Algorithms for Dynamic Memory Management (236780)

Lecture 2

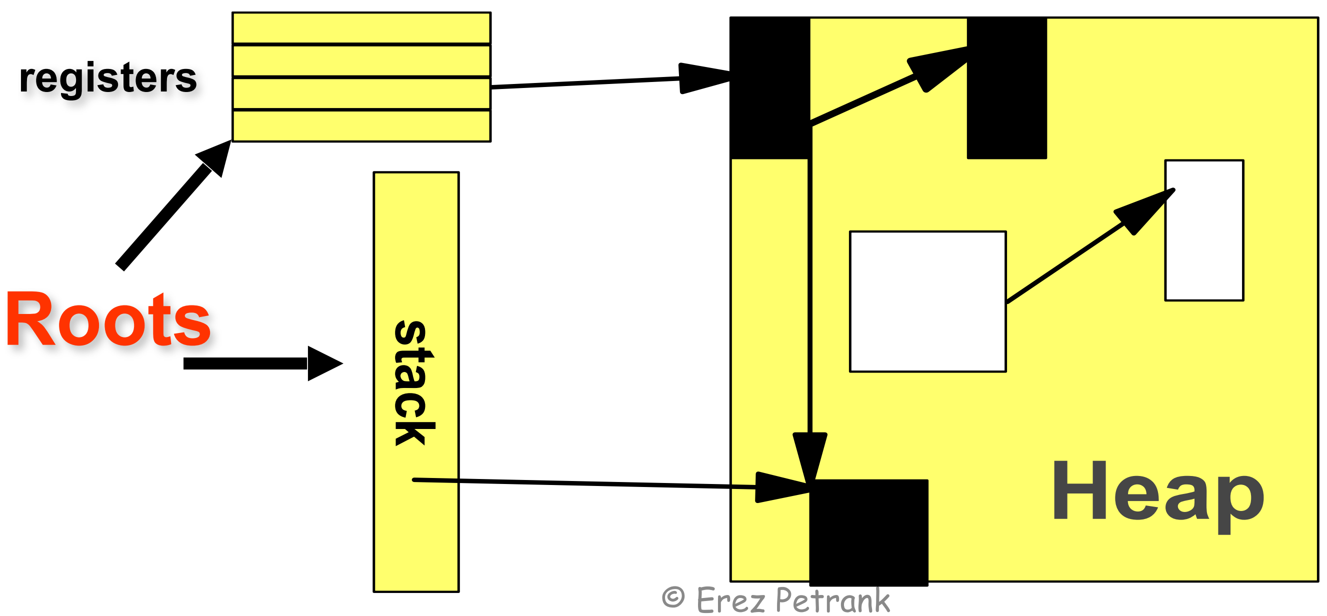
Erez Petrank

Topics last week

- Overview on
  - Memory management
  - The 3 classic algorithms
  - Course topics
- The Mark & Sweep algorithm
  - Basics
  - Recursion explicit, pointer reversal, mark-bit table, lazy sweeping, bitwise sweep

The Mark-Sweep algorithm

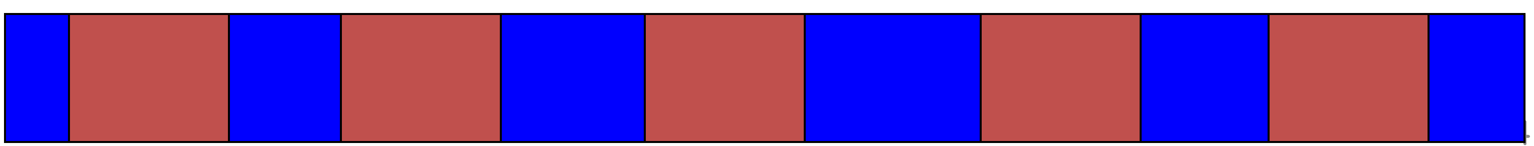
- Traverse live objects & mark black.
- White objects can be reclaimed.



Mark-Compact

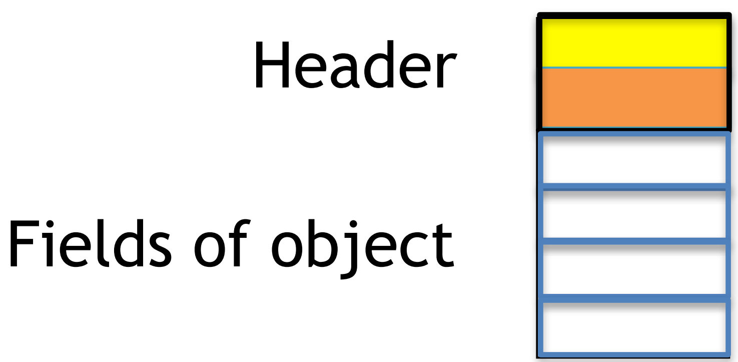
- With time the heap gets fragmented.
- When space is too fragmented to allocate, a compaction algorithm is used.

The Heap



A Header

- The memory manager keeps a header for each object.
- User allocates 24 bytes, the actual allocation is larger!
- Header typically has: length, control bits (for marking an object, synchronization, hashing, etc), pointer to class (for methods and fields types).



Memory Management

Compaction



Overview

- Motivation
  - Fragmentation – problem and solutions.
- Five Algorithms:
  - Two-finger Alg – for objects of equal size.
  - Lisp 2 Alg.
  - Jonkers threaded algorithm
  - SUN's parallel algorithm
  - IBM's parallel algorithm
  - (The Compressor, a more advanced algorithm is presented in lecture 10)
- Summary.

Motivation

- Fragmentation is the main drawback of the mark-sweep algorithms.
  - Large objects cannot be allocated (even after GC).
  - Allocation becomes difficult (and inefficient).
  - Increasing heap size means page faults and cache misses.
  - Longer sweep
  - Locality: objects allocated together tend to be accessed together. Thus, mixing allocated objects with “old” objects increases cache-misses.
- Compaction algorithms fix above problems by moving all live objects together.

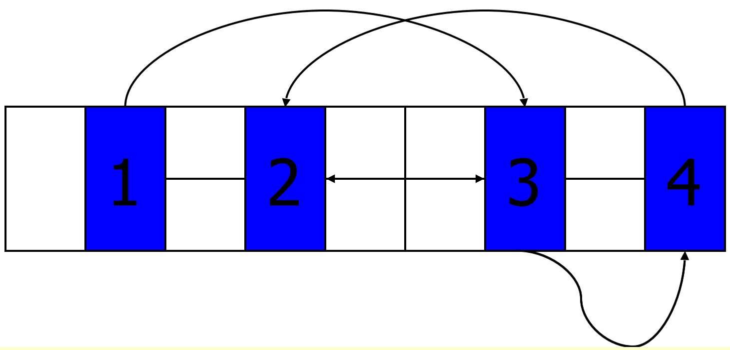
The Generic Task

- Assume live objects are marked.
- Move objects to one (or a small number of) areas in the heap
- Modify pointers to reference the new locations.

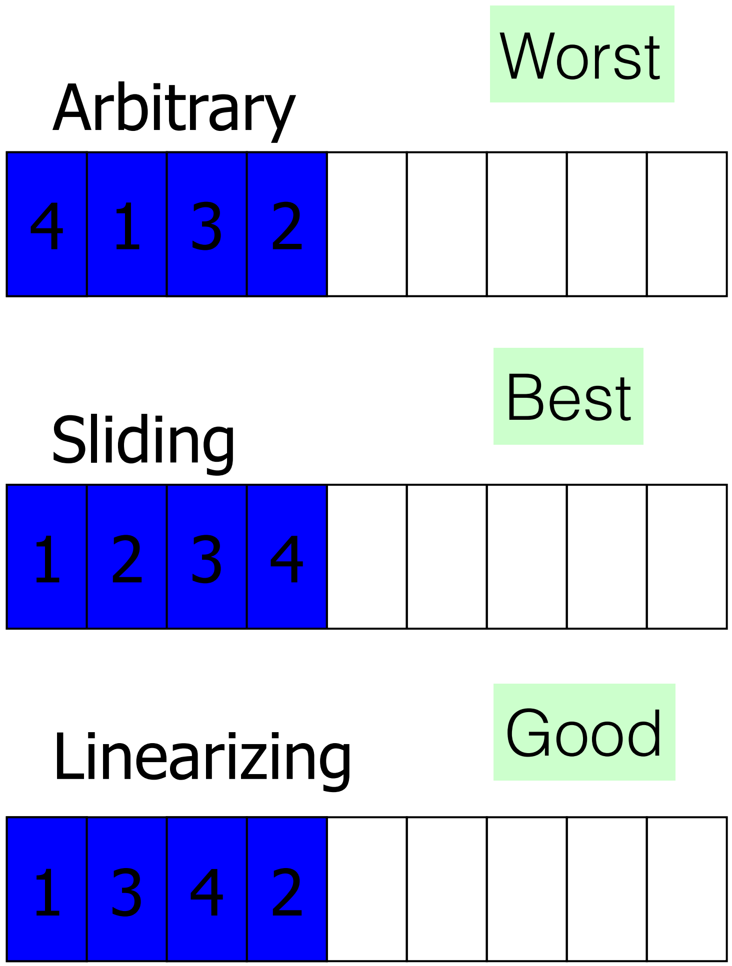
Comparison Criteria

- Complexity:
  - Number of heap passes.
  - Passes over auxiliary tables.
  - Cache performance.
- Extra space required.
- Restrictions on objects (e.g., equal size).
- Compaction quality:
  - Order of objects in output.
  - Number of packed areas (best: 1 area).

Object Ordering



- Arbitrary – no guaranteed order.
- Linearizing – objects pointing to one another are moved into adjacent positions.
- Sliding – maintaining the original order of allocation.

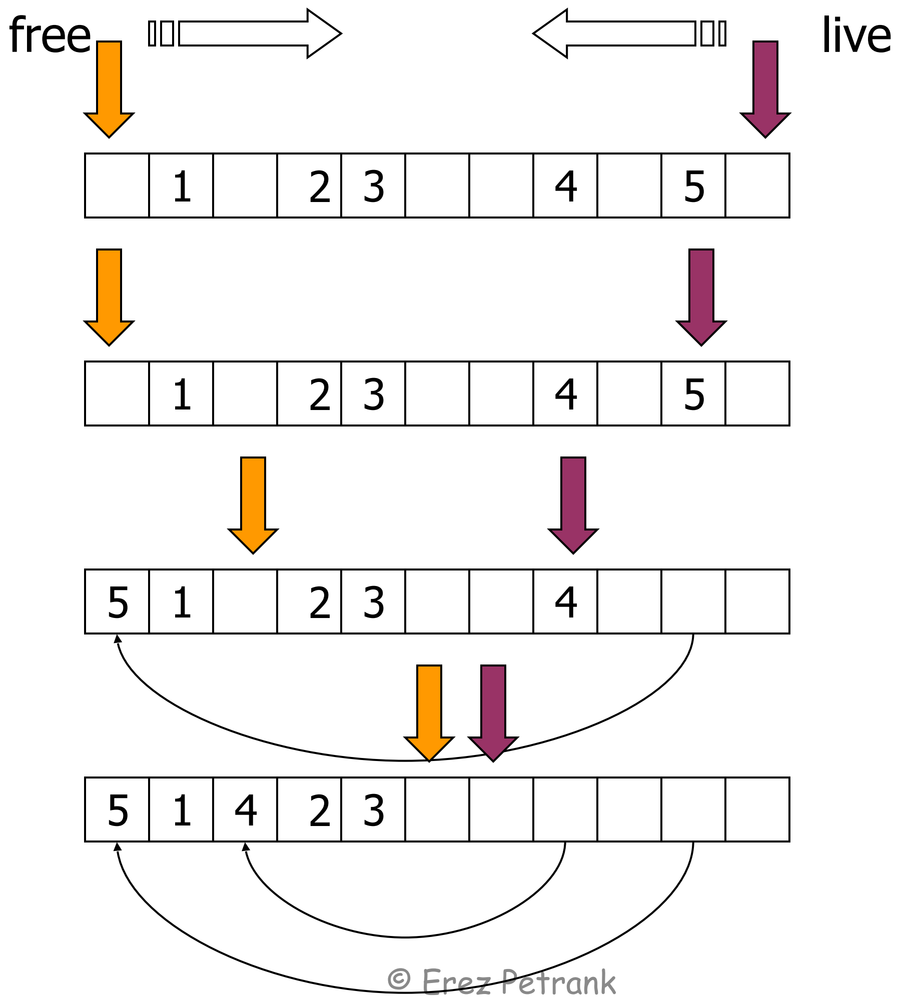


The Two Finger Algorithm [Edwards 1974]

- Simplest algorithm:
  - Designed for objects of equal size
  - Order of objects in output is arbitrary.
  - Two passes.

- First pass: compact.
- Second pass: update pointers.

Two finger, pass I - Example

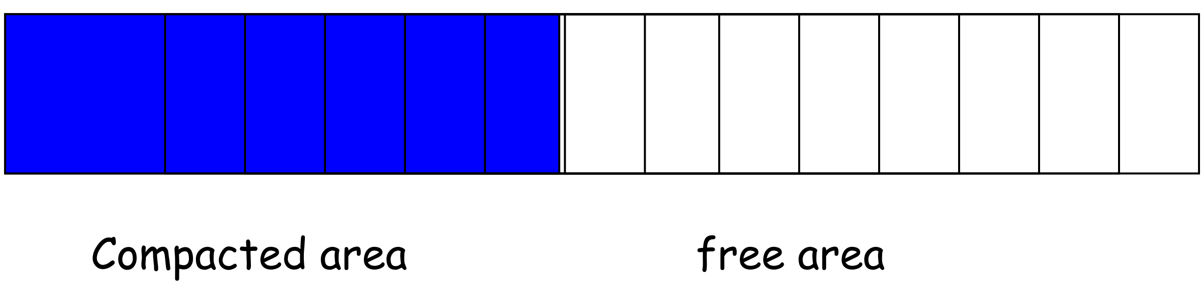


Pass I: Compact

- Use two pointers:
  - free: search from heap start for free space.
  - Live: search from heap end for a live object.
  - When both find, move object to free spot.
- When an object is moved, a pointer to its new location is left at its old location.

Pass II: Fix Pointers

- Go over live objects in the heap
- For each pointer
  - If points to free area: fix it using the forwarding pointer.



Partial Adaption to Variable Sized Objects

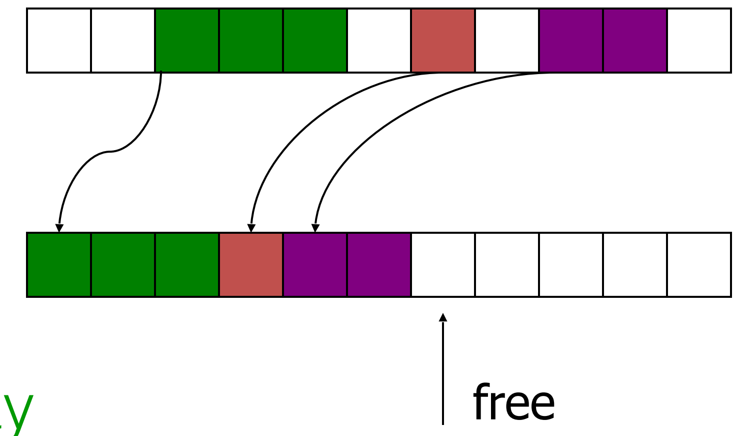
- Divide heap to regions.
- Each region has one size objects.
- Perform compaction via two fingers for each region separately.

Two finger – Properties

- ☺️ Simple!
- ☺️ Relatively fast: One pass + pass on live objects (and their previous location).
- ☺️ No extra space required!
- ☹ Objects restricted to equal size.
- ☹ Order of objects in output is arbitrary.
  - ☹ This significantly deteriorates program efficiency! Thus – not used in practice.

The Lisp2 Algorithm

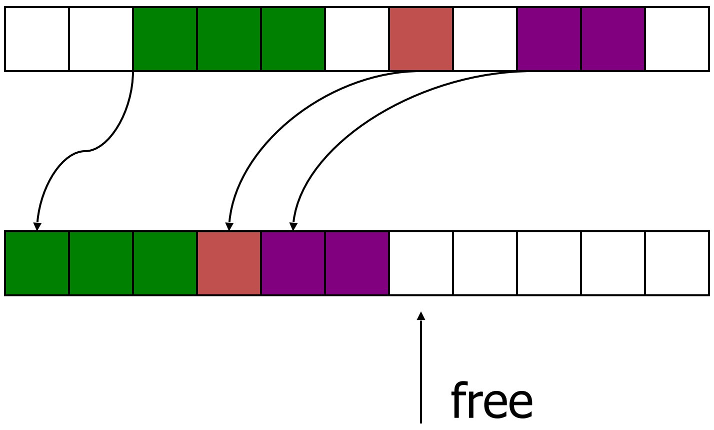
- Goals: handle variable sized objects, keep order of objects.
- Requires one additional pointer field for each object.
- The picture:



- Note: cannot simply keep forwarding pointer in original address. It may be overwritten by a moved object.

The Lisp2 Algorithm

- Pass 1: Address computation. Keep new address in an additional header field.
- Pass 2: pointer modification.
- Pass 3: Move.



two pointers (free & live) run from the bottom. Live objects are moved to free space keeping their original order.

Lisp 2 – Properties

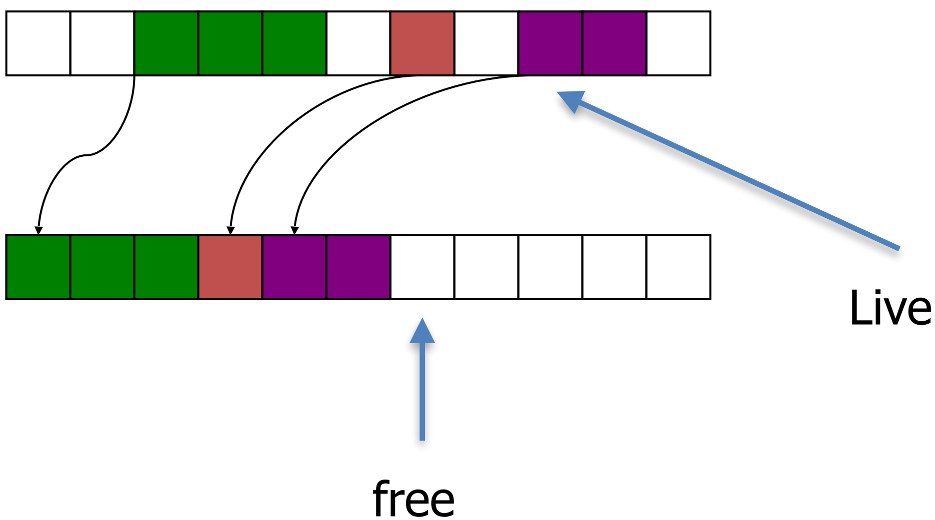
- ☺ Simple enough.
- ☺ No constraints on object sizes.
- ☺ Order of objects preserved.
- ☹ Slower: 3 passes.
- ☹ Extra space required – a pointer per object.

