

Lecture 12 – Garbage Collection

COSE212: Programming Languages

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2024 Fall

- Mutation makes it possible to **change the state** of a program by **updating the contents** of a data structure or a variable.
 - BFAE – FAE with **mutable boxes**
 - MFAE – FAE with **mutable variables**
 - Evaluation with **memories**, finite maps from addresses to values:

$$\begin{array}{l} \text{Memories} \quad M \in \mathbb{A} \xrightarrow{\text{fin}} \mathbb{V} \\ \text{Addresses} \quad a \in \mathbb{A} \end{array}$$

- In this lecture, we will learn **memory management** techniques to **deallocate** unreachable memory cells:
 - **Stack and Heap**
 - **Manual Memory Management**
 - **Garbage Collection (GC)**

1. Stack and Heap

Tail-Call Optimization (TCO)

2. Manual Memory Management

3. Garbage Collection

Reference Counting

Mark-and-Sweep GC

Copying GC (Two-Space GC)

Other GC Algorithms

1. Stack and Heap

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Other GC Algorithms

In the previous lecture, we have seen the memory in the following MFAE expression has **unreachable** memory cells as follows:

```

/* MFAE */
var y = 1;
var f = x => {
  x = x + y;
  x * x
};
f(5);          /* 36 */
y = 3;
f(5);          /* 64 */

```

$$\sigma = [$$

$$y \mapsto a_0$$

$$f \mapsto a_1$$

$$]$$

$$\mathbb{A} : a_0 \quad a_1 \quad a_2 \quad a_3 \quad \dots$$

$$M = \begin{array}{|c|c|c|c|c|} \hline 3 & v & 6 & 8 & \dots \\ \hline \end{array}$$

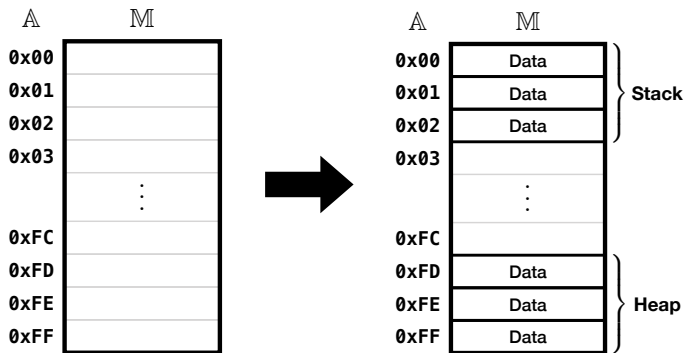
where $v = \langle \lambda x. (x = x + y; x * x), [y \mapsto a_0] \rangle$

Then, how to **detect** and **deallocate** unreachable memory cells?

Let's delete **unreachable** memory cells when the program **exits** functions!

We can **divide** the memory into two parts:

- **Stack** – for **local variables** and **function parameters**
- **Heap** – for **dynamically allocated** memory cells



Create a **new stack frame** when the program **enters** a function, and **delete** the stack frame when it **exits** the function.

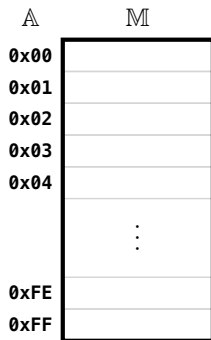
For example, consider the following Scala program:

```
case class Box(var k: Int)

def f(x: Int): Int =
  var y = Box(1)
  var z = g(2)
  x + y.k + z

def g(b: Int): Int =
  var c = Box(b)
  c.k + 3

var a = 1
var d = f(42)
a + d
```



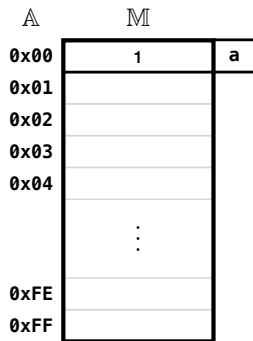
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  var c = Box(b)
  c.k + 3

var a = 1                /* a -> 0x00 */ *
var d = f(42)
a + d
```



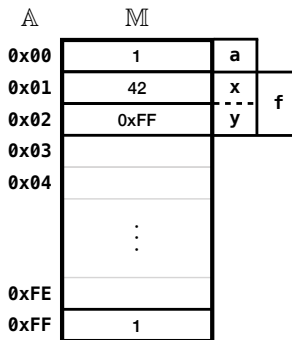
For example, consider the following Scala program:

```
case class Box(var k: Int)

def f(x: Int): Int = /* x -> 0x01 */
  var y = Box(1)      /* y -> 0x02 */ *
  var z = g(2)
  x + y.k + z

def g(b: Int): Int =
  var c = Box(b)
  c.k + 3

var a = 1             /* a -> 0x00 */
var d = f(42)
a + d
```



A **new stack frame** is created when it enters the function `f`.

For example, consider the following Scala program:

```

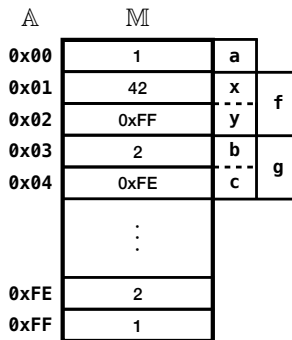
case class Box(var k: Int)

def f(x: Int): Int = /* x -> 0x01 */
  var y = Box(1)      /* y -> 0x02 */
  var z = g(2)
  x + y.k + z

def g(b: Int): Int = /* b -> 0x03 */
  var c = Box(b)     /* c -> 0x04 */
  c.k + 3            /* 5 */
                    *

var a = 1           /* a -> 0x00 */
var d = f(42)
a + d

```



A **new stack frame** is created when it enters the function `g`.

For example, consider the following Scala program:

```

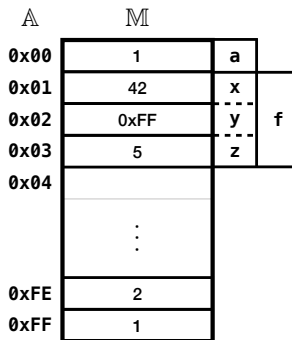
case class Box(var k: Int)

def f(x: Int): Int = /* x -> 0x01 */
  var y = Box(1)      /* y -> 0x02 */
  var z = g(2)        /* z -> 0x03 */
  x + y.k + z        /* 48 */ *

def g(b: Int): Int =
  var c = Box(b)
  c.k + 3

var a = 1             /* a -> 0x00 */
var d = f(42)
a + d

```



After exiting the function `g`, its stack frame is **deleted**. The memory cells allocated for `b` and `c` in the stack frame are **deallocated**.

For example, consider the following Scala program:

```

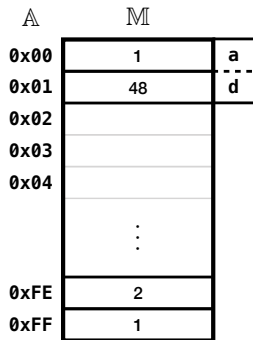
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  var c = Box(b)
  c.k + 3

var a = 1           /* a -> 0x00 */
var d = f(42)      /* d -> 0x01 */
a + d              /* 49 */

```



After exiting the function `f`, its stack frame is **deleted**. The memory cells allocated for `x`, `y`, and `z` in the stack frame are **deallocated**.

Tail-Call Optimization (TCO)

Here is another example with a recursive function:

```
def sum(x: Int, acc: Int): Int =  
  if (x < 1) acc  
  else sum(x - 1, x + acc)  
  
sum(1000, 0)
```

A	M		
0x00	1000	x	sum
0x01	0	acc	
0x02			
0x03			
0x04			
0x05			
	⋮		
0xFE			
0xFF			

Tail-Call Optimization (TCO)

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def sum(x: Int, acc: Int): Int =  
  if (x < 1) acc  
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```

A	M		
0x00	1000	x	sum
0x01	0	acc	
0x02	999	x	sum
0x03	1000	acc	
0x04			
0x05			
	⋮		
0xFE			
0xFF			

Tail-Call Optimization (TCO)

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sum(1000, 0)
```

A	M		
0x00	1000	x	sum
0x01	0	acc	
0x02	999	x	sum
0x03	1000	acc	
0x04	998	x	sum
0x05	1999	acc	
	⋮	⋮	
0xFE	873	x	sum
0xFF	118999	acc	

It fails with a **stack overflow** error.

However, is it really necessary to keep **all the stack frames**? **No!**

Scala supports **tail-call optimization** (TCO).

Tail-Call Optimization (TCO)

Here is another example with a recursive function:

```
def sum(x: Int, acc: Int): Int =  
  if (x < 1) acc  
  else sum(x - 1, x + acc) // tail-call  
  
sum(1000, 0)
```

A	M		
0x00	1000	x	sum
0x01	0	acc	
0x02			
0x03			
0x04			
0x05			
	⋮		
0xFE			
0xFF			

Why? the function call is in **tail-call position** (i.e., the final action in the function). It means that it directly returns the result without any further computation.

Thus, we can safely **discard** the current stack frame **before** calling the function, and it is called **tail-call optimization (TCO)**.

