Performance, Scalability, and Semantics of Concurrent FIFO Queues

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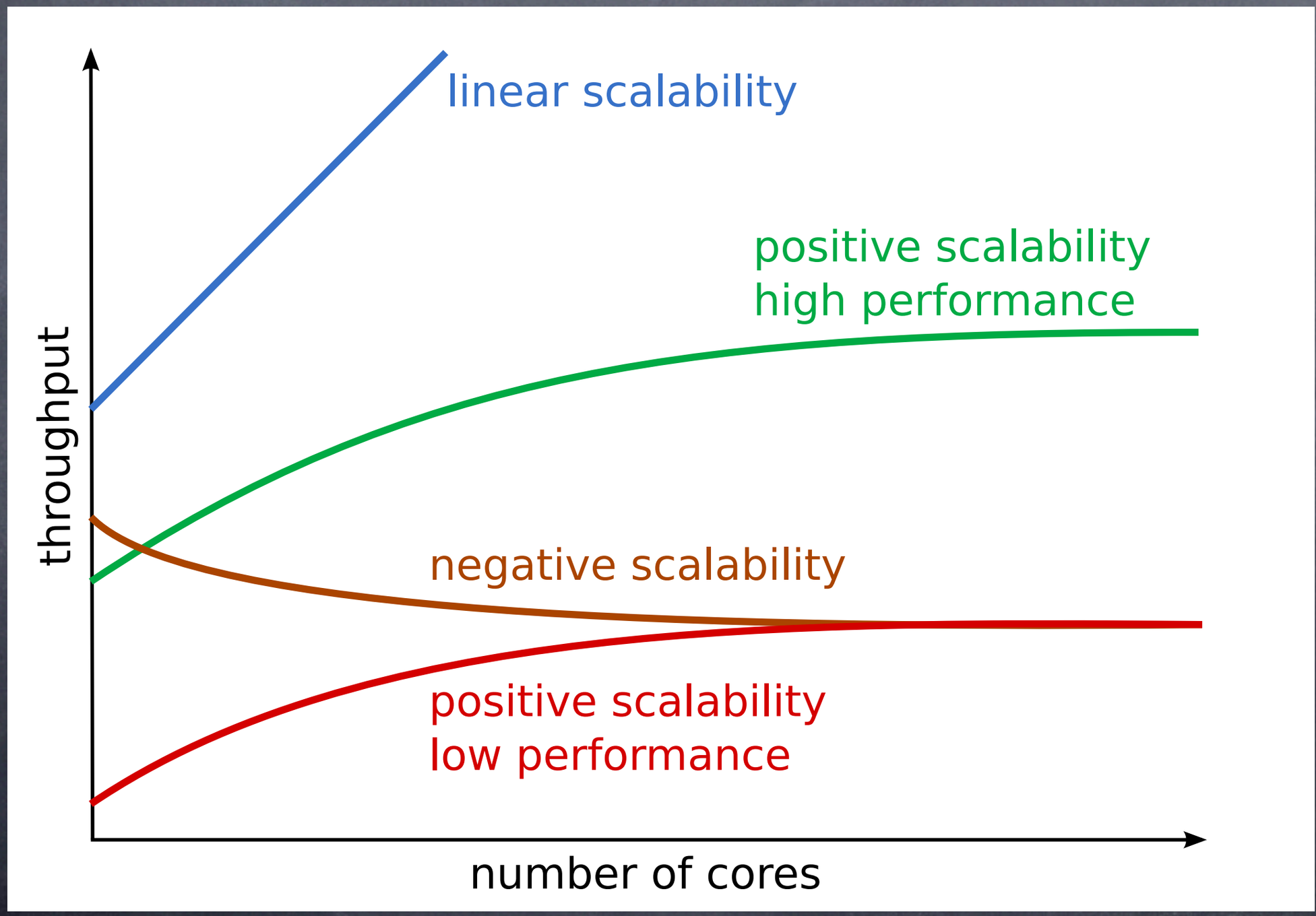
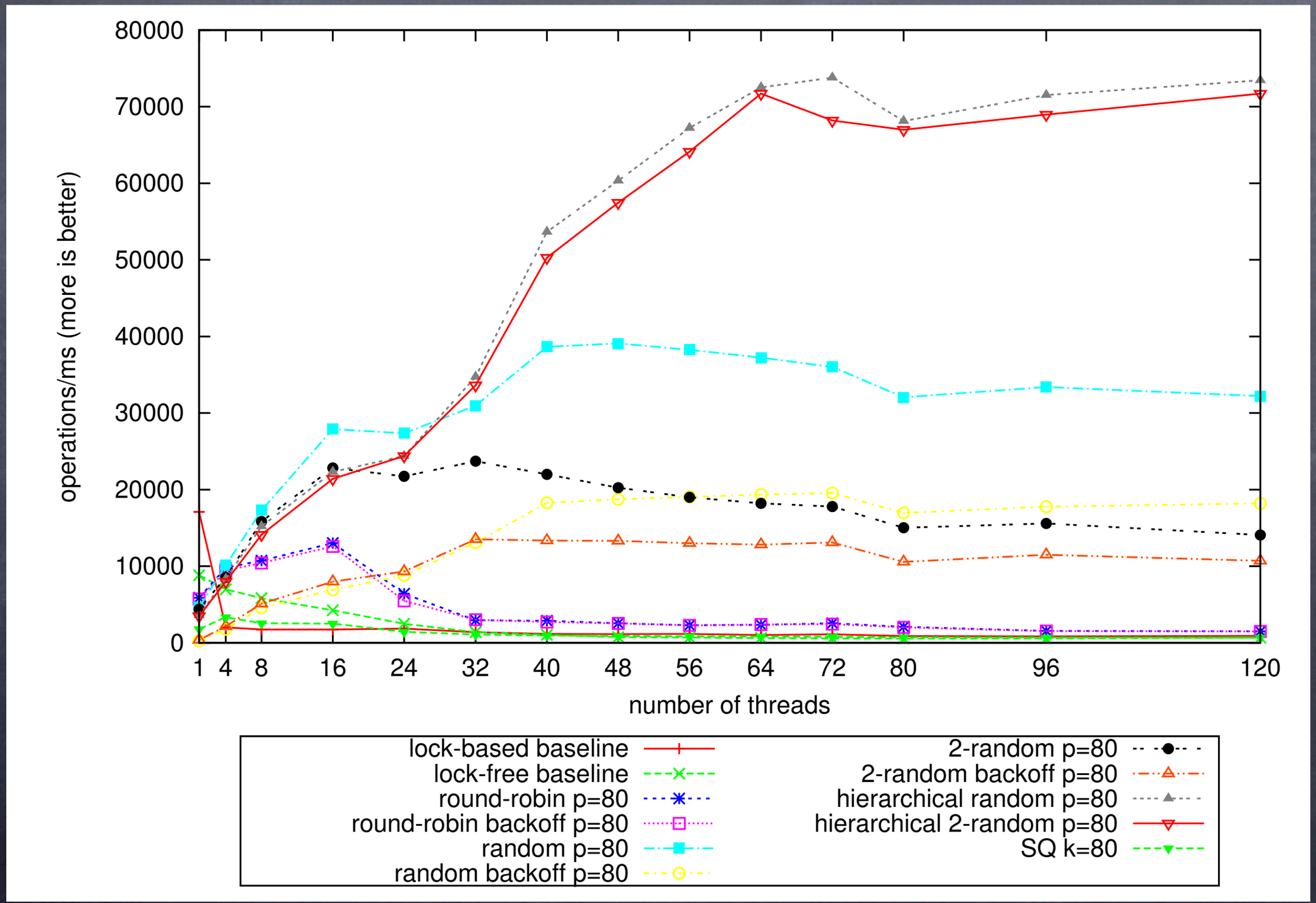
Universität Salzburg

Advanced Operating Systems Class, January 2012

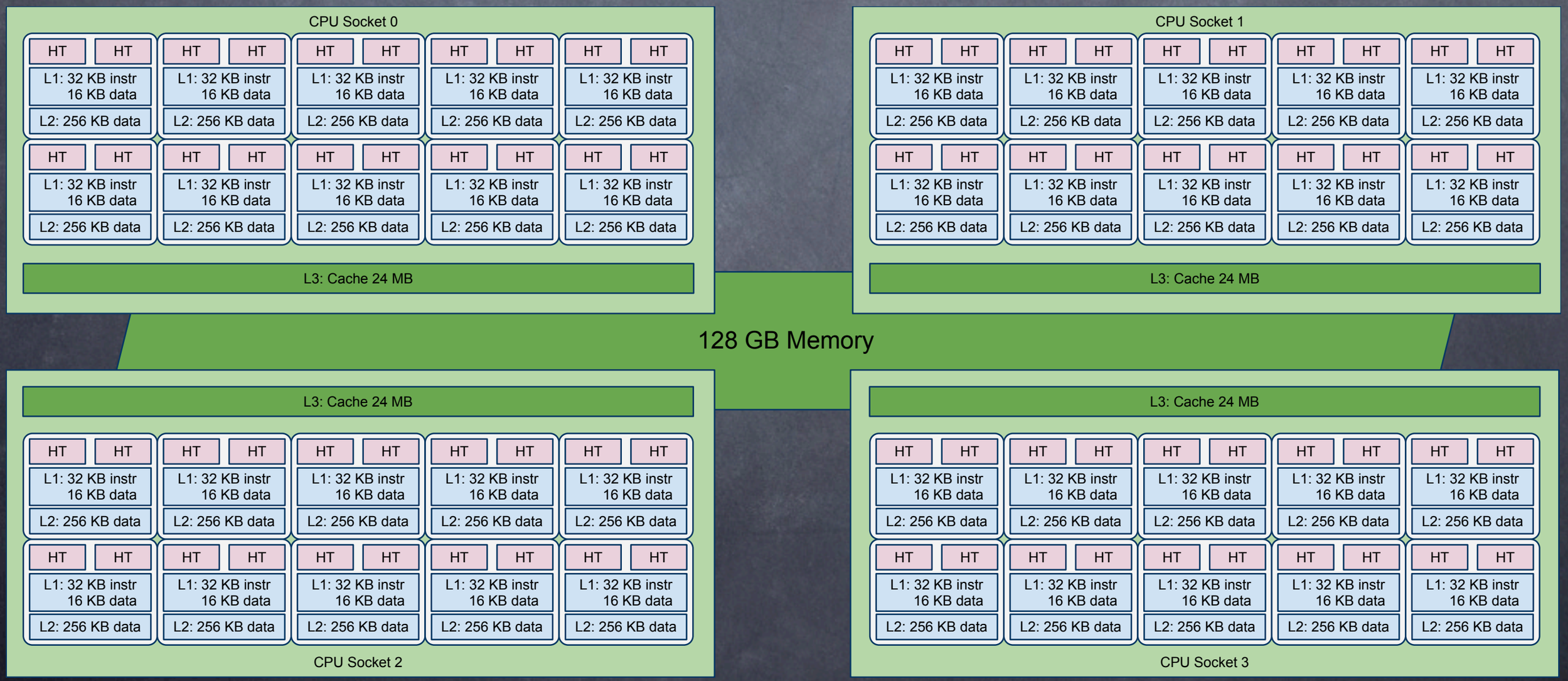
Performance & Scalability



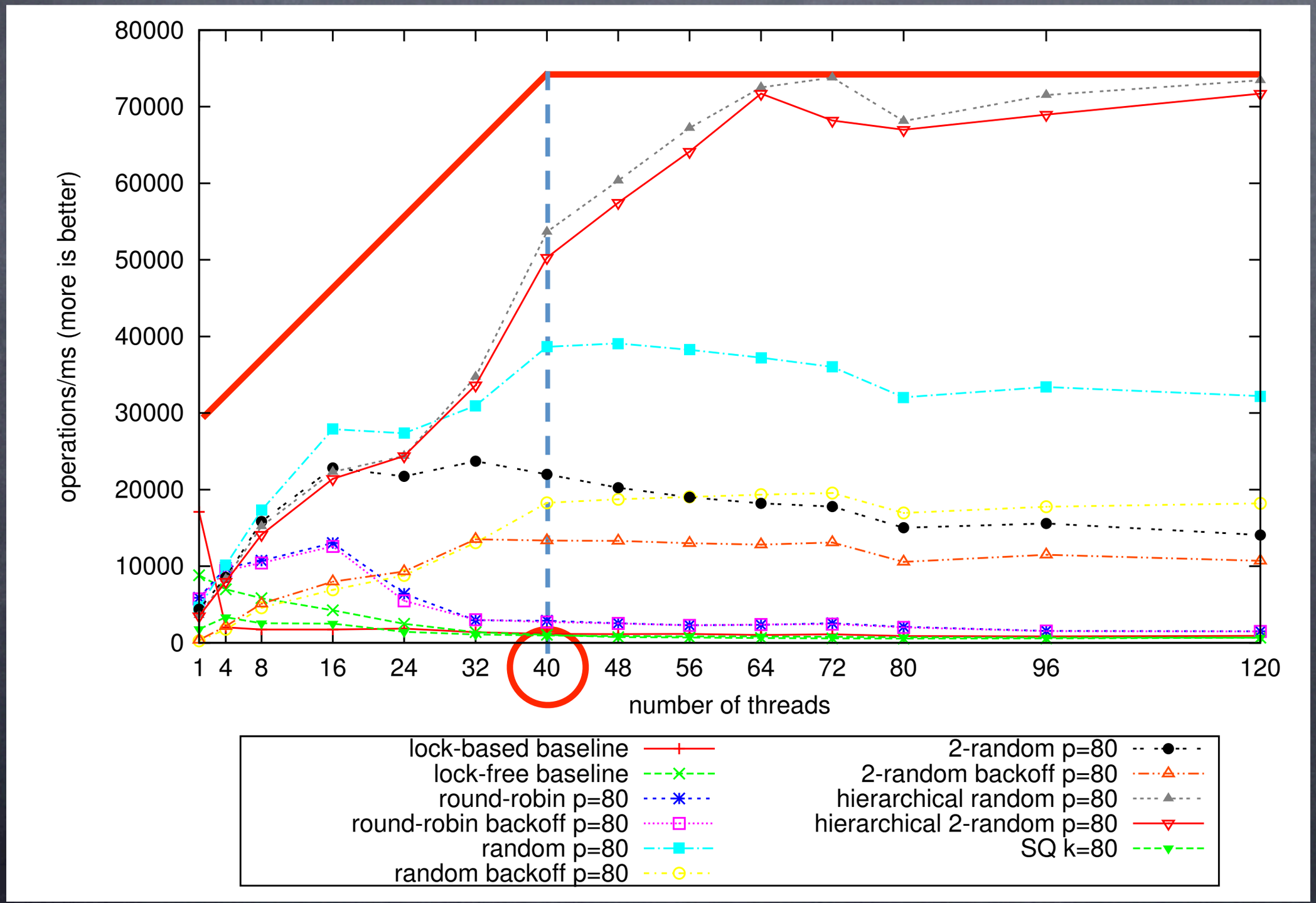
High Contention



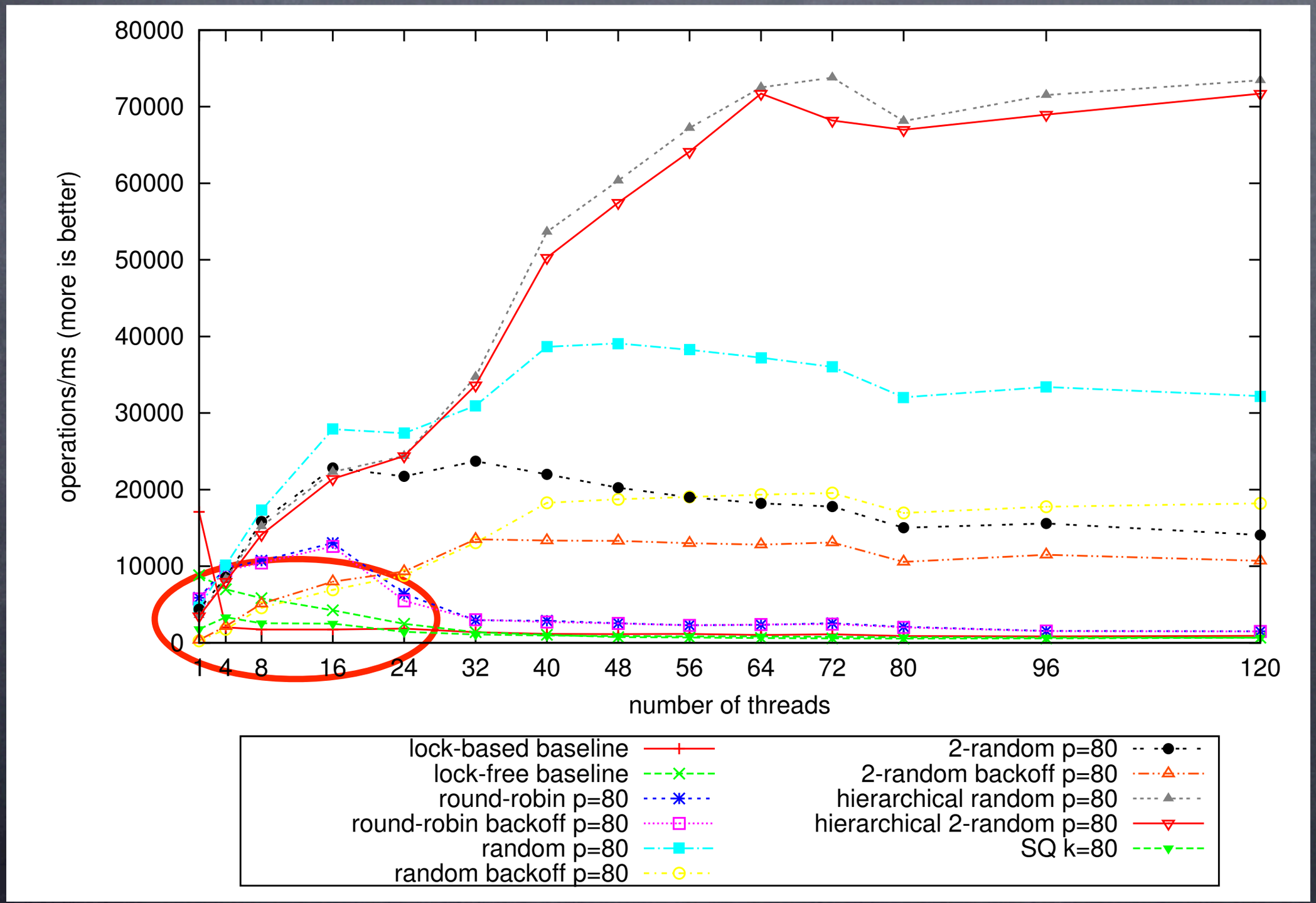
4 processors x 10 cores x 2 hardware threads = 80 hardware threads



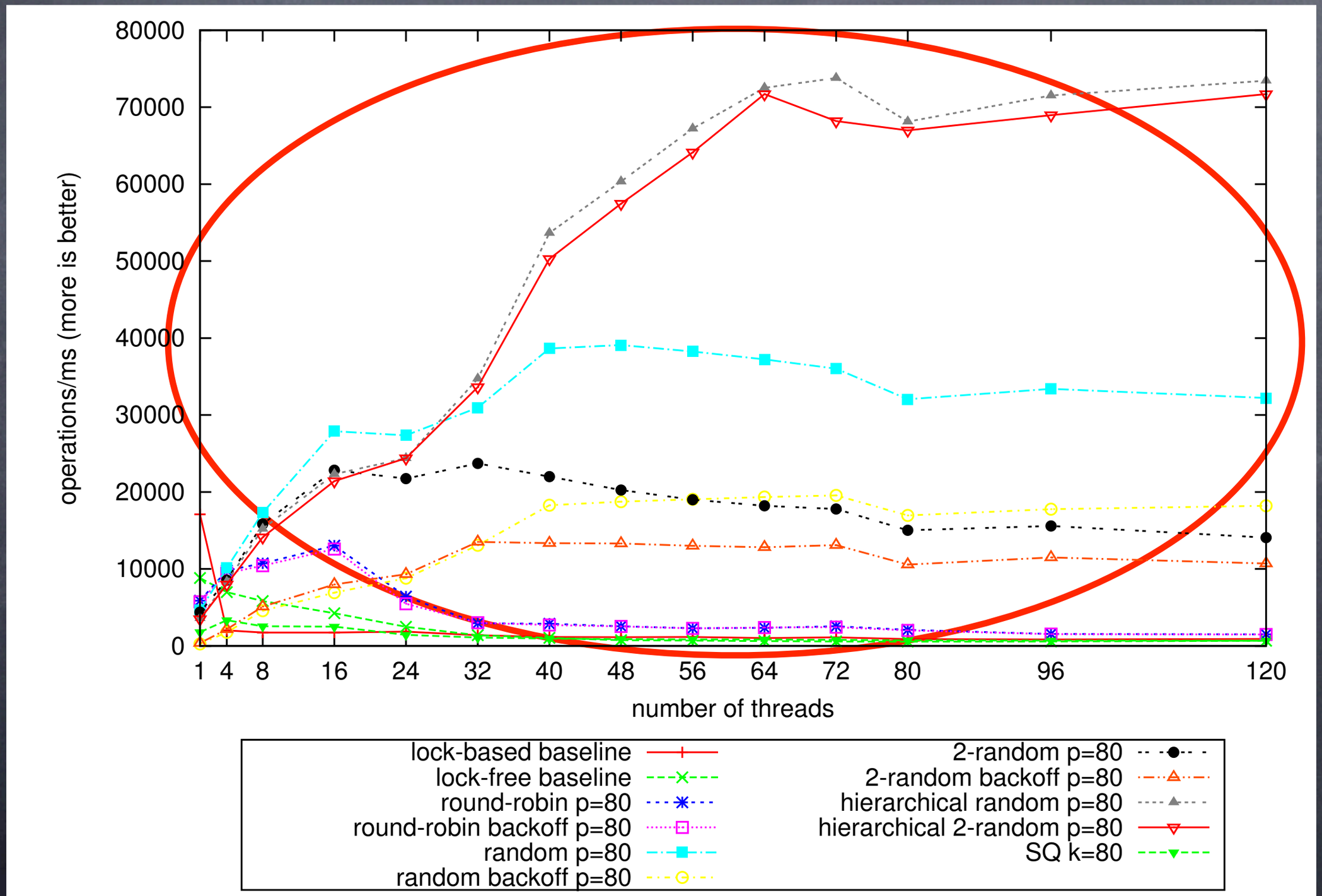
Ideal 40-Core Performance



Regular FIFO Queues



Our "Scal" Queues



Lock-Based (LB)

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Michael-Scott (MS)

[MS96]

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Flat Combining (FC)

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Workload-independent k-FIFO

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Workload-dependent k-FIFO

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Probabilistic k-FIFO

d-Random (dRA)
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k-FIFO Queues

- with a k-FIFO queue elements may be returned out-of-FIFO order up to k

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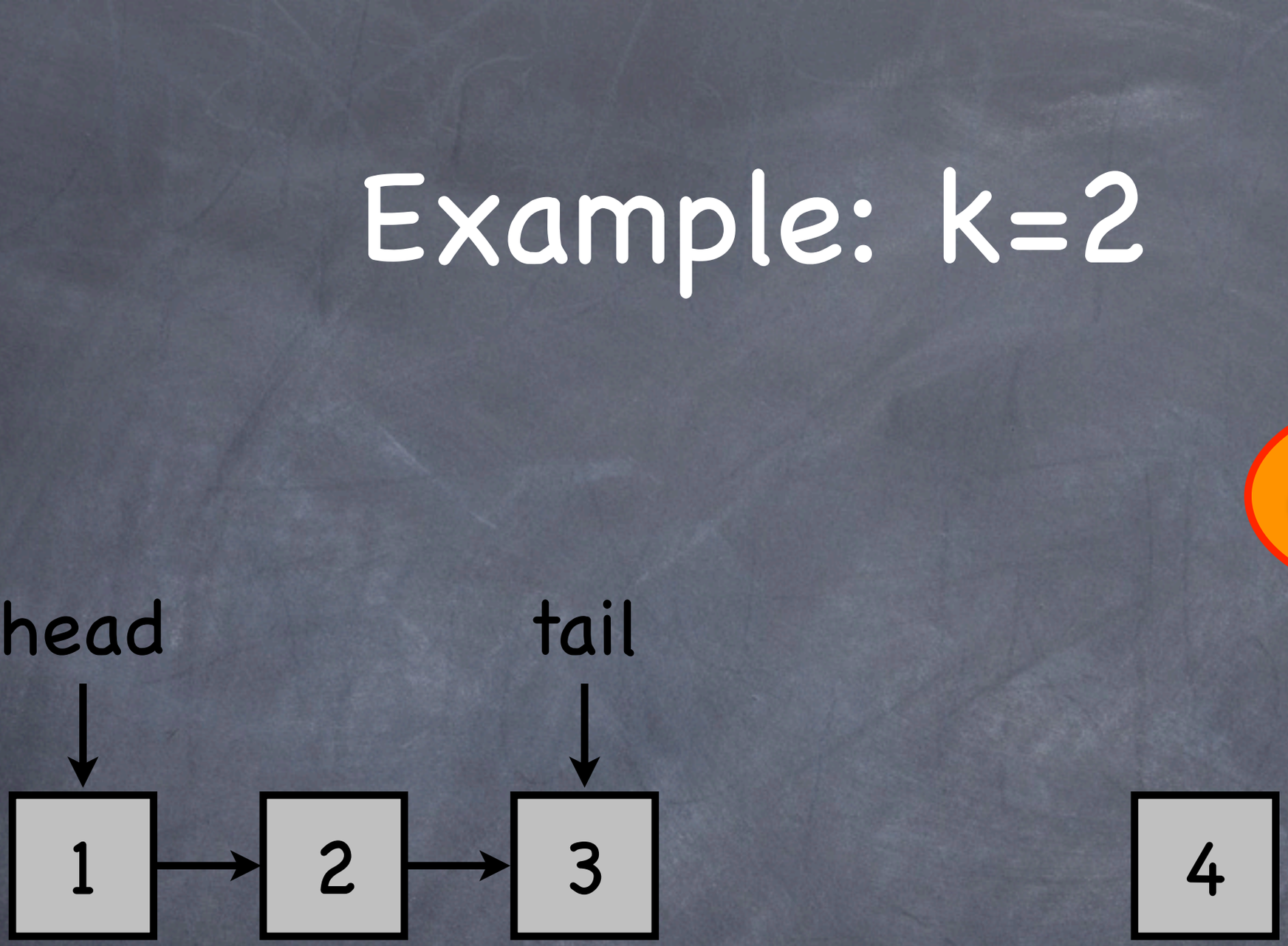
- the oldest element is returned after at most k+1 dequeue operations that may return elements not younger than k (or return nothing)
- starvation-free for finite k
- 0-FIFO queue = regular FIFO queue