Notes on Previous Algorithms

- LISP2: extra space for forwarding pointers & three passes..
- Two-fingers: creates arbitrary order.
- Pointer fix up: using forwarding pointers.
  - Either before moving the objects (LISP2)
  - or after (two fingers).
- The next algorithm is more complicated.
  - Fixing pointers while moving objects.
  - No extra space required.
  - Order of objects preserved.

Jonker's Algorithm [1979]: Eliminate Extra Space

- No extra space: can't keep new location for each object.
- Where do we move an object?
- An important point: we know where to move each object when we get to it. If we don't keep this information, we lose it.



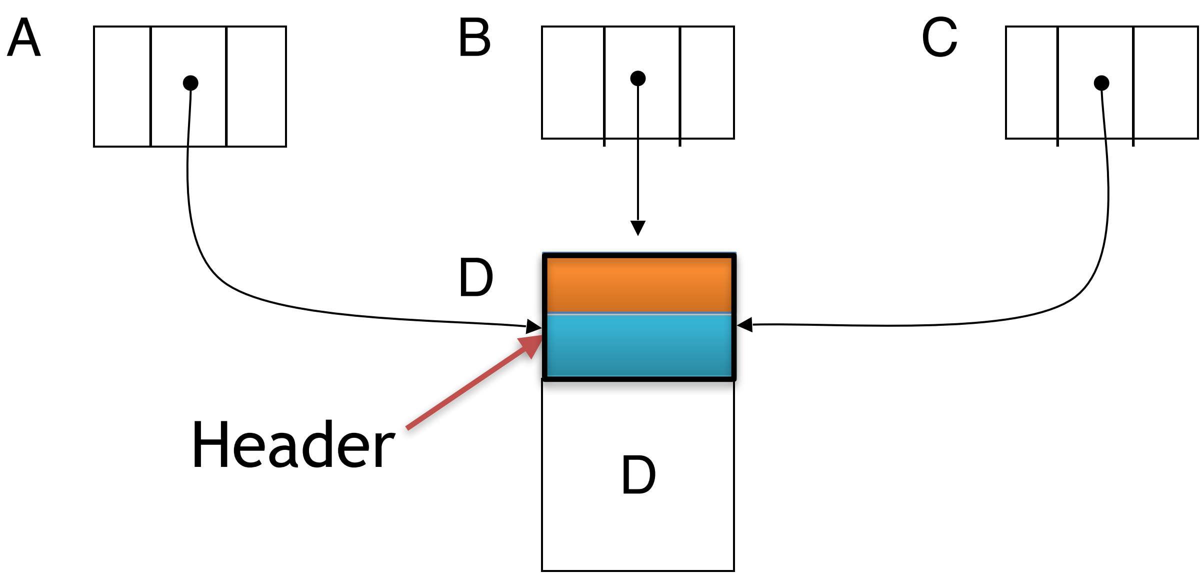
Jonker's Algorithm [1979]: Eliminate Extra Space

- No extra space: can't keep new location for each object.
- Where do we move an object?
- An important point: we know where to move each object when we get to it. If we don't keep this information, we lose it.
- Basic idea (threading method):
  for each object O, keep list of all pointers that reference it. (The pointers are "threaded".)
  Issues to solve:
  - list with no extra space = in objects,
  - objects that move foil the list structure.

Threading: a List with no Space Overhead

- Observations for a Java-Like Environments.
- Pointers only point to object head.
- JVM keeps a header for each object.
  - Size of header larger than a pointer.
  - Info in header distinguishable from a pointer (e.g., pointer to class info).
- Use this structure to "thread" pointers referencing an object.
  - Let's thread 3 pointers referencing object D…

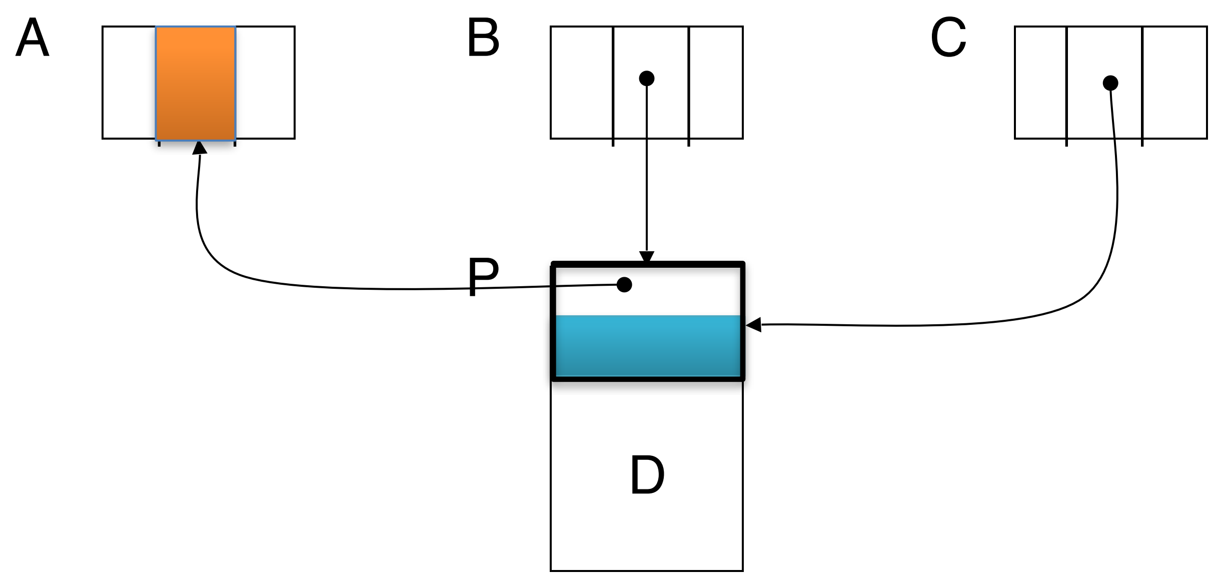
Threading Example



Before Threading D

1) header info moves to pointer
2) pointer location put in header.

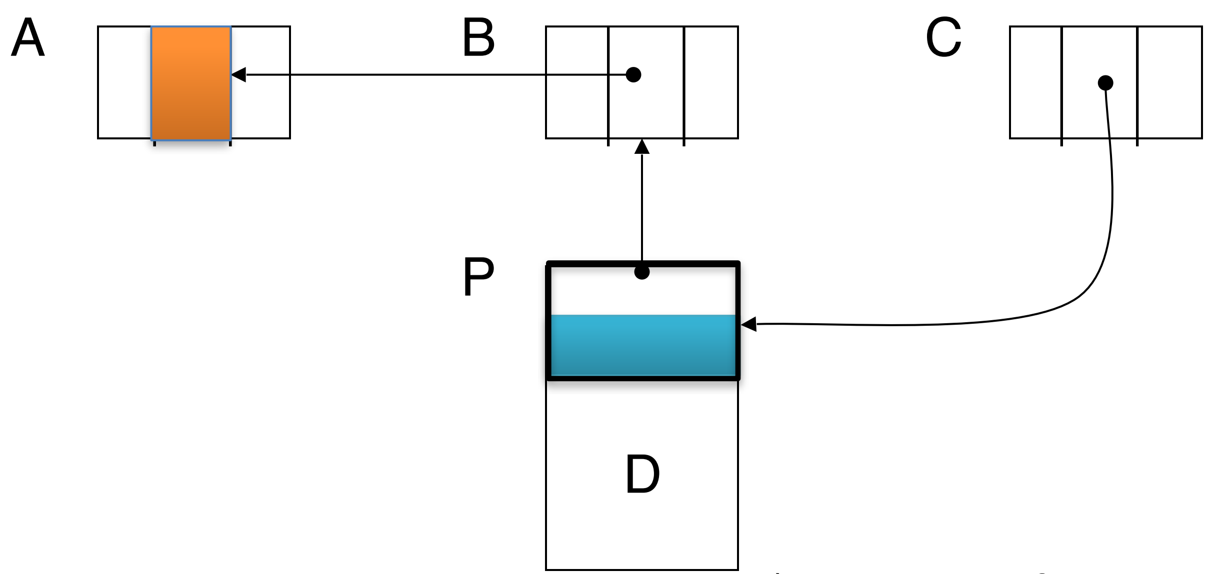
Threading Example



After threading D with A

1) header info moves to pointer
2) pointer location put in header.

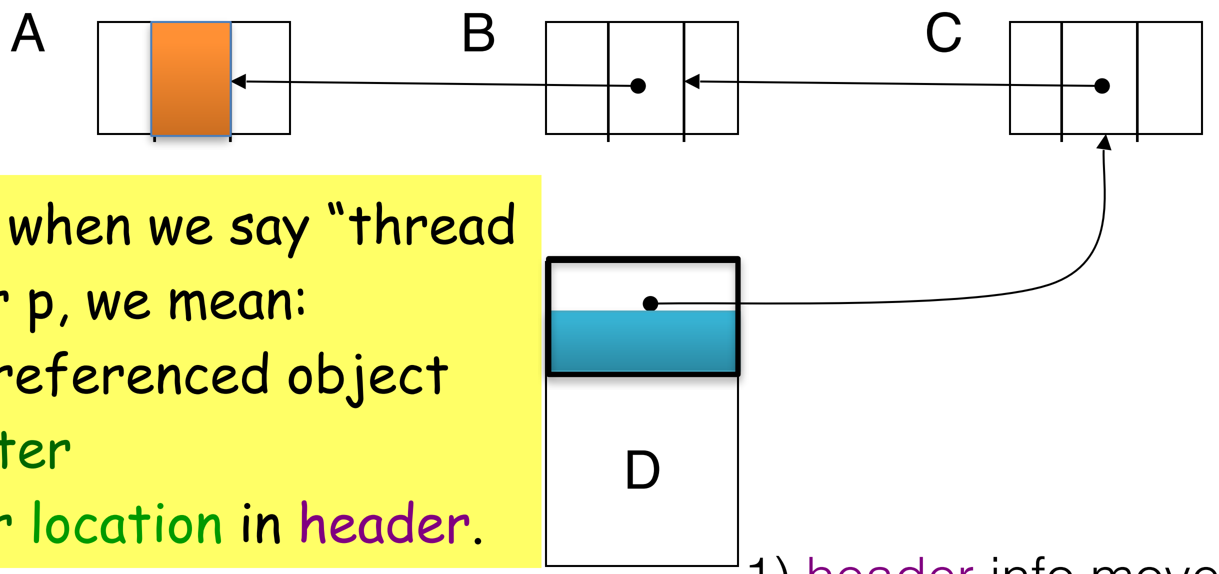
Threading Example



After threading D with A and B

1) header info moves to pointer
2) pointer location put in header.

Threading Example

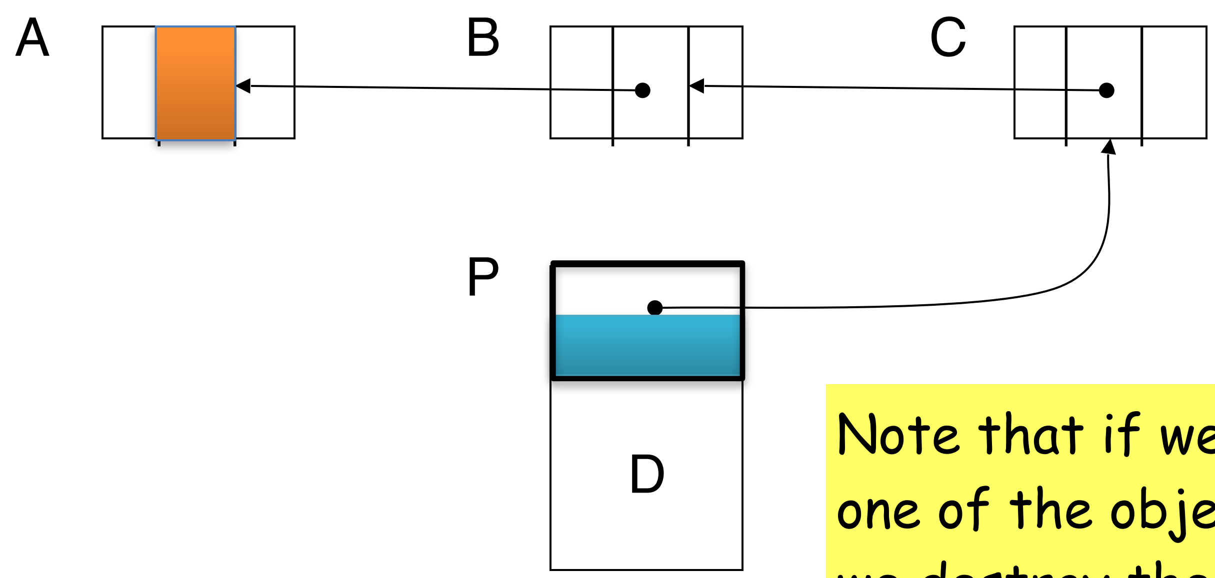


From now on, when we say "thread p" for pointer p, we mean:
1) header of referenced object replaces pointer
2) put pointer location in header.

1) header info moves to pointer
2) pointer location put in header.

After threading D with A, B and C

Threading Example



Note that if we move one of the objects now, we destroy the list!

After threading D with A, B and C

Modify pointers on a threaded list to reference a new location

```
// Update thread, starting from node P to point to new location of P  update( P,
    new-location ) {
    next = Heap[ P ];
    while pointer( next )       // Update thread to point to the location of
                                // P, free, till data different from pointer
                                // reached ('info' in our example)
        temp = Heap[next];
        Heap[next] = new-location;          // Point to new location
        next = temp;                        // Get next object to update

    Heap[ P ] = next;                       // Put 'info' back in P
}
```

A Simplified Version: 3 Passes

- Go over the heap once and thread all pointers.
- Go over the heap again and fix pointers:
  - When reaching an object O, its new address is known.
  - Use the threaded list to fix all pointers to O.
  - Un-thread O's list to restore the heap.
- Go over the heap again and move objects.

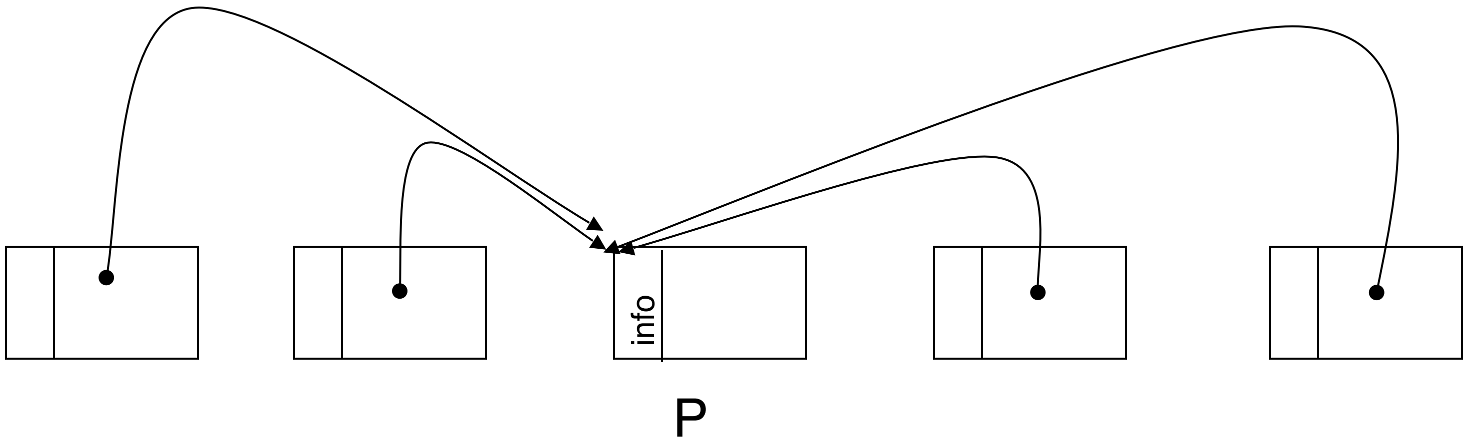
Can we do this with only 2 heap passes?

Forwards and Backwards Pointers

- While going over the heap and threading.
- **Observation 1**: when reaching an object in the first pass all forwards pointers to it are threaded.
- Action 1: at that time --- update these pointers.
- **Observation 2**: when completing the first pass, all objects have all backwards pointers threaded to them.
- During second pass: update the threaded backwards pointers and move the object.

