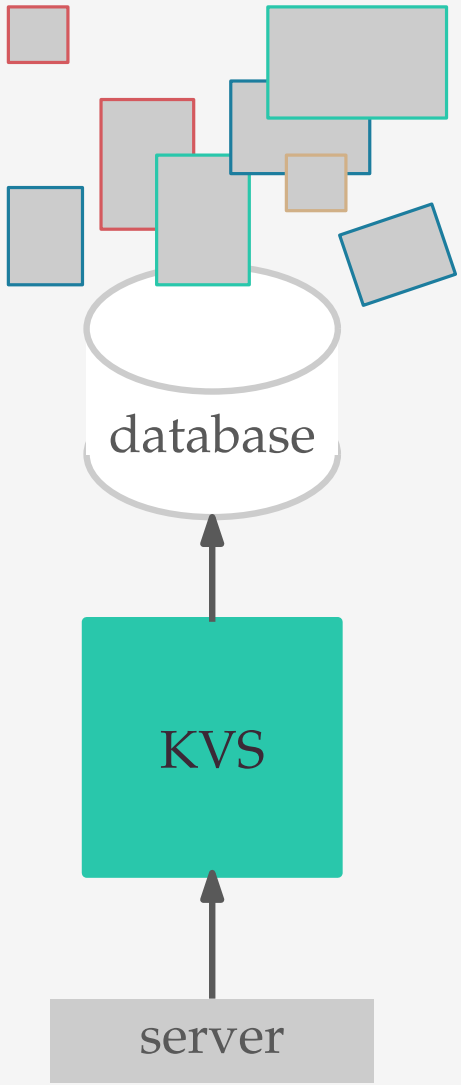
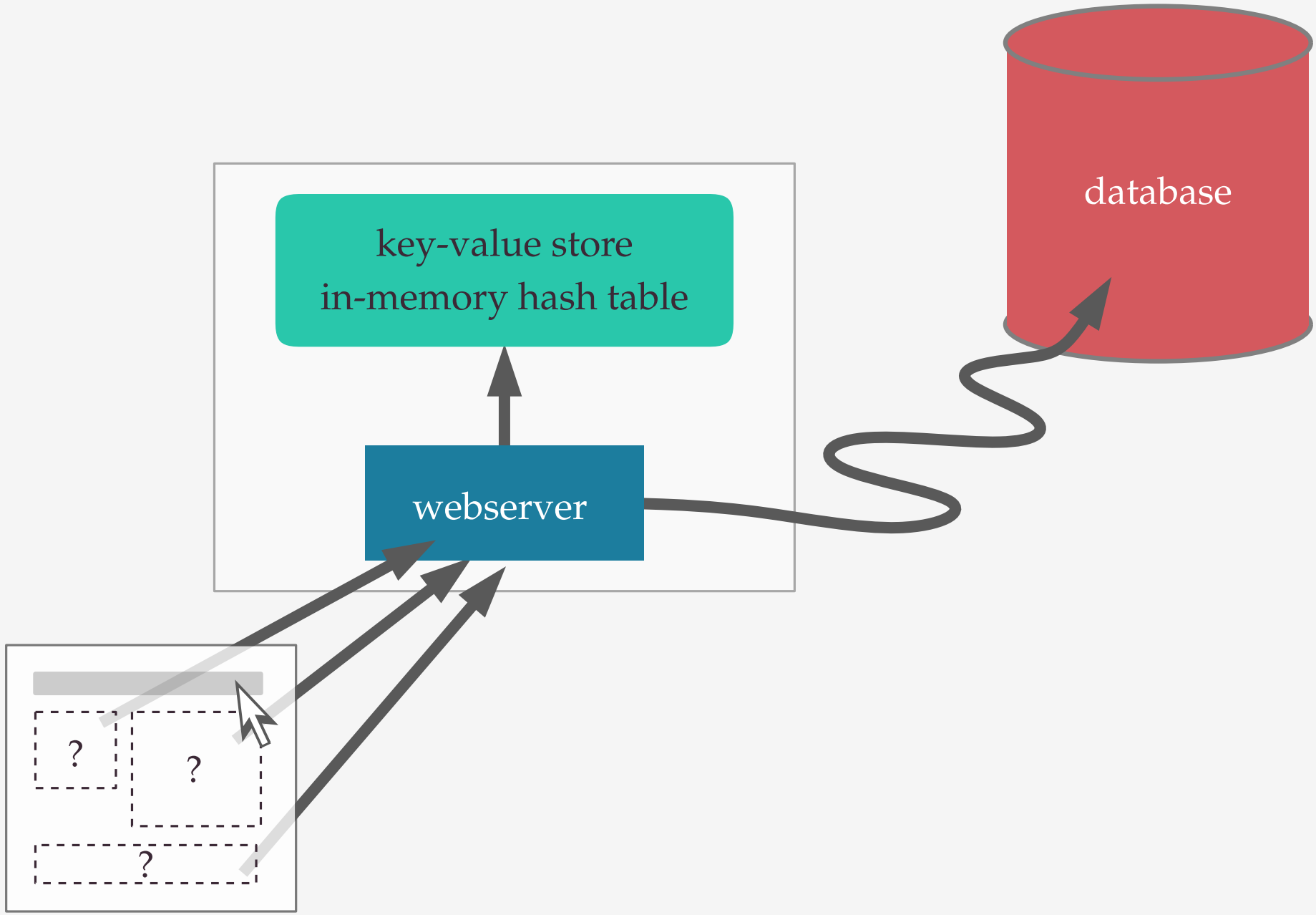
CACHE OPTIMIZATION FOR THE MODERN WEB

Jenny Lam

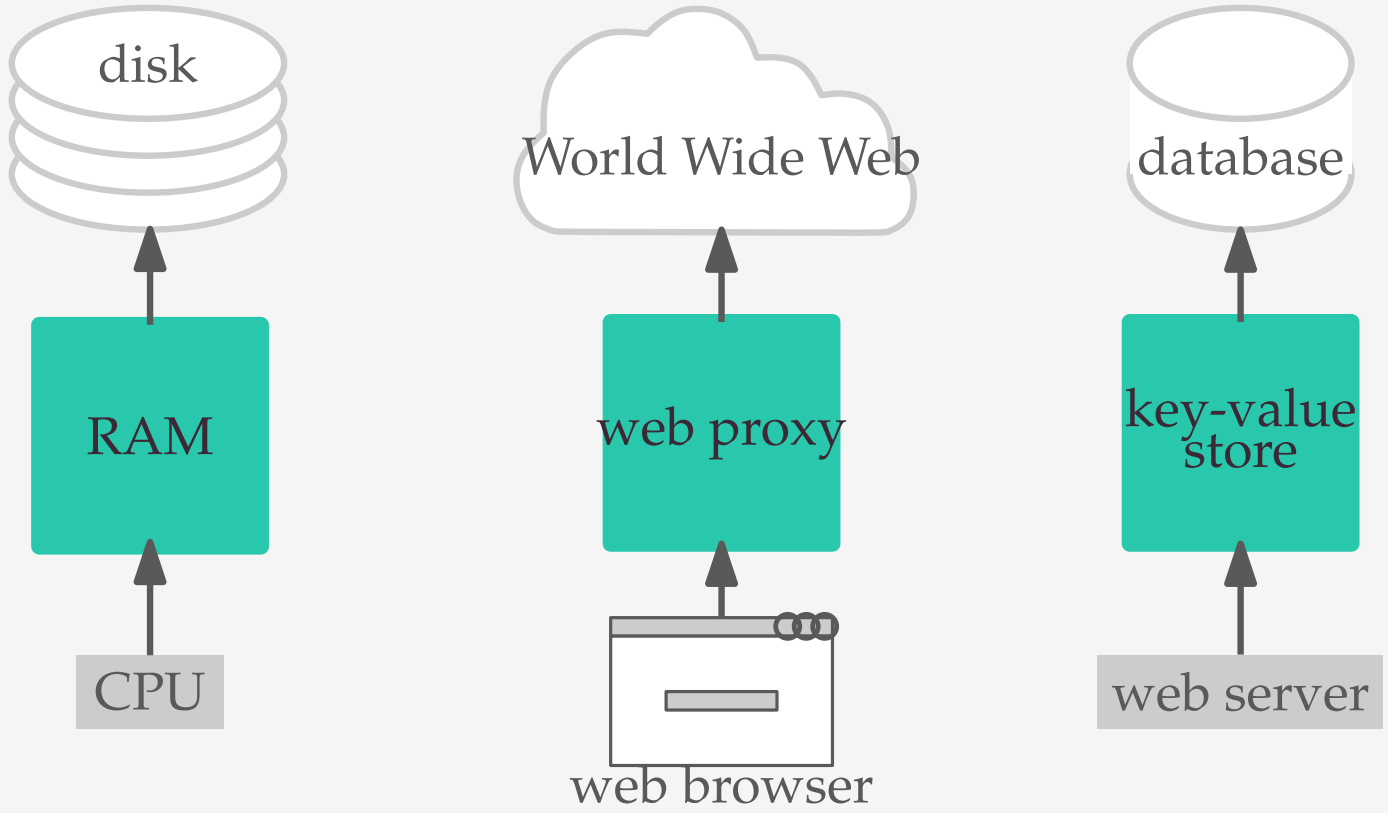


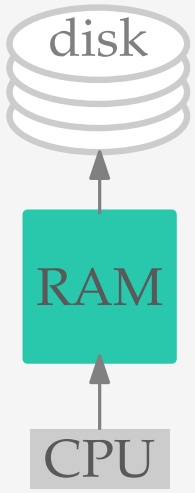
JOINT WORK WITH

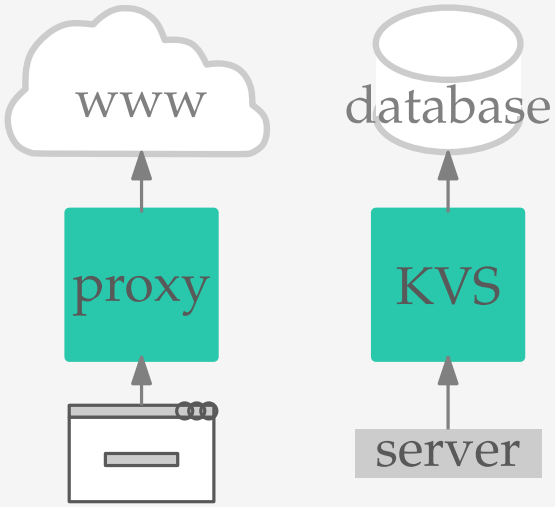
Shahram Ghandeharizadeh
Sandy Irani
Jason Yap

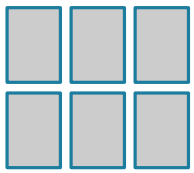


Scaling Memcache at Facebook, Nishtala et al., NSDI 2013.


disk
RAM
CPU
World Wide Web
web proxy
web browser
database
key-value store
web server



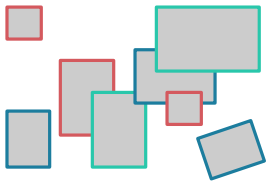




PAGING

minimize

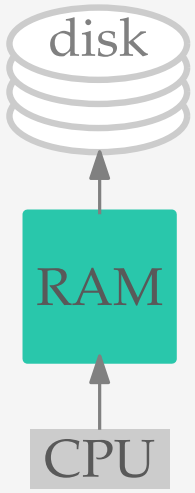
number of cache misses

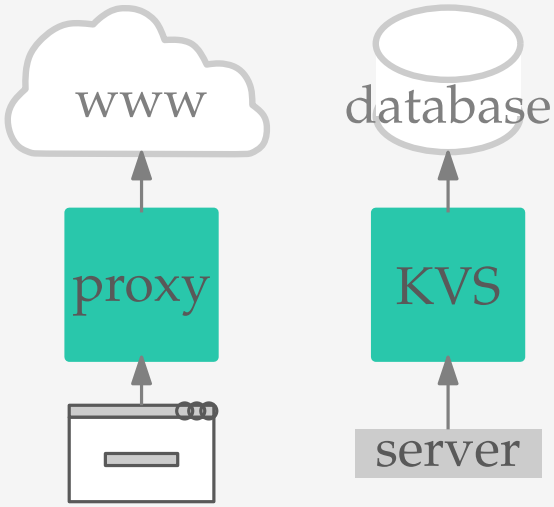


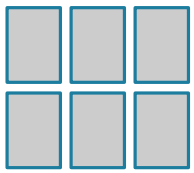
GENERALIZED CACHING

minimize

total cost of cache misses





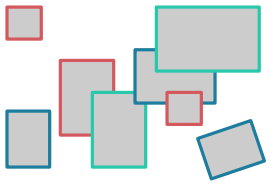


PAGING

minimize

number of cache misses

Least Recently Used (LRU)



GENERALIZED CACHING

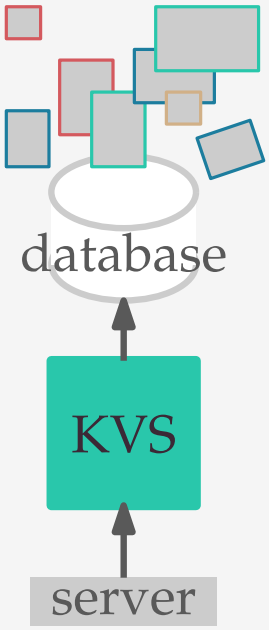
minimize

total cost of cache misses

GreedyDual-Size (GDS)

EVICTION POLICY

GDS → CAMP



PLACEMENT POLICY

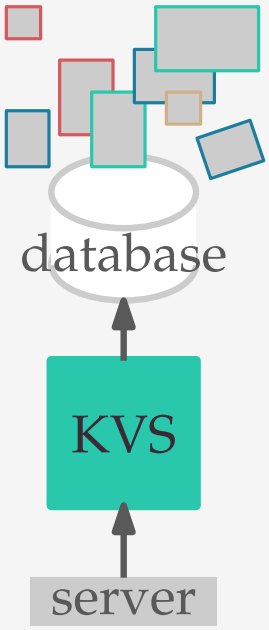
generalized caching → managed memory caching

MEMORY HIERARCHY

2-level cache → multi-level cache

EVICTION POLICY

GDS → CAMP



PLACEMENT POLICY

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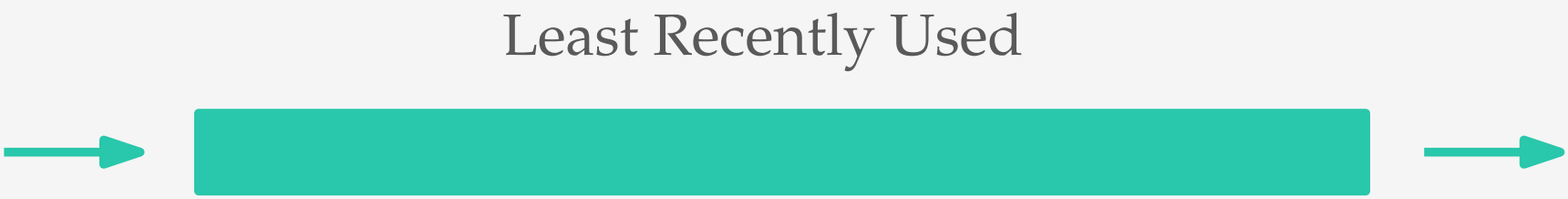
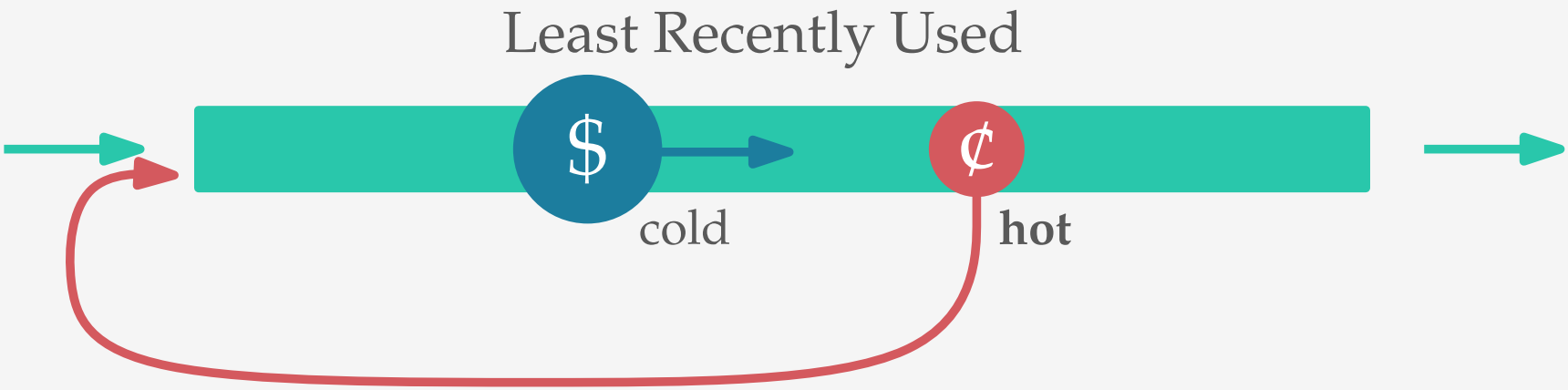
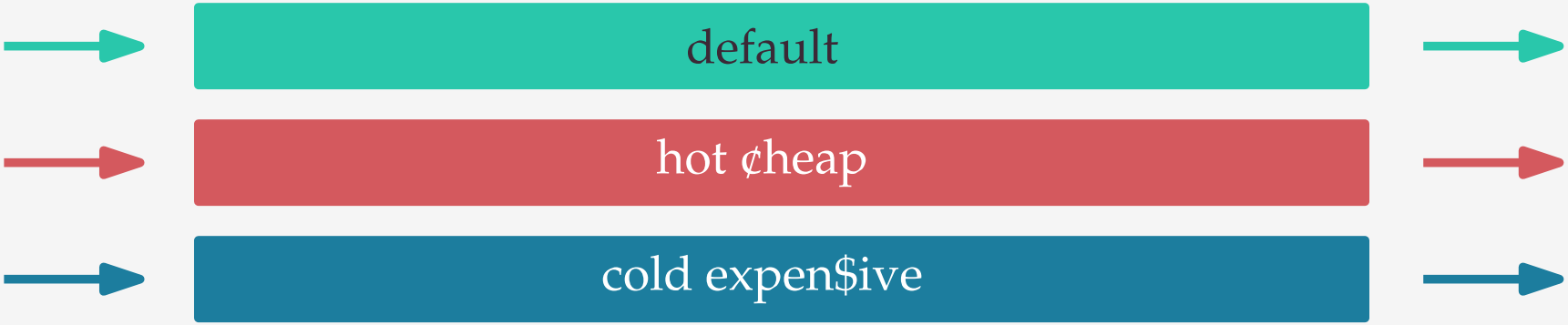

Least Recently Used

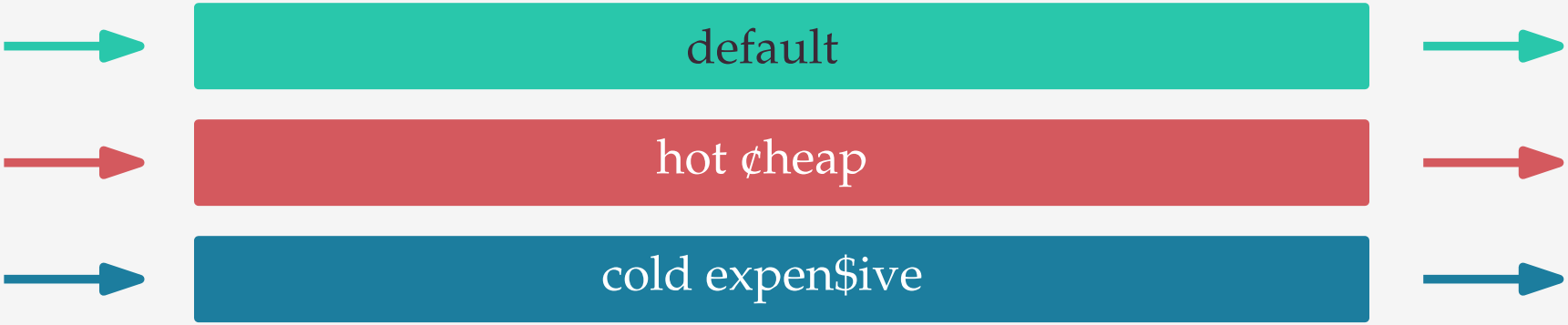

Least Recently Used
$
¢
cold
hot

pooled Least Recently Used



Scaling Memcache at Facebook, Nishtala et al., NSDI 2013.

pooled Least Recently Used



Scaling Memcache at Facebook, Nishtala et al., NSDI 2013.

need to take **recomputation cost** into consideration

GDS

p

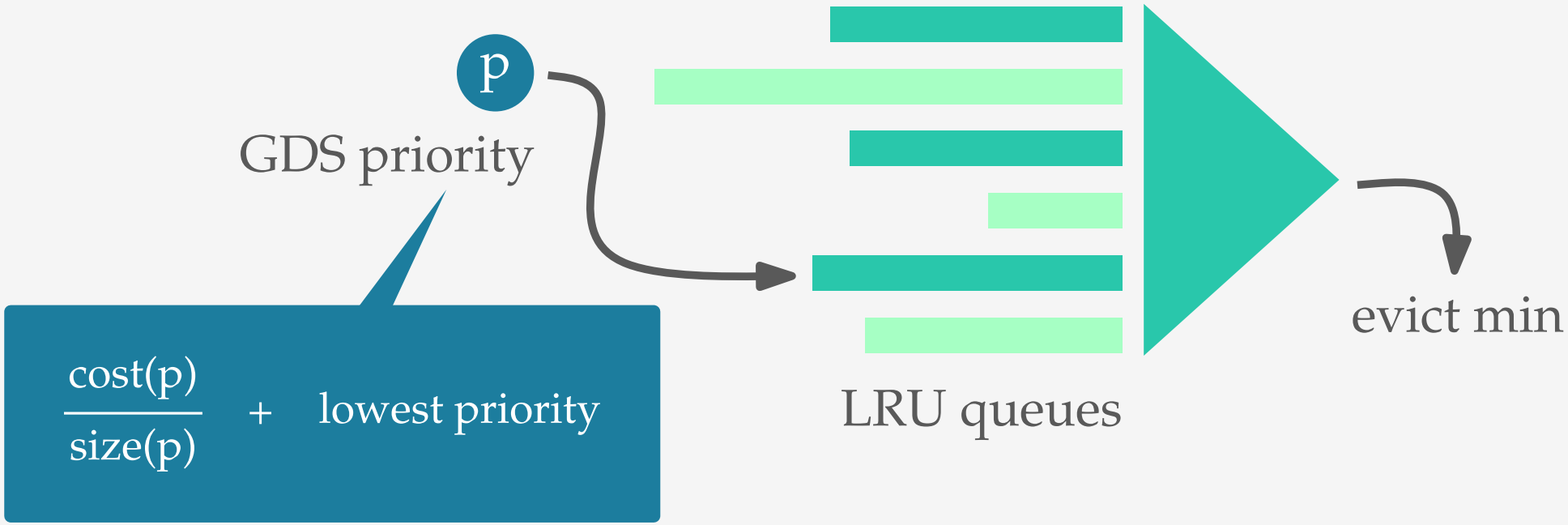
GDS priority

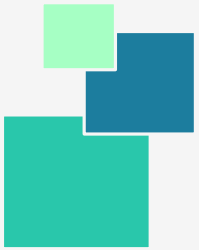
$$\frac{\text{cost(p)}}{\text{size(p)}} + \text{lowest priority}$$

priority queue

evict min

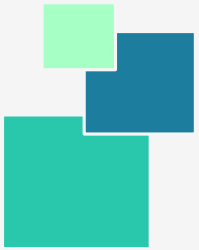
CAMP


p
GDS priority
cost(p)
size(p)
+
lowest priority
LRU queues
evict min

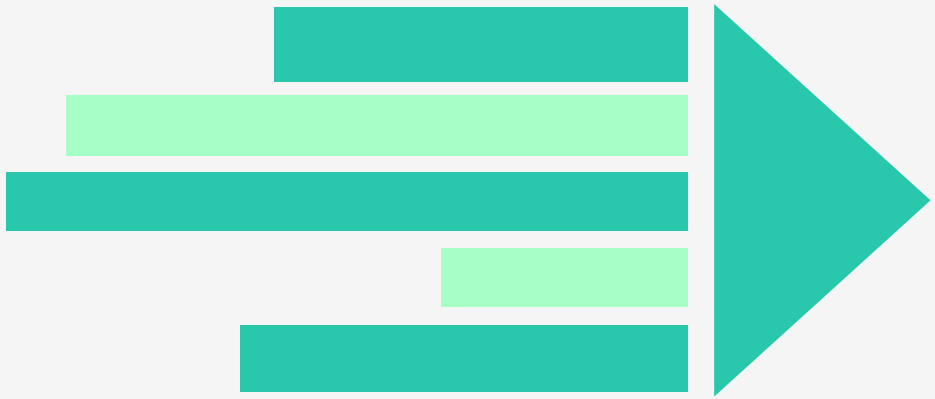


CAMP

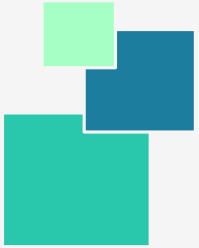
$$\text{round}\left(\frac{\text{cost(p)}}{\text{size(p)}}\right)$$



CAMP



$$\text{round}\left(\frac{\text{cost(p)}}{\text{size(p)}}\right)$$



CAMP

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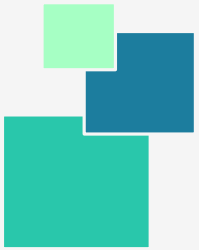


