Algorithms for Dynamic Memory Management Lecture 3

Lecturer: Erez Petrank

Last Week

- Compaction:
  - Two-finger Alg – for objects of equal size.
  - Lisp 2 Alg.
  - Jonkers threaded algorithm
  - SUN's parallel Lisp 2 algorithm
  - IBM's parallel algorithm

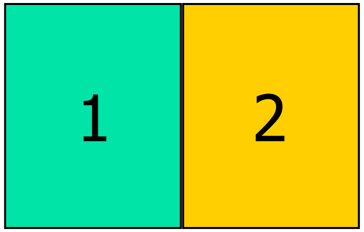
Copying Garbage Collection

3 classical collectors:

- Mark & Sweep
- Copying
- Reference Counting

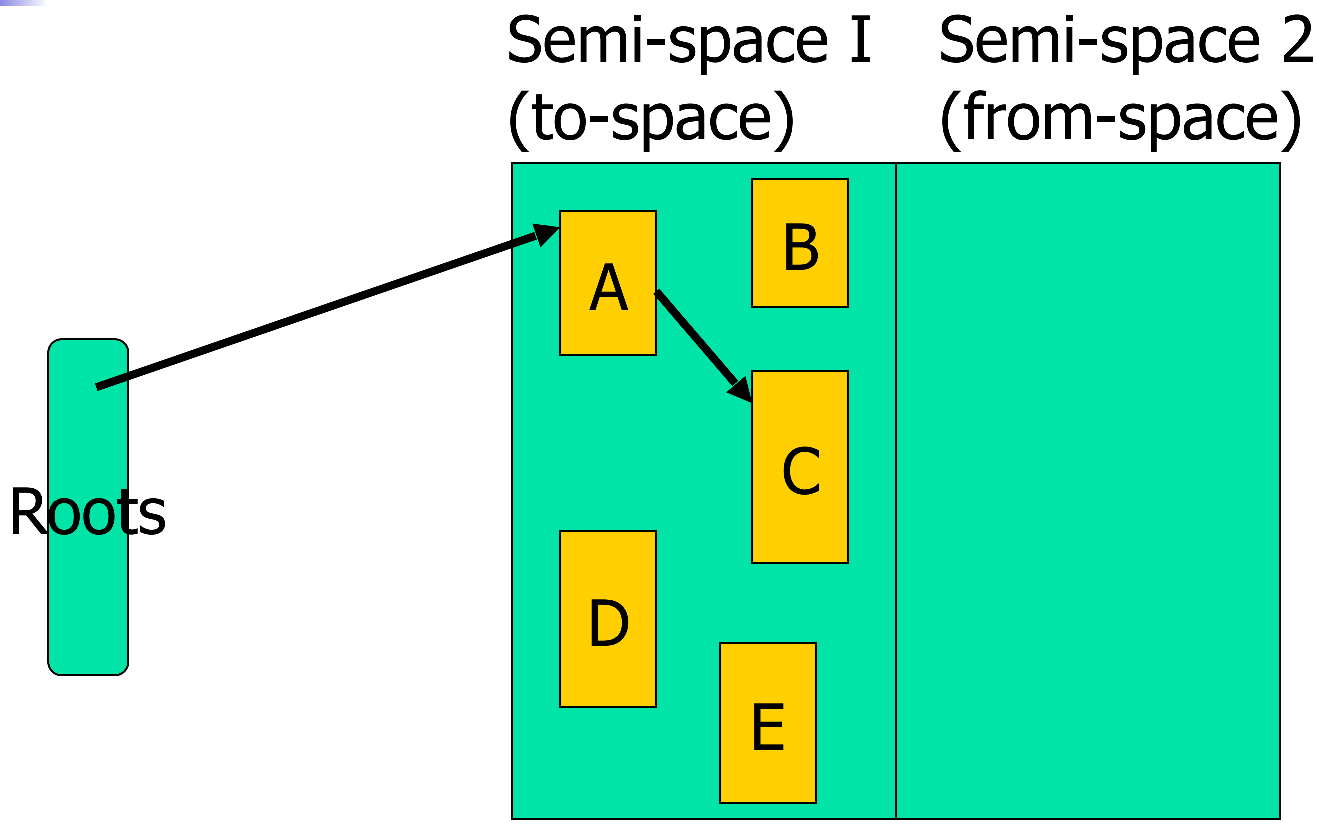
} Tracing

The Idea

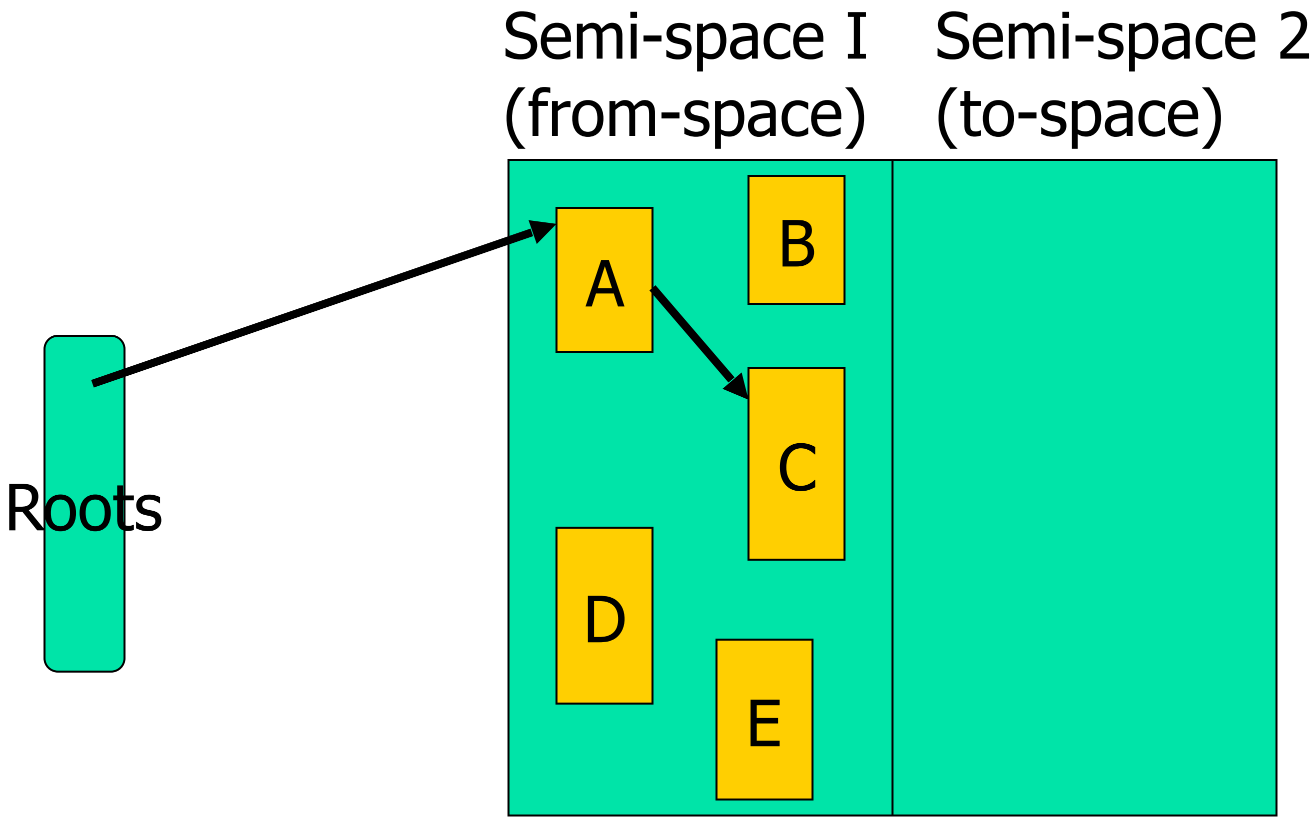


- Heap partitioned into two semi-spaces.
- Semi-space 1 takes all allocations.
- Semi-space 2 is reserved.
- During GC, the collector traces all reachable objects in from-space and copies them to semi-space 2 (to-space).
- After copying, activity goes to semi-space 2. Semi-space 1 is reserved till next collection.

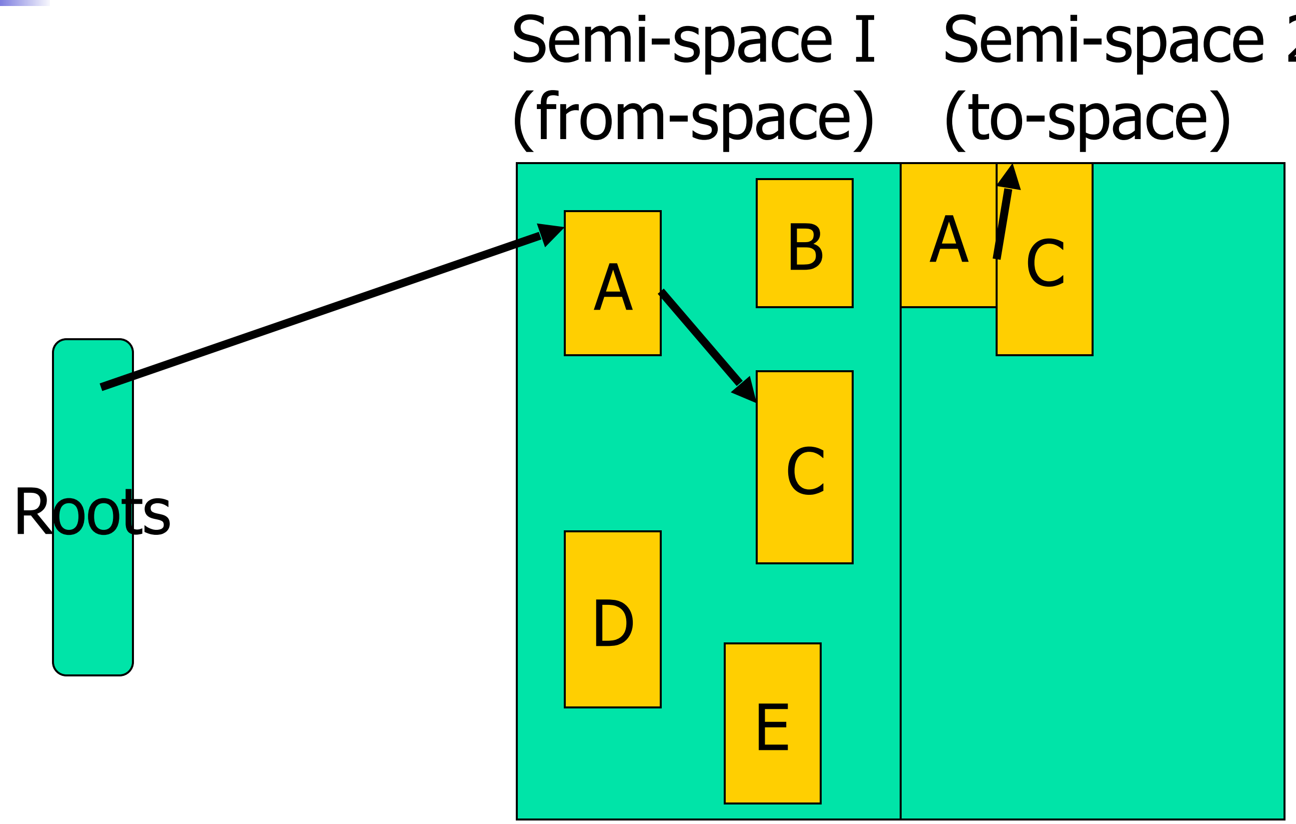
Copying garbage collection



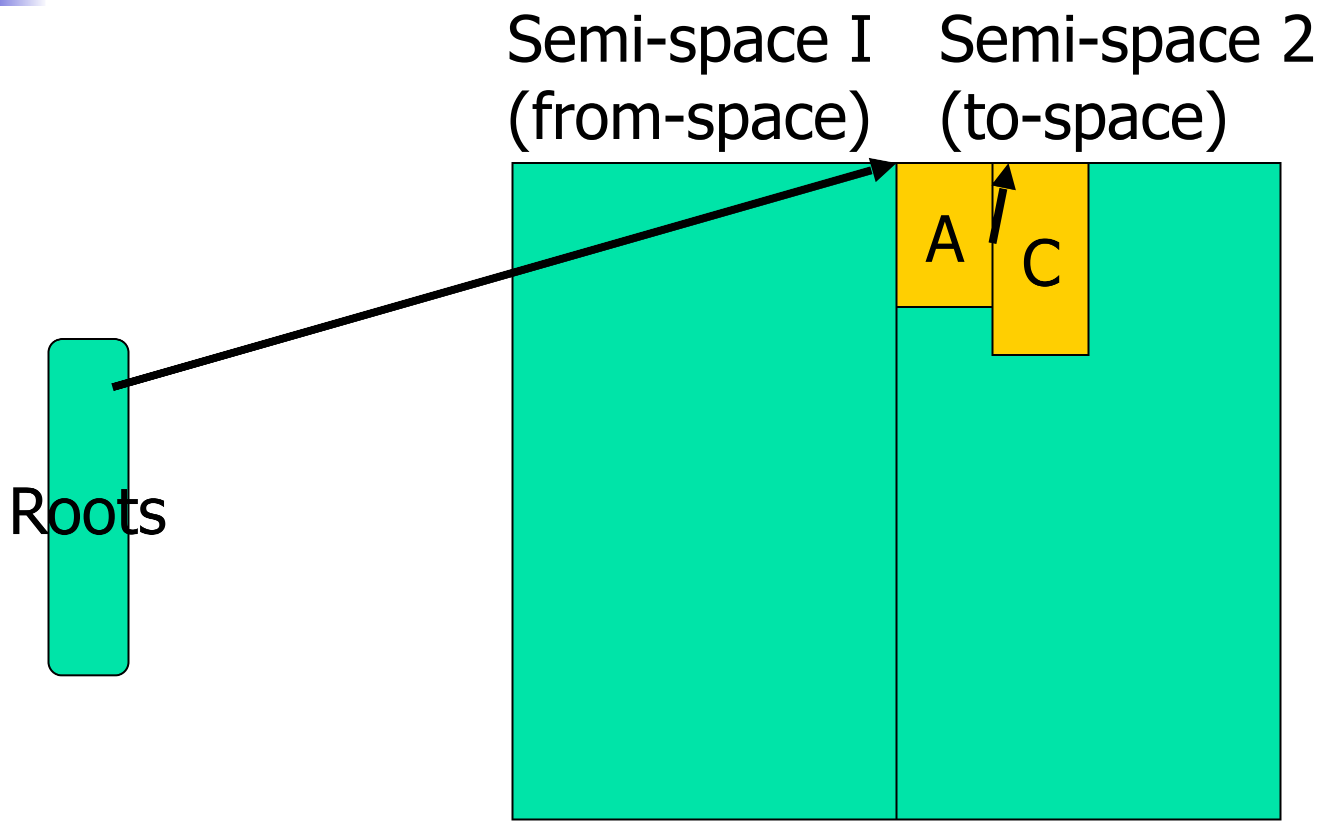
Copying garbage collection



The collection copies…



Roots are updated; space I reclaimed.



