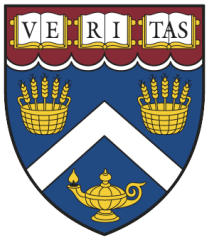
Compacting Collectors



Compacting Garbage Collection

- Copy reserve overhead can be significant
  - Later algorithms reduce it by a lot
- Can we get the benefits of copying without it?
- Compacting algorithms
  - Eliminate fragmentation by moving objects
  - Move objects within the same heap region

Compaction Algorithms

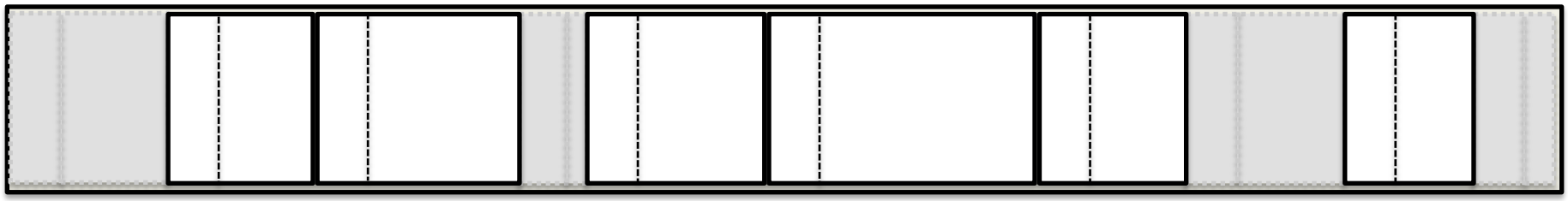
- Compacting happens in multiple passes
  - Figure out where objects will go
  - Update object references
  - Move the objects
- Need to track where the object goes after copy
  - Install forwarding pointers for copying GCs
  - We can overwrite headers because there is a copy
- Can't use forwarding pointers when compacting

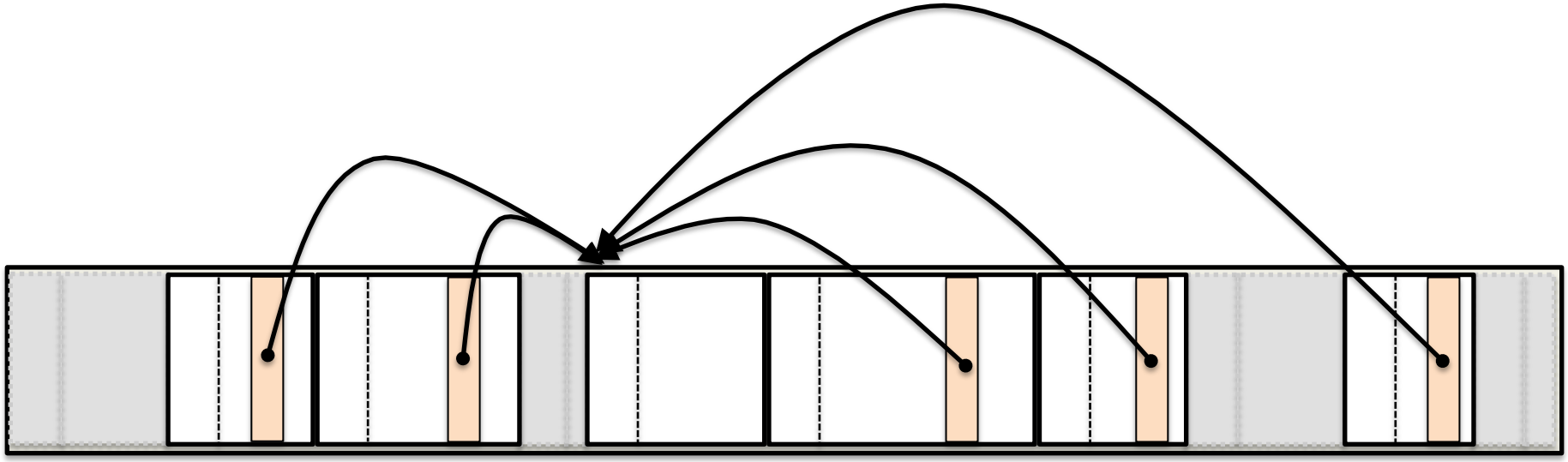
Tracking Forwarding Locations

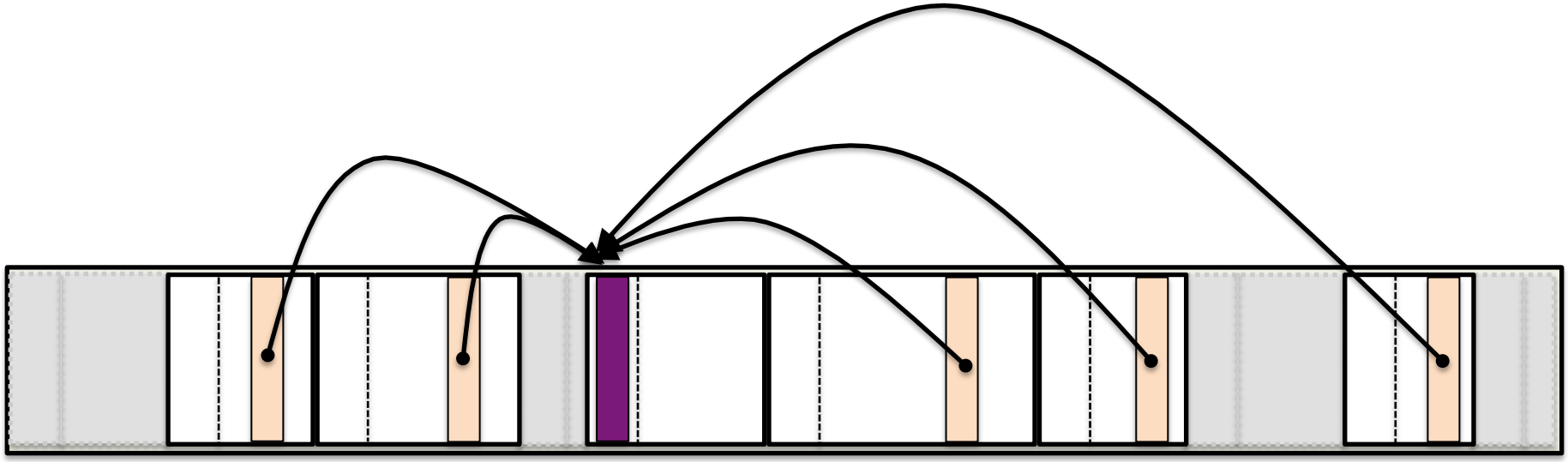
- Use an extra word per object
  - High per-object overhead
- Use a table off to the side
  - Table size scales with heap size
- Chain references

Reference Chaining

- Object graph is directional
  - Reference fields point to objects
  - No pointer in the other direction
- Can we reverse the direction of the graph?
  - Many-to-one problem
- We can build a linked list of references
  - Assume one word available in the header
  - Assume alignment gives us one free bit per pointer

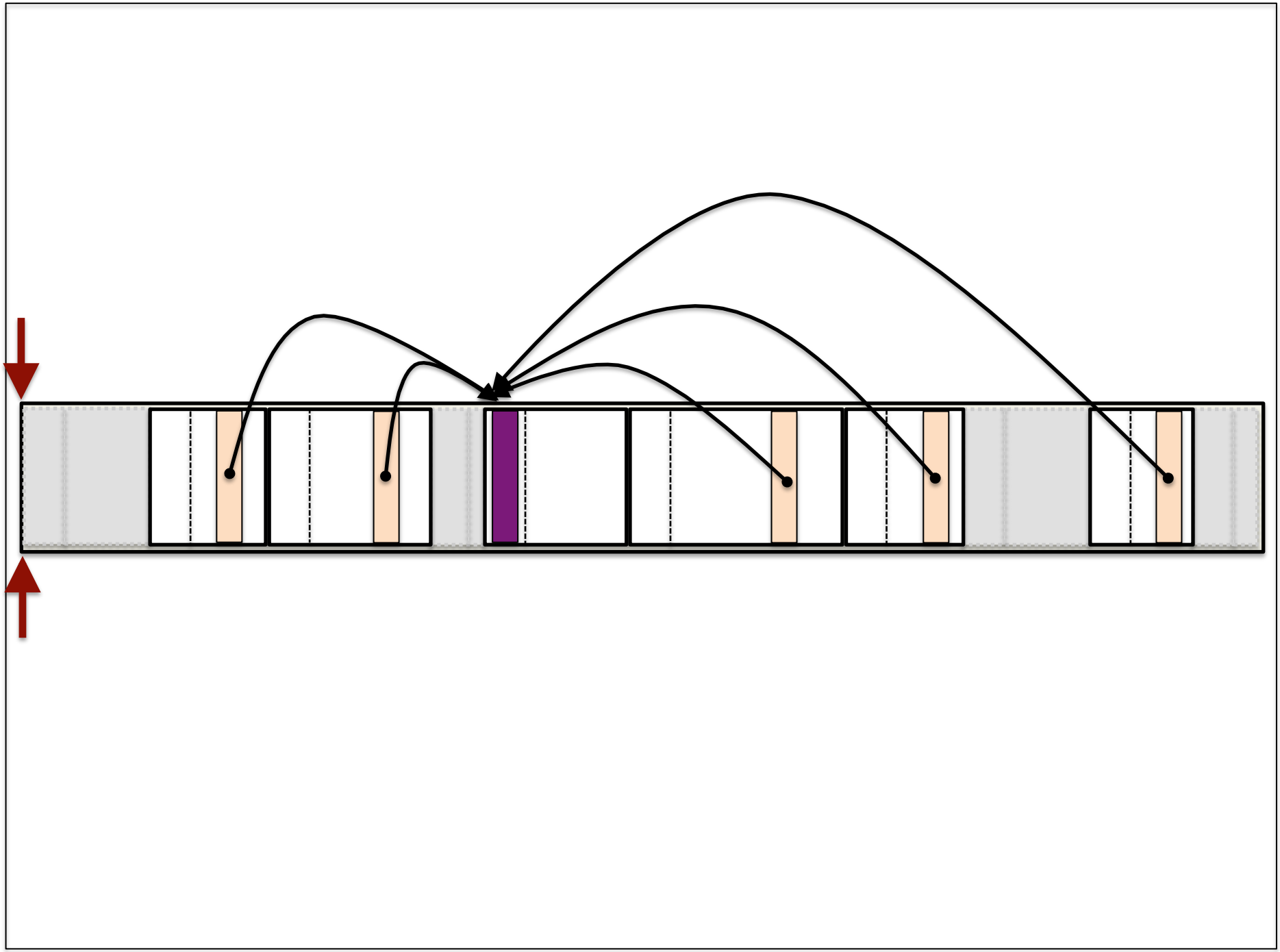


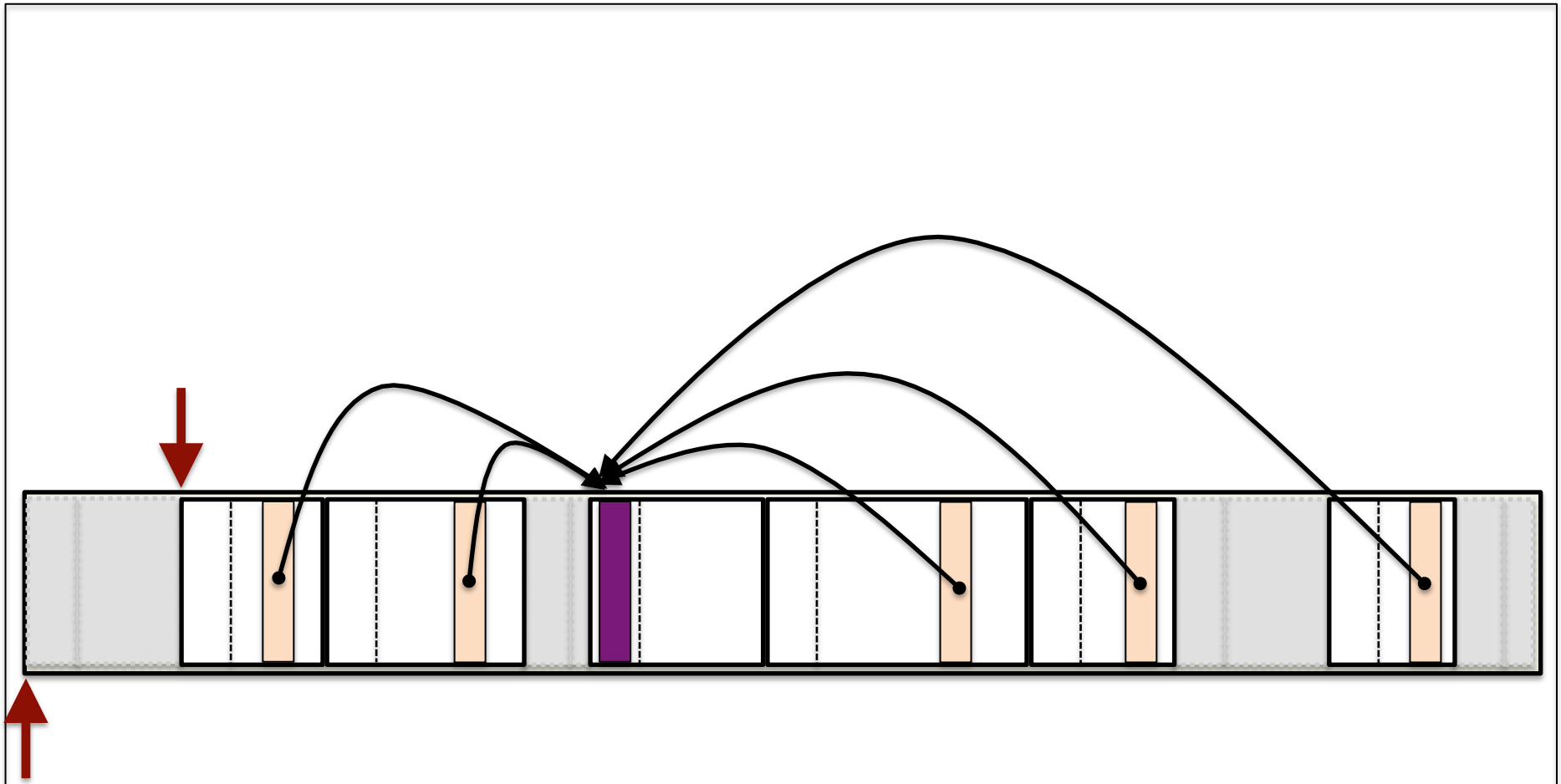


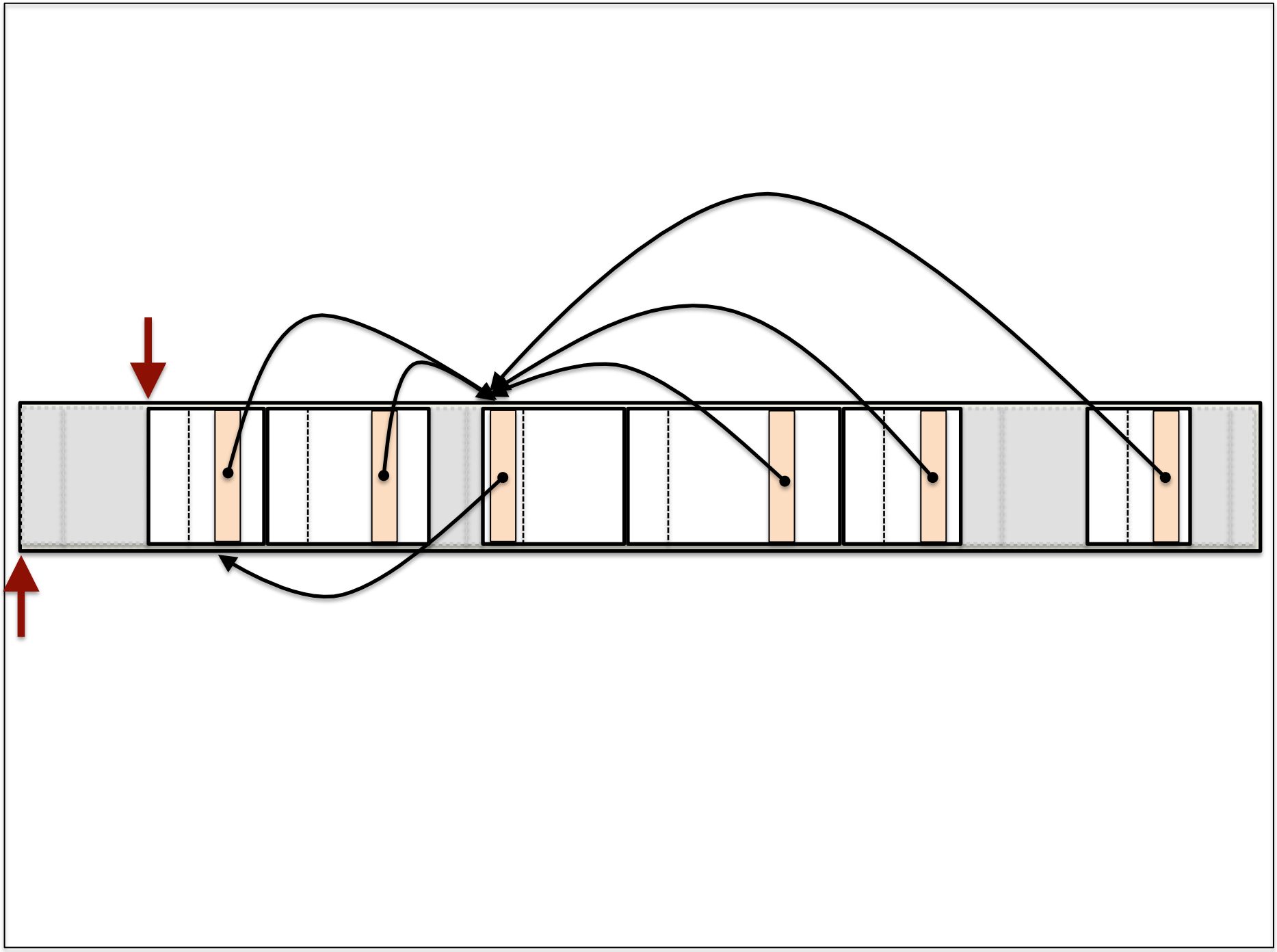


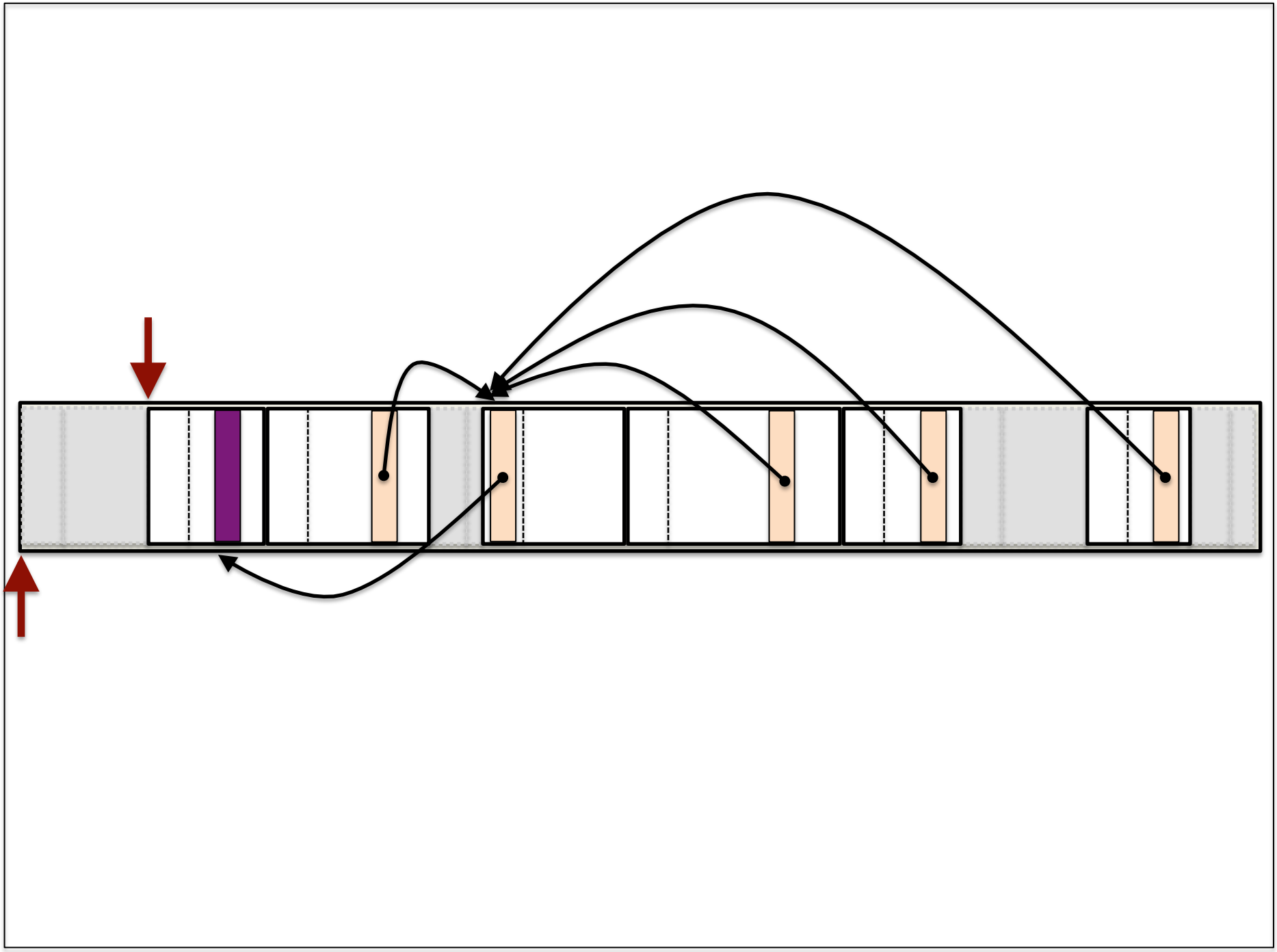
First Pass

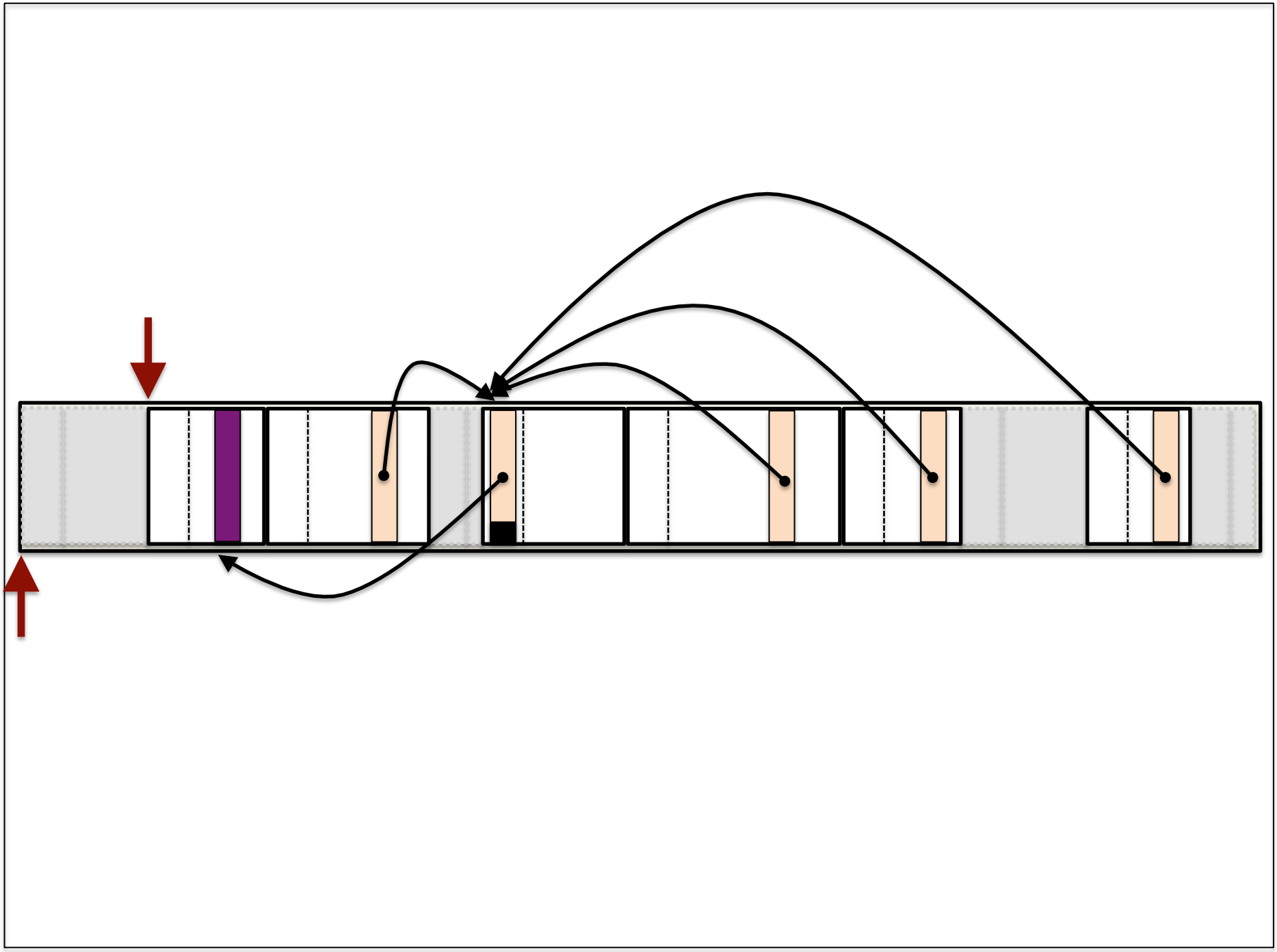
- Scan the heap linearly
  - We don't have to worry about holes
- Look only at references to live objects
  - Follows from tracing only marked objects
- Keep track of object sizes
- Reverse the direction of pointers
  - Use one bit as a flag to keep track