PERFORMANCE

log (#items) per update

cost(GDS) $\leq$ k cost(OPT)

log (#queues) per update

cost(CAMP) $\leq (1 + \varepsilon)$k cost(OPT)

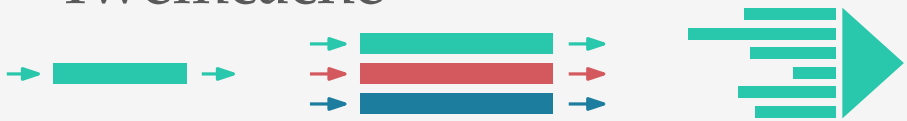
approximation parameter

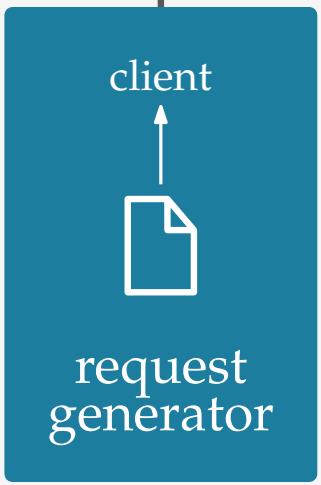
EXPERIMENTS

20,000 items

key-value store

Twemcache



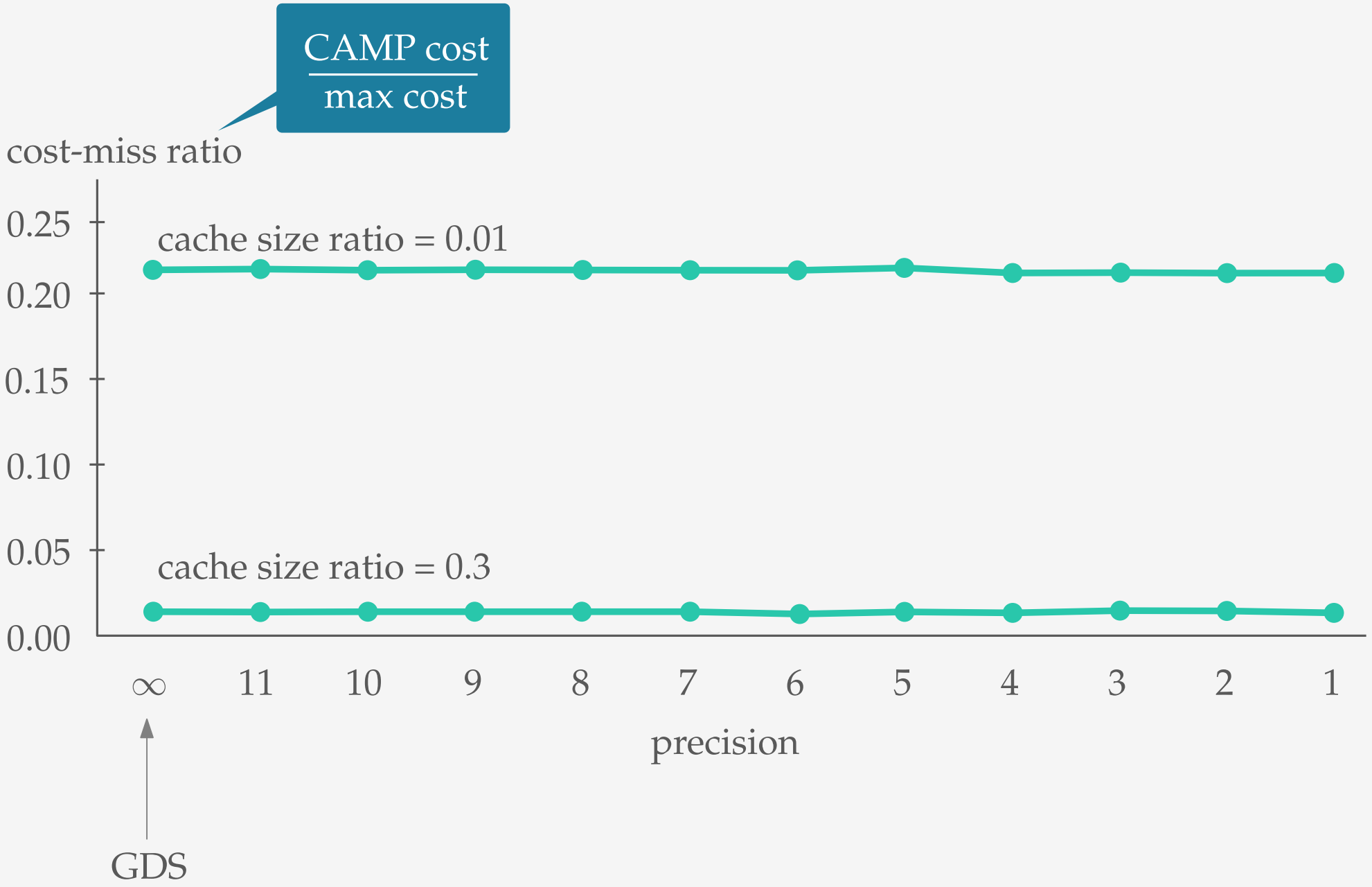


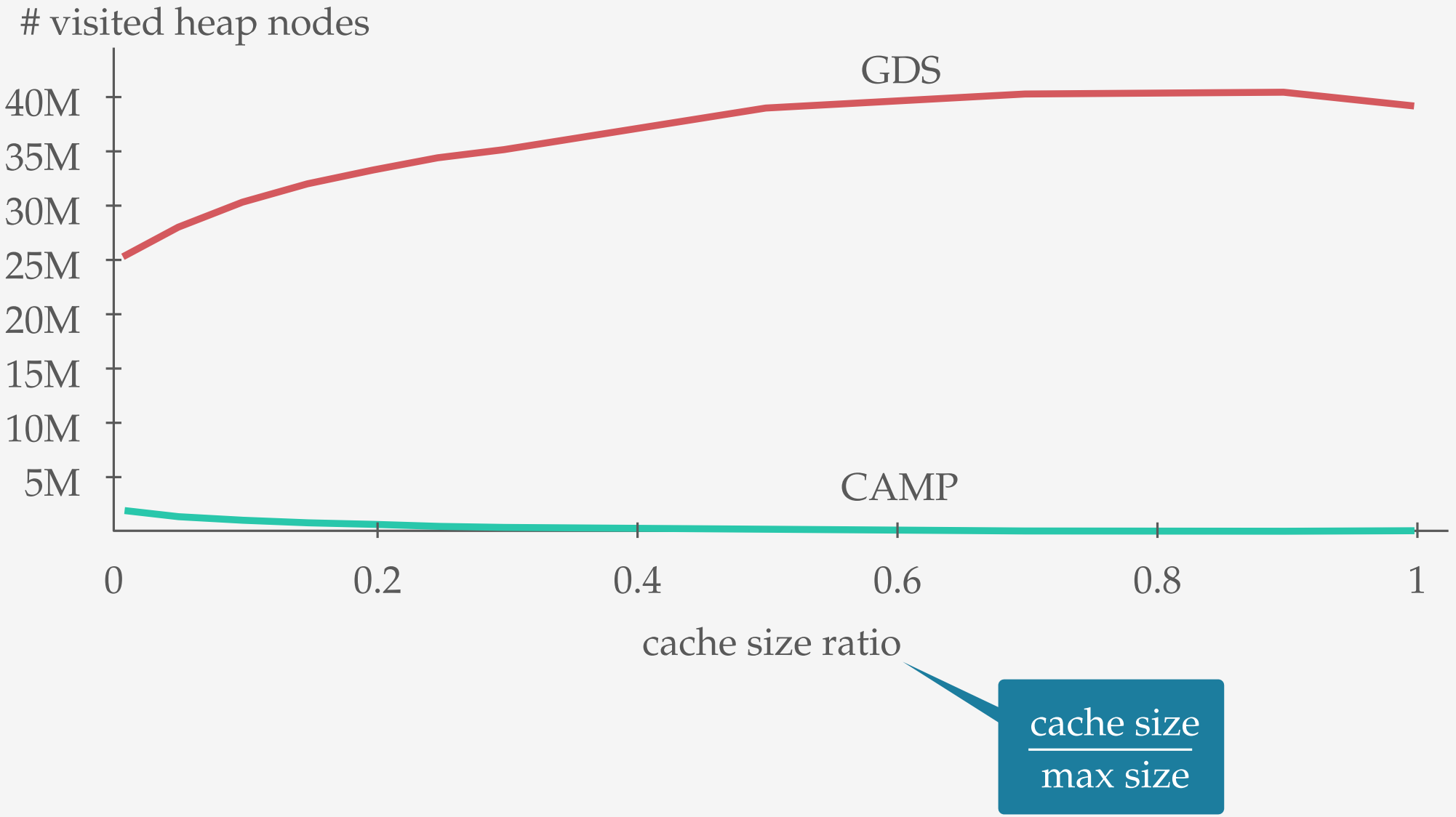
Whalin client for memcached

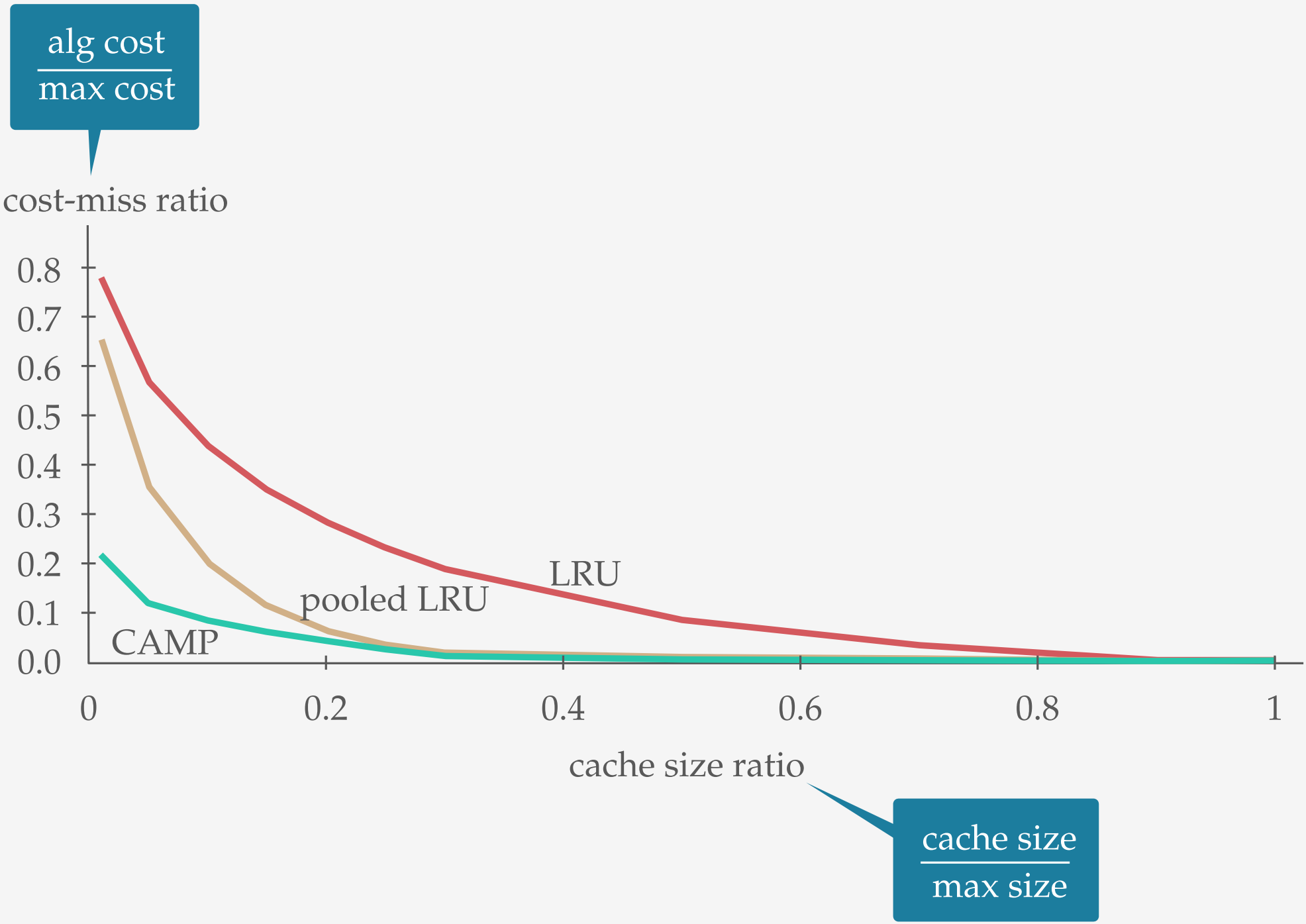
BG social networking benchmark

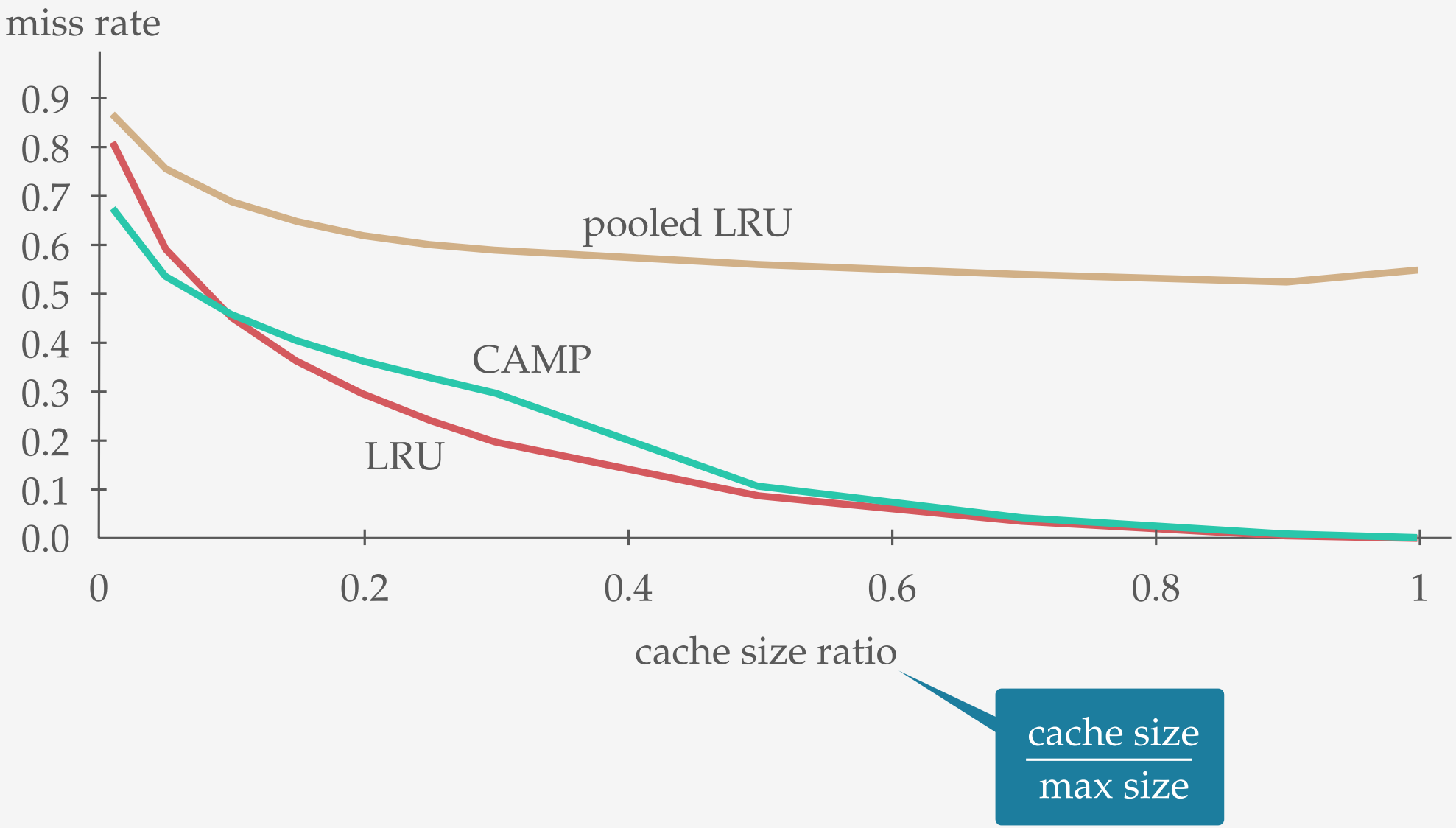
4 million requests

i.i.d. with 70% of requests to 20% of items


CAMP cost
max cost
cost-miss ratio
0.25
0.20
0.15
0.10
0.05
0.00
cache size ratio = 0.01
cache size ratio = 0.3
∞
11
10
9
8
7
6
5
4
3
2
1
precision
GDS

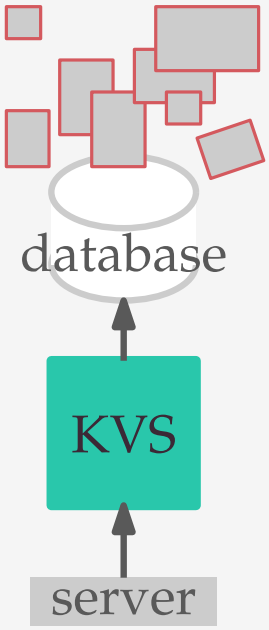

visited heap nodes
40M
35M
30M
25M
20M
15M
10M
5M
GDS
CAMP
0
0.2
0.4
0.6
0.8
1
cache size ratio
cache size
max size


alg cost
max cost
cost-miss ratio
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
LRU
pooled LRU
CAMP
0
0.2
0.4
0.6
0.8
1
cache size ratio
cache size
max size


miss rate
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
pooled LRU
CAMP
LRU
0
0.2
0.4
0.6
0.8
1
cache size ratio
cache size
max size

EVICTION POLICY

GDS ⟶ CAMP



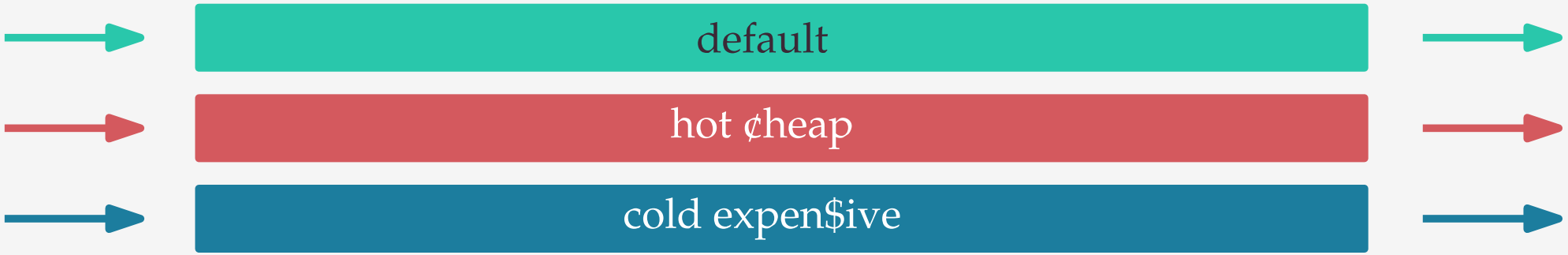
PLACEMENT POLICY

generalized caching ⟶ managed memory caching

MEMORY HIERARCHY

2-level cache ⟶ multi-level cache

pooled Least Recently Used



Scaling Memcache at Facebook, Nishtala et al., NSDI 2013.

