Heap Management

A very flexible storage allocation mechanism is *heap allocation.*

Any number of data objects can be allocated and freed in a memory pool, called a *heap*.

Heap allocation is enormously popular. Almost all non-trivial Java and C programs use **`new`** or **`malloc`**.

Heap Allocation

A request for heap space may be *explicit* or *implicit*.

An explicit request involves a call to a routine like **`new`** or **`malloc`**. An explicit pointer to the newly allocated space is returned.

Some languages allow the creation of data objects of unknown size. In Java, the + operator is overloaded to represent string catenation.

The expression **`Str1 + Str2`** creates a new string representing the catenation of strings **`Str1`** and **`Str2`**. There is no compile-time bound on the sizes of **`Str1`** and **`Str2`**, so heap space must be implicitly allocated to hold the newly created string.

Whether allocation is explicit or implicit, a *heap allocator* is needed. This routine takes a size parameter and examines unused heap space to find space that satisfies the request.

A *heap block* is returned. This block must be big enough to satisfy the space request, but it may well be bigger.

Heaps blocks contain a *header* field that contains the size of the block as well as bookkeeping information.

The complexity of heap allocation depends in large measure on how *deallocation* is done.

Initially, the heap is one large block of unallocated memory. Memory requests can be satisfied by simply modifying an “end of

heap” pointer, very much as a stack is pushed by modifying a stack pointer.

Things get more involved when previously allocated heap objects are deallocated and reused.

Deallocated objects are stored for future reuse on a *free space list*.

When a request for *n* bytes of heap space is received, the heap allocator must search the free space list for a block of sufficient size. There are many search strategies that might be used:

- **Best Fit**
  The free space list is searched for the free block that matches most closely the requested size. This minimizes wasted heap space, the search may be quite slow.

- **First Fit**
  The first free heap block of sufficient size is used. Unused space within the block is split off and linked as a smaller free space block. This approach is fast, but may "clutter" the beginning of the free space list with a number of blocks too small to satisfy most requests.
- **Next Fit**
  This is a variant of first fit in which succeeding searches of the free space list begin at the position where the last search ended. The idea is to "cycle through" the entire free space list rather than always revisiting free blocks at the head of the list.

- **Segregated Free Space Lists**
  There is no reason why we must have only *one* free space list. An alternative is to have several, indexed by the size of the free blocks they contain.

Deallocation Mechanisms

Allocating heap space is fairly easy. But how do we deallocate heap memory no longer in use?

Sometimes we may never need to deallocate! If heaps objects are allocated infrequently or are very long-lived, deallocation is unnecessary. We simply fill heap space with "in use" objects.

Virtual memory & paging may allow us to allocate a very large heap area.

On a 64-bit machine, if we allocate heap space at 1 MB/sec, it will take 500,000 *years* to span the entire address space! Fragmentation of a very large heap space commonly forces us to include some form of reuse of heap space.

User-controlled Deallocation

Deallocation can be manual or automatic. Manual deallocation involves explicit programmer-initiated calls to routines like **`free(p)`** or **`delete(p)`**.

The object is then added to a free-space list for subsequent reallocation.

It is the programmer's responsibility to free unneeded heap space by executing deallocation commands. The heap manager merely keeps track of freed space and makes it available for later reuse.

The really hard decision—when space should be freed—is shifted to the programmer, possibly leading to catastrophic *dangling pointer* errors.

Consider the following C program fragment

```
q = p = malloc(1000);
free(p);
/* code containing more malloc's */
q[100] = 1234;
```

After **p** is freed, **q** is a *dangling pointer*. **q** points to heap space that is no longer considered allocated.

Calls to **malloc** may reassign the space pointed to by **q**. Assignment through **q** is illegal, but this error is almost never detected.

Such an assignment may change data that is now part of another heap object, leading to very subtle errors. It may even change a header field or a free-space link, causing the heap allocator itself to fail!

Automatic Garbage Collection

The alternative to manual deallocation of heap space is *garbage collection*.

Compiler-generated code tracks pointer usage. When a heap object is no longer pointed to, it is *garbage*, and is *automatically* collected for subsequent reuse.

