BBQ: A Fast and Scalable Integer Priority Queue for Hardware Packet Scheduling

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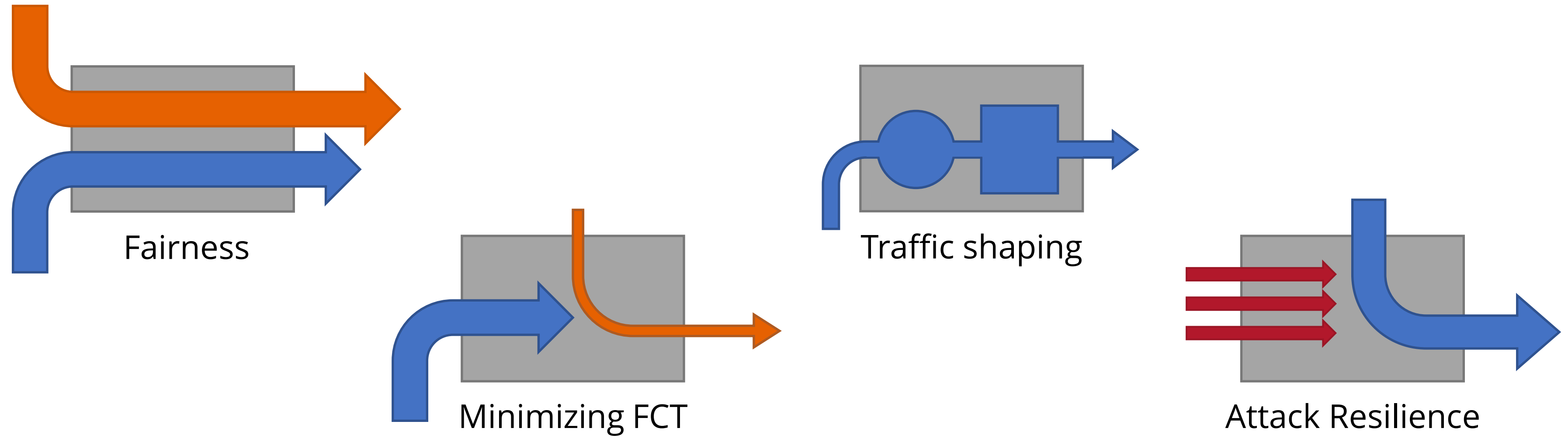
Packet Scheduling in the Wild

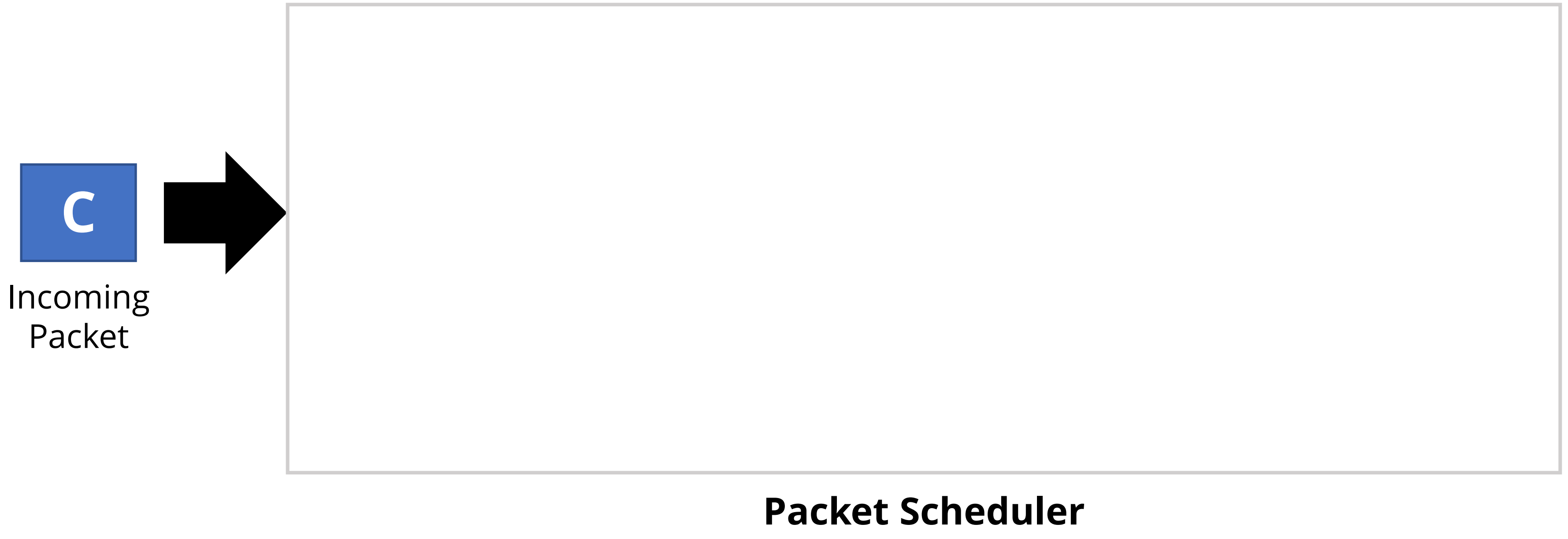
Rich literature on packet scheduling algorithms optimizing for different performance objectives in various network settings



The key to deployment is **programmable hardware packet scheduling**

Programmable Packet Scheduling

Programmable Packet Scheduling at Line Rate [SIGCOMM ’16]
→ **Push-In First-Out (PIFO)**



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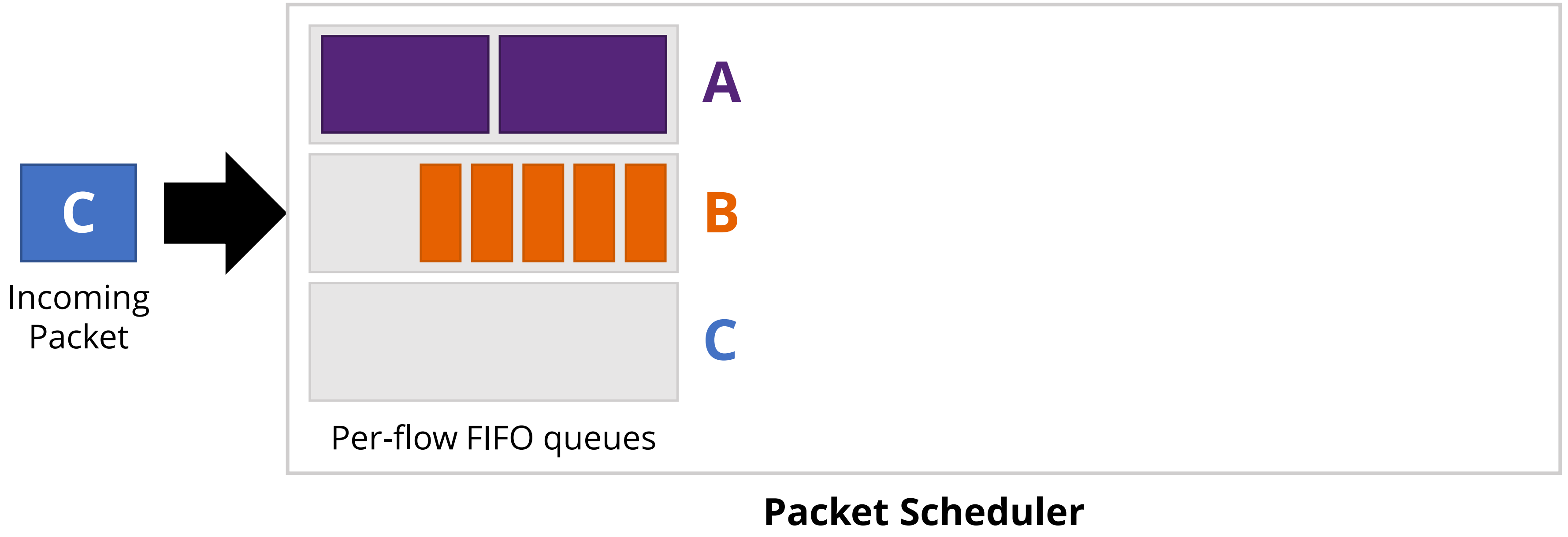

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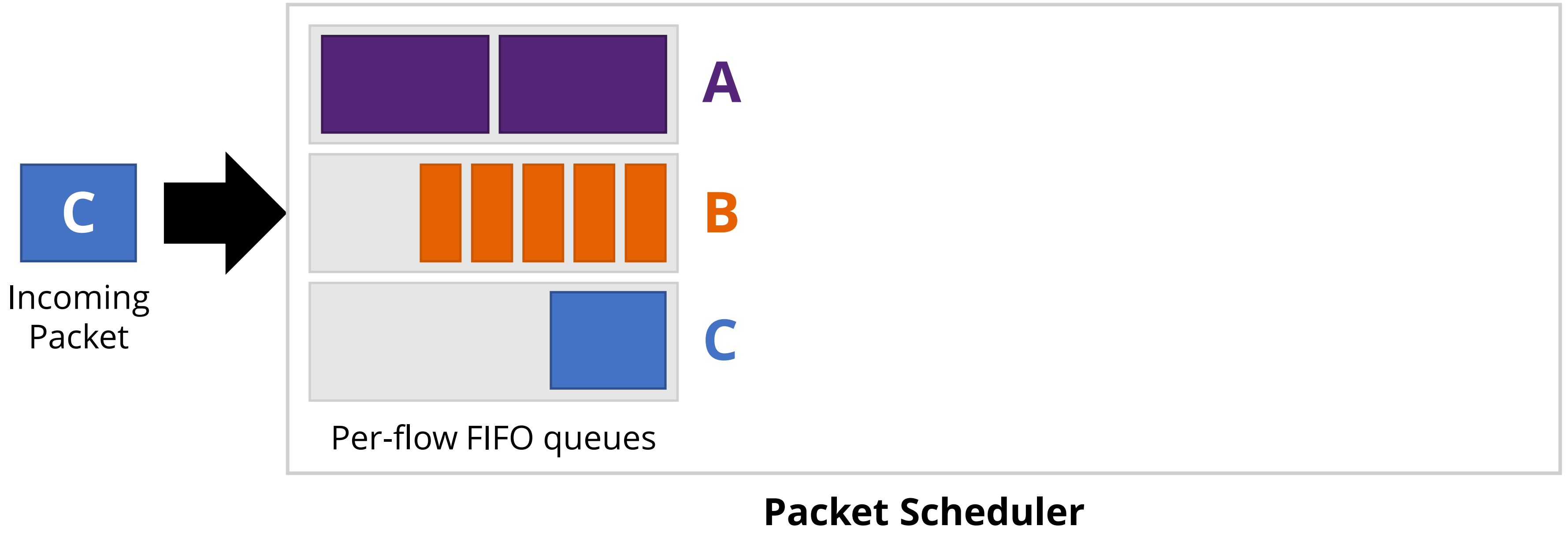

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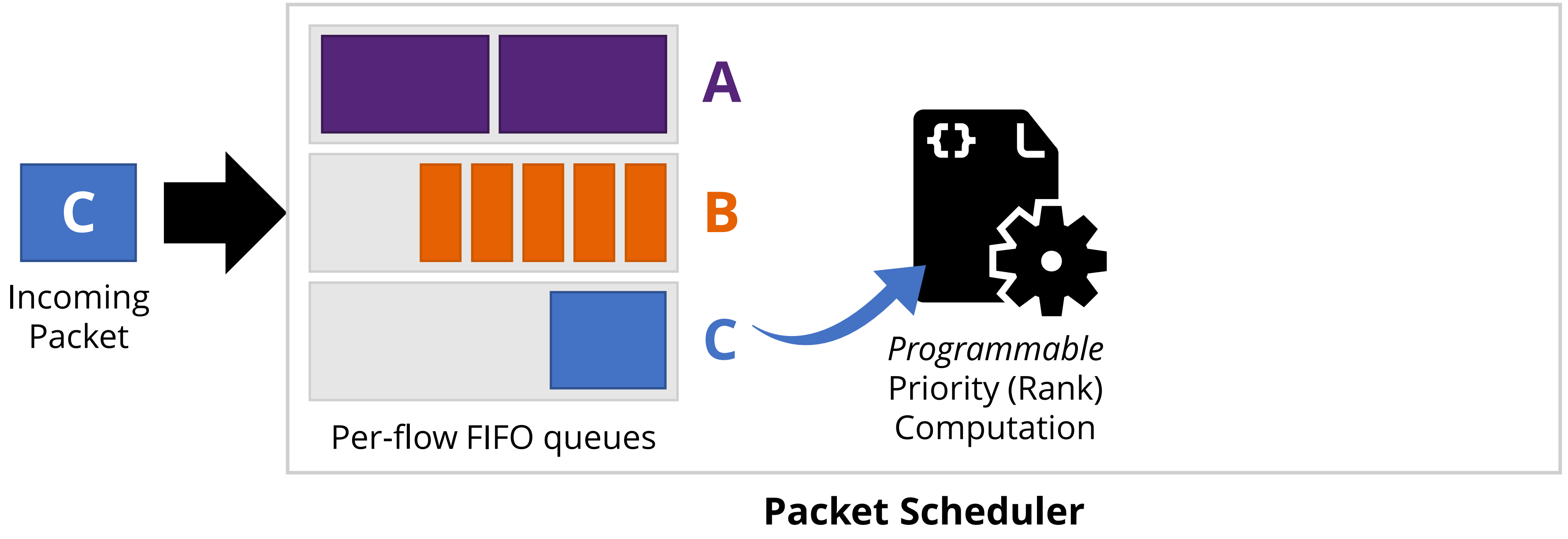

