Garbage Collection

Lecture Notes by Keith Schwarz

http://www.keithschwarz.com/cs143/WWW/sum2011/lectures/180_Garbage_Collection.pdf

Runtime Memory Management

- Most constructs in a programming language need memory.
- Some need a fixed amount of memory
  - *(such as?)*
- Some require a variable amount of memory:
  - Local variables
  - Objects
  - Arrays
  - Strings

Memory Management So Far

- Some memory is preallocated and persists throughout the program:
  - Global variables, virtual function tables, executable code, etc.
- Some memory is allocated on the runtime stack:
  - Local variables, parameters, temporaries.
- Some memory is allocated in the heap:
  - Arrays, objects.
- Memory management for the first two is trivial.
- How do we manage heap-allocated memory?

Manual Memory Management

- **Option One:** Have the programmer handle allocation and deallocation of dynamic memory.
- Approach used in C, C++.
- Advantages:
  - Programmer can exercise precise control over memory usage.
- Disadvantages:
  - Programmer **has to** exercise precise control over memory usage.

Strengths of Manual Management

- Comparatively easy to implement.
  - “Just” need a working memory manager.
- Allows programmers to make aggressive performance optimizations.
  - Programmer can choose allocation scheme that achieves best performance.

Problems with Manual Management

- Easily leads to troublesome bugs:
  - **Memory leaks** where resources are never freed.
  - **Double frees** where a resource is freed twice (major security risk).
  - **Use-after-frees** where a deallocated resource is still used (major security risk).
- Programming languages with manual memory management are almost always not type-safe.

Automatic Memory Management

- **Idea:** Have the runtime environment automatically reclaim memory.
- Objects that won't be used again are called **garbage**.
- Reclaiming garbage objects automatically is called **garbage collection**.
- Advantages:
  - Programmer doesn't have to reclaim unused resources.
- Disadvantages:
  - Programmer **can't** reclaim unused resources.

Preliminaries

What is Garbage?

- An object is called **garbage** at some point during execution if it will never be used again.
- What is garbage at the indicated points?

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```
int main() {
    Object x, y;
    x = new Object();
    y = new Object();
    /* Point A */