Example: k=2

enqueue



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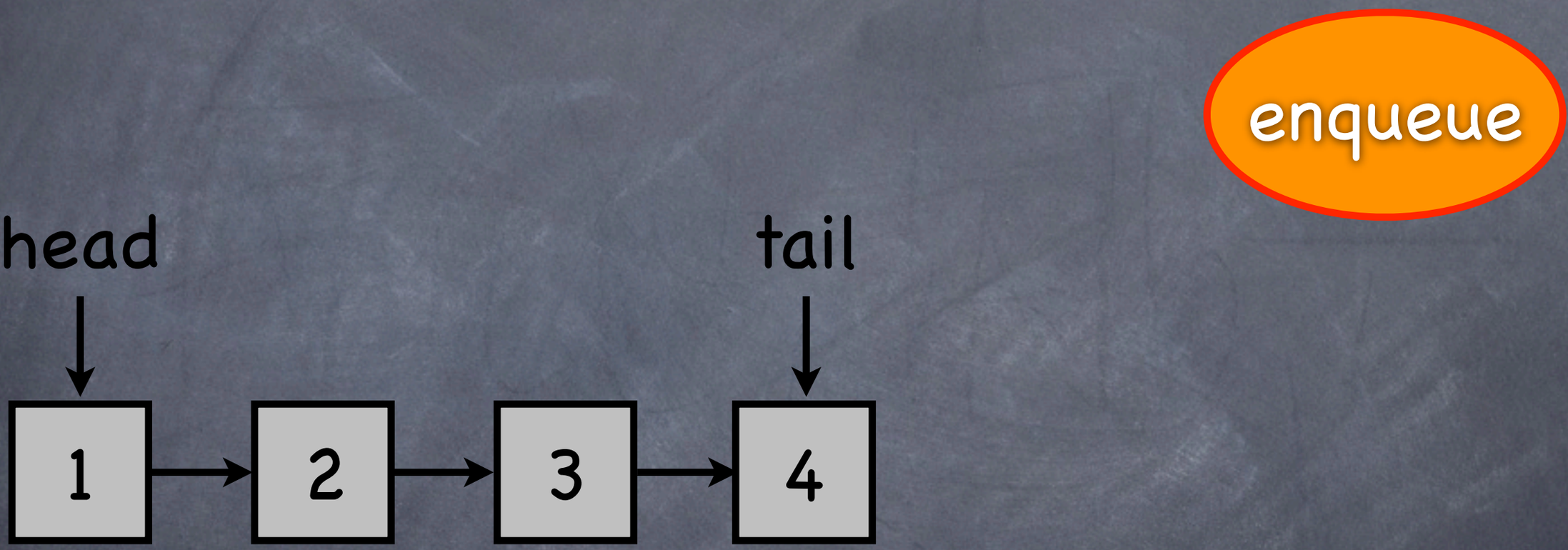

Example: k=2

dequeue

head

tail

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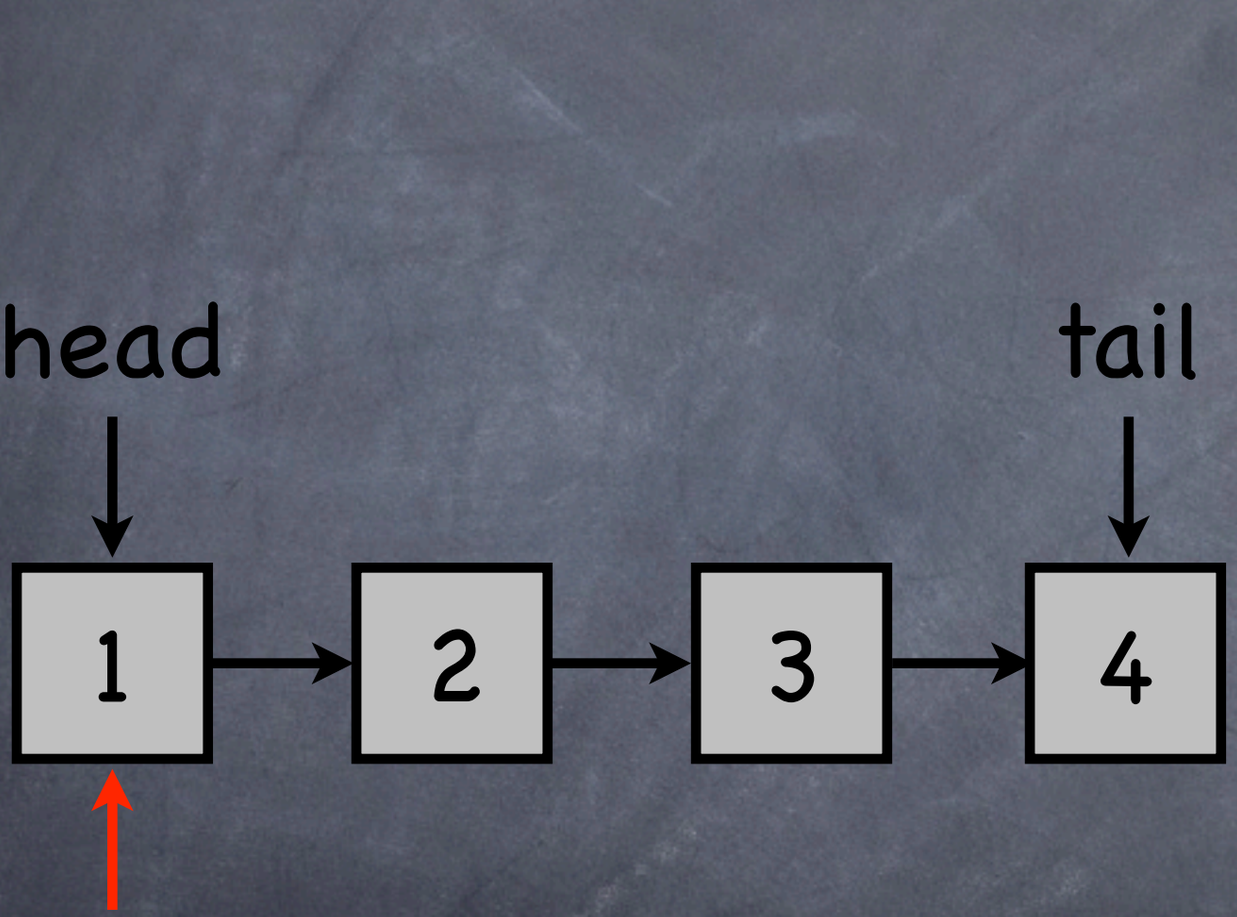

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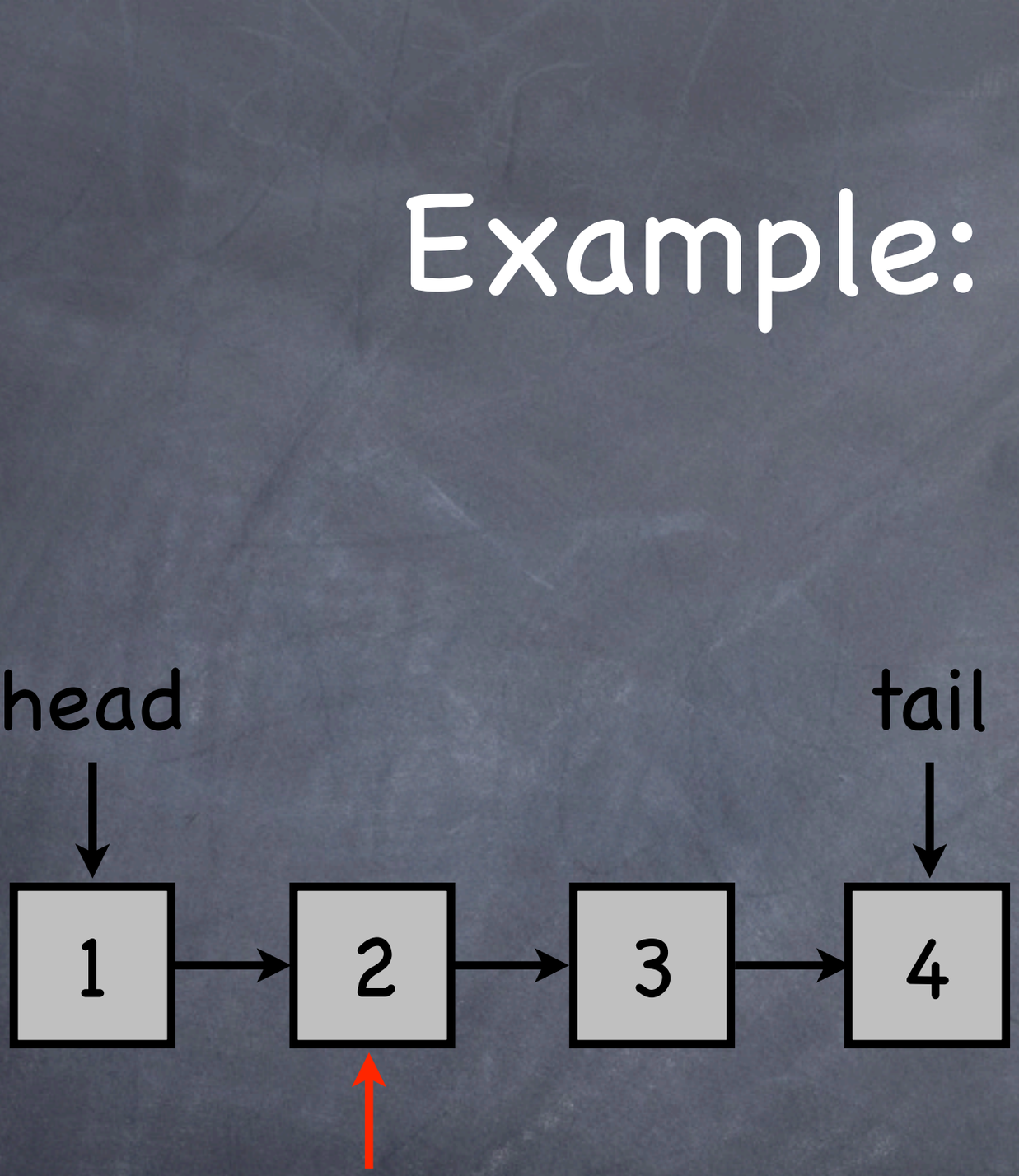

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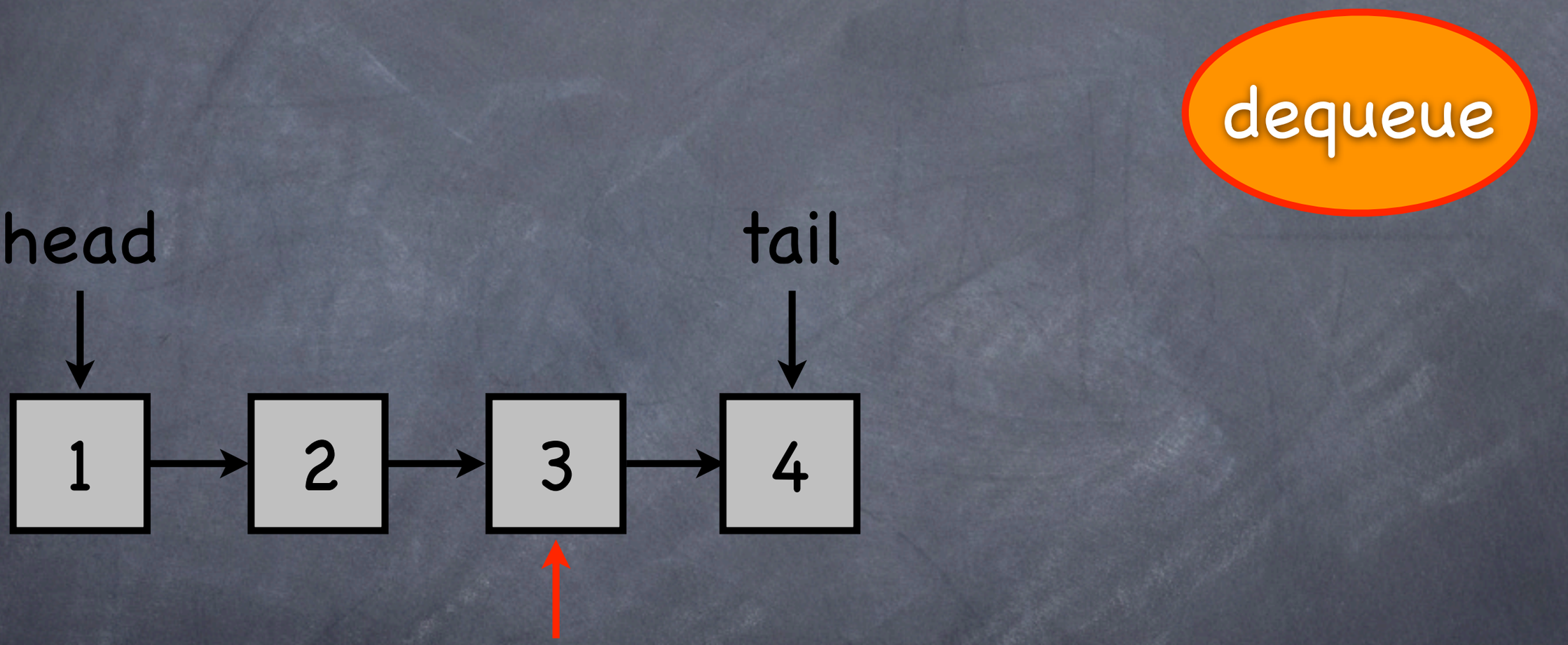

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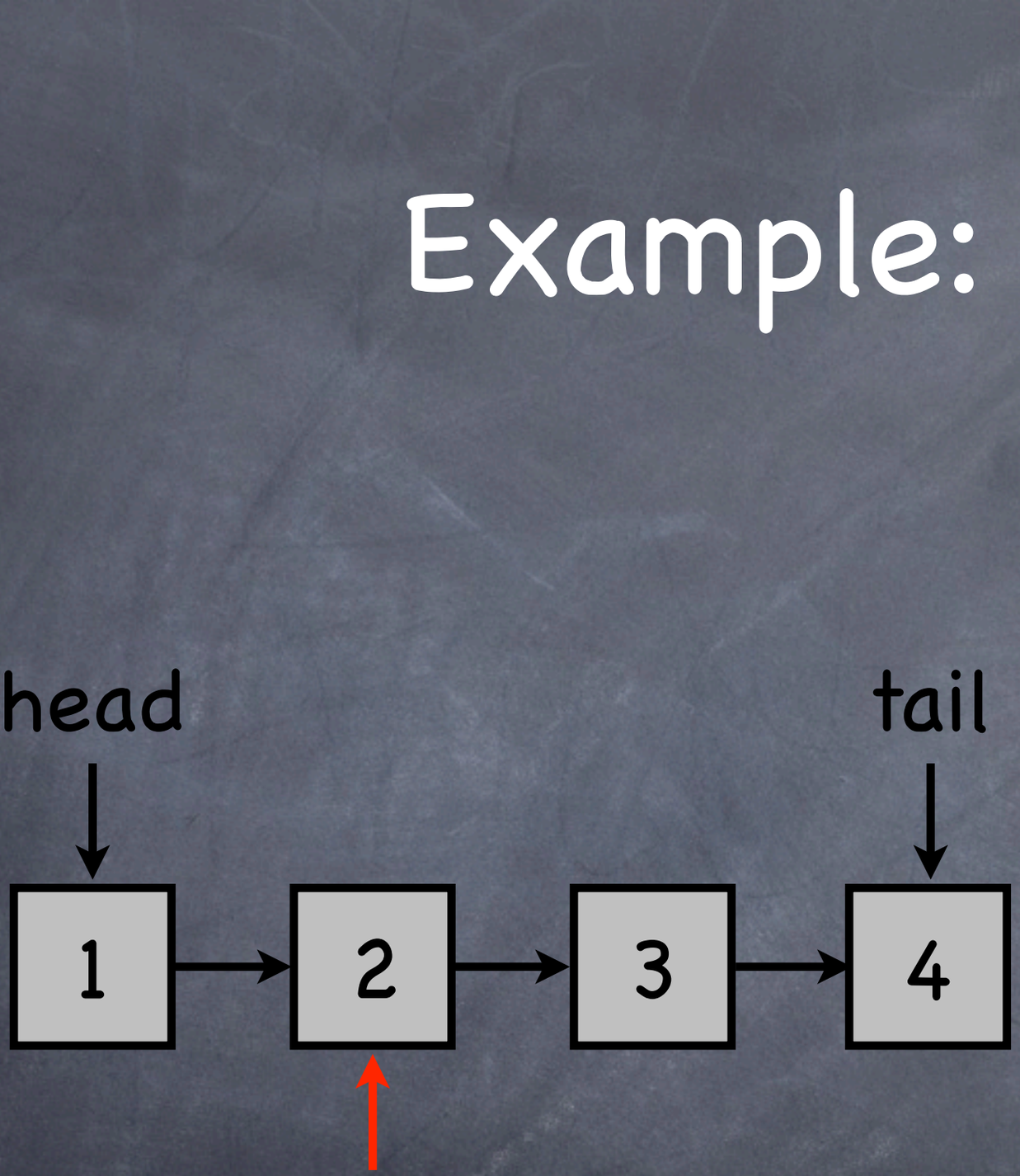

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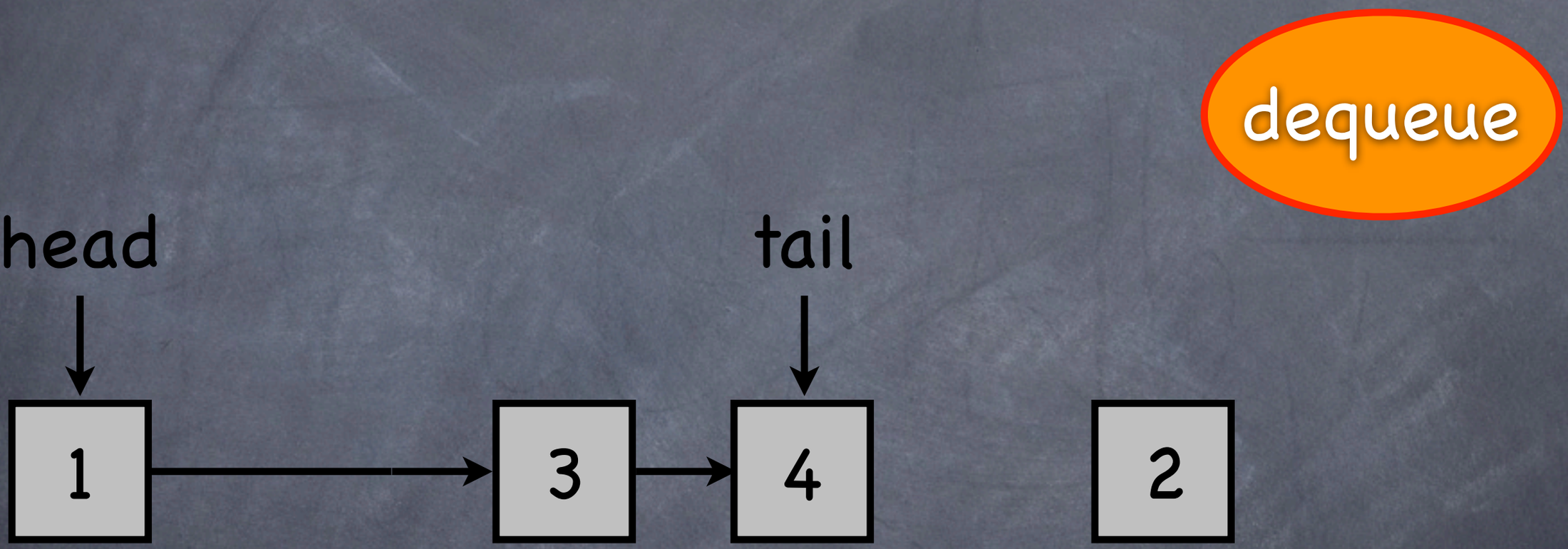

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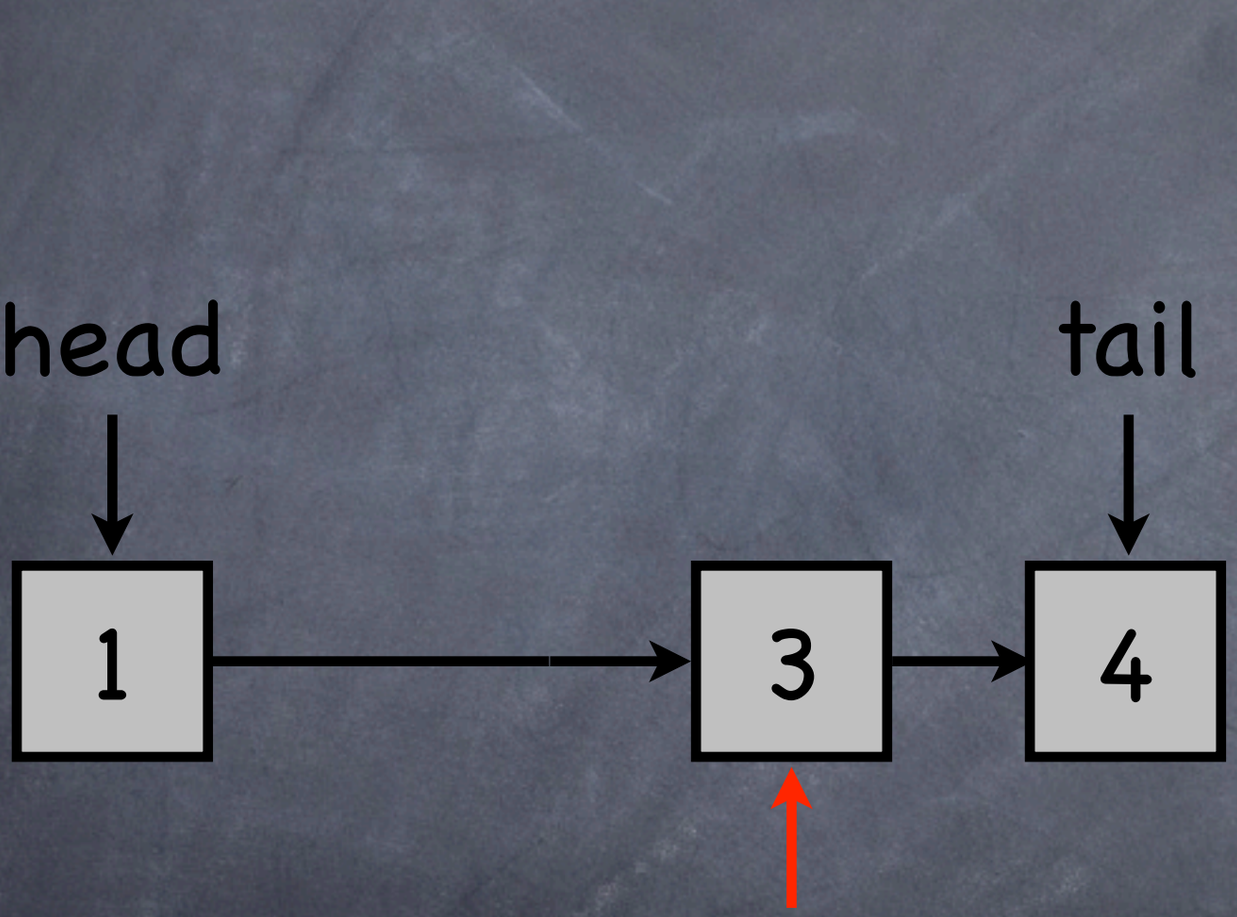

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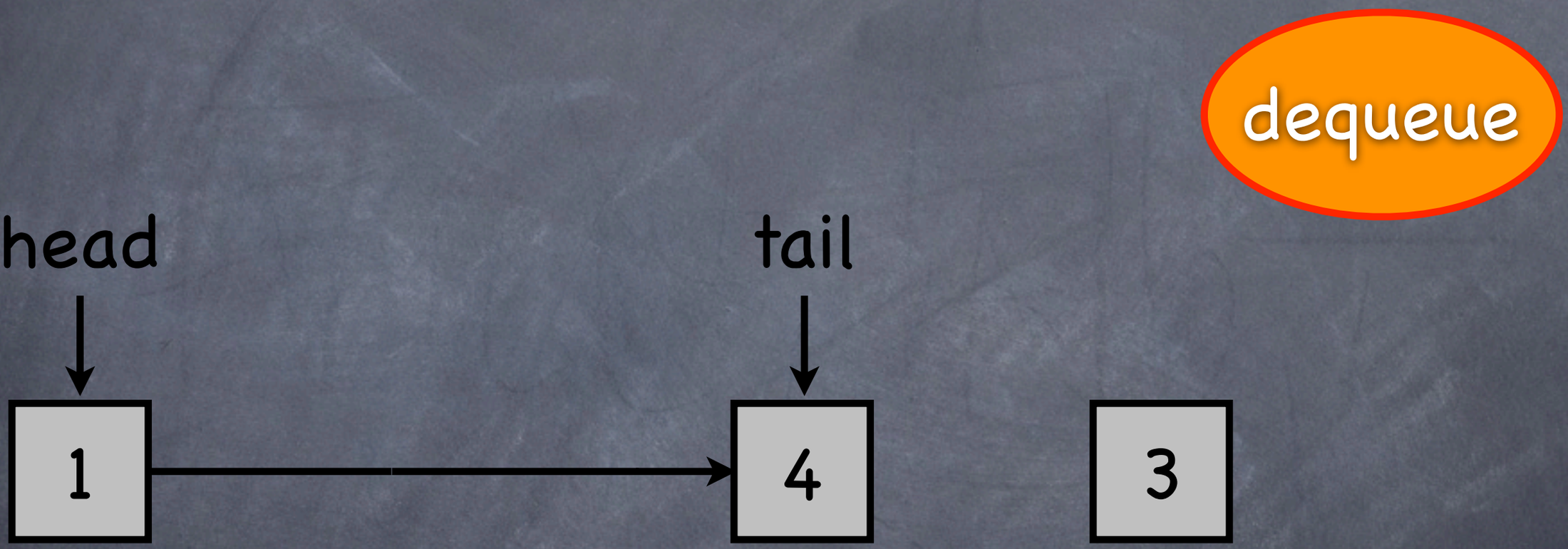

