Garbage Collection

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(Slides prepared by Marius Nita.)

Hoping to cover

- Motivation & basics
- Introduction to three families of collection algorithms:
  - Reference Counting
  - Mark & Sweep
  - Copying Collection
- Advanced issues and topics

Motivation

Problems with manual memory management:

- It is extremely tedious and error-prone.
- It introduces software engineering issues (Who is supposed to free the memory?)
- It is by no means intrinsically efficient. (`free` is not free.)
- In many cases, the costs outweigh the benefits.

Garbage Collection (GC)

- The automatic reclamation of unreachable memory (aka garbage).
- Universally used for high level languages with closures and complex data structures that are allocated **implicitly**.
- Useful for any language that supports heap allocation.
- It removes the need for explicit deallocation (no more `delete` and `free`).
- Let the GC implementor deal with memory corruption issues once and for all.

How does it work?

Typically:

- The user program (mutator) is linked against a library known as the runtime system (RTS) (e.g. `libc`).
- In the RTS resides the memory allocation service, which exposes an allocation routine to the user program.
- When the user program desires more memory, it invokes the allocation routine (e.g. `malloc`).
- The allocation service may then perform a collection to free unused memory before the allocation routine returns.

Terminology

Heap: A directed graph whose nodes are dynamically allocated records and whose edges are pointers between nodes. Typically laid out in a contiguous memory space.

Root set: The set of pointers **into** the heap from an external source (e.g. the stack, global variables).

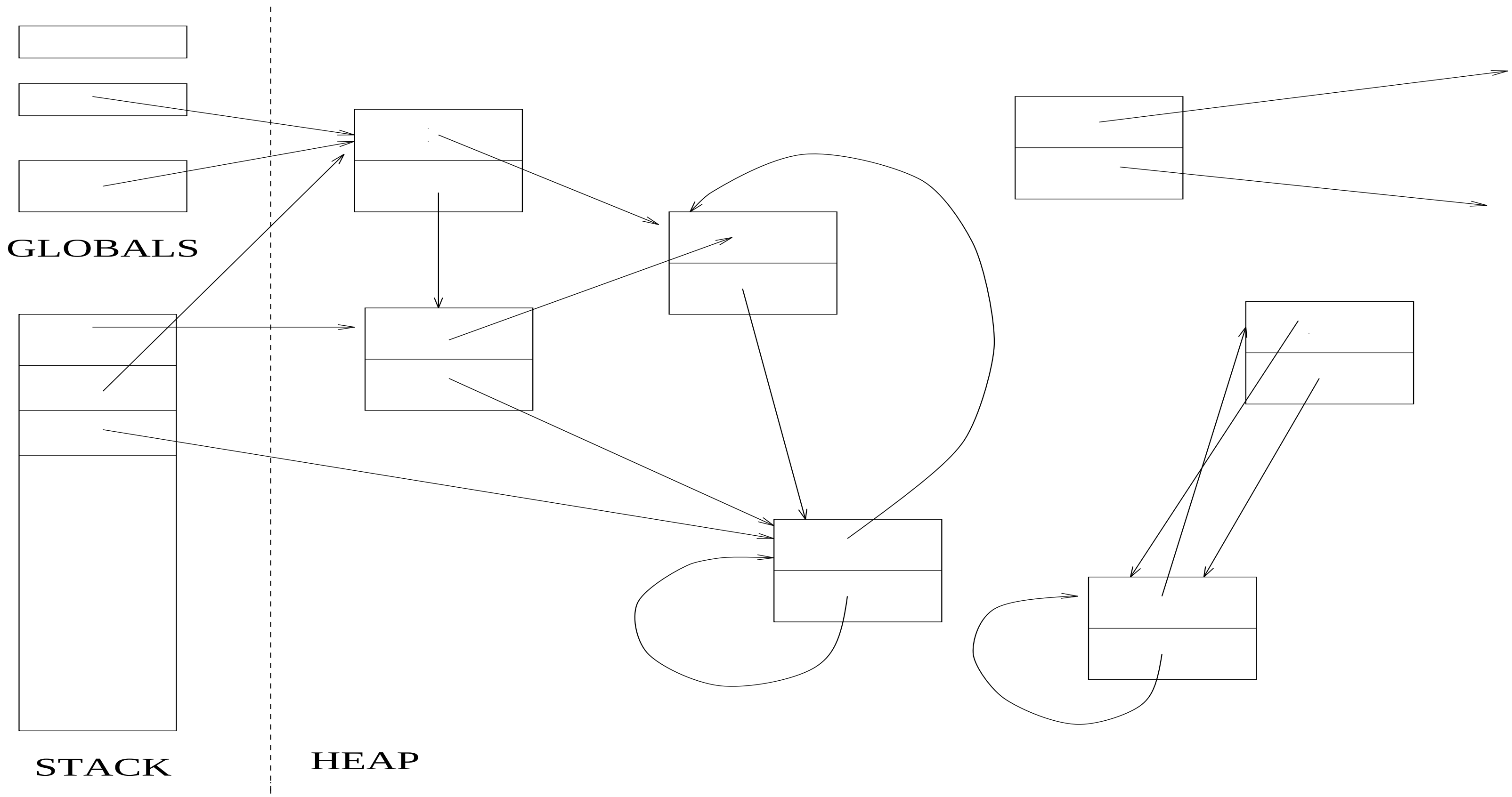
Live data: The set of heap records that are **reachable** by following paths starting at members of the root set.

