NetCrafter

Tailoring Network Traffic for Non-Uniform Bandwidth Multi-GPU Systems

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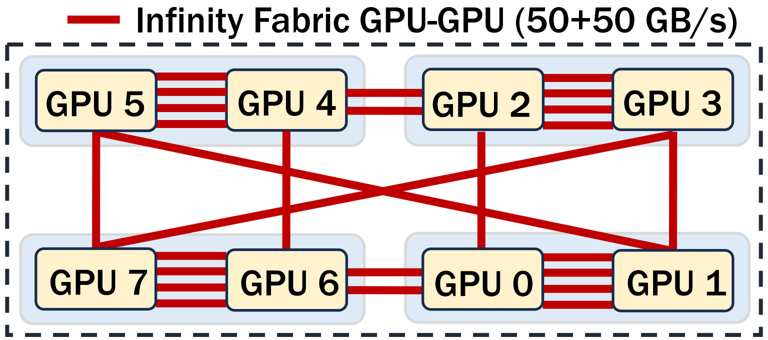
SUMMARY

Problem and Motivation

- Multi-GPU systems accelerate workloads by interconnecting **multiple GPUs**
- These interconnects often exhibit **non-uniform bandwidth** as systems scale
- **Slower links** become performance bottlenecks, limiting scalability

Key Ideas

- Target slower bandwidth links with two key strategies:
  - **Reduce** network traffic
  - **Manage** network traffic more efficiently
- We propose **NetCrafter**, a network crafting engine that:
  - **Stitches** partially empty flits to improve flit utilization
  - **Trims** network packets with redundant data
  - **Sequences** network traffic to prioritize latency-critical packets



Performance

- Up to 64% faster, and 16% average speedup over baseline non-uniform multi-GPU setups

OUTLINE

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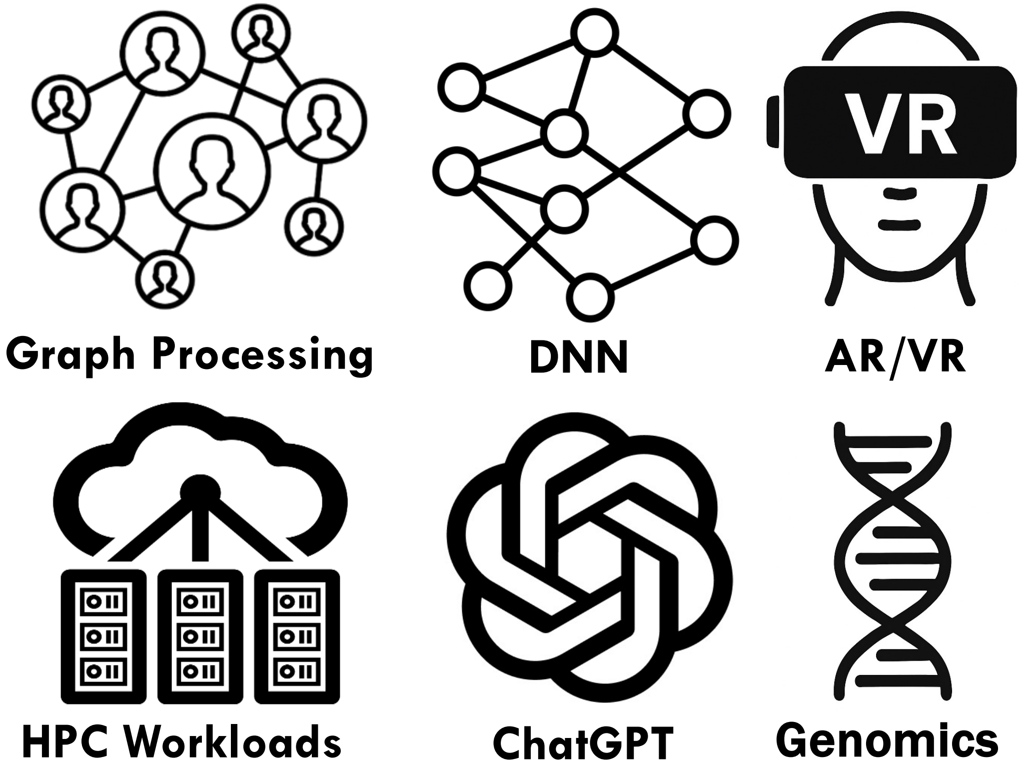
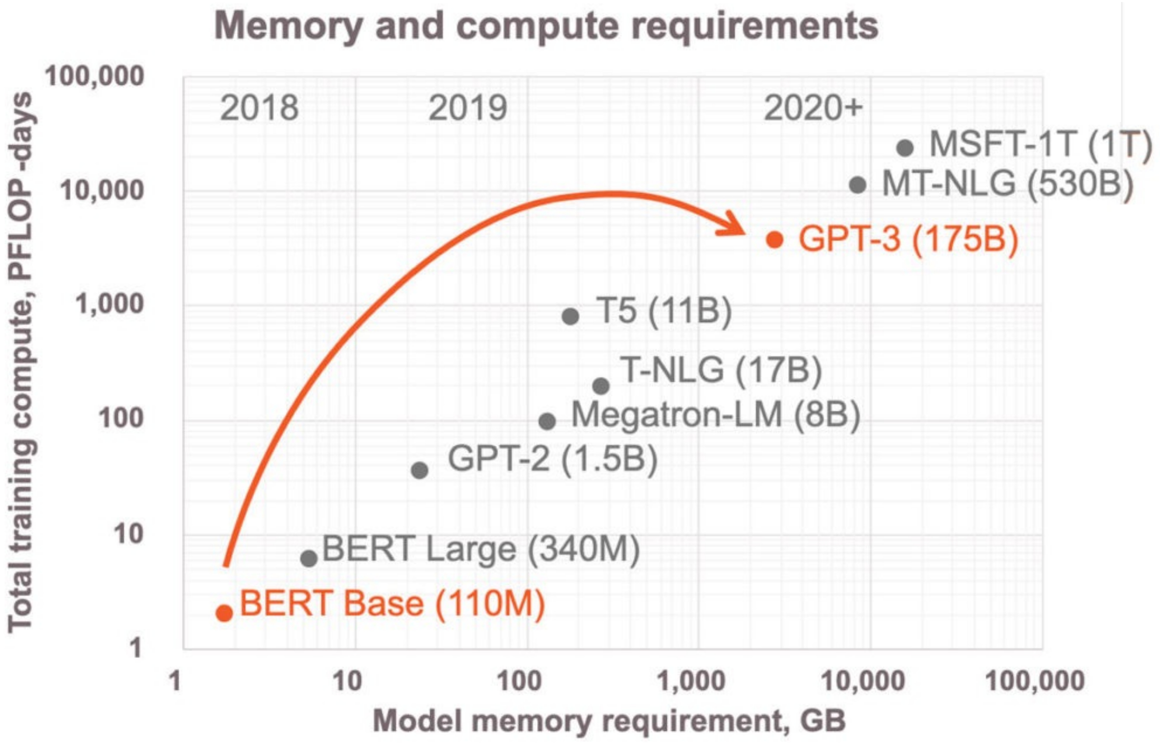
- BACKGROUND AND MOTIVATION
- GOAL
- OBSERVATIONS & KEY IDEAS
- NETCRAFTER DESIGN
- EVALUATION
- CONCLUSION

BACKGROUND

GPUs are used to accelerate a wide range of applications



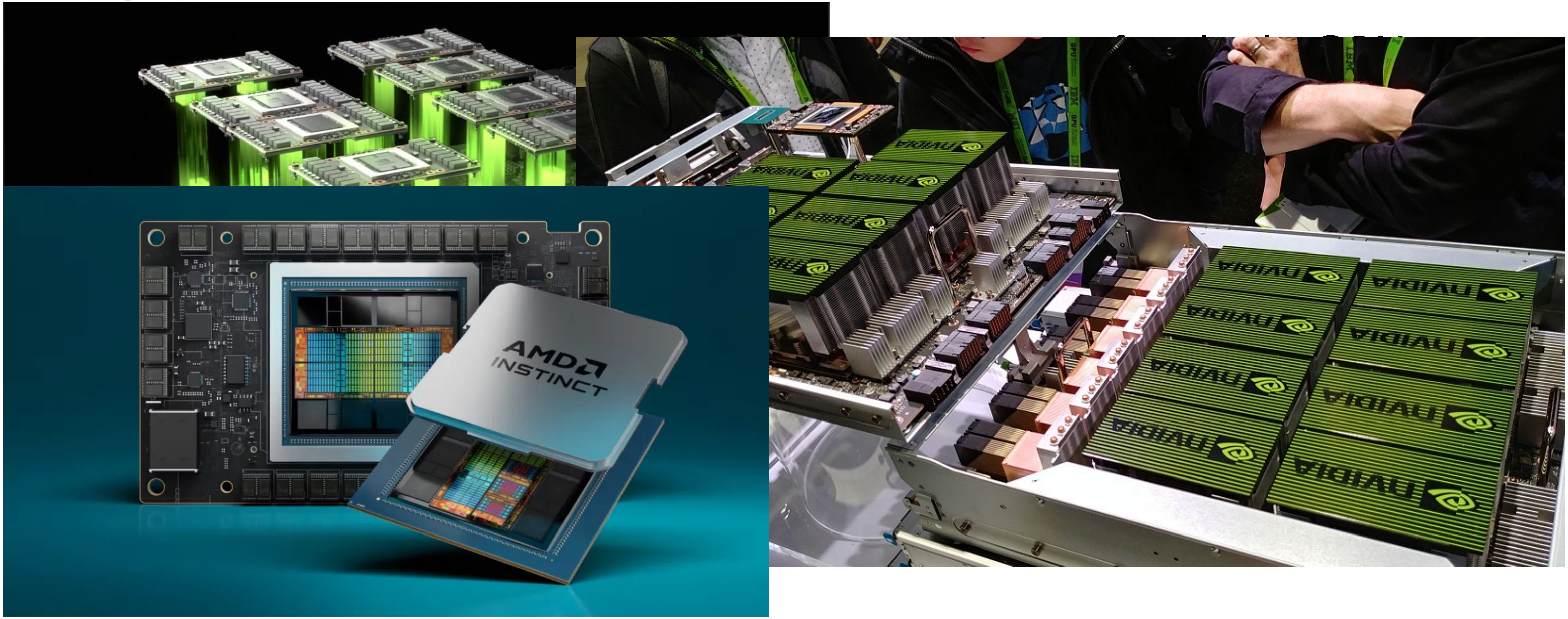


Rising application demands outgrow **single-GPU** capabilities

https://www.cerebras.net/blog/harnessing-the-power-of-sparsity-for-large-gpt-ai-models

MULTI-GPU SYSTEMS TO THE RESCUE

Multiple GPUs are connected over high bandwidth interconnects to scale:

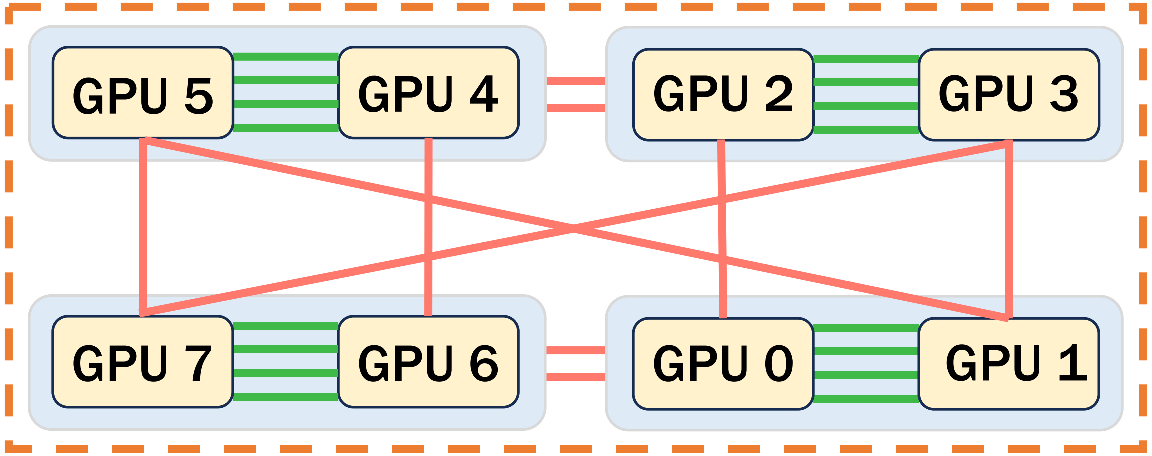


SCALING MULTI-GPU SYSTEMS

Multi-GPU systems must scale with growing application demands

These systems typically scale in a **hierarchical** manner

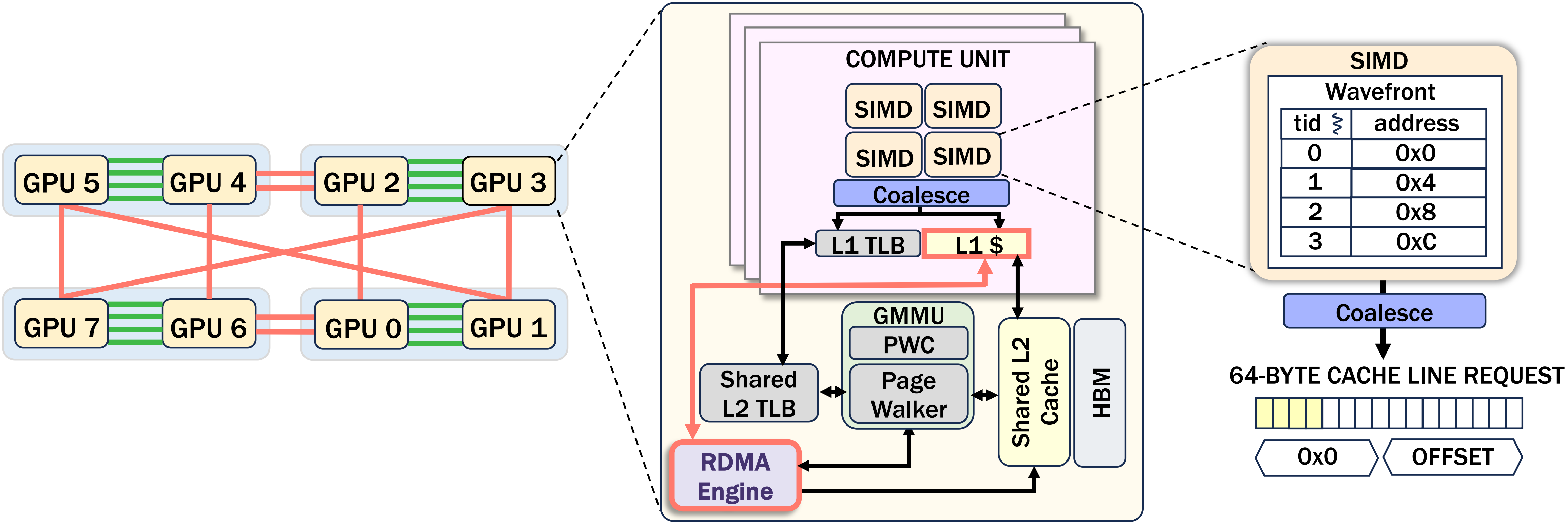
- Tightly coupled (e.g., MCM style): Linked via **higher-bandwidth** interconnects
- Loosely coupled (e.g., Multi-GPU style): Connected over **lower-bandwidth** interconnects



Multi-GPU scaling typically introduces bandwidth **non-uniformity** (e.g., Frontier, Summit, Aurora)

NON-UNIFORM BANDWIDTH -> NUMA

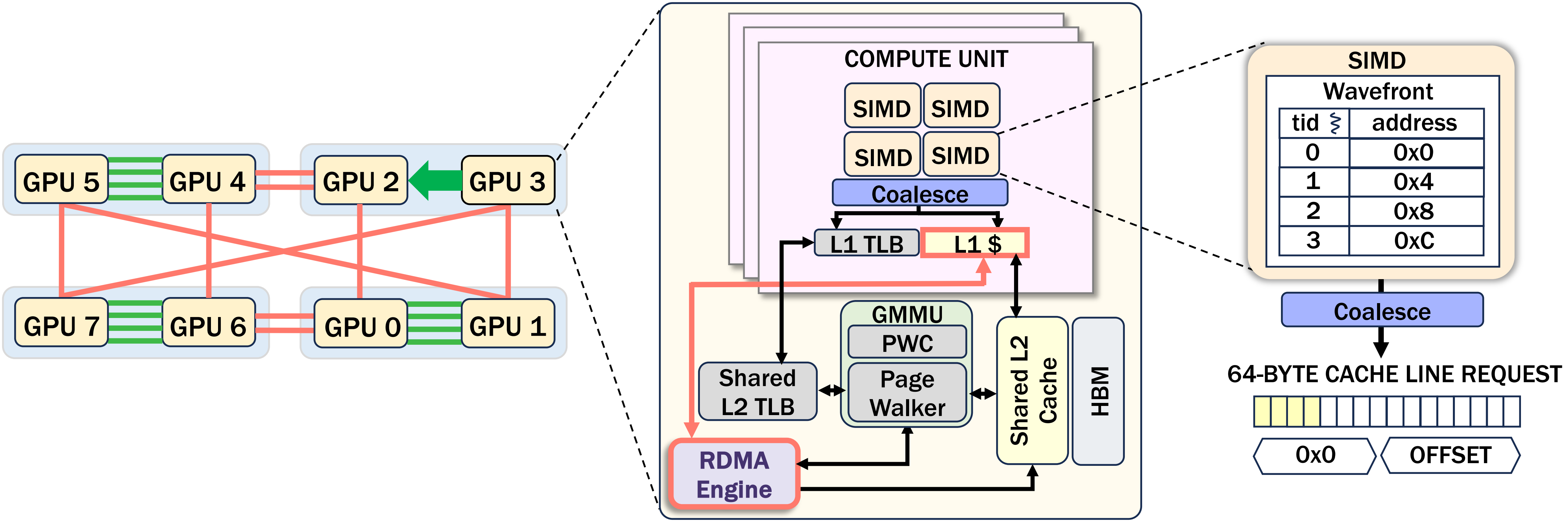
Memory access bandwidth varies across the system



NON-UNIFORM BANDWIDTH -> NUMA

Memory access bandwidth varies across the system

Nearby GPUs enjoy higher bandwidth and lower latency, and vice versa



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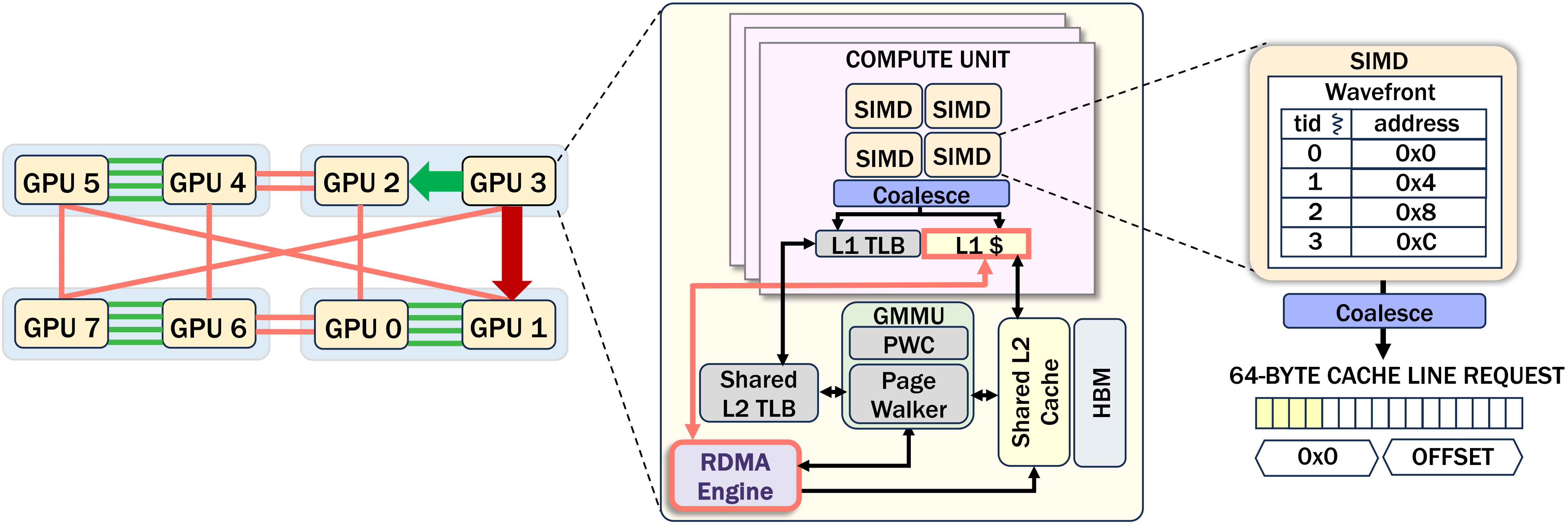
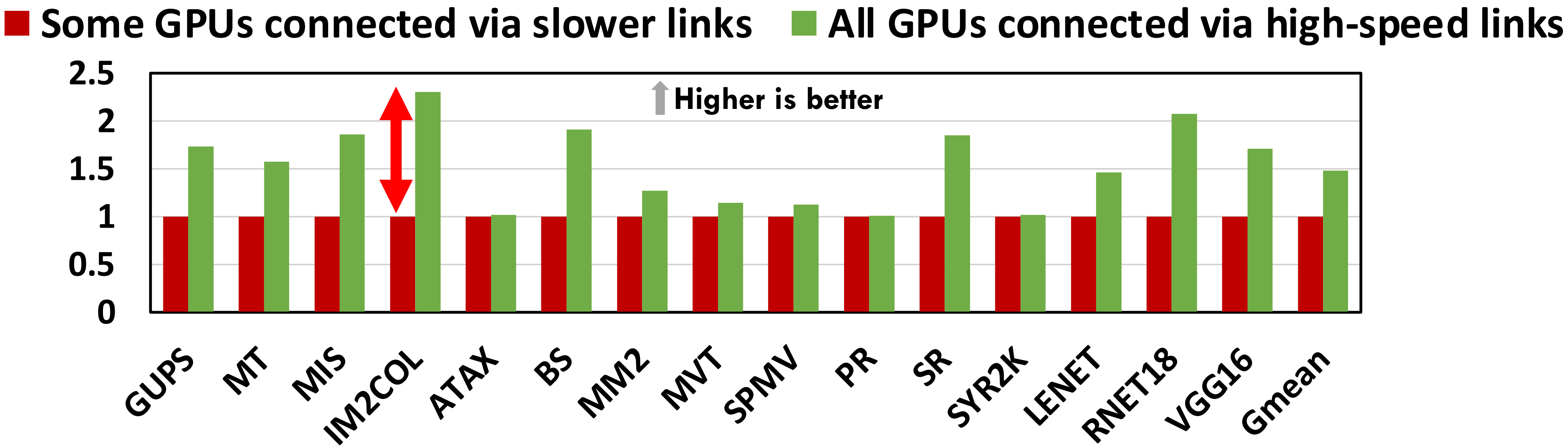


NON-UNIFORM BANDWIDTH -> NUMA

Non-uniform bandwidth multi-GPU systems are constrained by:

Slower bandwidth interconnects connecting the GPUs



Non-uniform bandwidth causes up to **2.3×** slowdown in GPU performance

Slower interconnects lead to performance bottlenecks. How can we minimize the impact of **non-uniform bandwidth** in emerging **multi-GPU systems**?

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GOAL

Optimize **slower bandwidth links**:

1. **Reducing network traffic** across these links

2. **Efficiently managing network traffic** across these links

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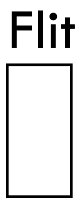
Transmitting packets across the network

Network Transfer through Flits

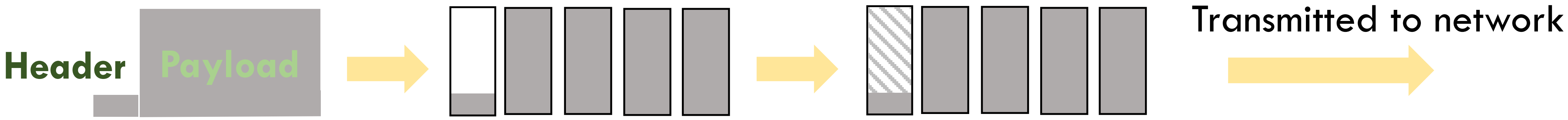
- Flit = fixed-size unit (x **bytes**), sent per cycle
- **Basic granularity** of data transfer in interconnects



GPU packet breakdown

- Packet = **Header** + **Payload**
- Split into flits (fixed-size units)
- Empty bytes padded to **align** the last flit with flit size

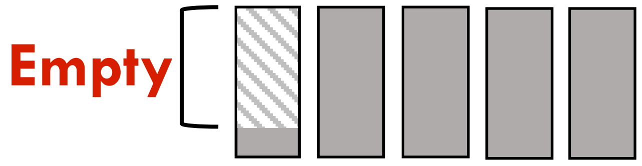
GPU request Packet



OBSERVATION #01

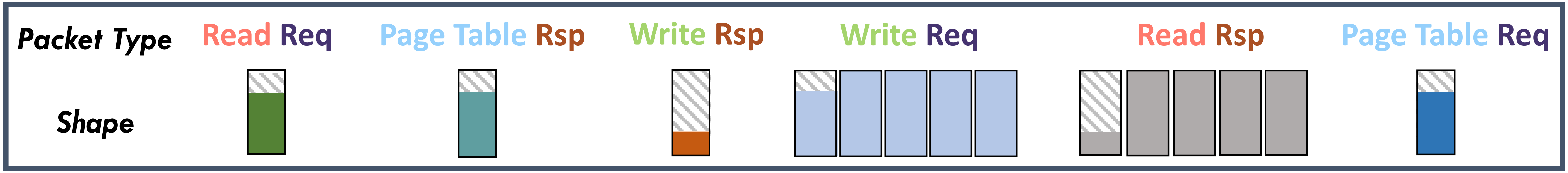
Inefficient Flit Utilization Due to Padding