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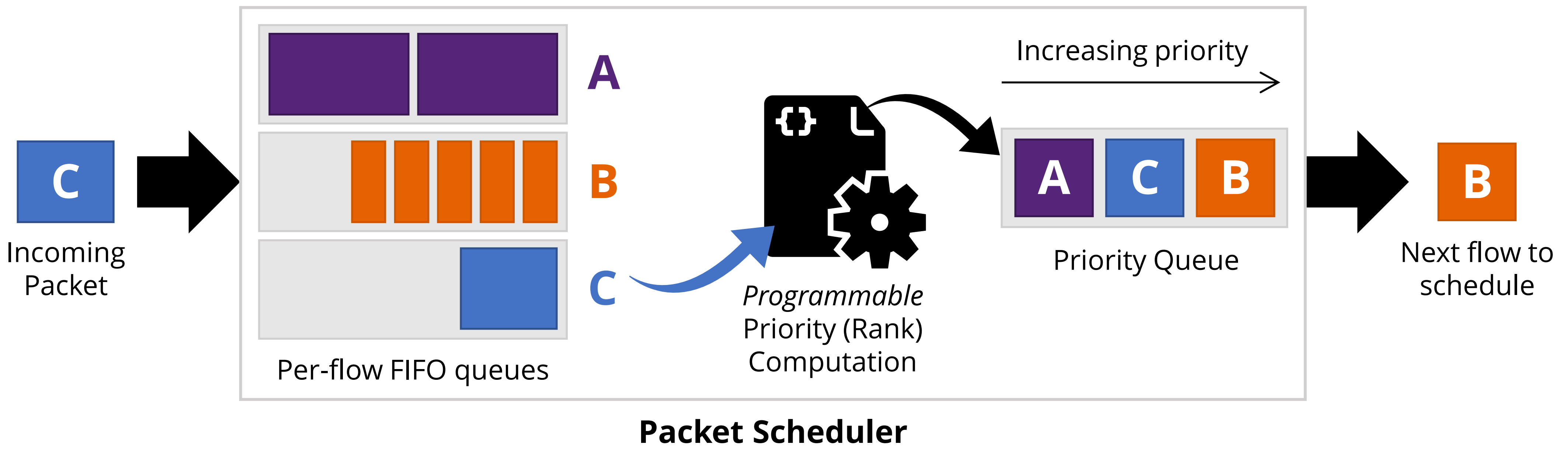

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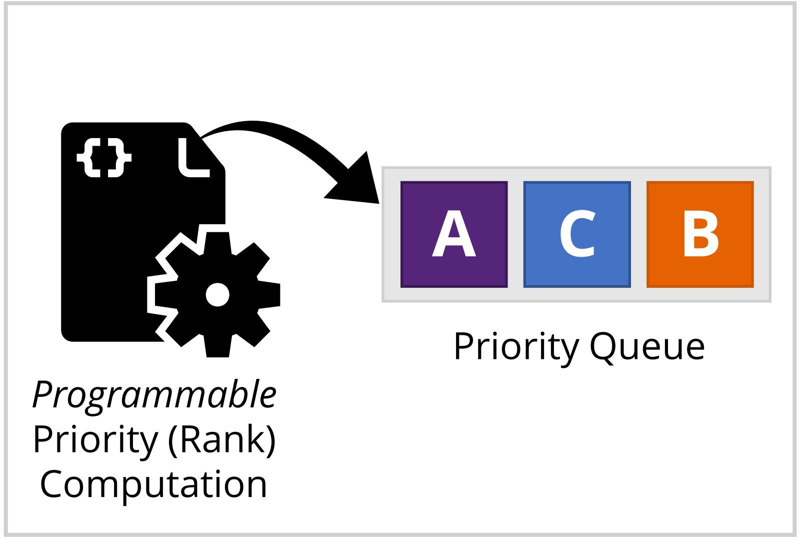

PIFO Abstraction

PIFO, proposed 8 years ago, supports practically any scheduling algorithm
Great! So today's routers must implement this abstraction, right?
...right?

Programmable Packet Scheduling

Programmable Packet Scheduling at Line Rate [SIGCOMM '16]
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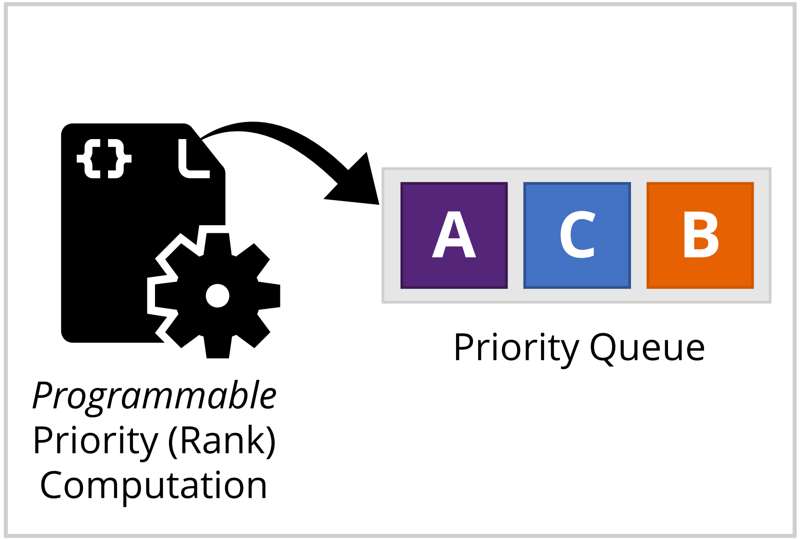

PIFO Abstraction

At the heart of PIFO is a **hardware priority queue** that provides, at minimum, enqueue and dequeue-max functionality

PIFO's vision is hampered by throughput, scalability, and resource overhead issues associated with existing priority queue designs

This Talk

- Minimum requirements for scheduling in switches and SmartNICs
- State-of-the-art priority queue designs are infeasible
- How do we get there?
- Evaluation

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Minimum requirements for scheduling in switches and SmartNICs

Flow Count Scalability

Support flow counts representative of modern networks: **O(100K)**

Single-Instance Performance

Sustain packet rates corresponding to today's line rates: **100Gbps+ (148.8 Mpps)**

Logical Partitioning

Statistically multiplex a single, **physical** priority queue between many independent **logical** priority queues

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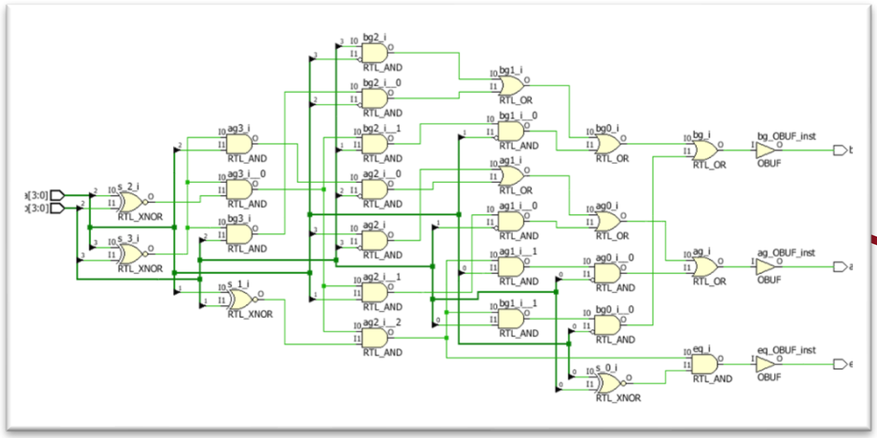
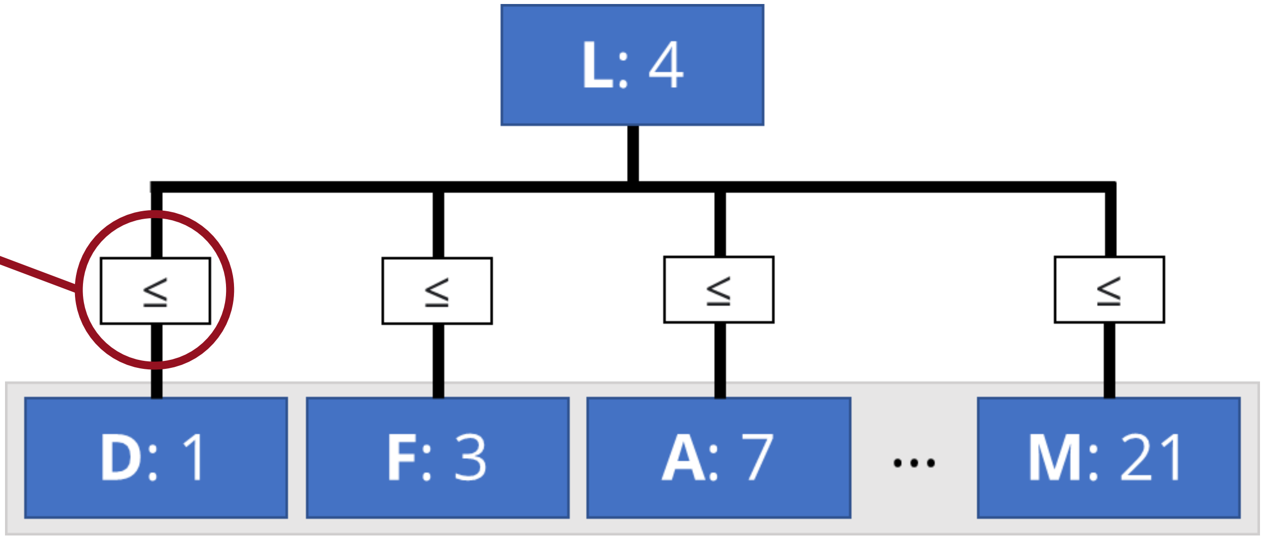
Existing designs are infeasible

PIFO [SIGCOMM '16]

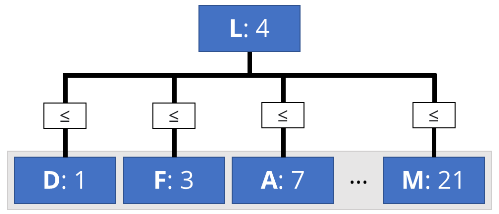




N comparators followed by priority decoding to decide where to insert the next entry → supports at most 4K flows

Poor Scalability

Existing designs are infeasible



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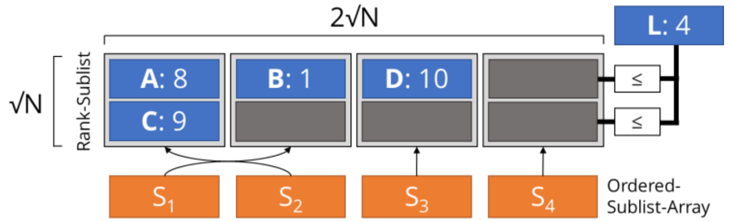
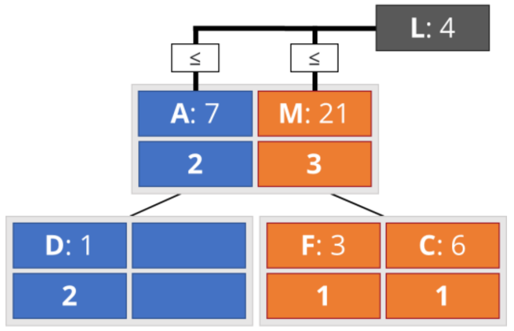


PIEO [SIGCOMM '19]



BMW-Tree [SIGCOMM '23]

Poor Scalability

4K flows

64K flows

100K+ flows

Flow Count Scalability

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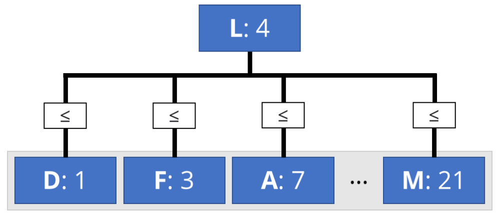