Garbage: The set of heap records that are **not** live.

Note: **reachability** is a conservative liveness estimate.

Simple heap model

For simplicity, consider a simple heap of “cons cells:” two-field records, both fields are pointers to other records.



Reference counting

Most straightforward collection strategy.

- Add a `counter` field to each record.
- Increment a record's counter when taking a new pointer to it.
- Decrement it when releasing a pointer to it.
- When it reaches `0`, put the record on a free list.
- When allocating a new record, check the free list first.

Reference counting

- simple, easy to understand and implement
- immediate reclamation of storage: no extended periods of time in which the collector might be running while the mutator waits

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- space overhead (extra field per record)
- speed overhead (every pointer assignment is wrapped in counter operations and checks)
- too simple-minded (can’t collect cyclic garbage)

Stop & Collect

There is no need to get rid of garbage if you do not need more space.

A better approach is to wait until the allocator fails to allocate new memory due to lack of space. Then,

- The collector takes over and frees enough memory to satisfy the allocation request.
- The allocation now succeeds (or we're out of memory).
- Control is returned to the mutator.

This is known as stop & collect; mutator is effectively paused while the collector runs.

Mark & Sweep

Two phases:

1. Mark each live record by tracing all pointers starting at the root.

2. Sweep unmarked records (garbage) onto a free list, making them available for reuse. Unmark marked cells at the same time.

Already marked records are ignored in the marking step, so termination is guaranteed.

M&S: implementation

```
struct cell {
  int mark:1;
  struct cell *c[2];
};
struct cell *free, heap[HEAPSIZE], *roots[ROOTS];
```

Initially all cells are on free list. Use `c[0]` to link members of free list.

```
void init_heap() {
  for (i=0; i < HEAPSIZE-1; i++)
    heap[i].c[0] = &(heap[i+1]);
  heap[HEAPSIZE-1].c[0] = 0;
  free = &(heap[0]);
}
```

M&S: implementation

```
struct cell *allocate() {
  struct cell *newCell;
  if (!free) {                    /* no more room => */
    gc();                         /*   try gc */
    if (!free)                    /* still no more room */
      die();
  };
  newCell = free;                 /* take the first free cell */
  free = free->c[0];              /*   off of the free list */
  return newCell;
}
```

M&S: implementation

```
void gc() {
  for (i=0; i<ROOTS; i++)
    mark(roots[i]);
  sweep();
}

void mark(struct cell *cell)
{
  if (!cell->mark) {
    cell->mark = 1;
    mark(cell->c[0]);
    mark(cell->c[1]);
  }
}
```

```
void sweep() {
   for (i=0; i<HEAPSIZE; i++)
     if (heap[i].mark)
       /* unmark live data */
       heap[i].mark = 0;
     else {
       /* sweep garbage */
       heap[i].c[0] = free;
       free = &(heap[i]);
     }
 }
```