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sum(1000, 0)
```

A	M		
0x00	999	x	sum
0x01	1000	acc	
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Tail-Call Optimization (TCO)

Here is another example with a recursive function:

```
def sum(x: Int, acc: Int): Int =  
  if (x < 1) acc  
  else sum(x - 1, x + acc) // tail-call  
  
sum(1000, 0) // 500500
```

A	M	x	sum
0x00	0	x	sum
0x01	500500	acc	
0x02			
0x03			
0x04			
0x05			
	⋮		
0xFE			
0xFF			

Why? the function call is in **tail-call position** (i.e., the final action in the function). It means that it directly returns the result without any further computation.

Thus, we can safely **discard** the current stack frame **before** calling the function, and it is called **tail-call optimization (TCO)**.

```
def factorial(x: Int): Int =  
  if (x < 2) 1  
  else factorial(x - 1) * x
```

Is it in the **tail-call position**? **No!**

After `factorial(x - 1)`, it needs to multiply the result by `x`.

```
def factorial(x: Int): Int =  
  if (x < 2) 1  
  else x * factorial(x - 1)
```

Is it in the **tail-call position**? **Still No!**

After `factorial(x - 1)`, it still needs to multiply the result by `x`.

Then, how to make it in the **tail-call position**?

One common pattern for TCO is to use an **accumulator**:

```
def factorial(x: Int, acc: Int): Int =  
  if (x < 2) acc  
  else factorial(x - 1, x * acc)  
  
factorial(5, 1) // 120
```

However, it is not a user-friendly interface because we need to pass the initial value of the accumulator (e.g., 1) every time.

We can define a nested function to hide the additional parameter:

```
def factorial(x: Int): Int =  
  def aux(x: Int, acc: Int): Int =  
    if (x < 2) acc  
    else aux(x - 1, x * acc)  
  aux(x, 1)  
  
factorial(5) // 120
```

Most modern programming languages support **tail-call optimization** (TCO) to avoid stack overflow errors.

In addition, Scala supports `@tailrec` annotation to check whether a function is in the tail-call position in compile time:

```
import scala.annotation.tailrec

// Passes the tail-call position check
@tailrec
def factorial(x: Int, acc: Int): Int =
  if (x < 2) acc
  else factorial(x - 1, x * acc)

// Compile-time error
@tailrec
def factorial(x: Int): Int =
  if (x < 2) 1
  else x * factorial(x - 1)
```

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Other GC Algorithms

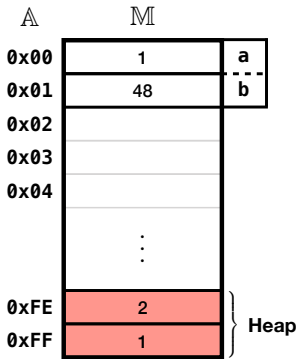
Let's see the previous example again:

```
case class Box(var k: Int)

def f(x: Int): Int =
  var y = Box(1)
  var z = g(2)
  x + y.k + z

def g(b: Int): Int =
  var c = Box(b)
  c.k + 3

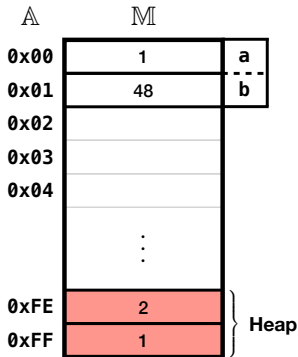
var a = 1          /* a -> 0x00 */
var b = f(42)     /* b -> 0x01 */
a + b             /* 49 */
```



Unfortunately, we still cannot deallocate memory cells (e.g., 0xFE and 0xFF) dynamically allocated in the **heap** rather than the **stack**.

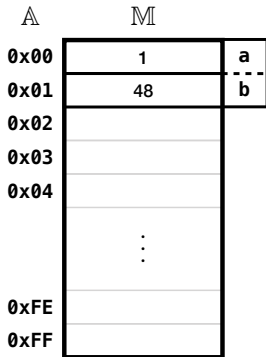
One way to resolve this is using the **manual memory management**, and C++ is an example language that supports it with special keywords for memory allocation (`new`) and deallocation (`delete`) in heap, respectively:

```
struct Box { int k; Box(int k): k(k) {} };
int f(int x) {
    Box* y = new Box(1);    // alloc 0xFF
    int z = g(2);
    int k = y->k;
    return x + k + z;
}
int g(int b) {
    Box* c = new Box(b);   // alloc 0xFE
    int k = c->k;
    return k + 3;
}
int a = 1;    /* a -> 0x00 */
int b = f(42); /* b -> 0x01 */
a + b;      /* 49 */
```



One way to resolve this is using the **manual memory management**, and C++ is an example language that supports it with special keywords for memory allocation (`new`) and deallocation (`delete`) in heap, respectively:

```
struct Box { int k; Box(int k): k(k) {} };
int f(int x) {
    Box* y = new Box(1);    // alloc 0xFF
    int z = g(2);
    int k = y->k; delete y; // dealloc 0xFF
    return x + k + z;
}
int g(int b) {
    Box* c = new Box(b);    // alloc 0xFE
    int k = c->k; delete c; // dealloc 0xFE
    return k + 3;
}
int a = 1;    /* a -> 0x00 */
int b = f(42); /* b -> 0x01 */
a + b;        /* 49 */
```



Pros:

- **Efficient** – Users can **explicitly** deallocate memory cells allocated in heap whenever they want.

Cons:

- **Error-prone** – Users have all the **responsibility** to deallocate memory cells allocated in heap:
 - **Memory Leak** occurs if users forget to deallocate memory cells.

```
b = new Box(42); ...
```

- **Use After Free (UAF)** occurs if users try to access memory cells already deallocated.

```
b = new Box(42); ... delete b; ... b->k;
```

- **Double Free** occurs if users deallocate memory cells more than once.

```
b = new Box(42); ... delete b; ... delete b;
```

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 - Reference Counting
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 - Other GC Algorithms

Is there any way to **automatically** deallocate memory cells in heap? **Yes!**

Garbage collection (GC) is a representative technique for **automatic memory management** that automatically **detects** and **deallocates** memory cells that are no longer reachable in heap.

Let's learn several GC algorithms:

- **Reference counting**
- **Mark-and-sweep GC**
- **Copying GC** (Two-space GC)
- Others

Before explaining them, let's represent memory cells in heap in a **graphical way** without actual addresses.

From now on, we will use the **graphical representation** of memory cells:

```
case class Box(var x: Box)
var a = Box(Box(Box(null))) *
var b = Box(Box(null))

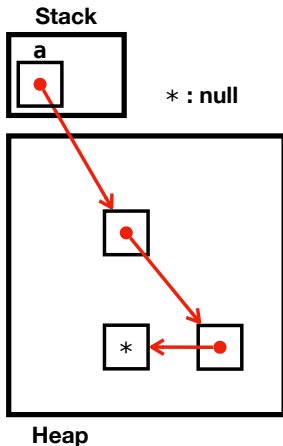
a.x.x.x = a.x

b.x = a

a.x = Box(null)

a = a.x

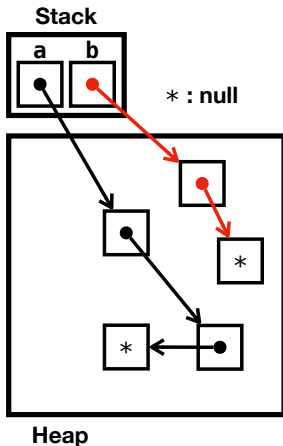
b = null
```



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case class Box(var x: Box)
var a = Box(Box(Box(null)))
var b = Box(Box(null)) *
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a.x = Box(null)
a = a.x
b = null
```