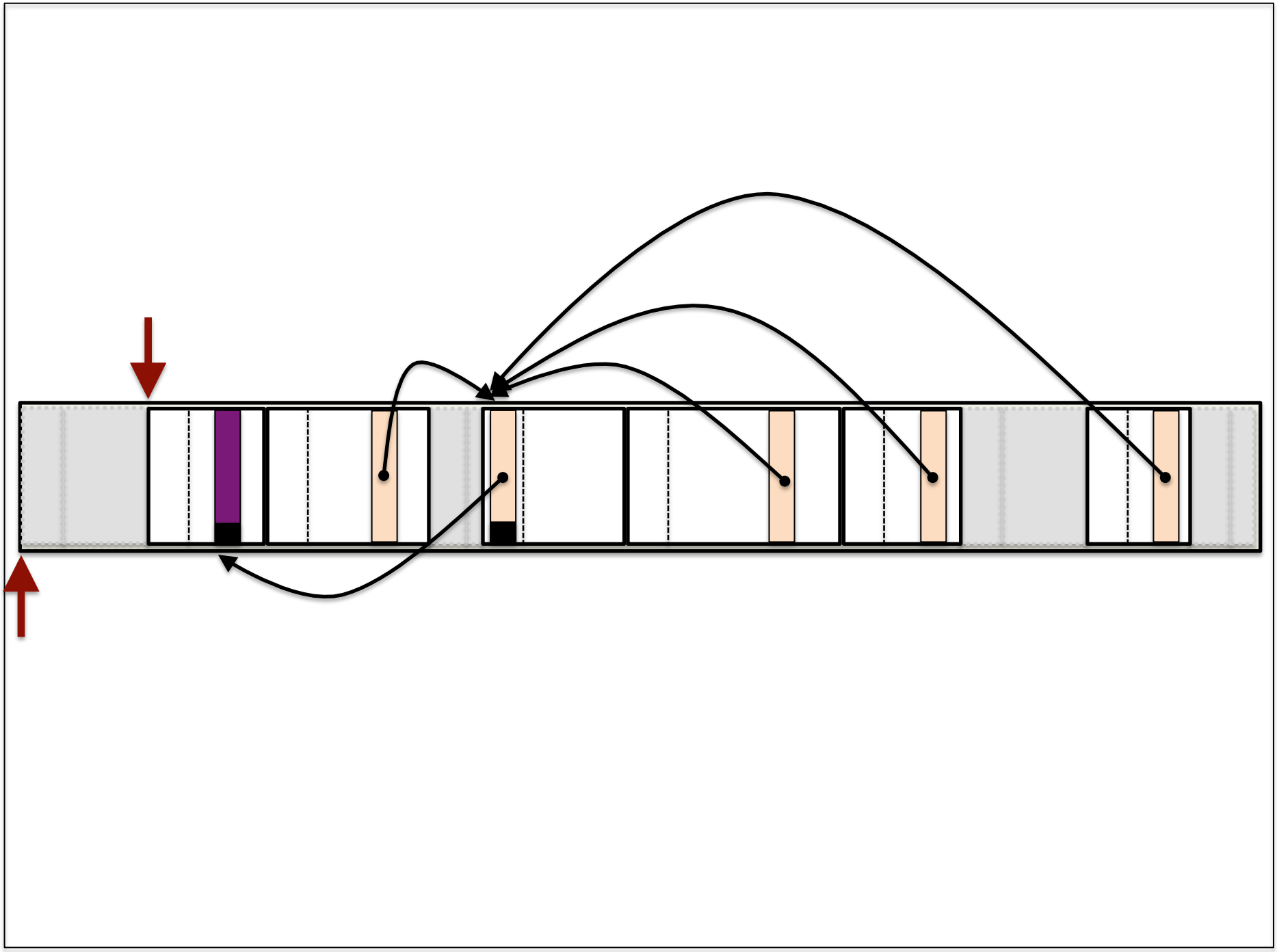


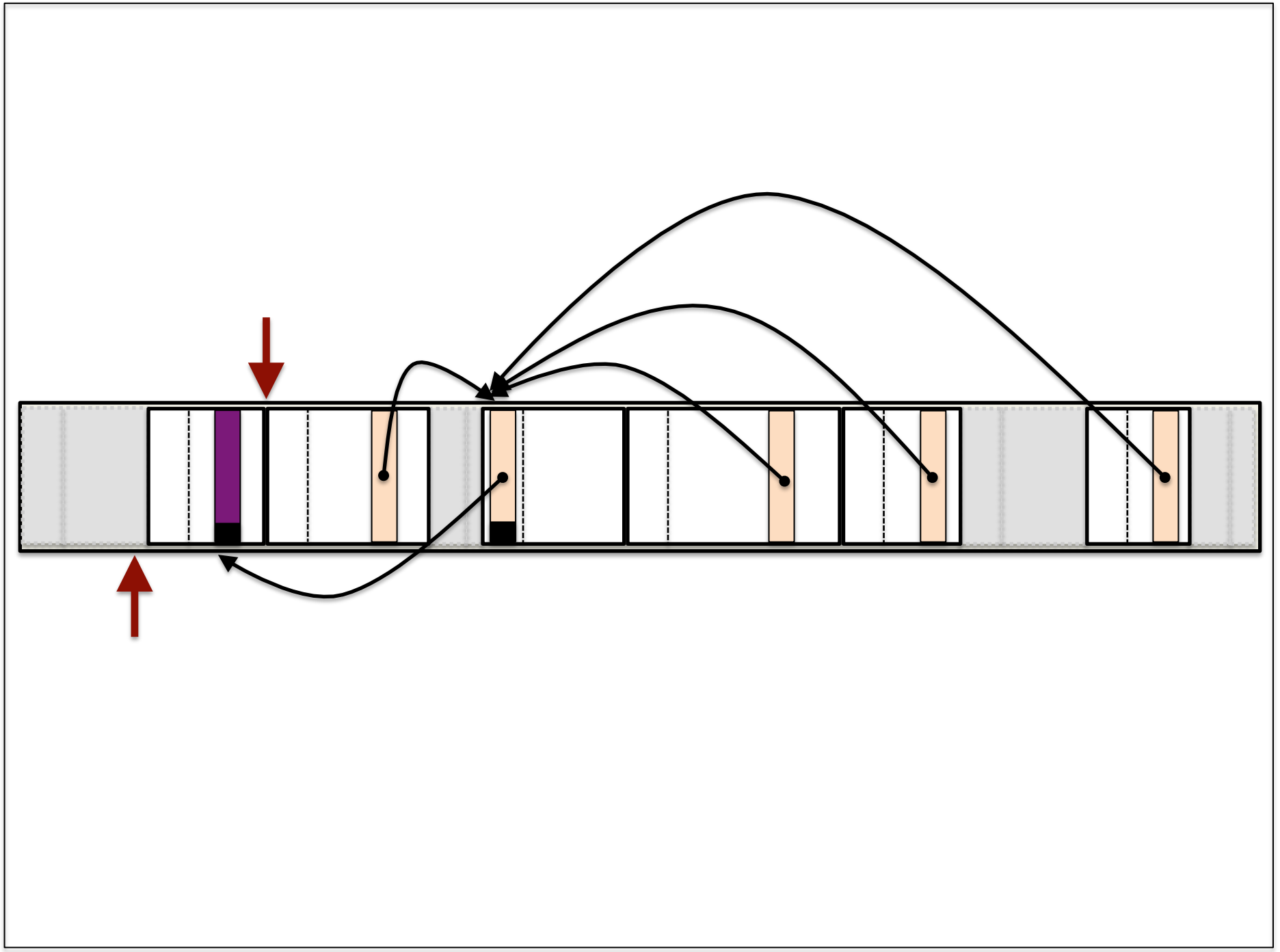


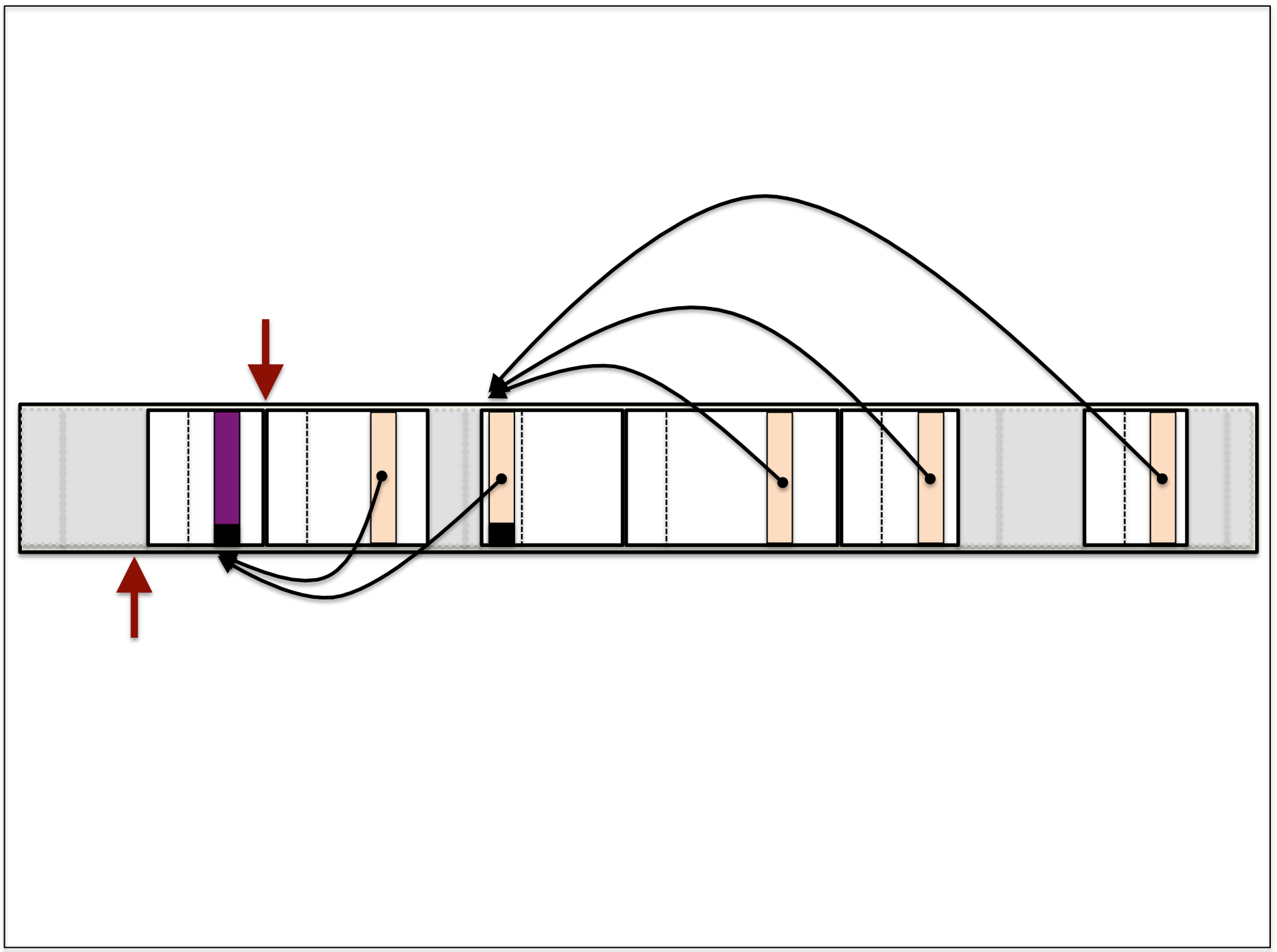


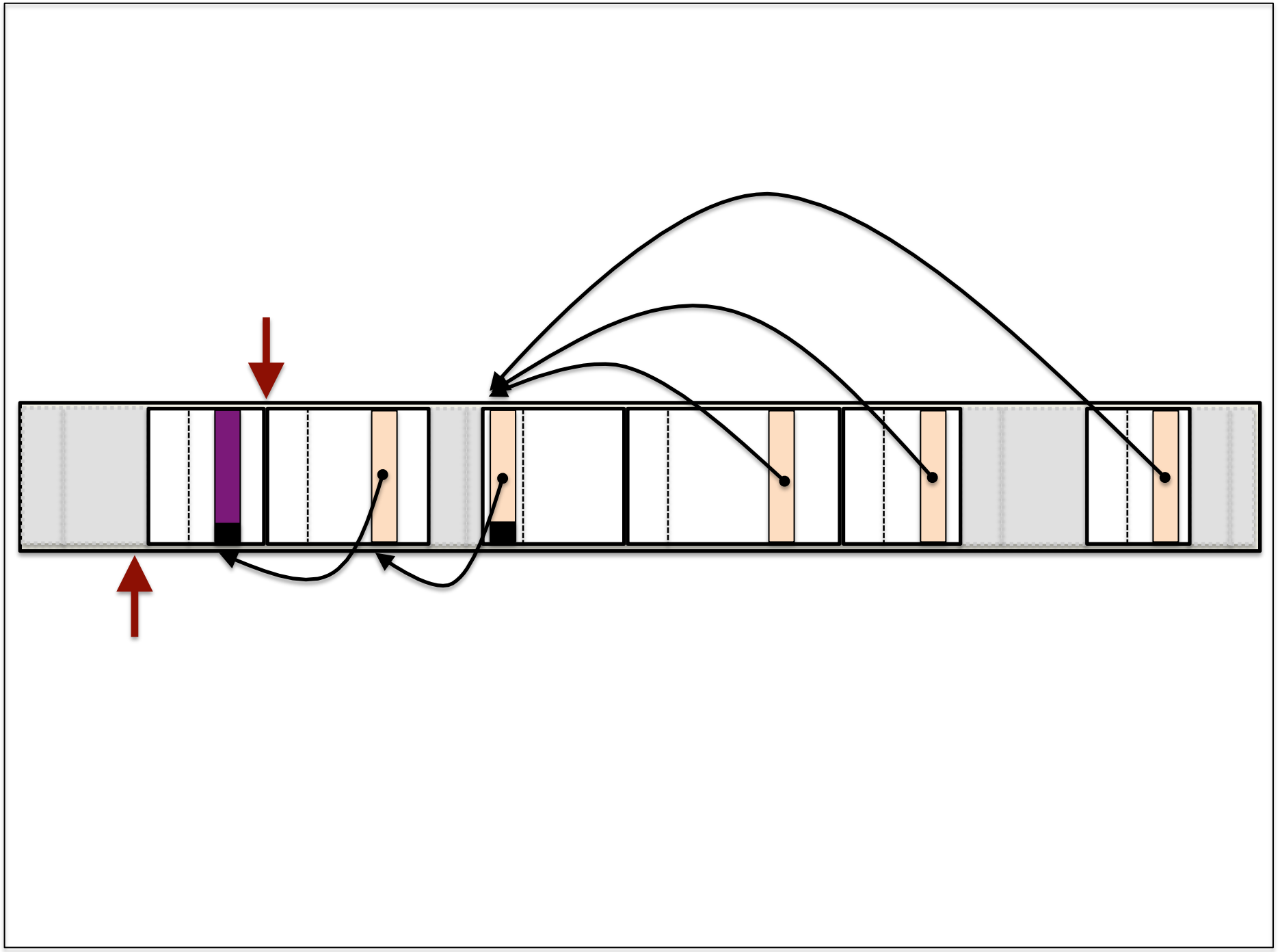


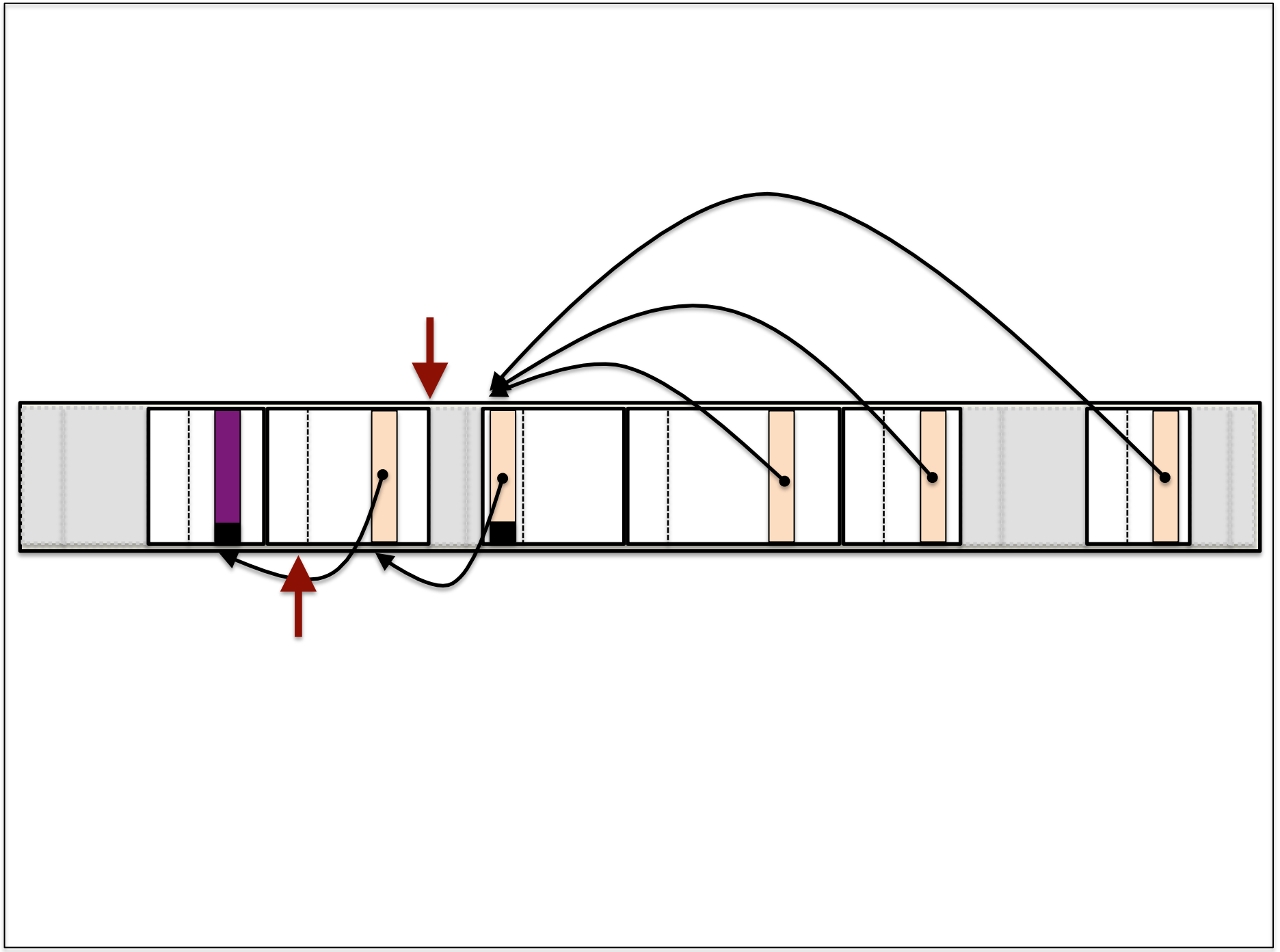


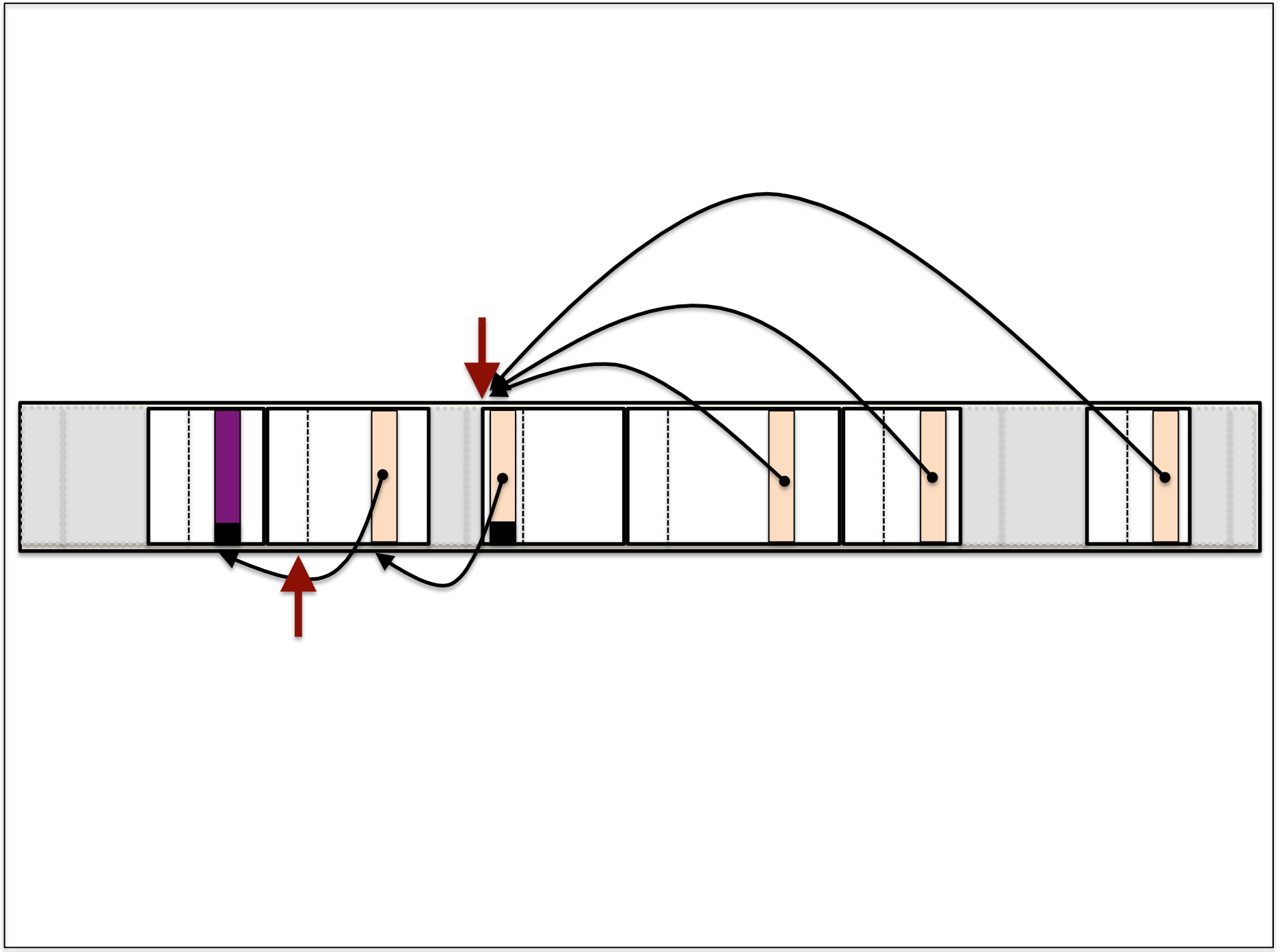






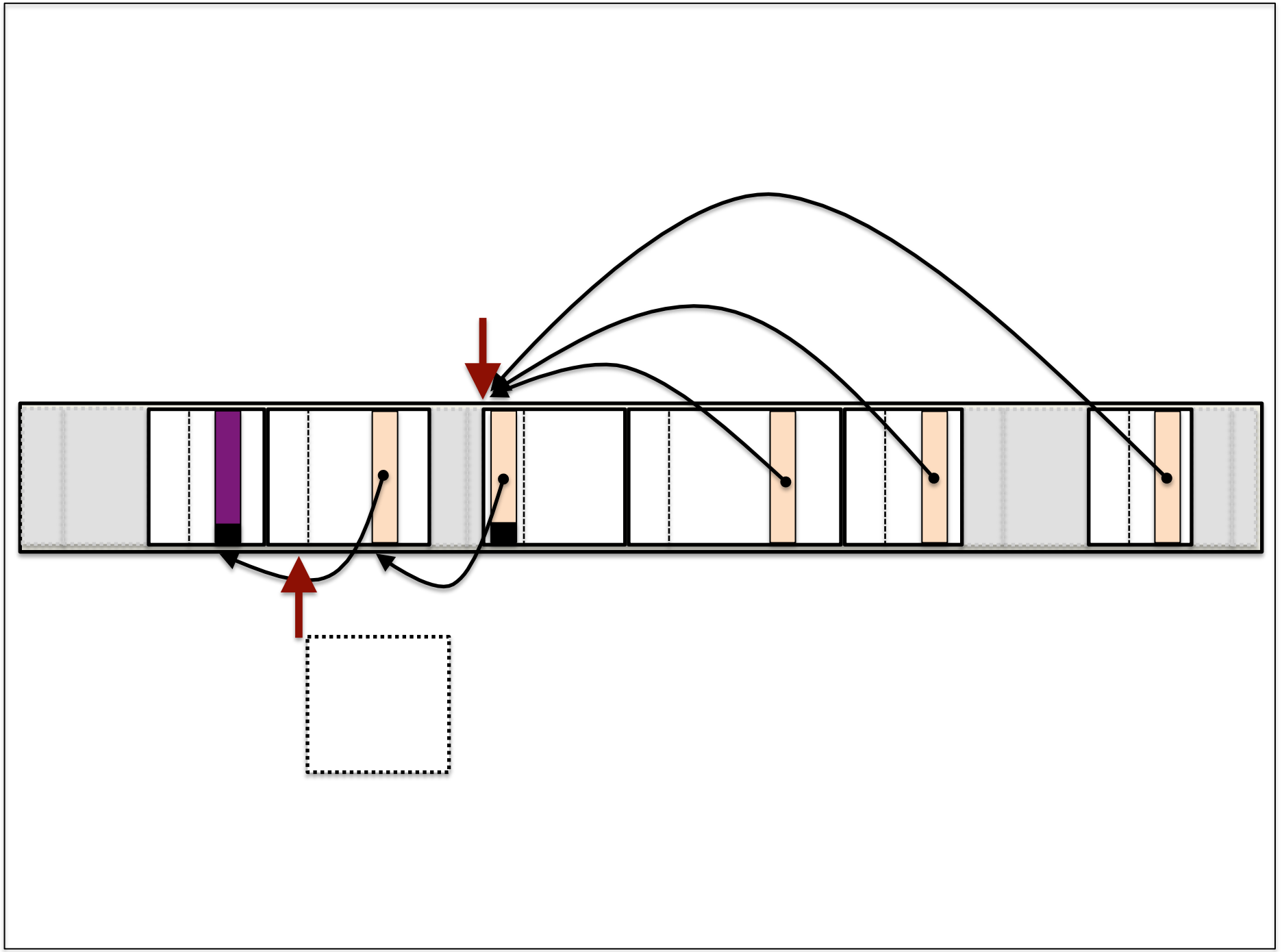


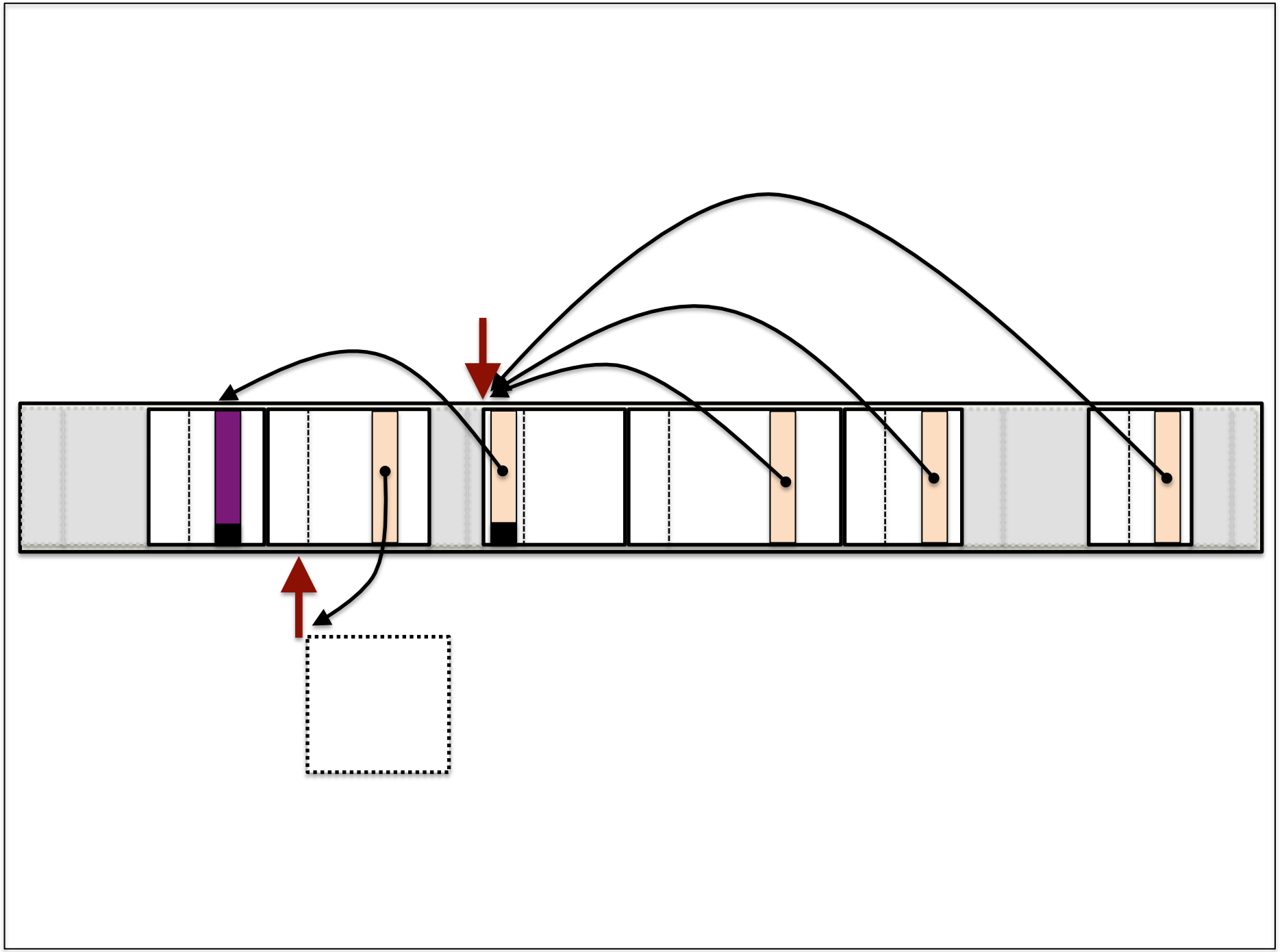


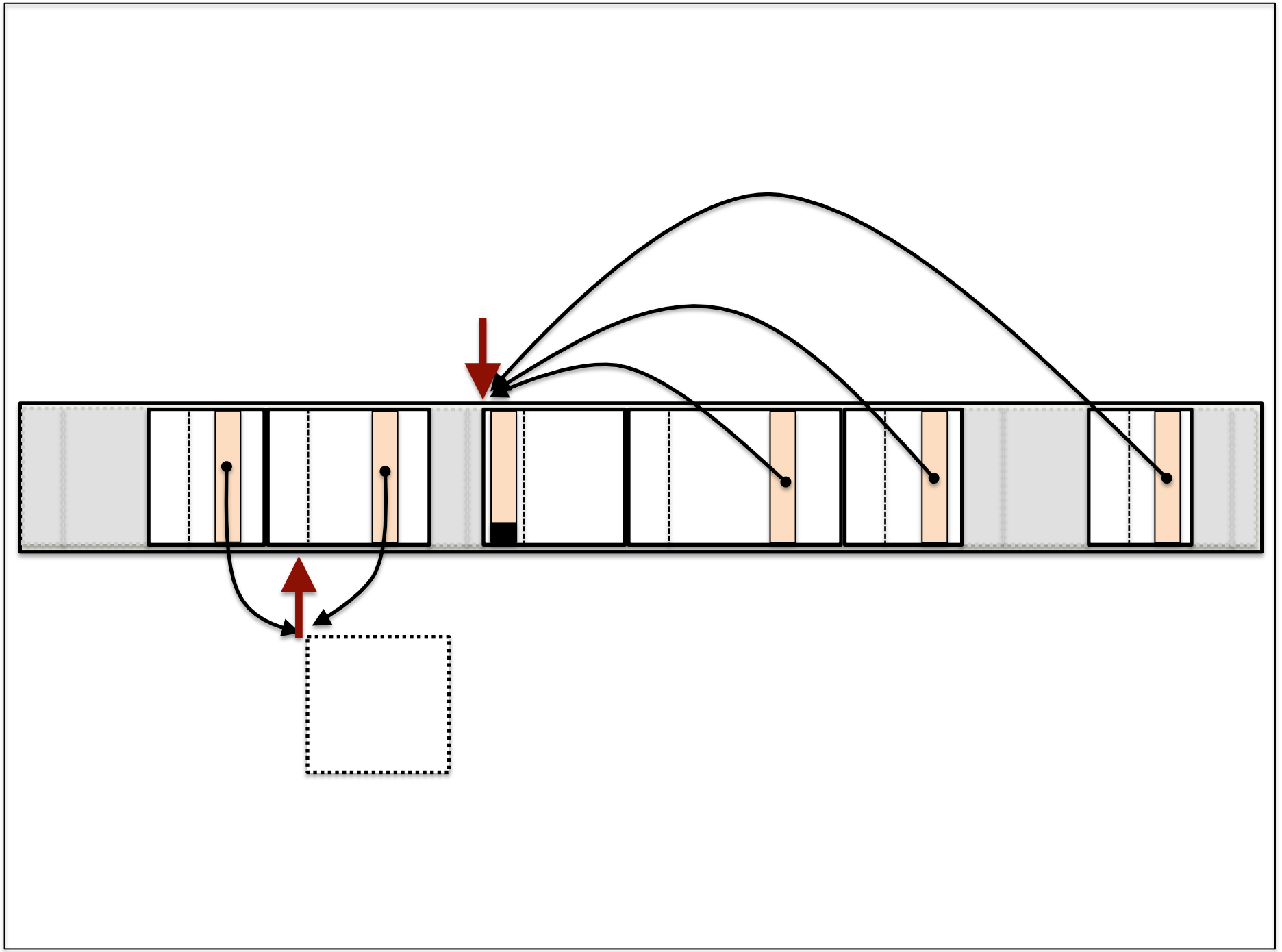


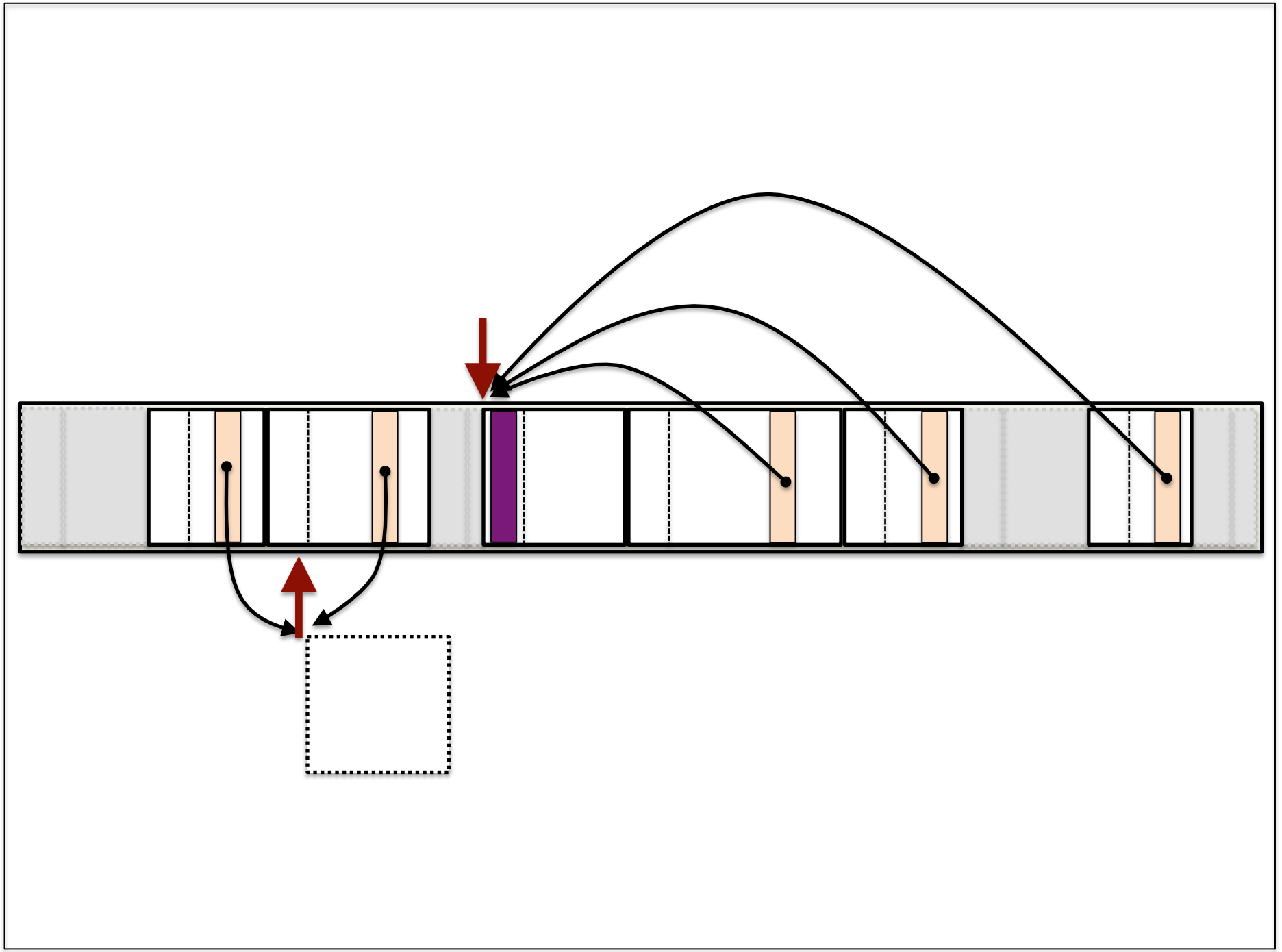
Compacted Offset

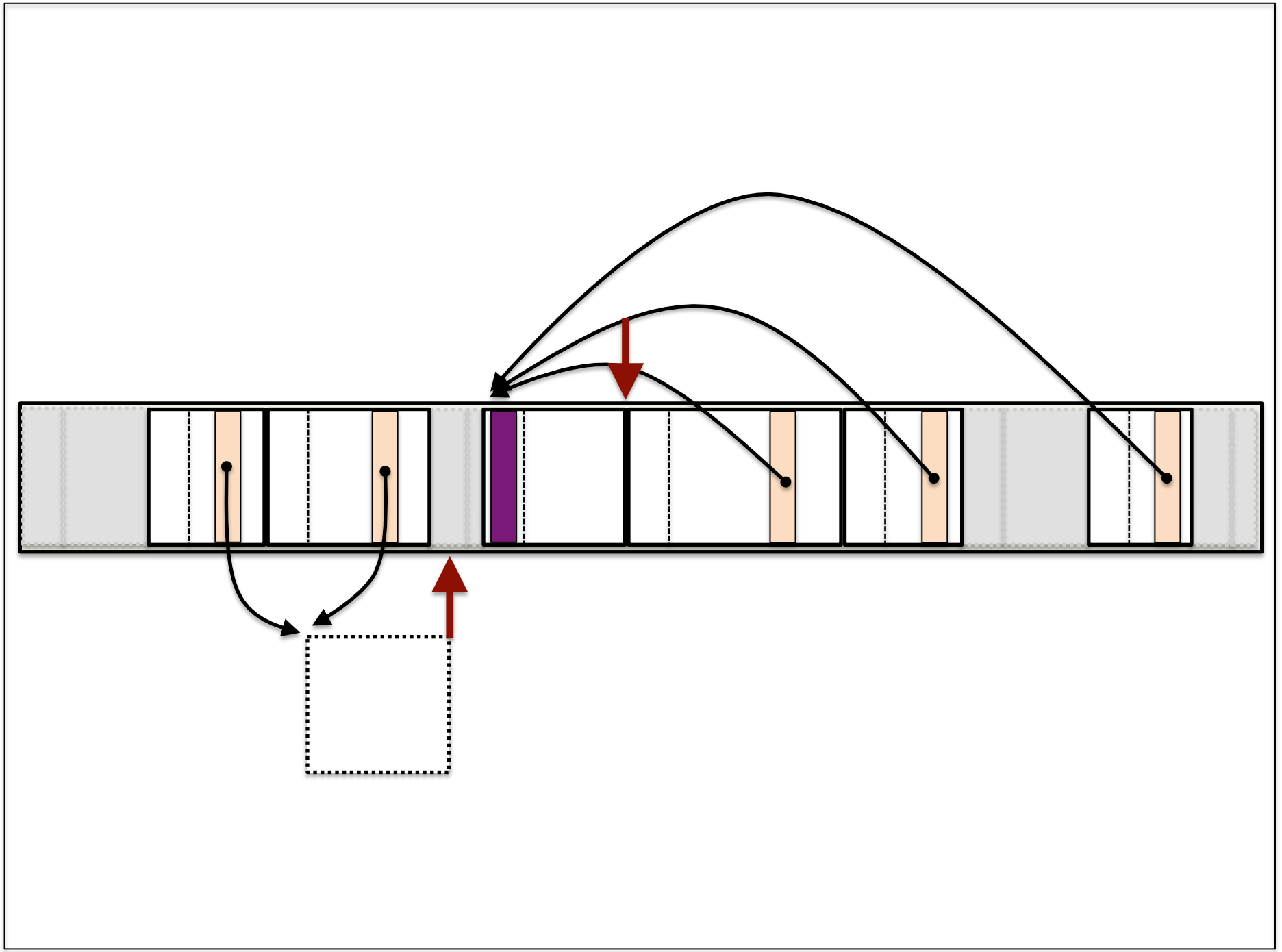
- We can compute where the object will go
  - We've scanned all objects lower in the heap
  - We can keep track of their sizes as we go
- Can't move the object just yet
  - Previous objects haven't been compacted
- Can't compact on first pass
  - There are still references that haven't been scanned