    x.doSomething();
    y.doSomething();
    /* Point B */

    y = new Object();
    /* Point C */
}
```

Approximating Garbage

- In general, it is **undecidable** whether an object is garbage.
  - Need to rely on a conservative approximation.
- An object is **reachable** if it can still be referenced by the program.
  - Goal for today: detect and reclaim unreachable objects.
- This does not prevent memory leaks!
  - Many reachable objects are never used again.
  - It is **very easy** to have memory leaks in garbage-collected languages.
- Interesting read: “Low-Overhead Memory Leak Detection Using Adaptive Statistical Profiling” by Chilimbi and Hauswirth.

Assumptions for Today

- Assume that, at runtime, we can find all existing references in the program.
  - Cannot fabricate a reference to an existing object *ex nihilo*.
  - Cannot cast pointers to integers or vice-versa.
- Examples: Java, Python, JavaScript, PHP, etc.
- Non-examples: C, C++
- Advance knowledge of references allows for precise introspection at runtime.

Types of Garbage Collectors

- Incremental vs stop-the-world:
  - An **incremental** collector is one that runs concurrently with the program.
  - A **stop-the-world** collector pauses program execution to look for garbage.
  - Which is (generally) more precise?
  - Which would you use in a nuclear reactor control system?
- Compacting vs non-compacting:
  - A **compacting** collector is one that moves objects around in memory.
  - A **non-compacting** collector is one that leaves all objects where they originated.
  - Which (generally) spends more time garbage collecting?
  - Which (generally) leads to faster program execution?

Reference Counting

Reference Counting

- A simple framework for garbage collection.
  - Though it has several serious weaknesses!
- Idea: Store in each object a **reference count** (**refcount**) tracking how many references exist to the object.
- Creating a reference to an object increments its refcount.
- Removing a reference to an object decrements its refcount.
- When an object has zero refcount, it is unreachable and can be reclaimed.
  - This might decrease other objects' counts and trigger more reclamations.

Reference Counting in Action

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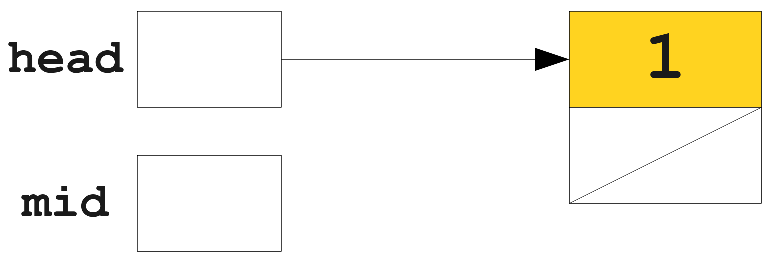

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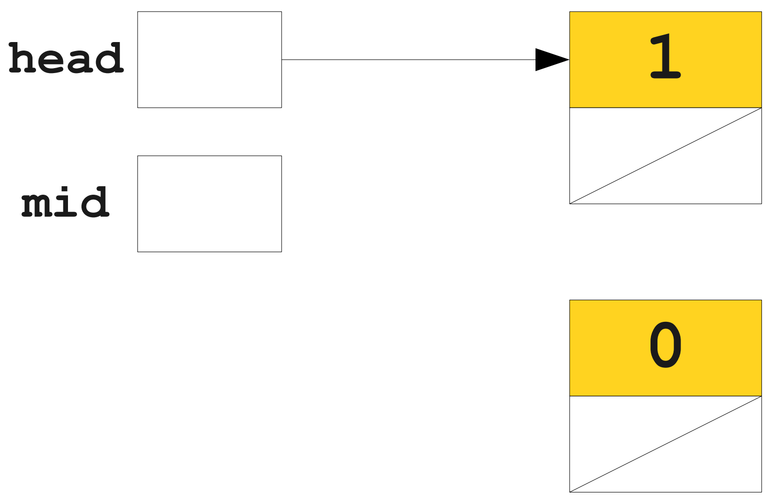

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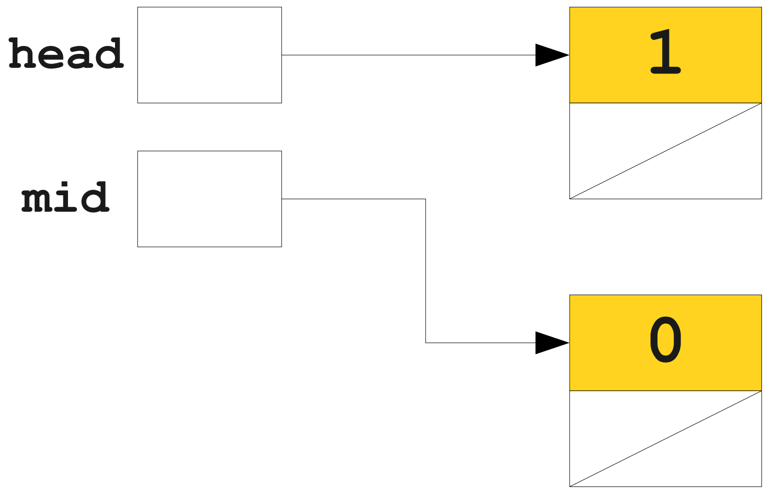

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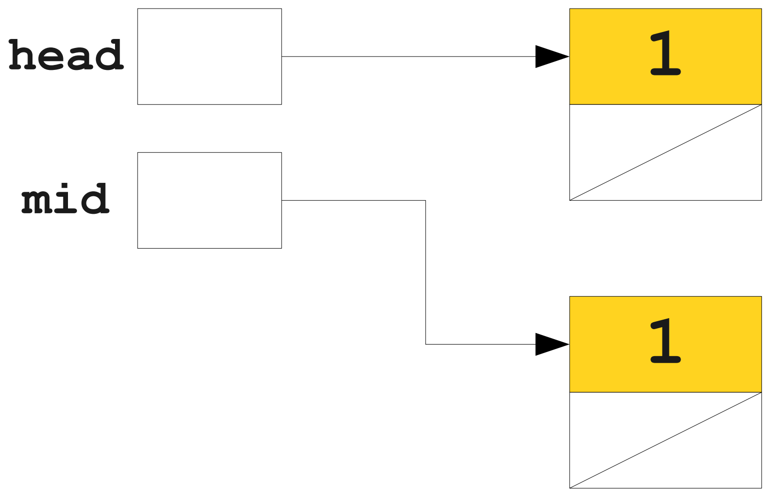

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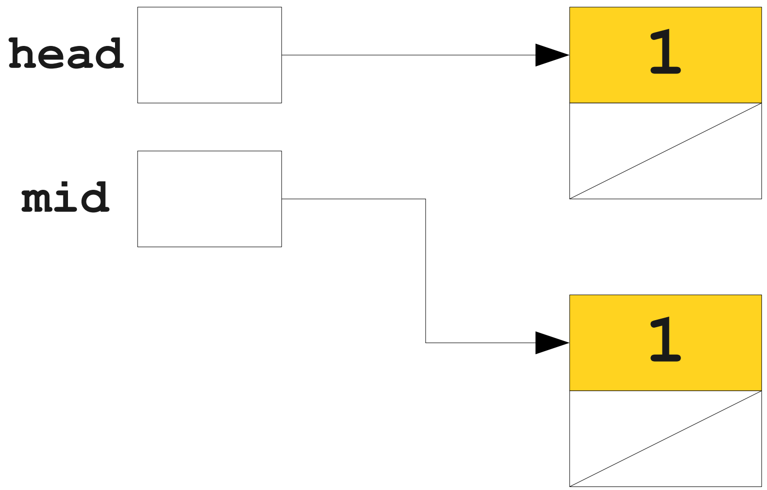

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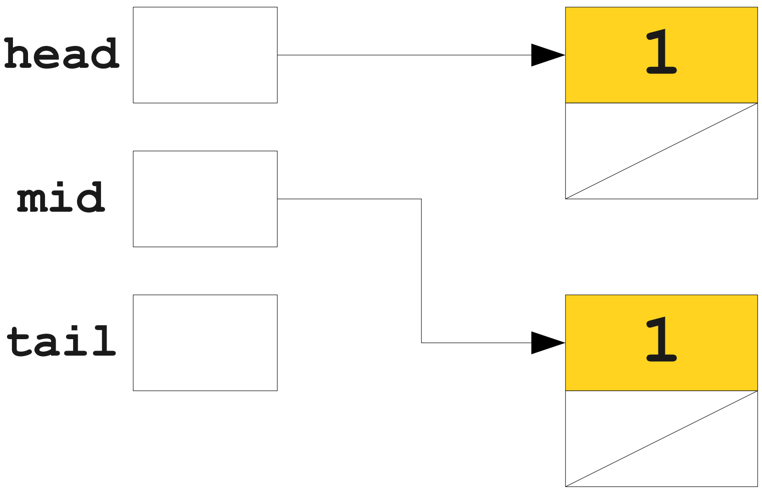

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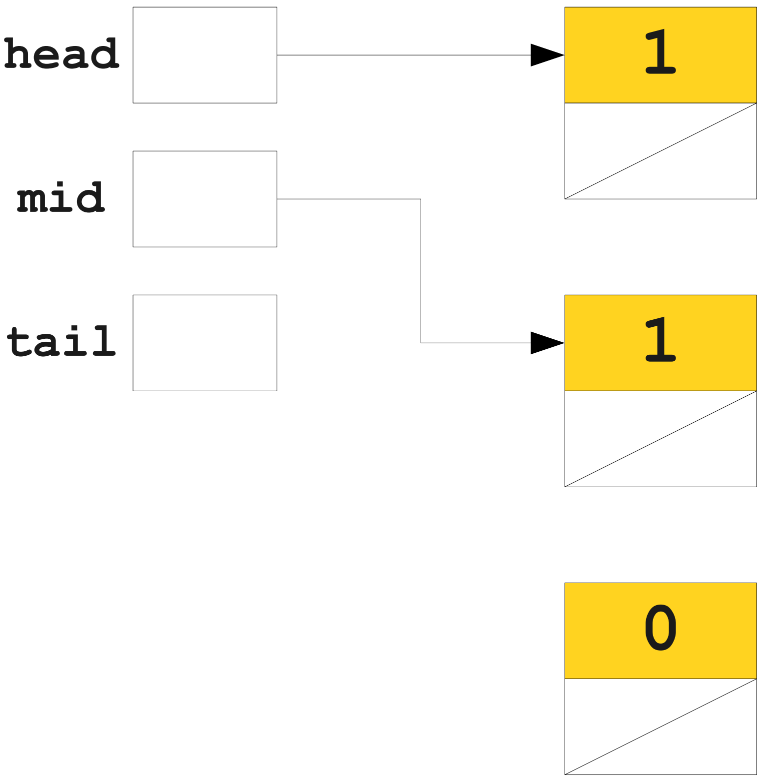

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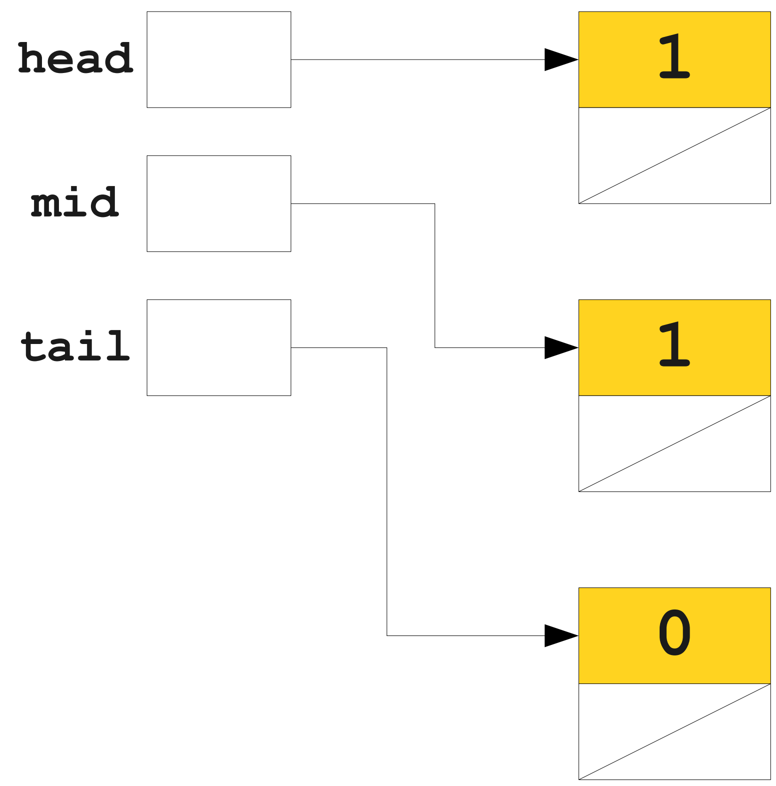

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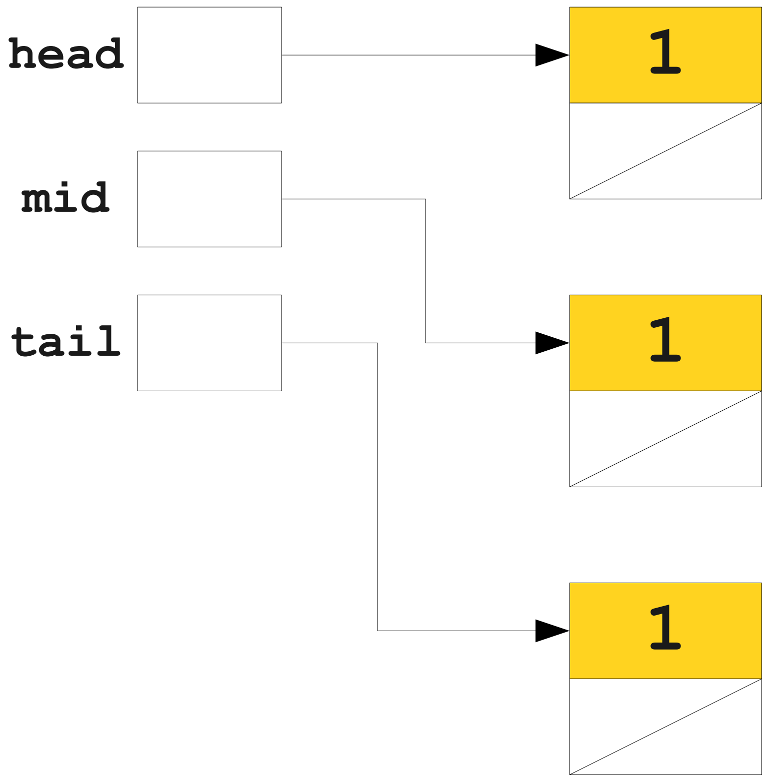

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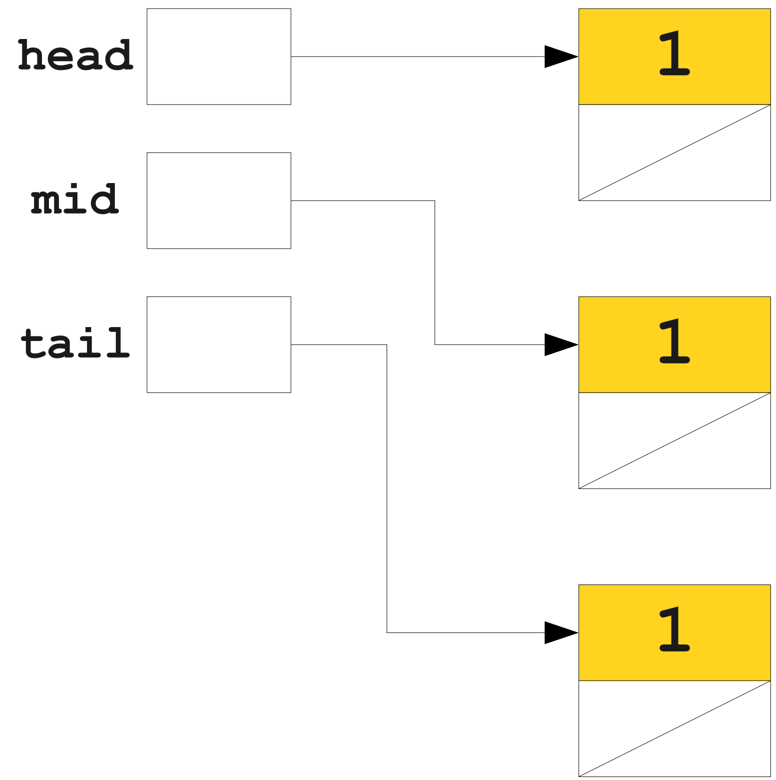

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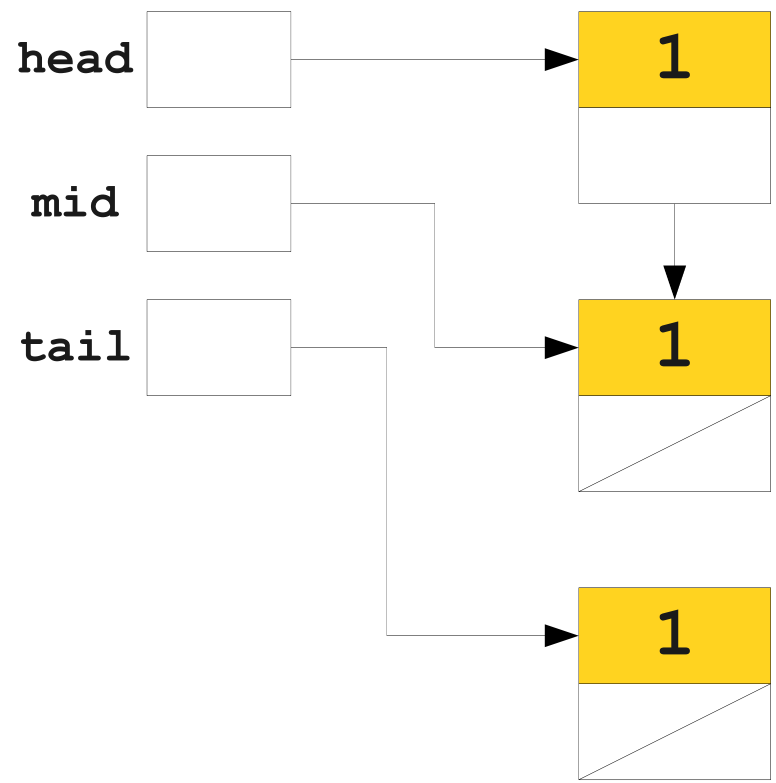

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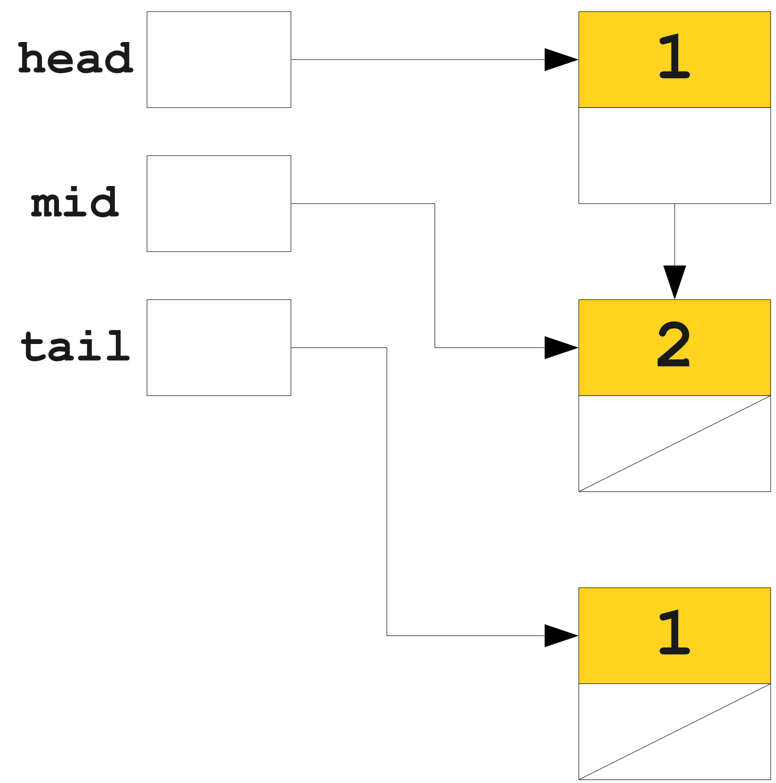

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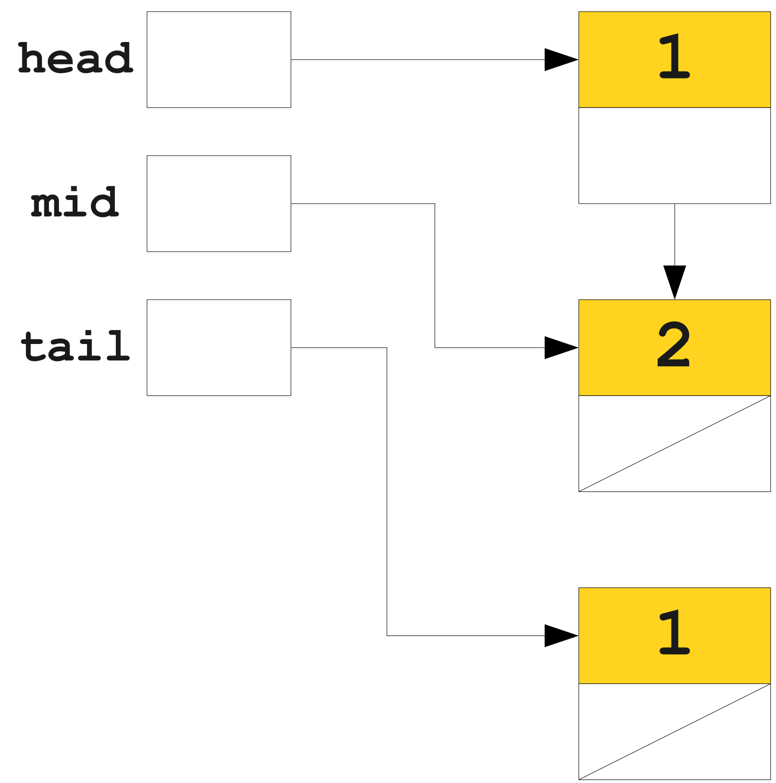

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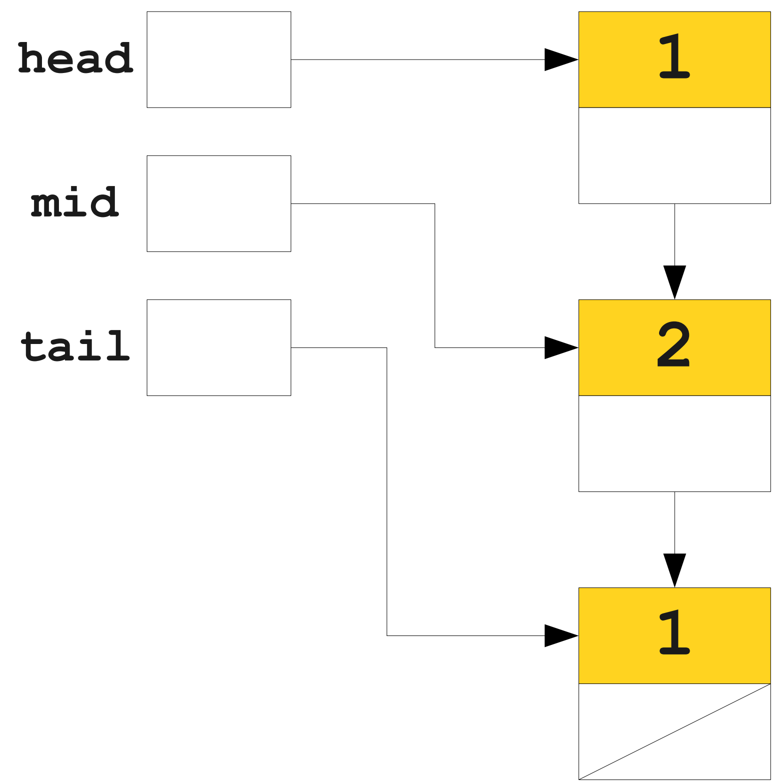

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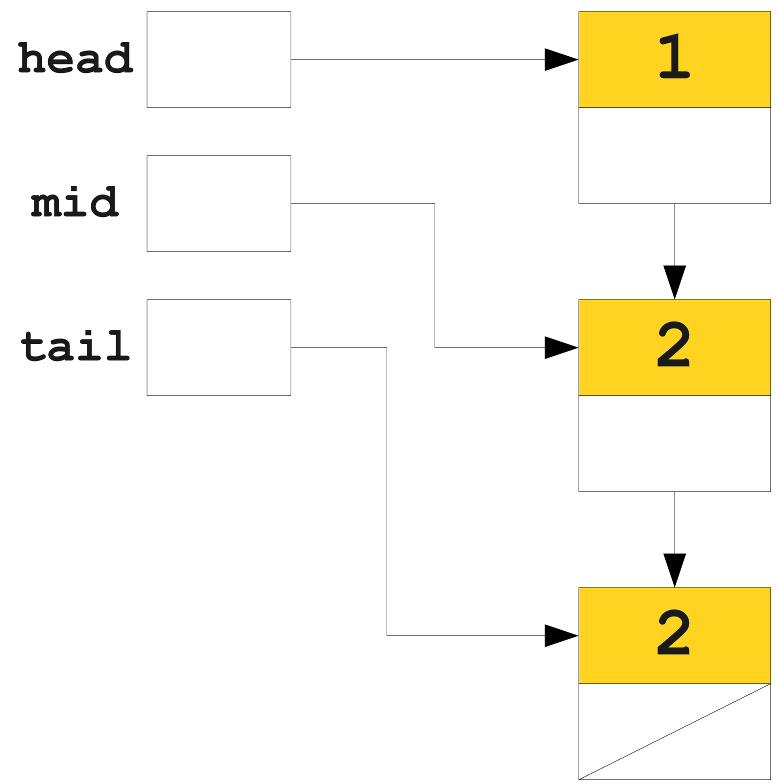

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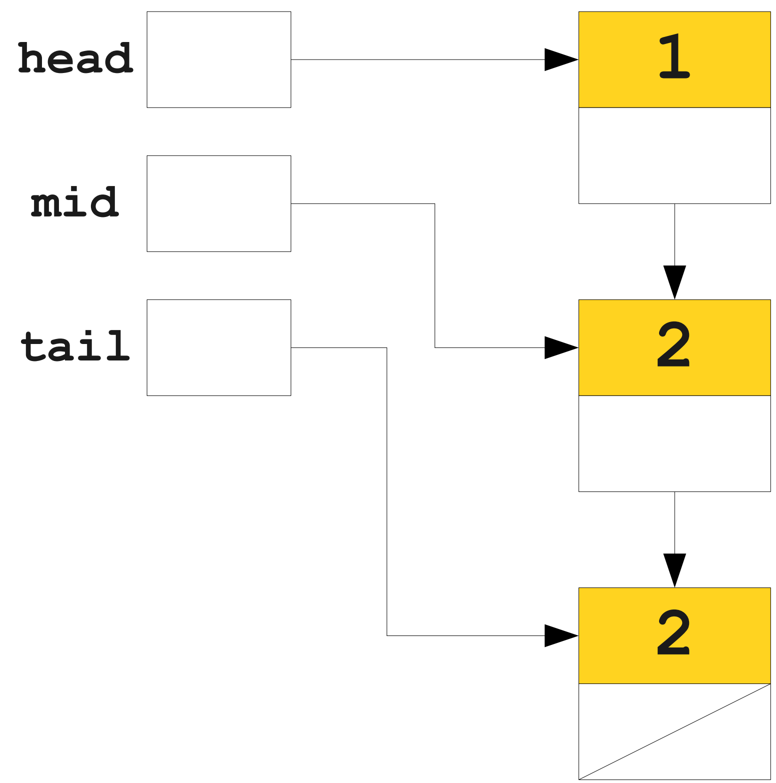

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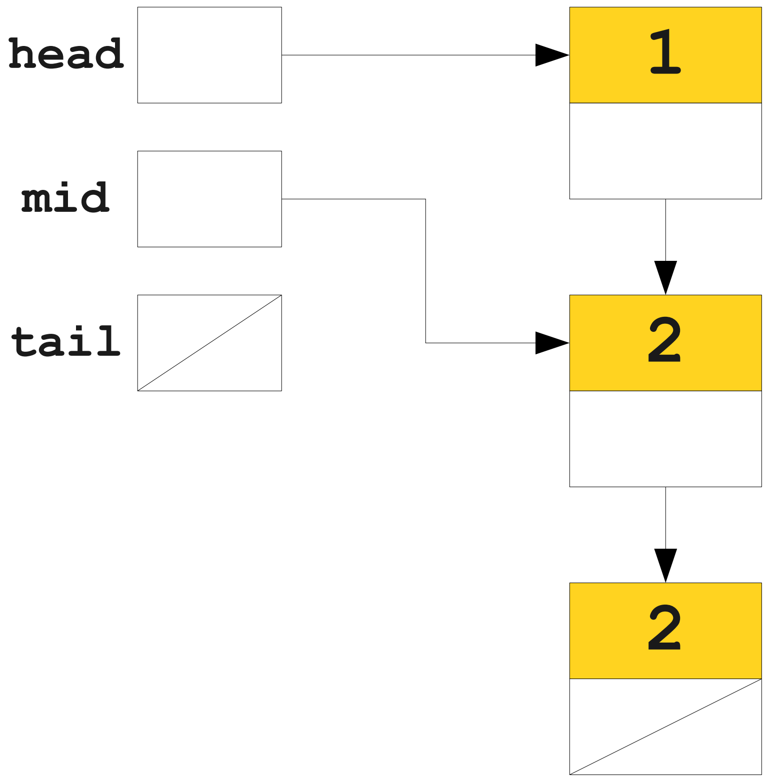

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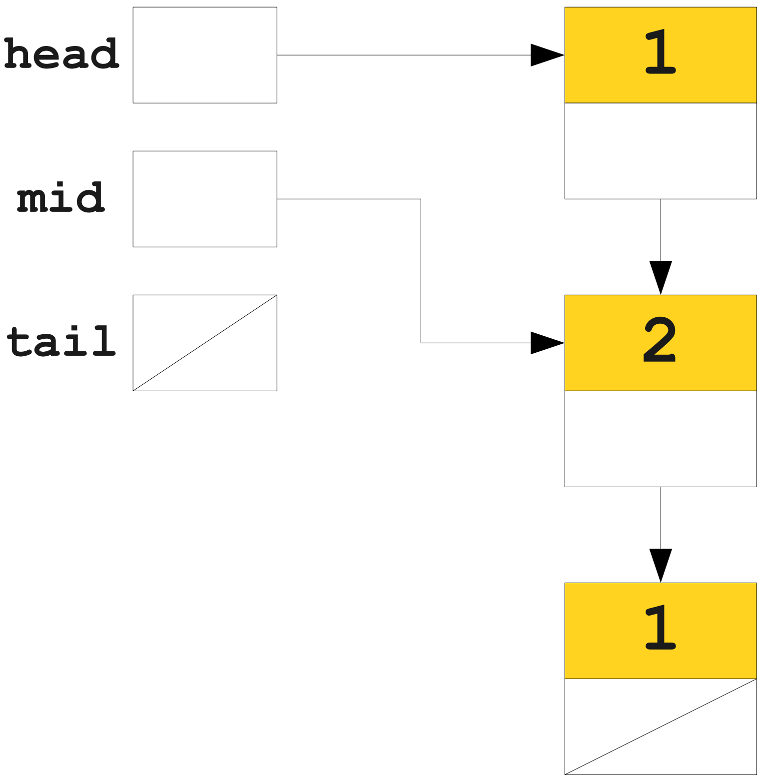

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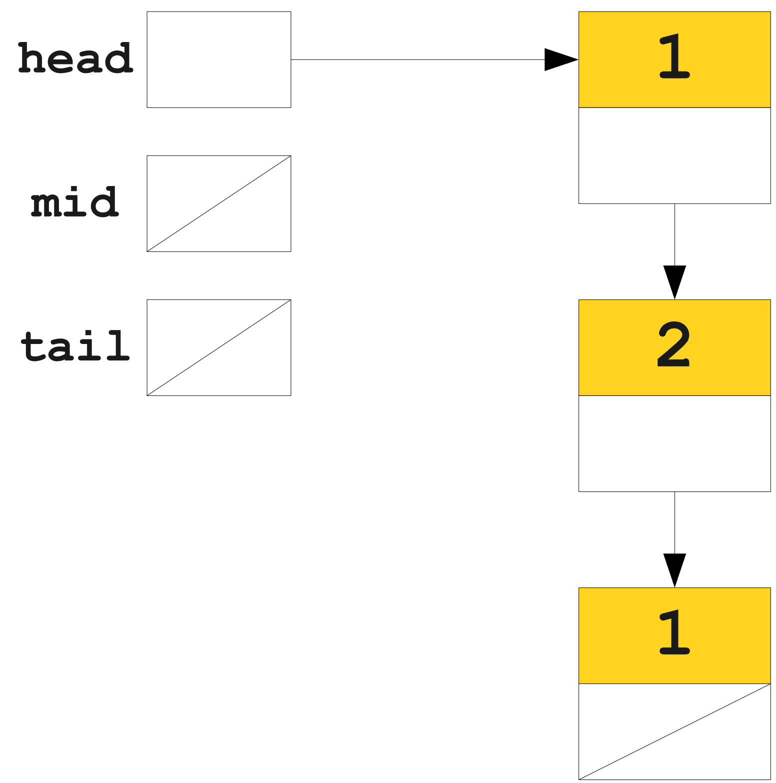

