Lecture 12 – Garbage Collection

COSE212: Programming Languages

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PLRG

2024 Fall

Recall

- 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:

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

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

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Stack and Heap

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 */     *
```

$$\sigma = [\; \mathtt{y} \mapsto a_0,\; \mathtt{f} \mapsto a_1 \;]$$

$\mathbb{A}$	:	a_0	a_1	a_2	a_3	$\ldots$
M	=	3	v	6	8	$\ldots$

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

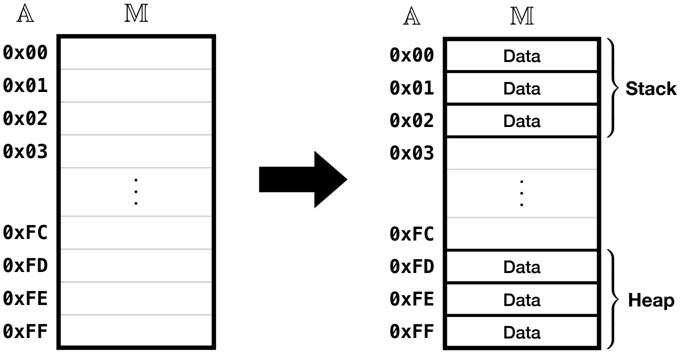
Then, how to **detect** and **deallocate** unreachable memory cells?

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

Stack and Heap

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.

Stack and Heap

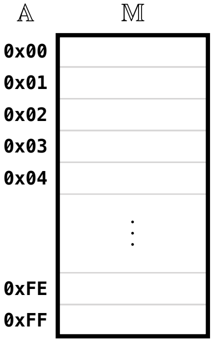
For example, consider the following Scala program:

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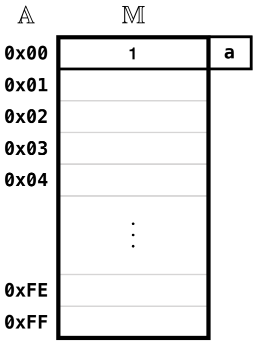
  var c = Box(b)
  c.k + 3

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



Stack and Heap

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
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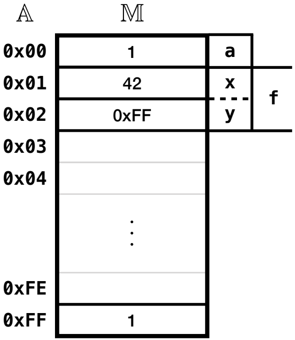

A **new stack frame** is created when it enters the function `f`.

Stack and Heap

For example, consider the following Scala program:

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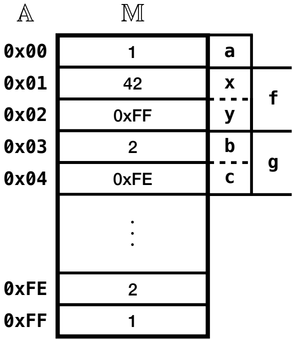
case class Box(var k: Int)

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.

Stack and Heap

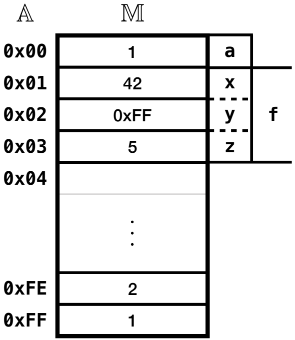
For example, consider the following Scala program:

```
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**.

Stack and Heap

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case class Box(var k: Int)

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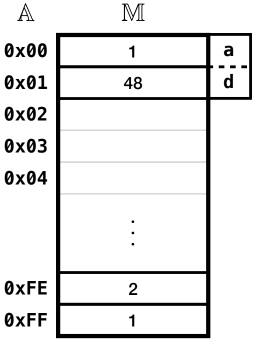



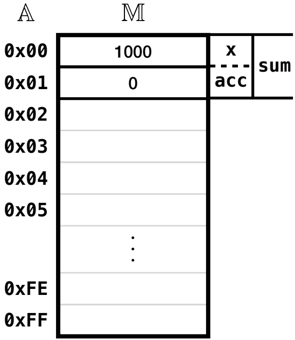
After exiting the function `f`, its stack frame is **deleted**. The memory cells allocated for `x`, `y`, and `z` in the stack frame are **deallocated**.

