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A GC pause will inevitably happen at the most inconvenient point in time

Normally when an object needs to be allocated and memory is full

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The more complex *concurrent GC* uses an extra thread to do the GC while the other threads continue to run

But it (a) uses a thread that could be working and (b) messes up memory accesses (caching) for the working threads causing them to slow down

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But they all increase other things, e.g., memory usage or allocation time or overall CPU usage

So comparing GC algorithms purely by pause time is an incomplete picture

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Low level programs often need to keep a close control on where things are located in memory and this would be a huge complicating factor

Plus they don't like the potentially non-deterministic behaviour of GC (when will the GC happen?), and again prefer the deterministic behaviour of manual memory management

Memory Management

GC vs. Manual

Note that manual memory management does have a cost (`malloc` and `free` are not free!) but that cost is spread throughout the running of the program, and not in big pauses when the GC runs

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GCs ignore information in the code that could help, e.g., when an object is no longer accessible might be possible to be determined from the code. But common language design means you can't *always* determine this, thus the need for GC in such languages

Memory Management

GC vs. Manual

GC code tends to have a larger memory footprint as it might need up to twice the space that data would normally require: the space for the data plus an equal amount of space for the allocation and GC mechanisms

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Sprawl can be a problem in memory-limited embedded systems

Memory Management

GC vs. Manual

But on the plus side, a GC deallocates many objects in one sweep which might be less overhead than deallocating many objects individually in manual system (amortisation of deallocation costs, particularly in parallel systems where memory allocation might need to acquire locks)

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In a world of big memory and “fast enough” processors development time might be the most important factor!

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Or code correctness (get the customer to find the bugs)

But there are a *lot* of cases (embedded systems) where the processor is not particularly fast, or where there is not a huge amount of memory

Or where customer-discovered bugs are not acceptable (safety-critical systems)

Memory Management

Exercise Find out the overhead of `malloc` and `free` in C, or the equivalent in your favourite language

Exercise Read about the concurrent GC in Go

Note for Gamers: at 60fps you only have 16ms per frame. So even 1ms for a GC is troublesome

Exercise Using Java for high-frequency trading (in banks) has problems with GC latency. Read about this

Exercise There has been talk of building specific hardware support for GC: a “GC coprocessor”. Read about this.

Other Memory Management

So the problem is we need something to keep track of values (objects/data) so that the bytes they occupy can be reclaimed and reused when that value is no longer needed by the program

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While these two cases cover a lot of existing languages, there are other approaches the try to tackle the above two's shortcomings

Namely relying on the programmer is not a good idea and GCs have unpredictable or undesirable behaviour

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Runtime Tracking of Allocations

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Swift and Python (amongst others) use runtime *reference counting* to keep track of values

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Swift and Python (amongst others) use runtime *reference counting* to keep track of values

Each value has an internal counter that is incremented every time a new reference is made to that value; and decremented when a reference is dropped

When the counter reaches zero, the value's memory is deallocated

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y = x
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the count of the value that `y` used to refer to is decremented while the count of the value that `x` refers to is incremented

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If there *are* other references, its count will be non-zero, so the value is not deallocated

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Runtime Tracking

Advantages: no GC, no `free`, as the runtime does this automatically

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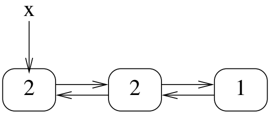
Disadvantages: a runtime overhead on every assignment (and most programs have lots of assignments!); reference loops (a circle of values, each containing a reference to the next) can hold on to inaccessible memory

Other Memory Management

Runtime Tracking

For example, a doubly-linked list:



Initial refcounts

Other Memory Management

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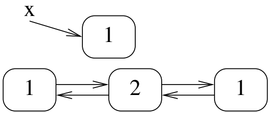

Inaccessible after `x` is reassigned

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In certain cases, a good compiler might be able to eliminate some of these overheads if it can determine statically (i.e., by analysis of the code) it is not needed

But this is very hard in general, often even impossible, so not often well supported

Other Memory Management

Runtime Tracking

Exercise Look up `sys.getrefcount()` in Python

Exercise Python also has a GC. Why?