Many garbage collection techniques exist. Here are some of the most important approaches:

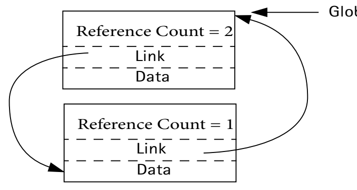
Reference Counting

This is one of the oldest and simplest garbage collection techniques.

A *reference count* field is added to each heap object. It counts how many references to the heap object exist. When an object's reference count reaches zero, it is garbage and may collected.

The reference count field is updated whenever a reference is created, copied, or destroyed. When a reference count reaches zero and an object is collected, all pointers in the collected object are also be followed and corresponding reference counts decremented.

As shown below, reference counting has difficulty with *circular structures*. If pointer **P** is



set to null, the object's reference count is reduced to 1. Both objects have a non-zero count, but neither is accessible through any external pointer. The two objects are garbage, but won't be recognized as such.

If circular structuresare common, then an auxiliary technique, like mark-sweep collection, is needed to collect garbage that reference counting misses.

Mark-Sweep Collection

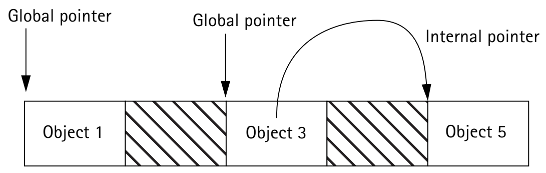
Many collectors, including mark & sweep, do nothing until heap space is nearly exhausted.

Then it executes a *marking phase* that identifies all live heap objects.

Starting with global pointers and pointers in stack frames, it marks reachable heap objects. Pointers in marked heap objects are also followed, until all live heap objects are marked.

After the marking phase, any object not marked is garbage that may be freed. We then *sweep* through the heap, collecting all unmarked objects. During the sweep phase we also clear all marks from heap objects found to be still in use.

Mark-sweep garbage collection is illustrated below.



Objects 1 and 3 are marked because they are pointed to by global pointers. Object 5 is marked because it is pointed to by object 3, which is marked. Shaded objects are not marked and will be added to the free-space list.

In any mark-sweep collector, it is vital that we mark *all* accessible heap objects. If we miss a pointer, we may fail to mark a live heap object and later incorrectly free it.

Finding all pointers is a bit tricky in languages like Java, C and C++, that have pointers mixed with other types within data structures, implicit pointers to temporaries, and so forth. Considerable information about data structures and frames must be available at run-time for this purpose. In cases where we can’t be sure if a value is a pointer or not, we may need to do *conservative garbage collection*.

In mark-sweep garbage collection *all* heap objects must be swept. This is costly if most objects are dead. We’d prefer to examine *only* live objects.

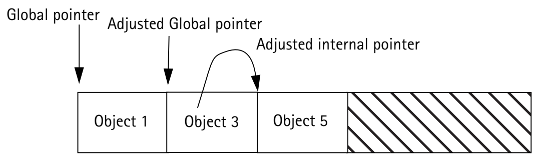
Compaction

After the sweep phase, live heap objects are distributed throughout the heap space. This can lead to poor locality. If live objects span many memory pages, paging overhead may be increased. Cache locality may be degraded too.

We can add a *compaction phase* to mark-sweep garbage collection.

After live objects are identified, they are placed together at one end of the heap. This involves another tracing phase in which global, local and internal heap pointers are found and adjusted to reflect the object’s new location.

Pointers are adjusted by the total size of all garbage objects between the start of the heap and the current object. This is illustrated below:



Compaction merges together freed objects into one large block of free heap space. Fragments are no longer a problem.

Moreover, heap allocation is greatly simplified. Using an "end of heap" pointer, whenever a heap request is received, the end of heap pointer is adjusted, making heap allocation no more complex than stack allocation.

Because pointers are adjusted, compaction may not be suitable for languages like C and C++, in which it is difficult to unambiguously identify pointers.

Copying Collectors

Compaction provides many valuable benefits. Heap allocation is simple end efficient. There is no fragmentation problem, and because live objects are adjacent, paging and cache behavior is improved.