- Flits contain substantial empty bytes
- These empty bytes are padded with redundant data
- Redundant data increases unnecessary network load



Each packet type contributes differently to this network load

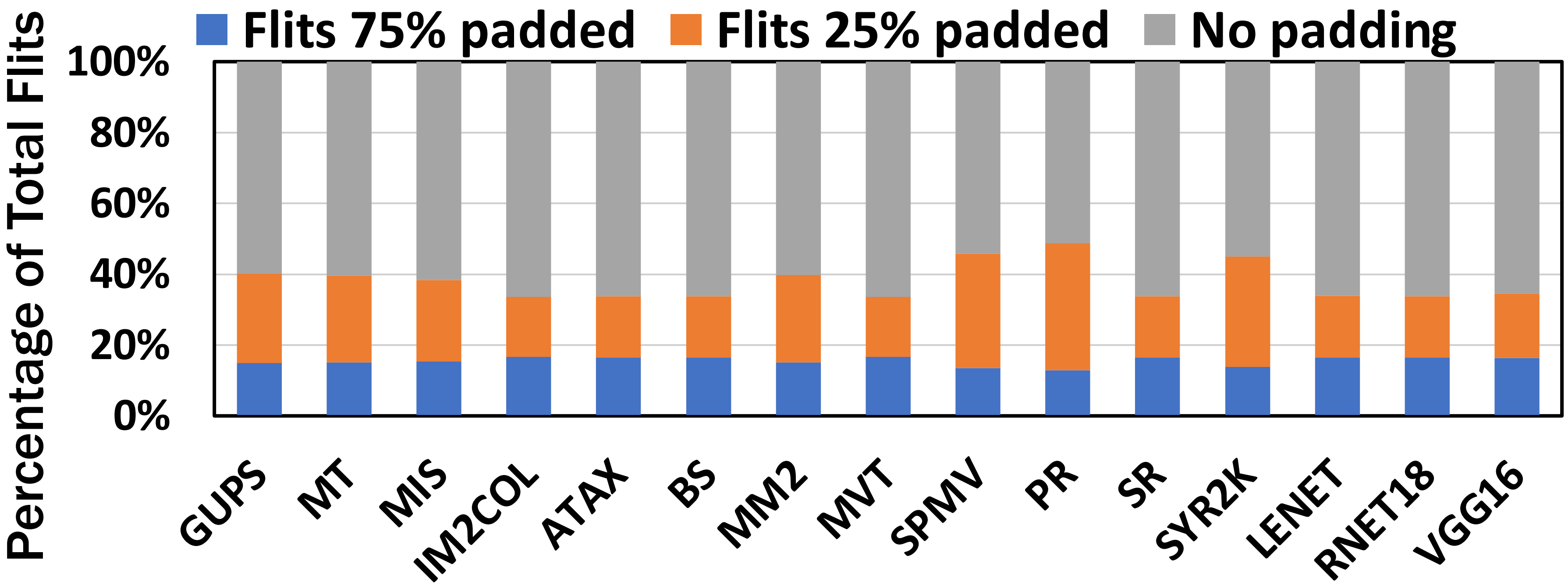
- Read Req (Header + Address)
- Write Req (Header + Data + Address)
- Page Table Req (Header +Address)
- Read Rsp (Header + Data)
- Write Rsp (Header)
- Page Table Rsp (Header + Address)



OBSERVATION #01

Different packet types introduce varying padding overhead

Packet Type	Read Req	Page Table Rsp	Write Rsp	Write Req	Read Rsp	Page Table Req
Shape						
%Padded	25%	25%	75%	25% + No padding	25% + No padding	25%



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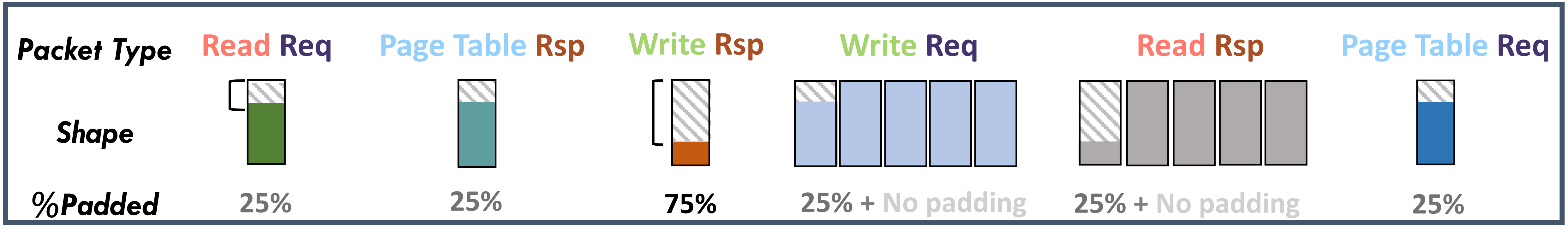

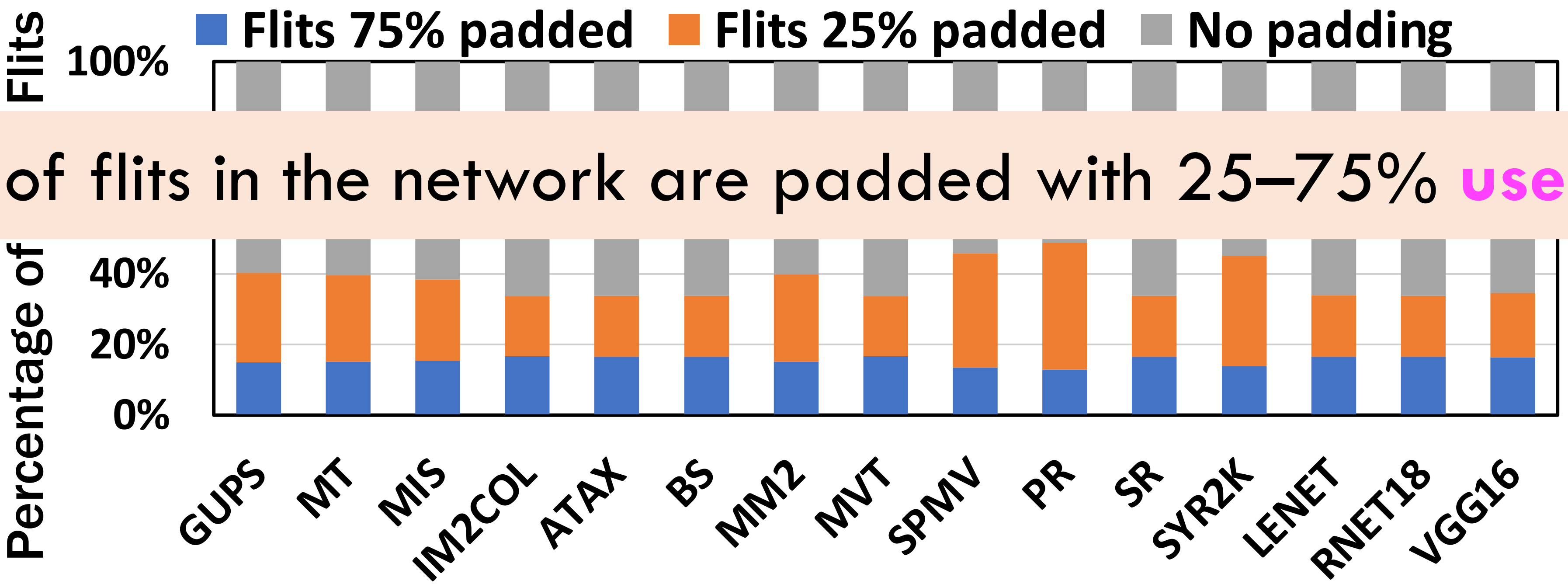

~40% of flits in the network are padded with 25–75% **useless data**

KEY IDEA I: STITCHING

Stitch flits across request categories to reduce network traffic overhead

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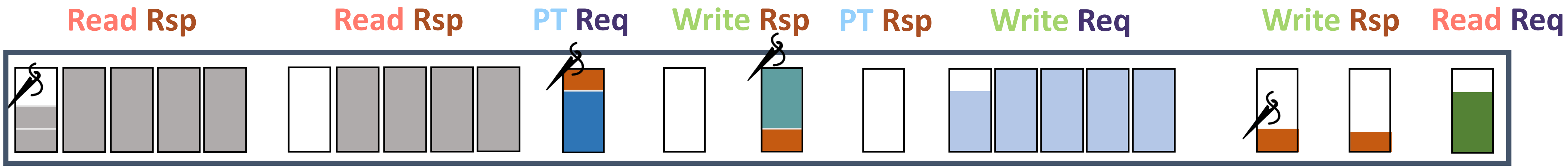

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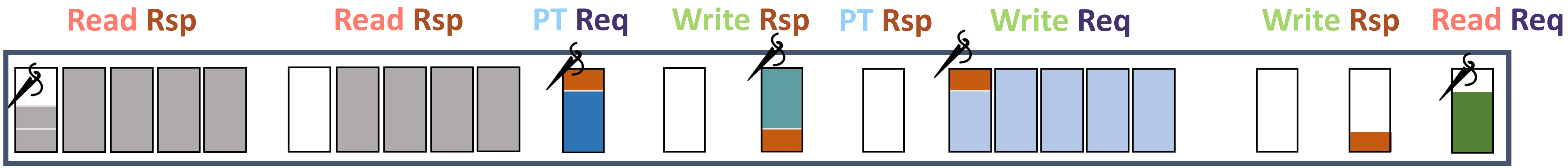

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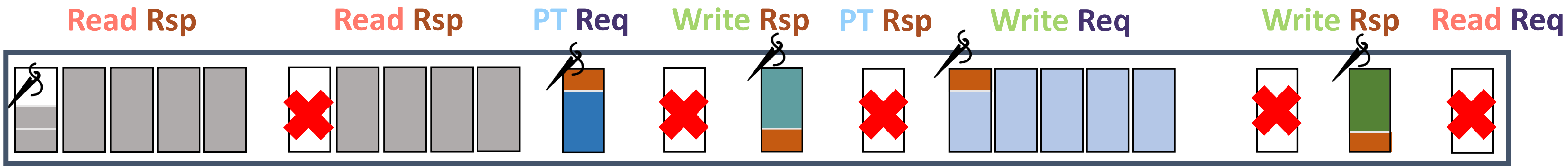

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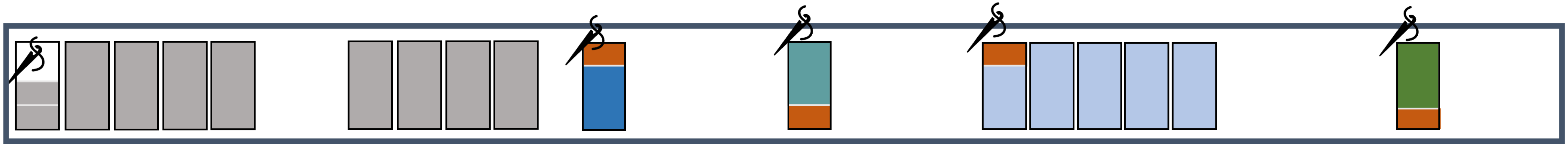

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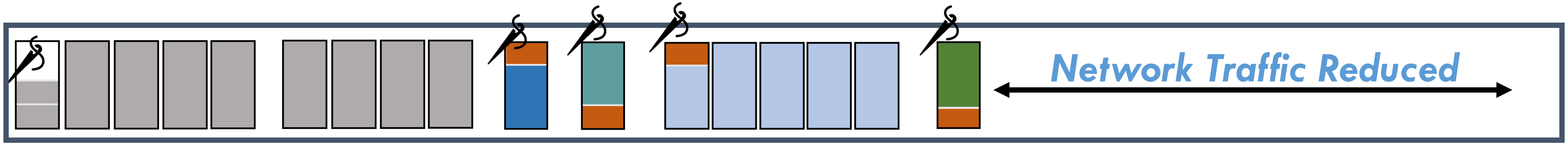