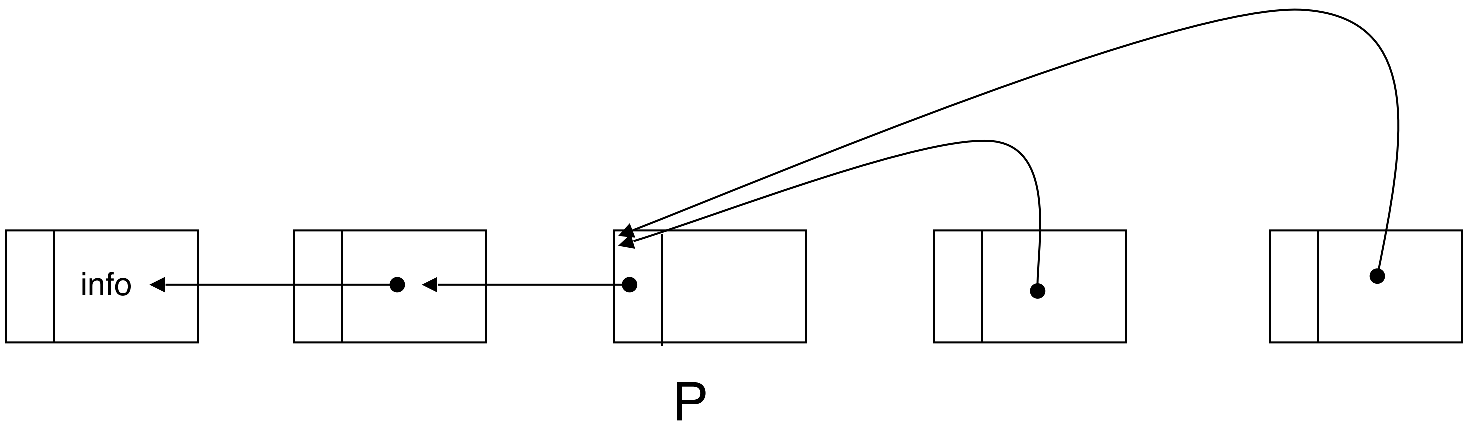
Note different terms:
Forwarding pointer: a pointer that shows where object has moved
Forwards pointer: a property of a pointer (points to higher addresses)

Threaded Methods – P's Point of View



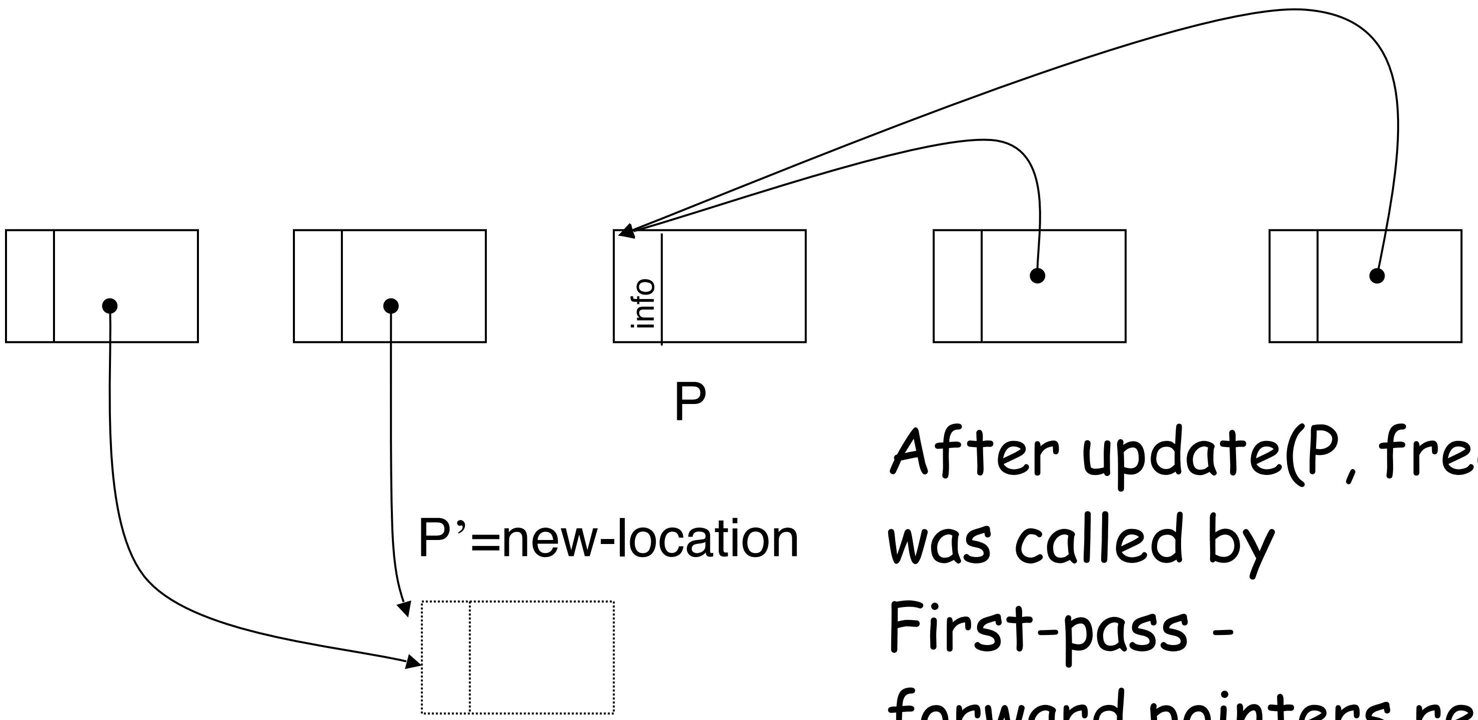
Initial configuration - forward and backward pointers to P.

Threaded Methods – P's Point of View



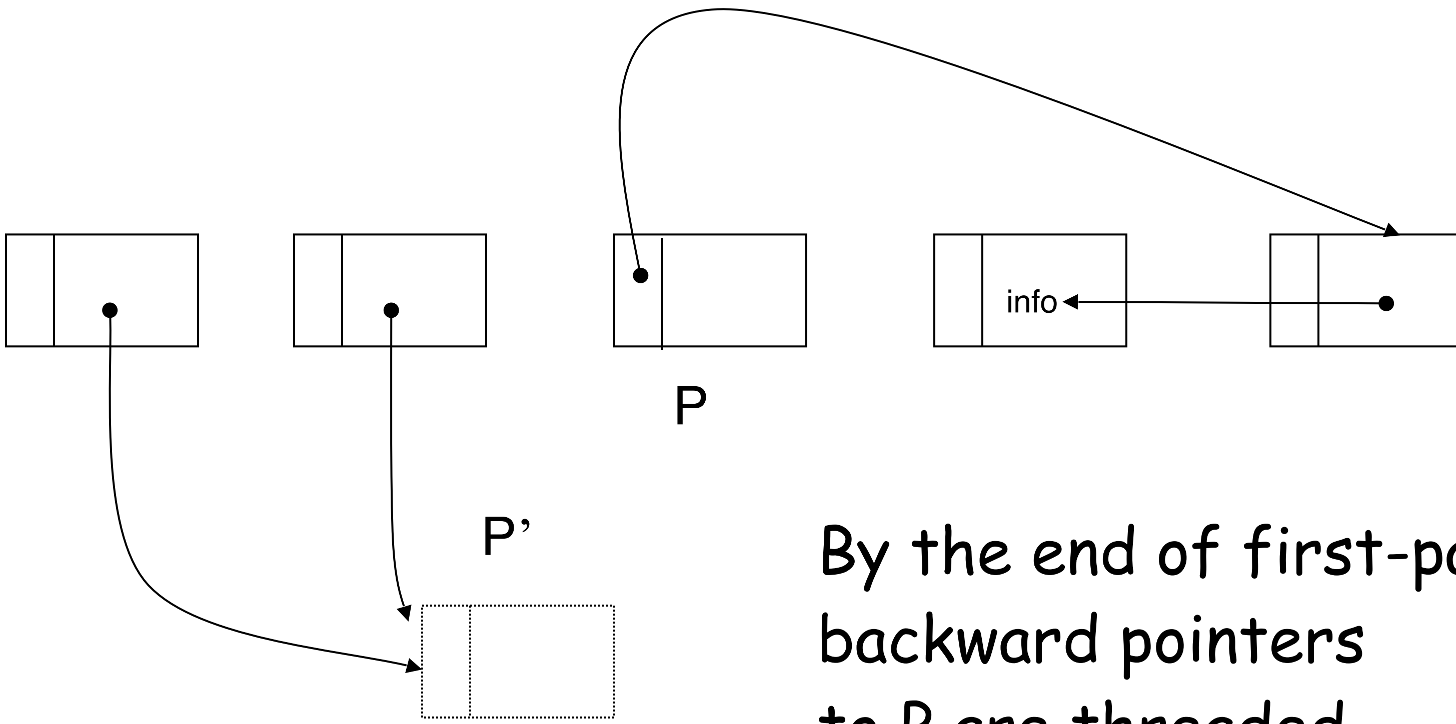
When P is first reached in first pass- all forward pointers to P are threaded.

Threaded Methods – P's Point of View



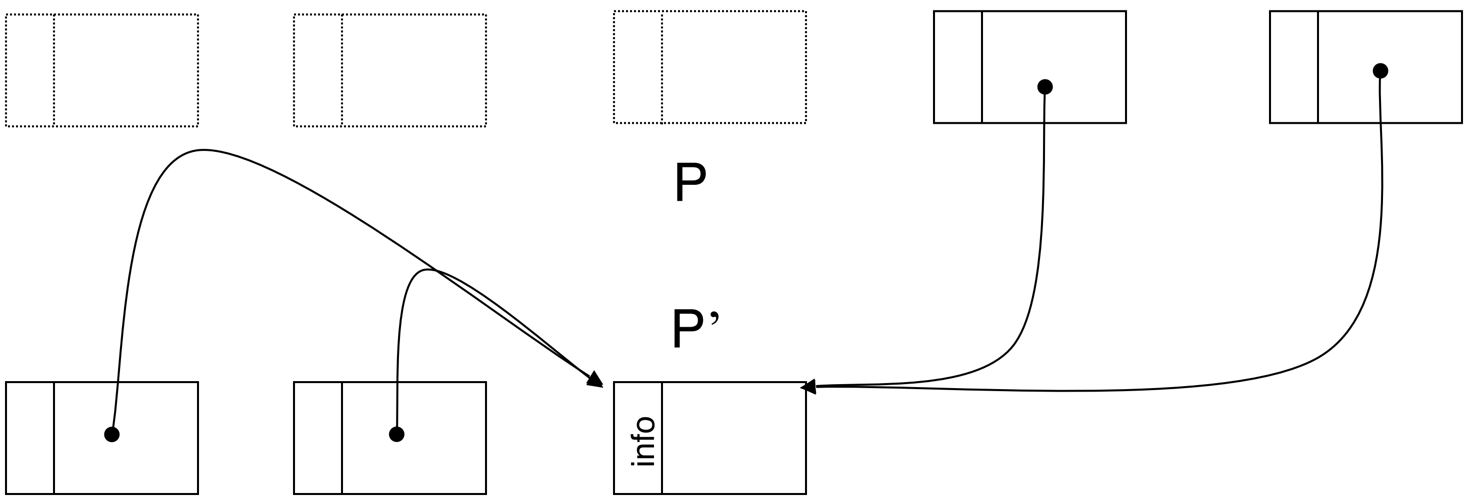
After update(P, free) was called by First-pass - forward pointers refer to P's new location.

Threaded Methods – P's Point of View



By the end of first-pass backward pointers to P are threaded.

Threaded Methods – P's Point of View

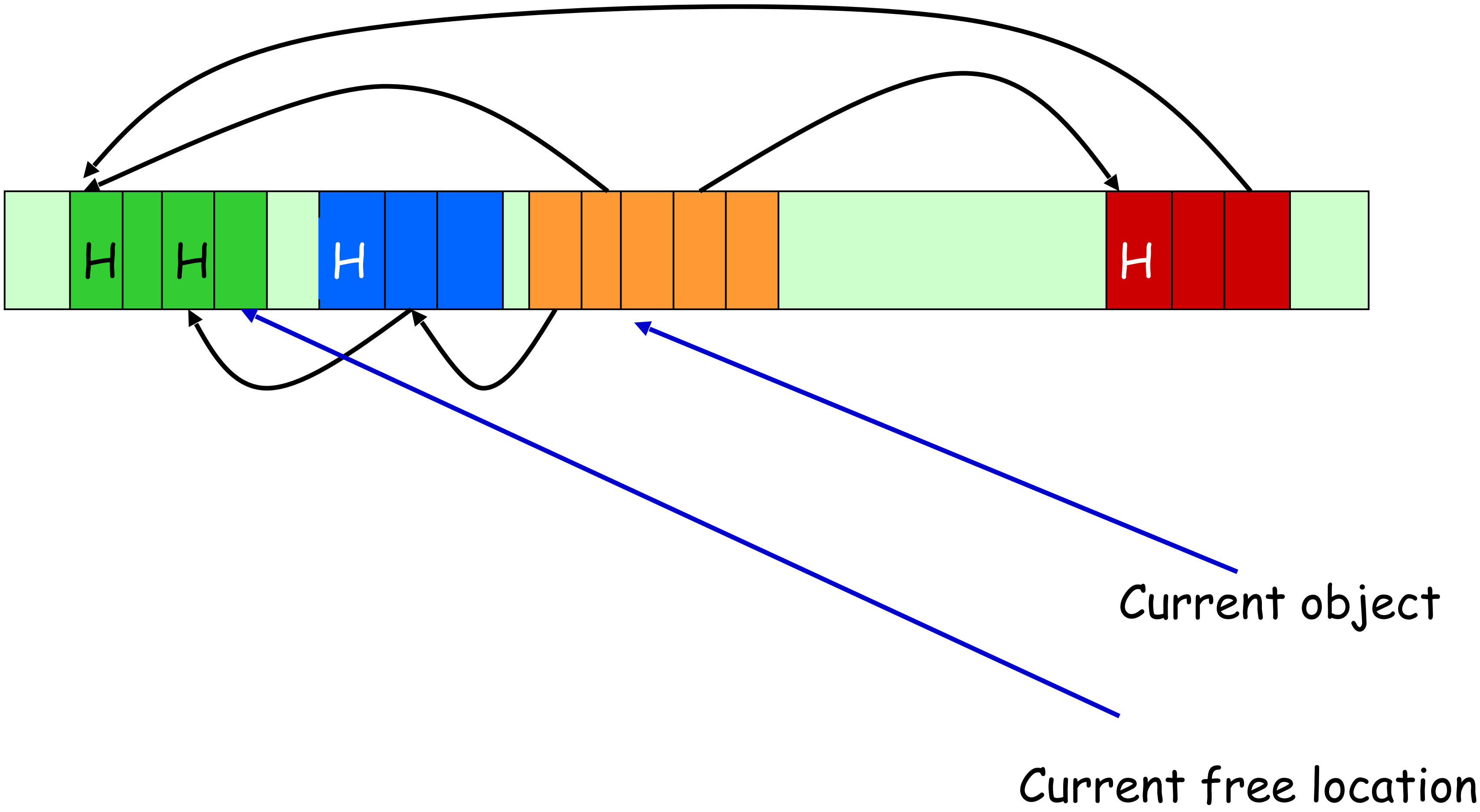


At the end of update_backward_pointers - backward pointers are updated and P is moved.

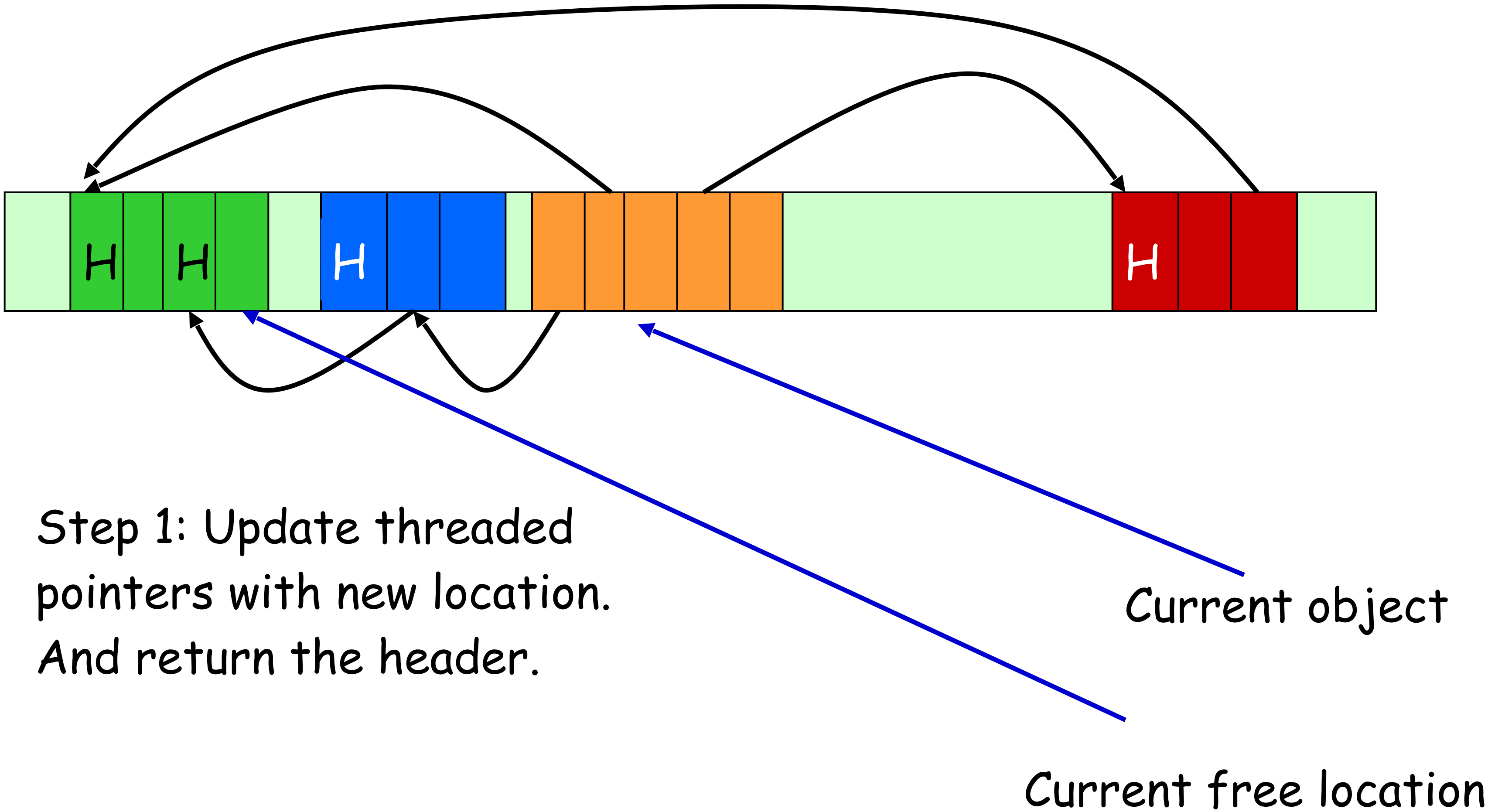
Jonker's Algorithm

- First heap pass: for each object O
  - **Determine** where O should move
  - **Update** all (incoming) forwards pointers to O (already threaded)
  - **Thread** O's (outgoing) forwards & backwards pointers
- Second heap pass: for each object
  - **Determine** where it should move
  - **Update** all (incoming) backward pointers (already threaded)
  - **Move** object

Jonker's Algorithm – Pass I

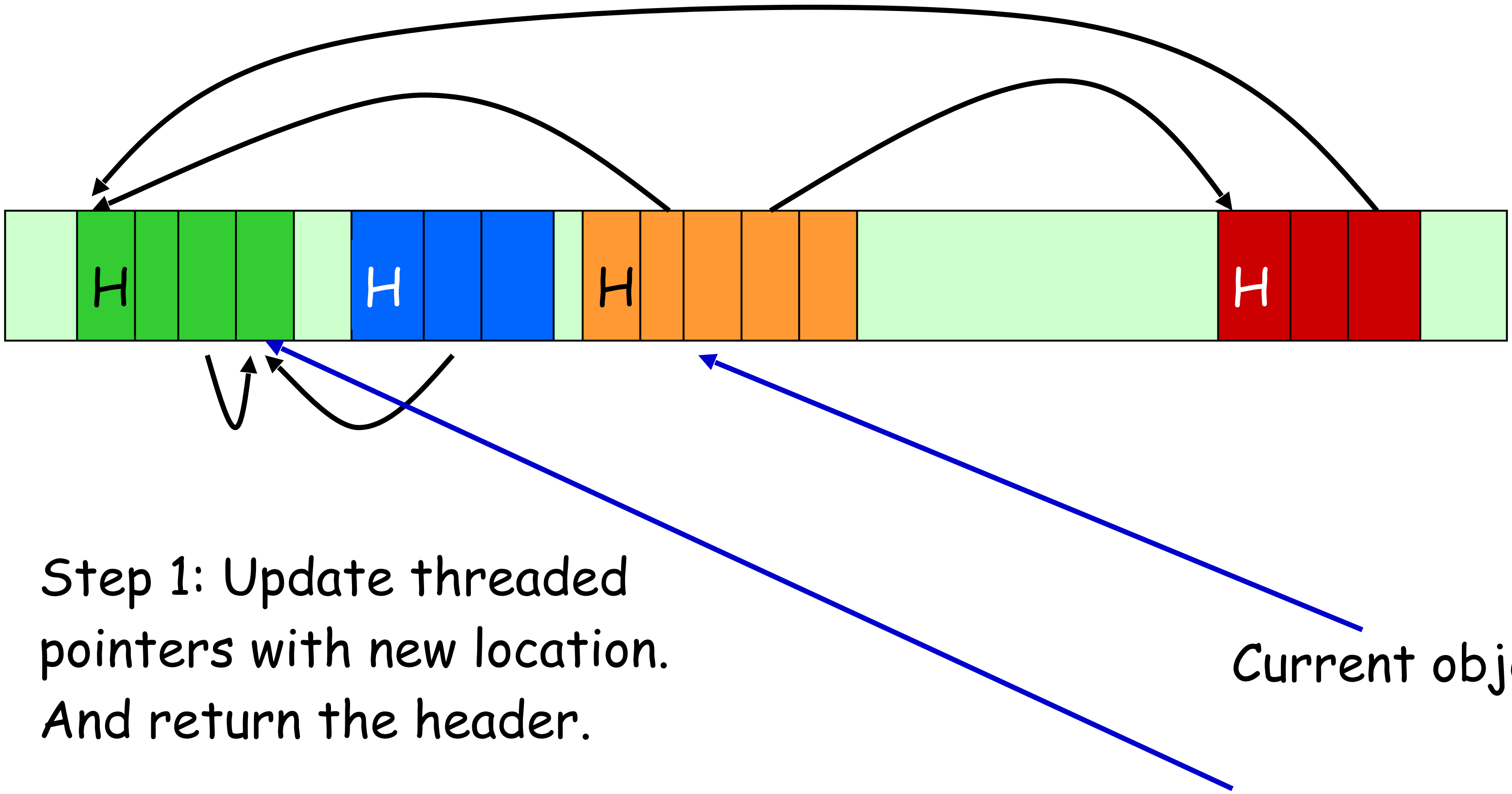


Jonker’s Algorithm – Pass I



Step 1: Update threaded pointers with new location. And return the header.