An entire family of garbage collection techniques, called *copying collectors* are designed to integrate copying with recognition of live heap objects. Copying collectors are very popular and are widely used.

Consider a simple copying collector that uses *semispaces*. We start with the heap divided into two halves—the *from* and *to spaces*.

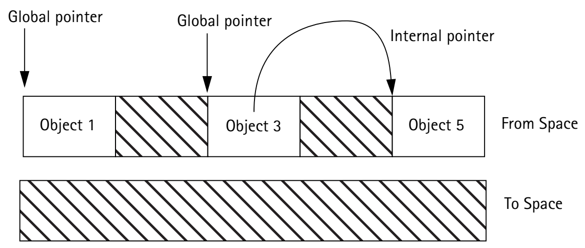
Initially, we allocate heap requests from the from space, using a simple "end of heap" pointer. When the from space is exhausted, we stop and do garbage collection.

Actually, though we *don't* collect garbage. We collect live heap objects—garbage is never touched.

We trace through global and local pointers, finding live objects. As each object is found, it is moved from its current position in the from space to the next available position in the to space.

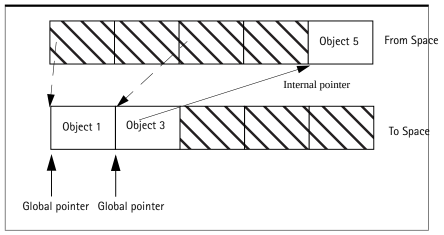
The pointer is updated to reflect the object's new location. A "forwarding pointer" is left in the object's old location in case there are multiple pointers to the same object.

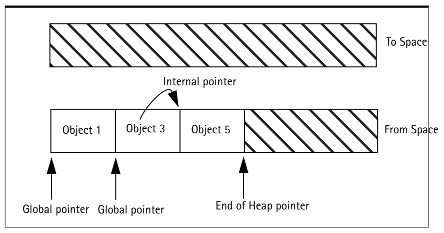
This is illustrated below:



The from space is completely filled. We trace global and local pointers, moving live objects to the to space and updating pointers. This is illustrated below. (Dashed arrows are forwarding pointers). We have yet to handle pointers internal to copied heap objects. All copied heap objects are traversed. Objects referenced are copied and internal pointers

are updated. Finally, the to and from spaces are interchanged, and heap allocation resumes just beyond the last copied object. This is illustrated in the lower figure.





The biggest advantage of copying collectors is their speed. Only live objects are copied; deallocation of dead objects is essentially free. In fact, garbage collection can be made, on average, as fast as you wish—simply make the heap bigger. As the heap gets bigger, the time between collections increases, reducing the number of times a live object must be copied. In the limit, objects are never copied, so garbage collection becomes free!

Of course, we can't increase the size of heap memory to infinity. In fact, we don't want to make the heap so large that paging is required, since swapping pages to disk is dreadfully slow. If we can make the heap large enough that the lifetime of most heap objects

is less than the time between collections, then deallocation of short-lived objects will appear to be free, though longer-lived objects will still exact a cost.

Aren't copying collectors terribly wasteful of space? After all, at most only half of the heap space is actually used. The reason for this apparent inefficiency is that *any* garbage collector that does compaction must have an area to copy live objects to. Since in the worst case *all* heap objects could be live, the target area must be as large as the heap itself. To avoid copying objects more than once, copying collectors reserve a to space as big as the from space. This is essentially a space-time trade-off, making such collectors very fast at the expense of possibly wasted space.

If we have reason to believe that the time between garbage collections will be greater than the average lifetime of most heaps objects, we can improve our use of heap space. Assume that 50% or more of the heap will be garbage when the collector is called. We can then divide the heap into 3 segments, which we'll call A, B and C. Initially, A and B will be used as the from space, utilizing 2/3 of the heap. When we copy live objects, we'll copy them into segment C, which will be big enough if half or more of the heap objects are garbage. Then we treat C and A as the from space, using B as the to space for the next collection. If we are

unlucky and more than 1/2 the heap contains live objects, we can still get by. Excess objects are copied onto an auxiliary data space (perhaps the stack), then copied into A after all live objects in A have been moved. This slows collection down, but only rarely (if our estimate of 50% garbage per collection is sound). Of course, this idea generalizes to more than 3 segments. Thus if 2/3 of the heap were garbage (on average), we could use 3 of 4 segments as from space and the last segment as to space.