OBSERVATION #02

Prefetched unused data wastes bandwidth

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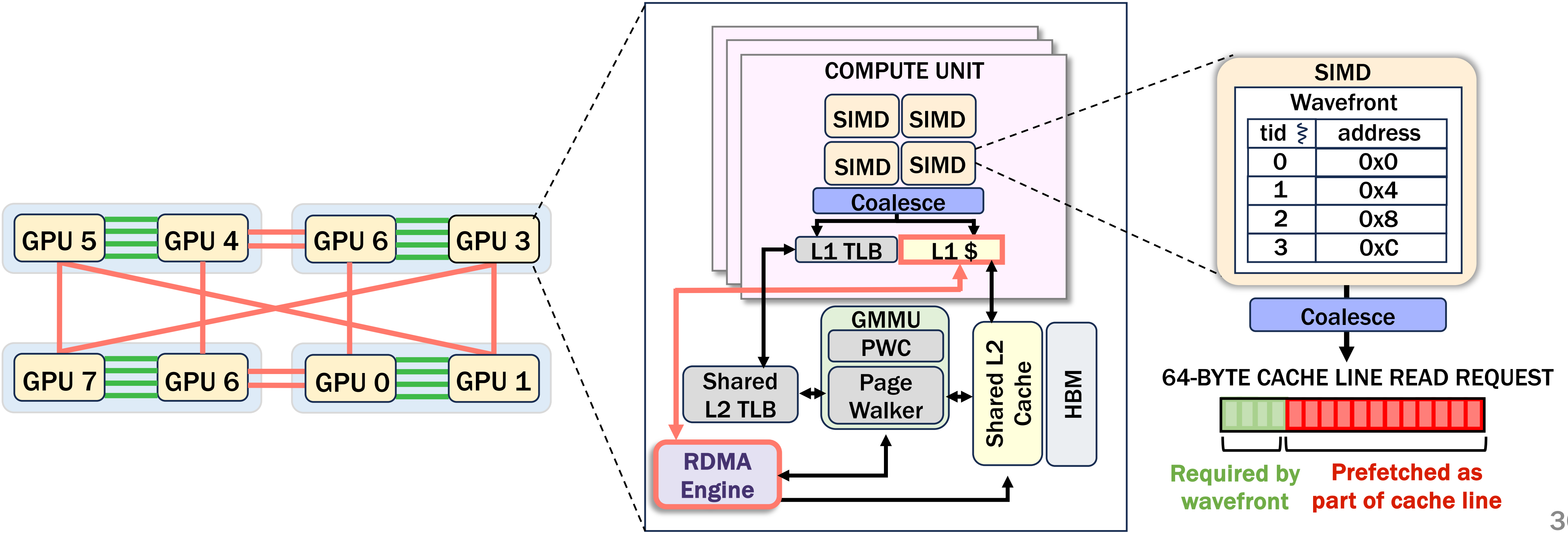
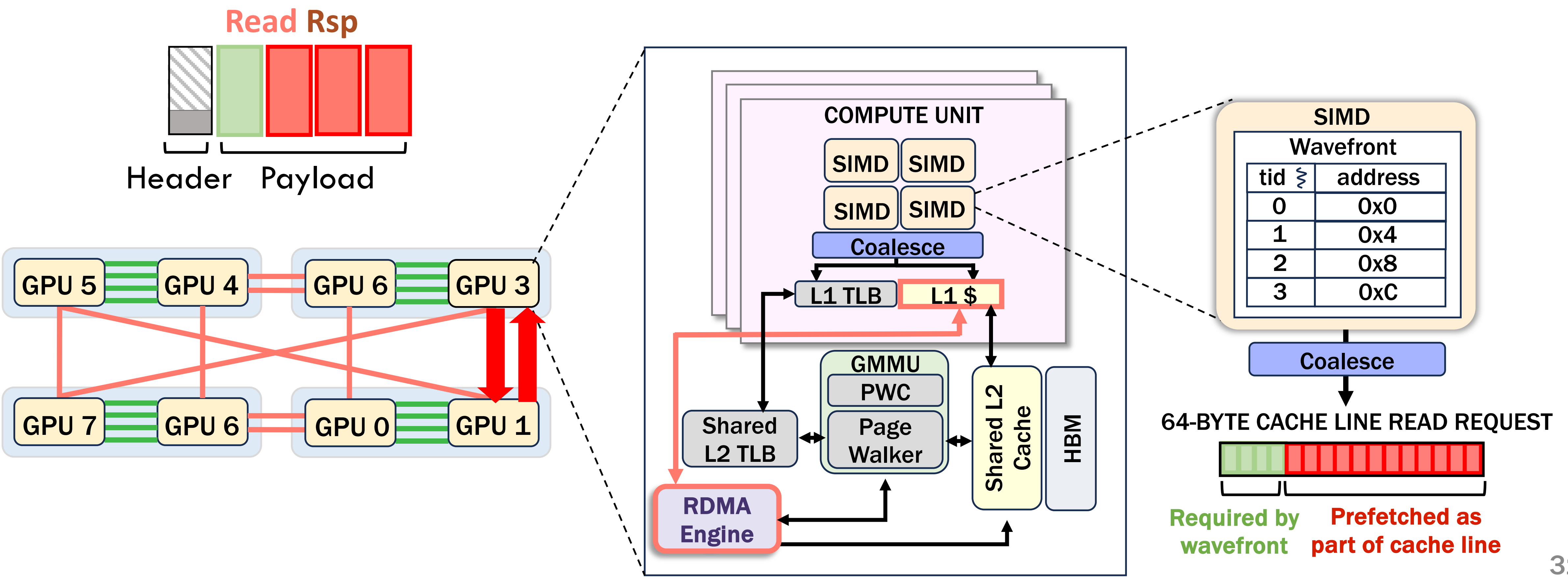


OBSERVATION #02

Prefetched unused data wastes bandwidth

- Read response includes more data than requested



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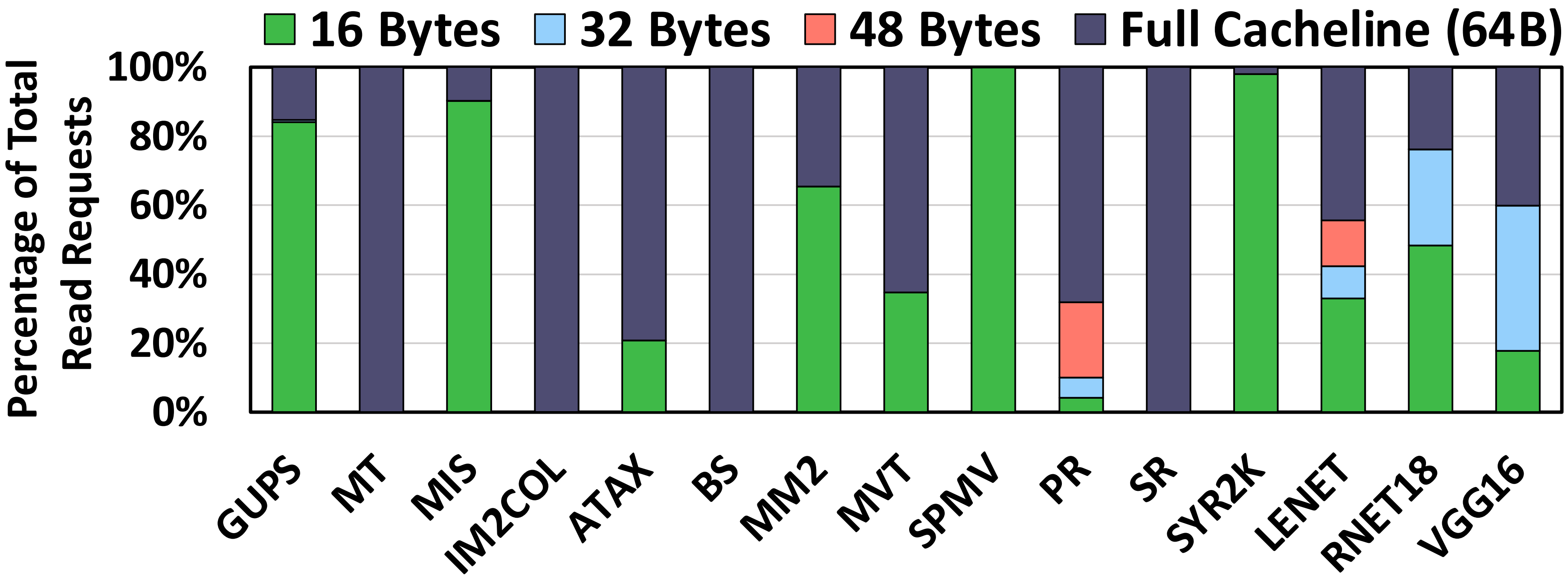
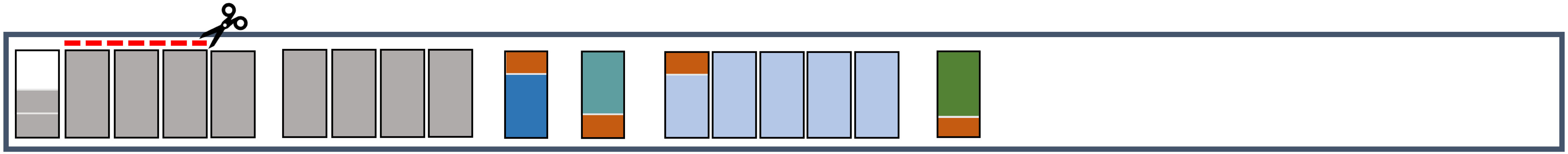


Most applications require ≤16B from each 64B GPU cache line

KEY IDEA II: TRIMMING

Trim redundant flits to cut network overhead



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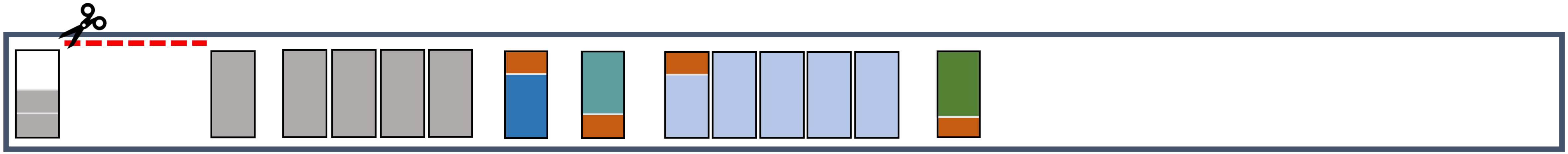

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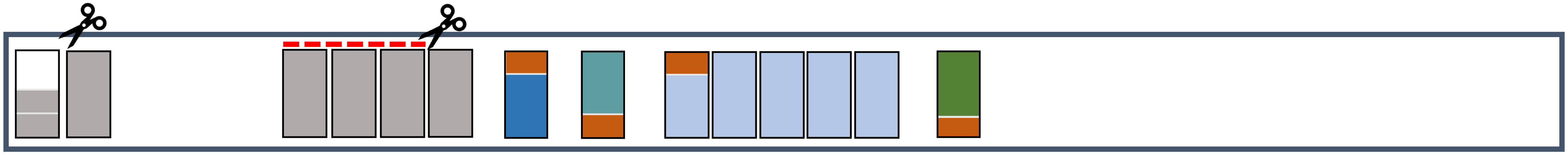

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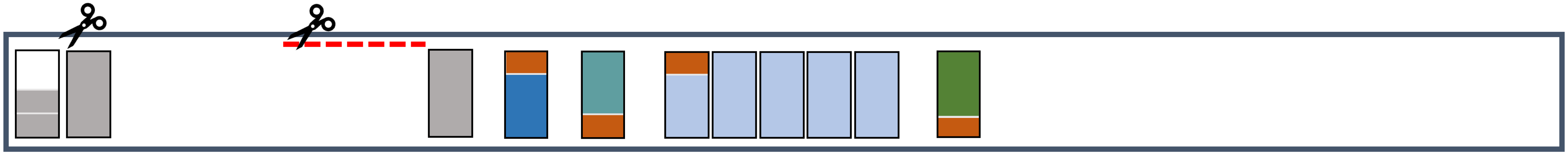

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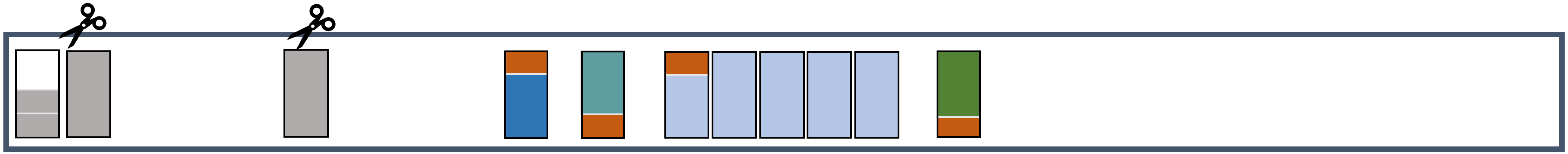