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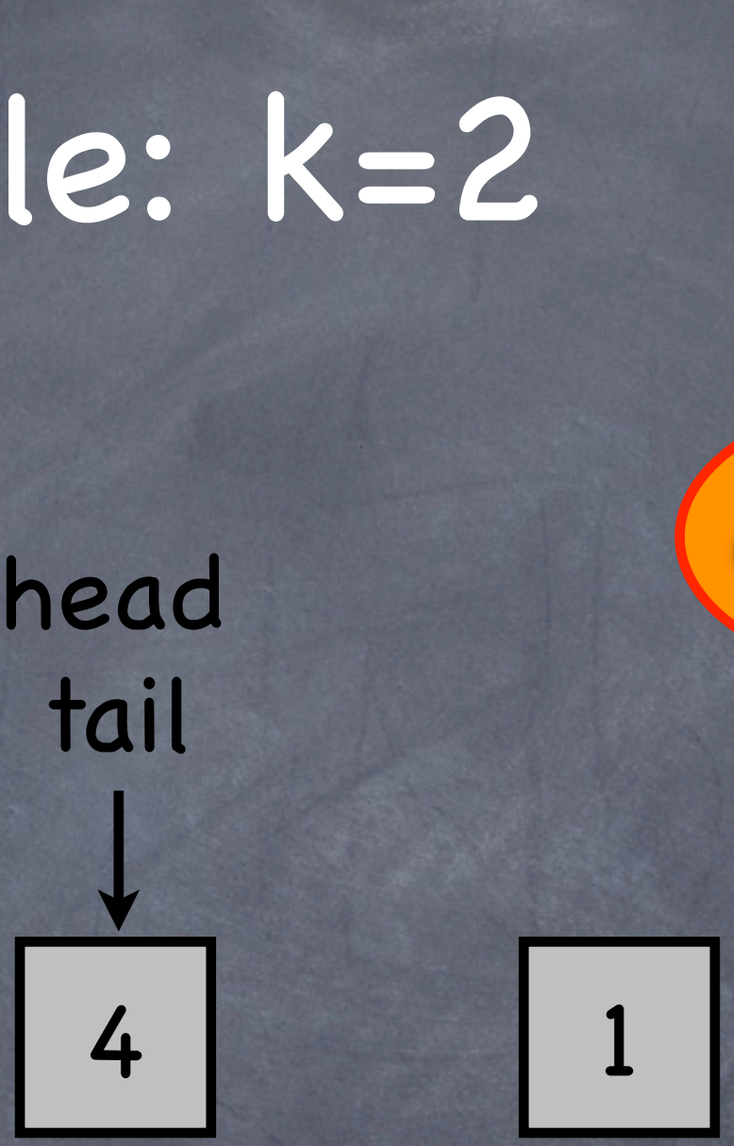

Worst-case Semantical Deviation (WCSD)

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- k may be zero, i.e., there is no semantical deviation (LB, MS, FC)

- k may be configurable and independent of any workload (RD, SQ)

- k may also be workload-dependent (RR) and even probabilistic (RA, dRA)

WCSD of existing k-FIFO Queue Implementations

Queue Implementation	k	o
Lock-Based (LB)	0	0
Lock-free Michael-Scott (MS) [1]	0	0
Flat Combining (FC) [2]	0	0
Random Dequeue Queue (RD) [3]	r	0
Segment Queue (SQ) [3]	s	∞

[1] M. Michael and M. Scott. Simple, fast, and practical non-blocking and blocking concurrent queue algorithms. In Proc. PODC, pages 267-275. ACM, 1996.
[2] D.H.I. Incze, N. Shavit, and M. Tzafrir. Flat combining and the synchronization-parallelism tradeoff. In Proc. SPAA, pages 355-364. ACM, 2010
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workload-independent constant bounds

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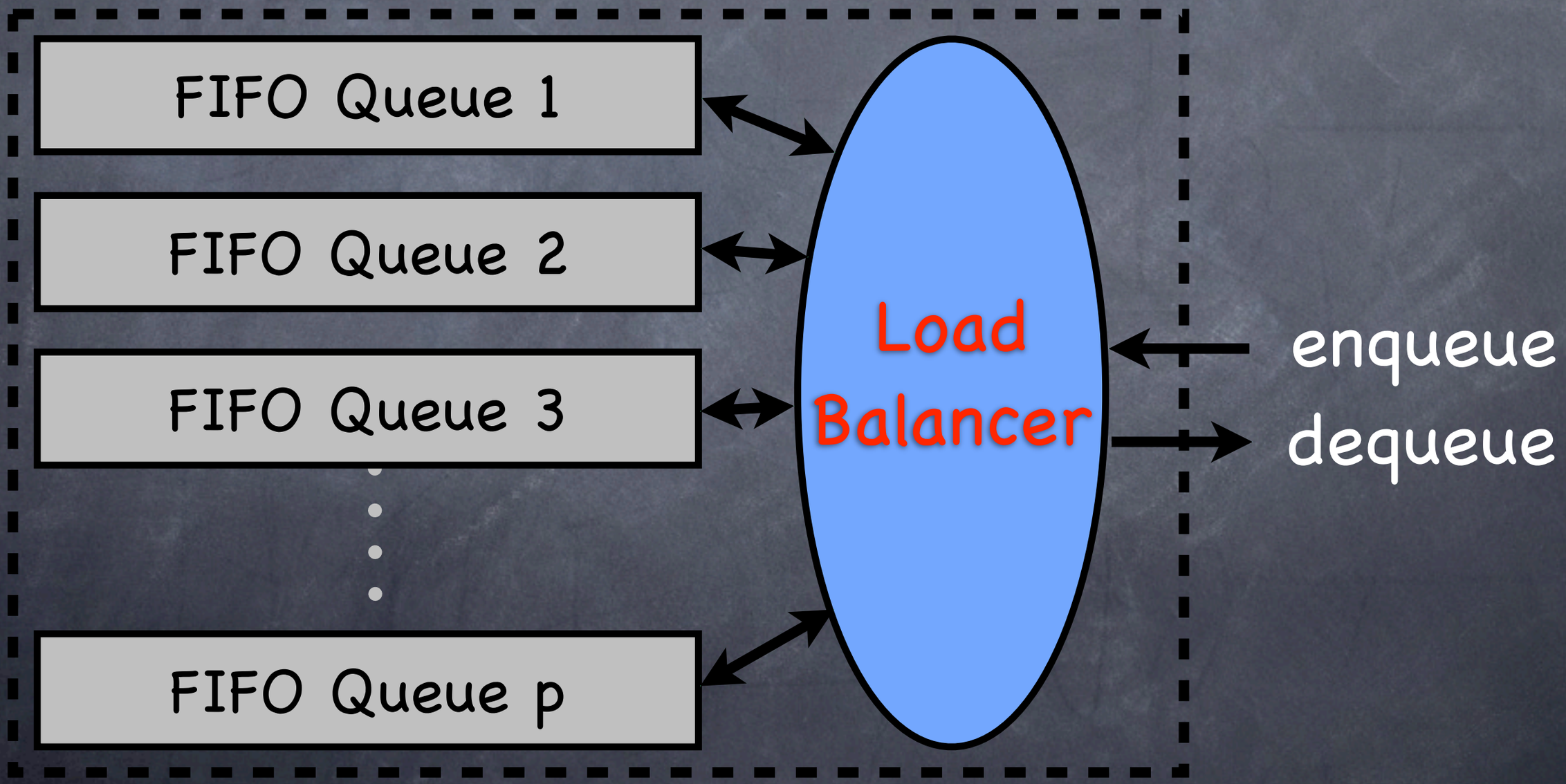
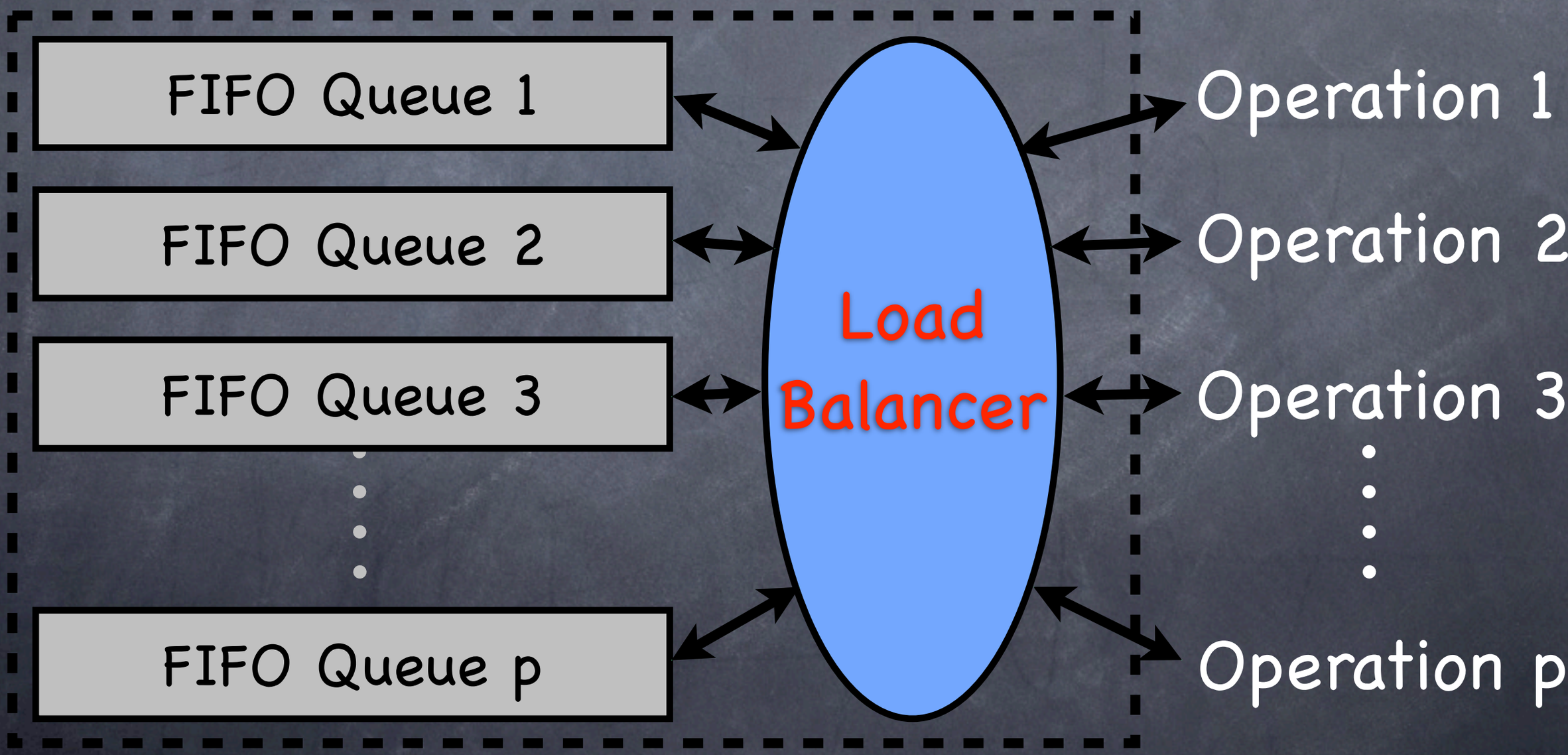
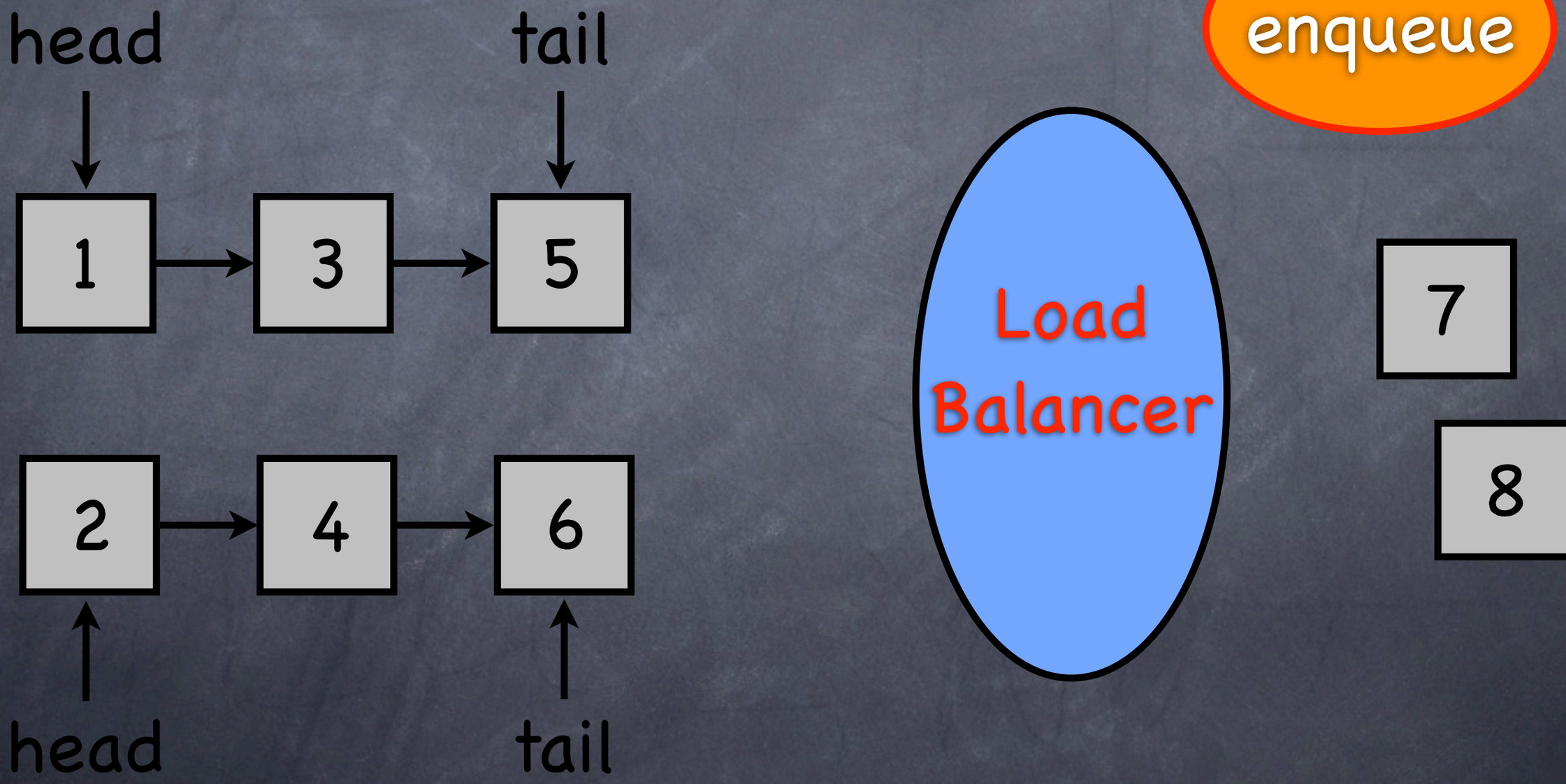
Scal Queue:
p FIFO Queues



Scal Queue:
Up to p Parallel Operations



Scal Queue: Load Balancing



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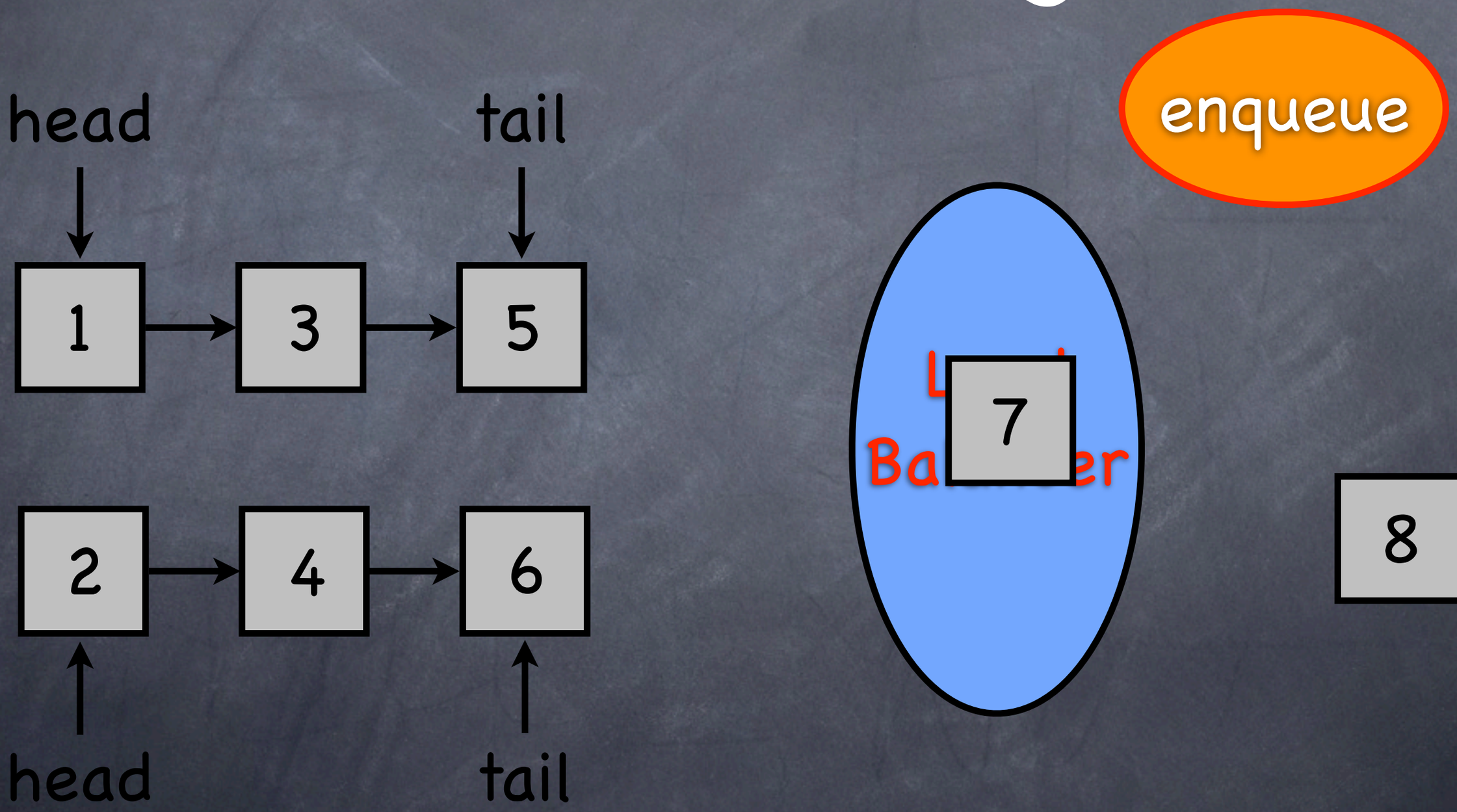

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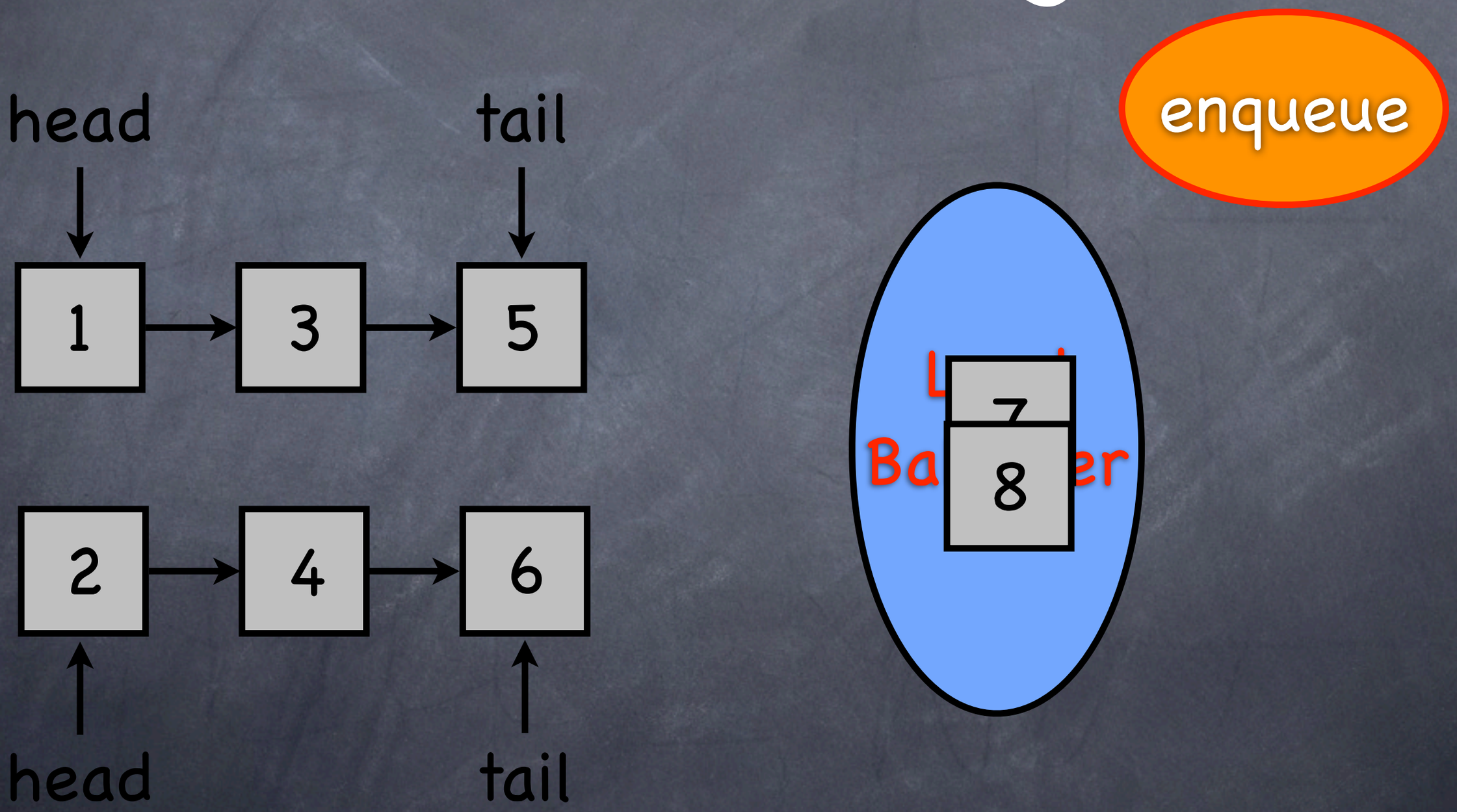

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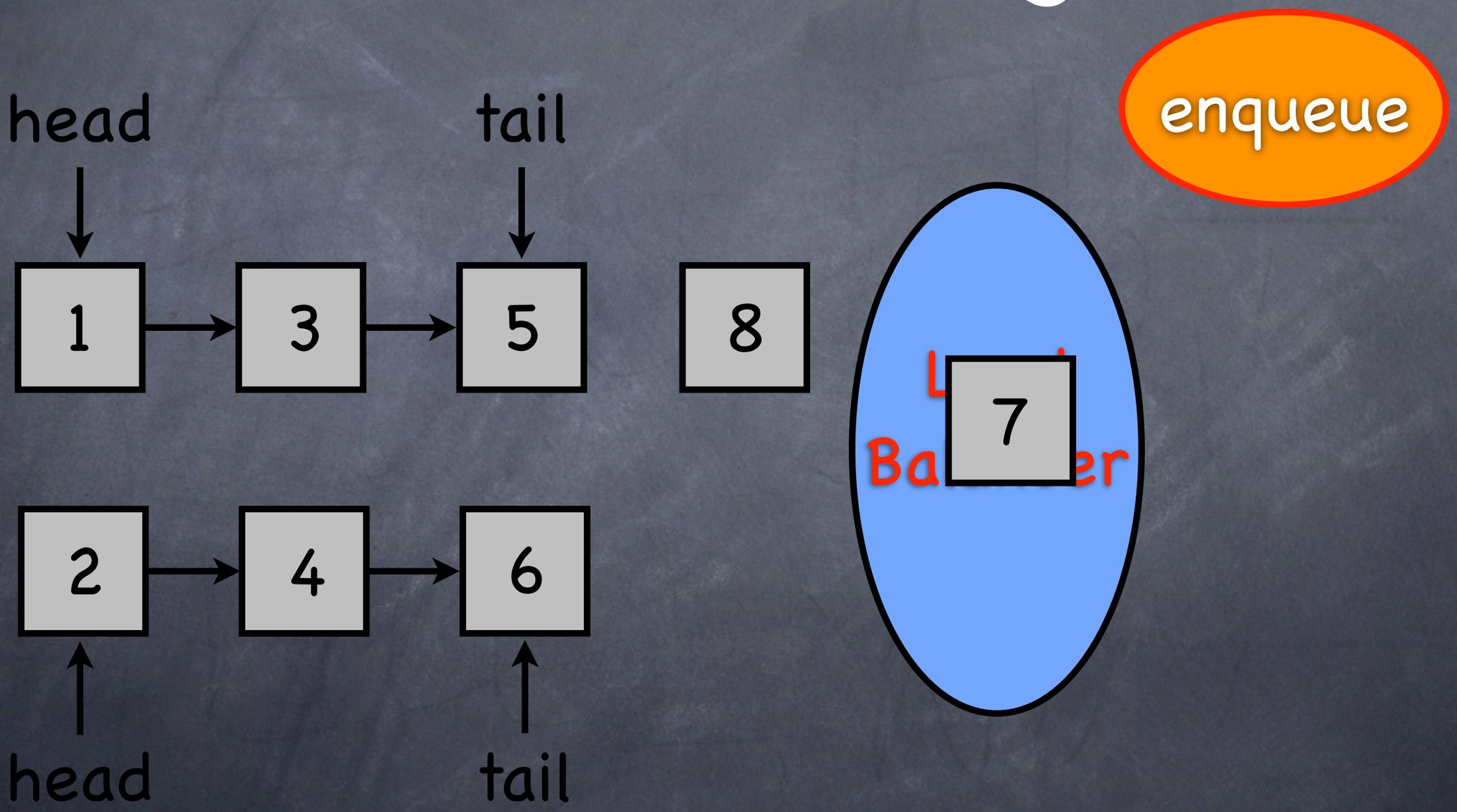