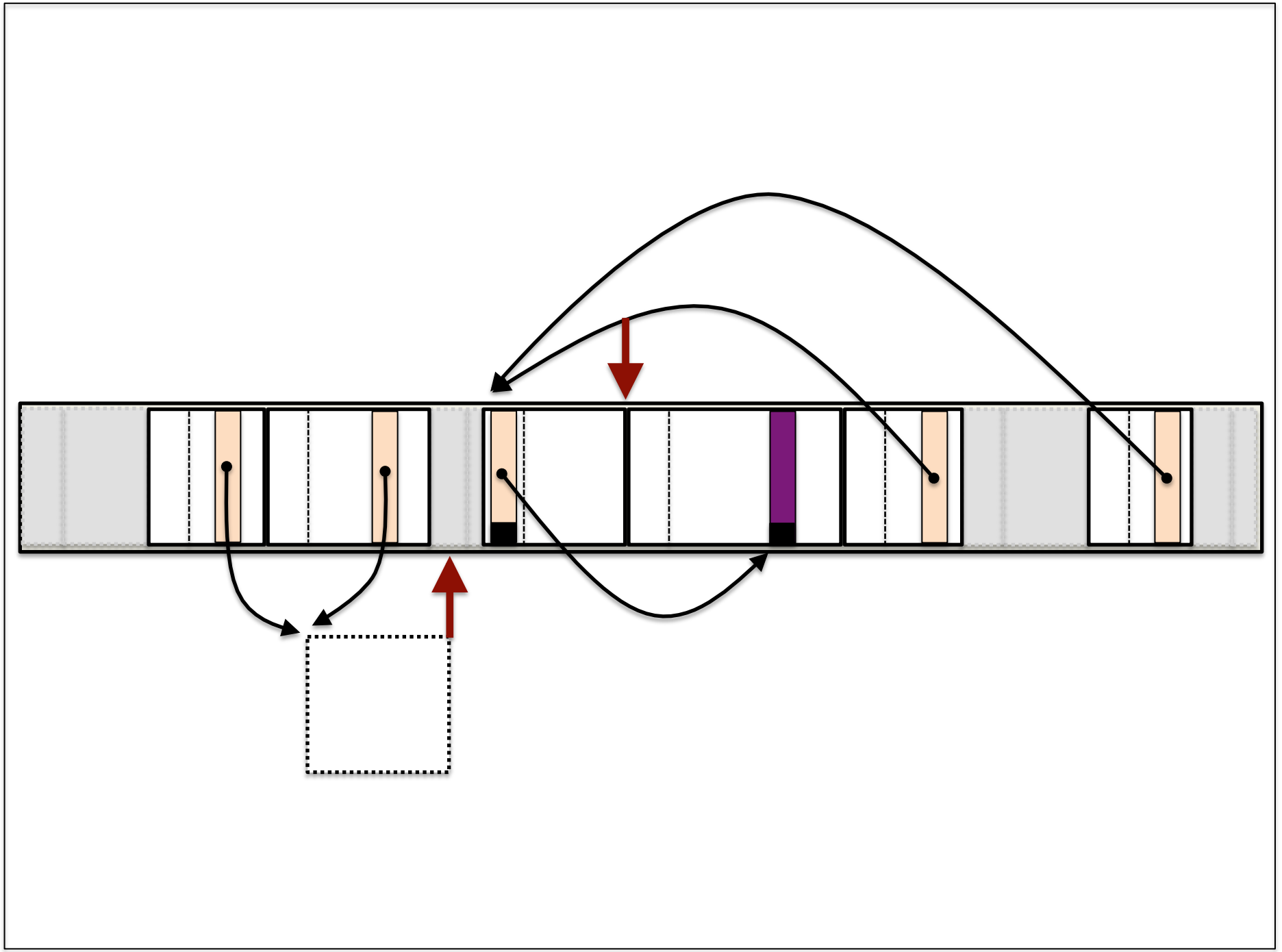


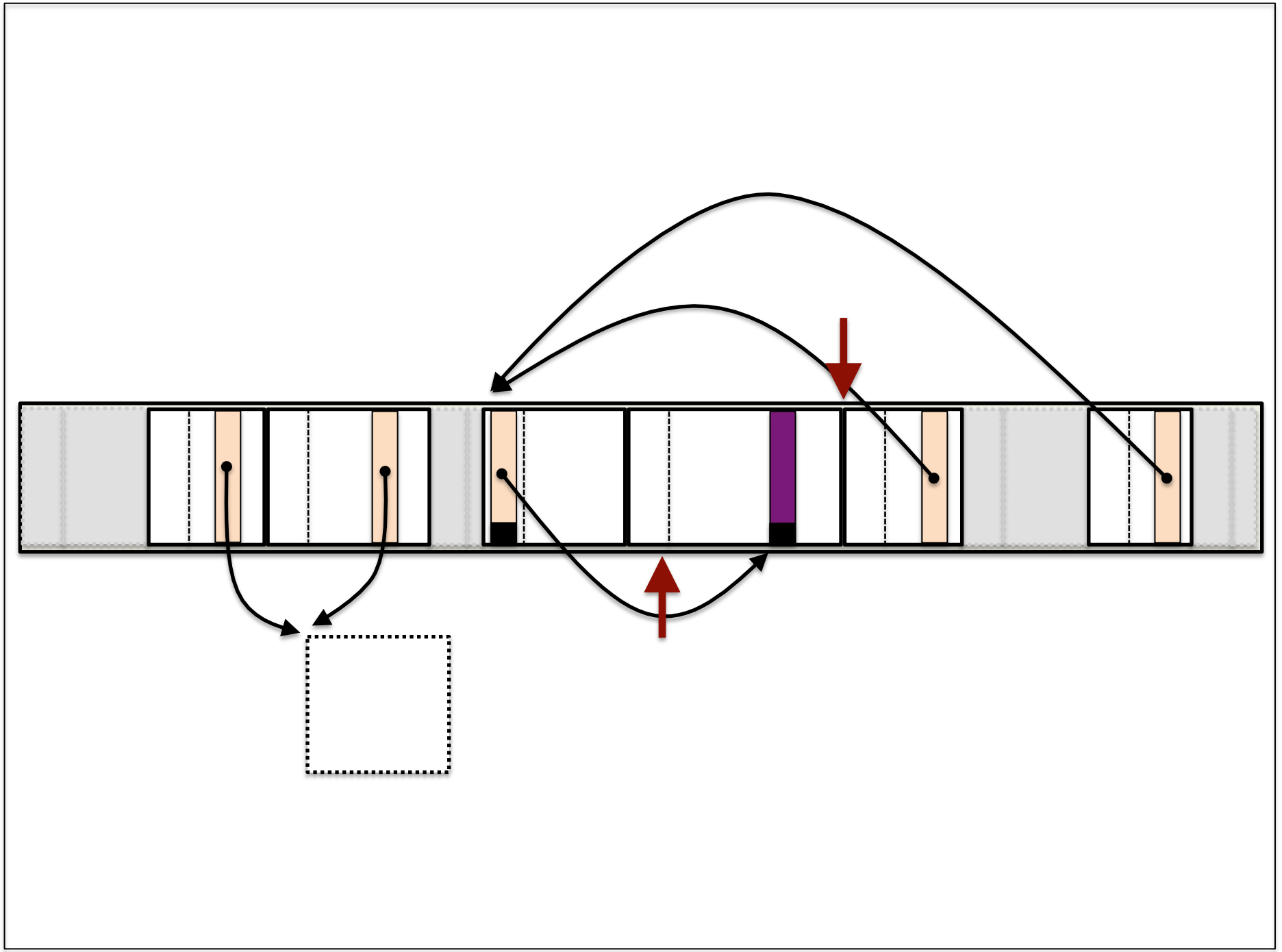


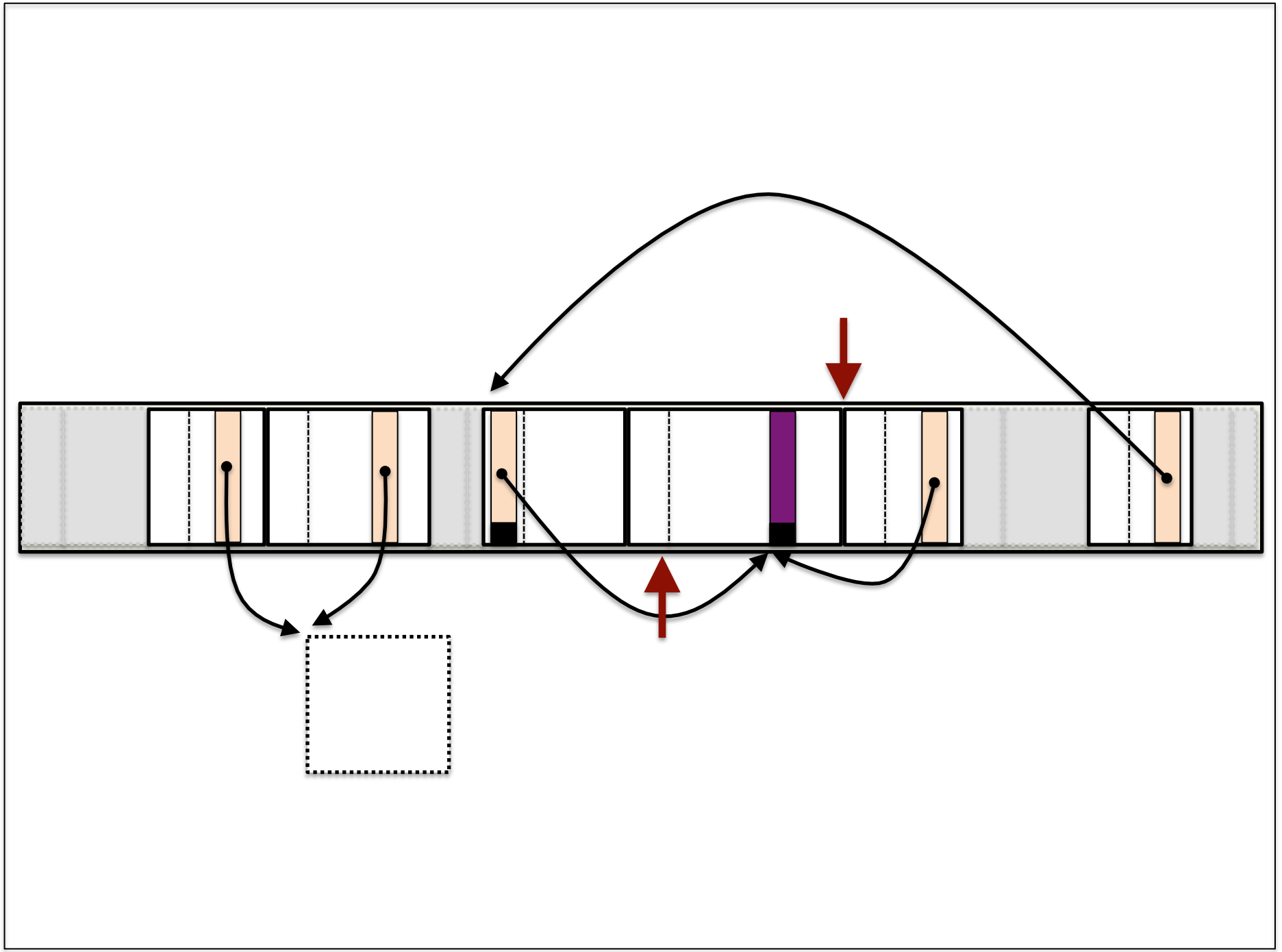


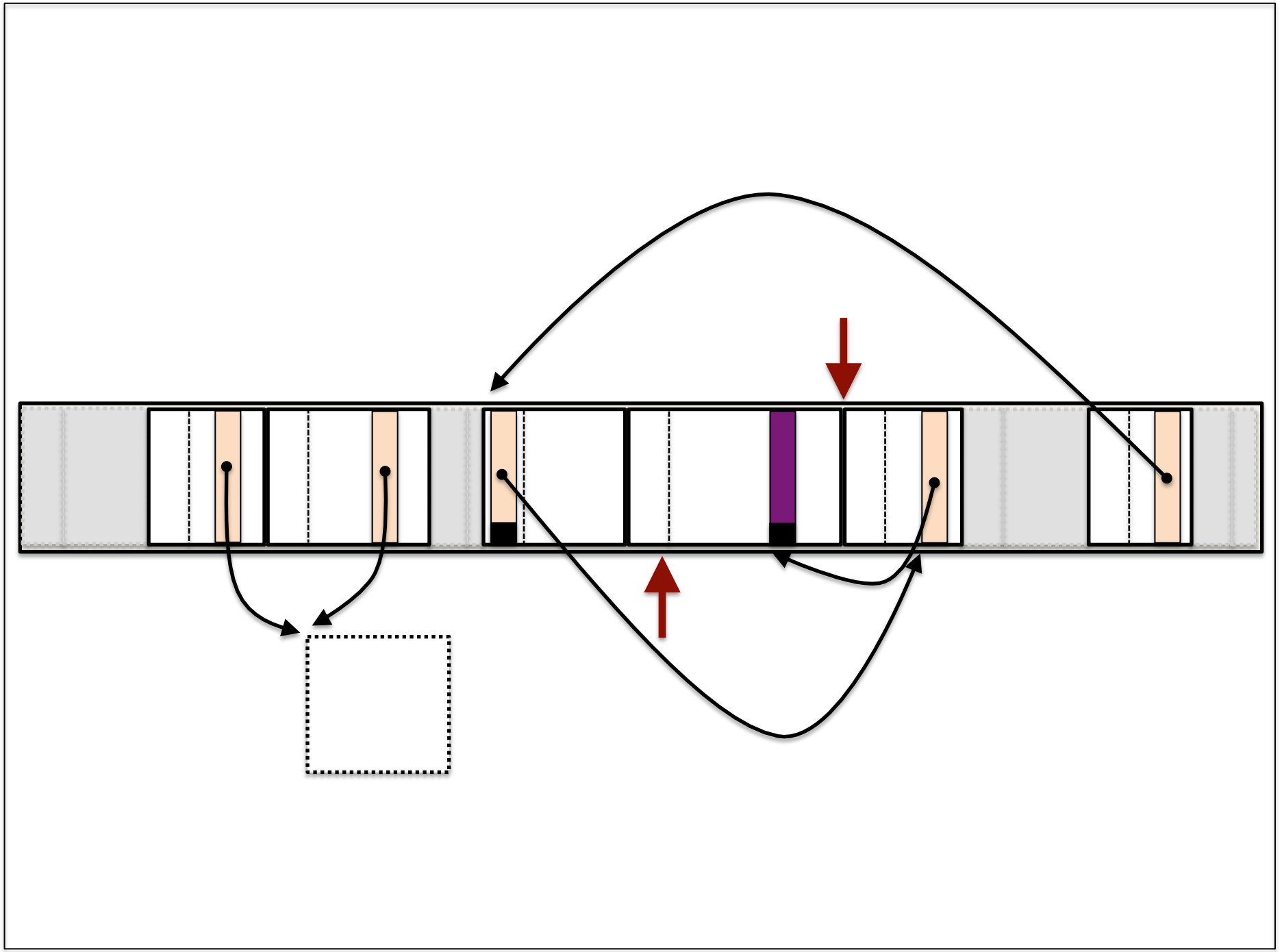


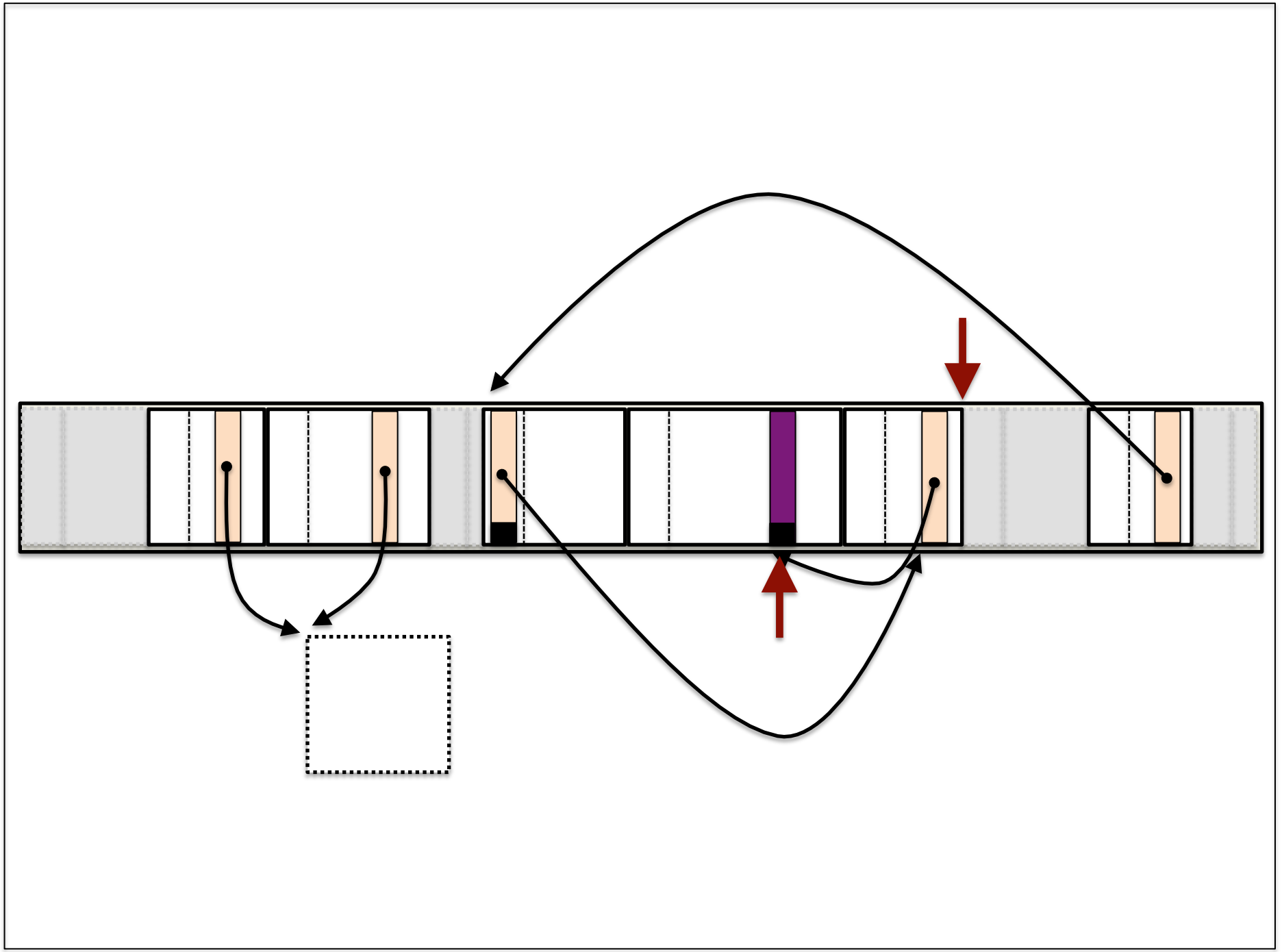


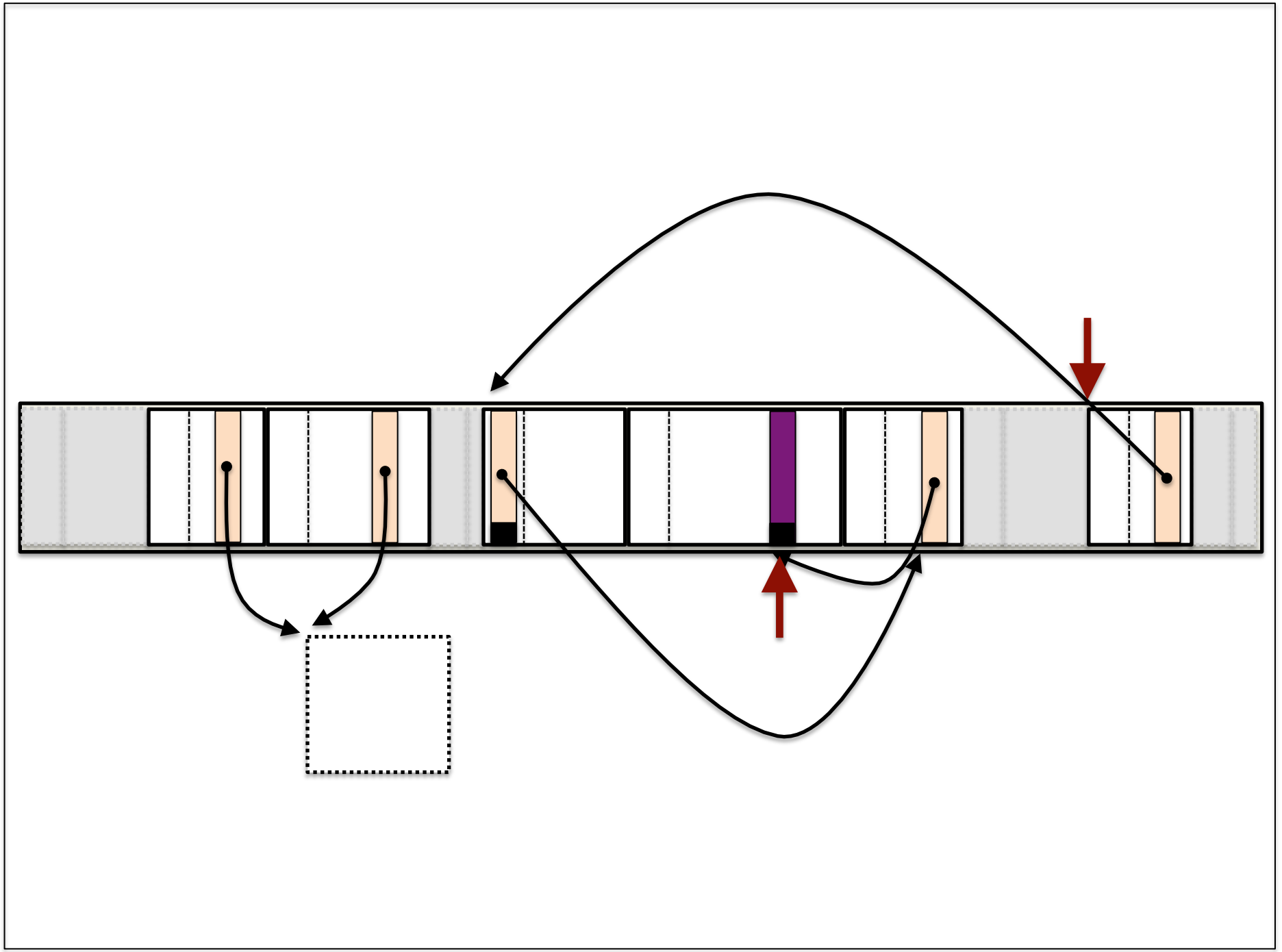


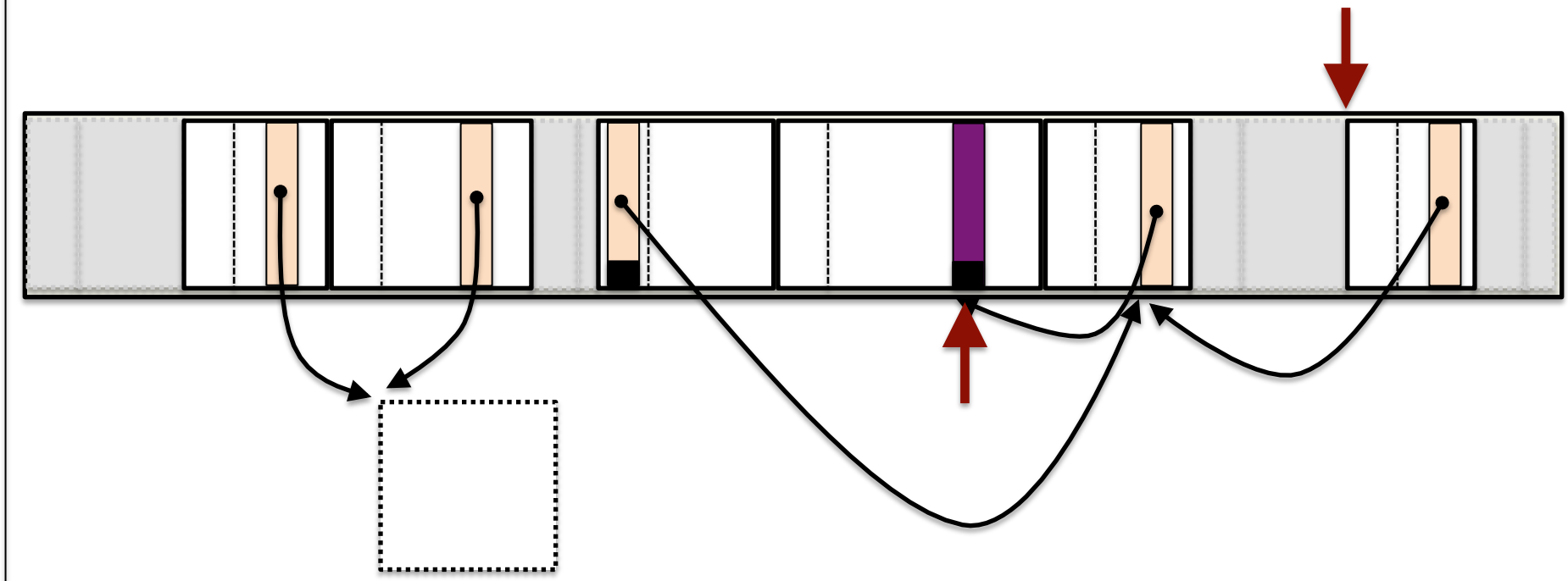


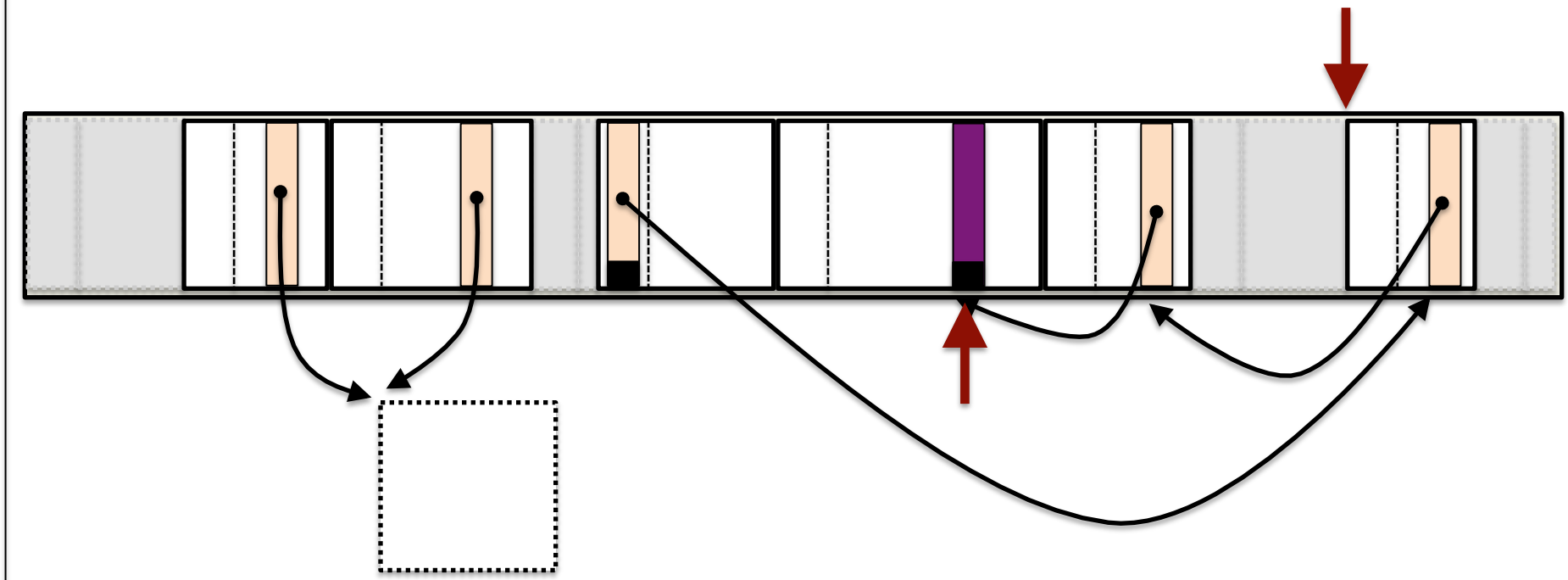


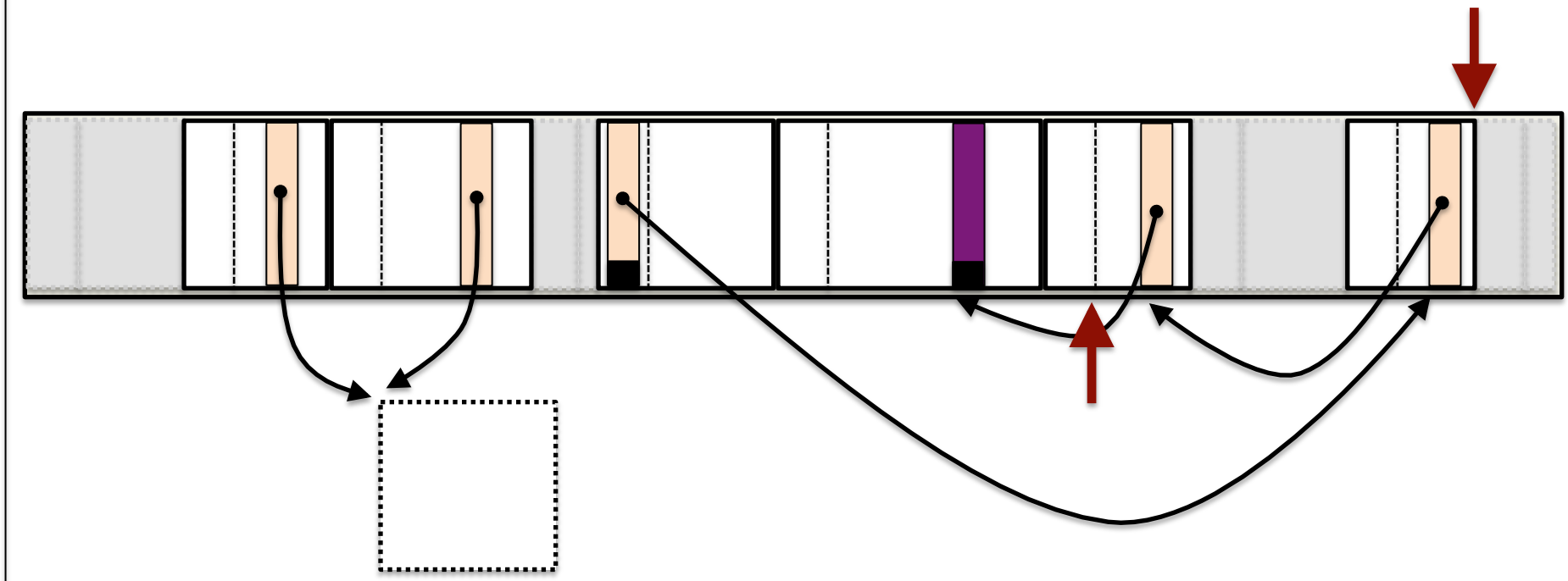


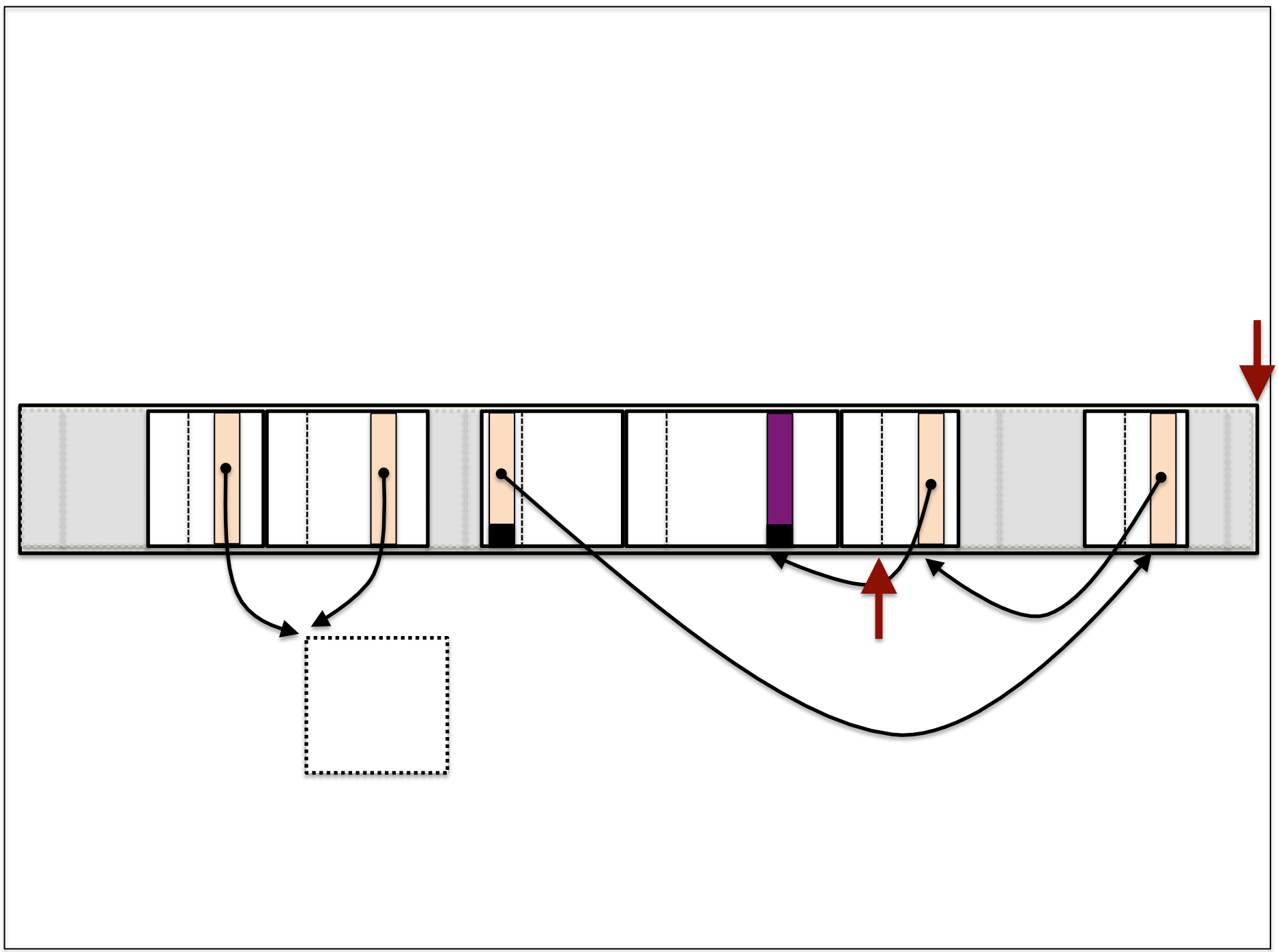