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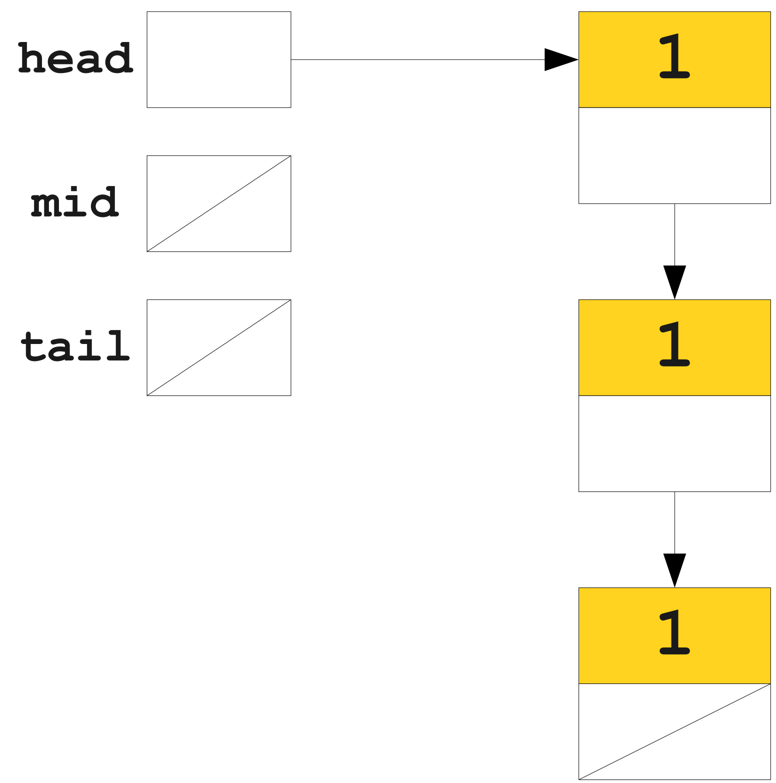

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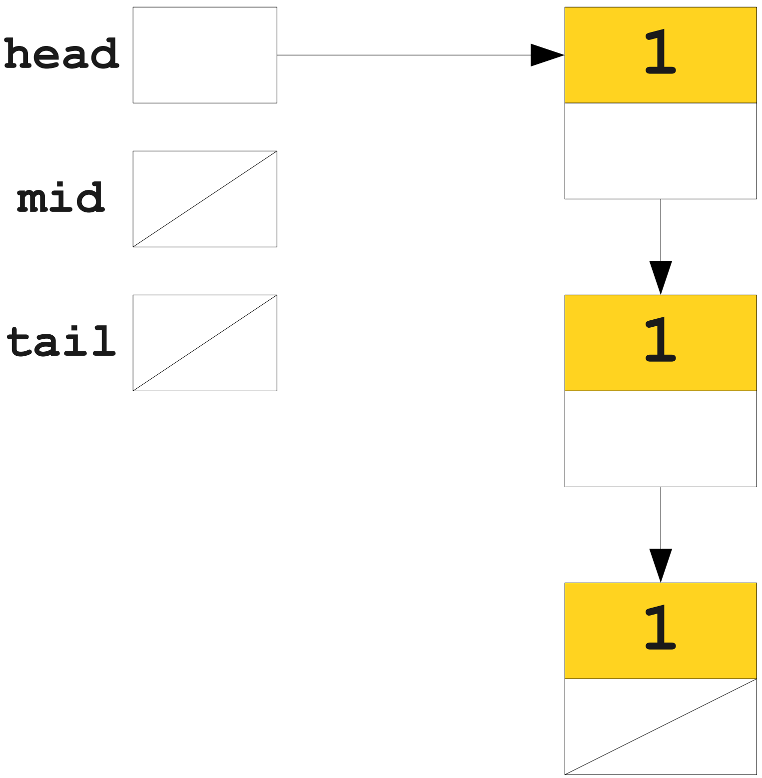

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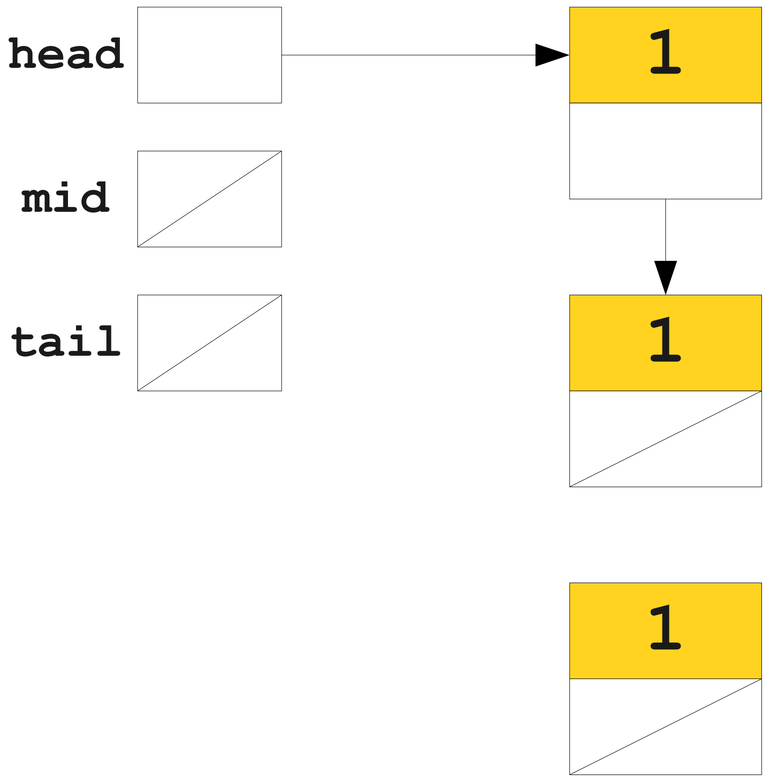

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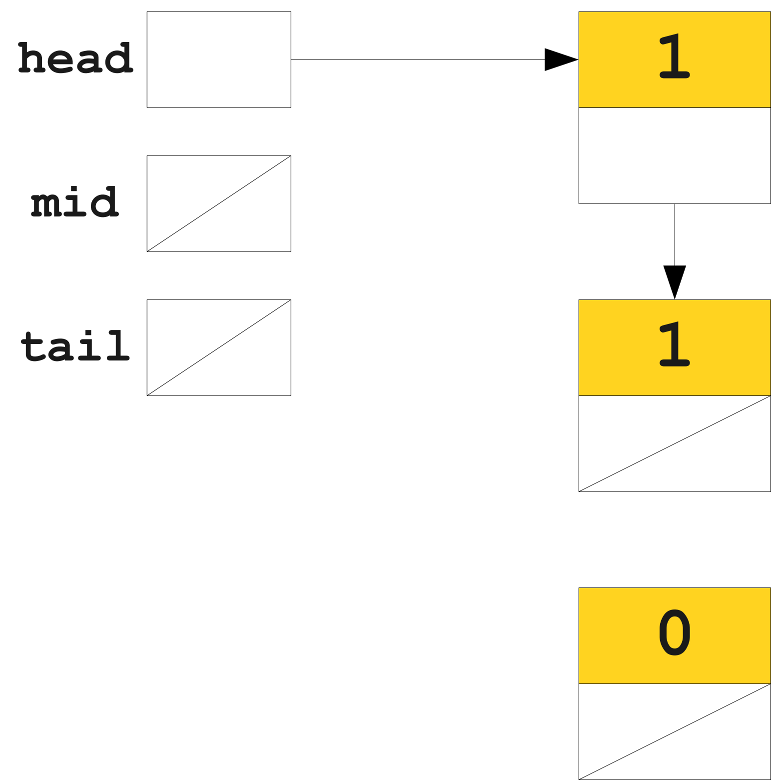

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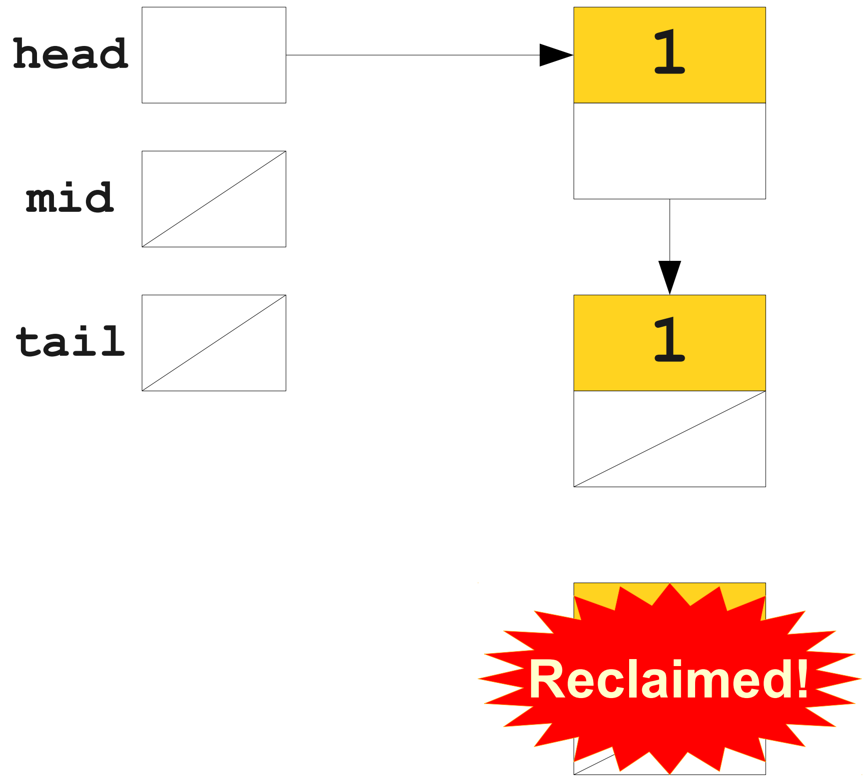

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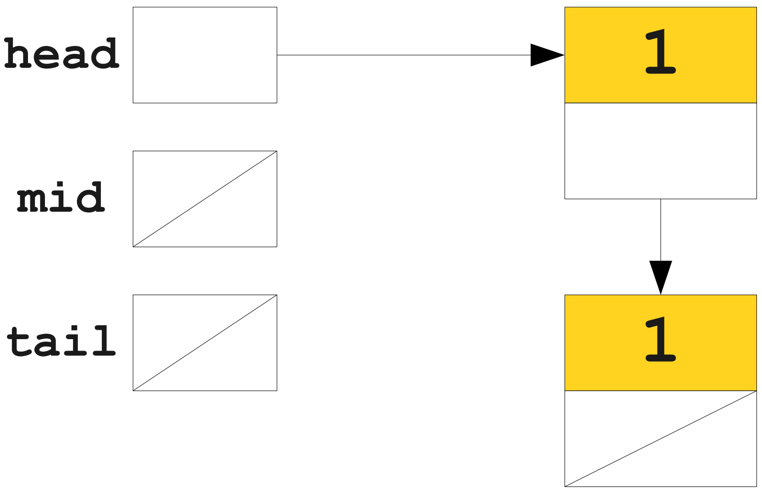

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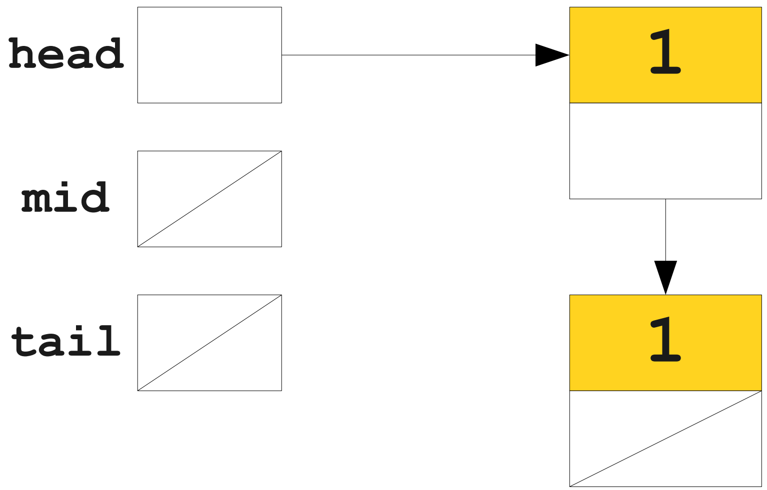

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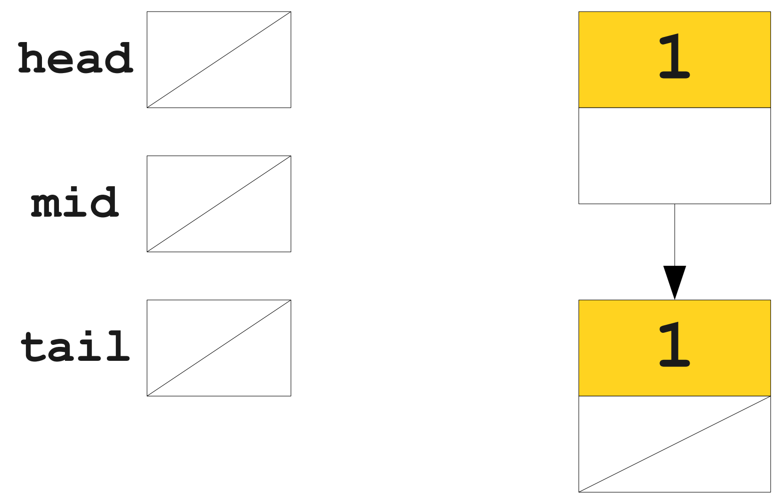

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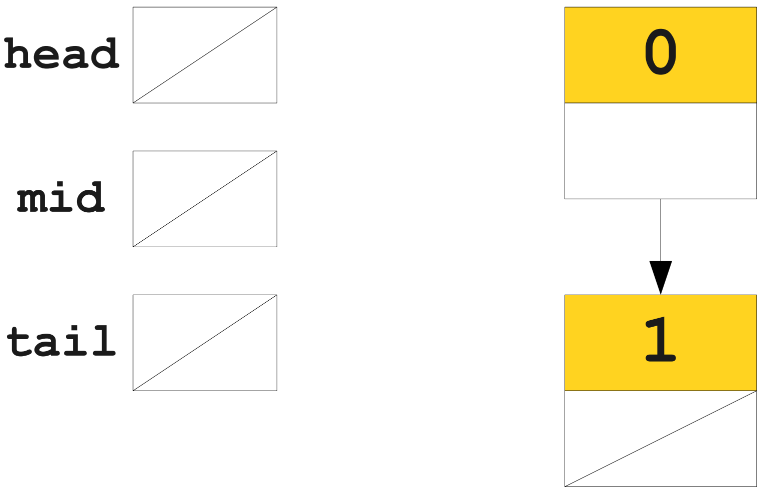

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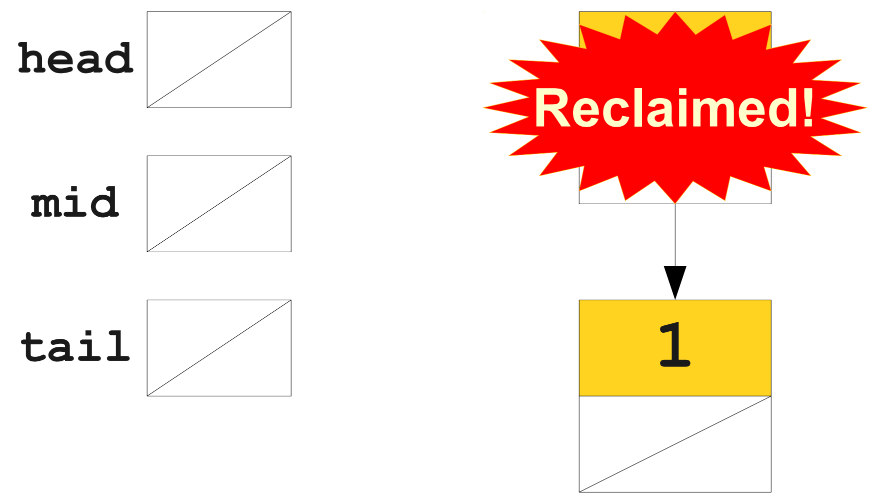

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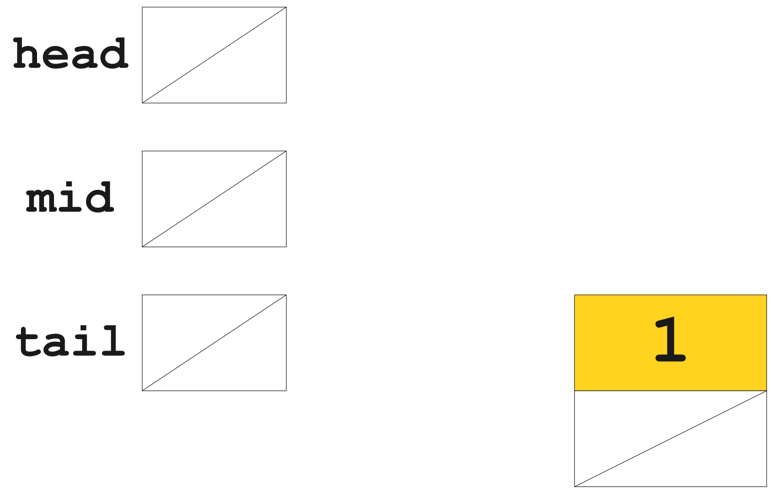

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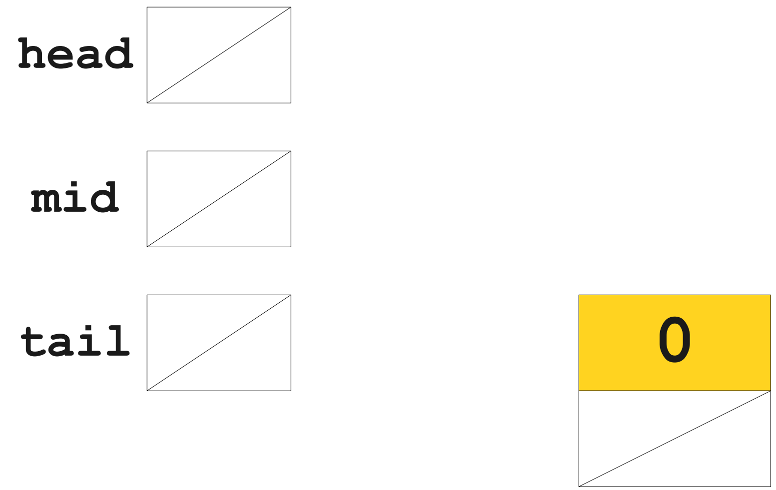

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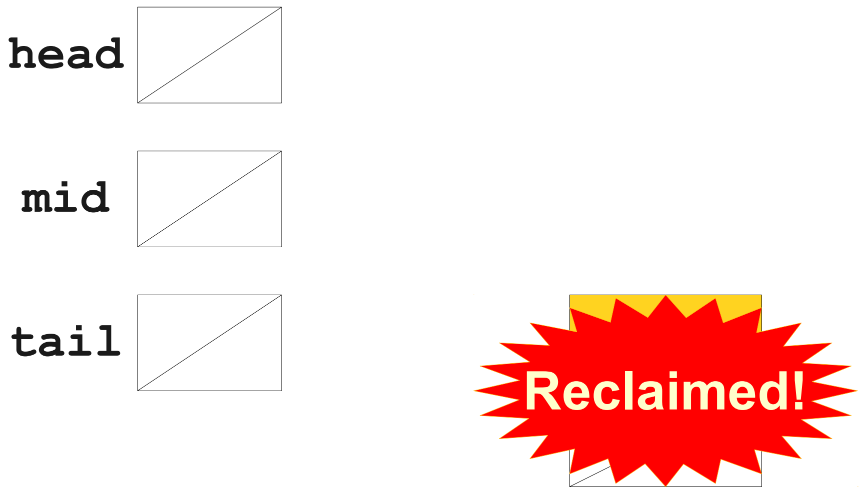

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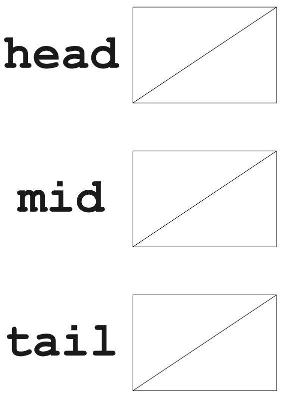

Reference Counting Details

- When creating an object, set its refcount to 0.
- When creating a reference to an object, increment its refcount.
- When removing a reference from an object:
  - Decrement its refcount.
  - If its refcount is zero:
    - Remove all outgoing references from that object.
    - Reclaim the memory for that object.

One Major Problem

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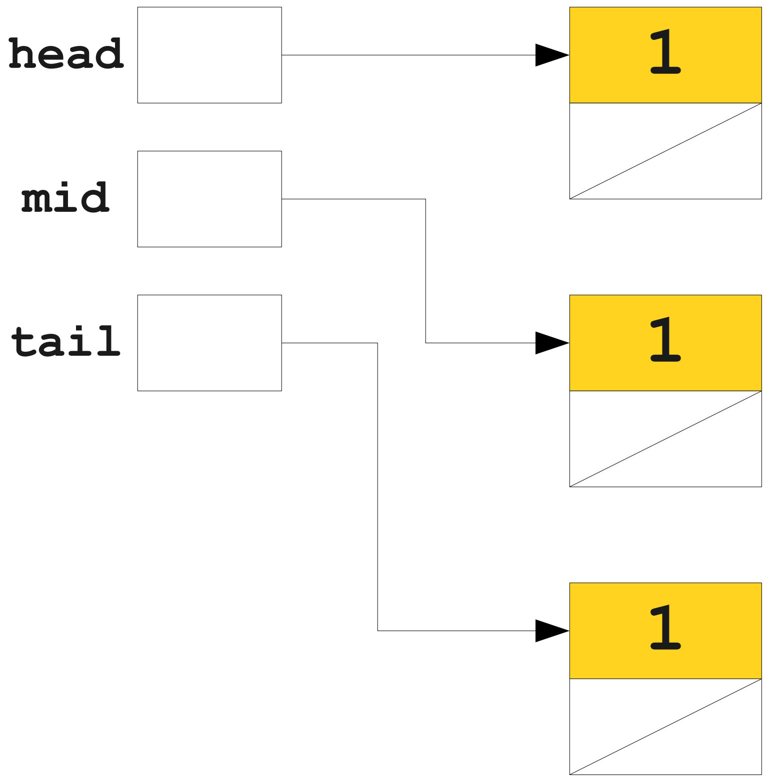

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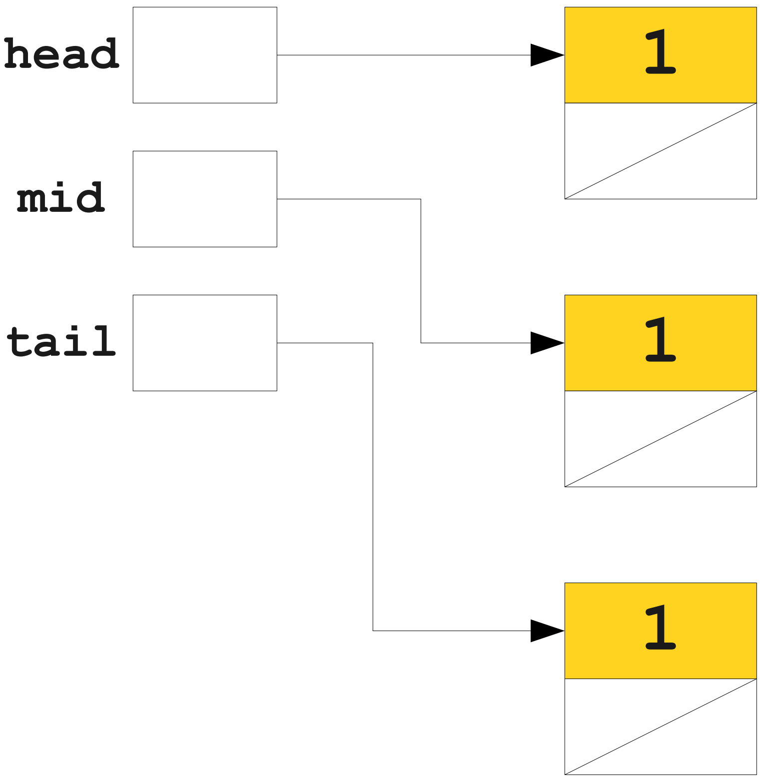

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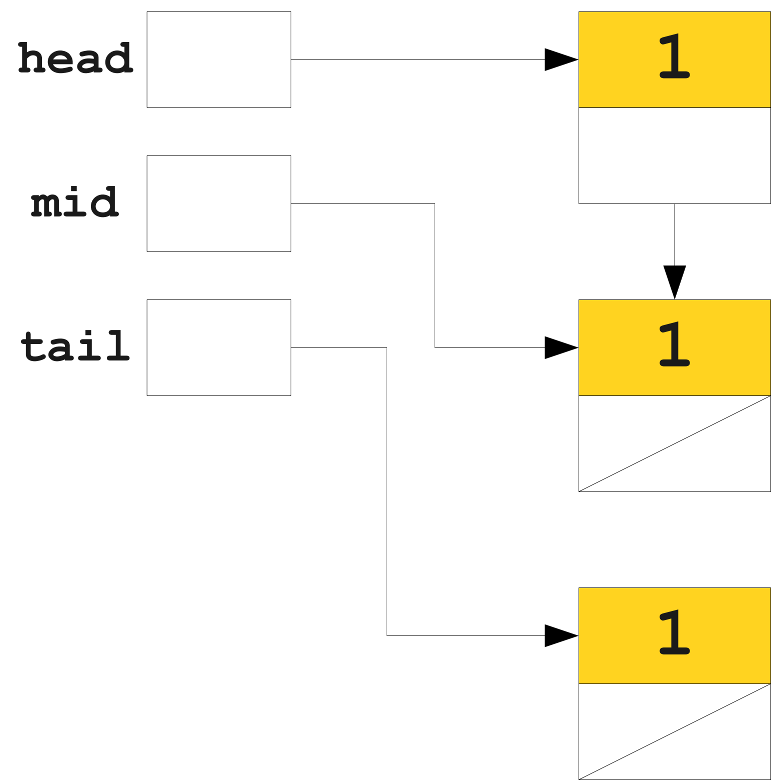

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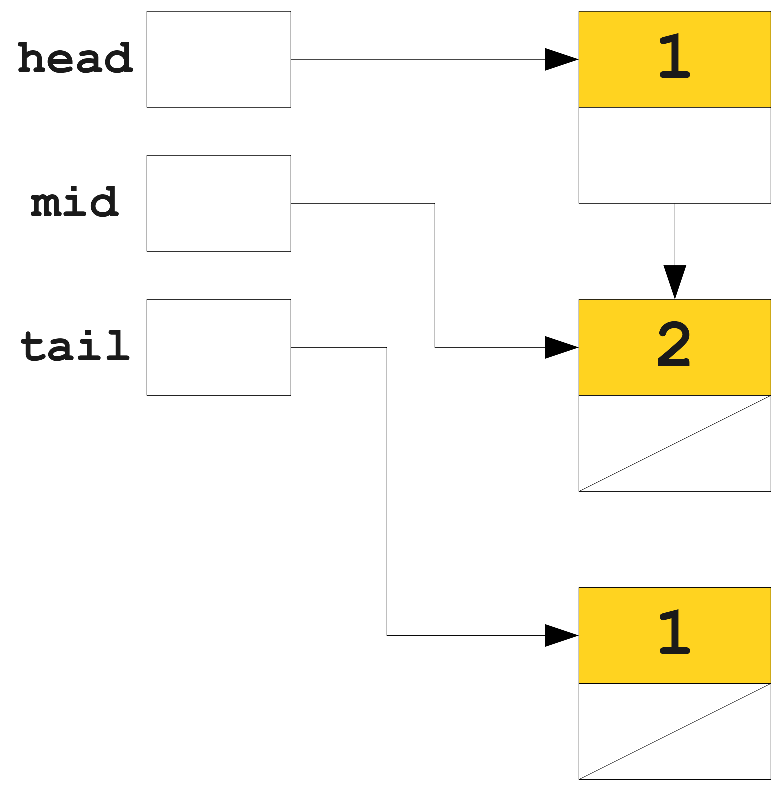

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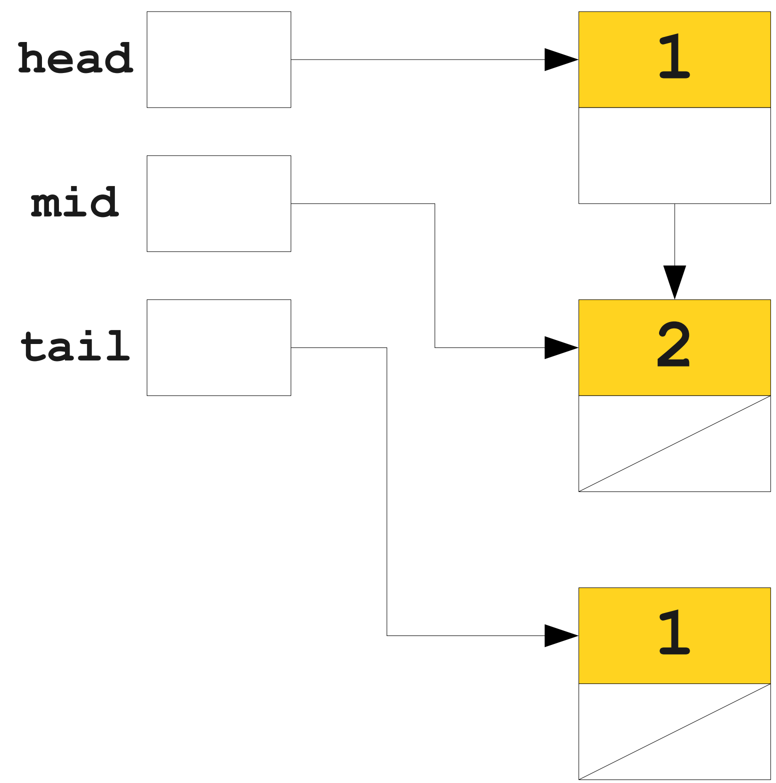

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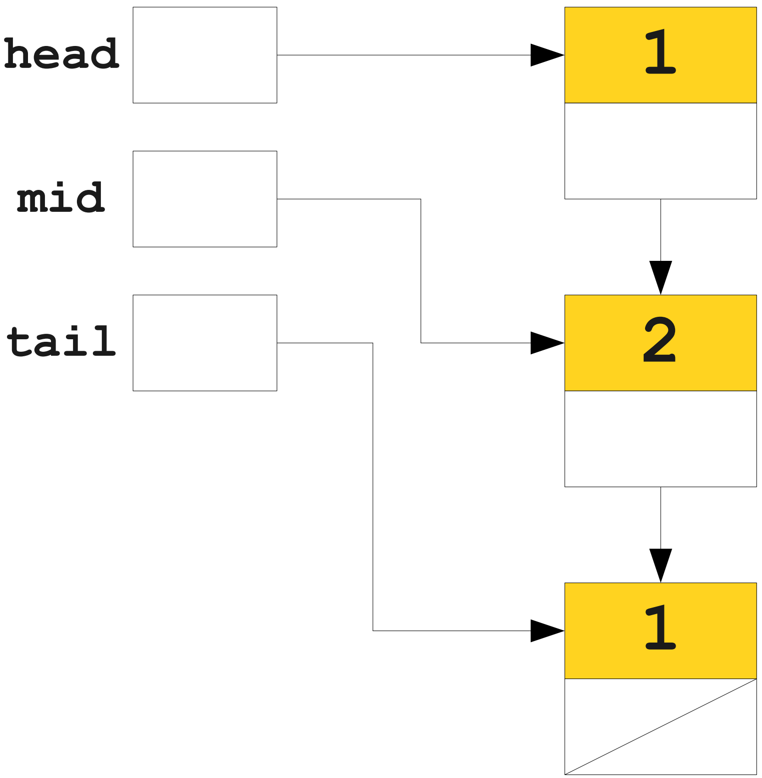

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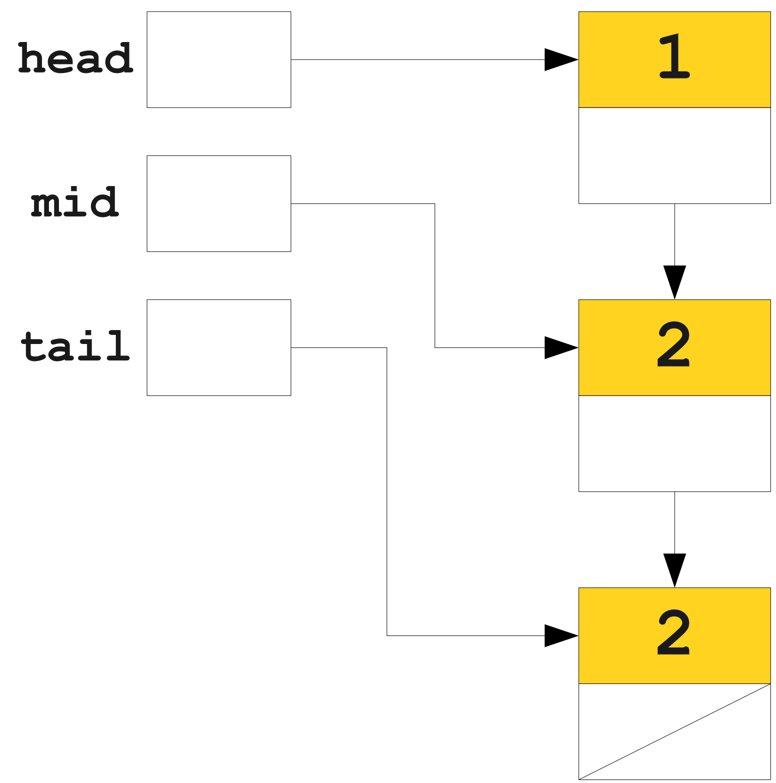

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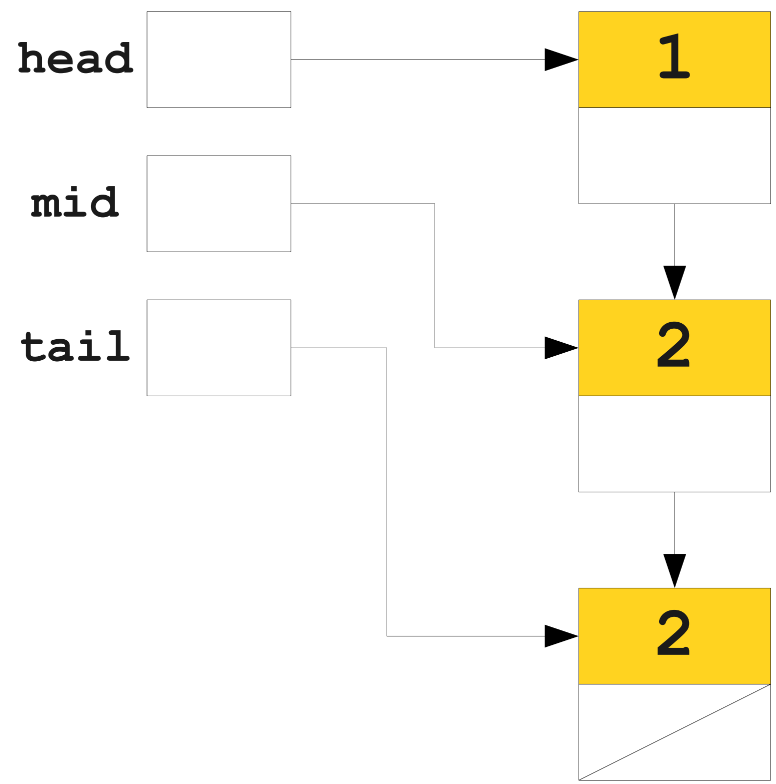

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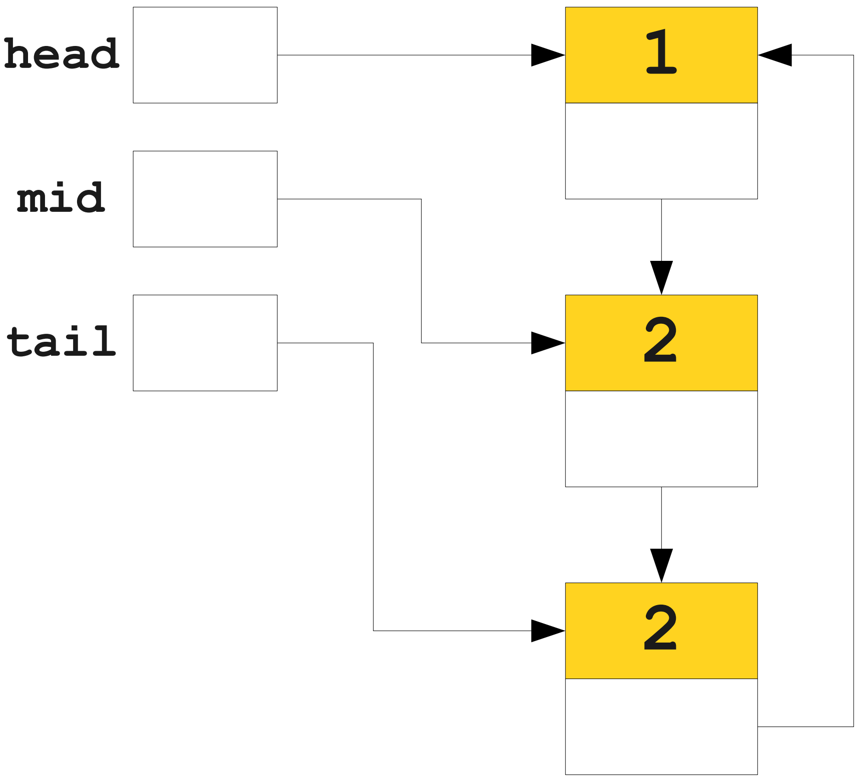

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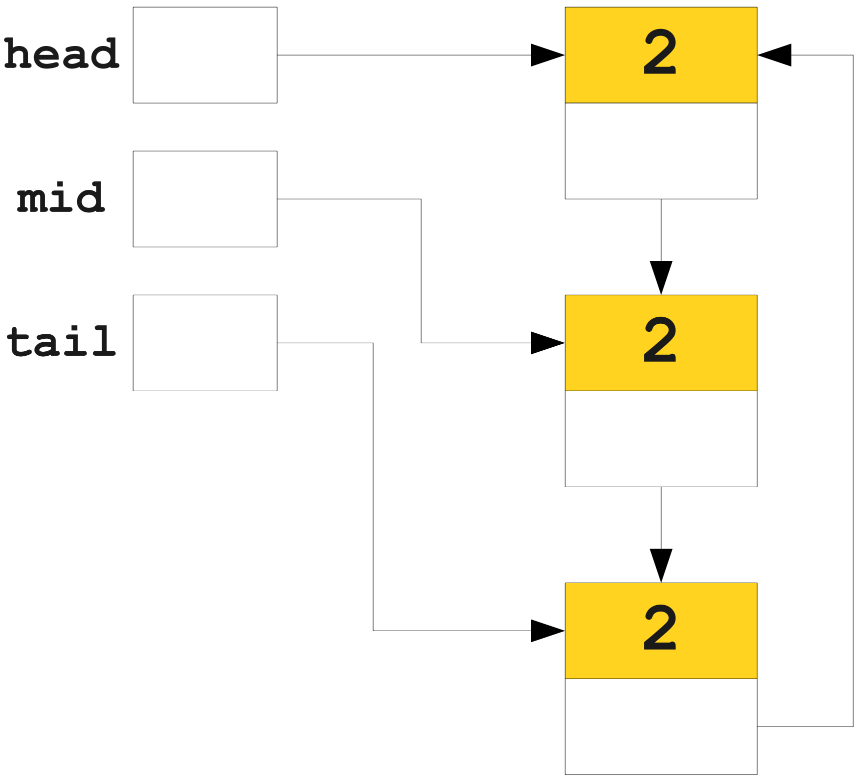

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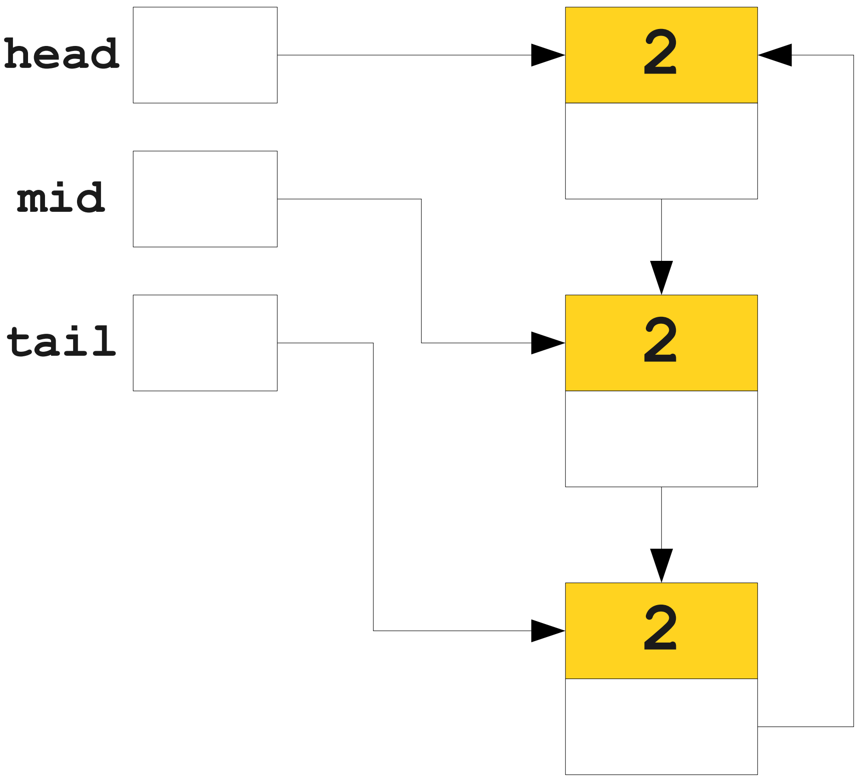

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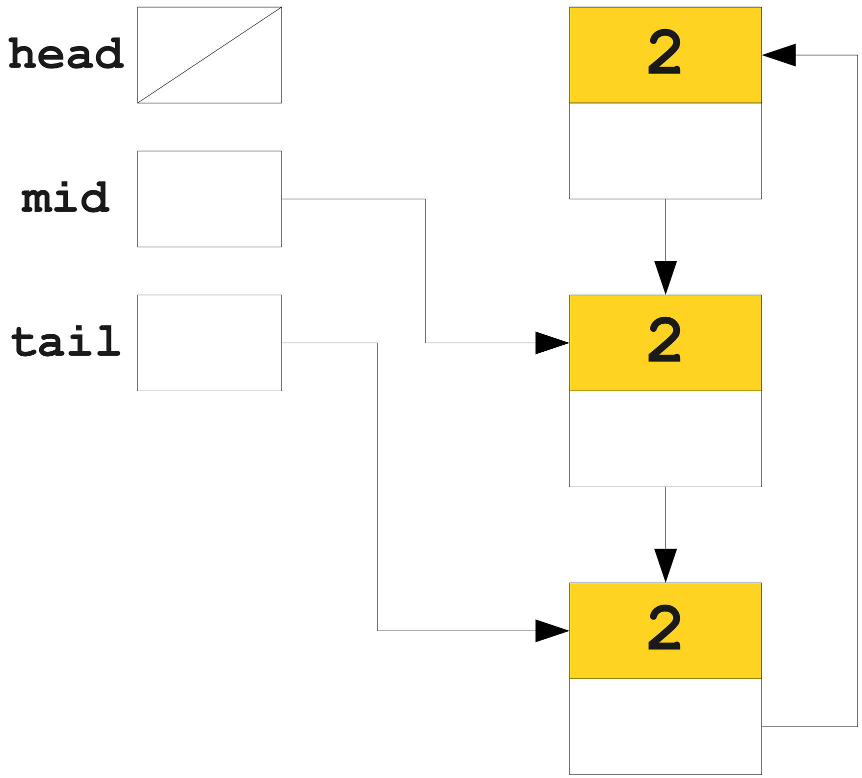

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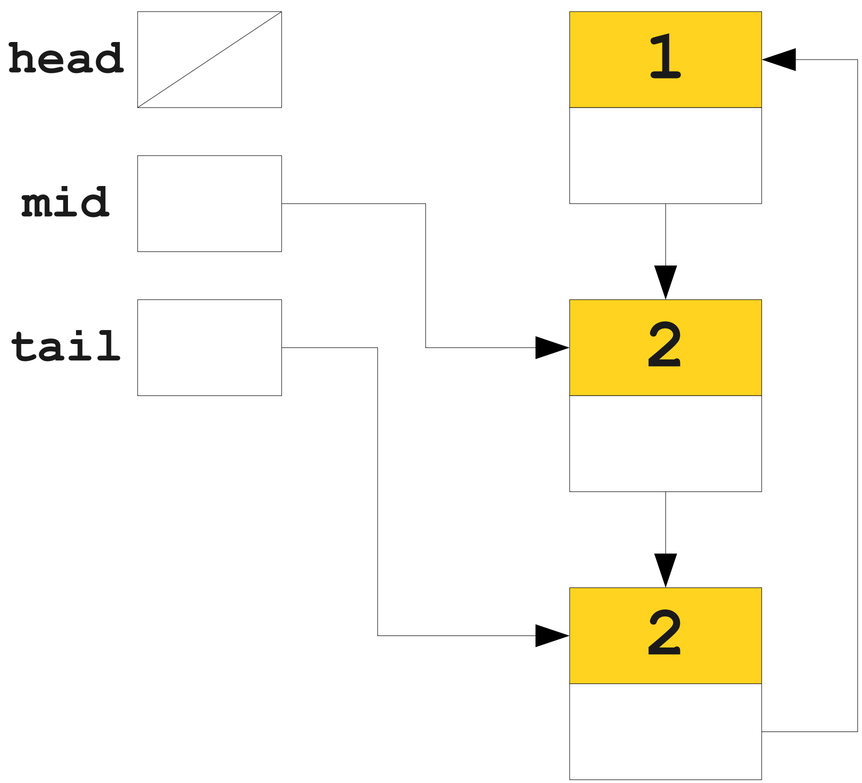

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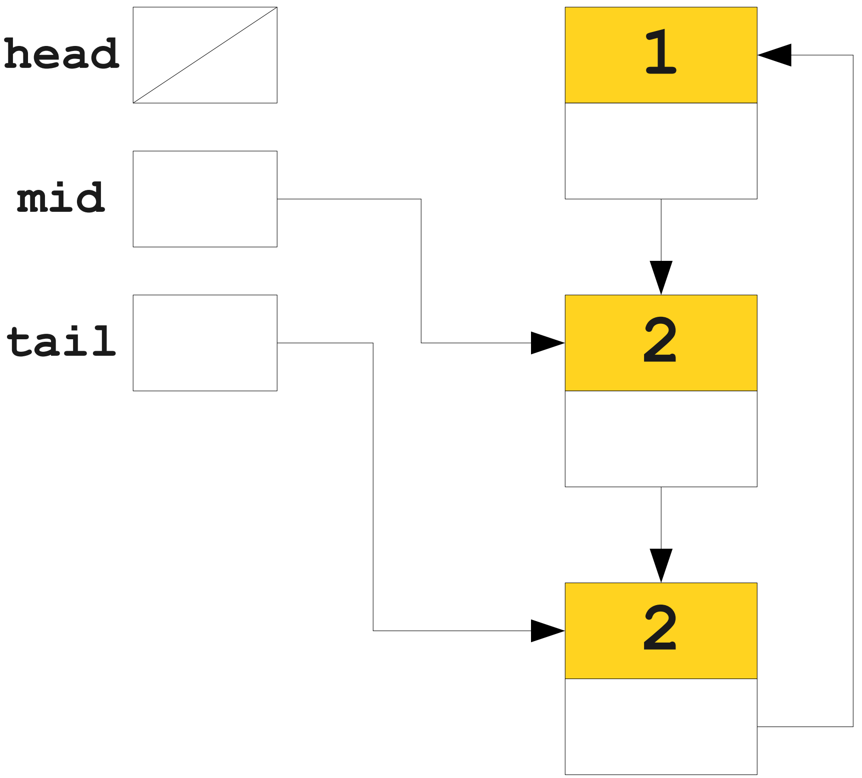

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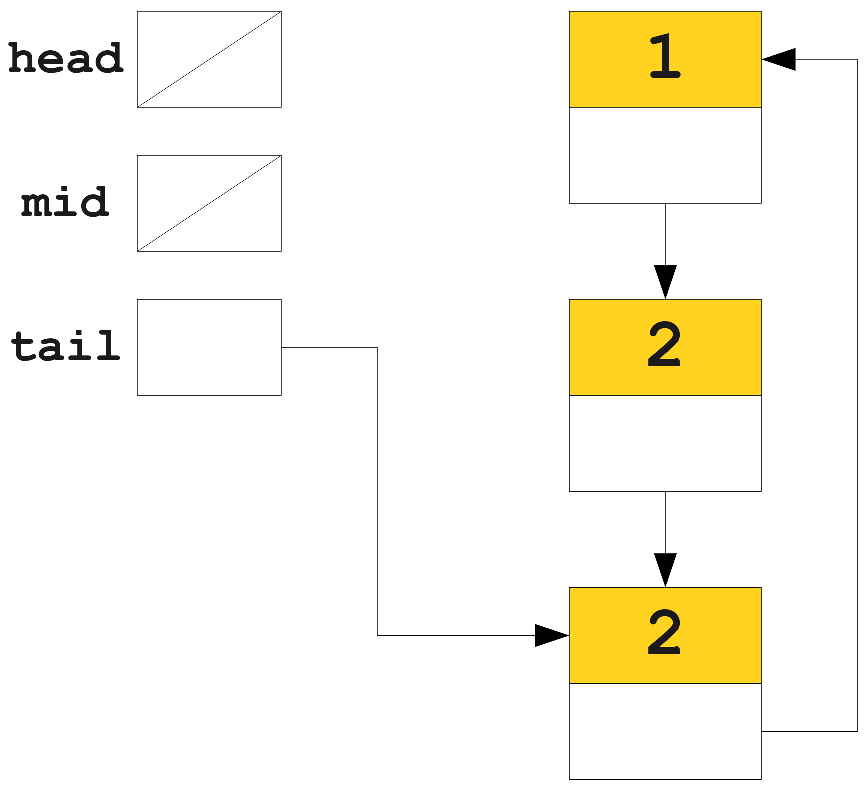

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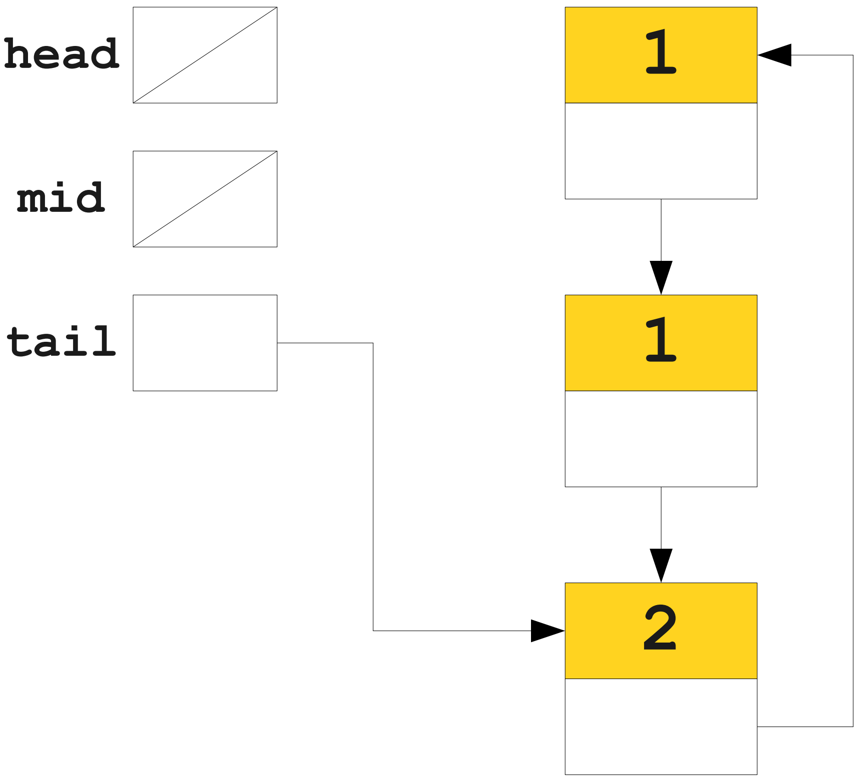

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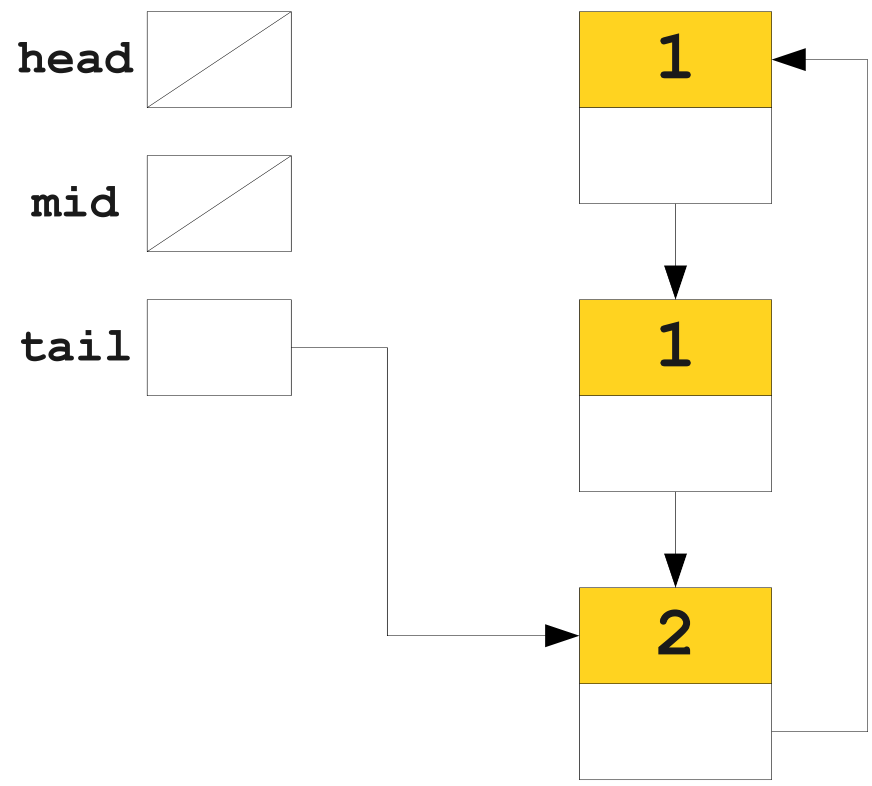

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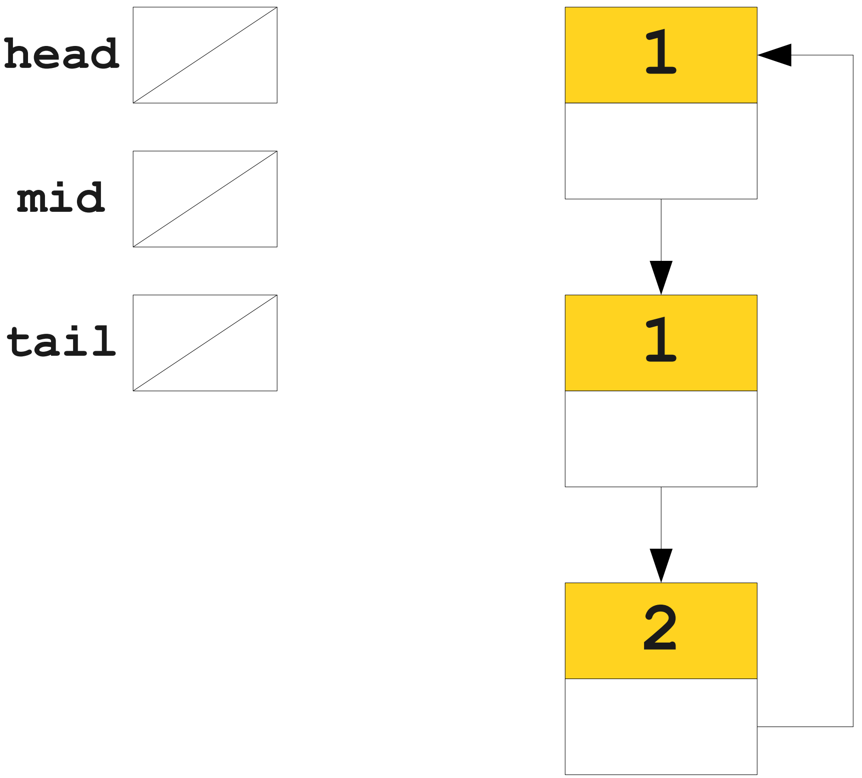

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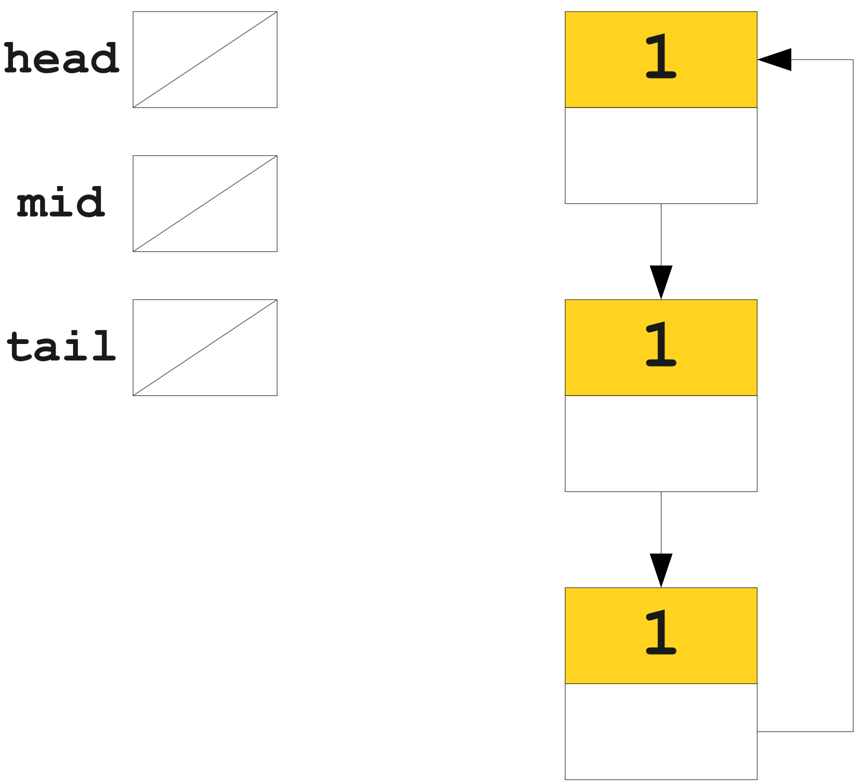

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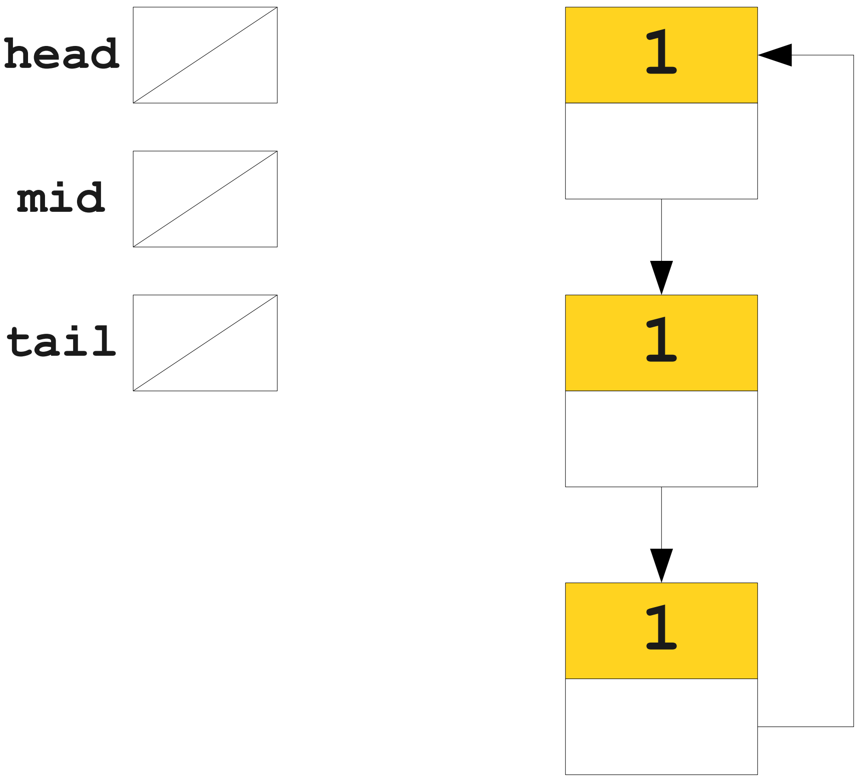

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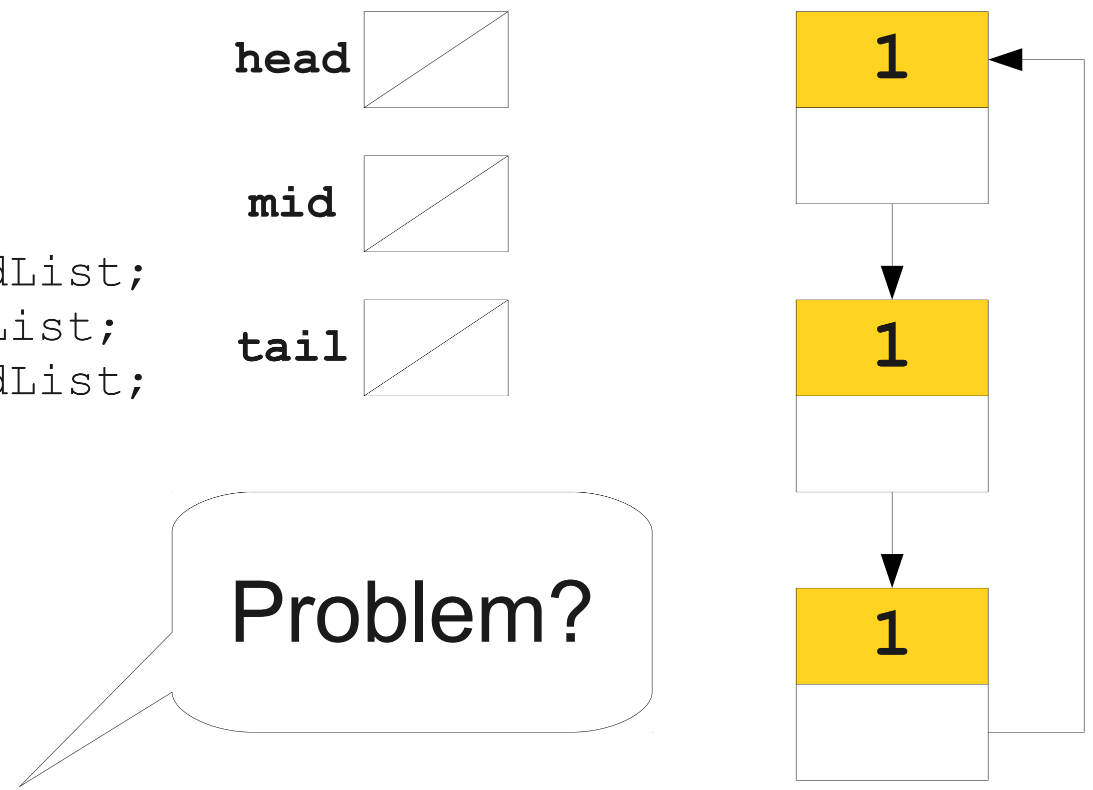


Reference Cycles

- A **reference cycle** is a set of objects that cyclically refer to one another.
- Because all the objects are referenced, all have nonzero refcounts and are never reclaimed.
- Issue: Refcount tracks number of references, not number of *reachable* references.
- Major problems in languages/systems that use reference counting:
  - e.g. Perl, Firefox 2.

Analysis of Reference Counting

- Advantages:
  - Simple to implement.