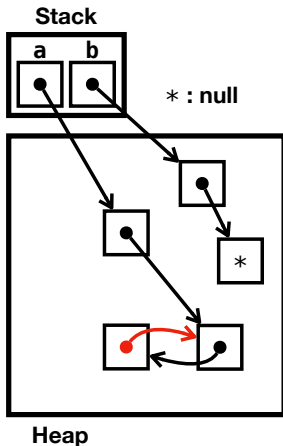
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b.x = a
a.x = Box(null)
a = a.x
b = null
```



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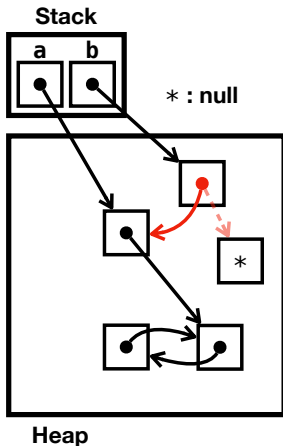
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```

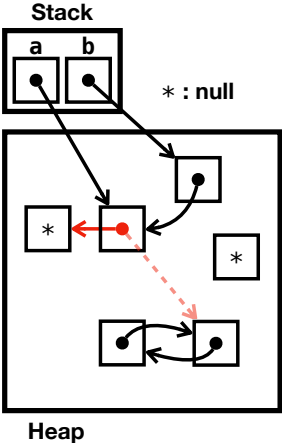


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a = a.x
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```

*

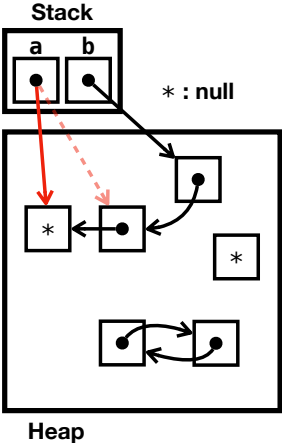


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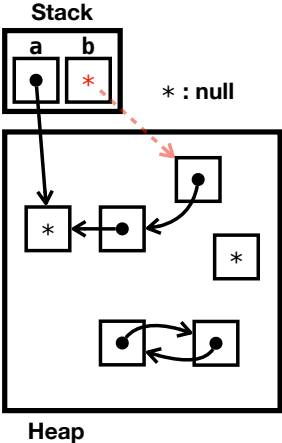

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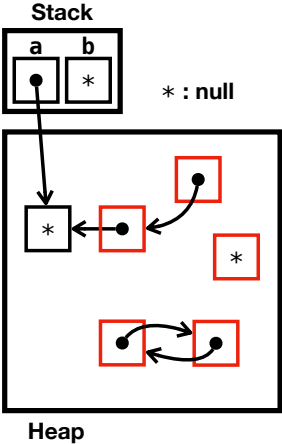
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case class Box(var x: Box)
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var b = Box(Box(null))

a.x.x.x = a.x
b.x = a
a.x = Box(null)
a = a.x
b = null

```

*



We need to deallocate five unreachable memory cells in heap.

Reference counting is a simple GC algorithm that keeps track of the **number of references** to each memory cell in heap.

- 1 **Initialize** the reference count of each cell to 0.
- 2 When a reference to a cell is created, **increment** its reference count.
- 3 When a reference to a cell is deleted, **decrement** its reference count.
- 4 When the reference count of a cell reaches 0, **deallocate** the cell.

Many programming languages use reference counting to implement GC:

- Python, Swift, Perl, Objective-C, etc.

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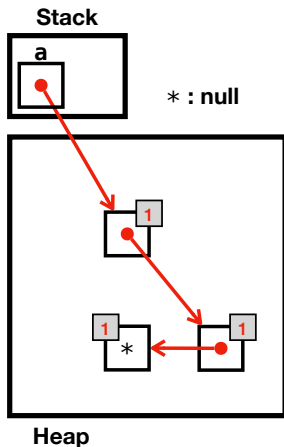
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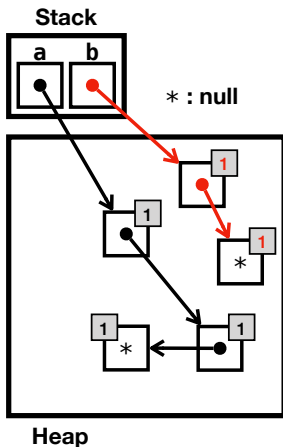
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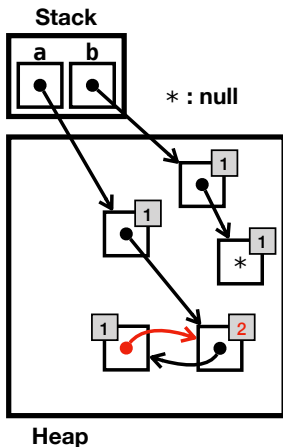
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b.x = a
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a = a.x
b = null
```



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b.x = a
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```

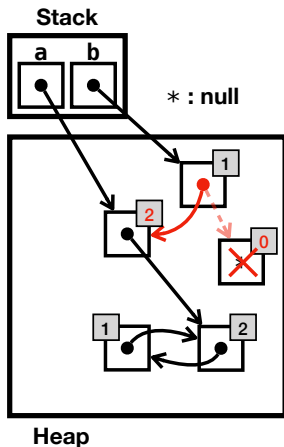


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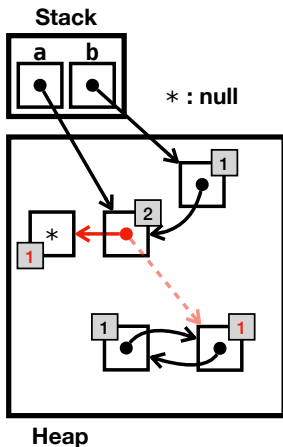


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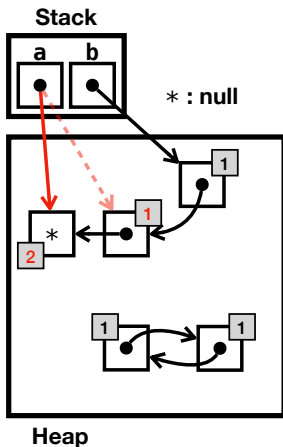


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var a = Box(Box(Box(null)))
var b = Box(Box(null))

a.x.x.x = a.x
b.x = a
a.x = Box(null)
a = a.x
b = null
```