Update Pointers

- Copied objects have wrong pointers!
- Keep **forwarding pointers** inside objects in from-space.
- Scan live objects in to-space and fix pointers.

- Naïve implementation DFS with a mark-stack.
  - Additional space overhead…
- Cheney's algorithm needs only two pointers!

Cheney's idea

- Start: copy objects reachable directly from the roots into to-space.
- Next: copy objects reachable from the objects currently in to-space (and fix the pointers).
- Finish when all pointers in to-space point to to-space.
  - This means that all objects reachable from roots have been copied.

Copying: Collection Cycle

- Stop all threads
- Flip sub-spaces; i.e., change roles of from-space and to-space
- Copy objects directly reachable from roots to to-space
- Scan to-space and fix pointers to from-space.
  - Fix: copy object if not yet copied & fix pointer.
- Collection complete when all objects in to-space scanned.

Basic Action: Scan a pointer p

- If p points to to-space then do nothing.
- Elseif from-space referent has a forwarding ptr, then update pointer-slot.
- Otherwise (this is a reachable object that has not yet been copied):
  - copy object into to-space,
  - record forwarding pointer,
  - update pointer-slot.

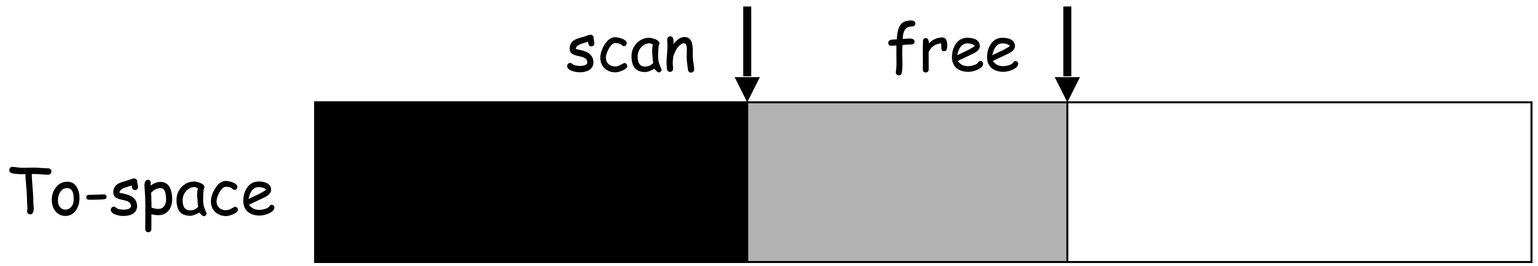
Overall Algorithm

- Flip sub-spaces
- Scan roots
- Scan all pointers in to-space.

Cheney's Algorithm: Two pointers (and no stack)

Keep two pointers to monitor the collection progress.

- **Scan:** points beyond scanned (black) objects.
- **Free:** points beyond copied (gray) objects and before the free space.



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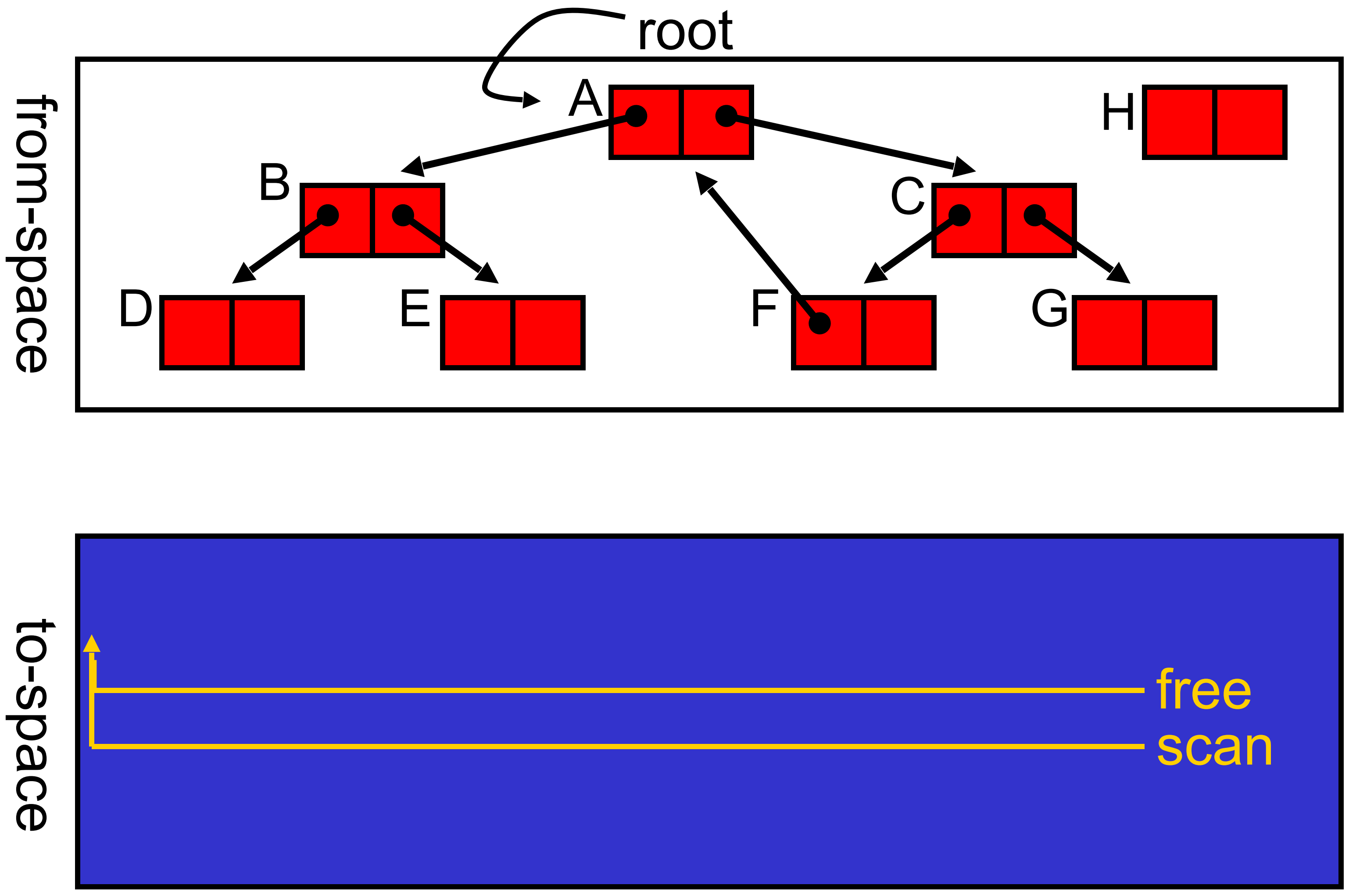

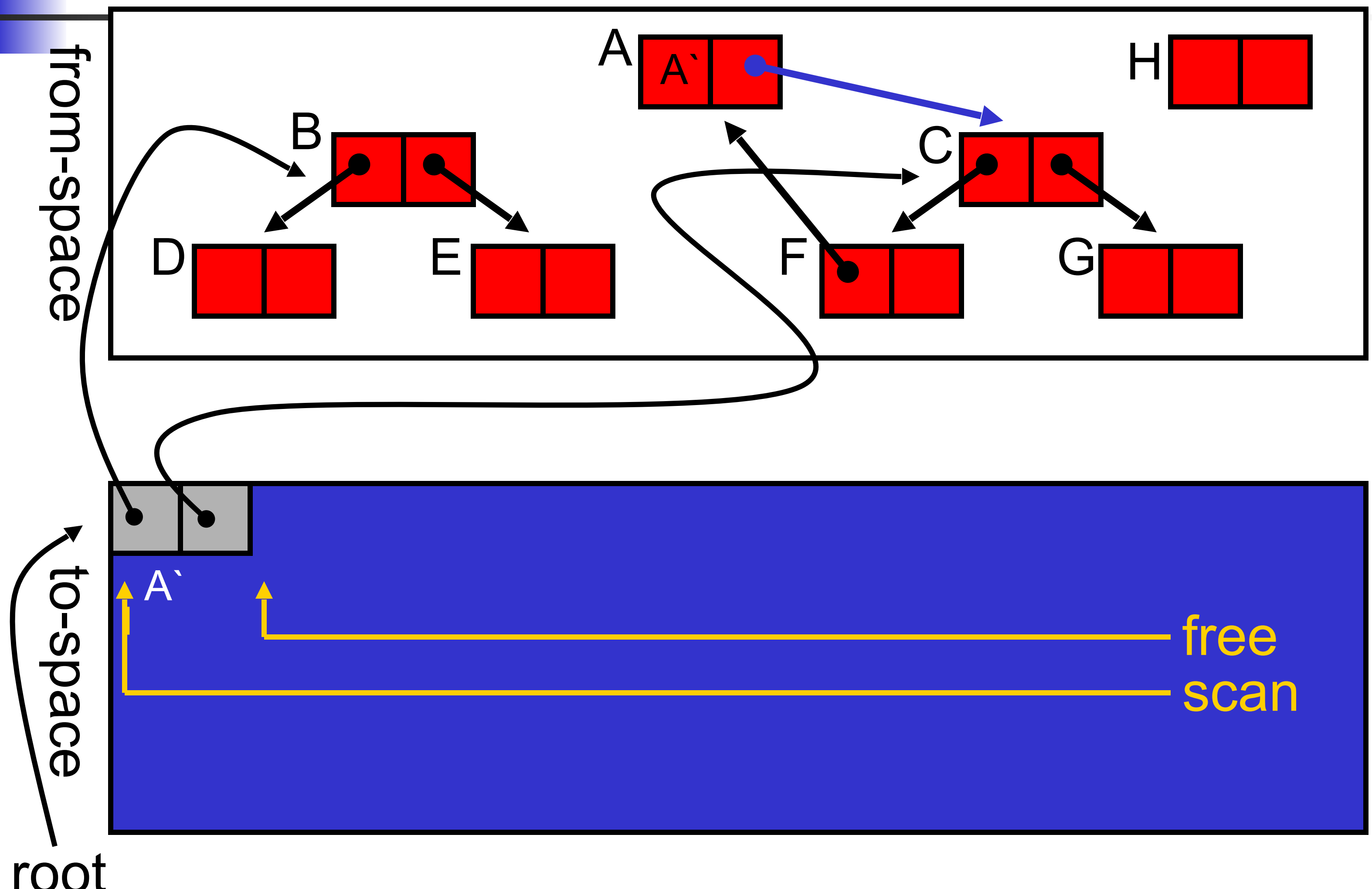

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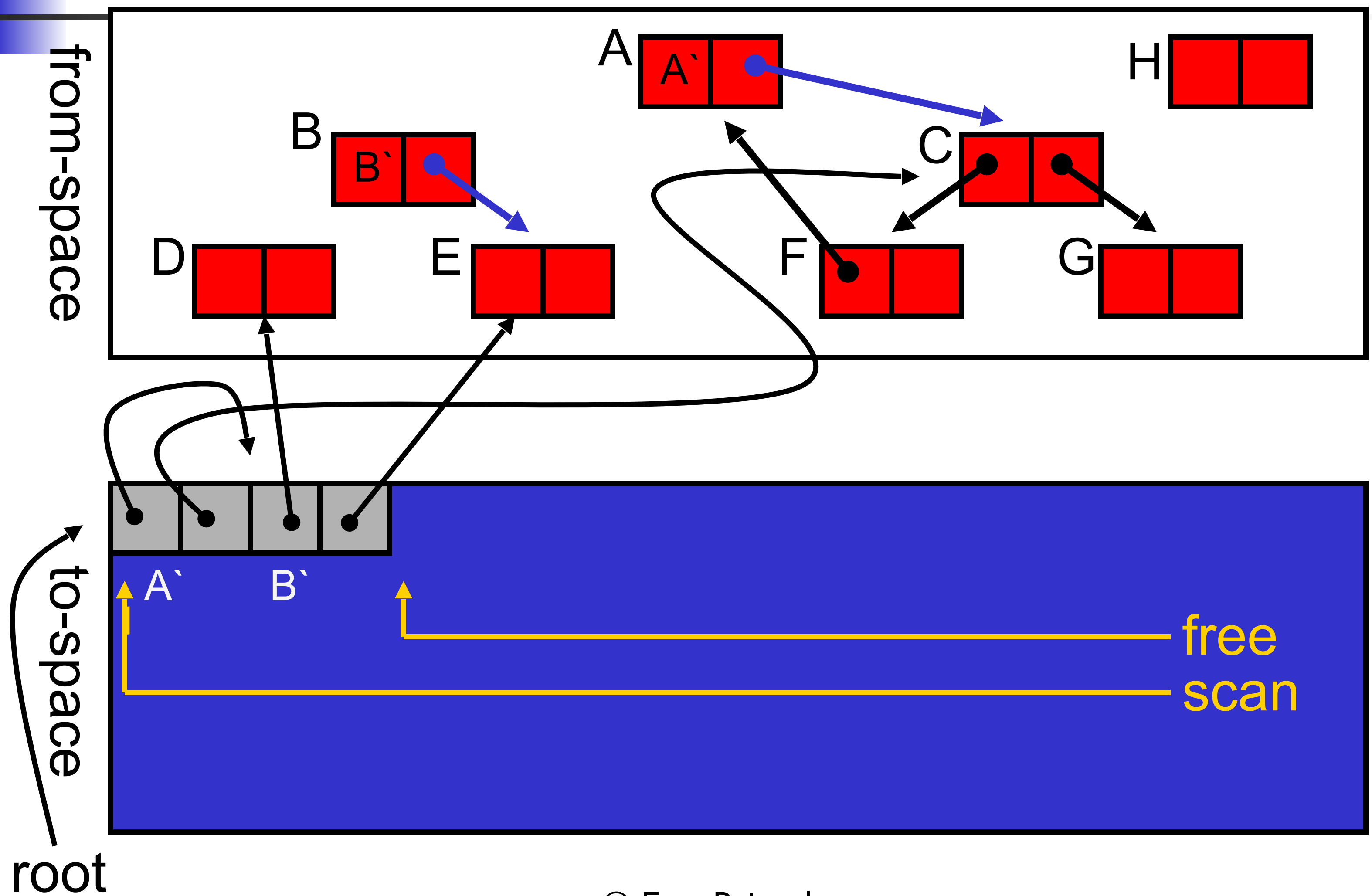
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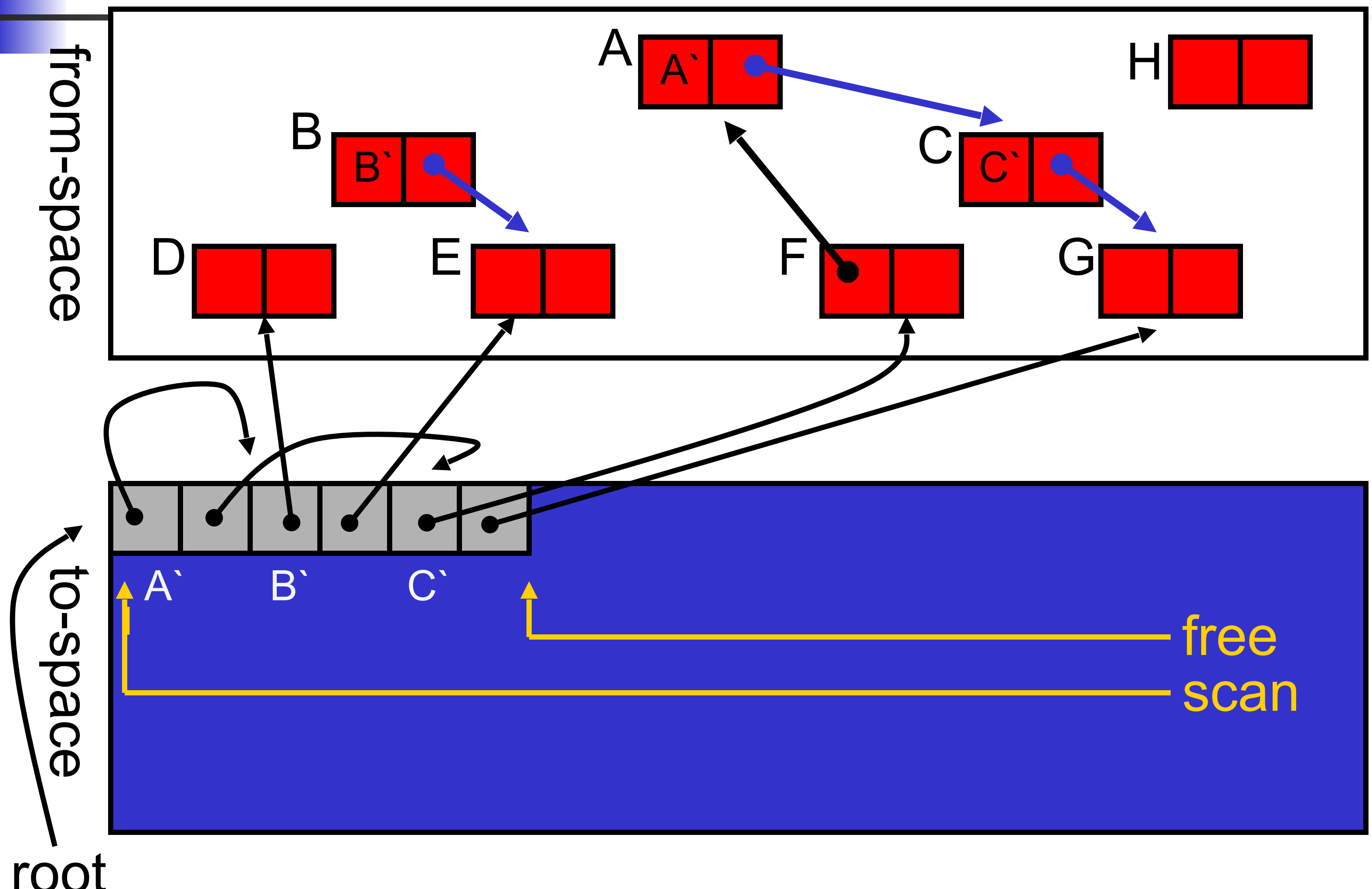