  - Can be implemented as a library on top of explicit memory management (see C++ **`shared_ptr`**).
- Disadvantages:
  - Fails to reclaim all unreachable objects.
  - Can be slow if a large collection is initiated.
  - Noticeably slows down assignments.

Mark-and-Sweep

Reachability Revisited

- Recall that the goal of our garbage collector is to reclaim all unreachable objects.
- Reference counting tries to find unreachable objects by finding objects with no incoming references.
- Imprecise because we forget **which** references those are.

Mark-and-Sweep: The Intuition

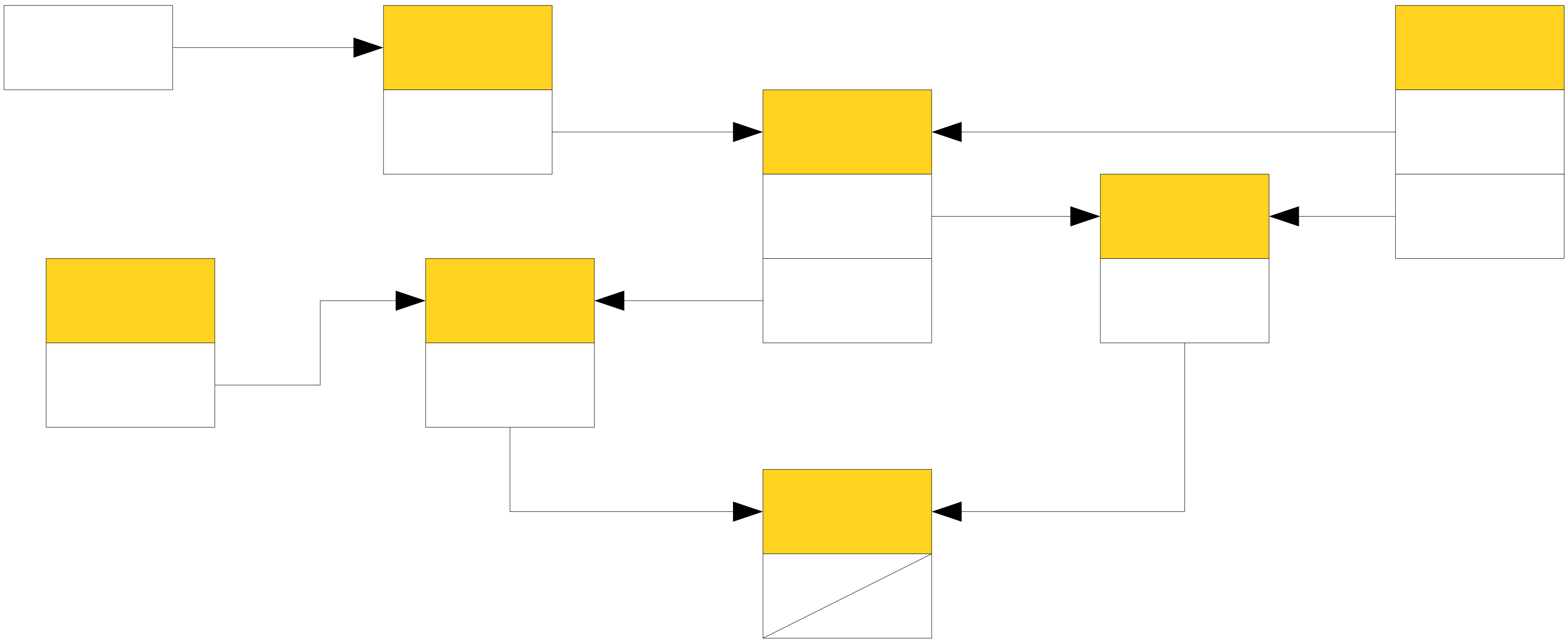
- **Intuition**: Given knowledge of what's immediately accessible, find everything reachable in the program.
- The **root set** is the set of memory locations in the program that are known to be reachable.
  - such as?
- Any objects reachable from the root set are reachable.
- Any objects not reachable from the root set are not reachable.
- Do a **graph search** starting at the root set!

Mark-and-Sweep: The Algorithm

- Mark-and-sweep runs in two phases.
- **Marking phase**: Find reachable objects.
  - Add the root set to a worklist.
  - While the worklist isn't empty:
    - Remove an object from the worklist.
    - If it is not **marked**, mark it and add to the worklist all objects reachable from that object.
- **Sweeping phase**: Reclaim free memory.
  - For each allocated object:
    - If that object isn't **marked**, reclaim its memory.
    - If the object is marked, **unmark** it (so on the next mark-and-sweep iteration we have to mark it again).

Mark-and-Sweep In Action

Mark-and-Sweep In Action



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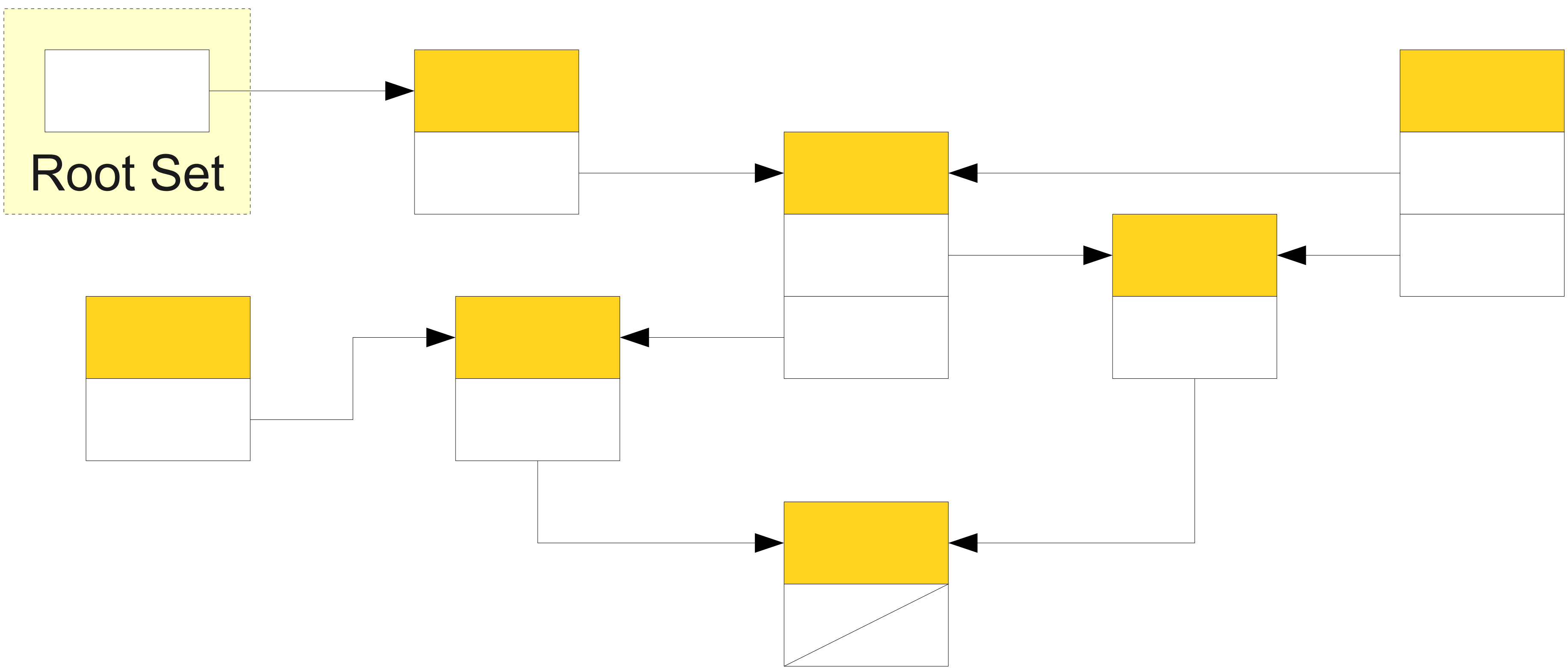

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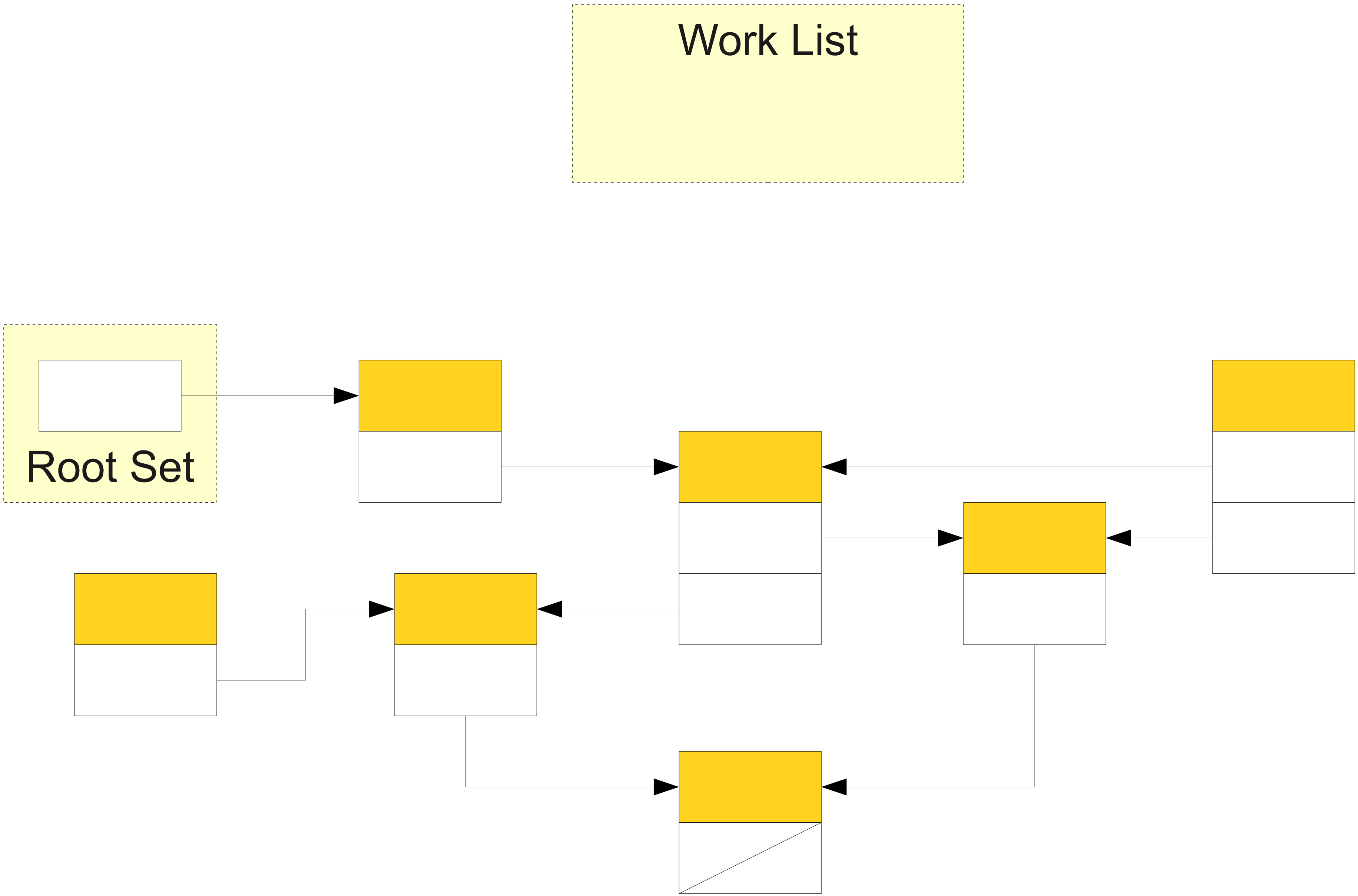

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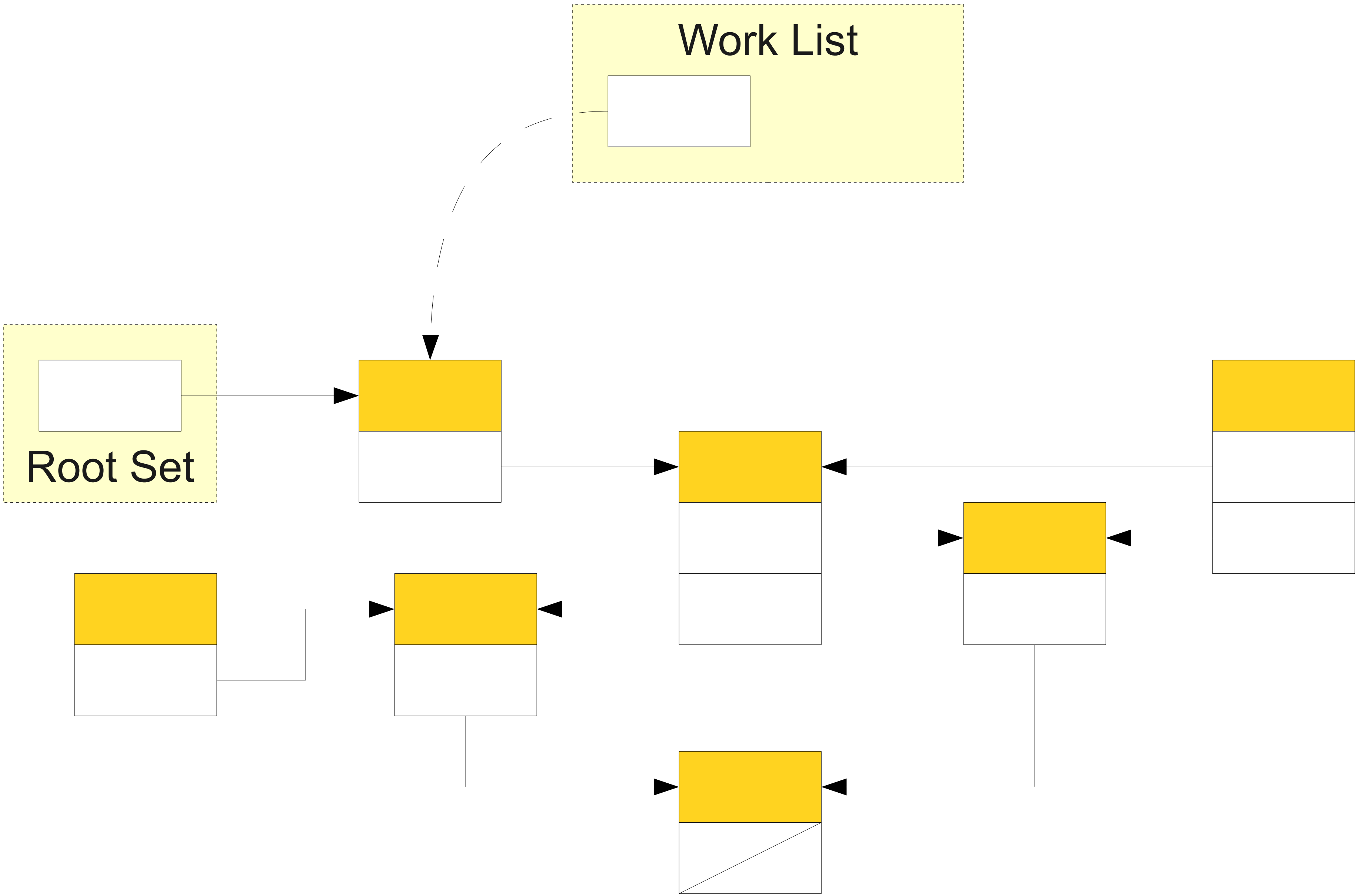

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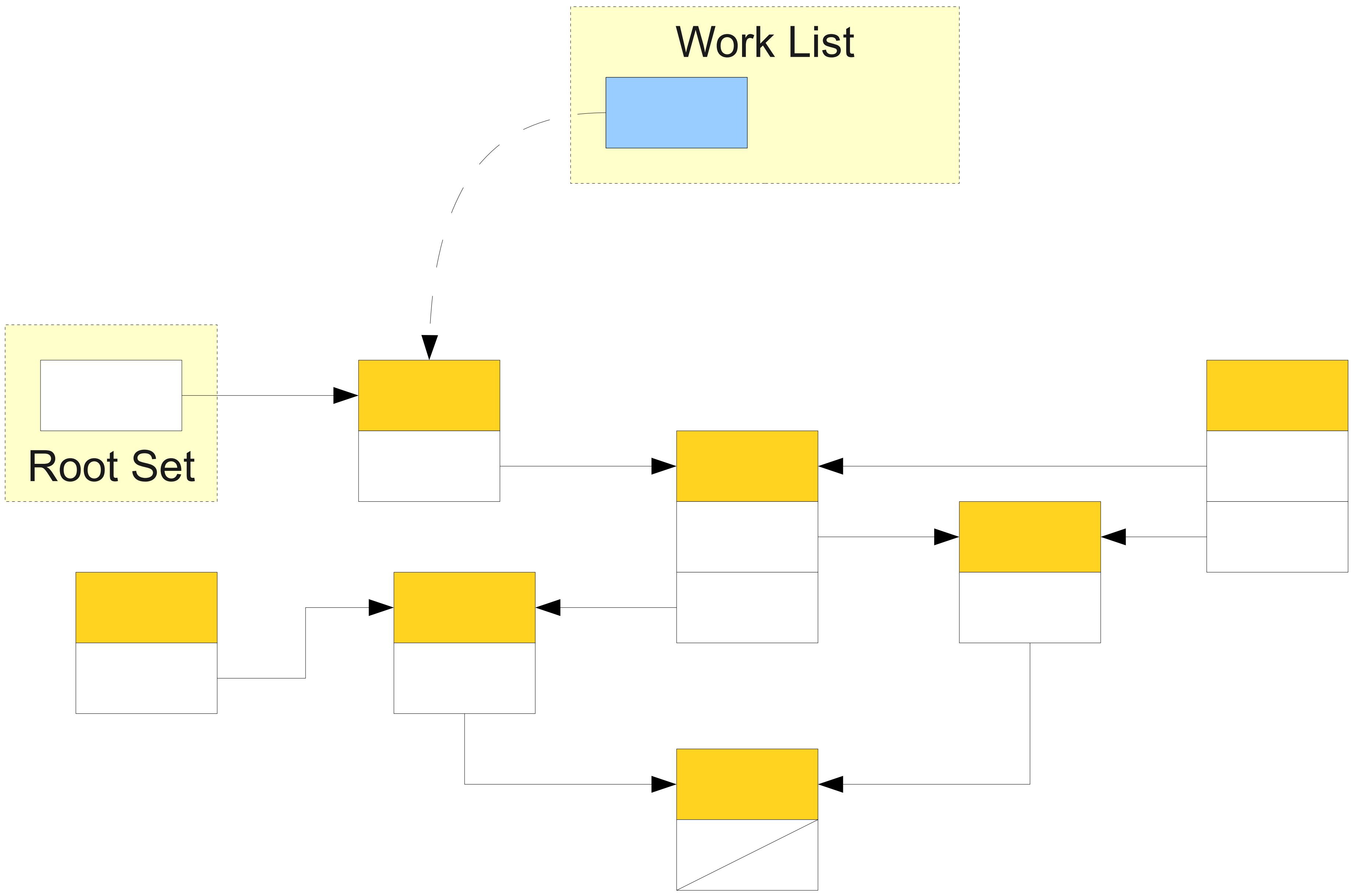

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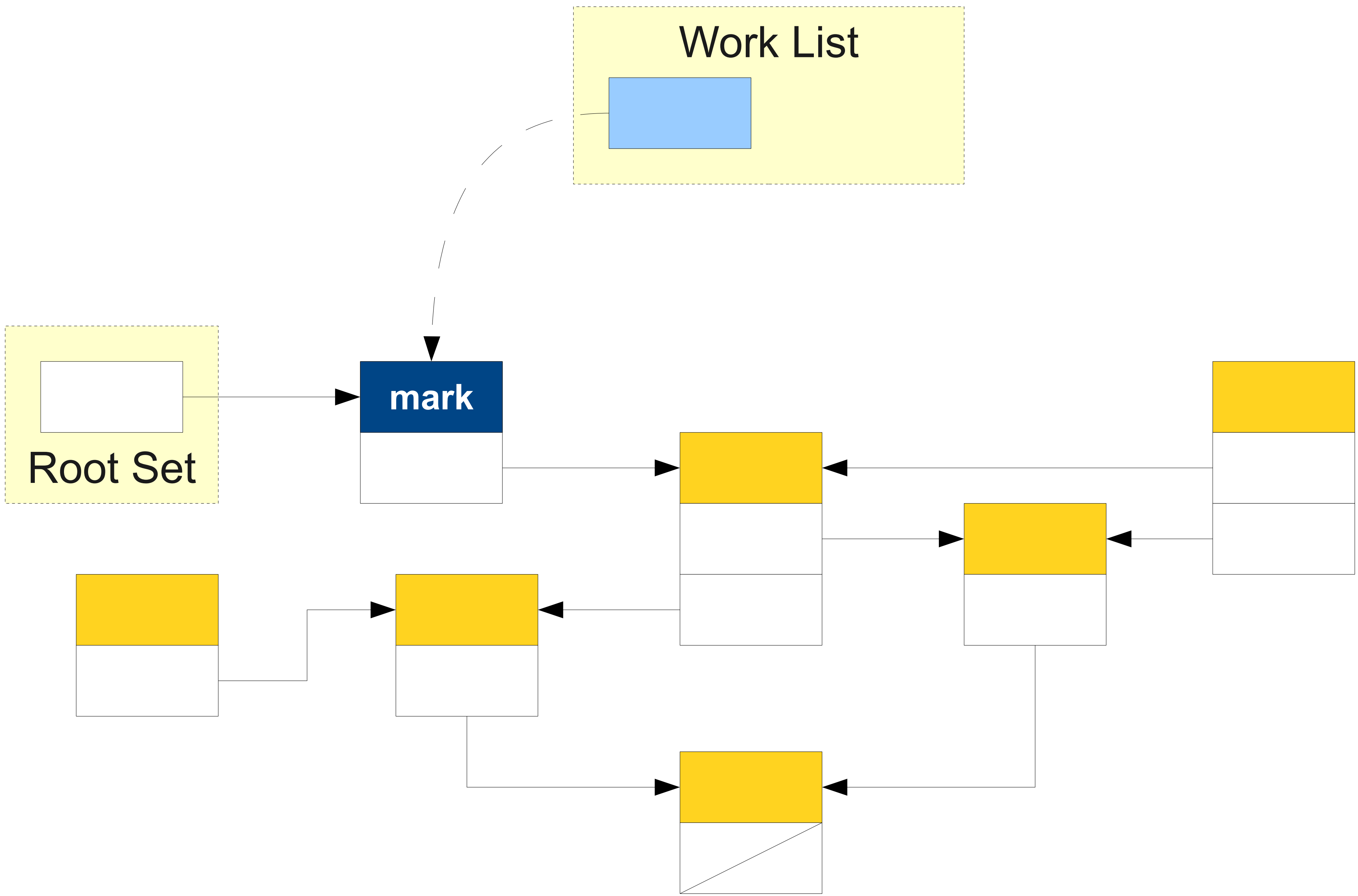

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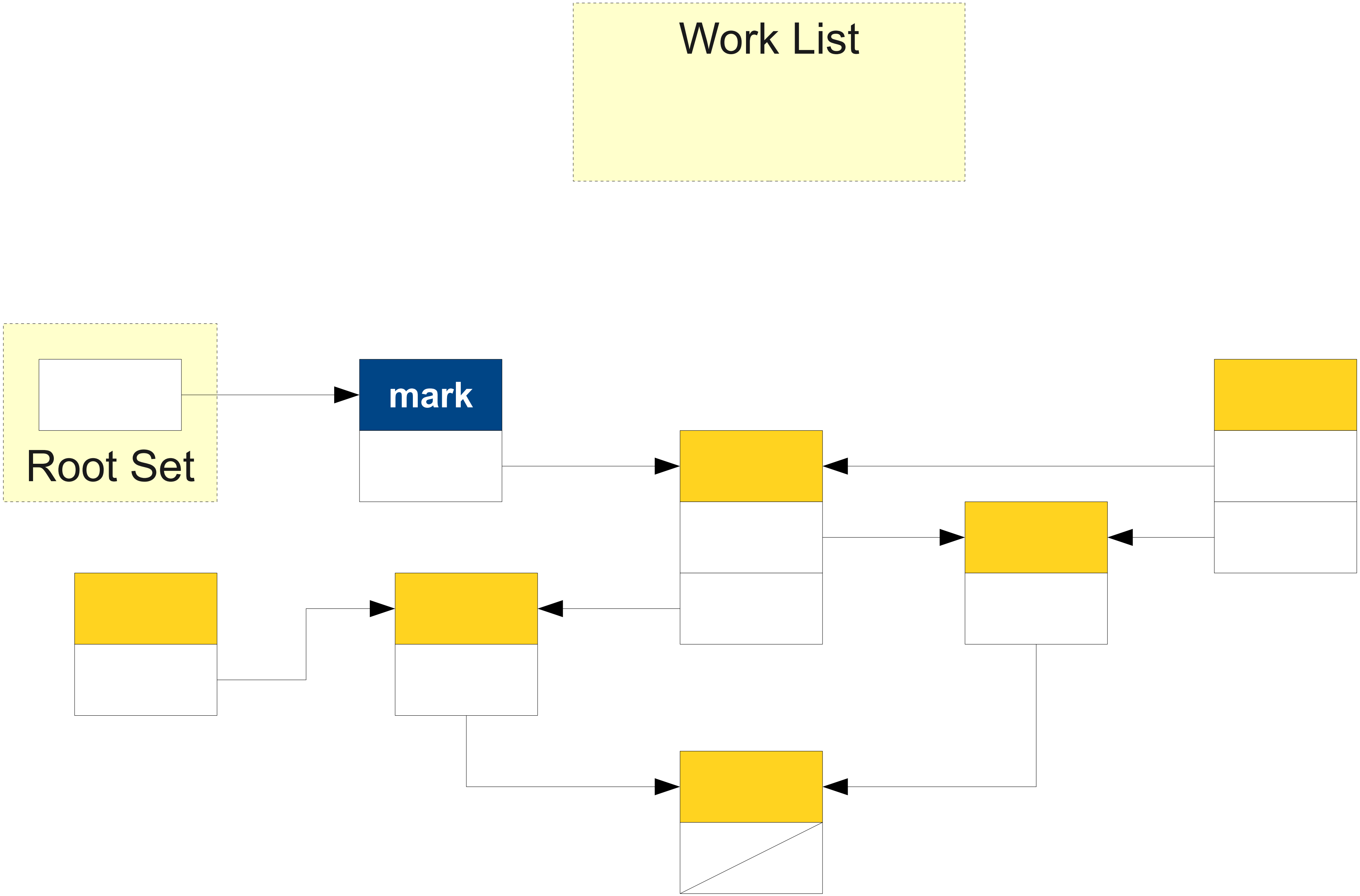

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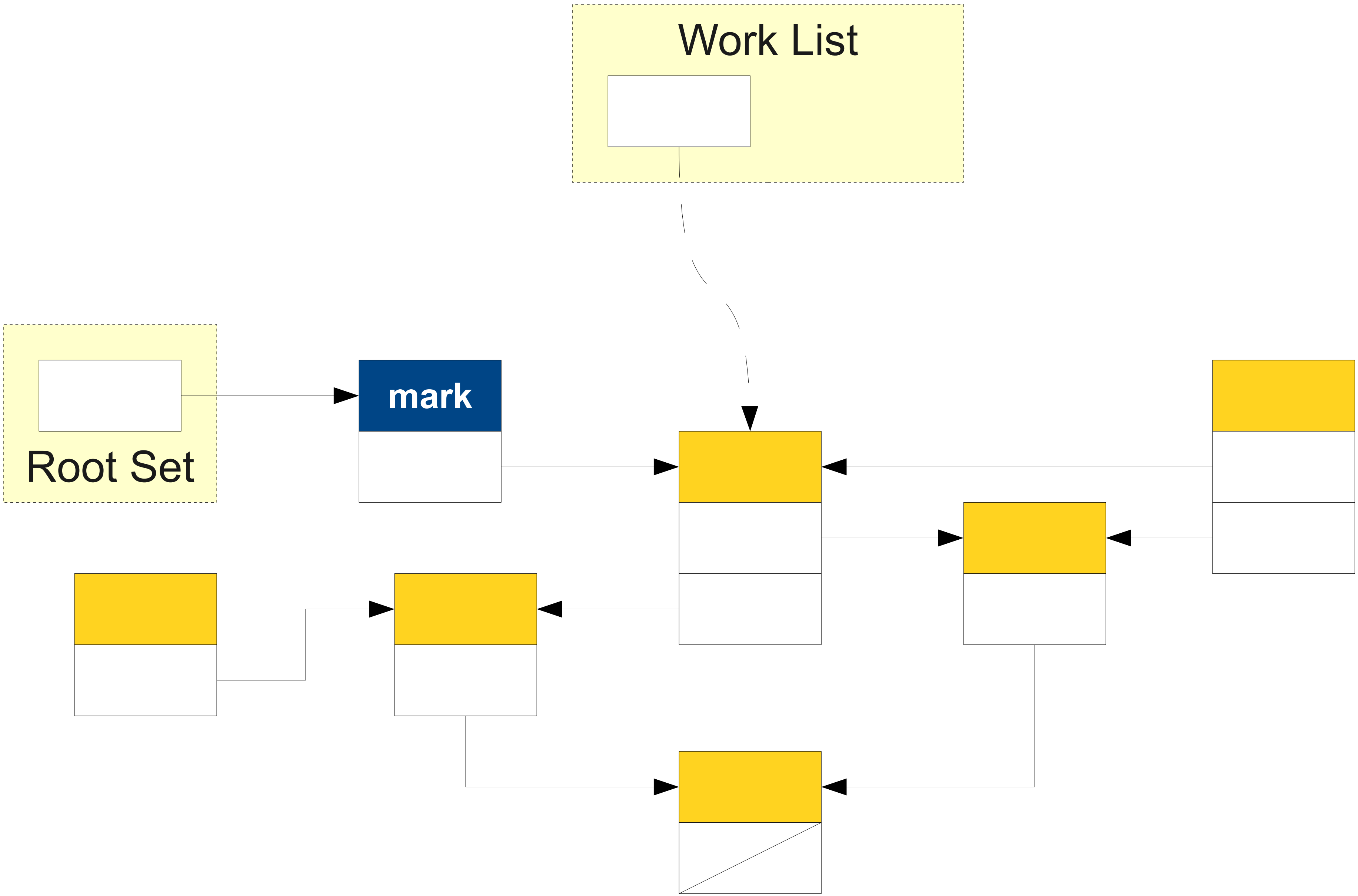

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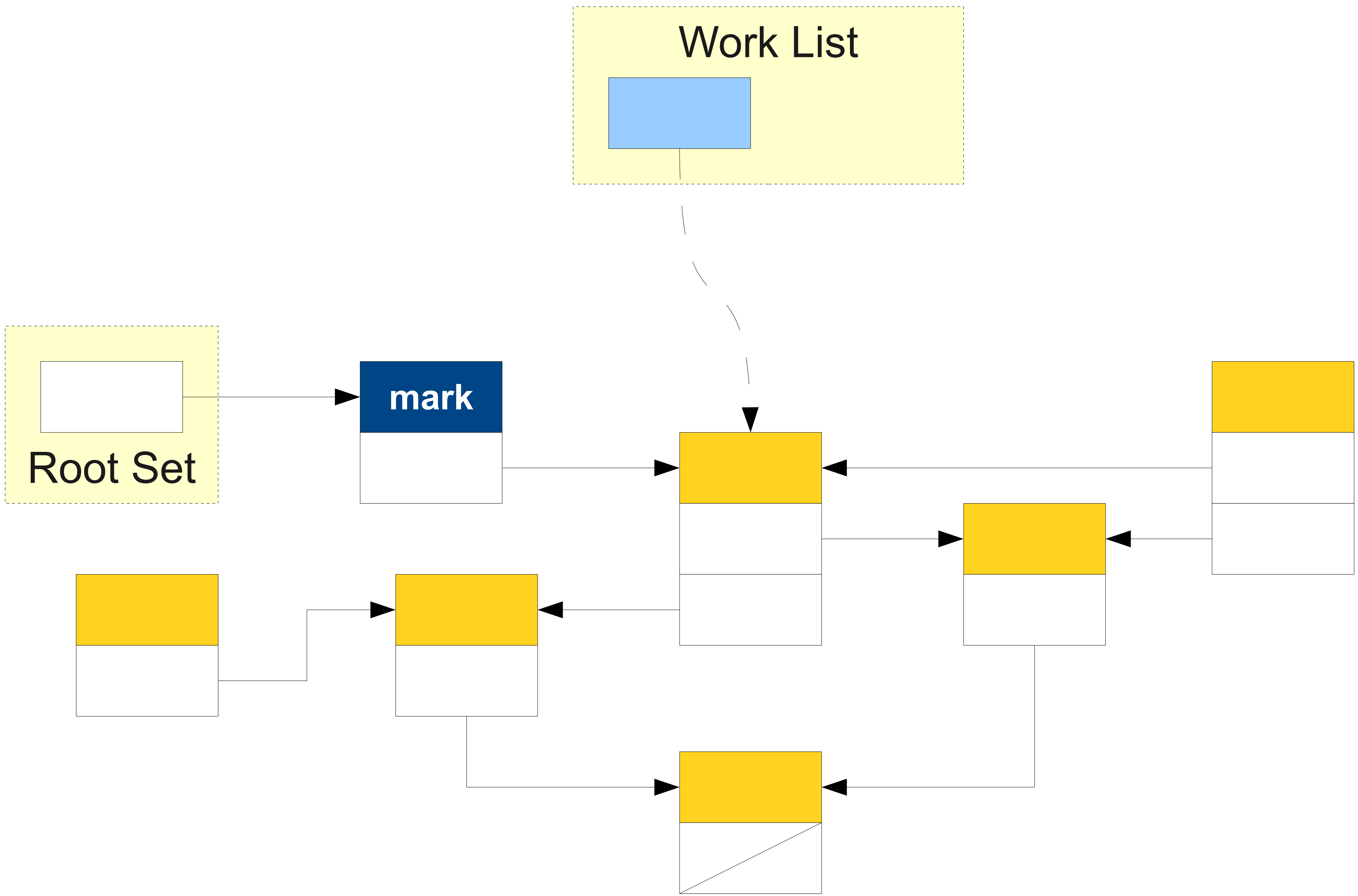

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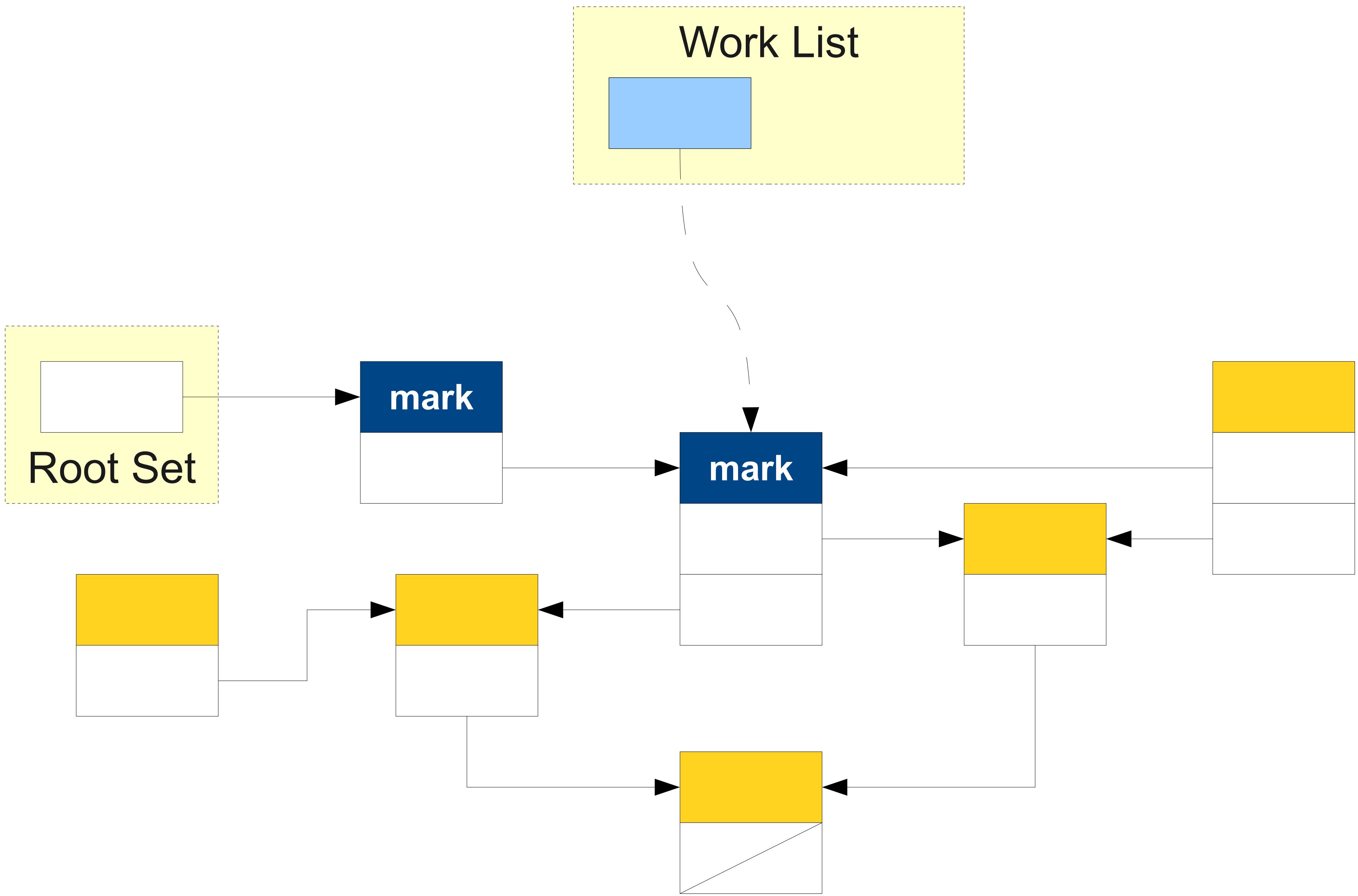

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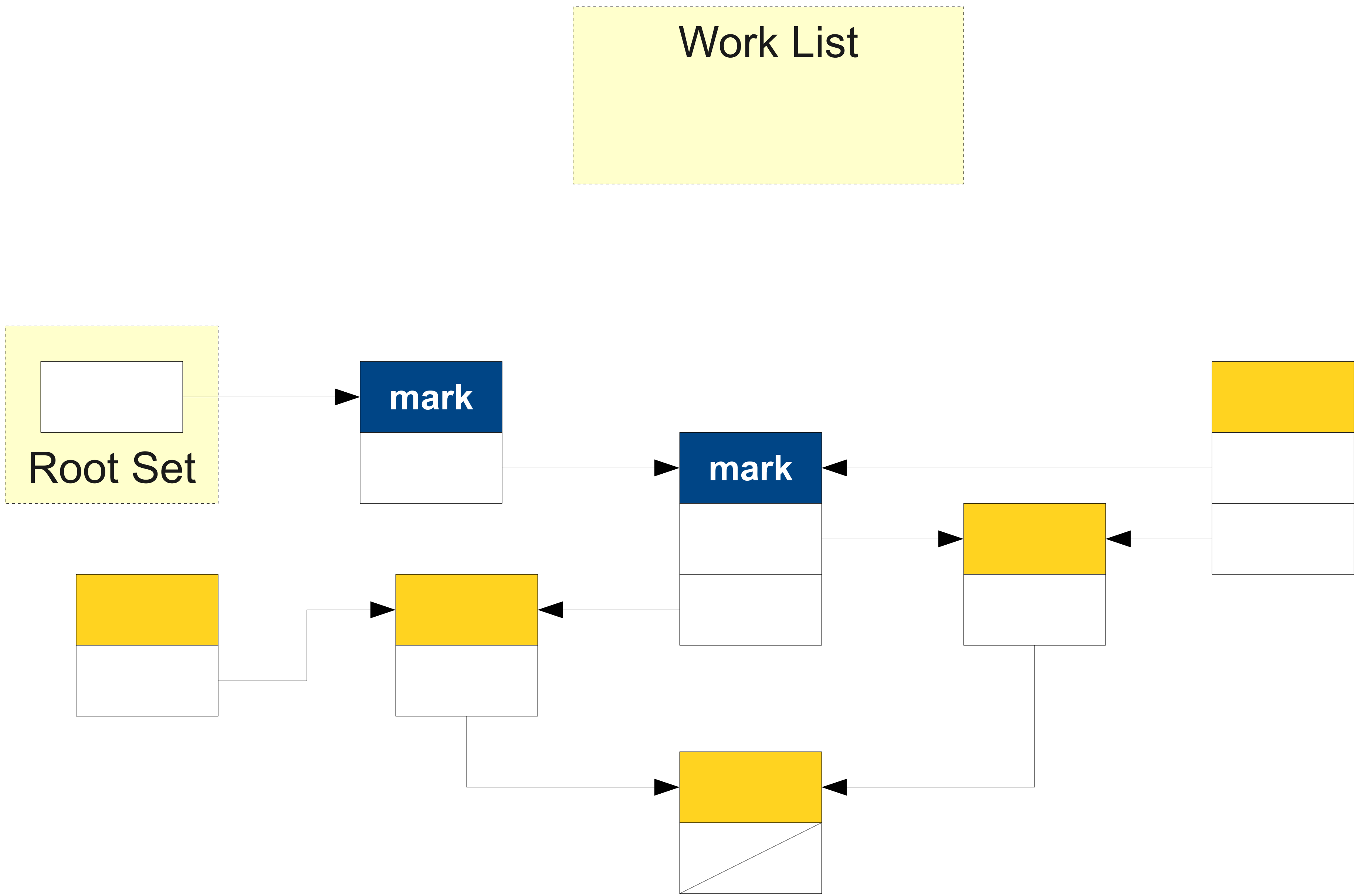

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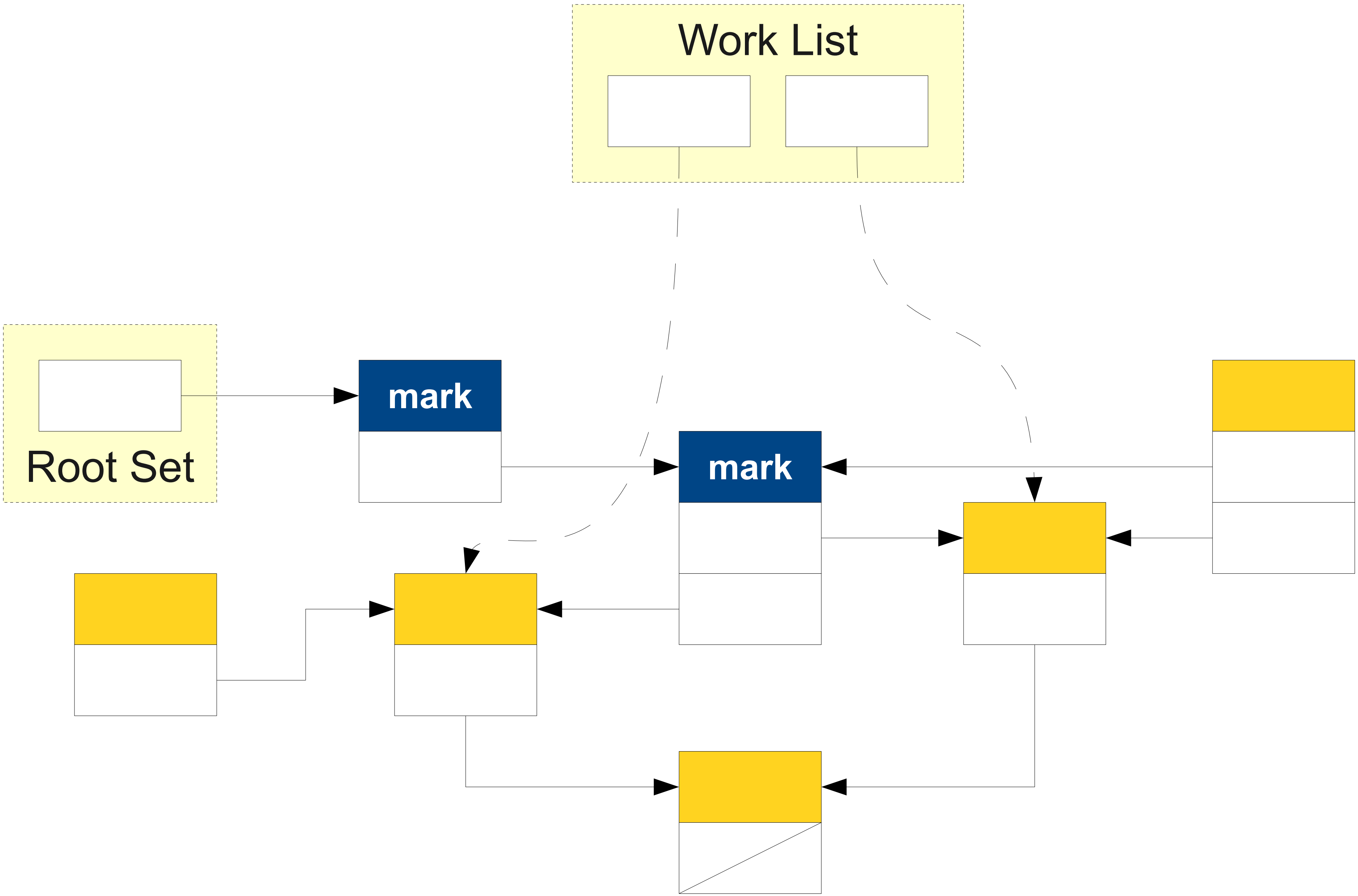
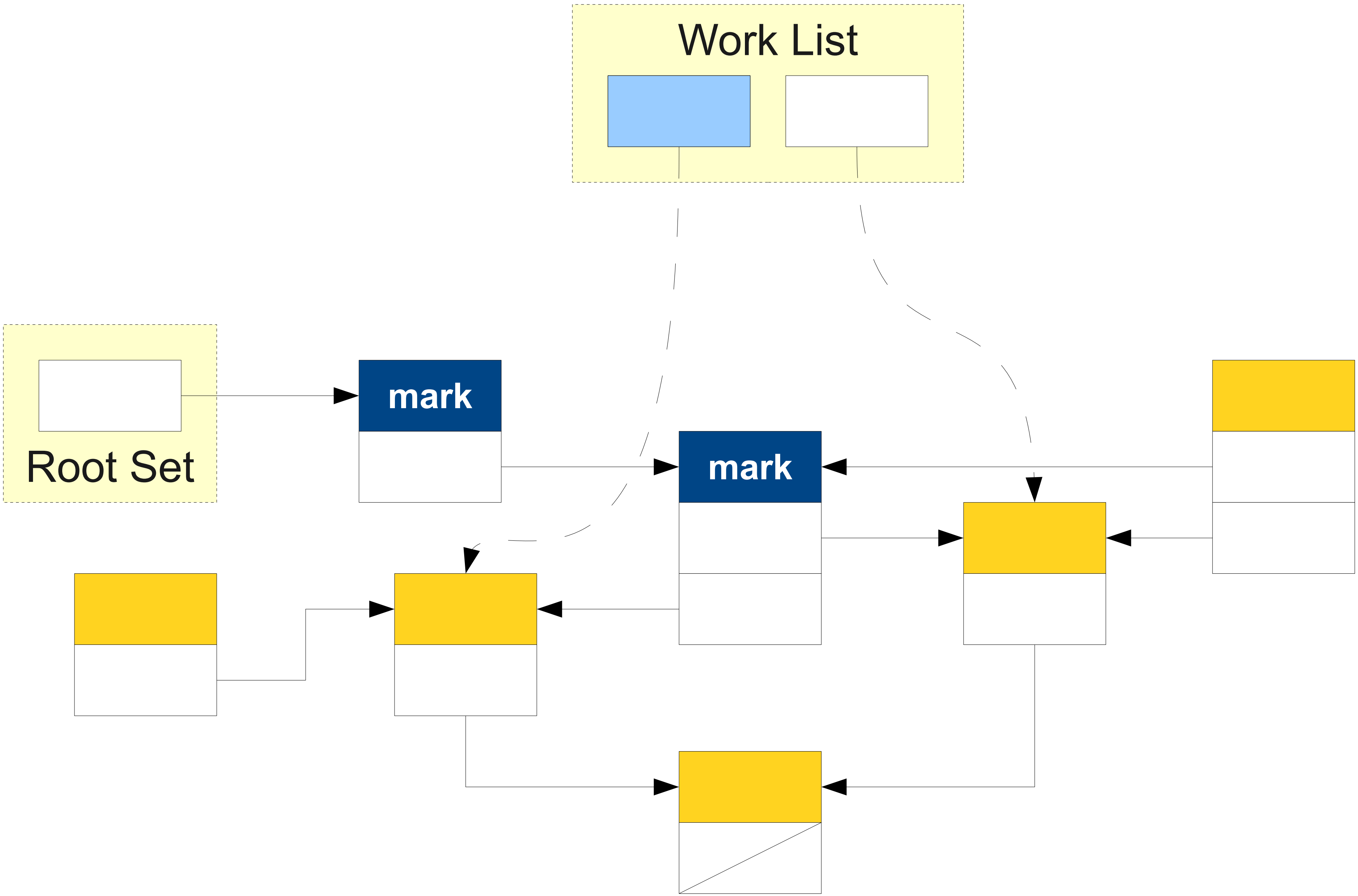


Mark-and-Sweep In Action



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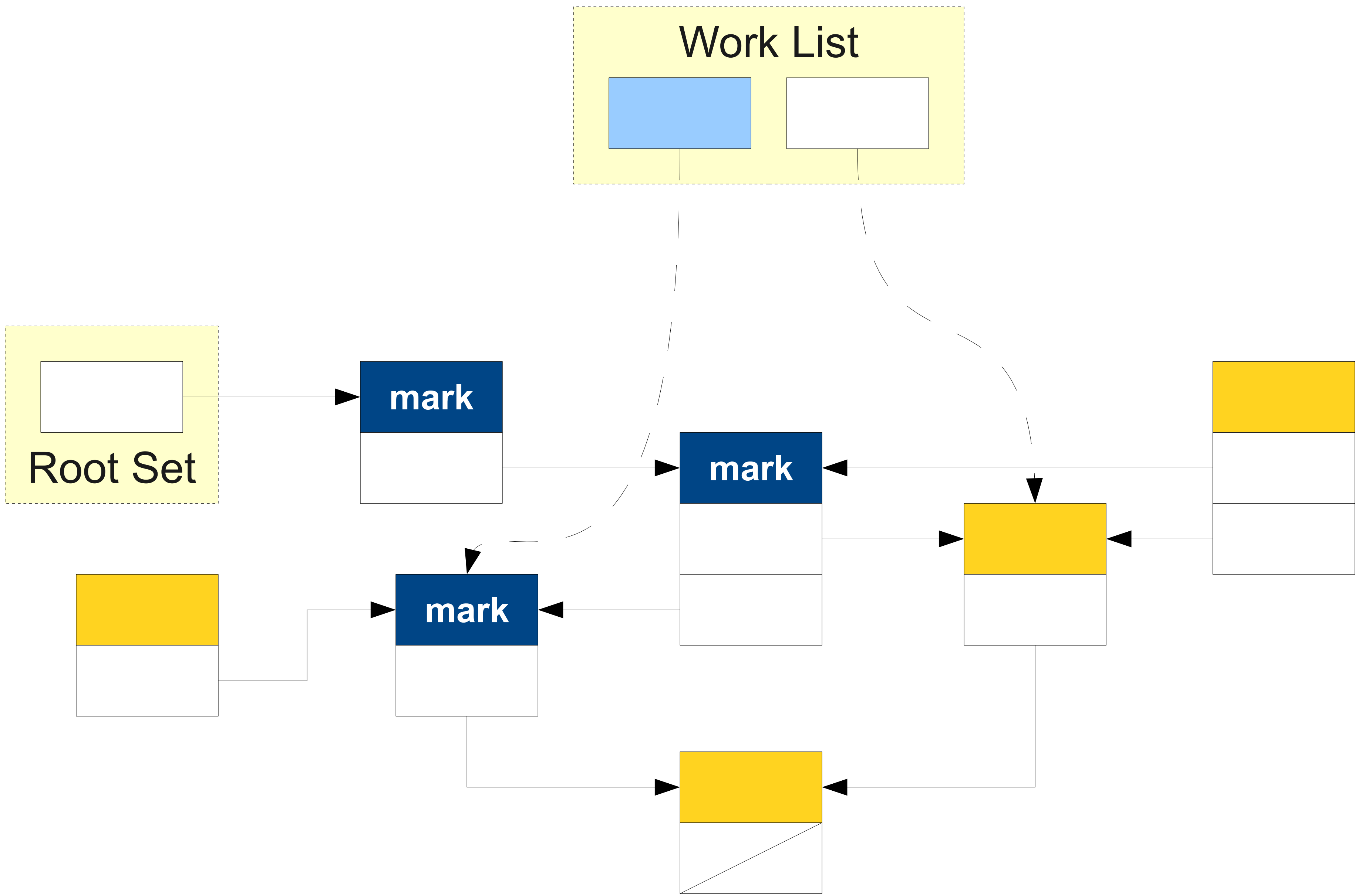

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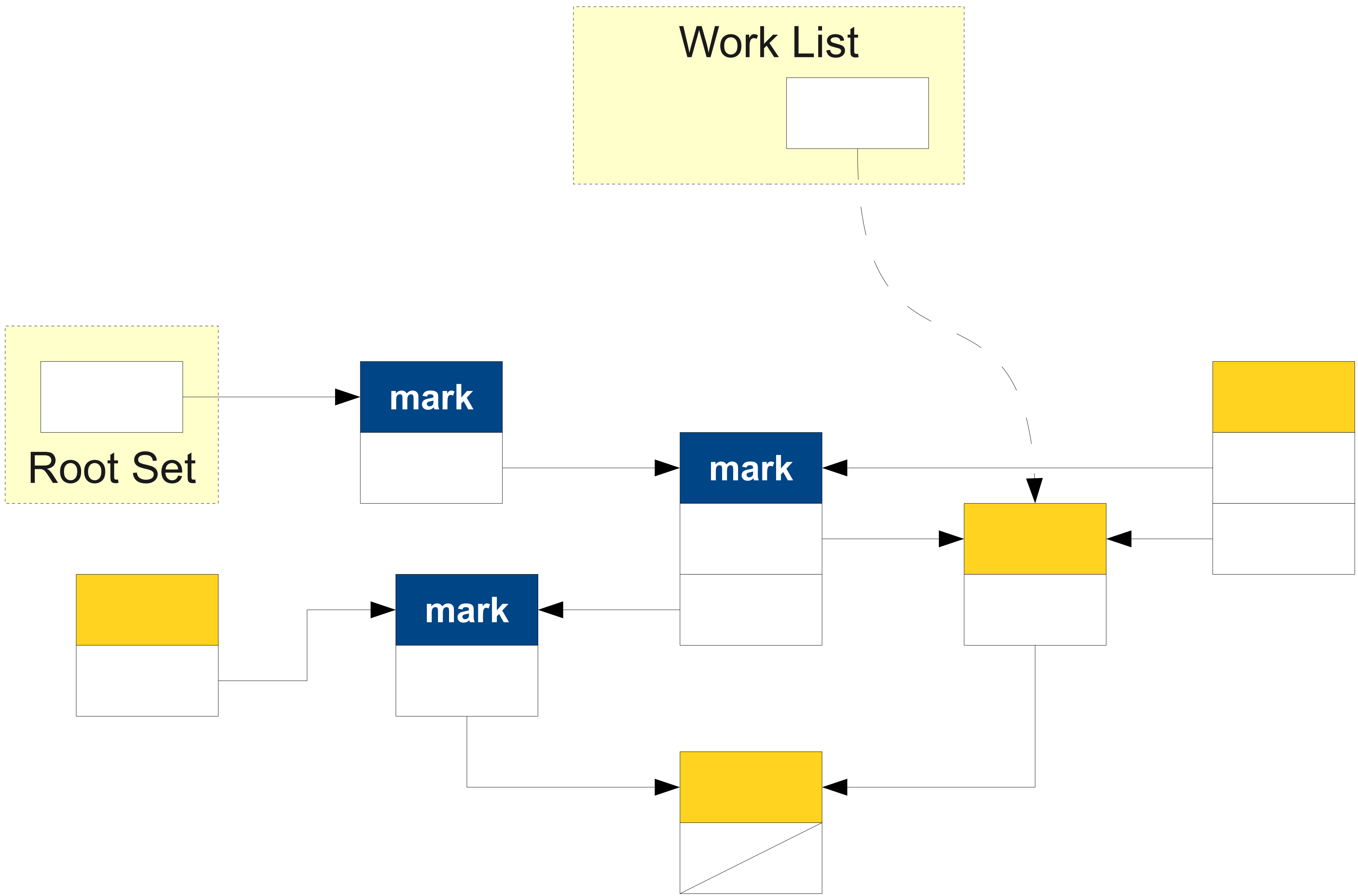

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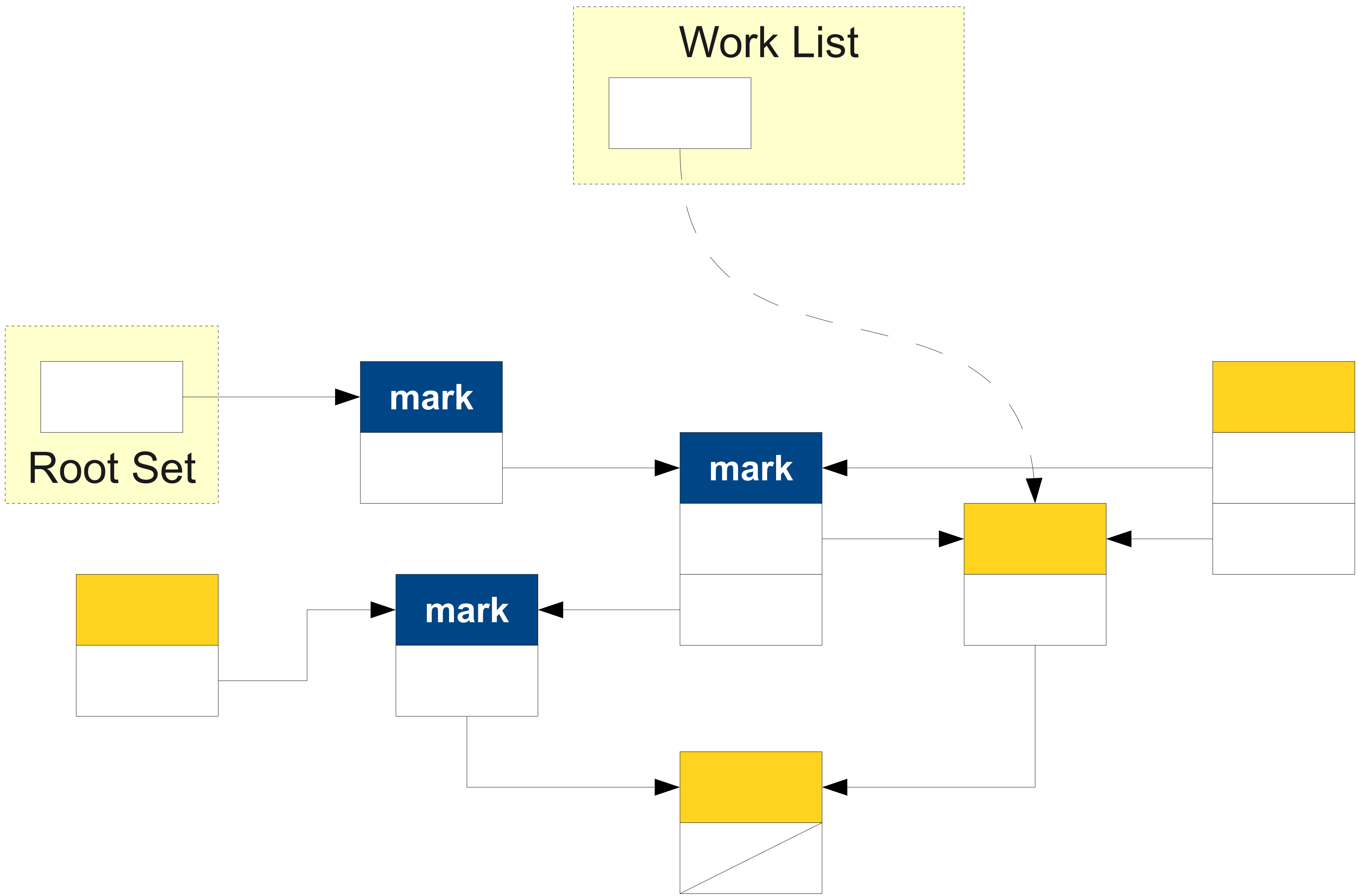

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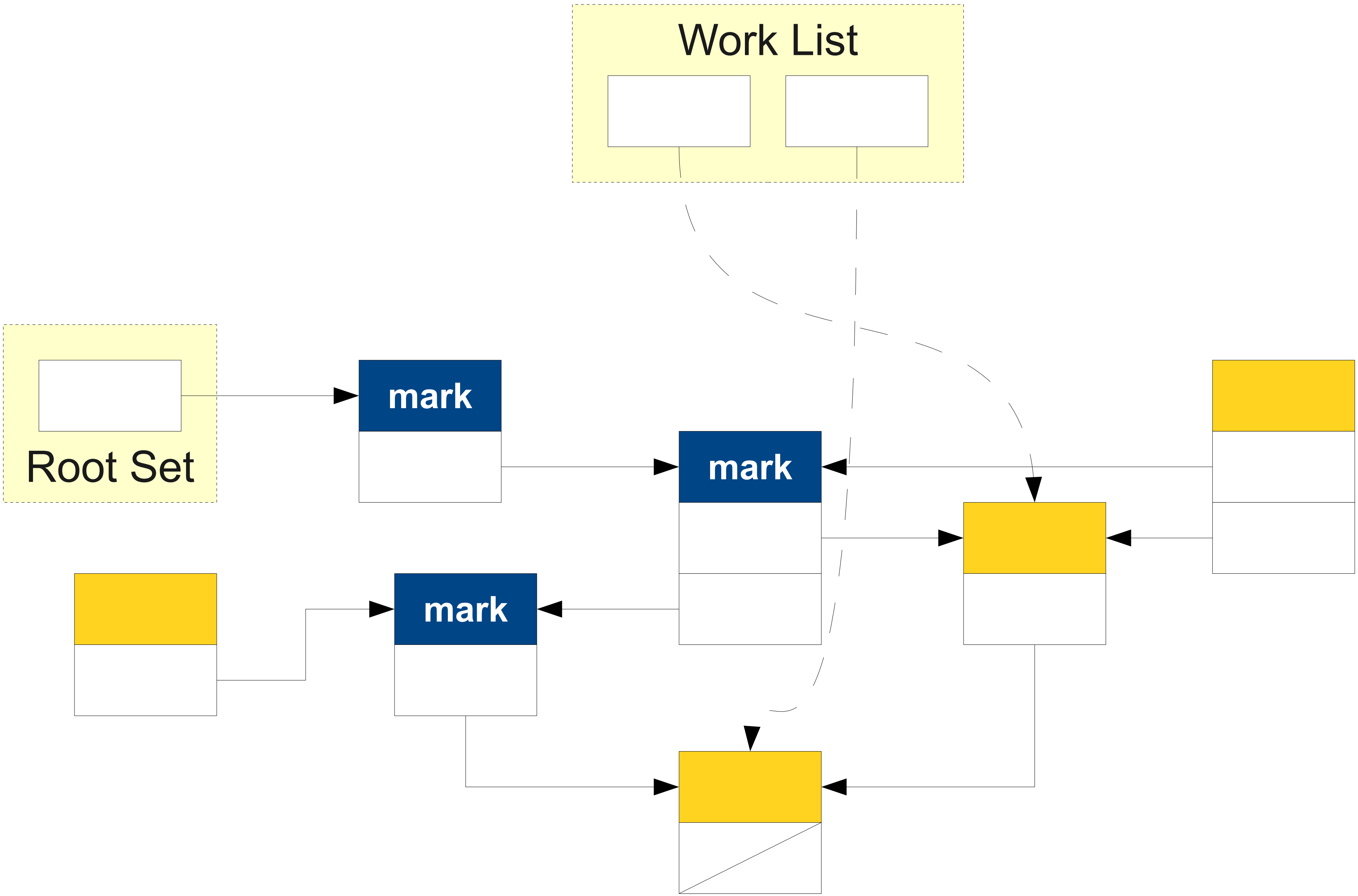

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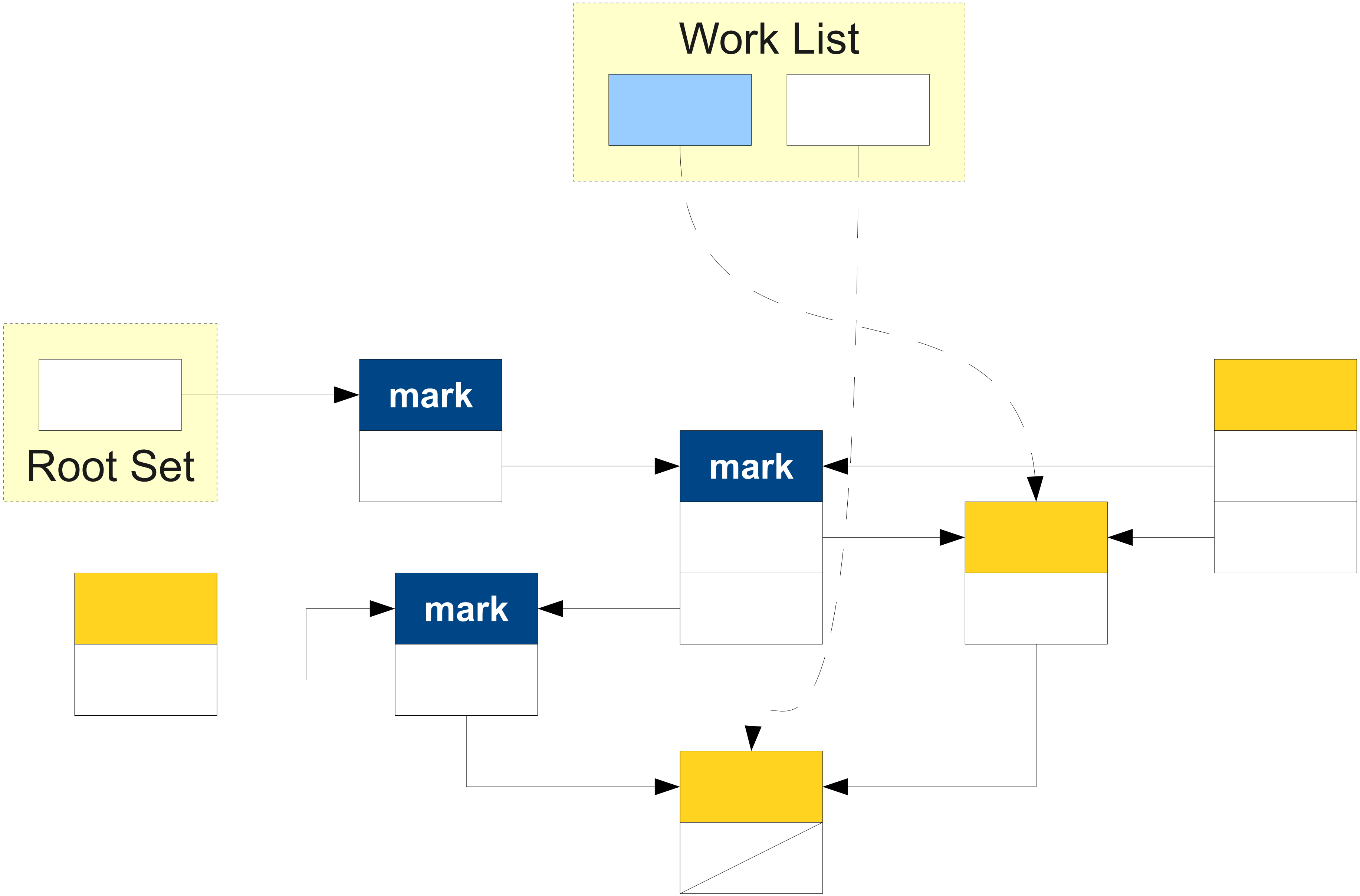

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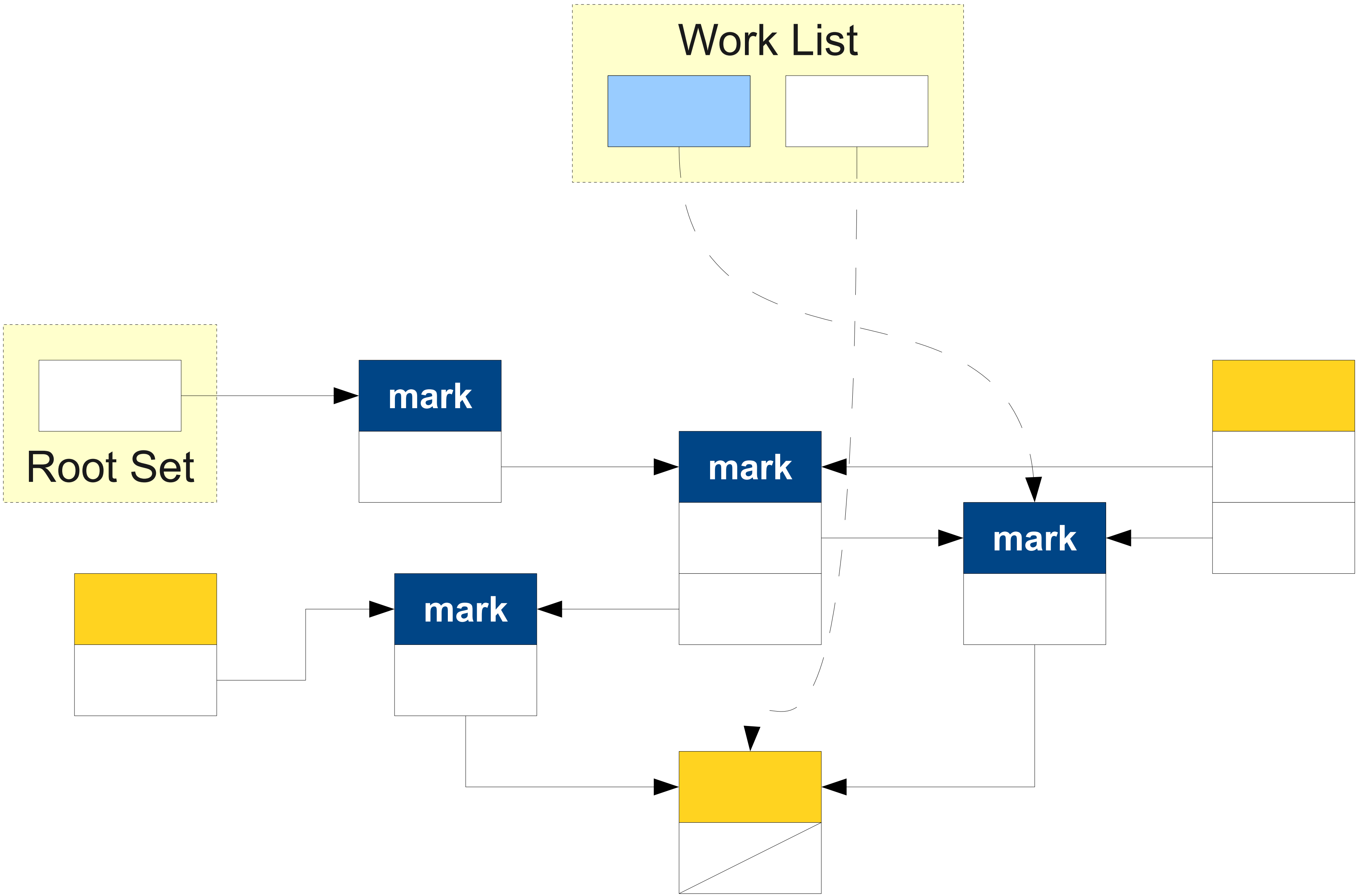

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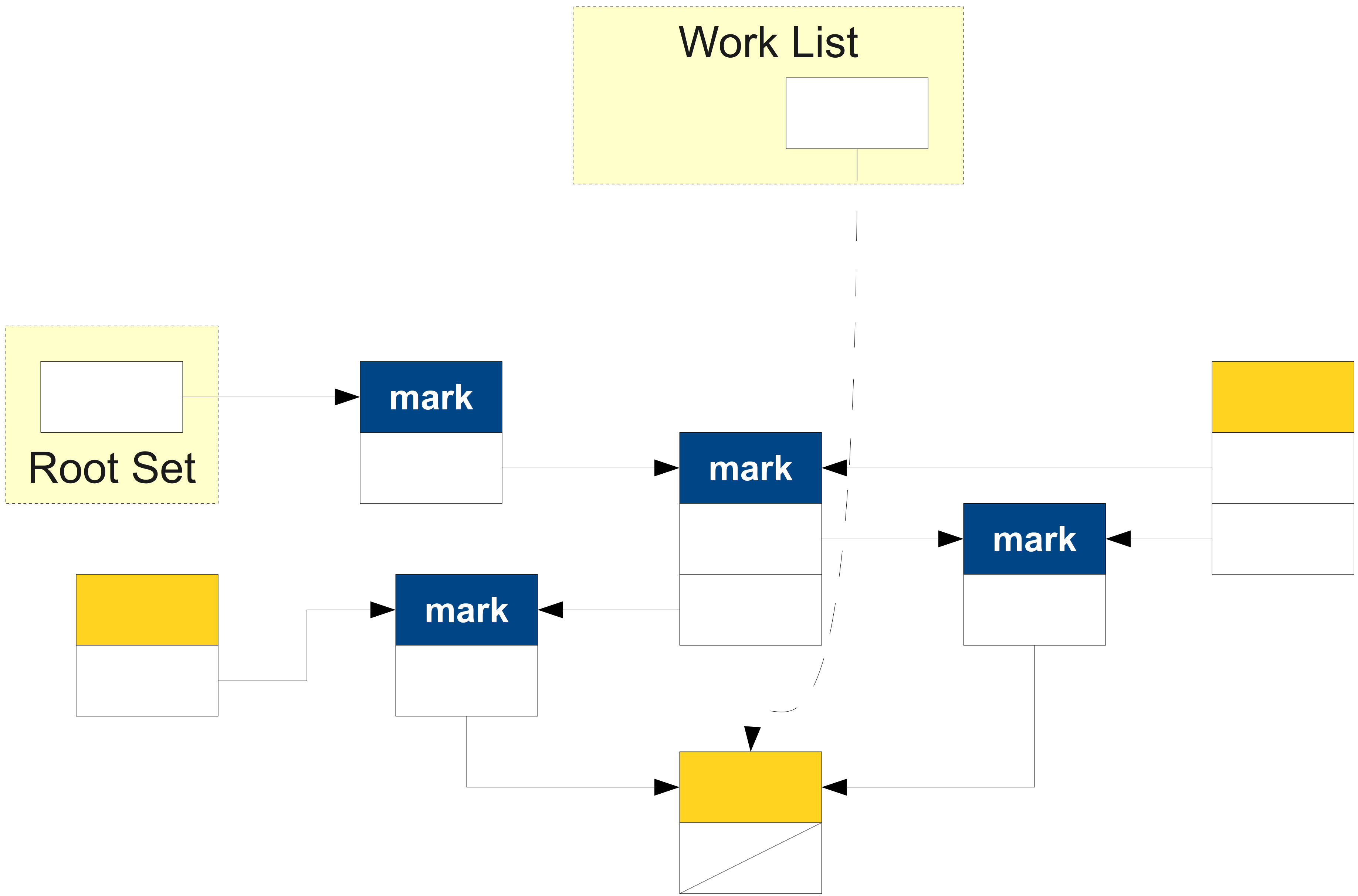

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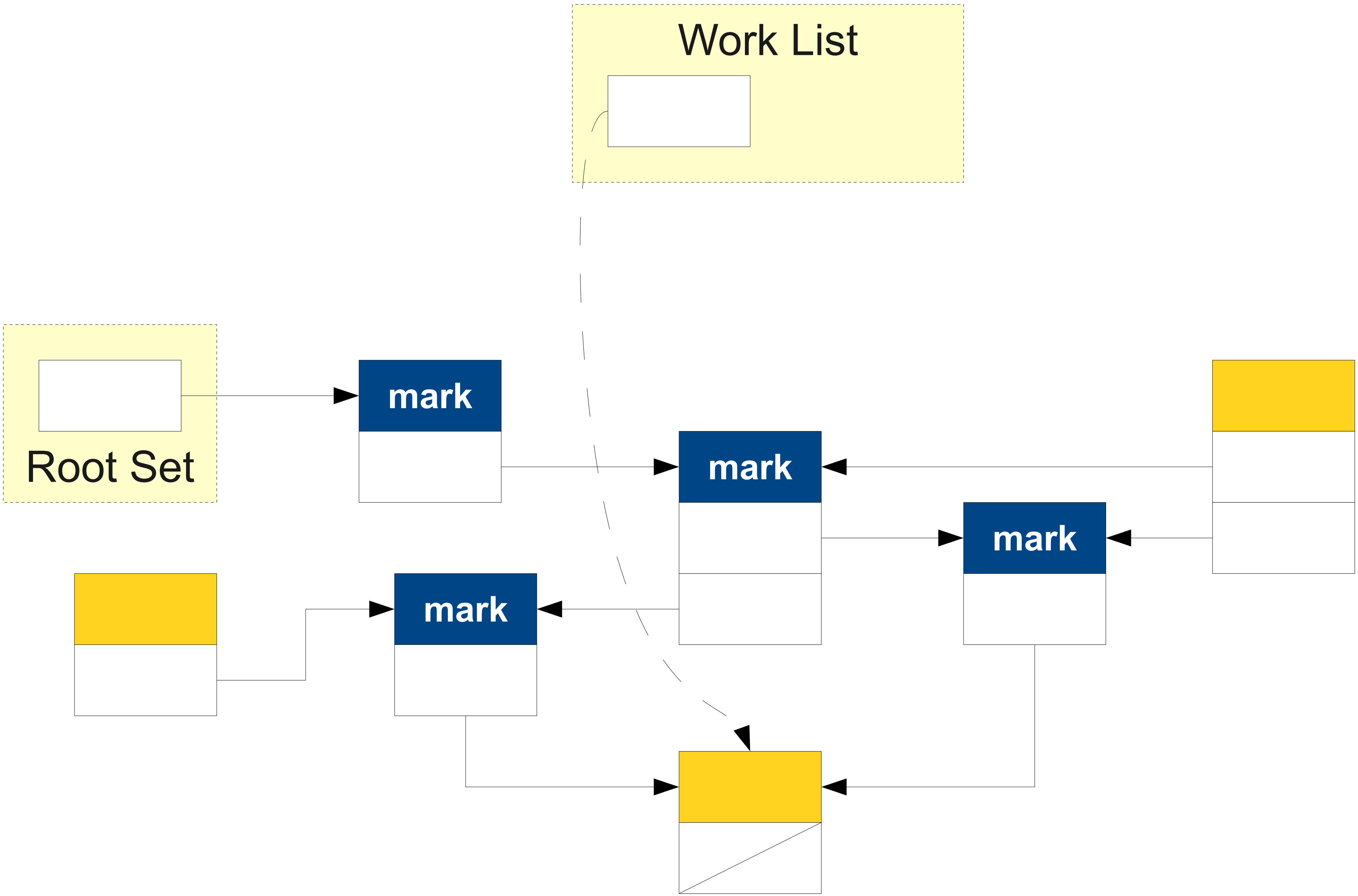

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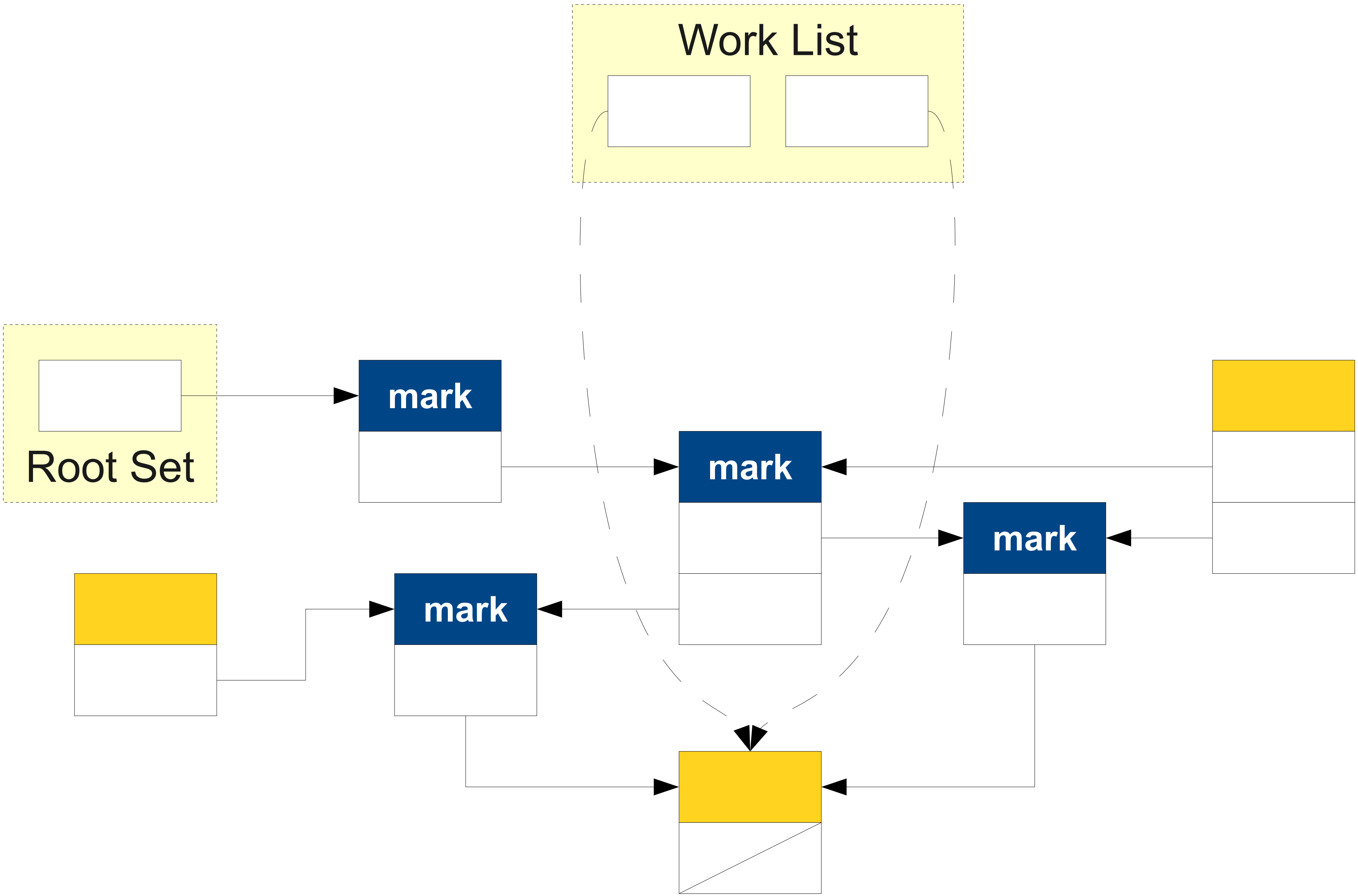

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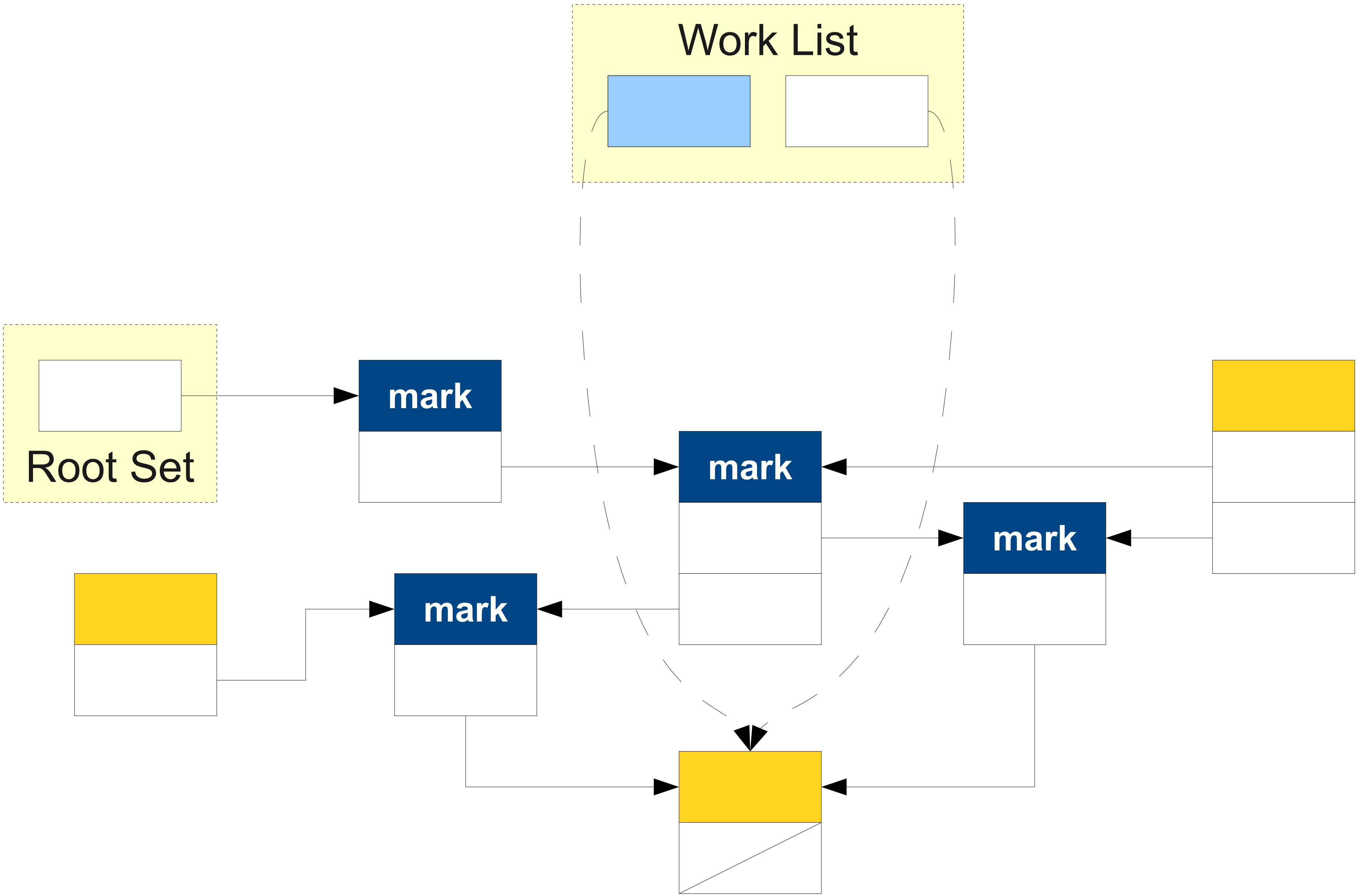

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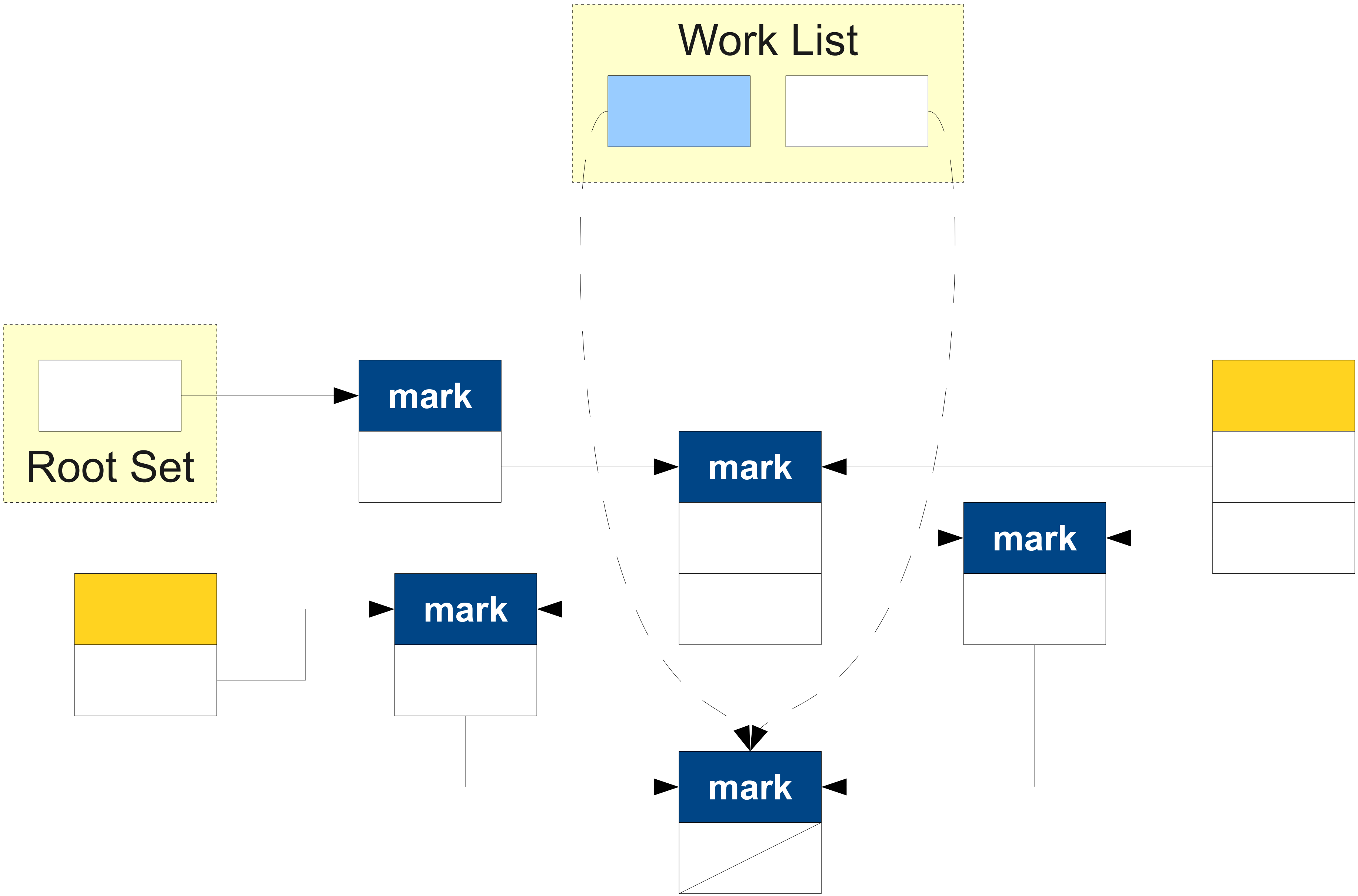

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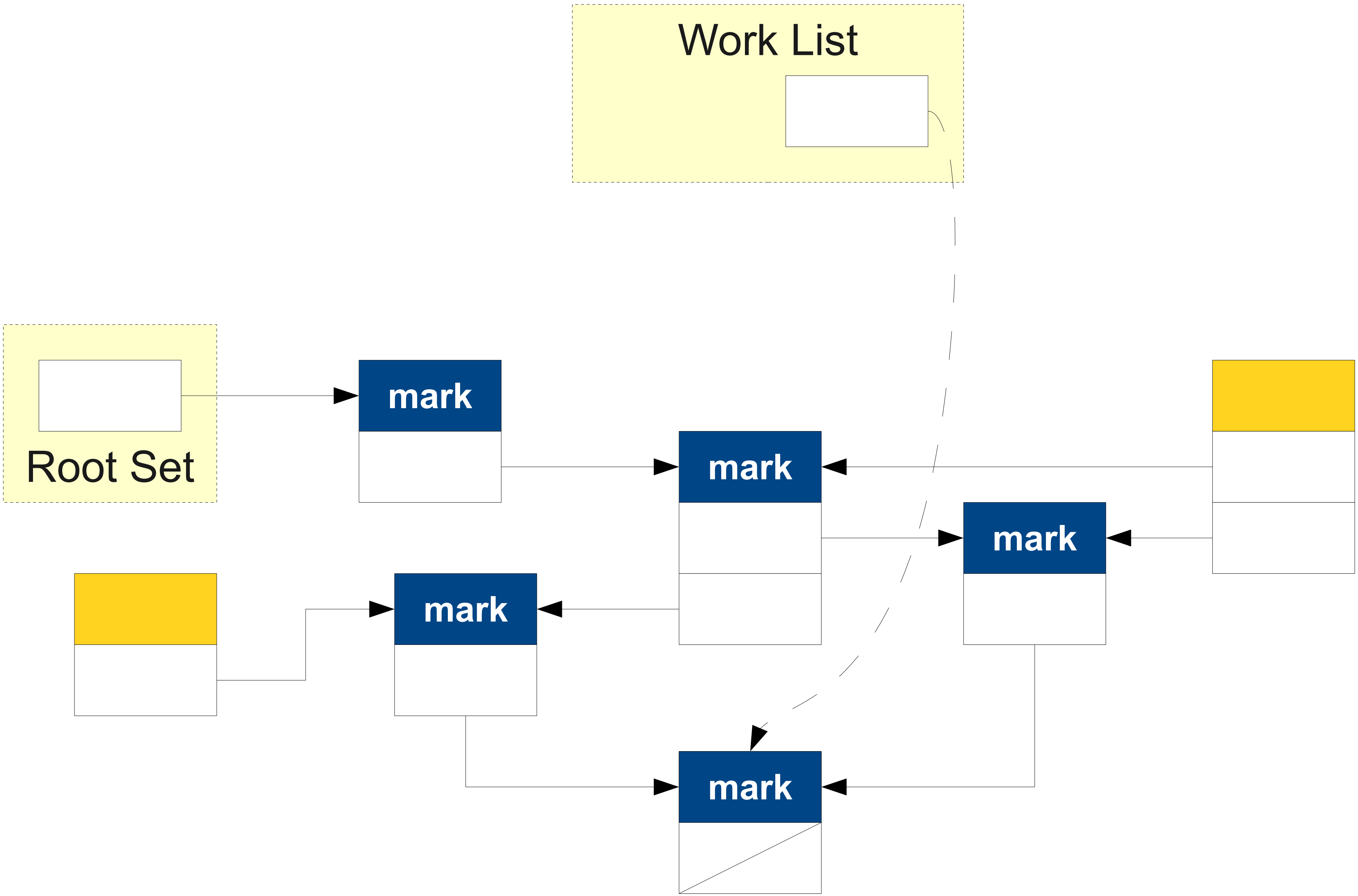

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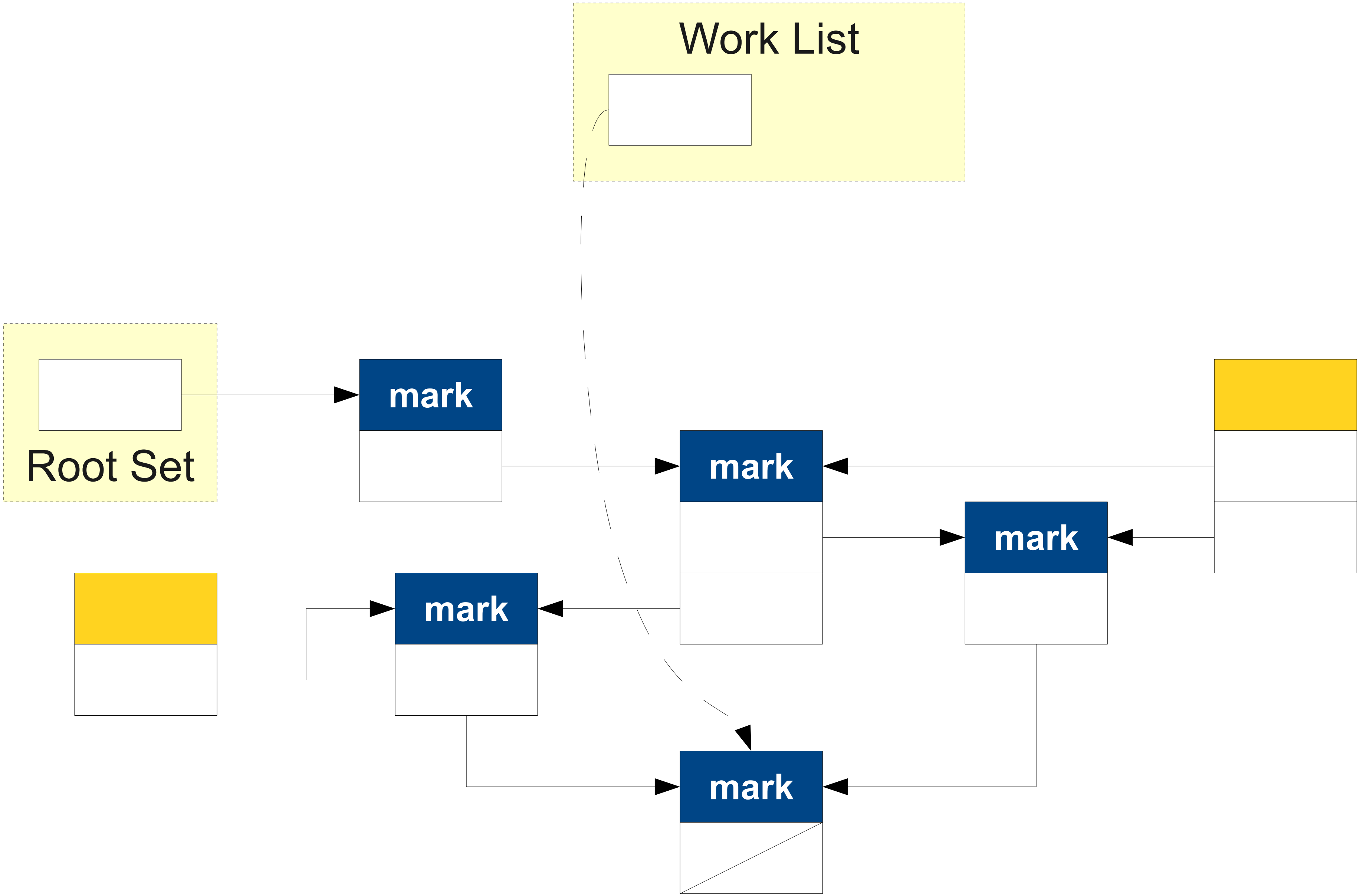

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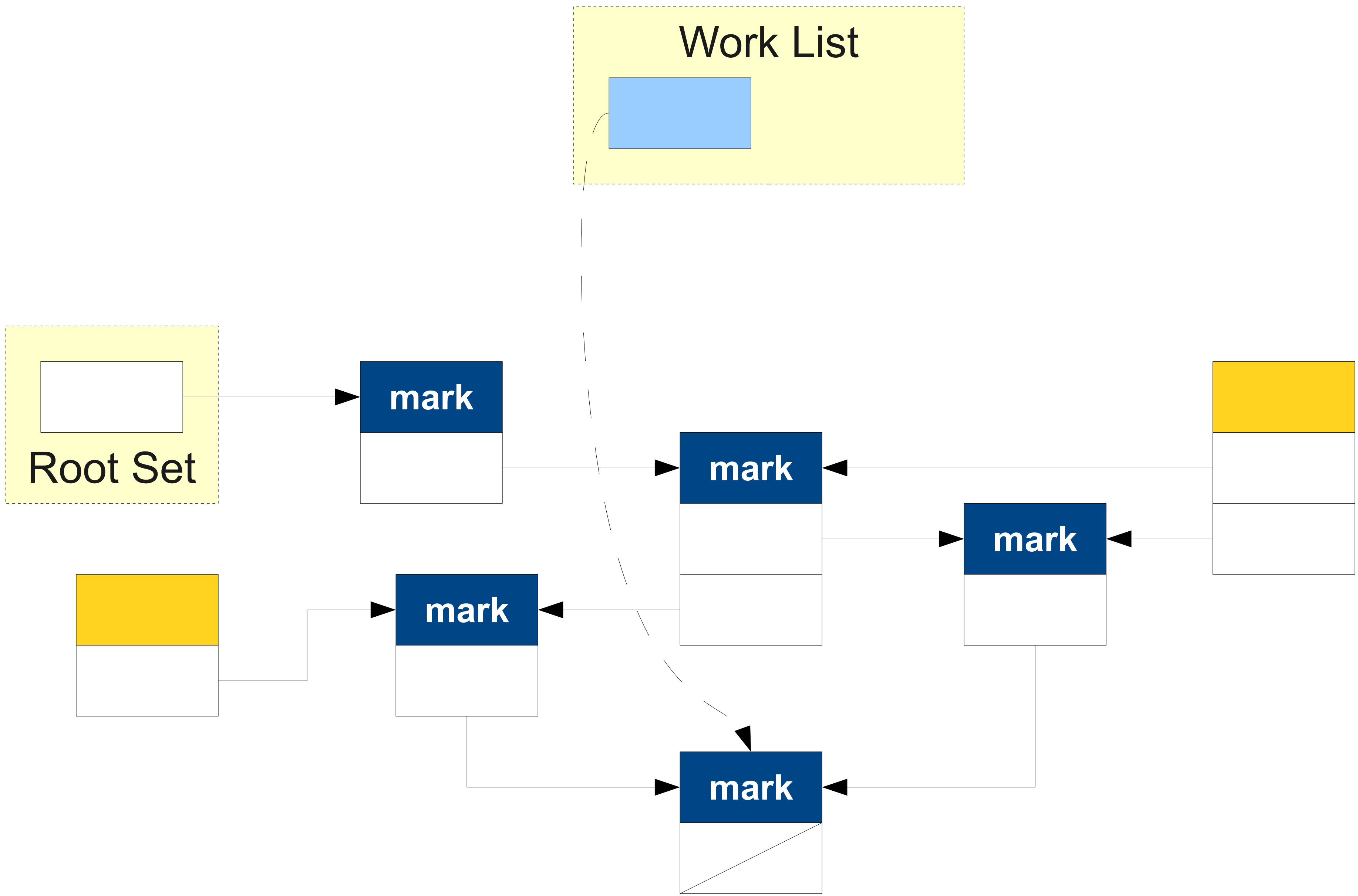