Tail-Call Optimization (TCO)

Here is another example with a recursive function:

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

sum(1000, 0)
```



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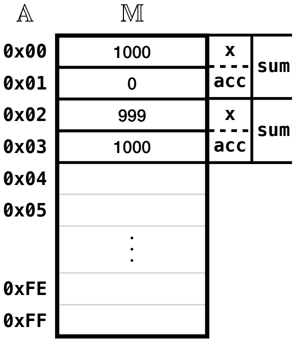

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def sum(x: Int, acc: Int): Int =
  if (x < 1) acc
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sum(1000, 0)
```

$\mathbb{A}$	$\mathbb{M}$		
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!**

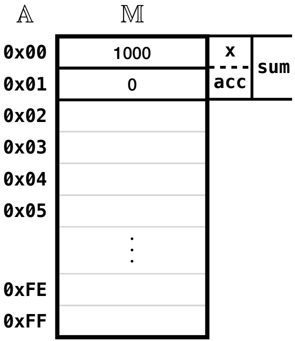
Scala supports **tail-call optimization** (TCO).

Tail-Call Optimization (TCO)

Here is another example with a recursive function:

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

sum(1000, 0)
```



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).

Tail-Call Optimization (TCO)

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sum(1000, 0)
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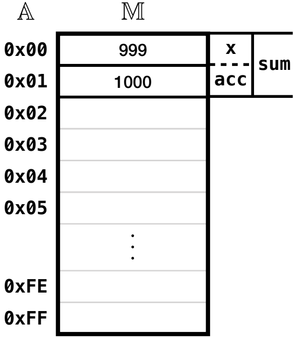

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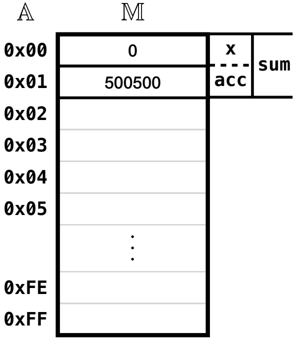
def sum(x: Int, acc: Int): Int =
  if (x < 1) acc
  else sum(x - 1, x + acc) // tail-call

sum(1000, 0) // 500500
```



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

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**?

Tail-Call Optimization (TCO)

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
```

Tail-Call Optimization (TCO)

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:

```scala
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)
```

Contents

Manual Memory Management

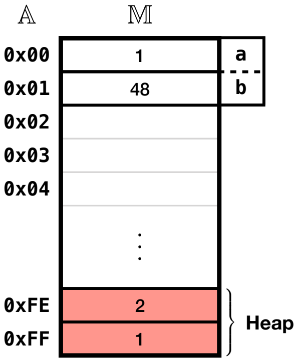
Let's see the previous example again:

```
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 */       *
```



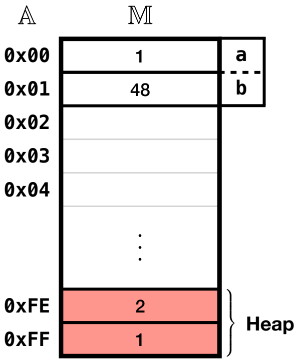
Unfortunately, we still cannot deallocate memory cells (e.g., `0xFE` and `0xFF`) dynamically allocated in the **heap** rather than the **stack**.

Manual Memory Management

PLRG

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:

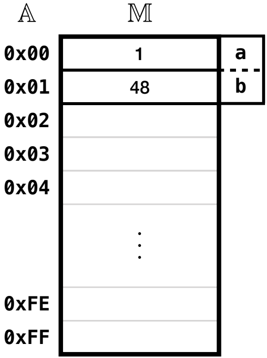
```
struct Box { int k; Box(int k): k(k) {} };
int f(int x) {
  Box* y = new Box(1);     // alloc   0xFF
  int z = g(2);
  int k = y->k;
  return x + k + z;
}
int g(int b) {
  Box* c = new Box(b);     // alloc   0xFE
  int k = c->k;
  return k + 3;
}
int a = 1;       /* a -> 0x00 */
int b = f(42);  /*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