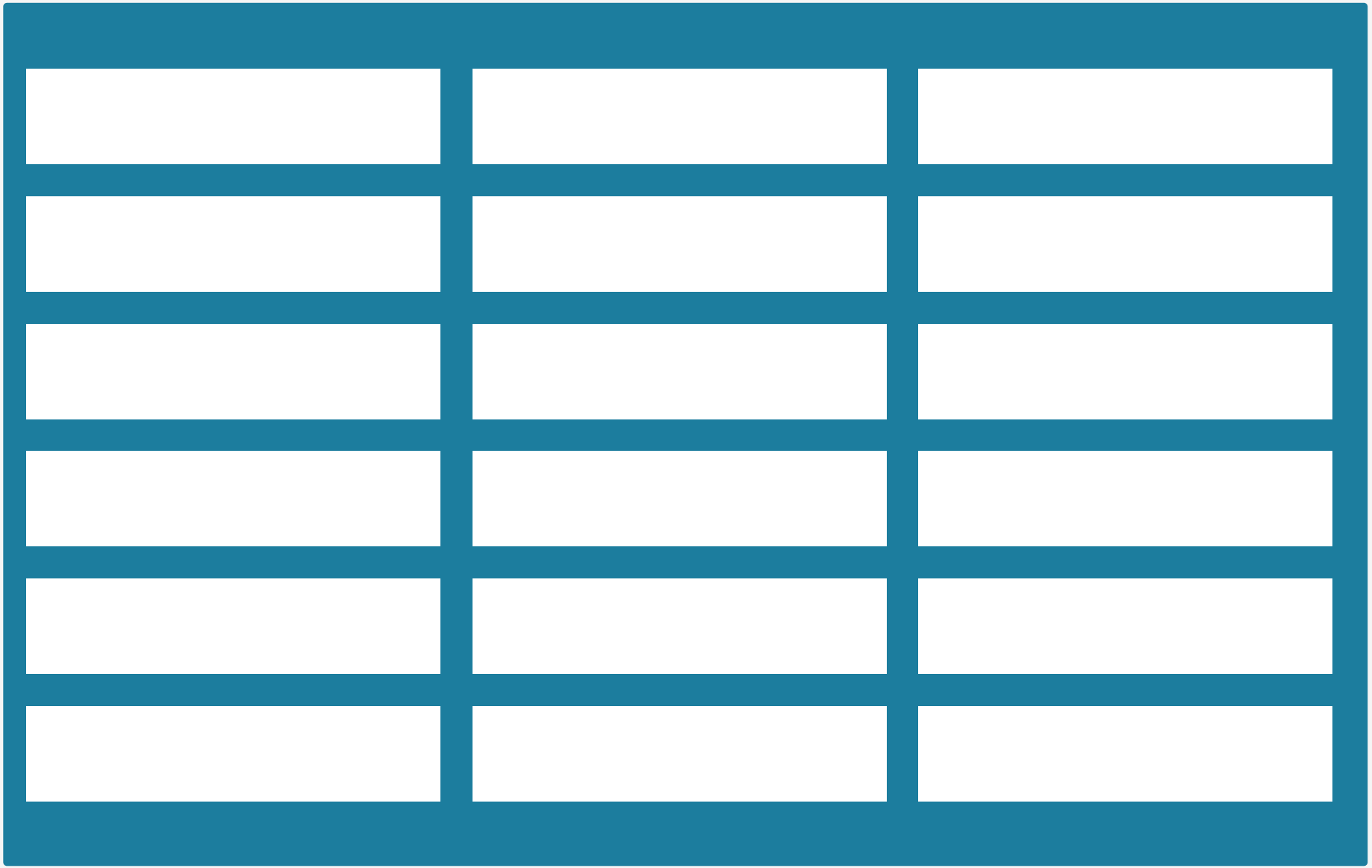

cold expen$ive

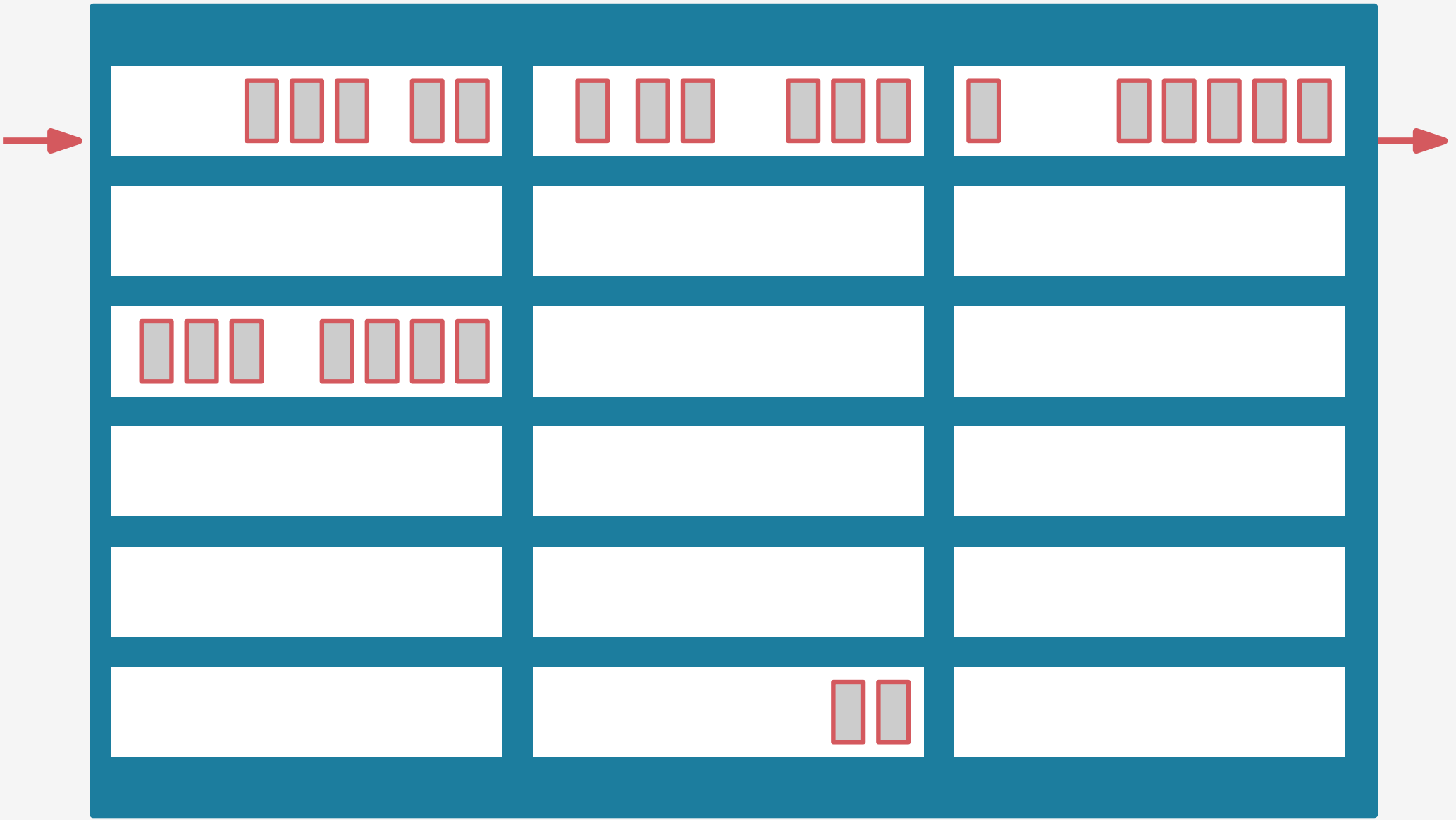

cold expen$ive

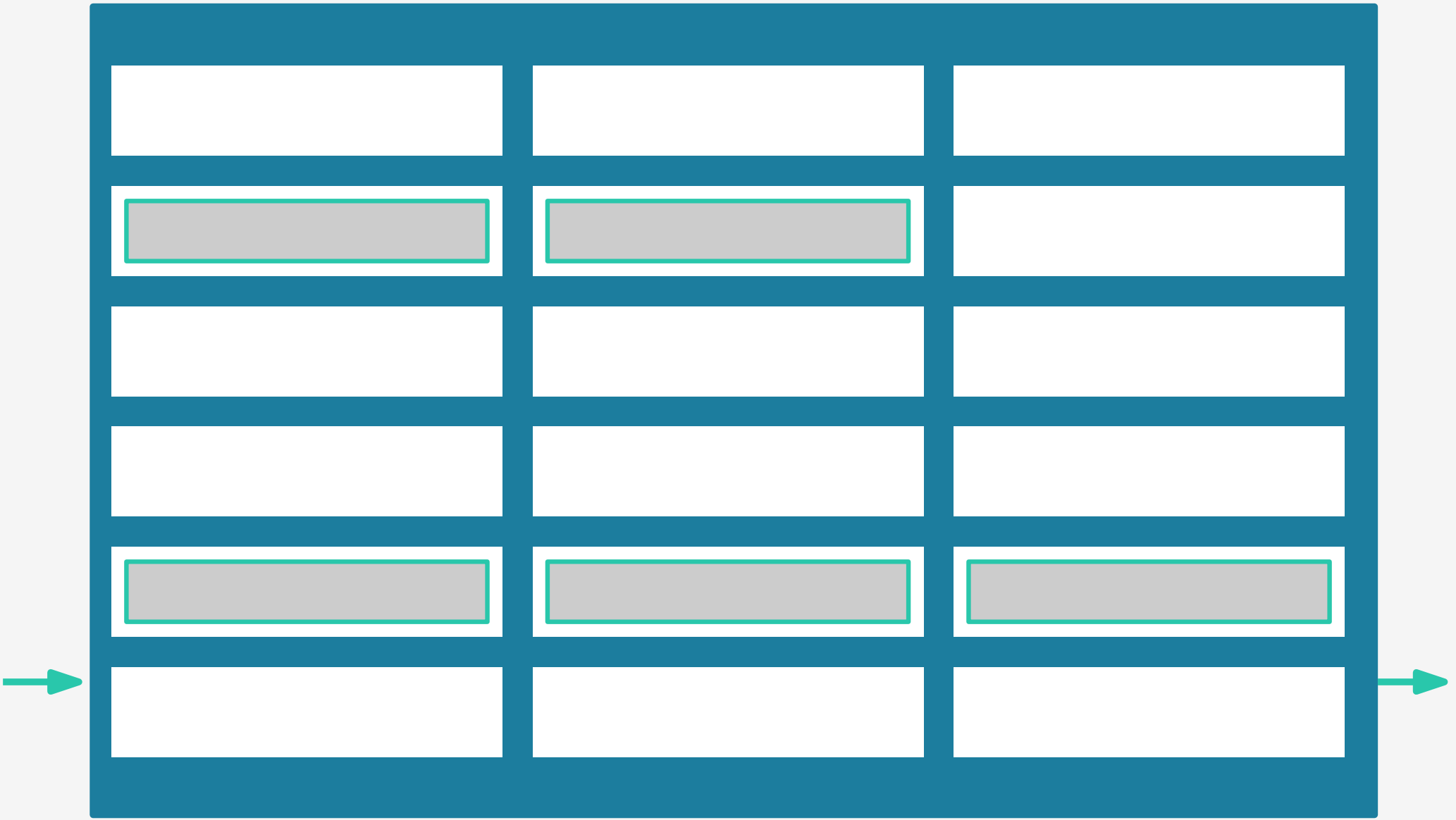

cold expen$ive

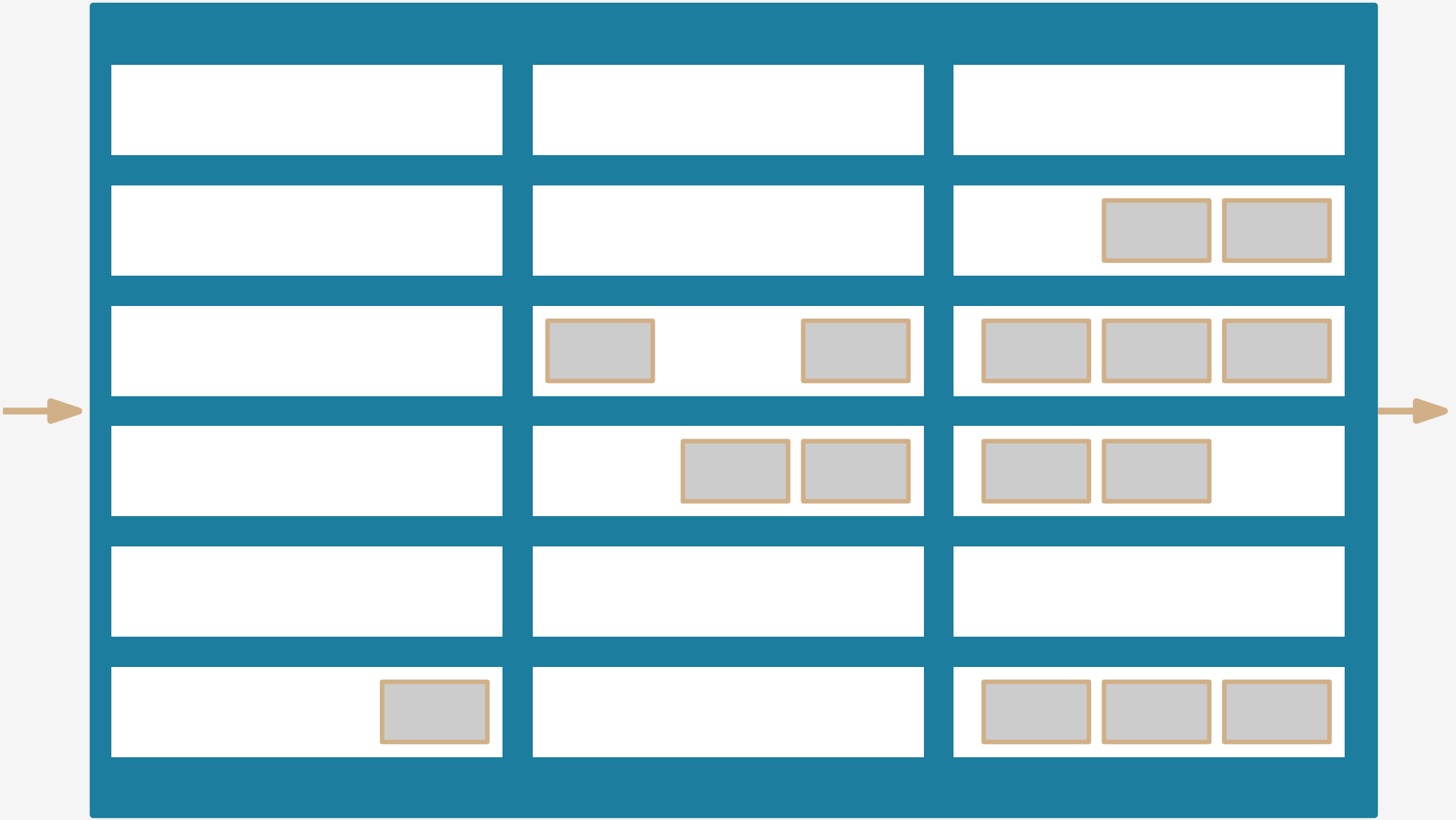

cold expen$ive

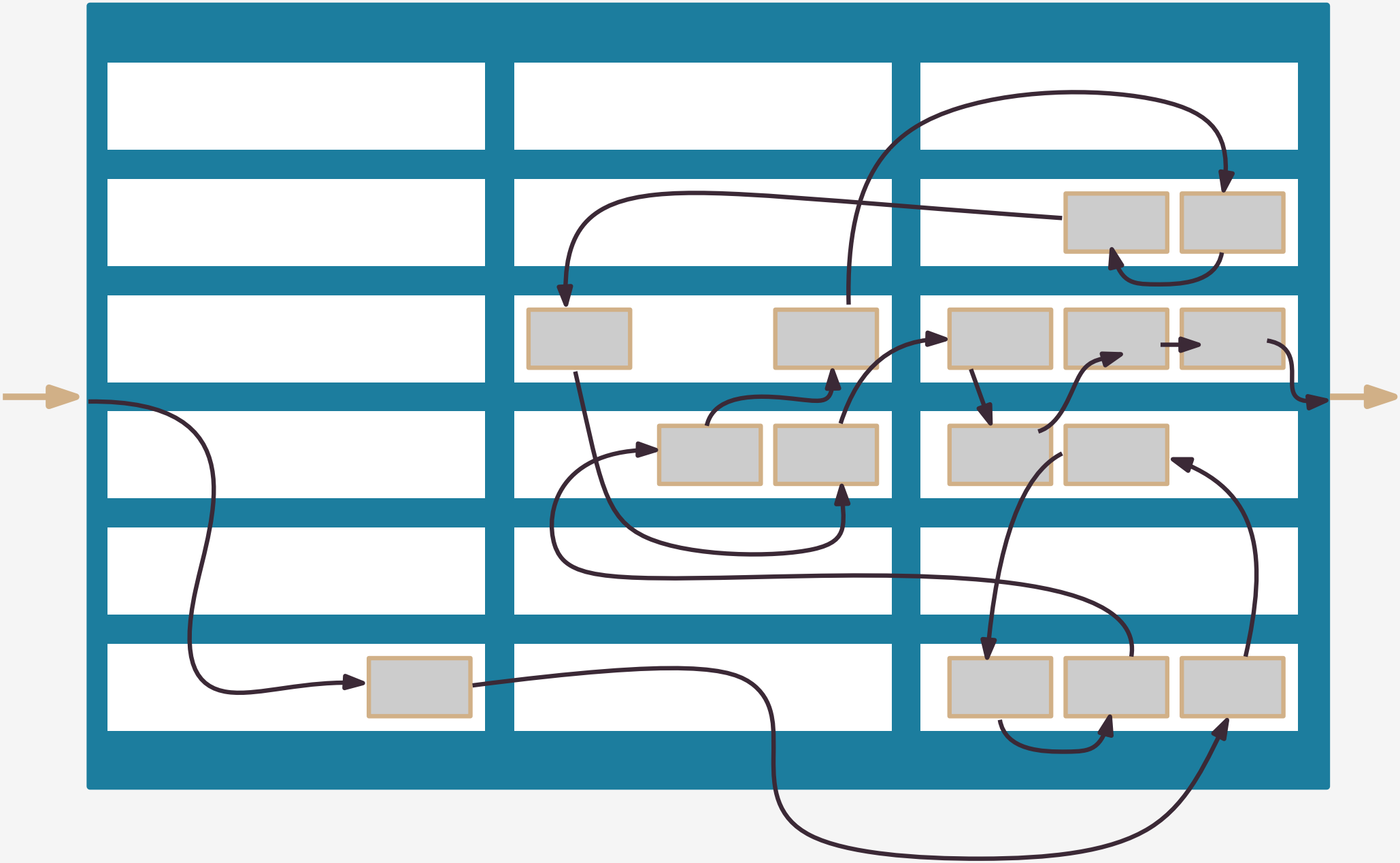

cold expen$ive

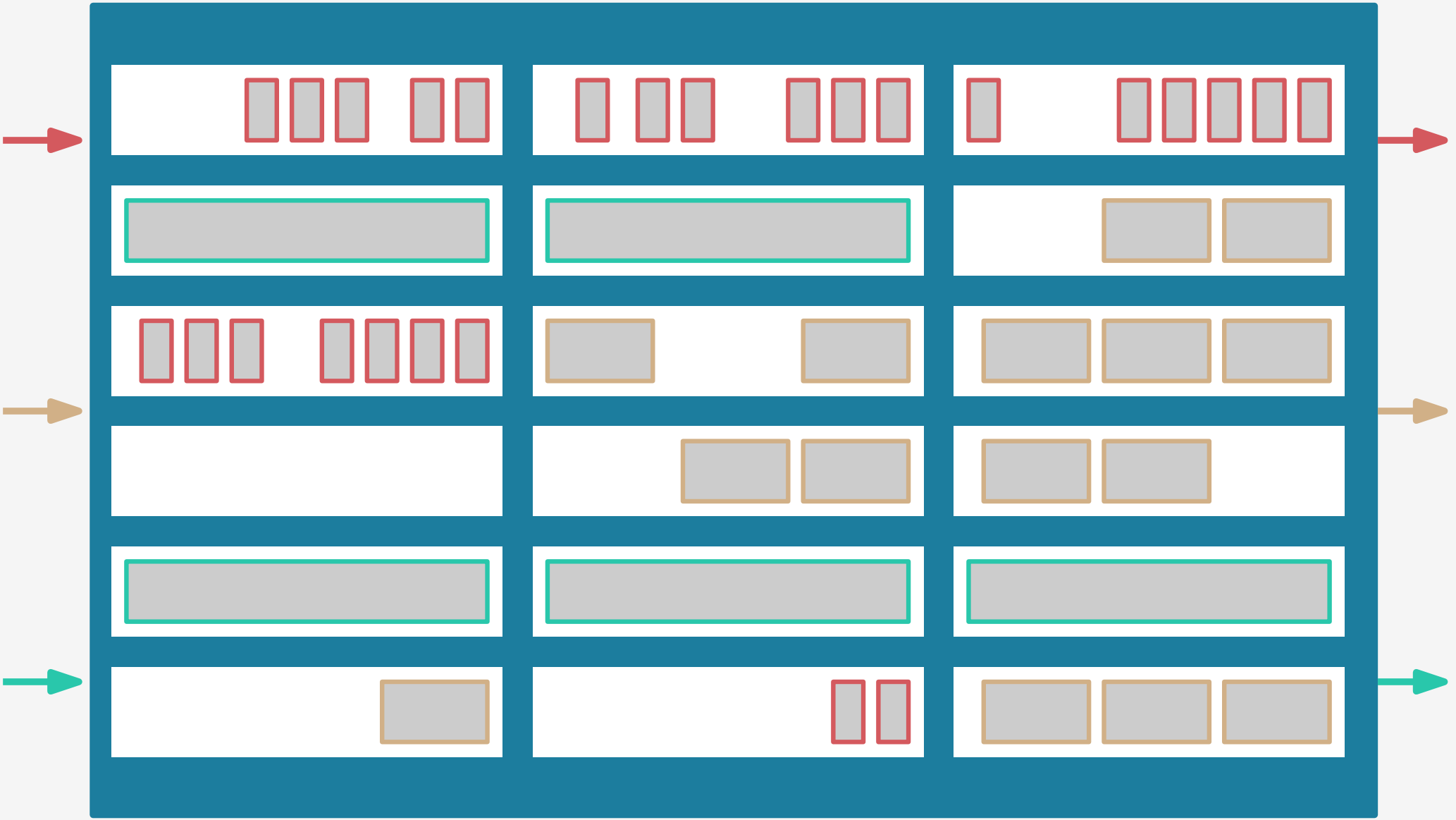


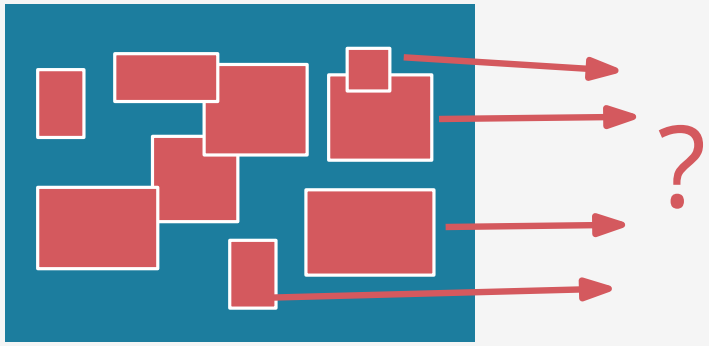




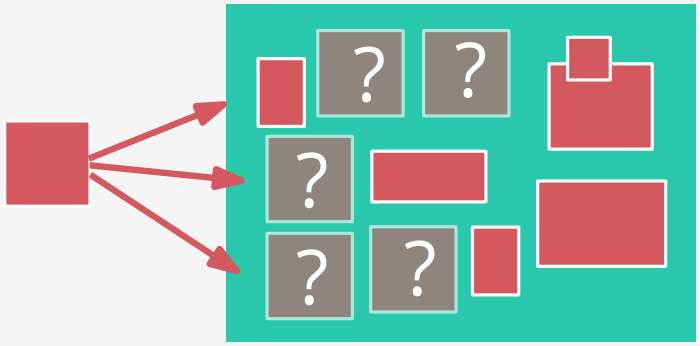








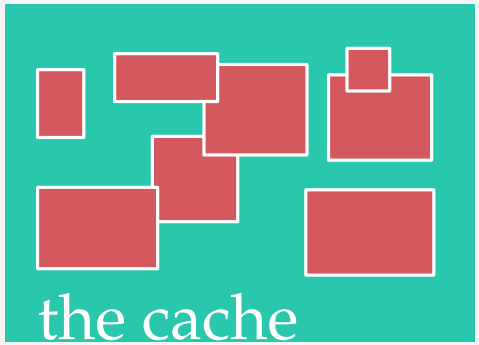
EVICTION POLICY



PLACEMENT POLICY

THE GENERALIZED CACHING PROBLEM

variable size and cost



GOAL

minimize **total cost** of cache misses

SUBJECT TO

total size of items in cache
cannot exceed the cache size

THE MANAGED MEMORY CACHING PROBLEM

variable size and cost

every item must fit in a contiguous segment of memory

CACHE REPLACEMENT

MEMORY ALLOCATION

CAMP-MALLOC

LRU queues

CAMP-MALLOC

FIFO queues

CAMP-MALLOC

FIFO queue

CAMP-MALLOC

FIFO queue

CAMP-MALLOC

FIFO queue

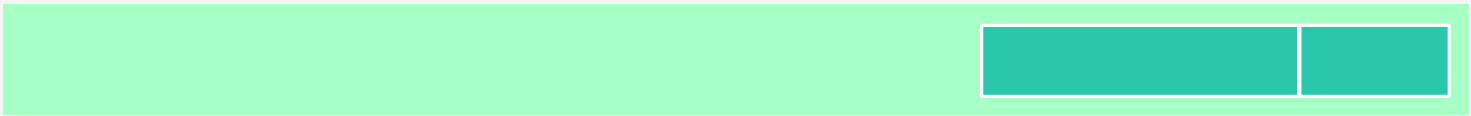
CAMP-MALLOC

FIFO queue

CAMP-MALLOC

FIFO queue

CAMP-MALLOC

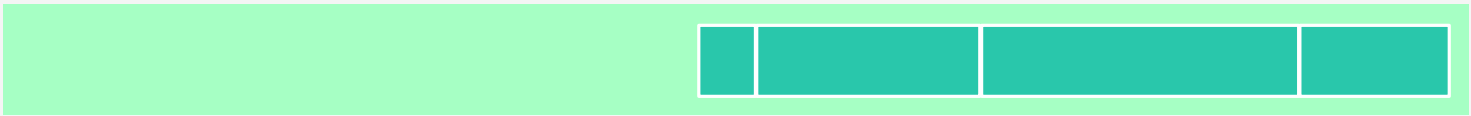


FIFO queue

CAMP-MALLOC

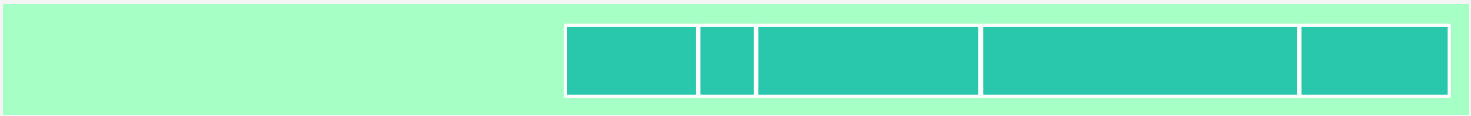
FIFO queue

CAMP-MALLOC



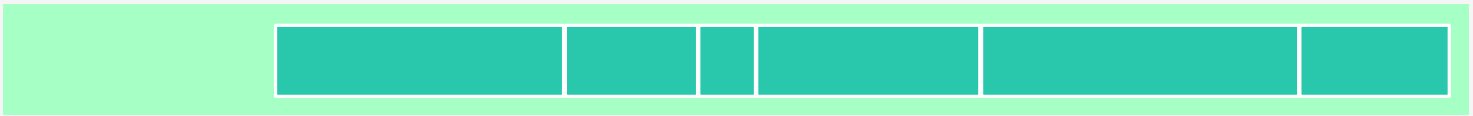
FIFO queue

CAMP-MALLOC



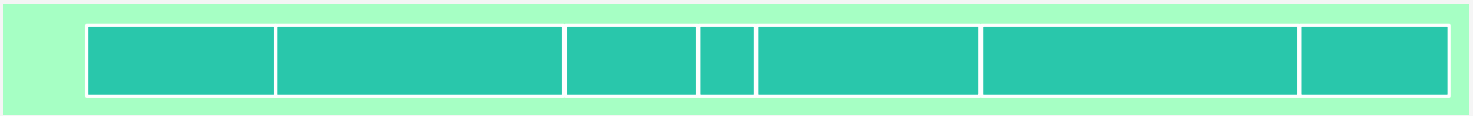
FIFO queue

CAMP-MALLOC



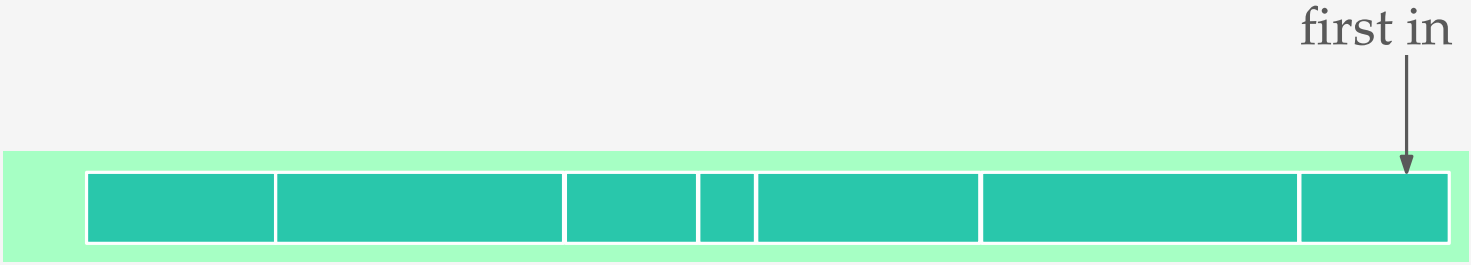
FIFO queue

CAMP-MALLOC



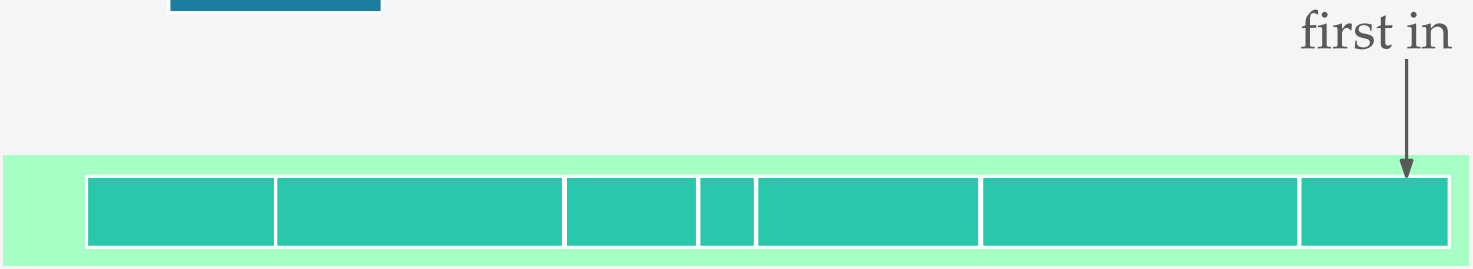
FIFO queue

CAMP-MALLOC



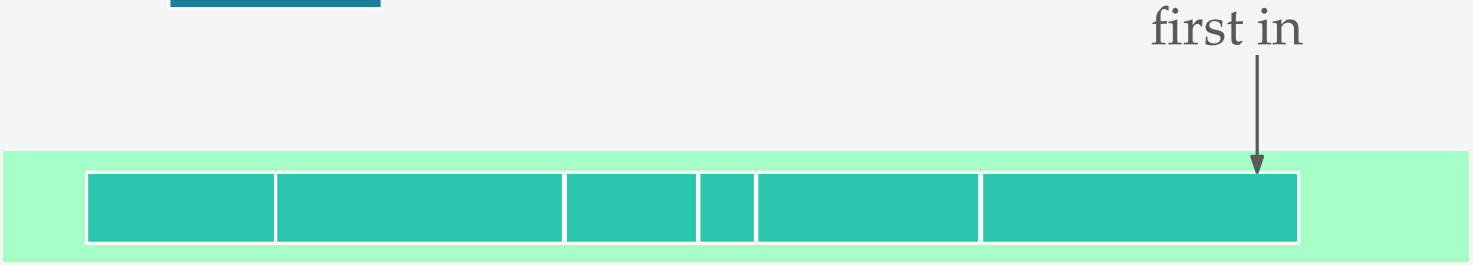
FIFO queue

CAMP-MALLOC



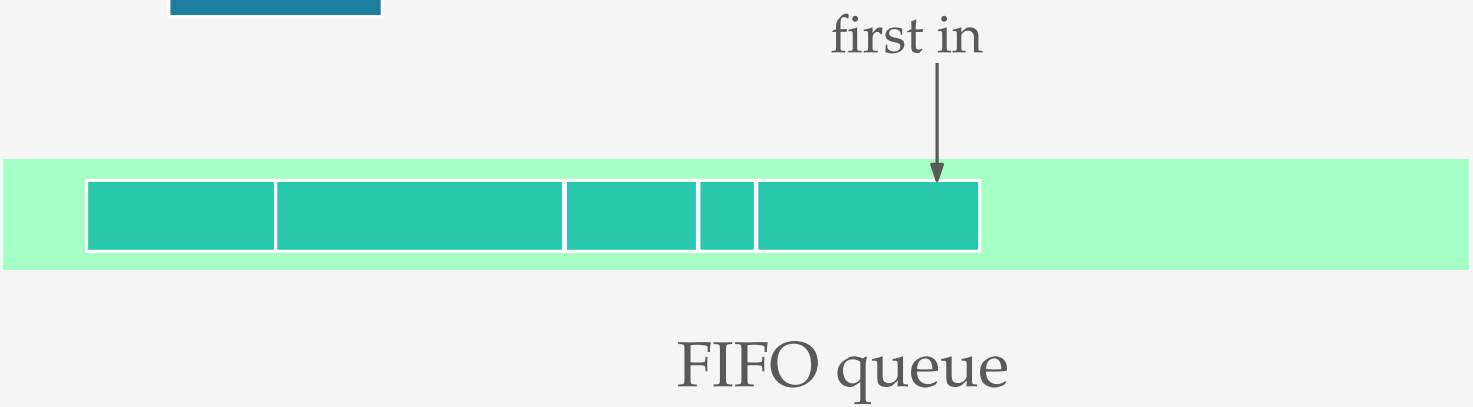
FIFO queue

CAMP-MALLOC



FIFO queue

CAMP-MALLOC



FIFO queue

CAMP-MALLOC

FIFO queue

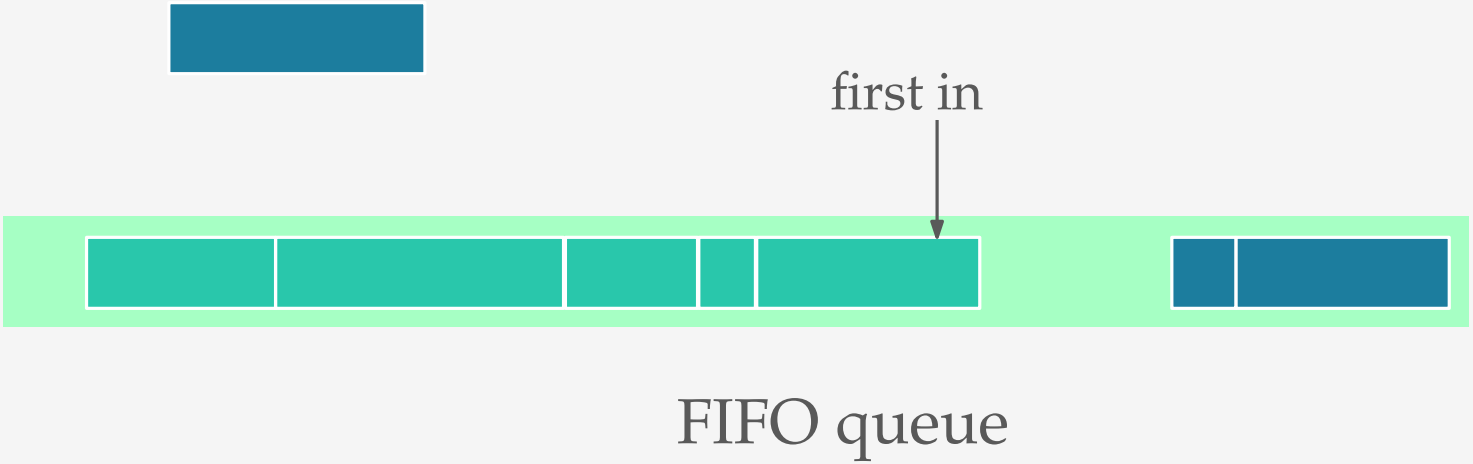
CAMP-MALLOC

FIFO queue

CAMP-MALLOC

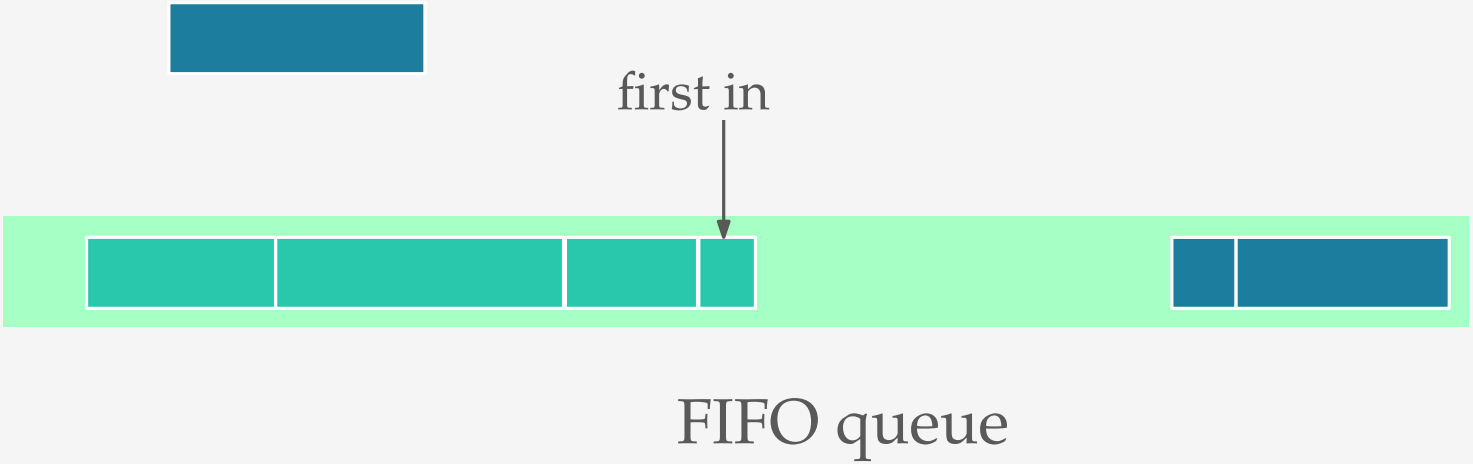
FIFO queue

CAMP-MALLOC

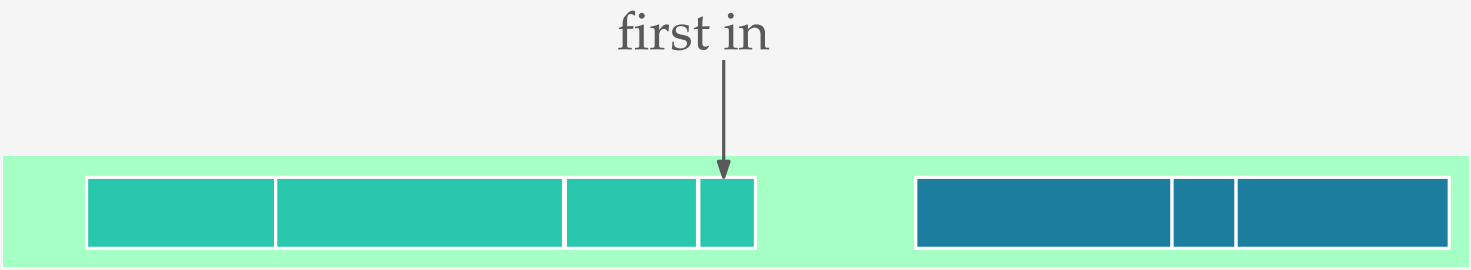


FIFO queue

CAMP-MALLOC



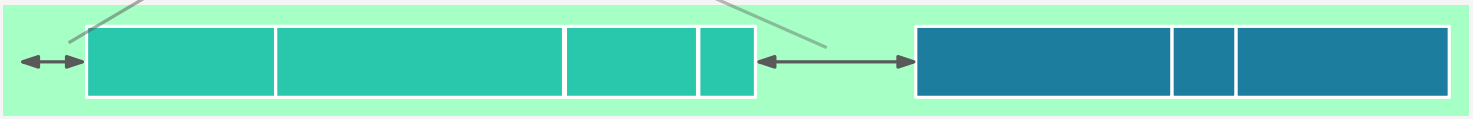
CAMP-MALLOC



FIFO queue

CAMP-MALLOC

fragmentation $\leq$ 2 (max item size)