*

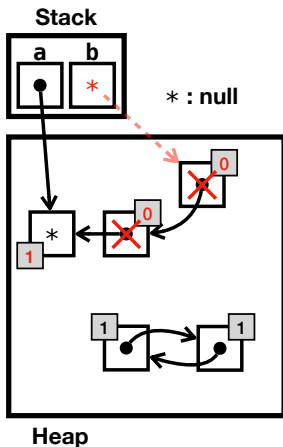


Reference counting is a simple GC algorithm that keeps track of the **number of references** to each memory cell in heap.

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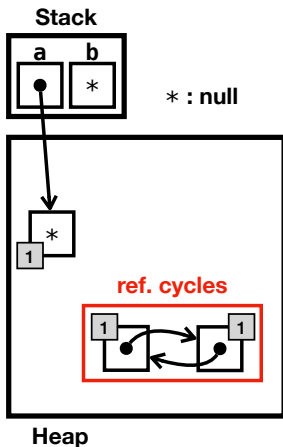
b.x = a

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a = a.x

b = null
```

*



Unfortunately, we cannot deallocate unreachable **reference cycles**.

Reference counting is a simple GC algorithm that keeps track of the **number of references** to each memory cell in heap.

Pros:

- **Easy to implement** – Simply increment and decrement the reference count when a reference is created and deleted.
- **Low overhead** – Deallocation is immediate and takes a short time.

Cons:

- **Reference cycles** – It cannot deallocate unreachable reference cycles.
- **Reference count cost** – It requires space to store reference counts.
- **Free List and Fragmentation** – It requires a **free list** to keep track of available free memory cells in heap, and it also suffers from **fragmentation** making it difficult to allocate large objects.

Mark-and-Sweep GC is one of **tracing GC** algorithms that **traverses the heap** to find unreachable objects when it is **triggered** under some conditions.

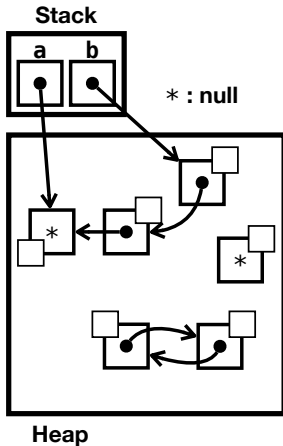
- 1 **Mark** all memory cells as **unreachable** (white).
- 2 **Mark** all memory cells referenced by roots as **unscanned** (gray).
- 3 Repeat until there are no unscanned (gray) memory cells:
 - 1 **Pick** an unscanned (gray) memory cell.
 - 2 **Mark** memory cells referenced by the picked one as **unscanned** (gray).
 - 3 **Mark** the picked memory cell as **scanned** (black).
- 4 **Deallocate** (sweep) all memory cells that are still marked as **unreachable** (white).

Assume that the GC is triggered at the following program point, and let's perform **mark-and-sweep** GC.

```
case class Box(var x: Box)
var a = Box(Box(Box(null)))
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a.x = Box(null)
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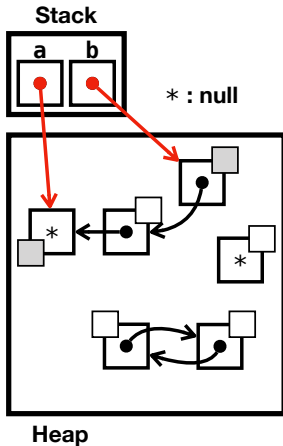


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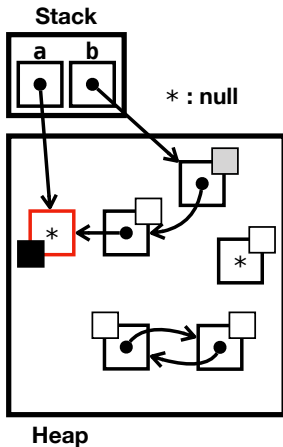


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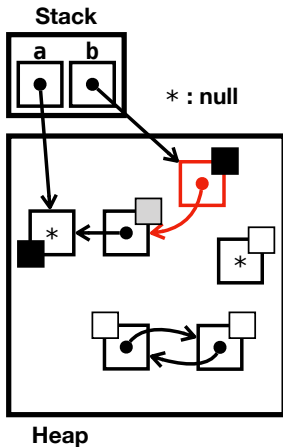