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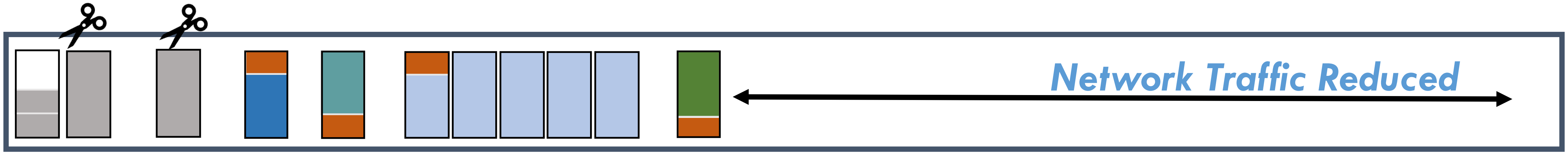
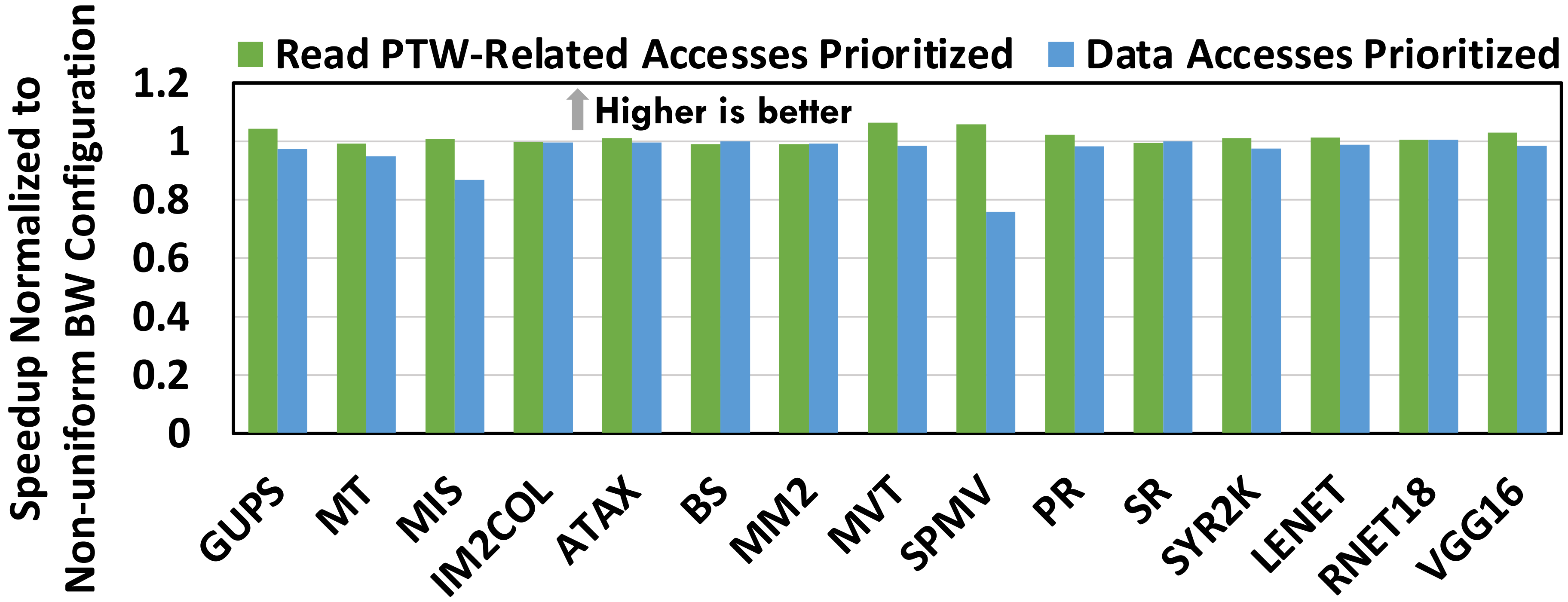


OBSERVATION#03

PTW-related flits are more latency critical than other flits



KEY IDEA III: SEQUENCING

Prioritize flits in flight so latency-critical packets lead the line on slow links

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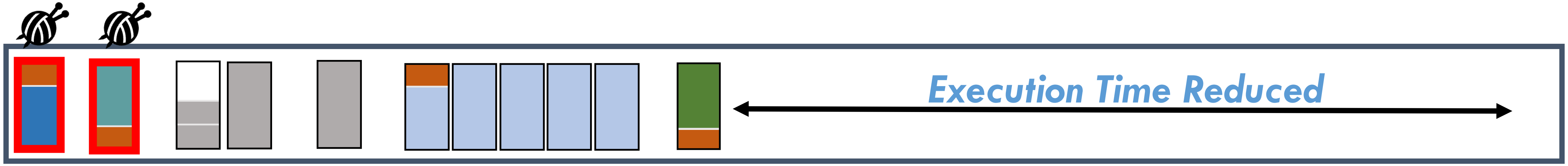
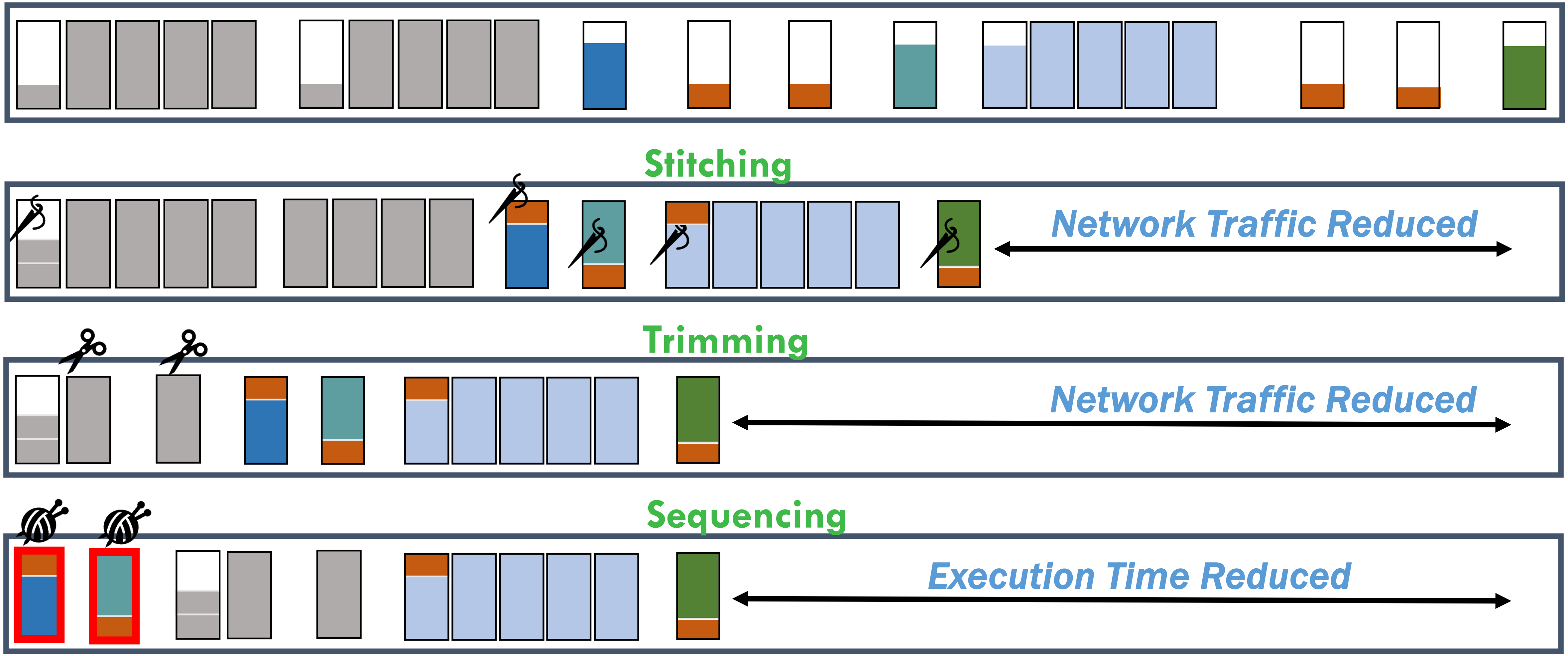


PUTTING IT TOGETHER



1. Reducing network traffic across these links
2. Efficiently managing network traffic across these links

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Mechanism: NetCrafter

Each cluster switch includes an integrated NetCrafter controller

NetCrafter Controller

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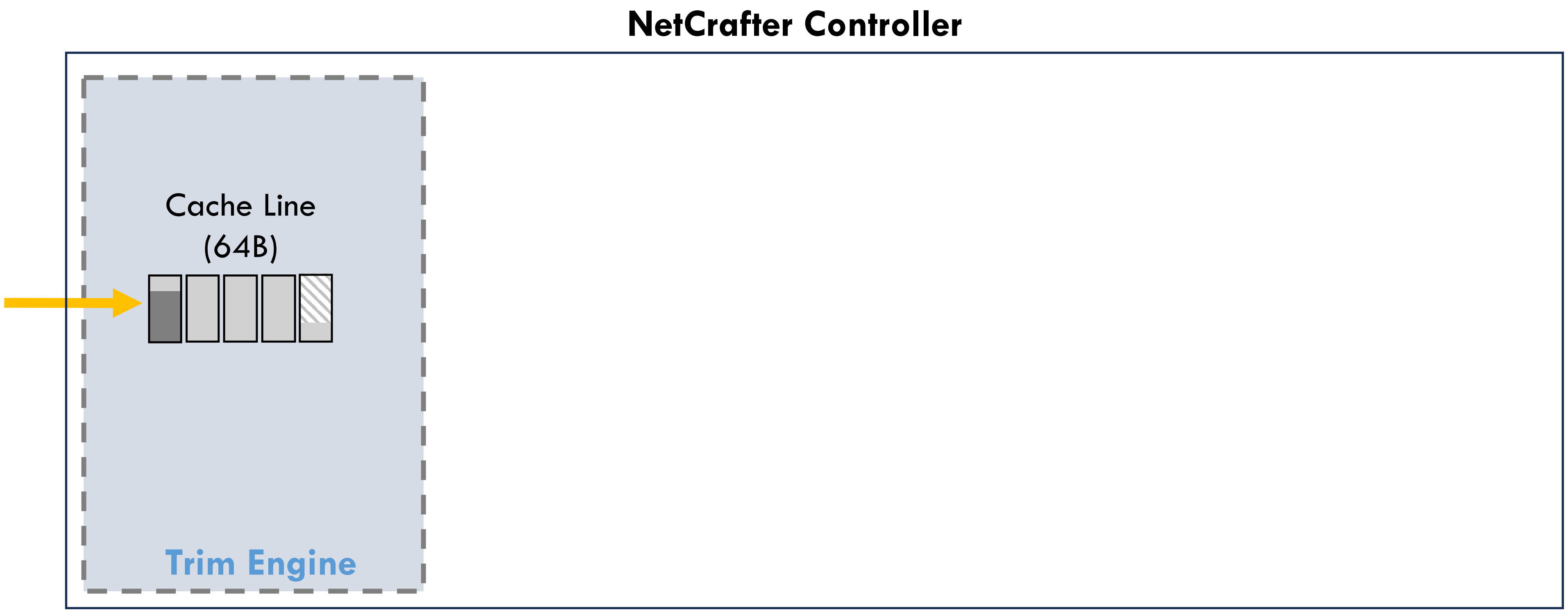

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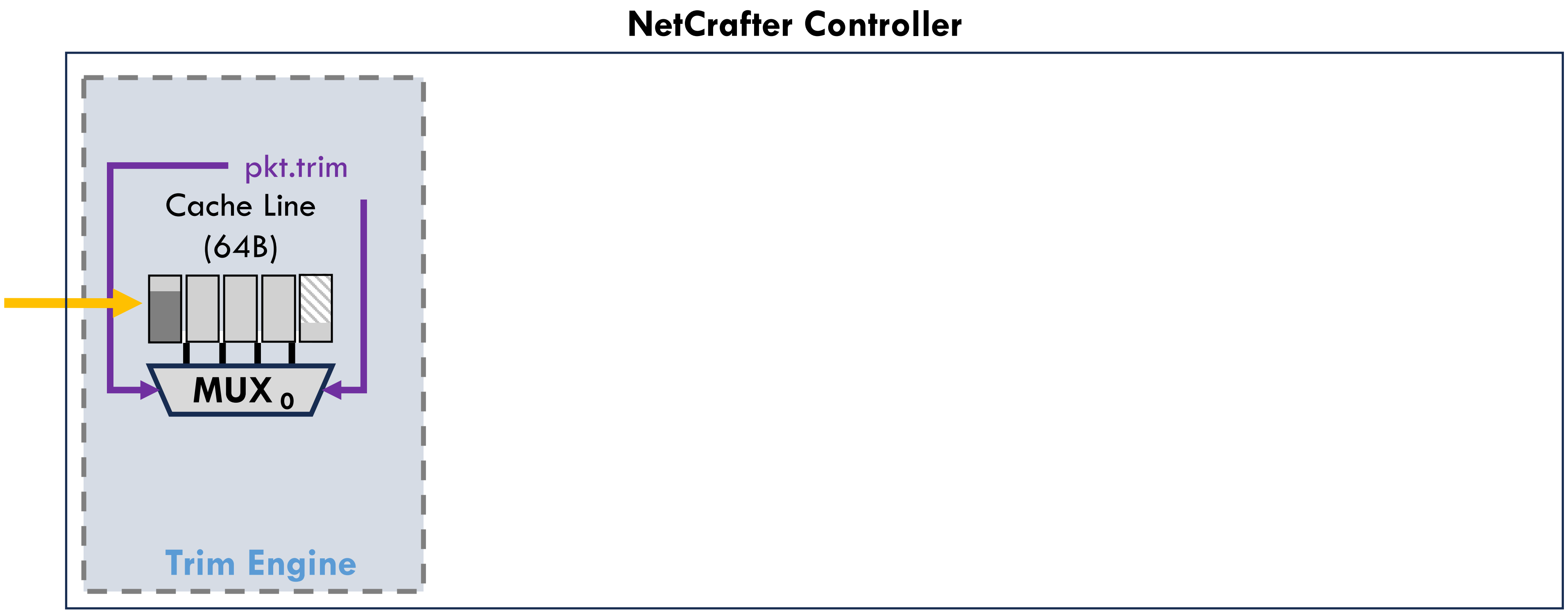