FIFO queue

CAMP-MALLOC

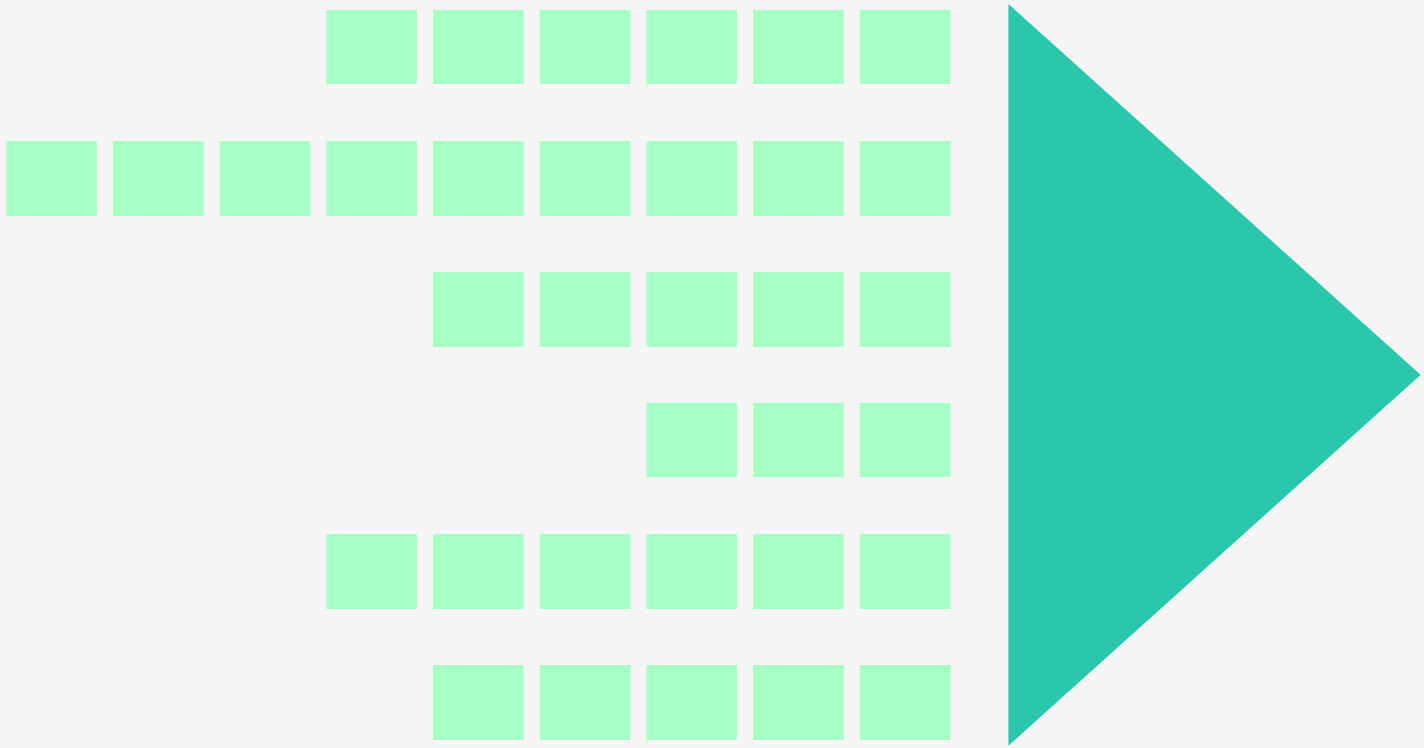
CAMP-MALLOC

CAMP-MALLOC

CAMP-MALLOC

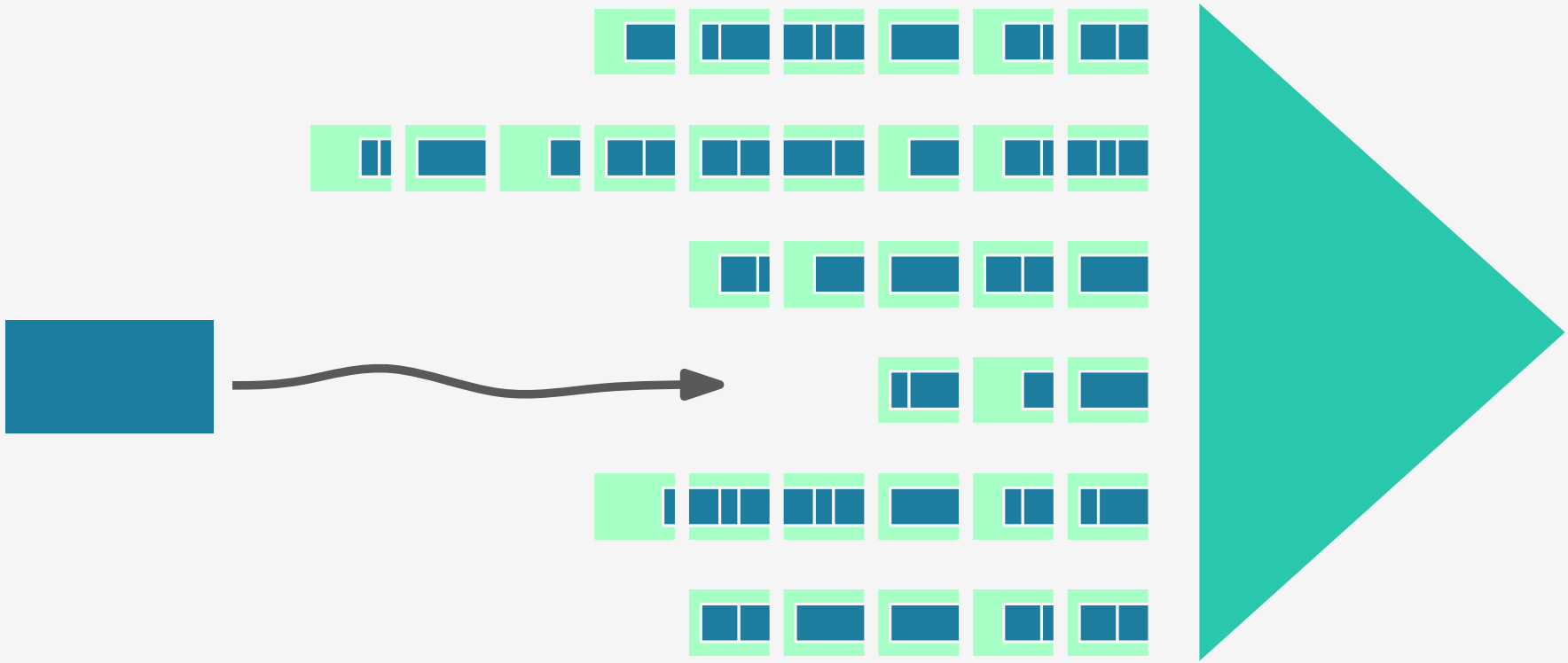
CAMP-MALLOC

CAMP-MALLOC

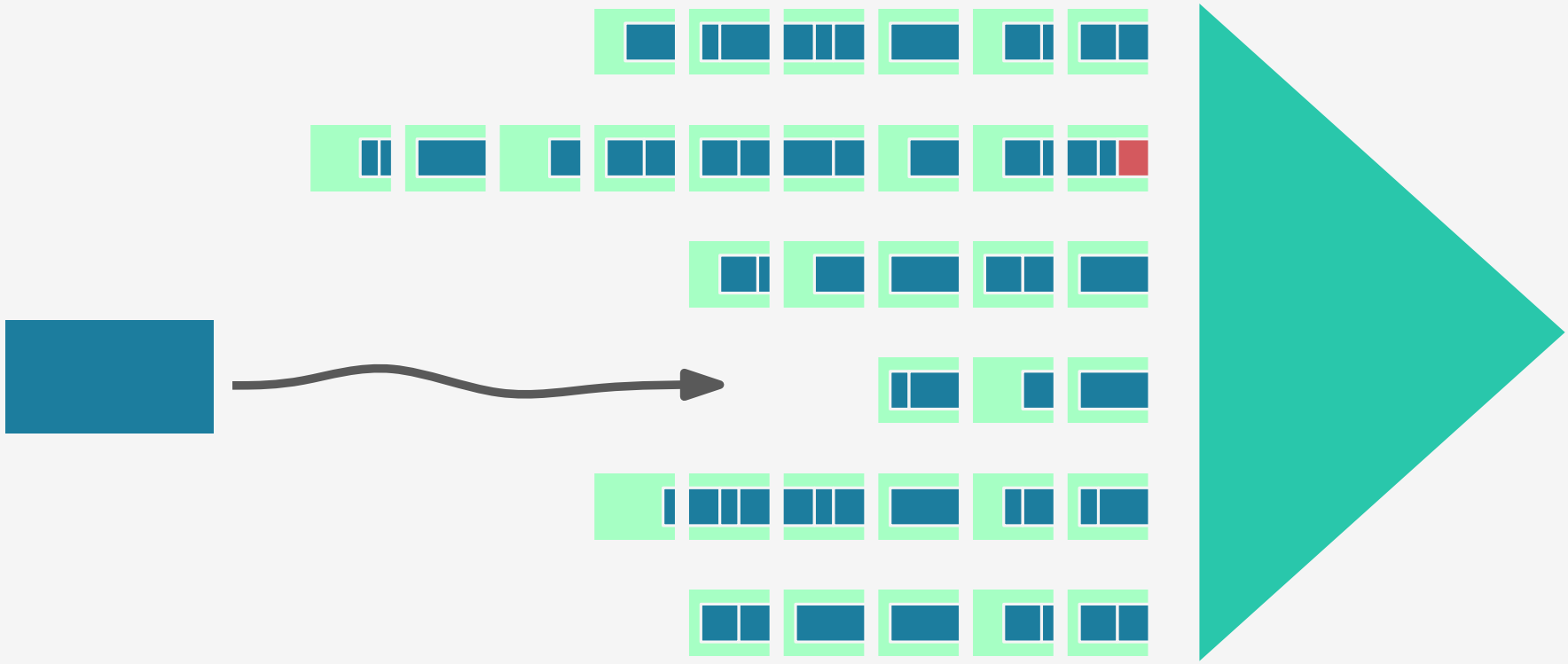


CAMP-MALLOC

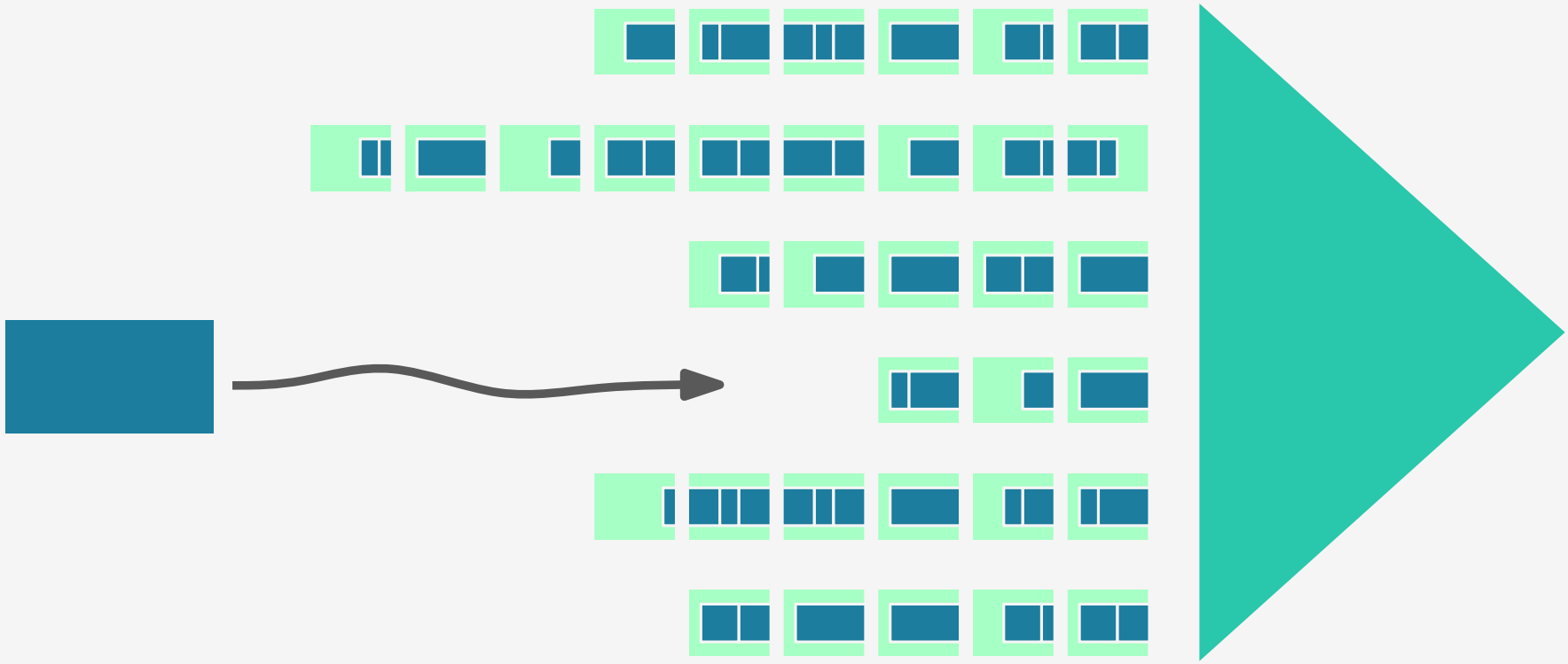
CAMP-MALLOC



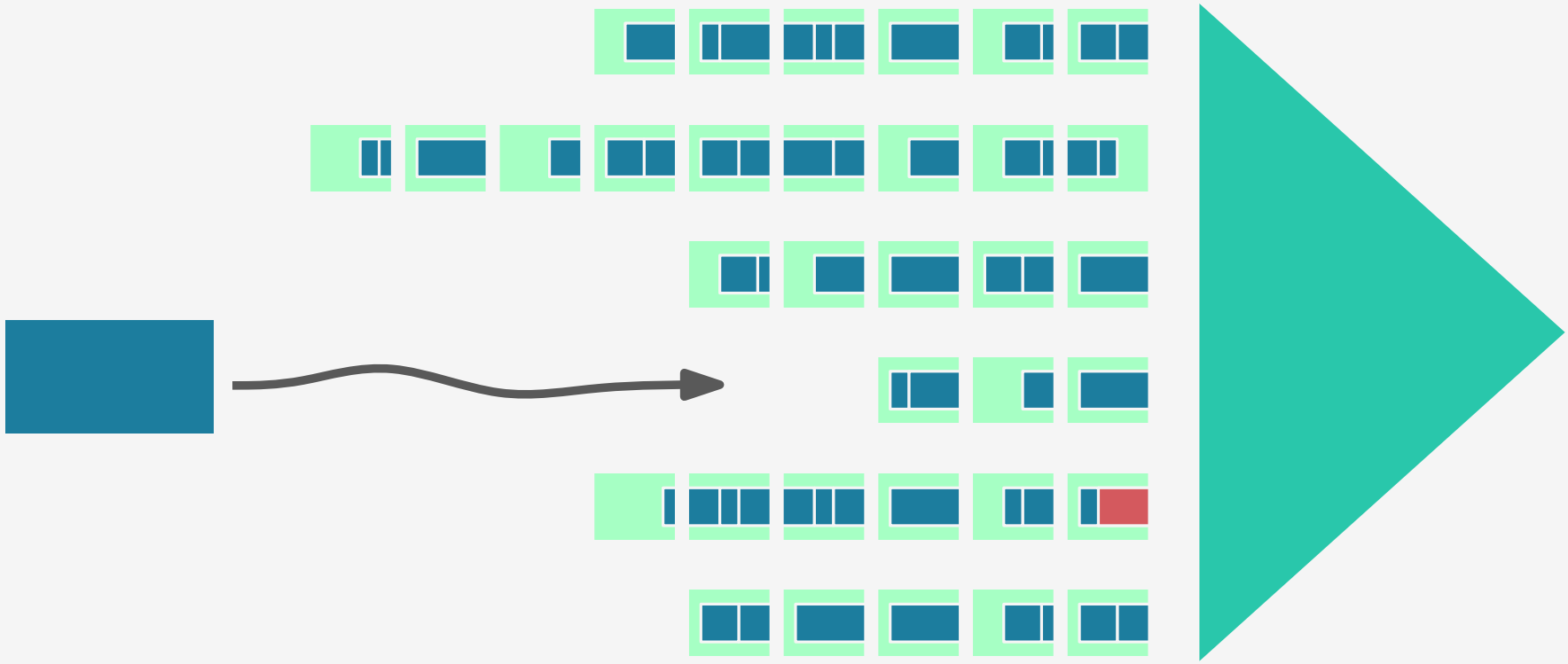
CAMP-MALLOC



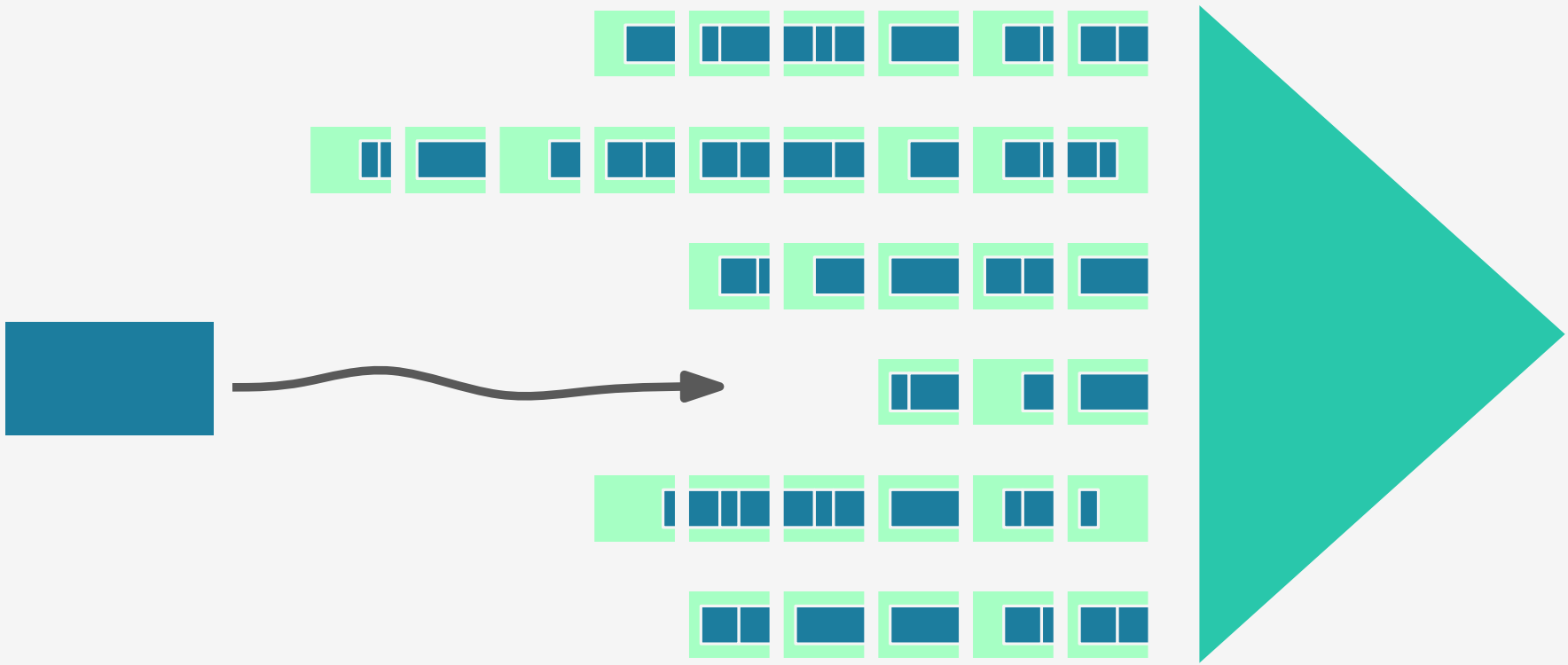
CAMP-MALLOC



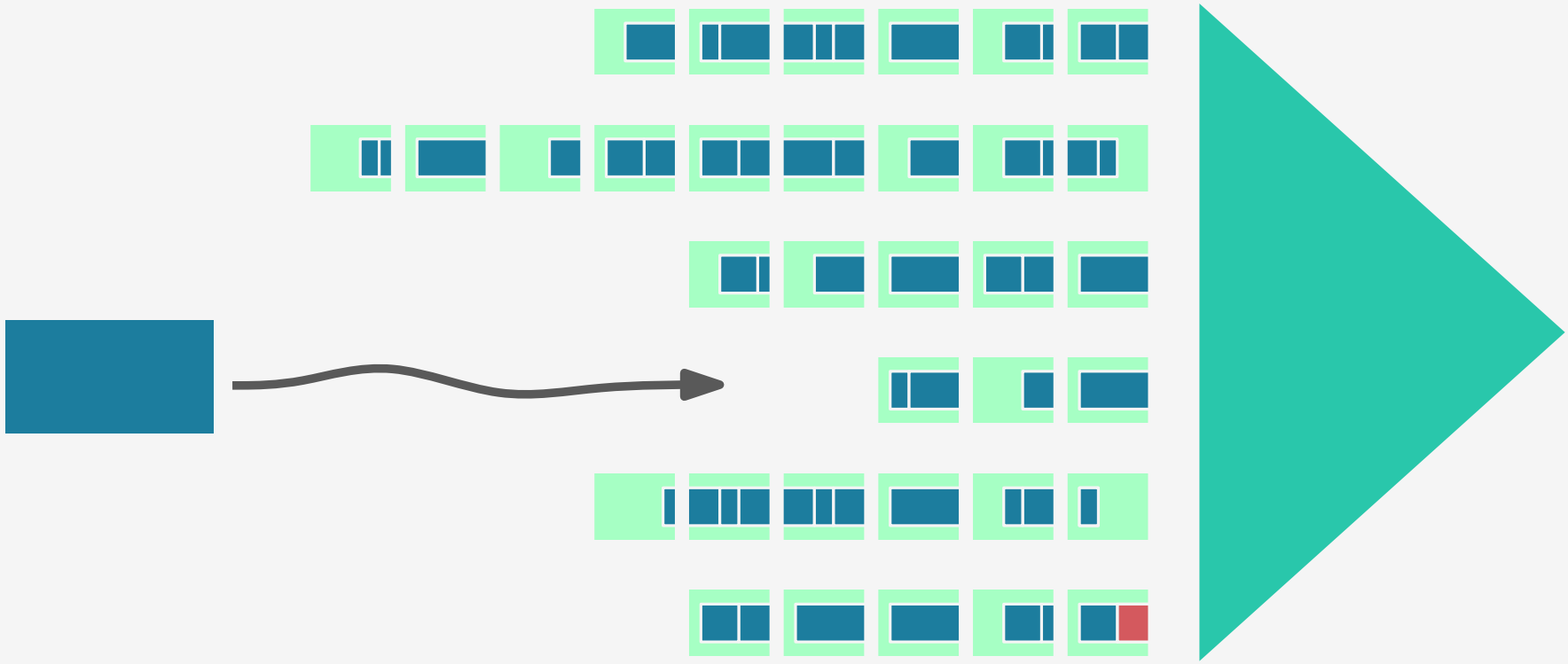
CAMP-MALLOC



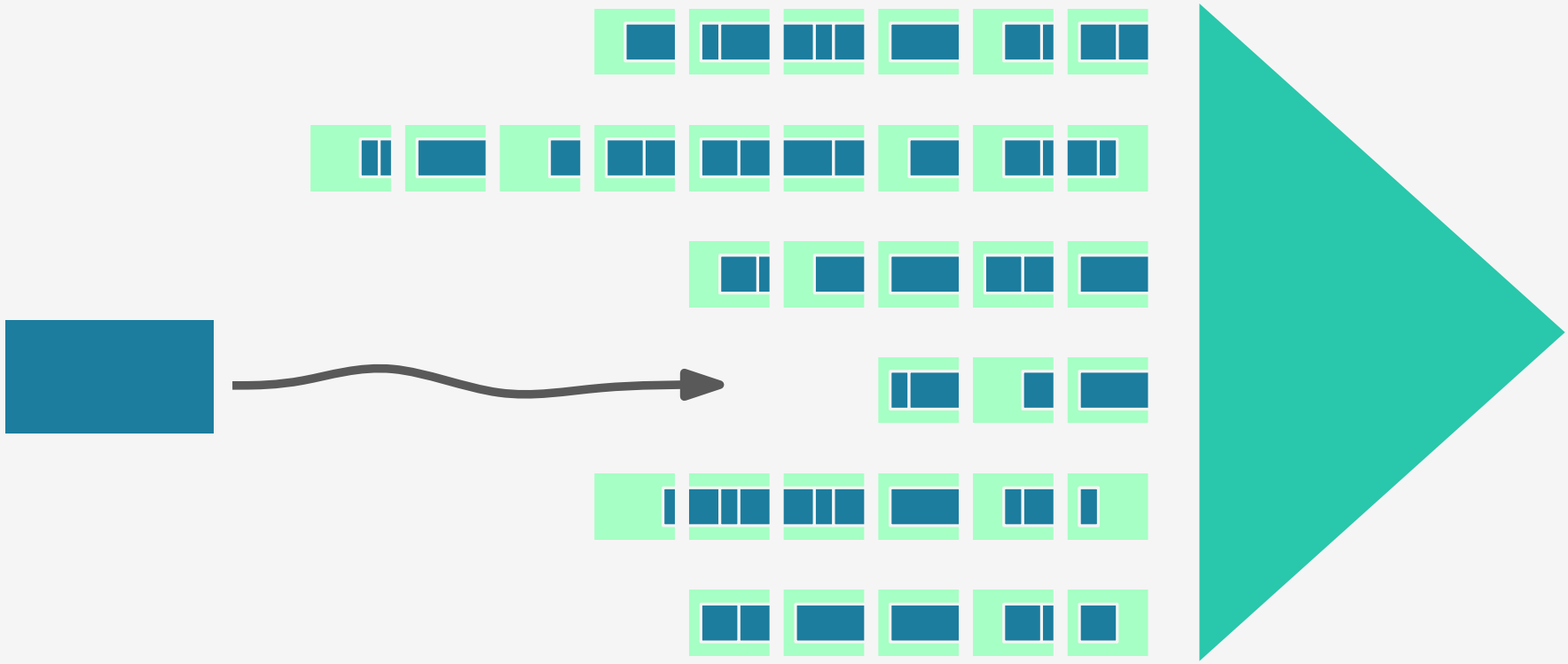
CAMP-MALLOC



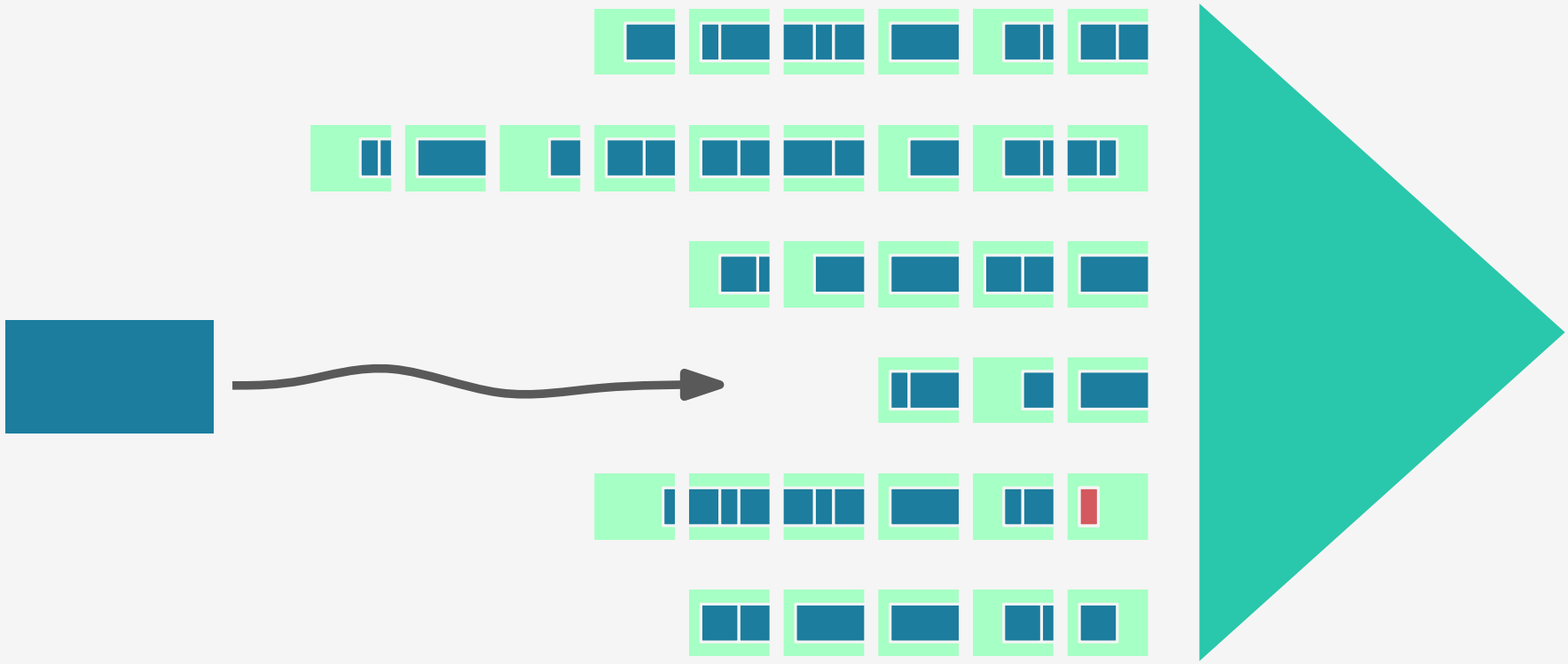
CAMP-MALLOC



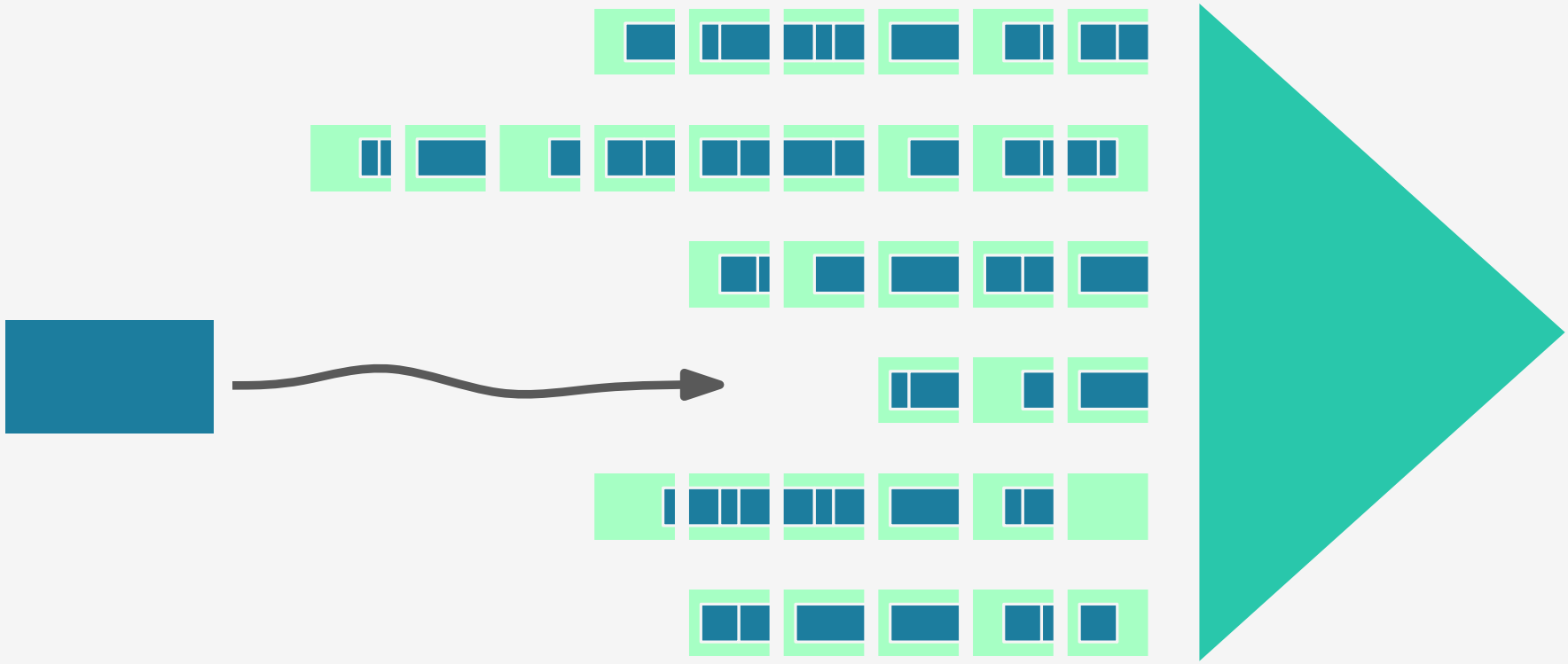
CAMP-MALLOC



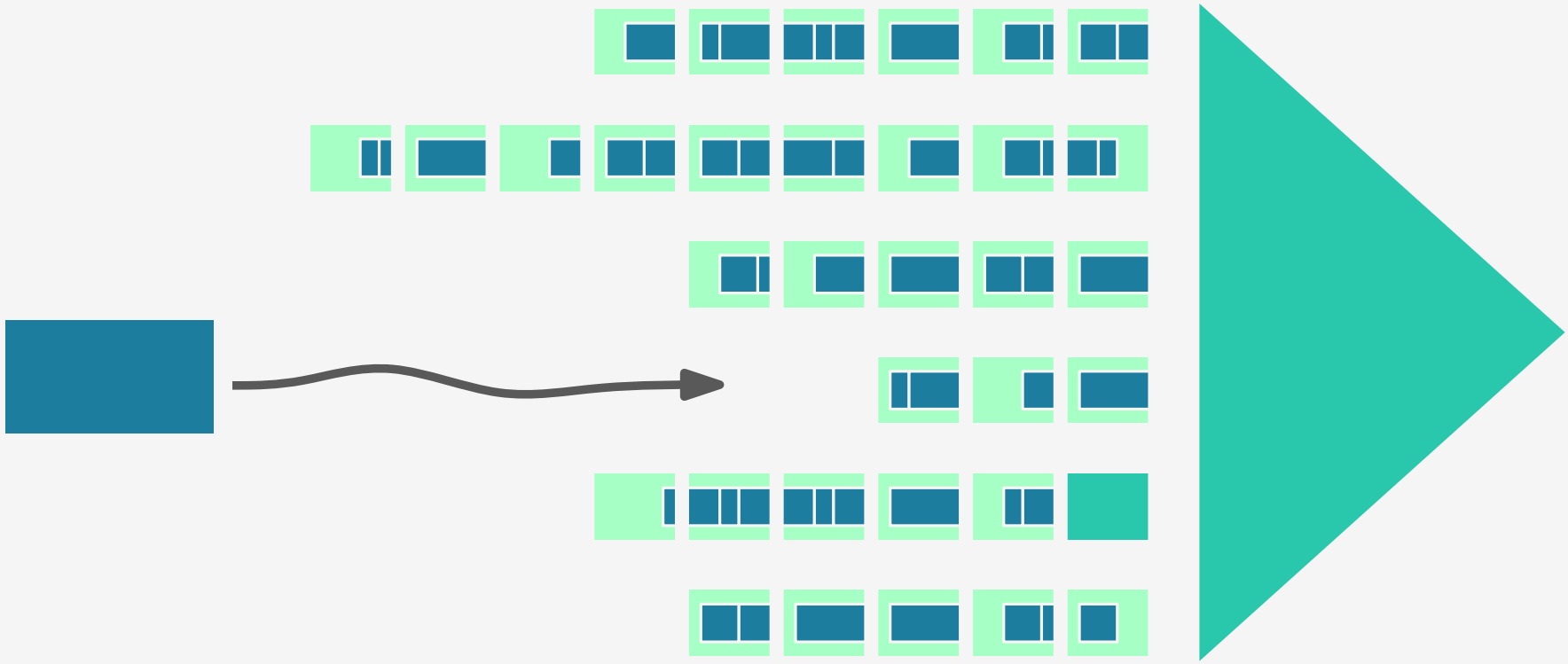
CAMP-MALLOC