Jonker's Algorithm – Pass I

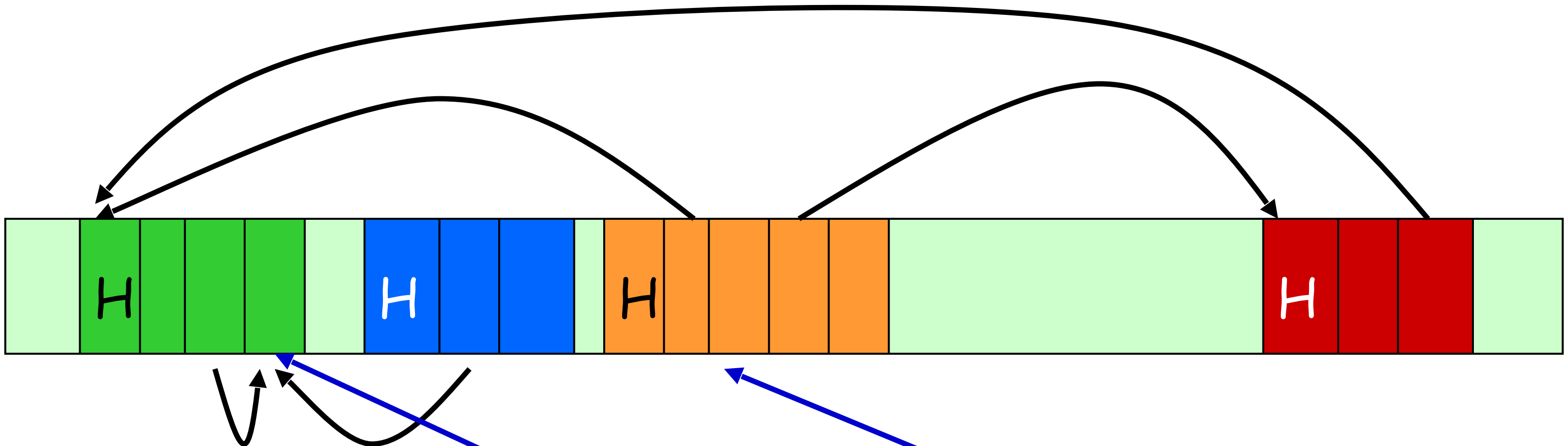


Step 1: Update threaded pointers with new location. And return the header.

Current object

Current free location

Jonker's Algorithm – Pass I

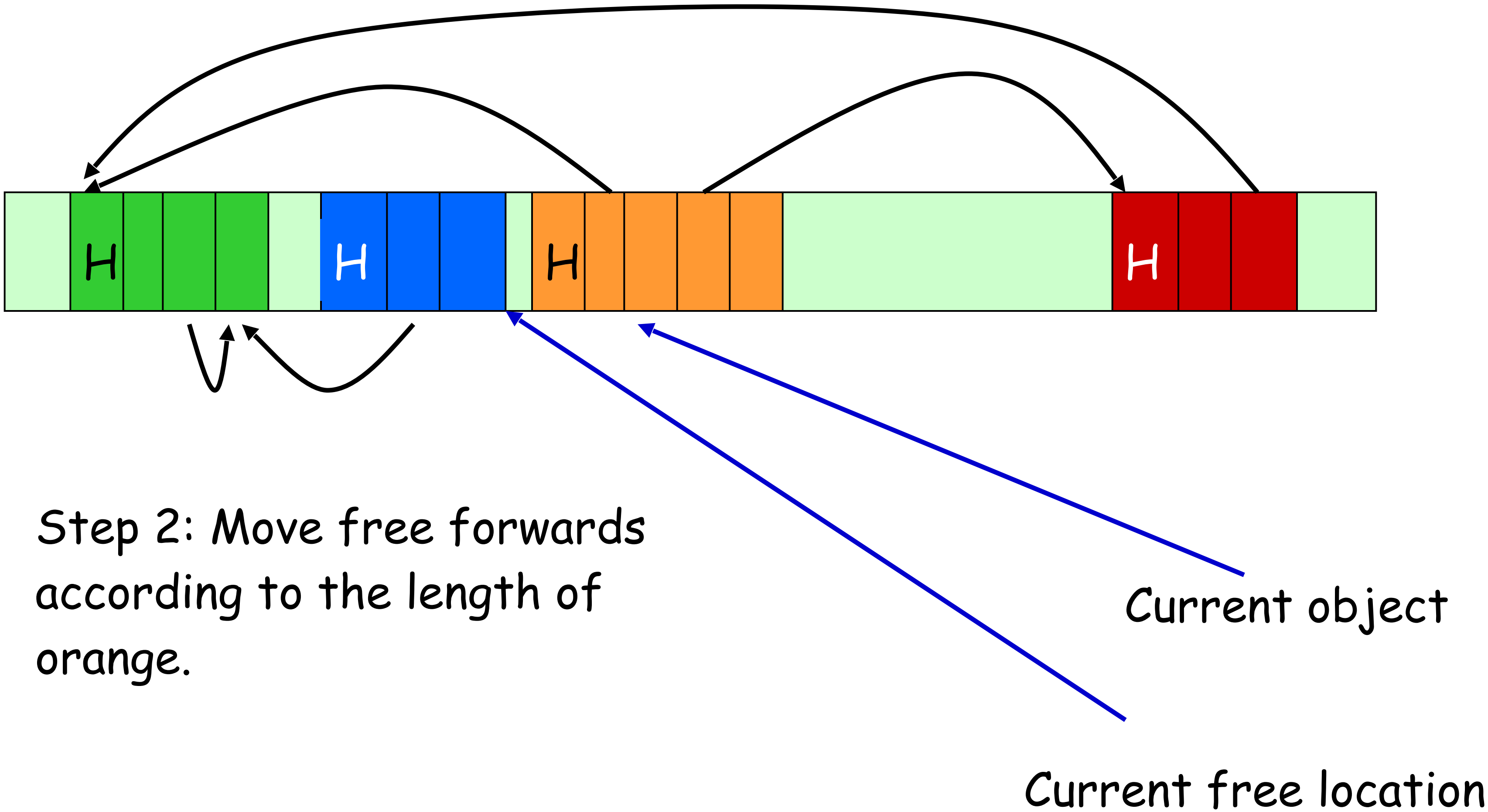


Step 2: Move free forwards according to the length of orange.

Current object

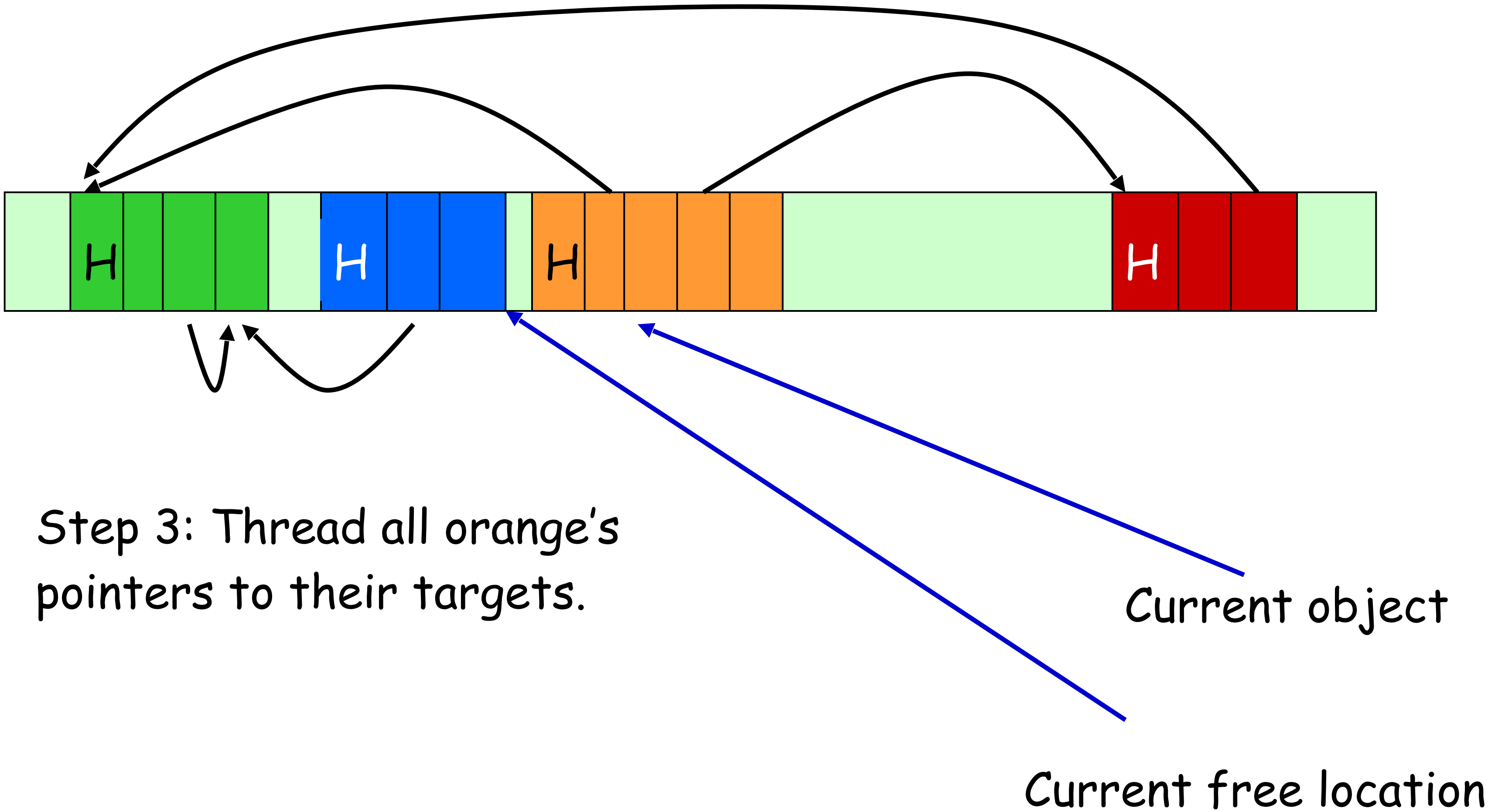
Current free location

Jonker's Algorithm – Pass I



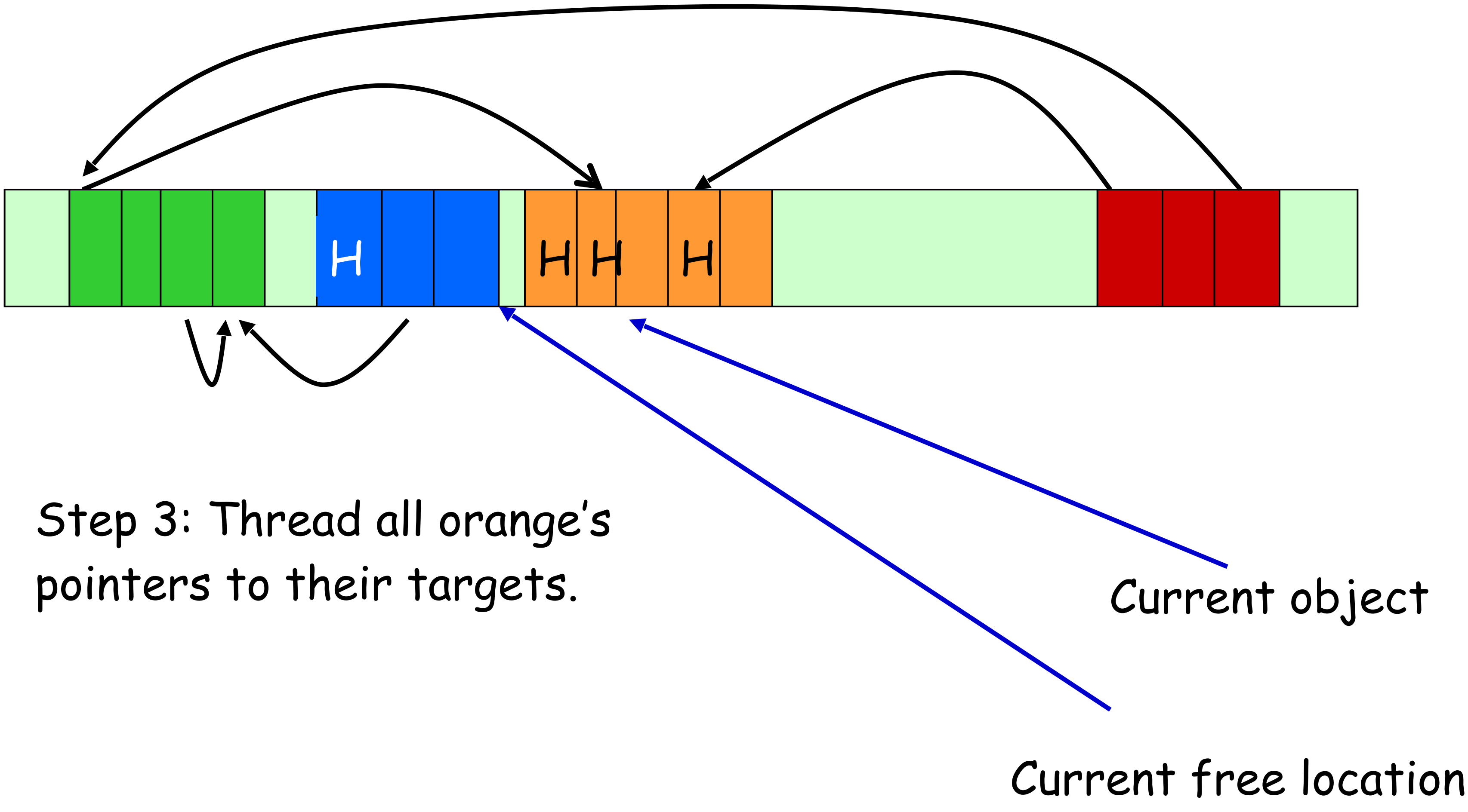
Step 2: Move free forwards according to the length of orange.

Jonker's Algorithm – Pass I



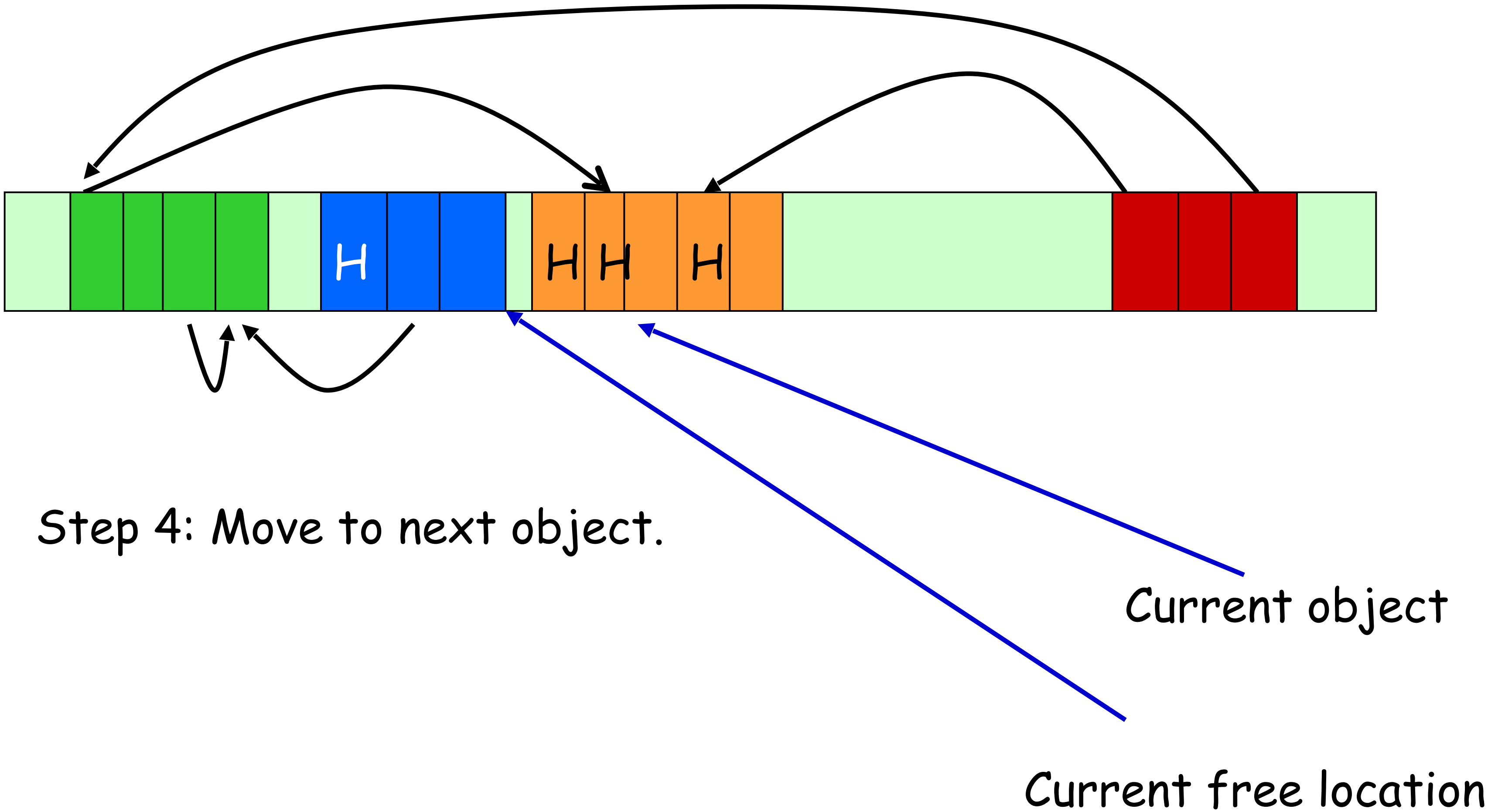
Step 3: Thread all orange's pointers to their targets.