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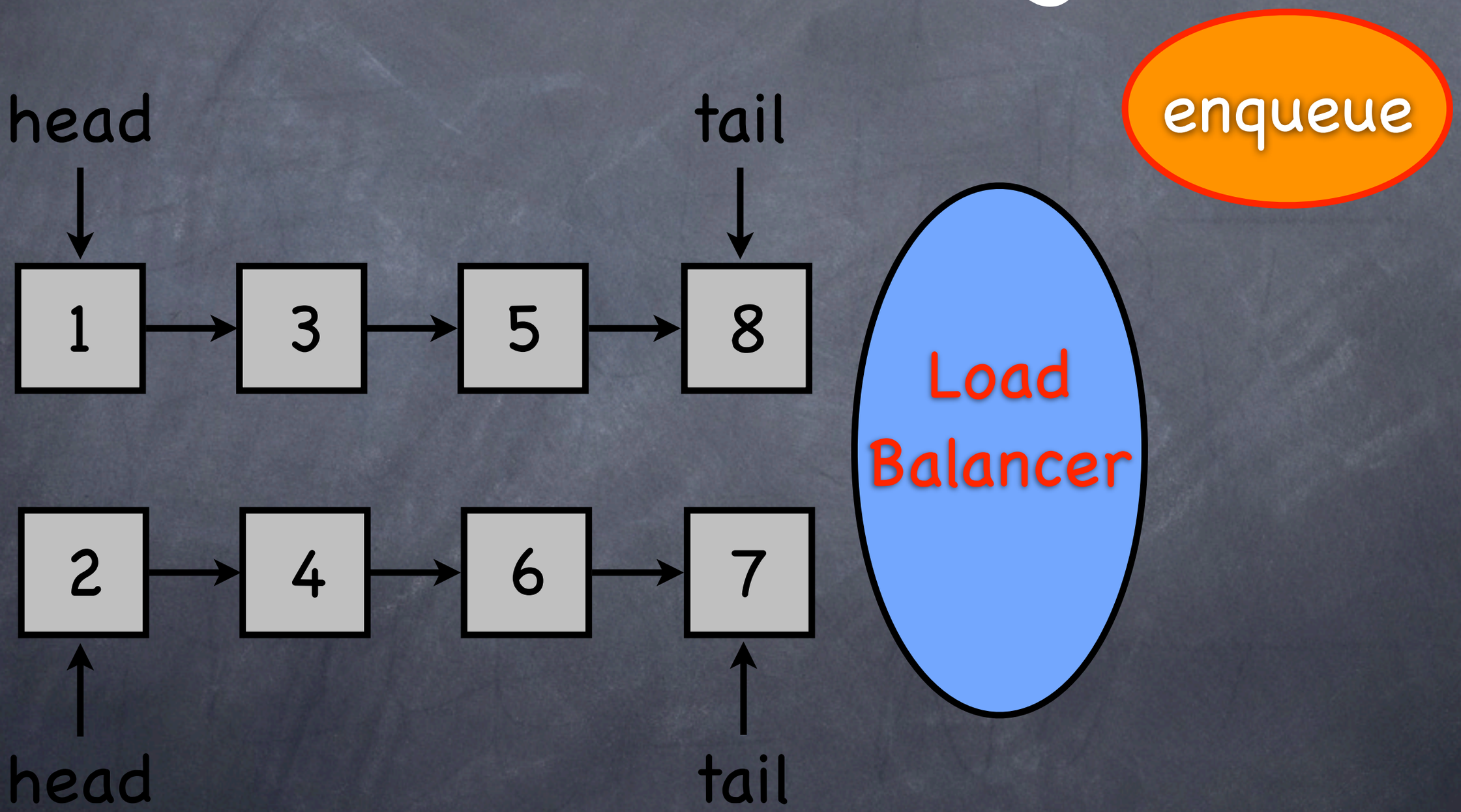

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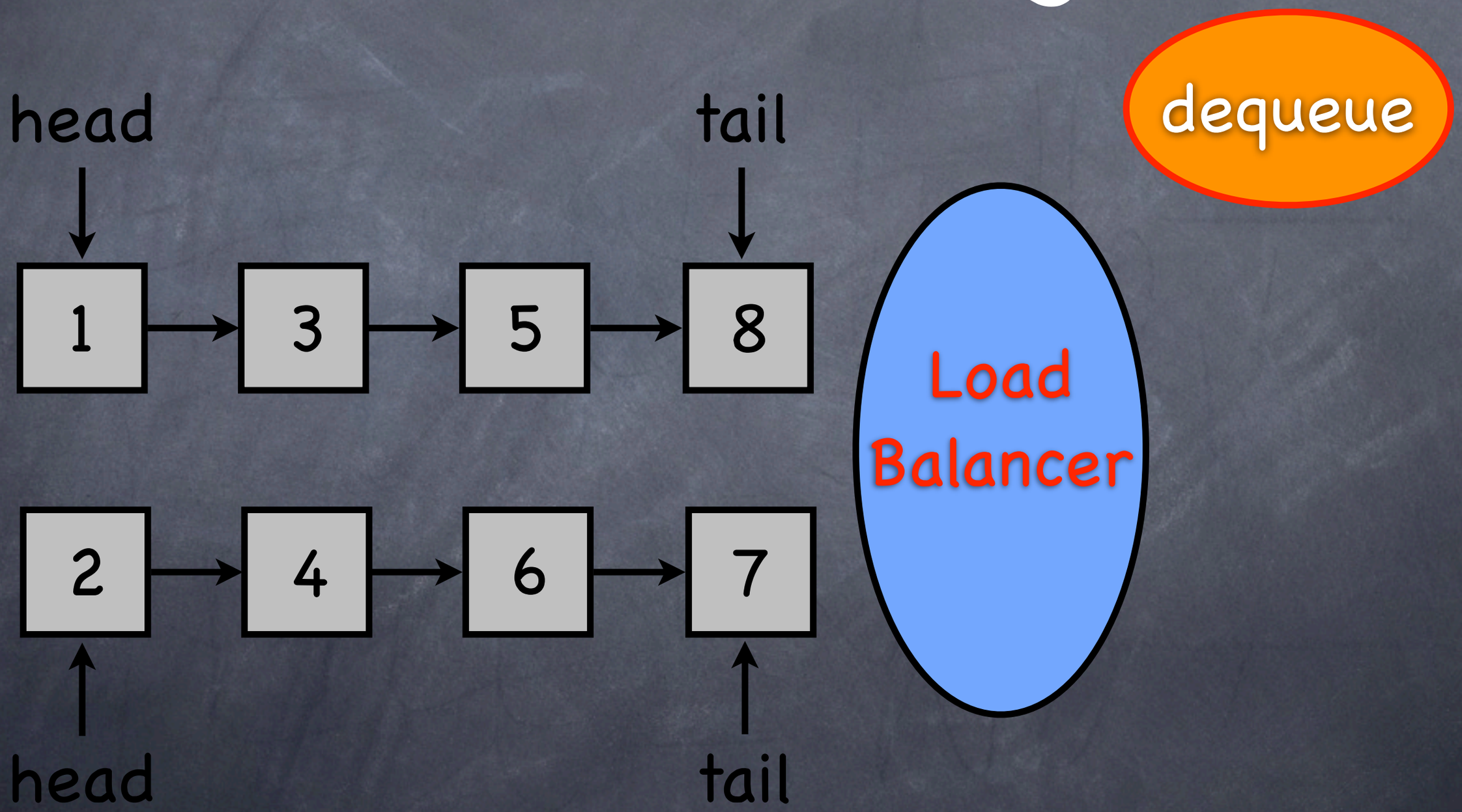

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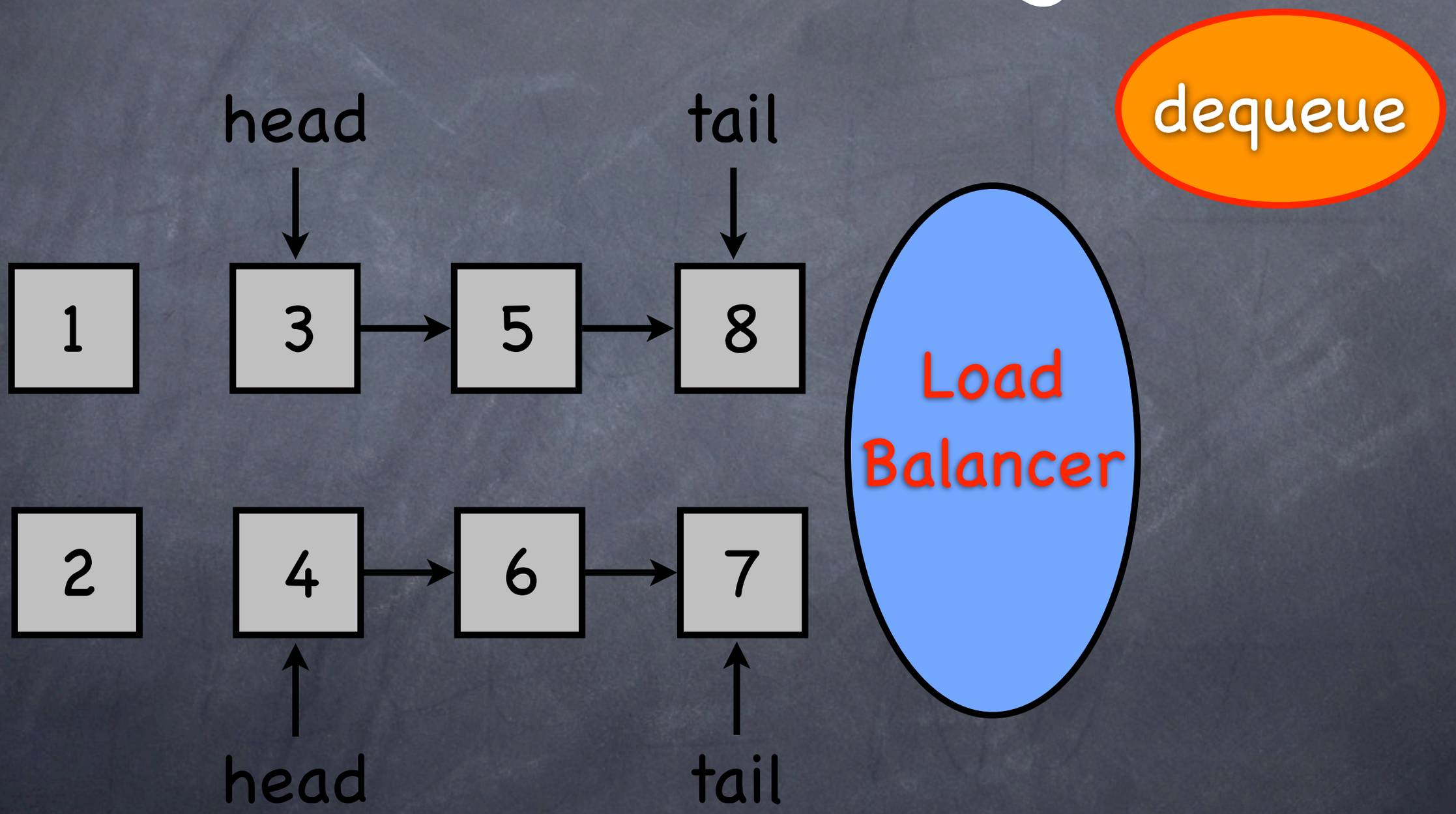

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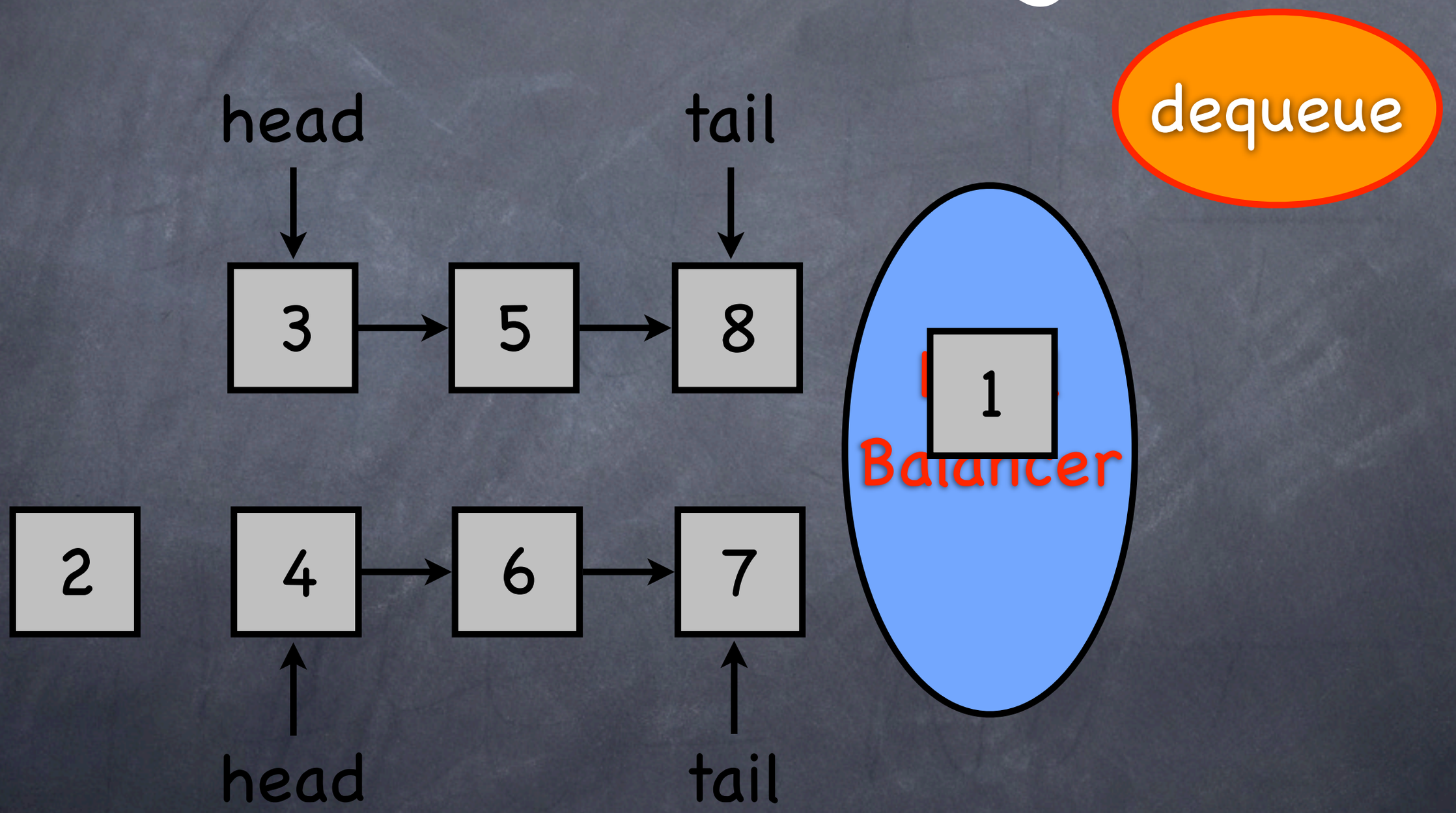

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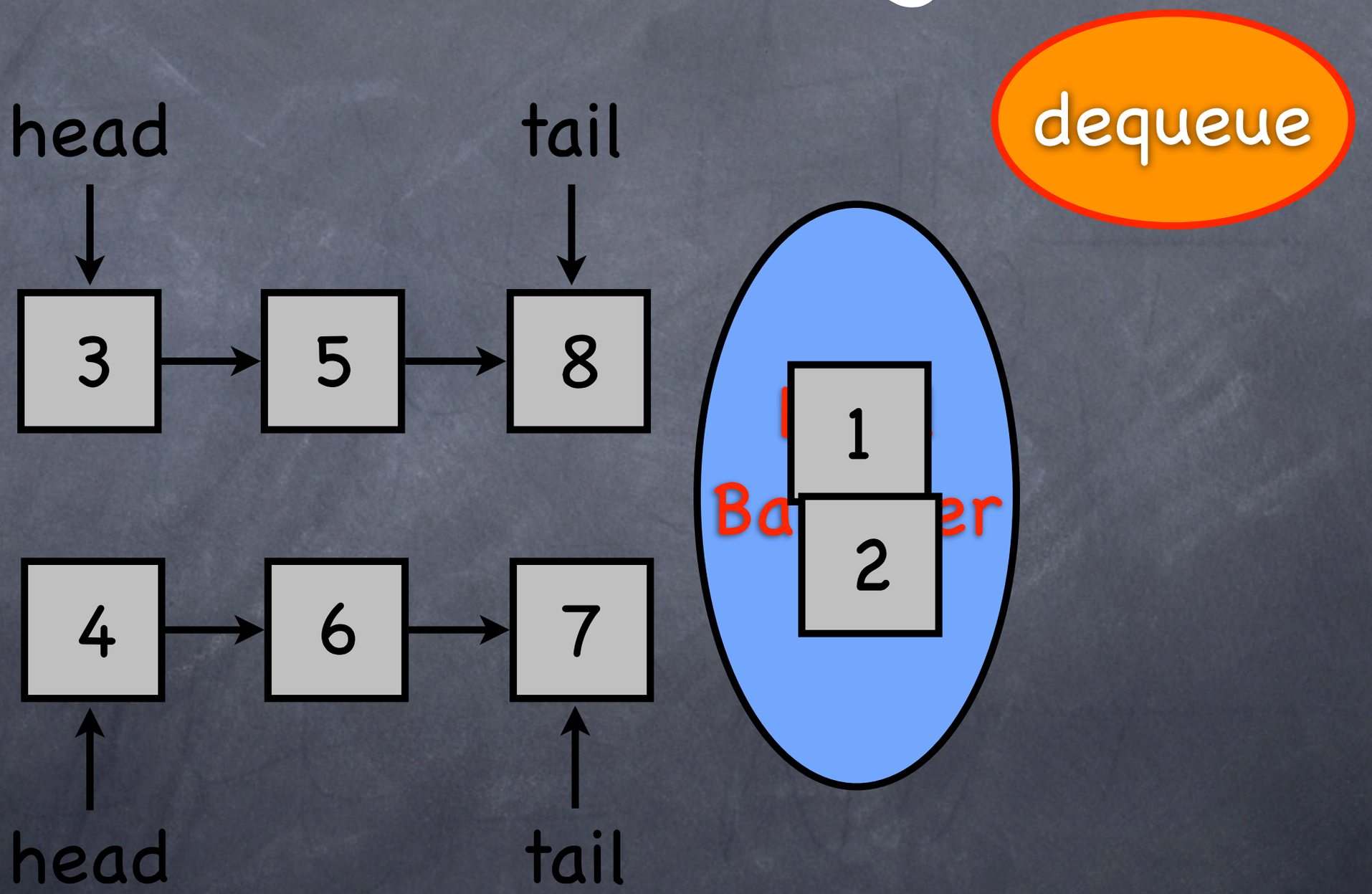

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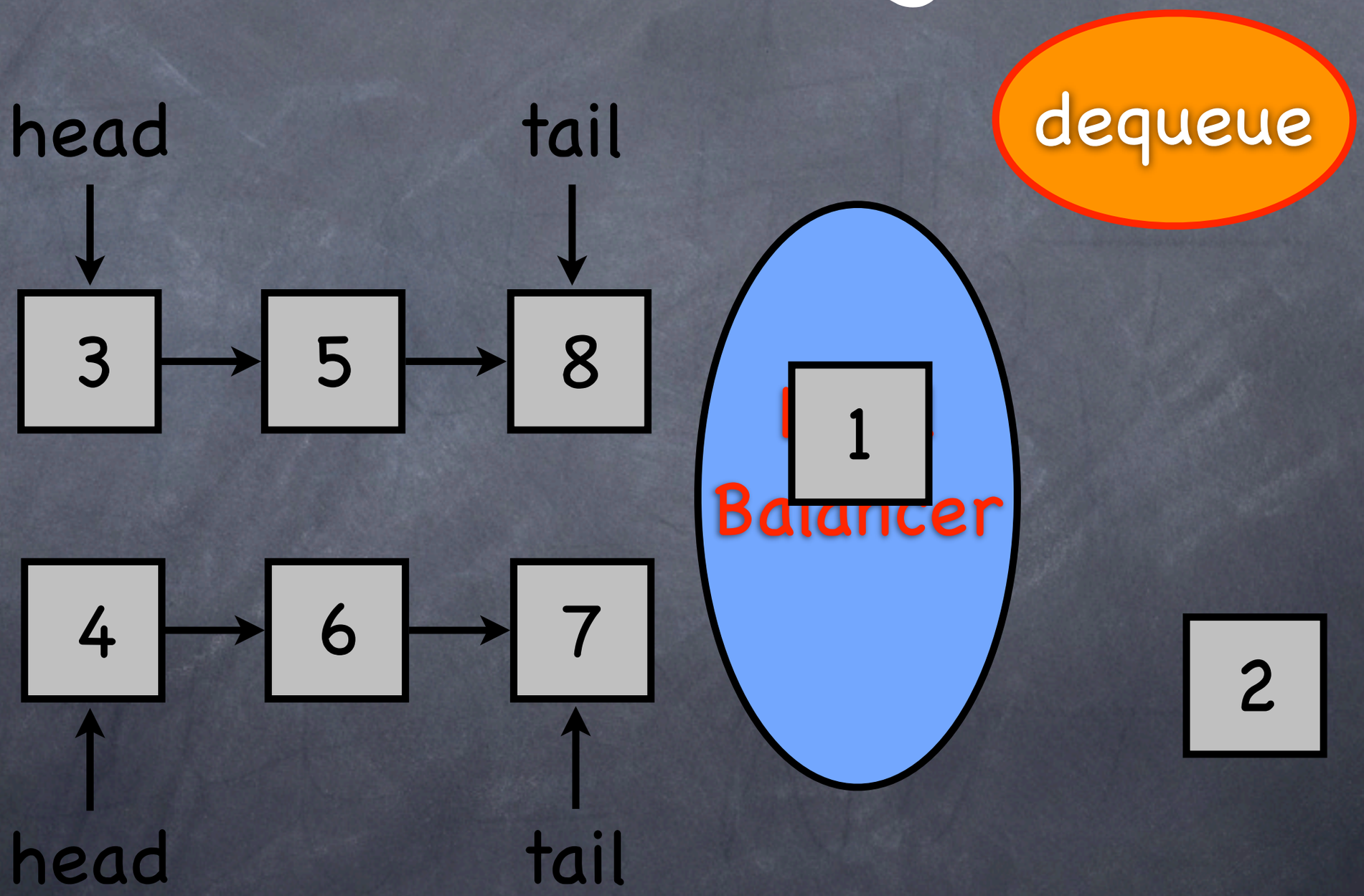