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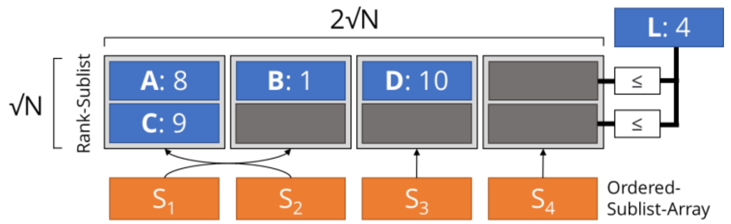
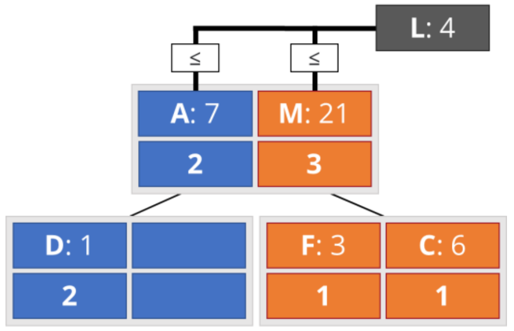


PIEO [SIGCOMM '19]

Poor Performance

64K flows

15 Mpps (10% of line rate at 100 Gbps) on an **FPGA SmartNIC**



BMW-Tree [SIGCOMM '23]

No Logical Partitioning

100K+ flows

1.5 – 6X chip area to implement on a 32-port **Switch ASIC**

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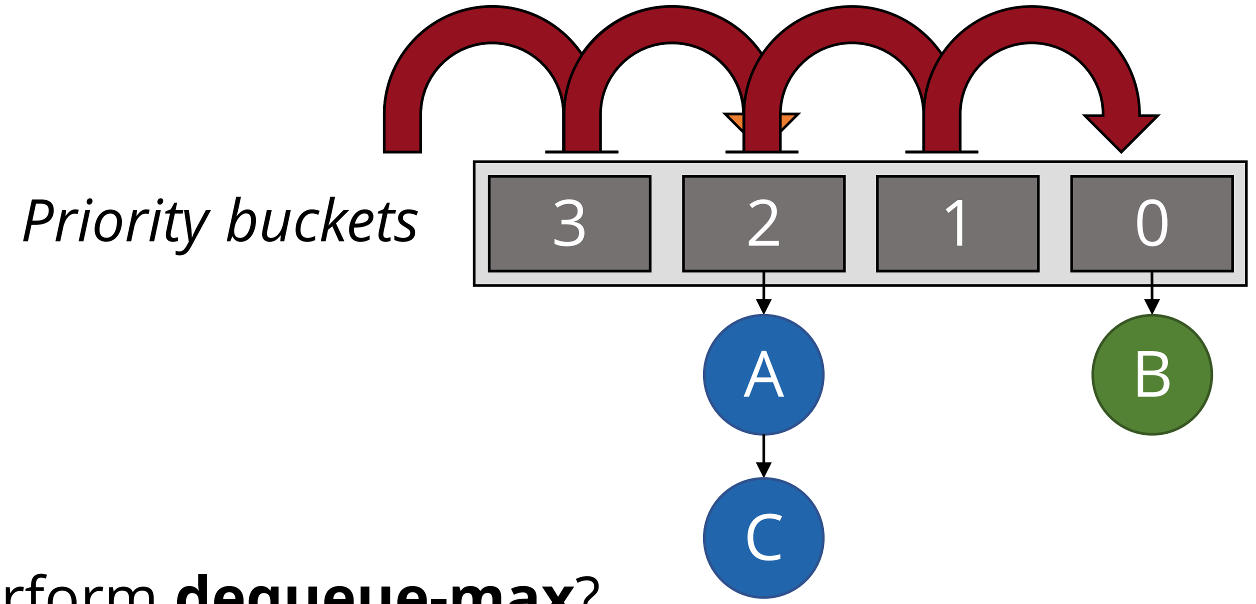
Key Idea

If the priority span is bounded, we can achieve all 3 properties (**scalability**, **performance**, and **logical partitioning**) using non-comparison-based sorting.

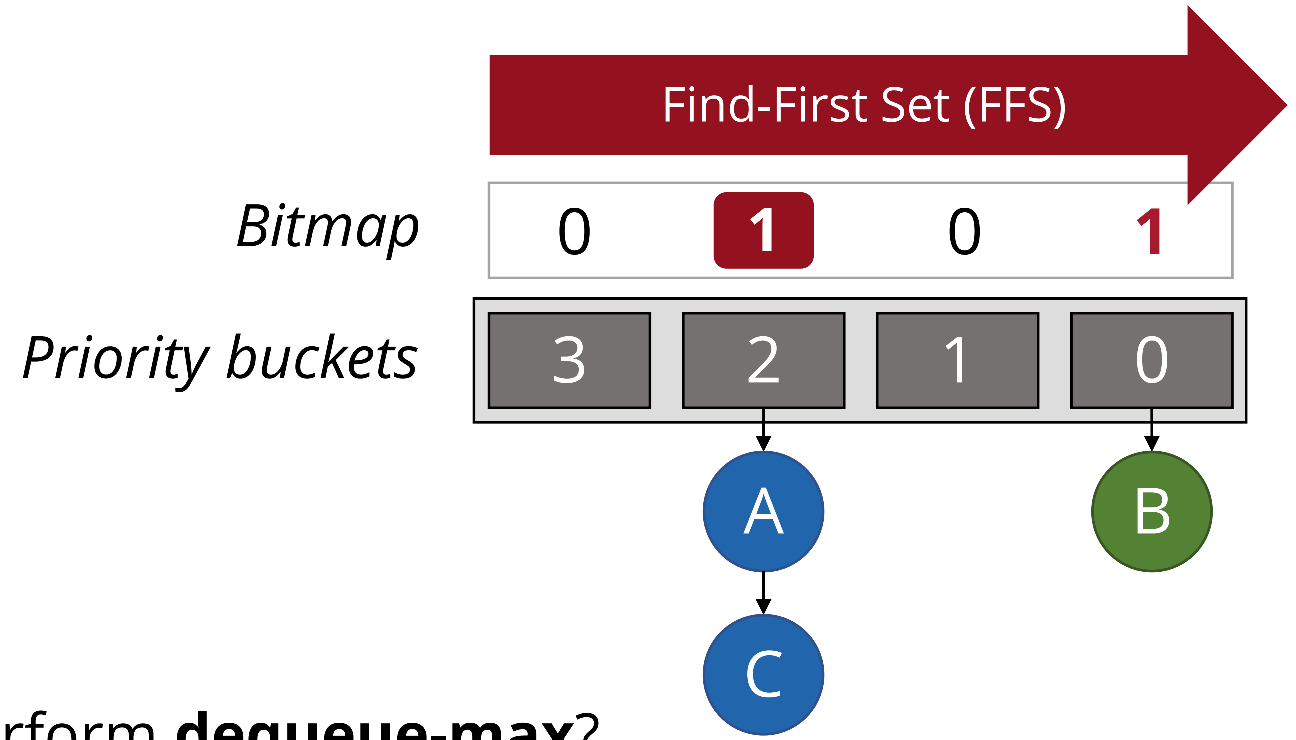
Integer Priority Queueing (IPQ)



How to perform **dequeue-max**?

- Iteratively checking each bucket is slow!

Integer Priority Queueing (IPQ)



How to perform **dequeue-max**?

- Augment with a *bitmap* encoding bucket occupancy, then use *Find-First Set*

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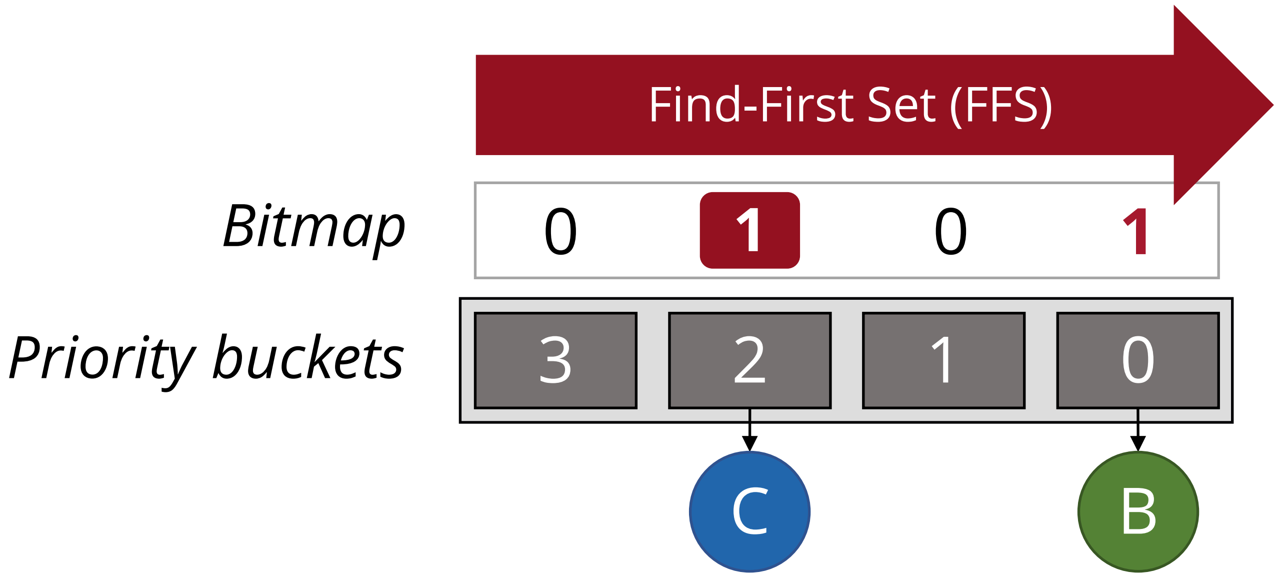