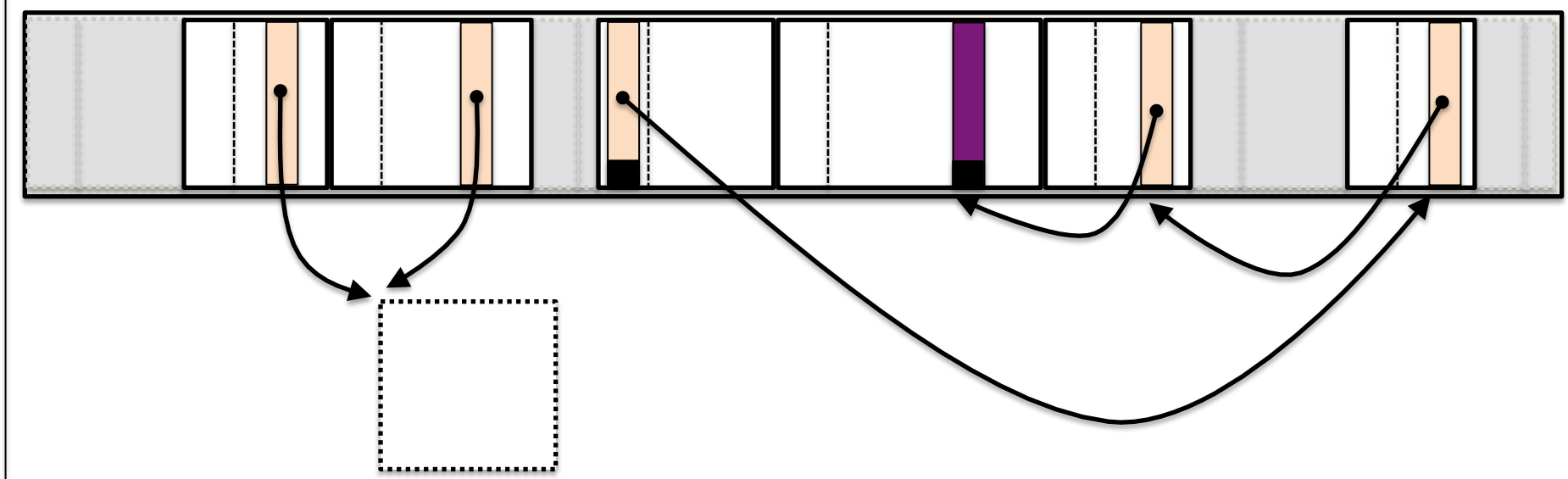


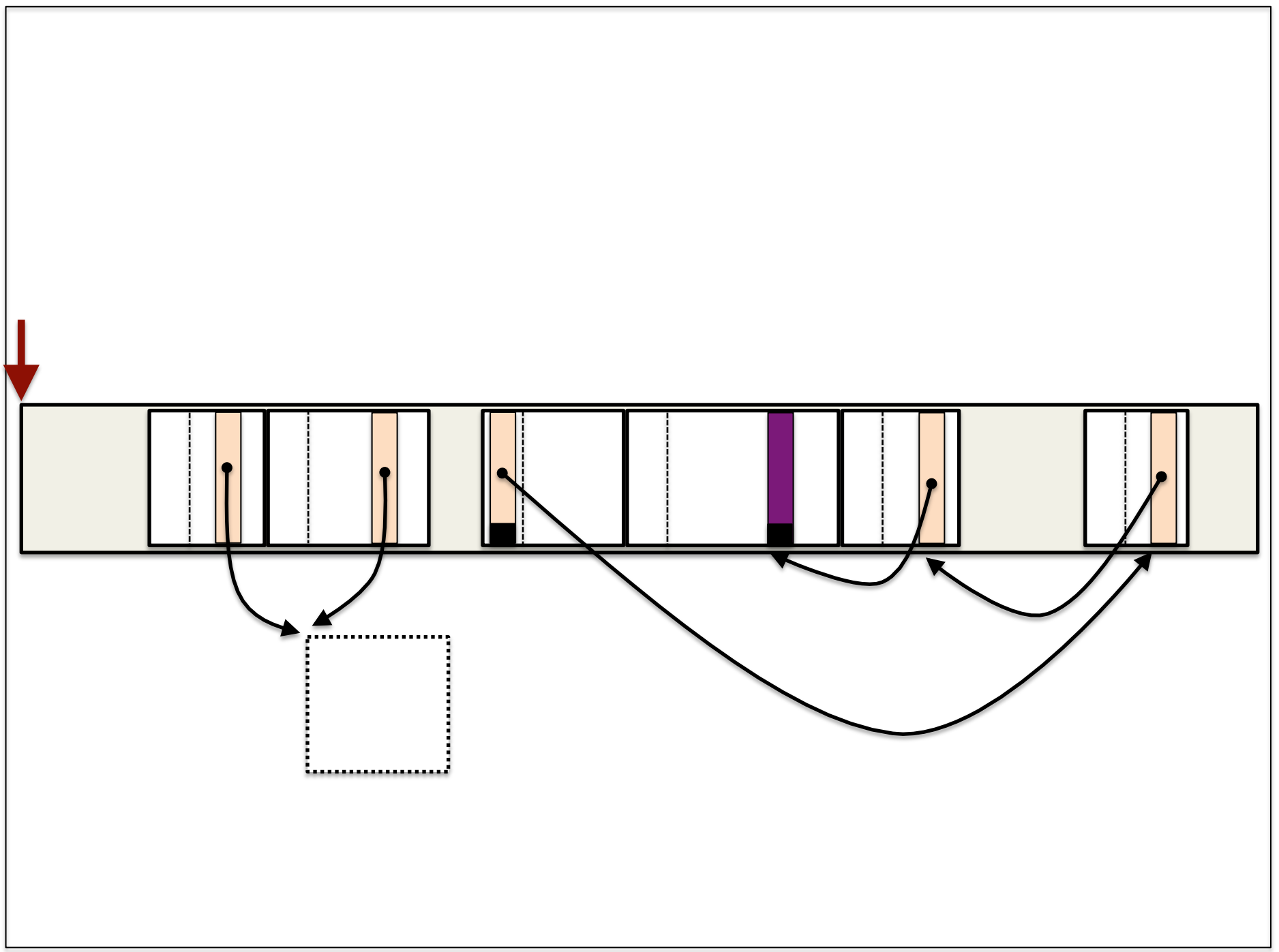


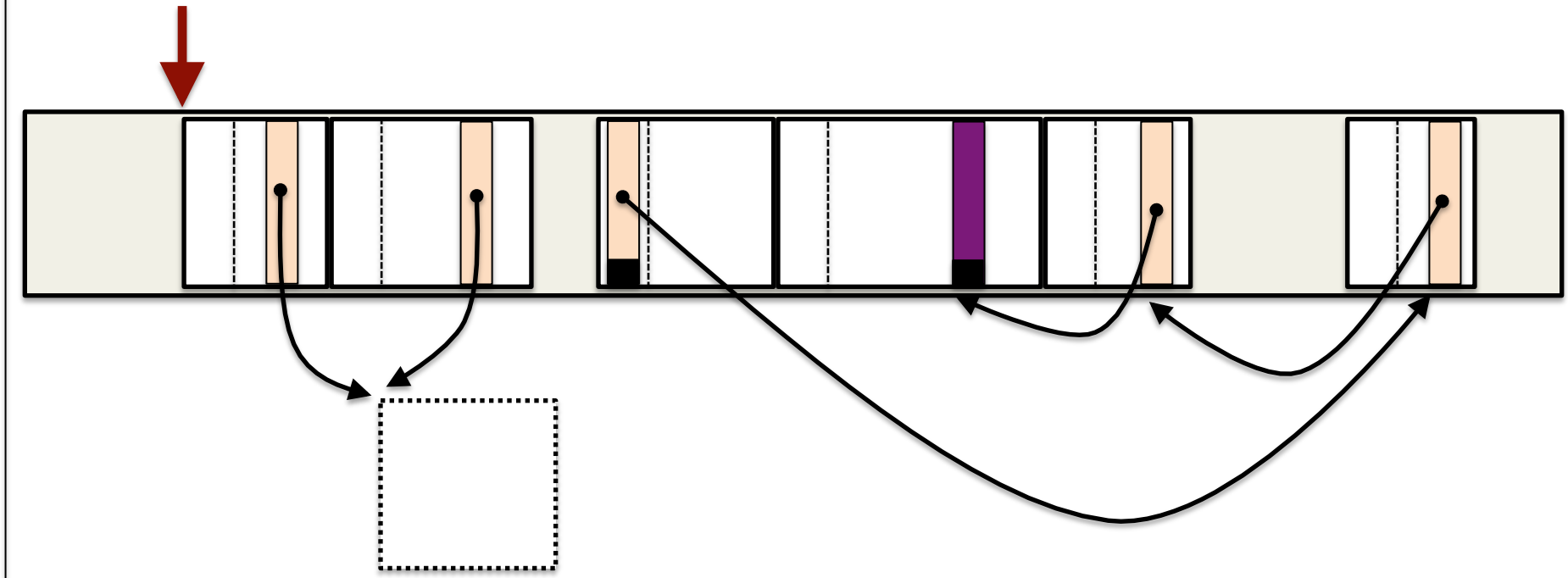


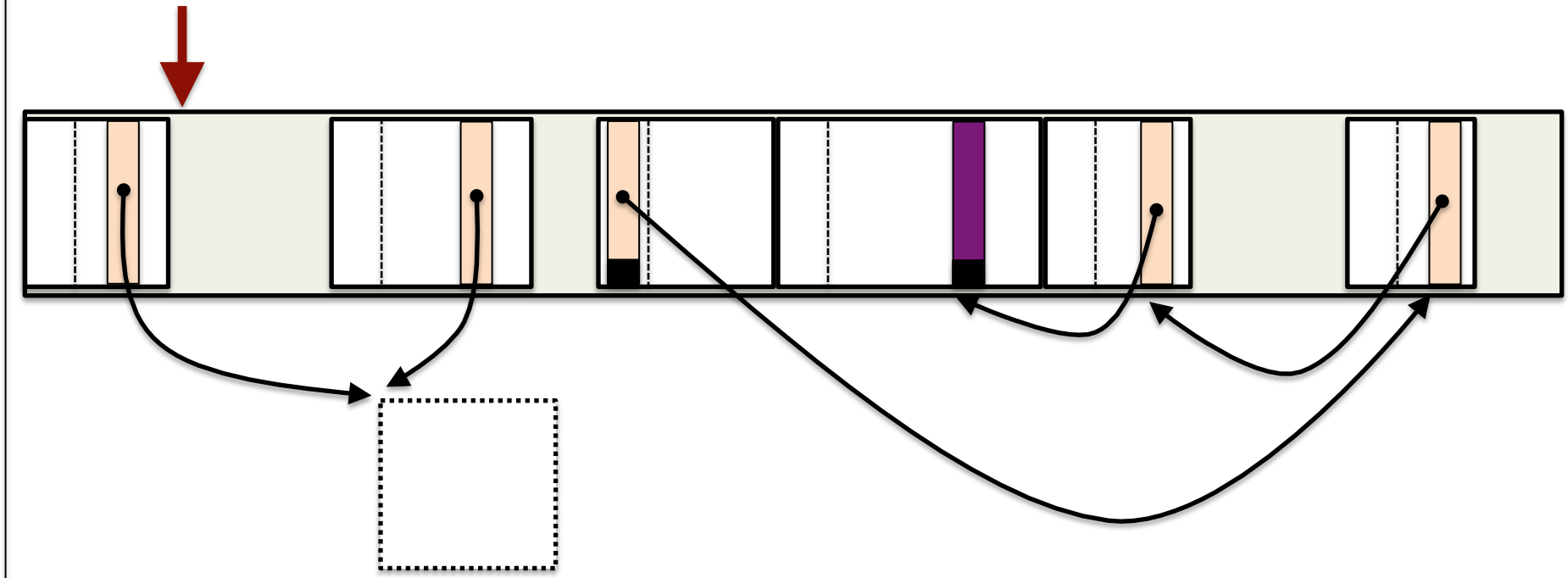
Second Pass

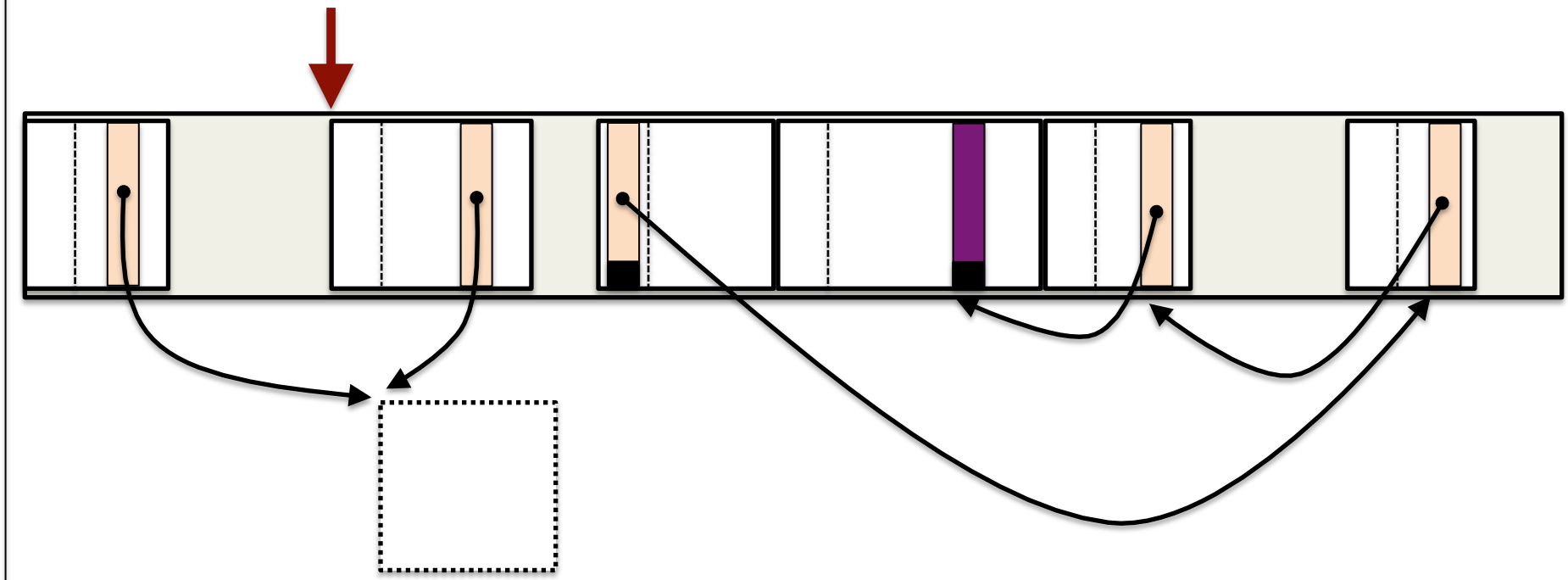
- After the first pass we know two things
  - All forward references point to new address
  - All backward references are chained
- Second pass completes the collection
  - Moves objects to their new locations
  - Updates chained backward references