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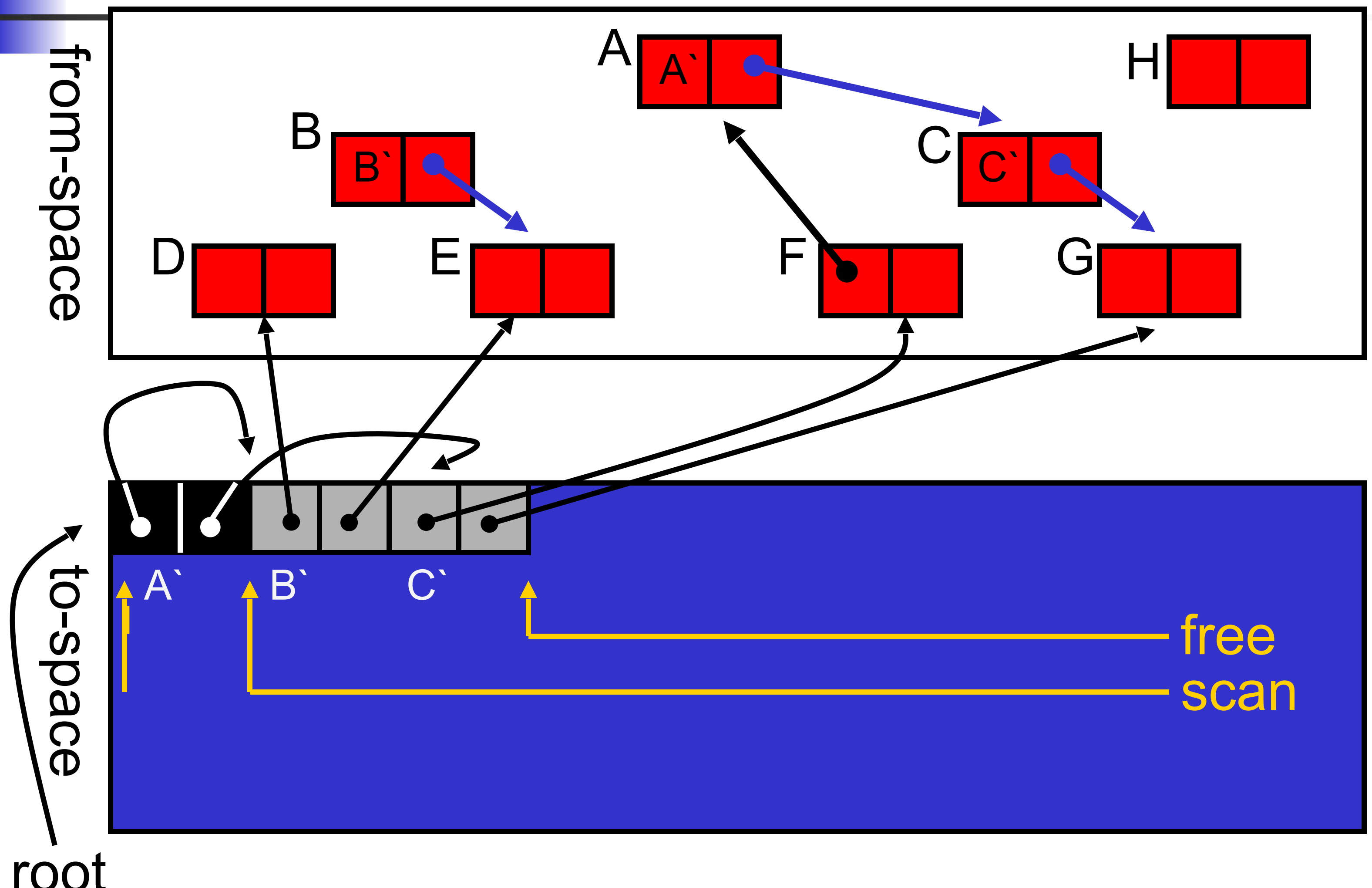
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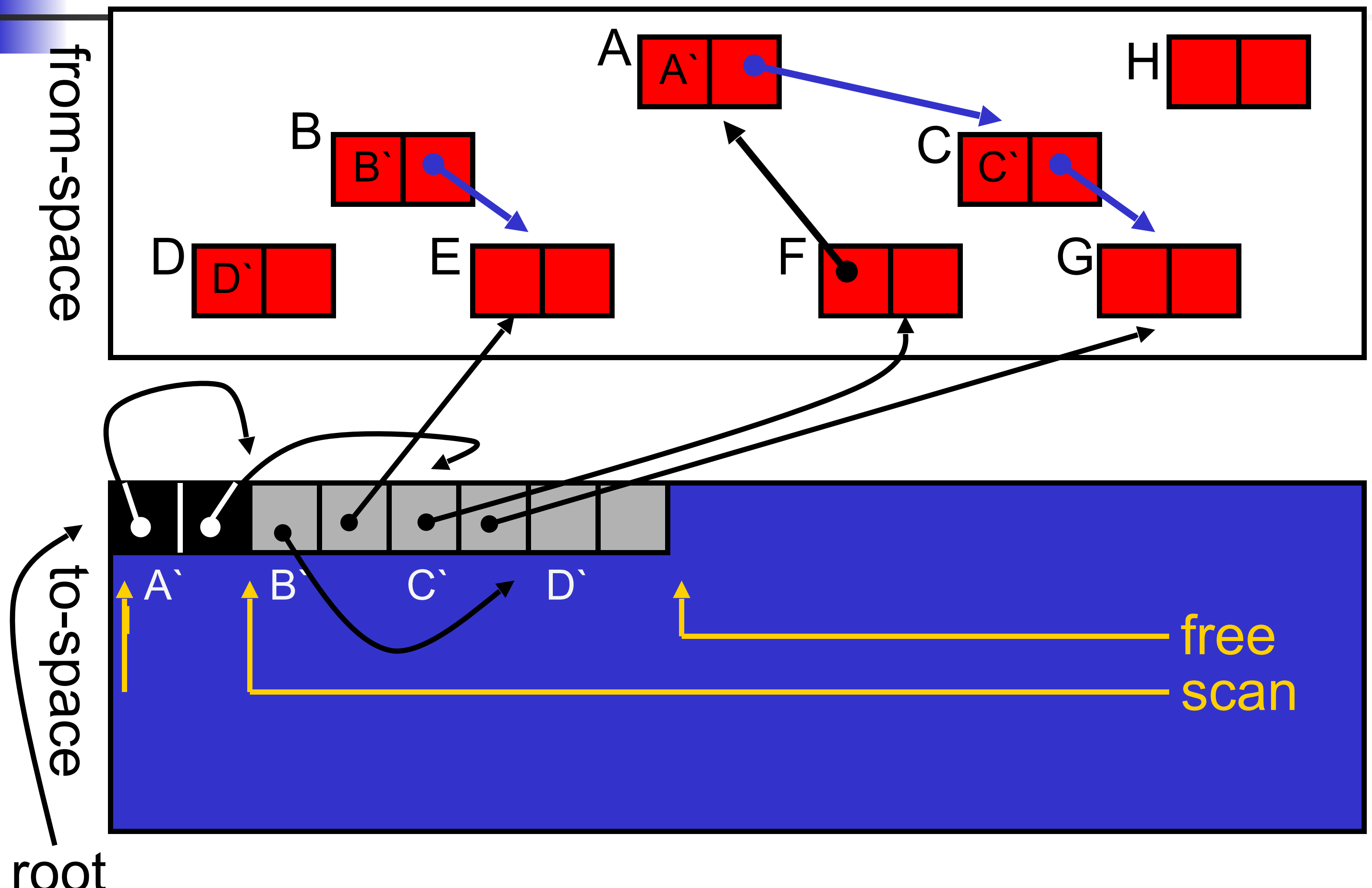
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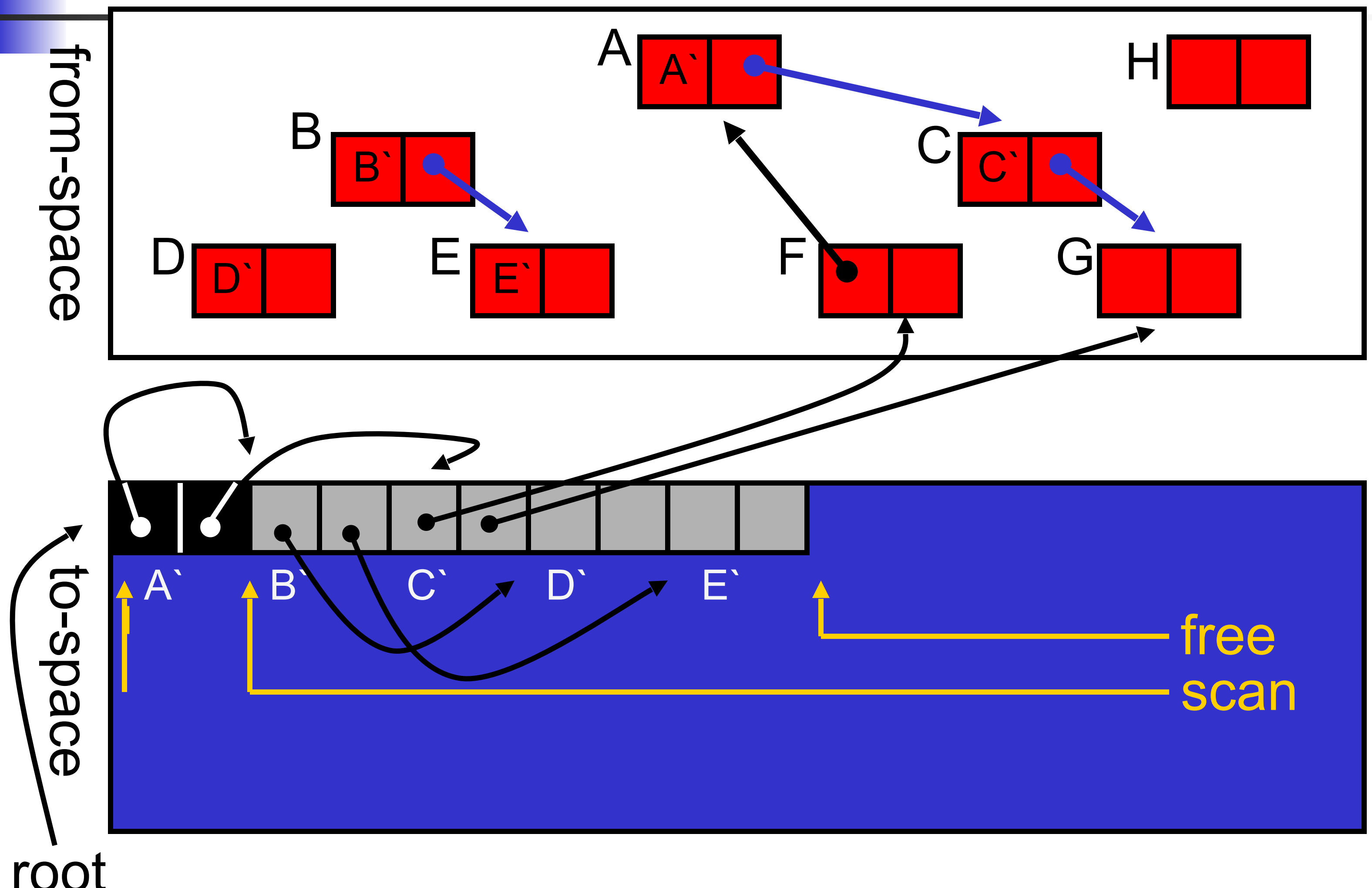
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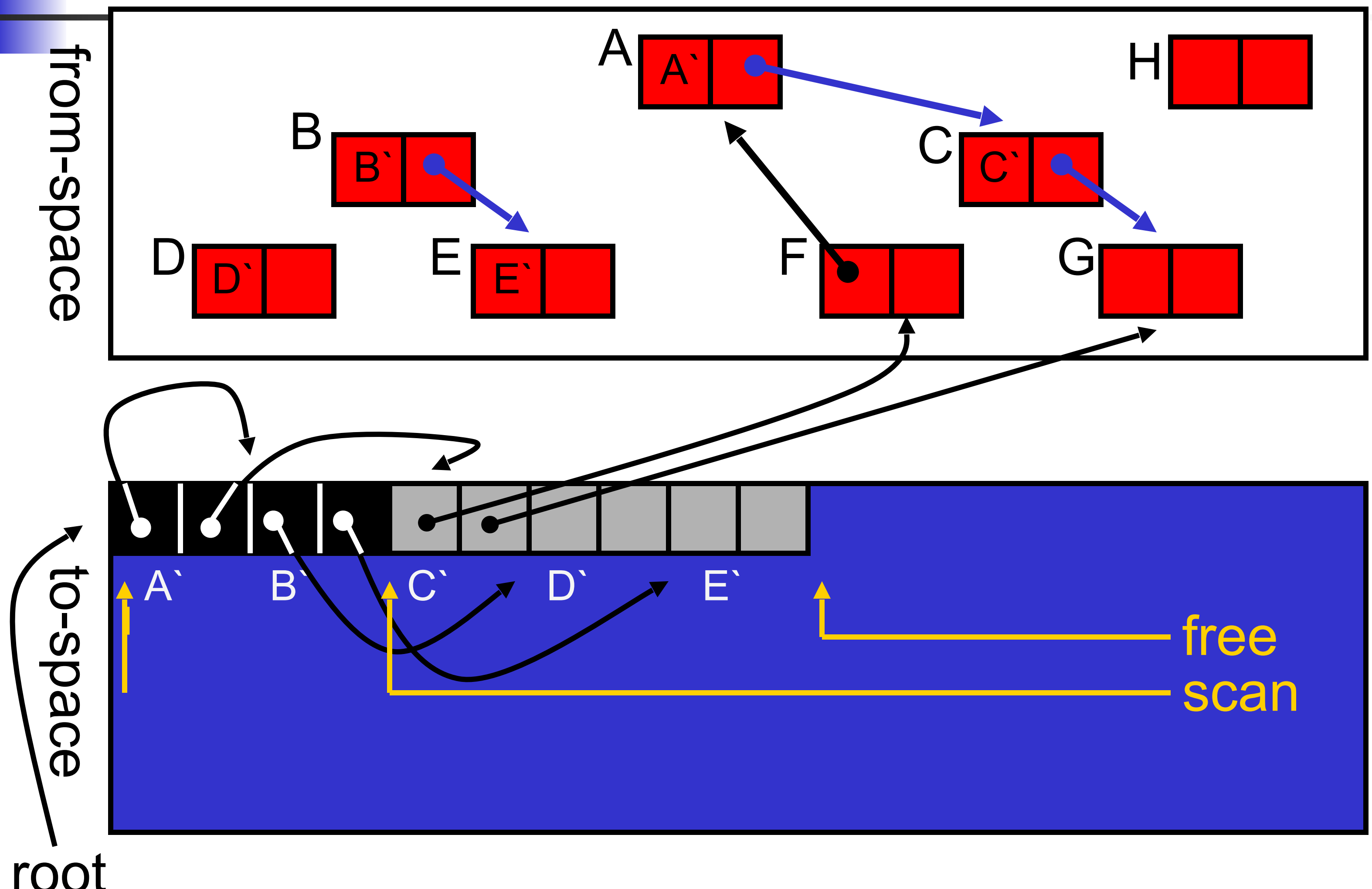
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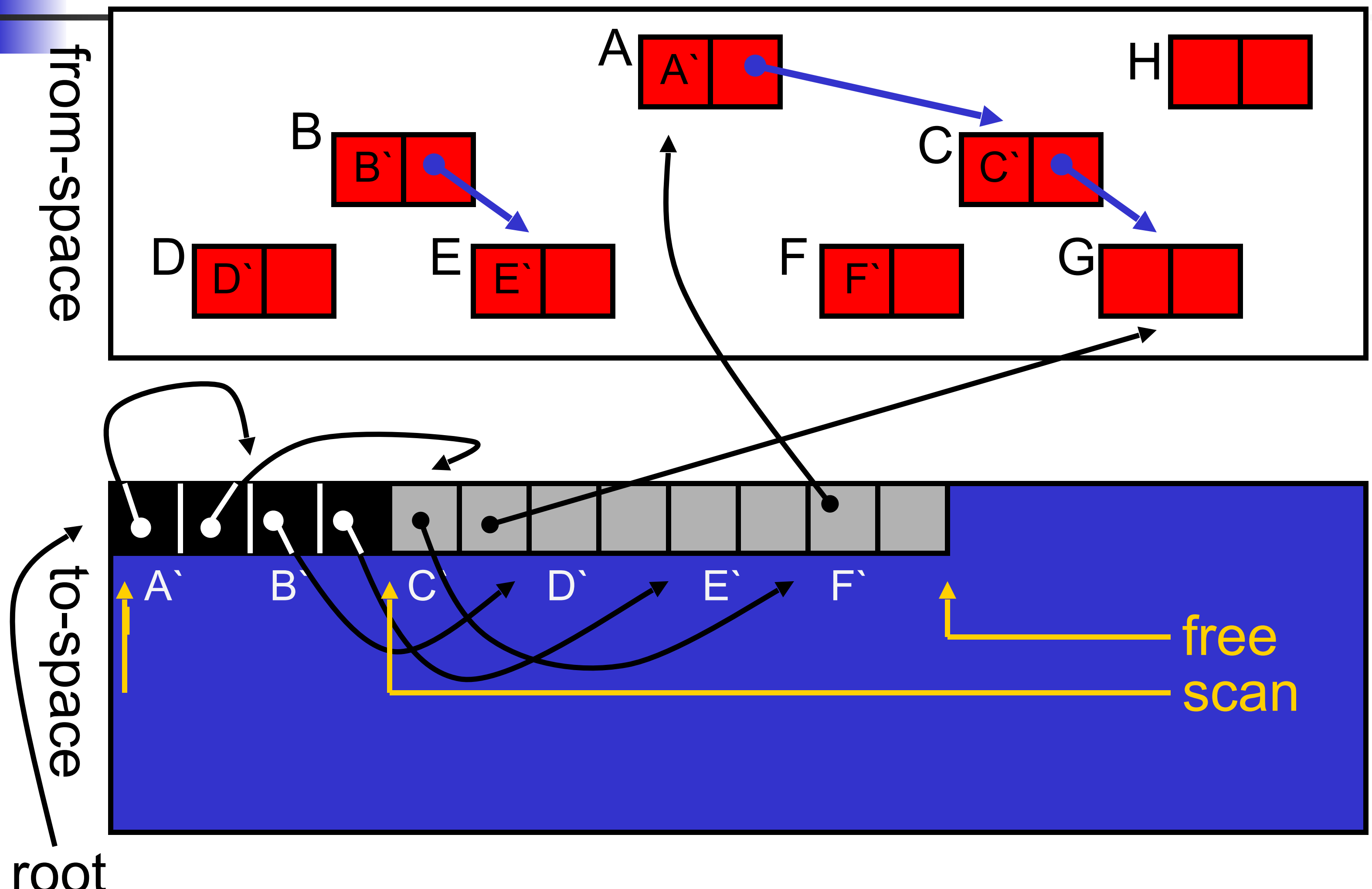
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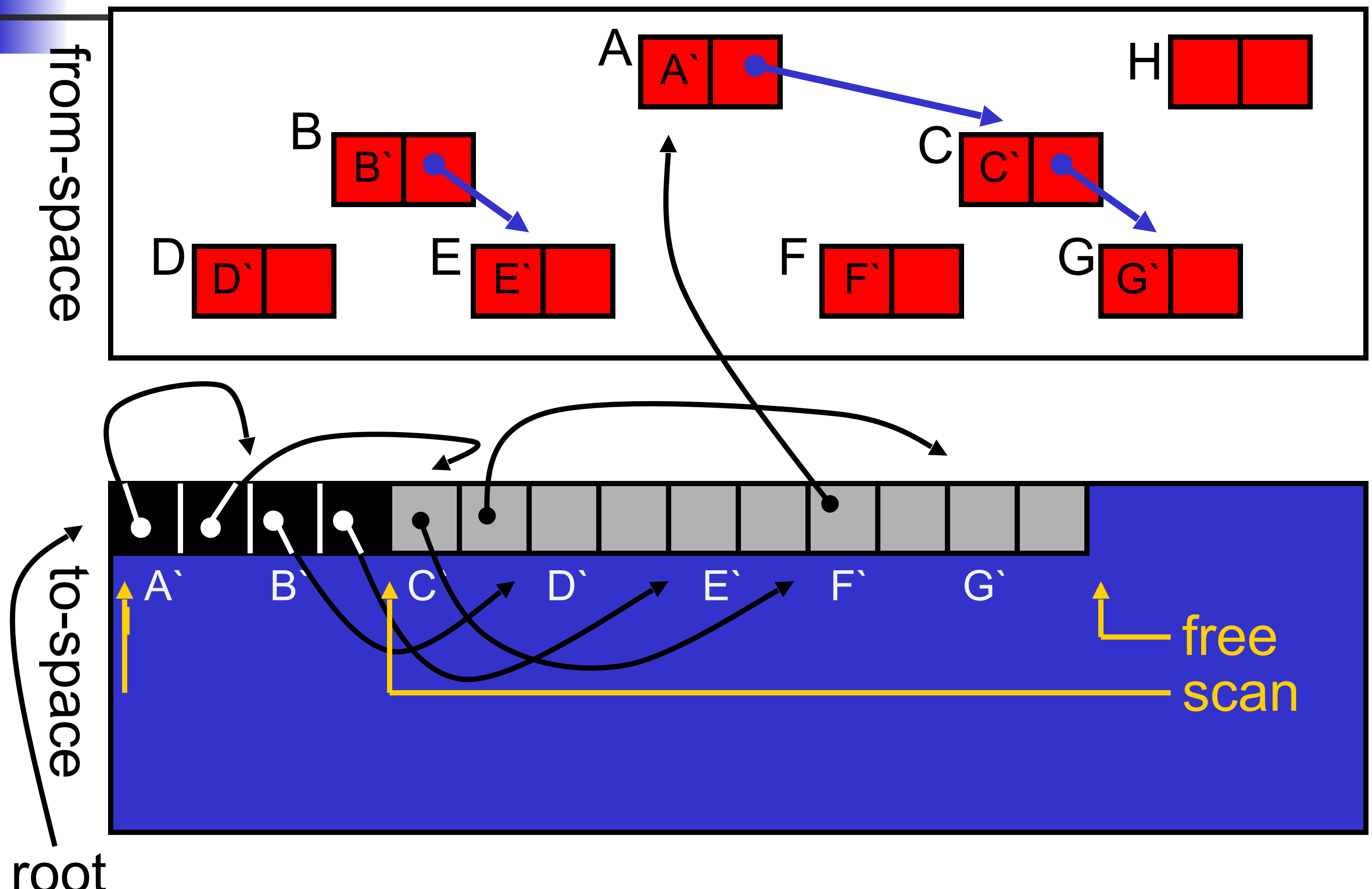