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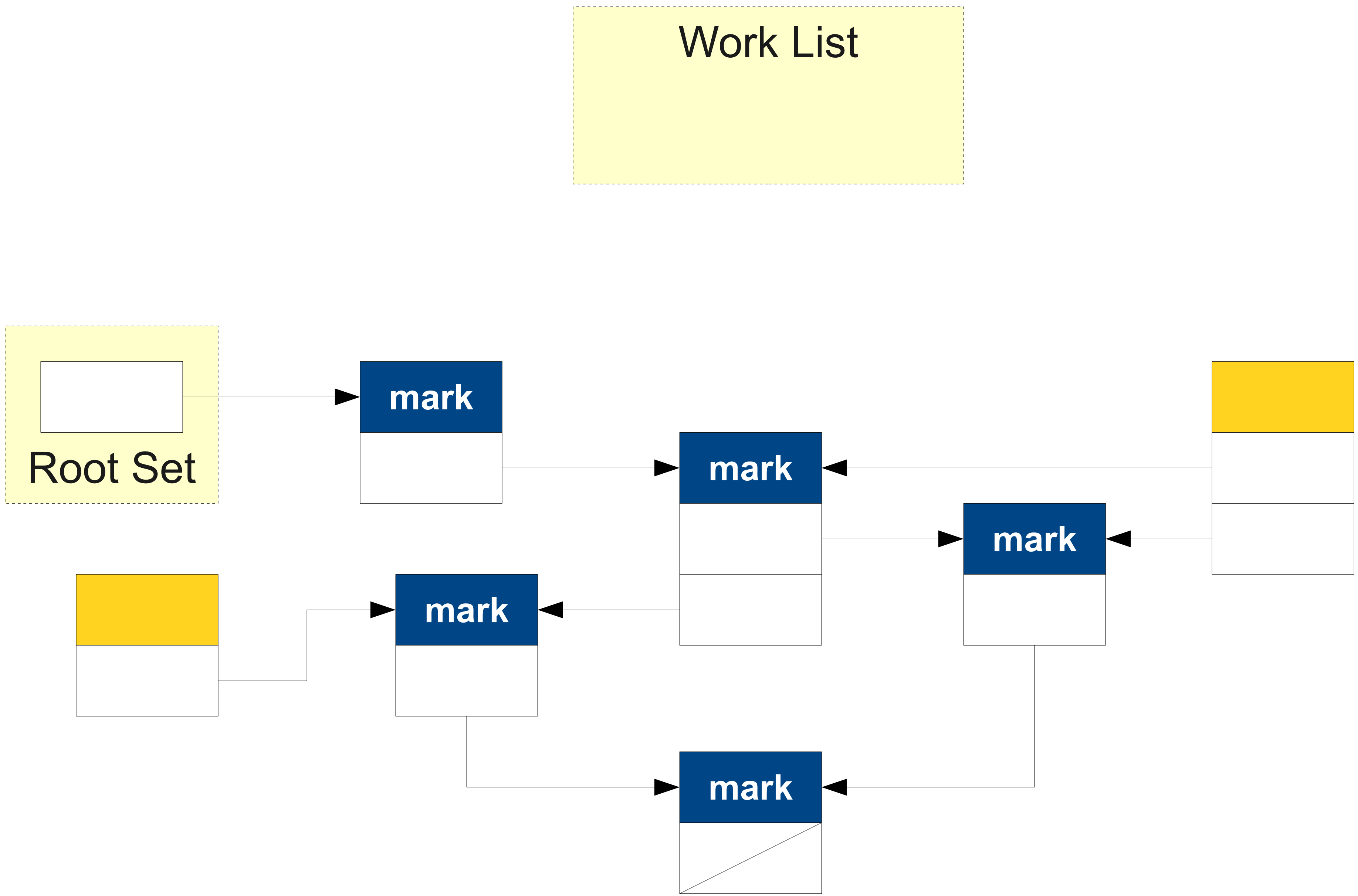

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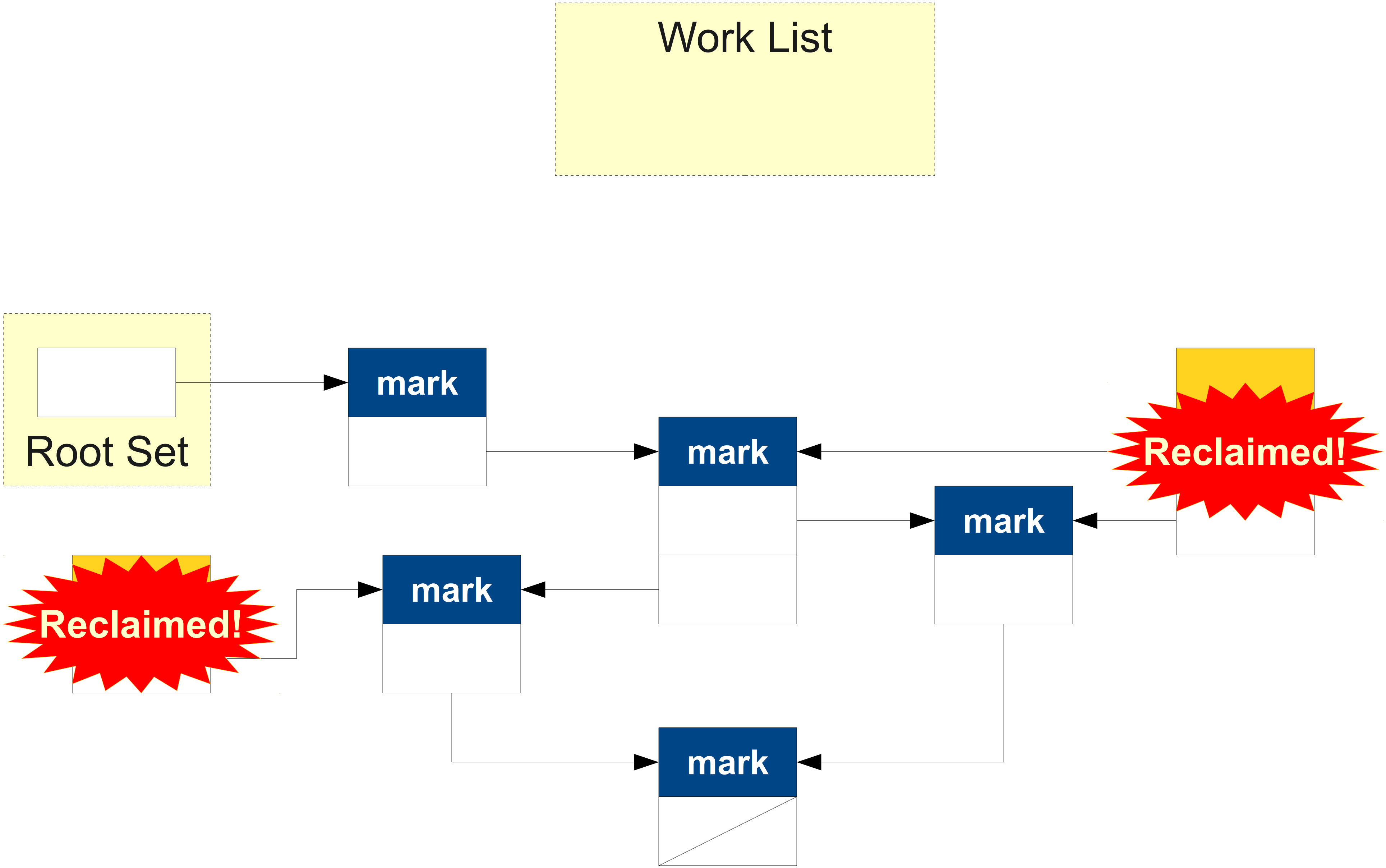

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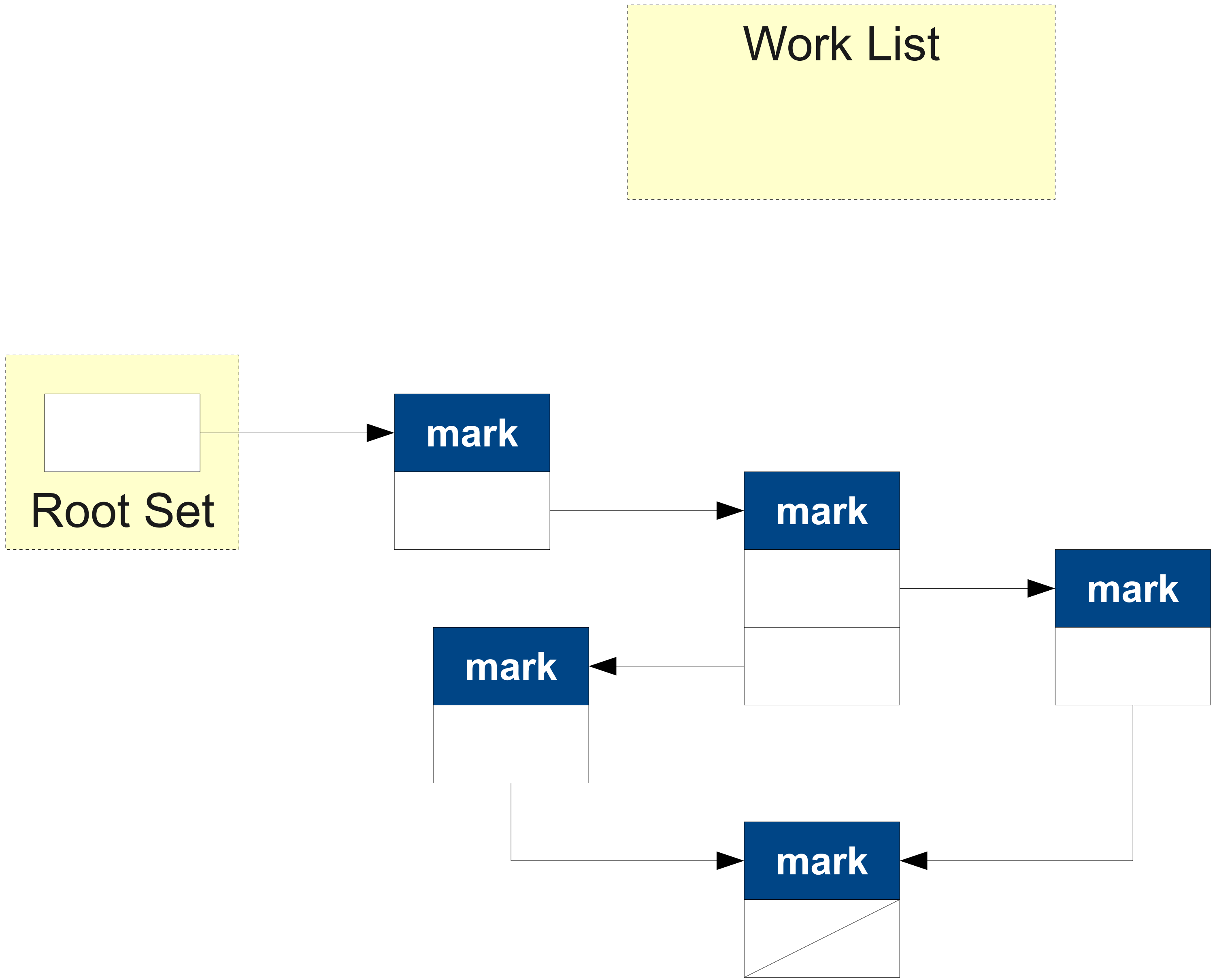

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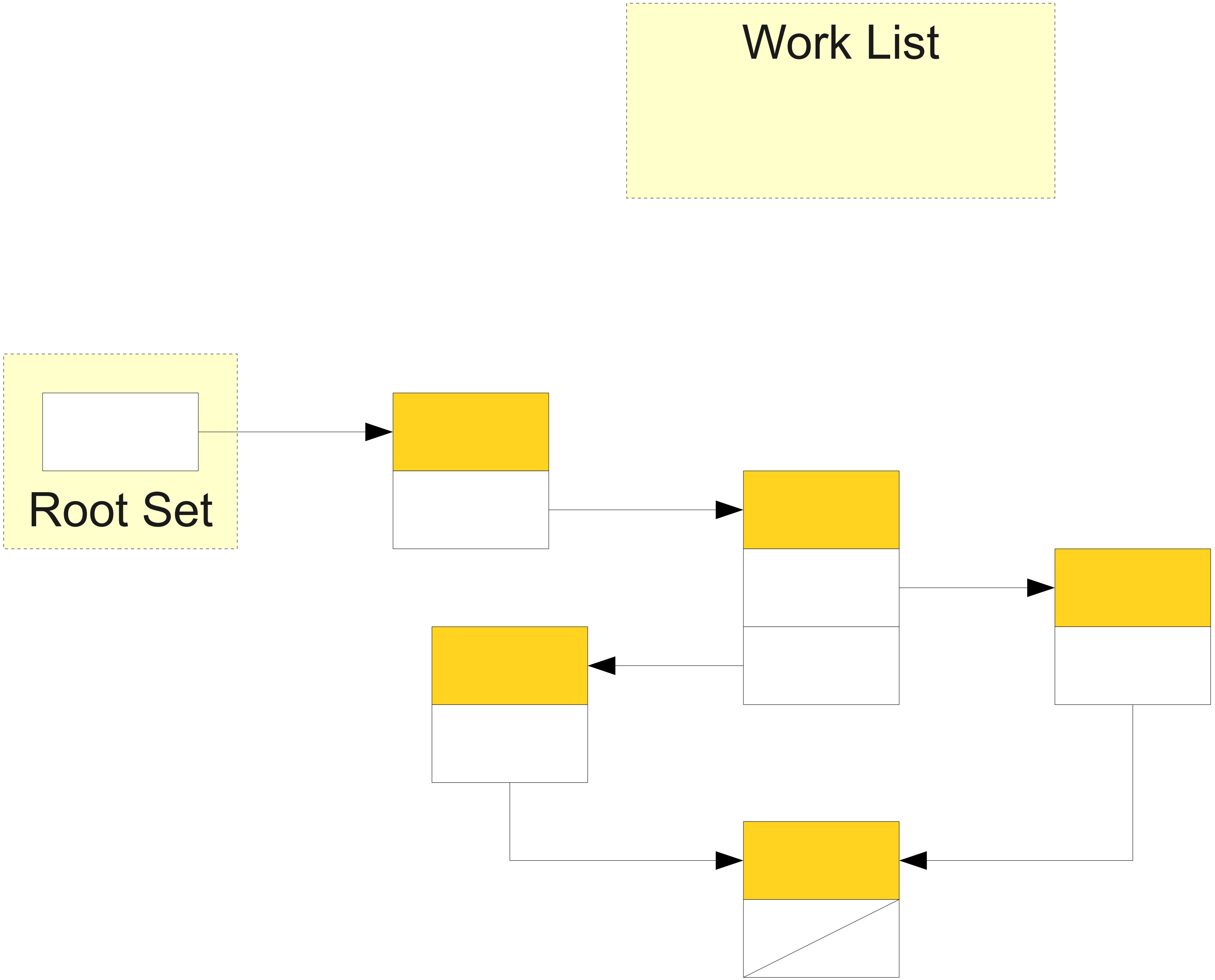

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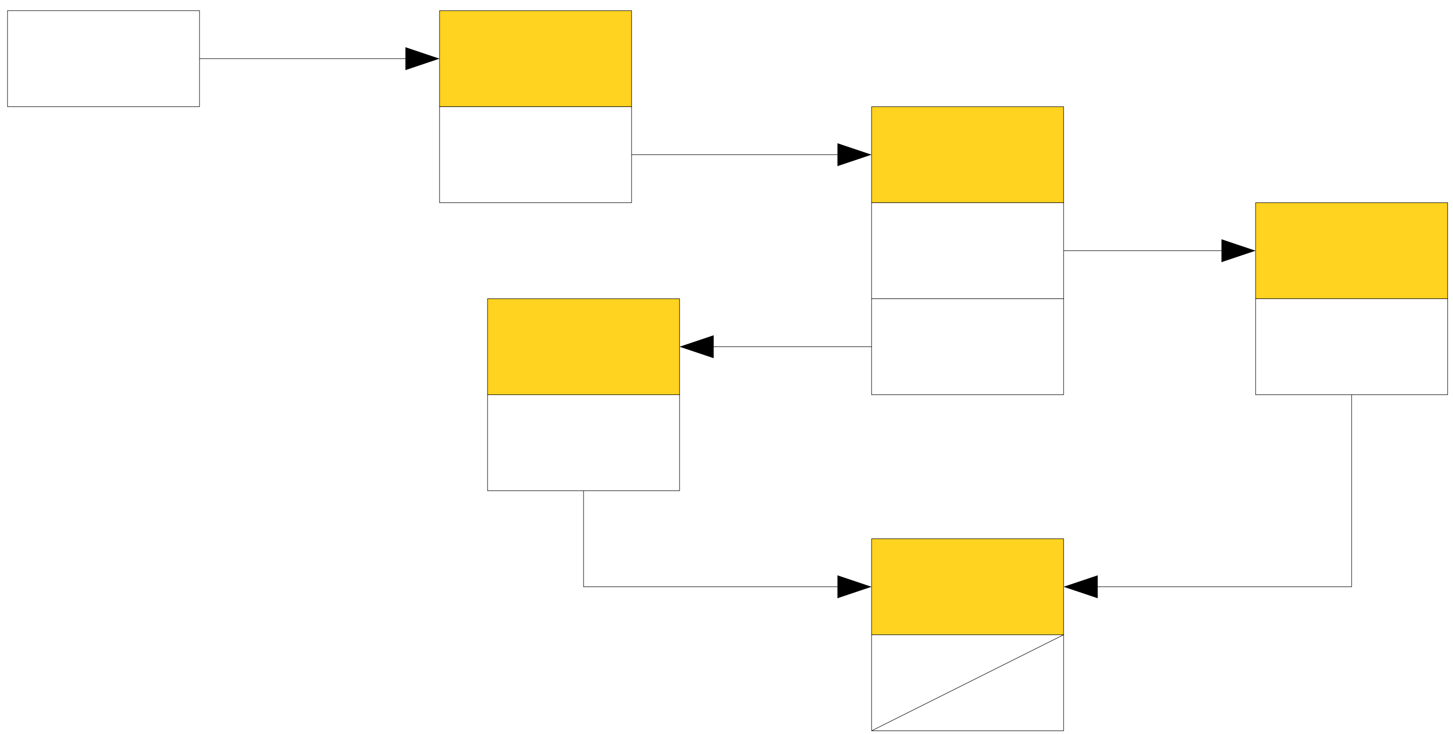


Implementing Mark-and-Sweep

- The mark-and-sweep algorithm, as described, has two serious problems.
- **Runtime proportional to number of allocated objects.**
  - Sweep phase visits all objects to free them or clear marks.
- **Work list requires lots of memory.**
  - Amount of space required could potentially be as large as all of memory.
  - Can't preallocate this space!

The Key Idea

- During a mark-and-sweep collection, every allocated block must be in exactly one of four states:
  - **Marked**: This object is known to be reachable.
  - **Enqueued**: This object is in the worklist.
  - **Unknown**: This object has not yet been seen.
  - **Deallocated**: This object has already been freed.
- Augment every allocated block with two bits to encode which of these four states the object is in.
- Maintain doubly-linked lists of all the objects in each of these states.

Baker's Algorithm

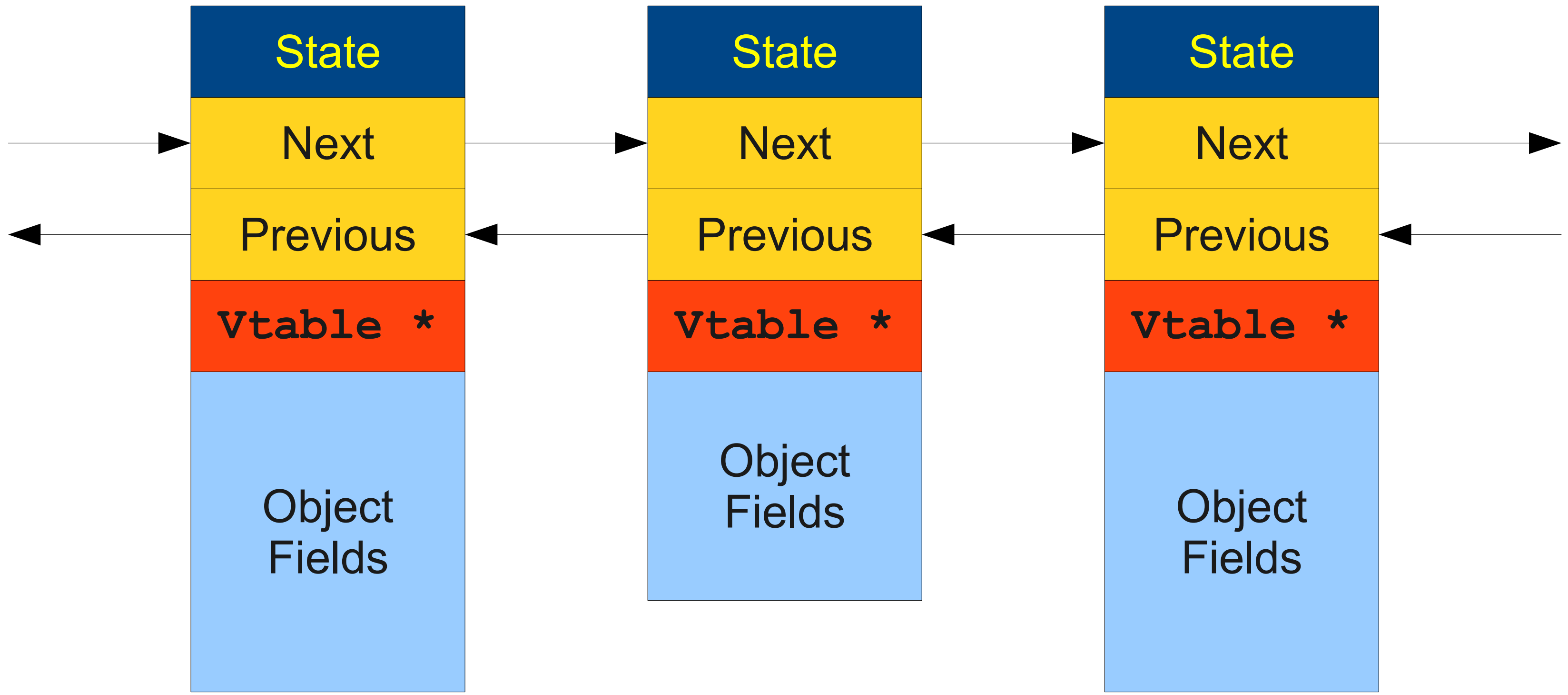
- Move all of the root set to the **enqueued** list.
- While the **enqueued** list is not empty:
  - Move the first object from the **enqueued** list to the **marked** list.
  - For each **unknown** object referenced, add it to the **enqueued** list.
- At this point, everything reachable is in **marked** and everything unreachable is in **unknown**.
- Concatenate the **unknown** and **deallocated** lists
  - Deallocates all garbage in O(1).
- Move everything from the **marked** list to the **unknown** list.
  - Can be done in O(1).
  - Indicates objects again must be proven reachable on next scan.

One Last Detail

- But wait – if we're already out of memory, how do we build these linked lists?

One Last Detail

- But wait – if we're already out of memory, how do we build these linked lists?
- **Idea**: Since every object can only be in one linked list, embed the next and previous pointers into each allocated block.



Analysis of Mark-and-Sweep

- Advantages:
  - Precisely finds exactly the reachable objects.
  - Using Baker's algorithm, runs in time proportional to the number of reachable objects.
- Disadvantages:
  - Stop-the-world approach may introduce huge pause times.
  - Linked list / state information in each allocated block uses lots of memory per object.

Stop-and-Copy

Improving Performance

- There are many ways to improve a program's performance, some of which can be improved by a good garbage collector:
- **Increasing locality**.
  - Memory caches are often designed to hold adjacent memory locations.
  - Placing objects consecutively in memory can improve performance by reducing cache misses.
- **Increasing allocation speed**.
  - Many languages (Java, Haskell, Python, etc.) allocate objects frequently.
  - Speeding up object allocation can speed up program execution.

Increasing Locality

- **Idea**: When doing garbage collection, move all objects in memory so that they are adjacent to one another.
  - This is called **compaction**.
- Ideally, move objects that reference one another into adjacent memory locations.
- Garbage collector must update all pointers in all objects to refer to the new object locations.
- Could you do this in Java?
- Could you do this in C++?

Increasing Allocation Speed

- Typically implementations of **`malloc`** and **`free`** use **free lists**, linked lists of free memory blocks.
- Allocating an object requires following these pointers until a suitable object is found.
  - Usually fast, but at least 10 assembly instructions.
- Contrast with stack allocation – just one assembly instruction!
- Can we somehow get the performance speed of the stack for dynamic allocation?