M&S: implementation

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void gc() {
  for (i=0; i<ROOTS; i++)
    mark(roots[i]);
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}

void mark(struct cell *cell)
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  if (!cell->mark) {
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```

```
void sweep() {
   for (i=0; i<HEAPSIZE; i++)
     if (heap[i].mark)
       /* unmark live data */
       heap[i].mark = 0;
     else {
       /* sweep garbage */
       heap[i].c[0] = free;
       free = &(heap[i]);
     }
 }
```

Notice anything “strange” about `mark`?

M&S: pointer reversal

It's recursive!

```
void mark(struct cell *cell)
{
  if (!cell->mark) {
    cell->mark = 1;
    mark(cell->c[0]);
    mark(cell->c[1]);
  }
}
```

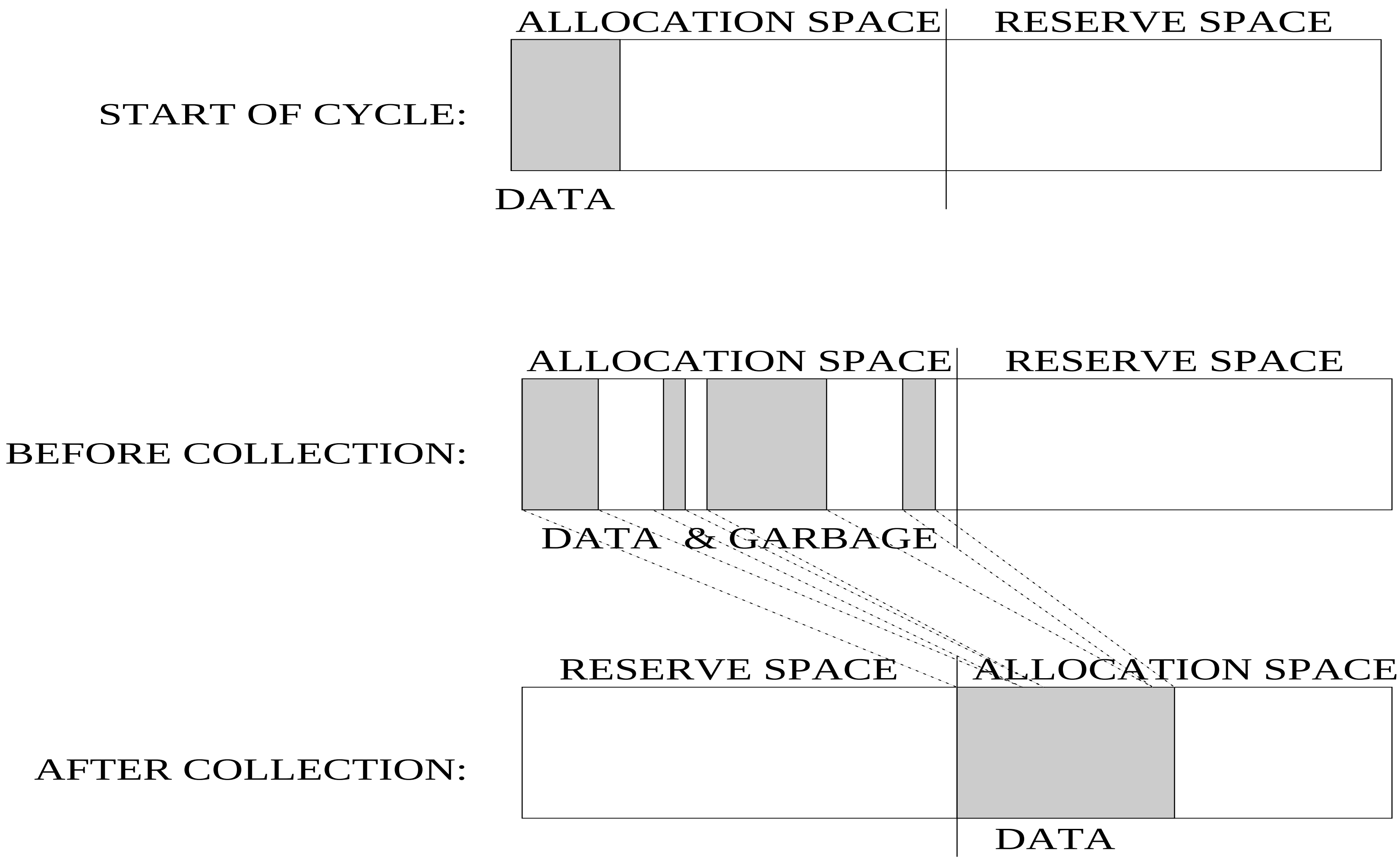
It could use a **lot** of stack, hence a lot of memory!