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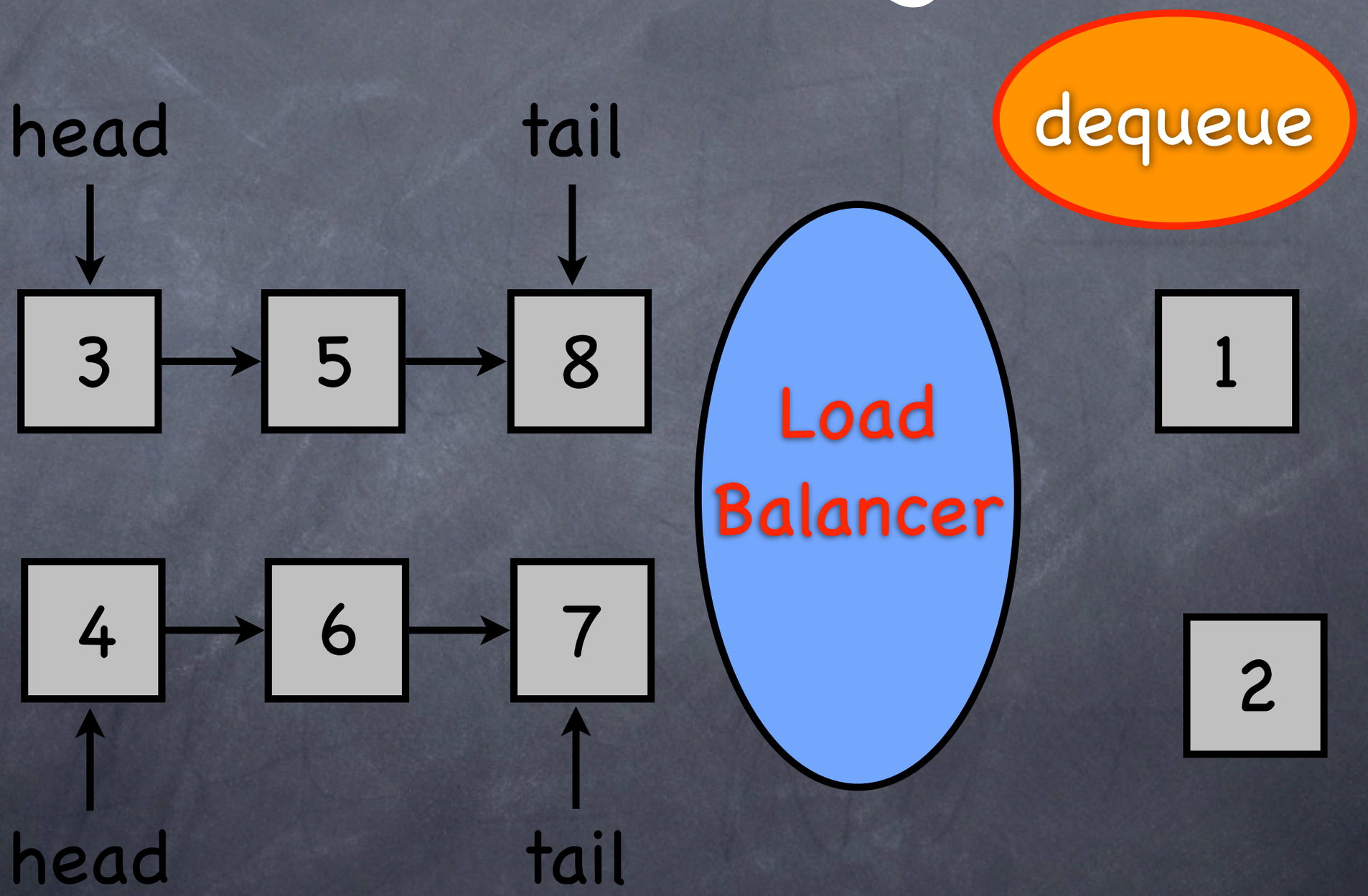
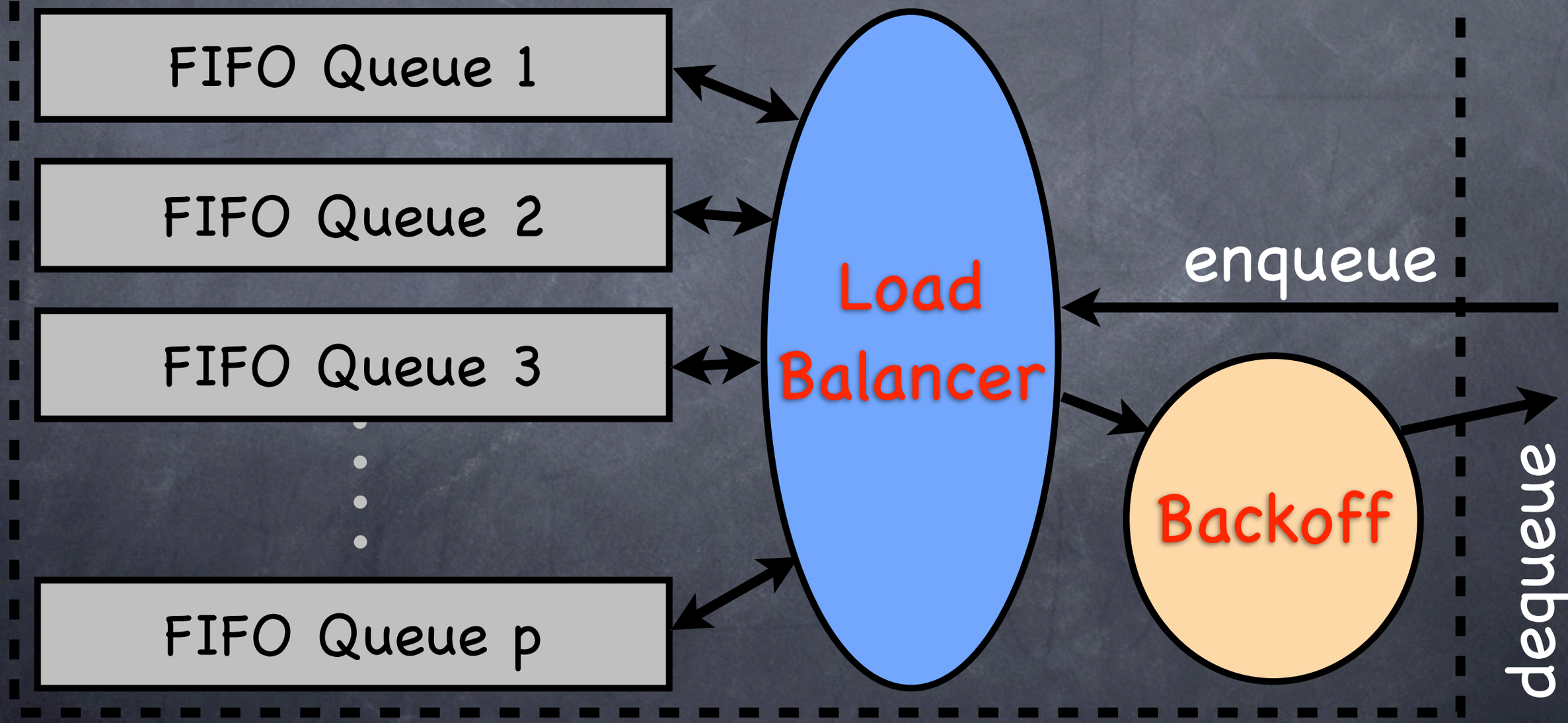


Scal Queue: Backoff



WCSD of Scal Queues

Load balancer	k	o
Round-Robin (RR)	$t \cdot (p-1)$	$t \cdot (p-1)$
Round-Robin Backoff (RR-B)	$t \cdot (p-1)$	0
Random (RA)	$2 \cdot R \cdot (p-1)$	$2 \cdot R \cdot (p-1)$
Random Backoff (RA-B)	$2 \cdot R \cdot (p-1)$	0
2-Random (2RA)	$2 \cdot Q \cdot (p-1)$	$2 \cdot Q \cdot (p-1)$
2-Random Backoff (2RA-B)	$2 \cdot Q \cdot (p-1)$	0
Hierarchical 2-Random (H-2RA)	$2 \cdot Q \cdot (p-1)$	$2 \cdot Q \cdot (p-1)$
Hierarchical 2-Random Backoff (H-2RA-B)	$2 \cdot Q \cdot (p-1)$	0

$$t \text{ threads}, R = \Theta\left(\sqrt{\frac{t \cdot m \cdot \log p}{p}}\right), Q = \Theta\left(\frac{\log \log p}{d}\right)$$

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Random	$2 \cdot R \cdot (p-1)$	$2 \cdot R \cdot (p-1)$
Random	$(p-1)$	0
2-R	$1)$	$2 \cdot Q \cdot (p-1)$
2-Random	$-1)$	0
Hierarchical 2-R	$Q \cdot (p-1)$	$2 \cdot Q \cdot (p-1)$
Hierarchical 2-Random Backoff (H-2RA-B)	$2 \cdot Q \cdot (p-1)$	0

bounded in number of threads (t) and partial FIFO queues (p)

$$t \text{ threads}, R = \Theta\left(\sqrt{\frac{t \cdot m \cdot \log p}{p}}\right), Q = \Theta\left(\frac{\log \log p}{d}\right)$$

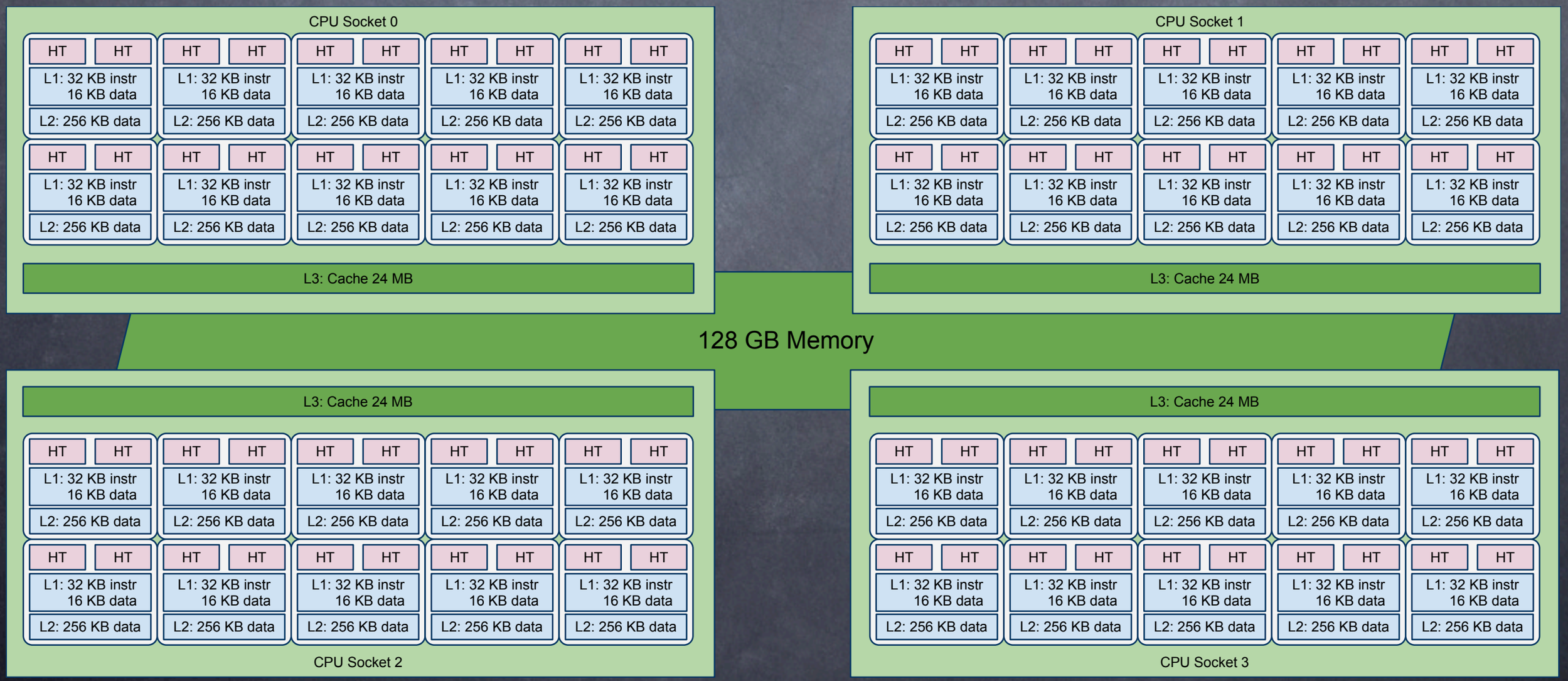
WCSD of Scal Queues

Load b	k	o
Roun		t · (p–1)
Round-Robin Ba	(p–1)	0
Random (RA)	2 · R · (p–1)	2 · R · (p–1)
Random Backoff (RA-B)	2 · R · (p–1)	0
2-Random (2RA)	2 · Q · (p–1)	2 · Q · (p–1)
2-Random Backoff (2RA-B)	2 · Q · (p–1)	0
Hierarchical 2-Random (H-2RA)	2 · Q · (p–1)	2 · Q · (p–1)
Hierarchical 2-Random Backoff (H-2RA-B)	2 · Q · (p–1)	0

bounded probabilistically

$$t \text{ threads}, R = \Theta\left(\sqrt{\frac{t \cdot m \cdot \log p}{p}}\right), Q = \Theta\left(\frac{\log \log p}{d}\right)$$

4 processors x 10 cores x 2 hardware threads = 80 hardware threads



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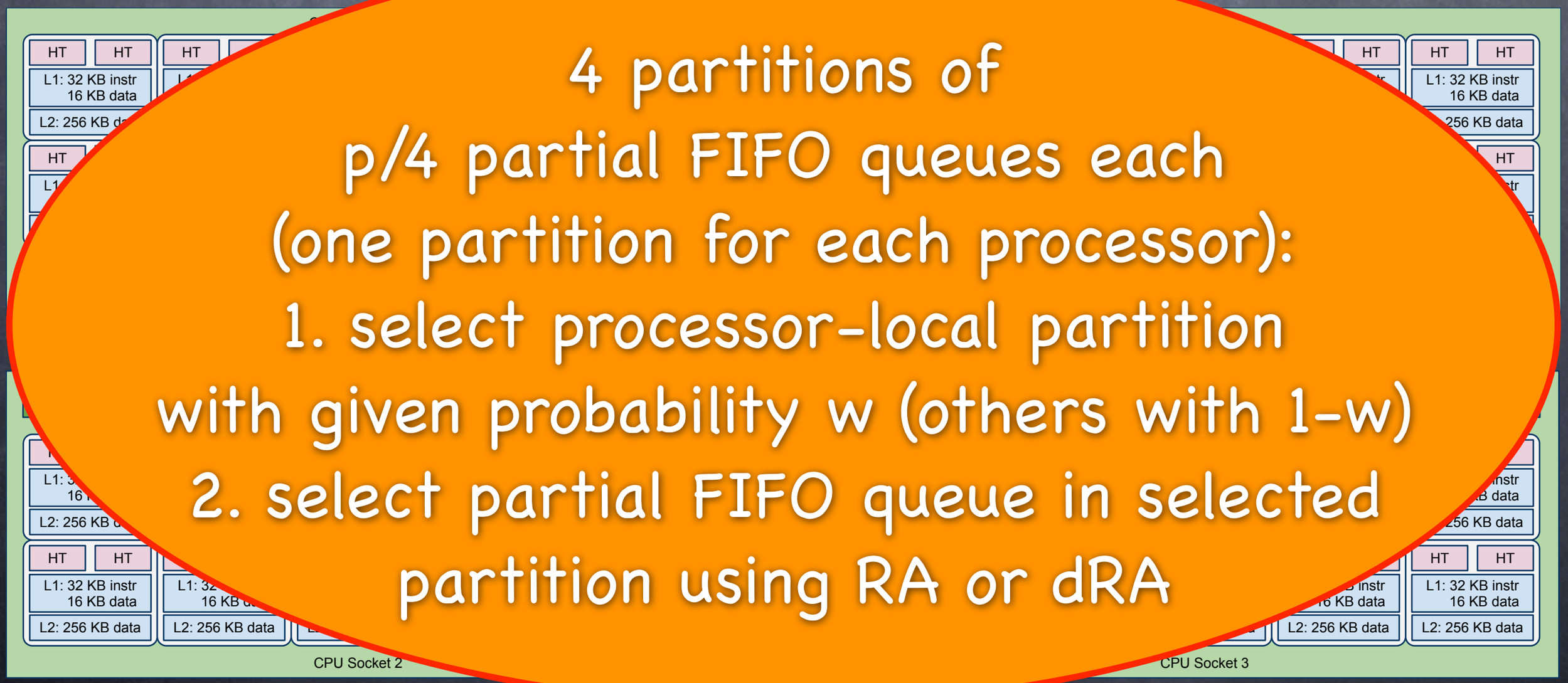
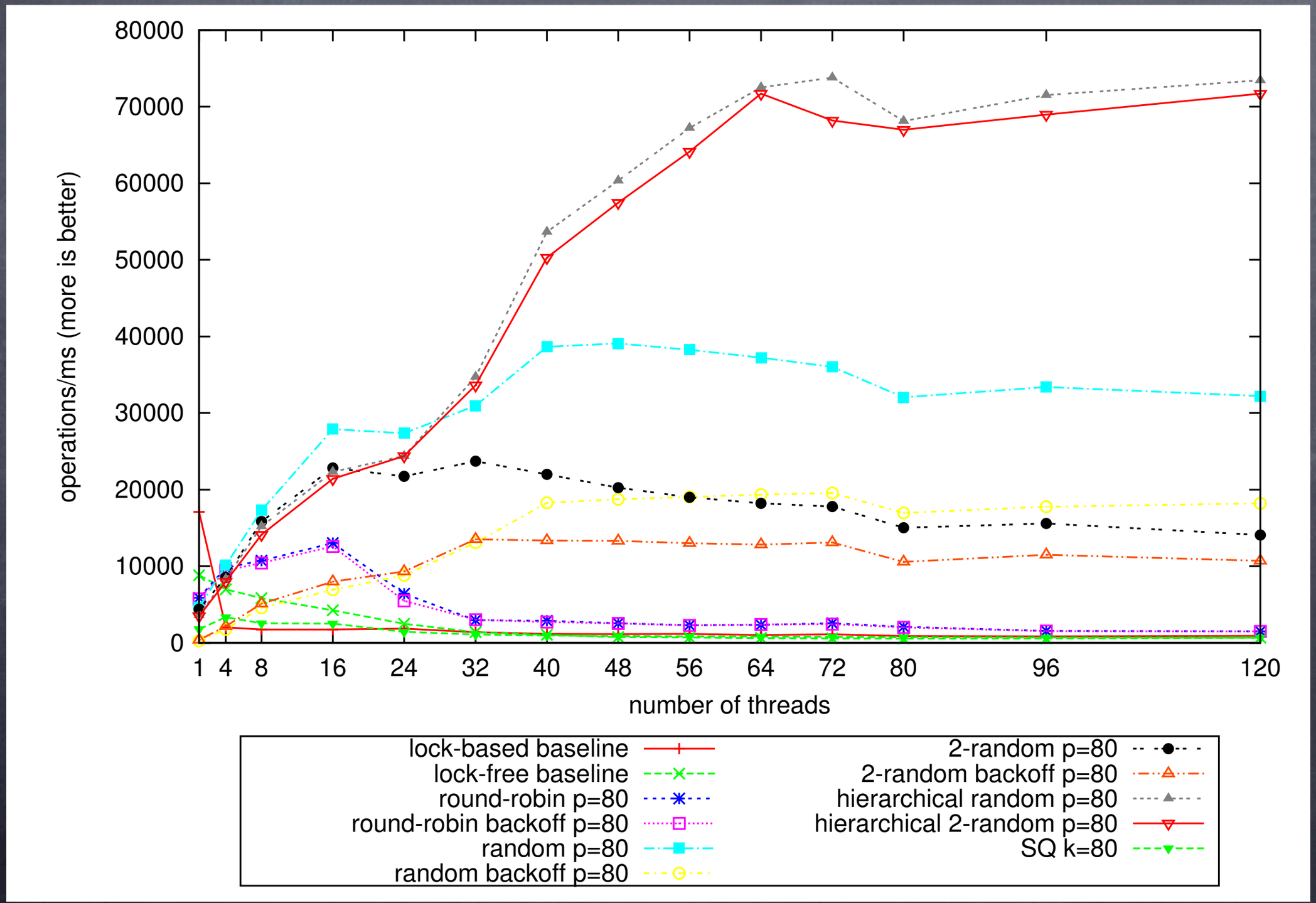


4 partitions of p/4 partial FIFO queues each (one partition for each processor):

1. select processor-local partition with given probability w (others with 1-w)
2. select partial FIFO queue in selected partition using RA or dRA

Performance & Scalability



Execution History

Sequence of Time-Stamped Invocation and Response Events

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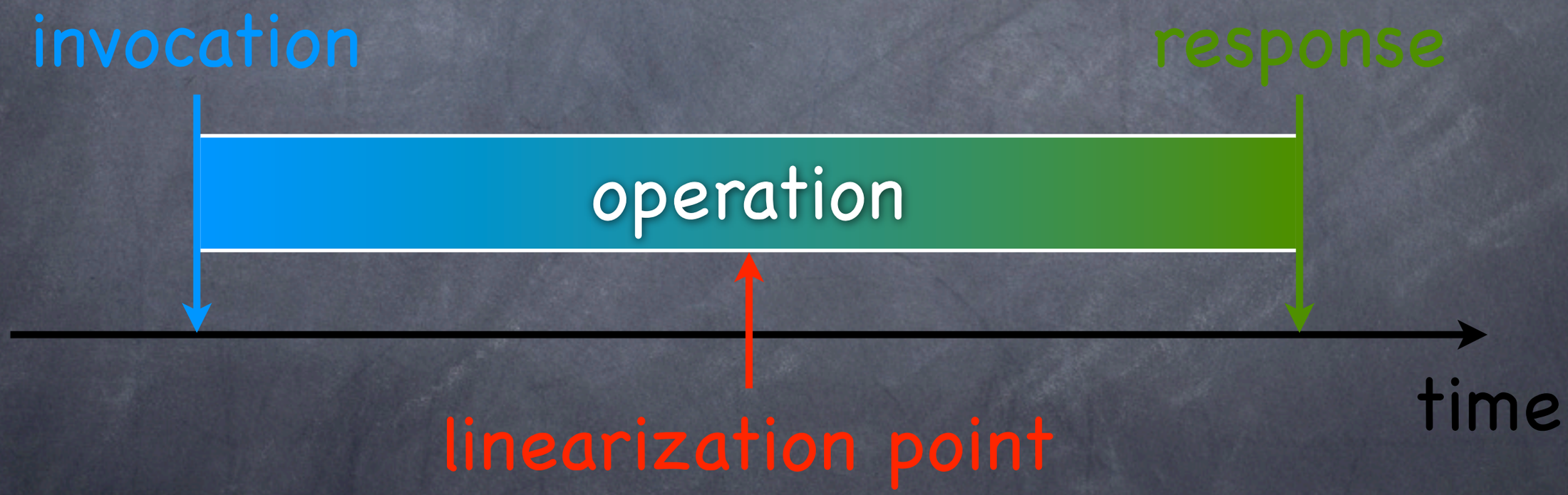
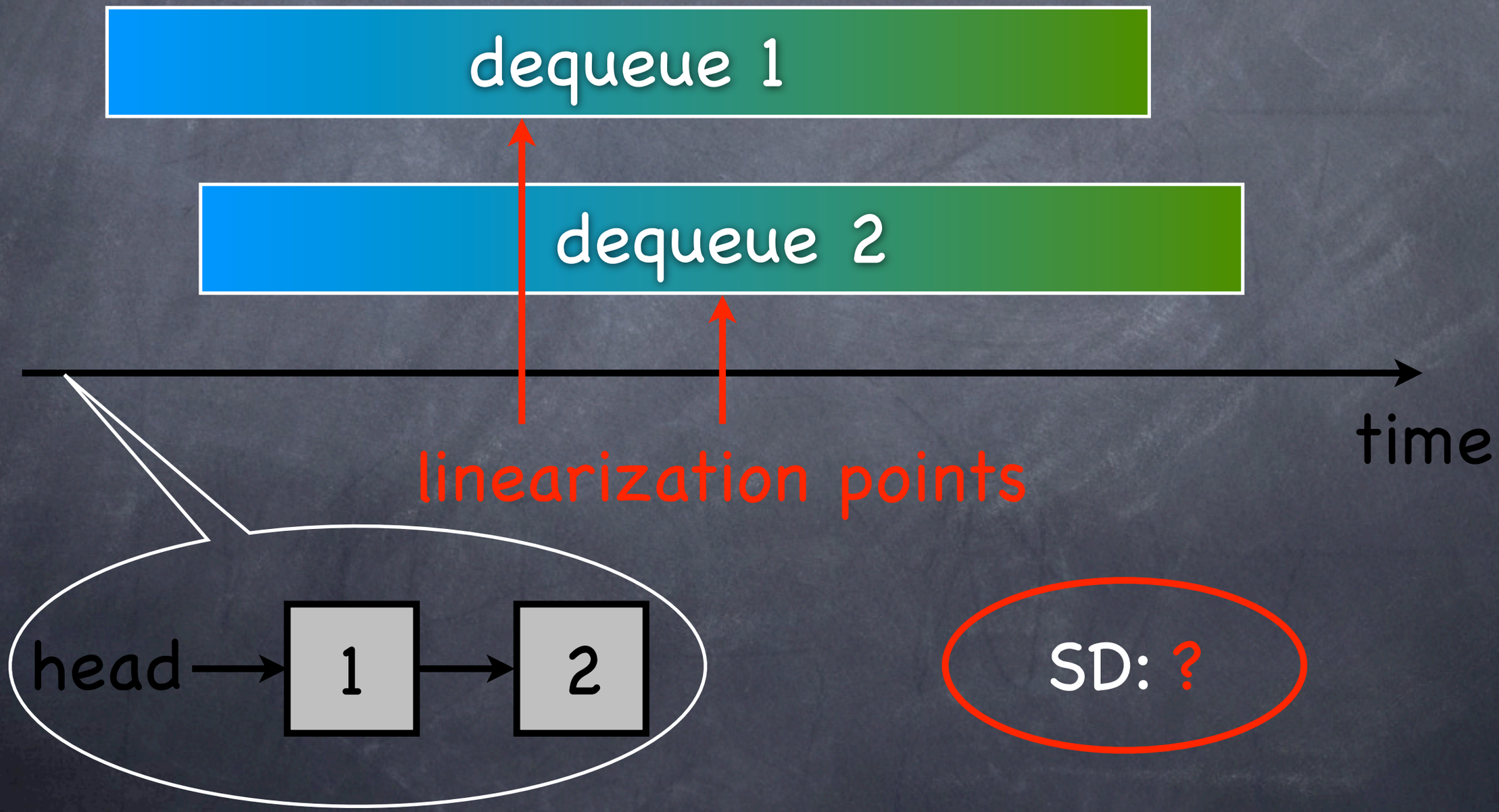


Measuring Semantical Deviation (SD)



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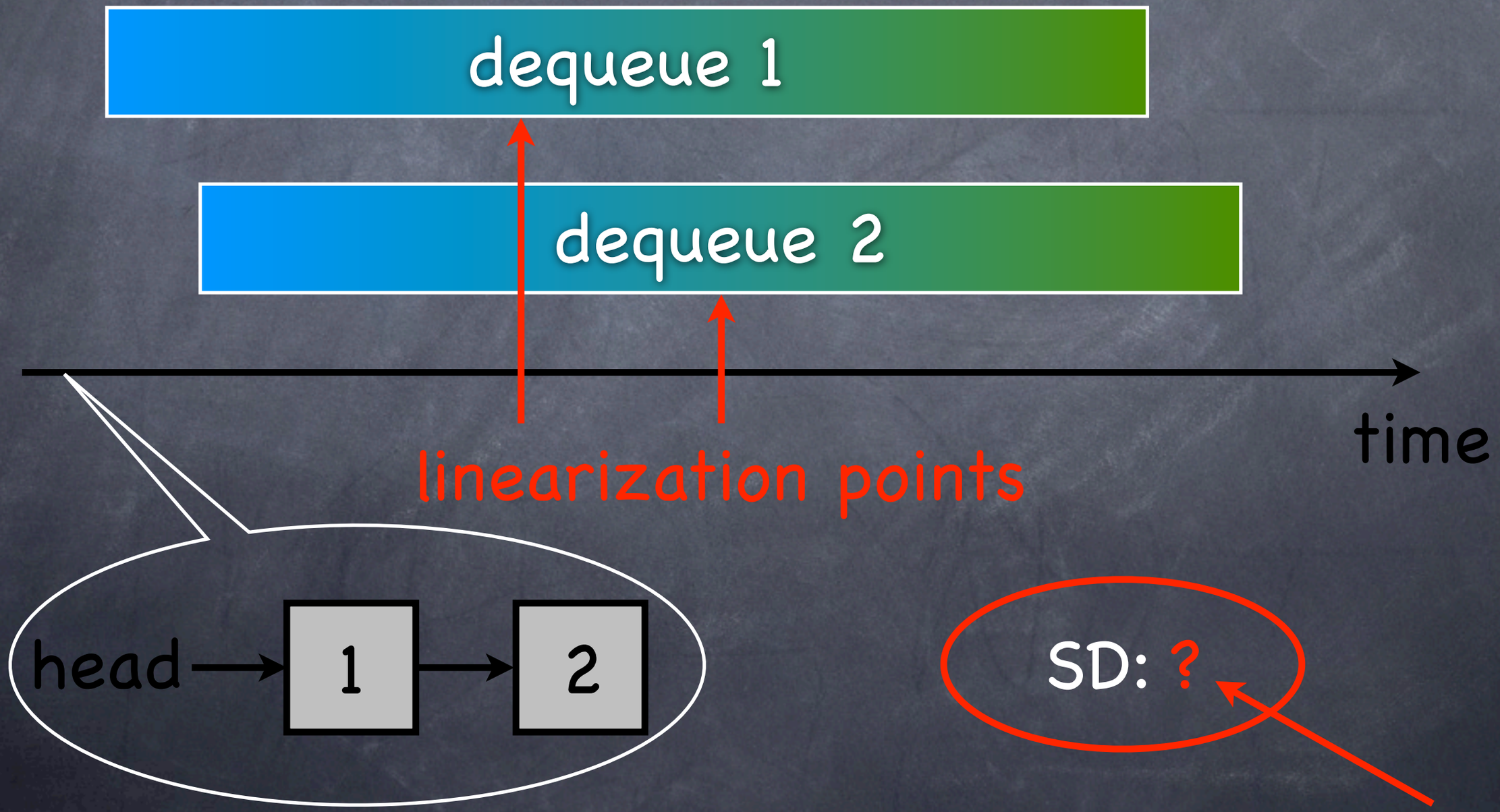