The Stop-and-Copy Collector

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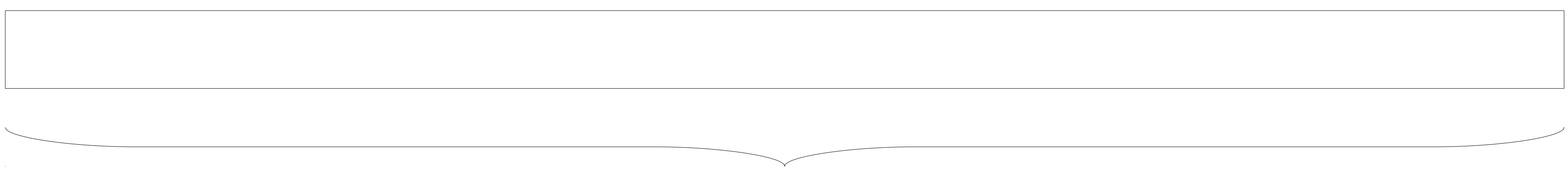

All of memory

The Stop-and-Copy Collector

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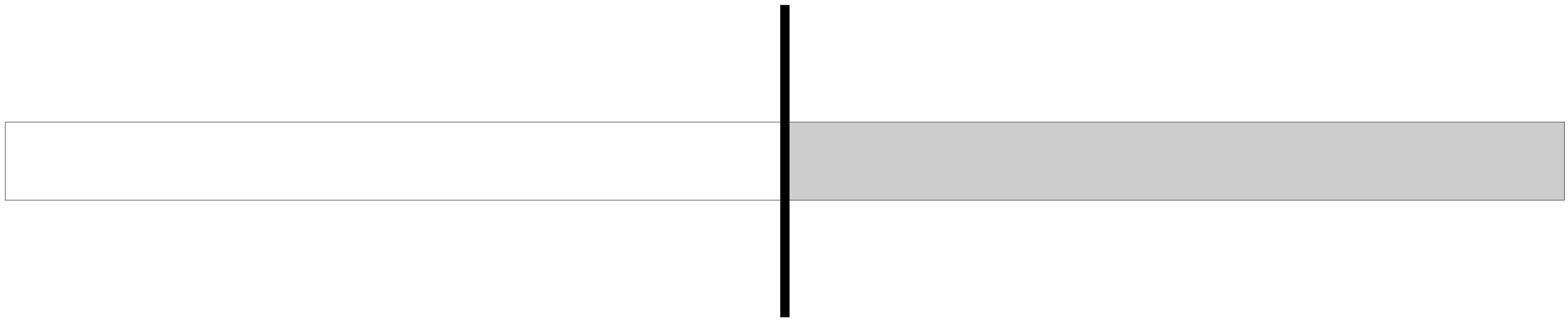

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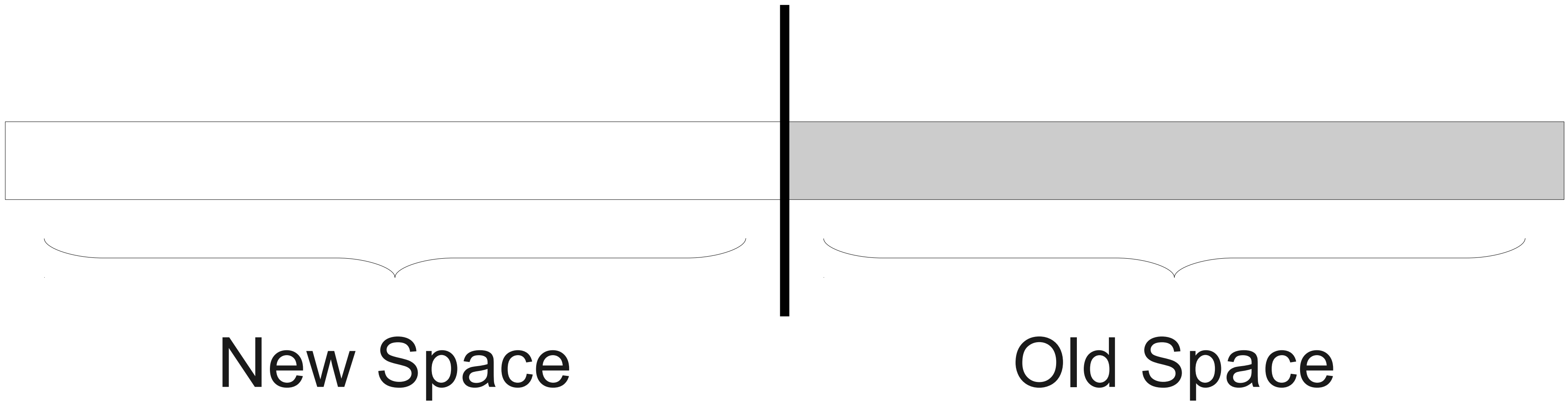

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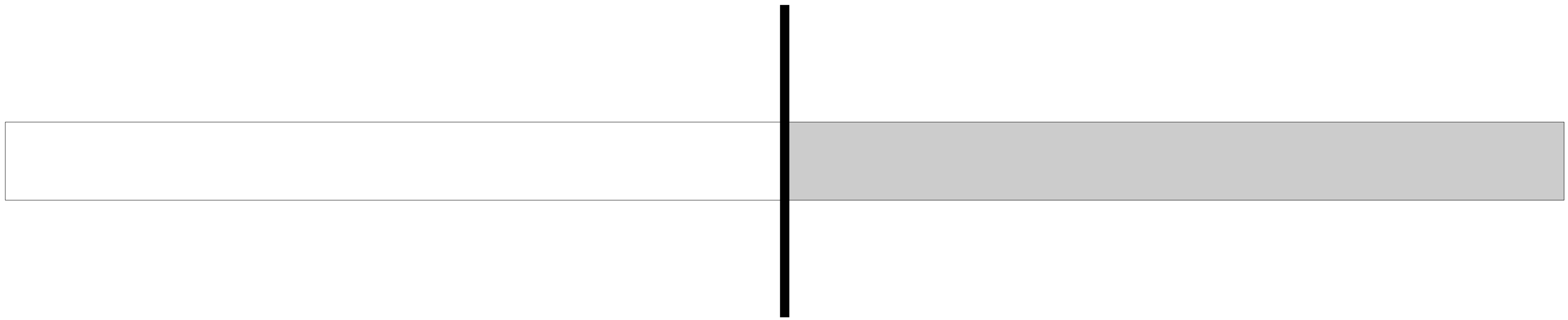

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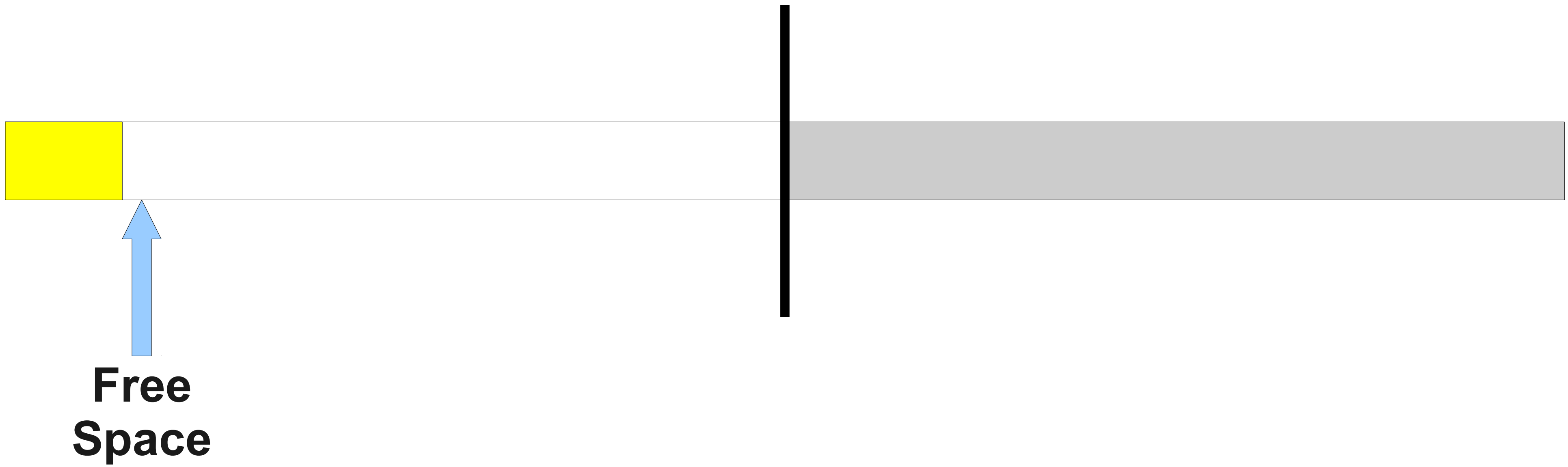

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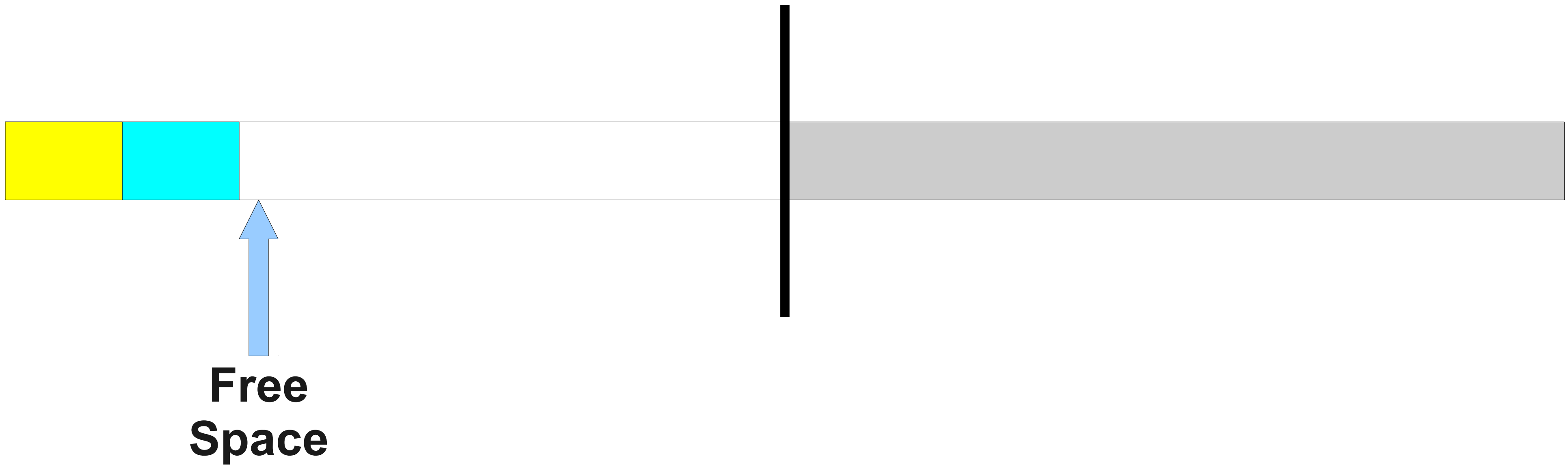

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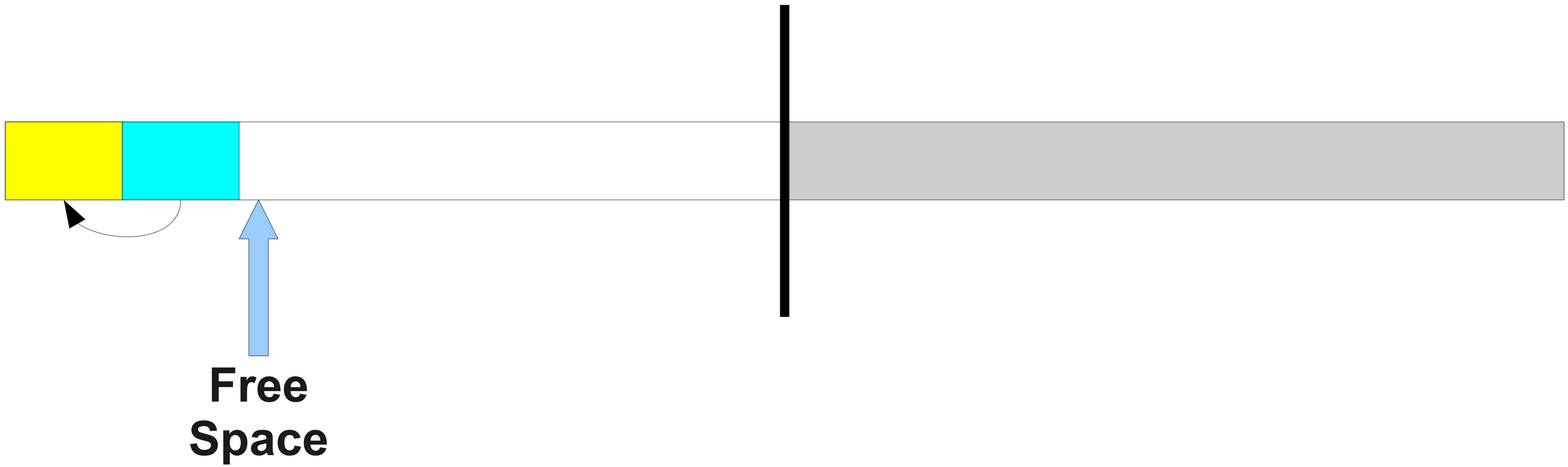

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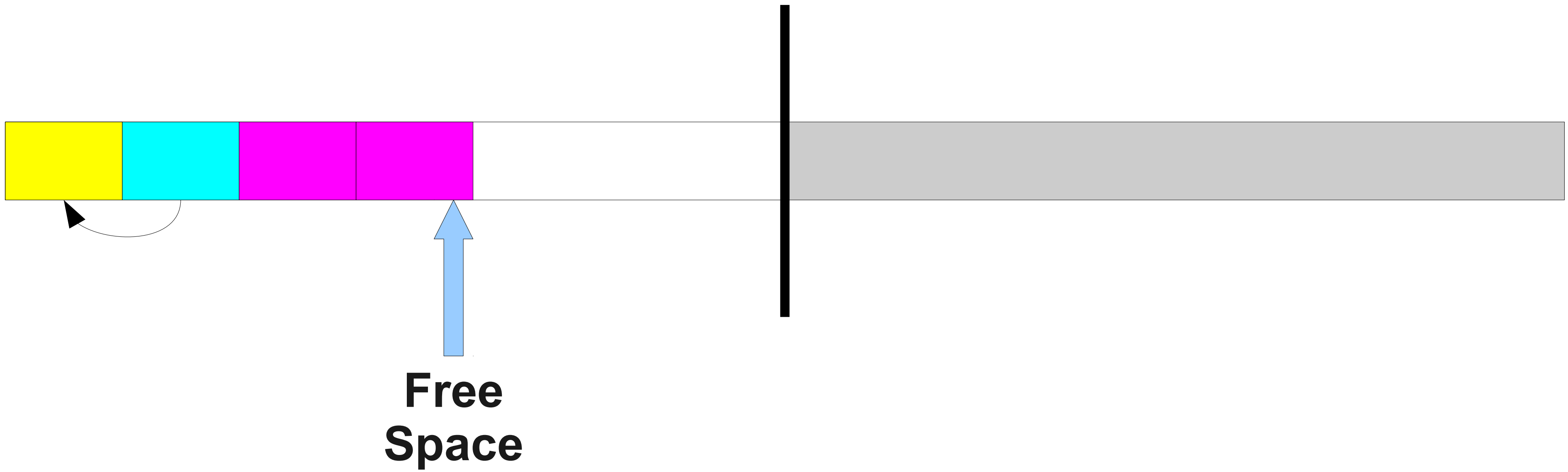

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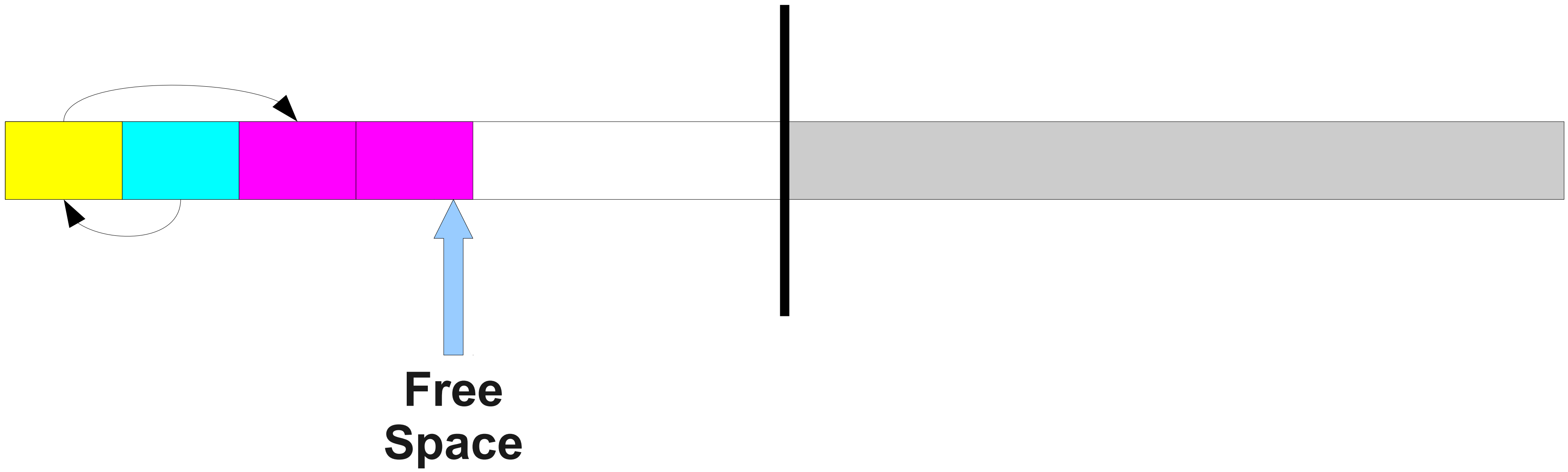

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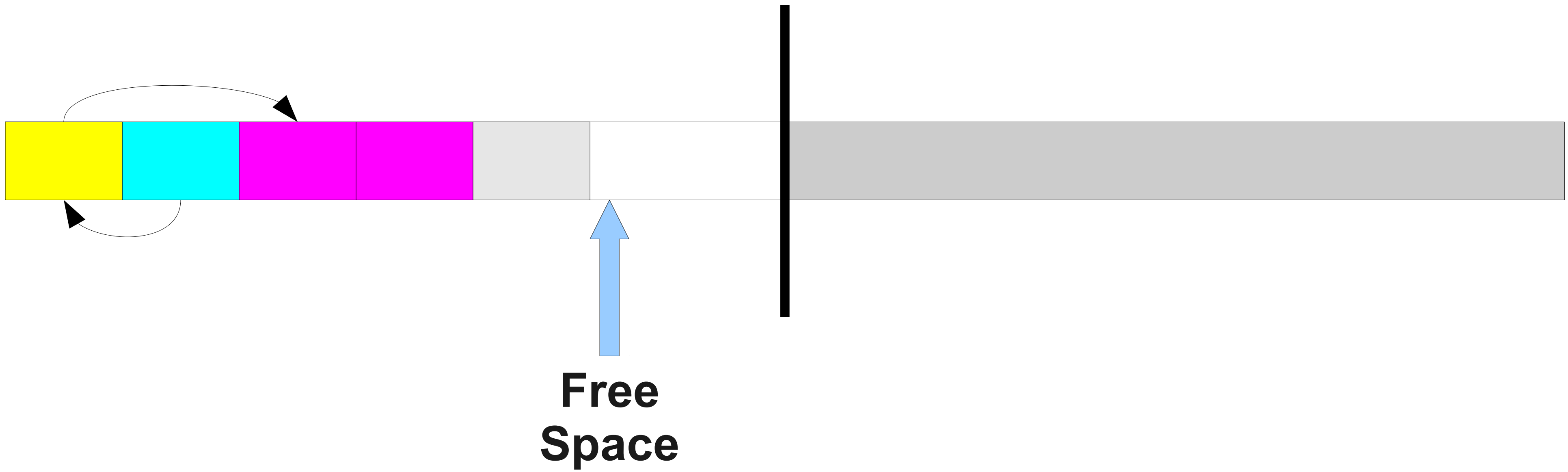

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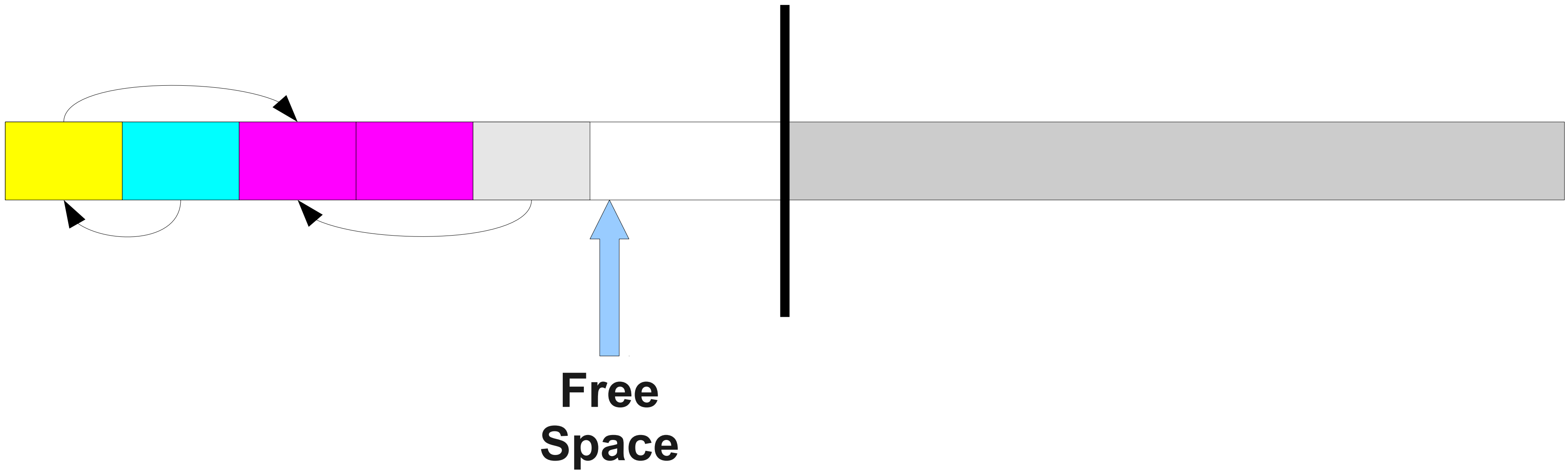

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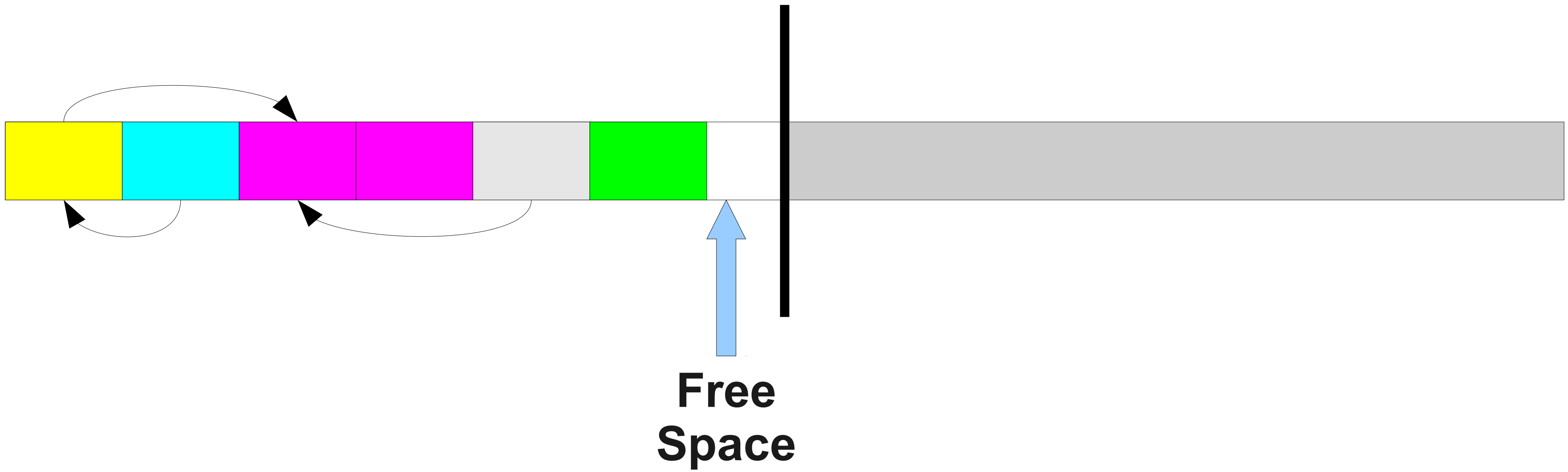

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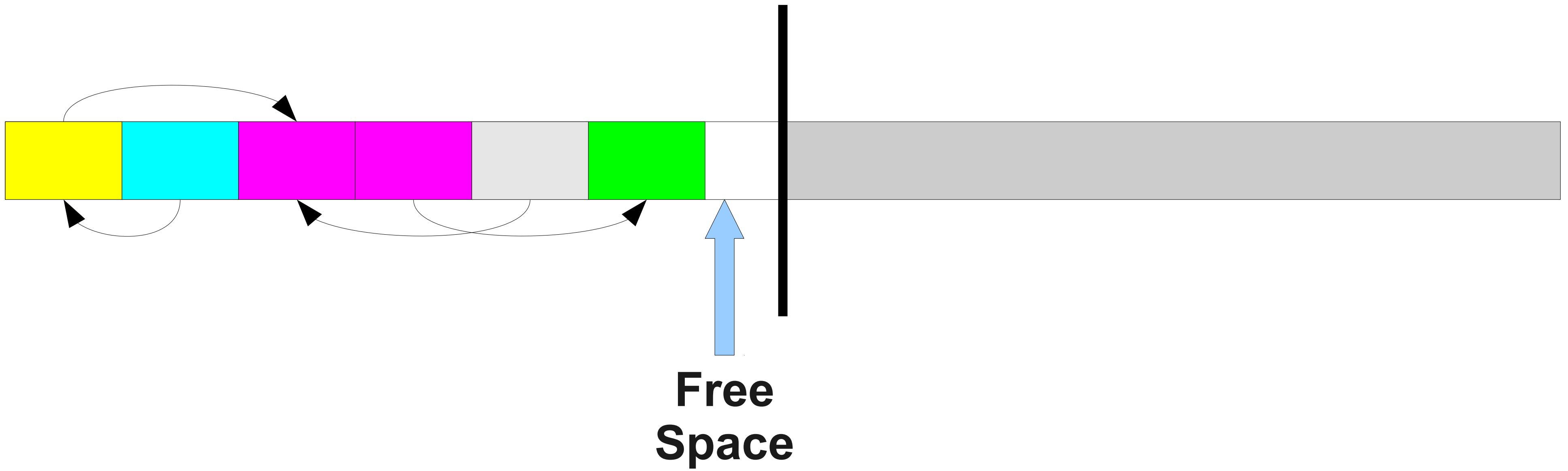

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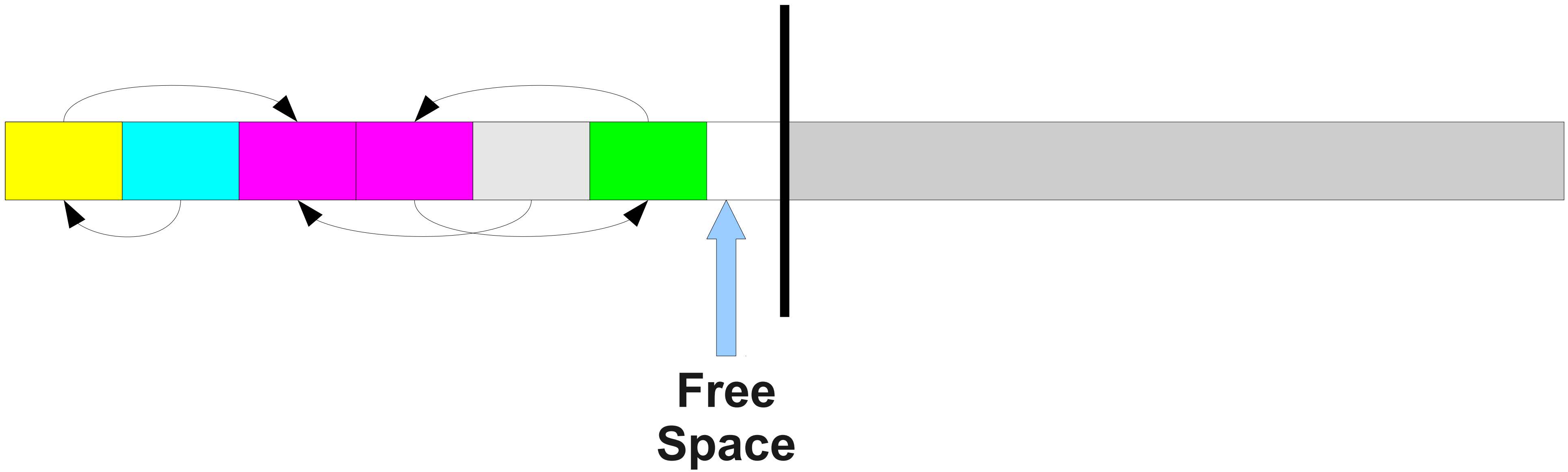

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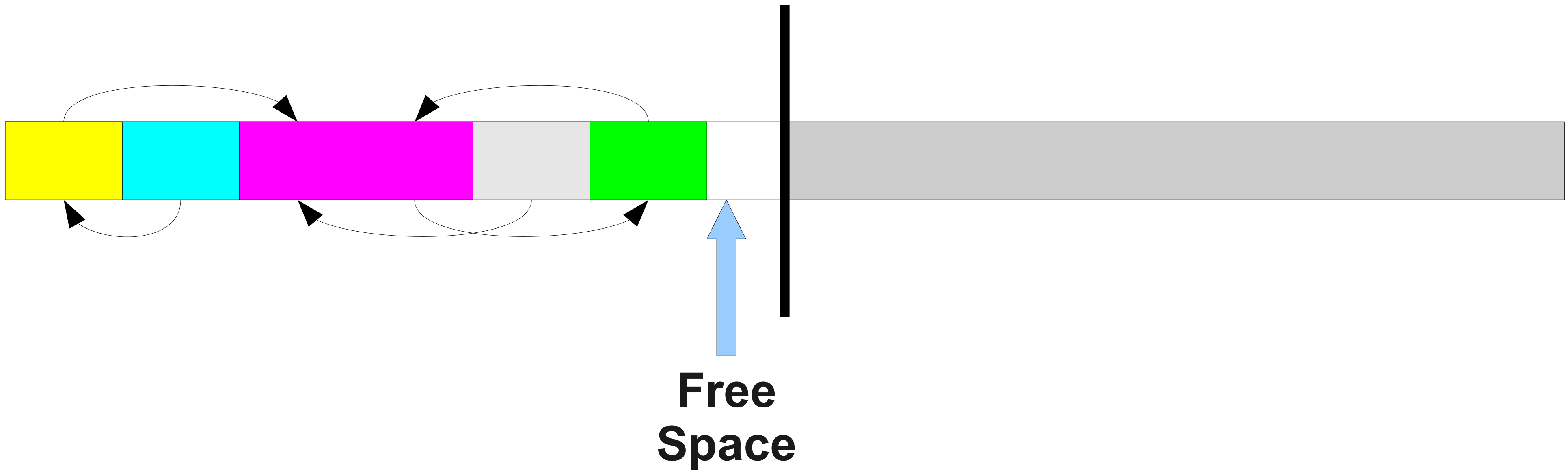
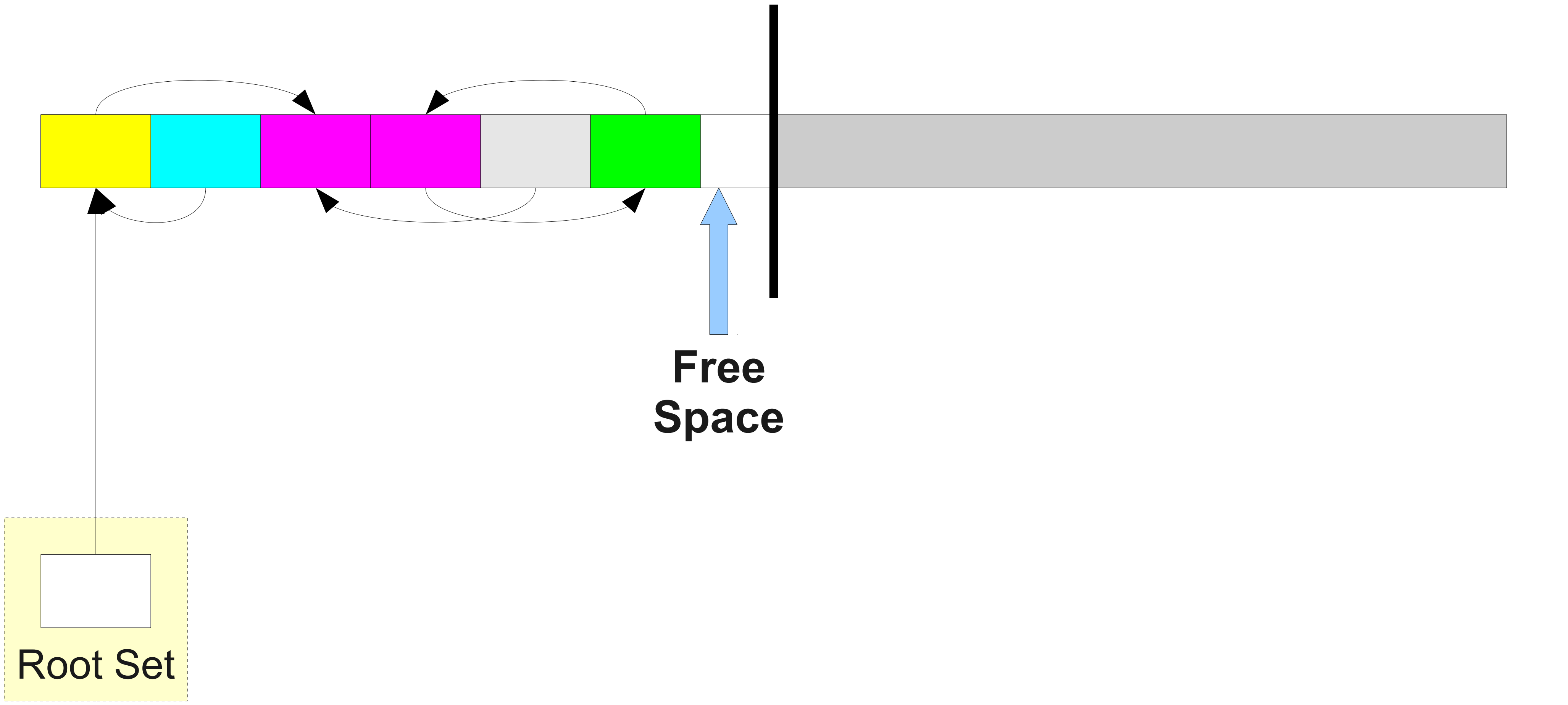


Out of space!

The Stop-and-Copy Collector



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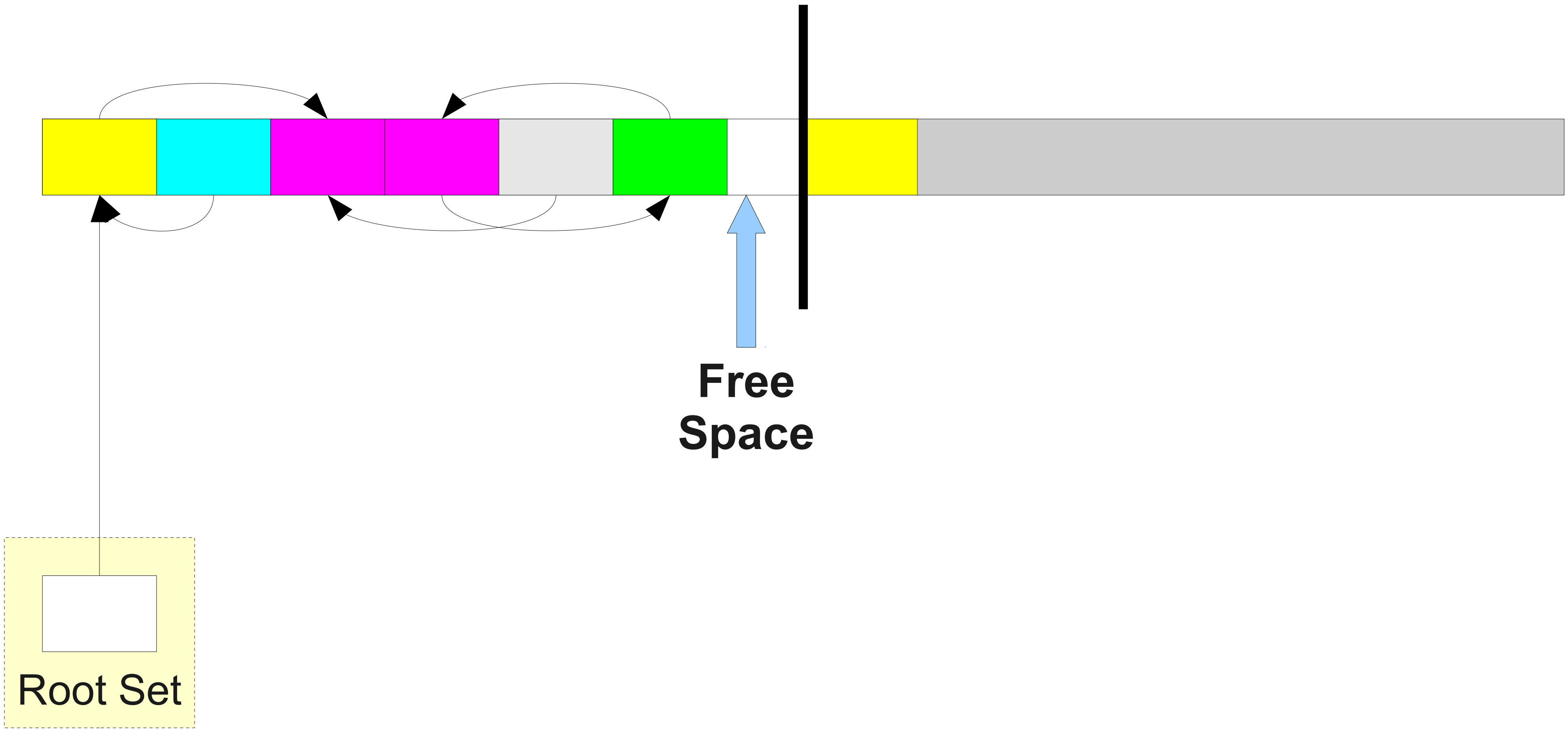

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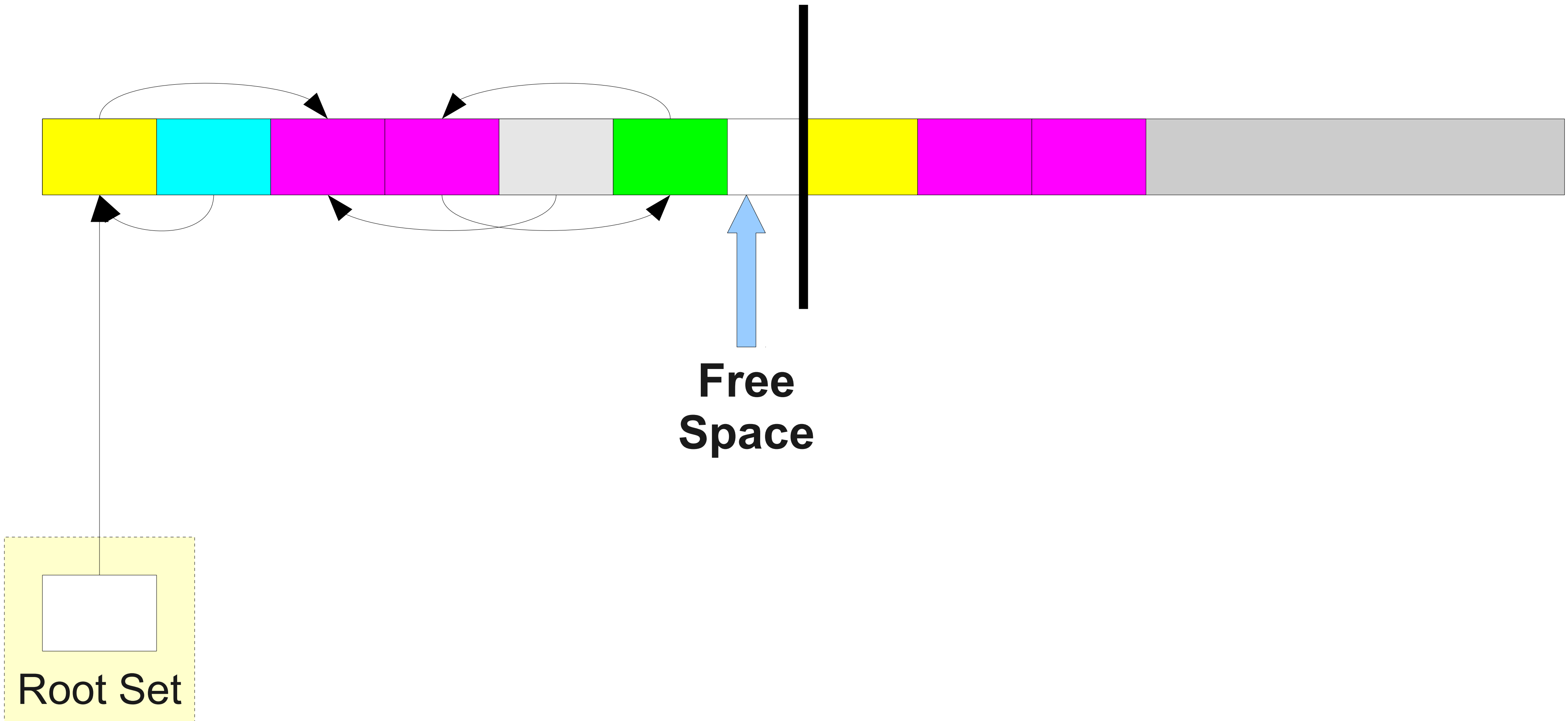

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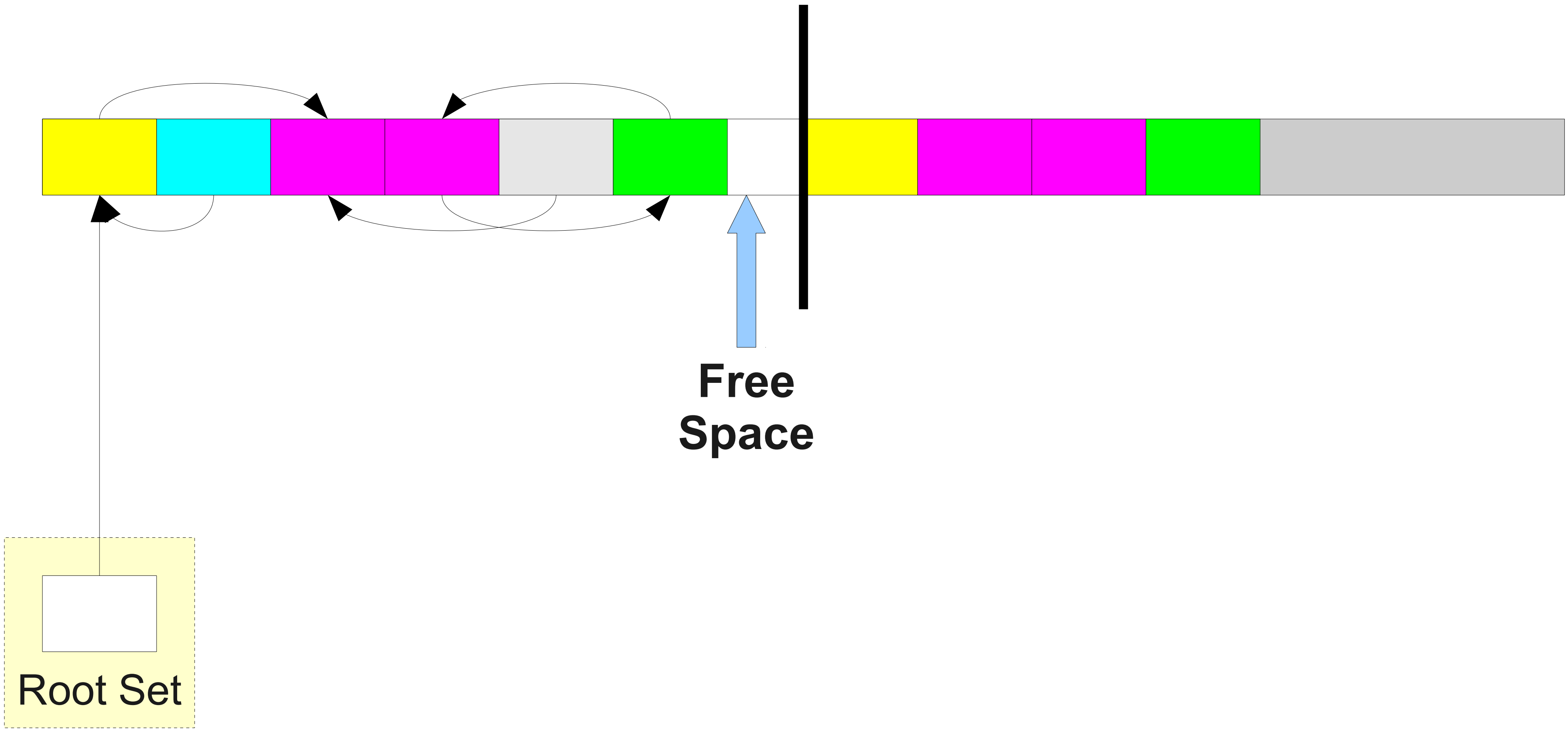

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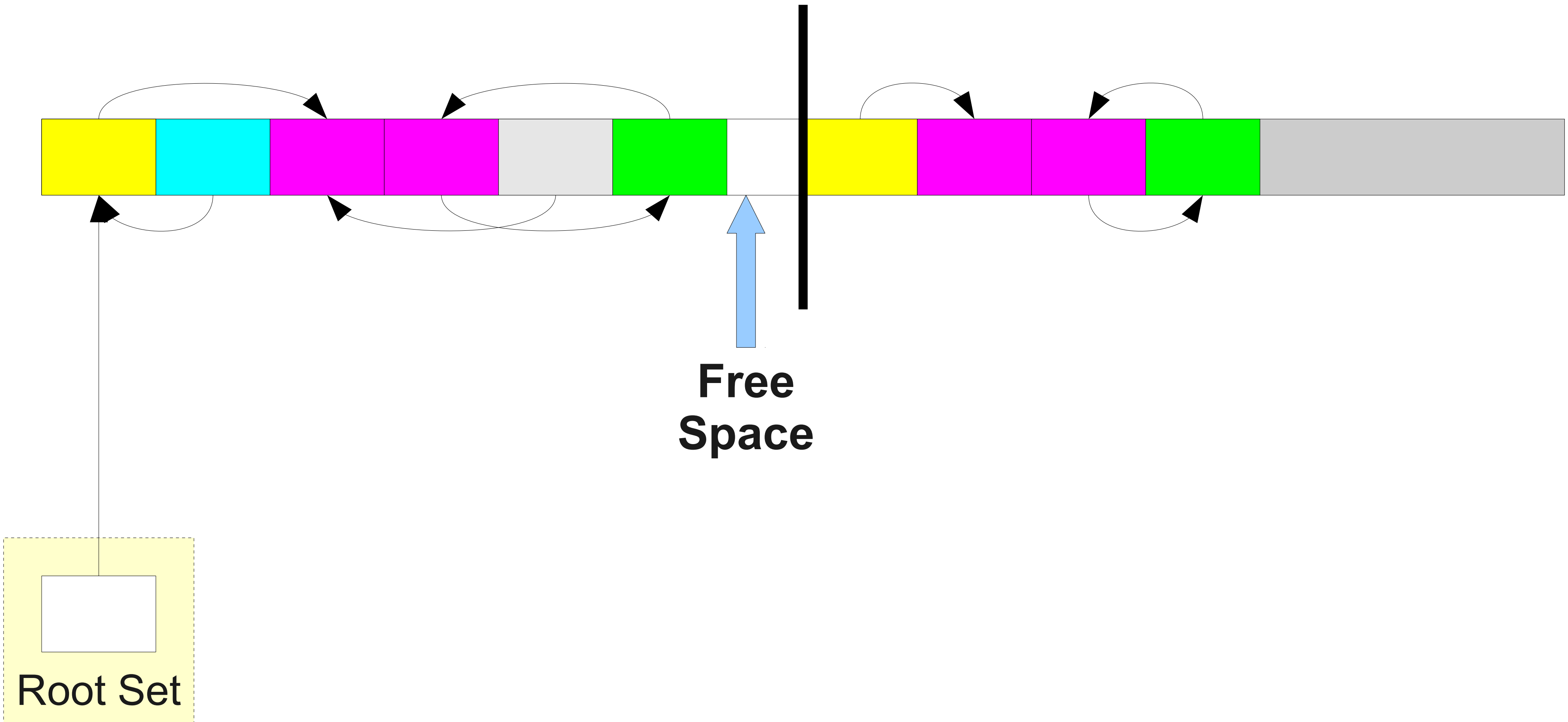

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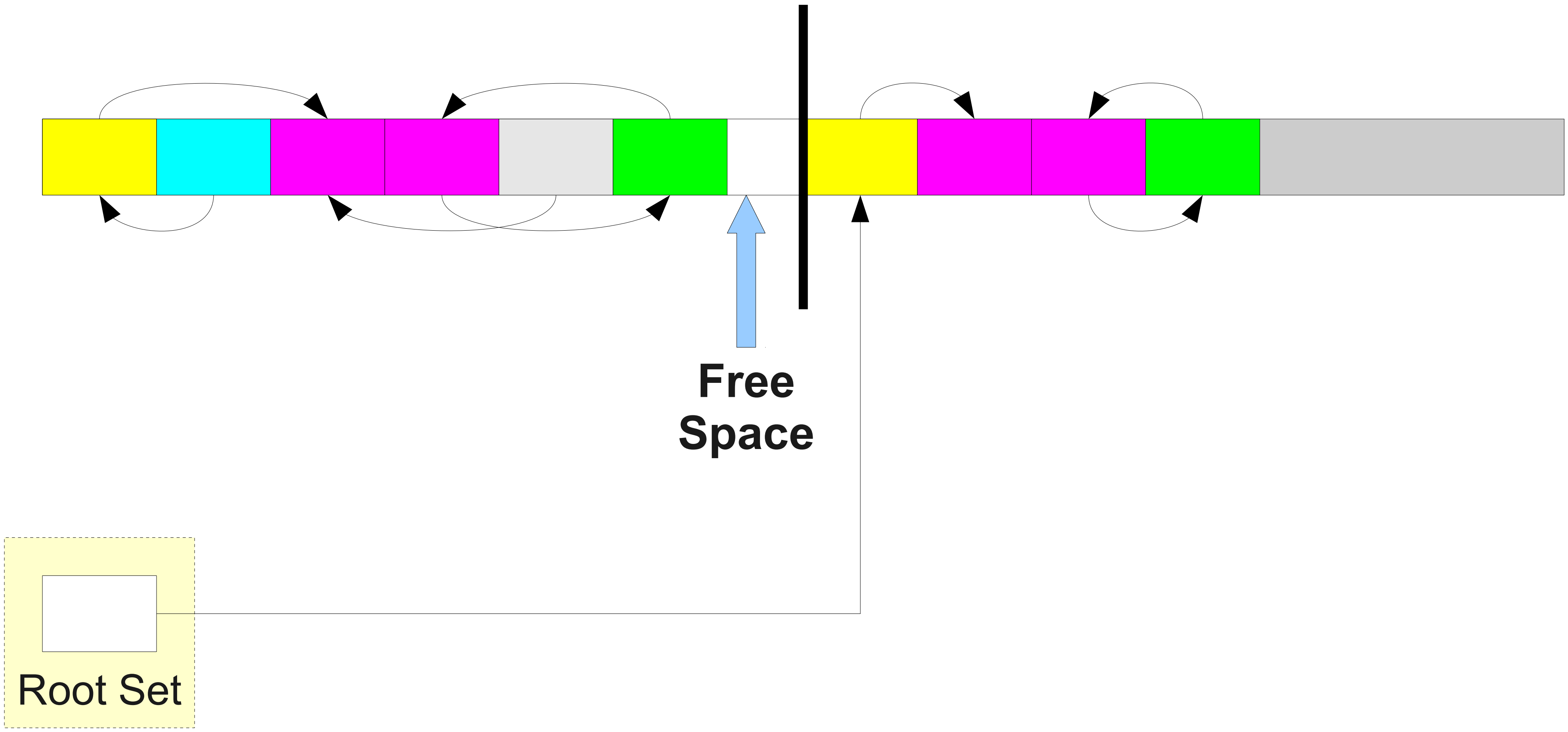

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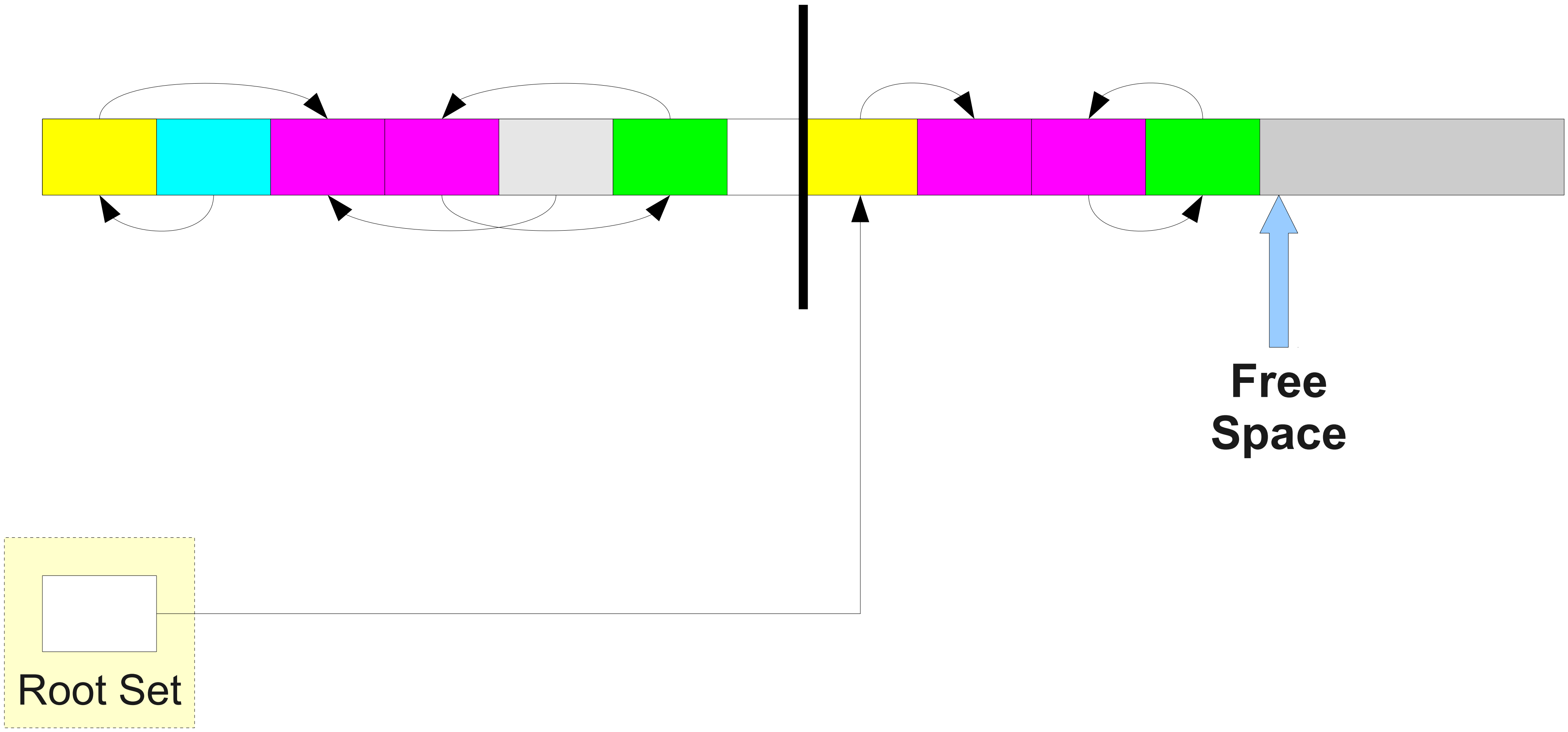

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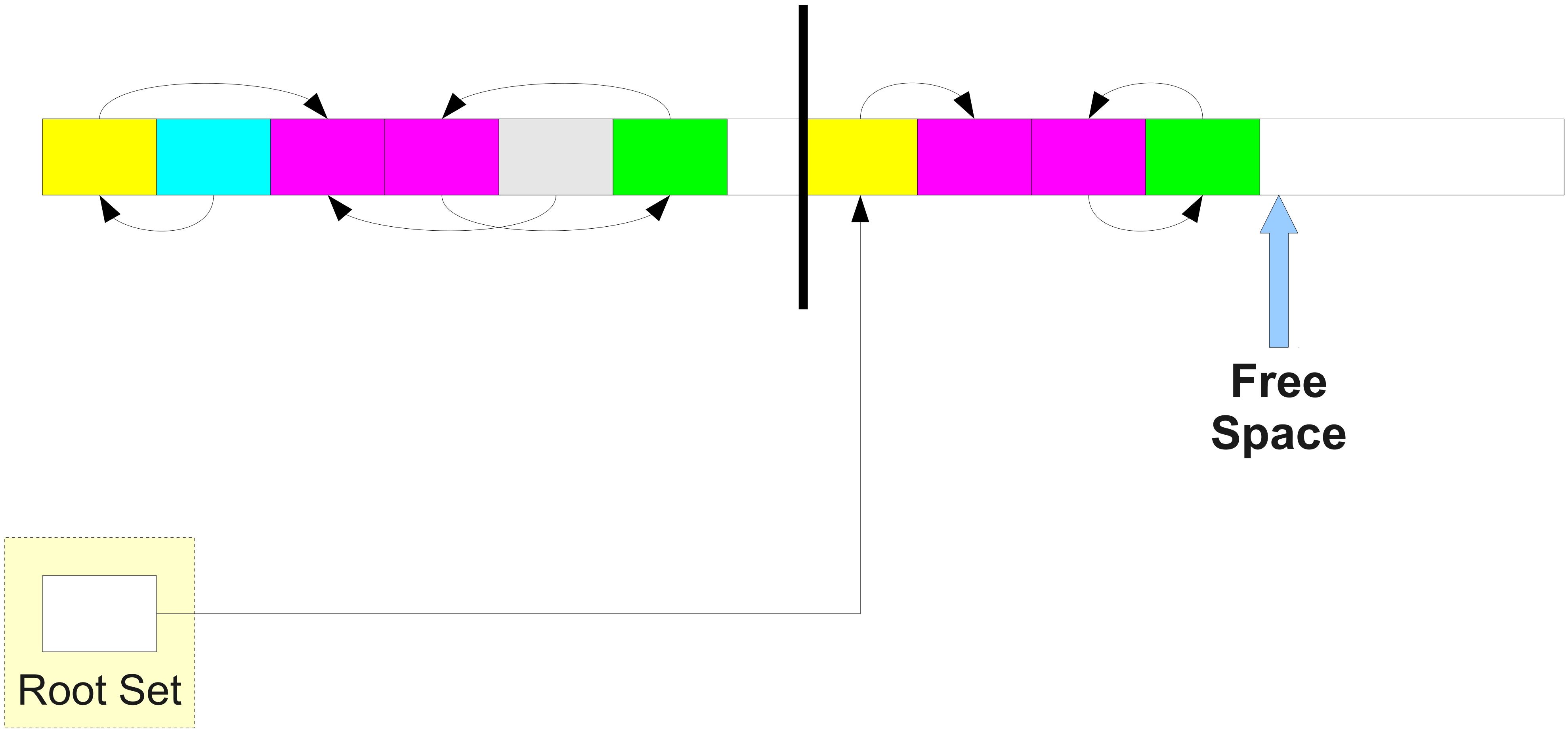

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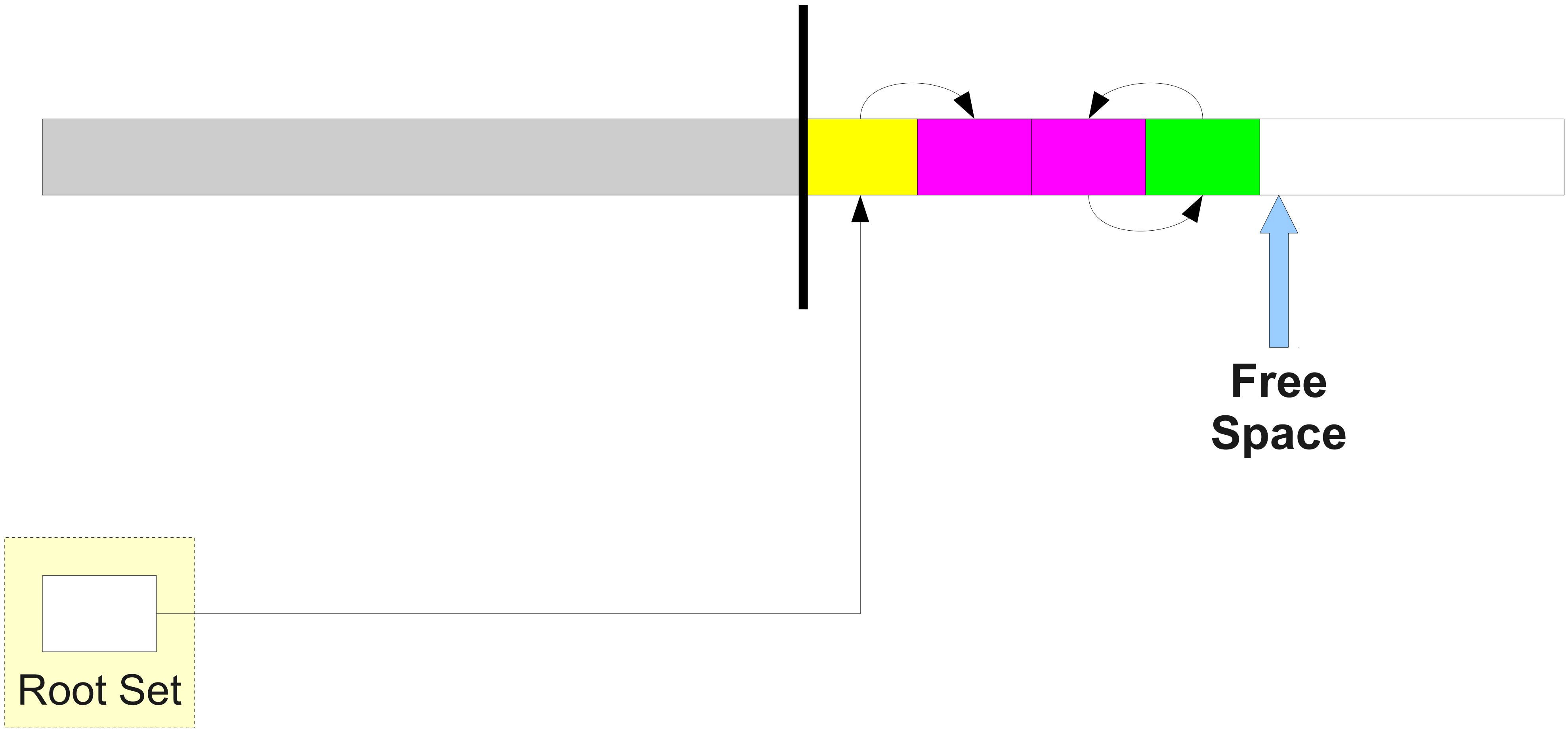

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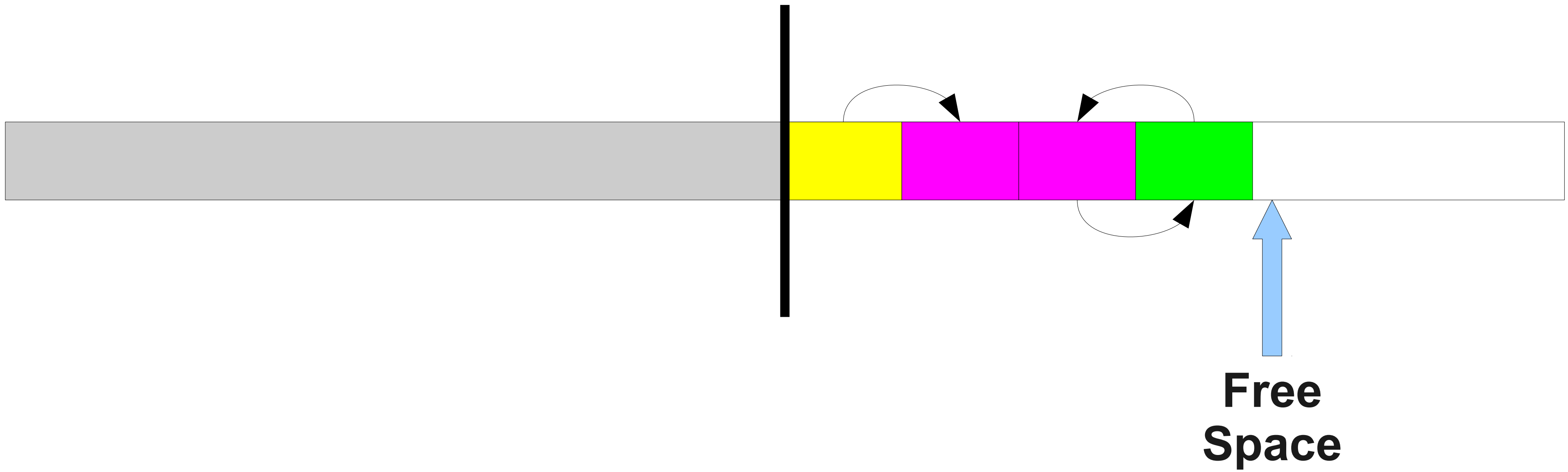

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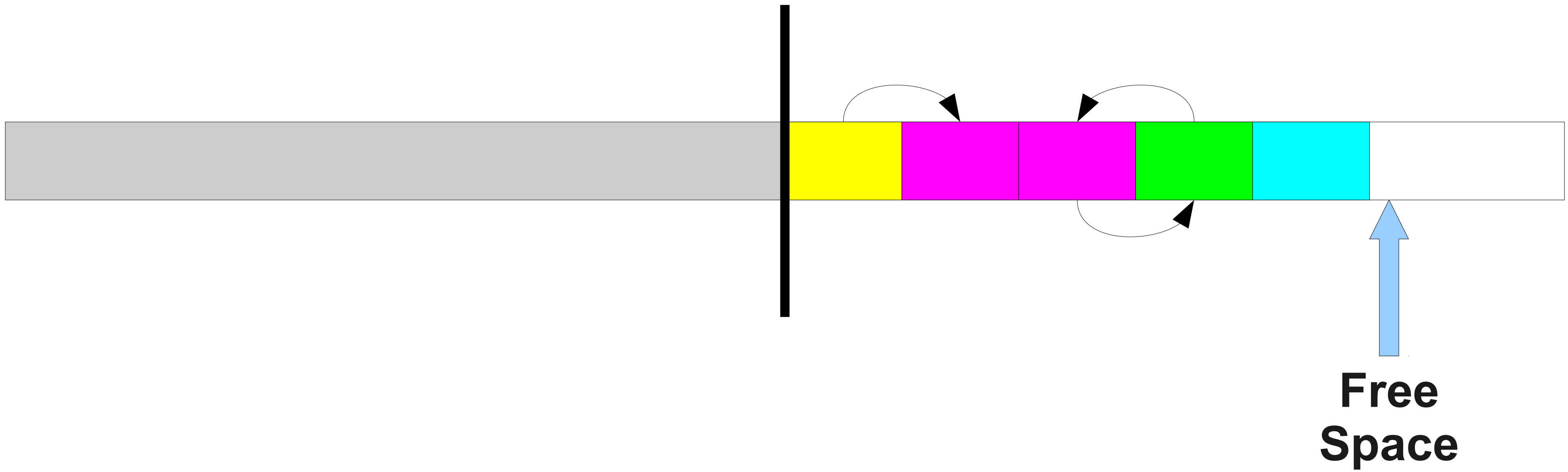

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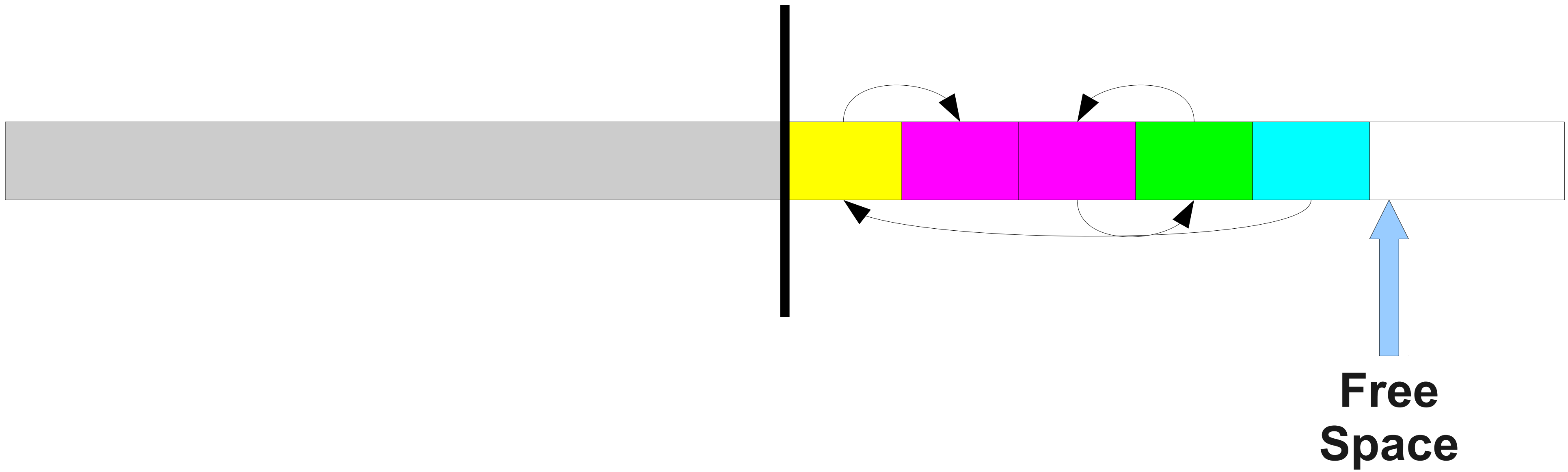

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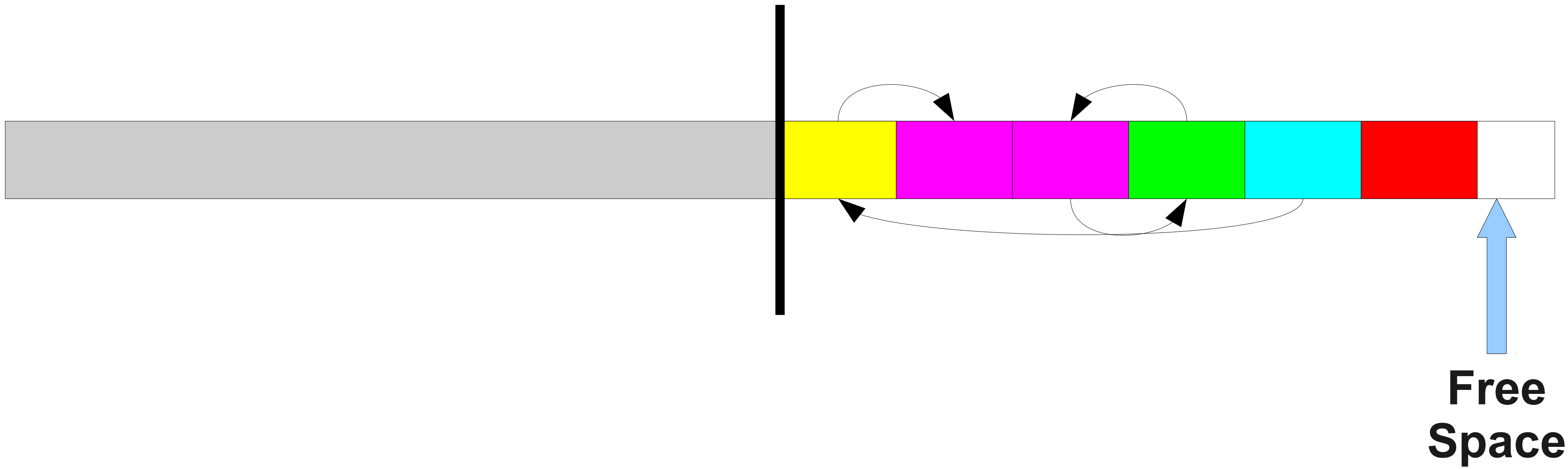

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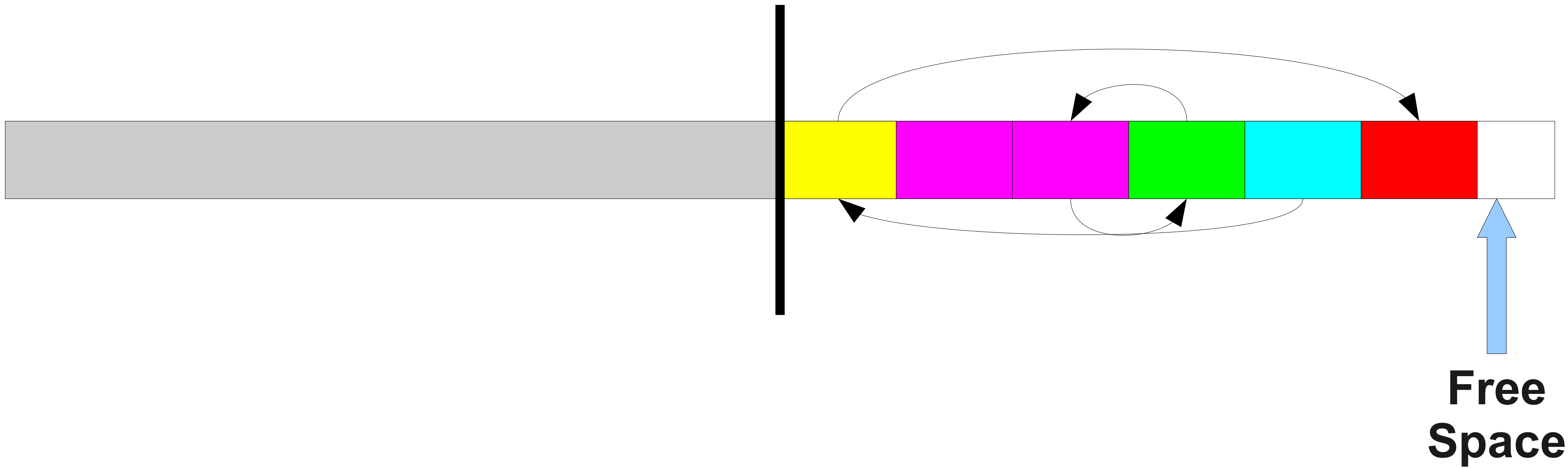

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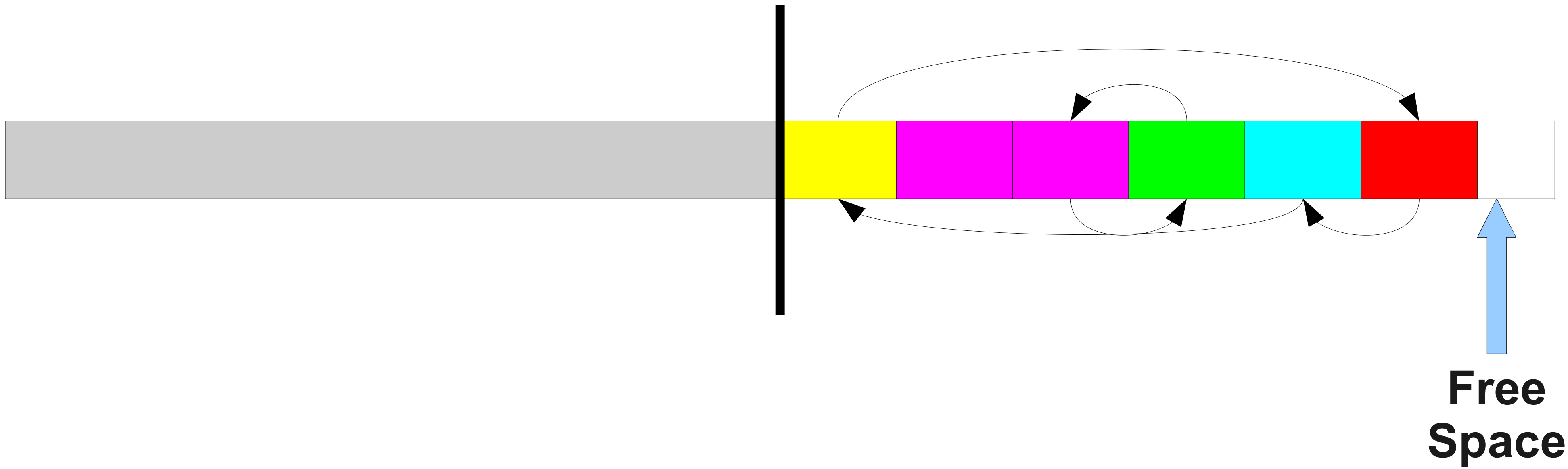

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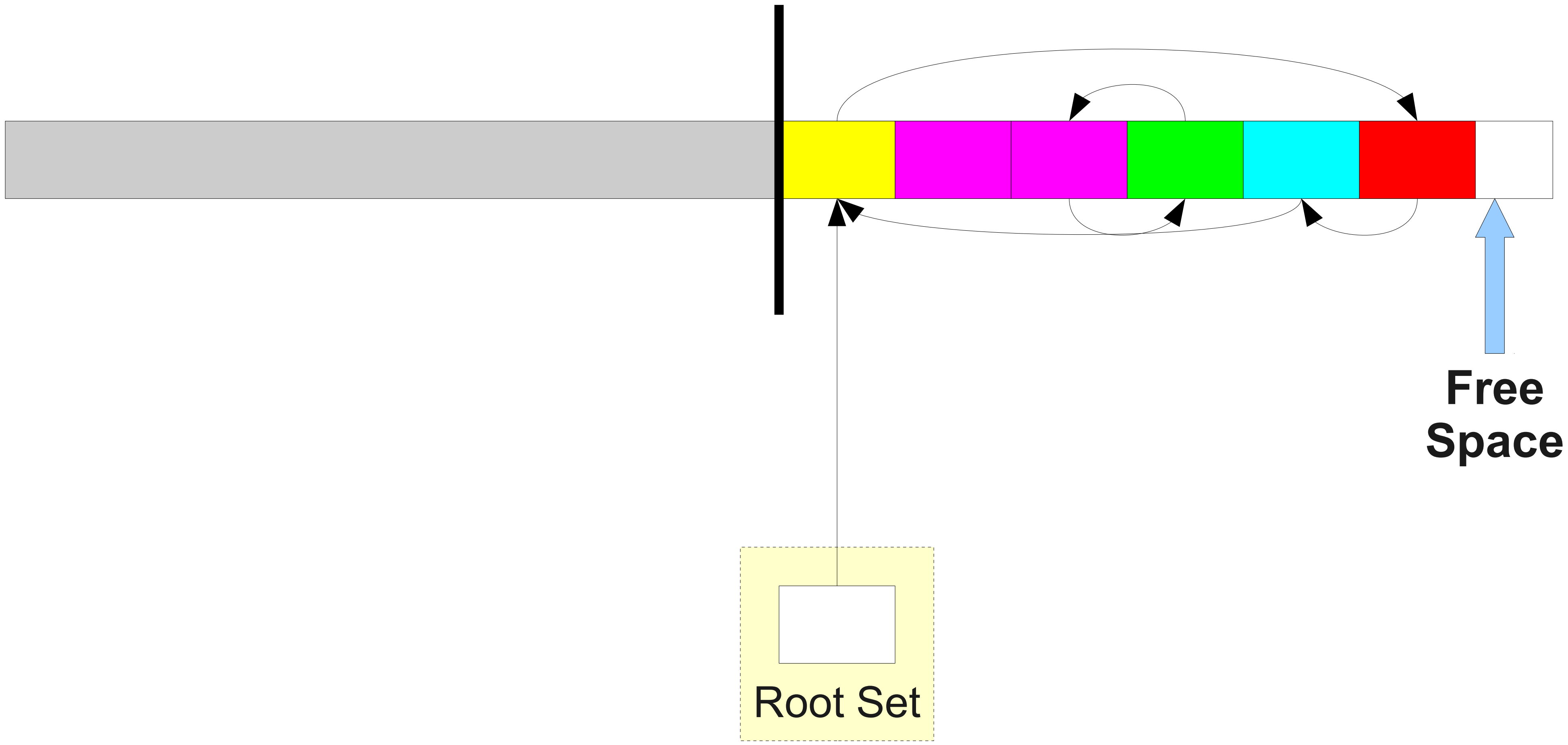

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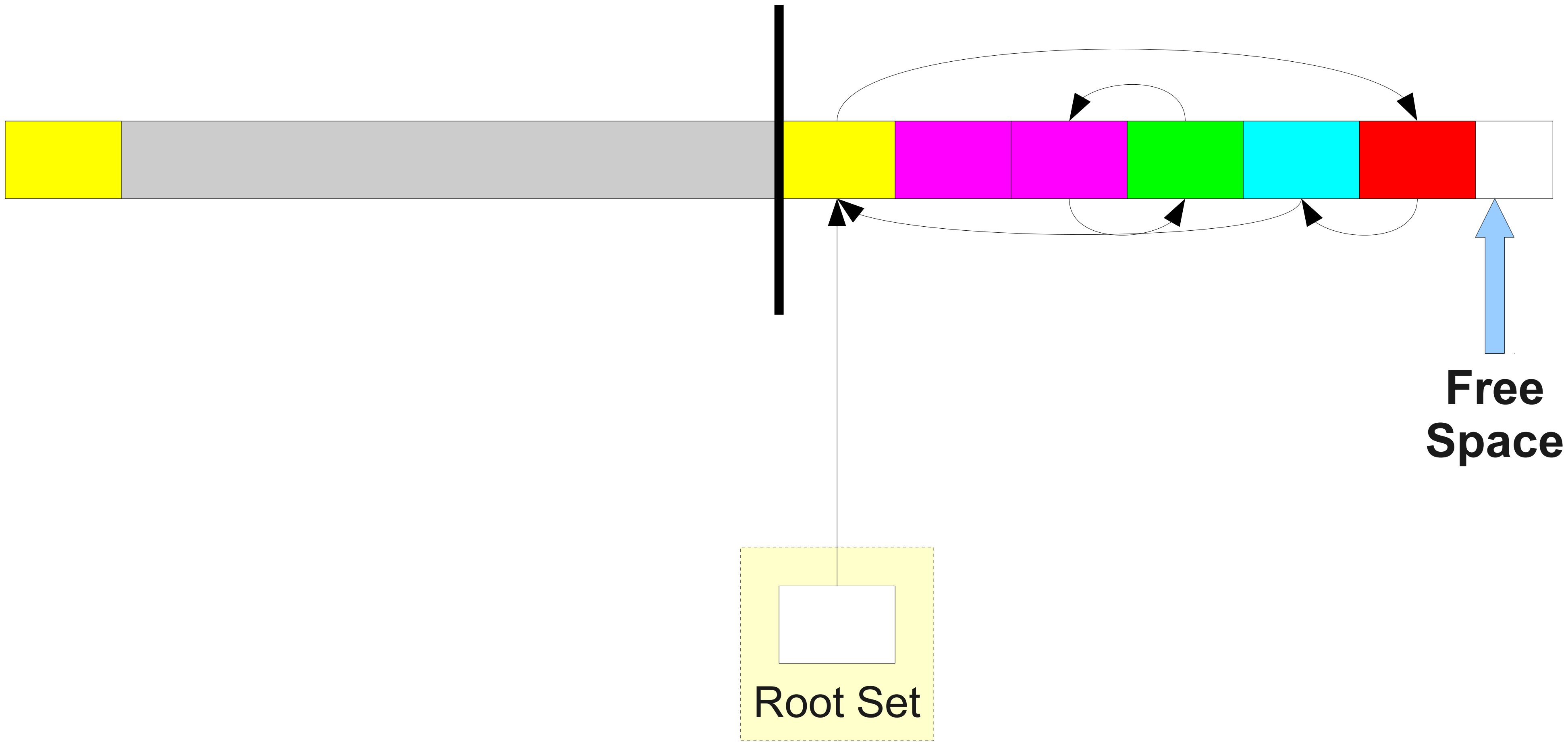

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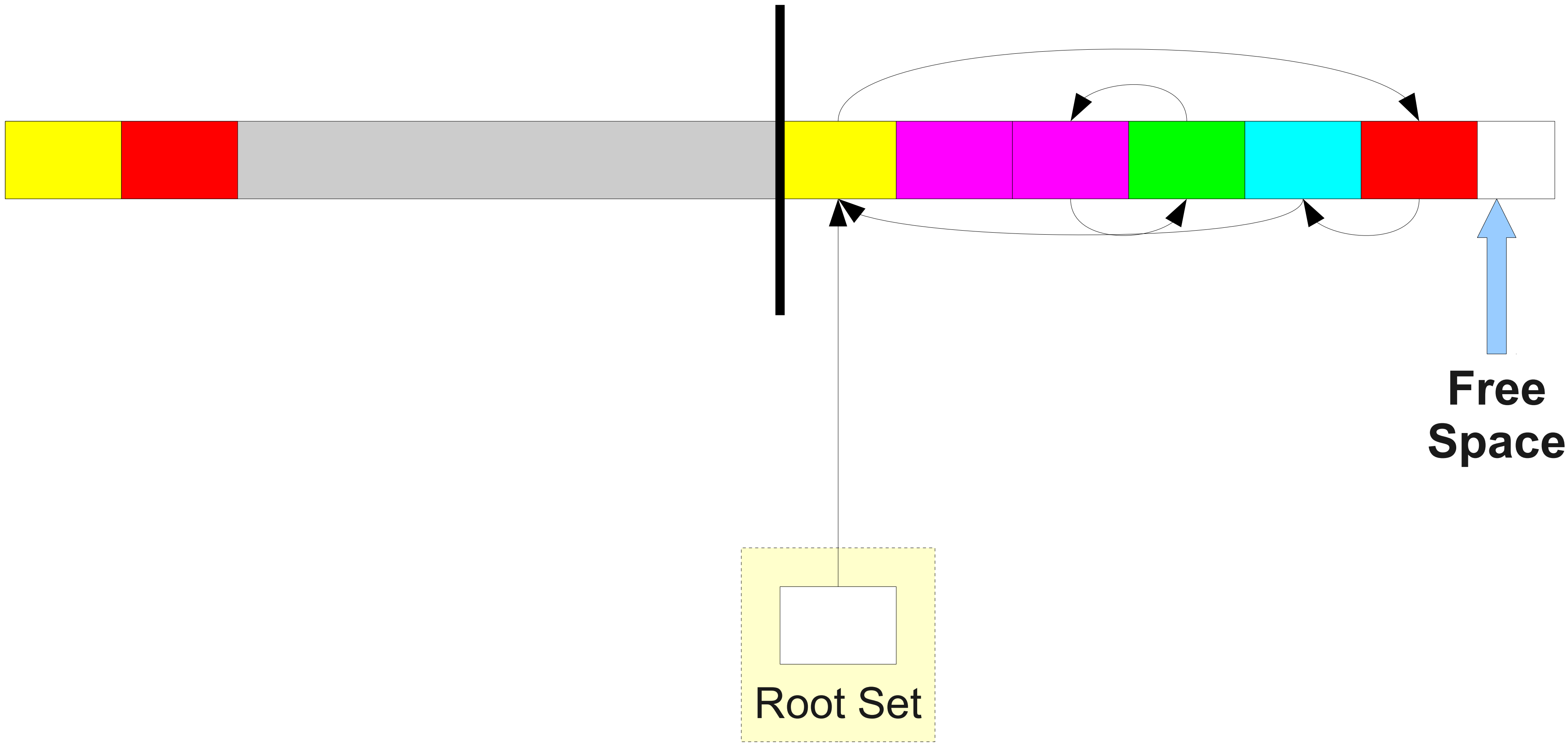

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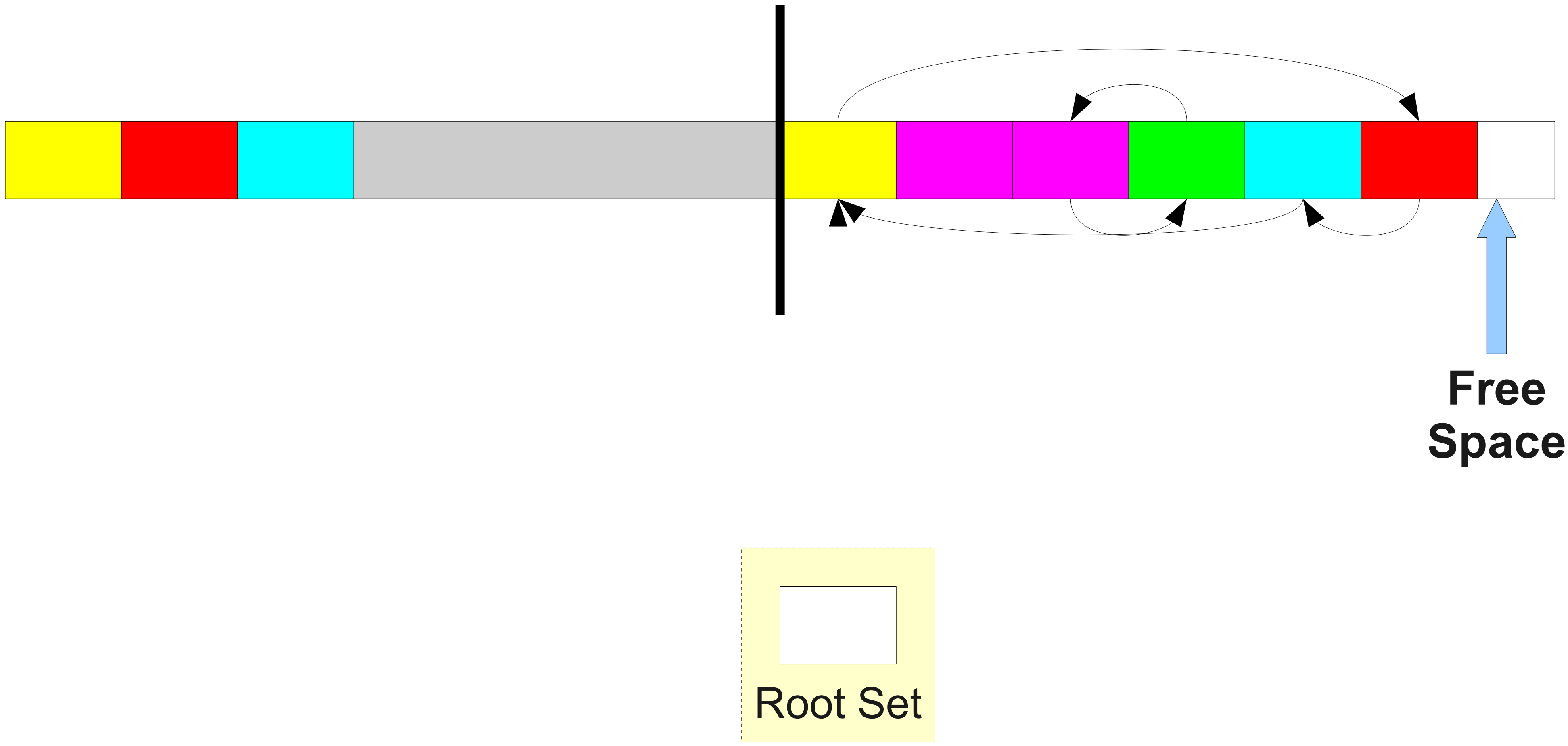

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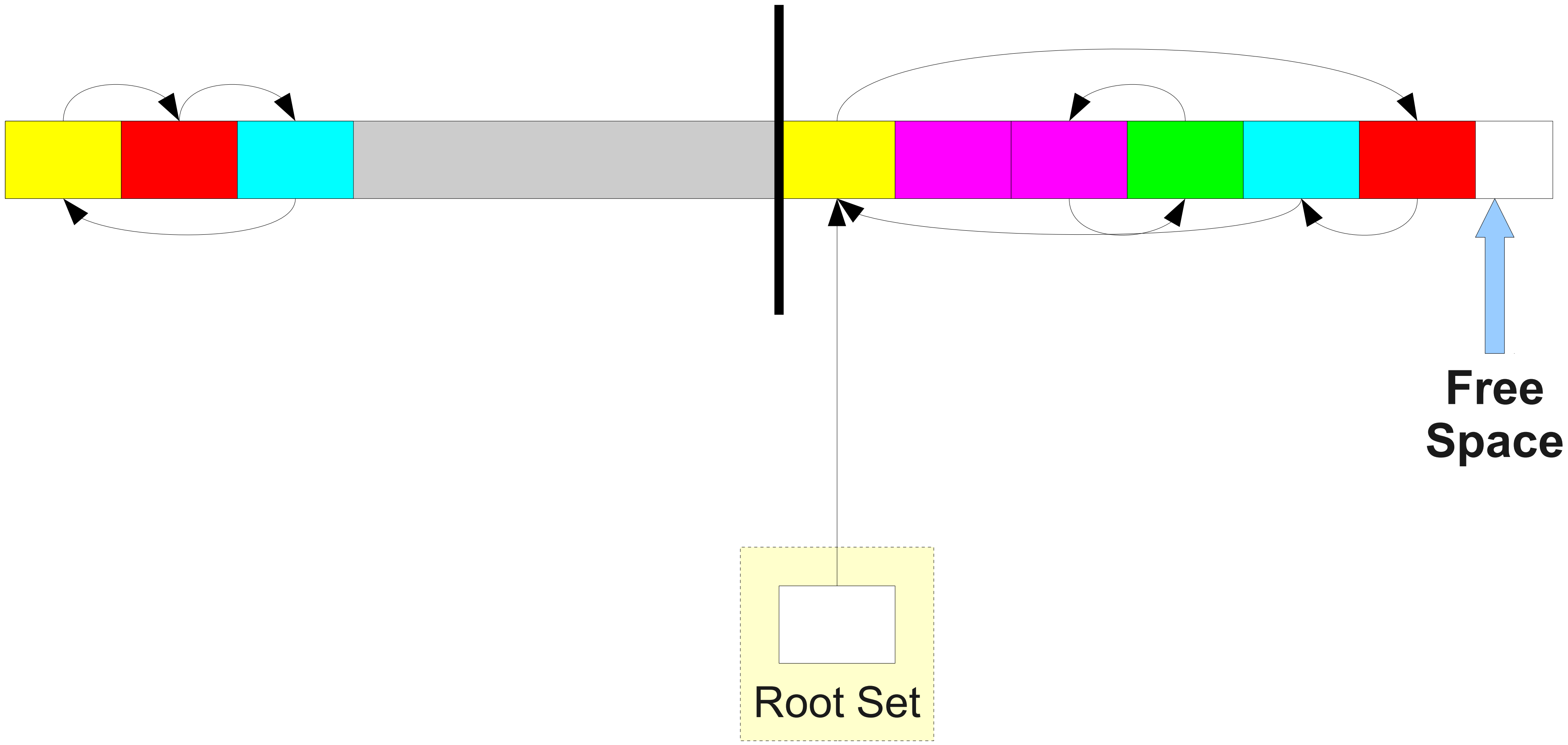

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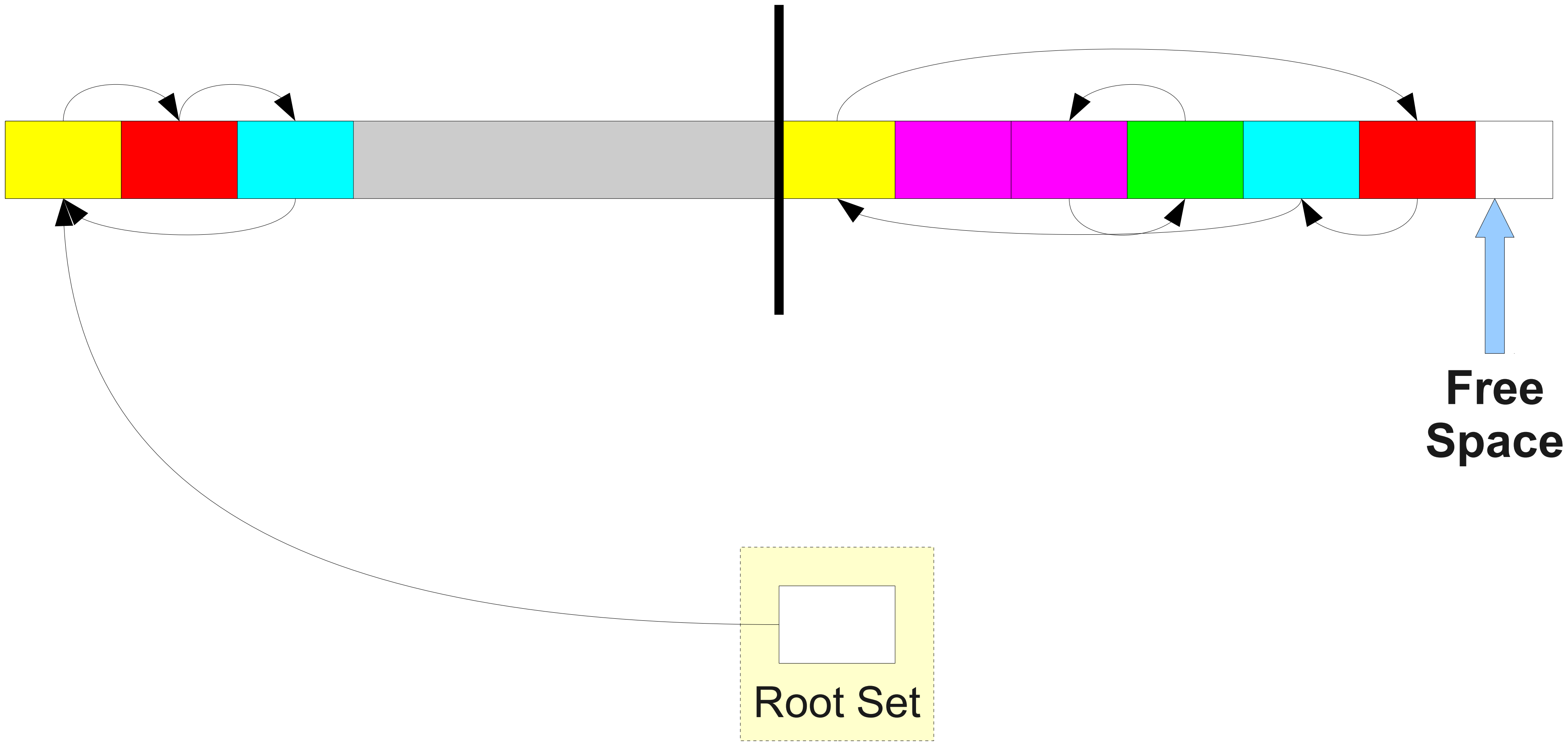

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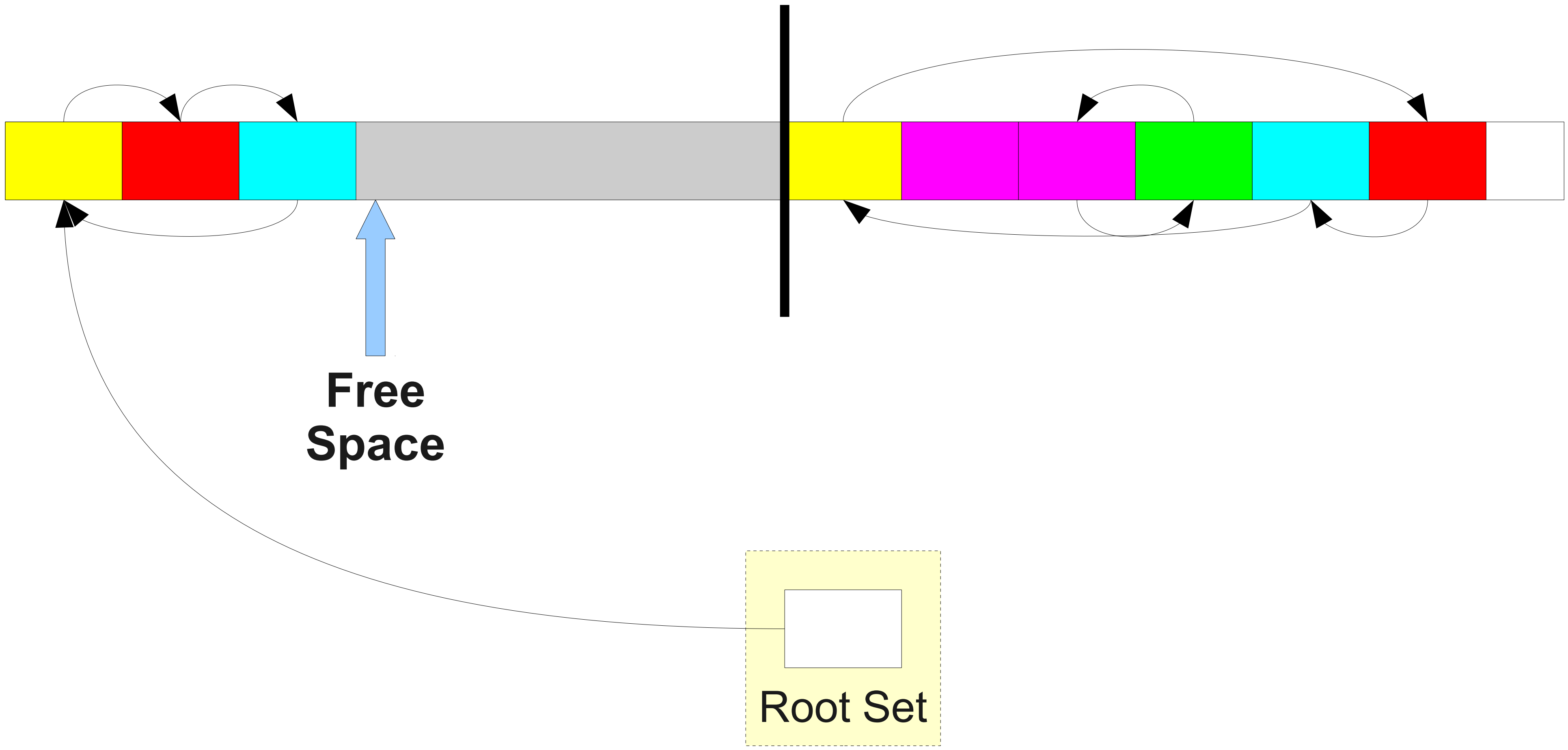

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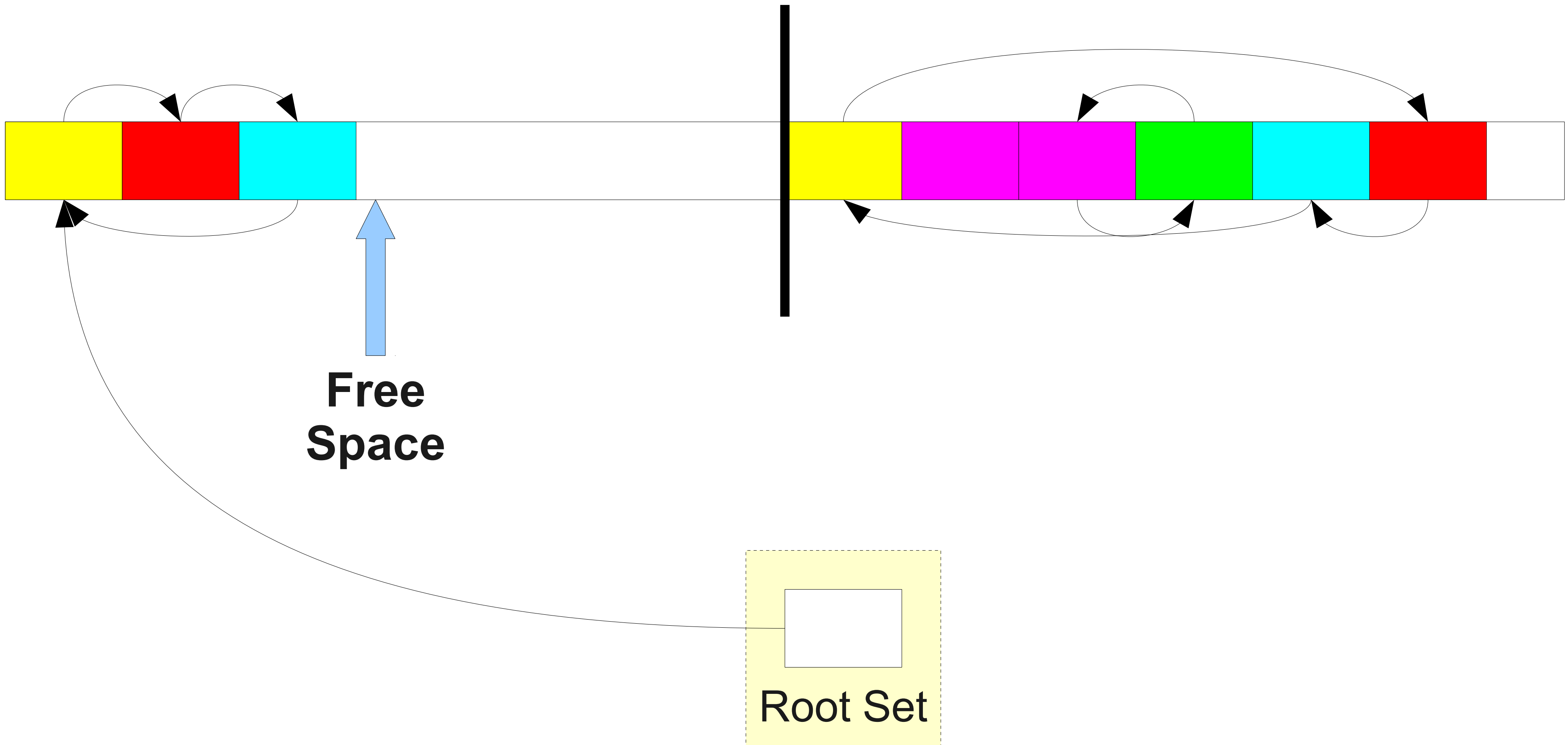

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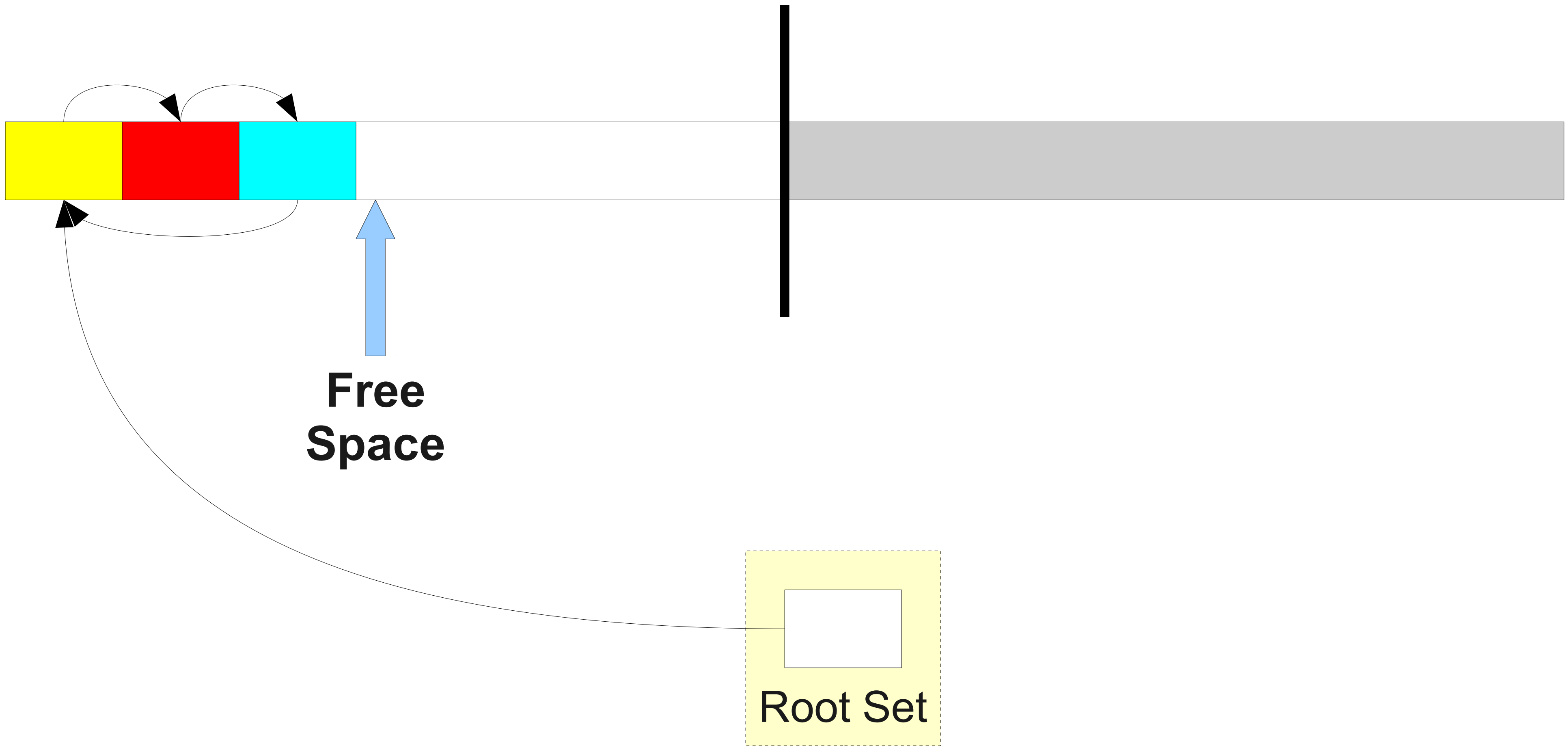

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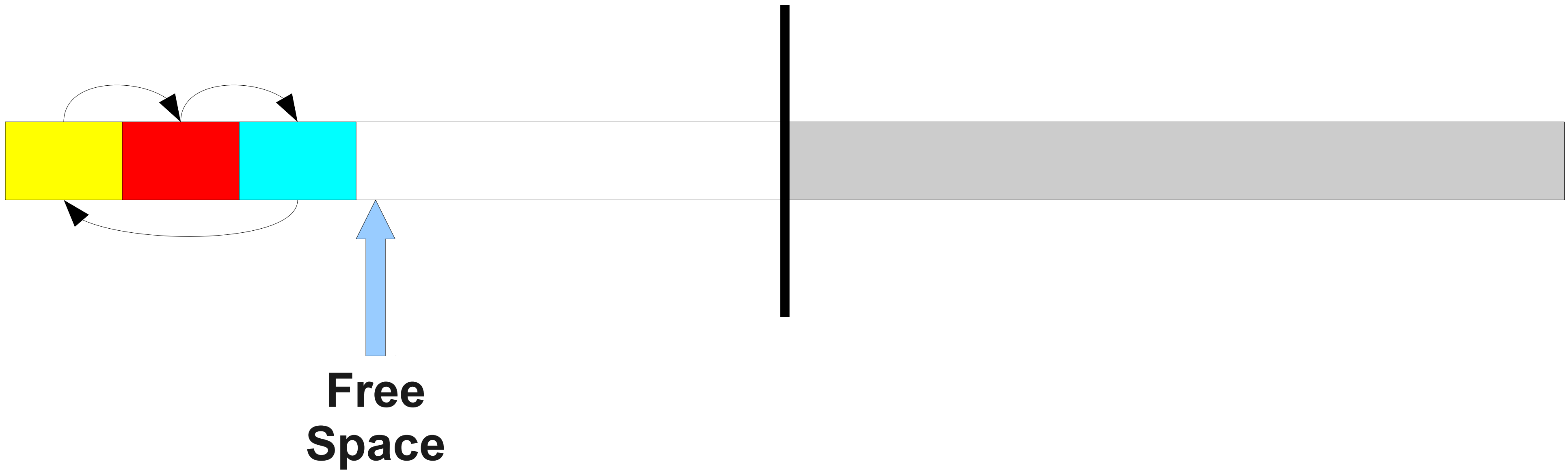


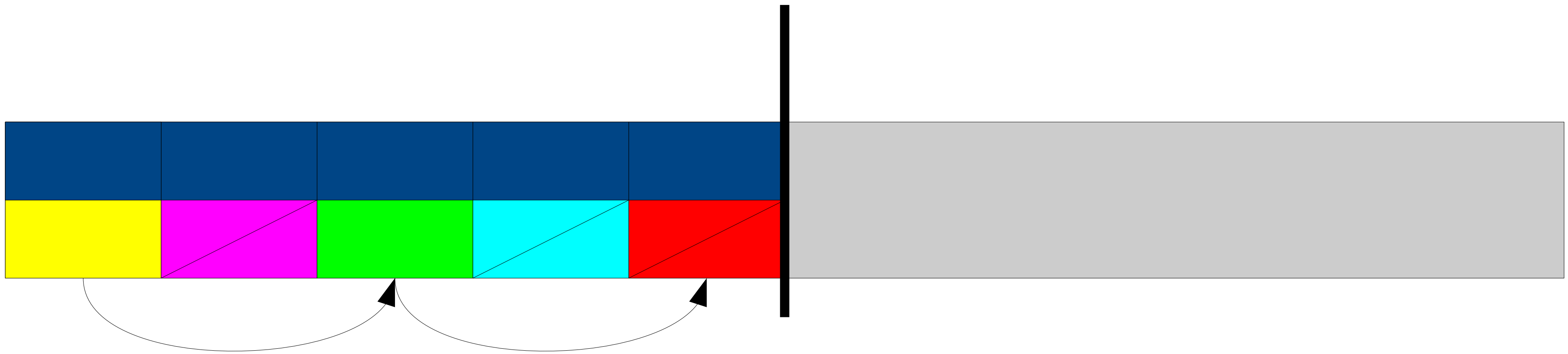
Stop-and-Copy in Detail

- Partition memory into two regions: the **old space** and the **new space**.
- Keep track of the next free address in the **new** space.