A trick called **pointer reversal** can be used to avoid this problem.

Copying collection

- Divide the heap into **two semi-spaces.**
- Allocate into one space (the **to-space**).
- When it fills up, **move** the **live data** to the **from-space** and reverse the roles of the two spaces.
- Must reassign all pointers as a consequence. (Can't have a copying collector for C!)
- Inherently compacting – no fragmentation problems, good spatial locality.

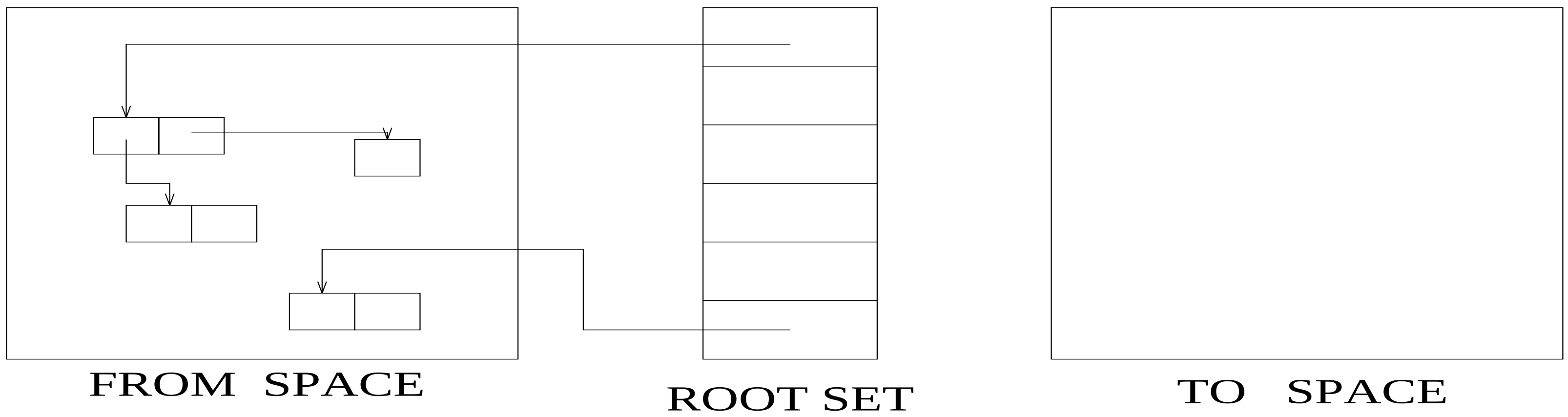
Copying (cont'd)