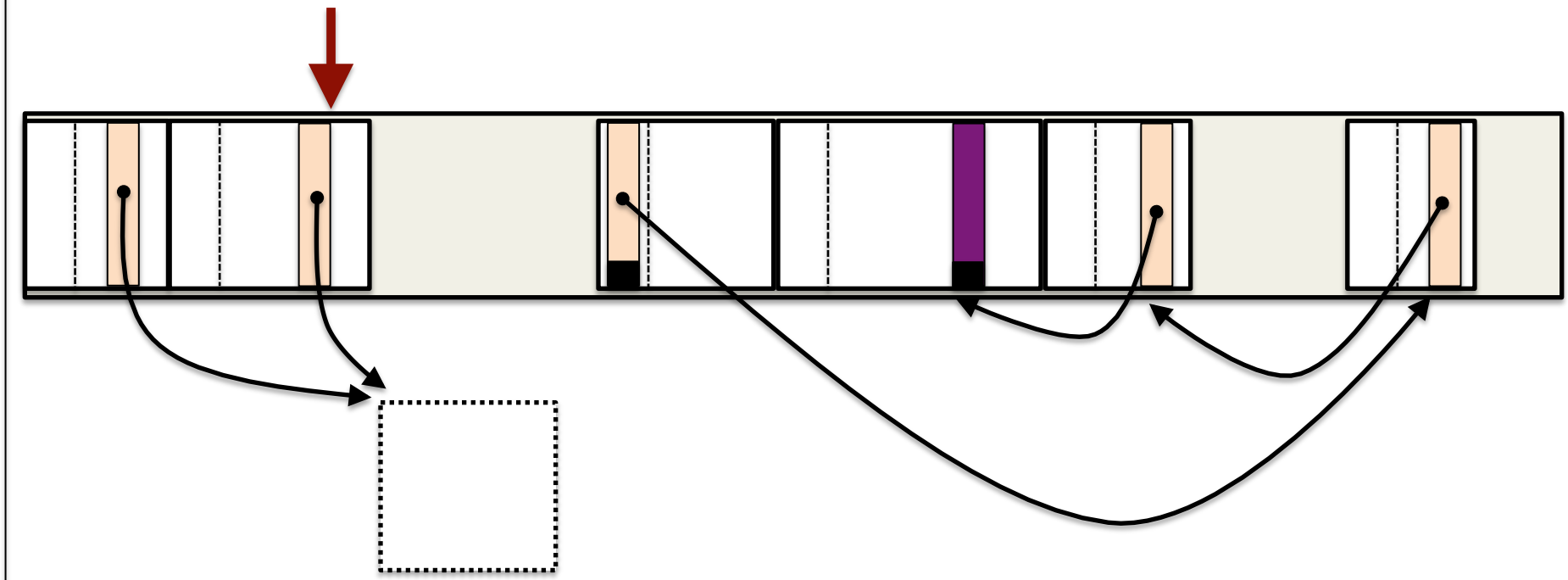


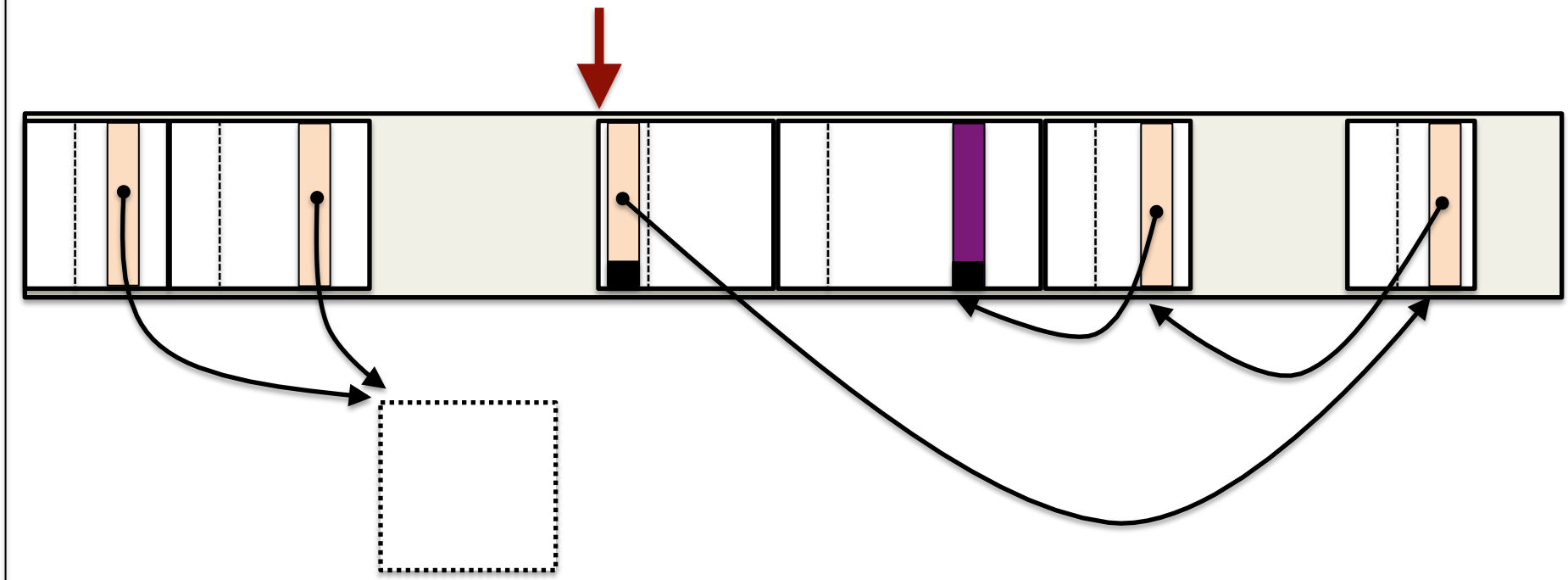


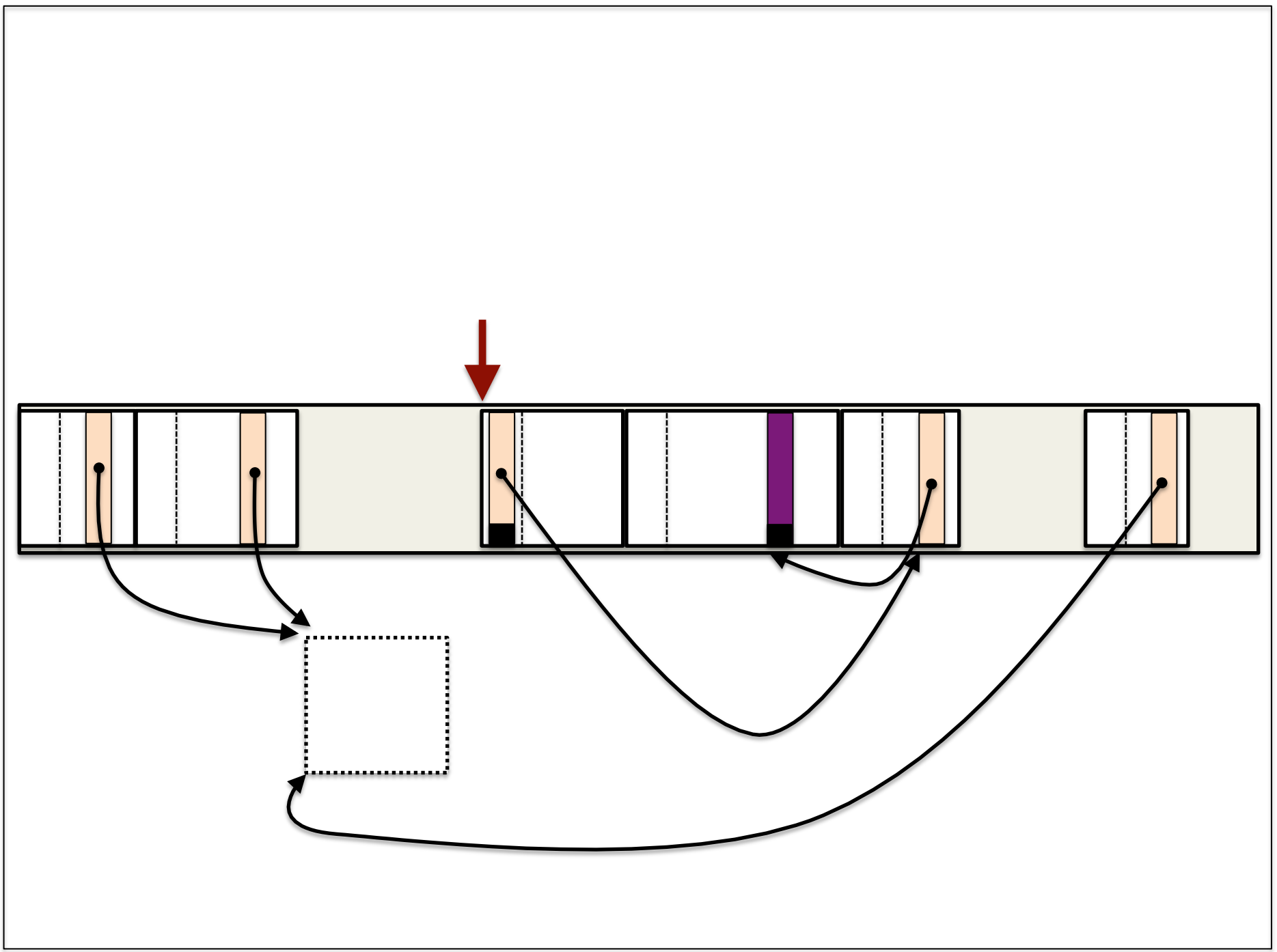


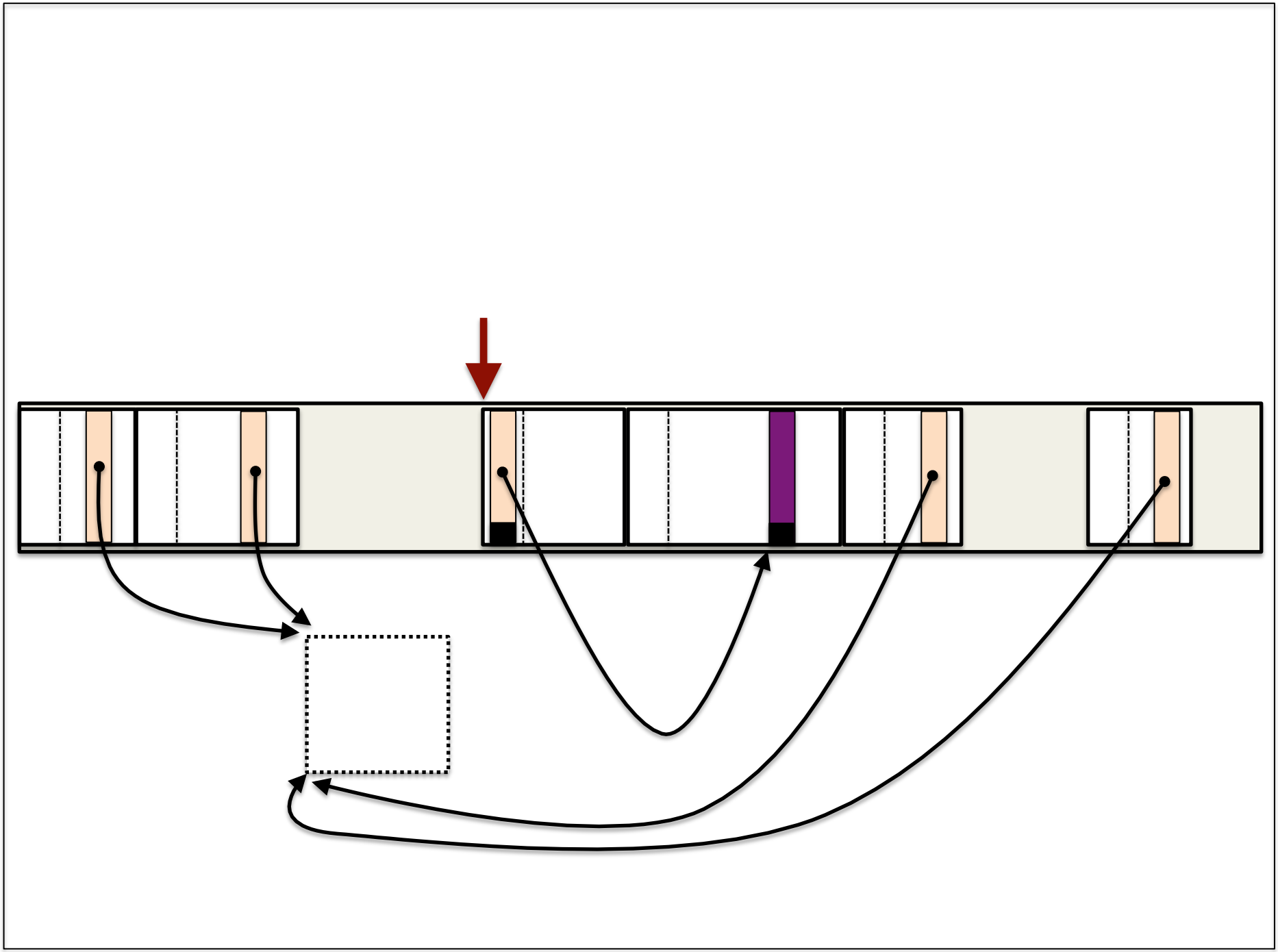


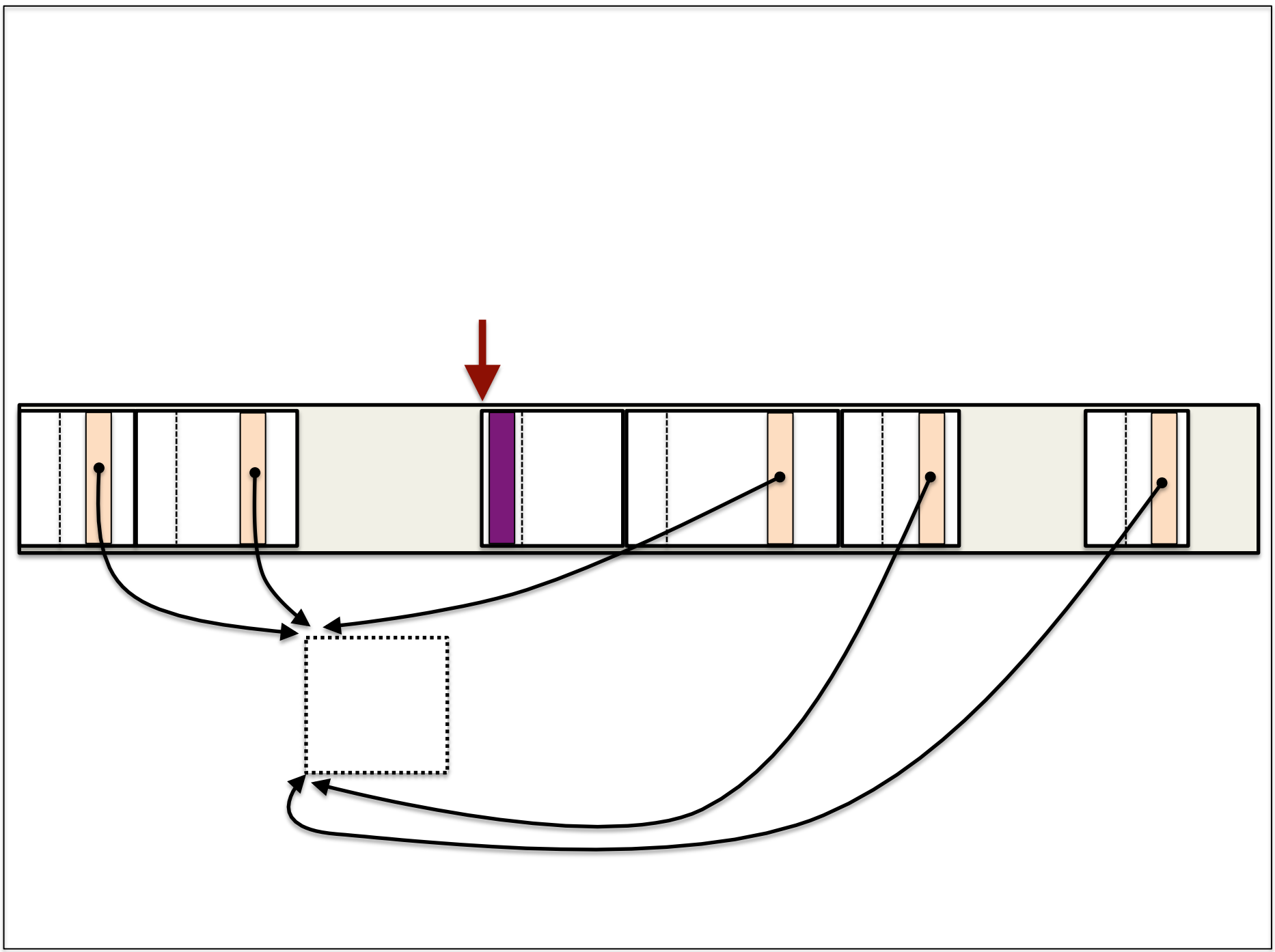


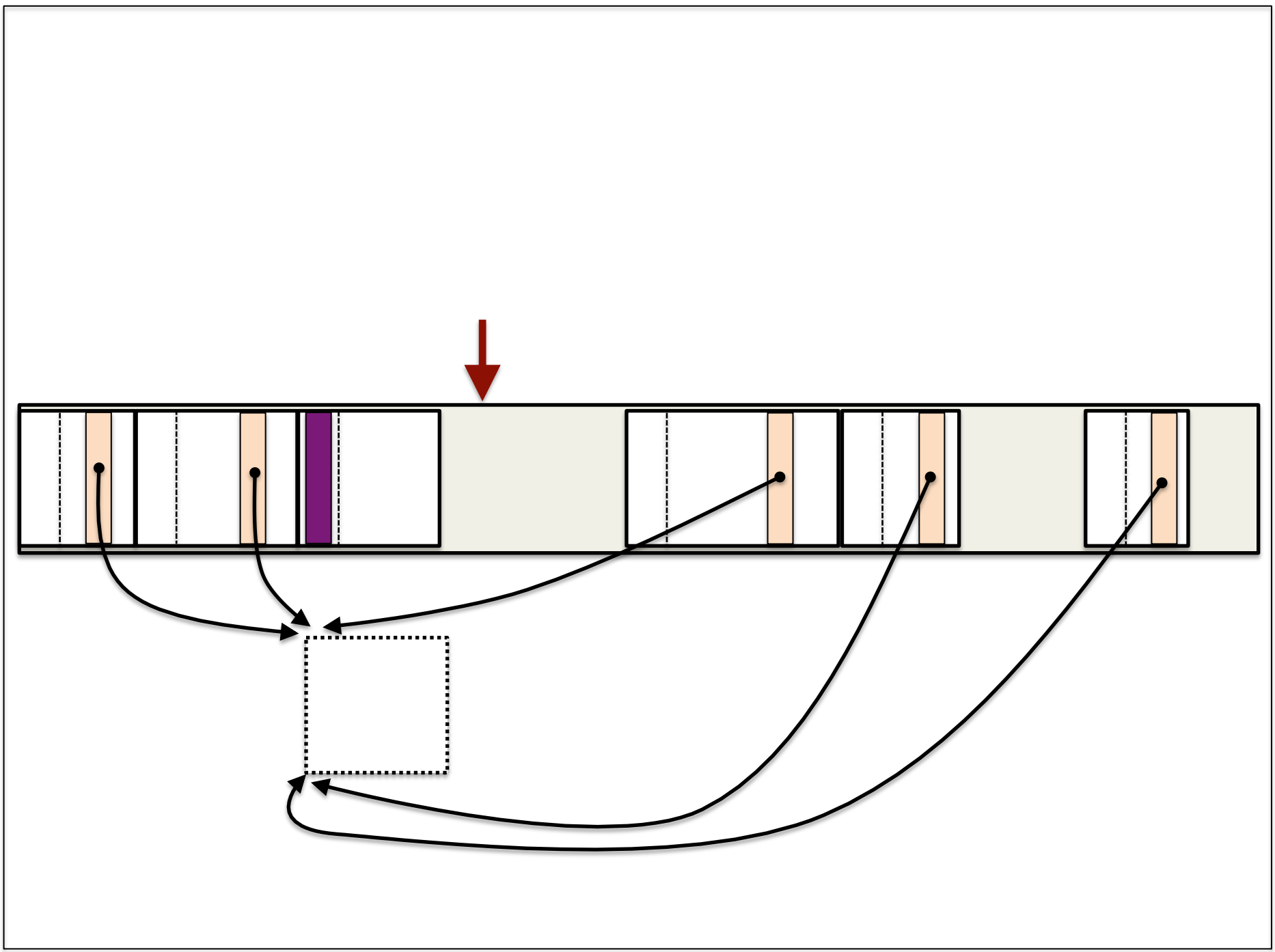


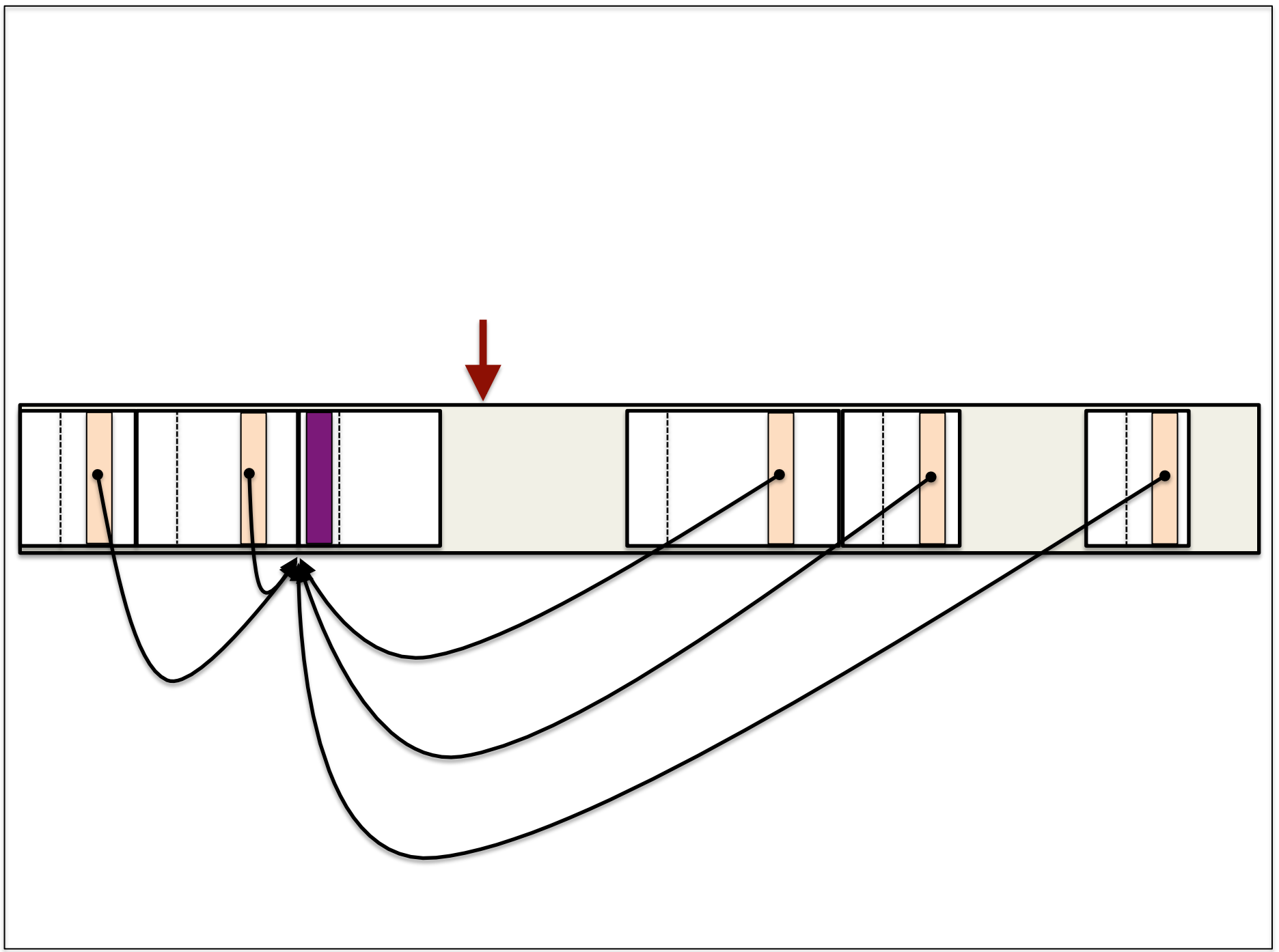


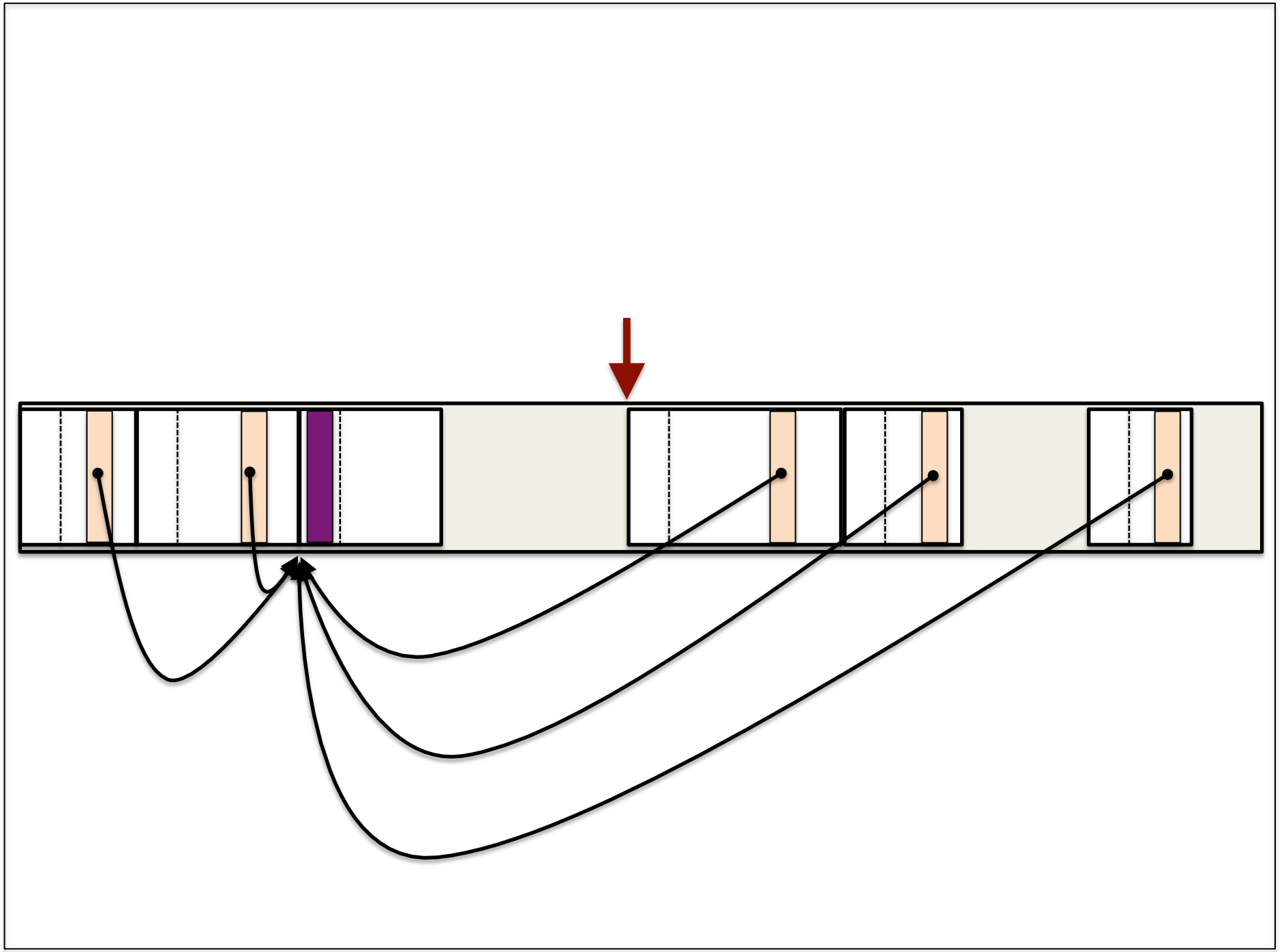


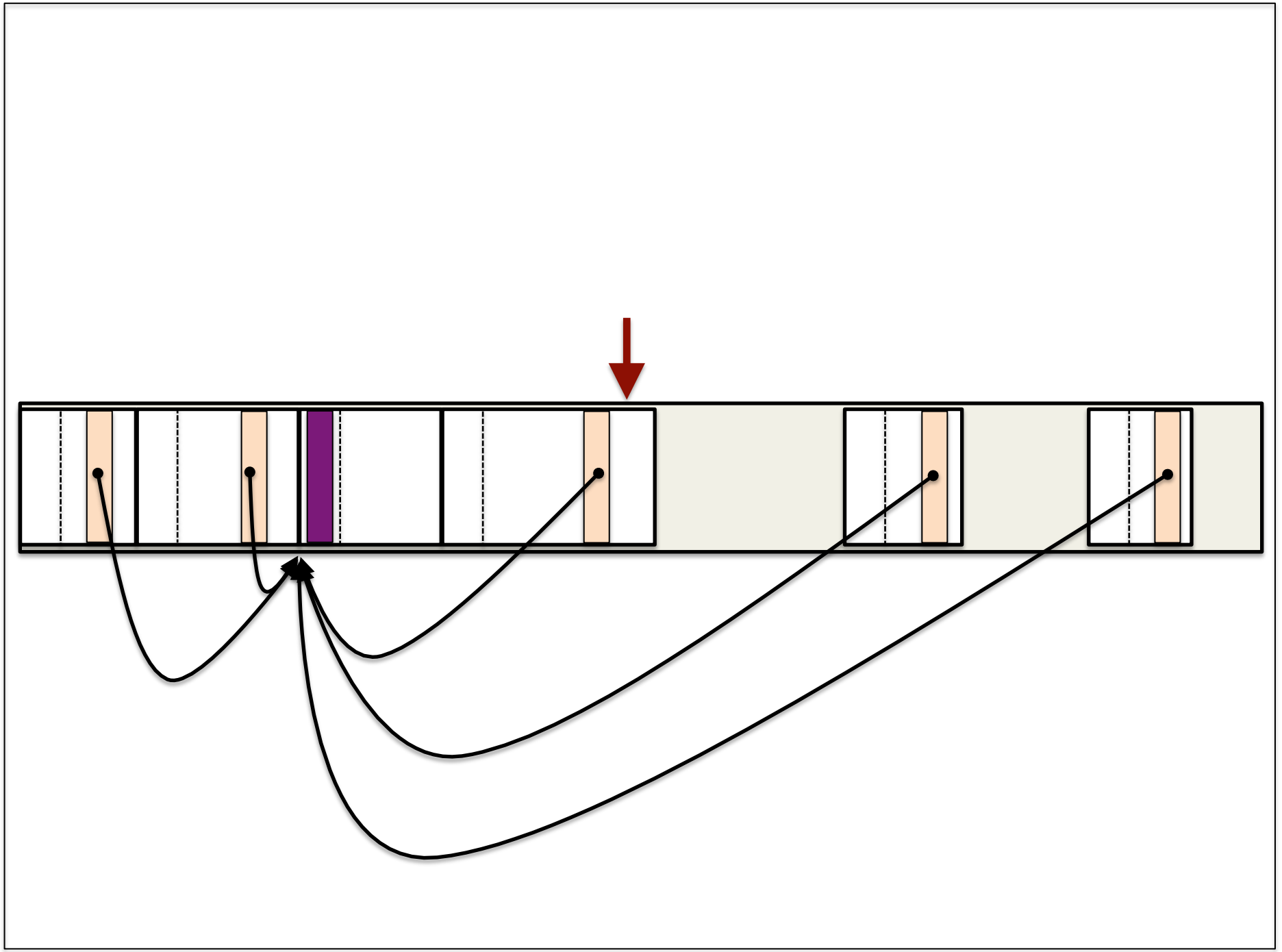


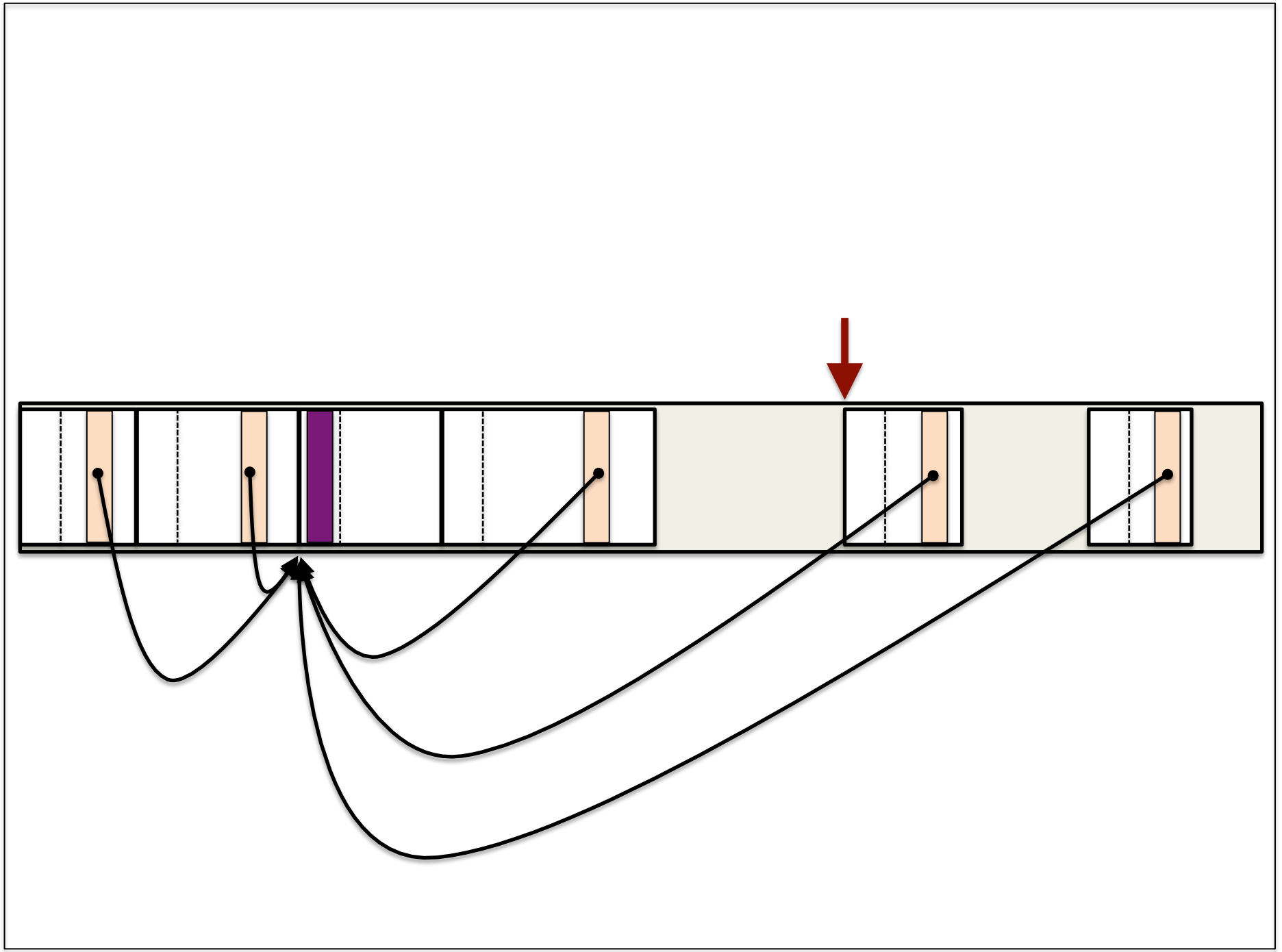


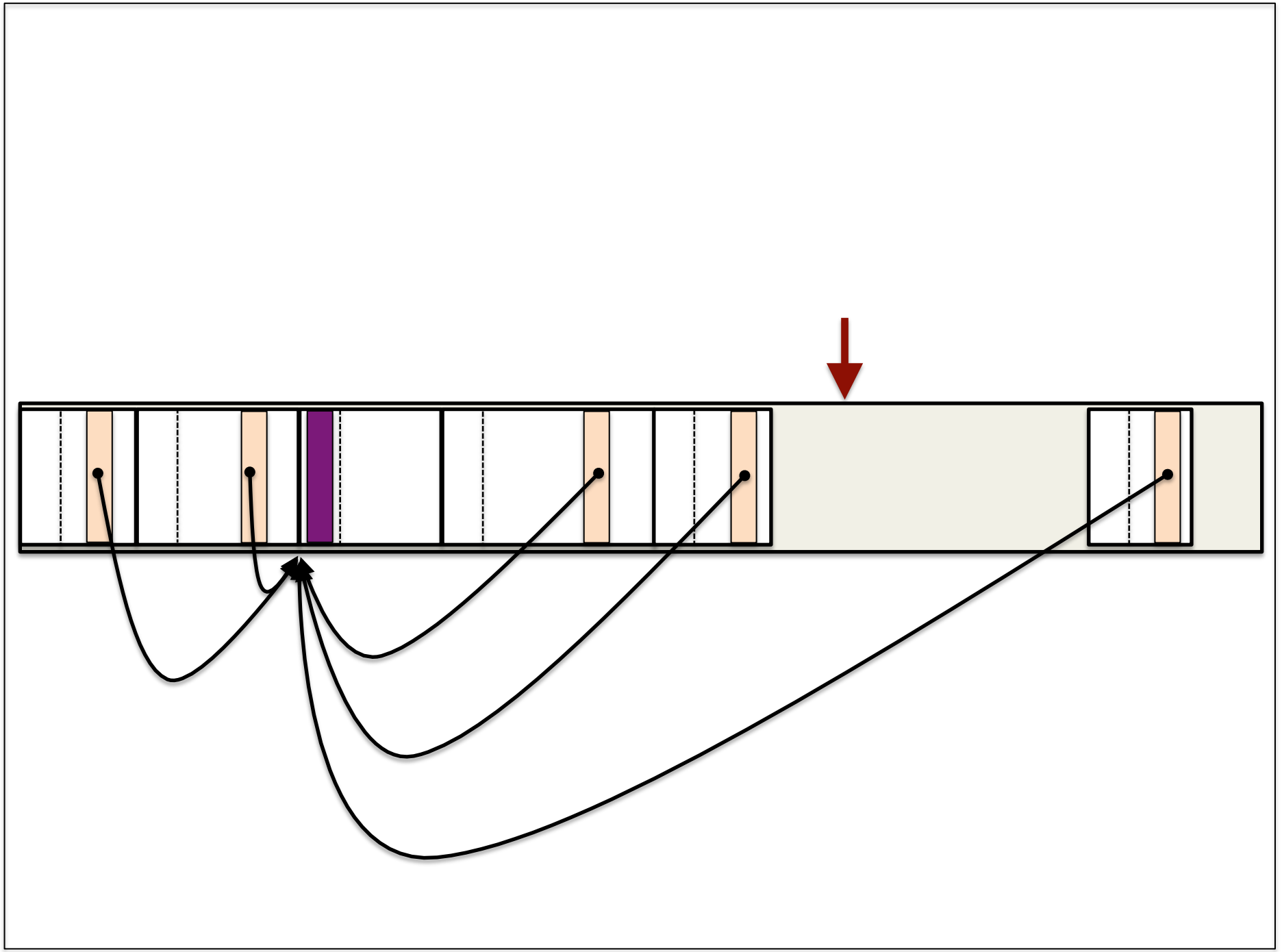


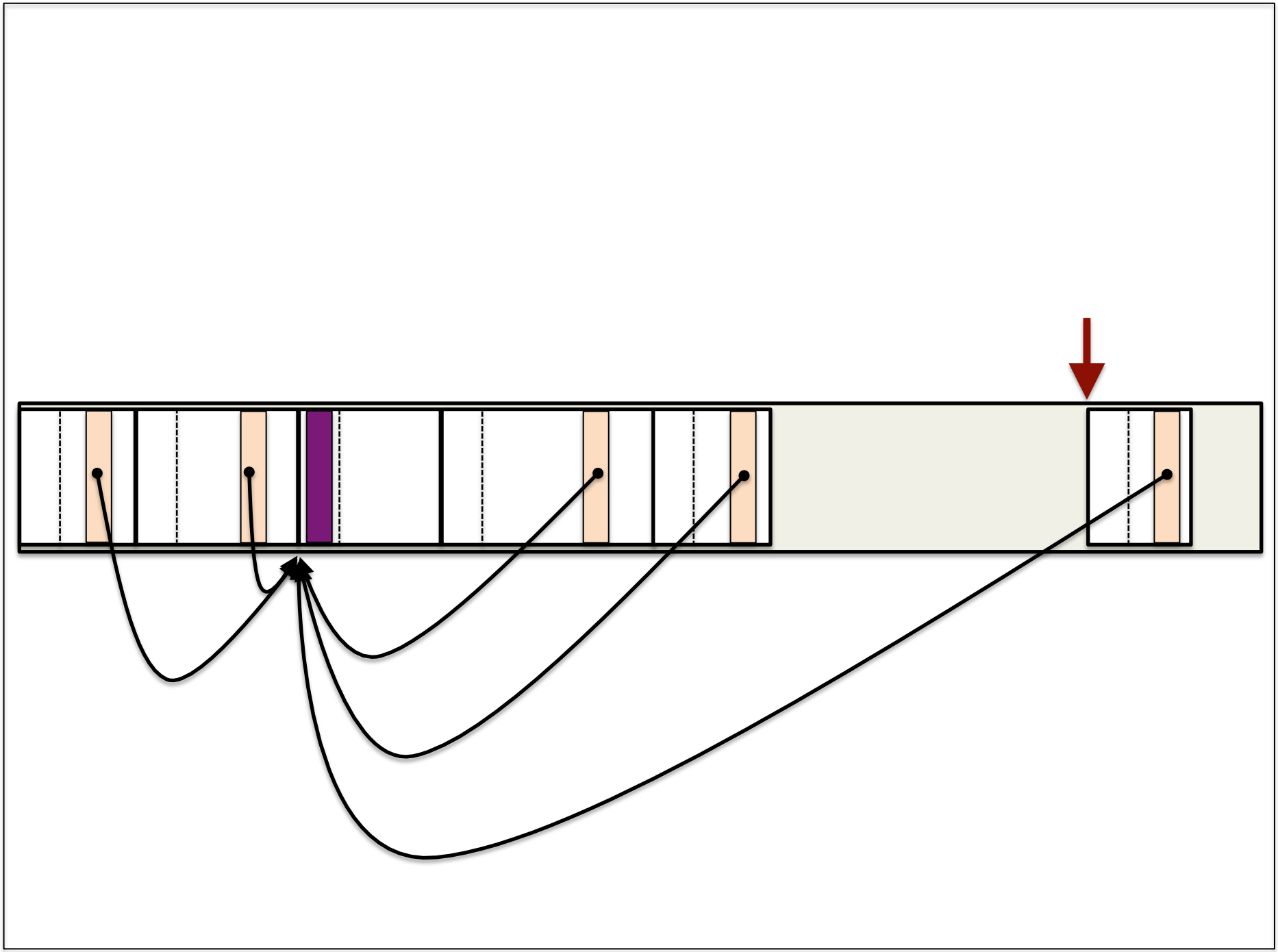


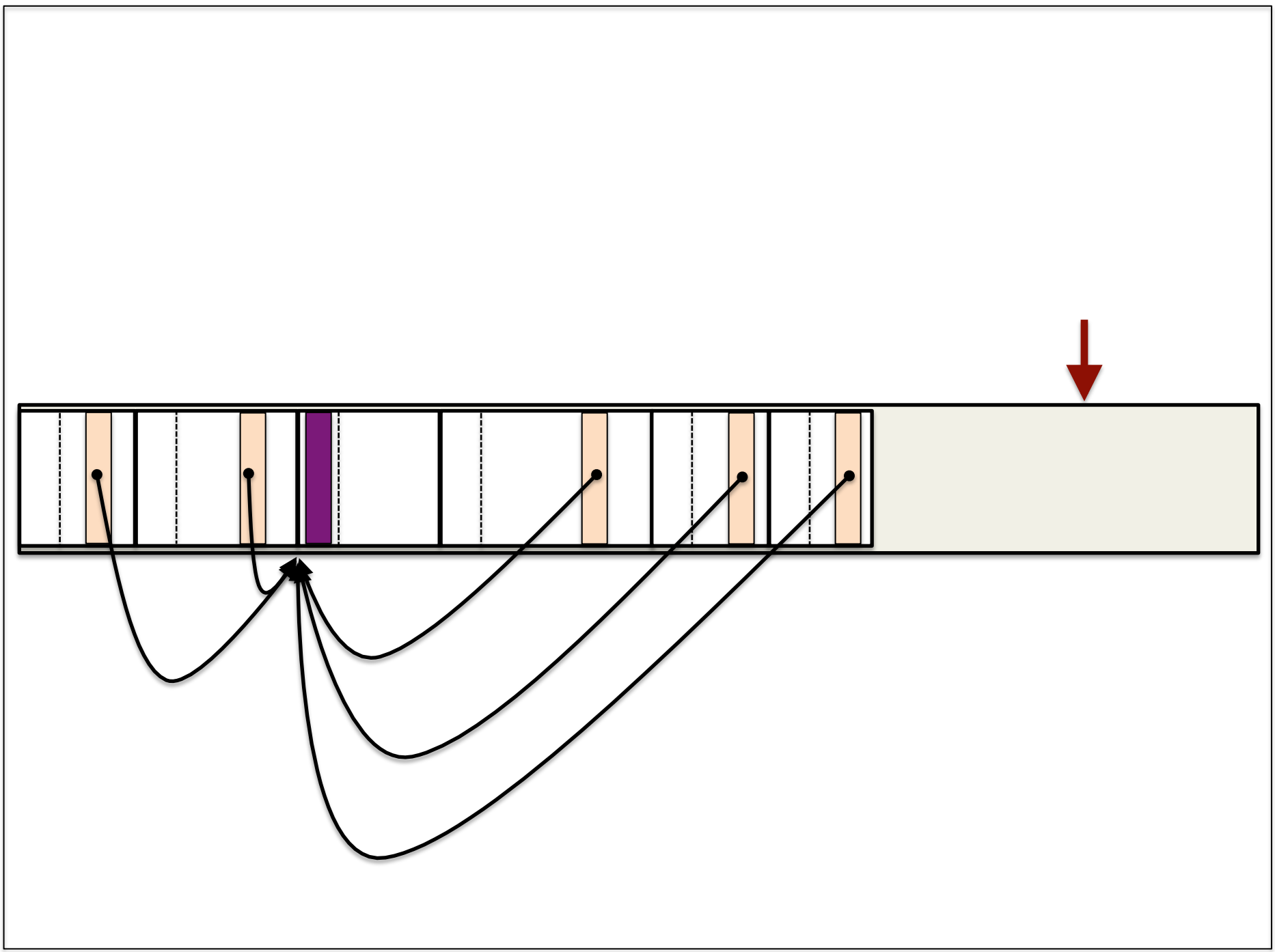


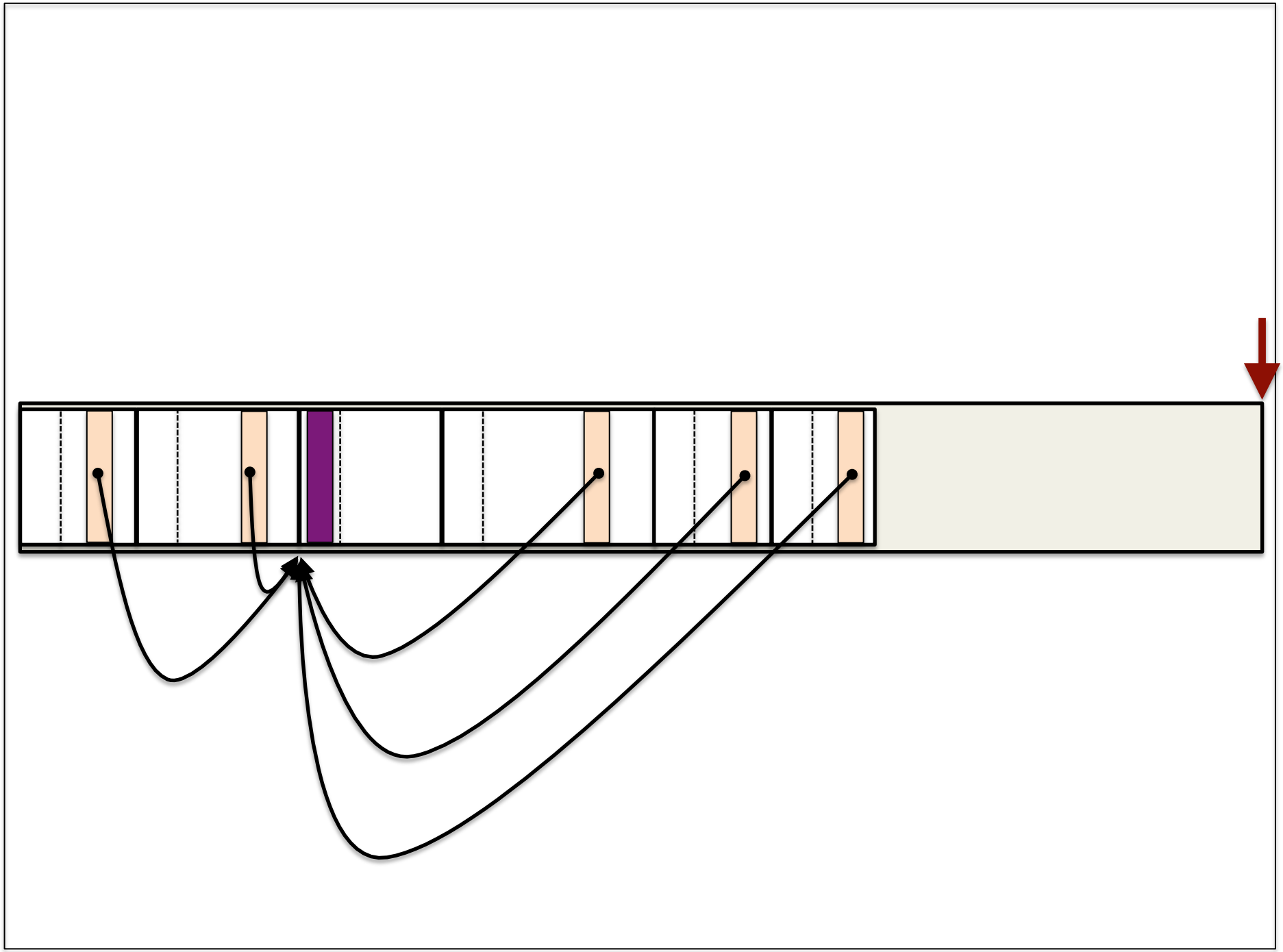












Compacting Collectors

- Compacting good for constrained architectures
  - No copy reserve needed
- Need one available bit
  - Memory is normally aligned at least that much
- Need one available word
  - Can generally use existing header structures

Compacting Collectors

- Complicated
  - Implementation trickier than other algorithms
- Requires multiple passes of the heap
  - At least two linear scans
  - Jumping around memory to chain pointers
- Hard to make concurrent
  - The heap is inconsistent for a long time

Comparing Garbage Collectors

	Reference Counting	Mark and Sweep	Semi-Space Copying	Compacting

Comparing Garbage Collectors

	Reference Counting	Mark and Sweep	Semi-Space Copying	Compacting
Incrementality	High	Low	Low	Low

Comparing Garbage Collectors