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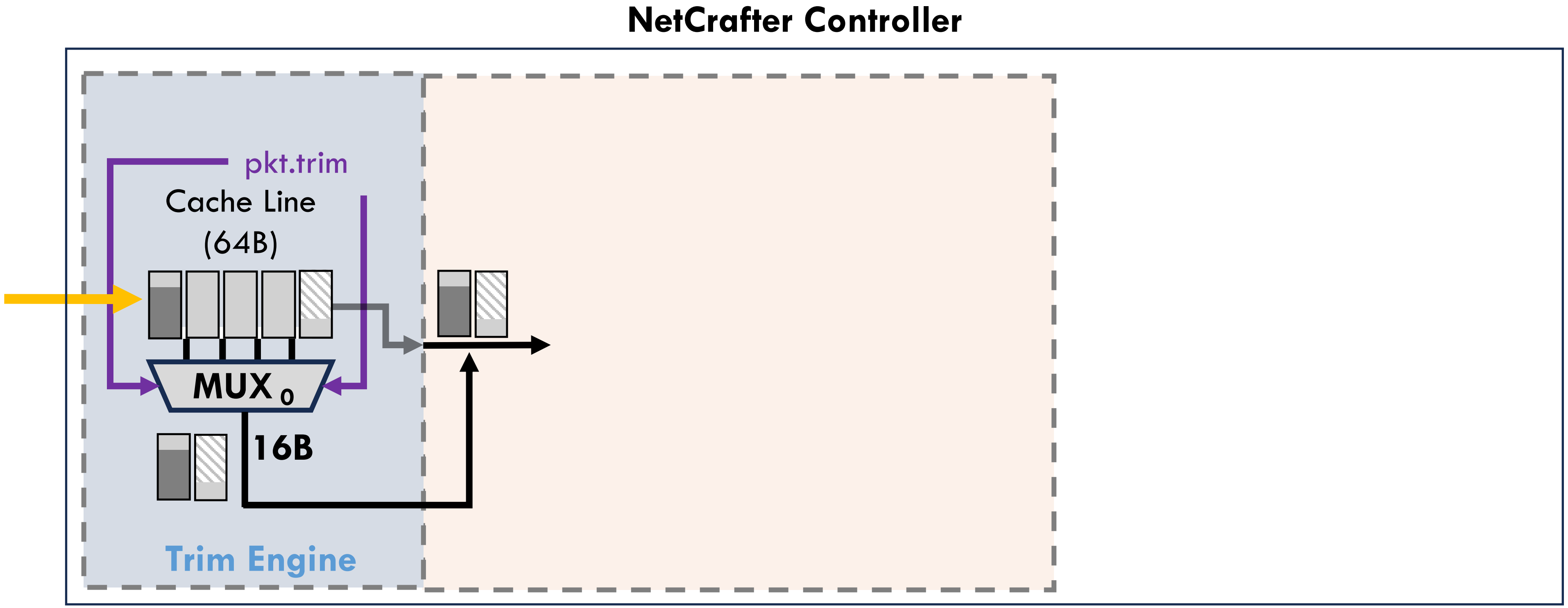

Decide the granularity

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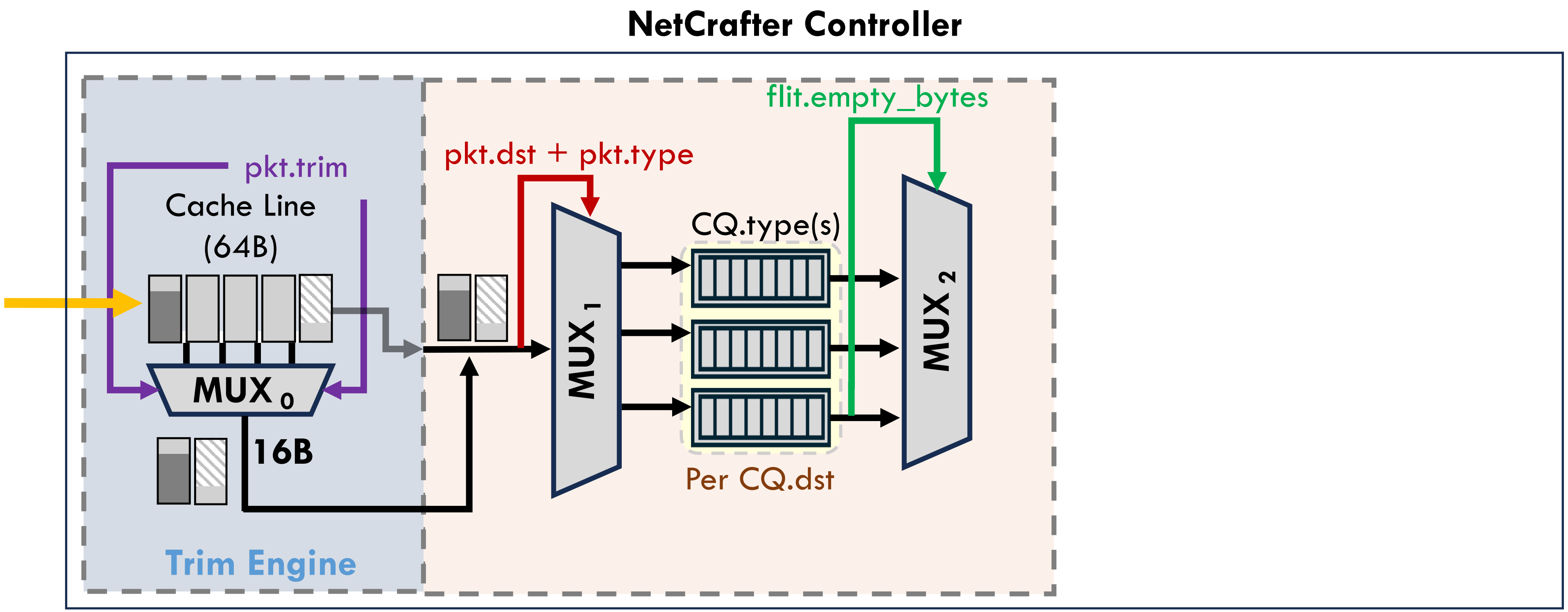

Decide the granularity

Choose the stitching candidates

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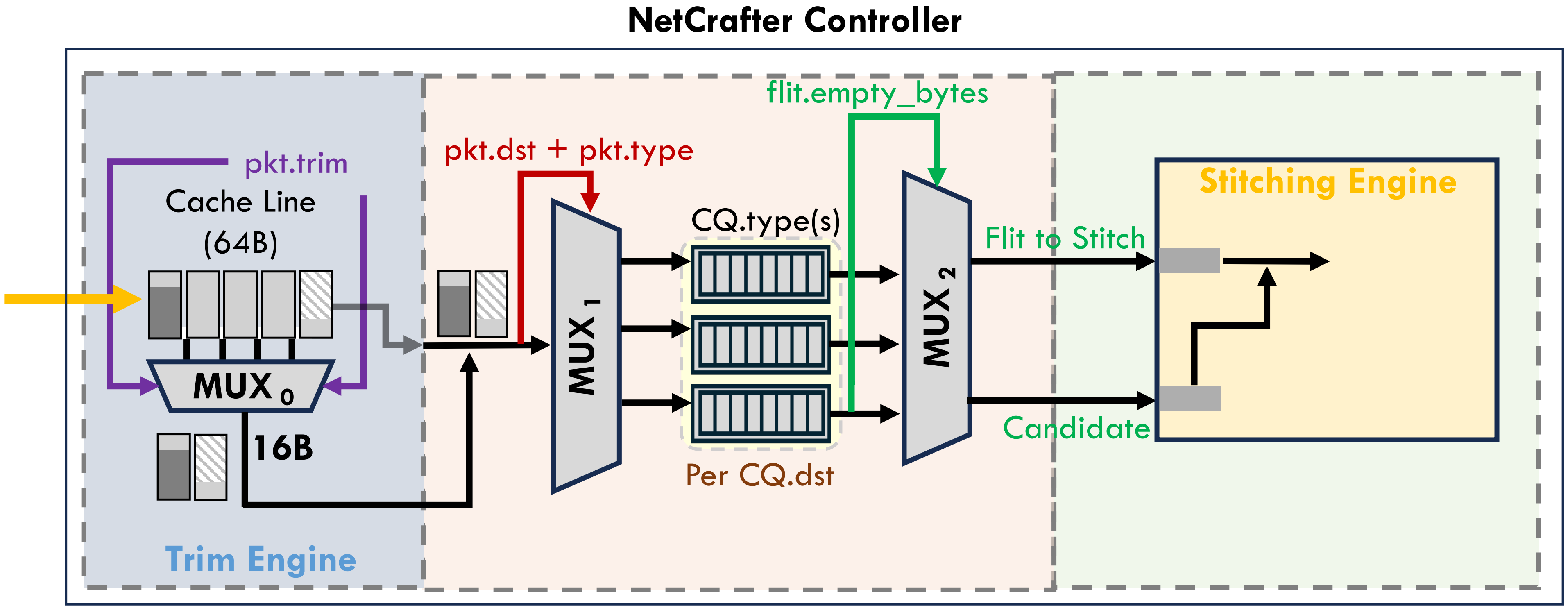

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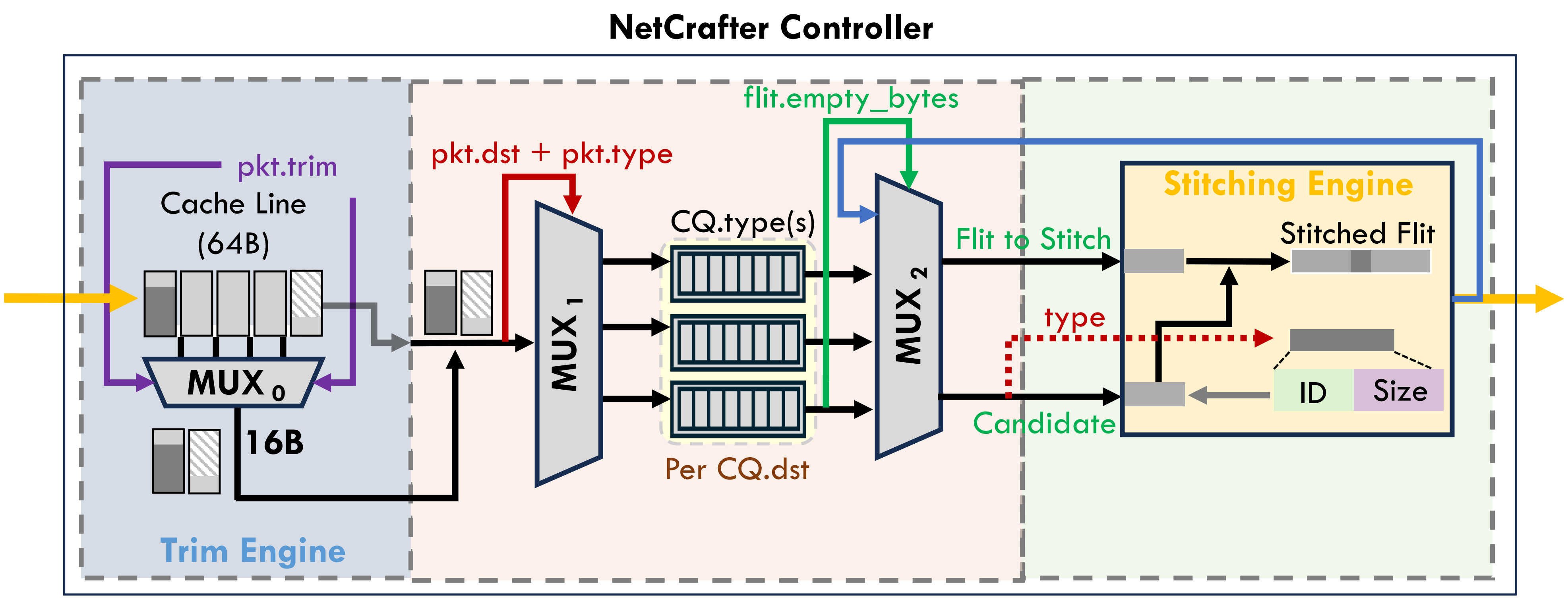