Manual Memory Management

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 */        *
```



Manual Memory Management

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);  ...
    ```

  - **Dangling pointer** occurs if users deallocate memory cells too early.

    ```
    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;
    ```

Contents

Garbage Collection

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

Garbage collection (GC) is a representative technique for **automatic memory management**.

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 A(var x: A)

var a = A(A(A(null)))   *

var b = A(A(null))

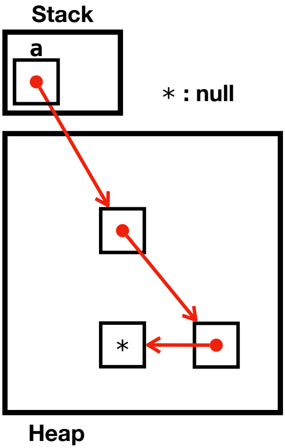
a.x.x.x = a.x

b.x = a

a.x = A(null)

a = a.x

b = null
```



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a.x.x.x = a.x

b.x = a

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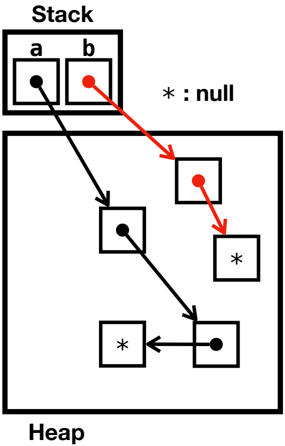

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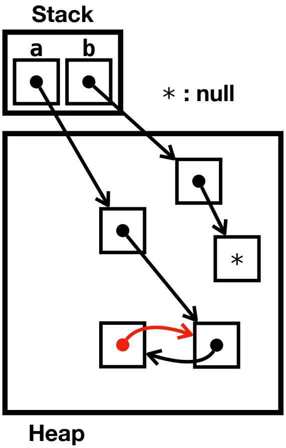

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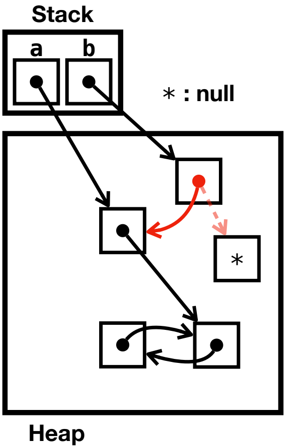

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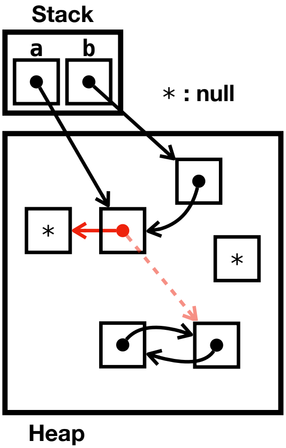

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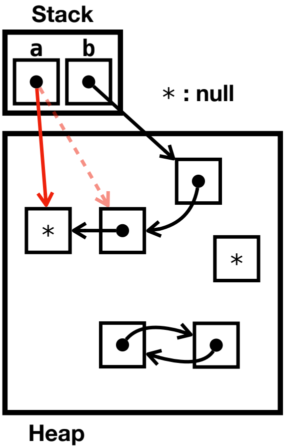

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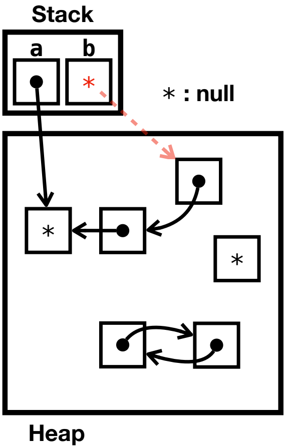

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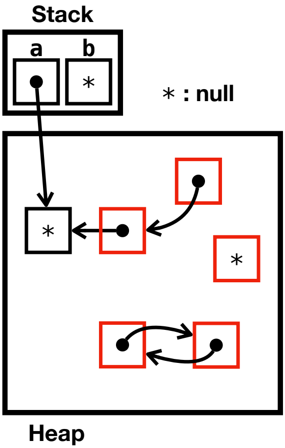

We need to deallocate five unreachable memory cells in heap.