	Reference Counting	Mark and Sweep	Semi-Space Copying	Compacting
Incrementality	High	Low	Low	Low
Tracing	No	Yes	Yes	Yes

Comparing Garbage Collectors

	Reference Counting	Mark and Sweep	Semi-Space Copying	Compacting
Incrementality	High	Low	Low	Low
Tracing	No	Yes	Yes	Yes
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Comparing Garbage Collectors

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Complexity	Low	Medium	Medium	High
Garbage Object Overhead	High	High	Low	Low
Live Object Overhead	None	Low	High	High

Live to Garbage Ratio

- Amount of data that survives a collection
  - Important metric when choosing collector
  - Very widely studied in practice
- Moving collectors pay cost per live object
  - Copying overhead
- Others pay cost per garbage object
  - Freeing objects individually

Cache Behavior

- Memory latency a major factor in performance
  - CPU architecture tries to minimize its effect
  - Best way to do this is through the cache
- We're interested in cache behavior in two places
  - During garbage collector
  - During mutator operation
- We can use GC to optimize mutator performance

Principal of Locality

- Also known as Locality of Reference
- Suggests that cache behavior can be predicted
  - For some value of predicted
  - Knowing the future is hard
- Processors are designed with locality in mind
  - Principal developed over decades of observation
  - Consistently found to be accurate

Temporal Locality

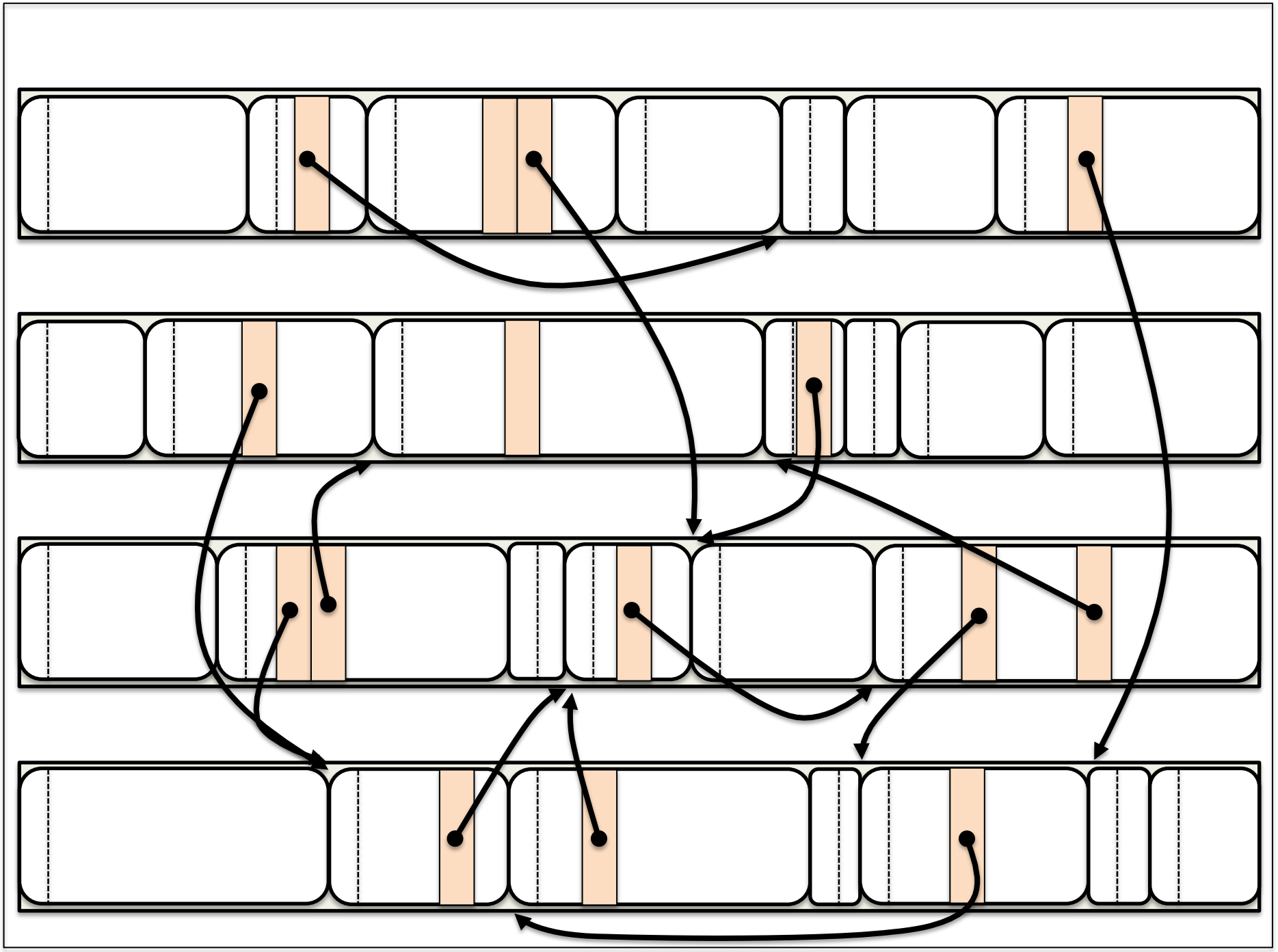
- Accesses to values tend to be bursty
  - Once you use a value, you likely use it again soon
  - Afterwards it may be a long time before using it again
- Hardware caches retain data after use
  - Replacement policies favor recently-used data

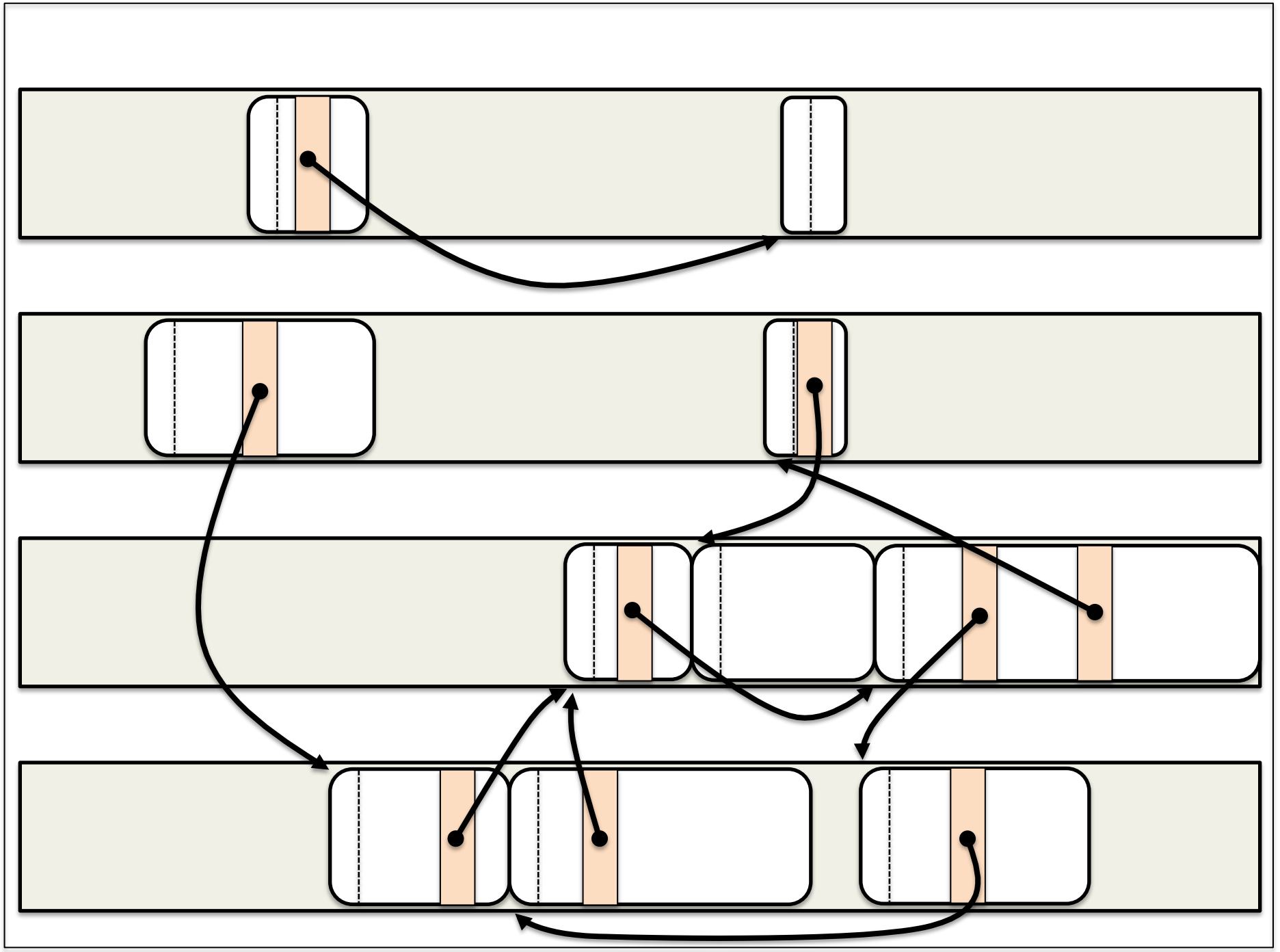
Spatial Locality

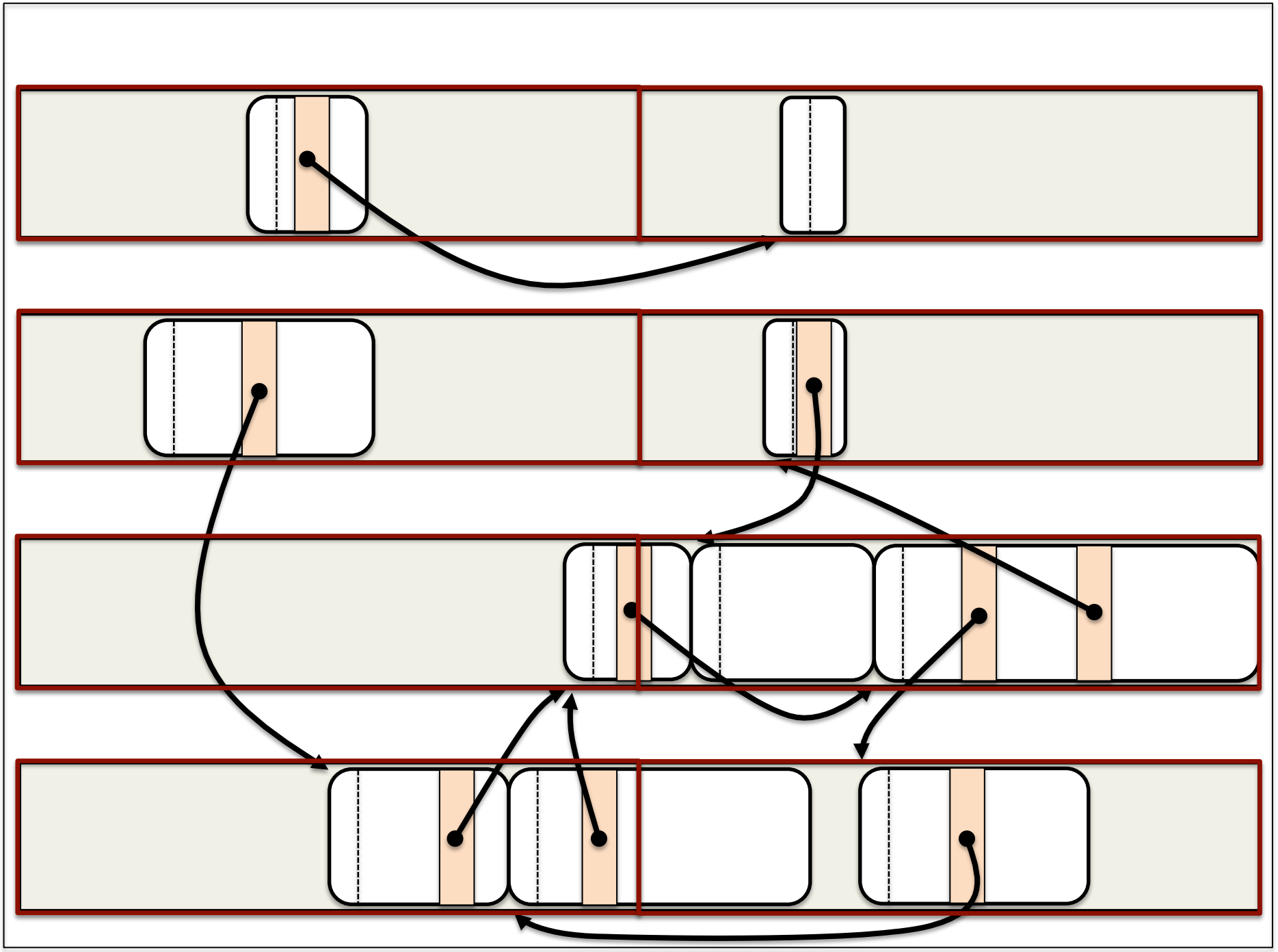
- Nearby objects tend to be used together
  - Think of scanning through an array
  - Accessing fields in an object
- Hardware caches read data in lines
  - Bring in the requested address plus nearby data
  - Likely to have the next object already in the cache
- Caches best at going in a straight line

Maximizing Locality

- Garbage collection is an artificial process
  - Doesn't necessarily follow locality principle
  - Touches much of the heap at once
- Design of a collector can make a big difference
  - Linear scan better than random access
  - Clustering updates close in time
- Compacting collectors bring live objects together

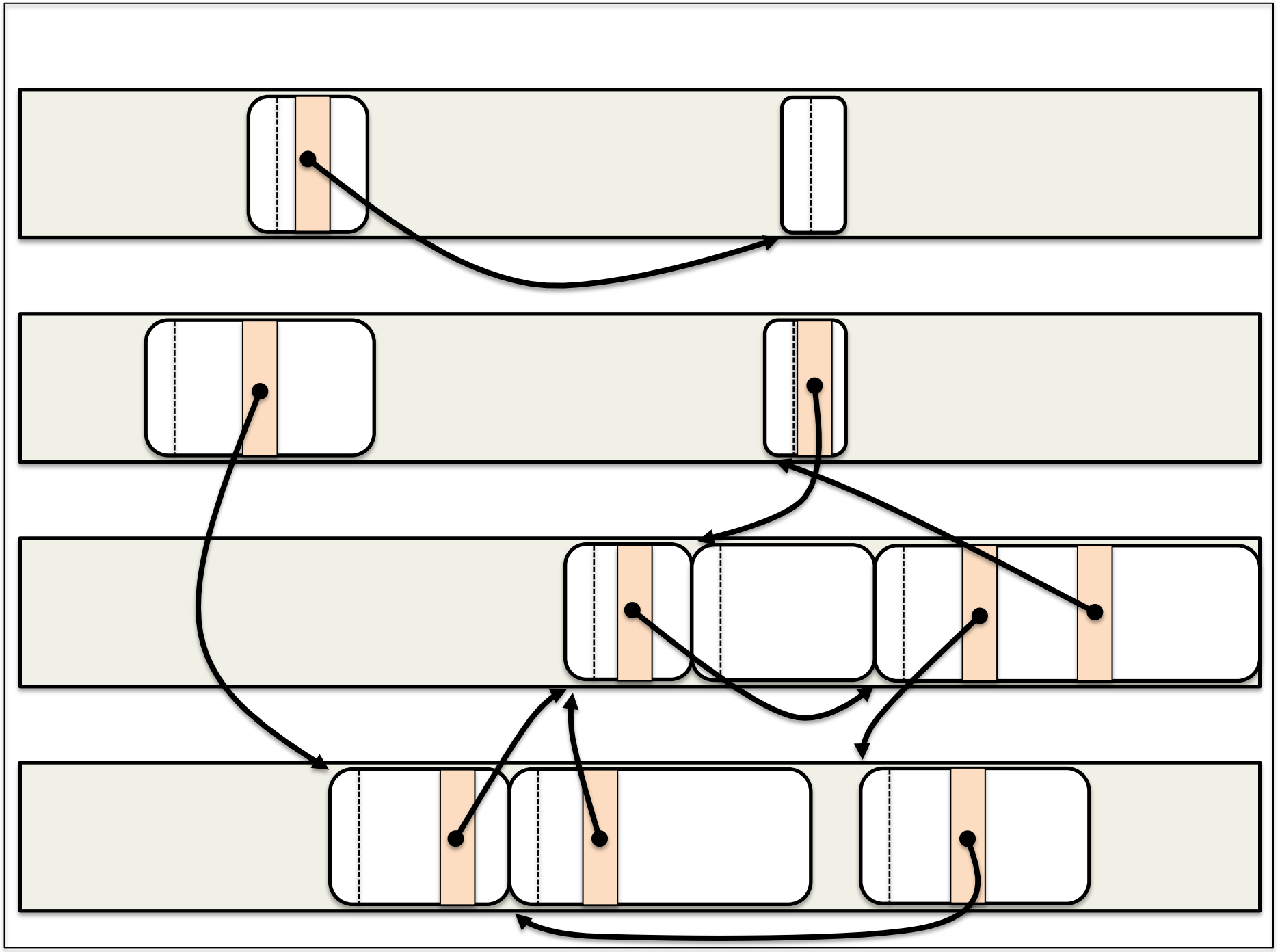


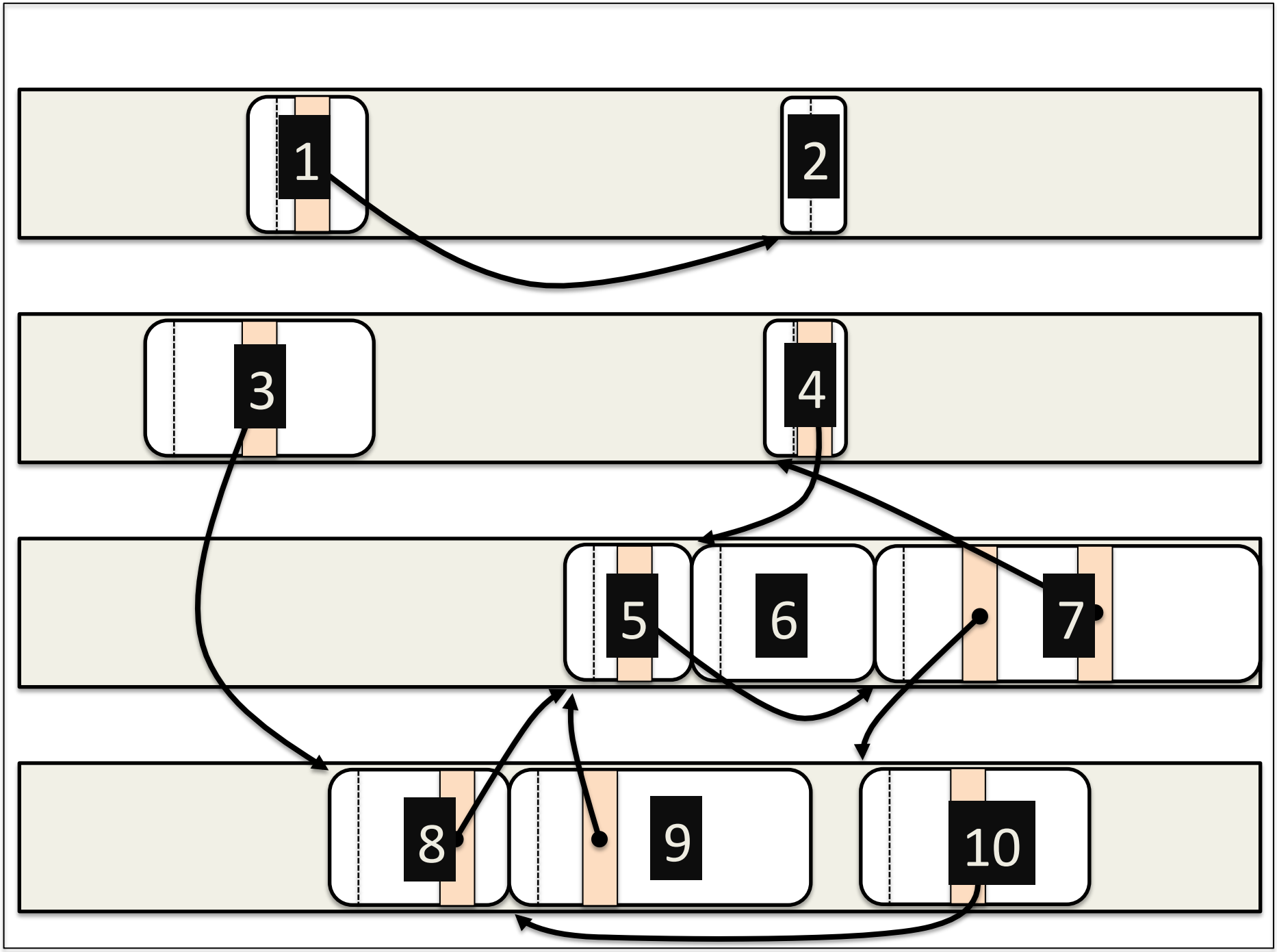




Locality in Mark and Sweep

- Fragmentation affects cache behavior
  - Cache blocks contain empty space
  - Unrelated data fills in gaps
  - We'll see next week why high fragmentation is usual

