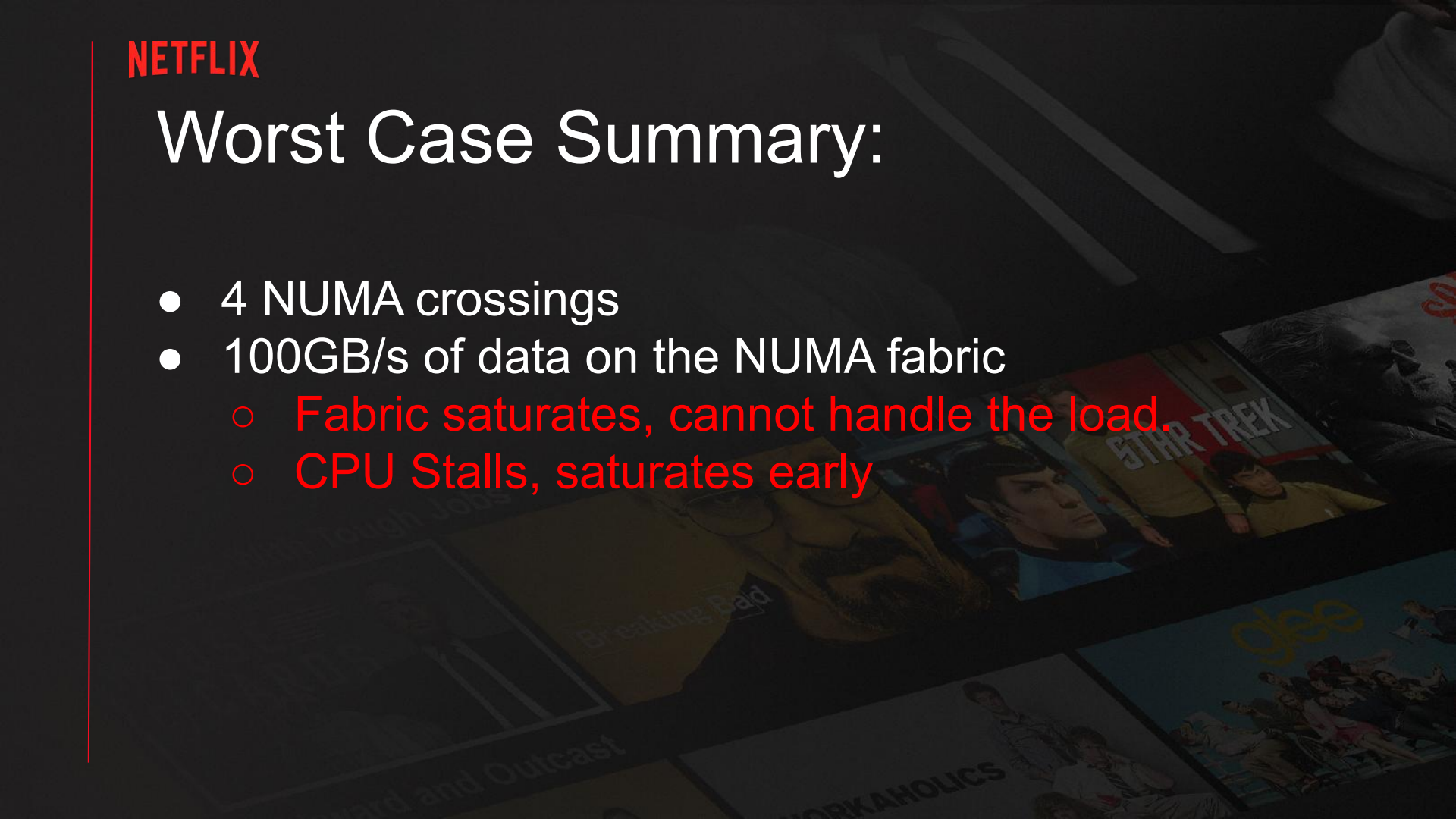
Worst Case Summary:

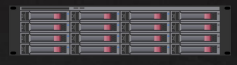
- 4 NUMA crossings
- 100GB/s of data on the NUMA fabric
  - Fabric saturates, cannot handle the load.
  - CPU Stalls, saturates early



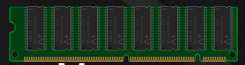
NETFLIX Dual Xeon: Best Case Data Flow

Steps to send data:

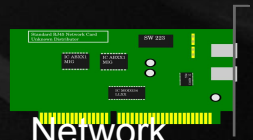
- DMA data from disk to memory



Disks



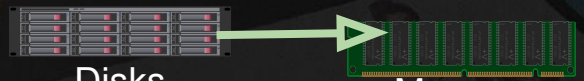
Memory



Network Card

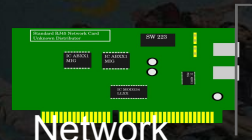
CPU

CPU



Disks

Memory

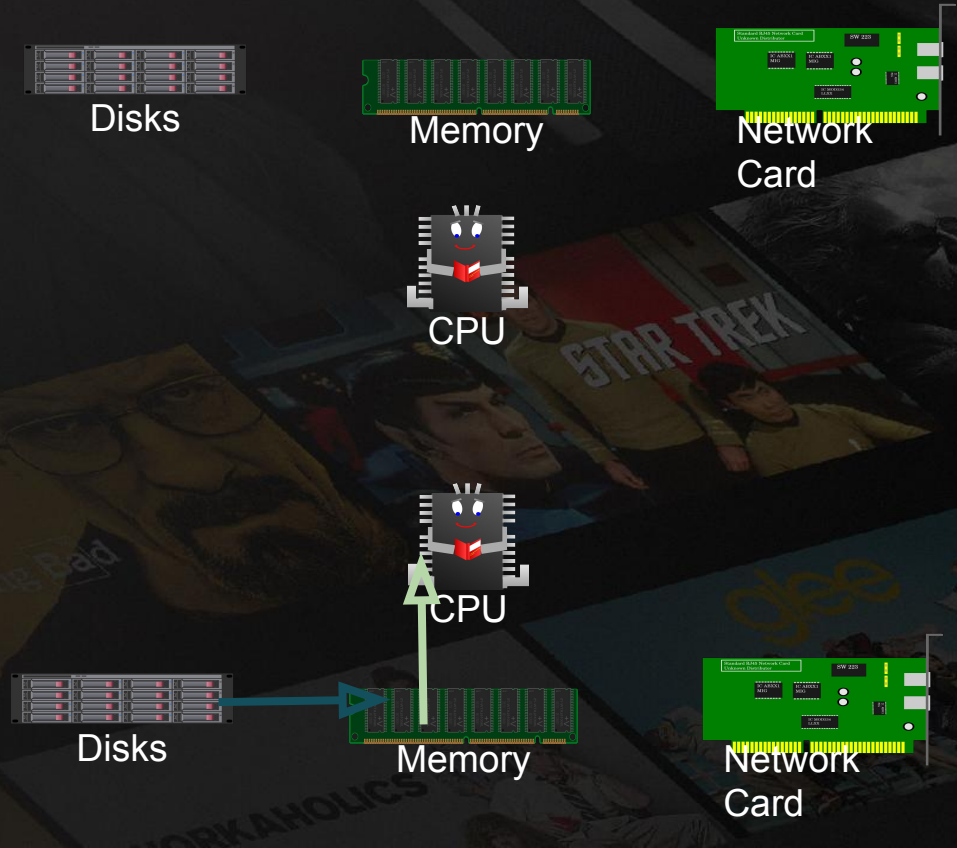


Network Card

NETFLIX Dual Xeon: Best Case Data Flow

Steps to send data:

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



Dual Xeon: Best Case Data Flow

Steps to send data:

- DMA data from disk to memory
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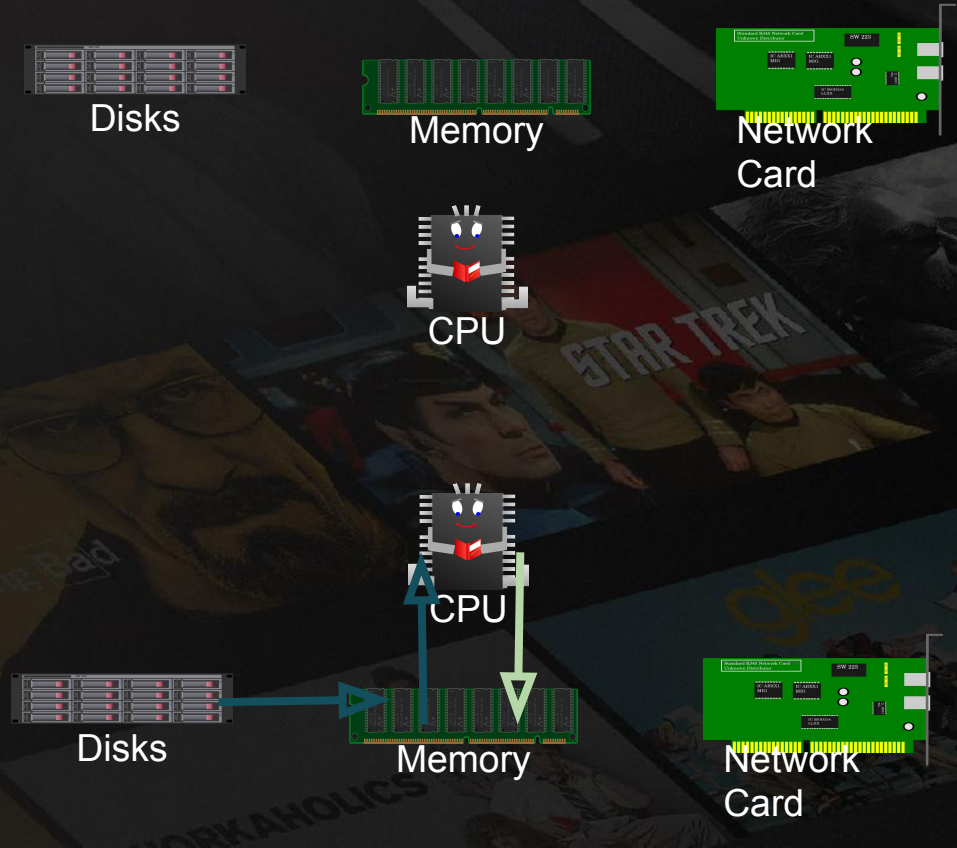
- CPU Writes encrypted data

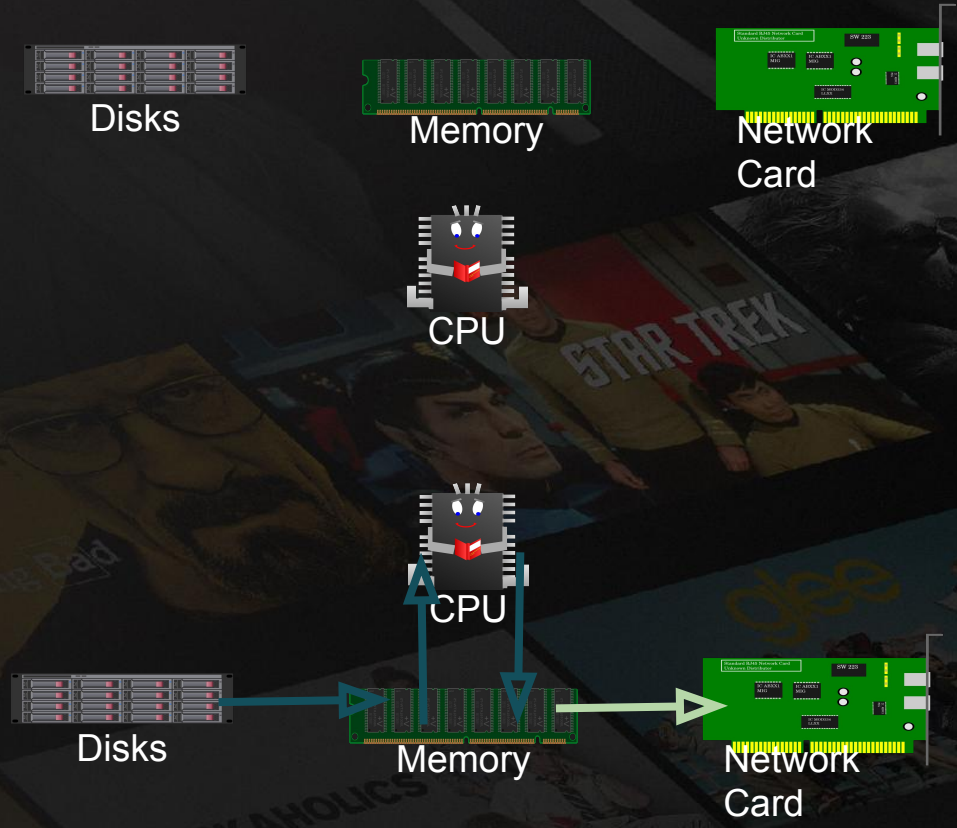


NETFLIX Dual Xeon: Best Case Data Flow

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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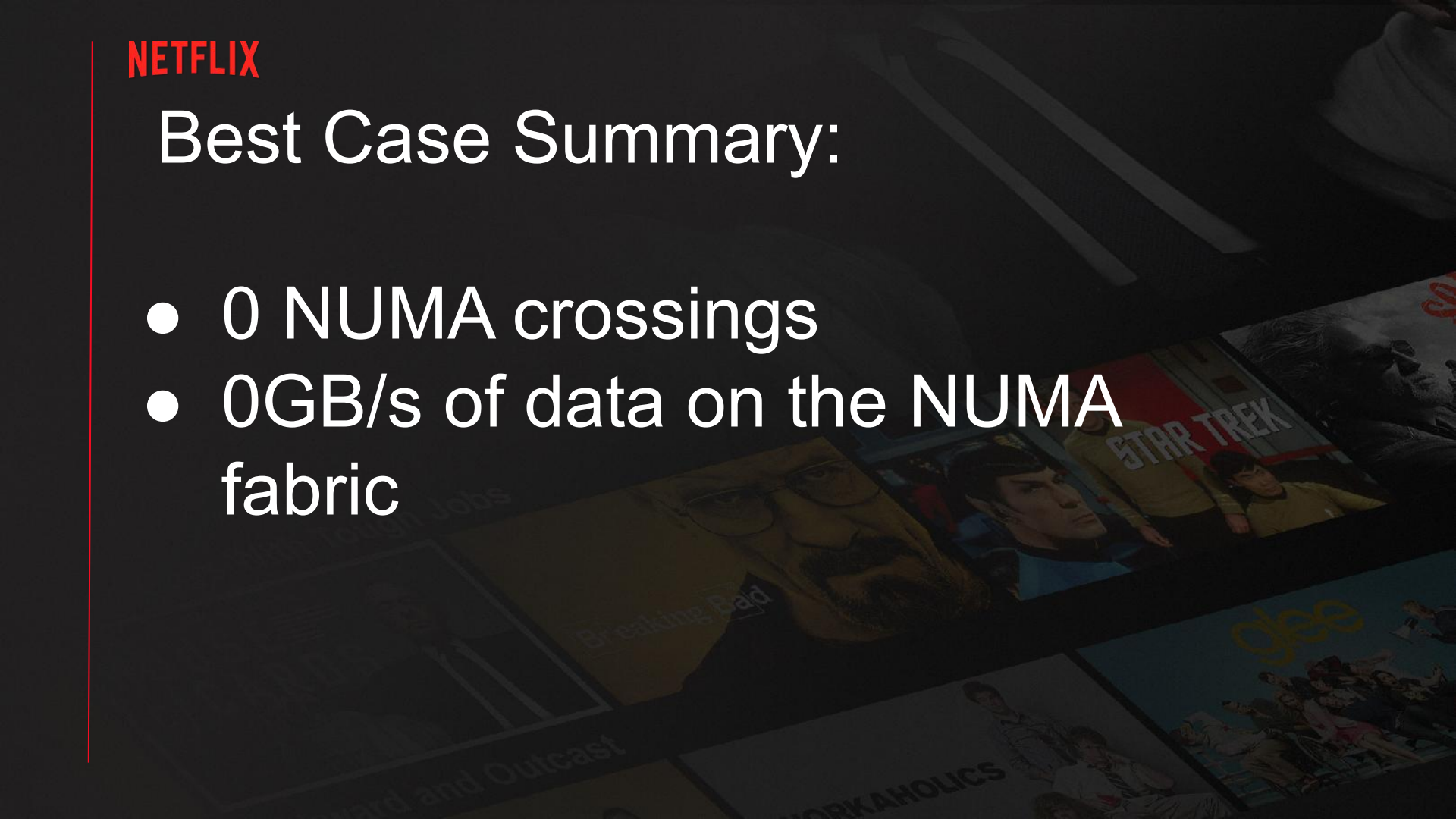
Best Case Summary:

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



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

1 bhyve VM per NUMA Node, passing through NIC and disks?

- Doubles IPv4 address use
- More than 2x AWS cloud management overhead
  - Managing one physical & two virtual machines
- non-starter

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

Content aware steering using multiple IP addresses?