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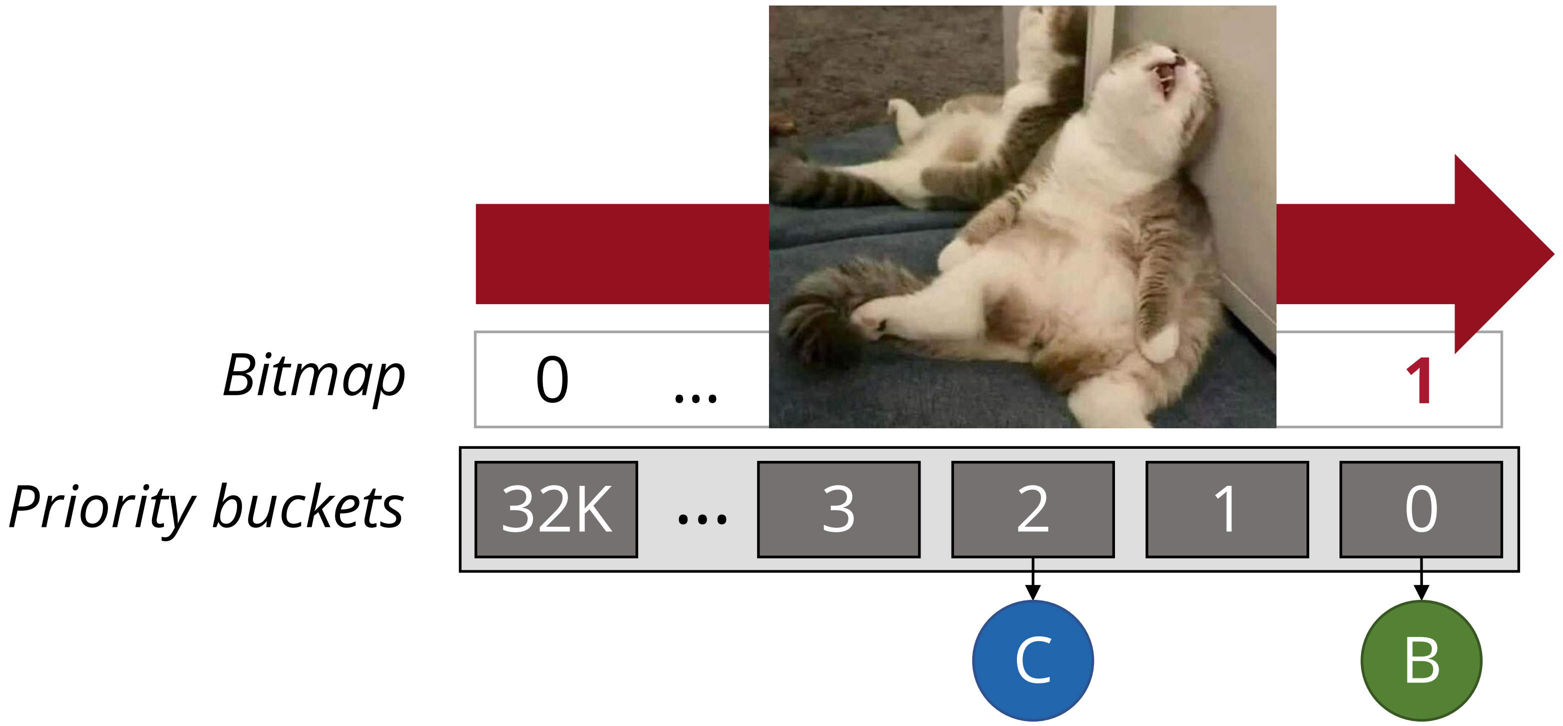
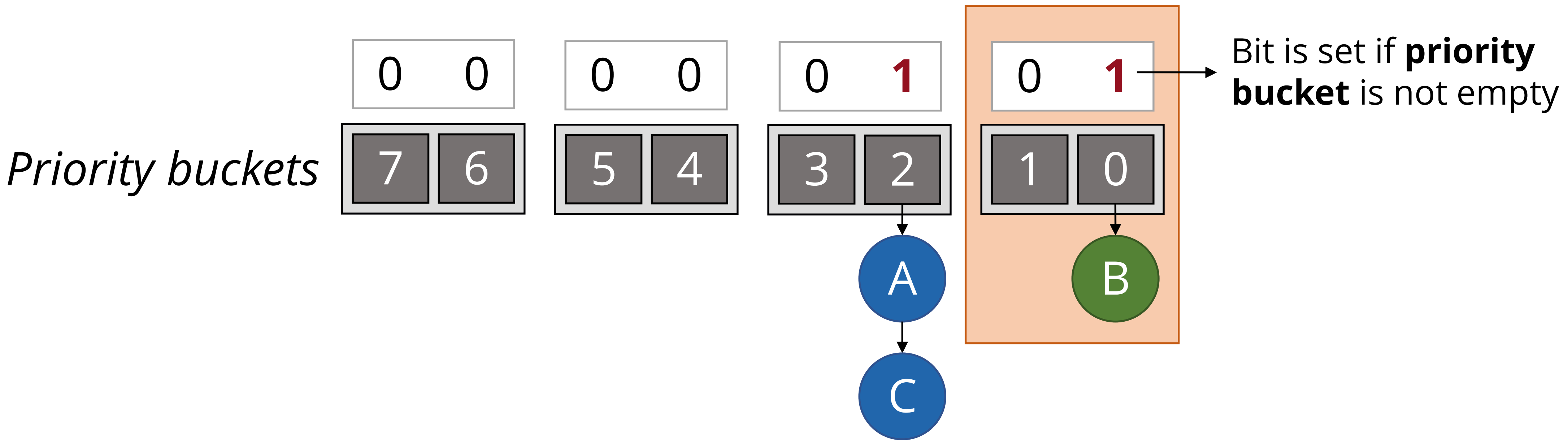


What if we need to support a **huge number of priorities** (*e.g.*, 32K)?

- Can't do FFS on a 32K-bit bitmap

Integer Priority Queueing (IPQ)



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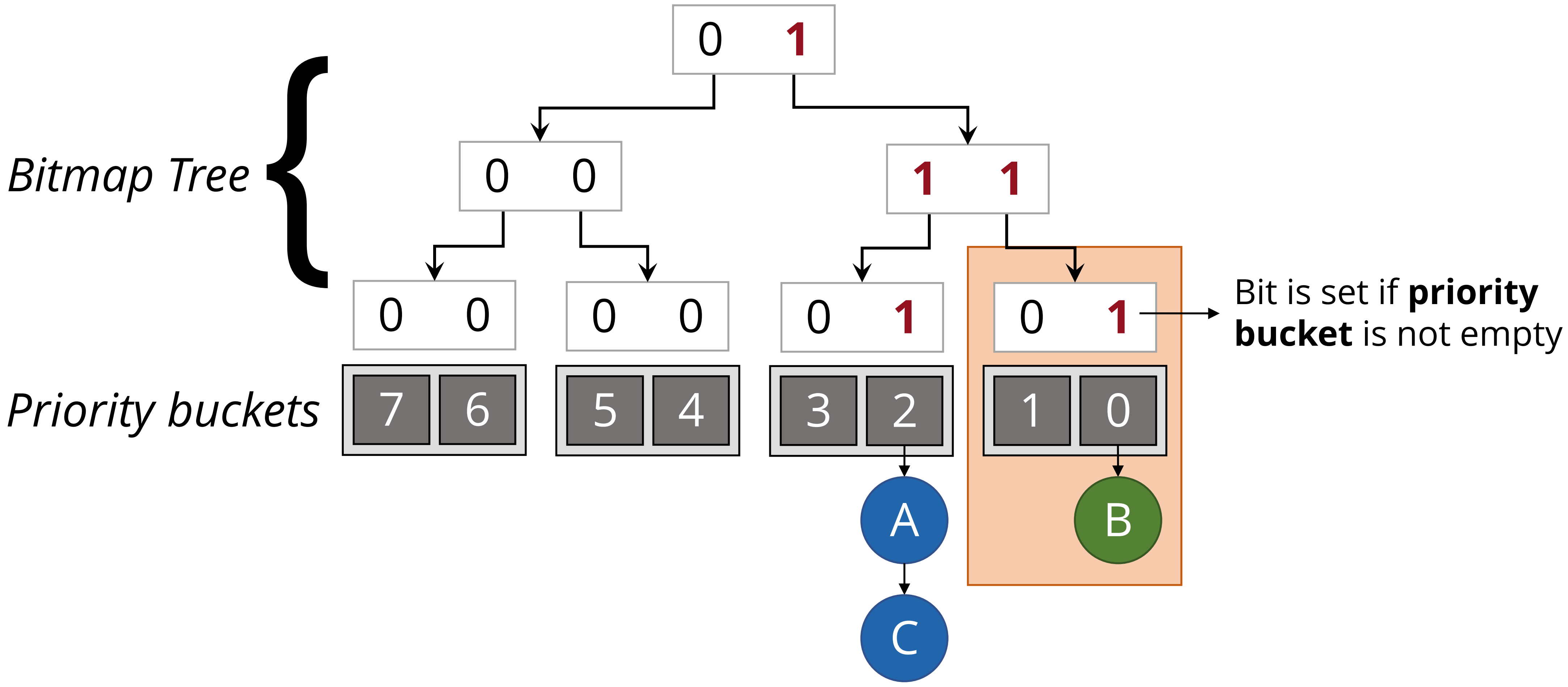

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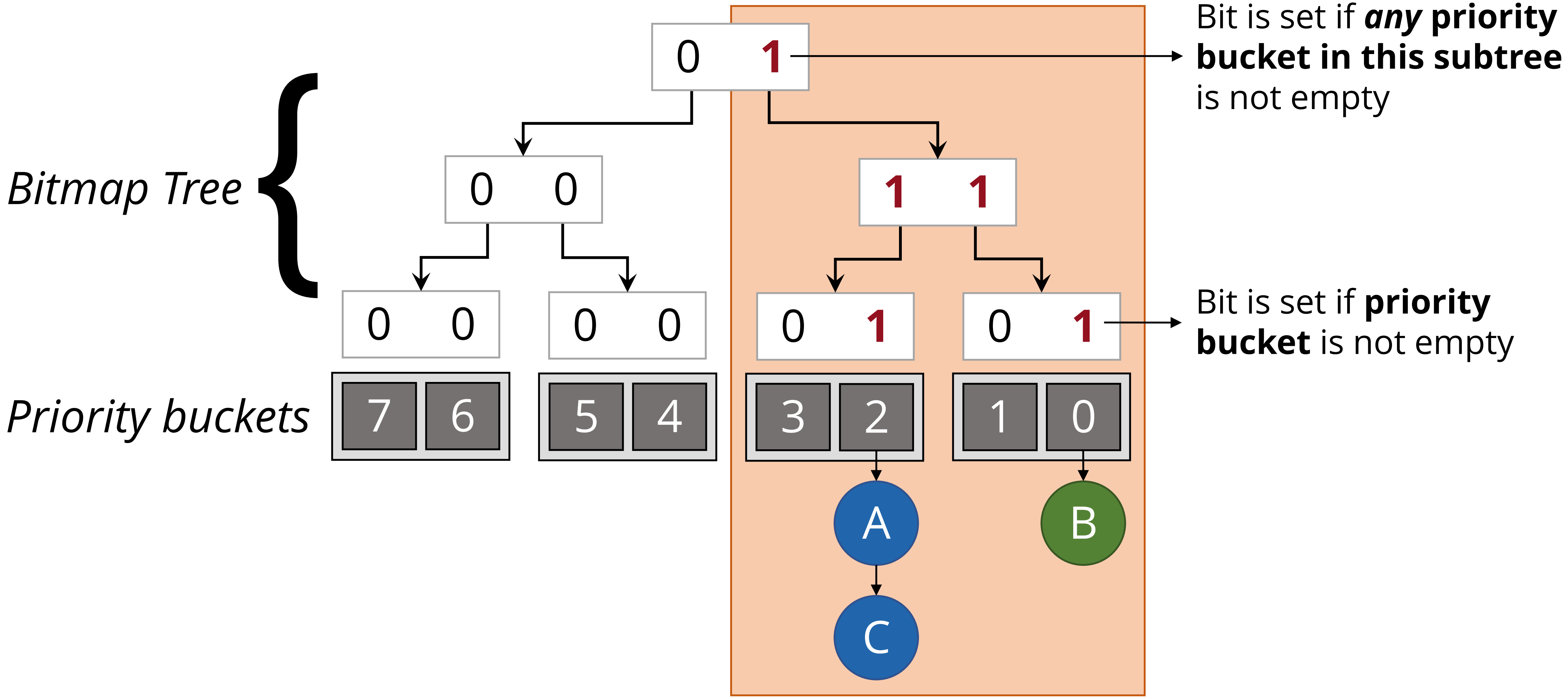
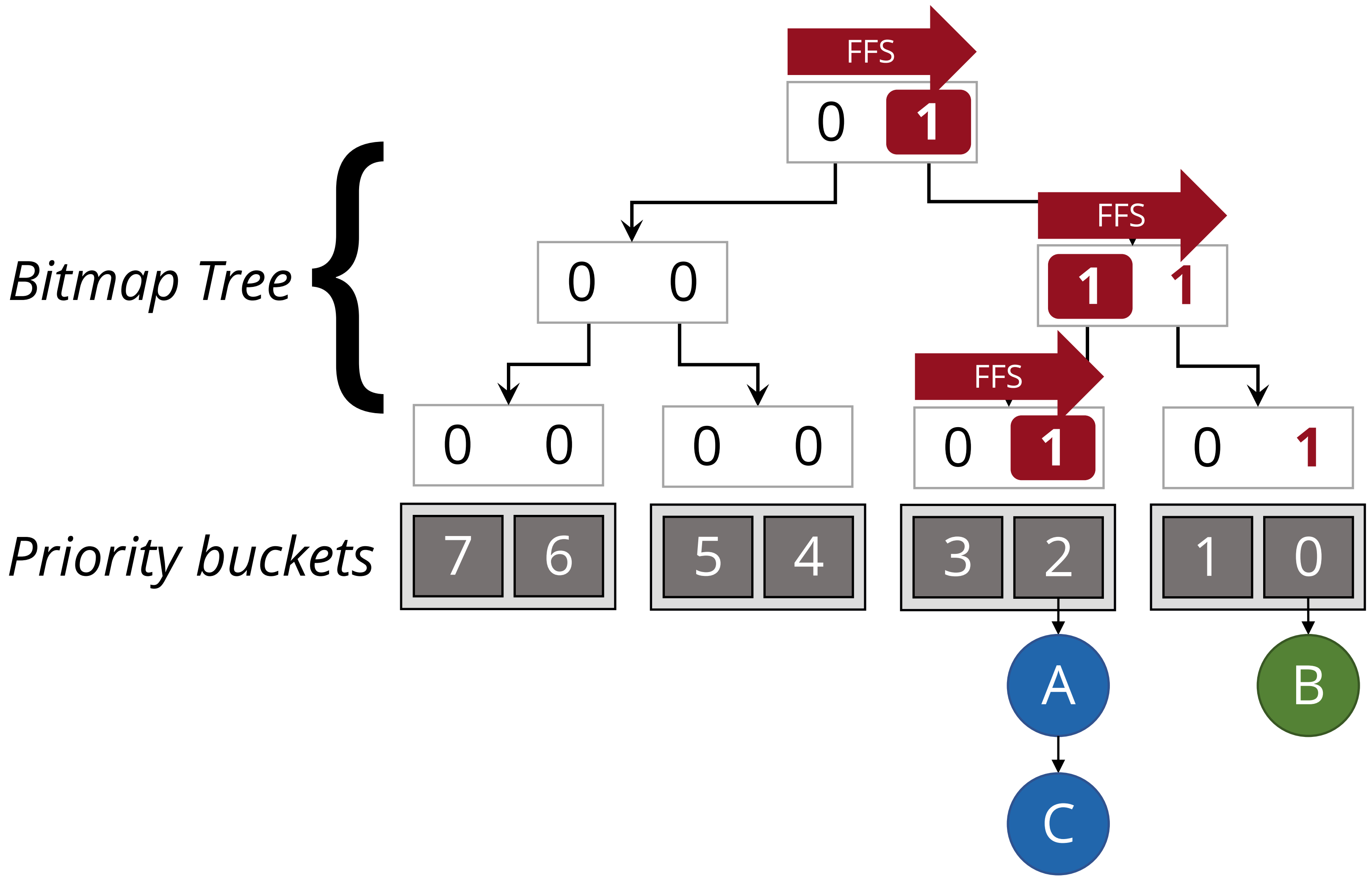