Reference Counting

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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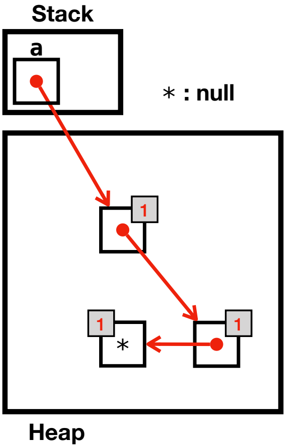

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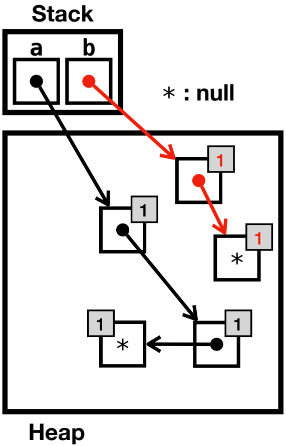

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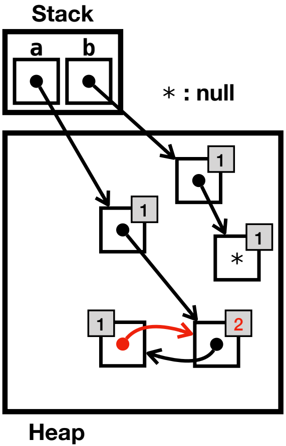

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a.x = A(null)

a = a.x

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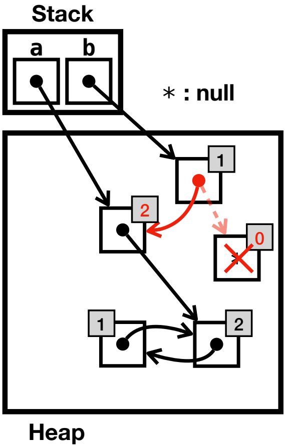

Reference Counting

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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case class A(var x: A)

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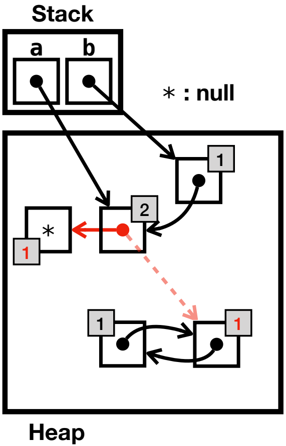

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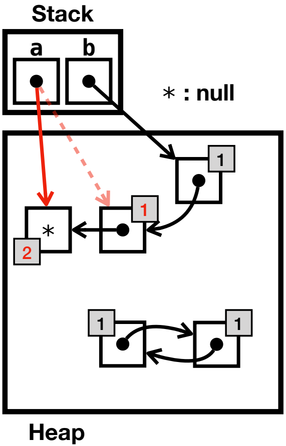

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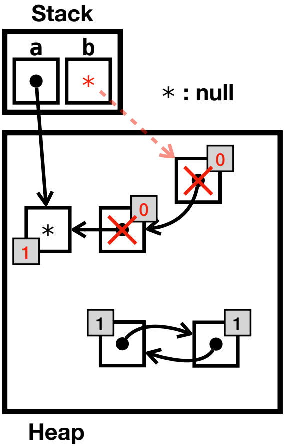

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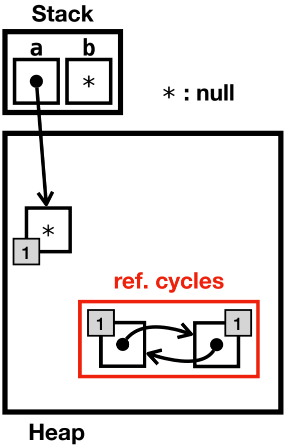

Unfortunately, we cannot deallocate unreachable **reference cycles**.

Reference Counting

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

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).