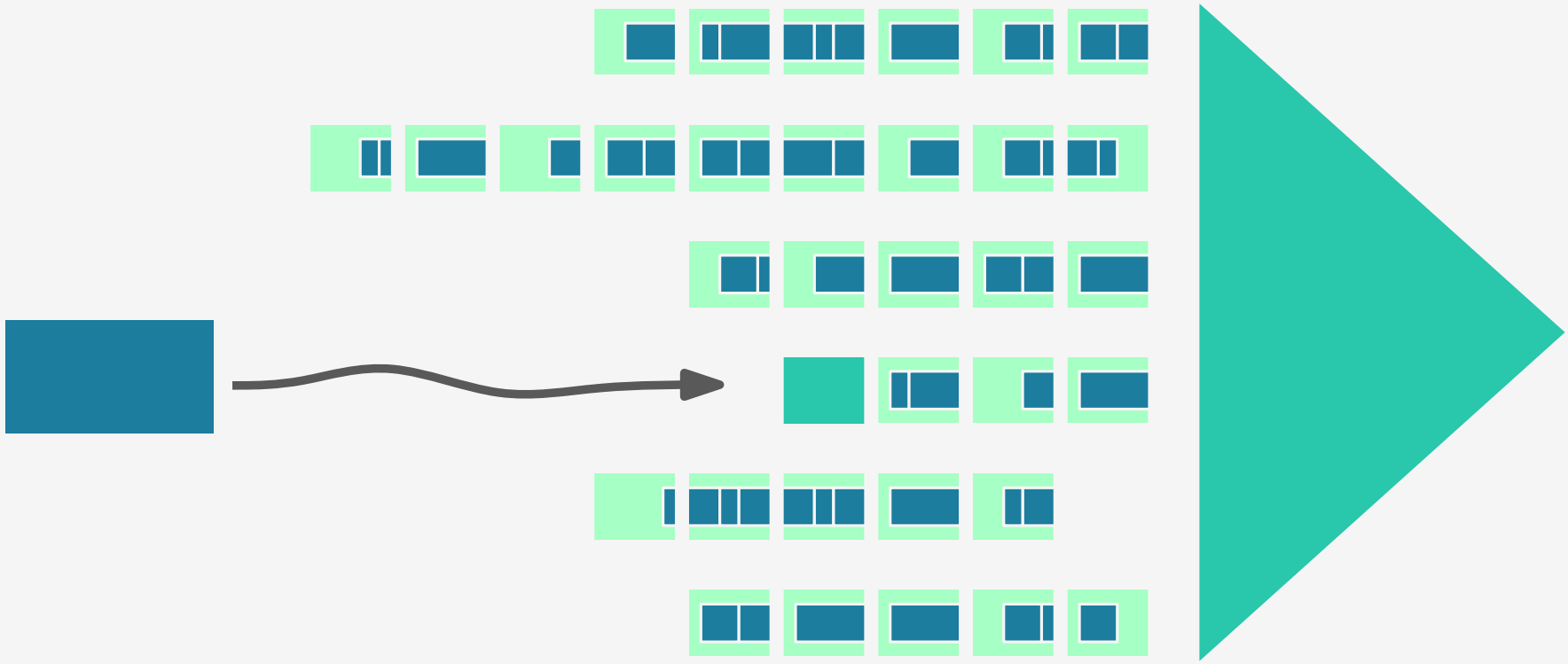
CAMP-MALLOC



CAMP-MALLOC

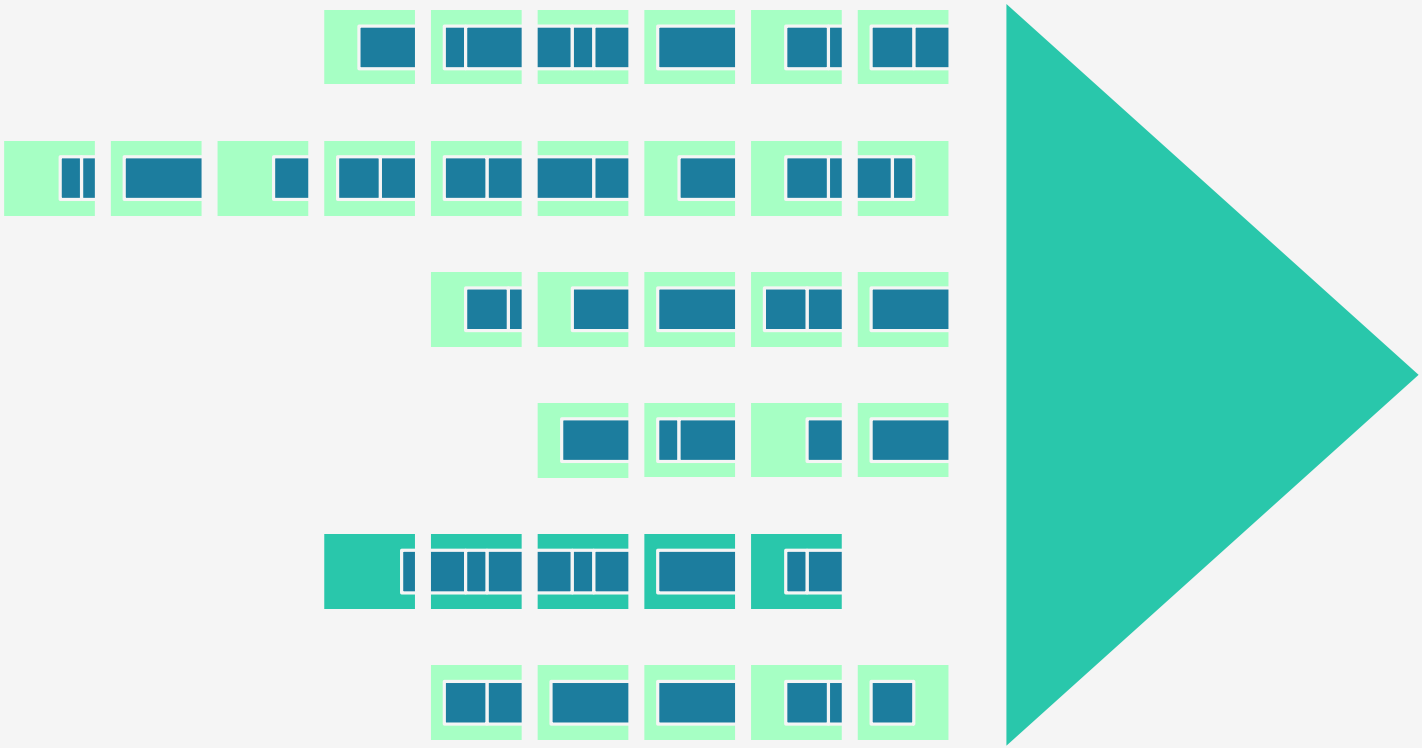


CAMP-MALLOC

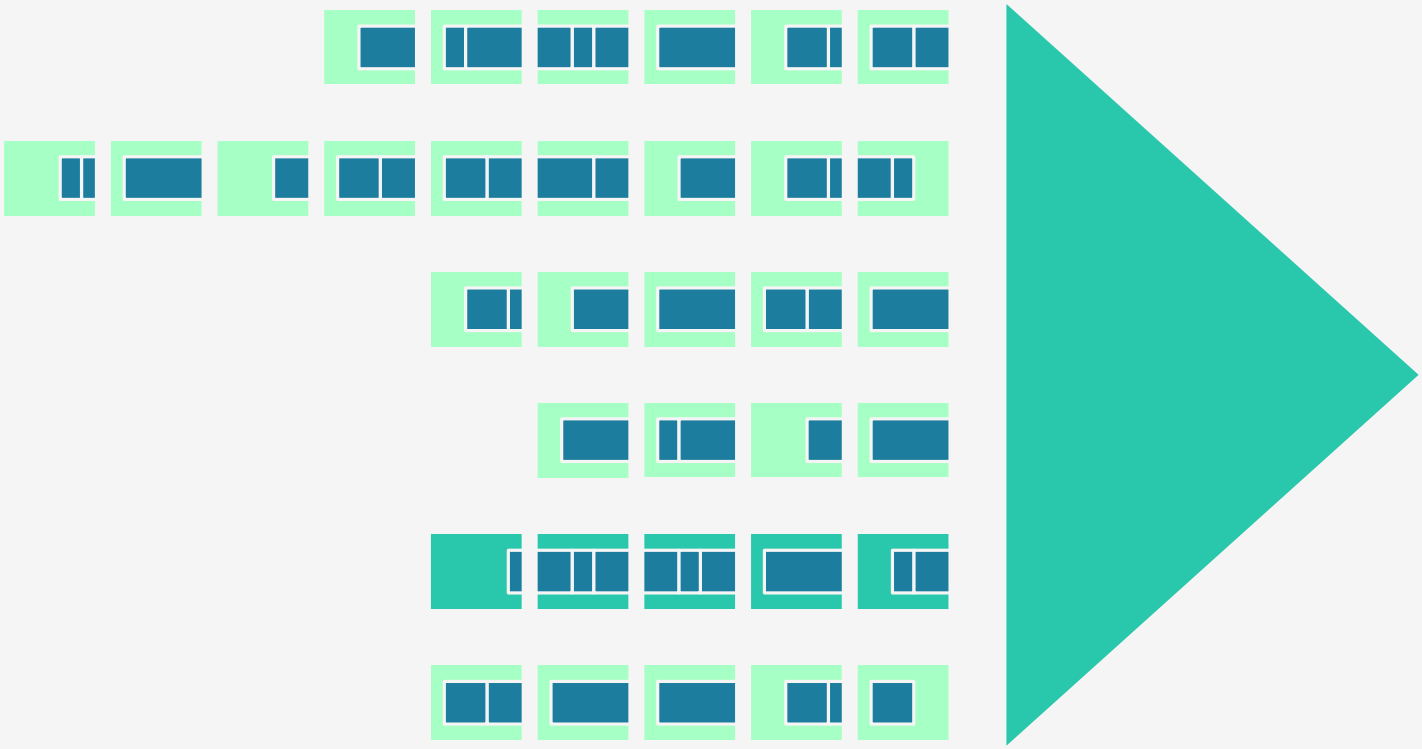


CAMP-MALLOC

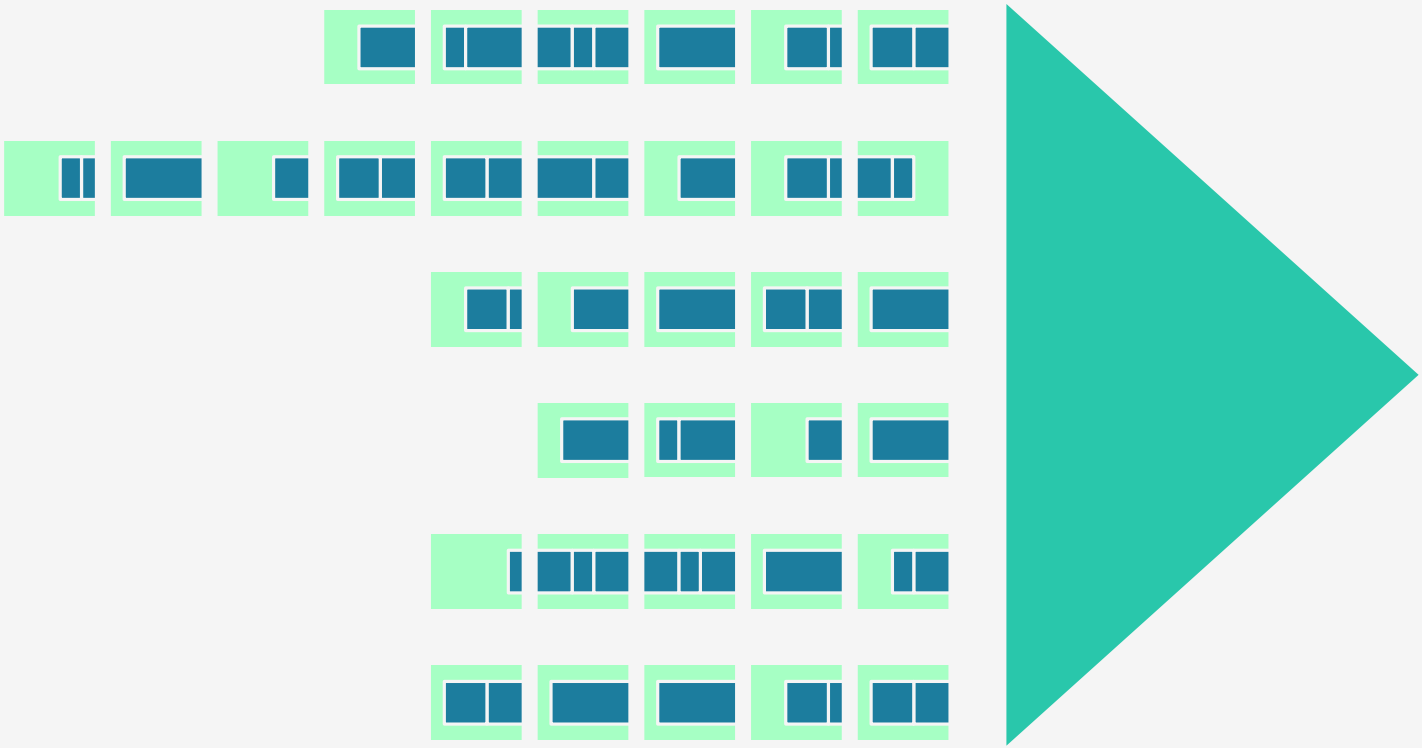
CAMP-MALLOC



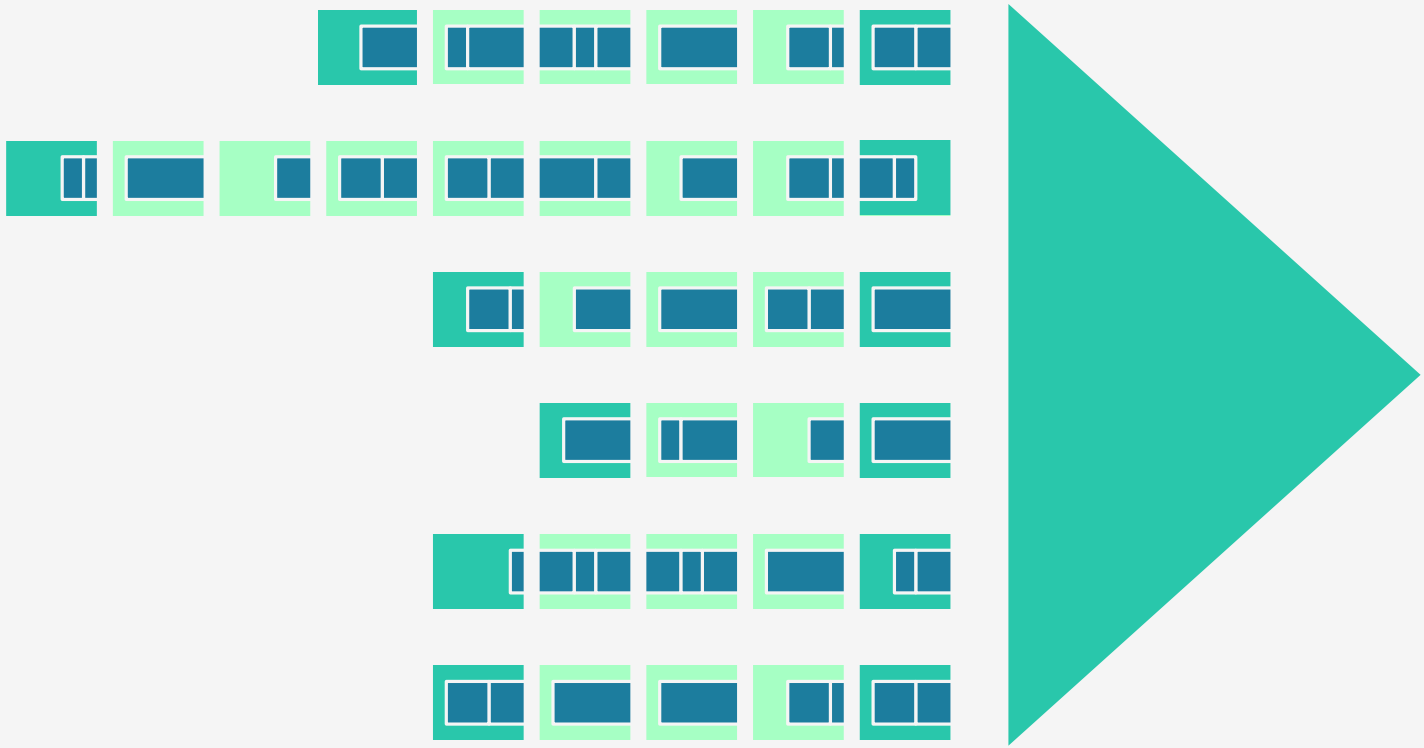
CAMP-MALLOC



CAMP-MALLOC



CAMP-MALLOC



fragmentation $\leq$ 2 (num queues) (block size) + (num blocks) (max item size)

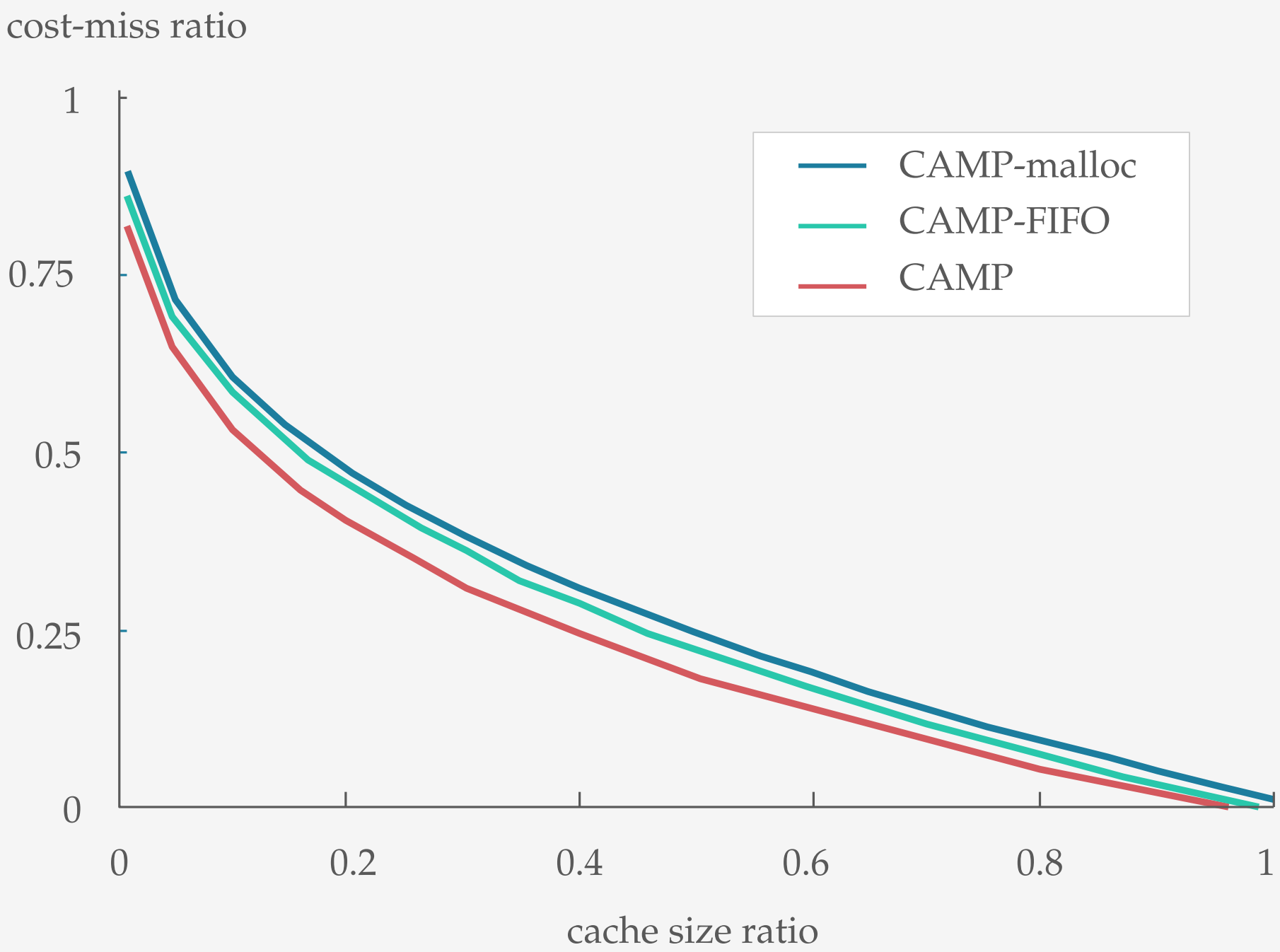
CAMP-MALLOC

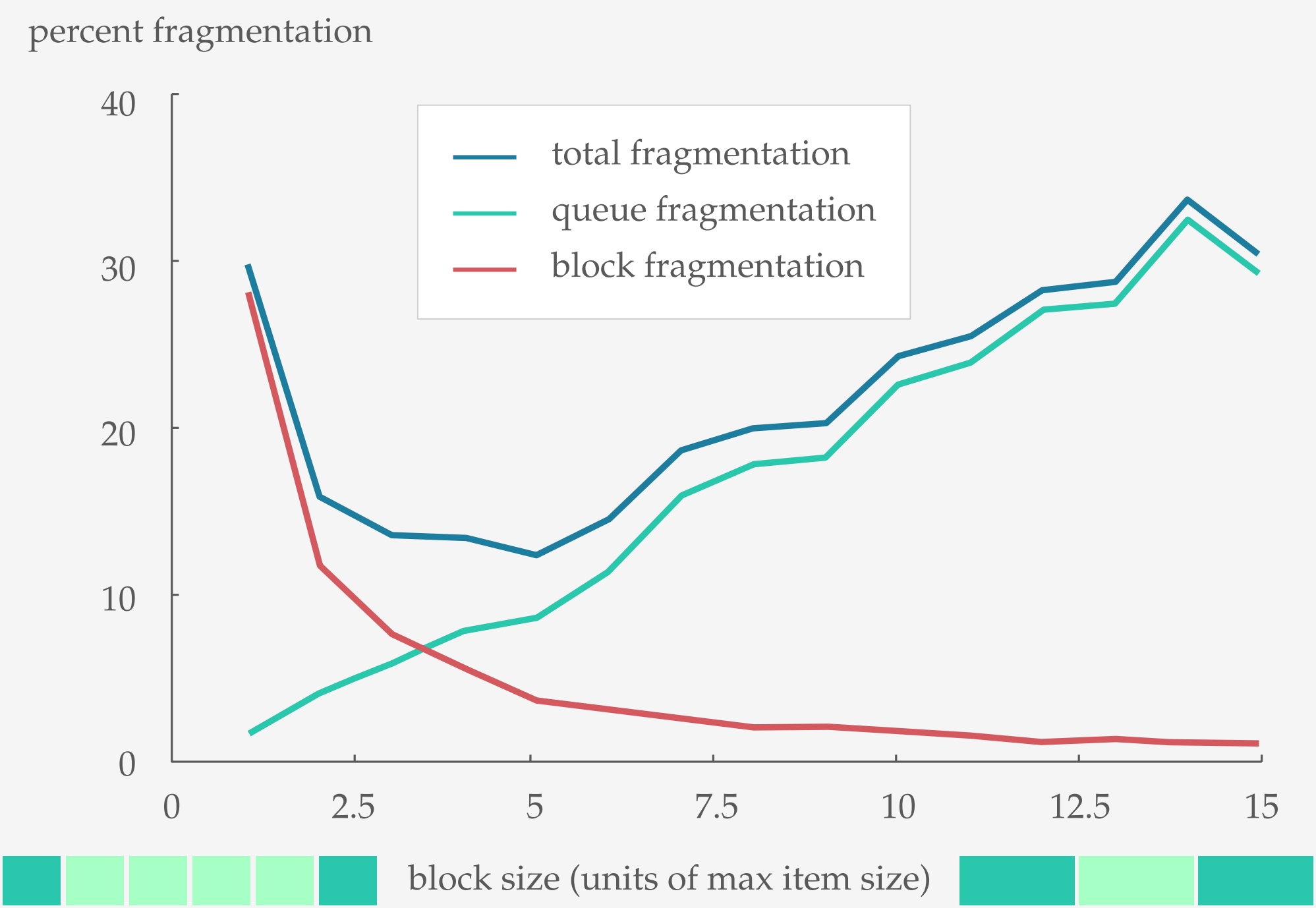
is competitive if memory augmented

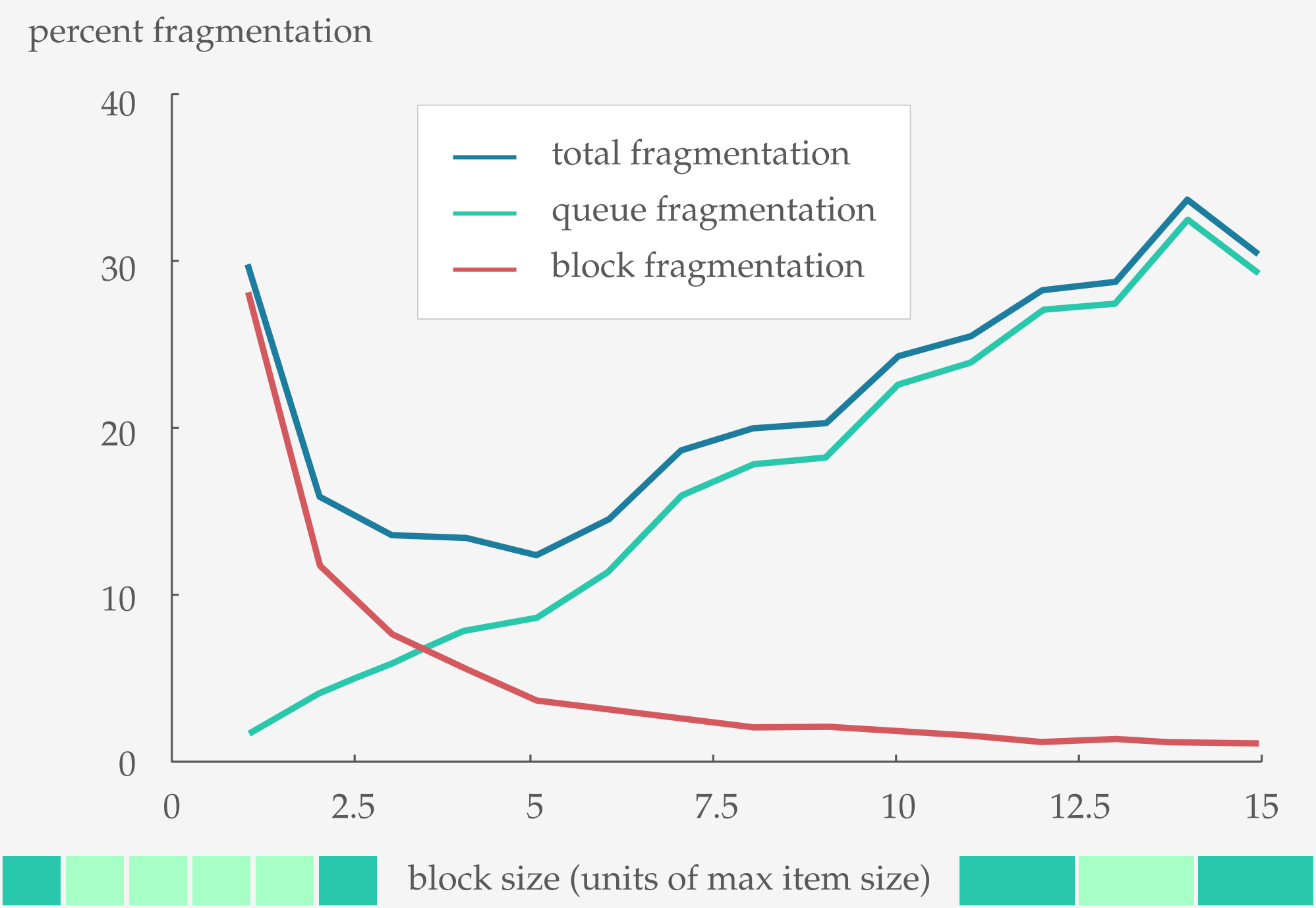
$$\text{if} \quad \text{OPT's cache size} \leq \text{C-M's cache size} - \text{fragmentation bound}$$