Bit is set if ***any* priority bucket in this subtree** is not empty
Bitmap Tree
0 1
0 0
1 1
0 0
0 0
0 1
0 1
Bit is set if **priority bucket** is not empty
Priority buckets
7 6
5 4
3 2
1 0
A
B
C

Integer Priority Queueing (IPQ)



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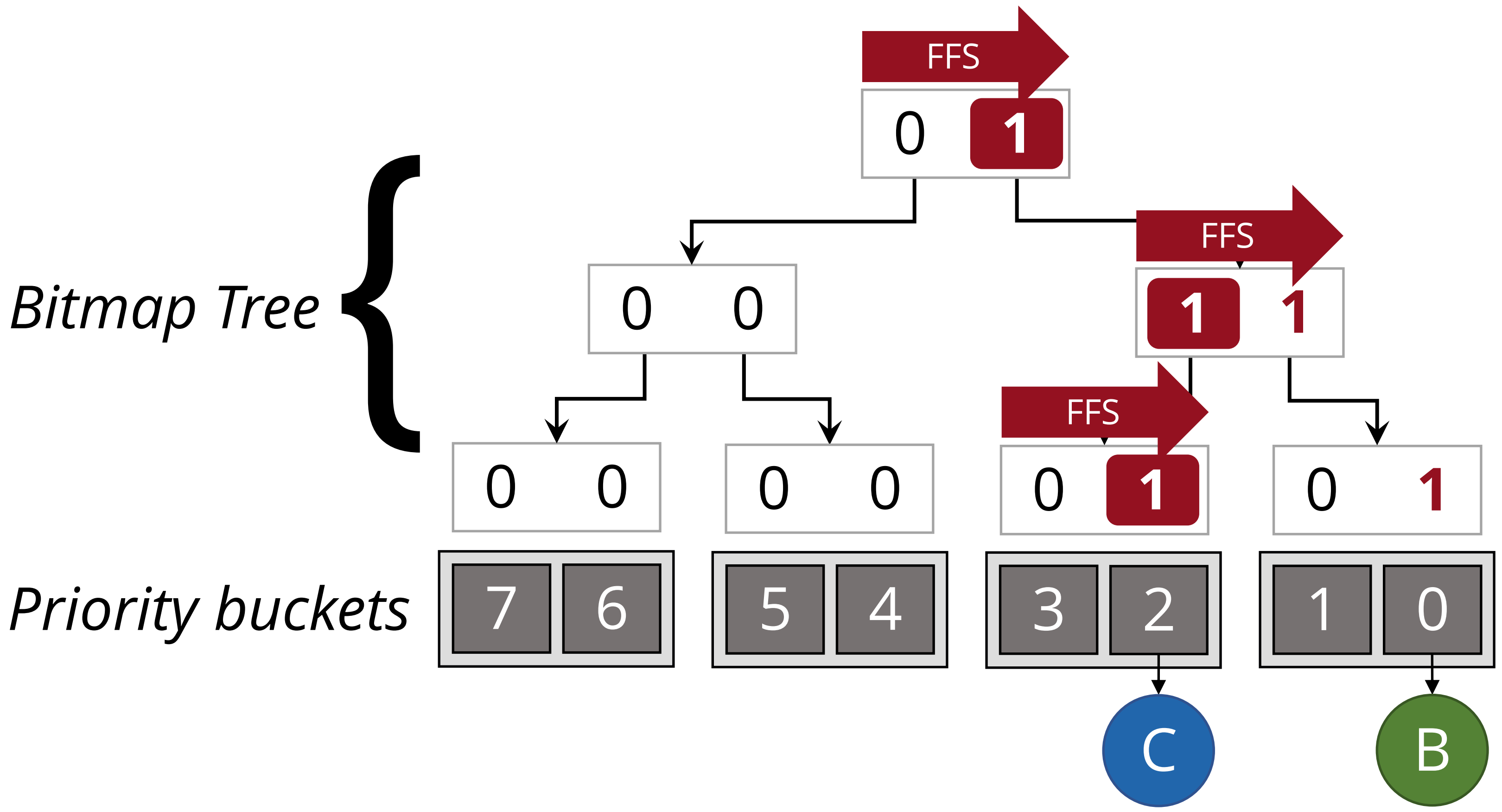


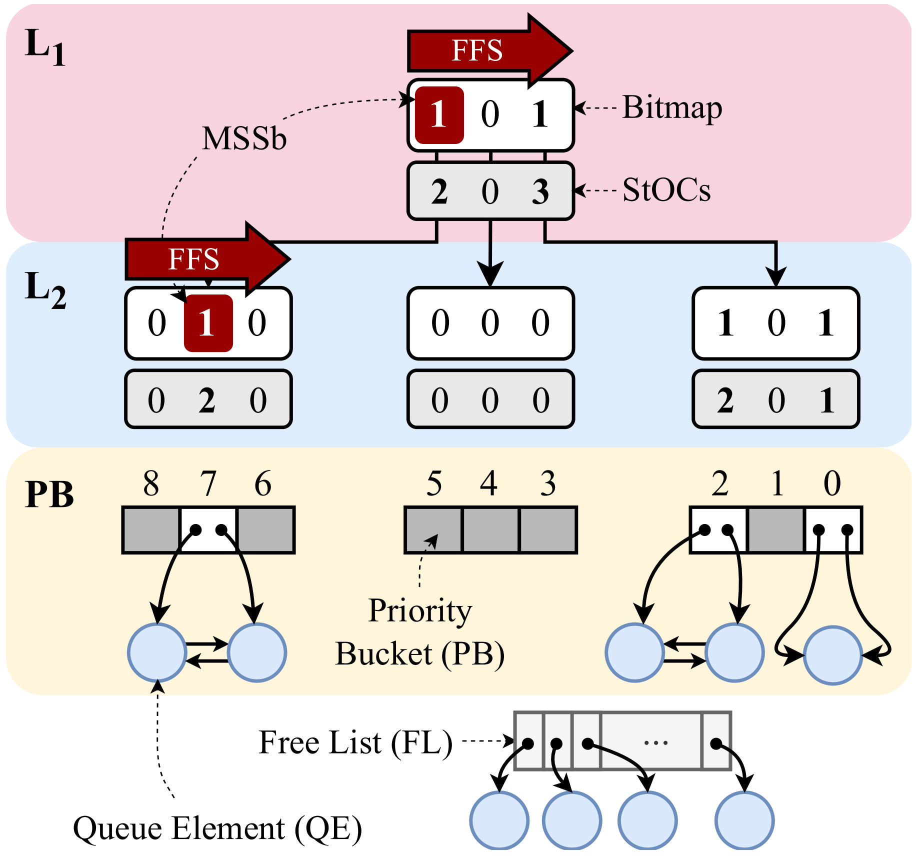
Data-structure is called a **Hierarchical Find-First Set (HFFS) Queue**

Bitmapped Bucket Queue (BBQ)

Data-structure is called a **Hierarchical Find-First Set (HFFS) Queue**

Many software systems use FFS-based priority queueing (*e.g.*, Linux scheduler for process scheduling, and Eiffel [NSDI '19] for packet scheduling).

Our insight is that this data-structure is amenable to a *high-performance, **fully-pipelined** hardware implementation*.



Scalability comes for free

BBQ uses an IPQ-based design, breaking the dependence between queue size and run-time complexity of operations.

Scalability “falls out” of this high-level design choice.

BBQ is ***highly optimized*** for performance

(1) Need a high **operating frequency** (f_{max})

(2) Need to maximize **operations-per-cycle** (OPC)

$$\boxed{\text{Performance (ops/sec)} = f_{max}\ \text{(cycles/sec)} \times \text{OPC (ops/cycle)}}$$

BBQ is *highly optimized* for performance

(1) Need a high **operating frequency** (f_{max})

BBQ achieves this by using a deep pipeline where individual stages are designed to do both *little* and *roughly equal* amounts of work.

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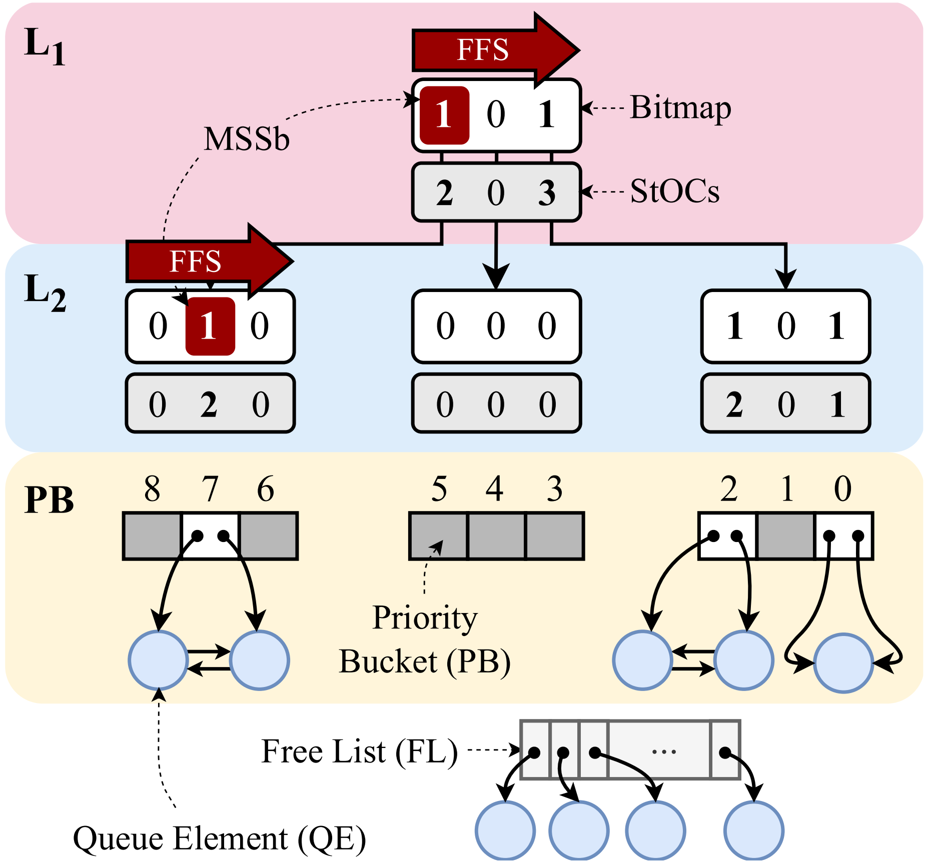
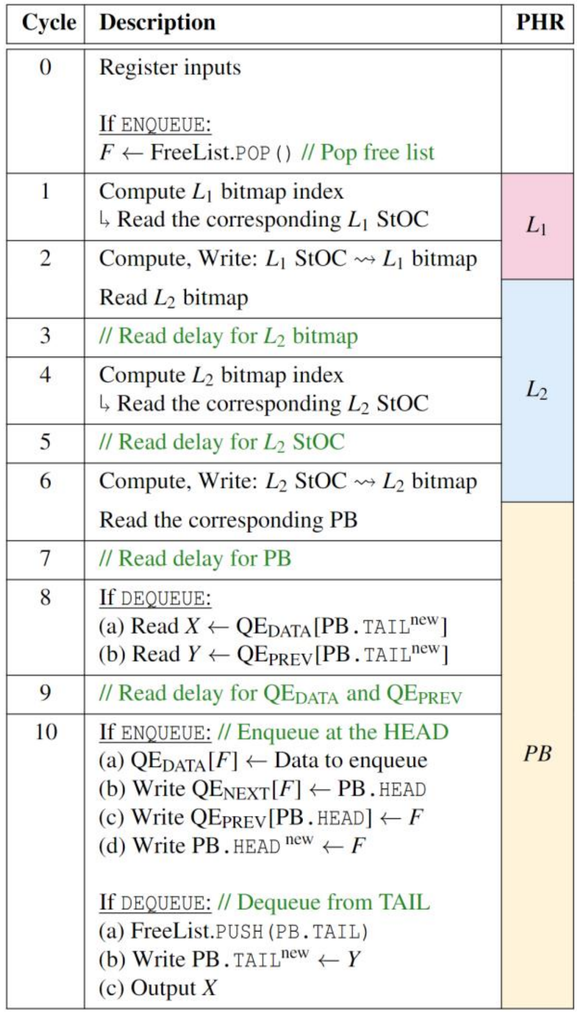