Mark-and-Sweep GC

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

```
case class A(var x: A)

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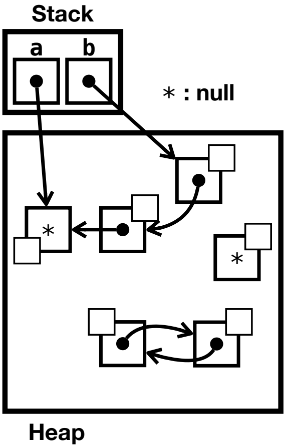

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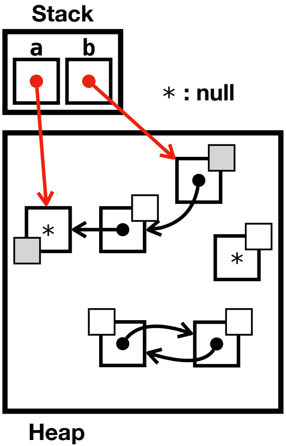

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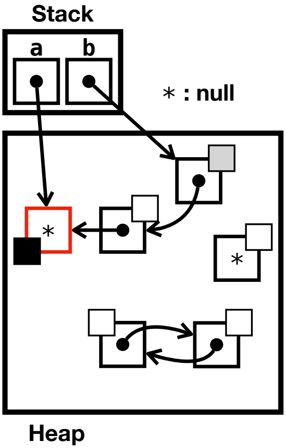

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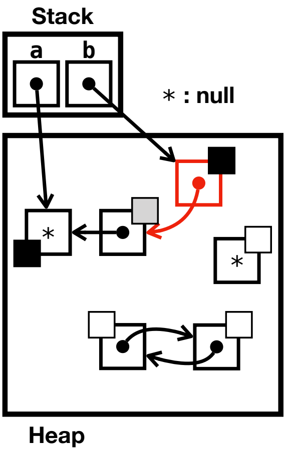

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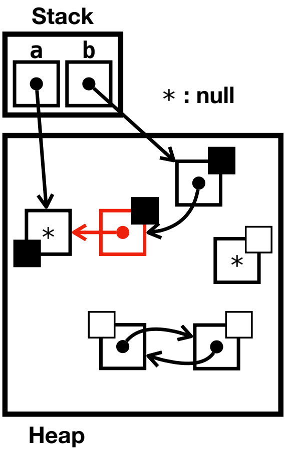

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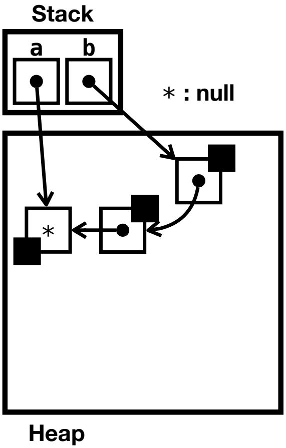

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- **Reference cycles** – It can deallocate unreachable reference cycles.

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.

Copying GC (Two-Space GC)

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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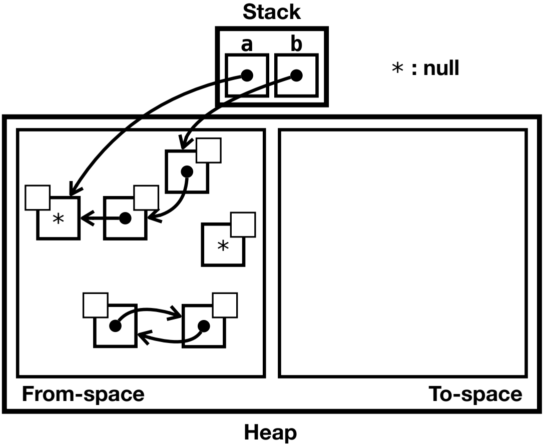

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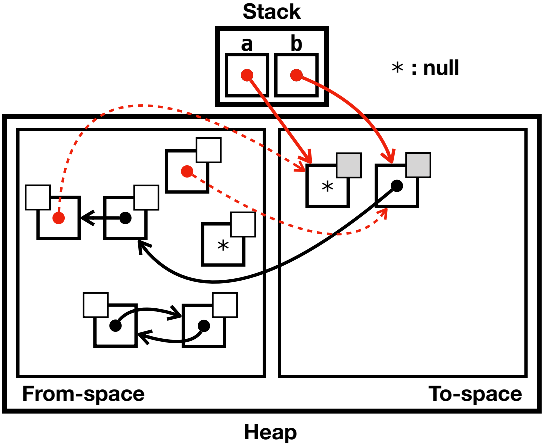