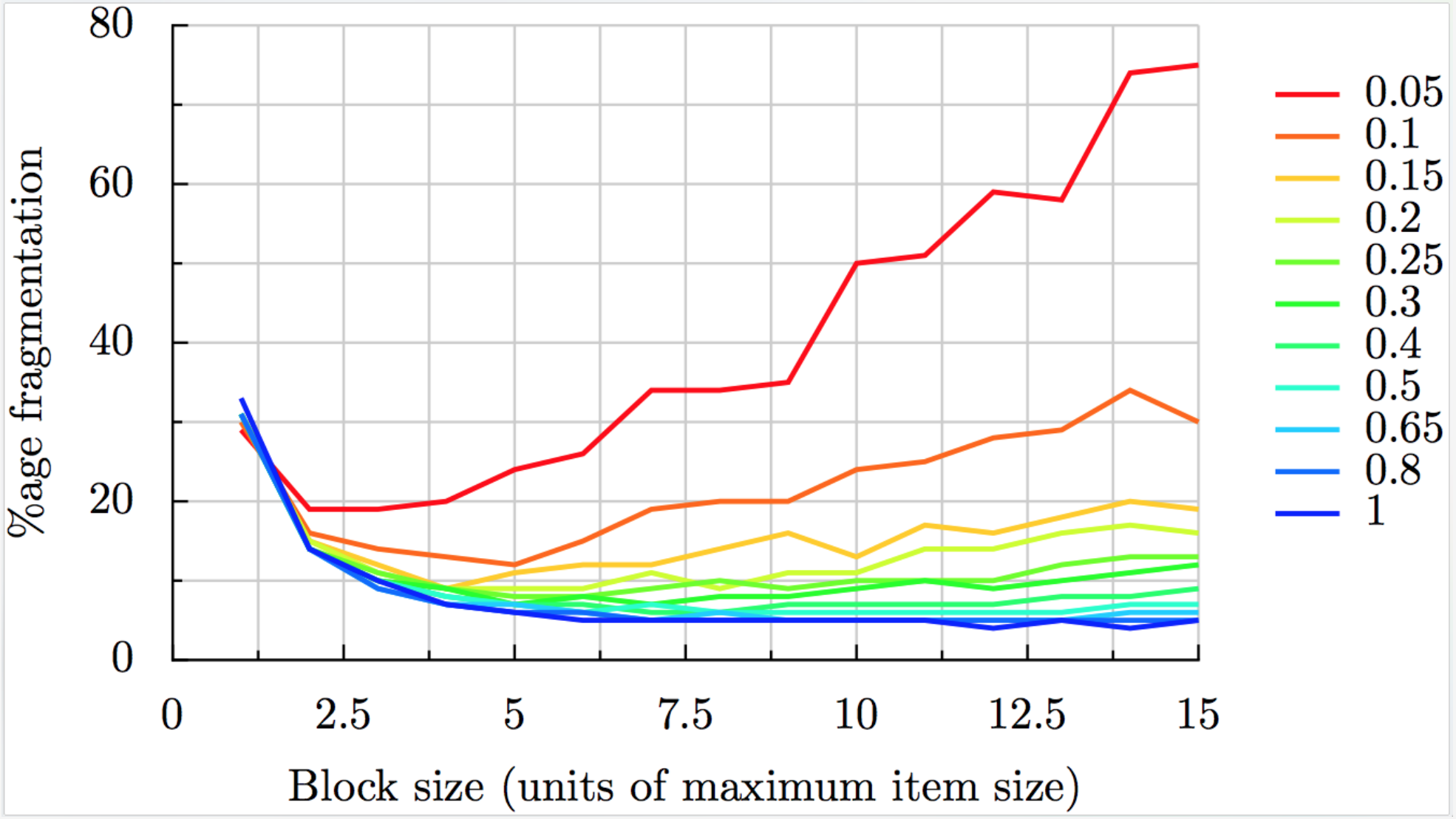
$$\text{then} \quad \text{cost(C-M)} \leq \frac{\text{C-M's cache size}}{\text{min item size}} \text{cost(OPT)}$$

fragmentation $\leq$ 2 (num queues) (block size) + (num blocks) (max item size)


cost-miss ratio
1
0.75
0.5
0.25
0
0
0.2
0.4
0.6
0.8
1
cache size ratio
CAMP-malloc
CAMP-FIFO
CAMP


percent fragmentation
40
30
20
10
0
total fragmentation
queue fragmentation
block fragmentation
0
2.5
5
7.5
10
12.5
15
block size (units of max item size)


percent fragmentation
40
30
20
10
0
total fragmentation
queue fragmentation
block fragmentation
0
2.5
5
7.5
10
12.5
15
block size (units of max item size)