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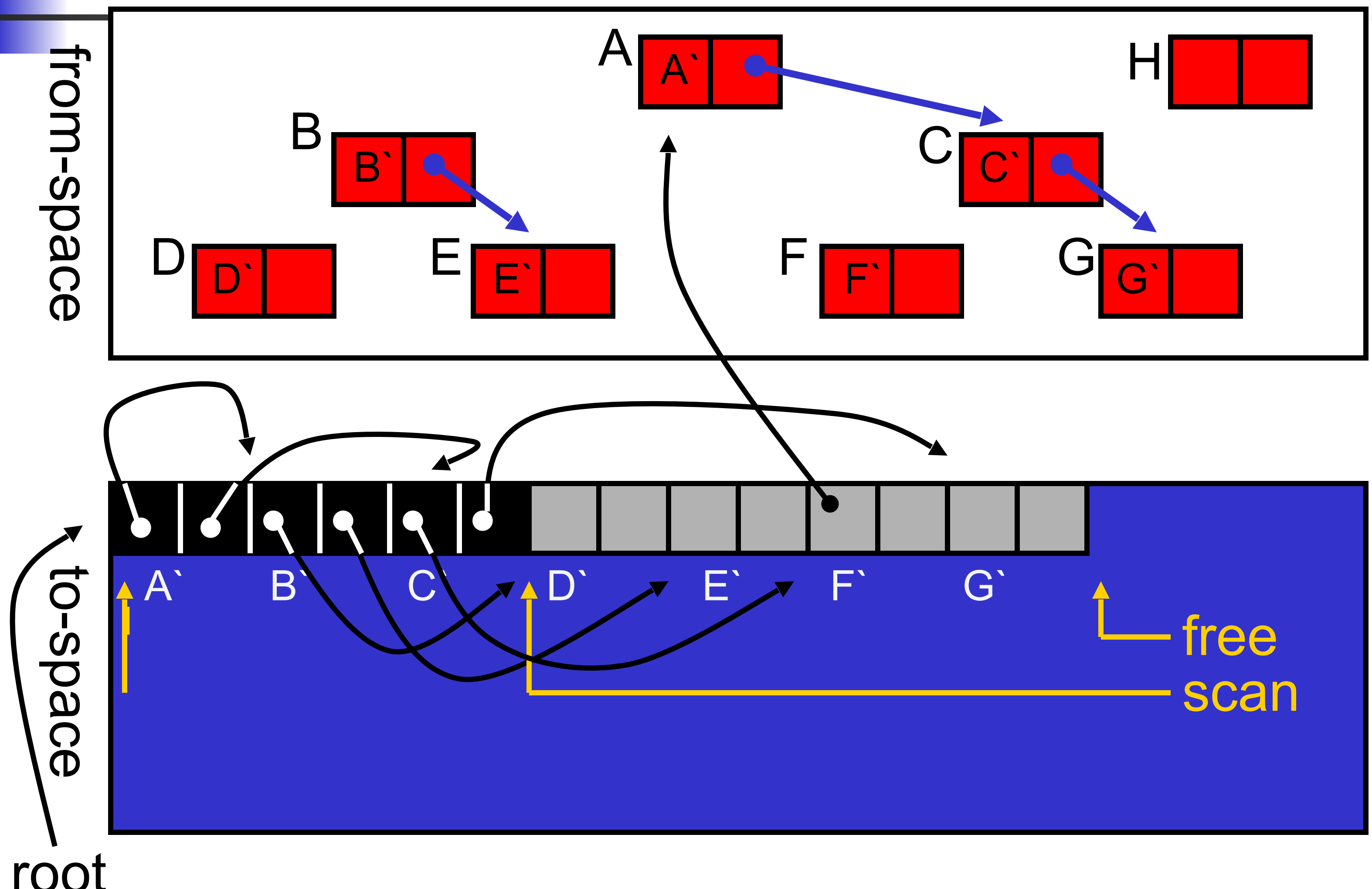
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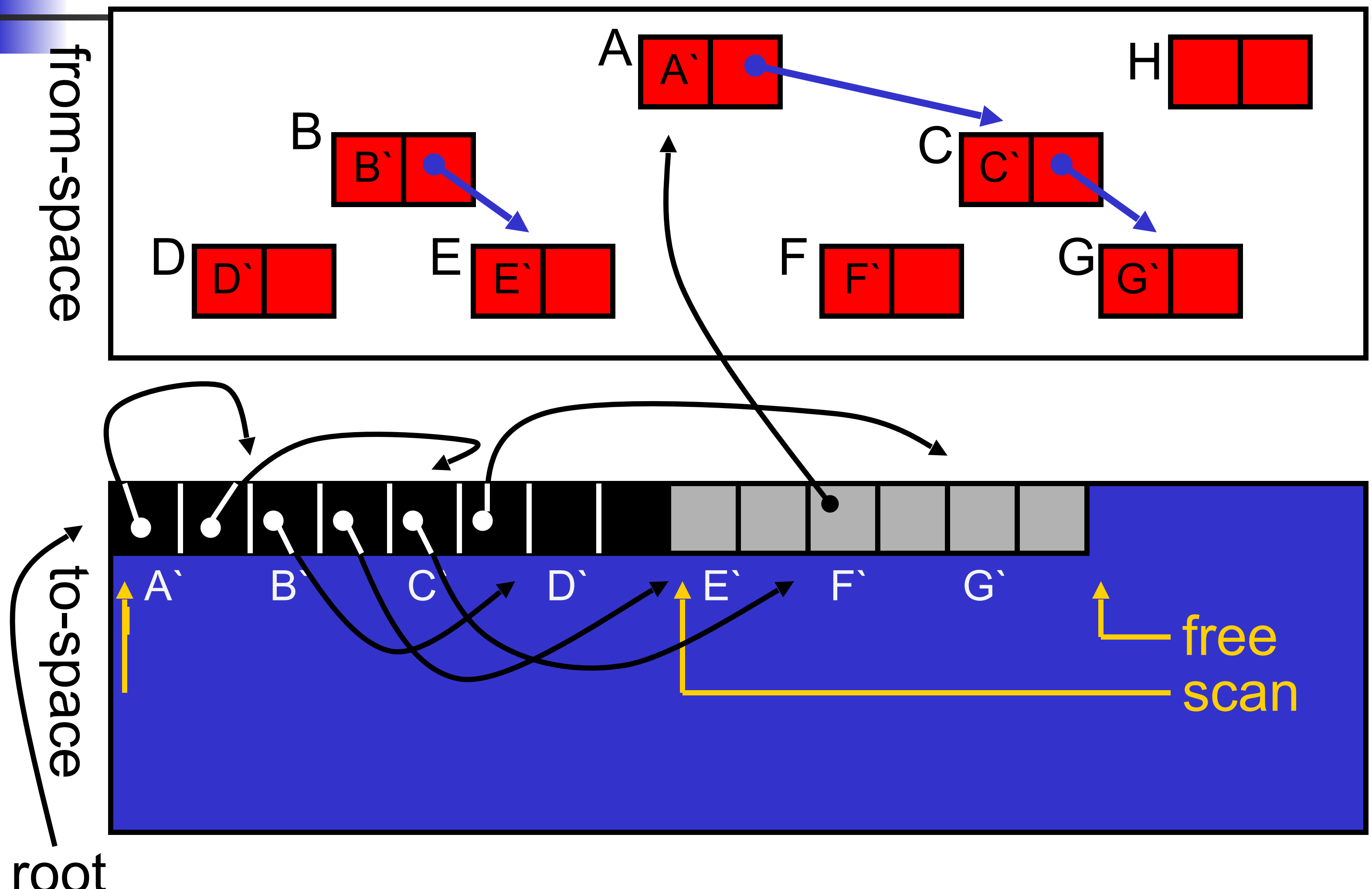
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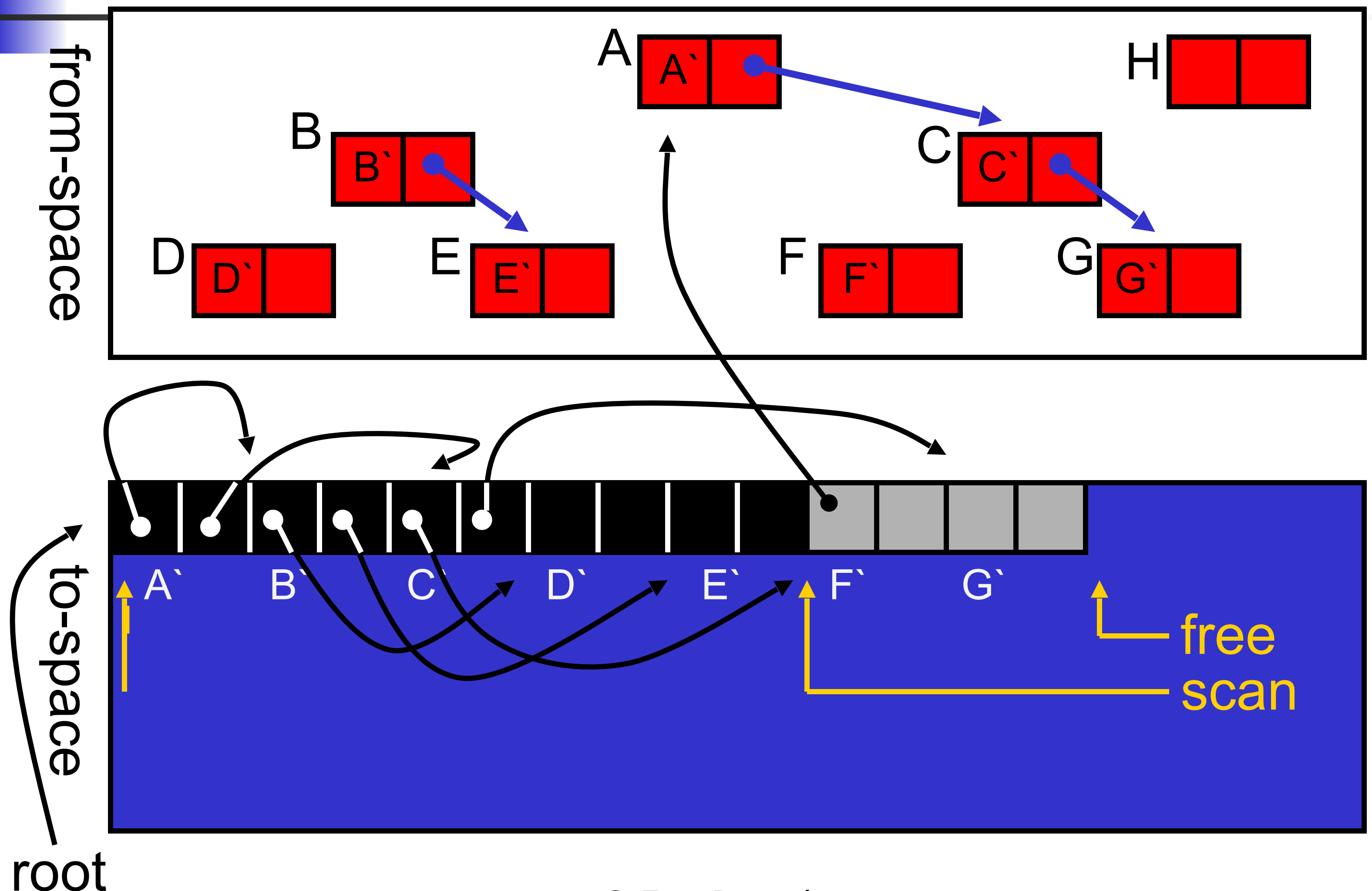