- To allocate **n** bytes of memory:
  - If **n** bytes space exist at the free space pointer, use those bytes and advance the pointer.
  - Otherwise, do a **copy** step.
- To execute a **copy** step:
  - For each object in the root set:
    - Copy that object over to the start of the **old** space.
    - Recursively copy over all objects reachable from that object.
  - Adjust the pointers in the **old** space and root set to point to new locations.
  - Exchange the roles of the **old** and **new** spaces.

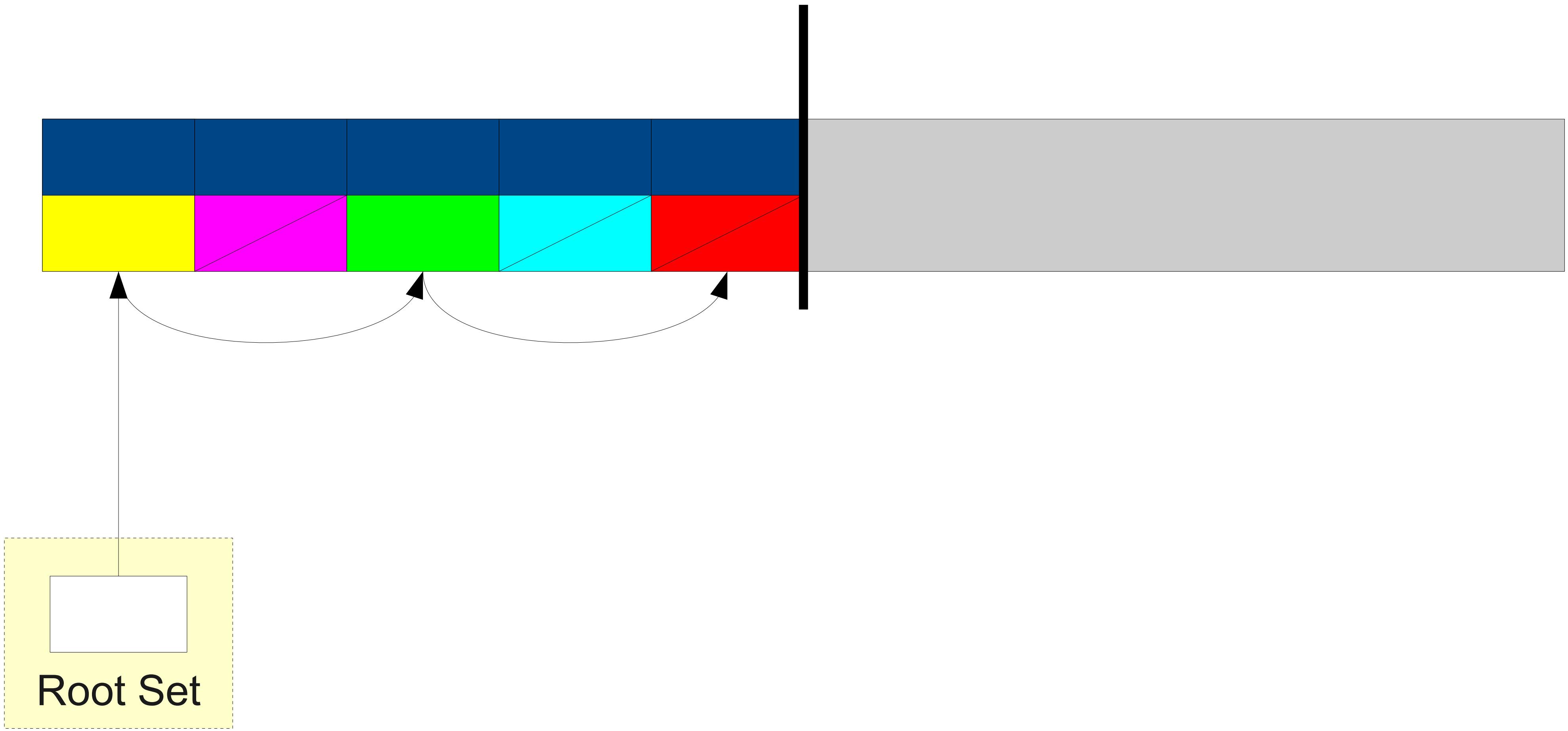
Implementing Stop and Copy

- The only tricky part about stop-and-copy is adjusting the pointers in the copied objects correctly.
- **Idea**: Have each object contain a extra space for a **forwarding pointer**.
- To clone an object:
  - First, do a complete bitwise copy of the object.
    - All pointers still point to their original locations.
  - Next, set the **forwarding pointer** of the original object to point to the new object.
- Finally, after cloning each object, for each pointer:
  - Follow the pointer to the object it references.
  - Replace the pointer with the pointee's forwarding pointer.

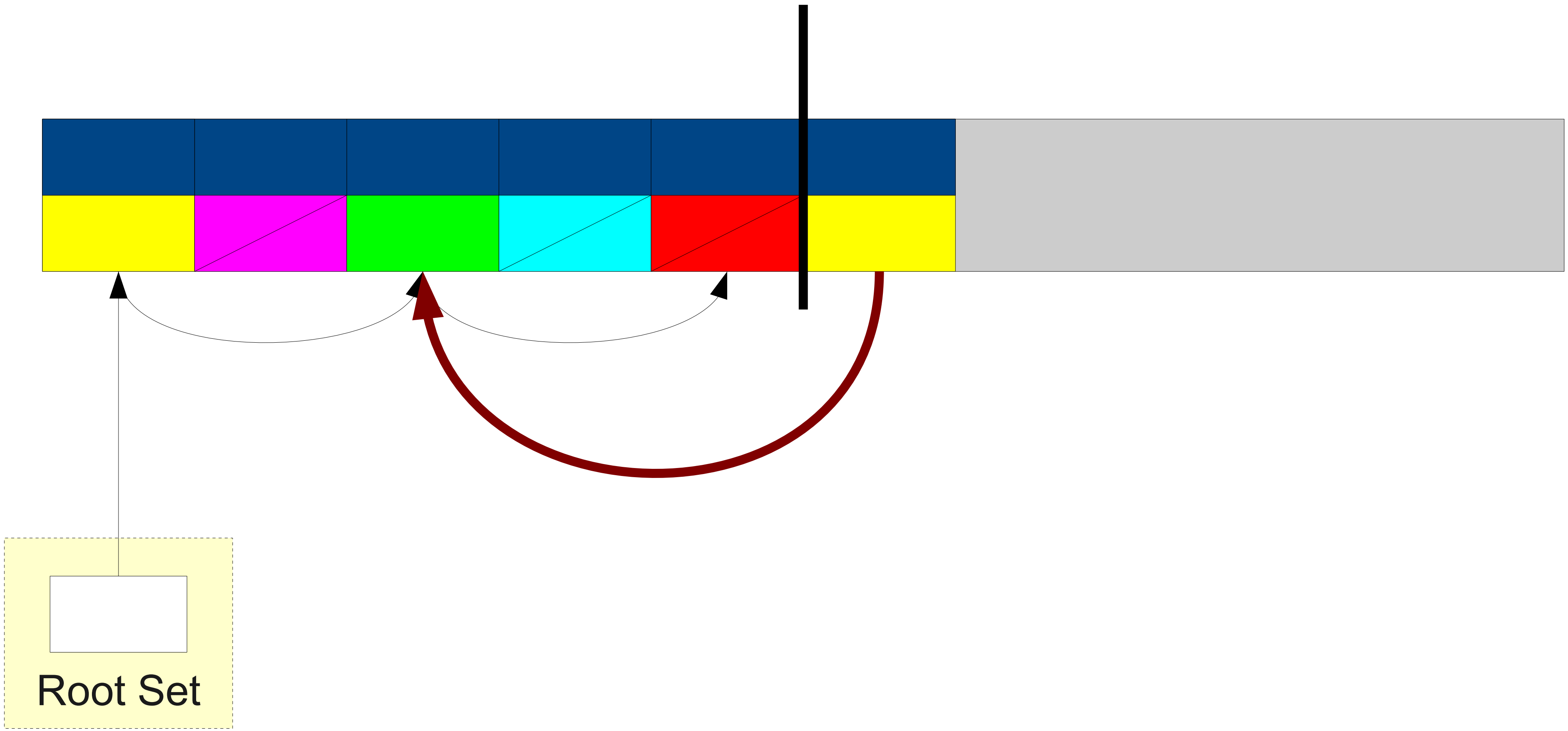
Forwarding Pointers



Forwarding Pointers



Forwarding Pointers



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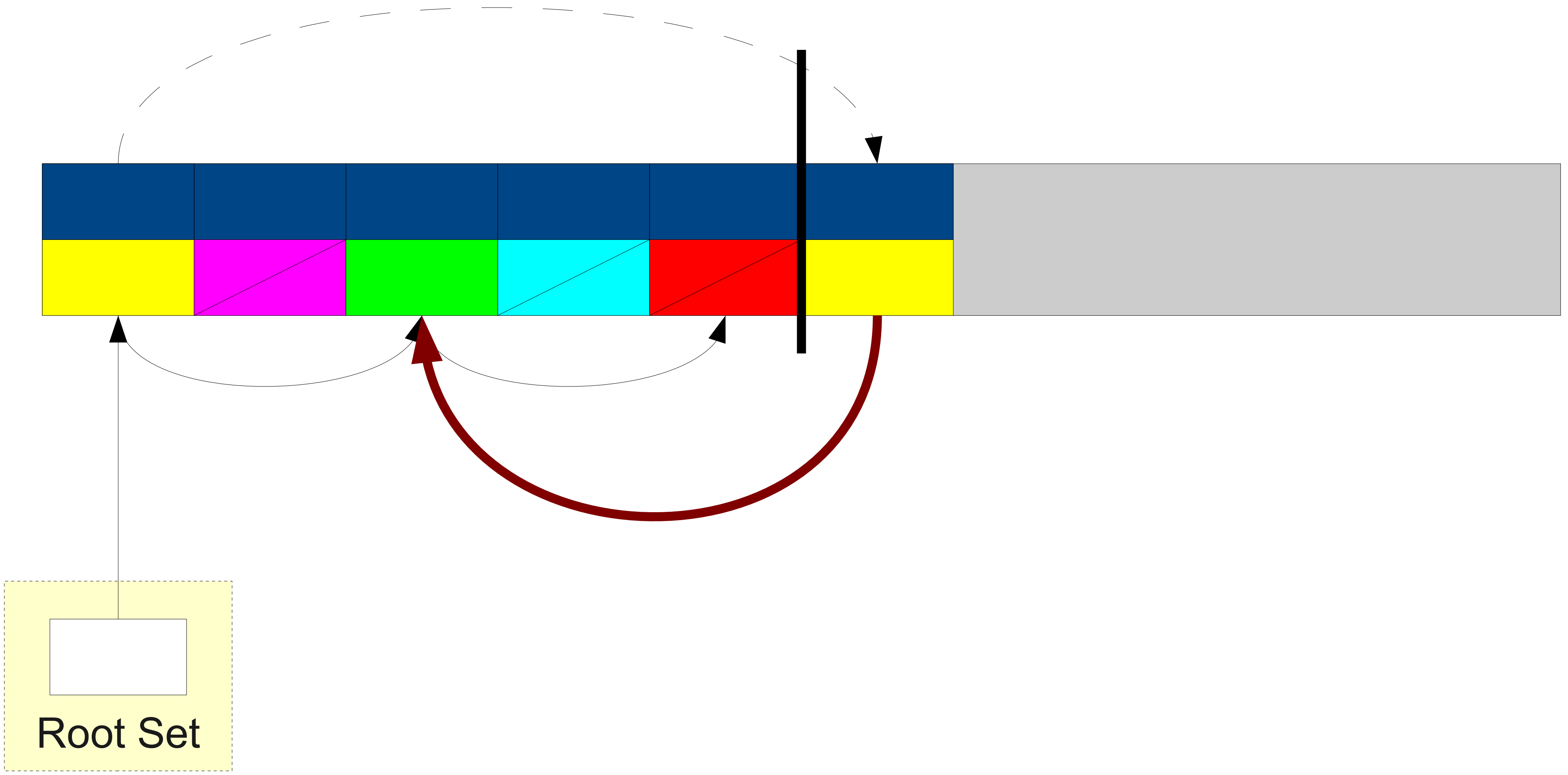

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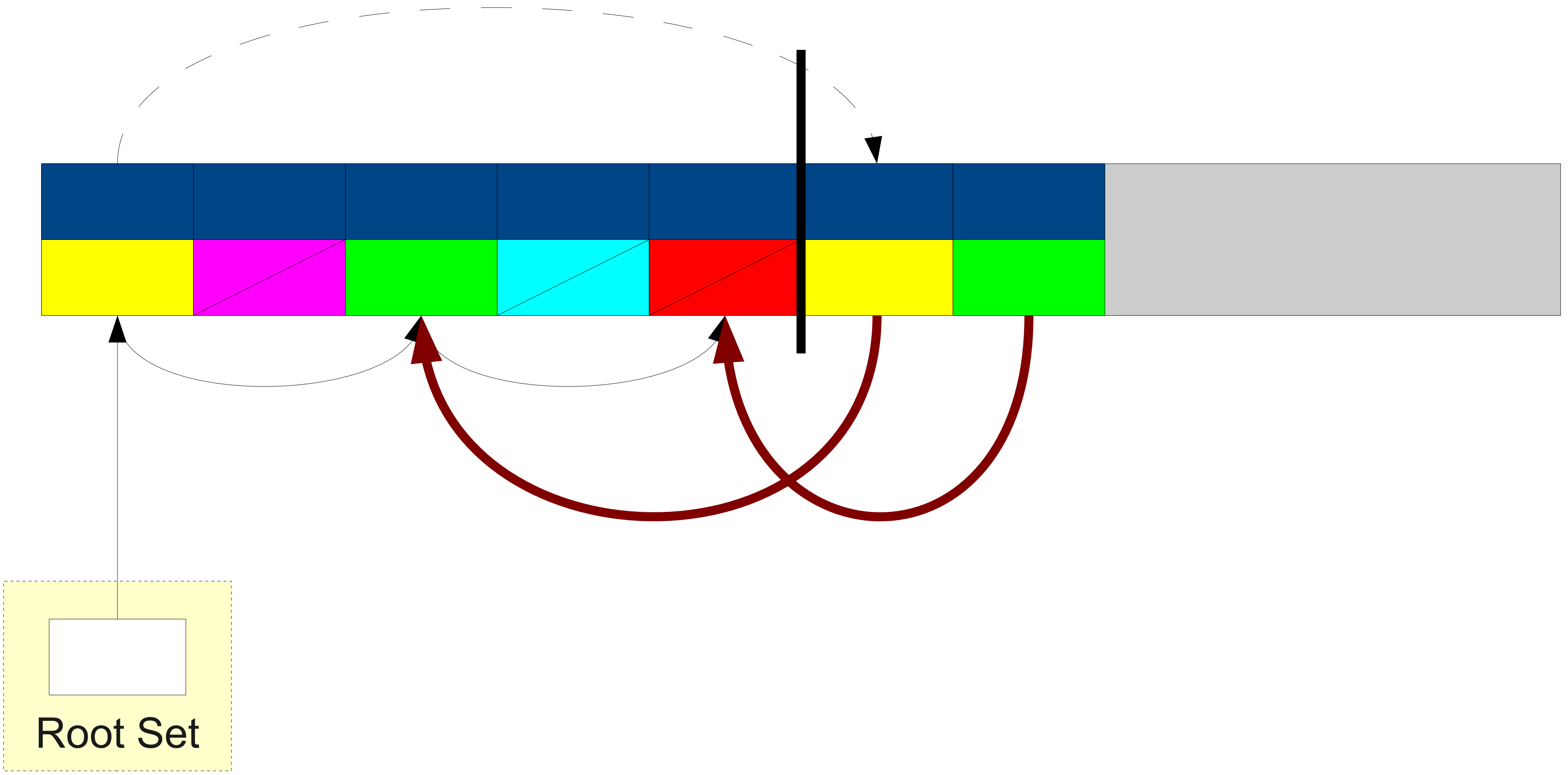

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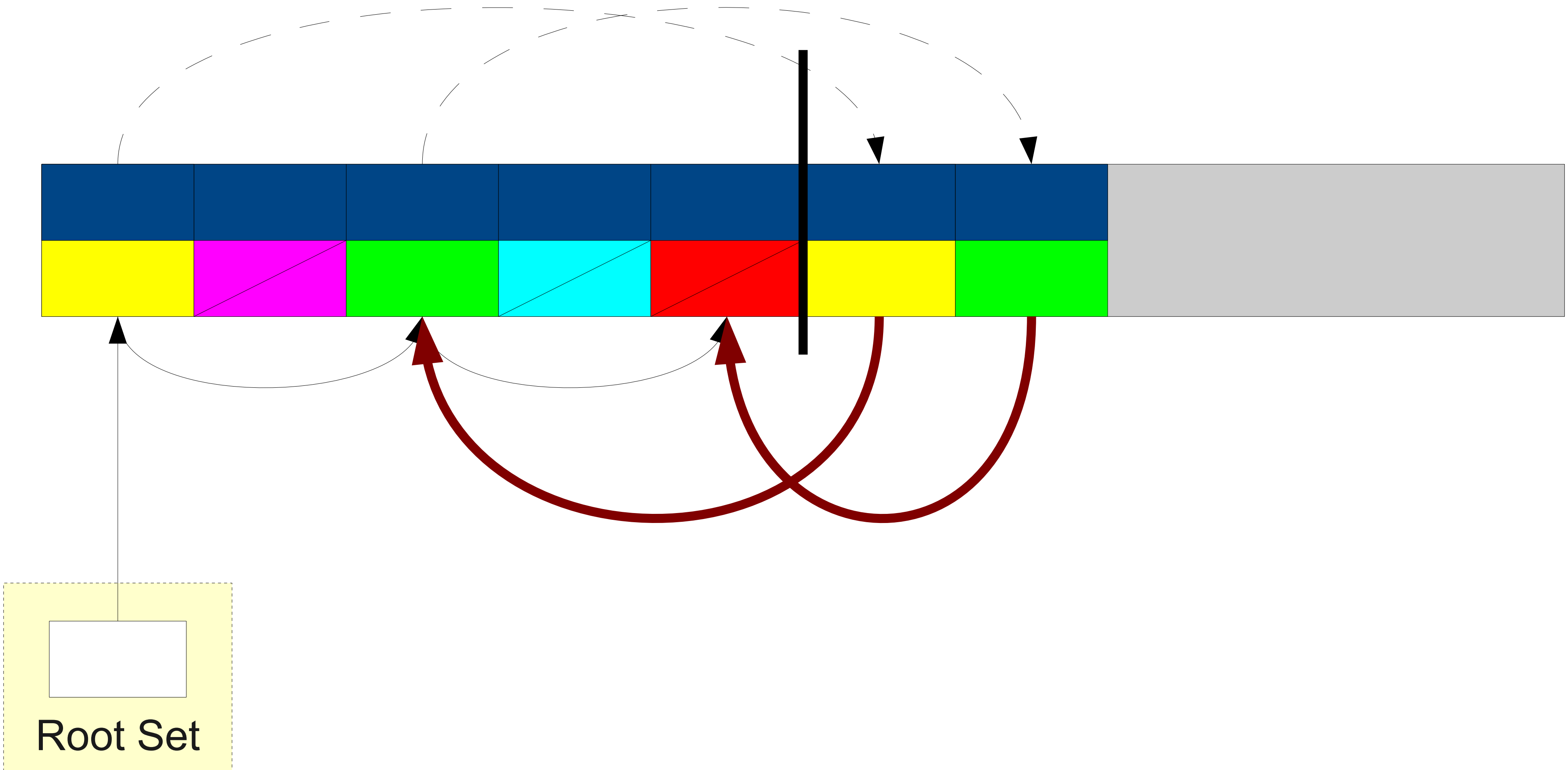

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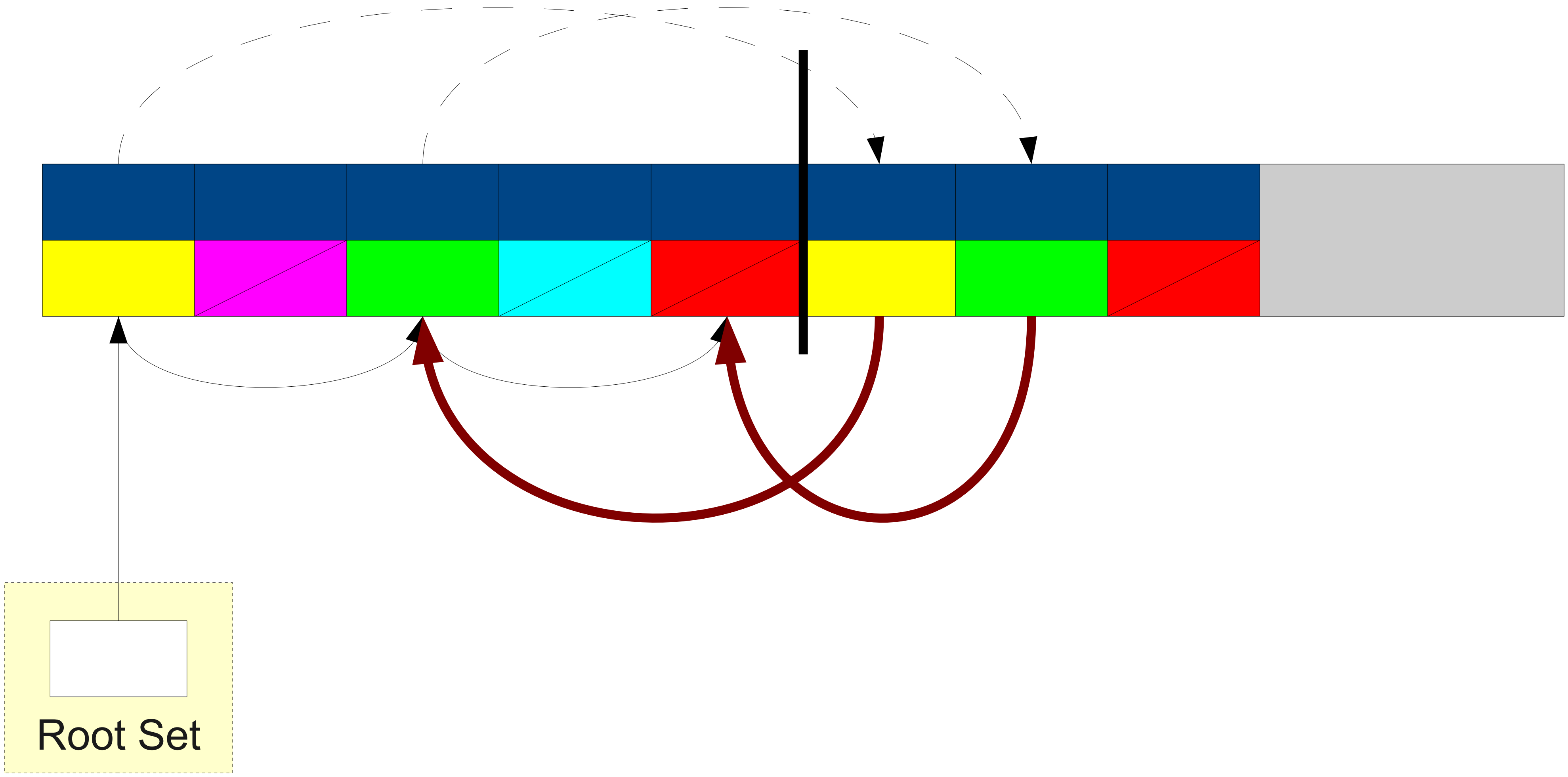

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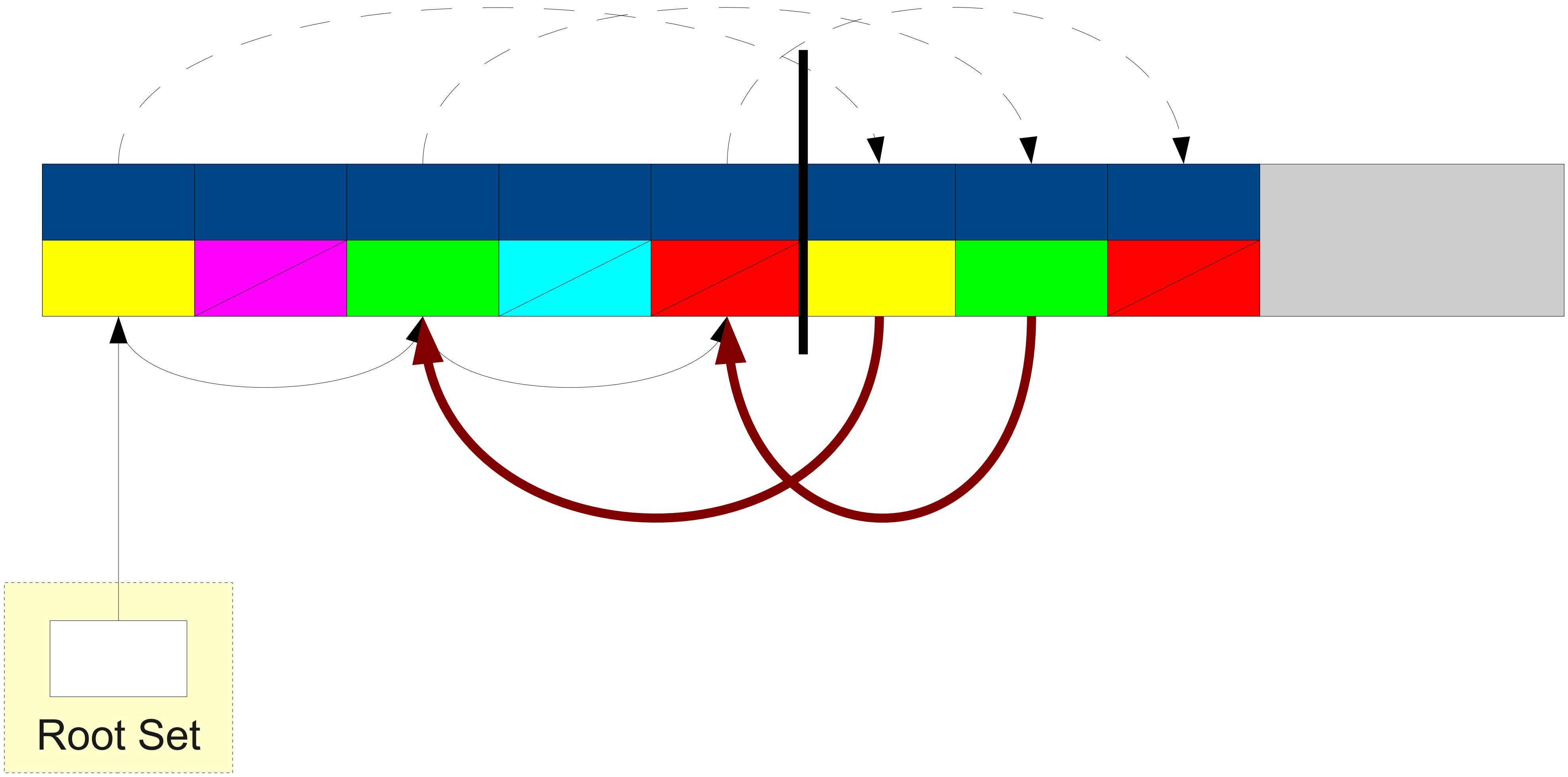

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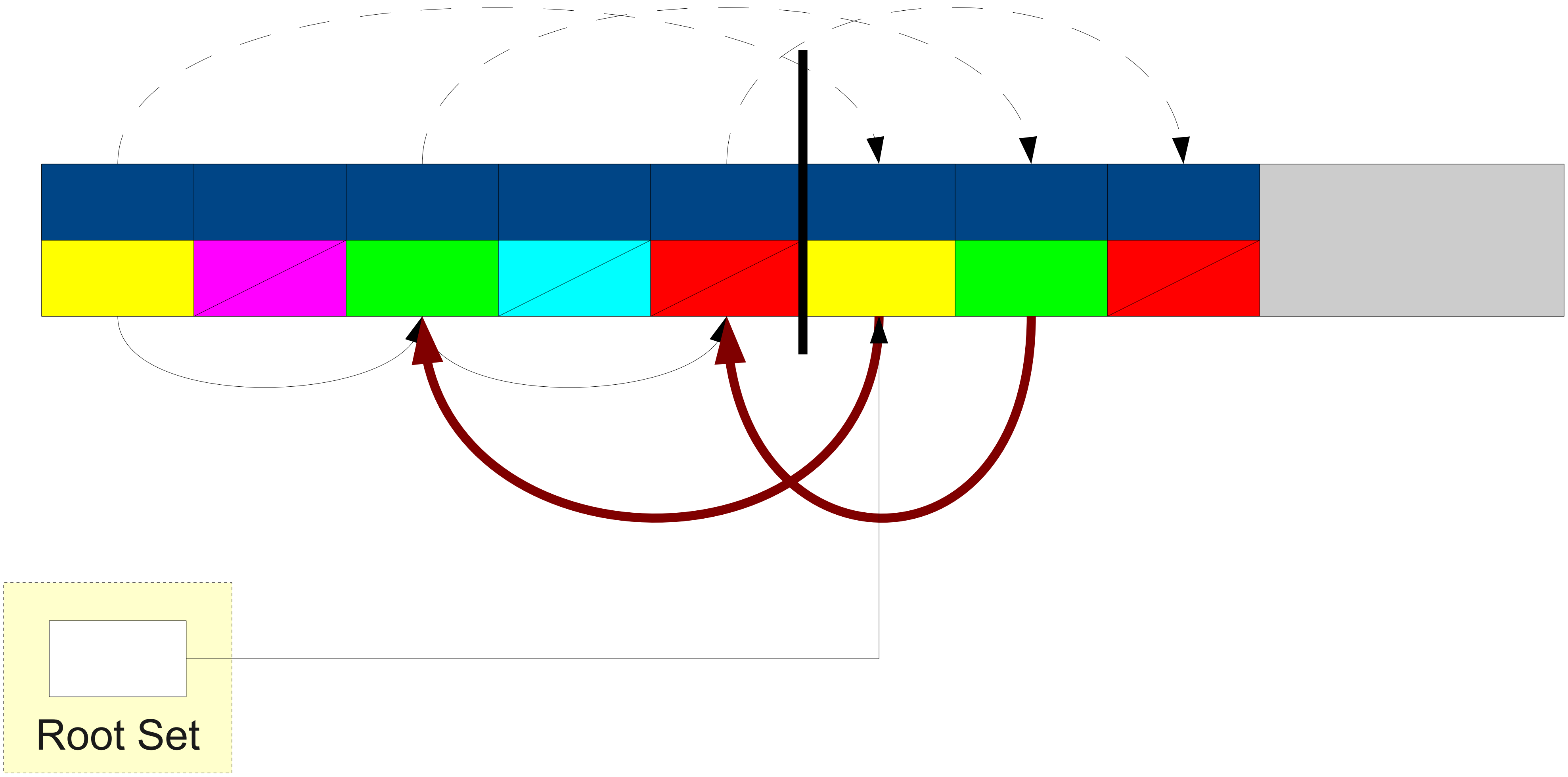

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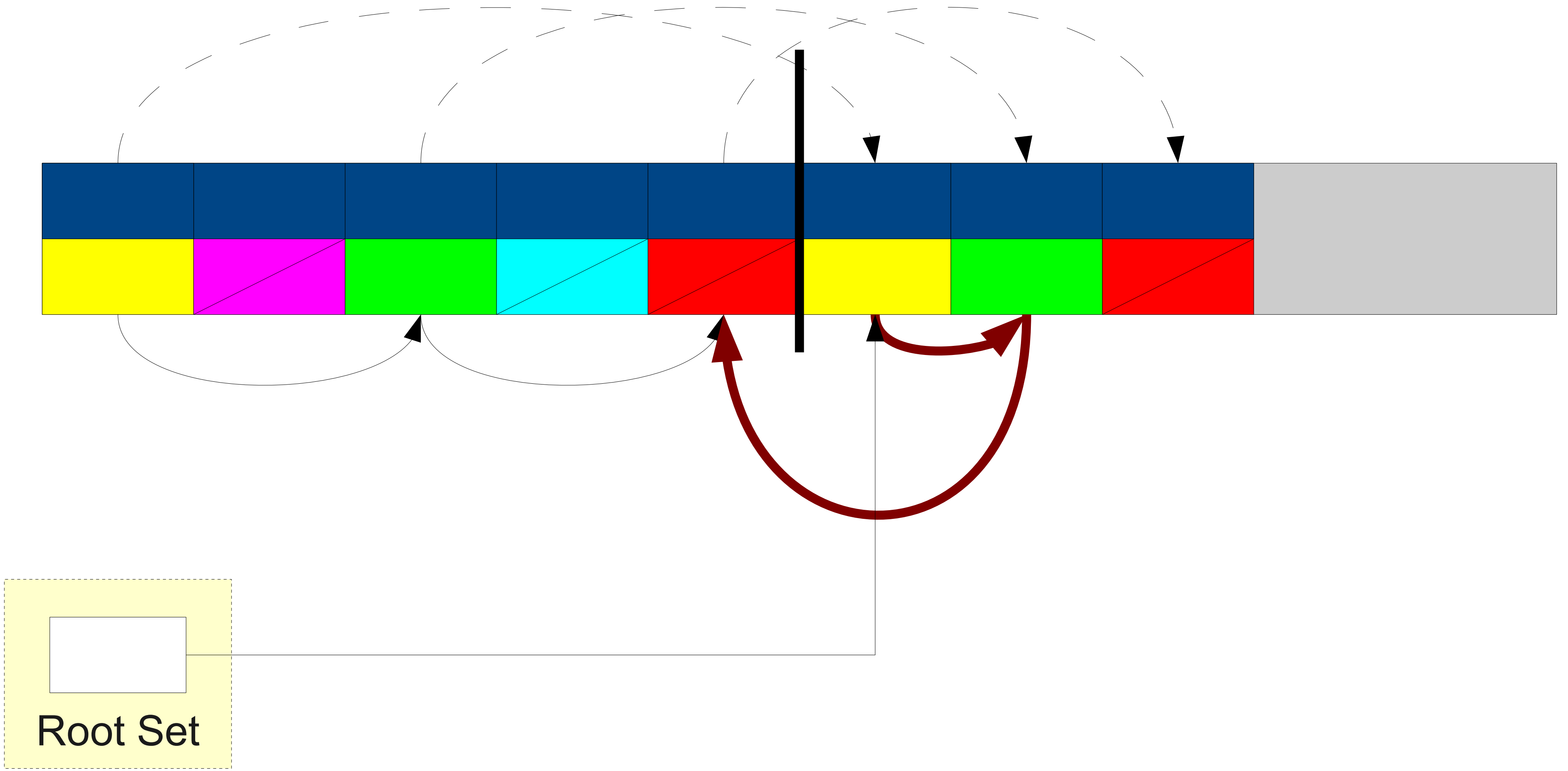

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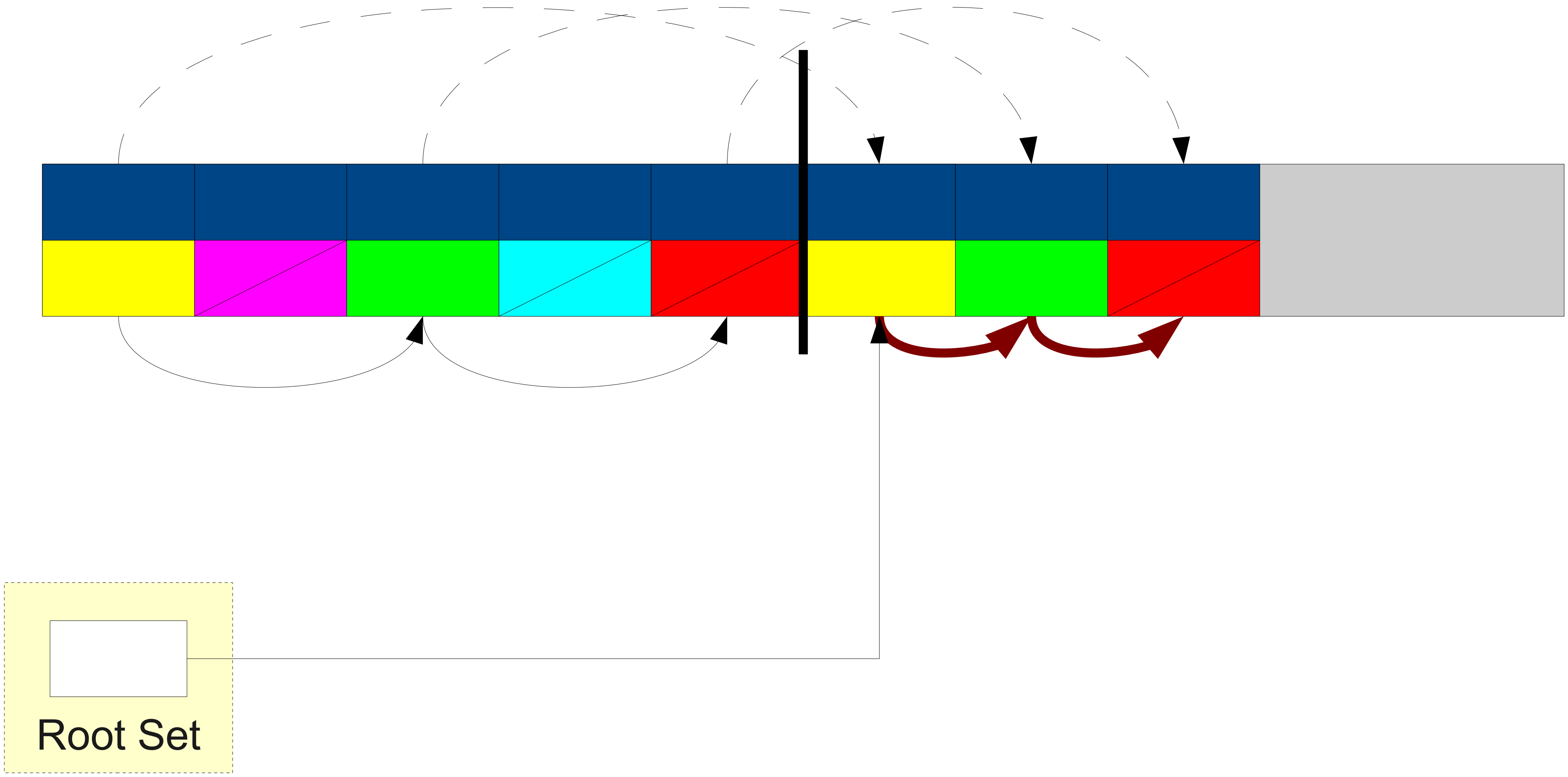
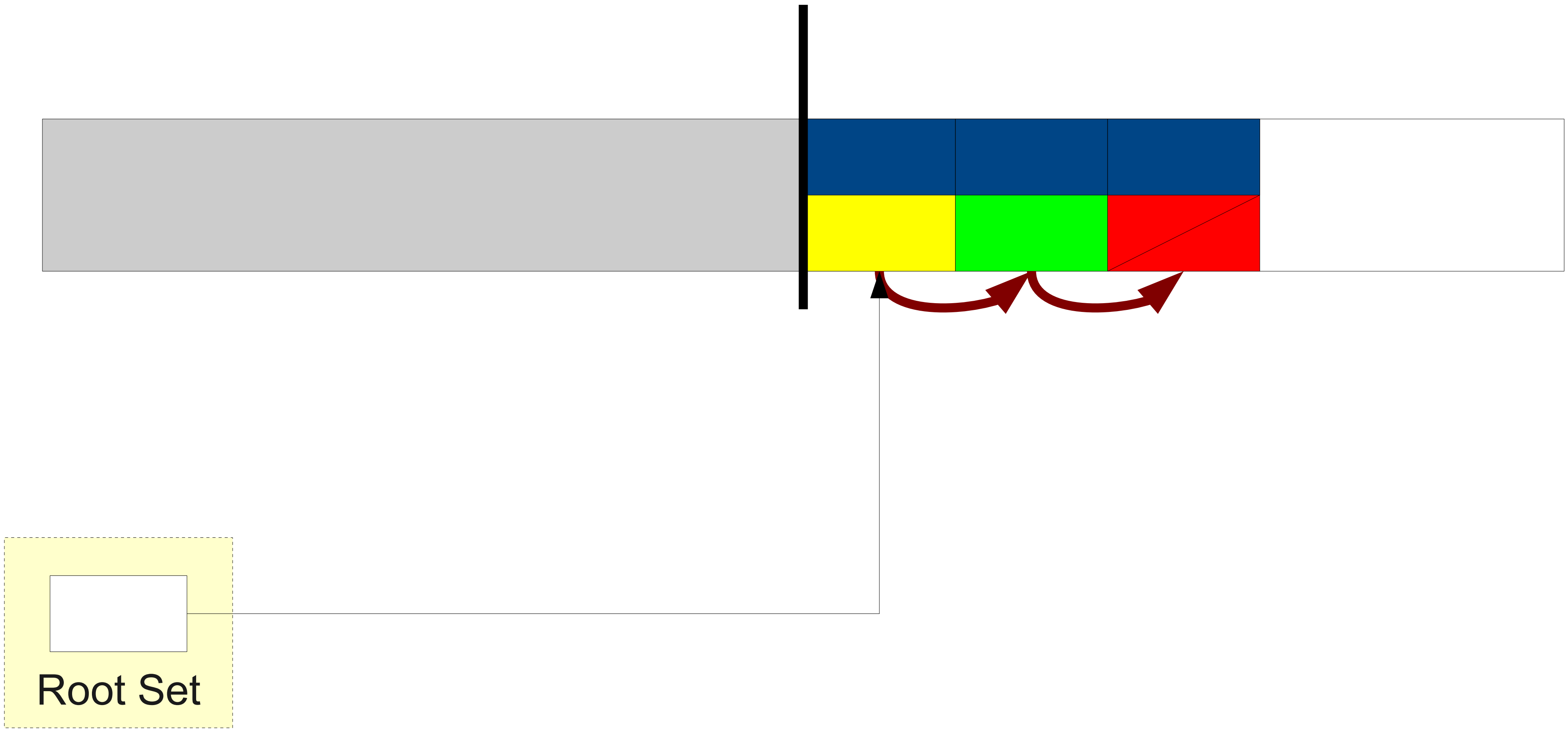


Forwarding Pointers



Analysis of Stop-and-Copy

- Advantages:
  - Implementation simplicity (compared to mark-and-sweep).
  - Fast memory allocation; using OS-level tricks, can allocate in a single assembly instruction.
  - Excellent locality; depth-first ordering of copied objects places similar objects near each other.
- Disadvantages:
  - Requires half of memory to be free at all times.
  - Collection time proportional to number of bytes used by objects.

Hybrid Approaches

The Best of All Worlds

- The best garbage collectors in use today are based on a combination of smaller garbage collectors.
- Each garbage collector is targeted to reclaim specific types of garbage.
- Usually has some final “fallback” garbage collector to handle everything else.

Objects Die Young

- The Motto of Garbage Collection: **Objects Die Young**.
- Most objects have extremely short lifetimes.
  - Objects allocated locally in a function.
  - Temporary objects used to construct larger objects.
- Optimize garbage collection to reclaim young objects rapidly while spending less time on older objects.

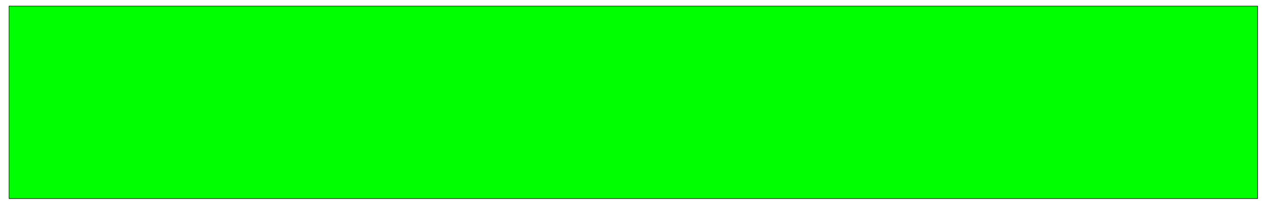
Generational Garbage Collection

- Partition memory into several "generations."
- Objects are always allocated in the first generation.
- When the first generation fills up, garbage collect it.
  - Runs quickly; collects only a small region of memory.
- Move objects that survive in the first generation long enough into the next generation.
- When no space can be found, run a full (slower) garbage collection on all of memory.

Garbage Collection in Java

Garbage Collection in Java

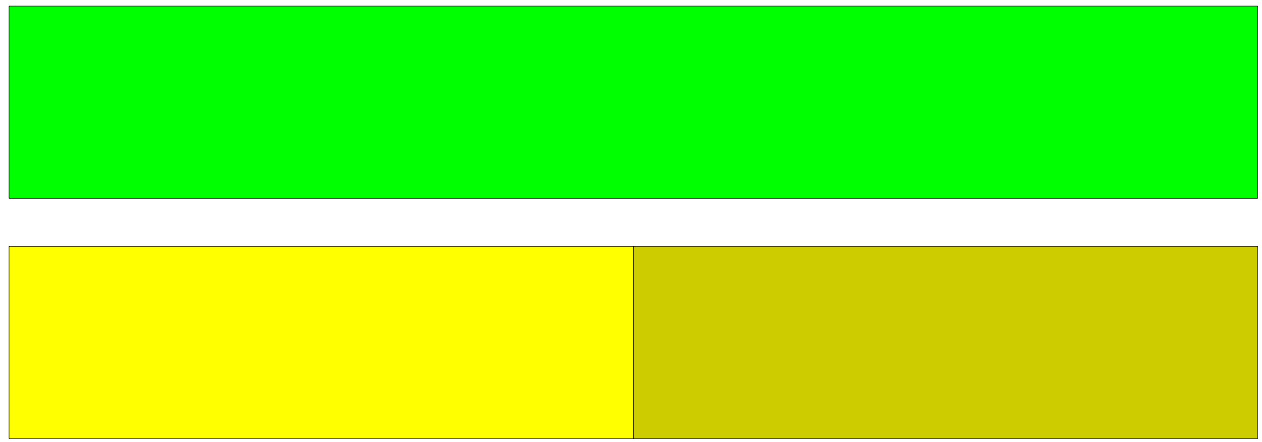
Eden



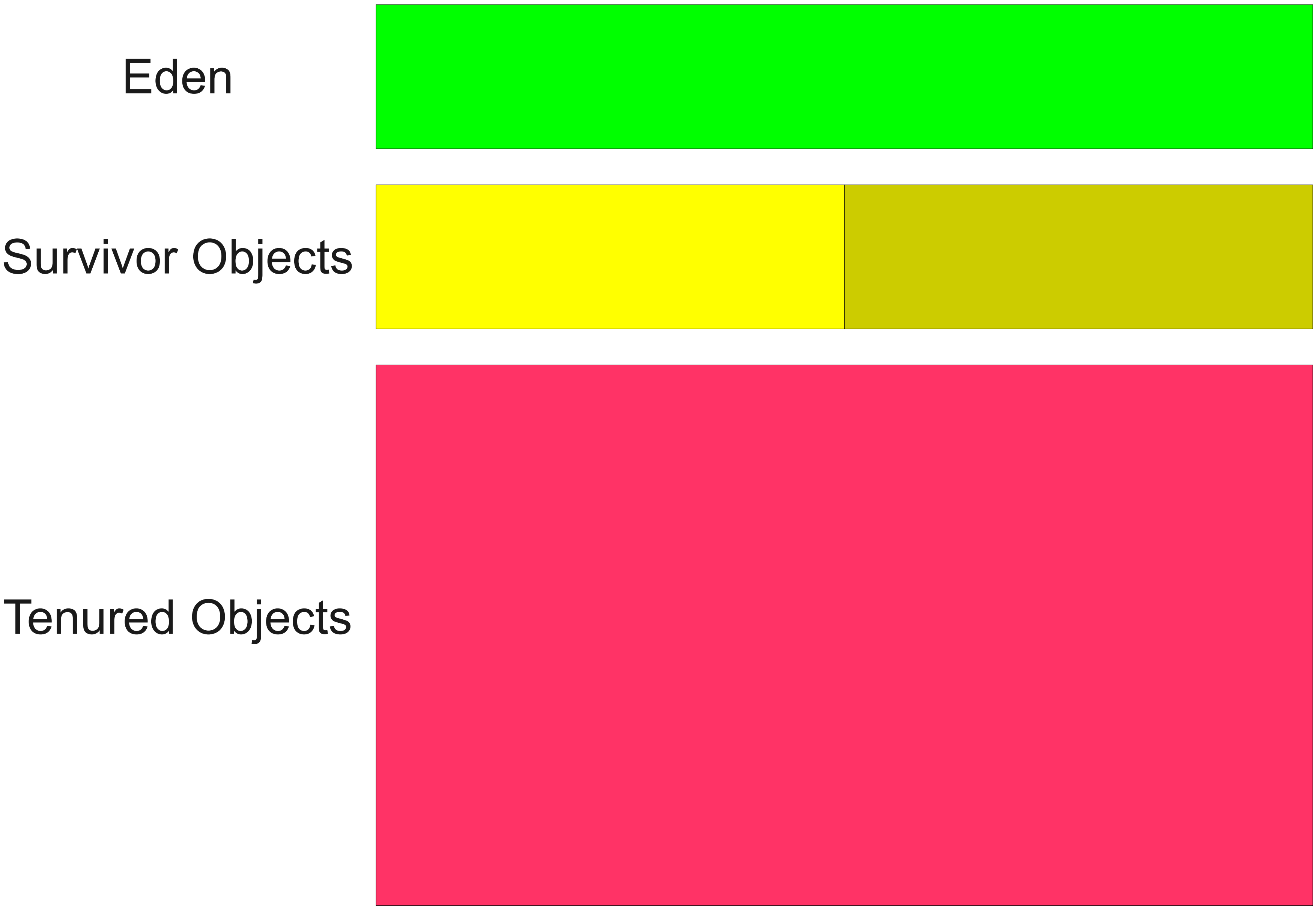
Garbage Collection in Java

Eden

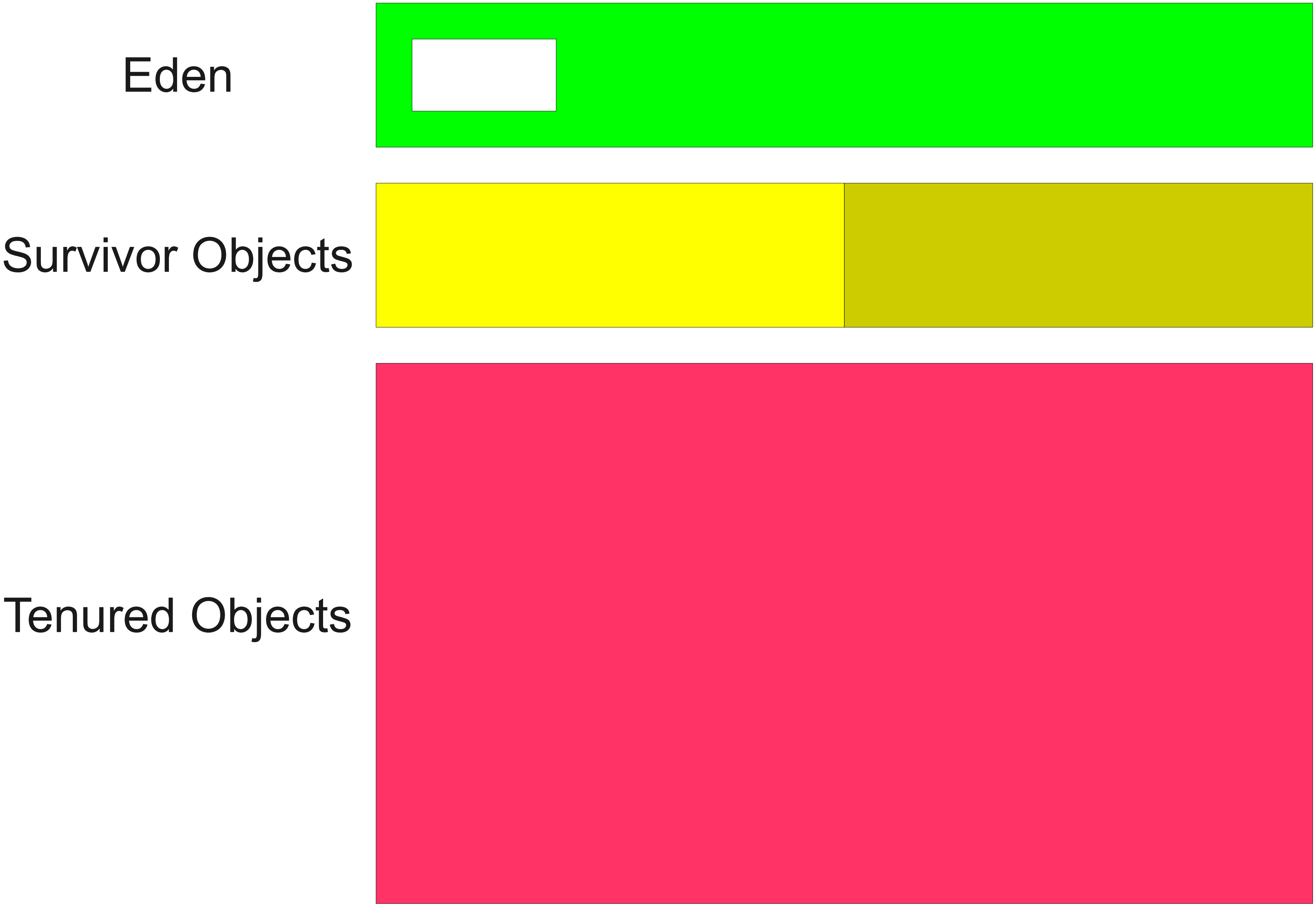
Survivor Objects



Garbage Collection in Java



Garbage Collection in Java



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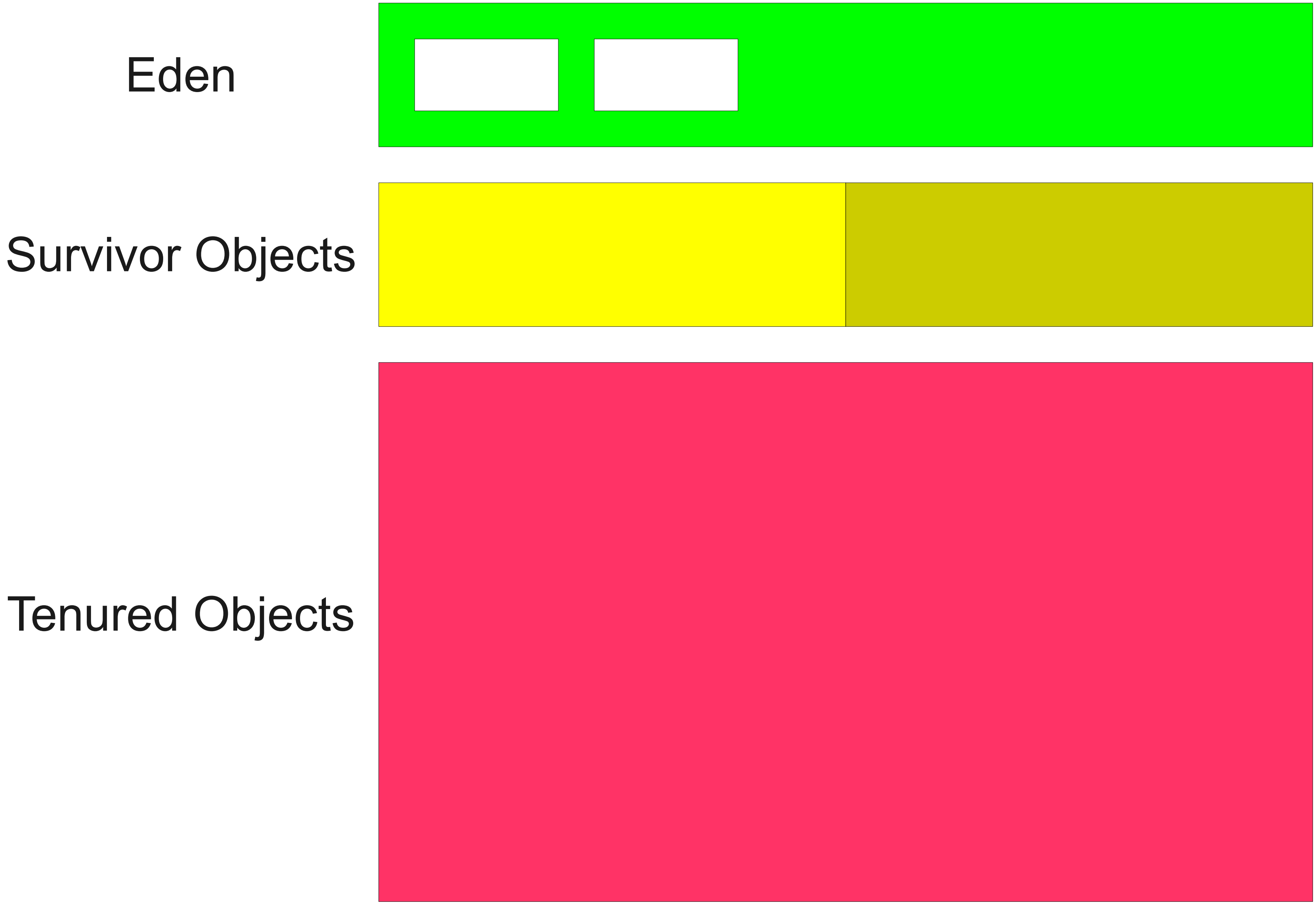