- Doubles IPv4 address use
- Increases AWS cloud management overhead
- non-starter

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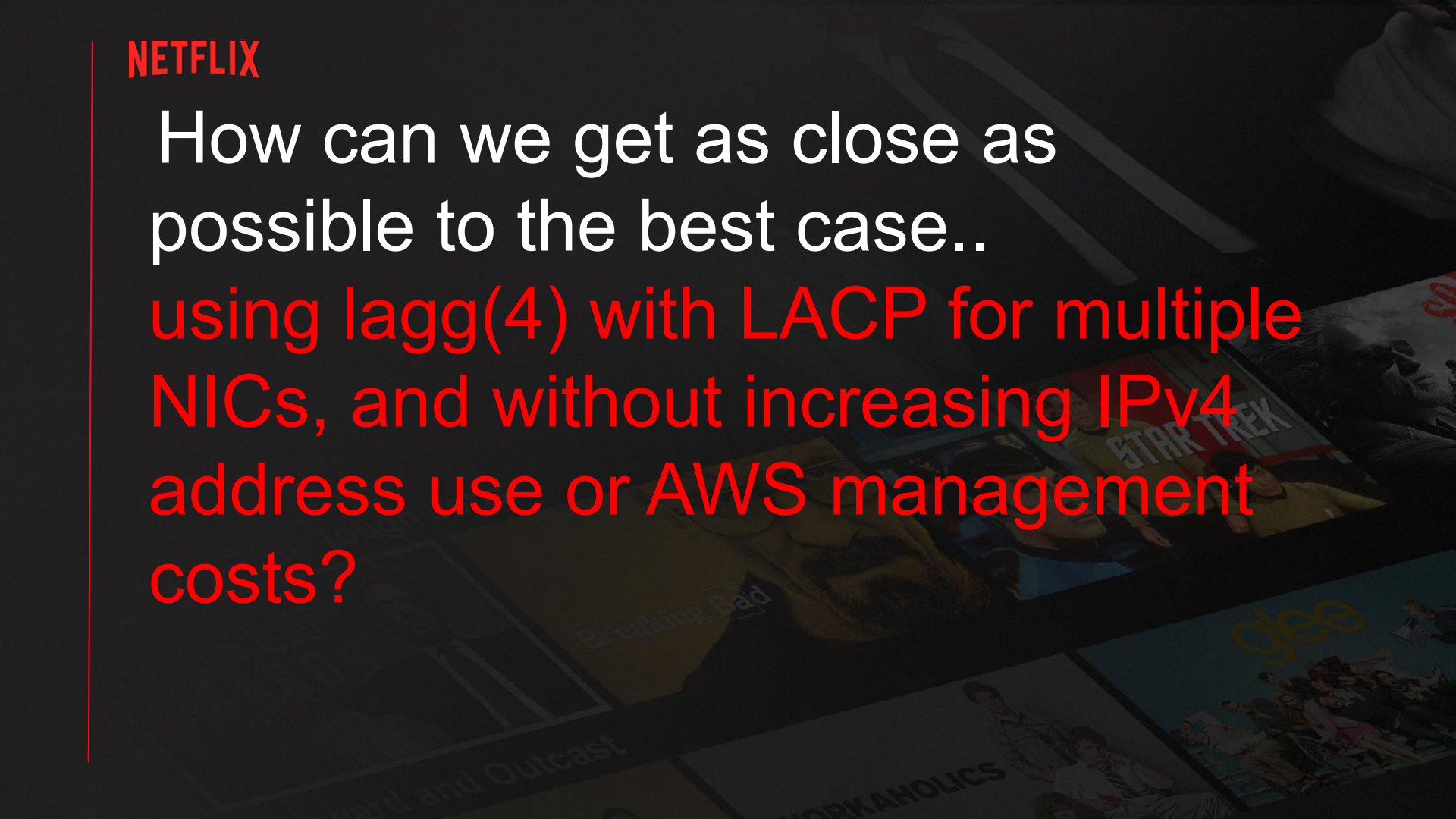
How can we get as close as possible to the best case..

using lagg(4) with LACP for multiple NICs, and without increasing IPv4 address use or AWS management costs?



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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

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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!

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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!

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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 RACK / BBR TCP pacers with domain affinity
- Choose local lagg(4) egress port

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Associate network connections with NUMA nodes:

- Add a NUMA domain field to struct mbuf
  - r346281
- Embed device's NUMA domain struct ifnet
  - r346579
- Drivers tag received mbufs w/NUMA domain
  - r346677
- Add NUMA domain to struct inpcb
  - r346677

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Associate network connections with NUMA nodes (continued):

- Record NUMA domain into struct inpcb when TCP connection is “born”
  - r346677
- Ensure that a connection is given to an nginx worker bound to the correct domain
  - More on this later

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Allocate NUMA local memory to back video files

- Surprisingly easy.. Just run nginx with worker_cpu_affinity set to auto
- Default first-touch policy will cause the VM system to allocate pages on the same node as the nginx worker
- Thanks to kib@ and alc@ for pointing out a large patch that I had to sendfile() and vm_page_alloc() was not needed

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Allocate local memory for TLS crypto destination buffers & do SW crypto locally

- kTLS worker threads are run with domain affinity
- kTLS worker threads have a domain allocation policy to prefer the local NUMA domain
  - This ensures crypto destination buffers are allocated on the local NUMA domain
  - D21648

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How to choose local lagg(4) egress port?

- Outgoing mbufs tagged with NUMA domain of TCP connection
  - r346677
- Lagg ports are organized into a hierarchical model, where we limit our choice of NICs to the set of NICs on the desired NUMA domain. (when ifconfig lagg0 use_numa is set)
  - r347055

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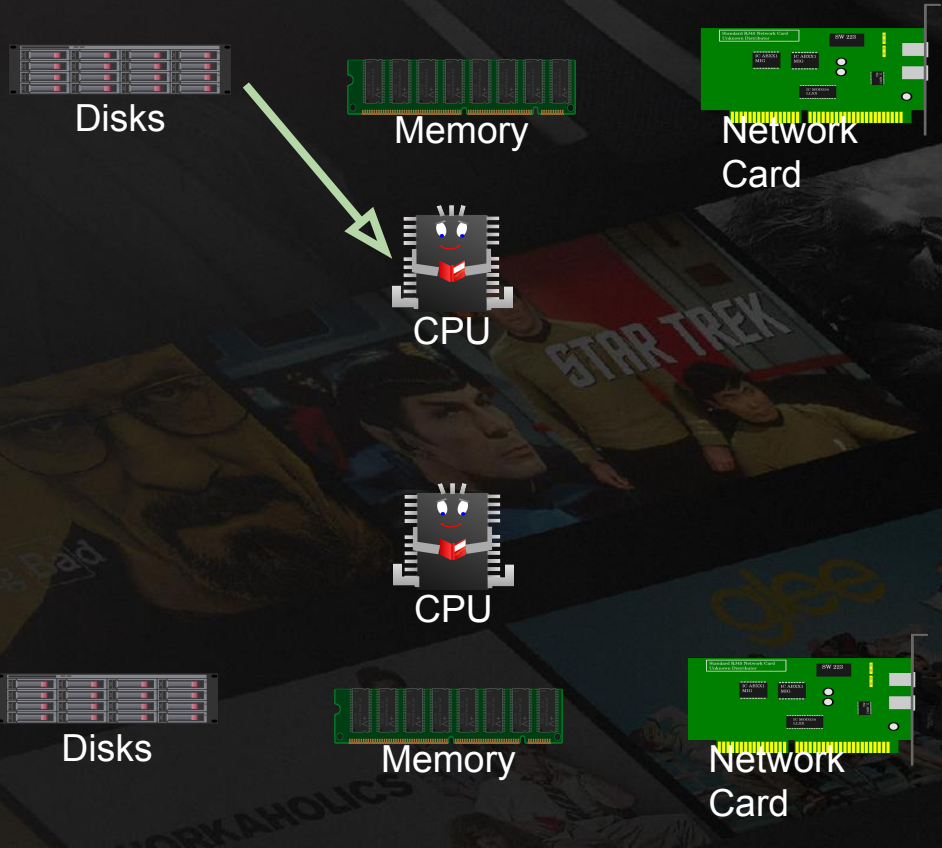
How to choose the correct nginx worker?