Jonker's Algorithm – Pass I



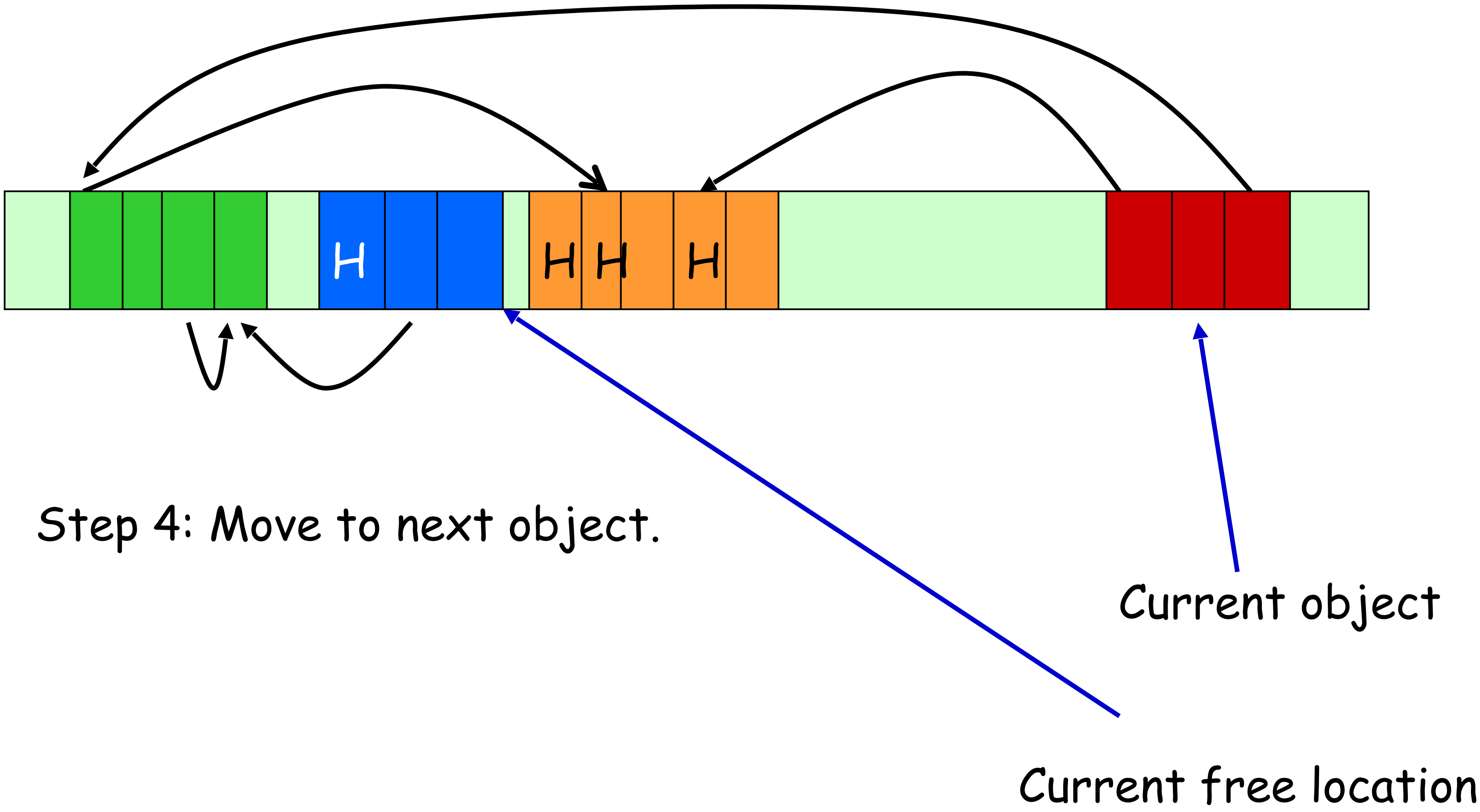
Step 3: Thread all orange's pointers to their targets.

Jonker's Algorithm – Pass I



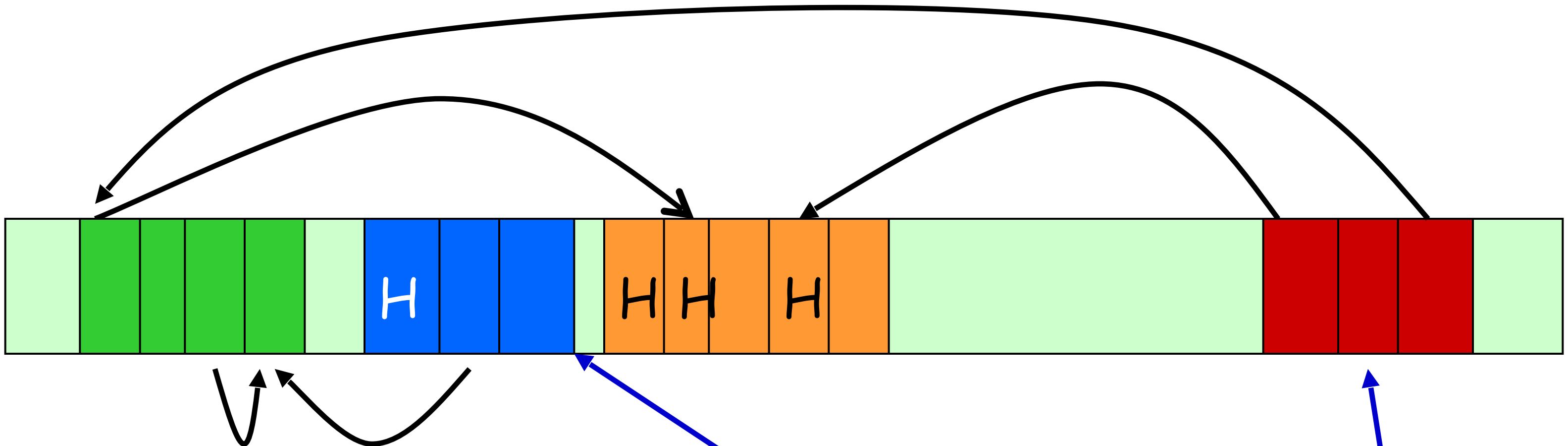
Step 4: Move to next object.

Jonker's Algorithm – Pass I



Step 4: Move to next object.

Jonker's Algorithm – Pass I

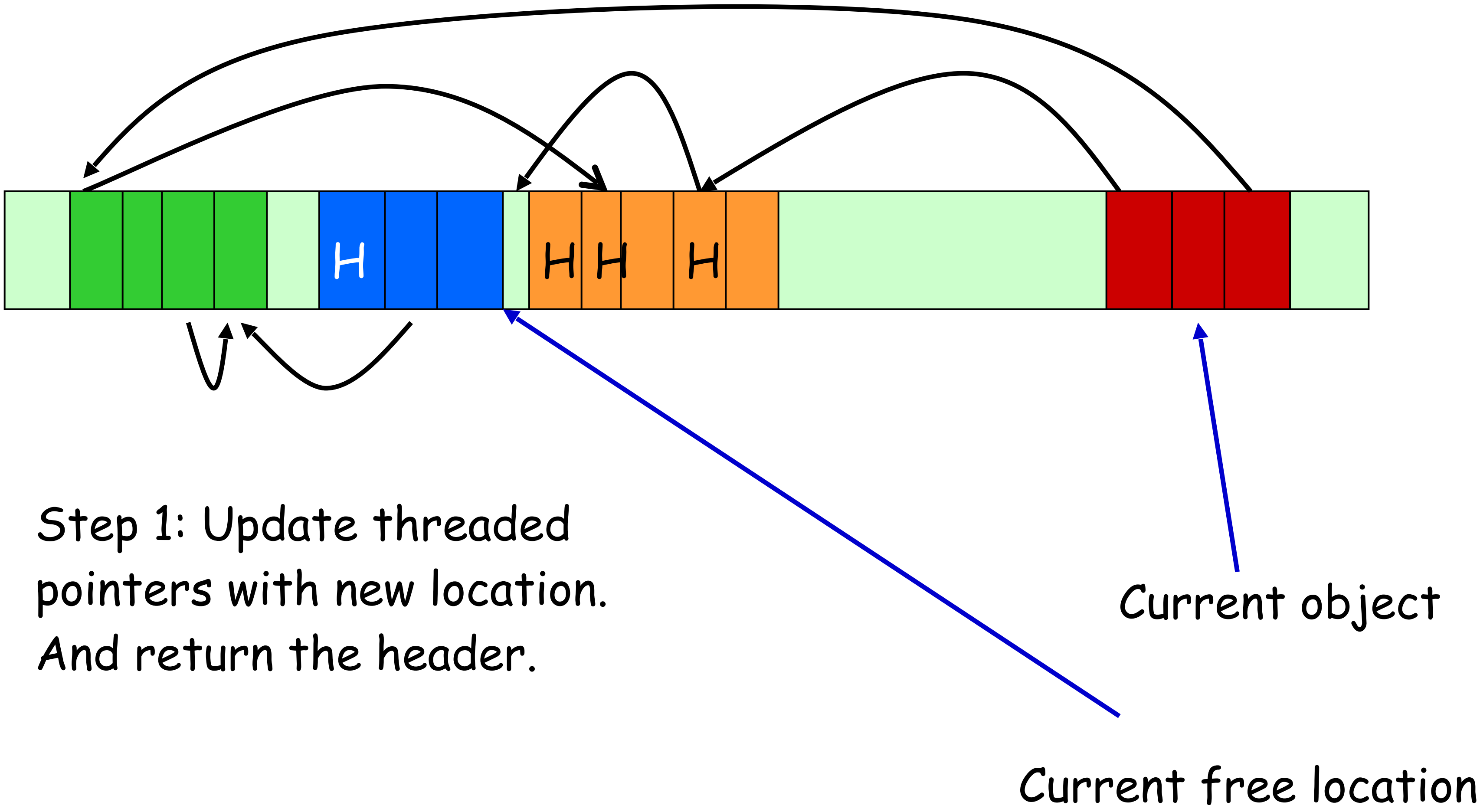


Step 1: Update threaded pointers with new location. And return the header.

Current object

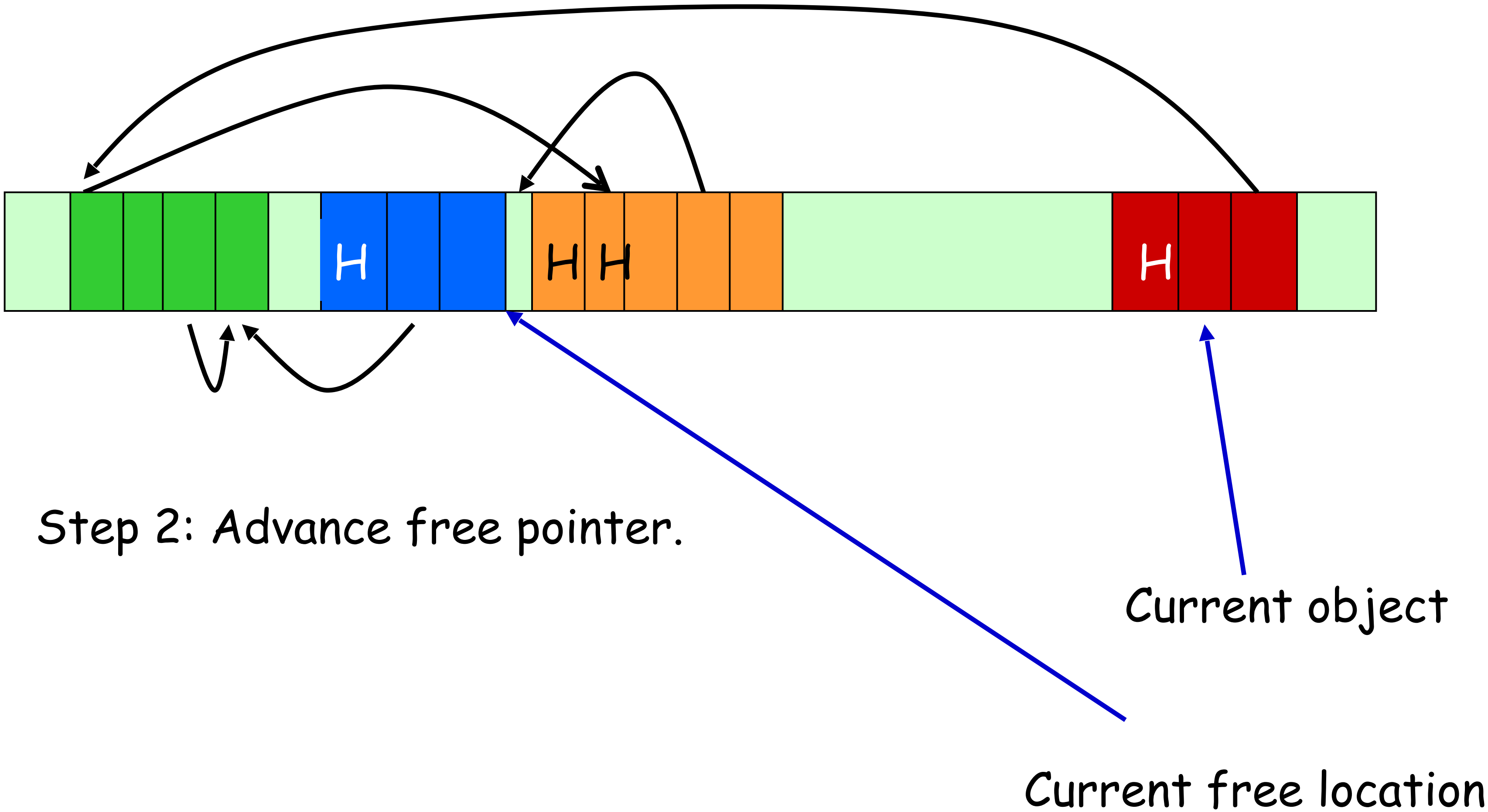
Current free location

Jonker's Algorithm – Pass I



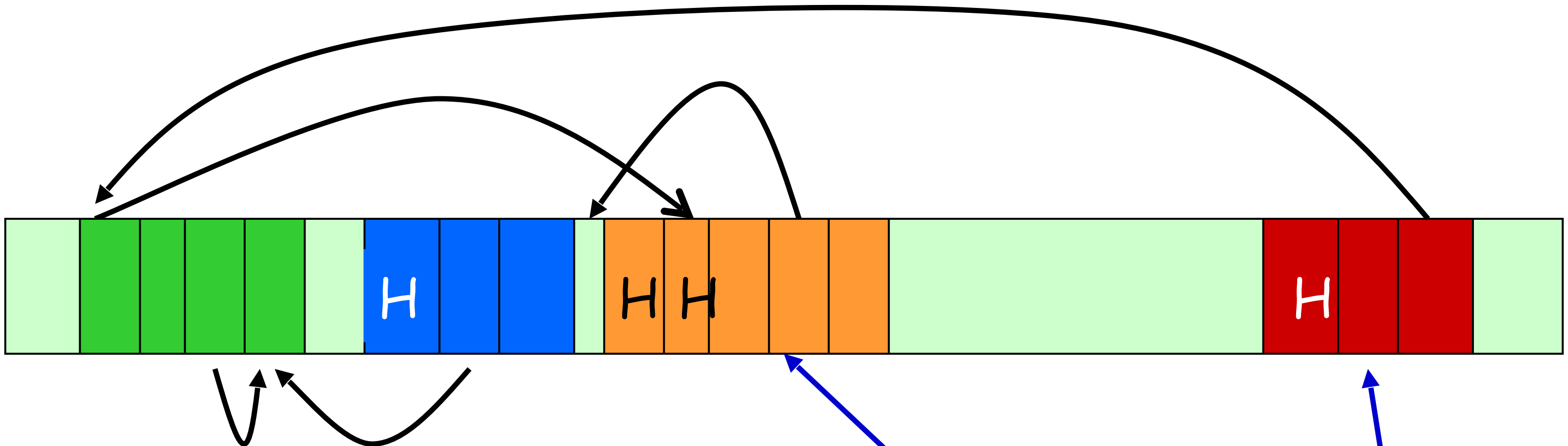
Step 1: Update threaded pointers with new location. And return the header.

Jonker's Algorithm – Pass I

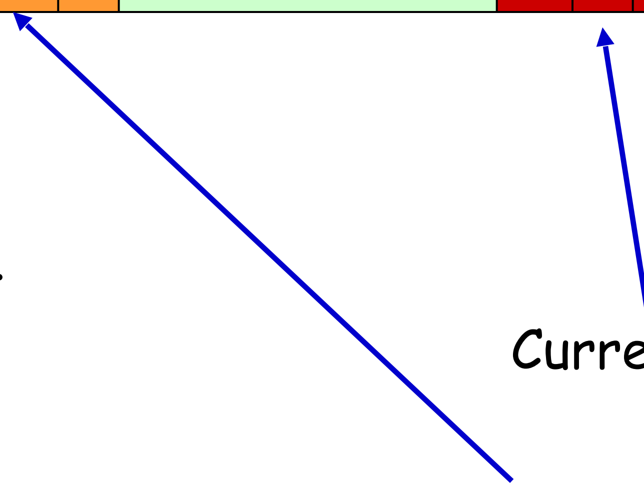


Step 2: Advance free pointer.