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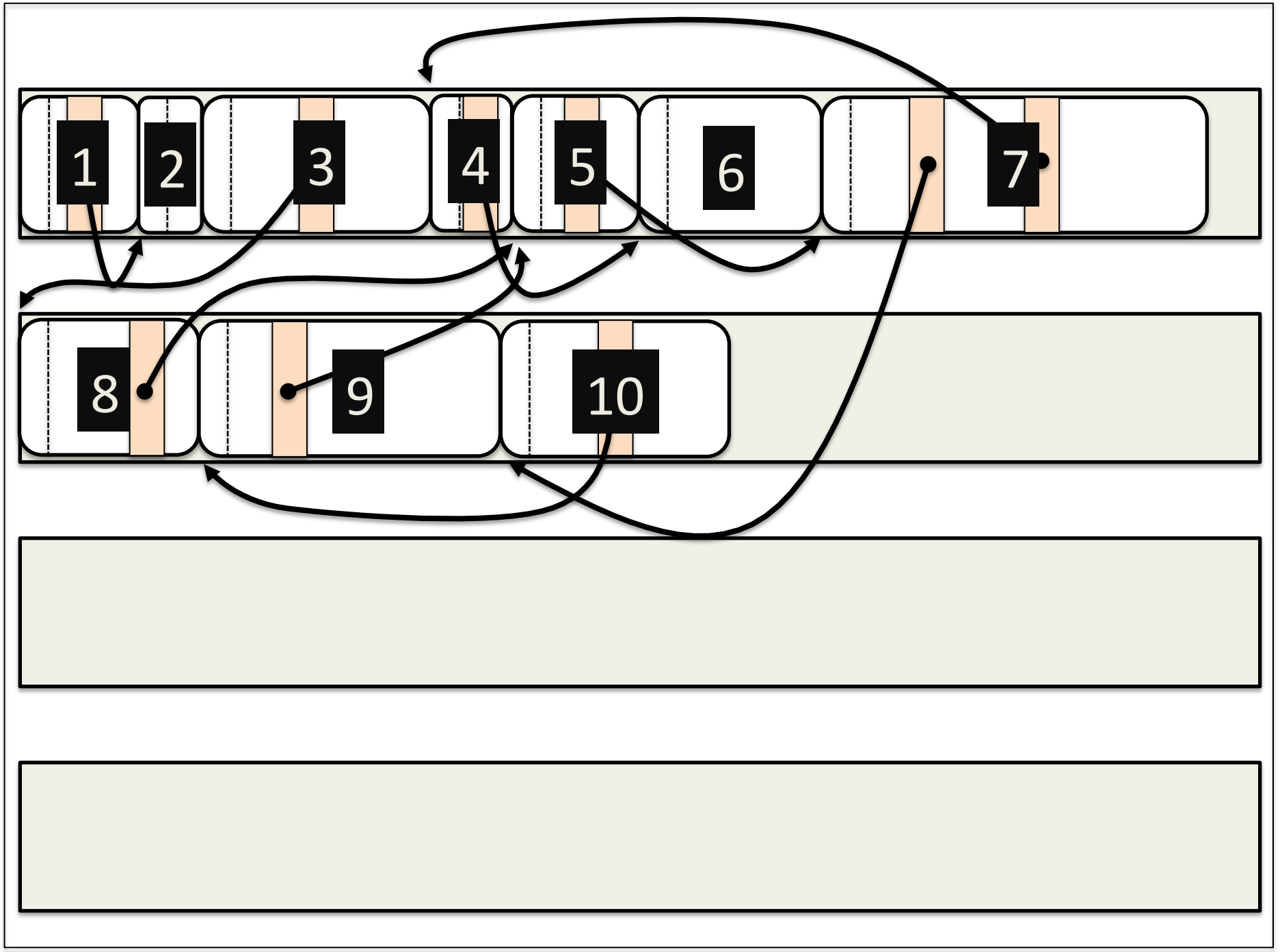
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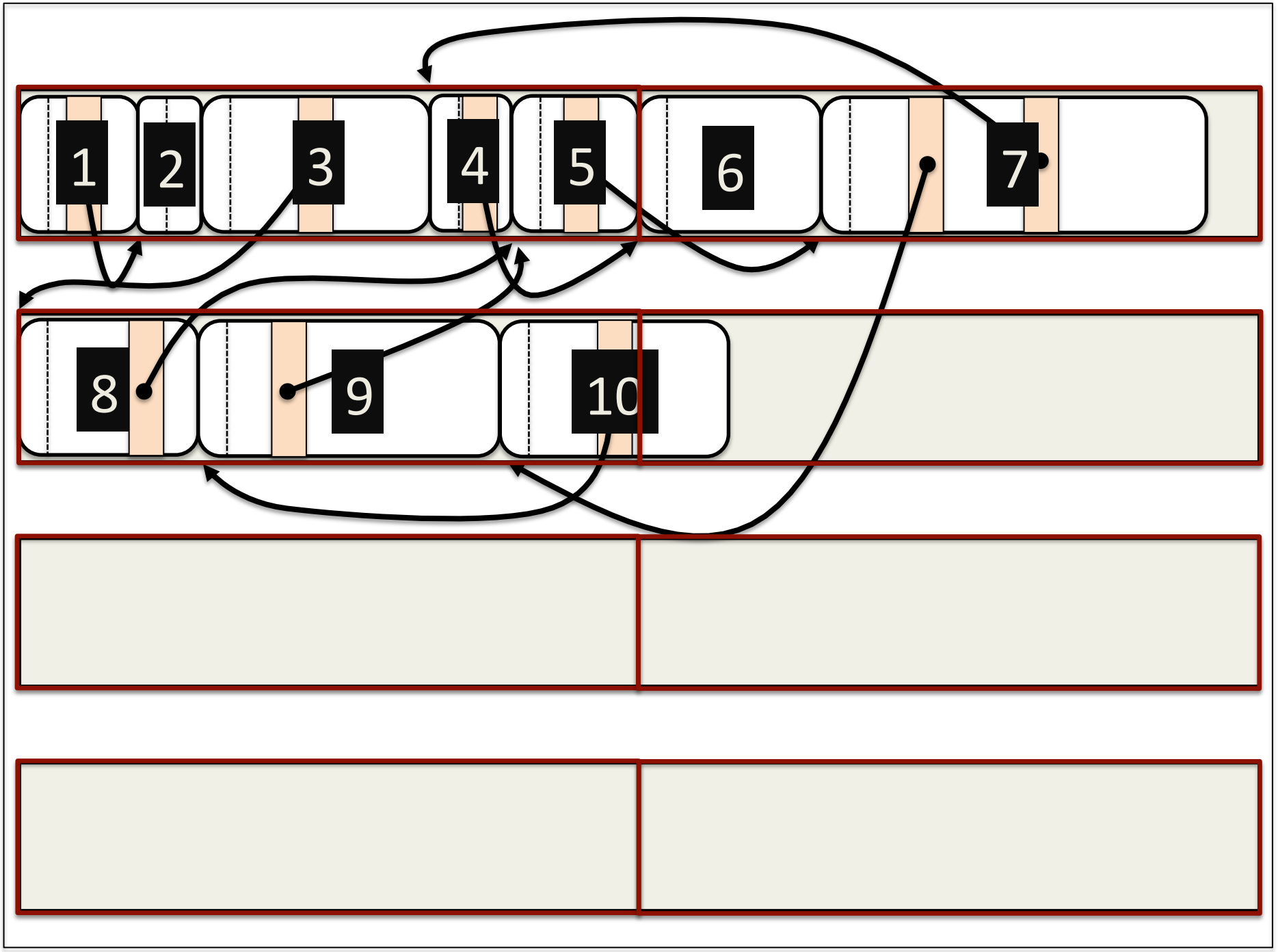
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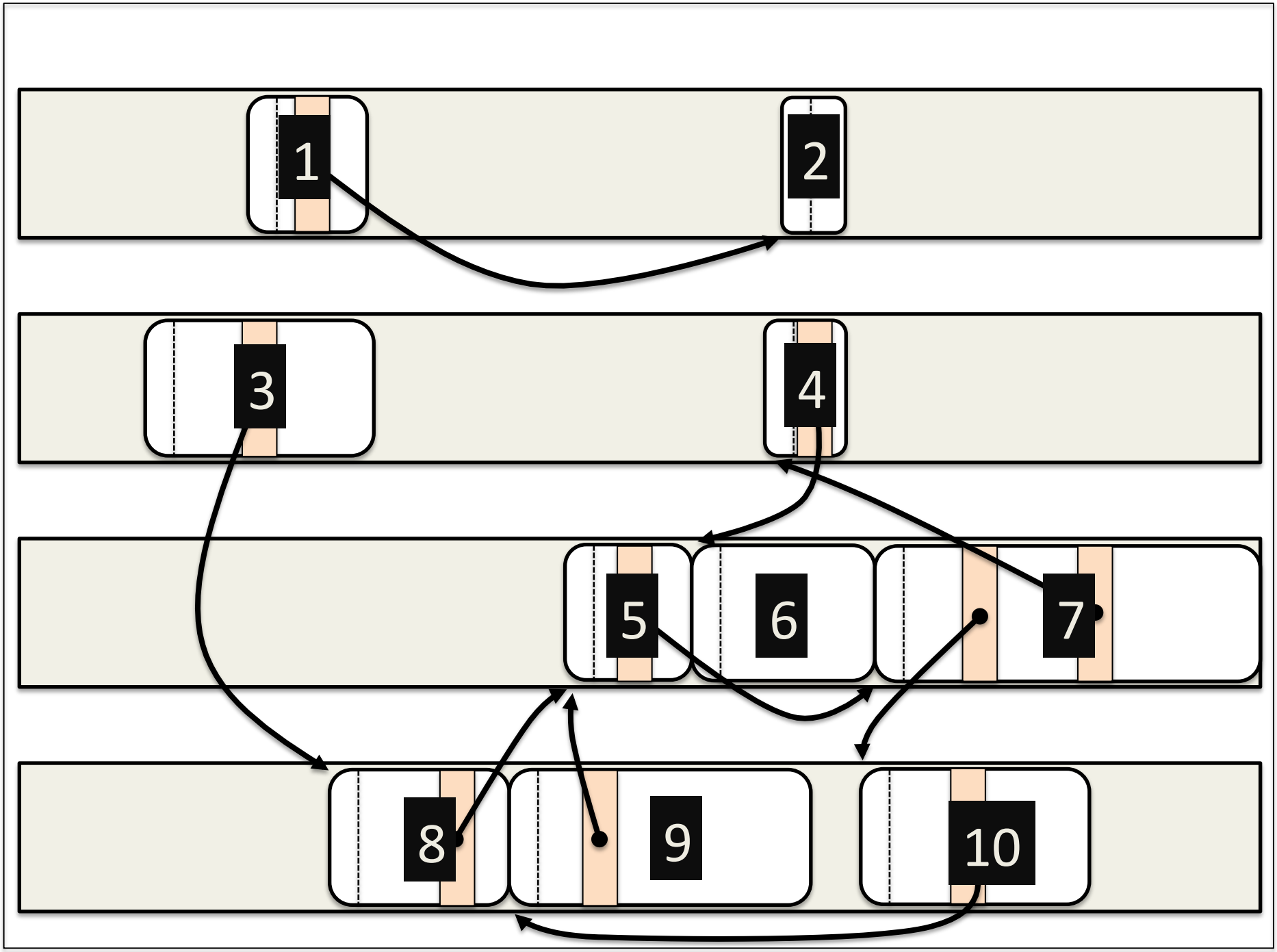
Locality in Compacting Collectors

- Compaction pass eliminates fragmentation
  - No holes in the cache line
- Objects maintain allocation order
  - Good spatial locality
- Is there a better ordering?

Object Oriented Languages

- Spatial locality extends to references
  - Objects that point to one another accessed together
- References between objects can change
  - Object graph mutated over time
  - Allocation order may no longer be optimal
- Mark Sweep and Compaction can't exploit changes
  - Objects stay in allocation order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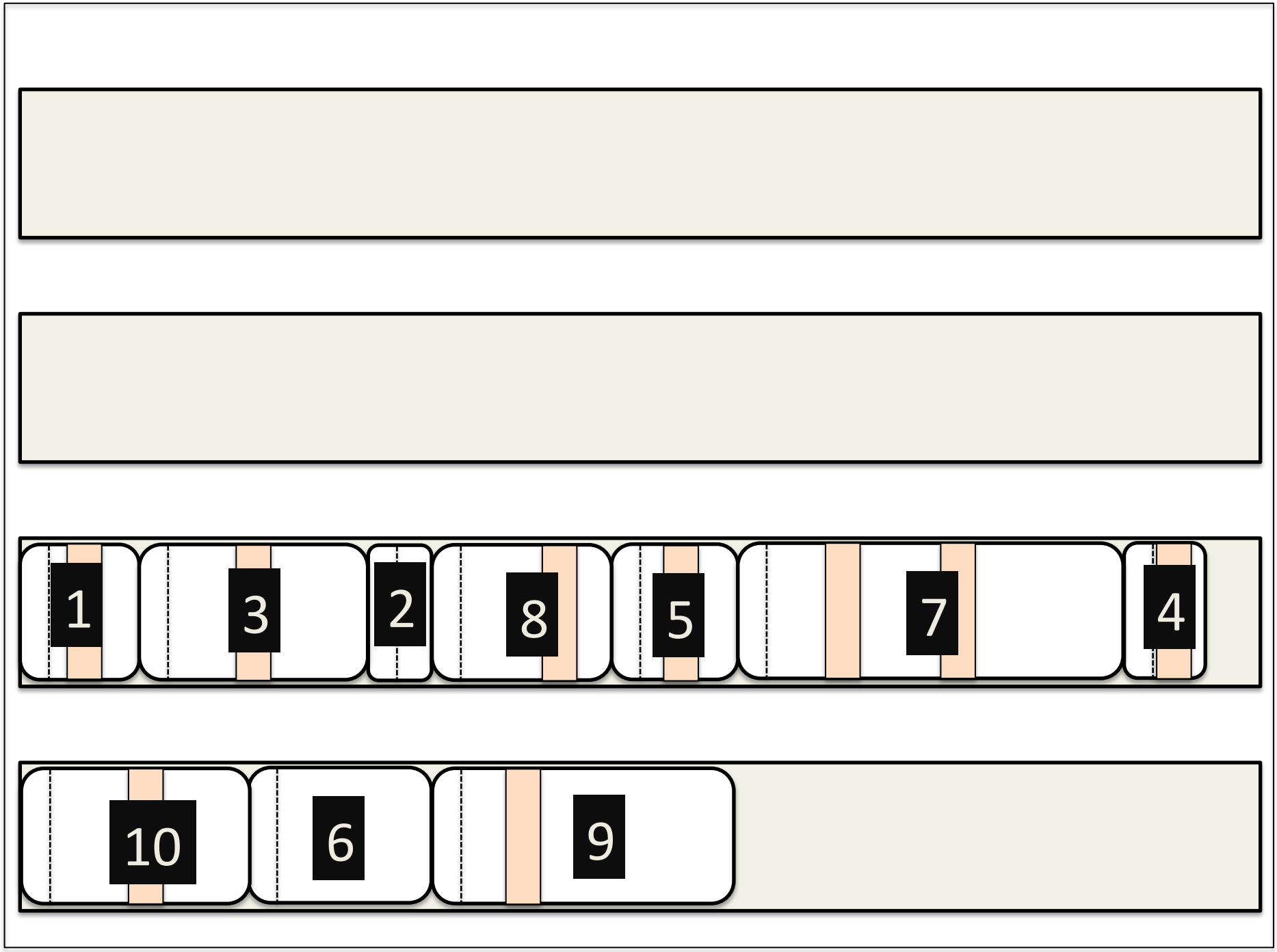
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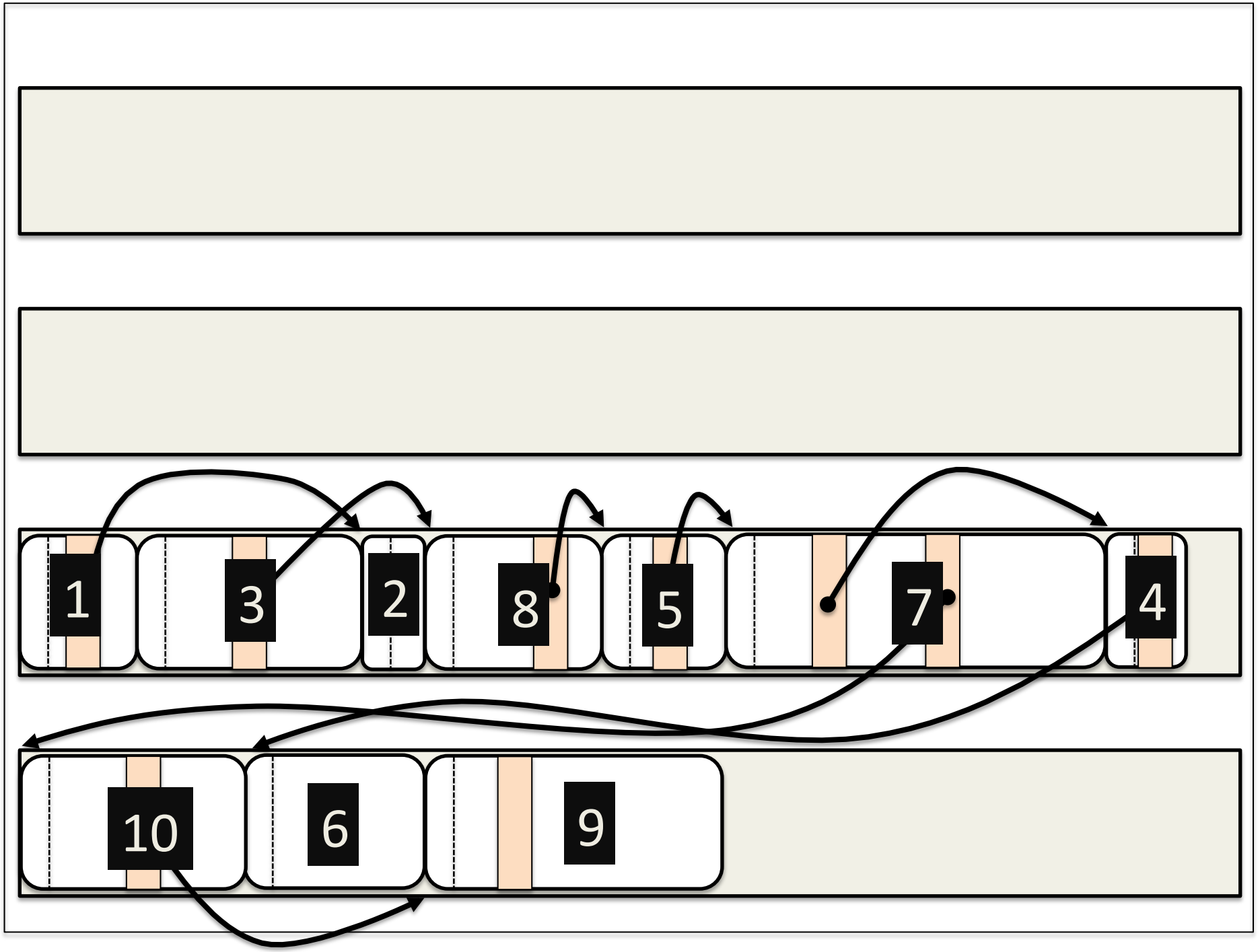
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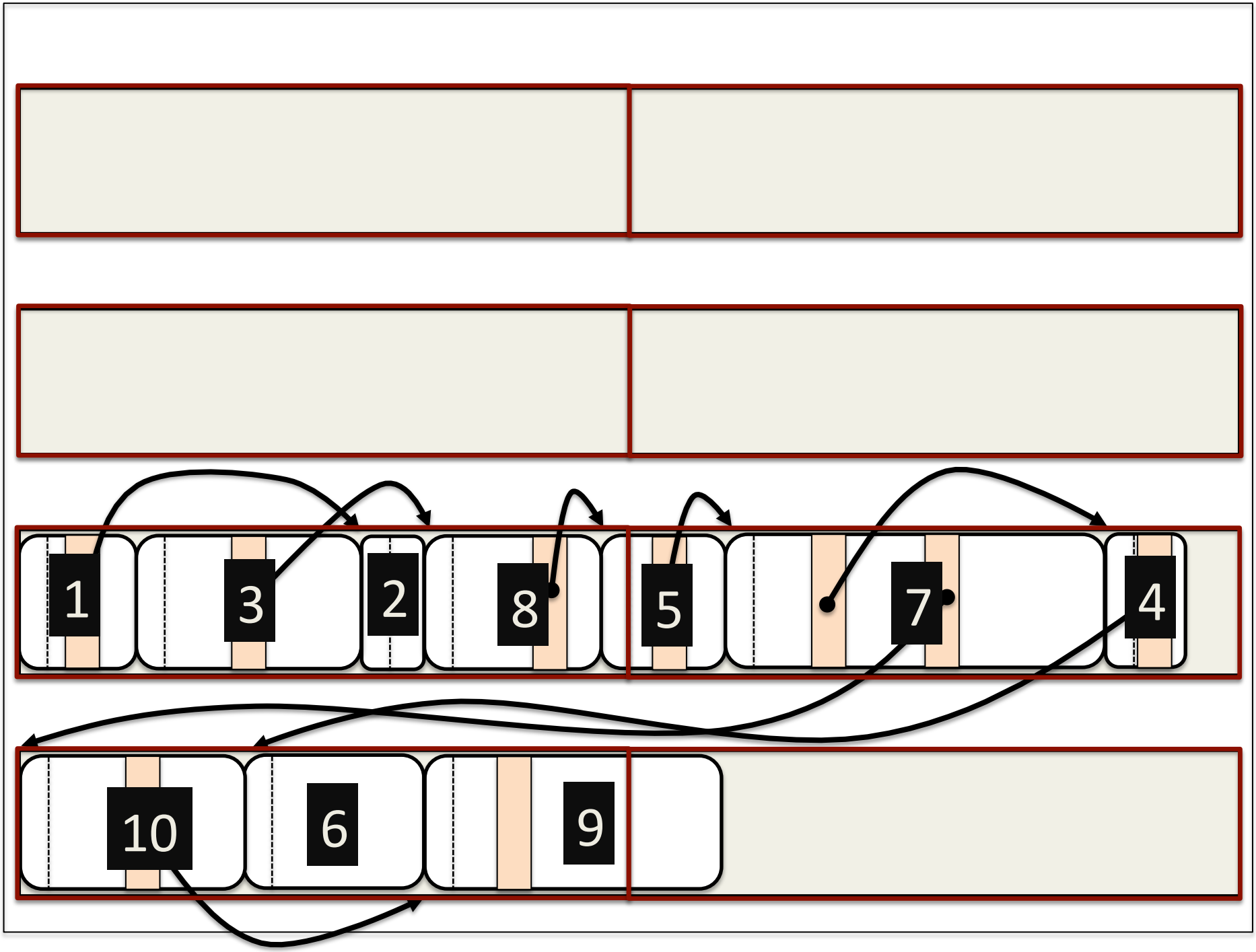
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Dynamic Locality

- Appel-style collectors copy in breadth-first order
  - Objects are copied as references are found
- Resulting order reflects connectivity
- Later collections can reorder objects
  - Can be useful if access patterns shift
- Generally get the most effect the first time
  - Cost of moving dominates application improvement

Conservative GC Revisited

- Conservative GCs can't move objects
  - Don't know for certain if a value is a pointer
  - May update an integer
- Most high-performing GCs do some copying
  - Sometimes a hybrid approach
- Imposes a limit on GC performance