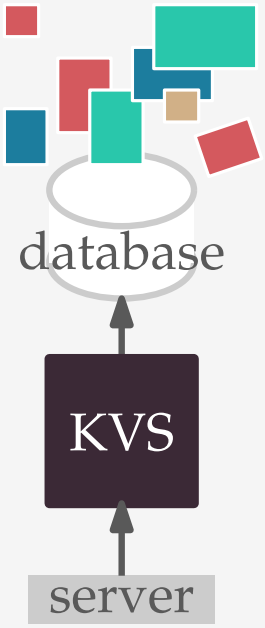

80
60
40
20
0
%age fragmentation
0
2.5
5
7.5
10
12.5
15
Block size (units of maximum item size)
0.05
0.1
0.15
0.2
0.25
0.3
0.4
0.5
0.65
0.8
1

EVICTION POLICY

GDS → CAMP

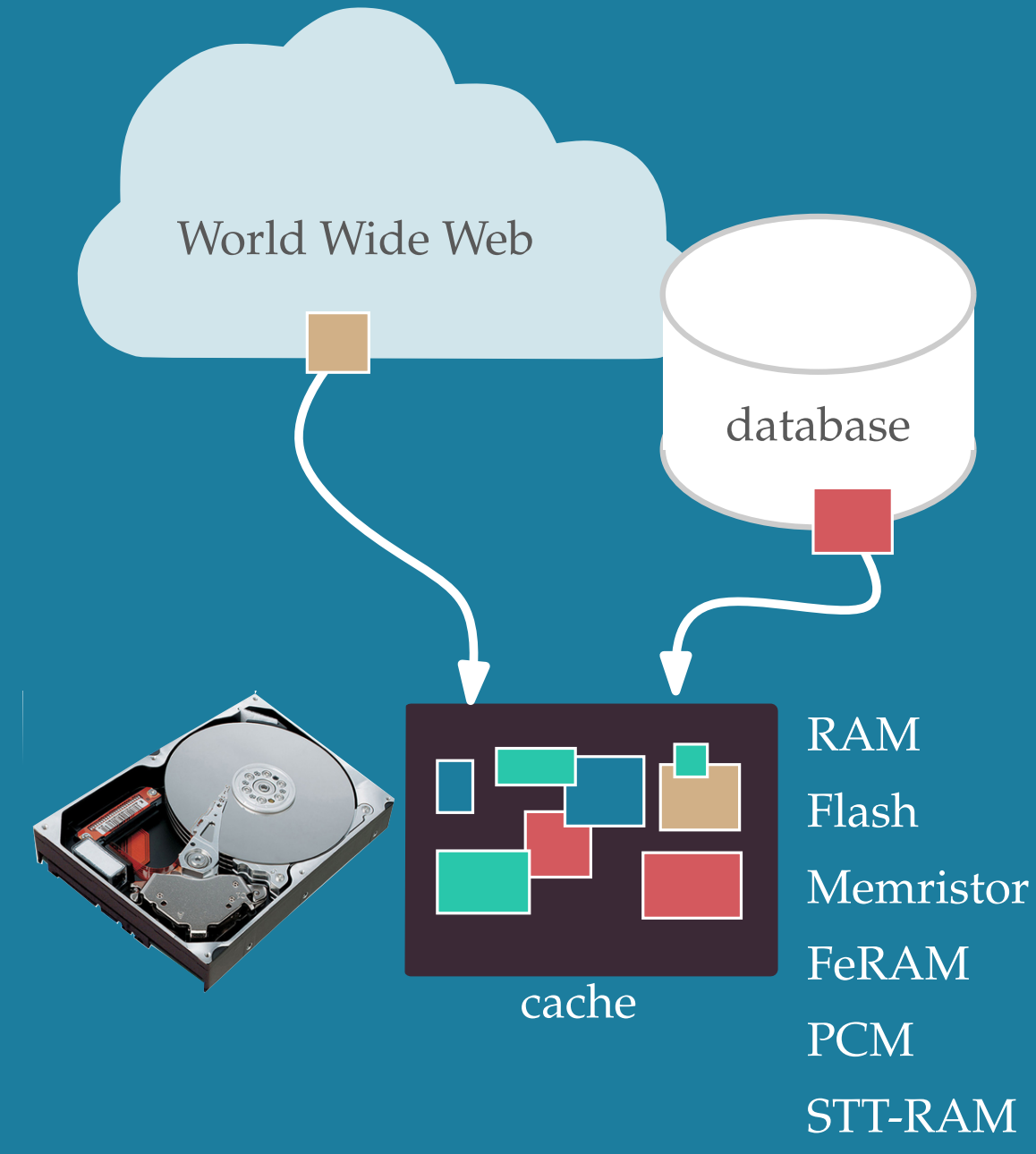
PLACEMENT POLICY

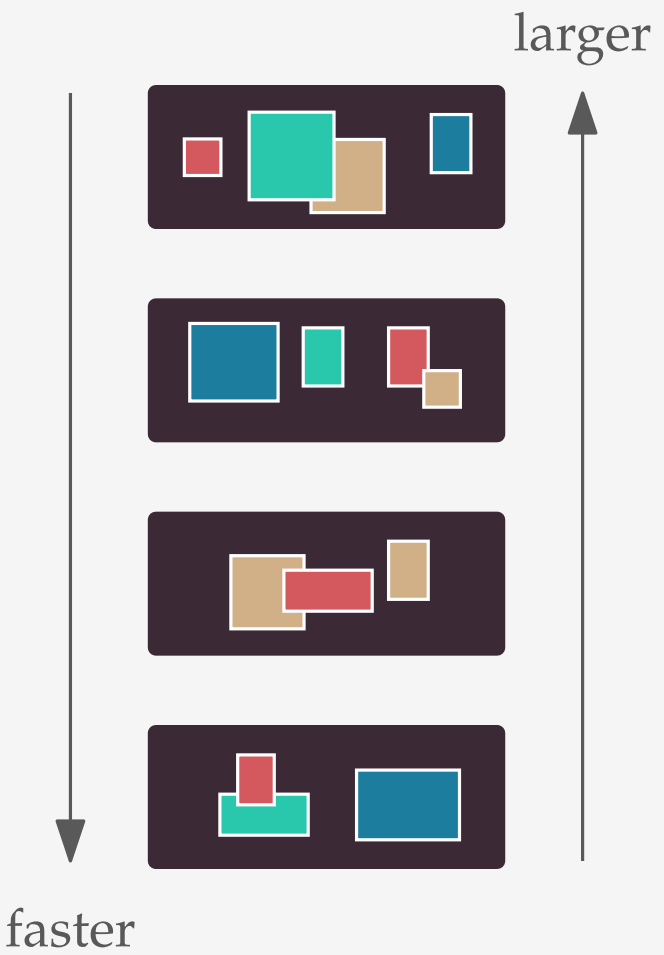
generalized caching → managed memory caching



MEMORY HIERARCHY

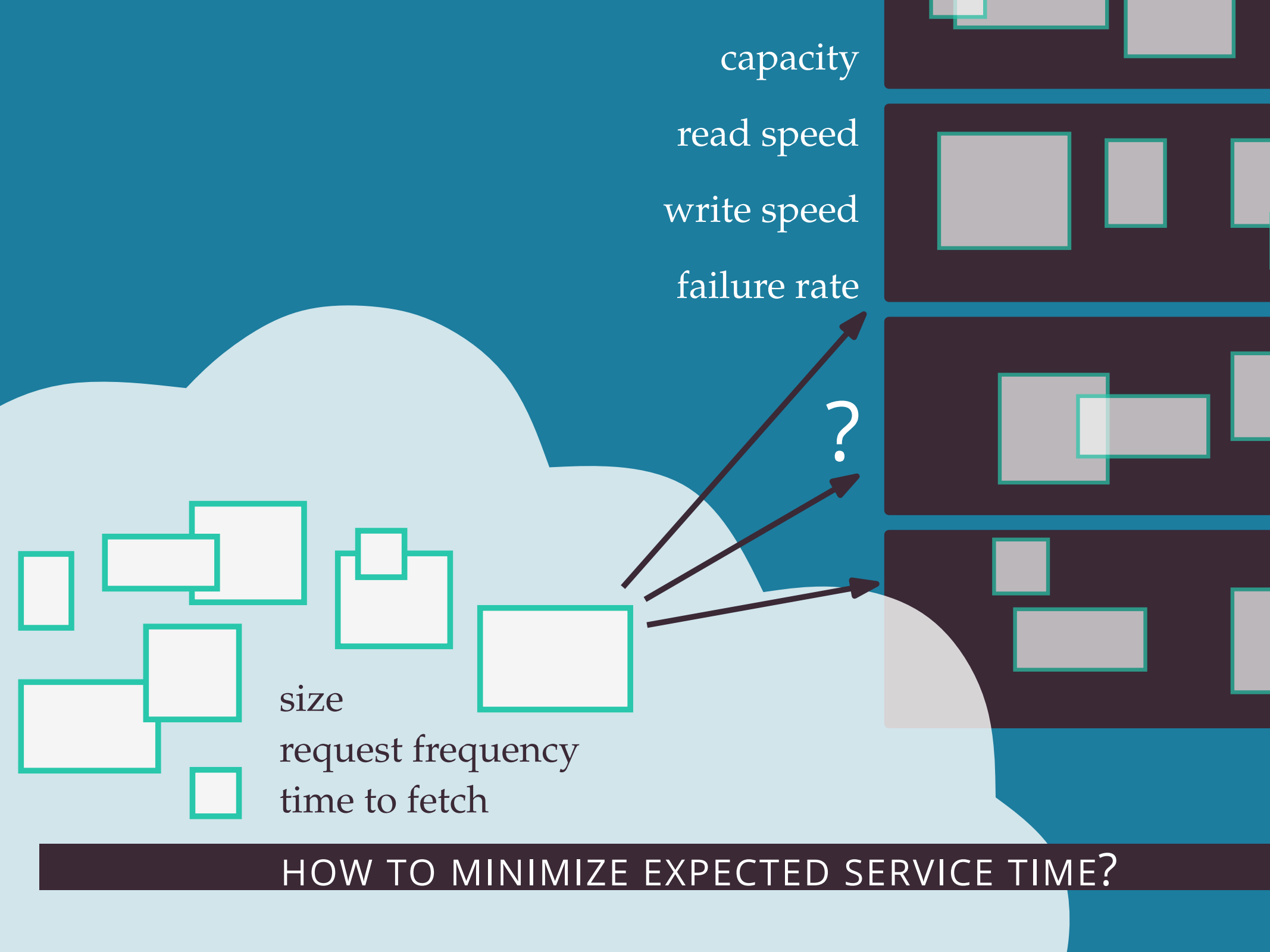
2-level cache → multi-level cache



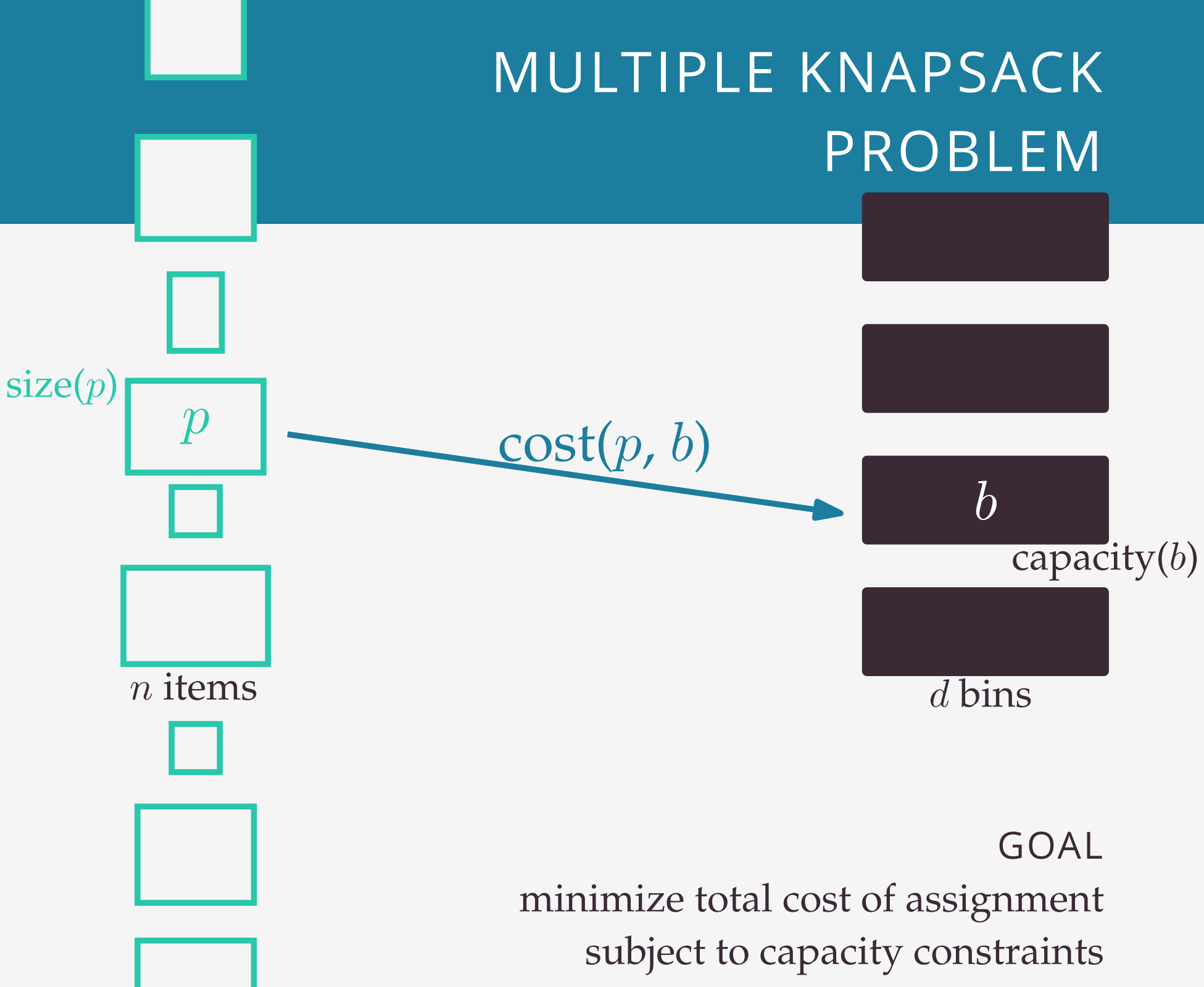


TIERED MEMORY ARCHITECTURE

GENERALIZED CACHING


capacity
read speed
write speed
failure rate
?
size
request frequency
time to fetch
HOW TO MINIMIZE EXPECTED SERVICE TIME?

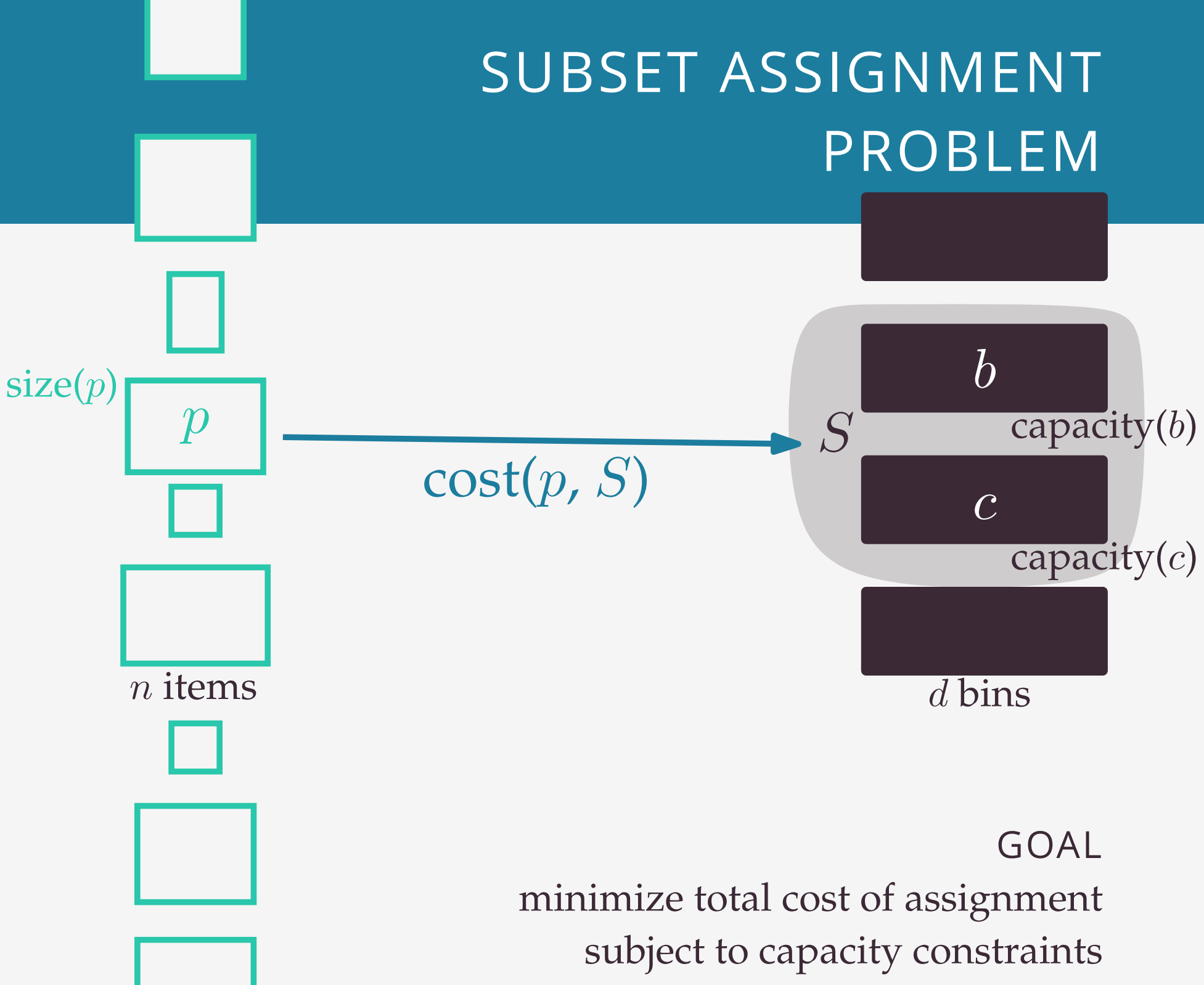
MULTIPLE KNAPSACK PROBLEM



GOAL

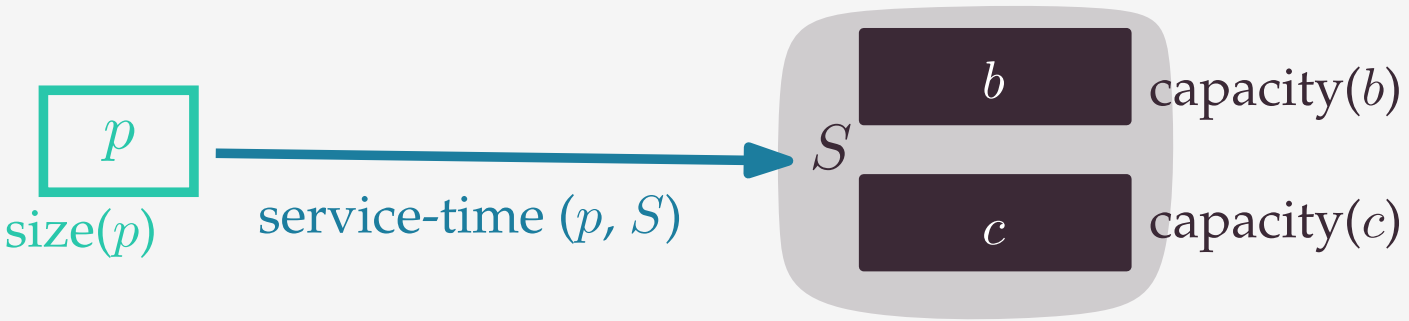
minimize total cost of assignment
subject to capacity constraints

SUBSET ASSIGNMENT PROBLEM

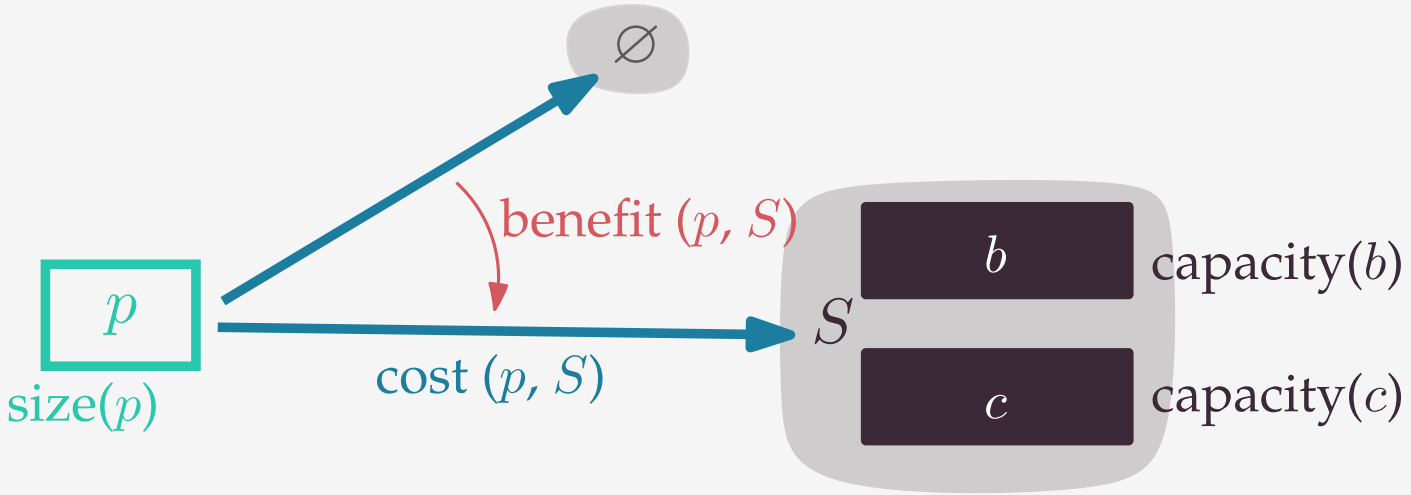


GOAL

minimize total cost of assignment
subject to capacity constraints



$$
\begin{aligned}
\text{service-time}(p, S) \;=\;& \text{read-frequency}(p) \quad \text{read-time}(p, S) \\
&+ \quad \text{write-frequency}(p) \quad \text{write-time}(p, S) \\
&+ \quad \sum_{F \subseteq S} \text{fail-freq}(F) \quad \Big(\text{read-time}(p, S \setminus F) \\
&\qquad\qquad\qquad\qquad + \text{write-time}(p, S \cap F) \Big)
\end{aligned}
$$