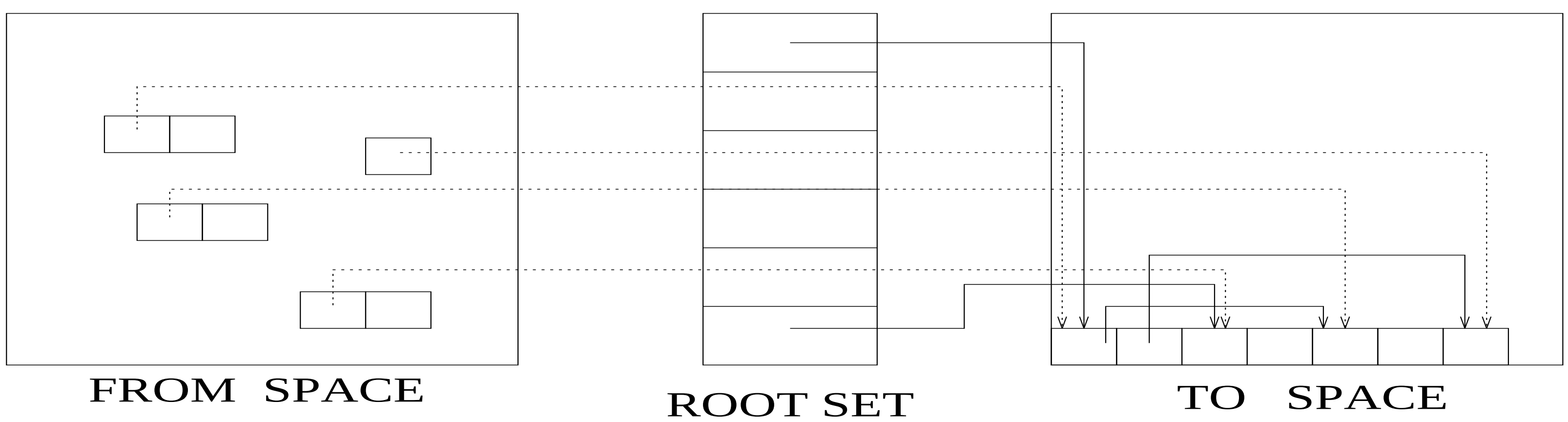
Copying (cont'd)

- The live data is traversed breadth-first using the to-space itself as the queue (Cheney's algorithm).
- When a record is copied, a forwarding pointer pointing to the new location is left in the original.
- Subsequent attempts to forward that same record will immediately observe the forwarding pointer.

Copying (cont'd)