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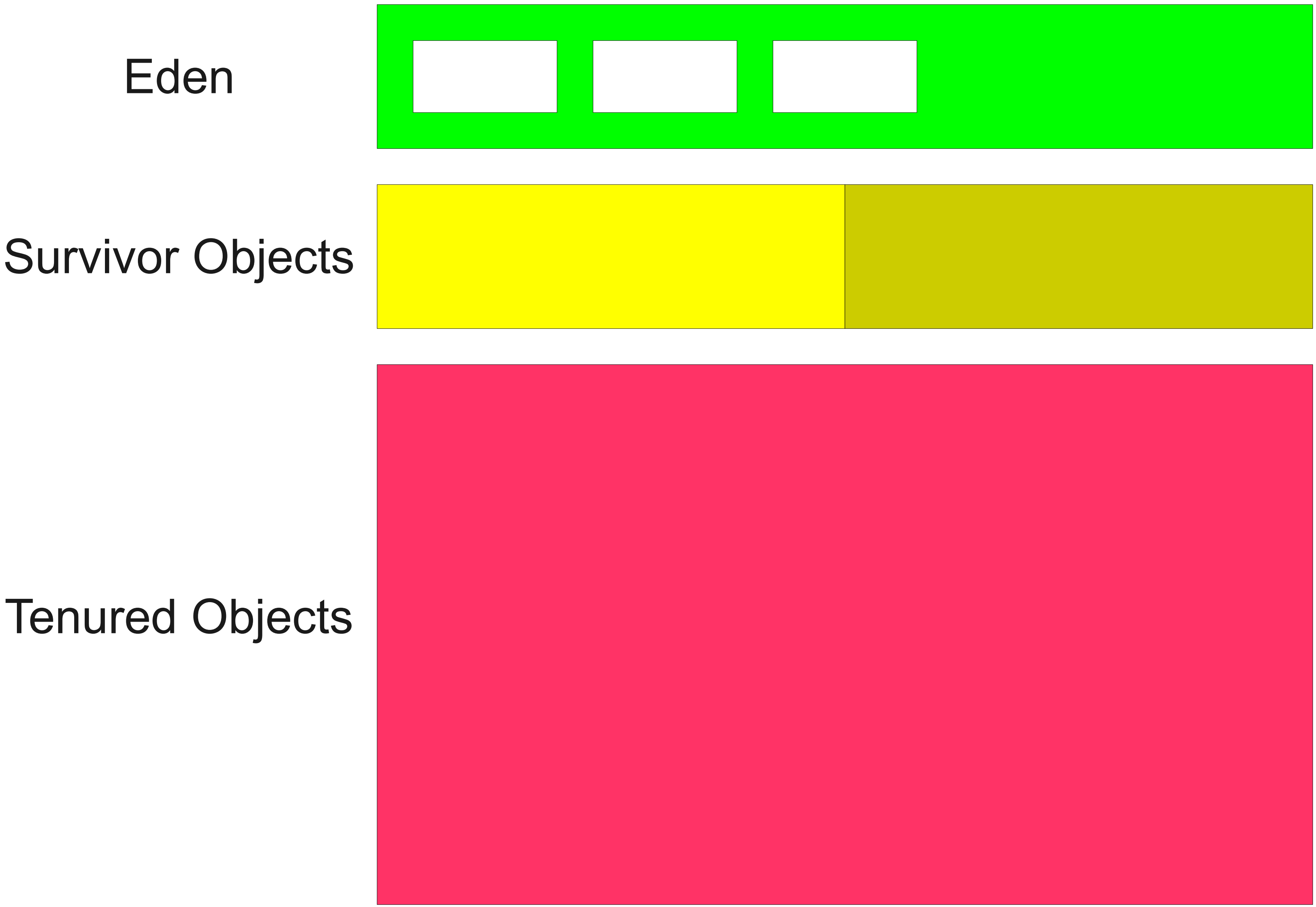

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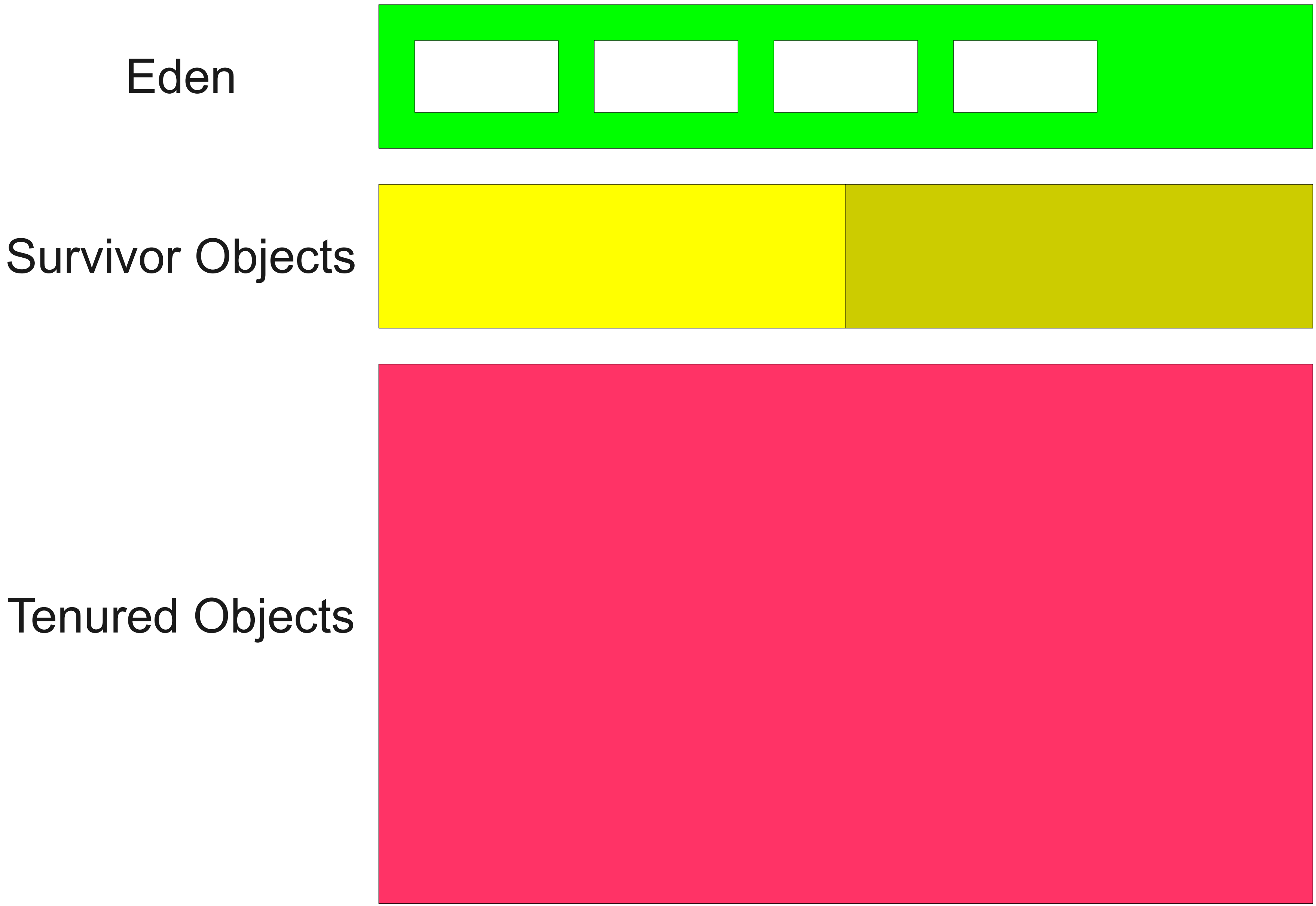

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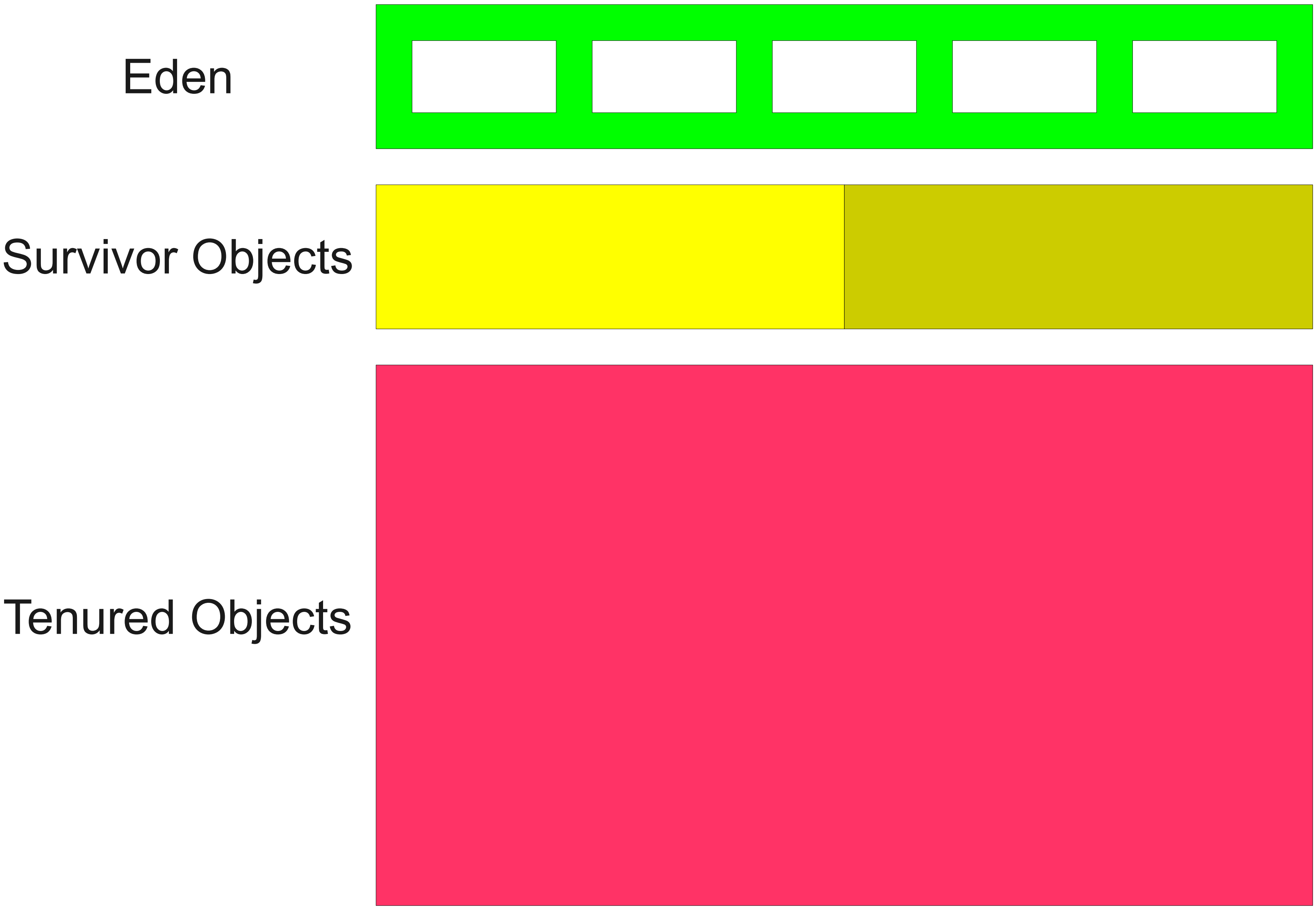

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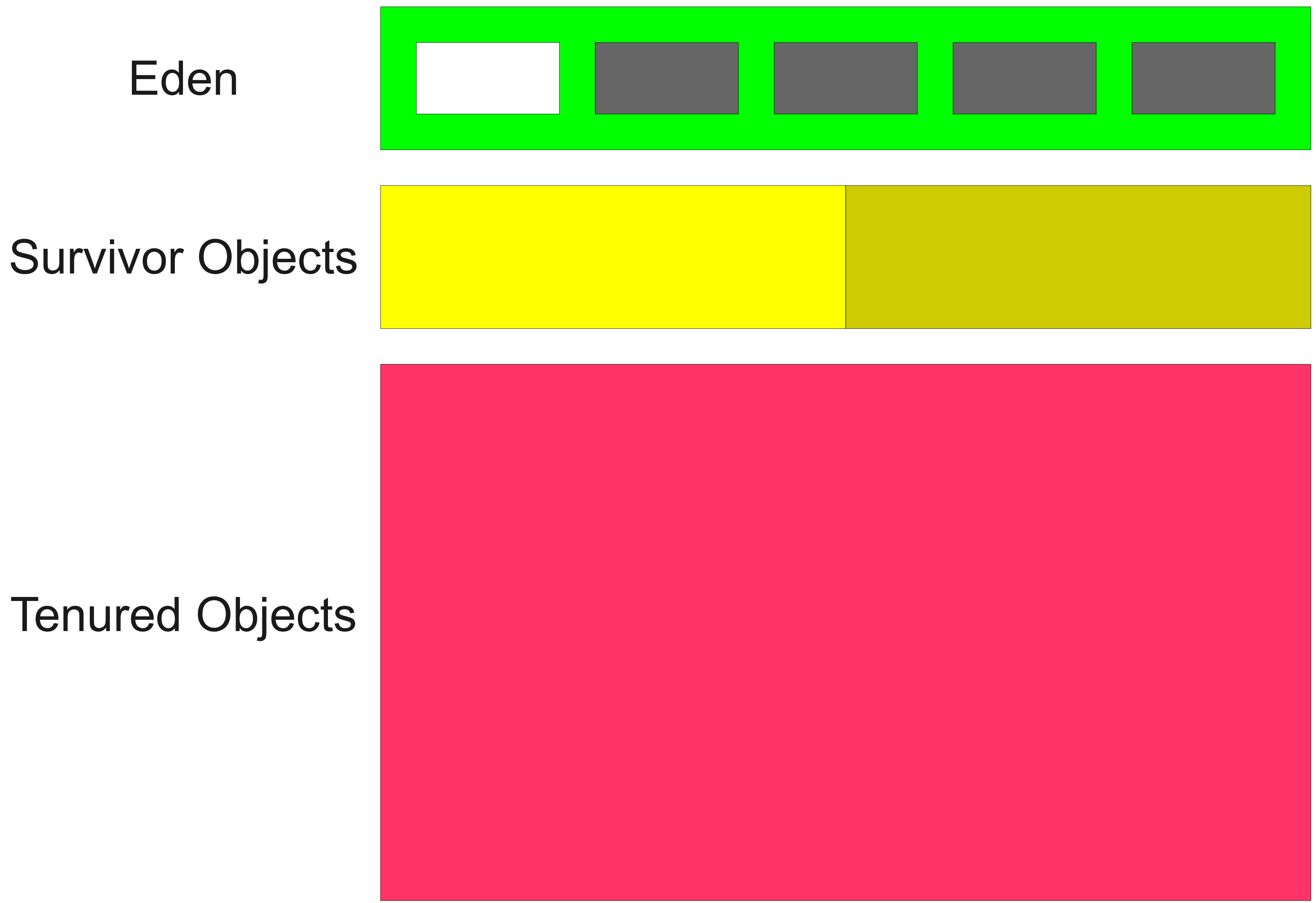

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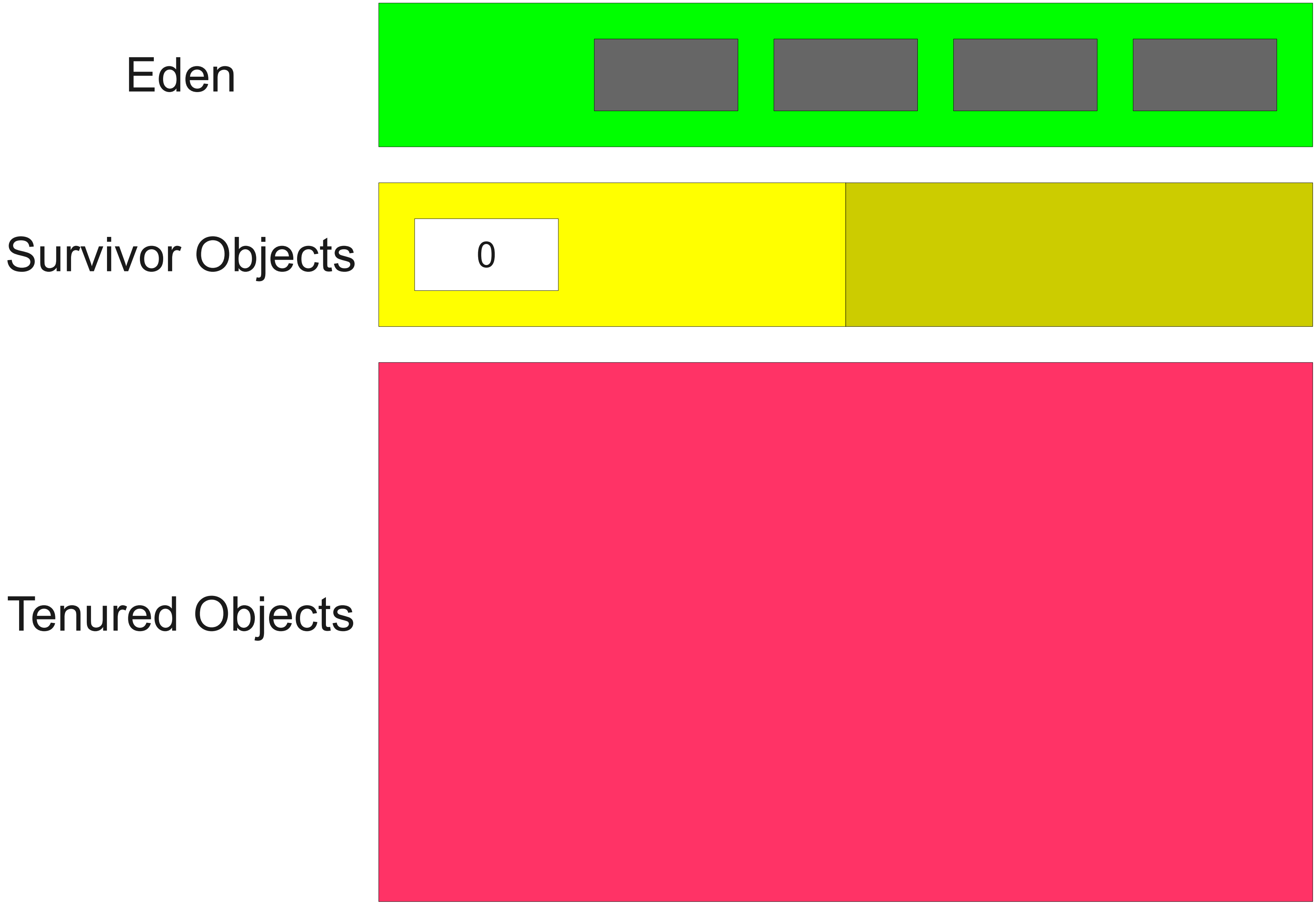

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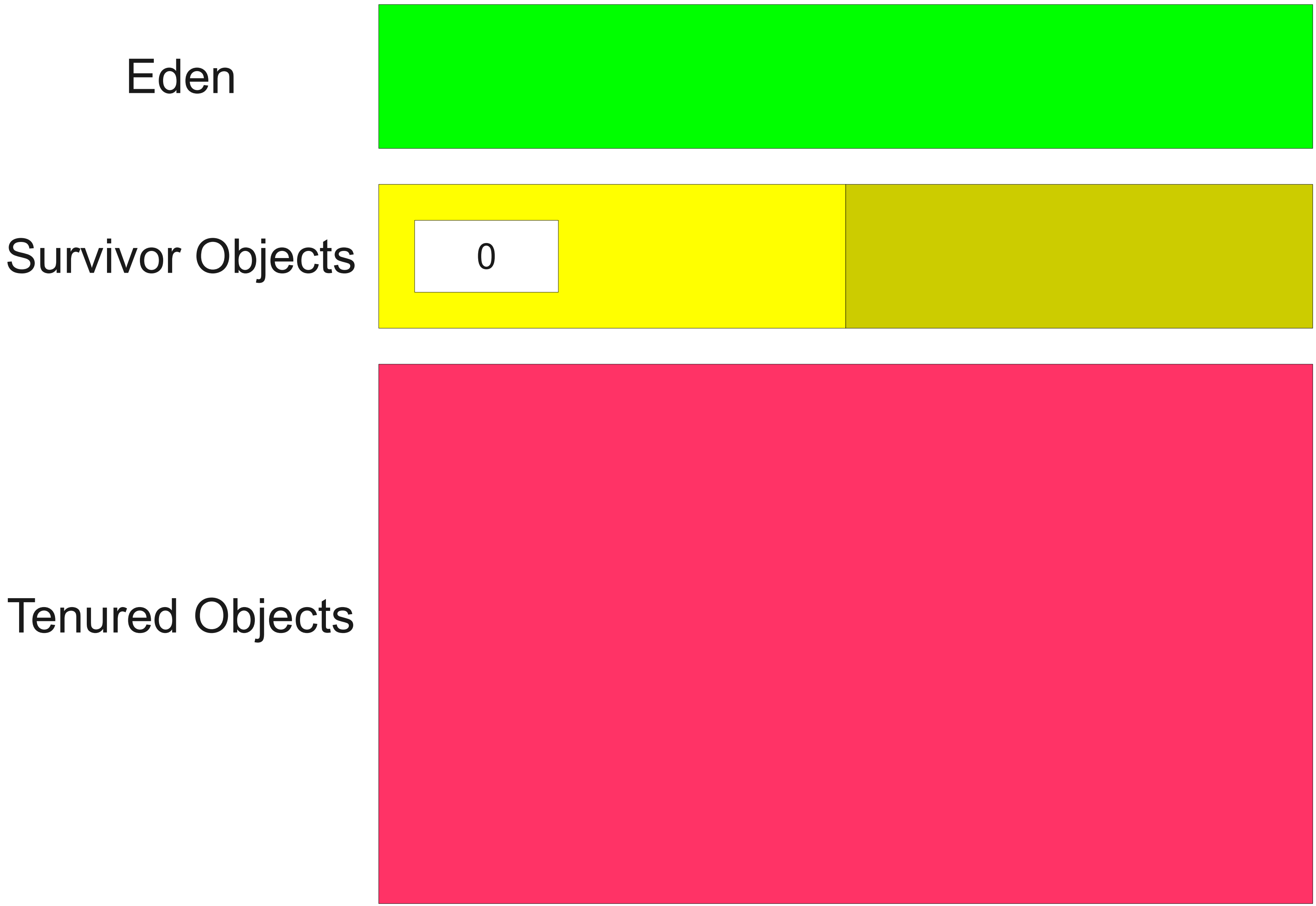

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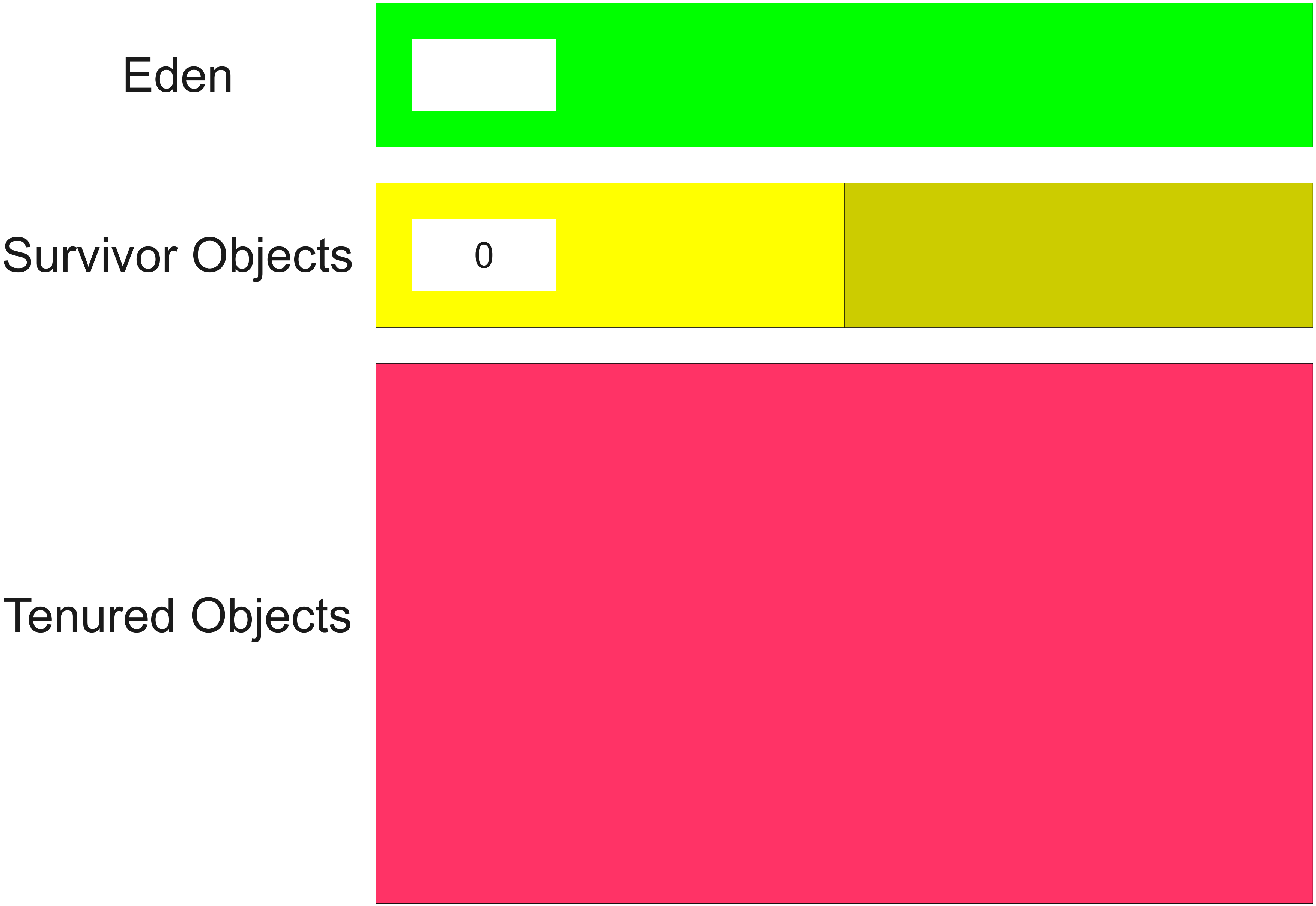

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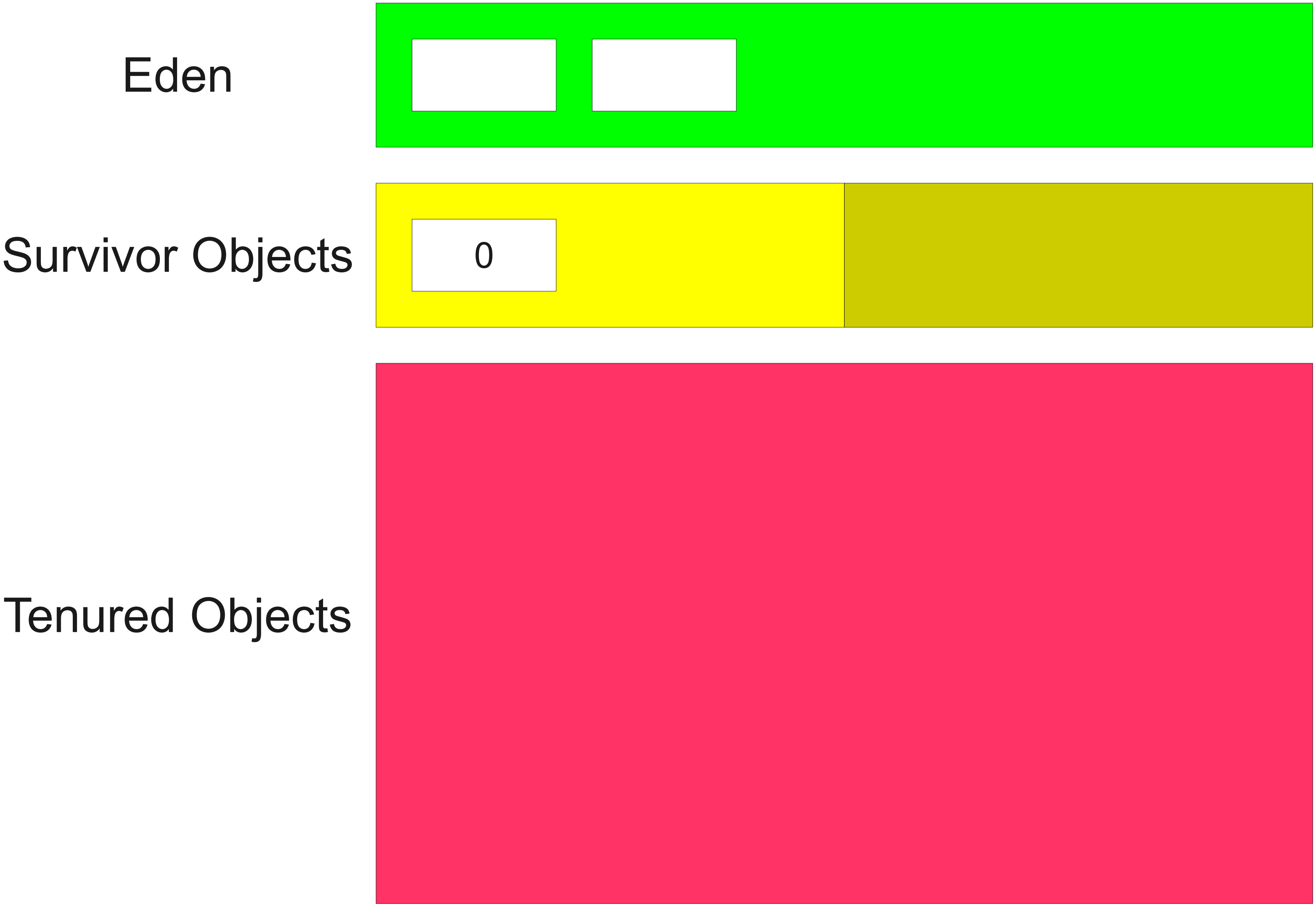

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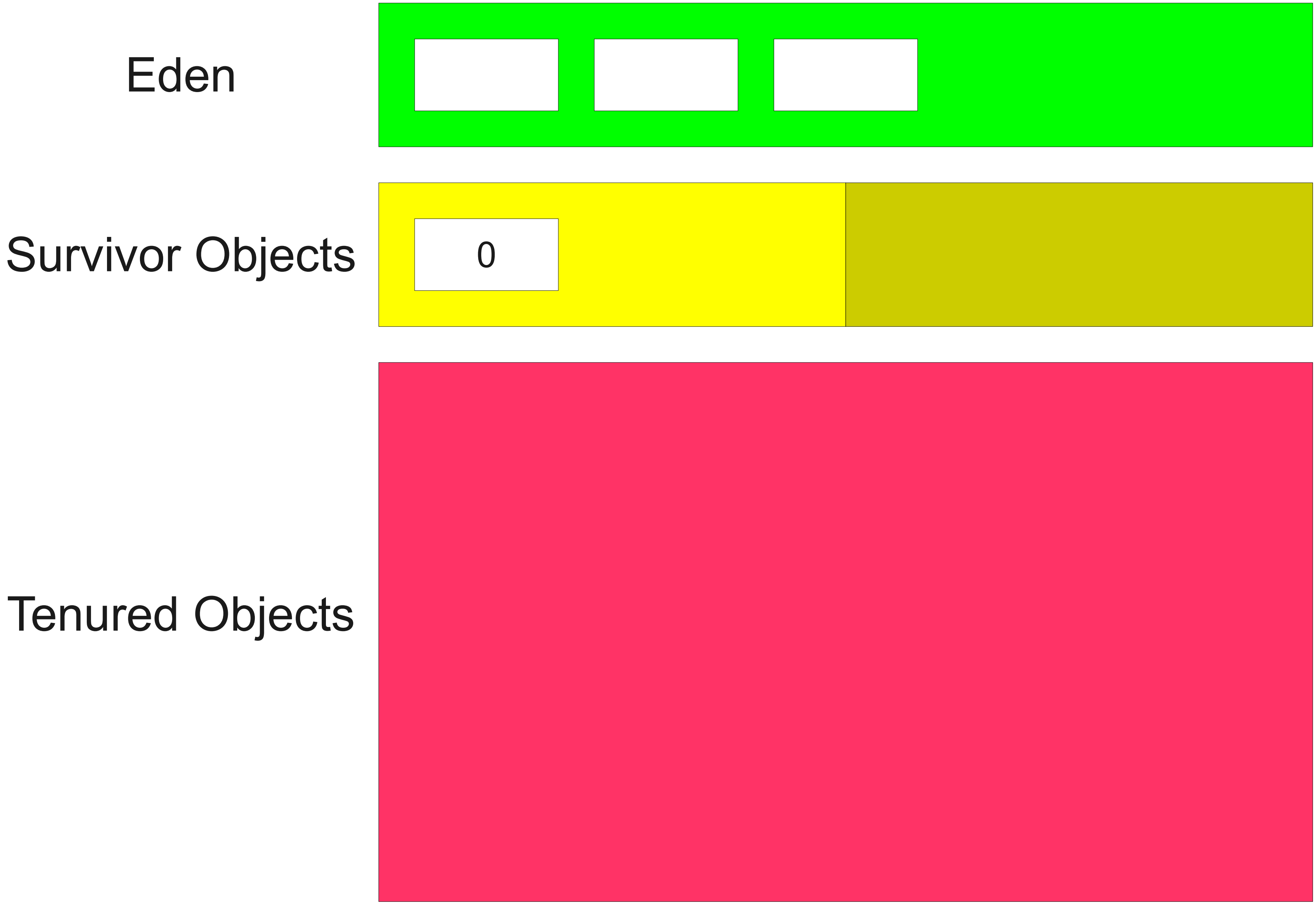

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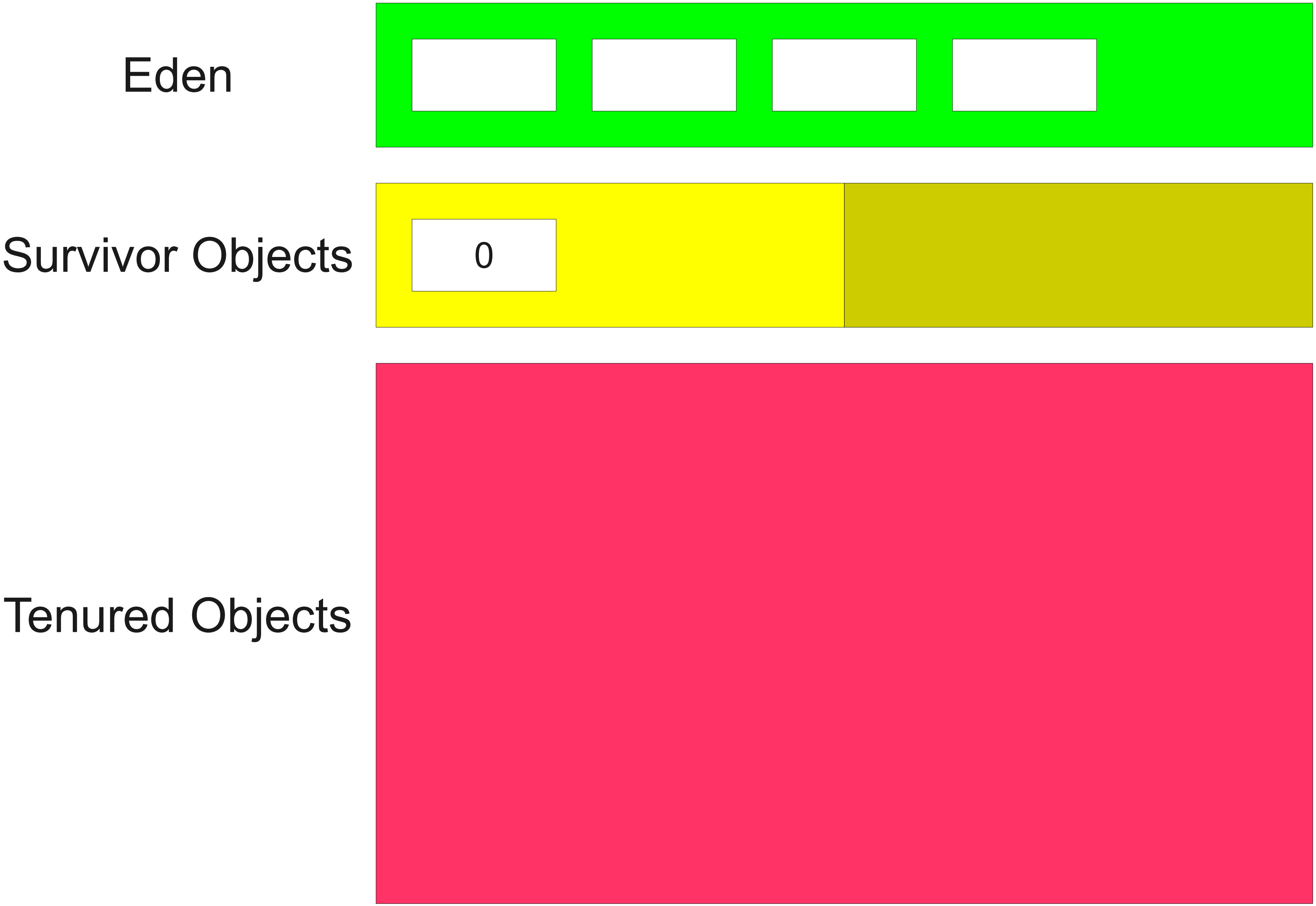

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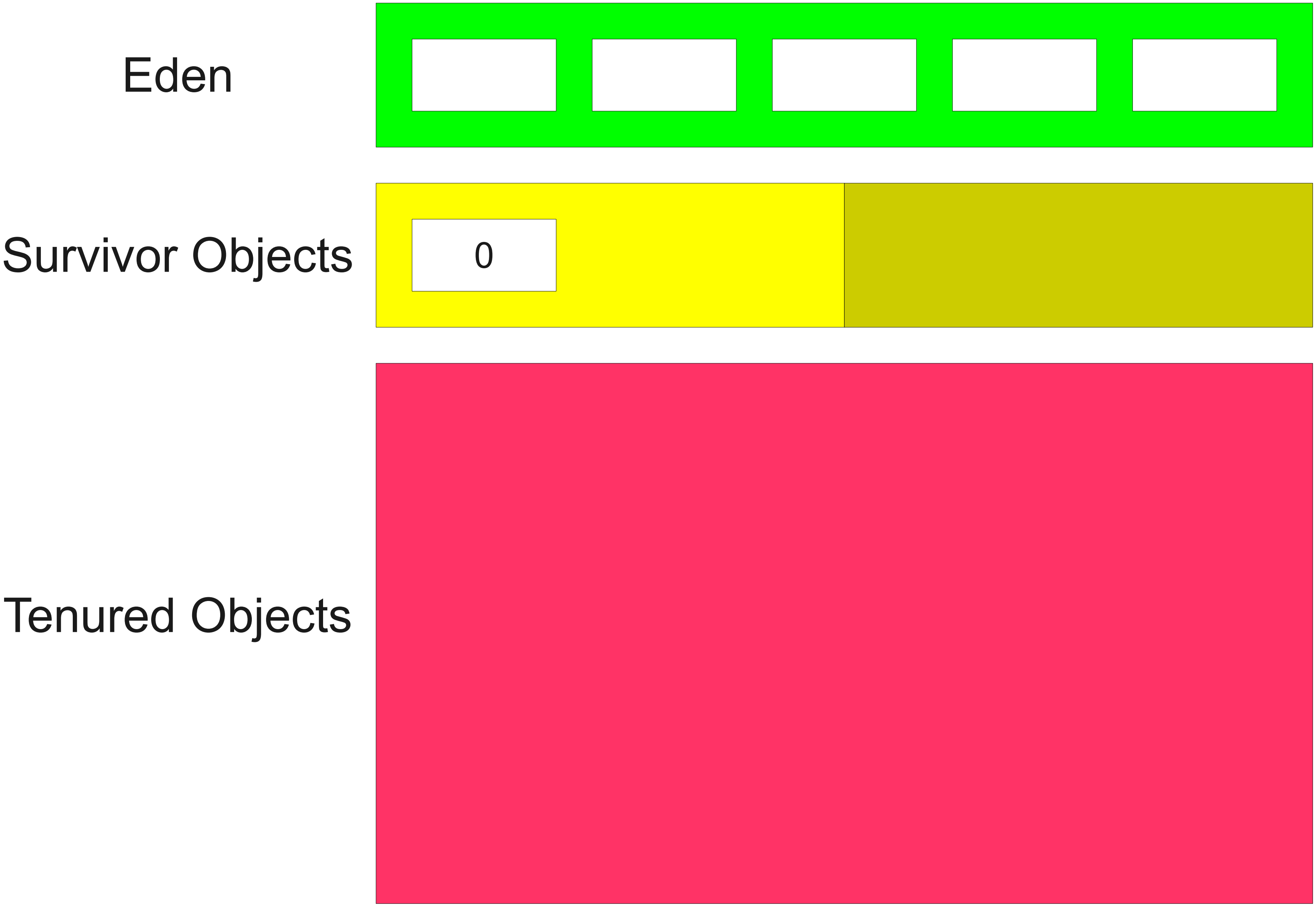

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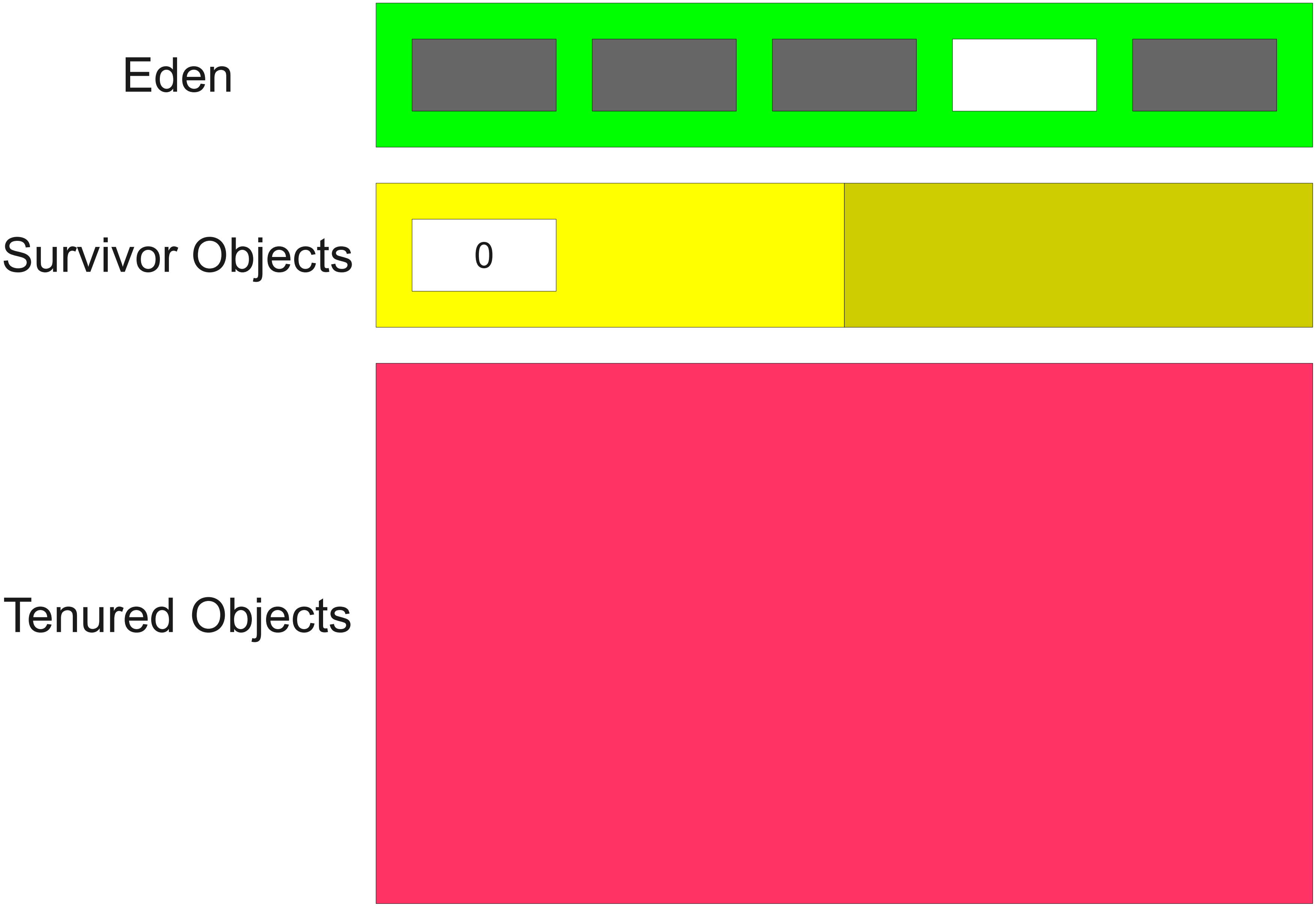

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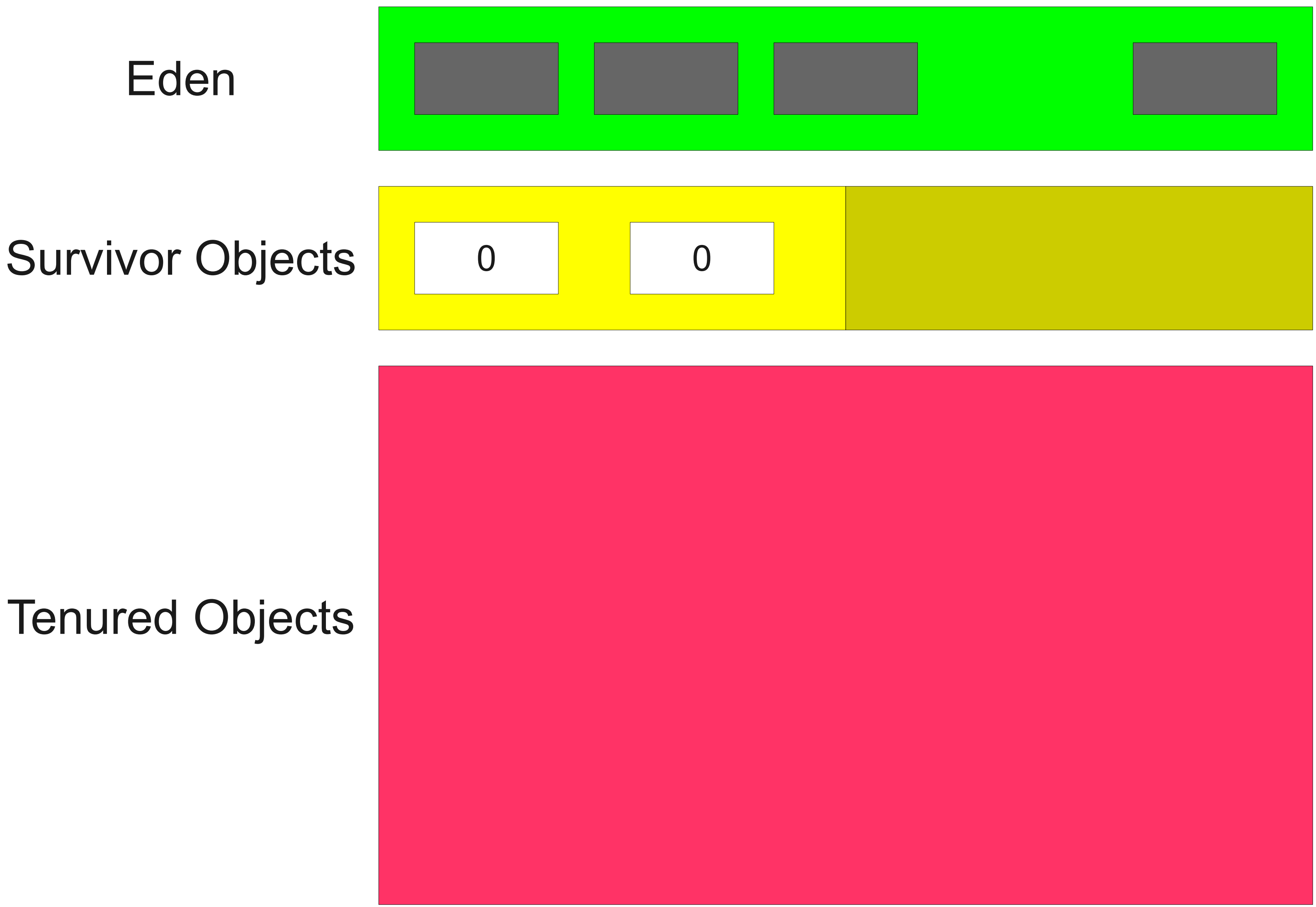

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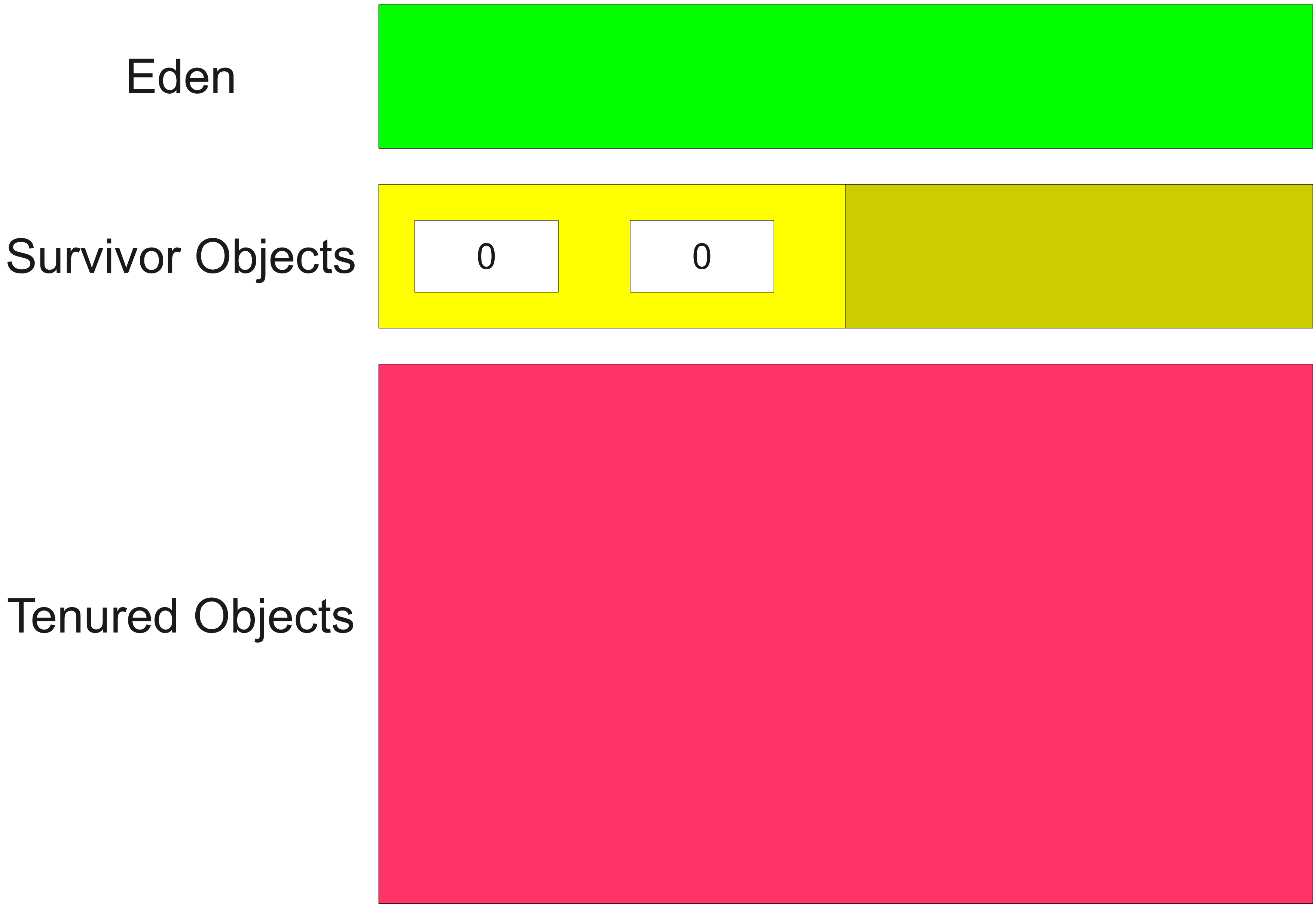

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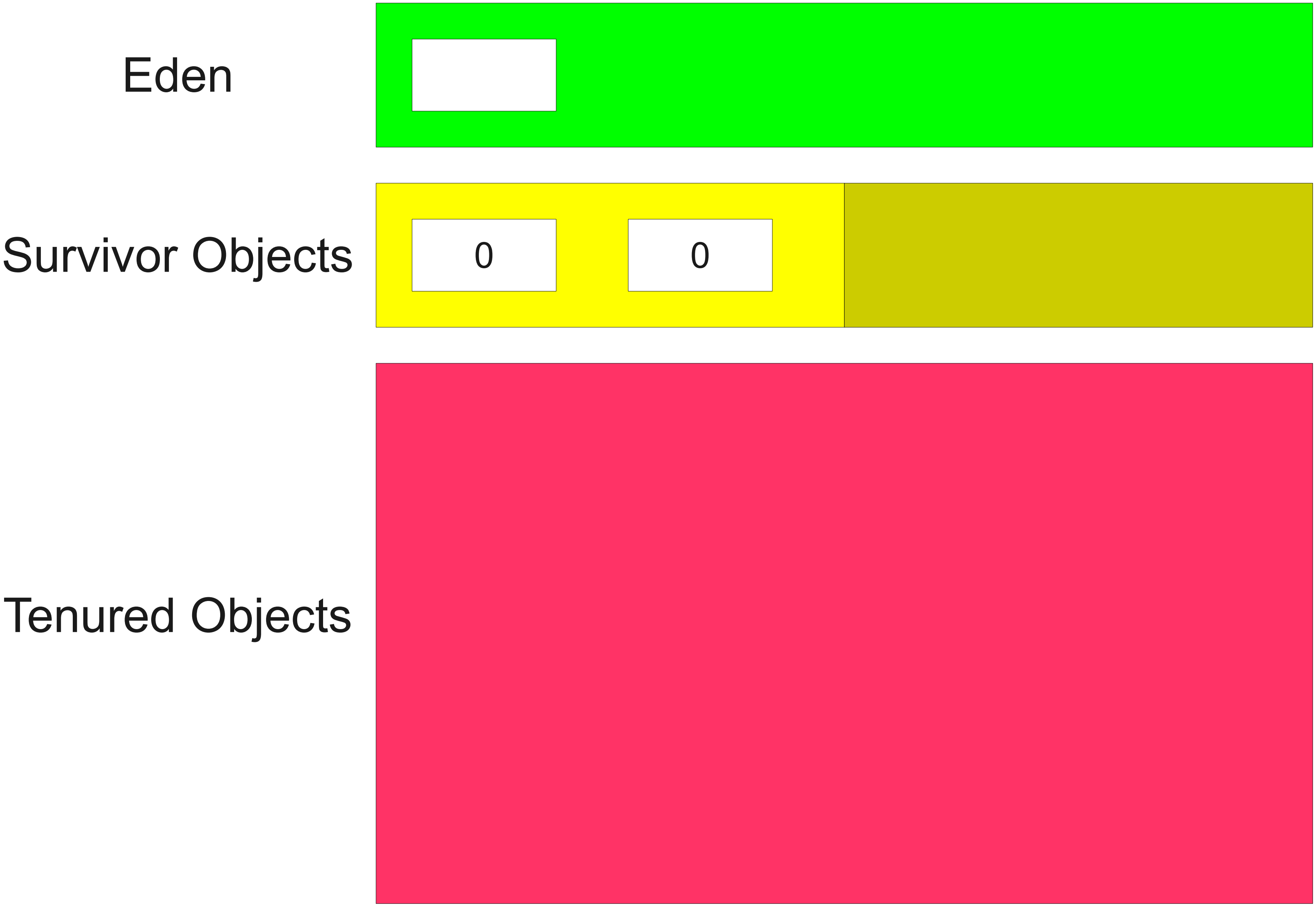

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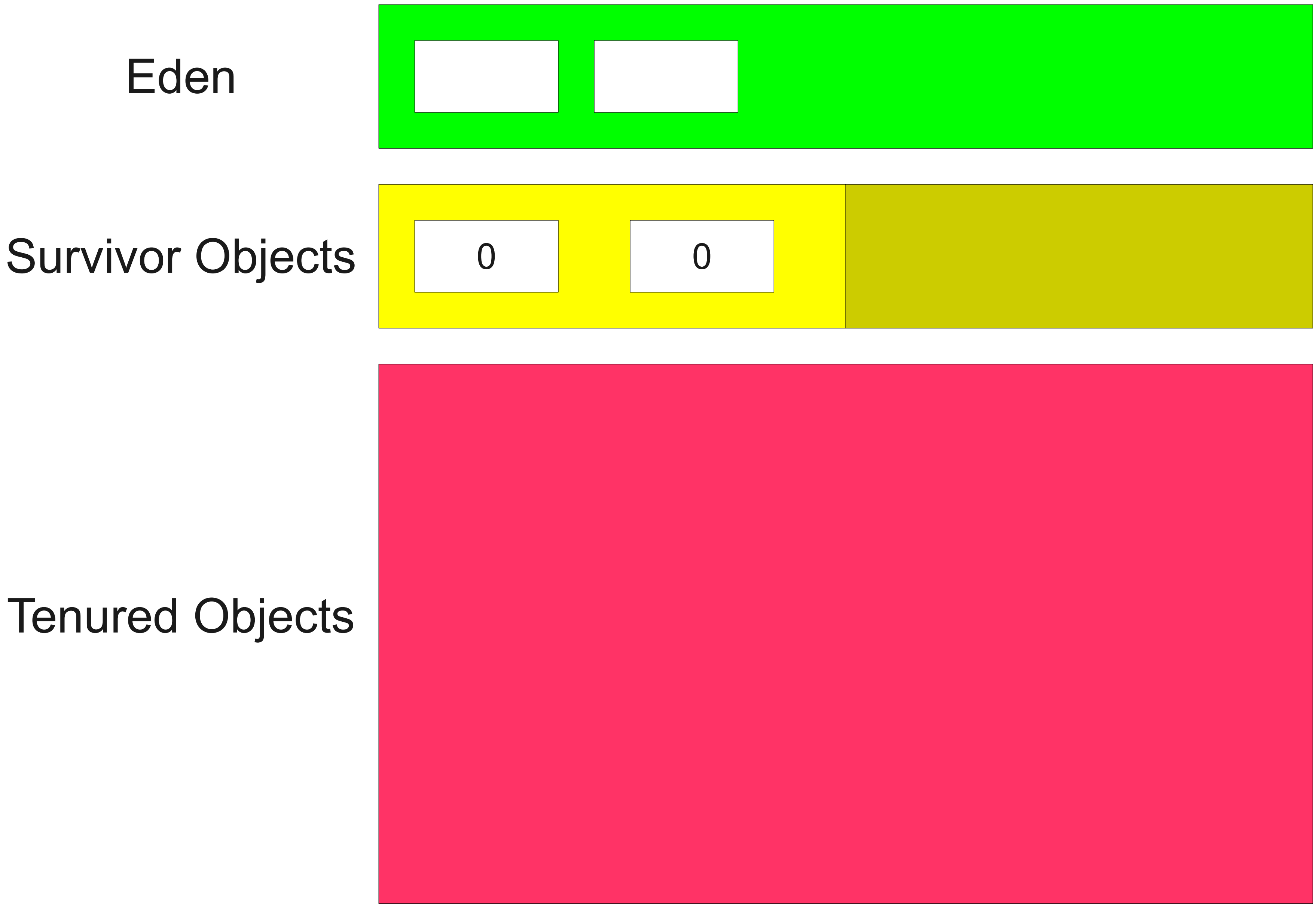

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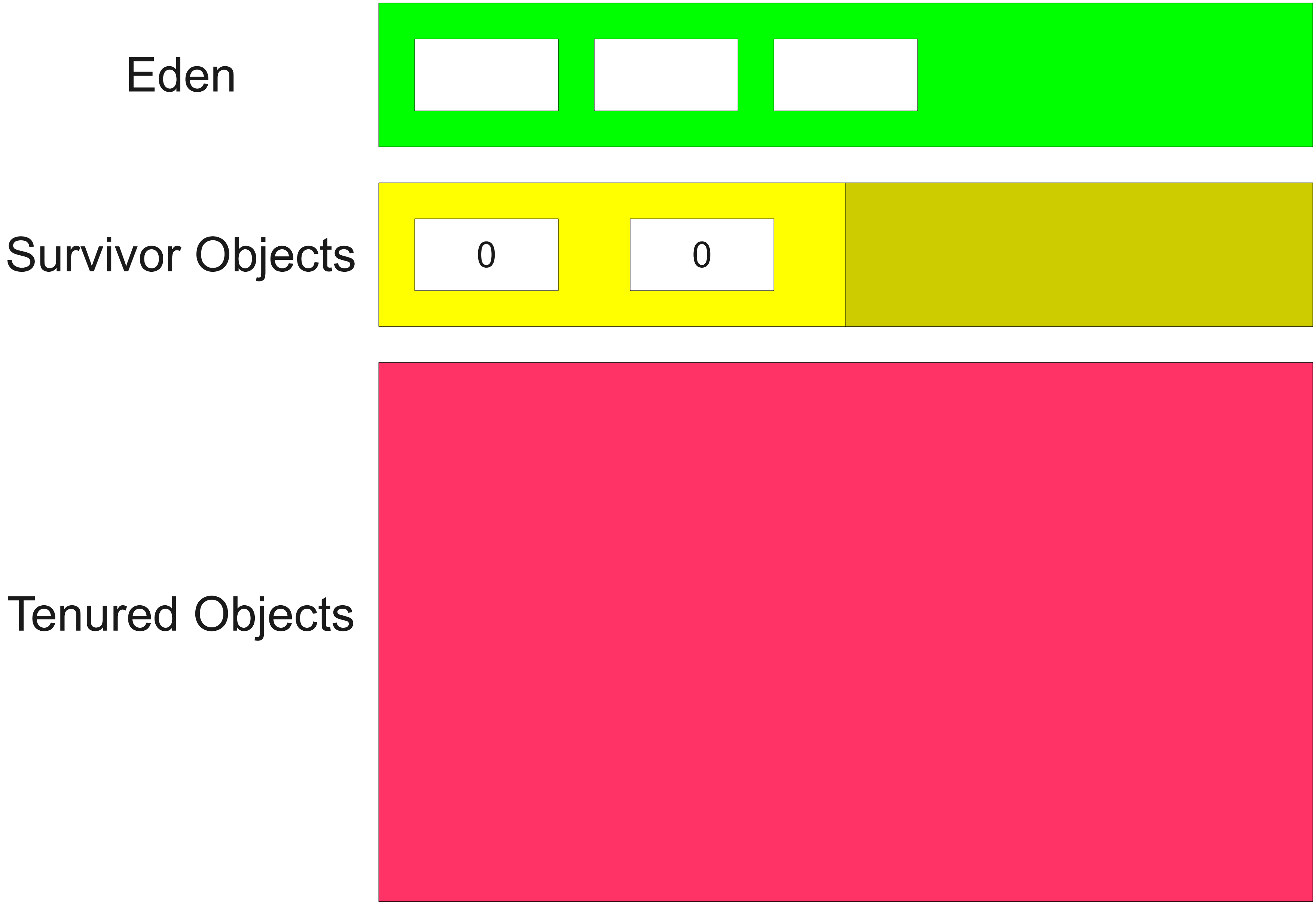

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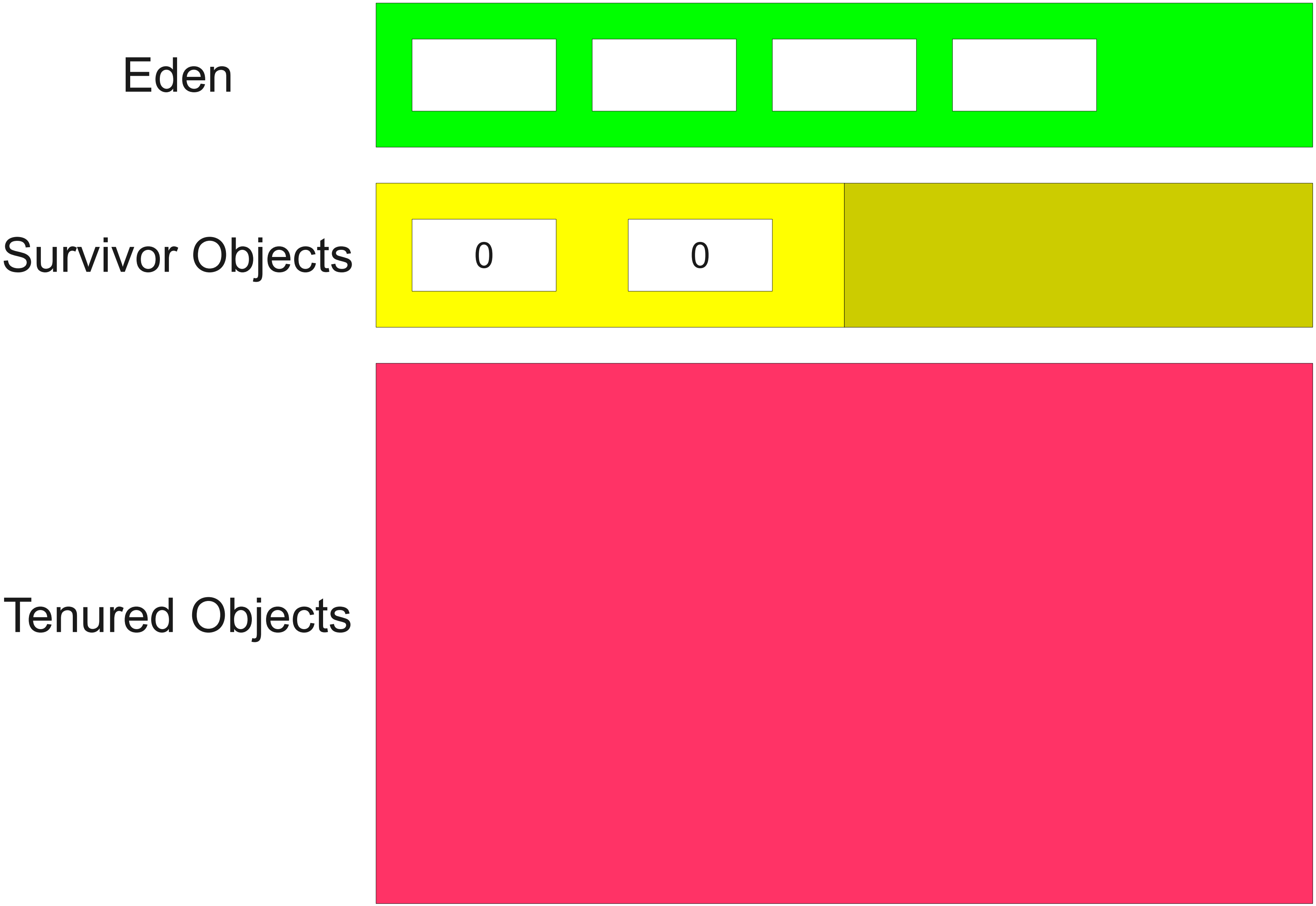

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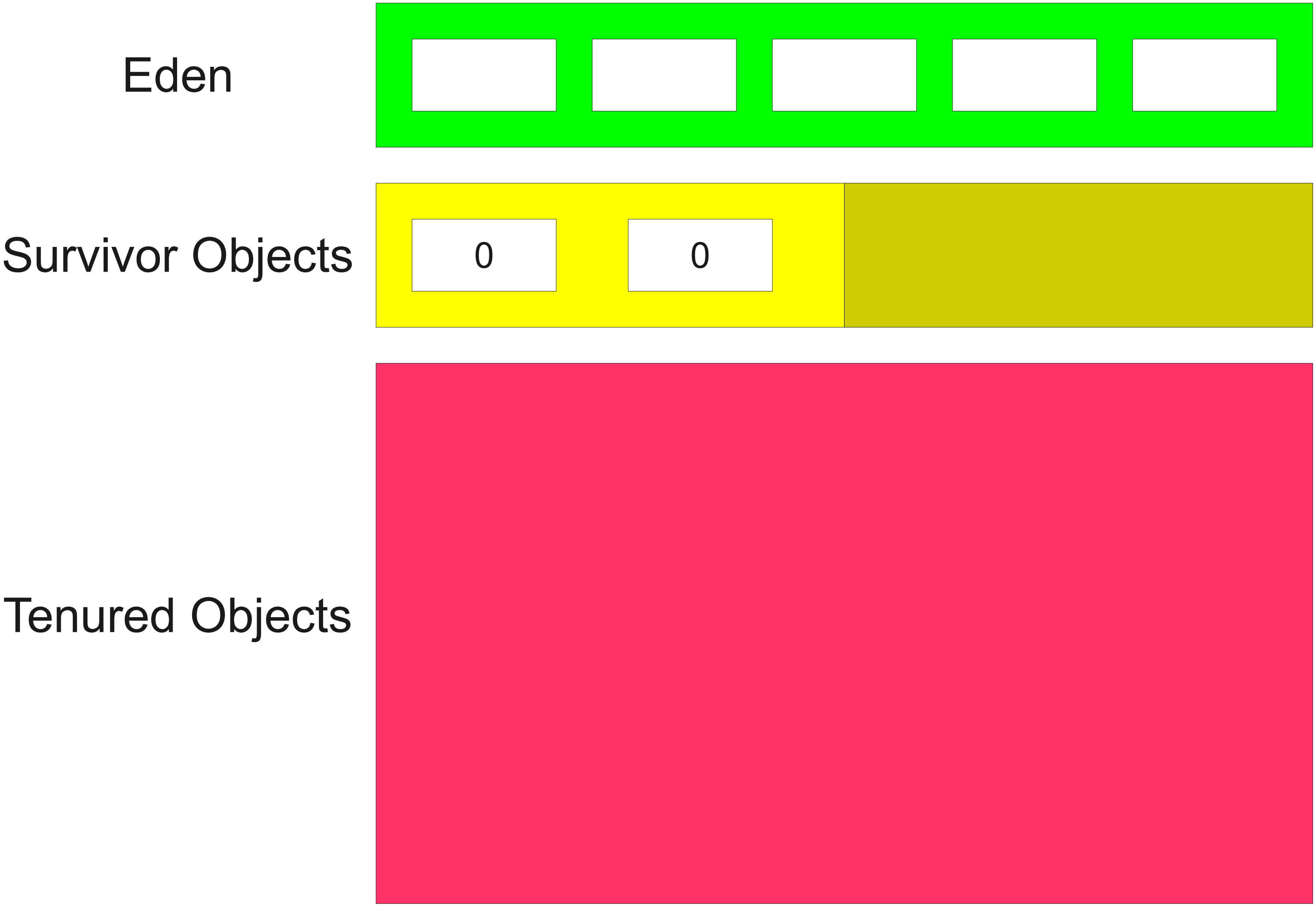

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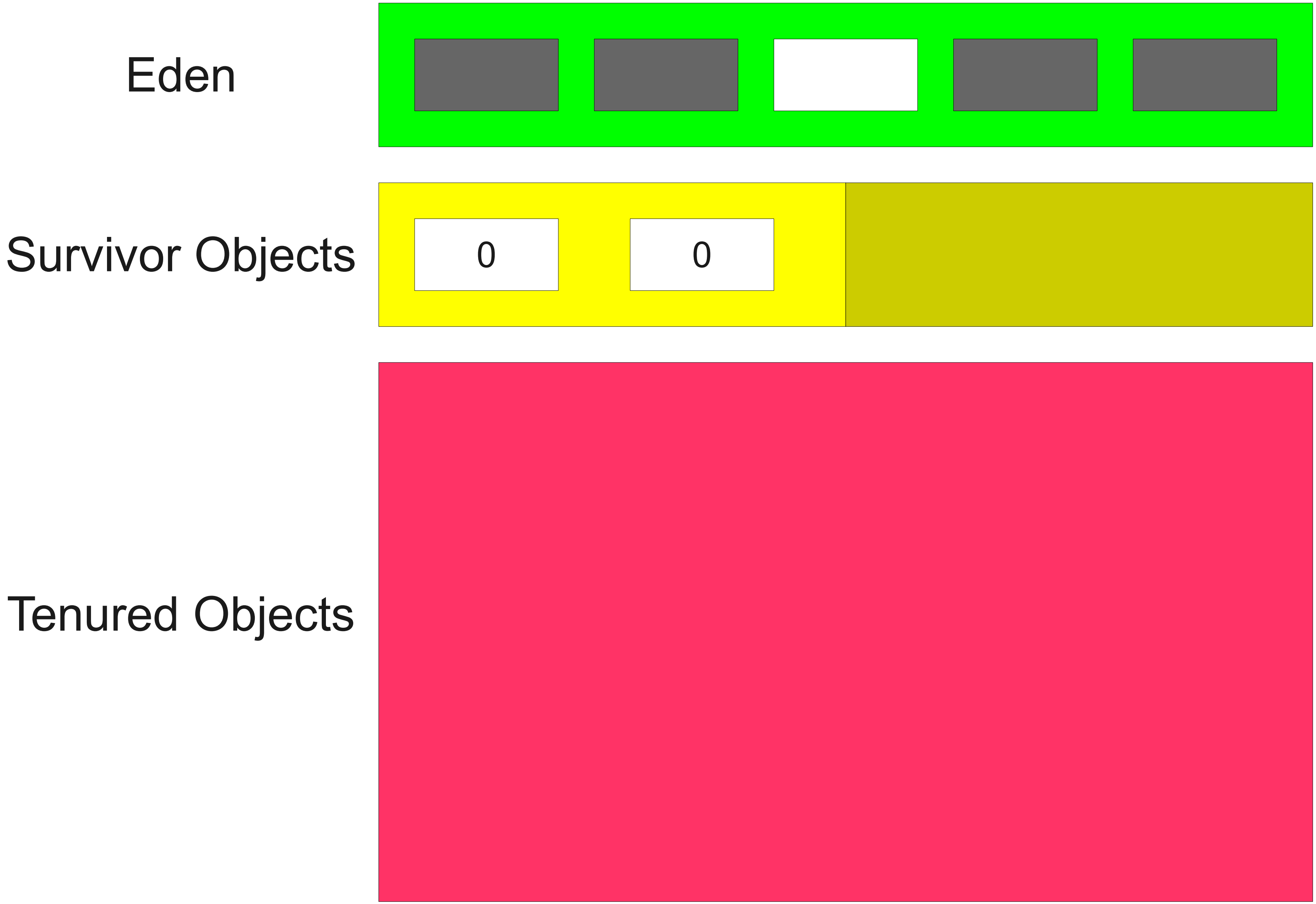

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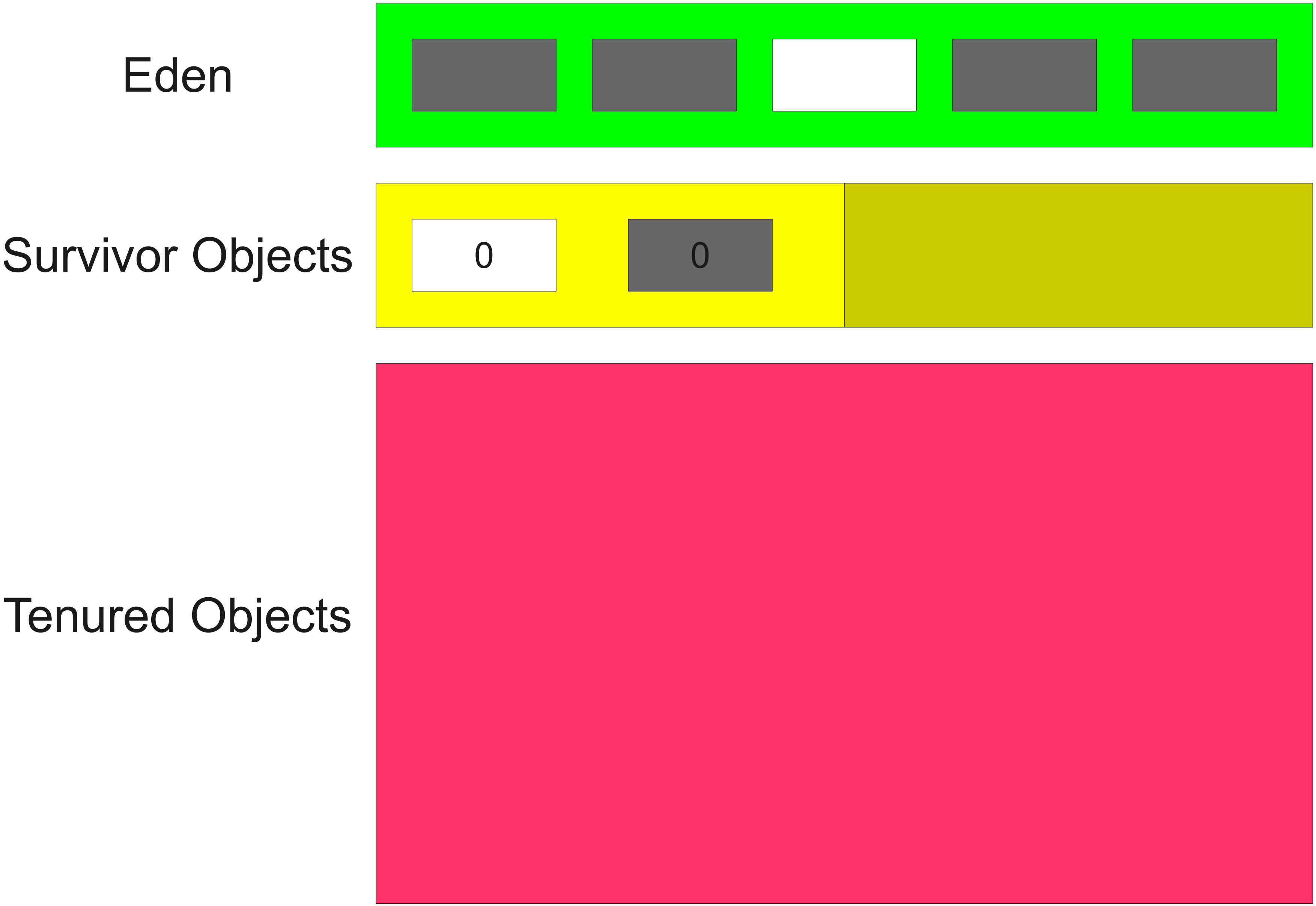

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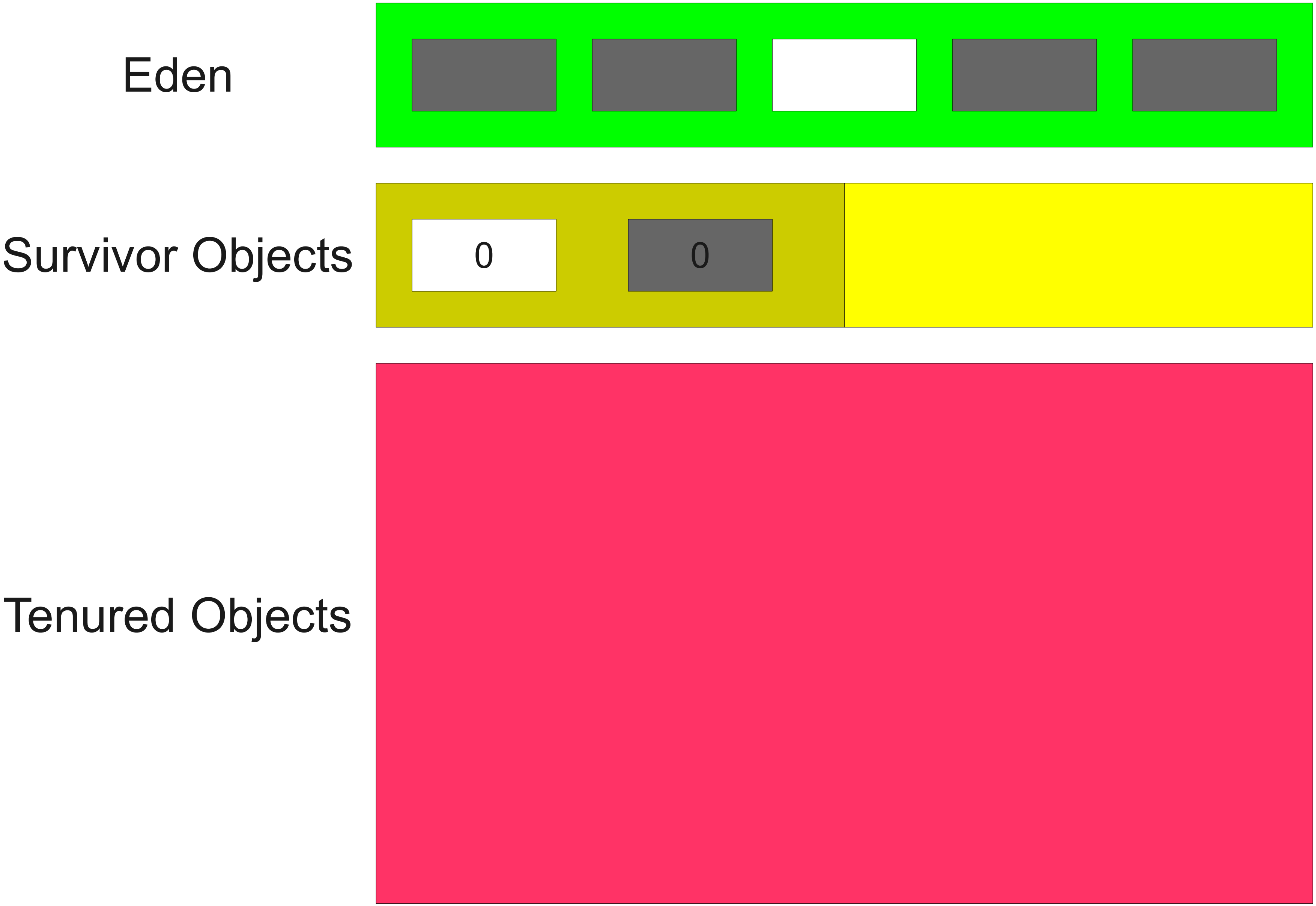

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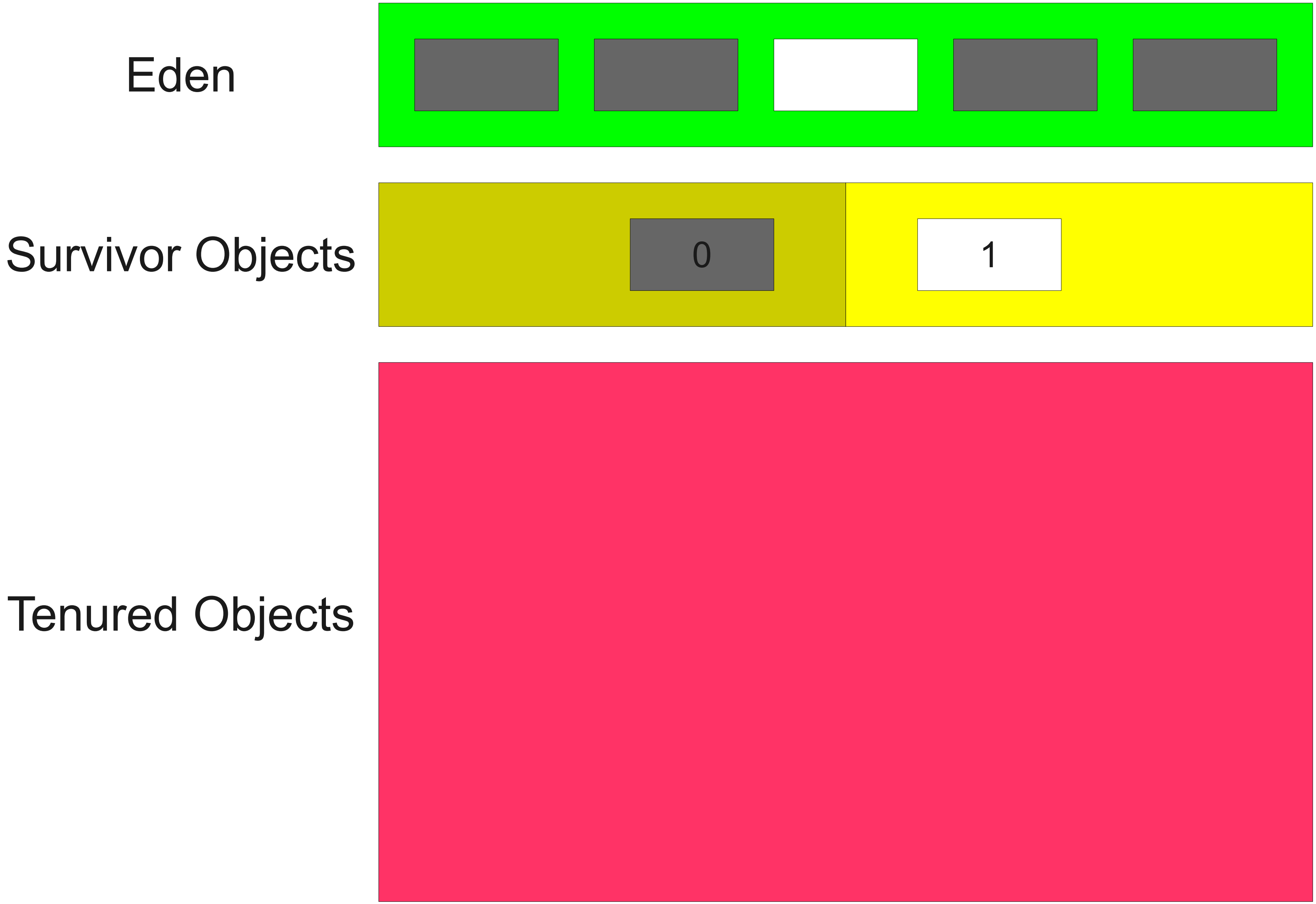

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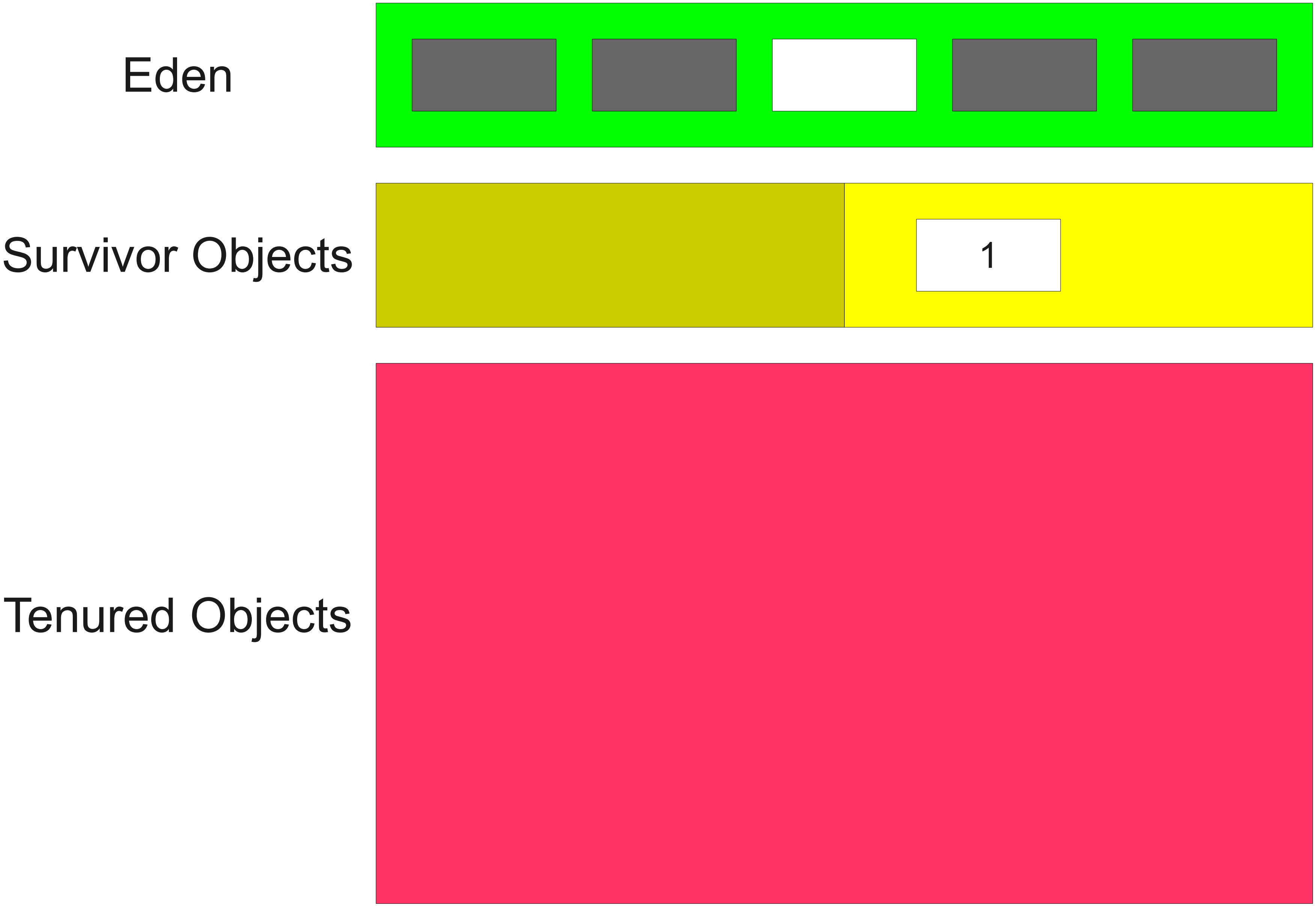

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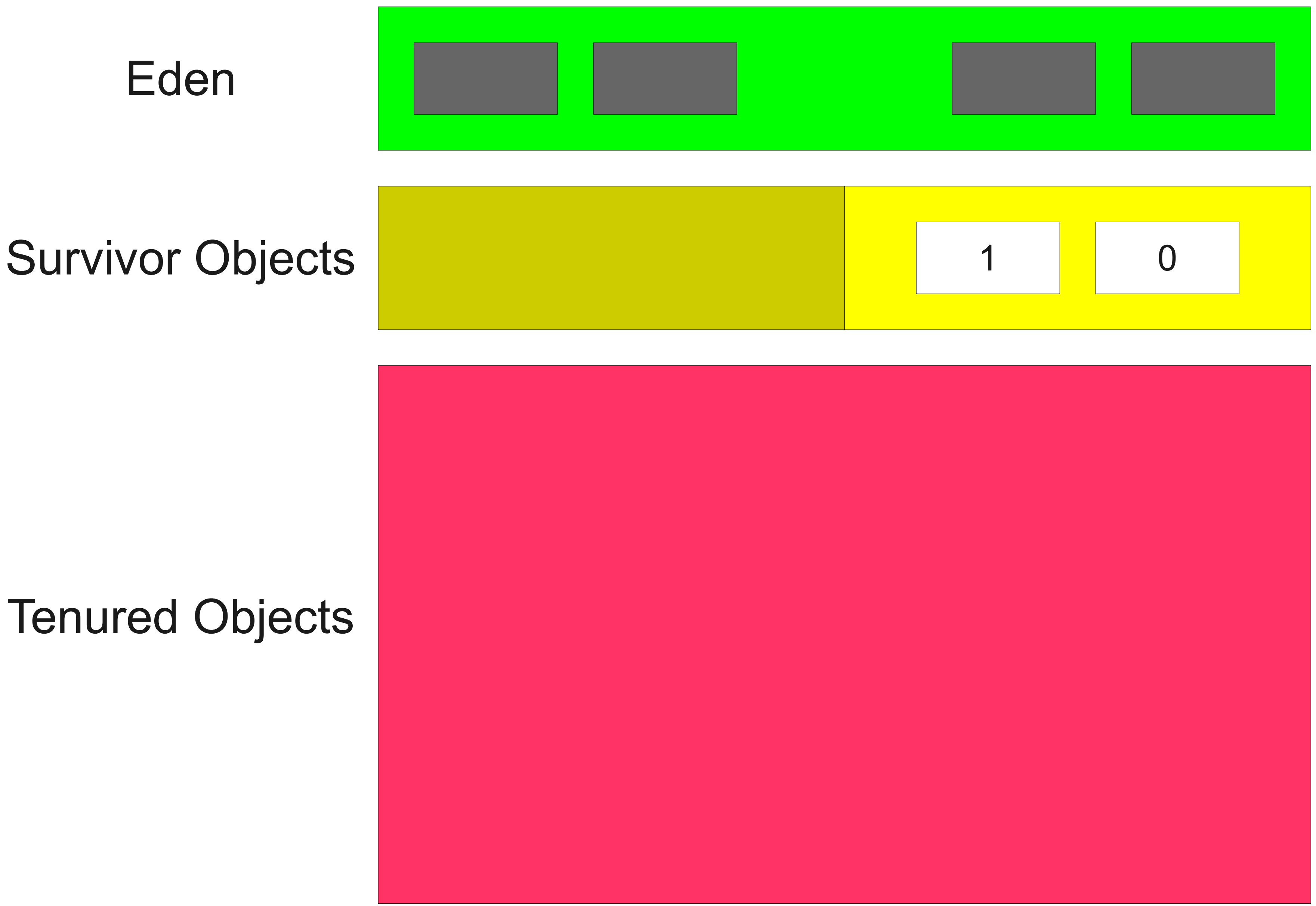

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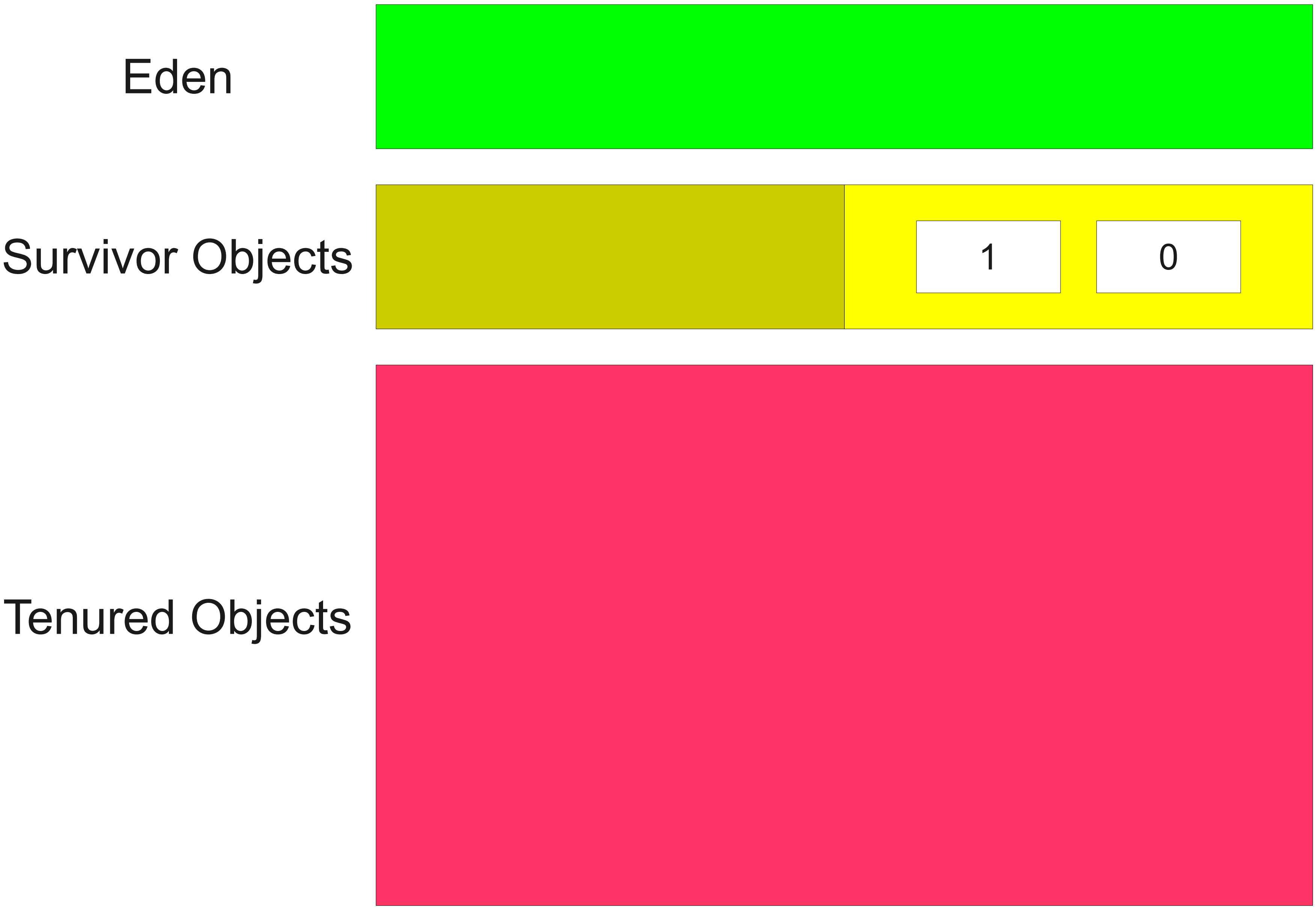

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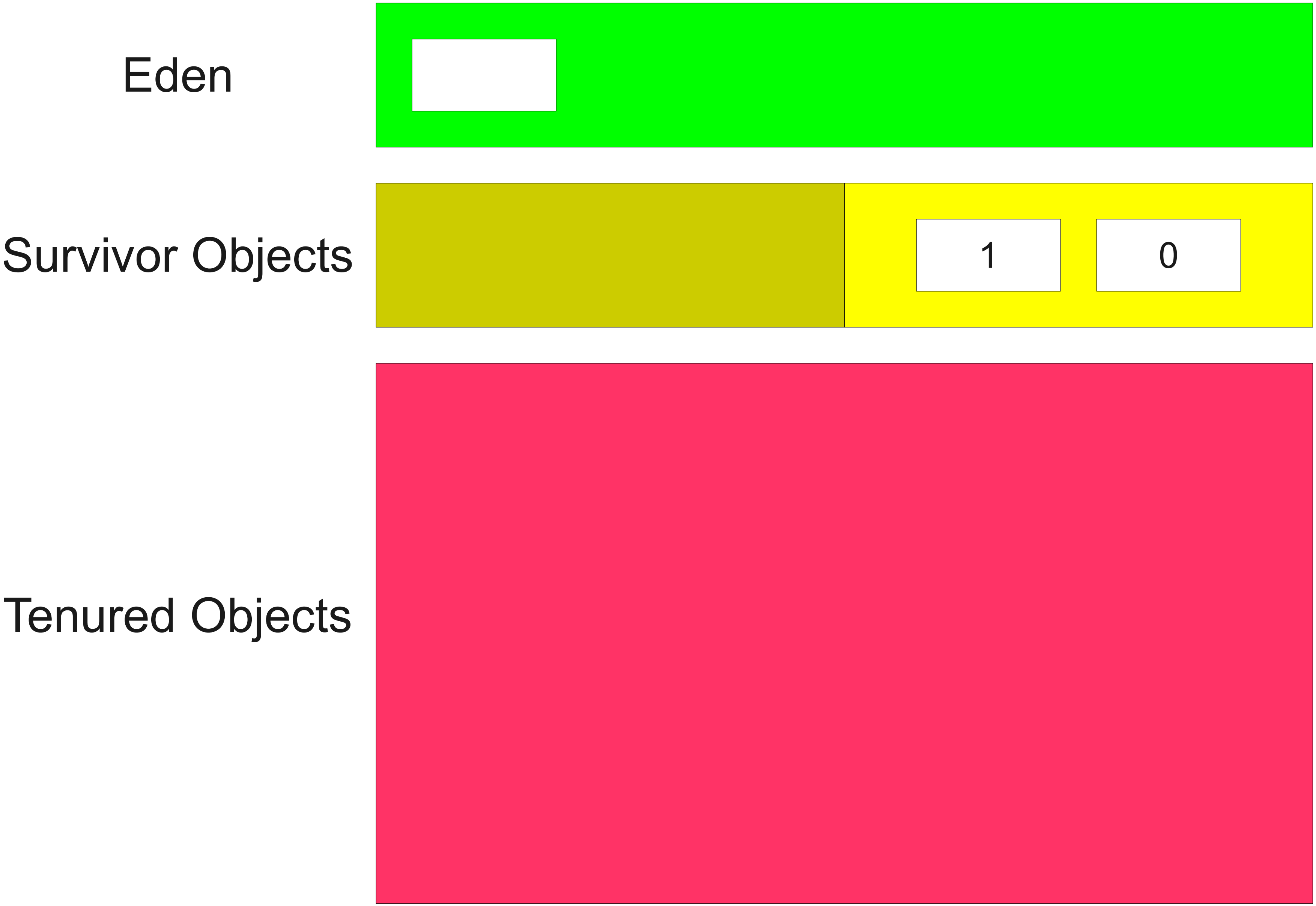

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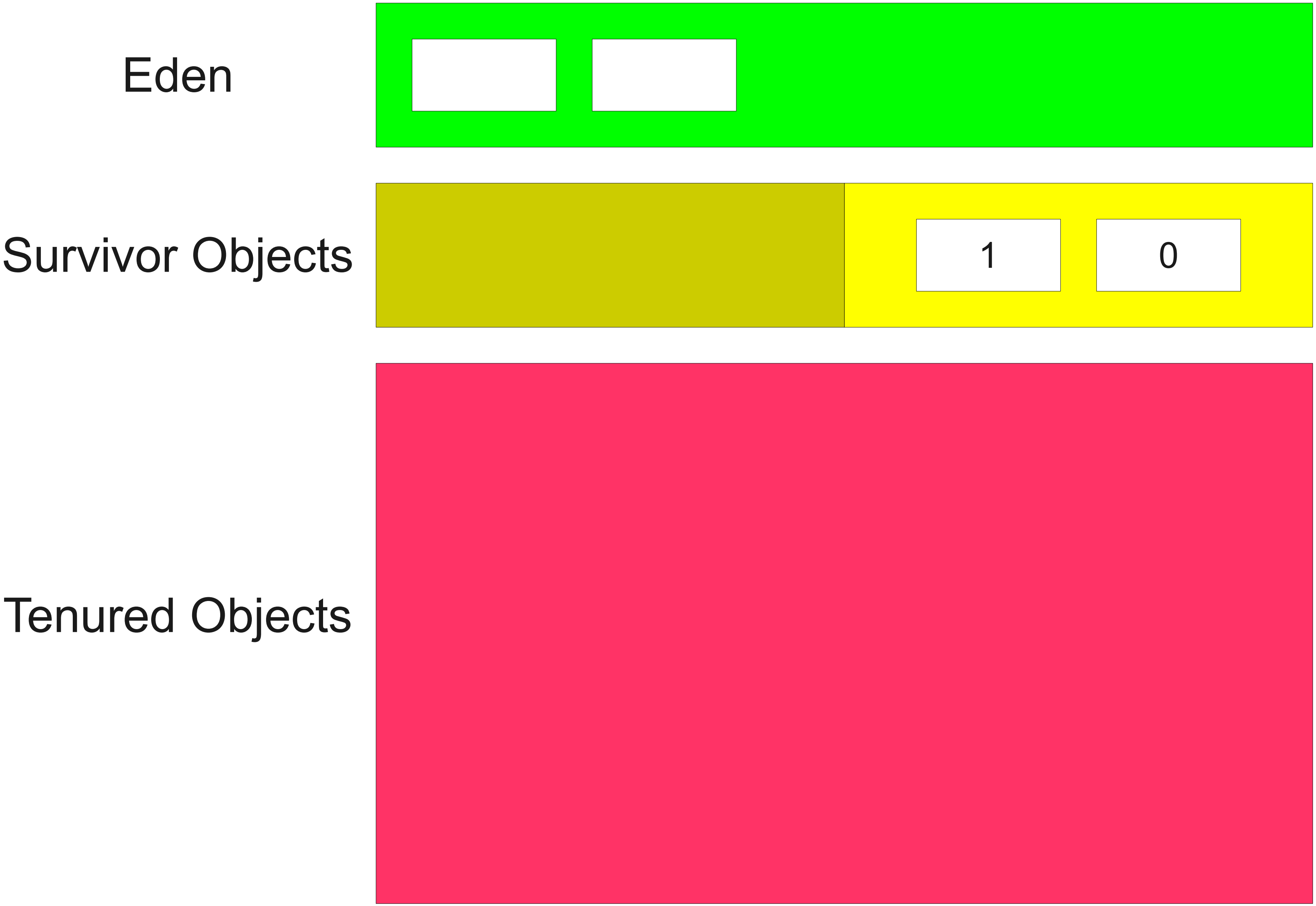

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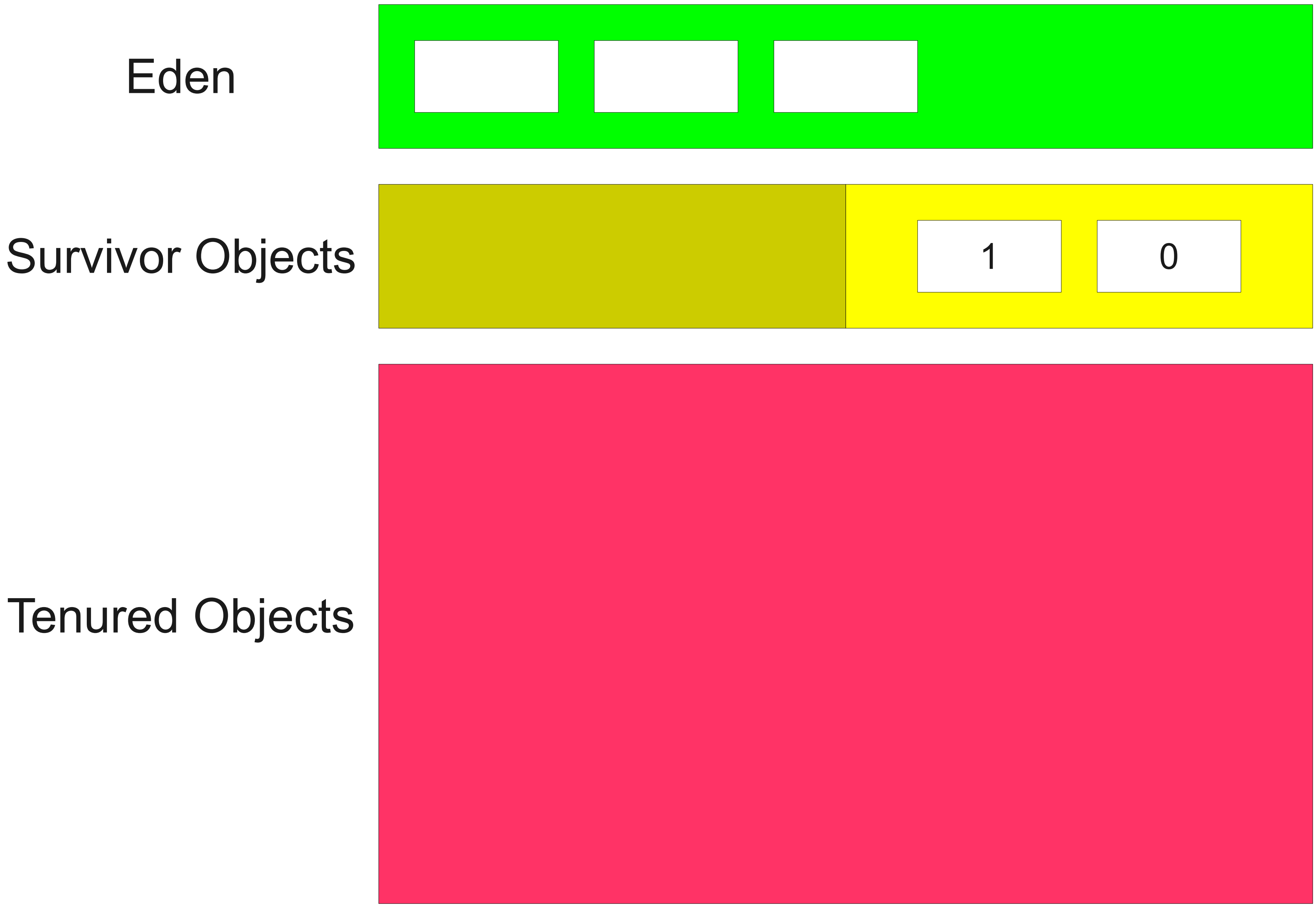

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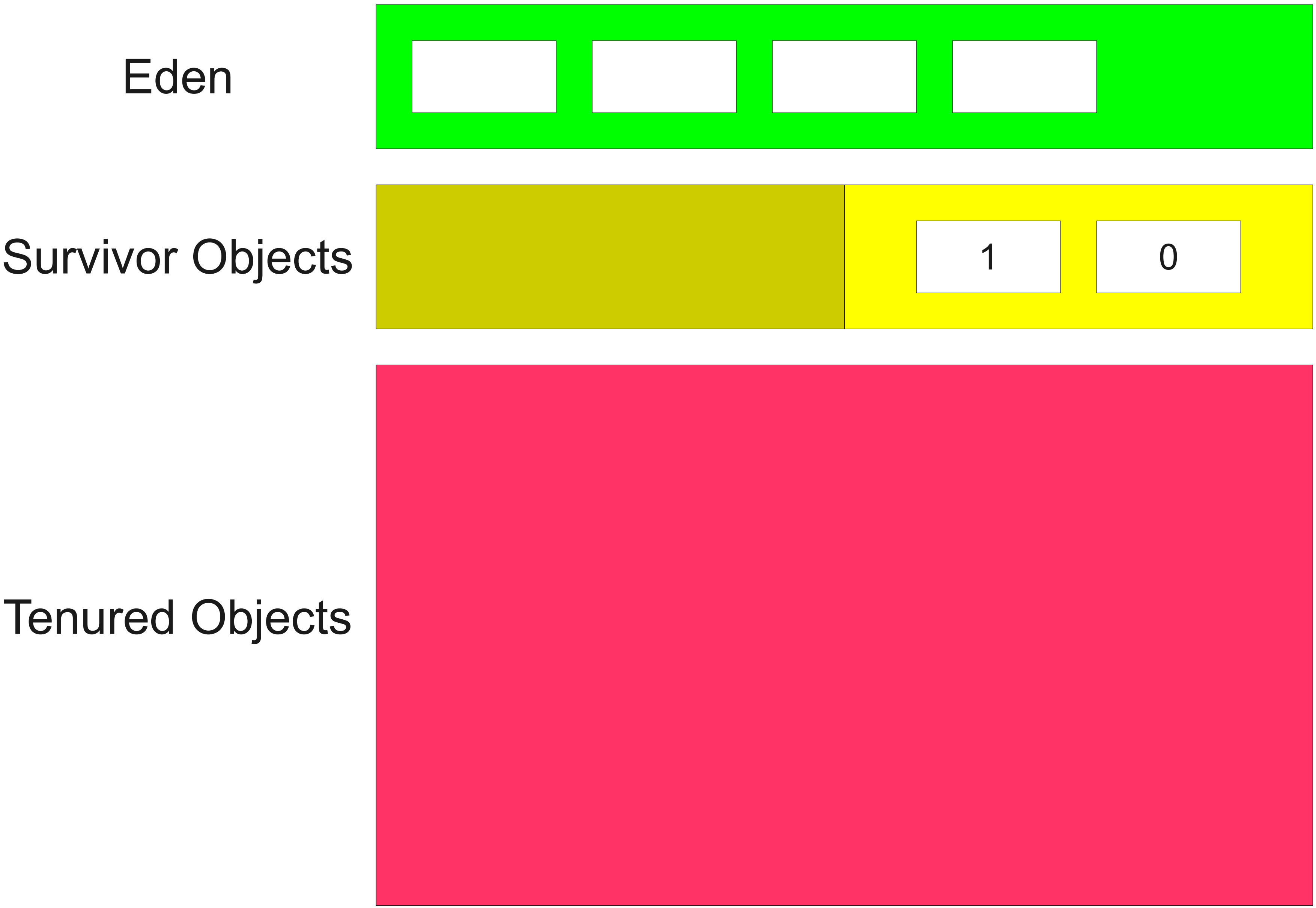

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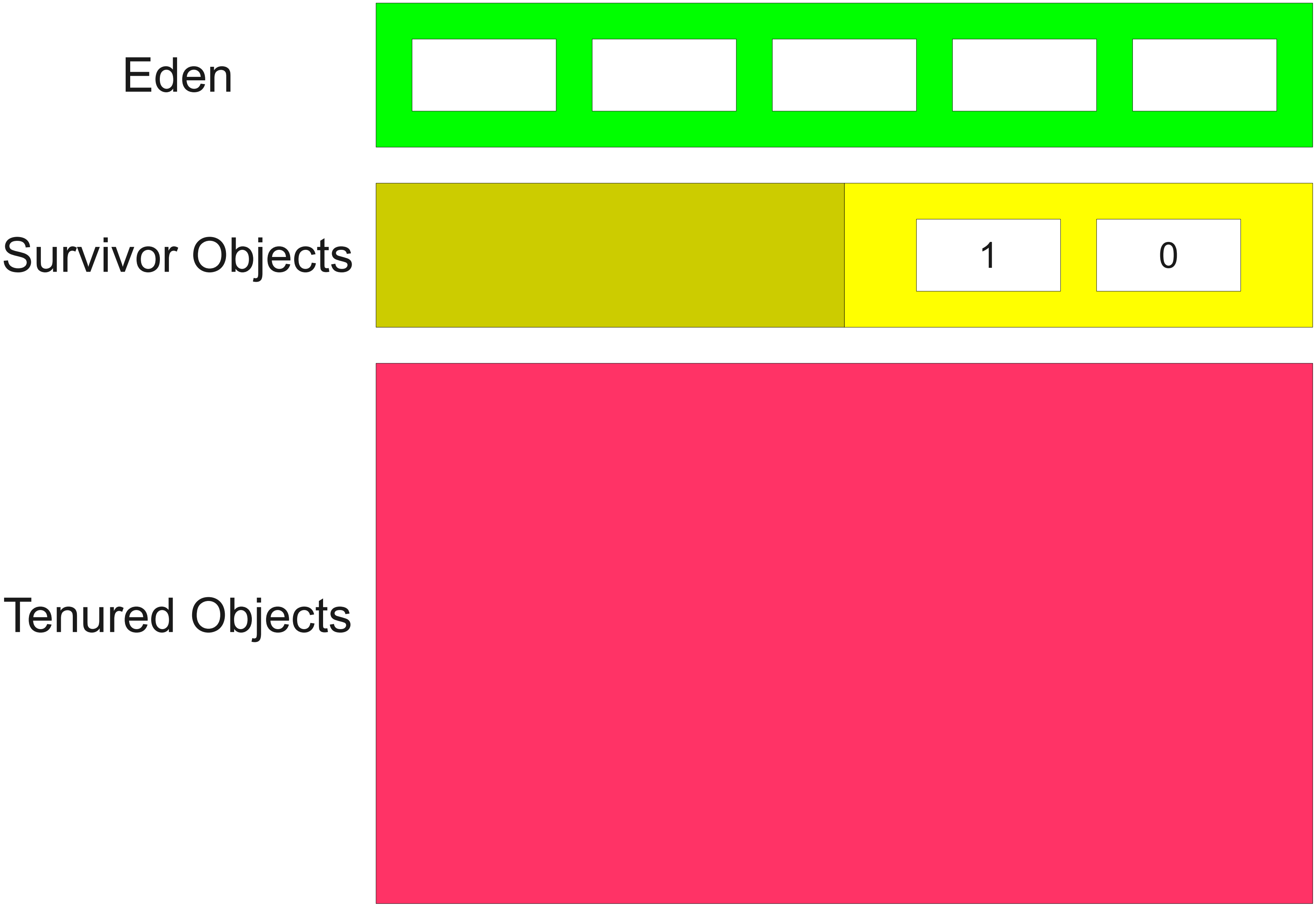

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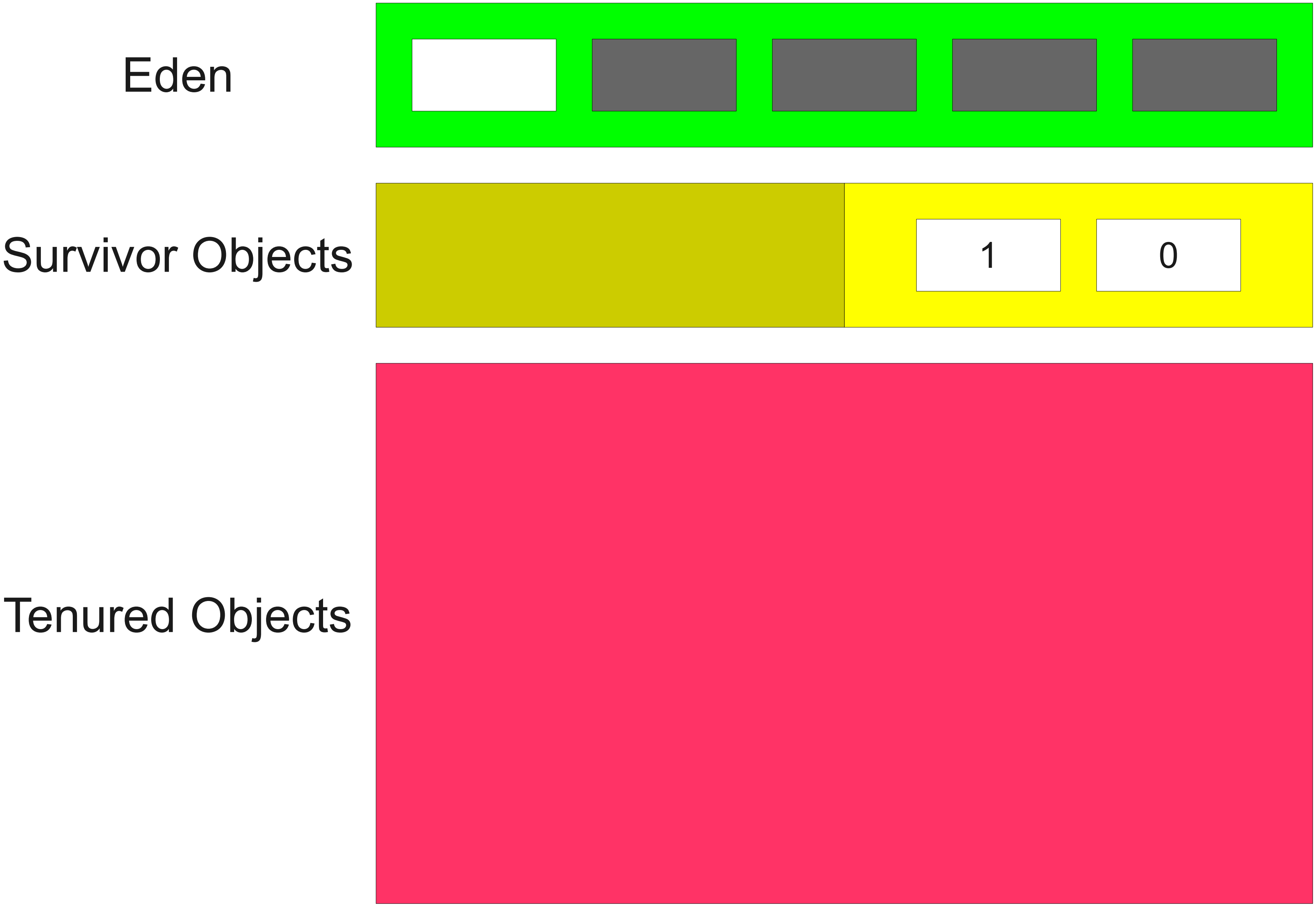

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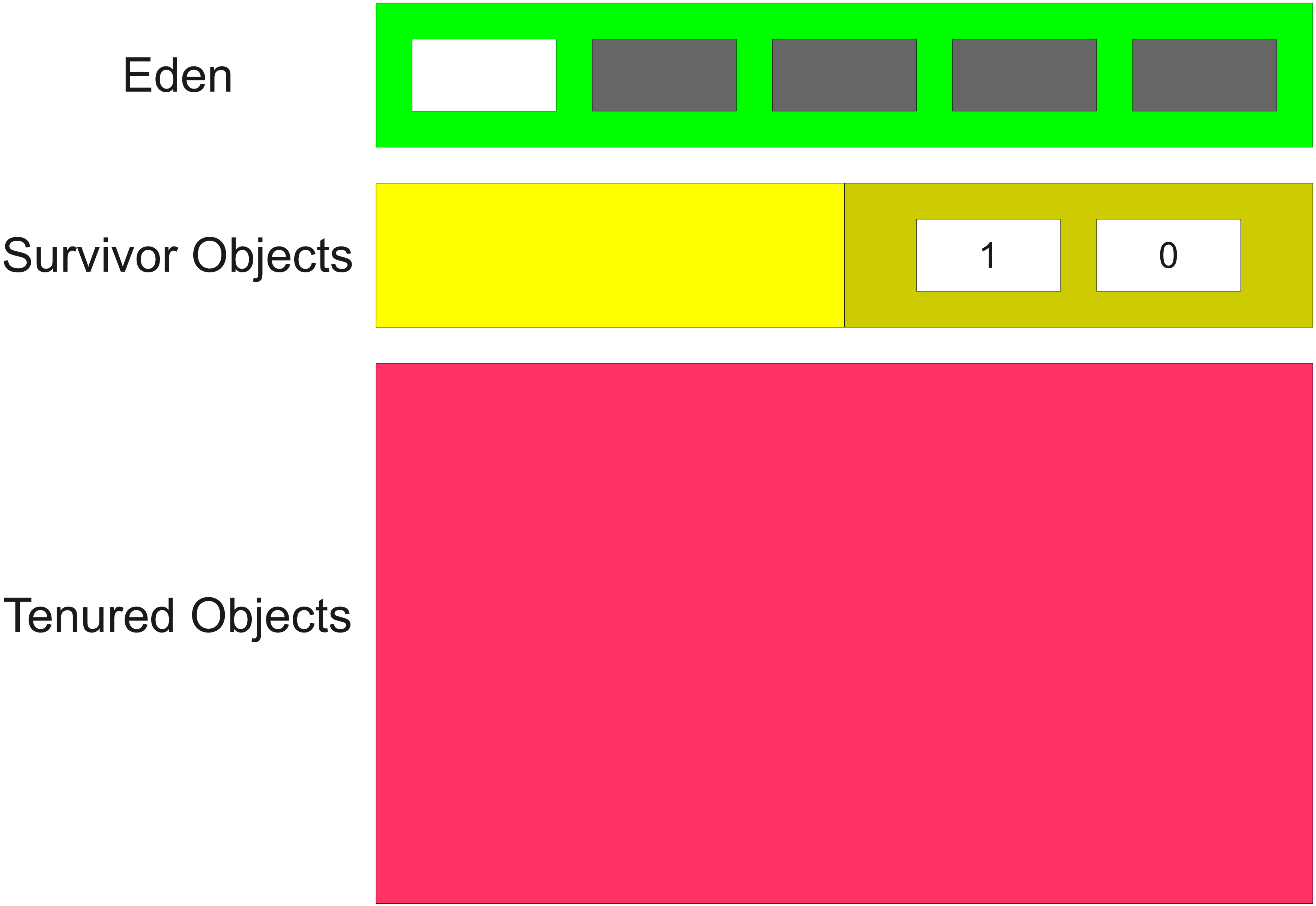

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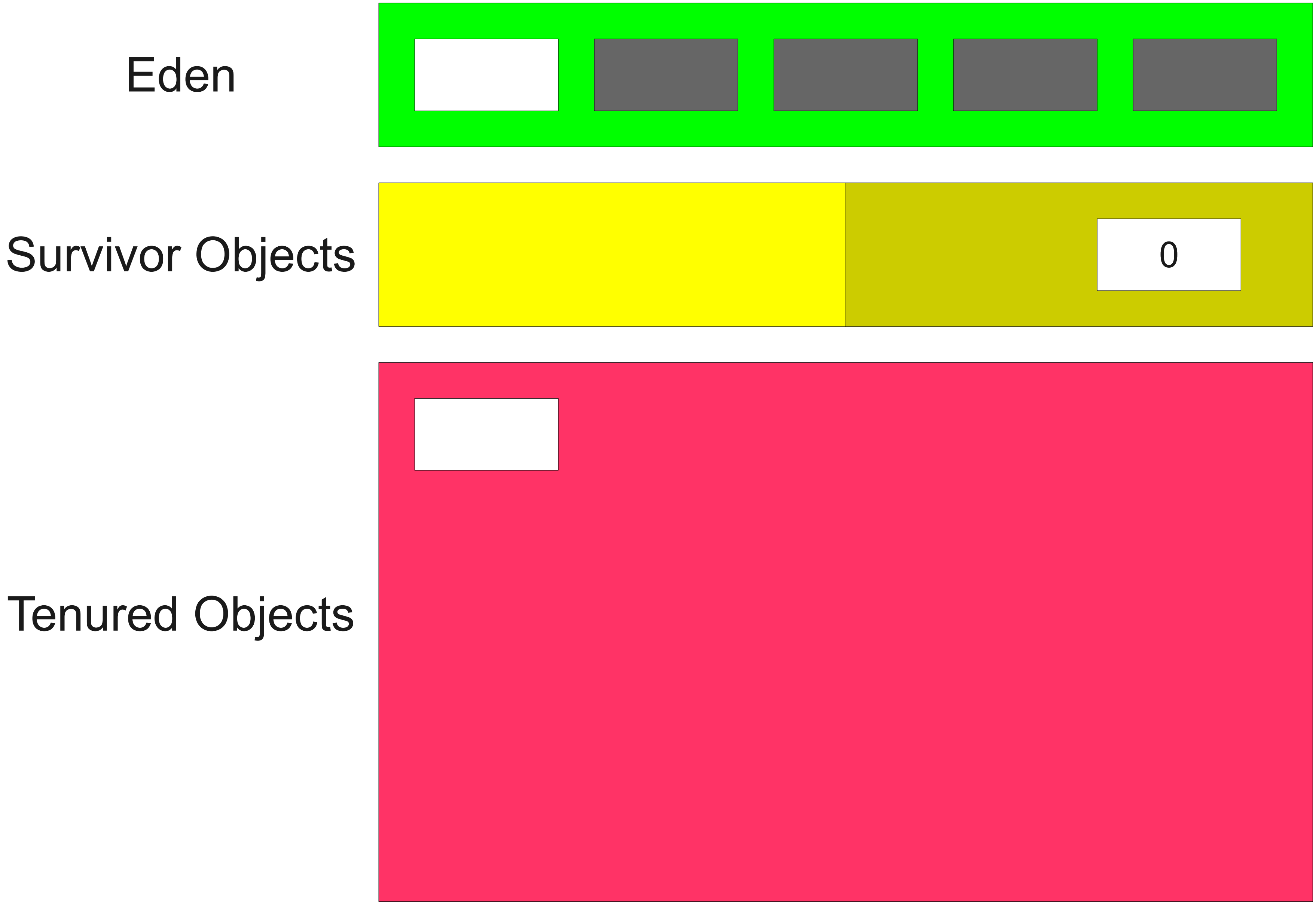

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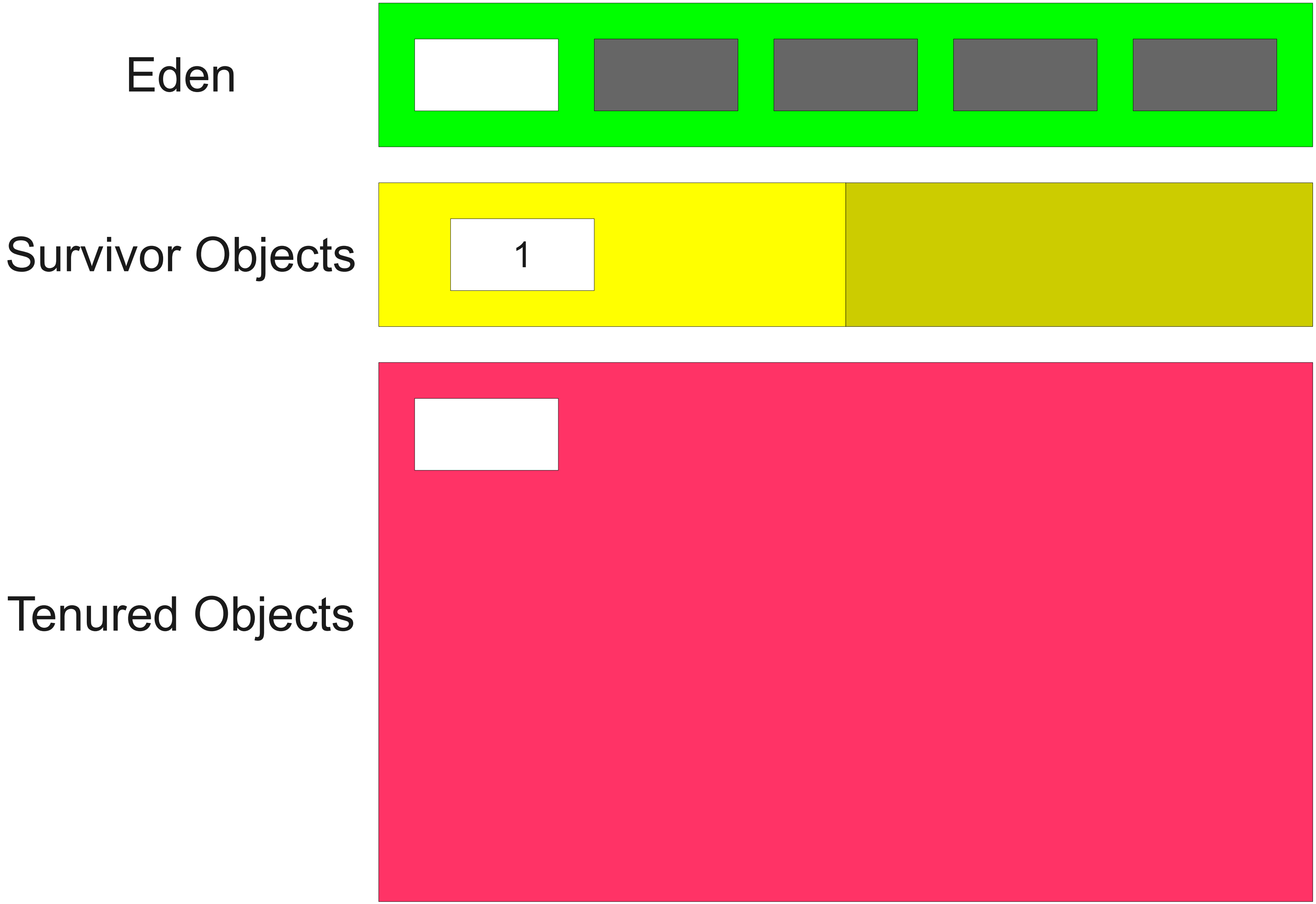

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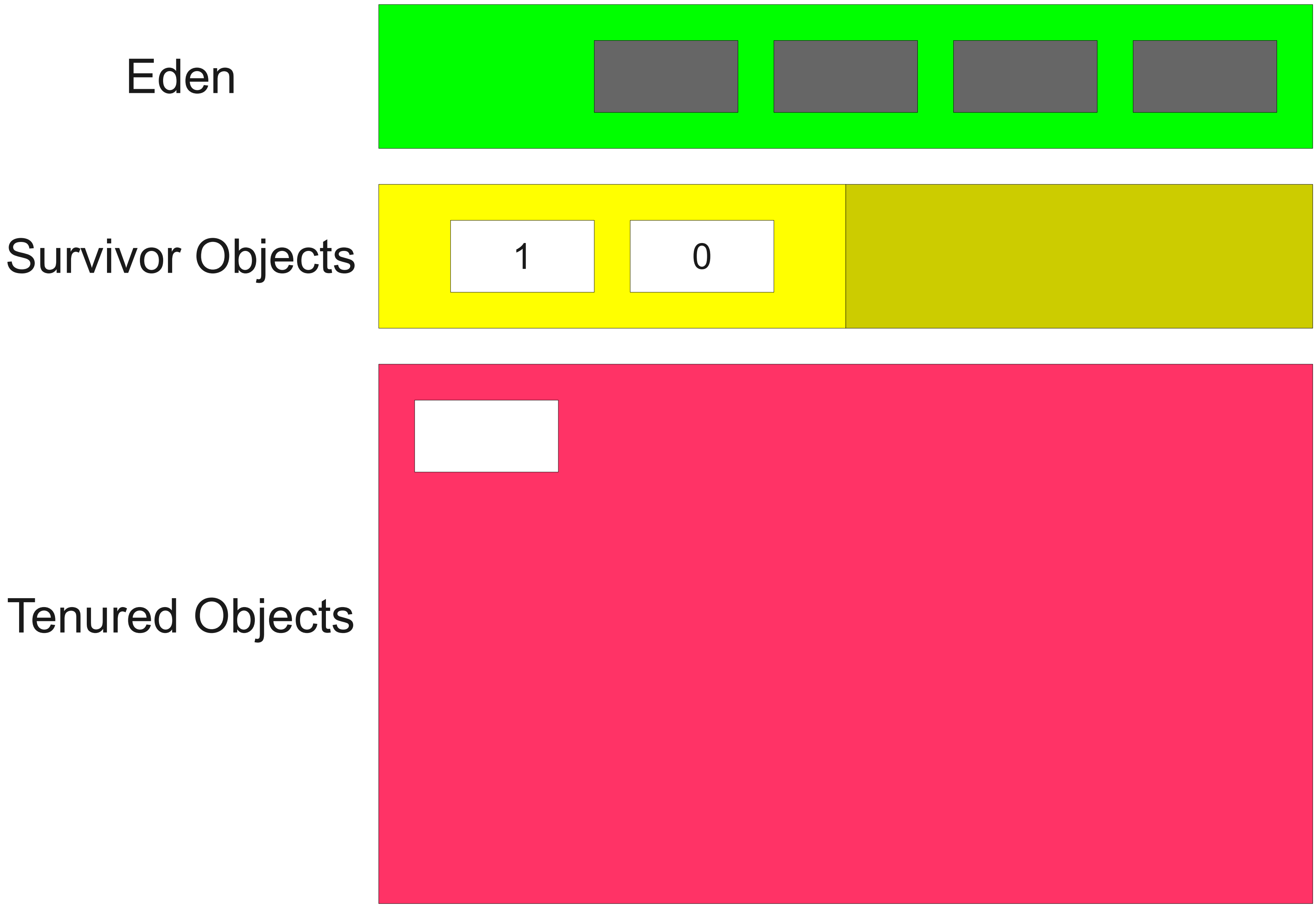

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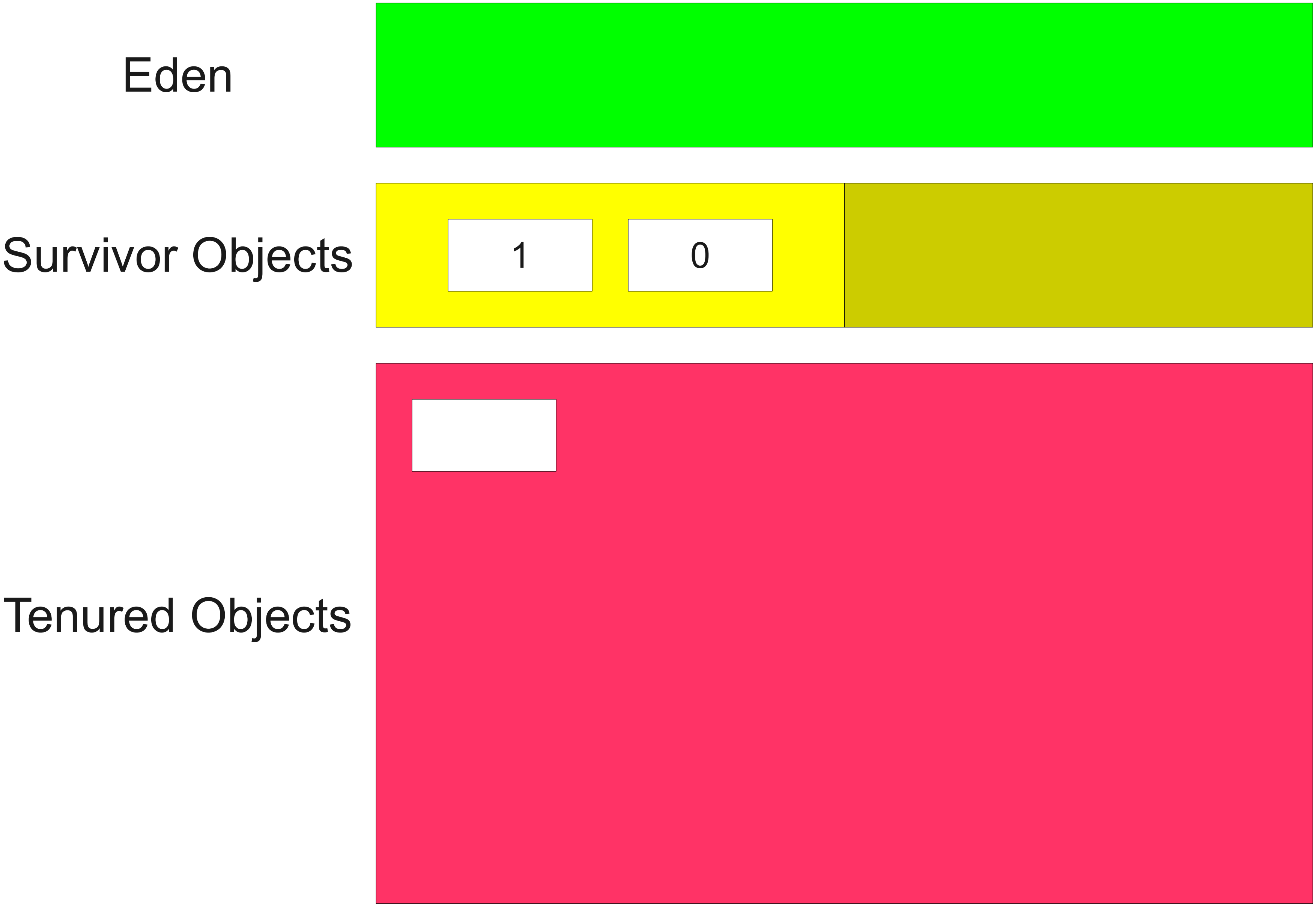

HotSpot Garbage Collection

- New objects are allocated using a modified stop-and-copy collector in the **Eden** space.
- When Eden runs out of space, the stop-and-copy collector moves its elements to the **survivor space**.
- Objects that survive long enough in the survivor space become **tenured** and are moved to the **tenured space**.
- When memory fills up, a full garbage collection (perhaps mark-and-sweep) is used to garbage-collect the tenured objects.

Next Time

- **Final Code Optimization**
  - Instruction scheduling.
  - Locality optimizations.
- **Where to Go From Here**
- **Final Thoughts**