Generational Techniques

The great strength of copying collectors is that they do no work for objects that are born and die between collections. However, not all heaps objects are so short-lived. In fact, some heap objects are very long-lived. For example, many programs create a dynamic data structure at their start, and utilize that structure throughout the program. Copying collectors handle long-lived objects poorly. They are repeatedly traced and moved between semispaces without any real benefit.

Generational garbage collection techniques were developed to better handle objects with varying lifetimes. The heap is divided into two or more *generations*, each

with its own to and from space. New objects are allocated in the youngest generation, which is collected most frequently. If an object survives across one or more collections of the youngest generation, it is “promoted” to the next older generation, which is collected less often. Objects that survive one or more collections of this generation are then moved to the next older generation. This continues until very long-lived objects reach the oldest generation, which is collected very infrequently (perhaps even never).

The advantage of this approach is that long-lived objects are “filtered out,” greatly reducing the cost of repeatedly processing them. Of course, some long-lived objects will die and these will be caught when their generation is eventually collected.

An unfortunate complication of generational techniques is that although we collect older generations infrequently, we must still trace their pointers in case they reference an object in a newer generation. If we don't do this, we may mistake a live object for a dead one. When an object is promoted to an older generation, we can check to see if it contains a pointer into a younger generation. If it does, we record its address so that we can trace and update its pointer. We must also detect when an existing pointer inside an object is changed. Sometimes we can do this by checking "dirty bits" on

heap pages to see which have been updated. We then trace all objects on a page that is dirty. Otherwise, whenever we assign to a pointer that already has a value, we record the address of the pointer that is changed. This information then allows us to only trace those objects in older generations that might point to younger objects.

Experience shows that a carefully designed generational garbage collectors can be very effective. They focus on objects most likely to become garbage, and spend little overhead on long-lived objects. Generational garbage collectors are widely used in practice.

Conservative Garbage Collection

The garbage collection techniques we've studied all require that we identify pointers to heap objects accurately. In strongly typed languages like Java or ML, this can be done. We can table the addresses of all global pointers. We can include a code value in a frame (or use the return address stored in a frame) to determine the routine a frame corresponds to. This allows us to then determine what offsets in the frame contain pointers. When heap objects are allocated, we can include a type code in the object's header, again allowing us to identify pointers internal to the object.

Languages like C and C++ are weakly typed, and this makes identification of pointers much harder. Pointers may be type-cast into integers and then back into pointers. Pointer arithmetic allows pointers into the middle of an object. Pointers in frames and heap objects need not be initialized, and may contain random values. Pointers may overlay integers in unions, making the current type a dynamic property.

As a result of these complications, C and C++ have the reputation of being incompatible with garbage collection. Surprisingly, this belief is false. Using *conservative garbage collection*, C and C++ programs *can* be garbage collected.

The basic idea is simple—if we can't be sure whether a value is a pointer or not, we'll be conservative and assume it is a pointer. If what we think is a pointer isn't, we may retain an object that's really dead, but we'll find all valid pointers, and never incorrectly collect a live object. We may mistake an integer (or a floating value, or even a string) as an pointer, so compaction in any form *can't* be done. However, mark-sweep collection will work.

Garbage collectors that work with ordinary C programs have been developed. User programs need not be modified. They simply are linked to different library routines, so that **`malloc`** and **`free`** properly support the garbage collector. When new heap space is

required, dead heap objects may be automatically collected, rather than relying entirely on explicit **`free`** commands (though **`free`**s are allowed; they sometimes simplify or speed heap reuse).

With garbage collection available, C programmers need not worry about explicit heap management. This reduces programming effort and eliminates errors in which objects are prematurely freed, or perhaps never freed. In fact, experiments have shown that conservative garbage collection is very competitive in performance with application-specific manual heap management.