- Augment SO_REUSEPORT to make a new TCP_REUSEPORT_NUMA socket option
  - SO_REUSEPORT allows multiple threads / processes to share a listen socket
  - TCP_REUSEPORT_NUMA causes incoming connections to be filtered to only listen sockets on the same domain (with a fallback if there are no listeners on the same domain)
    - D21636

Dual Xeon: Worst Case Data Flow with NUMA siloing

Steps to send data:

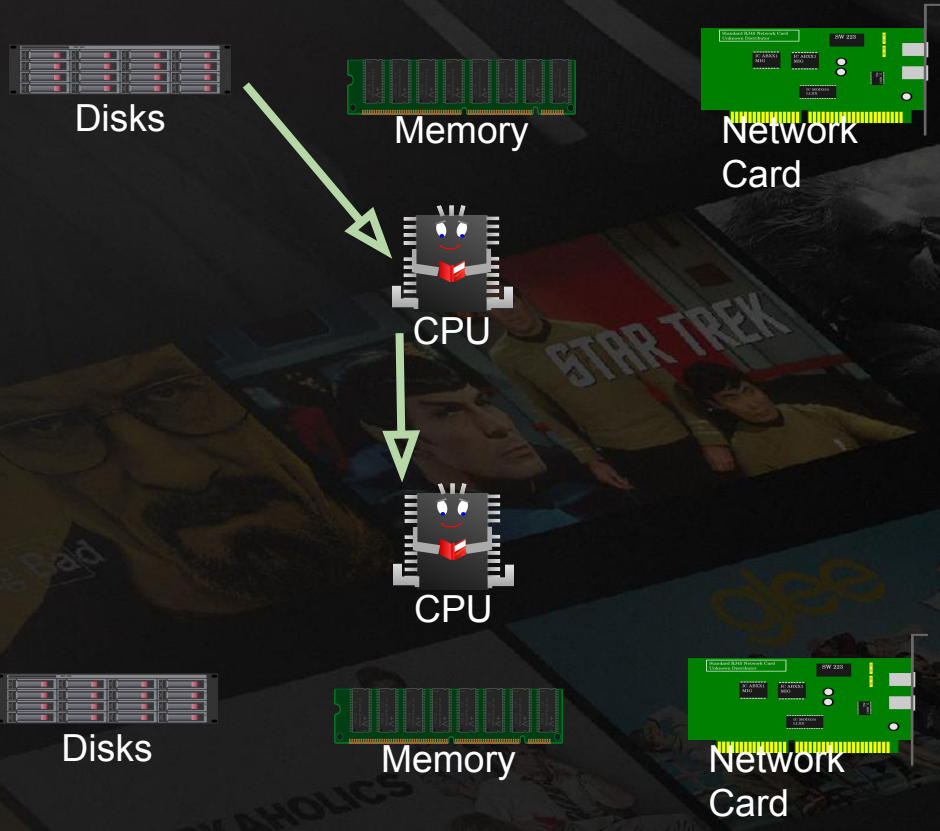
- DMA data from disk to memory



Dual Xeon: Worst Case Data Flow with NUMA siloing

Steps to send data:

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



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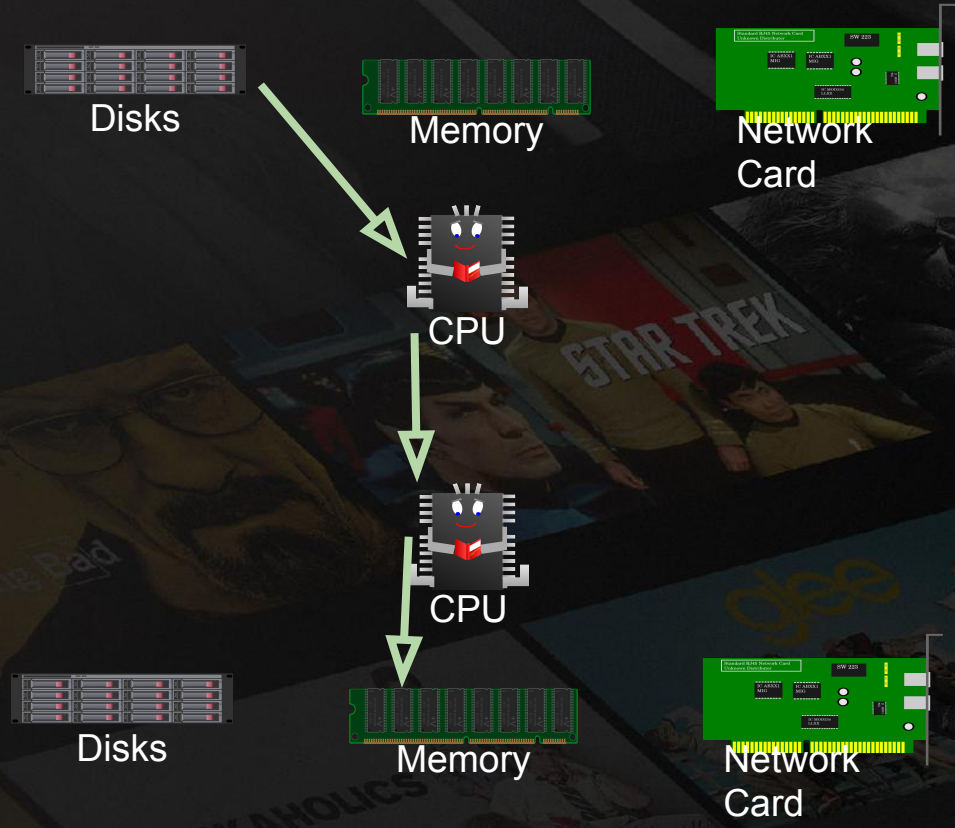
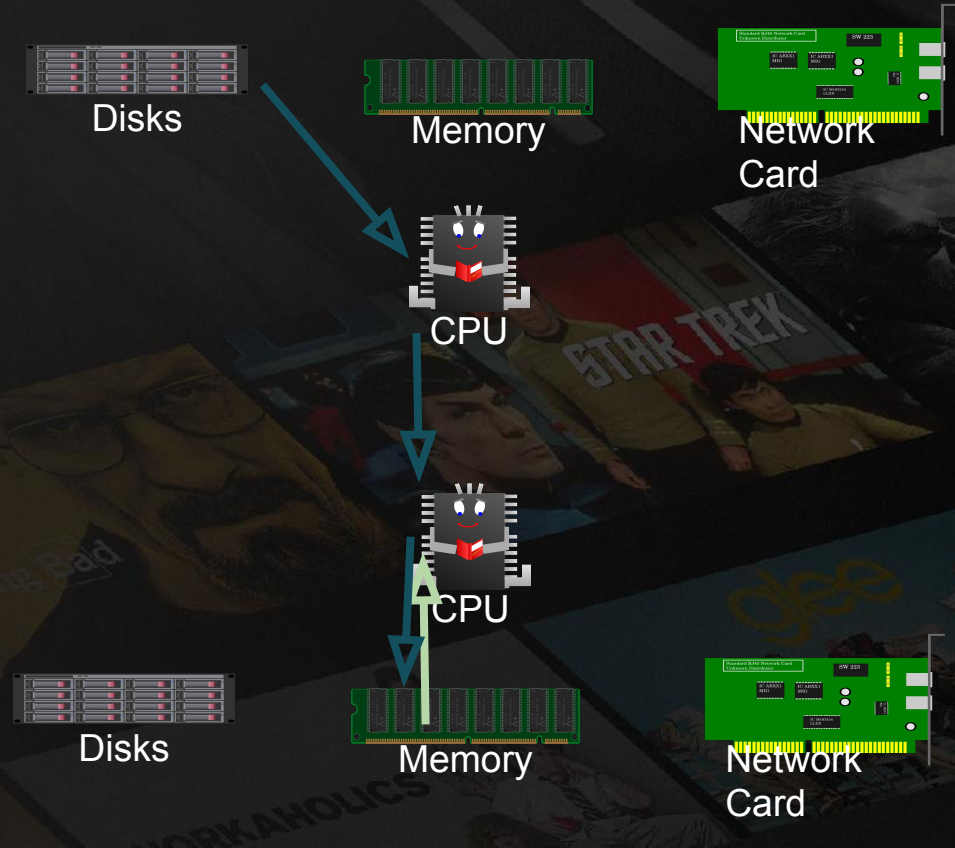


Dual Xeon: Worst Case Data Flow with NUMA siloing

Steps to send data:

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



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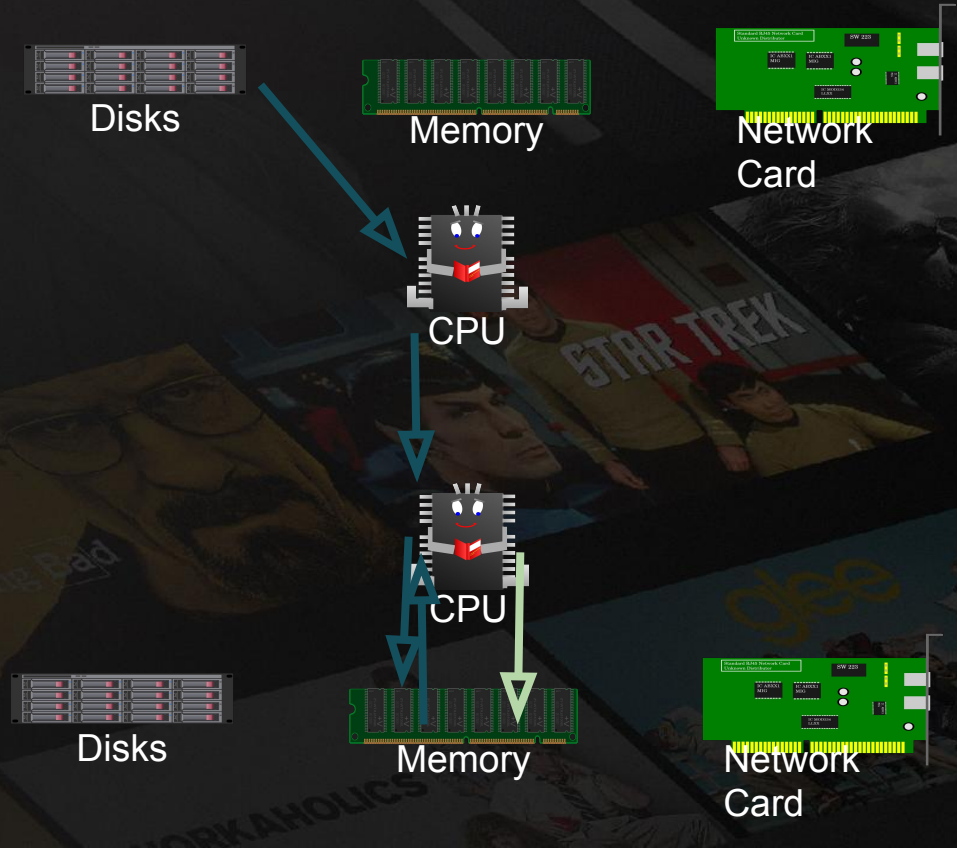
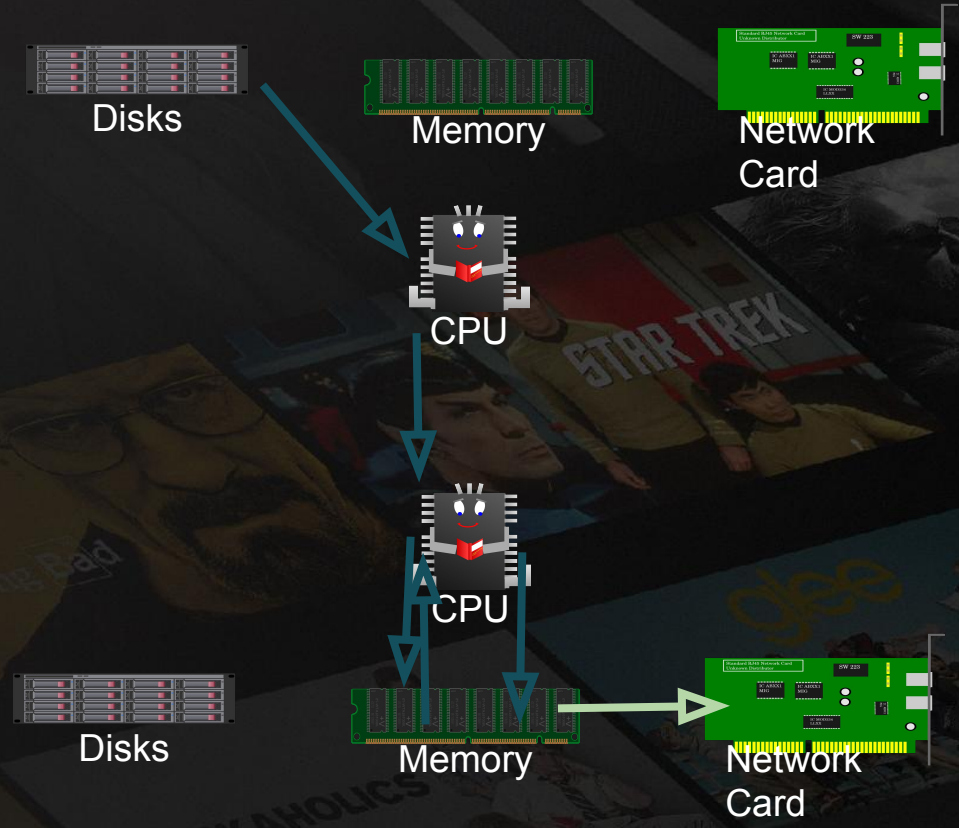


Dual Xeon: Worst Case Data Flow with NUMA siloing

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

1 NUMA bus crossing!



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Worst Case Summary:

- 1 NUMA crossing on average
  - 100% of disk reads across NUMA
- 25GB/s of data on the NUMA fabric
  - Still much less than 40GB/sec fabric bandwidth

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Average Case Summary Xeon (2 NUMA nodes):

- 0.5 NUMA crossings on average
  - 50% of disk reads across NUMA
- 12.5GB/s of data on the NUMA fabric
  - CPU does not saturate, we exceed 190Gb/s

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Average Case Summary EPYC (4 NUMA nodes):

- 0.75 NUMA crossings on average
  - 75% of disk reads across NUMA
- 18.75GB/s of data on the NUMA fabric
  - CPU does not saturate, we exceed 190Gb/s

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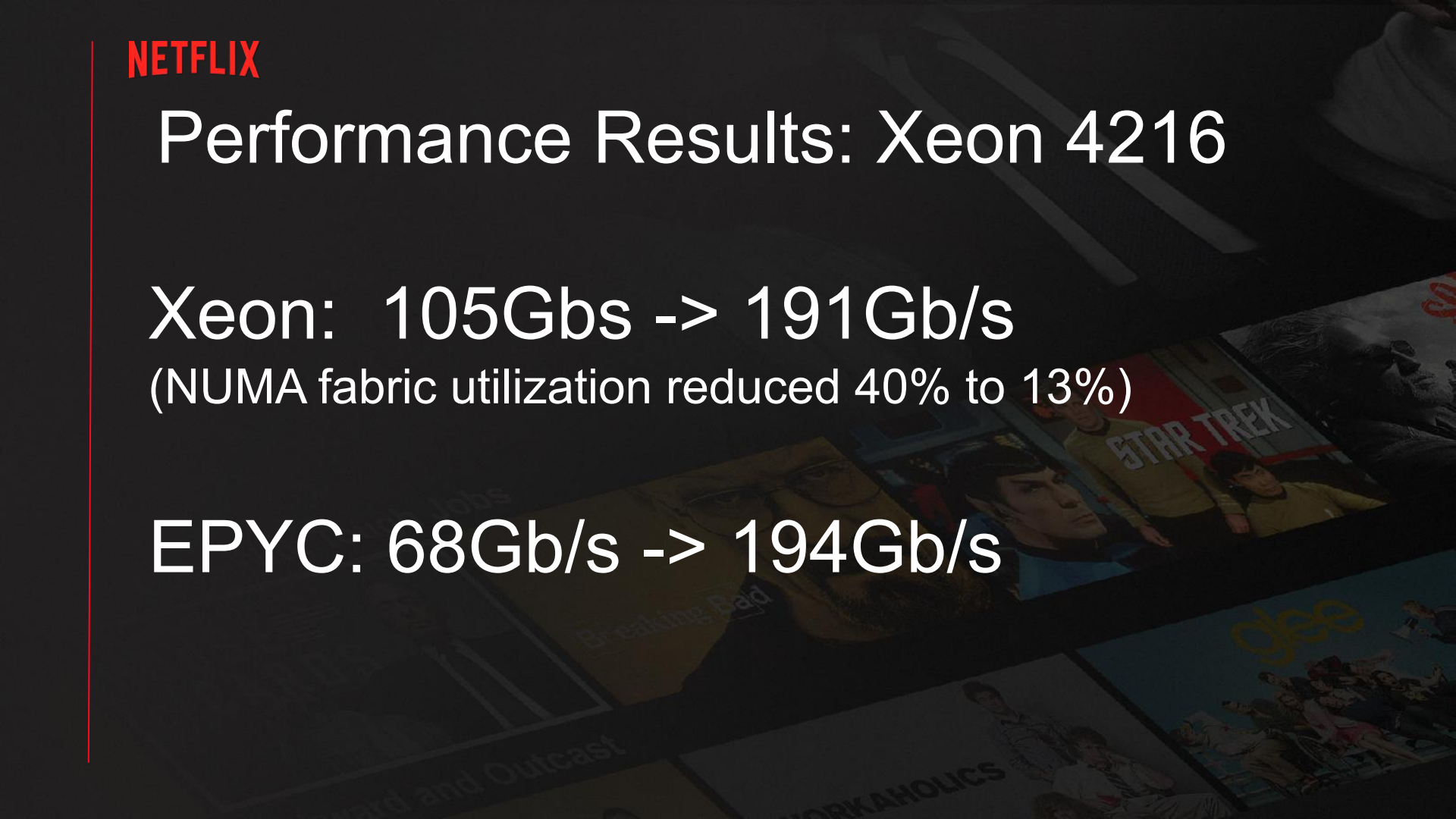
Performance Results: Xeon 4216

Xeon: 105Gbs -> 191Gb/s

(NUMA fabric utilization reduced 40% to 13%)