Cycle	Description	PHR
0	Register inputs If ENQUEUE: $F \leftarrow$ FreeList.POP() // Pop free list	
1	Compute L_1 bitmap index ↳ Read the corresponding L_1 StOC	L_1
2	Compute, Write: L_1 StOC $\rightsquigarrow$ L_1 bitmap Read L_2 bitmap	
3	// Read delay for L_2 bitmap	
4	Compute L_2 bitmap index ↳ Read the corresponding L_2 StOC	L_2
5	// Read delay for L_2 StOC	
6	Compute, Write: L_2 StOC $\rightsquigarrow$ L_2 bitmap Read the corresponding PB	
7	// Read delay for PB	
8	If DEQUEUE: (a) Read $X \leftarrow \mathrm{QE}_{\mathrm{DATA}}[\mathrm{PB.TAIL}^{new}]$ (b) Read $Y \leftarrow \mathrm{QE}_{\mathrm{PREV}}[\mathrm{PB.TAIL}^{new}]$	
9	// Read delay for $\mathrm{QE}_{\mathrm{DATA}}$ and $\mathrm{QE}_{\mathrm{PREV}}$	
10	If ENQUEUE: // Enqueue at the HEAD (a) $\mathrm{QE}_{\mathrm{DATA}}[F] \leftarrow$ Data to enqueue (b) Write $\mathrm{QE}_{\mathrm{NEXT}}[F] \leftarrow$ PB.HEAD (c) Write $\mathrm{QE}_{\mathrm{PREV}}[\mathrm{PB.HEAD}] \leftarrow F$ (d) Write PB.HEAD$^{new} \leftarrow F$ If DEQUEUE: // Dequeue from TAIL (a) FreeList.PUSH(PB.TAIL) (b) Write PB.TAIL$^{new} \leftarrow Y$ (c) Output X	*PB*

$\}$ Deep (11-stage) hardware pipeline for a 2-level BBQ

BBQ is *highly optimized* for performance

(1) Need a high **operating frequency** (f_{max})

BBQ achieves this by using a deep pipeline where individual stages are designed to do both *little* and *roughly equal* amounts of work

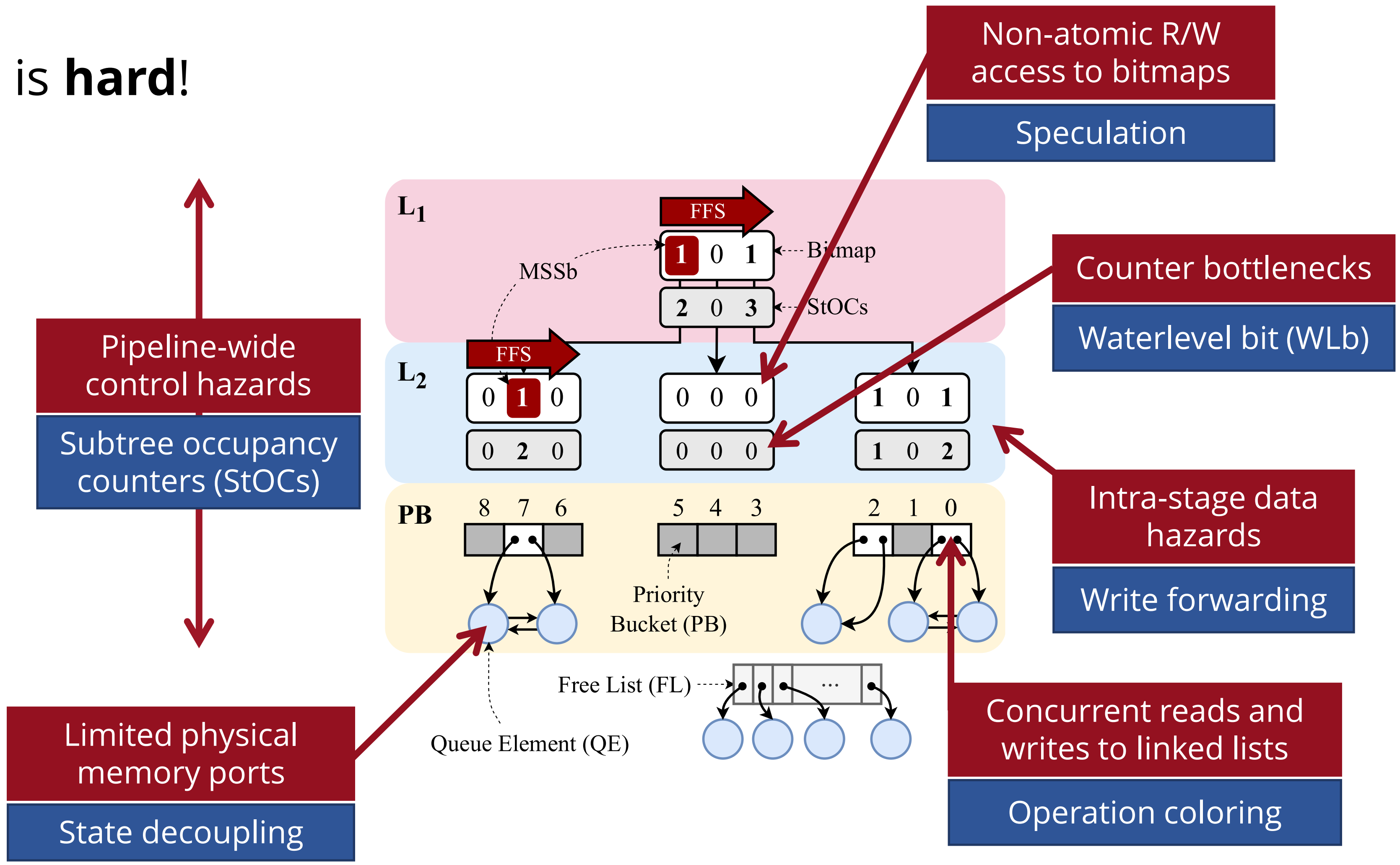
(2) Need to maximize **operations-per-cycle** (OPC)

BBQ realizes a fully-pipelined architecture (OPC of 1) agnostic of workload

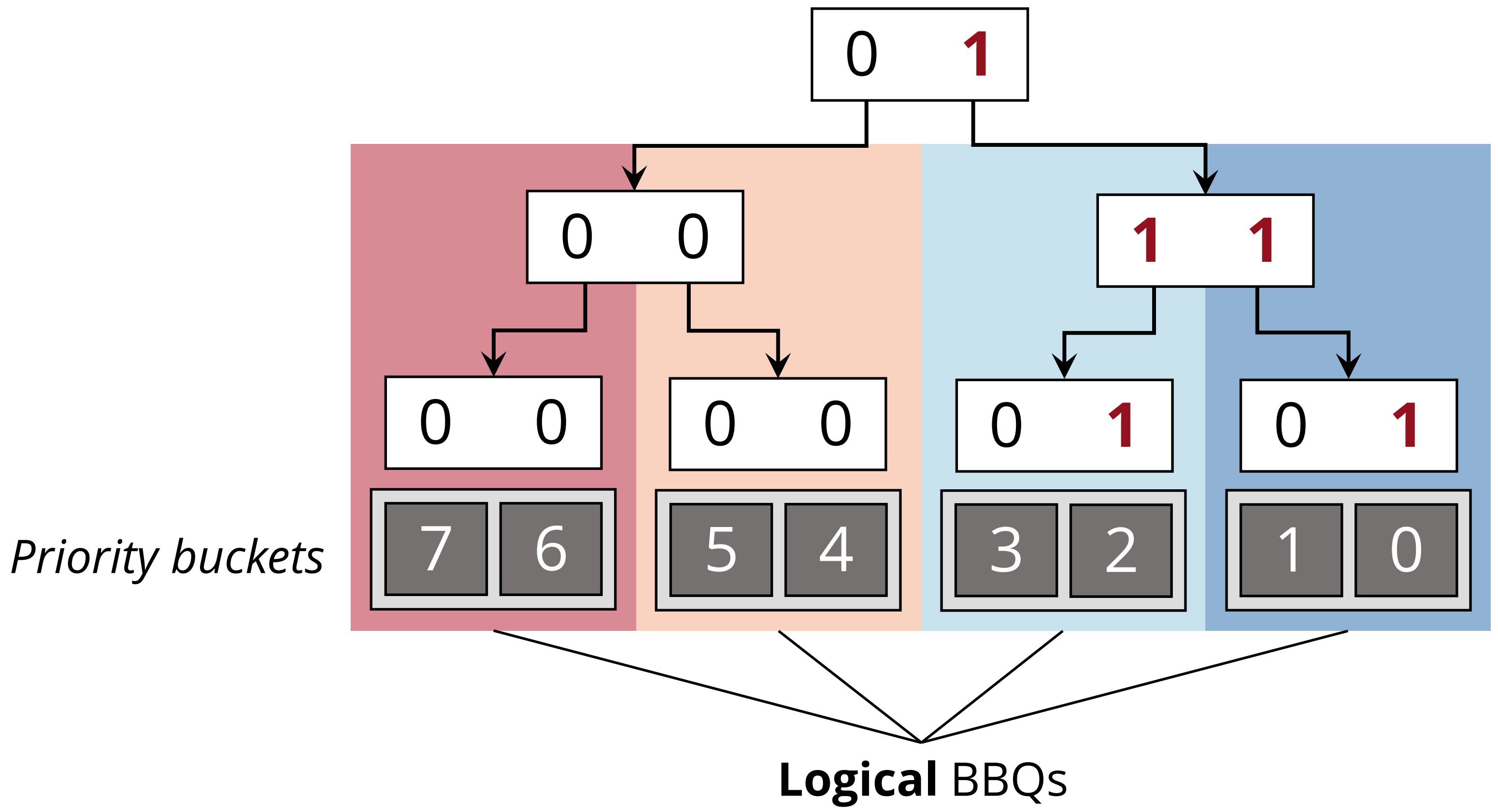
$$\boxed{\text{Performance (ops/sec)} = f_{max} \text{ (cycles/sec)} \times \text{OPC (ops/cycle)}}$$

BBQ is *highly optimized* for performance

Pipelining is **hard**!