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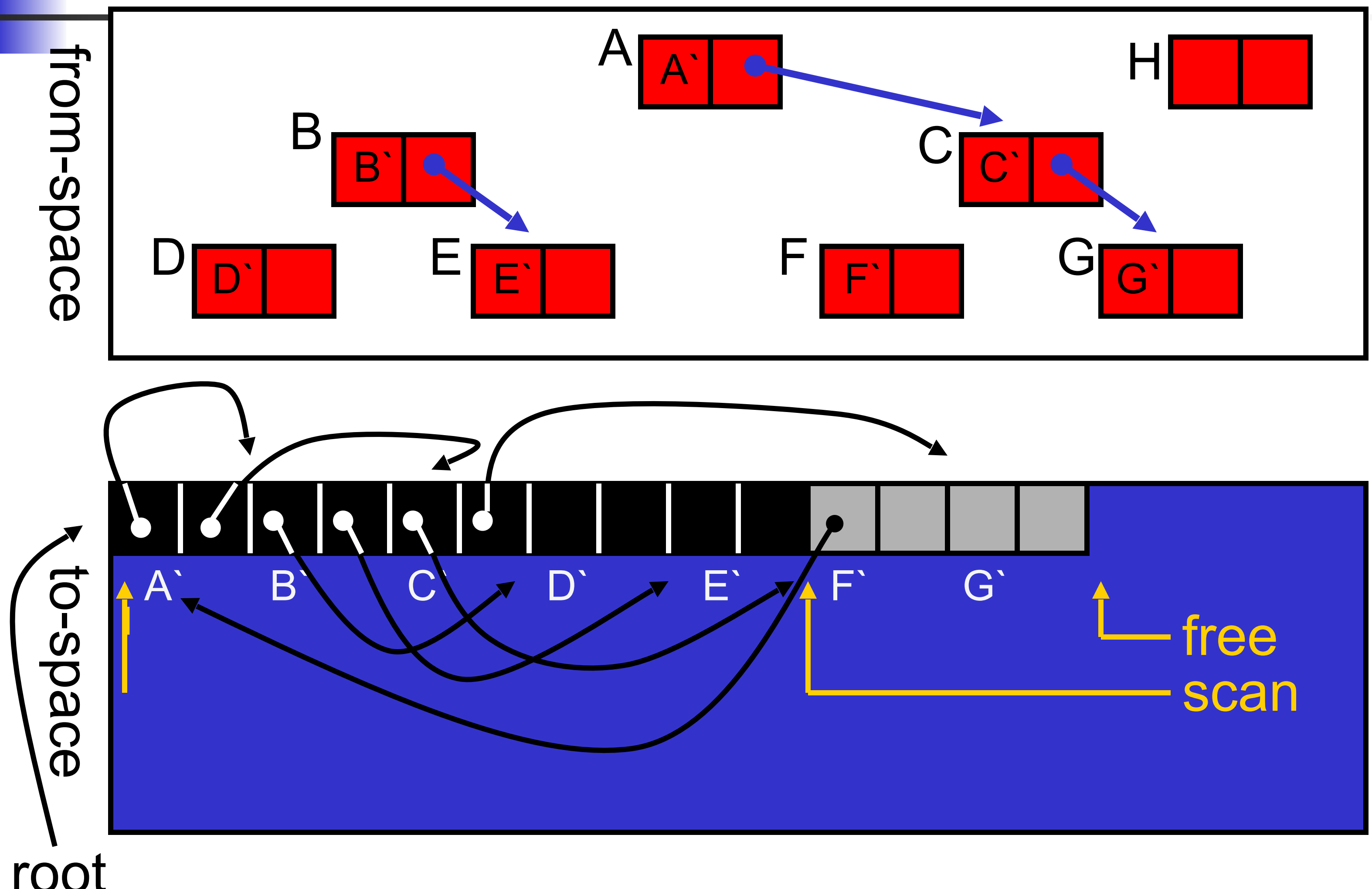
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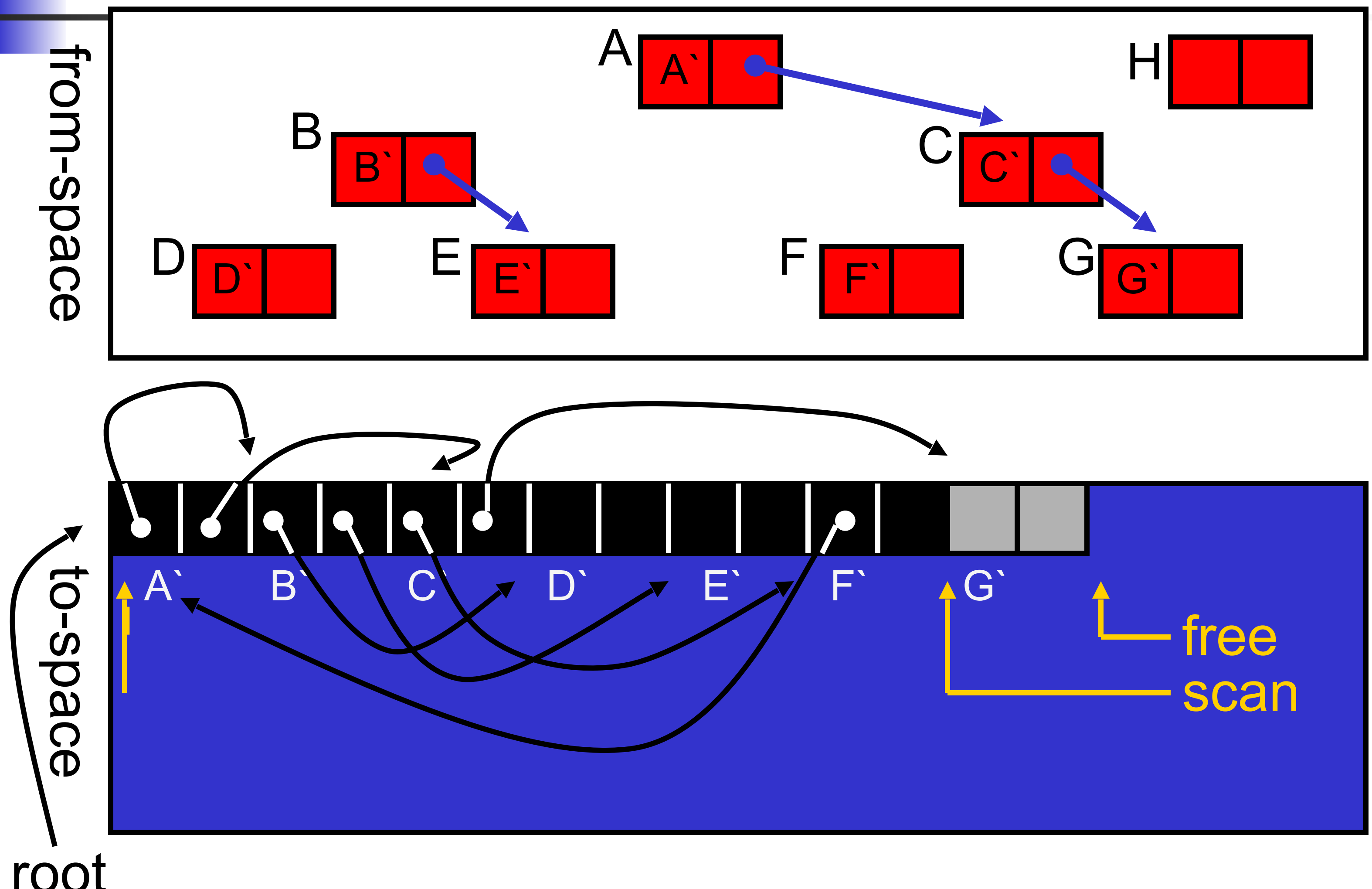
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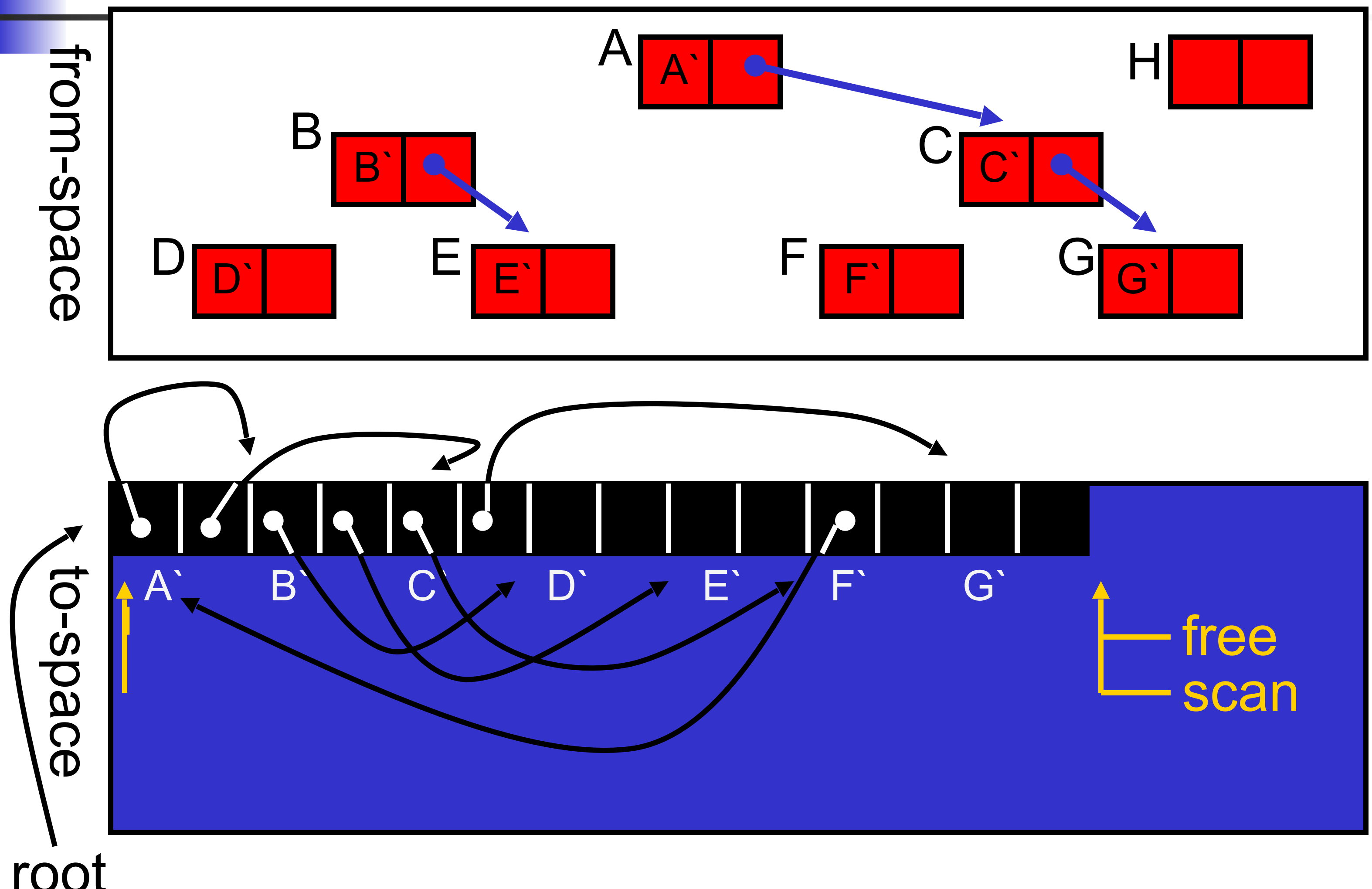
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Properties