EPYC: 68Gb/s -> 194Gb/s



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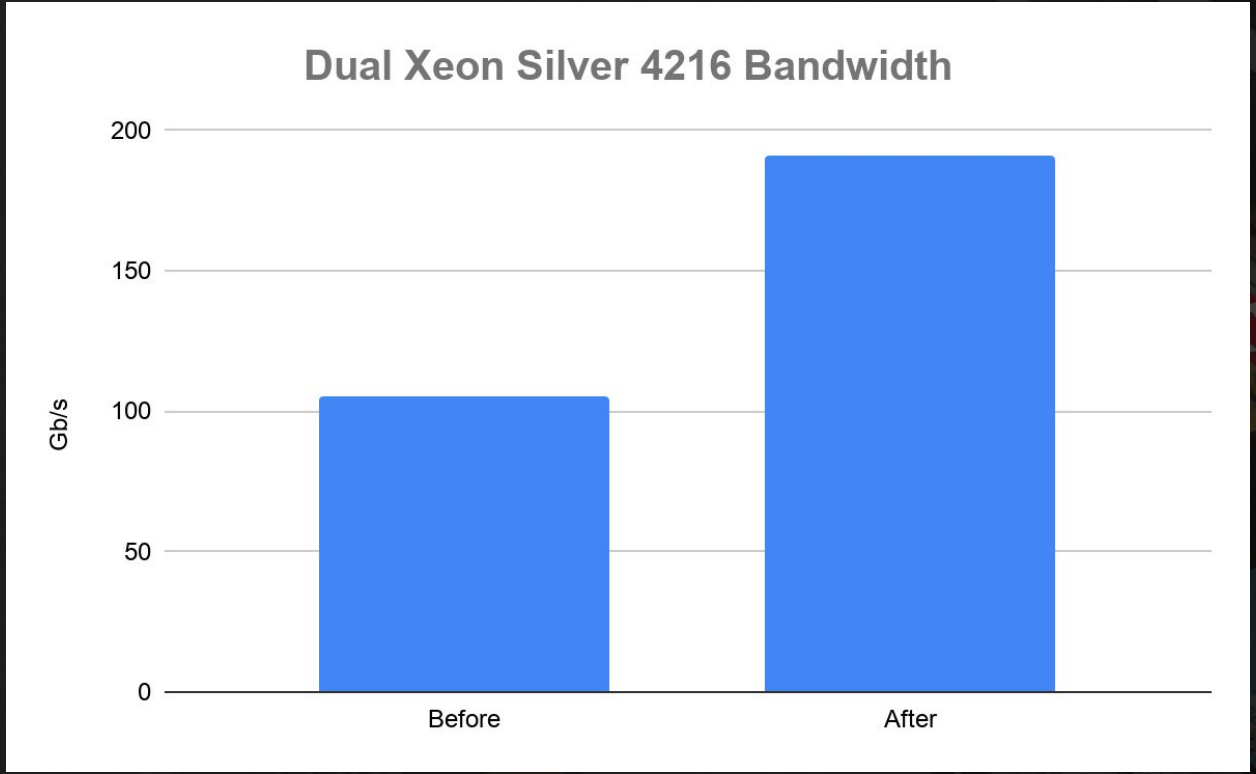
Performance Results: Intel



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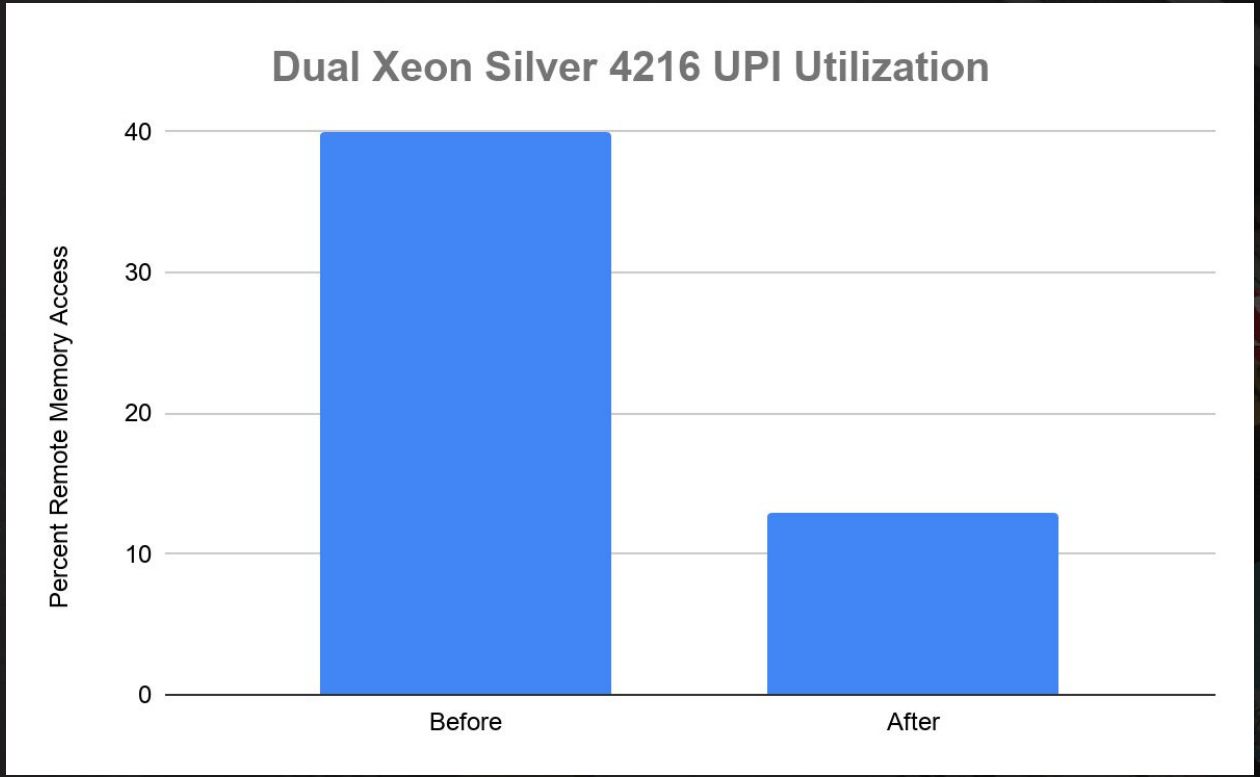
Performance Results: Intel



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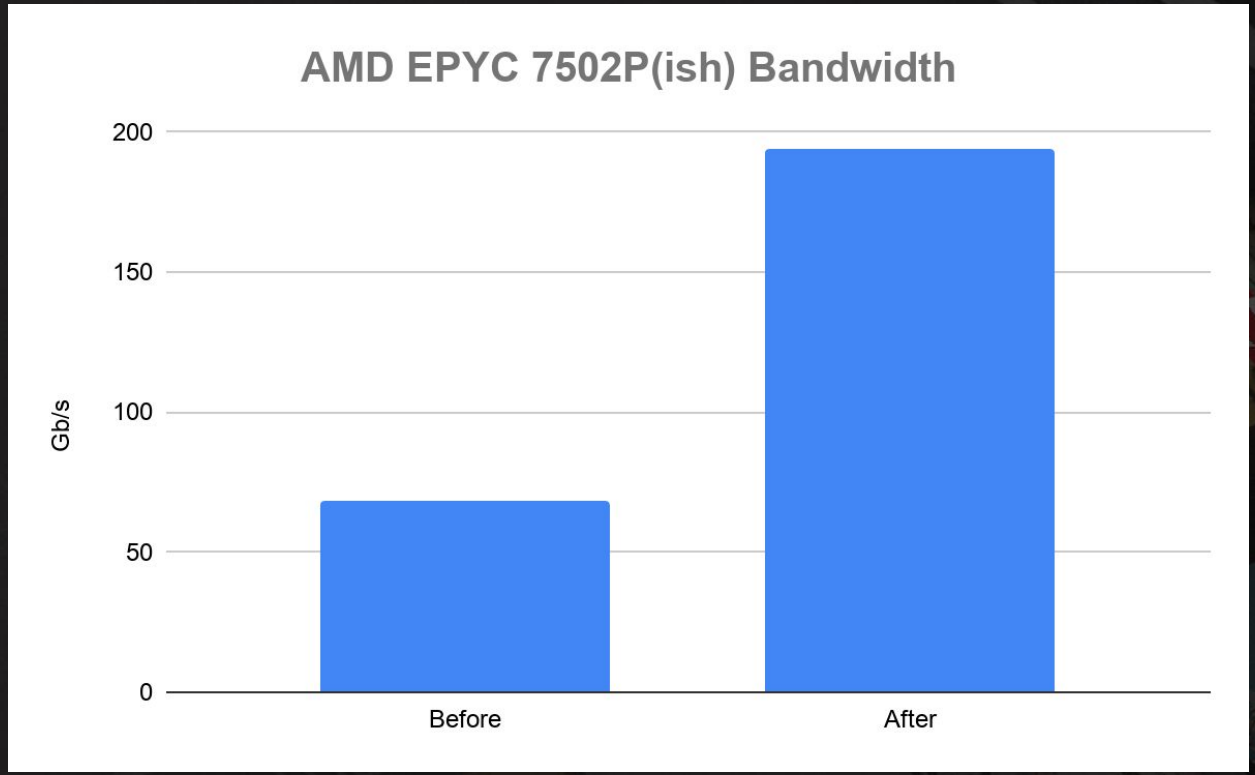
Performance Results: AMD