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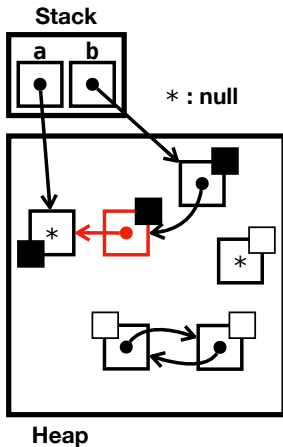


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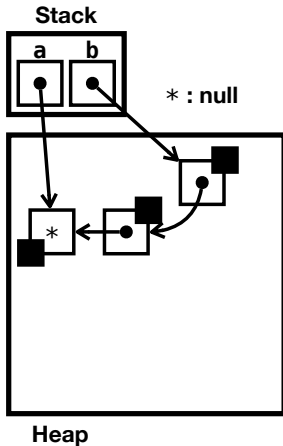


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Mark-and-Sweep GC is one of **tracing GC** algorithms that **traverses the heap** to find unreachable objects when it is **triggered** under some conditions.

Pros:

- **Handle Reference Cycles** – It can deallocate unreachable reference cycles.

Cons:

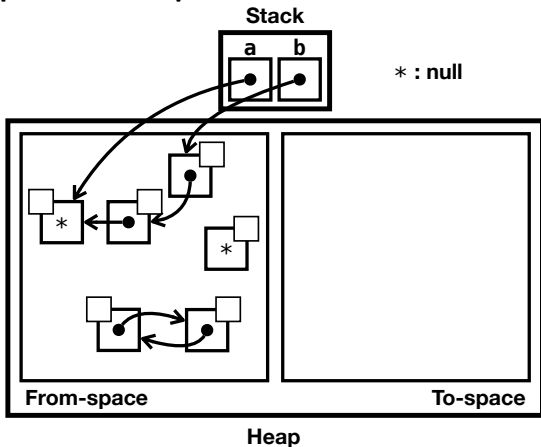
- **Stop-the-world** – It **stops** the program execution during GC.
- **Free List and Fragmentation** – It requires a **free list** to keep track of available free memory cells in heap, and it also suffers from **fragmentation** making it difficult to allocate large objects.

Similar to mark-and-sweep GC, **copying GC** (Two-space GC) is another **tracing GC** algorithm. However, it **copies** all the reachable objects and reorganizes them in a **compact** layout by splitting the heap into two spaces: **from-space** and **to-space**.

- **Allocation** – It allocates memory cells only in **from-space**.
- **Deallocation** – It deallocates all the unreachable objects as follows:
 - ① **Mark** all memory cells as **unreachable** (white).
 - ② **Copy** all memory cells referenced by roots as **unscanned** (gray) and copy them from the **from-space** to the **to-space**
 - ③ **Update** the data of the original memory cell to point to the copied one.
 - ④ Repeat until there are no unscanned (gray) memory cells
 - ① **Pick** an unscanned (gray) memory cell in the **from-space**.
 - ② **Copy** memory cells referenced by the picked one as **unscanned** (gray).
 - ③ **Update** the data of the original memory cell to point to the copied one.
 - ④ **Mark** the picked memory cell as **scanned** (black).
 - ⑤ **Swap** from-space and to-space.