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Packet support + Sequence

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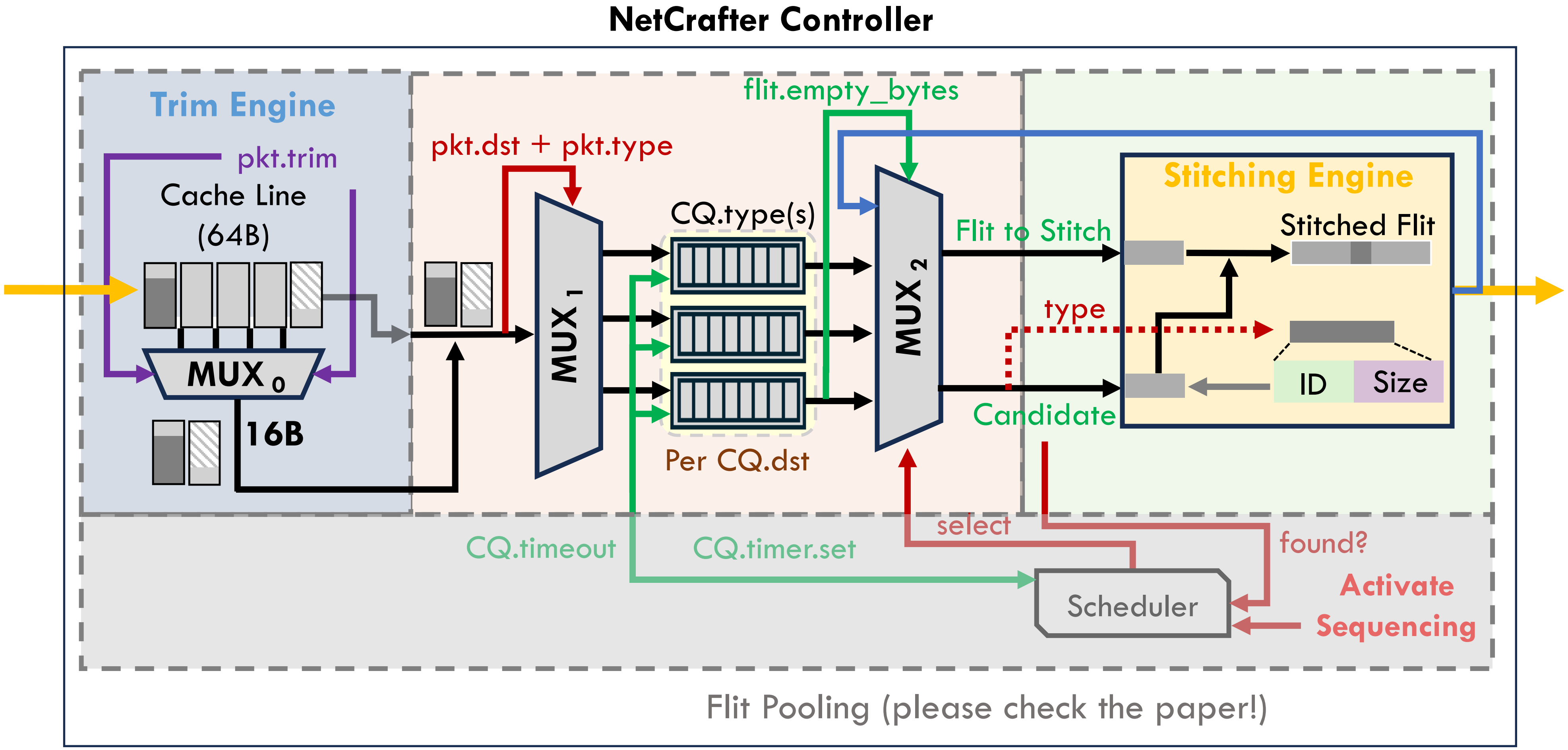

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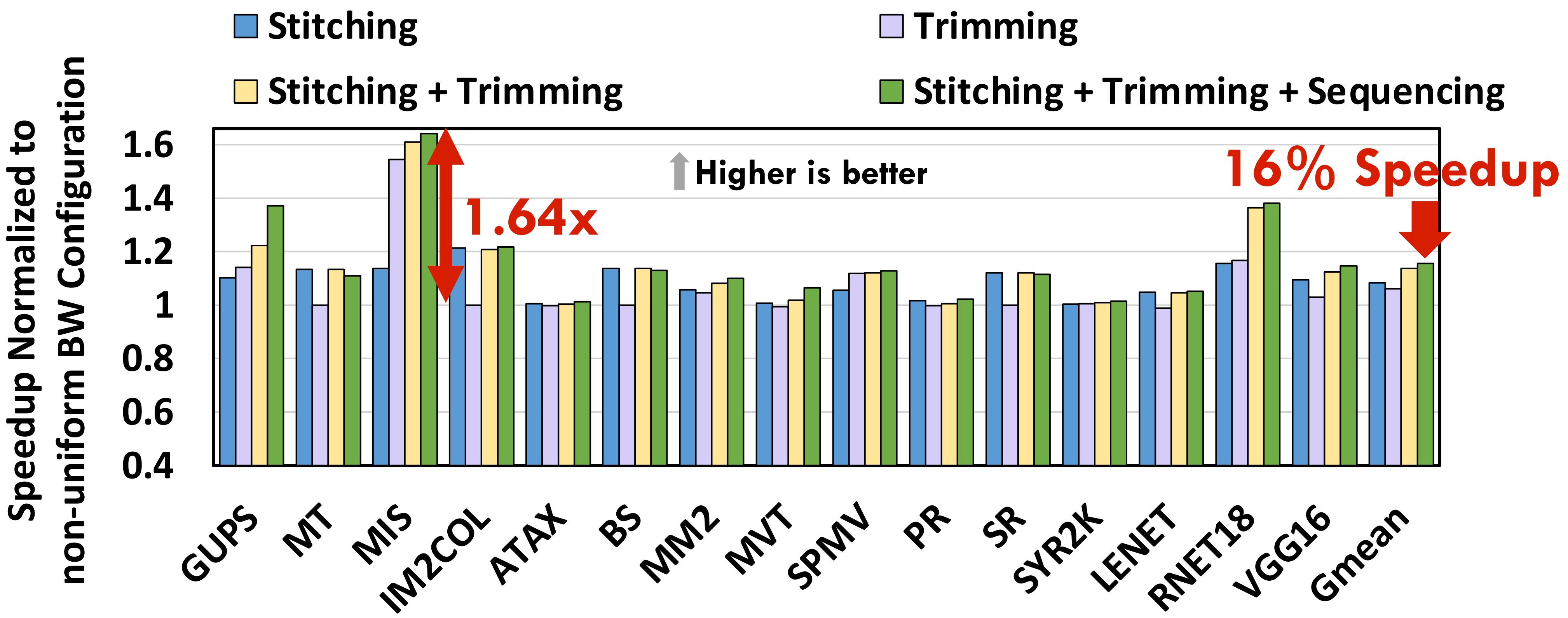
METHODOLOGY

- **MGPUSim Simulator:**

Compute Unit	1GHz, 64 per GPU (4 GPUs in total)
L1 D/I, L2 cache	64/32KB, 4MB per GPU (shared)
Heterogeneous Interconnect	Inter-GPU-cluster - 16GBps, bi-directional Intra-GPU-cluster - 128GBps, bi-directional
CTA/Page Scheduling	LASP (Locality-Aware Scheduling and Placement)
NetCrafter Parameters	Cluster Queue - 1024 Entries (16B each)

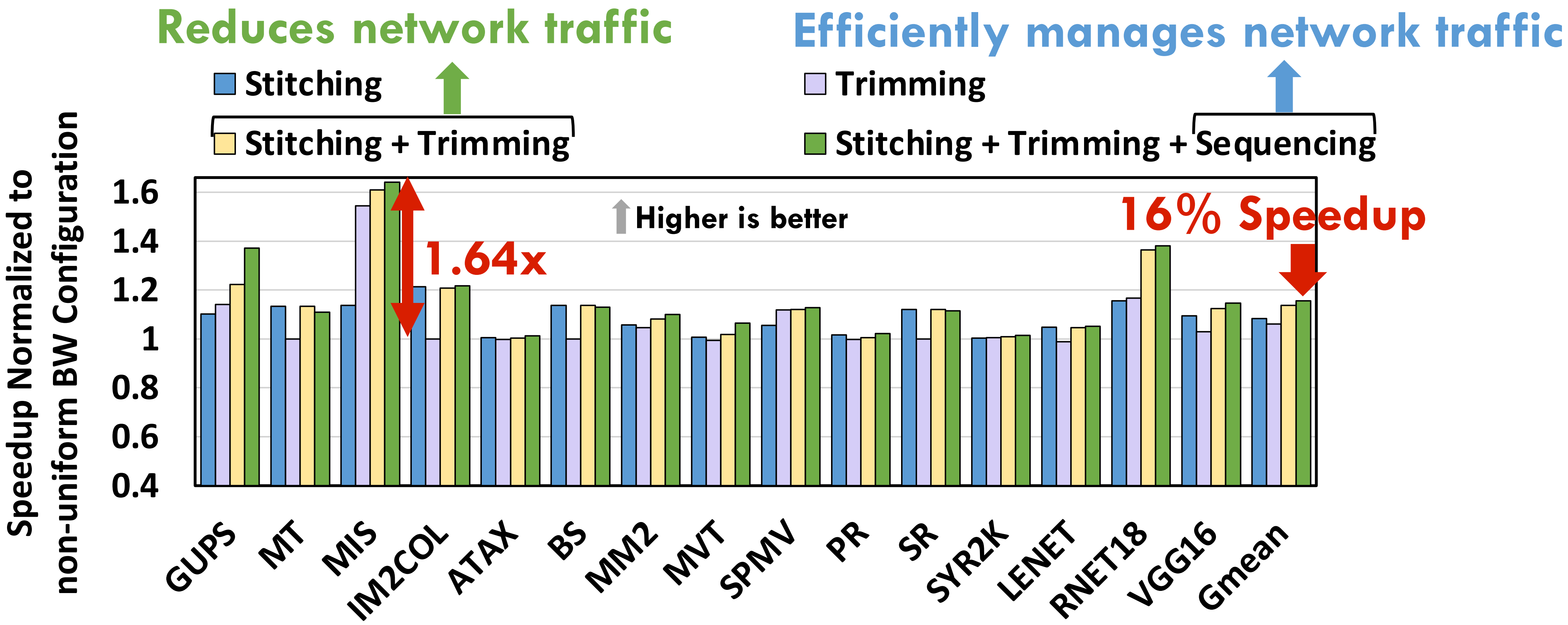
- **Design points:**
  - Baseline: non-uniform bandwidth configuration without NetCrafter
  - Sector Cache: baseline configuration with sector cache
  - NetCrafter: non uniform system with **Stitching, Trimming & Sequencing**

NetCrafter vs. Baseline



NetCrafter provides 16% speedup on average

NetCrafter vs. Baseline



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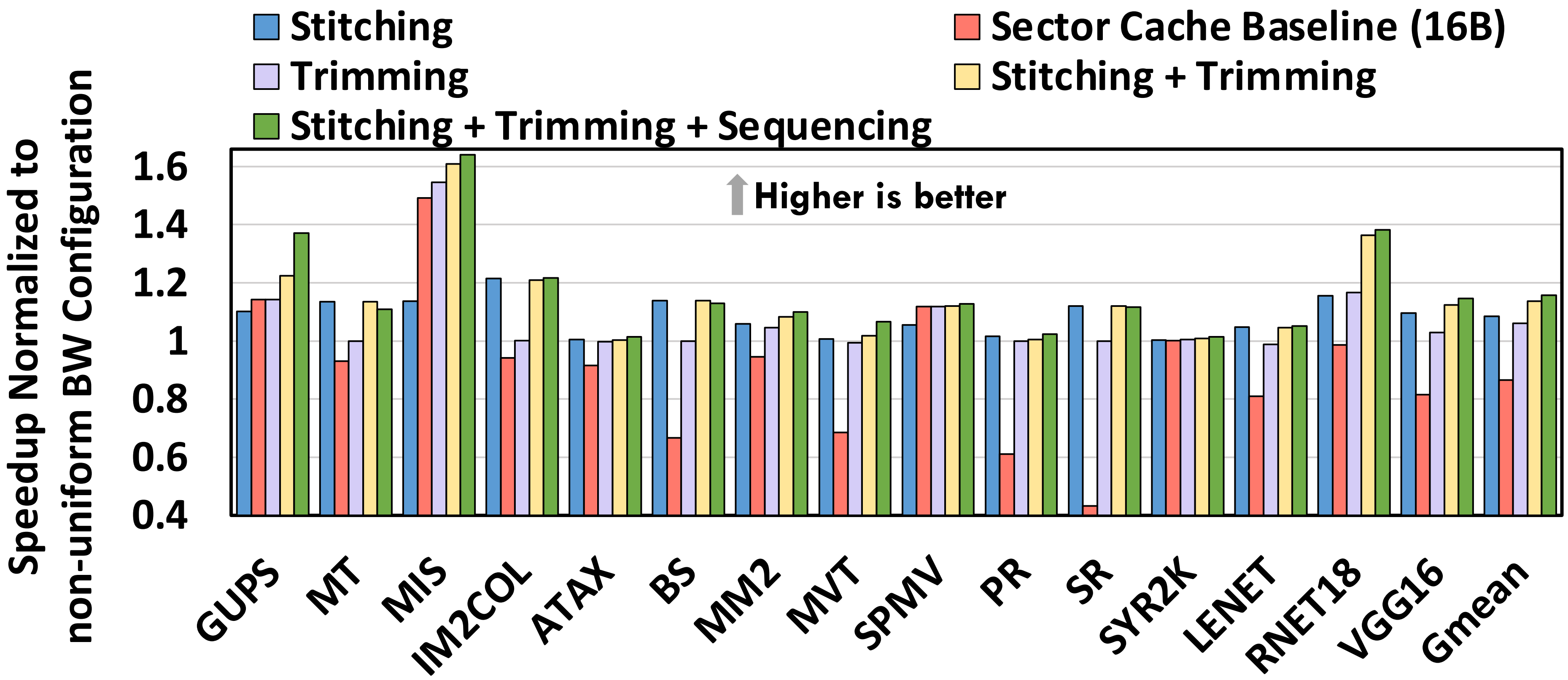
NetCrafter vs. Baseline + Sector Cache



NetCrafter provides 16% speedup on average

More Details…

- Flit Pooling and Selective Flit Pooling
- Impact of trimming on cache MPKI
- Modifications to the packet structure
- Hardware overhead
- Latency overhead
- CTA/data placement
- Coherence implications
- Handling deadlocks
- Packet unstitching details at the target
- Sensitivity studies with varied :
  - Flit-Pooling windows
  - Bandwidth numbers and ratios
  - Flit sizes

Please check our paper!