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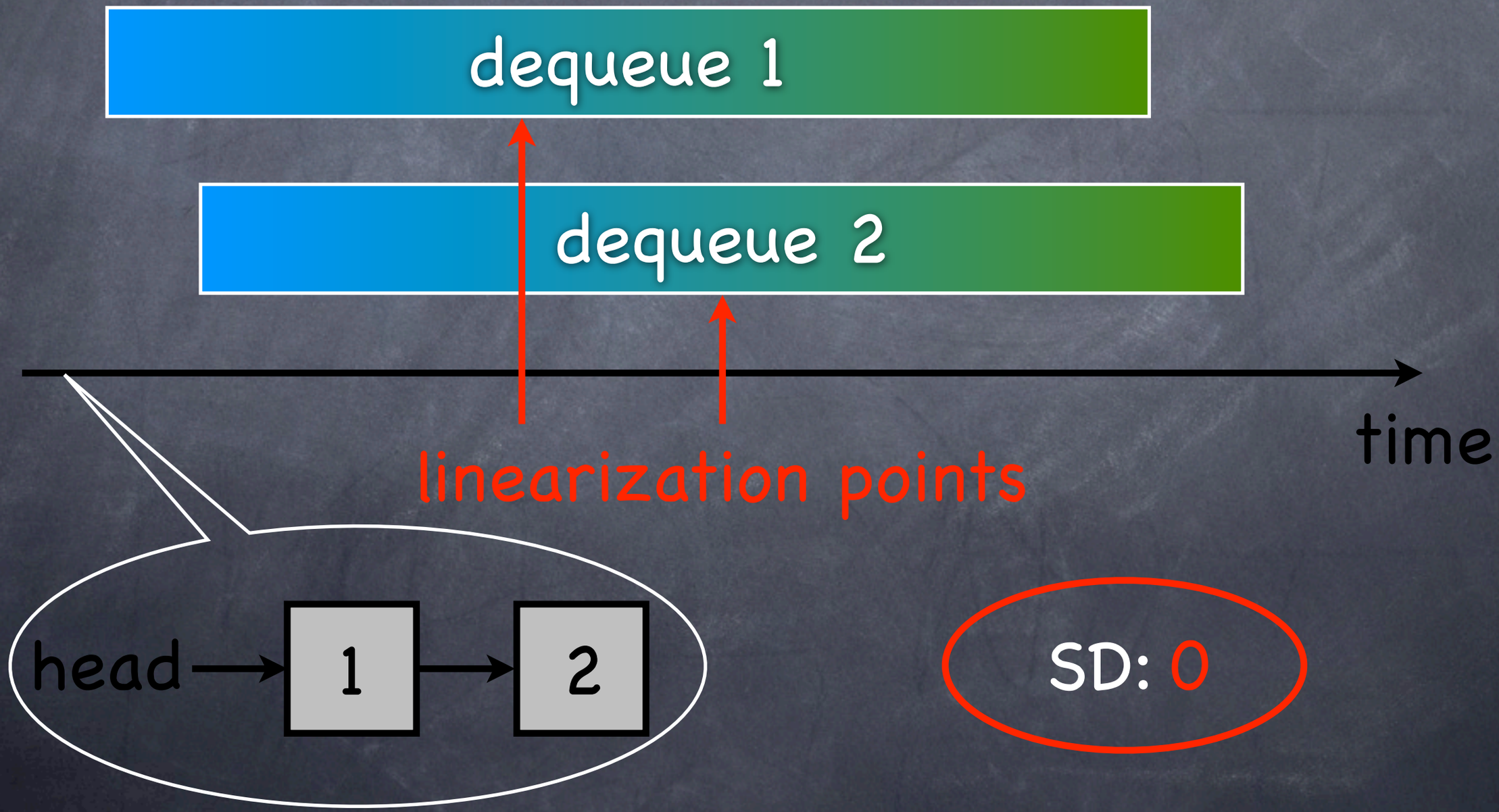

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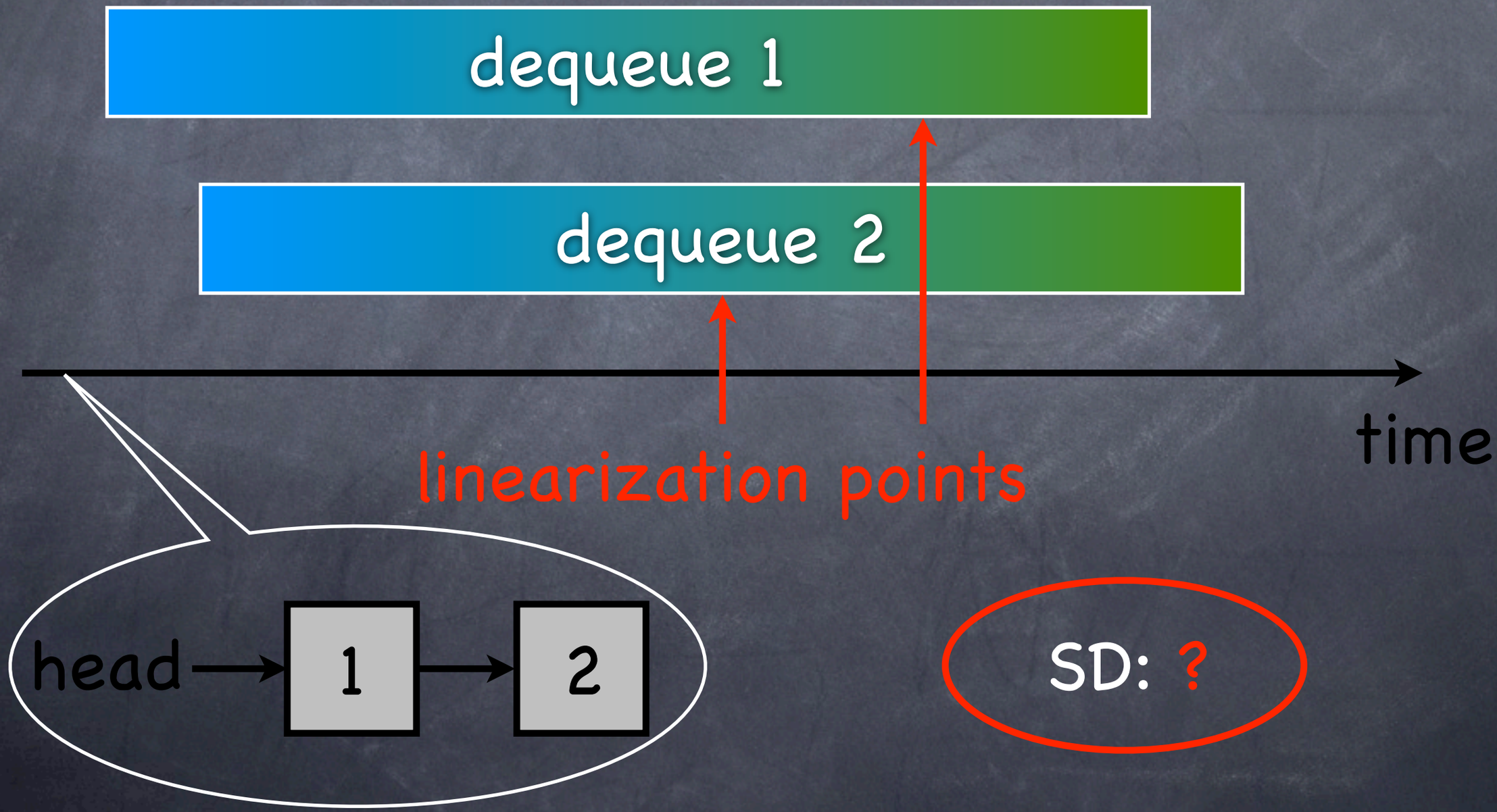

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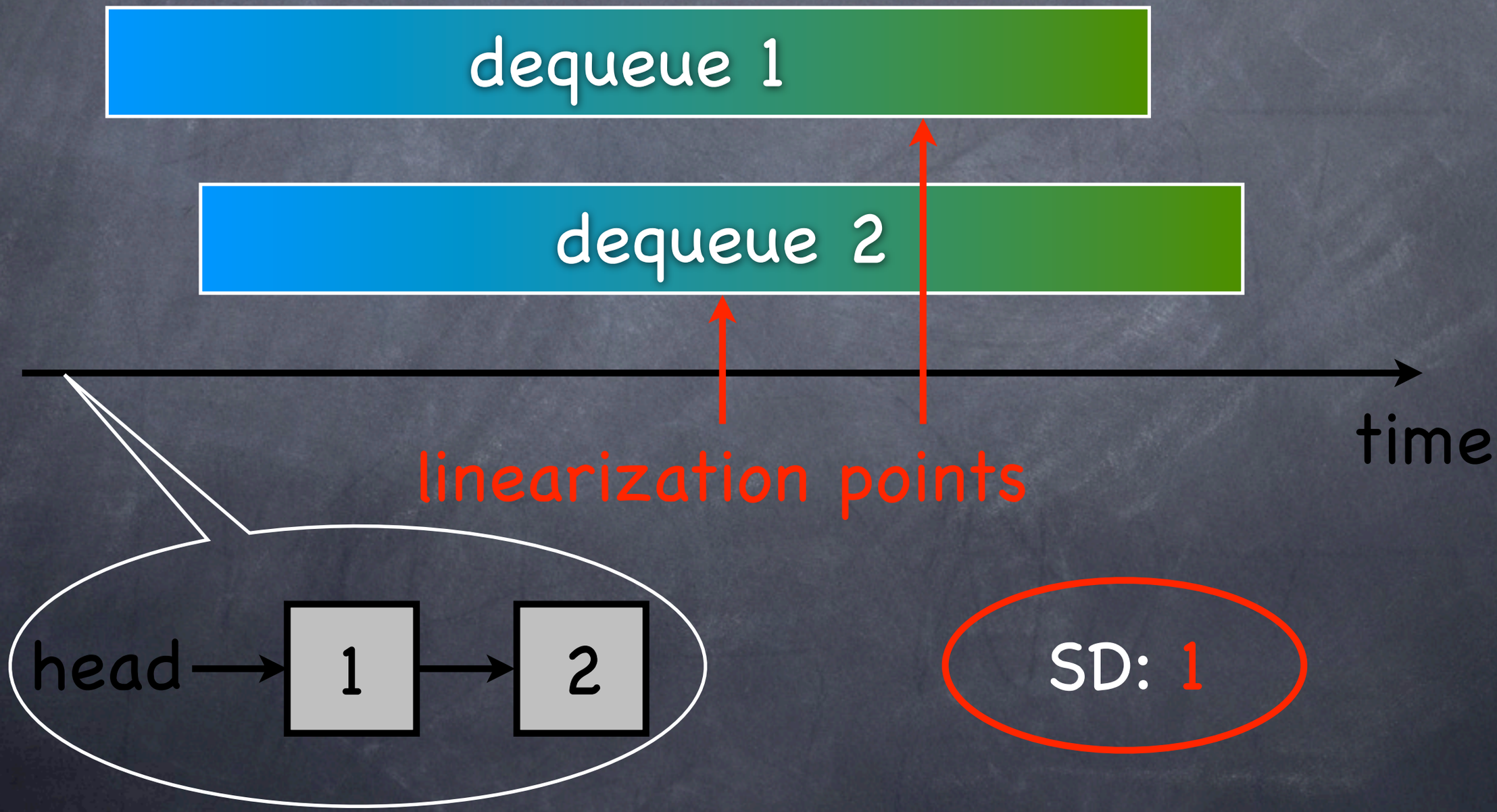
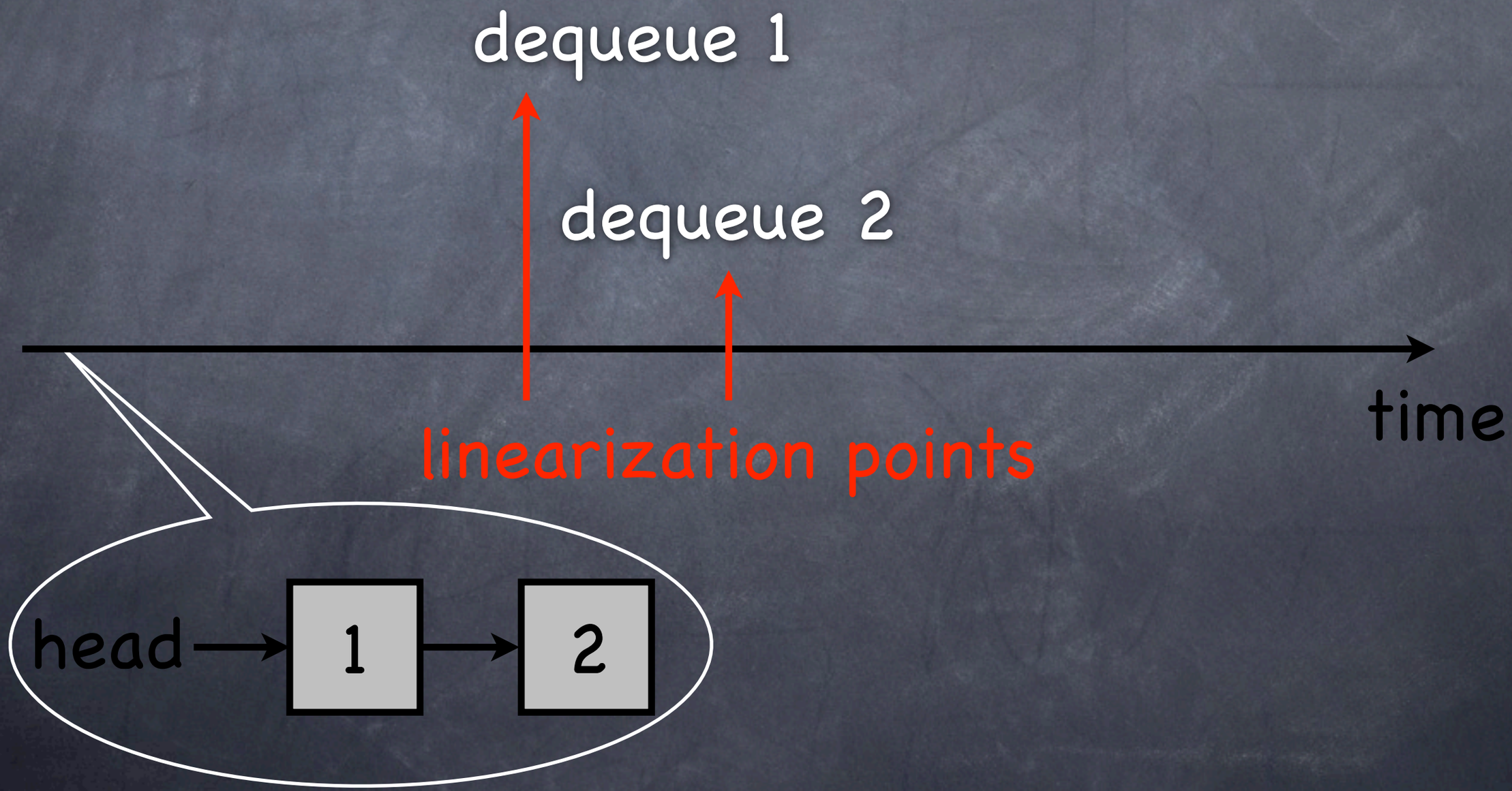


Sequential History

Sequence of Operations (Linearization Points)



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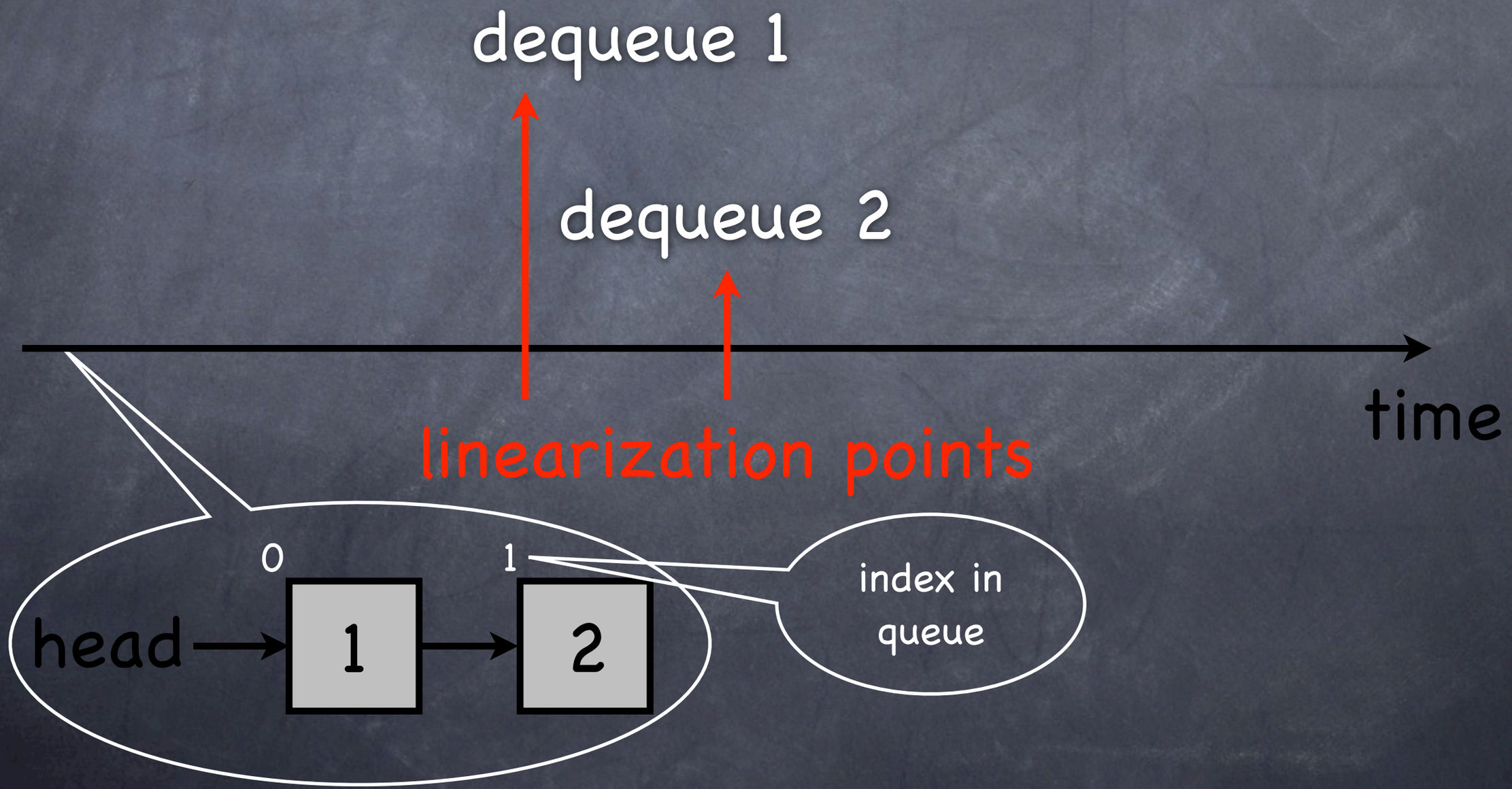

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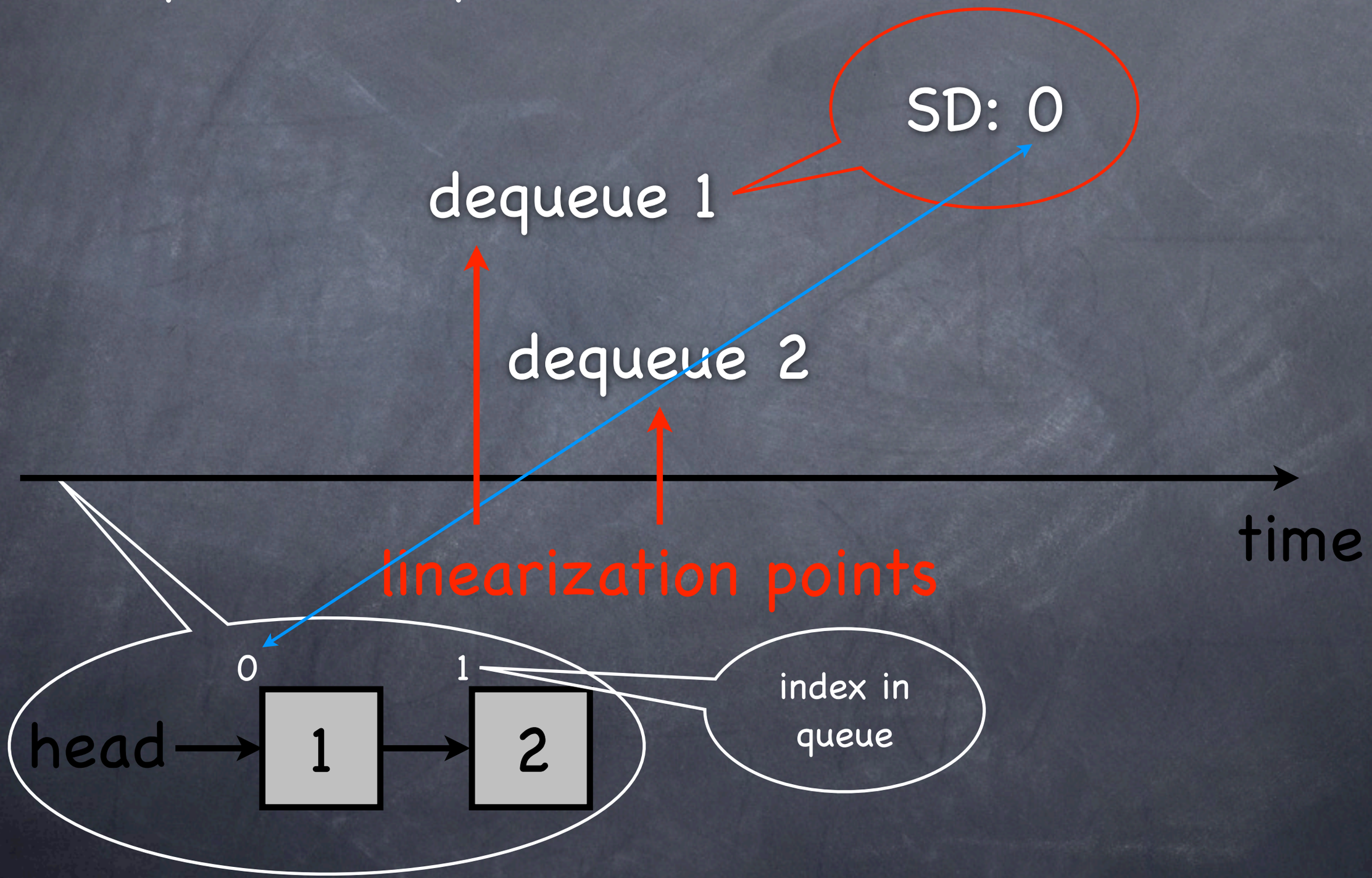

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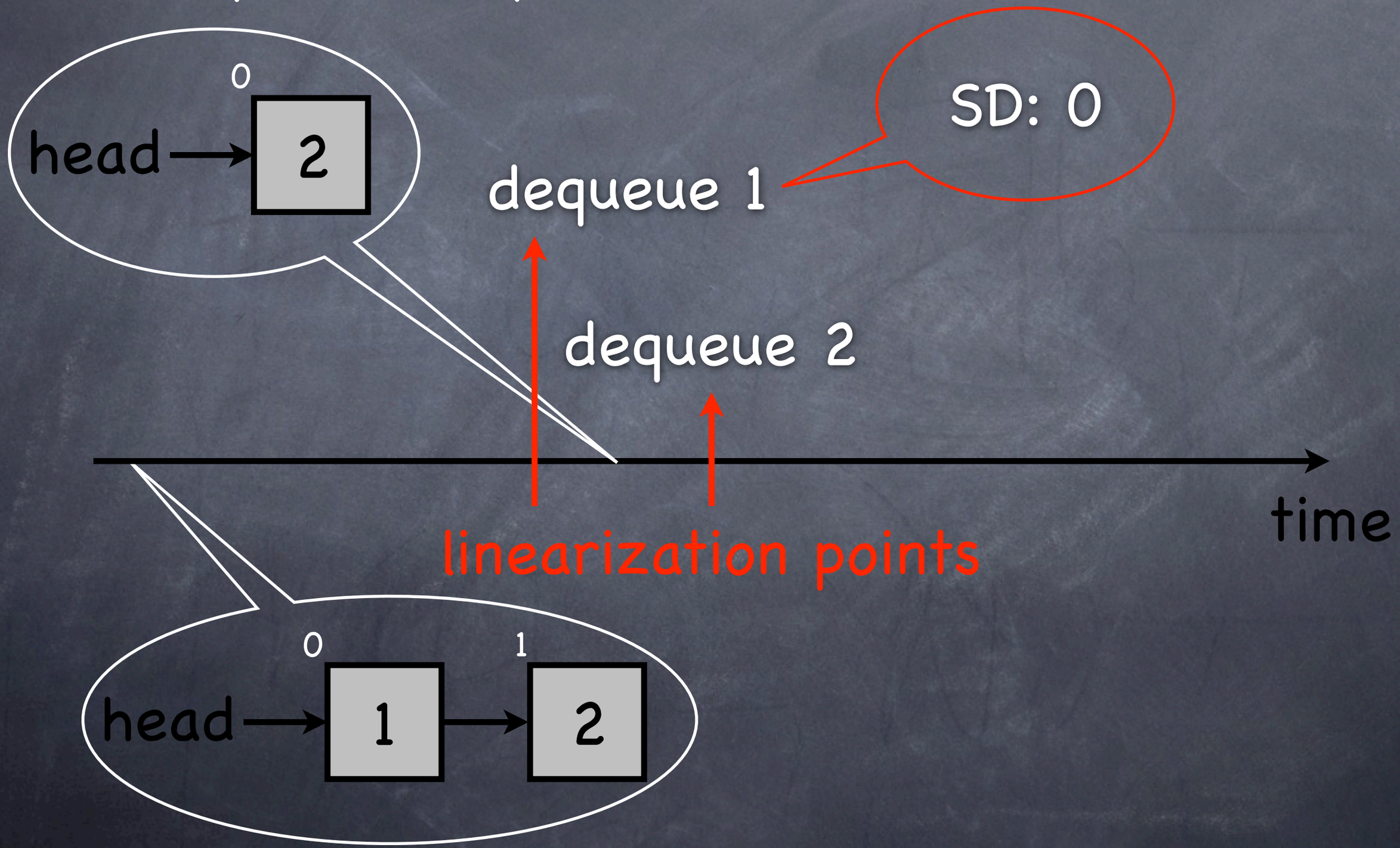