- Space overhead:
  - Half the heap reserved (wasted)!
  - But: no auxiliary structures (no mark-stack, no bitmaps) and compaction for free: fragmentation space saved.
- Complexity proportional to live data
  - Recommended when survival rate is low.
  - Yet, cost of copying is larger than marking the object.
- Simple and efficient allocation ("linear").

The algorithm (init)

```
Init() =
    Tospace = Heap_bottom
    space_size = Heap_size / 2
    top_of_space = Tospace + space_size
    Fromspace = top_of_space + 1
    free = Tospace
```

The algorithm (Allocation)

```
New(n) =
    if free + n > top_of_space
        Collect()
        if free + n > top_of_space
            abort "Memory exhausted"
    new-object = free
    free = free + n
    return (new-object)
```

The algorithm (collect)

```
collect() =
    from-space, to-space =
                          to-space, from-space  //swap
    scan = free = Tospace
    top_of_space = Tospace + space_size
    for R in Roots
          R = copy(R)
    while  scan < free
          for P in children(scan)
                    *P = copy(P)
          scan = scan + size (scan)
```

Handling a pointer

```
copy(P) =
    if forwarded(P)
        return forwarding_address(P)
    else
        addr = free
        mem-copy(P, free)
        free = free + size(P)
        forwarding_address(P) = addr
        return (addr)
```

Garbage collector efficiency

- R = Number of reachable objects,
  then Cheney copying requires **cR** operations.
- c depends on time to copy an object and average number of pointers per object.

Garbage collector efficiency

- R = Number of reachable objects,
  then Cheney copying requires **cR** operations.
- M = size of each semi-space,
  s = average size of an object.
  Thus, number of objects allocated between gc's (& reclaimed during) is **M/s-R**.
- g = CPU cost of GC per object reclaimed:

$$g = \frac{cR}{M/s - R} = \frac{c}{M/(sR) - 1}$$

Garbage collector efficiency

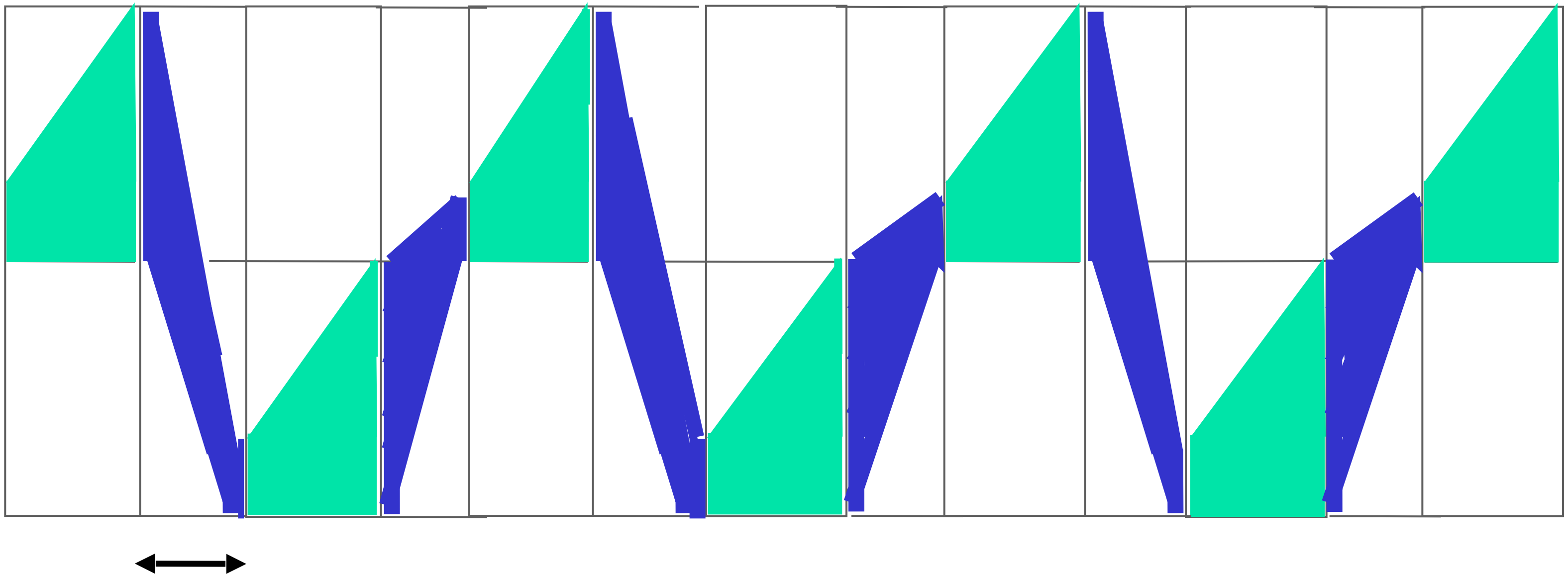
- Recall: R = number of reachable objects, M = size of each semi-space, s = average size of an object, g = CPU cost of GC per object reclaimed.
- R & s are application dependent.
- M may be determined by the system
- g, the cost, can be made arbitrarily small by increasing M. [Appel]: with sufficient memory (14 times the size of live space), it is cheaper to garbage collect than to free explicitly

$$g = \frac{cR}{M/s - R} = \frac{c}{M/(sR) - 1}$$

An Example:

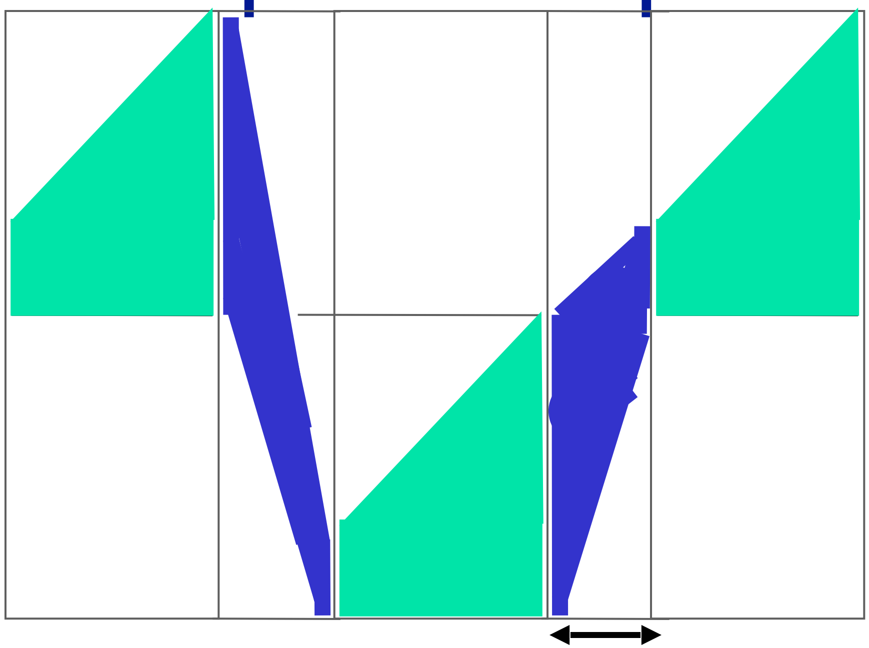
- Imagine that a program is run twice, once with semi-spaces of 350MB and then with semi-spaces of 700MB.
- Properties:
  - Suppose the amount of active memory used ($s \cdot R$) is 100MB (and is stable).
  - The program allocates 1800MB in total.

An Example: Heap Size 350MB



To complete the run with the smaller heap, program must collect 6 times, copying $6 \cdot 100 = 600$MB of data.

An Example: Heap Size 700MB



To complete, the run with the larger heap must garbage collect only twice, copying 2X100 = 200MB of data.

Historical review

- [Minsky 63] garbage collector for Lisp 1.5: secondary tape storage for other space.
- [Fenichel-Yochelson 69] copying algorithm with recursion for Lisp.
- [Cheney 70] efficient iterative copying garbage collection with the scan and free pointers.
- Lots of implementations variants since then.

Improvements and Ideas

- Large objects
- Incremental compaction
- Mark & Copy

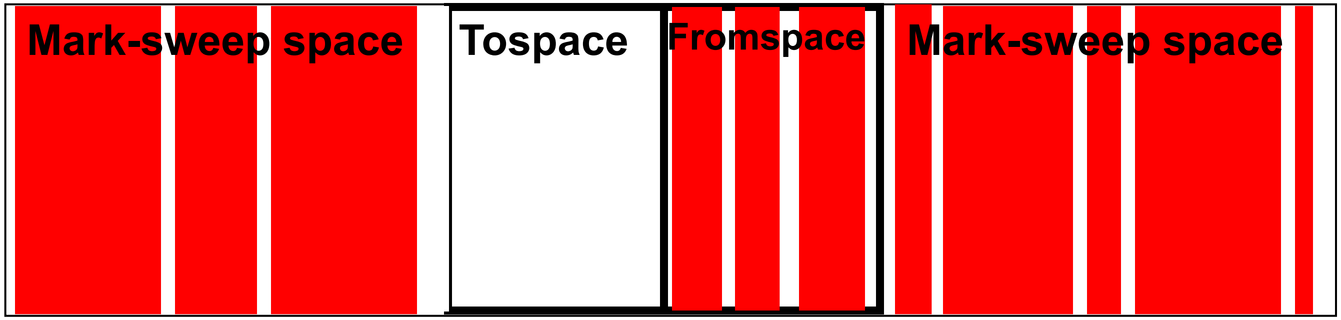
Large & Long-Lived Objects

- Copying GC copies surviving objects from one semi-space to the other.
- Good case: short lived small objects.
- Bad case: long lived large objects.
- Ideas:
  - Put large objects in a separate region collected by mark & sweep.
  - Put long lived objects in a separate region. Either collect infrequently or use mark & sweep there.
  - Main point: divide the heap into separately managed regions.

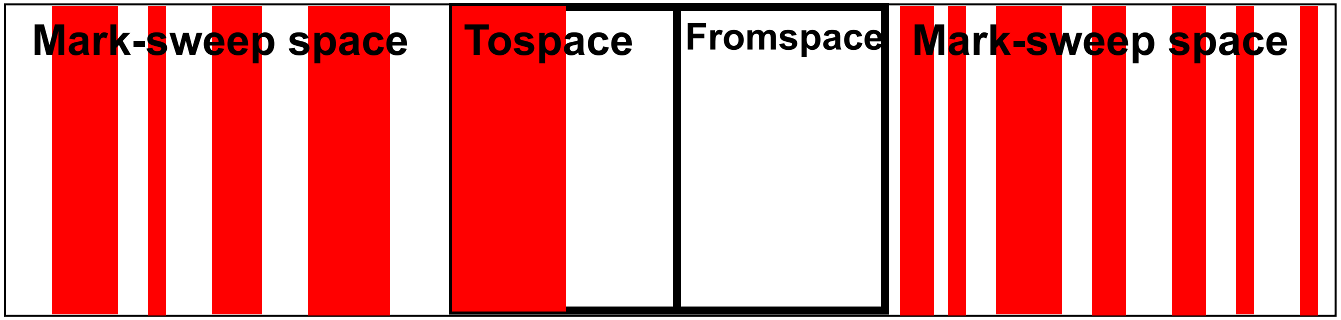
Incremental Compaction

- Compaction is time consuming, copying is space consuming.
- [Lang and Dupont 87]: use copying for incremental compaction.
- Divide the heap into n+1 equally sized areas. One area is unused and n areas are used for allocation.
- During collection, two of these areas are treated as a pair of semi-spaces and managed by copying collector while the rest of the heap is mark-swept.
- The pair of segments chosen as semi-spaces rotates through the address space at each collection, incrementally compacting the heap.