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Actual data from pcm.x @105Gb/s

```
Intel(r) UPI data traffic estimation in bytes (data traffic coming to CPU/socket through UPI links):

               UPI0    UPI1    |  UPI0   UPI1
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       26 G    26 G   |   40% 40%
 SKT    1       28 G    28 G   |   42% 42%
-------------------------------------------------------------------------------------------------------------
---
Total UPI incoming data traffic:  109 G      UPI data traffic/[illegible]ntroller traffic: [illegible].40

Intel(r) UPI traffic estimation in bytes (data and non-data traffic outgoing from CPU/socket through UPI
links):

               UPI0    UPI1    |  UPI0   UPI1
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       47 G    47 G   |   73% 73%
 SKT    1       46 G    46 G   |   69% 69%
-------------------------------------------------------------------------------------------------------------
---
Total UPI outgoing data and non-data traffic:  188 G
MEM (GB)->|  READ |  WRITE | PMM RD | PMM WR | CPU energy | DIMM energy |
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       122.34  136.19         0.00    0.00    272.51         58.37
 SKT    1       8.24    6.99    0.00   0.00    231.16         28.63
-------------------------------------------------------------------------------------------------------------
---
       *       130.57  143.18         0.00    0.00    503.68         87.01
```

NETFLIX

Actual data from nstat (Xeon)

```
c333.sjc002.dev# nstat 15
 InMpps OMpps  InGbs  OGbs err TCP Est %CPU syscalls csw    irq GBfree
  1.43   8.32   1.19  99.41  0  74690   62.96 176262 696238 157743 114.11
  1.50   8.69   1.22 103.86  0  76091   63.99 171871 698812 158257 113.44
  1.48   8.48   1.14 101.31  0  77022   64.09 178515 701432 157910 112.74
  1.49   8.56   1.17 102.22  0  78057   65.17 173108 696963 157307 111.95
  1.49   8.61   1.12 102.91  0  78654   64.65 169636 700402 157492 111.41
  1.51   8.81   1.09 105.27  0  79617   73.67 167101 683410 155796 111.05
  1.52   8.80   1.18 105.14  0  80721   69.15 173158 694059 156457 109.98
  1.48   8.38   1.13 100.03  0  81477   65.05 182784 698356 157515 109.25
  1.51   8.61   1.13 102.88  0  82449   65.90 181321 701593 157383 108.98
  1.49   8.64   1.13 103.23  0  82404   69.43 187668 697208 156812 108.39
  1.47   8.59   1.12 102.69  0  79792   63.68 149610 676066 155931 108.10
  1.56   9.01   1.30 107.76  0  78127   69.11 138318 685625 156429 107.79
^C
c333.sjc002.dev# sysctl hw.model
hw.model: Intel(R) Xeon(R) Silver 4216 CPU @ 2.10GHz
c333.sjc002.dev# sysctl hw.ncpu
hw.ncpu: 64
```

NETFLIX

Actual data from pcm.x @191Gb/s

```
Intel(r) UPI data traffic estimation in bytes (data traffic coming to CPU/socket through UPI links):

               UPI0    UPI1    |  UPI0   UPI1
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       3926 M   3930 M   |   18%     18%
 SKT    1       3958 M   3954 M   |   18%     18%
-------------------------------------------------------------------------------------------------------------
---
Total UPI incoming data traffic:   15 G      UPI data traffic/[illegible]ntroller traffic: [illegible].13

Intel(r) UPI traffic estimation in bytes (data and non-data traffic outgoing from CPU/socket through UPI
links):

               UPI0    UPI1    |  UPI0   UPI1
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       11 G    11 G   |   52% 53%
 SKT    1       11 G    11 G   |   52% 52%
-------------------------------------------------------------------------------------------------------------
---
Total UPI outgoing data and non-data traffic:   45 G
MEM (GB)->|  READ |  WRITE | PMM RD | PMM WR | CPU energy | DIMM energy |
-------------------------------------------------------------------------------------------------------------
---
 SKT    0       32.28   28.00   0.00    0.00    99.01   16.97
 SKT    1       32.77   28.18   0.00    0.00    100.75          18.31
-------------------------------------------------------------------------------------------------------------
---
       *       65.05   56.19   0.00    0.00    199.76          35.28
```

NETFLIX

Actual data from nstat (Xeon)

```
c333.sjc002.dev# nstat 15
 InMpps OMpps  InGbs  OGbs err TCP Est %CPU syscalls csw    irq GBfree
  2.78  15.90   1.89 190.33  0 150083   72.75 255685 1005743 167659  4.47
  2.81  15.94   1.97 190.83  0 150371   73.61 259173 1004664 167348  4.48
  2.80  15.93   1.88 190.67  0 150363   74.01 254862 997954 167199  5.09
  2.81  16.00   1.99 191.61  0 151127   73.54 257203 1000740 167202  5.21
  2.80  16.00   1.93 191.61  0 151216   74.38 257396 1001018 167243  4.58
  2.79  16.00   1.86 191.63  0 151559   73.53 256385 1001693 167205  4.60
  2.79  15.96   1.85 191.11  0 151548   74.65 256022 995630 166977  4.51
  2.82  16.00   1.93 191.62  0 152176   74.43 259680 1001880 166890  4.72
  2.83  16.00   1.87 191.61  0 152258   74.47 259494 1003018 166839  4.01
  2.84  16.00   1.88 191.62  0 152805   74.41 258864 1003171 166727  4.56
  2.85  15.98   1.89 191.47  0 153473   76.12 260823 995460 166377  3.84
  2.85  15.99   1.83 191.61  0 153864   74.90 259149 1003219 166484  4.44
  2.87  15.99   1.88 191.60  0 154081   76.02 261867 1001356 166192  3.80
  2.88  15.99   1.97 191.62  0 154421   75.73 262377 1003028 166250  4.76
^C
c333.sjc002.dev# sysctl hw.model
hw.model: Intel(R) Xeon(R) Silver 4216 CPU @ 2.10GHz
c333.sjc002.dev# sysctl hw.ncpu
hw.ncpu: 64
```

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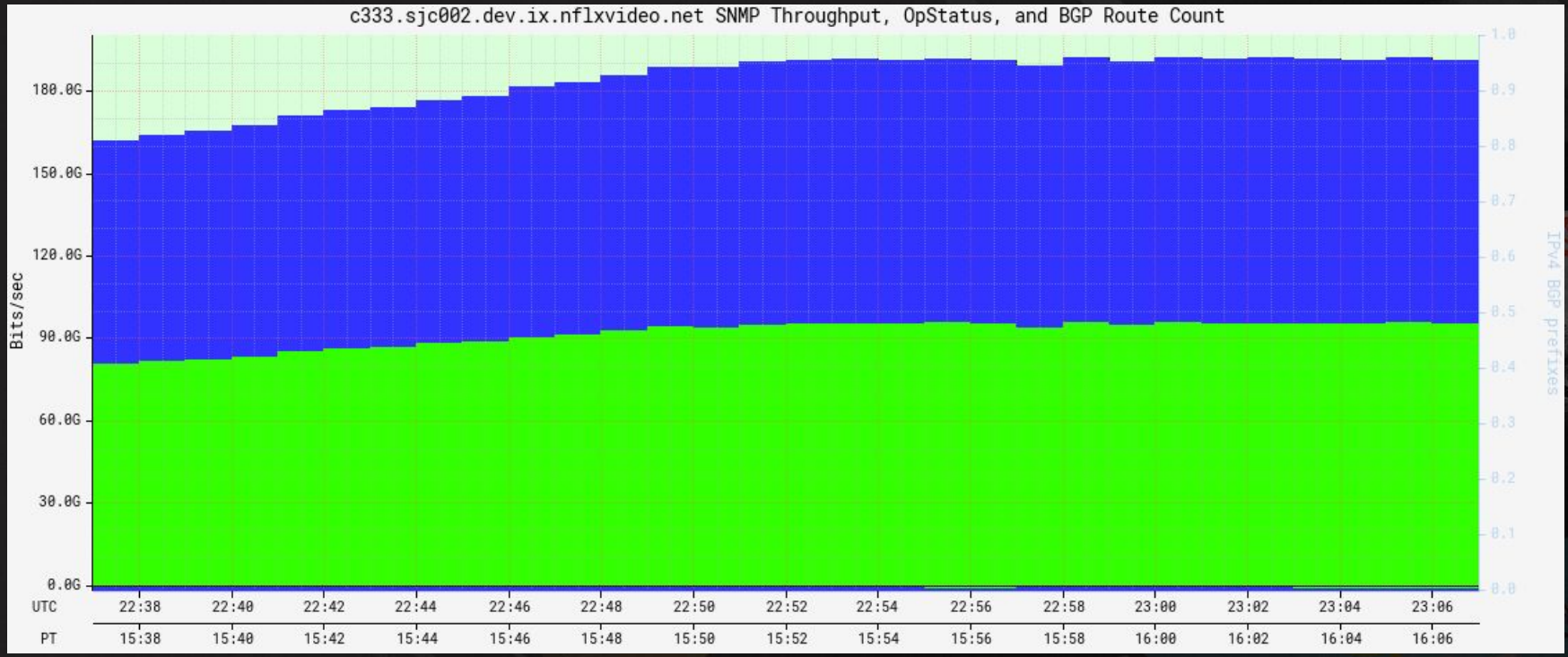
c333.sjc002.dev.ix.nflxvideo.net SNMP Throughput, OpStatus, and BGP Route Count
Bits/sec
180.0G
150.0G
120.0G
90.0G
60.0G
30.0G
0.0G
IPv4 BGP prefixes
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
UTC
22:38
22:40
22:42
22:44
22:46
22:48
22:50
22:52
22:54
22:56
22:58
23:00
23:02
23:04
23:06
PT
15:38
15:40
15:42
15:44
15:46
15:48
15:50
15:52
15:54
15:56
15:58
16:00
16:02
16:04
16:06