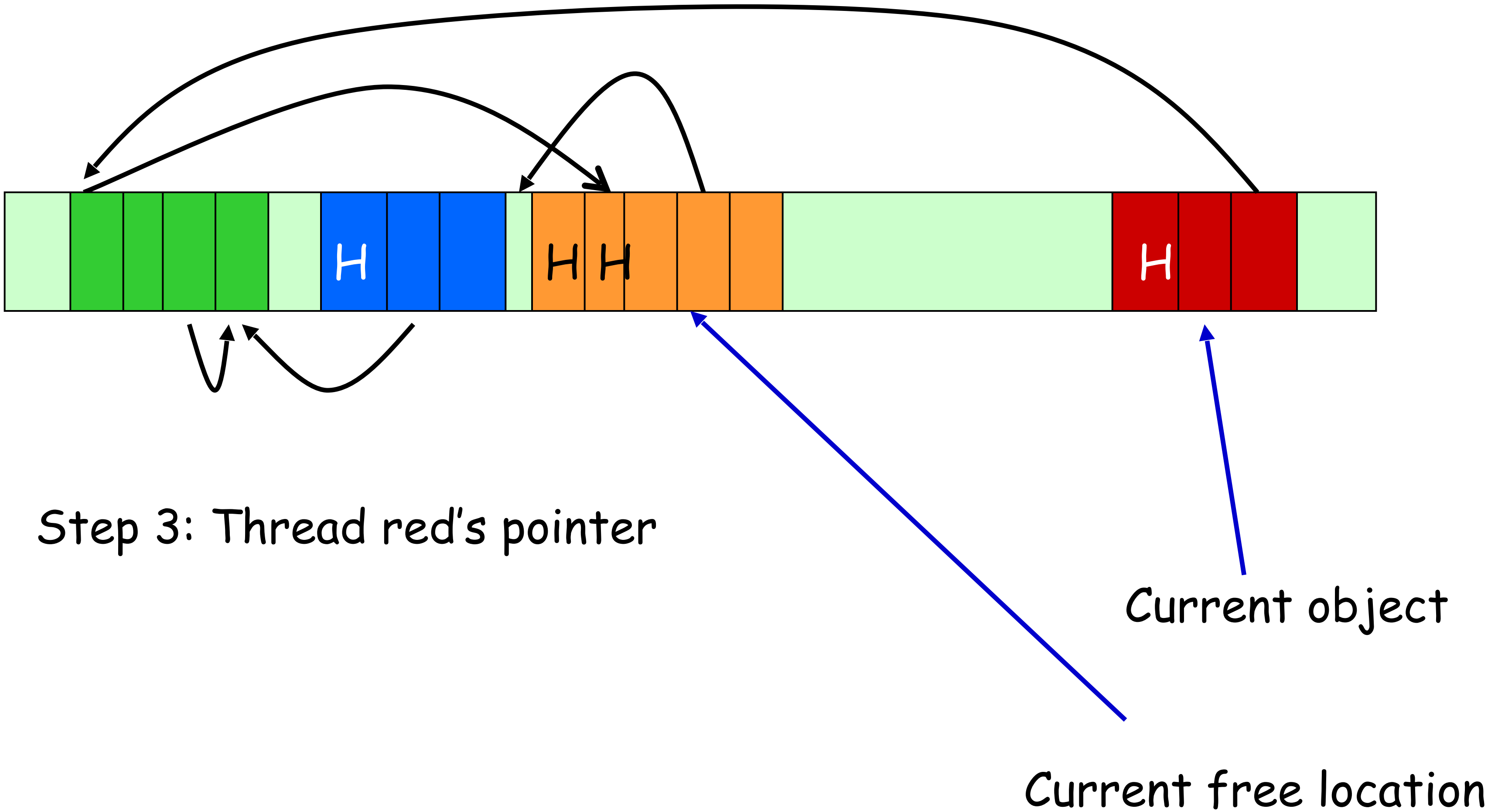
Jonker's Algorithm – Pass I



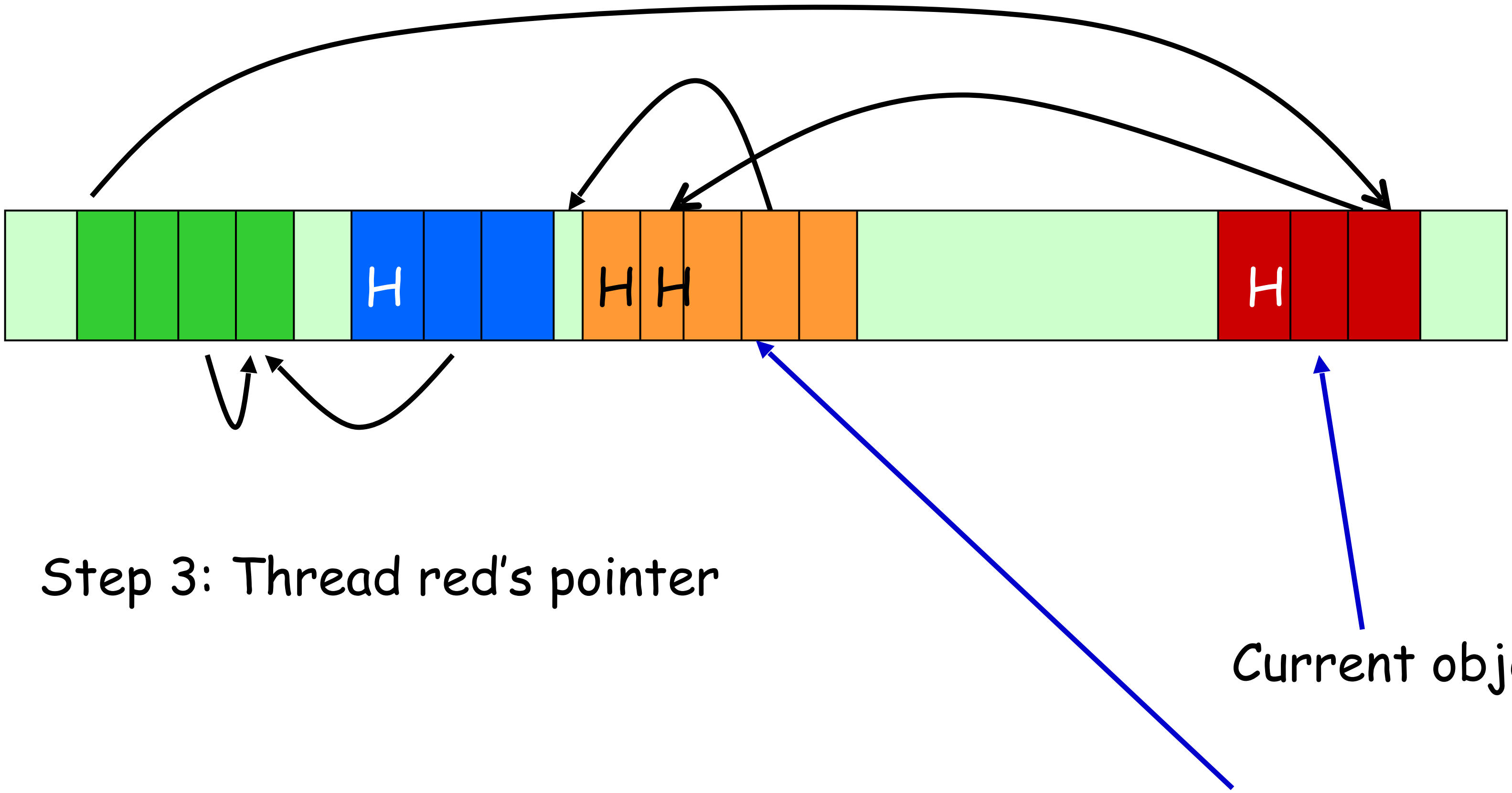
Step 2: Advance free pointer.



Jonker's Algorithm – Pass I



Jonker's Algorithm – Pass I

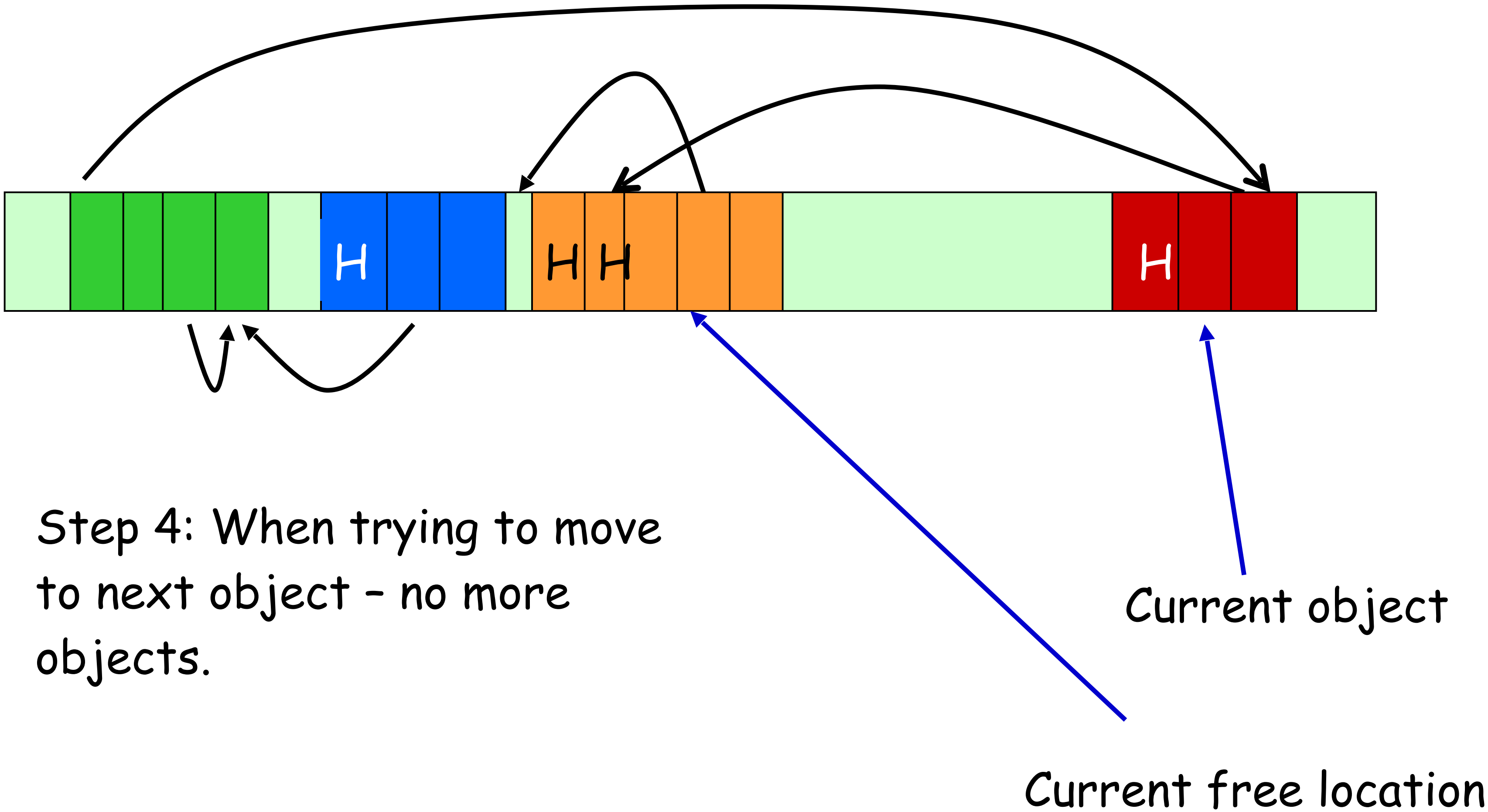


Step 3: Thread red's pointer

Current object

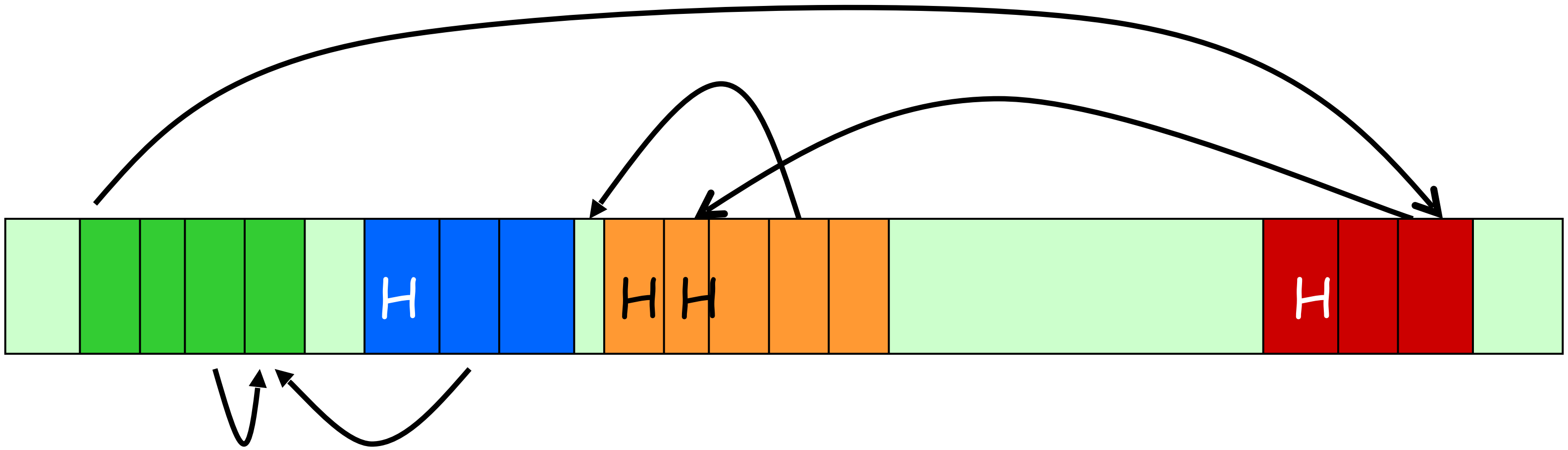
Current free location

Jonker's Algorithm – Pass I



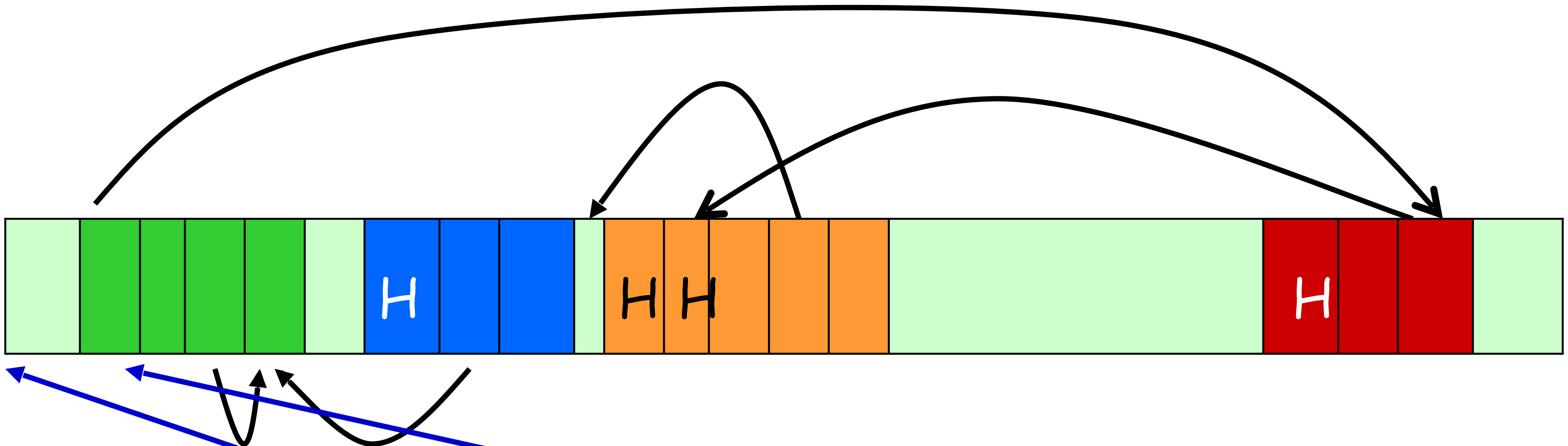
Step 4: When trying to move to next object – no more objects.

Jonker's Algorithm – Pass I



Step 4: When trying to move to next object – no more objects.

Jonker's Algorithm – Pass II

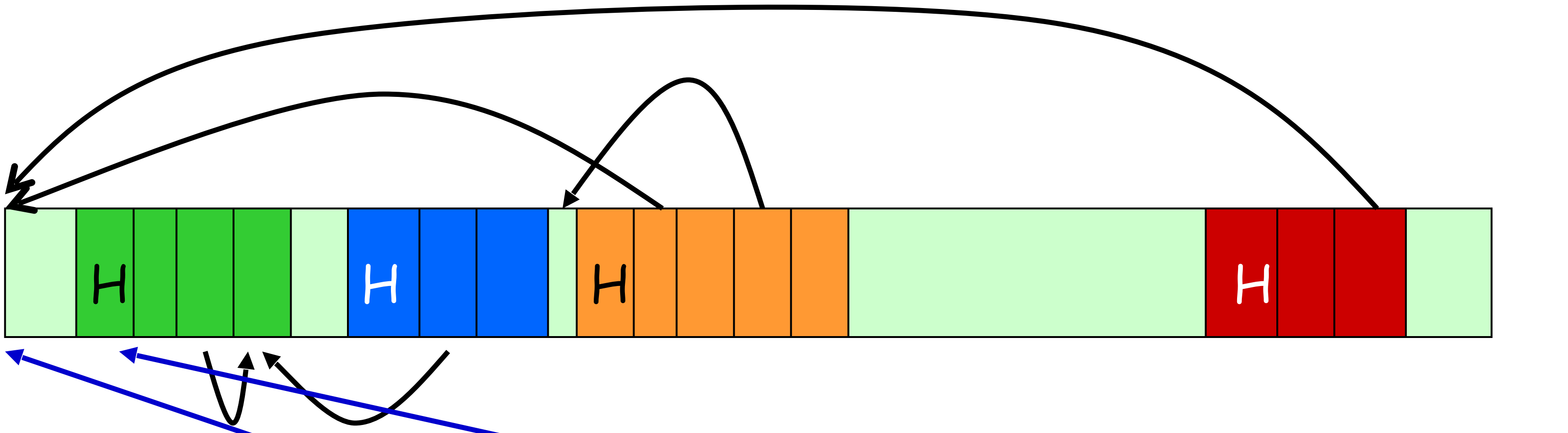


Step 1: find first (green) object and update pointers to object.