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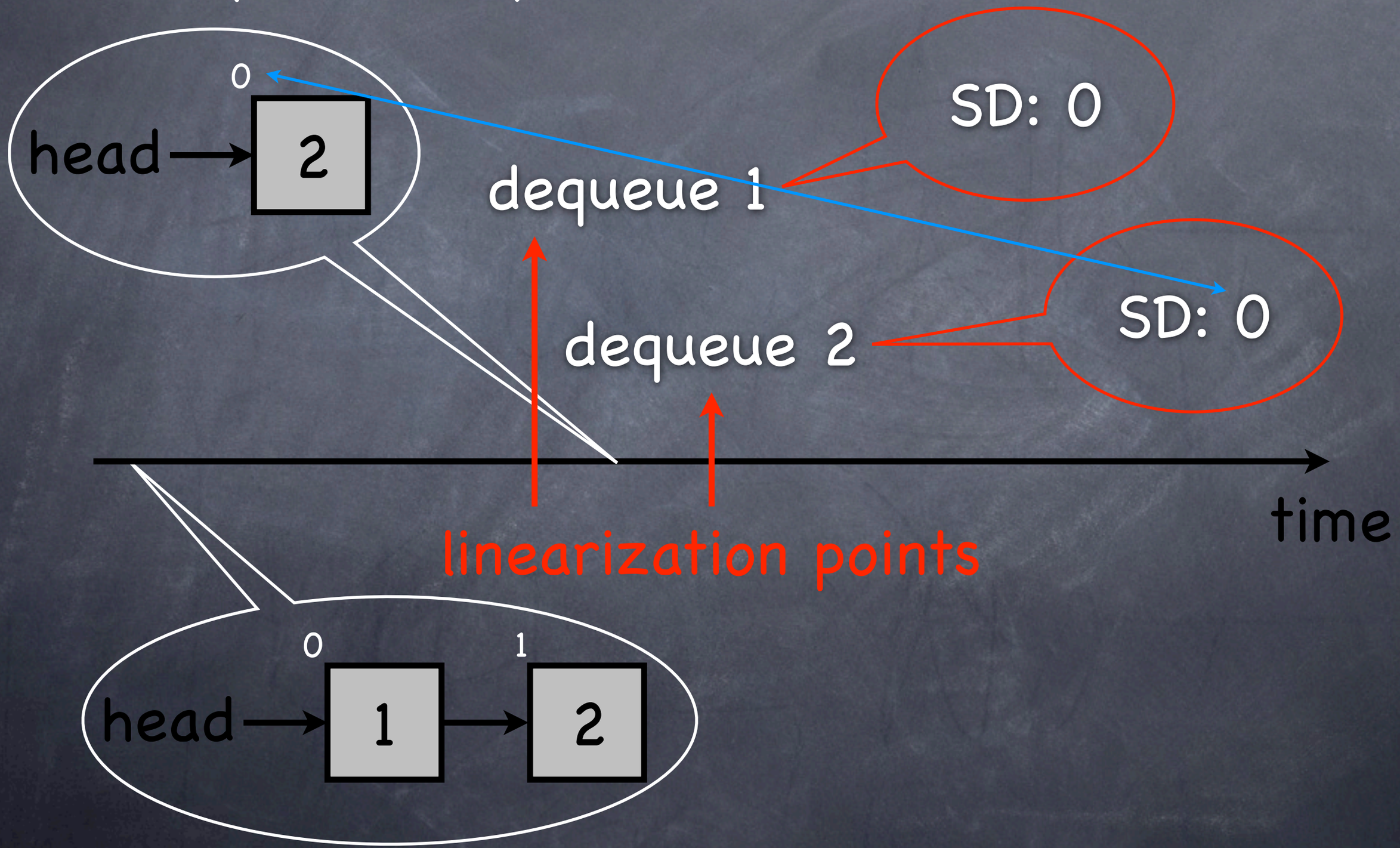

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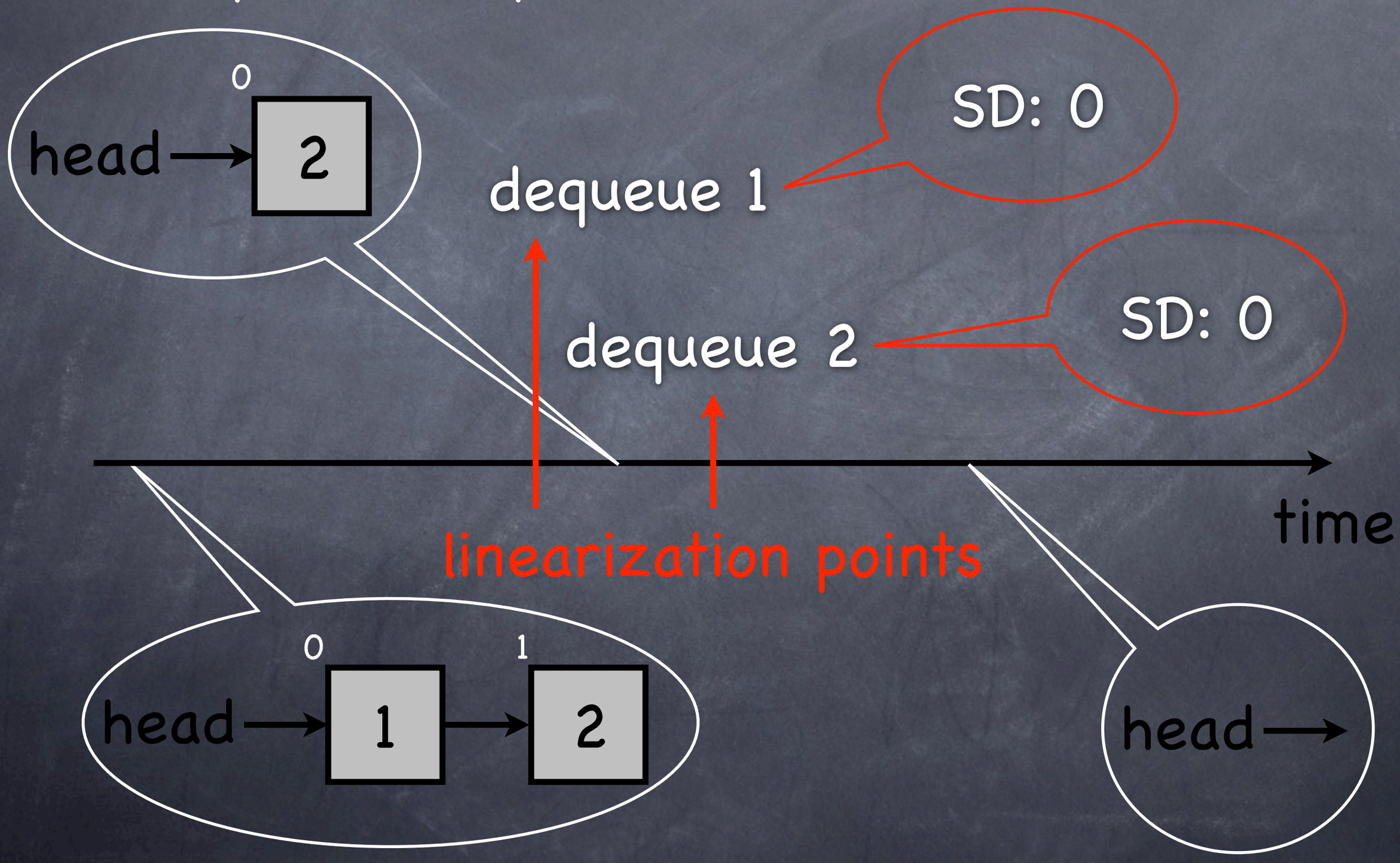
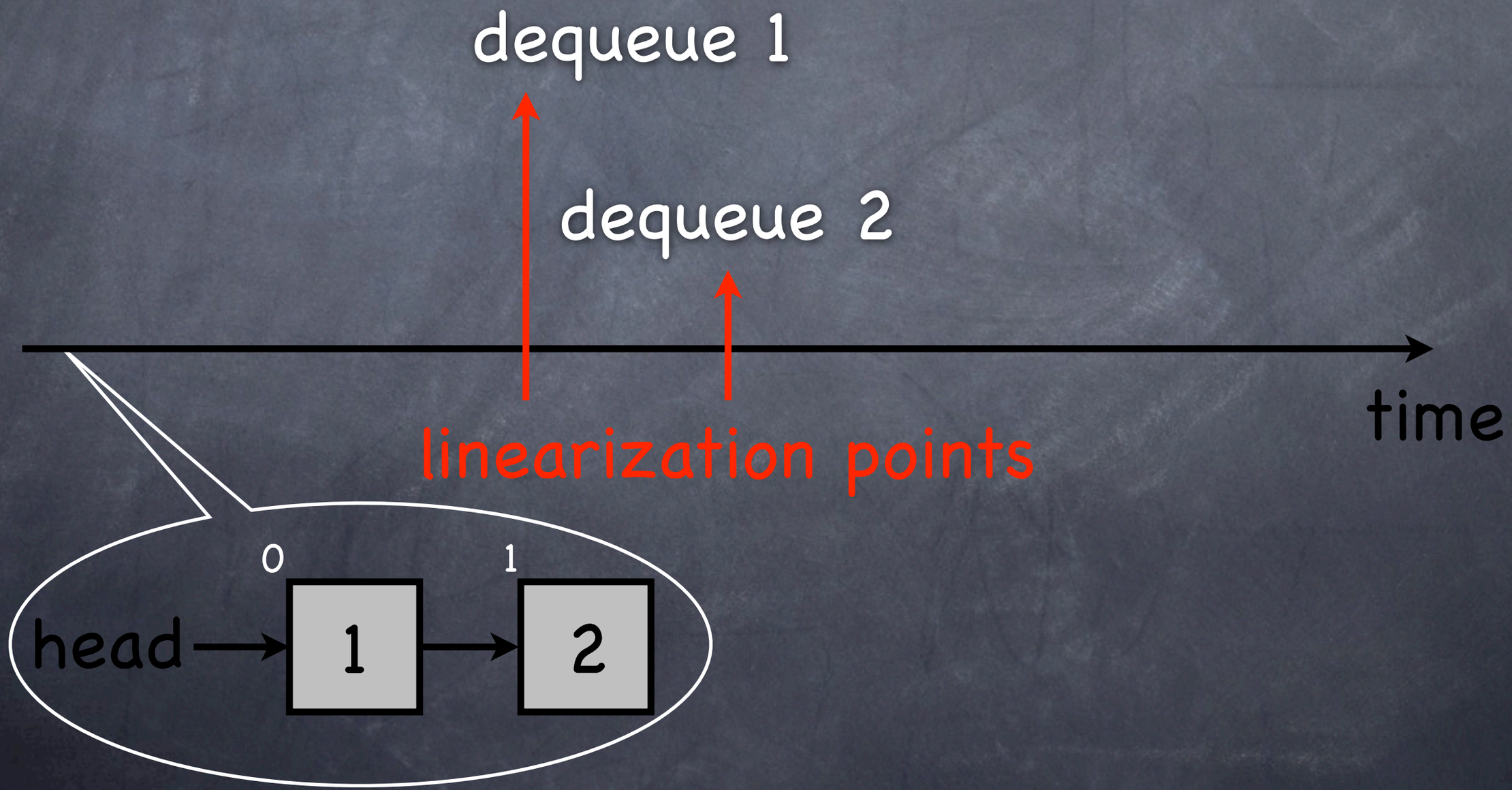
Sequence of Operations (Linearization Points)



Sequential History II

Sequence of Operations (Linearization Points)



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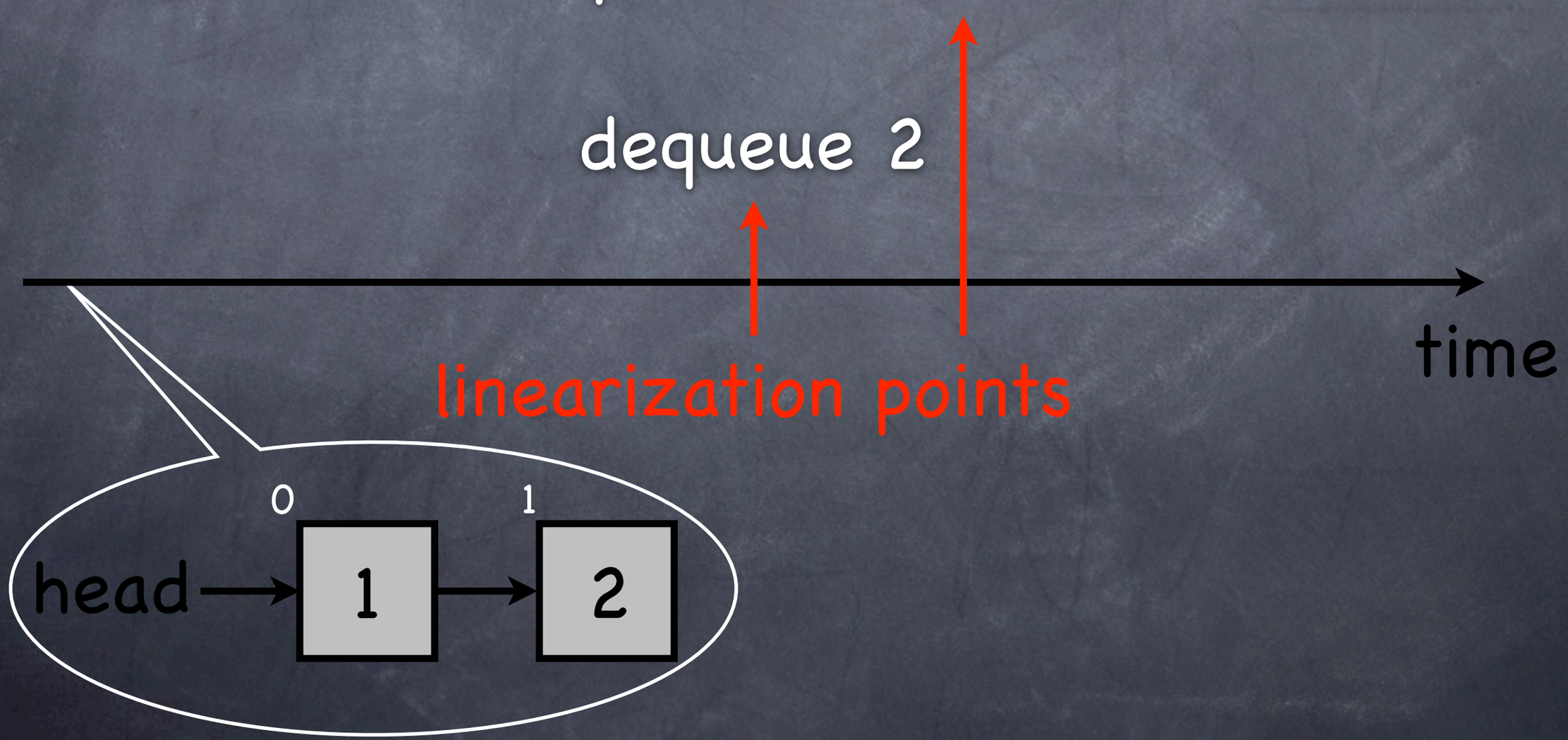
Sequence of Operations (Linearization Points)



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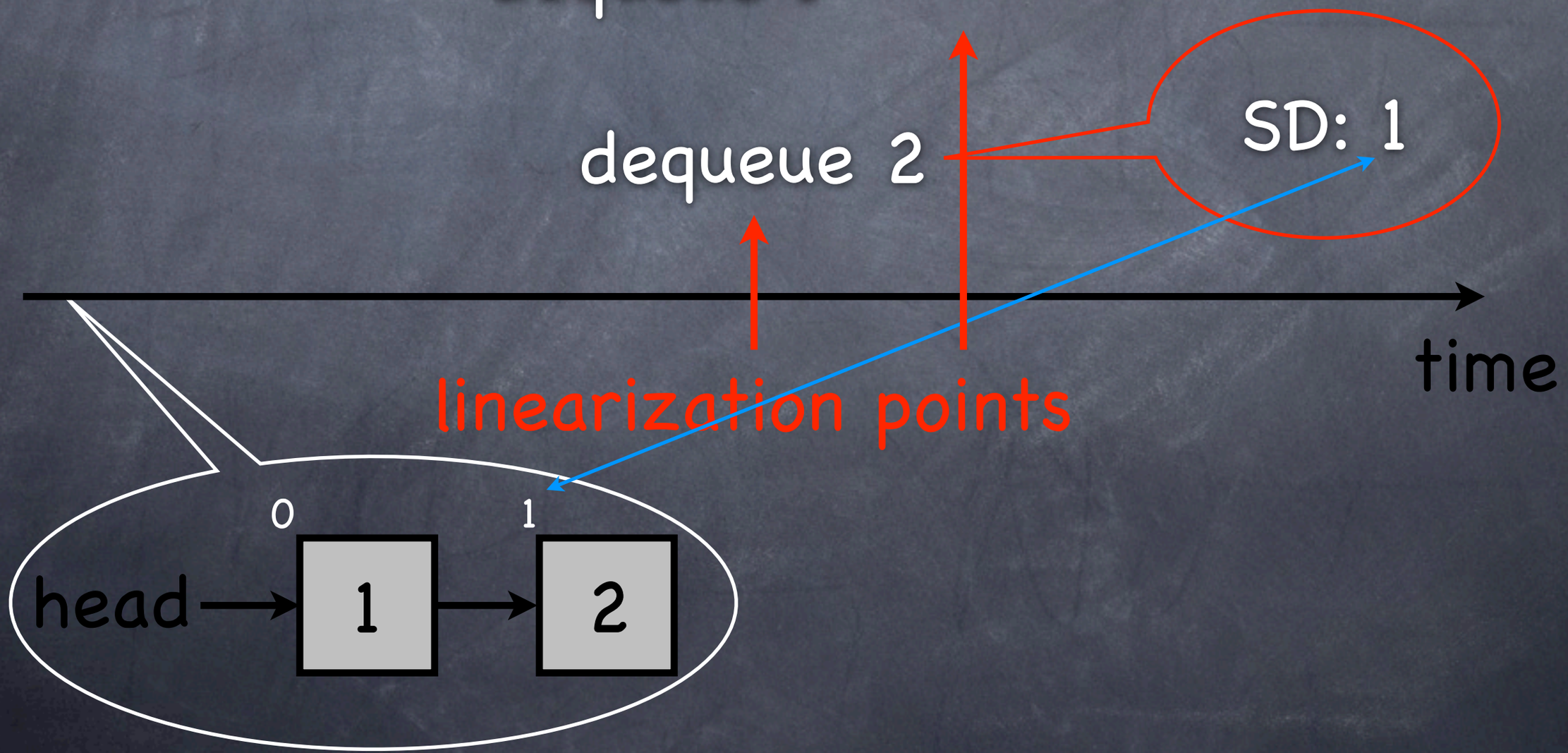

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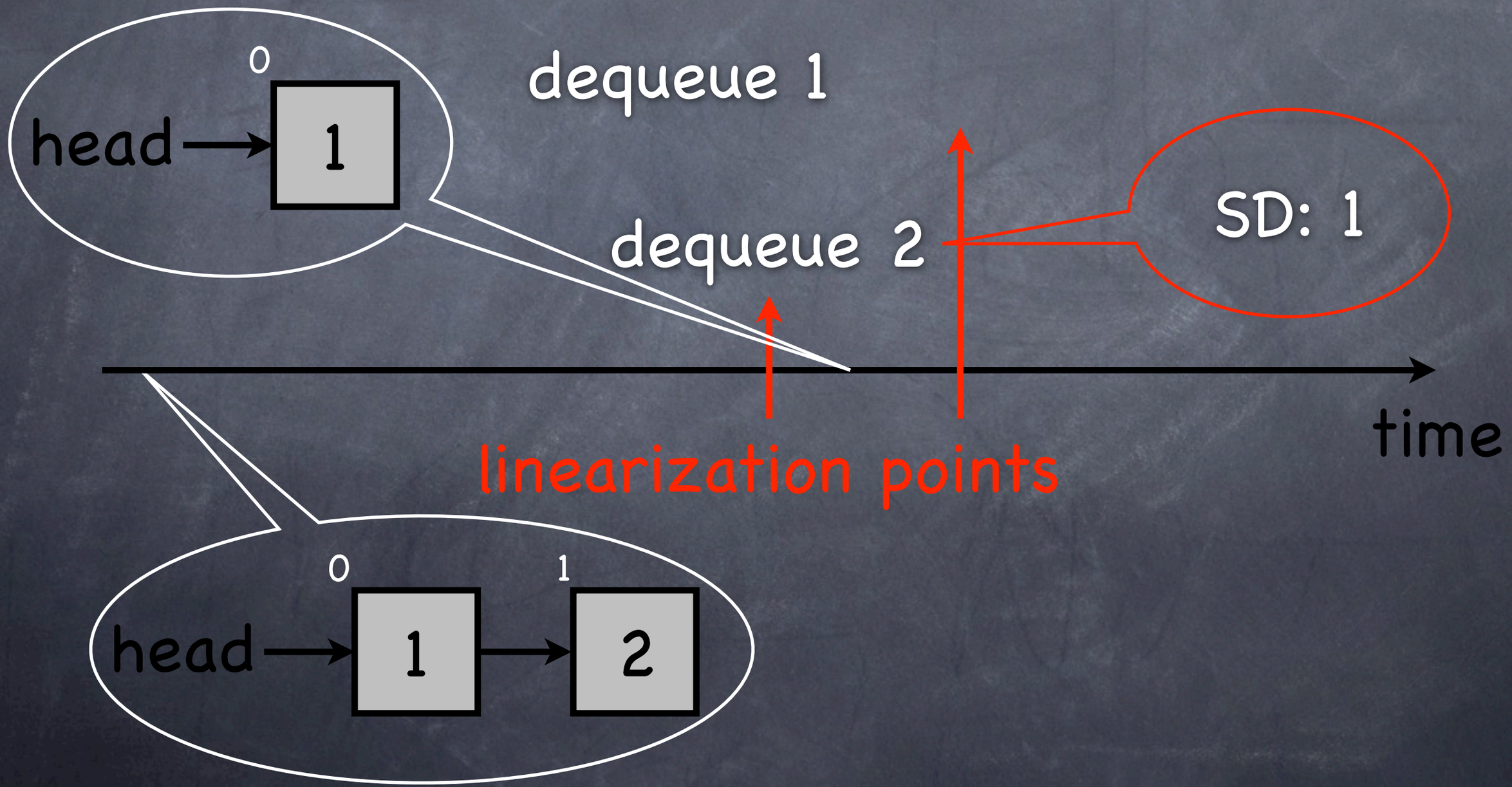