BBQ supports logical partitioning with zero fragmentation and performance overhead



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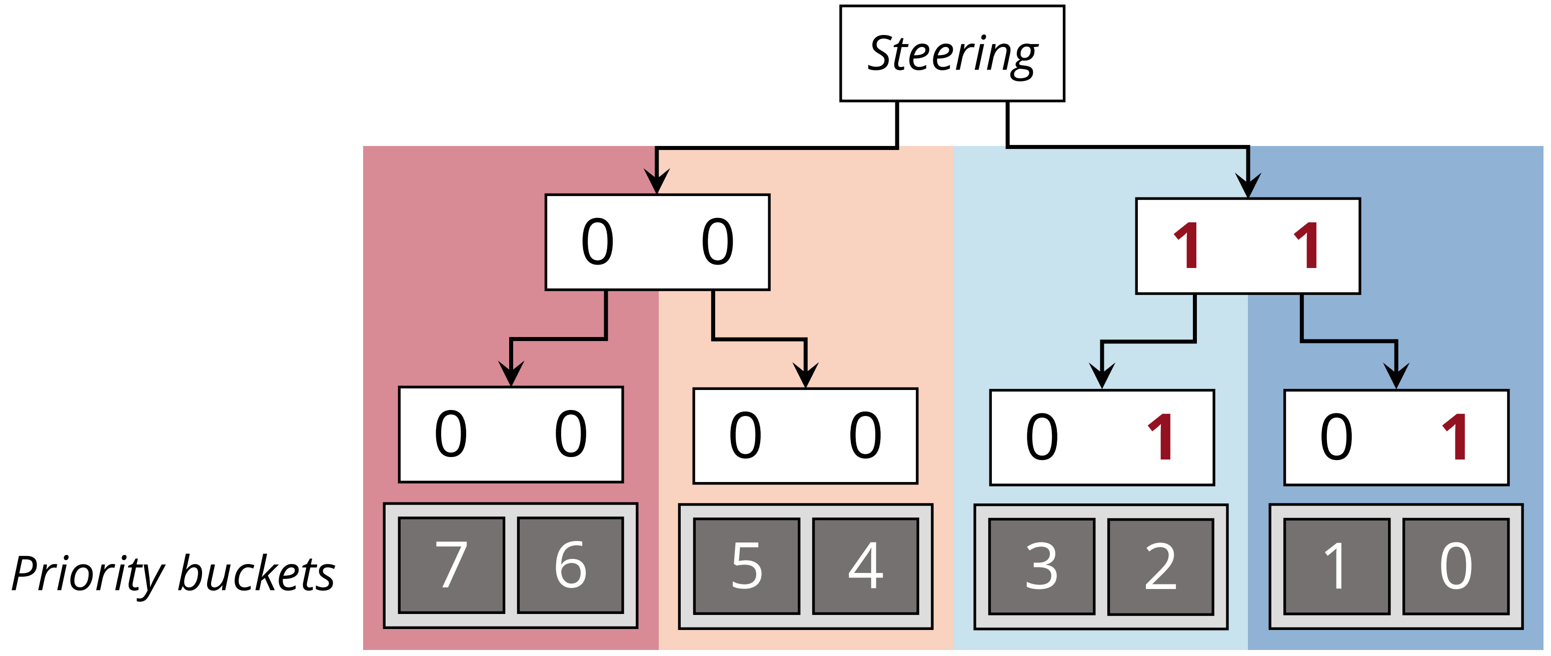

How does BBQ meet our requirements?

Flow Count Scalability

IPQ-based design allows scaling to O(100K) flows

Single-Instance Performance

Highly optimized, fully-pipelined design allows BBQ to support 150 Mpps (100 Gbps) on FPGAs and 1.5 Bpps (1 Tbps) on switch ASICs

Logical Partitioning

BBQ's **unique priority index structure** allows logical partitioning with no performance overhead

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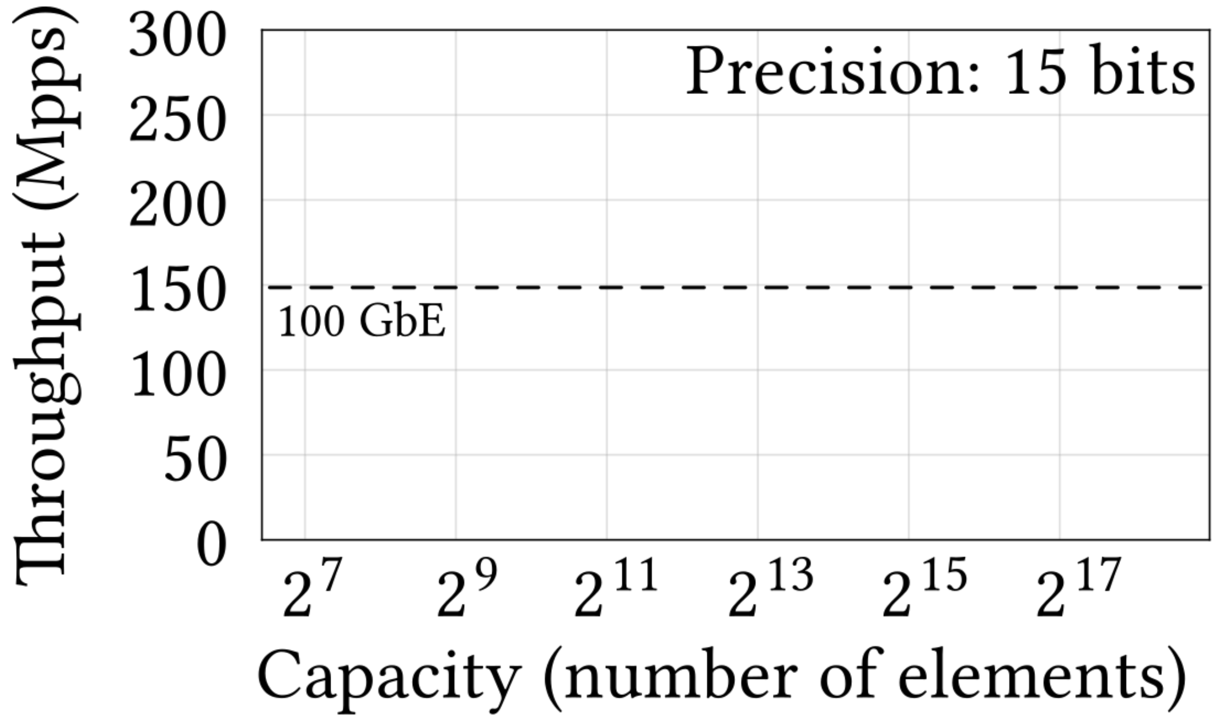
- **Evaluation**

BBQ Evaluation (FPGA): Performance



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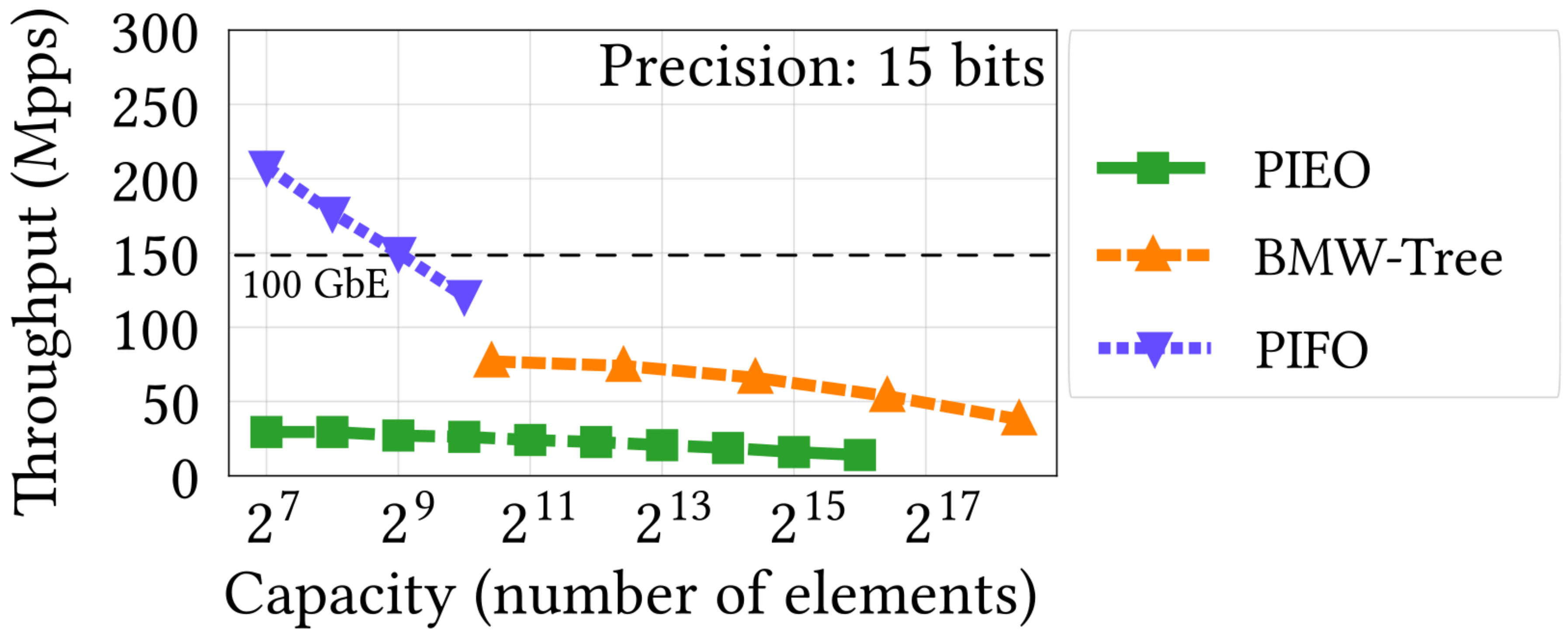

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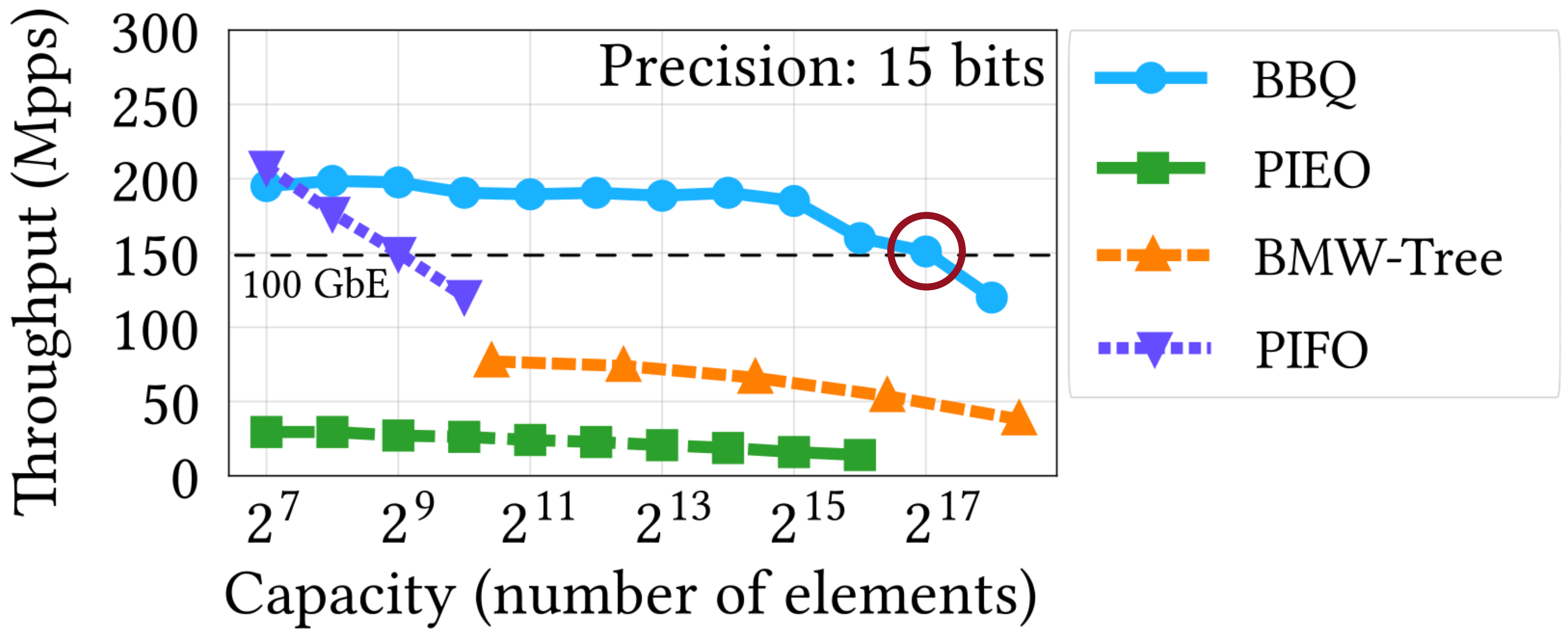


On a Stratix 10 FPGA, BBQ sustains **100 Gbps line rate** (148.8 Mpps) with 100K+ elements and 32K priorities, 3X the packet rate of state-of-the-art designs.