Current object

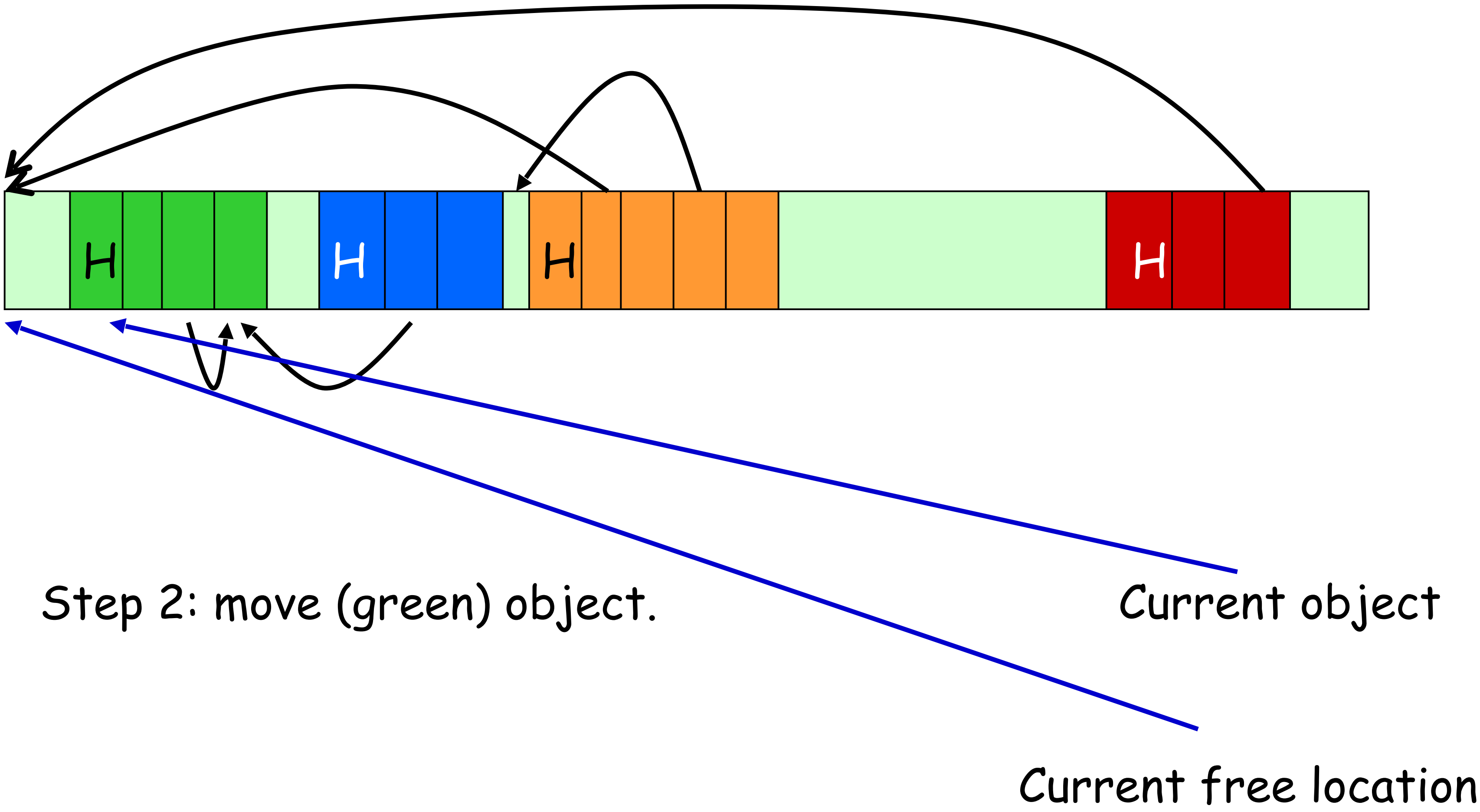
Current free location

Jonker's Algorithm – Pass II



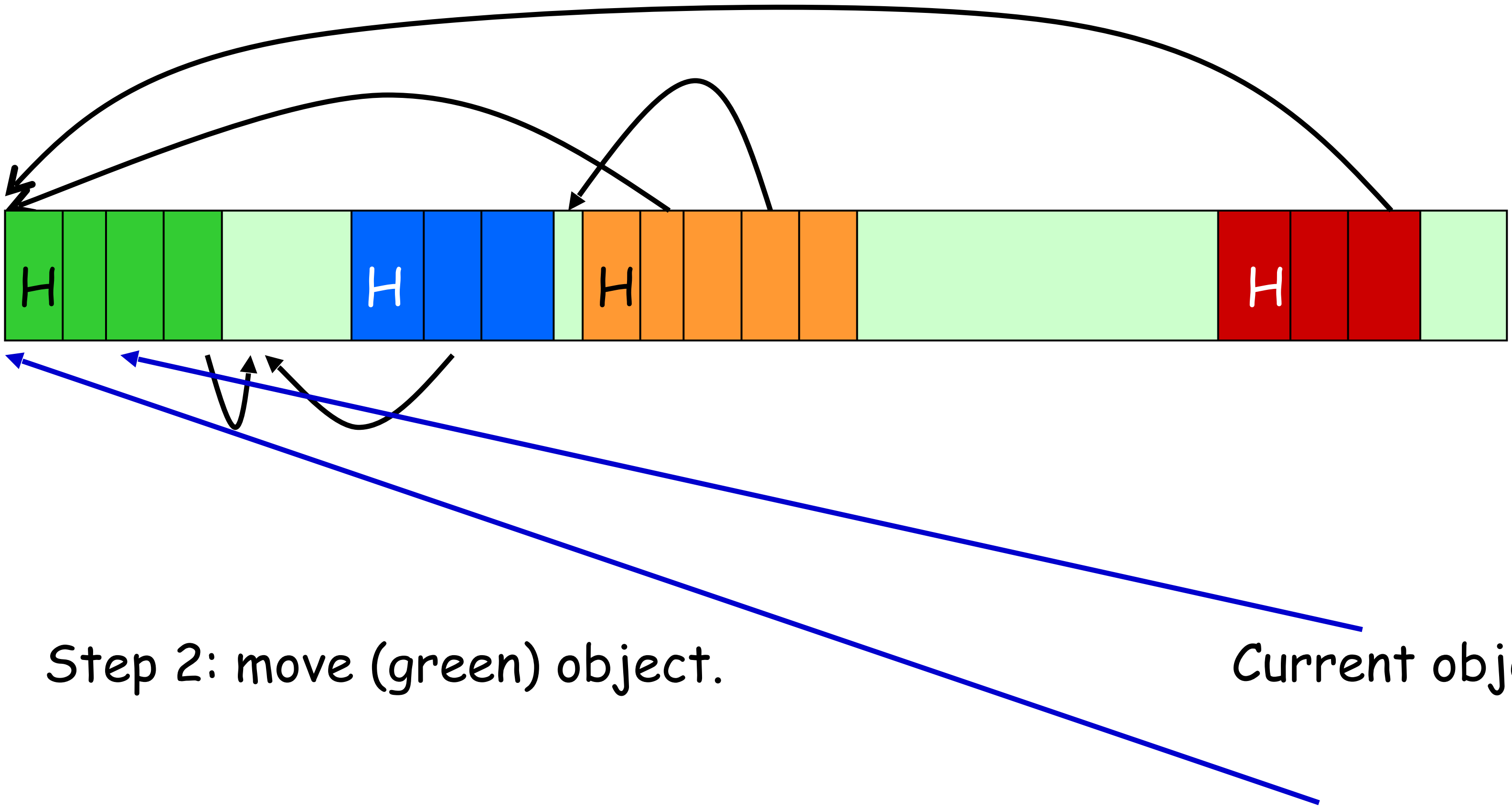
Step 1: find first (green) object and update pointers to object.

Jonker's Algorithm – Pass II



Step 2: move (green) object.

Jonker's Algorithm – Pass II



Step 2: move (green) object.

Current object

Current free location

Moving during Second Pass

- Can’t move an object if its fields are involved in a list.
- Claim: when moving an object (second phase) none of its fields are part of a threaded list.
- Threaded lists: due to its header or pointers.
- It’s header has been handled before move
- Forwards pointers: have already been handled in first pass.
- Backwards pointers (in this object) point to objects that we are done handling.

Threaded Methods - Forward pointers

```
First-pass( ) {
    for R in Roots                  // Thread the roots first
        thread ( R );
    free = Heap_bottom;             // 'free' is a next free space variable,
    P = Heap_bottom;                // P will be the "live" pointer
    while P <= Heap_top
        if marked( P )              // Check that P is a live object
            update( P, free );      // When P is reached, forward pointers are
                                    // threaded and can be updated with 'free'
            for Q a pointer in P    // Thread all pointers of a live object
                thread( Q );
            free = free + size( P ); // Location for the next live object
        P = P + size( P );          // Go to next object
}
```

Threaded Methods - Backward pointers

```
Second-pass( ) {
    free = Heap_bottom;
    P = Heap_bottom;
    while P <= Heap_top
        if marked( P )              // Check that P is a live object
            update( P, free );      // When P is reached again, backward pointers
                                    // are threaded and can be updated with ‘free’.
                                    // Self reference is treated as back pointer
            move( P, free );        // Move P to its new location - ‘free’
            free = free + size( P ); // Calculate the location for the next live cell
        P = P + size( P );          // Go to next object
}
```

Threaded Methods - Analysis

- No extra space required
- Variable size objects
- Preserves order
- Two passes
- But:
  - each iteration may touch several other objects.
  - requires a header distinguishable from pointer.

Threaded Methods - Analysis

- How many times is each object touched?
  - Once by first pass
  - Once by second pass
  - For each pointer referencing it, it is touched once when threading the pointer.
  - For each pointer in the object, it is touched during update.
- Asymptotic complexity O(M) (who cares?)

Summary --- Single Threaded Compaction

Algorithm	Space	Passes	Obj size	Order
Two-finger	None	2	Fixed	Arbitrary
LISP2	1 pointer-sized per object	3	Variable	Sliding
Threaded	(Pointer-sized headers)	2	Variable	Sliding

Parallel Compaction: SUN's Version

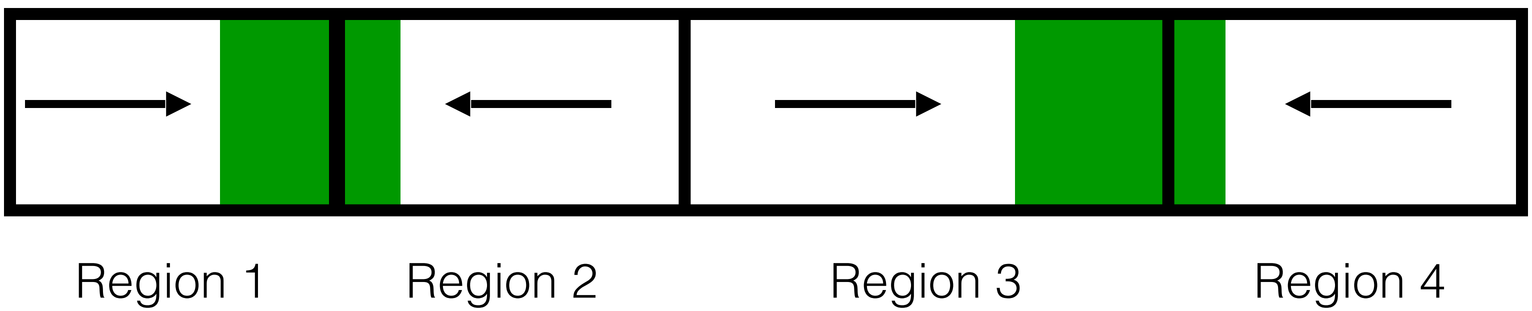
- [Flood Detlefs Shavit Zhang 2001]
- First parallel compaction
- 3 phases (similar to the LISP 2 algorithm):
  - Forwarding pointers installation
  - Fix up pointers phase
  - Move phase
- Each phase done in parallel

Splitting the work

- Heap divided to n regions
  - n is the number of compaction threads
  - Division not uniform; it balances work
- Each region compacted independently so compaction does not use synch'ed operations.
- Number of regions determines "quality" of compaction.
- Trade-off between quality of compaction and load balancing.

Improving quality

- In even regions – push left
- In odd regions – push right



Result: only n/2 piles of objects (rather than n)

Working in parallel

- Phase 1: each thread grabs a region and installs forwarding references.
- Phase 2: each thread grabs a region and updates its pointers
- Phase 3: each thread grabs a region and compacts the objects therein.

- Between phases threads wait for each other.
- Grabbing must be synchronized, the rest of the work is independent.

Properties

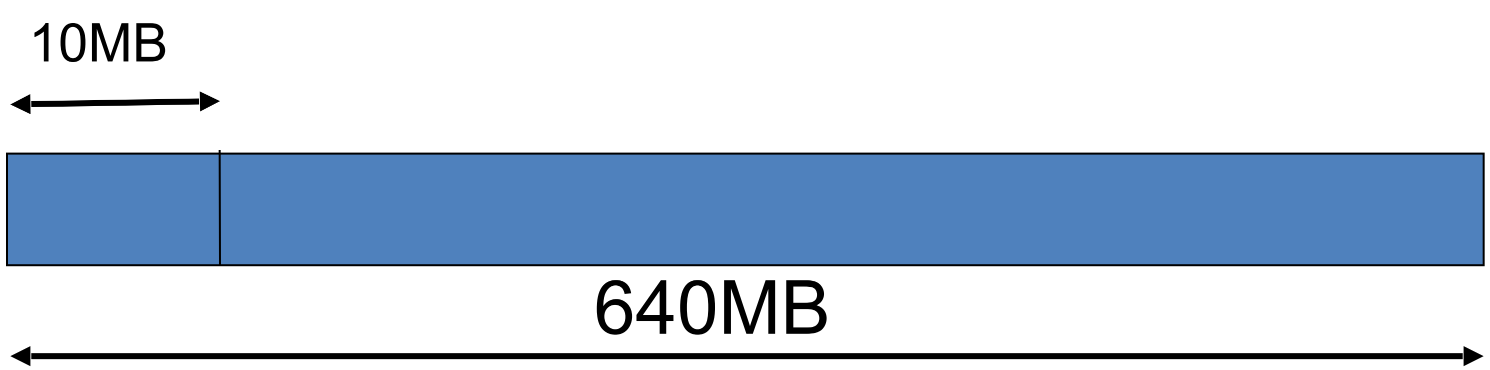
- ☺️ Runs in parallel – good scalability!
- ☺️ Keeps order of objects
- ☹ Objects are not fully packed
- ☹ Requires extra word per object (or a smart use of the reclaimable space)
- ☹ Coarse-grained load balancing
- ☹ 3 passes

IBM's Parallel Compaction

- [Abuaiadh-Ossia-Petrank-Silbershtein 2004]
- A more involved parallelization of the LISP-II compaction algorithm.
- Unlike SUN: Objects are packed to the bottom.
- Space overhead: replace forwarding pointer in each object with a smaller table.
- Two heap passes (each executed in parallel):
  - Move and keep some info
  - Use info to fix up pointers

Parallelism versus Compaction

- First goal: compact all objects together instead of creating several piles of objects.
- Heap is divided to n areas
- For example: n =64 was used for a 640MB heap and 8 processors.



Squeezing the Objects in Spite of Parallelism

- The goal: move all objects to the lower addresses.
- Each thread compacts one area at a time.
- Beginning: each area is compacted into itself.
- After a while:
  - vacant spaces appear in compacted areas.
  - compact objects of one area into the free space of a lower area

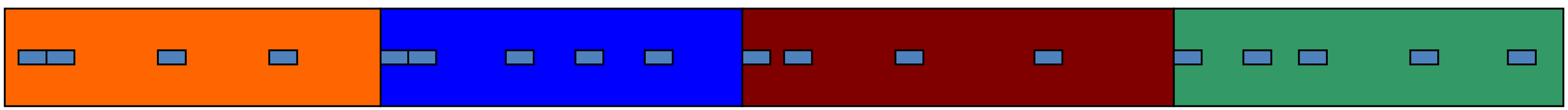
First Phase: Moving the Objects

- A thread picks the next area to be compacted;
- it finds a lowest area with empty space to compact into;
- if no such area exists, it compact to the bottom of the same area.

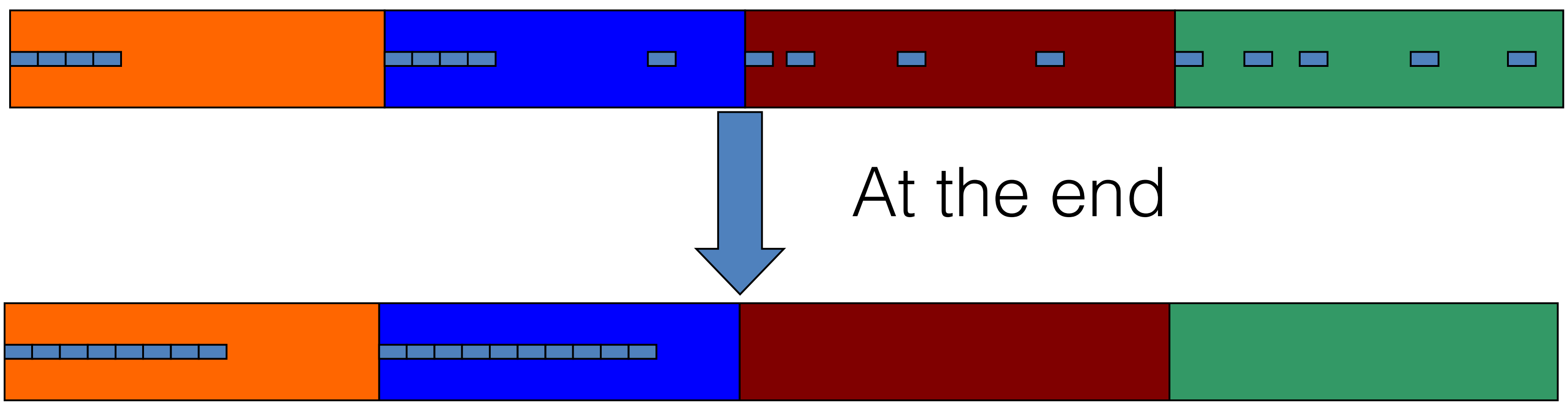
- While moving the objects, record information in a small additional table that will enable updating the pointers.
  - This replaces the forwarding pointers.
  - It implements a map from old to new addresses.