cache configuration

$$\text{maximize} \sum_{p,S} \text{benefit}(p,S)\, x(p,S)$$

$$\sum_{S} x(p,S) = 1$$

$$\sum_{p,S} \text{price}(p,S) x(p,S) \leq \text{budget}$$

$$x = 0, 1$$

subset assignment

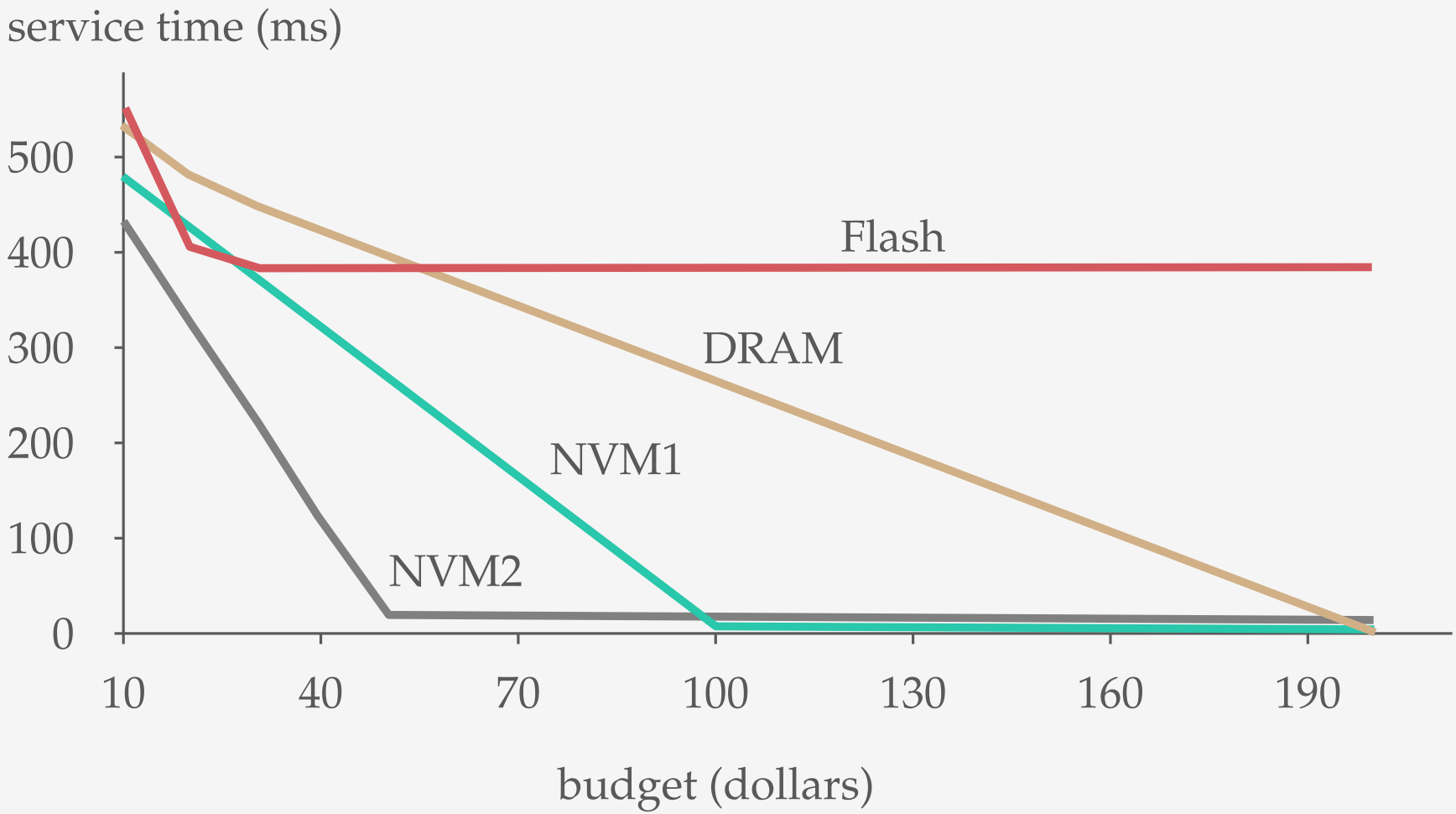
$$\text{minimize} \sum_{p,S} \text{cost}(p,S)\, x(p,S)$$

$$\sum_{S} x(p,S) = \text{size}(p)$$

$$\sum_{p,S \ni b} x(p,S) \leq \text{capacity}(b)$$

$$x(p,S) = 0, \text{size}(p)$$

CACHE CONFIGURATION



SUBSET ASSIGNMENT

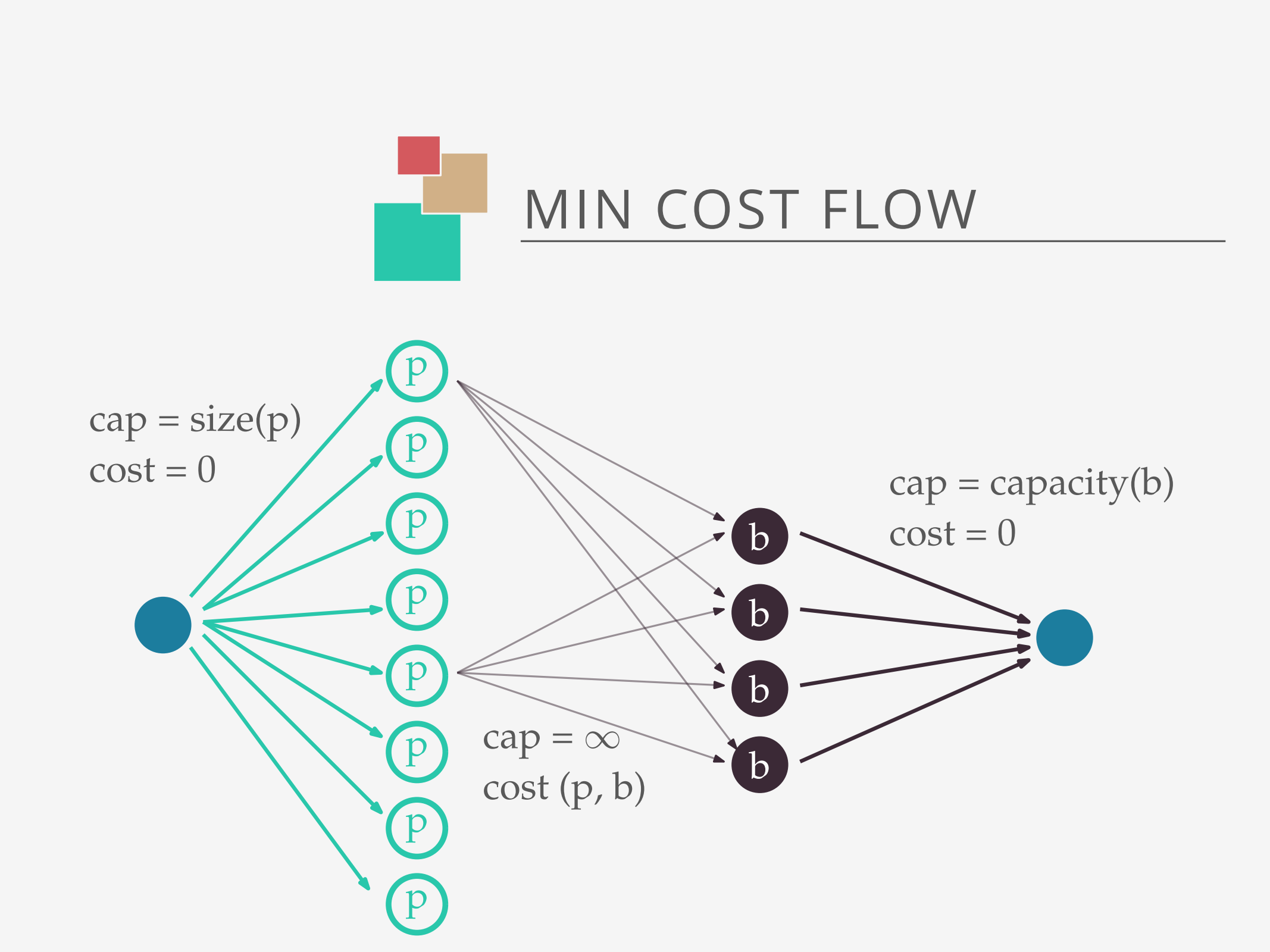
HAVE $d \ll n$

sol to LP relaxation has few fractional assignments

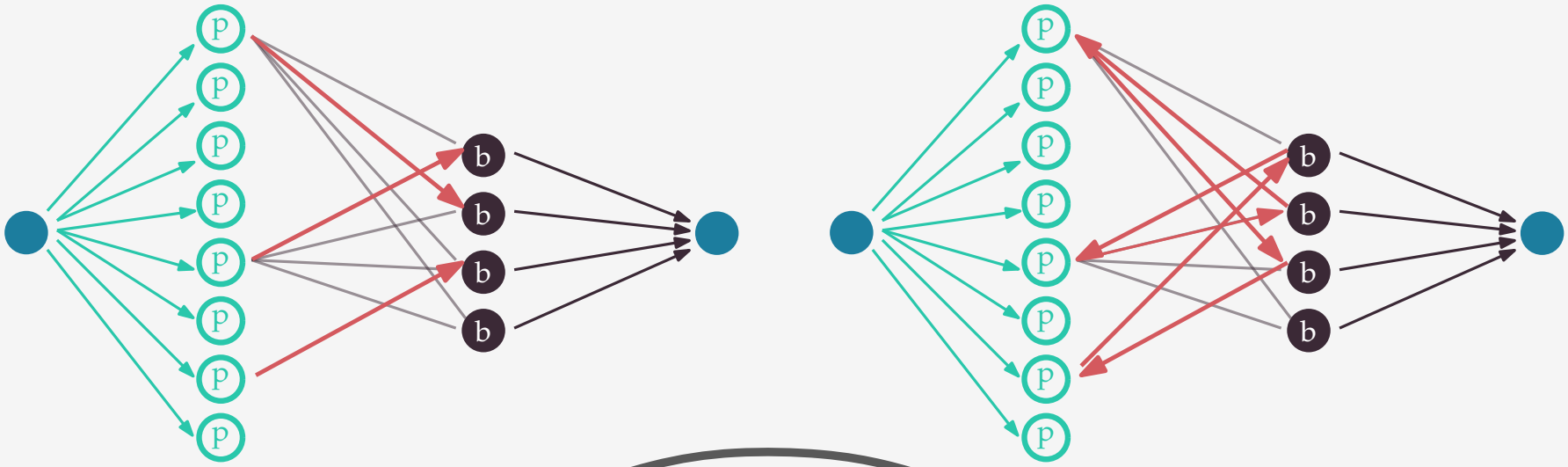
GOAL solve LP relaxation in f(d) poly(n)

1. cycle canceling algorithm

2. simplex algorithm


MIN COST FLOW
cap = size(p)
cost = 0
p
p
p
p
p
p
p
p
cap = ∞
cost (p, b)
b
b
b
b
cap = capacity(b)
cost = 0

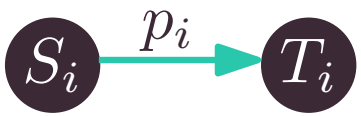
1. cycle canceling algorithm



feasible flow
in original network

negative cycle
in residual network

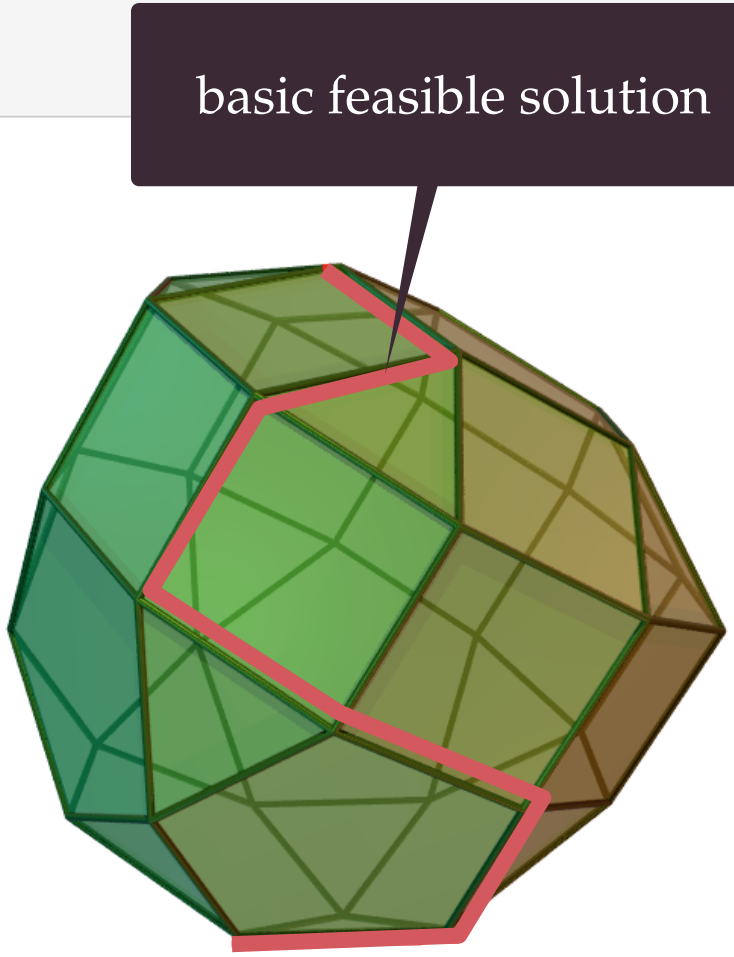
“cycle” in subset assignment problem

augmentation 

such that $\sum_i \alpha_i \overrightarrow{S_i T_i} = \vec{0}$

cost difference (negative) $\sum_i \alpha_i \ (\text{cost}(p_i, T_i) - \text{cost}(p_i, S_i))$

2. simplex algorithm



BASIC FEASIBLE ASSIGNMENT

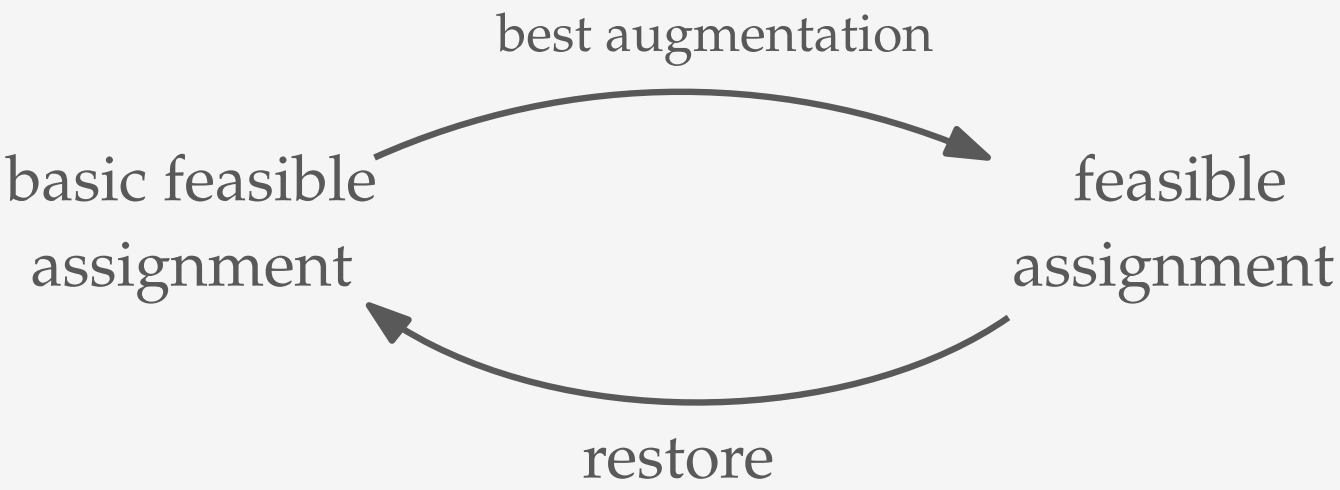
$< 2d$ fractional assignments

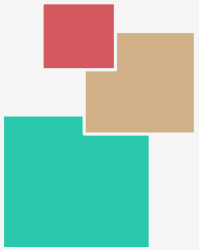
bound granularity of vars

$$x(p, S) = \frac{k}{\ell}$$

$< d^{d/2}$

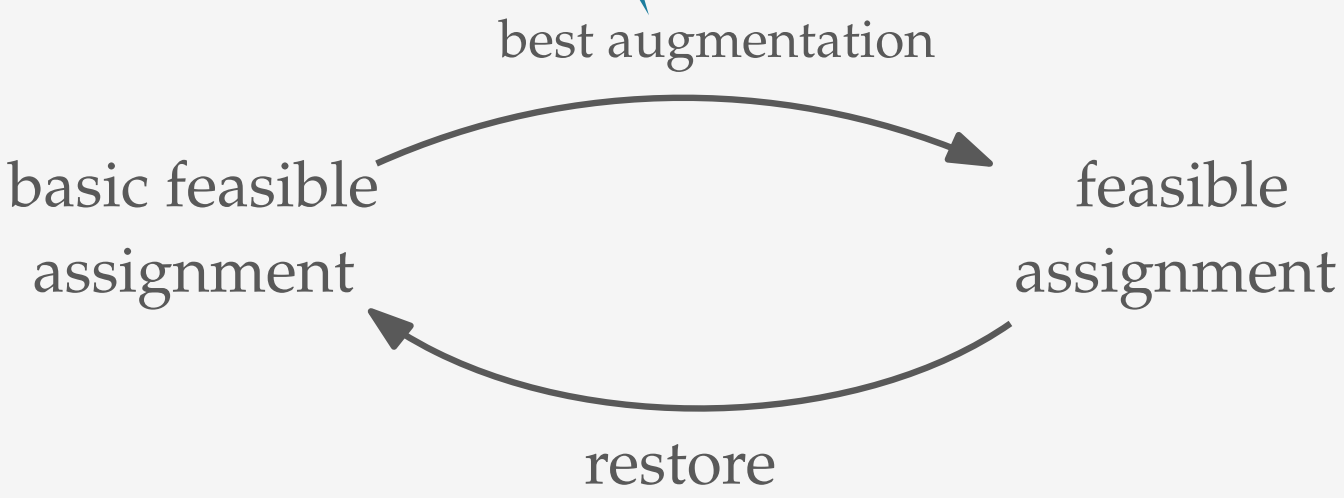
ALGORITHM


best augmentation
basic feasible assignment
feasible assignment
restore



ALGORITHM

preprocessing $\sum_i \alpha_i \overrightarrow{S_i T_i} = \vec{0}$



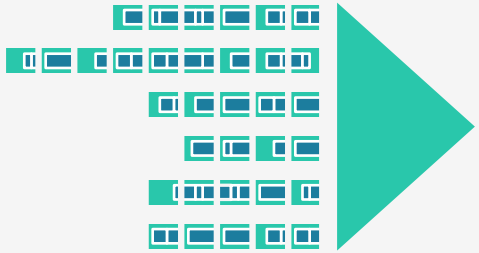
time $O(\exp(d(d+1)\text{poly}(d)\ \ n\log(n)\log(nC)\log(S))$

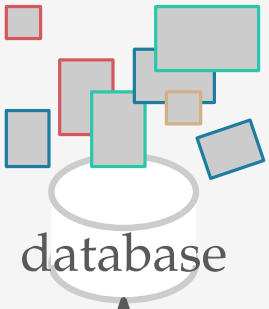
EVICTION POLICY

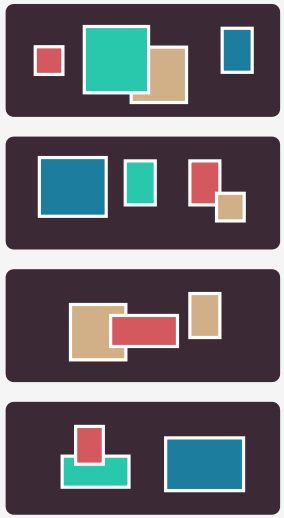
CAMP

PLACEMENT POLICY

CAMP-malloc







MEMORY HIERARCHY

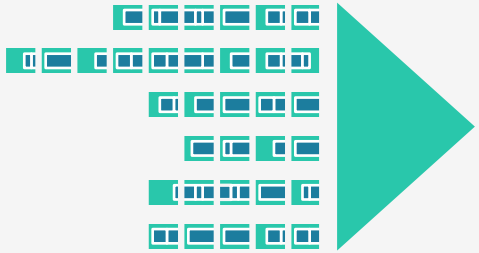
cache configuration

subset asssignment

EVICTION POLICY

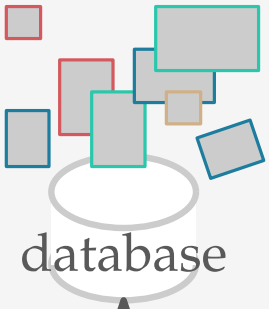
CAMP

PLACEMENT POLICY



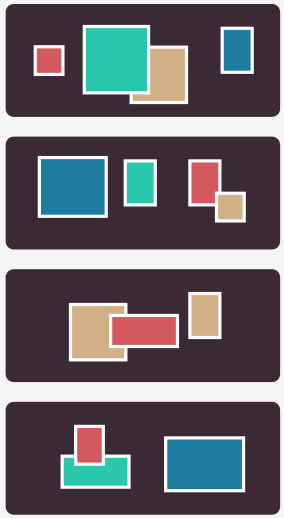
CAMP-malloc

LRU-FIFO hybrid?



KVS

server



MEMORY HIERARCHY

cache configuration

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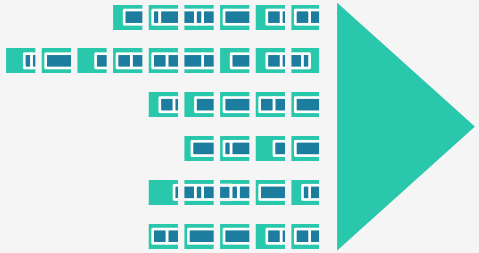
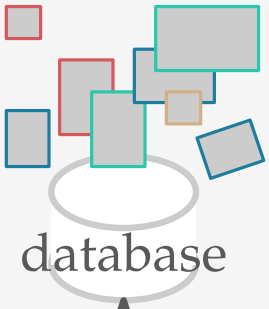
CAMP

PLACEMENT POLICY



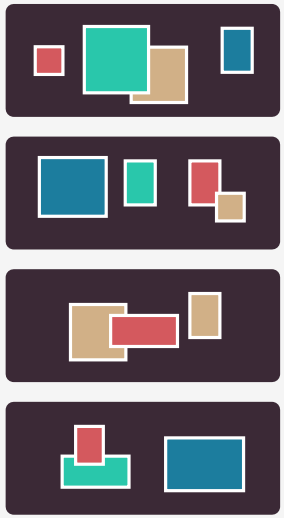
CAMP-malloc

LRU-FIFO hybrid?



KVS

server



MEMORY HIERARCHY

cache configuration

subset asssignment

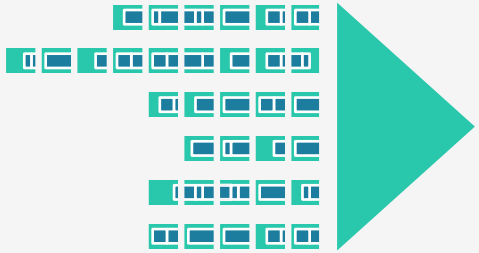
continual updates?

EVICTION POLICY

CAMP

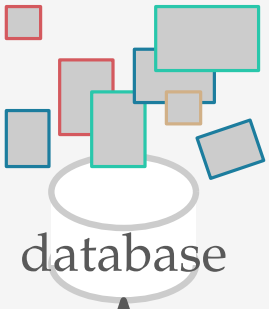
customer fairness?

PLACEMENT POLICY



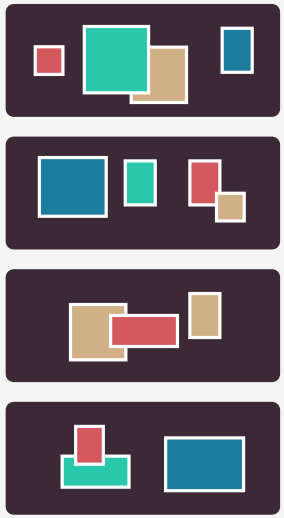
CAMP-malloc

LRU-FIFO hybrid?



KVS

server



MEMORY HIERARCHY

cache configuration

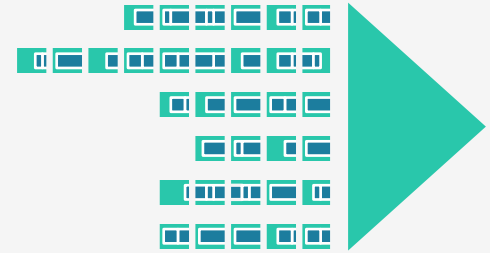
subset asssignment

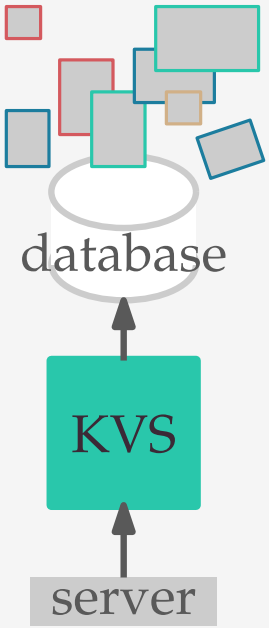
continual updates?

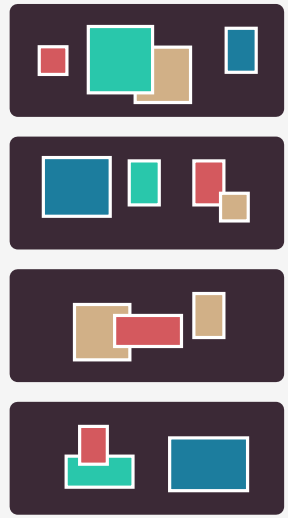
CAMP: a cost adaptive multi-queue eviction policy for key-value stores. Shahram Ghandeharizadeh, Sandy Irani, Jenny Lam, and Jason Yap. In Proceedings of the 15th International Middleware Conference, 2014.

A demonstration of KOSAR: an elastic, scalable, highly available SQL middleware. Shahram Ghandeharizadeh, Connor Gorman, Sandy Irani, Shiva Jahangiri, Jenny Lam, Hieu Nguyen, Ryan Tani and Jason Yap, Middleware 2014.

Cache replacement with memory allocation. Shahram Ghandeharizadeh, Sandy Irani, and Jenny Lam. In Proceedings of the 17th Workshop on Algorithm Engineering and Experiments (ALENEX), 2015.







Memory hierarchy design for caching middleware in the age of NVM. Shahram Ghandeharizadeh, Sandy Irani, and Jenny Lam. 7th Annual Non-Volatile Memories Workshop, 2016.

The subset assignment problem for data placement in caches. Shahram Ghandeharizadeh, Sandy Irani, and Jenny Lam. (in submission)