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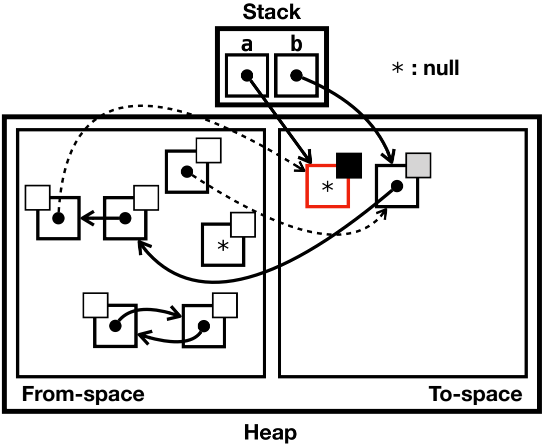

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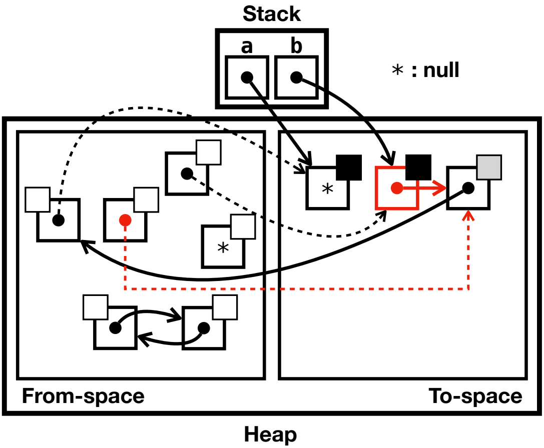

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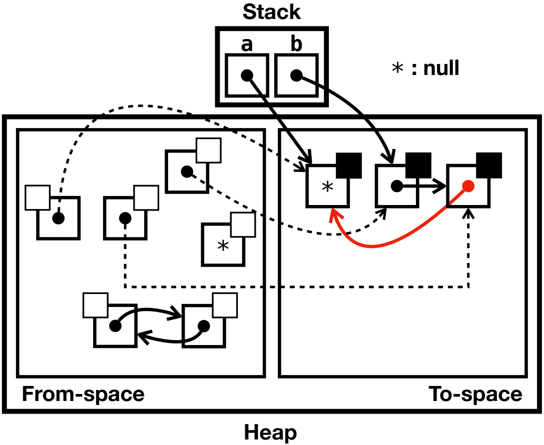

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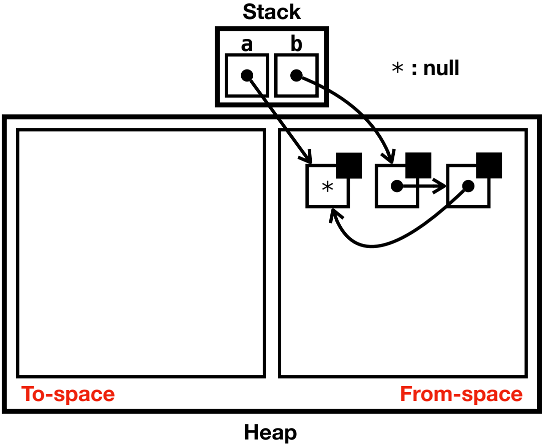

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Pros:

- **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 the from-space to the to-space.

Other GC Algorithms

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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, Java[1], Python[2]
- **Concurrent GC** – e.g., Java[3], Golang[4]
- **Escape Analysis** – e.g., Java[5]
- etc.

Or, a totally different approach called **Ownership** system is used in Rust[6]

[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

Summary

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

Next Lecture

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- Lazy Evaluation

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