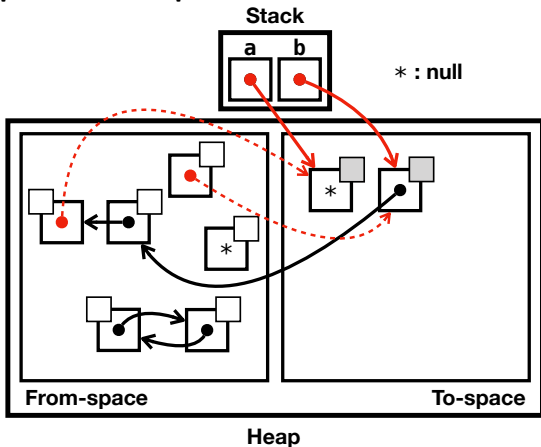
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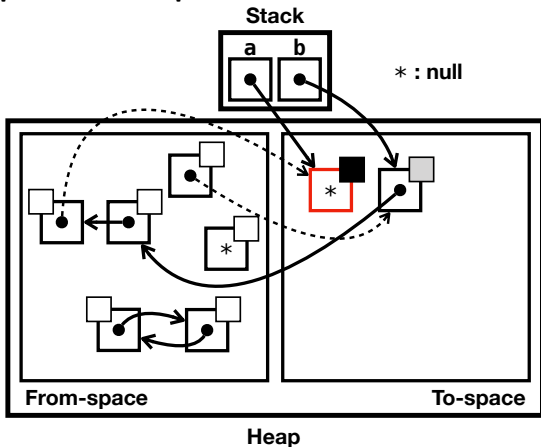
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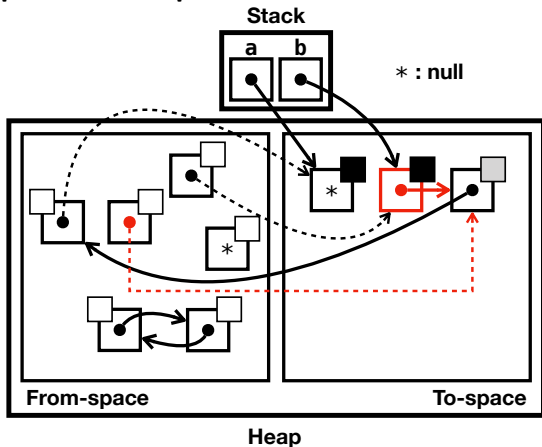
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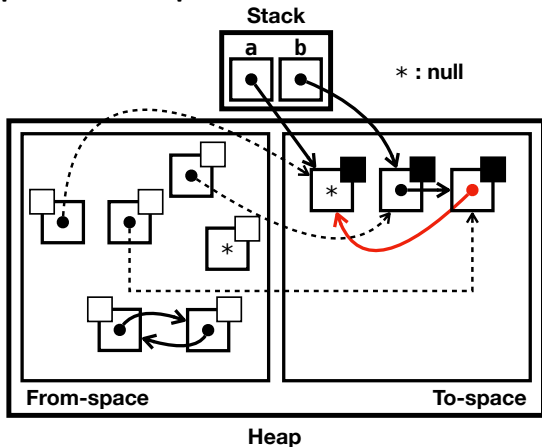
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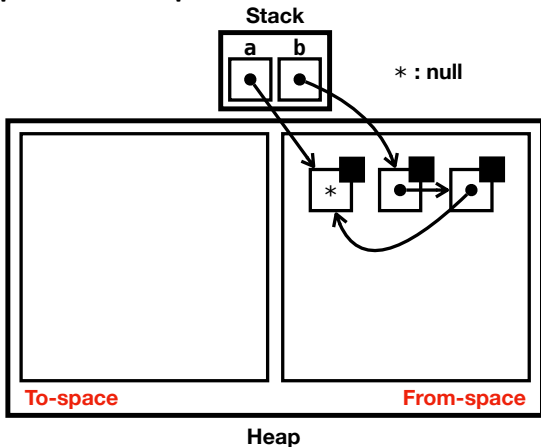
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Pros:

- **Handle Reference cycles** – It can deallocate unreachable reference cycles.
- No more **Free List** and **Fragmentation** – After deallocation process, the heap is always **contiguous**. Thus, it is enough to keep track of the first free memory cell for allocation.
- **Fast Allocation** – It does not require any extra work to find free memory cells in the free list for allocation.

Cons:

- **Stop-the-world** – It **stops** the program execution during GC.
- **Only half of the heap** (from-space) is used for allocation.
- **Expensive copying process** – It copies all the reachable objects from

Existing real-world programming languages utilize more sophisticated GC algorithms, mix diverse GC algorithms, or even provide options to choose different GC algorithms:

- **Generational GC** – e.g, Java¹, Python²
- **Concurrent GC** – e.g., Java³, Golang⁴
- **Escape Analysis** – e.g., Java⁵
- etc.

Or, a totally different approach called **Ownership** system is used in Rust⁶

¹ <https://www.oracle.com/webfolder/technetwork/tutorials/obe/java/gc01/index.html>

² <https://devguide.python.org/internals/garbage-collector/>

³ <https://docs.oracle.com/javase/8/docs/technotes/guides/vm/gctuning/cms.html>

⁴ <https://tip.golang.org/doc/gc-guide>

⁵ <https://blogs.oracle.com/javamagazine/post/escape-analysis-in-the-hotspot-jit-compiler>

⁶ <https://doc.rust-lang.org/book/ch04-01-what-is-ownership.html>

1. Stack and Heap

Tail-Call Optimization (TCO)

2. Manual Memory Management

3. Garbage Collection

Reference Counting

Mark-and-Sweep GC

Copying GC (Two-Space GC)

Other GC Algorithms

- Lazy Evaluation

Jihyeok Park
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<https://plrg.korea.ac.kr>