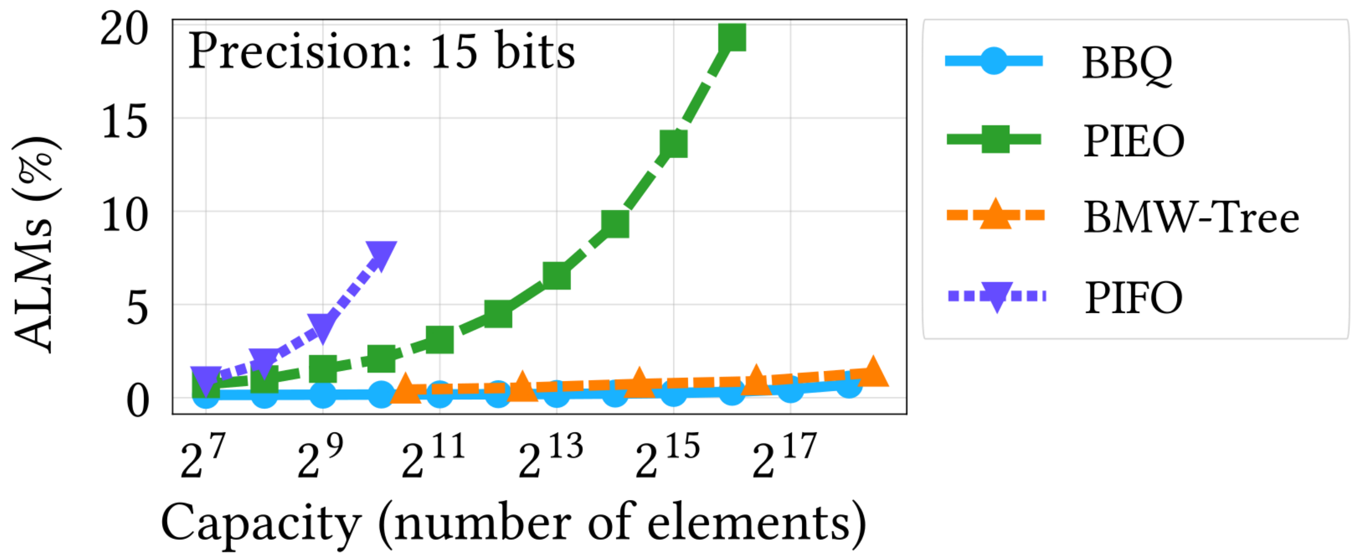
Conclusion

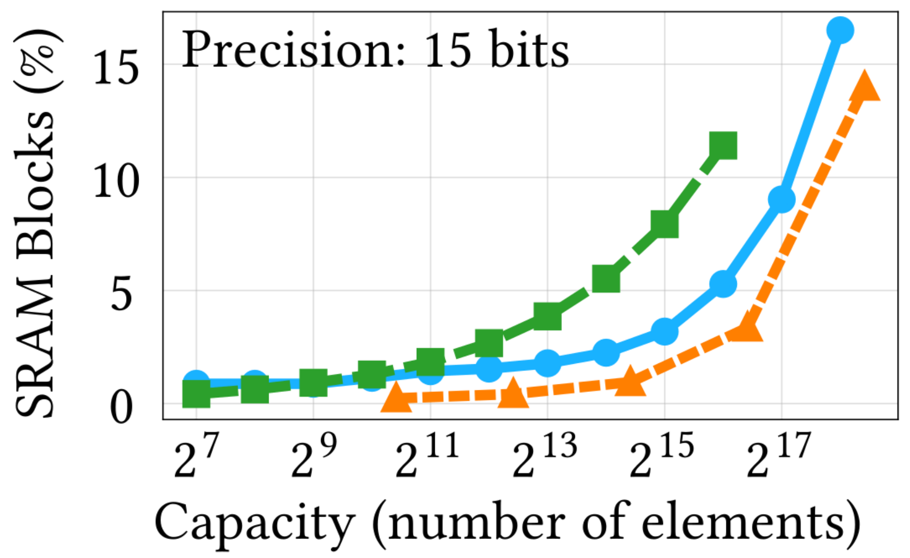
Existing hardware priority queues do not meet the stringent requirements imposed by modern schedulers. We design BBQ, an IPQ that – for the first time – makes it *feasible* to implement priority packet scheduling on line rate switches and SmartNICs.

BBQ supports 100K+ entries and 32K priorities at 100 Gbps line-rate (148.8 Mpps) on an FPGA, and 1 Tbps (1.5 Bpps) on an ASIC.

Open-source code:
https://github.com/cmu-snap/BBQ

BBQ Evaluation (FPGA): Resources





BBQ requires very few ALMs. Its SRAM usage is between PIEO and BMW-Tree (but requires fewer copies to meet the same performance target)

How does BBQ fit in the context of approximate priority queue designs?

1. BBQ is *complementary* to approaches that assume a small set of priority queues as a hardware primitive (SP-PIFO, PCQ, Sifter)
   - Accuracy improves with more strict-priority queues
   - BBQ's priority index structure (bitmap tree) is an efficient priority decoder, which is how we can scale to larger priority spans

2. BBQ's design shows that is possible to scale to a large number of queue elements without sacrificing accuracy

Accuracy

Want the execution output of BBQ to be identical to an “ideal” priority queue… *unfortunately, pipelining breaks this property!*

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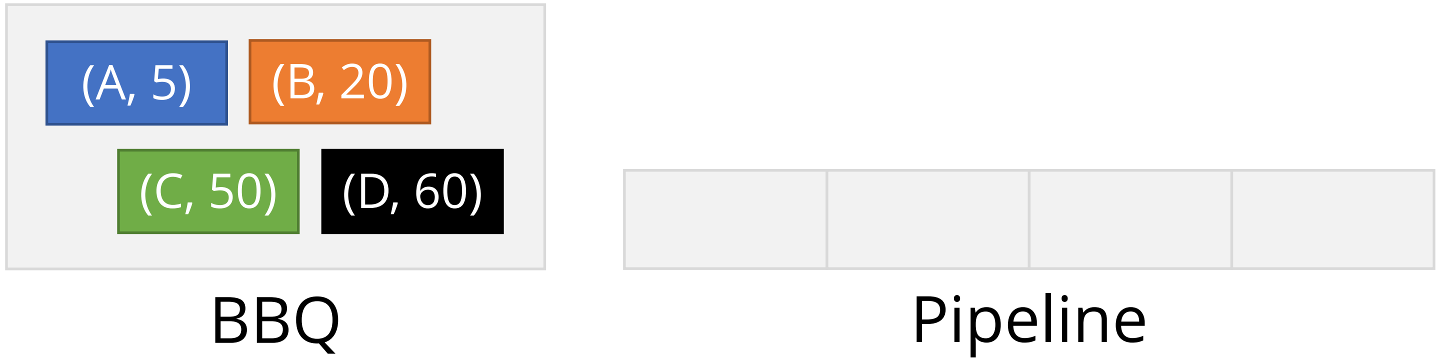

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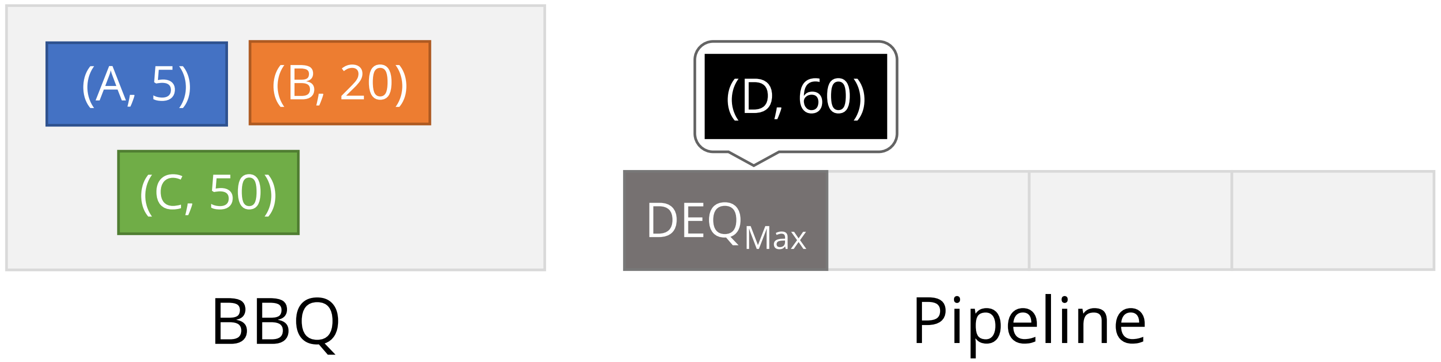

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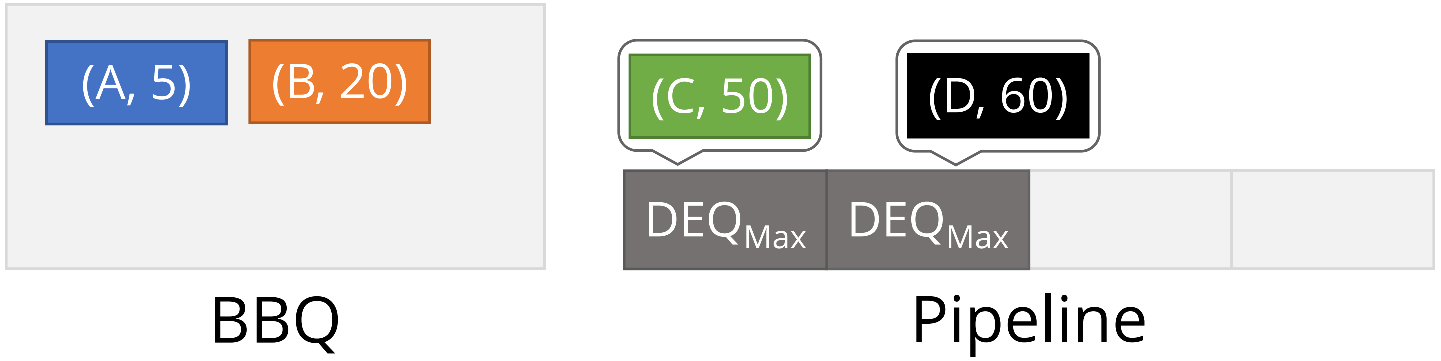

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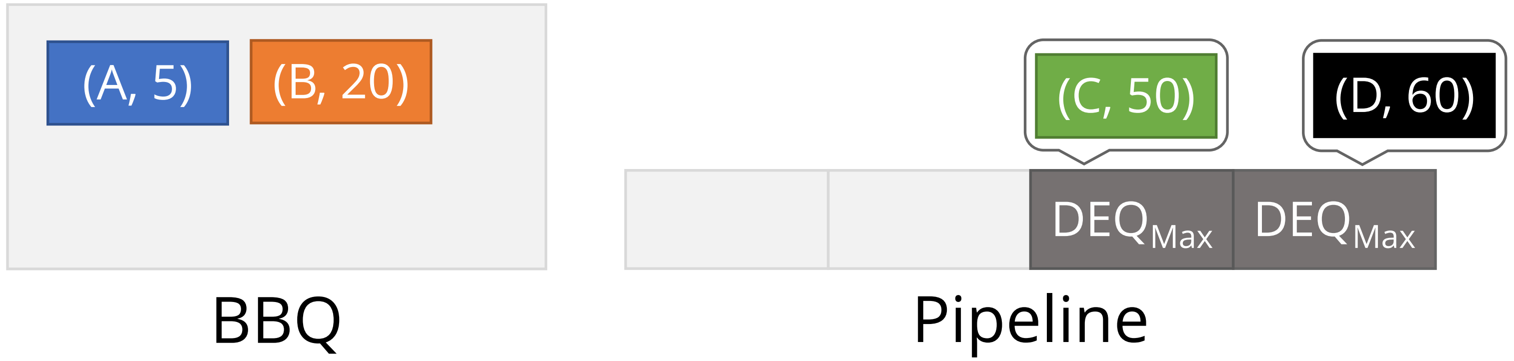
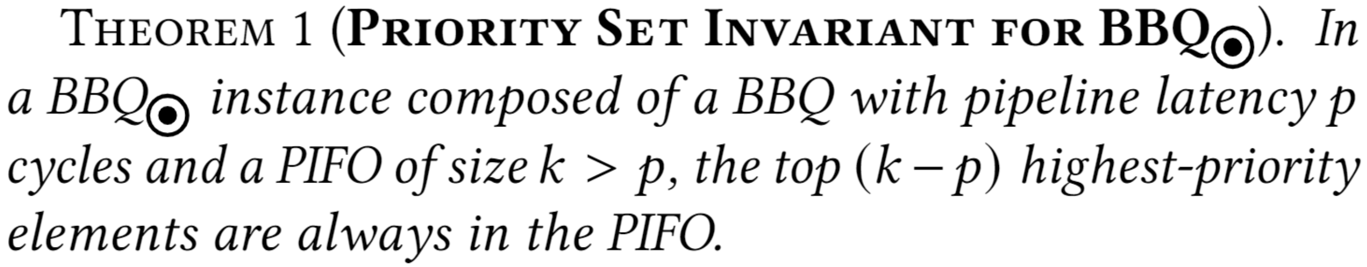


The highest-priority element in the system is not always in the BBQ, creating potential scheduling inaccuracies.

Accuracy

We prove that combining BBQ with a tiny PIFO recovers accuracy. The composite design has all the nice properties of BBQ, but without the pipeline latency.



THEOREM 1 (**PRIORITY SET INVARIANT FOR** $\mathbf{BBQ_{\odot}}$). *In a* $\mathit{BBQ}_{\odot}$ *instance composed of a BBQ with pipeline latency p cycles and a PIFO of size $k > p$, the top $(k - p)$ highest-priority elements are always in the PIFO.*