Lang & Dupont – Heap Partition



Before collection



After collection

The L&D Collector

- Segment i free at start (current to-space).
- Segment i+1 serves as from-space (and to-space of the next collection).
- Copying and Mark-Sweep happen simultaneously:
  - When visiting the descendants of an object:
  - If descendant not in from-space then mark it.
  - Otherwise, (in from-space) “scan”:
    - If not copied yet – copy to to-space, leave a forwarding pointer, and update the pointer.
    - If copied – update pointer using forwarding pointer.
- Finally, sweep all segments except i,i+1.

Properties

- A small space overhead (depending on n)
- A small payment in time (extra “if” in the marking procedure, plus copying is a bit more expensive.)
- No extra passes are required.
- After n collections the whole heap has been compacted incrementally (speed depends on n).
- Compaction quality is low (depending on n).
- Allocation cannot use “bump pointer” style.

Lang-Dupont Collector Versus Traditional

Compared to mark-compact

- A small space overhead.
- Much more efficient.
- Compaction is slow and its quality is low (depending on n).

Compared to copying

- Better space efficiency (depending on n).
- Collection efficiency similar to mark-sweep.
- Allocation cannot use "bump pointer" style.

MC (Mark-Copy) and MC^2

- Narendran Sachindran, Eliot Moss, Emery Berger [2003,2004]

Virtual Memory Reminder

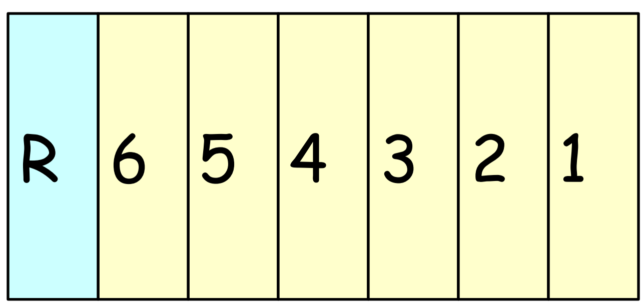
- A process has a large virtual (memory) address space.
- This space is divided into virtual pages (typically 4KB)
- Some of the virtual pages are kept on physical memory while the rest reside on the hard disk.
- The system has a map from virtual to physical pages.
- Due to locality of computation, page faults (pages that are not available in the memory and must be retrieved from the disk) are seldom.

Virtual Memory Primitives

- A virtual page is mapped into a physical page when a space on that page is allocated.
- Virtual pages consume "real" resources (such as space on disk and memory) when mapped.
- A virtual page can be released or unmapped when the process does not need the data on it anymore.

MC (Mark-Copy) and MC^2

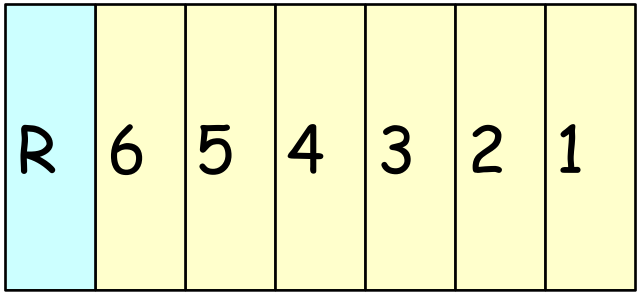
- Sachindran, Moss, and Berger
- Problem: copying requires double space.
- Solution: add some work, but save space.
- Partition the heap H into n small sub-heaps.
- Keep only one extra space of size H/n.



In the example, 6 areas, and an additional reserved 1/6 (wasted 1/7)

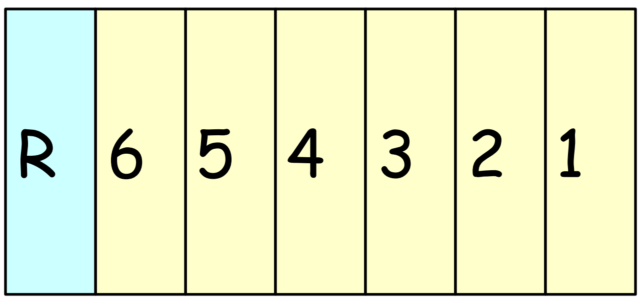
MC (Mark-Copy)

- Naively, when heap full, stop the program and:
  - Collect area 1 into area R,
  - Collect area 2 into area 1,
  - …
  - Collect area n into area n-1.
- MC extends this simple scheme.



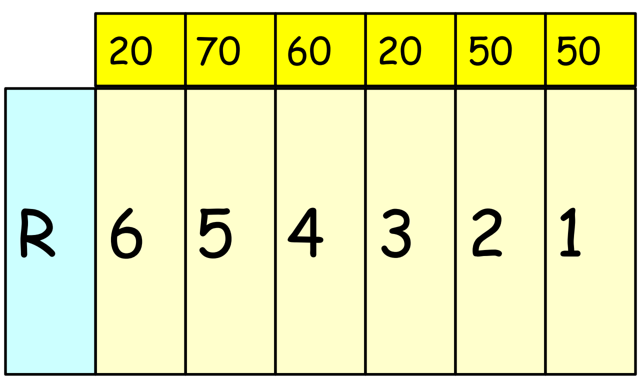
MC (Mark-Copy)

- Naively, when heap full, stop the program and:
  - Collect area i into area i+1…
- Problem 1: low-quality compaction,
- Problem 2: how do we know which object is alive in space i?
- Problem 3: how do we update the pointers?



An Initial Marking Phase

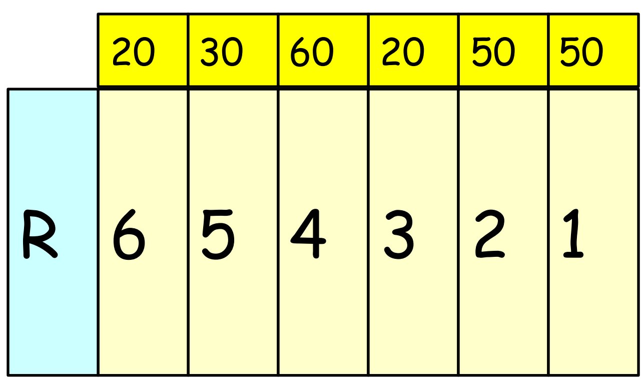
- Add a marking phase that goes over all live objects
  - Now we know which objects are alive.
  - Also, create remembered sets. One for each area recording pointers referencing it from higher areas (for pointer updates.)
  - Finally, sum up used space in each area.



Say, each area can hold 100MB

Copy Passes

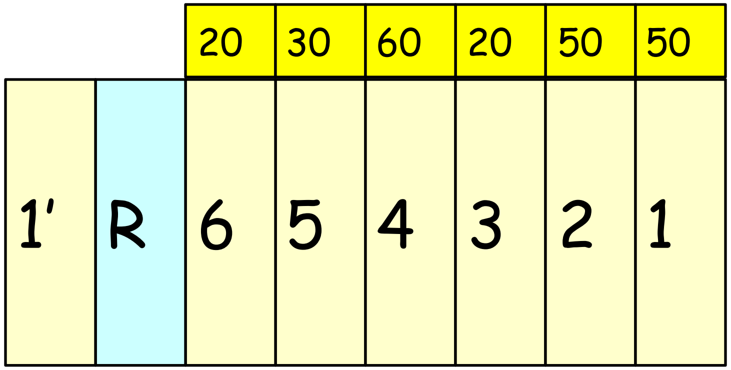
- Pass I: Compute How many spaces (1,2,…) can fit into R.
- Copy the live elements in these spaces into R using a copying collector, using roots + remembered set.
- “Unmap” areas 1 and 2; Map a new area 1’.



In the example,
Pass I: 1 & 2 into R;

Copy Passes

- Pass I: Compute How many spaces (1,2,…) can fit into R.
- Copy the live elements in these spaces into R using a copying collector, using roots + remembered set.
- "Unmap" areas 1 and 2; Map a new area 1'.
- Pass II: Compute the next spaces that can be copied into area 1', copy live objects, un-map them, map 2', ...



In the example,
Pass I: 1 & 2 into R;
Pass II: 3 & 4 into 1'
Pass III: 5 & 6 into 1' and 2'.

Tuning

- A larger number of areas means
  - Smaller space overhead
  - More overhead on remembered sets, and collection passes.

Properties of MC

- Advantages of a copying collector:
  - Fast allocation, with good locality, heap compaction, touch only live objects.
  - Much smaller space overhead.
- Disadvantages:
  - An additional tracing phase (with mark-stack space overhead),
  - An additional remembered-set space and time overhead.
  - Several (extended) root scanning,

Improvements in MC^2

- Do not use virtual memory services.
  - Areas are maintained by the collector, each area has a logical number determining it's order.
- Do not copy all objects in old space
  - High occupancy areas: objects are never copied from them. Instead, their logical number is made high.
- Reduce space overhead of remembered sets.
  - The collector computes groups of areas whose accumulated live set fits into a single empty area.

- We will not discuss:
  - Integrate with generations
    - The original papers put it all in a generational setting, to be discussed next week. The old generation is managed with MC (or MC^2).
  - Increased incrementality.

Summary: Copying Collection

- Cheney's collector
- Large objects
- Incremental compaction
- Mark-Copy

Mark-Sweep Versus Copying

- Efficiency
  - Marking vs. copying
  - Sweeping
- Space usage
  - Wasted semi-space vs. mark-stack and mark-bits
- Fragmentation
- Caching

- No real conclusion!
  Mark-and-sweep probably wins in popularity.
  Both serve in a standard generational collector.

Incremental Garbage Collection

Problem

- Long pauses disturb the user.
  - Real time cannot be guaranteed
  - Slow response time – lost clients
  - Sometimes even communication time-outs
- Response time may be bad for a long period after a pause: held transactions must wait for queue to be handled.

→ An important measure for the collection: length of pauses (average, maximum, distribution).

Solution: incremental Collection

- partition the collection work to “increments”..
- Baker’s copying collector [1977]:
  - During each allocation do some GC work.

Stop the world:

Incremental:

Not so simple!

- The heap changes while we collect.
- For example,
  - we scan Object B and before marking its children, the collector is stopped and the program resumes.
  - When the collector returns, the children may have been modified.

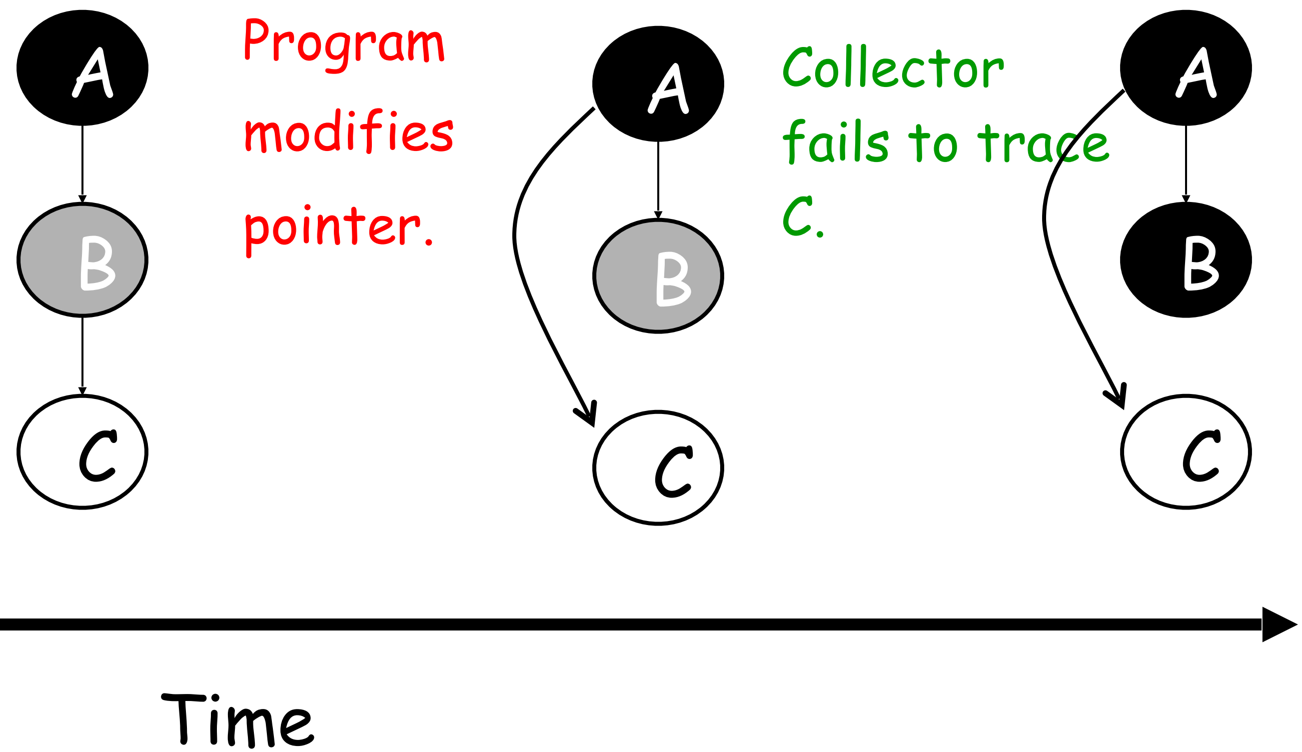
Incremental:

Example

GC marks A's children and makes A black.

Program modifies pointer.

Collector fails to trace C.



Three-Color Abstraction

- Black – objects in to-space that have been scanned (their children have been copied to to-space).
- Gray – objects in to-space, but have not been fully scanned yet.
- White – objects that have not yet been copied into to-space.