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Actual data from nstat (EPYC)

```
c368.sjc002.dev# nstat 15
  InMpps OMpps  InGbs  OGbs err TCP Est %CPU syscalls csw   irq GBfree5
  0.94   5.12   0.91  60.96  0  43687   30.53 151574 672314 100726 181.99
  0.97   5.26   0.80  62.68  0  45468   34.36 150603 666261  97171 178.94
  0.97   5.33   0.82  63.54  0  48308   47.74 147954 632247  90170 178.57
  0.99   5.49   0.75  65.49  0  50633   69.63 129971 565679  76805 178.57
  1.02   5.47   0.87  65.24  0  52431   73.24 127194 555176  74026 179.48
  1.02   5.45   0.78  64.97  0  53261   72.05 122047 553728  73717 178.82
  1.01   5.42   0.81  64.54  0  53534   72.13 118832 550171  74031 178.36
  1.01   5.47   0.77  65.25  0  53336   67.82 113505 561734  76411 178.58
  1.01   5.46   0.80  65.04  0  54342   66.57 113245 563114  77554 179.42
  1.01   5.43   0.73  64.66  0  55936   64.35 109110 565602  79069 178.87
  1.00   5.36   0.76  63.81  0  58181   62.75 106302 573547  82039 178.33
  0.99   5.39   0.63  64.32  0  55587   55.30  82142 565436  84060 180.00
  1.05   5.76   0.66  68.72  0  54378   53.83  80994 575478  85235 179.12
  0.92   5.03   0.57  60.06  0  53749   54.38  81413 563538  82983 178.60
  0.98   5.34   0.61  63.70  0  53911   53.30  81227 569083  84893 179.35
c368.sjc002.dev# sysctl hw.ncpu
hw.ncpu: 64
c368.sjc002.dev# sysctl hw.model
hw.model: AMD x
```

NETFLIX

Actual data from nstat (EPYC)

```
c368.sjc002.dev# nstat 15
  InMpps OMpps  InGbs  OGbs err TCP Est %CPU syscalls csw   irq GBfree5
  2.72  16.06   1.89 191.62  0 152688   63.18 239427 624677  64309  8.45
  2.72  16.11   1.77 192.28  0 153085   62.51 239378 629312  64761  8.43
  2.73  16.15   1.75 192.71  0 153462   63.56 241100 629712  64713  8.42
  2.74  16.15   1.76 192.80  0 153519   63.71 235867 628167  64608  8.42
  2.72  16.06   1.72 191.62  0 153445   62.12 237885 629998  64338  8.42
  2.72  16.15   1.73 192.72  0 153521   62.62 236958 627838  64571  8.41
  2.71  16.04   1.75 191.47  0 153659   62.43 239150 628649  64474  8.41
  2.72  16.12   1.74 192.36  0 153683   63.31 236789 627122  64427  8.37
  2.71  16.17   1.68 193.02  0 154106   63.69 237980 625786  64237  8.37
  2.70  16.08   1.73 191.98  0 154027   61.68 238149 627631  64273  8.36
  2.74  16.26   1.79 194.14  0 154469   64.59 240687 627712  64643  8.36
  2.74  16.28   1.80 194.29  0 154681   64.73 237997 627571  64813  8.33
^C
c368.sjc002.dev# sysctl hw.ncpu
hw.ncpu: 64
c368.sjc002.dev# sysctl hw.model
hw.model: AMD x[redacted]
```

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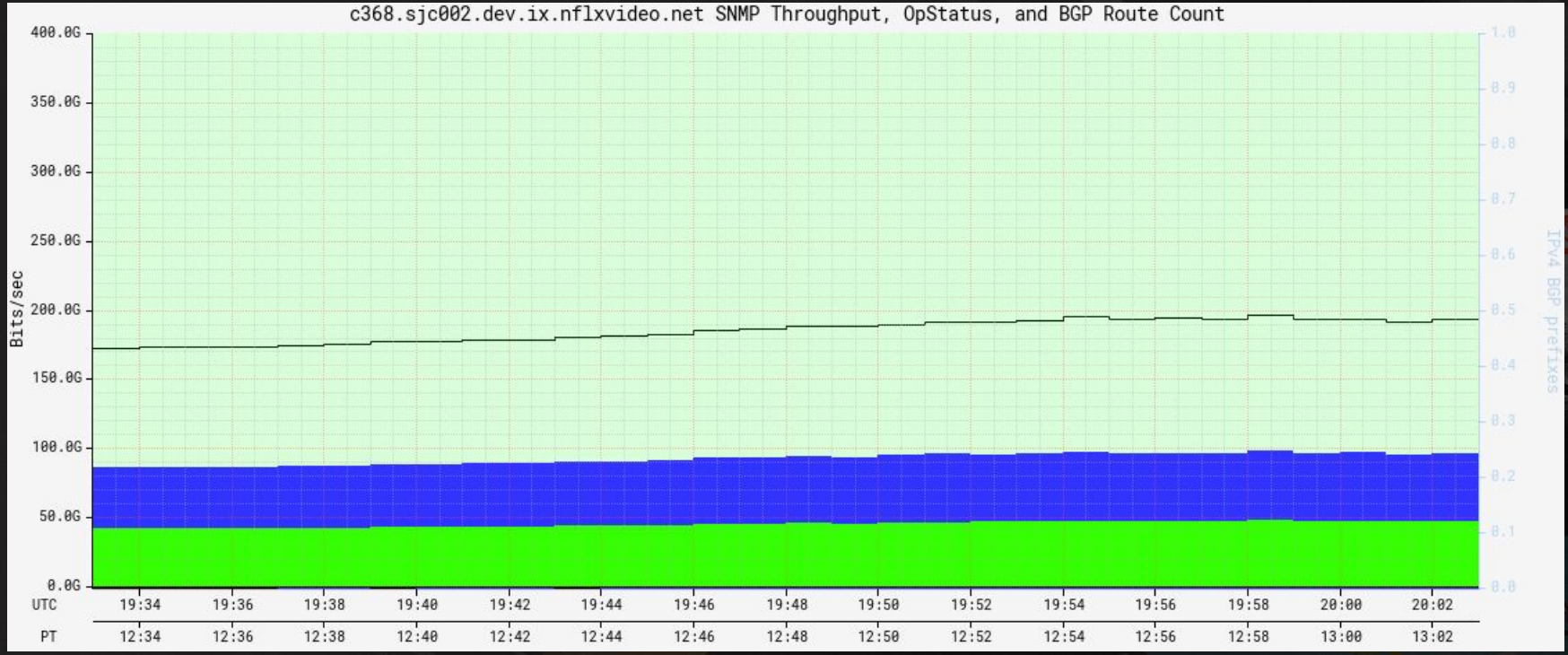
c368.sjc002.dev.ix.nflxvideo.net SNMP Throughput, OpStatus, and BGP Route Count
Bits/sec
400.0G
350.0G
300.0G
250.0G
200.0G
150.0G
100.0G
50.0G
0.0G
IPv4 BGP prefixes
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
UTC
19:34
19:36
19:38
19:40
19:42
19:44
19:46
19:48
19:50
19:52
19:54
19:56
19:58
20:00
20:02
PT
12:34
12:36
12:38
12:40
12:42
12:44
12:46
12:48
12:50
12:52
12:54
12:56
12:58
13:00
13:02

Thank you

Slides at:
https://people.freebsd.org/~gallatin/talks/euro2019.pdf

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