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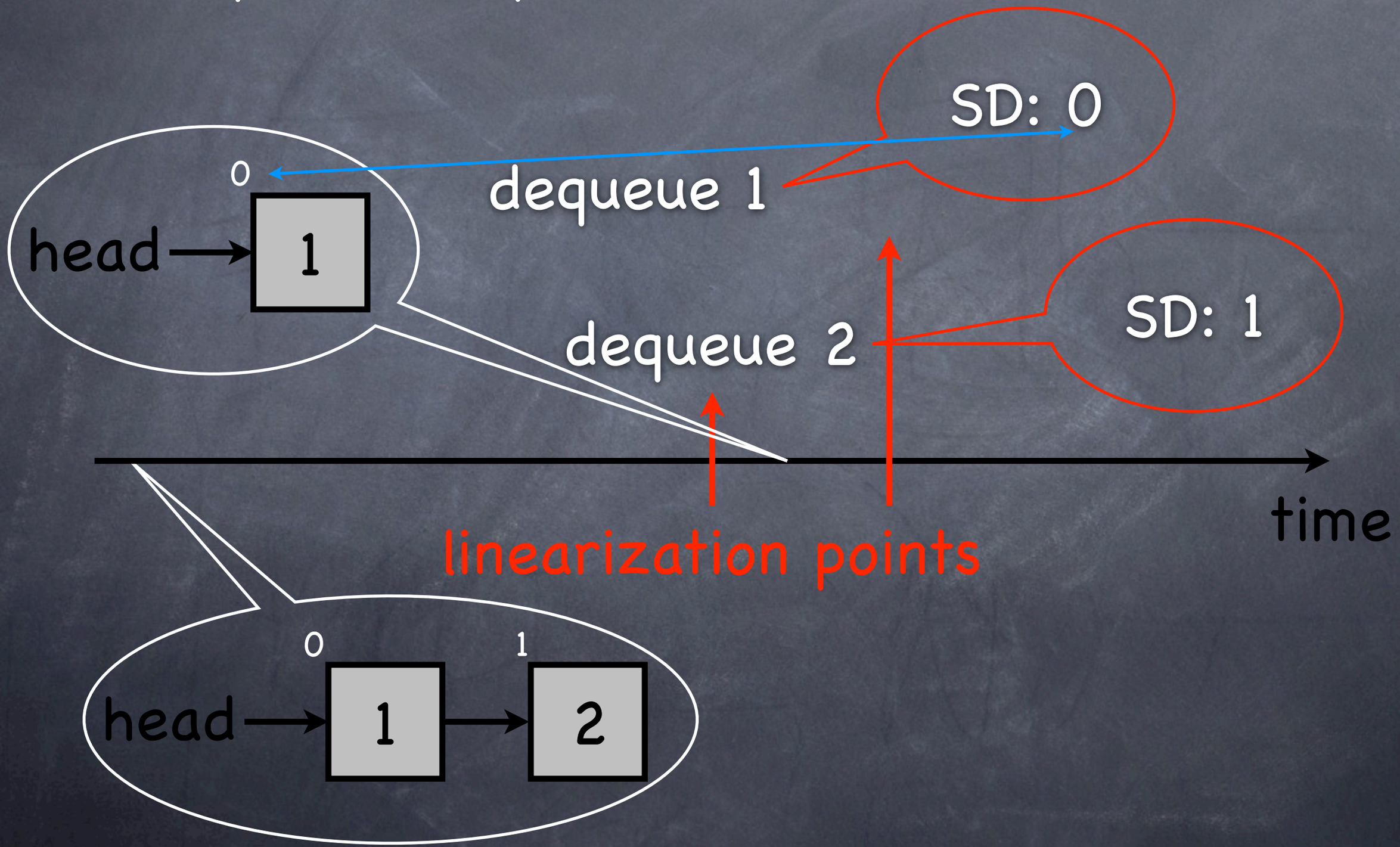
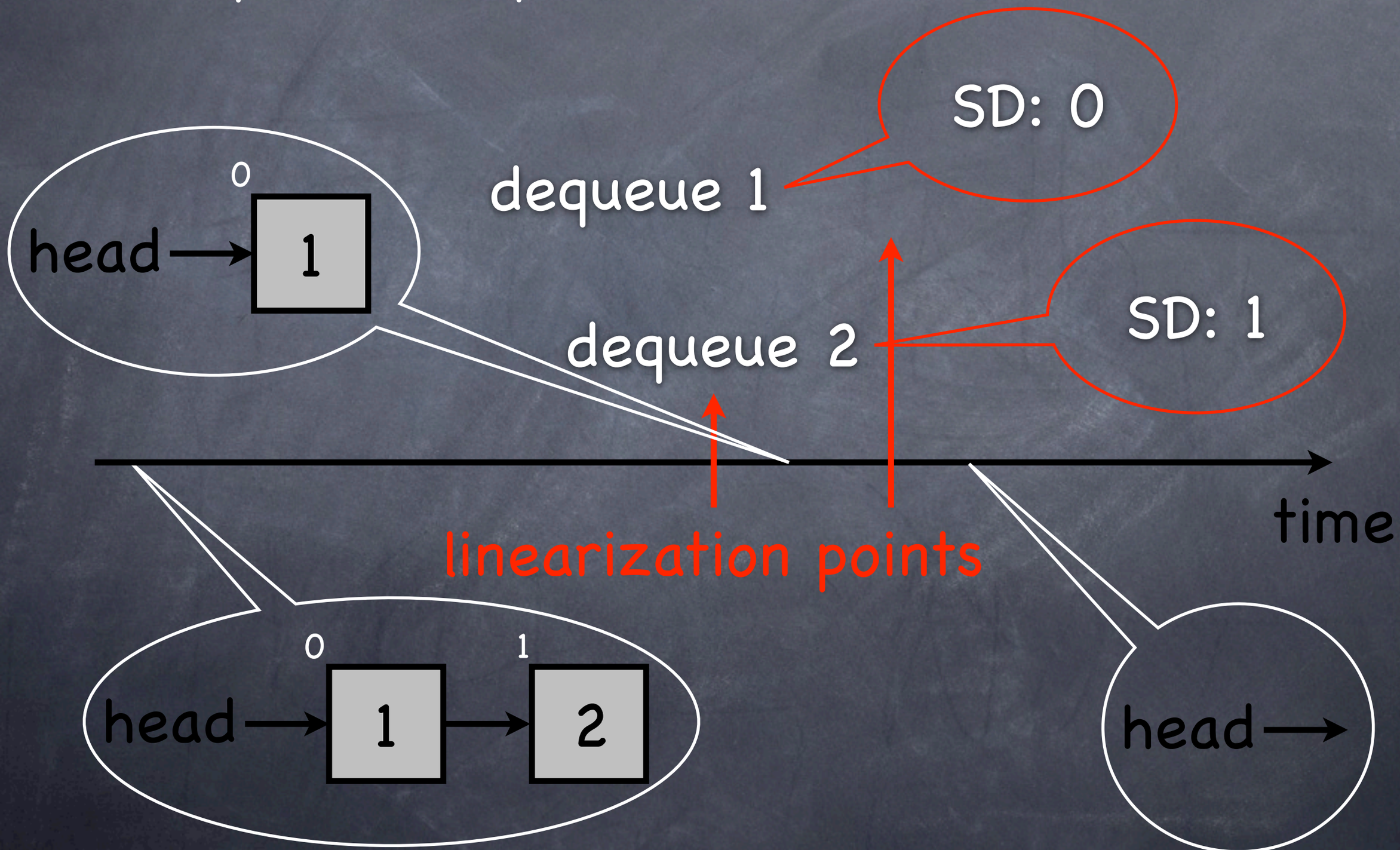


Sequential History II

Sequence of Operations (Linearization Points)



The semantical deviation (SD) of a sequential history is the maximum of the semantical deviations of all operations of that history

Actual Semantical Deviation (ASD)

- ASD is the semantical deviation of the (generally unknown) sequential history that *actually* took place

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Actual Semantical Deviation (ASD)

- ASD is the semantical deviation of the (generally unknown) sequential history that actually took place
- ASD denotes the semantical deviation of a k-FIFO queue implementation when applied to a given workload
- ASD can in general not be determined exactly, only approximated

ASD Analysis

First Attempt

1. Run a k-FIFO queue implementation on a given workload and obtain execution history

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Then: LSD ≤ ASD ≤ HSD

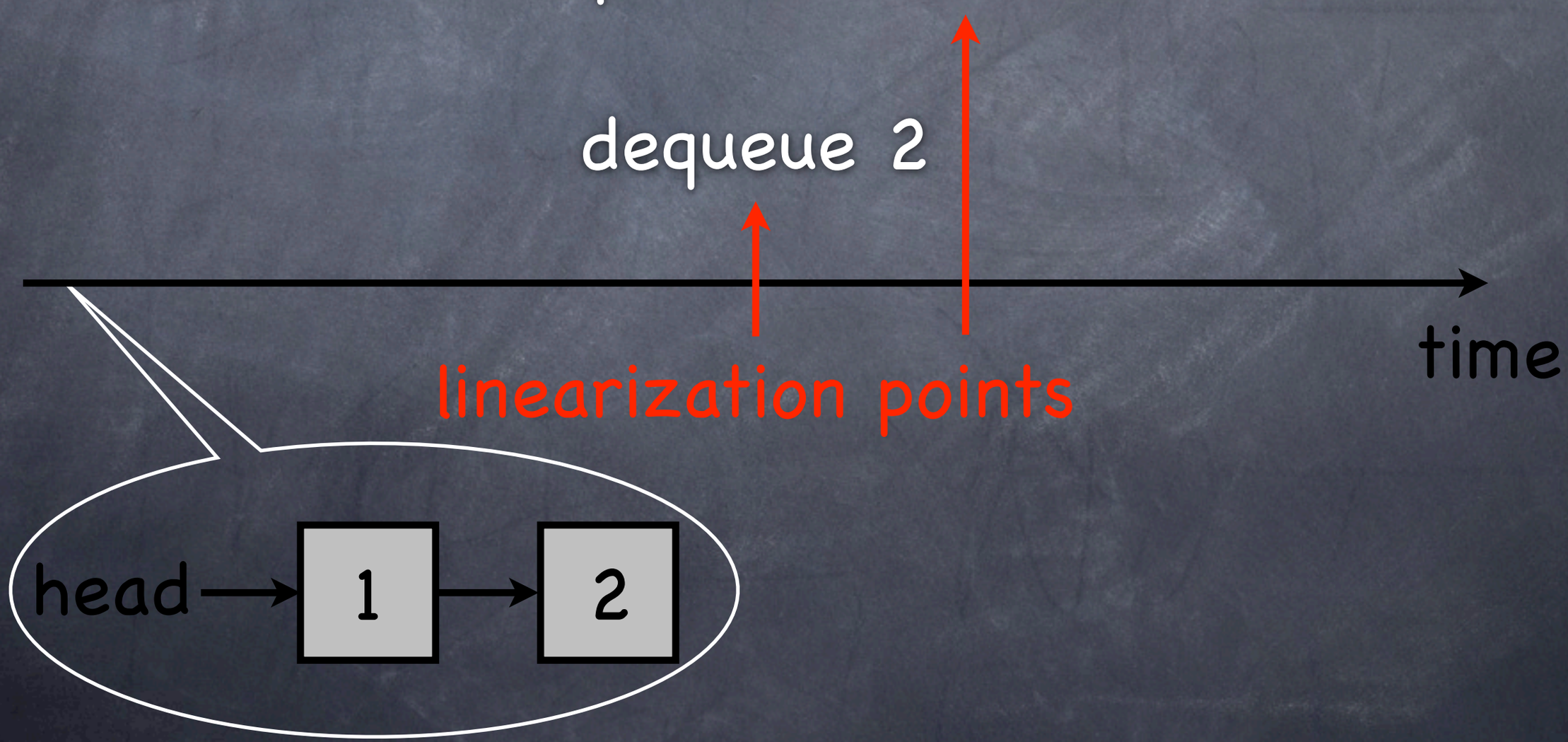
ASD Analysis

First Attempt

1. Run a k-FIFO queue implementation on a given workload and obtain execution history
2. Determine the sequential histories with the lowest (LSD) and the highest semantical deviation (HSD) among all sequential histories of the execution history

But: HSD ≤ WCSD may not hold

Invalid Sequential History (if k=0)



ASD Analysis

For small WCSD

1. Run a k-FIFO queue implementation on a given workload and obtain execution history
2. Determine the sequential histories with the lowest (LSD) and the highest semantical deviation (HSD) among all valid sequential histories of the execution history

ASD Analysis

For small WCSD

1. Run a k-FIFO queue implementation on a given workload and obtain execution history
2. Determine the sequential histories with the lowest (LSD) and the highest semantical deviation (HSD) among all valid sequential histories of the execution history

But what if WCSD is large or ∞ ?

ASD Analysis

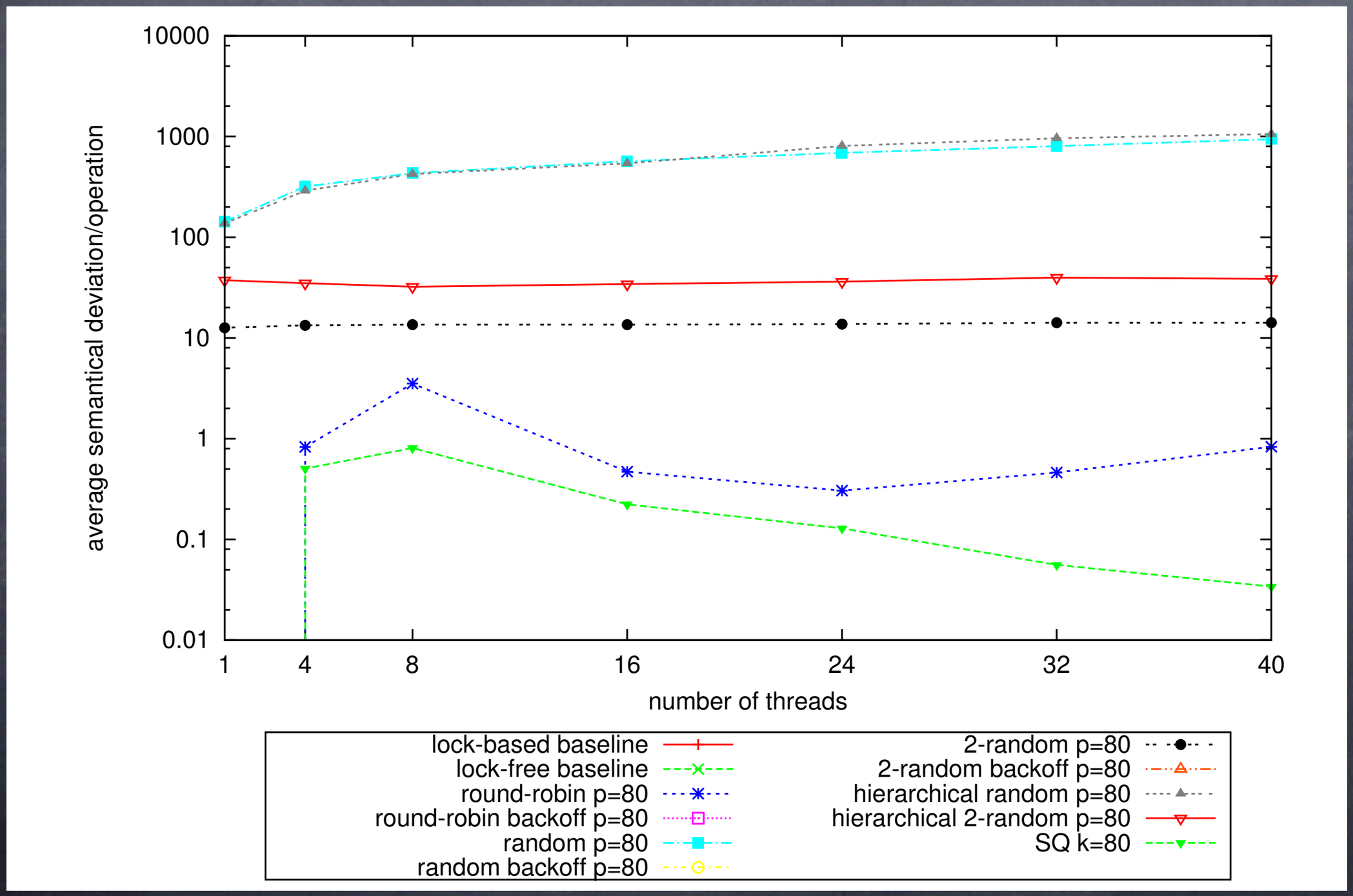
Current Version

1. Run a k-FIFO queue implementation on a given workload and obtain execution history

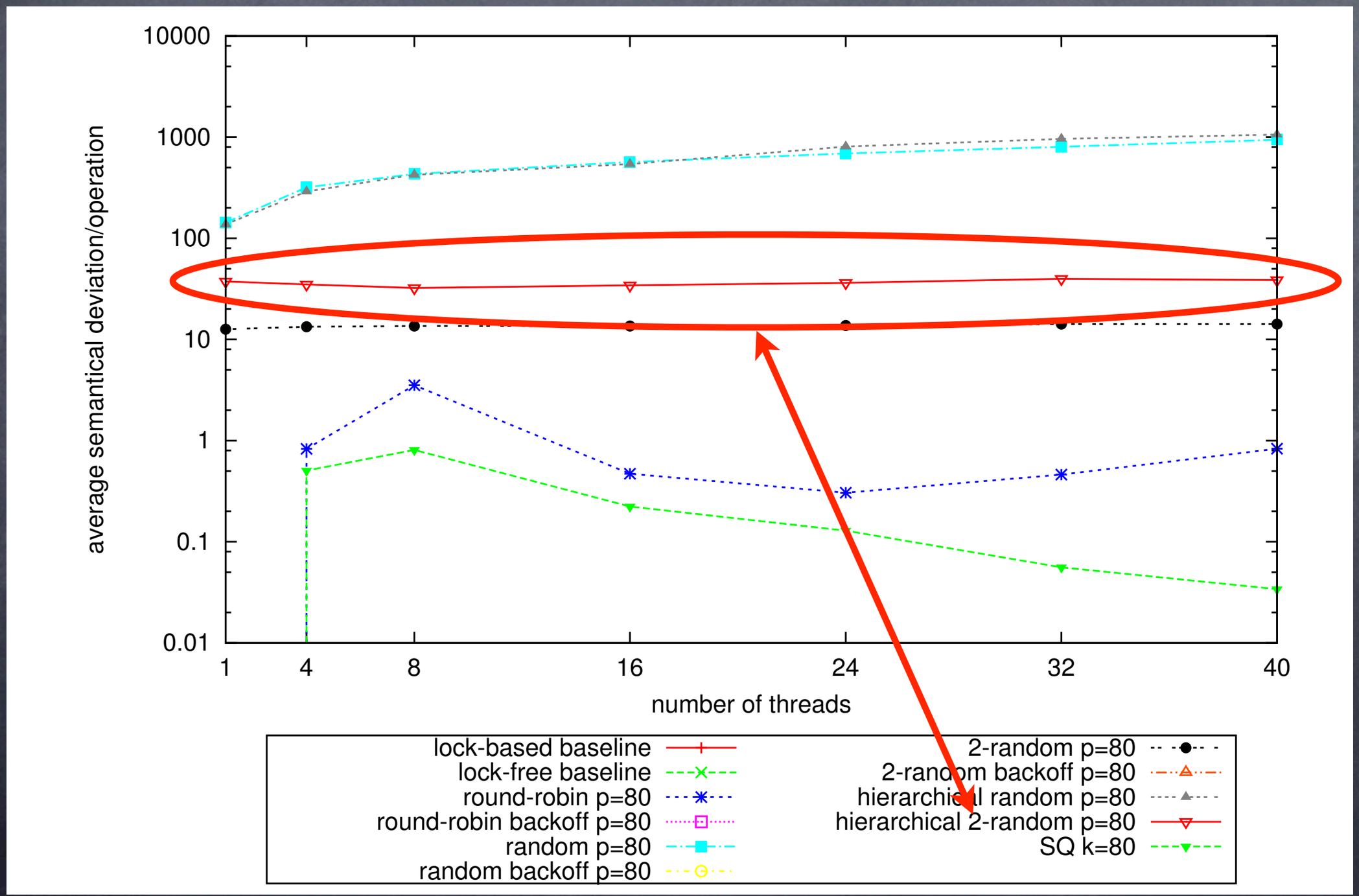
2. Determine the sequential history with the lowest semantical deviation (LSD) among all valid sequential histories of the execution history

3. Depict the average of the semantical deviation of the operations in that sequential history

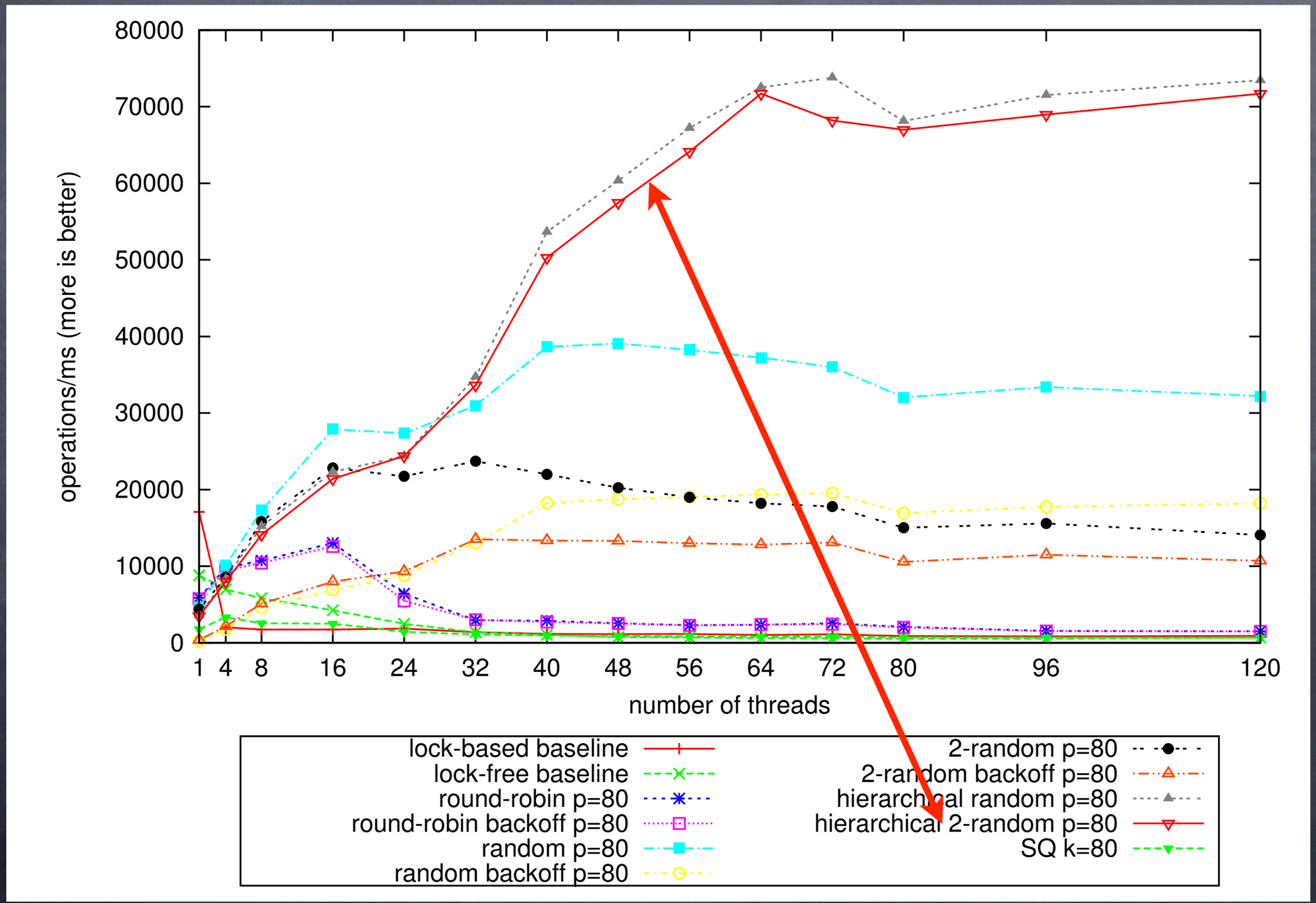
Average Semantical Deviation of LSD History



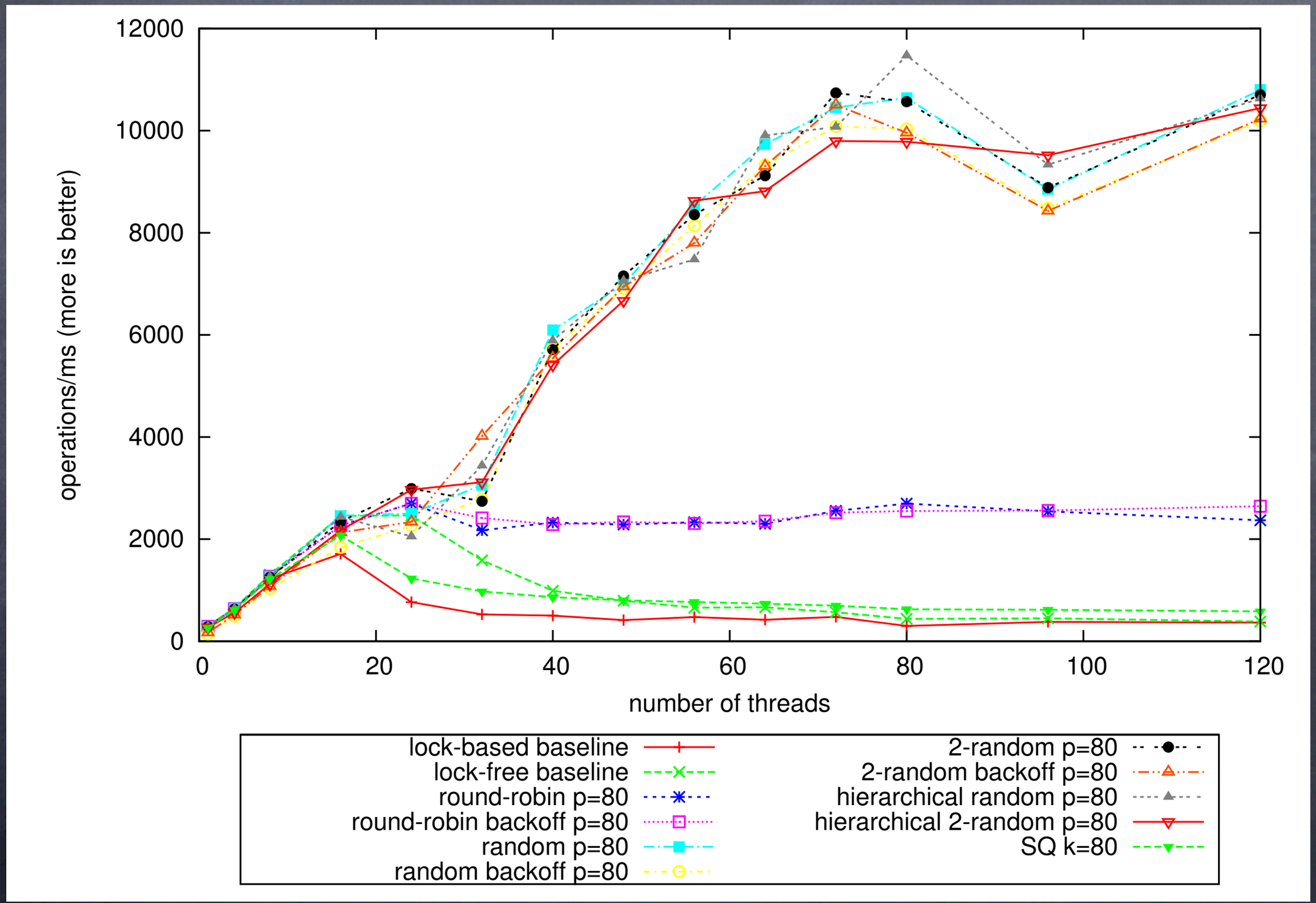
Best Trade-off



Hierarchical 2-Random



Low Contention



Performance-aware Programming

Future programming paradigms will need to incorporate performance as first-class concept!

But should we expose the machine architecture, in particular the memory hierarchy to the programmer?

Future Work

- Using k-FIFO queues in applications:
  - e.g. to construct concurrent and scalable real-time schedulers for multicore systems

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Future Work

- Using k-FIFO queues in applications:
  - e.g. to construct concurrent and scalable real-time schedulers for multicore systems
- Formally proving WCSD for given algorithms:
  - we have done this manually and informally
- Introducing WCSD to other data structures:
  - stacks, priority queues, hashtables, STM, ...

Thank you