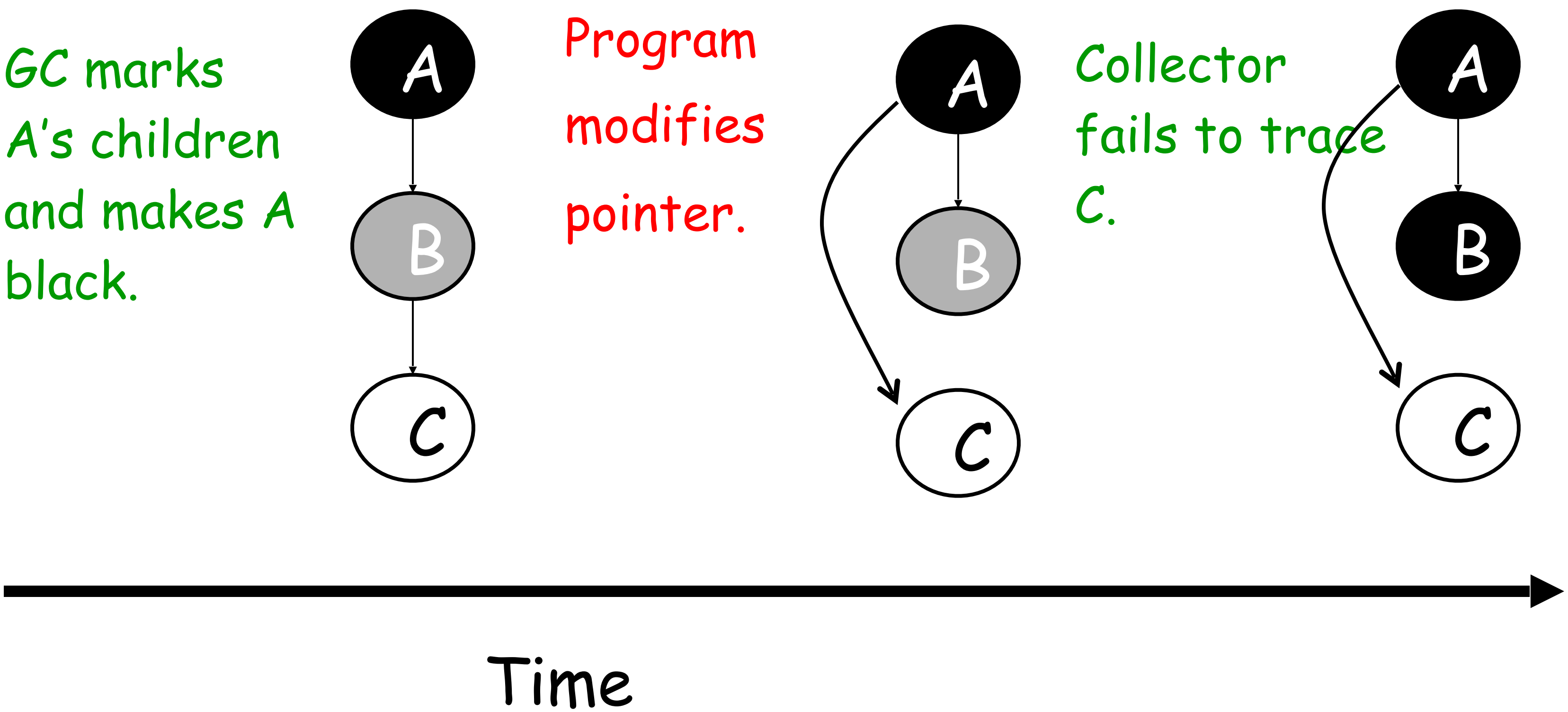
(A similar abstraction for mark and sweep exists.)

Problem: a pointer from black to white!

GC marks A's children and makes A black.

Program modifies pointer.

Collector fails to trace C.



Possible solutions

- “Aggressive” solution: do not allow black to white edges ([Baker], today).

- “Finer” solution: make sure that:
  for each white object O there is always a chain of references starting at a gray object, continuing with white objects ending in O ([Dijkstra et al], later in this course).

A Copying Problem: Consistency

- When two copies of an object exist in the system, it is important that all threads use the same object.
- If one thread copies the object to to-space and another has a pointer to from-space, then they may use different copies.
- Danger: One thread (reads and) writes to copy 1, other thread (reads and) writes to object 2.
  - Think of a counter.

- Baker's solution: threads only access to-space.

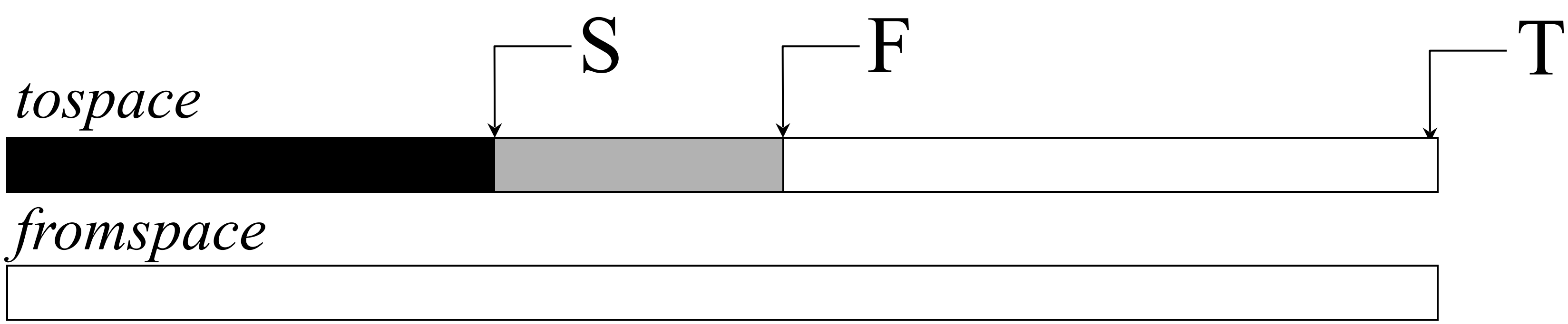
Baker's incremental copying

- Never let a black to white pointer be created.
- Program may only access gray/black objects (that have already been copied).
- A read barrier on each (heap) pointer read.
- When the program tries to access a from-space object A, A is first copied to to-space (becoming gray) and only then "given" to program.
- Program never holds a pointer to a white object, it can never write a black-to-white pointer.

Read Barrier

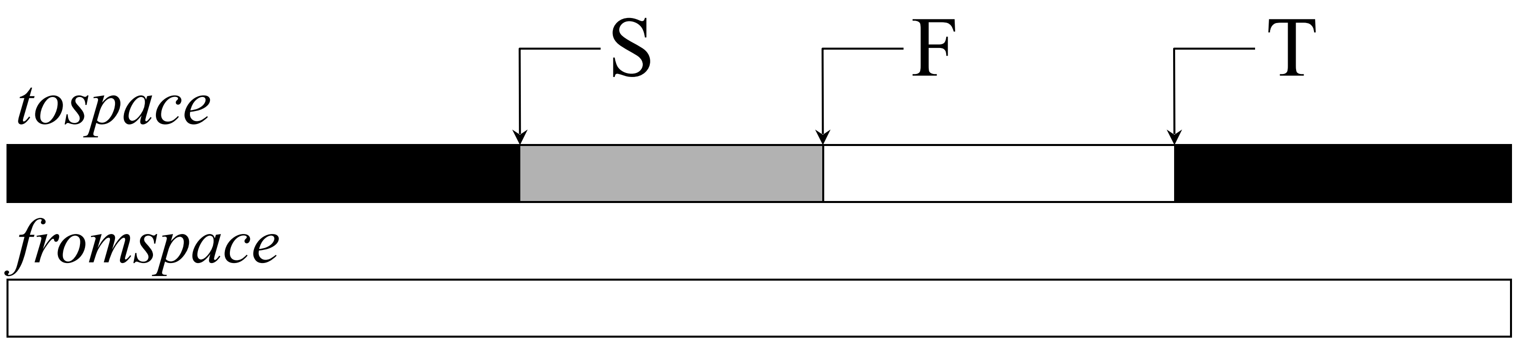
Recall Cheney's

- To-space is composed of
  - black objects (have been copied & scanned)
  - Gray objects (have been copied)
  - Free space (for allocation and copying)
- 3 pointers (scan, free, top) separate the semi-space.



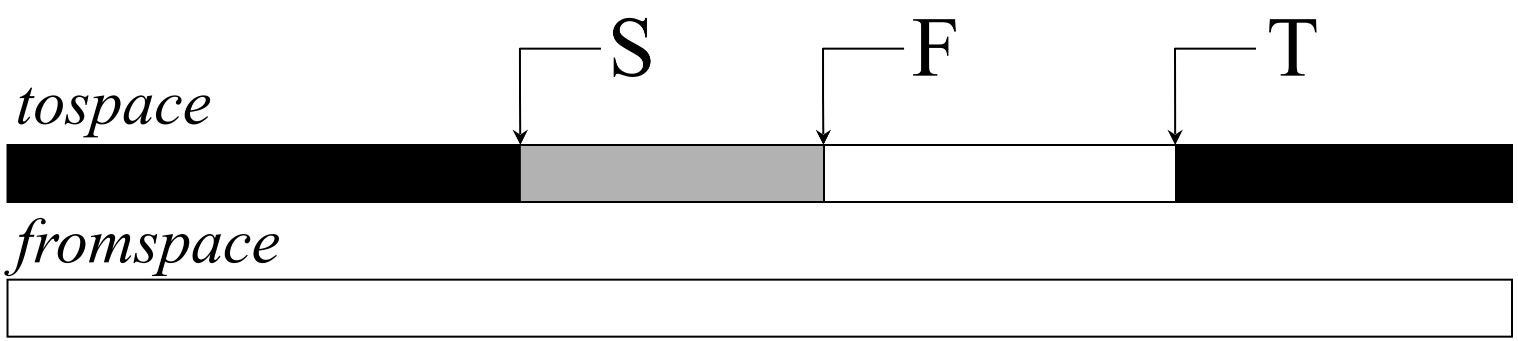
During collector work

- Program allocates objects black (no pointers there) via pointer T.
- Collector copies objects via pointer F.
- Collector scans objects via pointer S.
- Collection terminates when S=F.



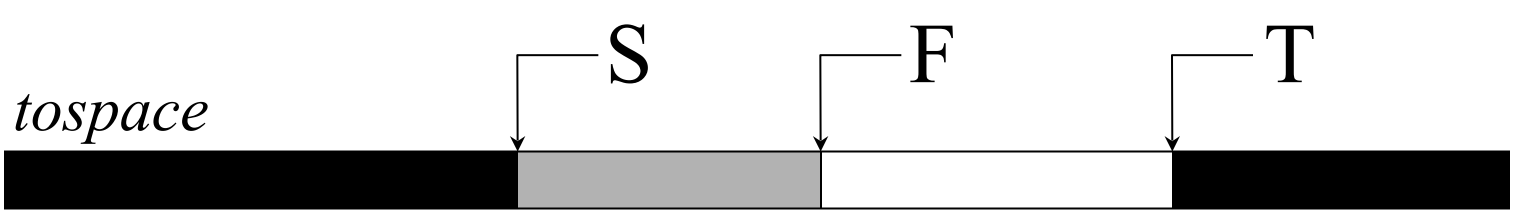
Modifying Cheney's Collector

- Collector first flips from-space & to-space.
- Objects pointed by roots copied to to-space; S→beginning, F → after copied objects, T → end of to-space. Program (root) pointers are now pointing to to-space only.
- Collector small incremental work: scan an object at location s. For any pointer to from-space
  - If object already copied – update pointer.
  - Otherwise – copy, leave forwarding pointer, update pointer.
  - Increment s.



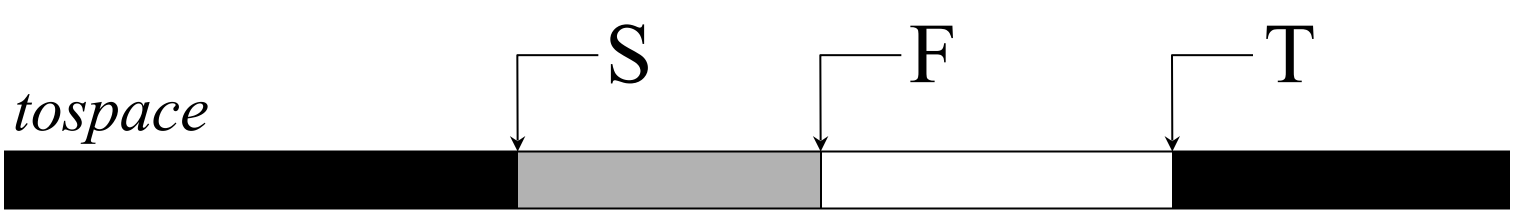
Cooperation of Program

- Allocation via the T pointer downwards.
- Any read operation of the program of a pointer-slot in the heap is trapped and causes invocation of the read barrier.
- Read barrier checks if pointer points to to-space.
- If yes – the read continues as usual.



Cooperation of Program

- Allocation via the T pointer downwards.
- Any read operation of the program of a pointer-slot in the heap is trapped and causes invocation of the read barrier.
- Read barrier checks if pointer points to to-space.
- If yes – the read continues as usual.
- If not – scan referred object: the referred object is copied into to-space (via pointer F), a forwarding pointer is set, and the pointer in the heap is updated. Only then the read operation continues.



Who Runs the Collector?

- Collector should make sufficient progress to prevent out-of-memory.
- A good collaboration: collect during each allocation.
- Program runs some collector code during allocation, length of time may be tuned.
- (Some more work by the read barrier.)

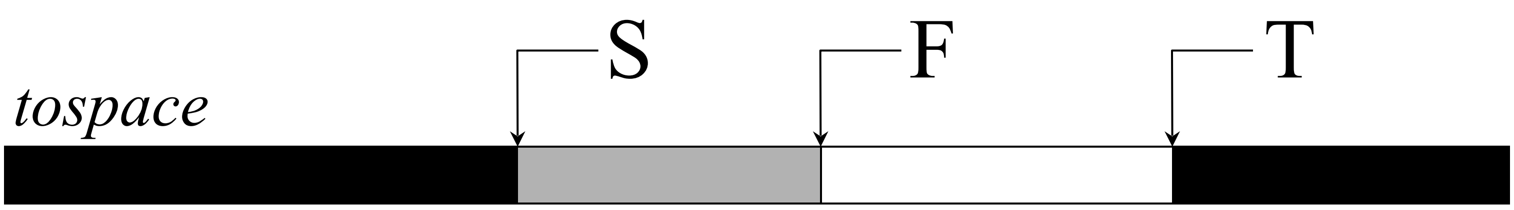
Making Enough Progress

- R = reachable space (to be traced) when collector starts.
- K = number of words scanned with allocation of each word.
- Copying terminates after R/k words are allocated.
- (New objects do not need to be traced.)
- Space required in to-space: $M \geq R(1+1/k)$.
- Tradeoff: small k ➜ short pauses, but larger heap.
- Given a program that has R live words, and if M is the size of a semi-space, we may set k to

$k \geq R/(M-R)$.

Allocation Failure

- If not enough space to allocate a new object, program switches from incremental mode to stop-the-world mode.
- Collector finishes the scan and a new incremental collection starts immediately.
- If there is no free space to finish the collection ? an out-of-memory exception.



Properties

- Good:
  - No long pauses
  - Garbage is collected when necessary (during new allocations).
- Bad:
  - Read barrier! (may add 30% to running time)
- Real time not fully obtained:
  - flipping (and scanning roots) time is not bounded.
  - Time for copying a large object is unbounded.
  - Maybe many short pauses occur frequently, not letting the program make any progress.

Replication Copying
Nettles and O'Toole [1992]

- A read barrier is too expensive, use a write barrier.
- Program threads access only from-space (white) objects.
- Copying is done "in the background".
- After copying completed, roots are modified to point to to-space replicas.

Replication Copying
Nettles and O'Toole [1992]

- A problem: program may modify from-space after a replica has been created in to-space.
- Solution: a write barrier.
- All modifications are recorded in a mutation-log.
- Collector applies modifications to to-space.
- Modifications to a data field are easily copied.
- Modifications to a pointer require care: pointer is in from-space.
- Collector checks if pointed object already copied.
- If yes – update the pointer.
- Otherwise – copy, set forwarding address, update pointer.

Termination

- Collection is complete when all objects in to-space are scanned and mutation log is empty.
- But, as the collector is incremental, mutation log keeps growing.
- When “not much” work is left, the collector is run alone to finish the scanning and mutation log.

Properties

- Good:
  - No long pauses
  - Write barrier instead of read-barrier
- Bad:
  - Each modification is done twice (and recorded)
  - An expensive write barrier – modern write barriers only trap pointer modifications.

Going on…

- We will get into more sophisticated incremental and concurrent collectors later in the course.

- But next we present a different type of solution for shortening pause times:
generational garbage collection.