Moving the objects: an Example

- Two threads, 4 area
- (Thread#1,red area), (Thread#2,blue area)

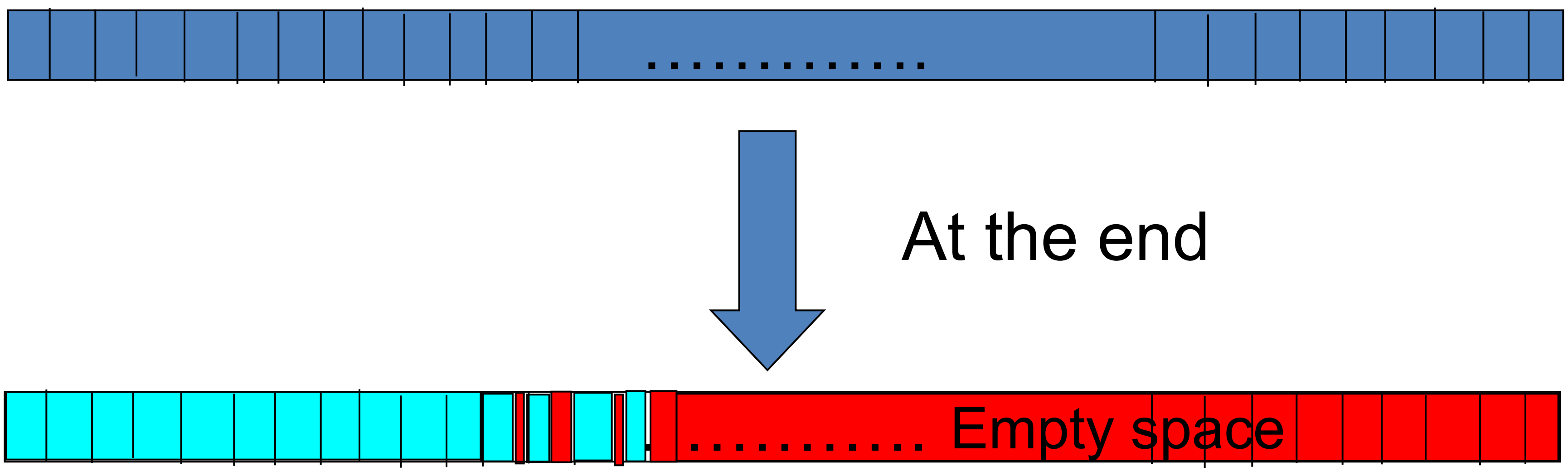


- (Thread#1,brown area), (Thread#2,green area)



More areas

- 4 threads, 64 areas,
- In the end we may have some holes at the last areas
- For a reasonable number of areas, these holes are insignificant.



Area Size Tradeoff

	“Holes” in the Heap	Preserve allocation order	Load balancing
Oversized areas	-	☺️	-
“Normal” size	☺️	☺️	☺️
Areas too small	☺️	-	☺️

Phase 2: Fix up

- Divide the heap to n areas.
- Each thread fixes up pointers in one area at a time.

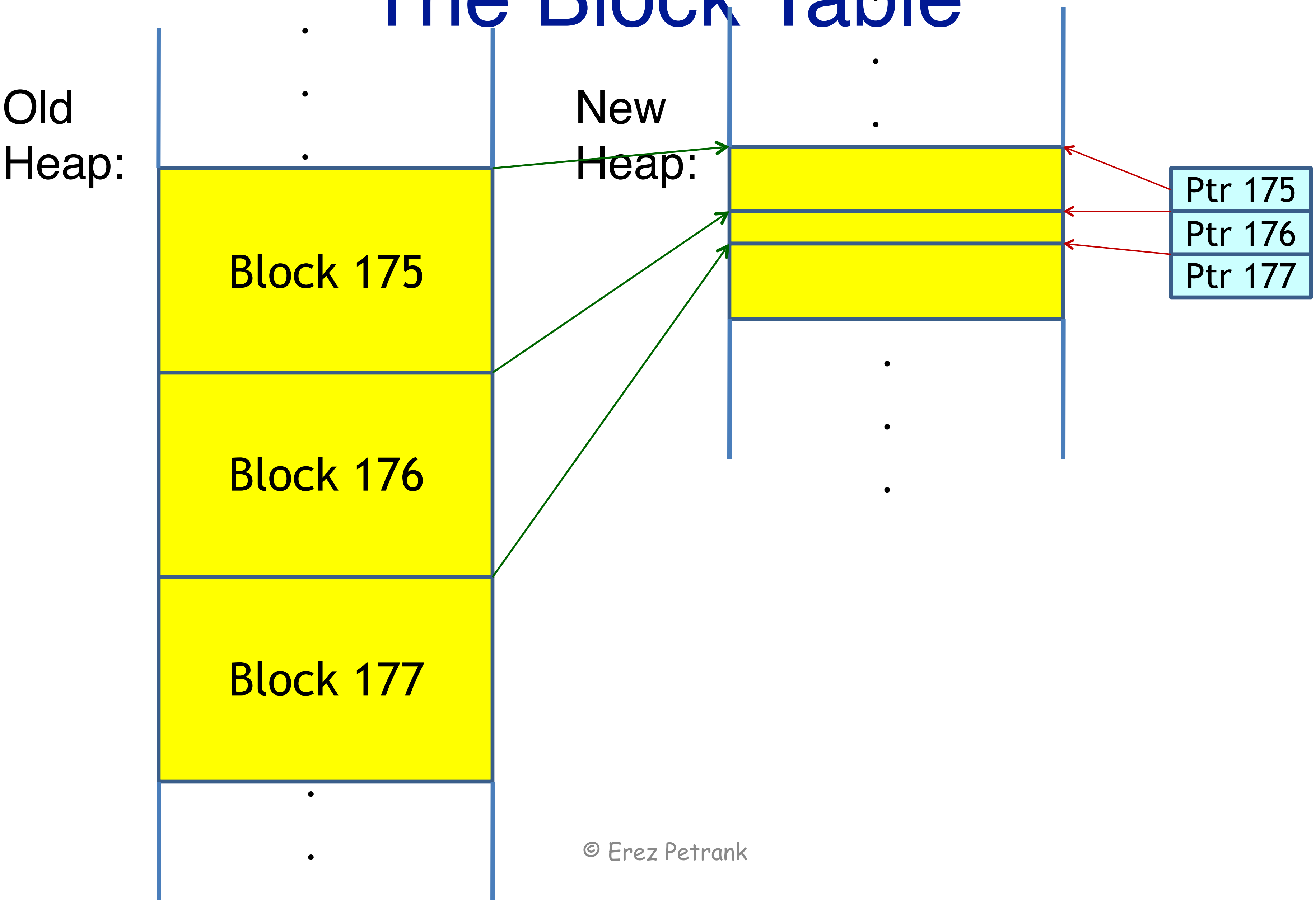
Remember: Information is recorded during the move phase to allow redirecting the pointers in the second phase.

Implementing the Fix-Up Map

- We consider the heap as a sequence of blocks (say, block = 256 bytes)
- Blocks (256 bytes) << areas (10 Mbytes).
- Information is recorded per block rather than per object.
  - Objects in a block are moved together;
    objects of different blocks are never interleaved.

- The idea: record less information per block, but perform more computation during fix up of each reference.

The Block Table



Recorded Information

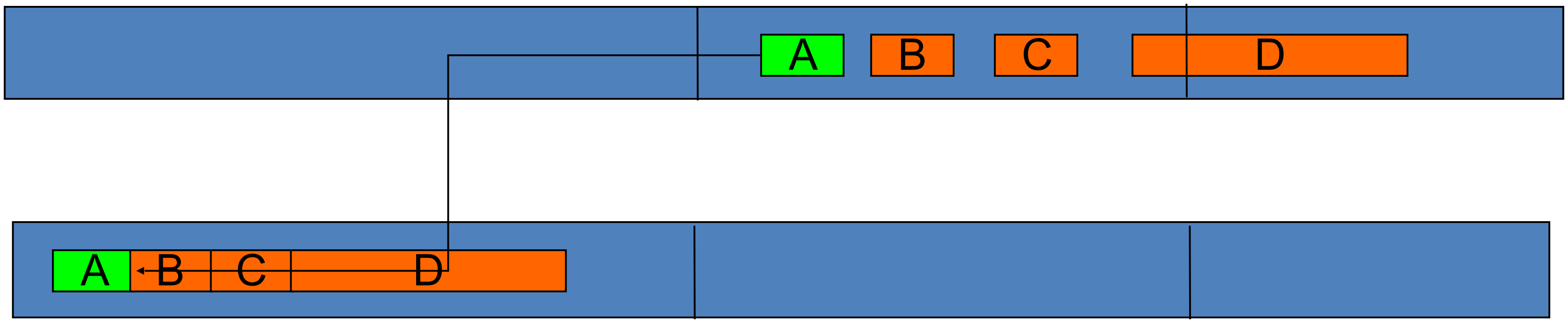
- Block table: For each block keep the new location of the first object in the block.
  - One pointer per block.
- Two bit maps (1 bit for any 8 bytes).
  - **Old bitmap** represents location of objects before the move (created while marking live objects)
  - **New bitmap** represents location of objects after the move (created while moving the objects).
  - One bit stands for 8 bytes in the heap (8-byte alignment)

Calculating a New Location

- Given an old address of an object A:
- Find A's block (its most significant bits)
- Using the block table, obtain the new address (**B)** of the first object in the block.
- Using the old bitmap: find the ordinal number (**i**) of the object in the block.
- Using the new bitmap: find the relative new location (**r**) of the **i**-th object in the block.
- Add **B+r** to obtain the new location.

Example

- Calculating the new location of object C.
- Old bitmap ➔ C is third in block (i=3)
- New bitmap ➔ relative address of C (to A) (r = 0x18)
- Block table ➔ new address of A = 0x58296200
- A + r = new location = 0x58296218



Space overhead

- For each block (say, 256 bytes),
  - A pointer: 4 (or 8 for 64-bits platforms) bytes
  - 2 Bitmaps: 4+4 bytes
  - Overall: 12 (or 16) bytes for each 256 bytes (4.7-6.2%)
- Existing data structures may be reused, e.g., the GC markbits table.
- Increasing the size of the block: reduces the extra space but increases the computation cost.

Properties

- Almost all objects are condensed to the bottom of the heap.
- Order of objects is essentially preserved.
- Good parallelism with almost no contention.
- Space overhead low compared to forwarding pointers.

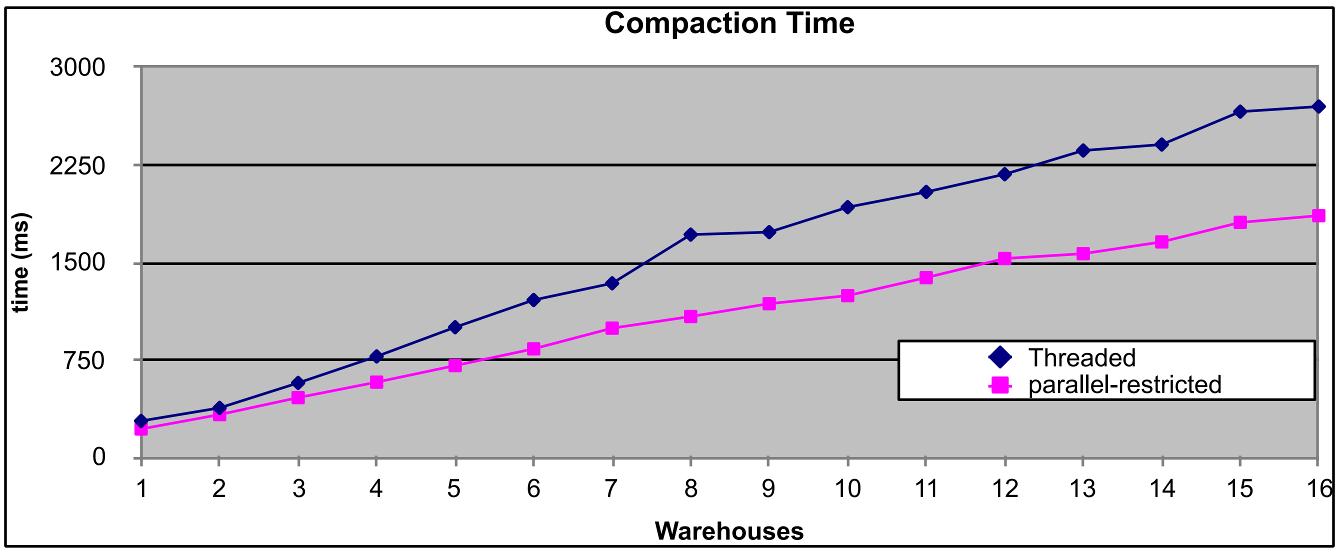
Measurements

- Algorithms compared:
  - Jonker's threaded algorithm
  - Restricted parallel algorithm (to a single thread)
  - Fully parallel algorithm
- Platform: AIX (on 8-way PPC, 64 bits) and NT (on 4-way Pentium, 32 bits)
- Benchmarks: Specjbb2000 and Trade 3 on Websphere.
- Heap size: determined so that live objects take 60% of the heap: 600MB for SPECjbb and 180MB for Trade3.

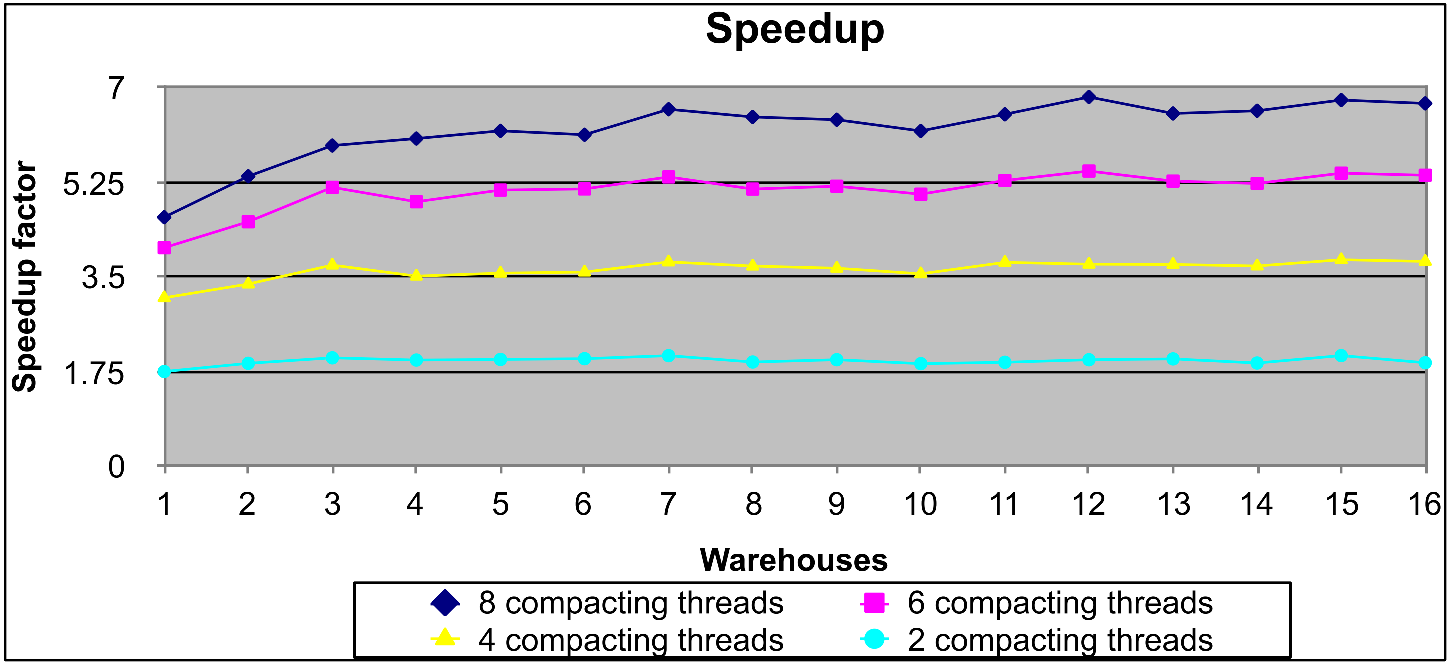
Specjbb2000

- Compaction runs when a warehouse is added, those (substantial) parts of the run are not considered for the measurements
- Thus, throughput is not affected by the compaction times.
  - May be affected by bad compaction quality.
- We measure compaction times.

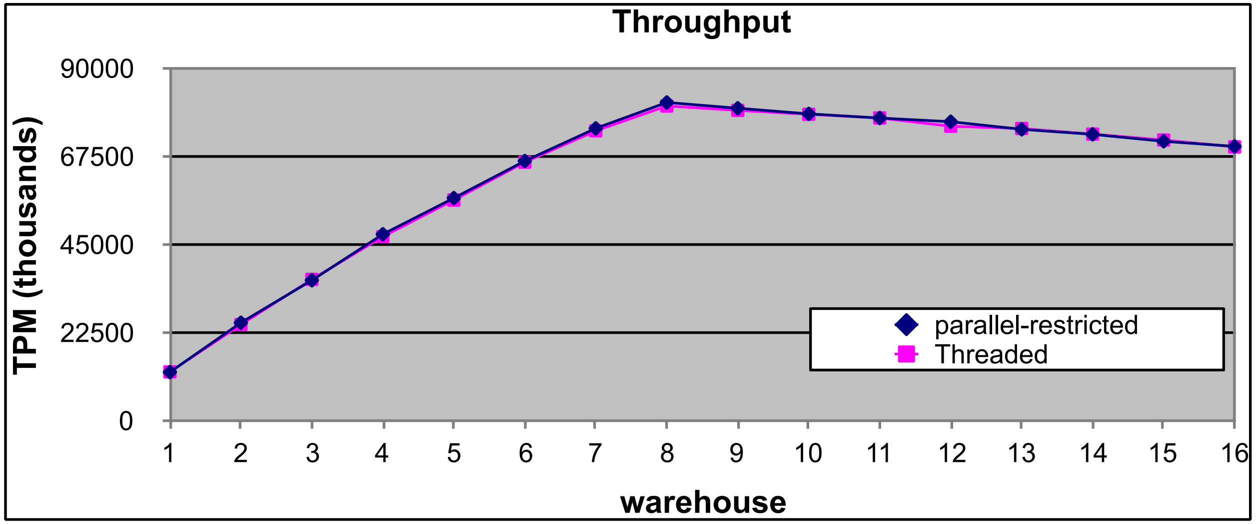
Results: Compaction Times for (Specjbb2000) on a Uniprocessor



Results: Speedup (Specjbb2000)



Results: Throughput (Specjbb2000)



Results: Trade3 (Websphere)

- 4-way NT machine
- Heap size: 180MB
- Additional test: we forced compaction each 20gc

Compaction type	Compaction time		#Requests per second	
Triggering	≈ 90 gc default	20gc	≈ 90 gc default	20gc
Threaded	1698	1671	219.8	224.5
Parallel-restricted	1387	1251	221.7	226.1
Parallel	499	440	222.4	229.1

Conclusion --- IBM's Parallel Compaction Algorithm

- More efficient than the previously used threaded algorithm even on a uniprocessor.
- Good speedup
- Good compaction quality.

The Compressor

- [Kermany-Petrank 2006]
- The goal: concurrent and parallel compaction with low overhead.
- Overhead reduction via a single heap pass.
- Extending with parallelism and concurrency:
- Objects are packed to the bottom, maintaining address order.
- We will study the Compressor around the 10^{th} lecture.

Conclusion --- Compaction

- Uniprocessor compaction:
  - Two fingers, Lisp2, Threaded (Yonkers)
- Parallel compaction:
  - Sun's compaction, IBM's compaction.
  - (Compressor: parallel and concurrent, delayed…)
- Issues considered:
  - Efficiency, space overhead, parallelism, compaction quality, locality.