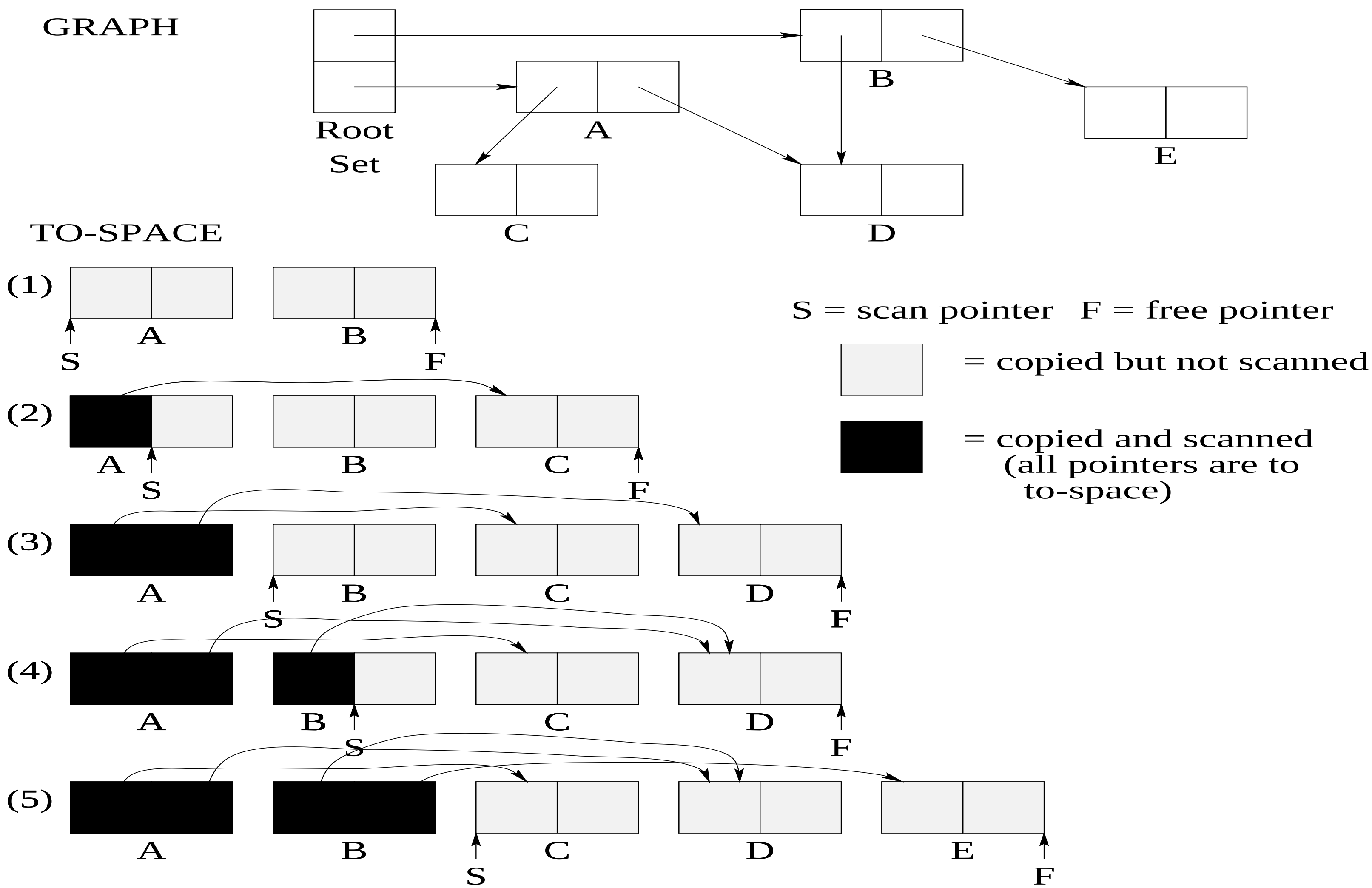


BEFORE COLLECTION



AFTER COLLECTION

Copying: details



Copying: implementation

```
struct cell {
  struct cell *c[2];
}

struct cell space[2][HALFSIZE];
struct cell *roots[ROOTS];
struct cell *free =
                &(space[0][0]);
struct cell *end =
         &(space[0][HALFSIZE]);

int from_space = 0;
int to_space = 1;
```

```
struct cell *allocate() {
  if (free == end) {
    /* no room */
    gc();
    if (free == end)
      /* still no room */
      die();
  };
  return free++;
}
```

Copying: implementation

```
gc() {
  int i;
  struct cell *scan = &(space[to_space][0]);
  free = scan;
  for (i = 0 ; i < ROOTS; i++)
    roots[i] = forward(roots[i]);
  while (scan < free) {
    scan->c[0] = forward(scan->c[0]);
    scan->c[1] = forward(scan->c[1]);
    scan++;
  };
  from_space = 1-from_space;
  to_space = 1-to_space;
  end = *(space[from_space][HALFSIZE]);
}
```

Copying: implementation

```
struct cell *forward(struct cell *p) {
  if (p >= &(space[from_space][0]) &&
       p < &(space[from_space][HALFSIZE]))
  {
     if (p->c[0] >= &(space[to_space][0]) &&
         p->c[0] <  &(space[to_space][HALFSIZE]))
        return p->c[0];
     else {
       *free = *p;
       p->c[0] = free++;
       return p->c[0];
     }
  }
  else return p;
}
```

Conclusions: M&S

Pros:

- Big win is that it can use the **whole heap** for allocation.
- Works well in systems with large amounts of live data – many long lived objects.

Cons:

- Fragmentation is a real problem.
- Allocation can be expensive in a heavily fragmented heap.
- Potential spatial locality issues, bad cache behavior.

Conclusions: Copying

Pros:

- Simple to understand and implement.
- Allocation is very fast: contiguous free memory.
- Good locality, favorable effect on cache behavior.

Cons:

- It can use only **half** the heap space for allocation – a real concern in systems with limited memory.
- Poor performance in systems with large amounts of live data.

Further Issues

- Distinguishing pointers from integers.
- Handling records of various sizes, arrays.
- Finding and passing the root set.
- Avoiding unnecessary scanning of long-lived data.
- Minimizing collection pauses.
- Improving memory utilization.

These lead to study of other varieties of collectors:

conservative, generational, incremental, compacting, etc.