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Conclusion

NetCrafter, a combination of novel approaches (***Stitching***, ***Trimming*** and ***Sequencing***) to deal with the **multi-GPU** network traffic, which provides up to **64%** speedup and **16%** speedup on average.

Our proposed techniques are ***generic*** and can be applied to ***any*** network. They are especially useful in alleviating the bottlenecks presented by ***lower-bandwidth networks*** connecting multiple groups of GPUs.

Thanks!
Questions?

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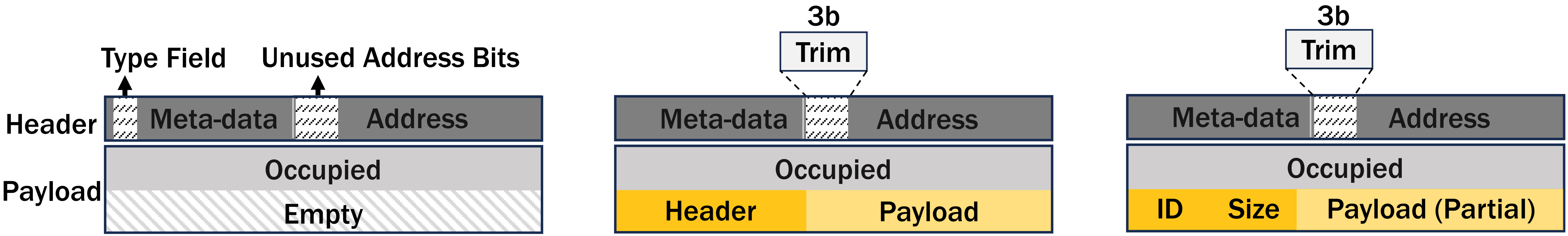
BACKUP SLIDES

Packet structure to support NetCrafter

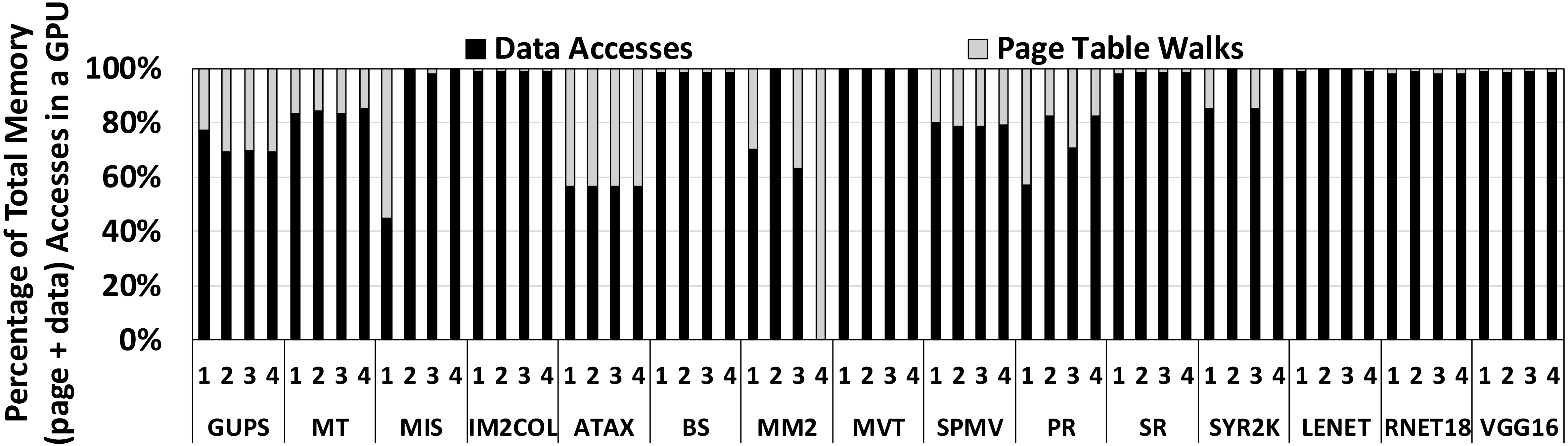


a) A typical PCIe Packet

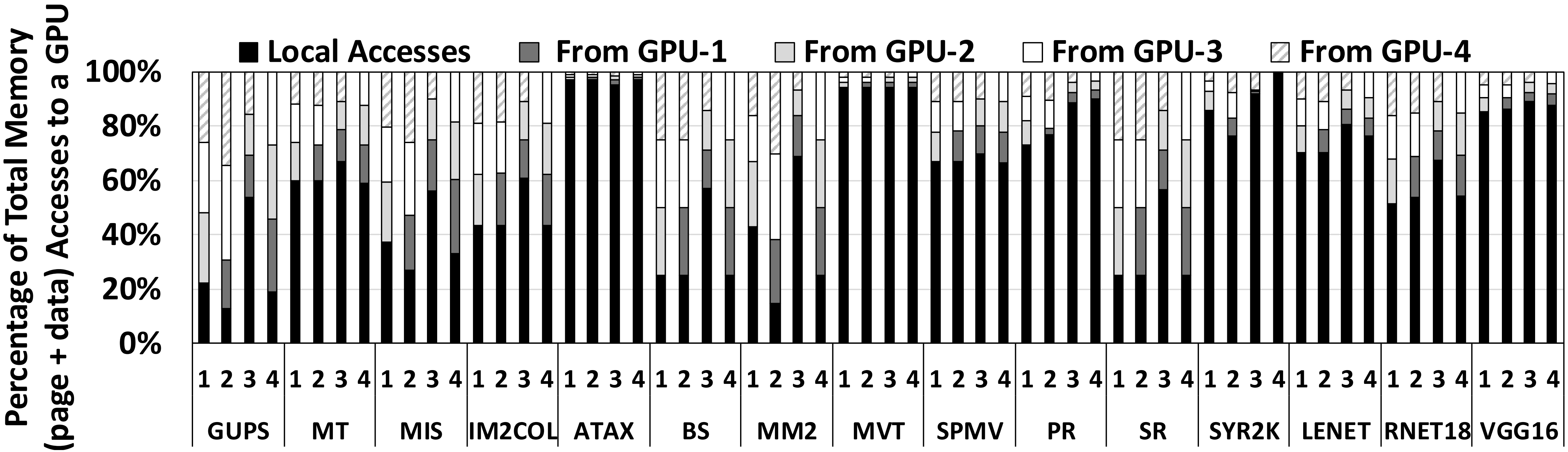
b) Stitching a complete packet

c) Stitching a partial packet

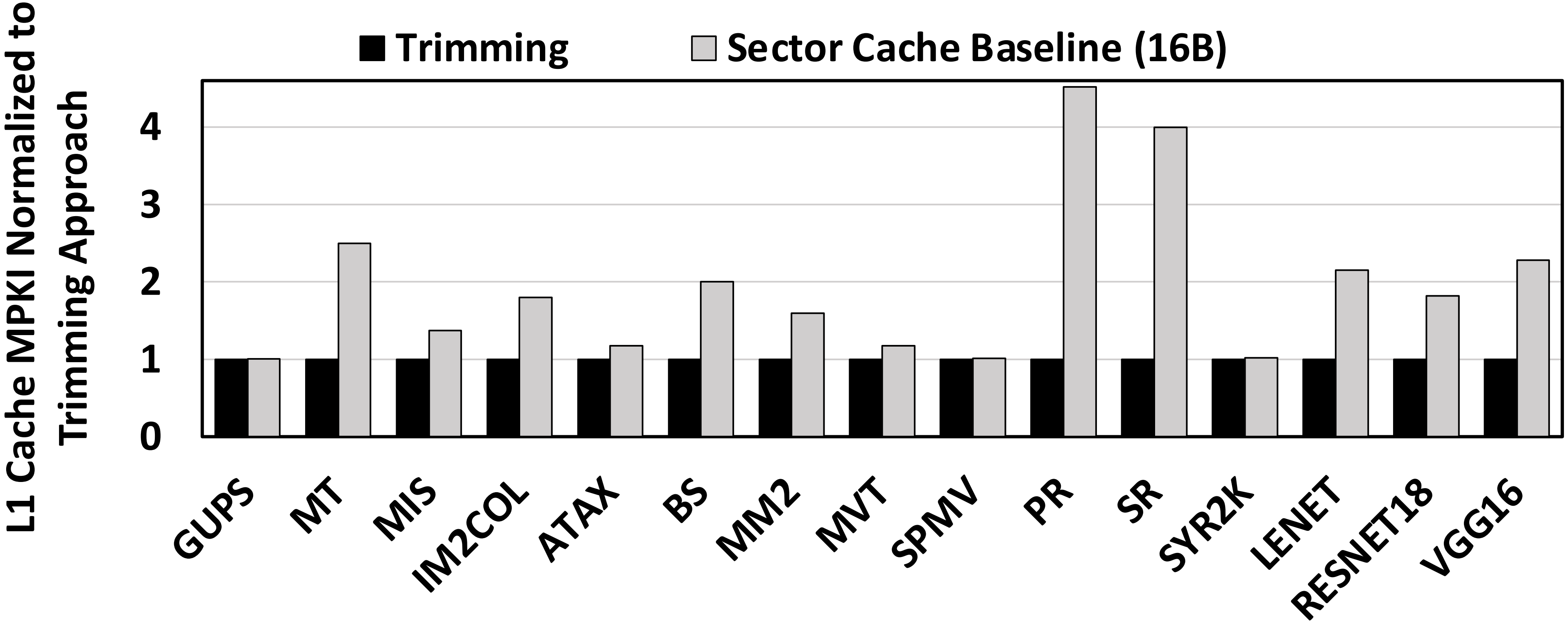
Ratio of Data vs Page Table Accesses per GPU



Distribution of Memory Access Requests/GPU



Cache MPKI Comparison with Sector Cache



```
Parameters      : Qx holding different packets
function STITCH ();
begin
  while True do
    /* select a valid queue through scheduler */
    while Qi.empty() or Qi.timer() do
      Qi ← Sched (QA, QB, QPTW);
    end
    pkt ← Qi[head];
    /* compute empty bytes in the last flit */
    sz ← SZflit-sizeof(pkt)%SZflit;
    /* last flit size equals sz in Qj */
    Qj ← PARTITION_QUEUE(sz);
    sc ← STITCH_CANDIDATE(sz, Qj);
    if sc == nil then
      /* prioritized packet */
      if pkt.type==latency_critical or
      sc.type==0 then
        Eject (pkt);
      end
      else if Qi.timer.timeout() then
        /* only wait for one period */
        Qi.timer.clear();
        Eject (pkt);
      end
      else
        /* wait for a period in wish to find a candidate */
        Qi.timer.set();
      end
    end
    else
      /* add sub-header for type-2 candidate */
      if sc.type==2 then
        pkt.add(sc.tag||sizeof(sc));
      end
      /* combine two flits */
      pkt.add(sc);
    end
  end
end
```

Algorithm 1: Stitching with Selective Flit Pooling

$$Q_i = Sched(Pkt_{dst}, Pkt_{type}) = P_{dst,type}$$
$$P_{dst} = P[dst]$$
$$P_{dst,type} = P_{dst}[Flit_{size} - (Pkt_{size} \ \% \ Flit_{size})]$$
$$where,$$
$$Q = Queue \ \& \ P = Partition \ \& \ Pkt = Network \ Packet$$
$$P : dst \rightarrow Q_f \ \& \ Q_f : size \rightarrow Q$$