Exercise Swift doesn't have a GC, but uses *weak references* to fix the doubly-linked list problem. Read about this

Advanced Exercise The new M1 chip from Apple has special support in its instruction set to support Swift's reference counting. Read about this

Other Memory Management

Compiletime Tracking of Allocations

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Rust uses compiler analysis of the source code to keep track of values

The compiler can determine exactly where in the code a value has no more references to it and so can compile exactly the deallocations needed

Various language restrictions on the use of values mean this is possible to do in Rust, while being impossible in other languages

Other Memory Management

Compiletime Tracking

For example, many languages can make references to values with no restriction and that makes this kind of compile time analysis impossible for those languages (so, e.g., Swift has to do this tracking at runtime by the reference count)

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if random() > 0.5 {
    y = x;
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if random() > 0.5 {
    y = x;
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else {
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How many references to the value in `x` are there now?

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Compiletime Tracking

Rust has a strict notion of which variable *owns* a value that makes this tracking possible by the compiler

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Exercise The above is a huge simplification. Read about what Rust actually does

Other Memory Management

Compiletime Tracking

Advantages: no GC; no `free`; no runtime overhead for tracking; makes many kinds of memory errors impossible; also makes certain kinds of parallelism errors impossible

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Compiletime Tracking

Advantages: no GC; no `free`; no runtime overhead for tracking; makes many kinds of memory errors impossible; also makes certain kinds of parallelism errors impossible

Disadvantages: the language has the concepts of *lifetimes* and *ownership* for values that programmers coming from other languages find hard to grasp and which (correctly) makes certain kinds of things you would do in those other languages impossible in Rust

Other Memory Management

Compiletime Tracking

Exercise For advanced C++ programmers: compare the idea of C++ `move` semantics

Exercise For advanced Swift programmers: compare the idea of exclusivity enforcement on variables

Advanced Exercise Read about *linear* and *affine types*

Memory Management

On the use of memory-safe (non-MMM) languages in Android (Rust, Java, Kotlin):

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2022 was the first year where memory safety vulnerabilities did not form a majority of Android’s vulnerabilities

And because memory safety flaws accounted for most of the critical issues, the vulnerabilities that have surfaced have proven to be less severe”

Jeffrey Vander Stoep, Google Security Blog, December 2022

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Similarly reference counting is GC for some people

We shall restrict ourselves to the most common usage of GC that means “subsystem that scans and collects inaccessible memory”

Memory Management

If Java had true garbage collection, most programs would delete themselves upon execution
Robert Sewell

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[C# is] sort of Java with reliability, productivity and security deleted
James Gosling

Types

We now look at how types are treated in various very different ways

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Note we are *not* specifically talking about OO languages here

Types vs. Classes

Types and Classes have an interesting relationship

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They are sometimes the same, but sometimes different

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Java has both `int` and `Integer`. Primitive types in Java are not classes (often regarded as a flaw in the design of Java!)

And, of course, C and Fortran and Pascal, etc., have types, but no classes

Types vs. Classes

We shall be talking about types as a separate concept from classes

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So the following also applies to non-OO languages like C

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Static typing is quite common in modern languages, and sometimes optional (Maple, Common Lisp)

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Dynamic typing: Lisp, Python, Perl, JavaScript, . . .

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Often scripting and prototyping languages are dynamically typed

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A given variable may hold values of different types at different times

```
x = 1;
x = "hello";
```

is valid in such a language, though arguably poor code as the programmer is clearly confused on the role of `x` in this program

Types

Exercise And the classifications are not exclusive: read about *gradual typing* that mixes static and dynamic

Exercise Find out how much overhead Java, Python, etc., have on each (non-primitive) value to encode its type (and other things)

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Strong typing: (a bit of a fuzzy concept) a value has a definite type and no implicit conversions between types

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"Strong" seems to cover different ideas in different peoples' minds, and possibly ought to be avoided as a concept

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Weak typing: not strongly typed

Types

For example, C is fairly weakly typed and it is common (and bad) to write:

```
double x = 1;     // poor code!
```

Here, the `int` value is automatically coerced to a `double` value before being bound to `x`

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Here, the `int` value is automatically coerced to a `double` value before being bound to `x`

Exercise Compare `sqrt(3/2)` with `sqrt(3.0/2.0)` in C. Then do the same in Python2, Python3, Haskell and other languages

Types

Remember: even though C `float` and `int` might both use 32 bits to represent a number, they are very different things: the integer 1 might be represented by

00000000 00000000 00000000 00000001

while the float 1.0 might be represented in IEEE by

00111111 10000000 00000000 00000000

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In programming languages, floating point and integers are different types that behave very differently and you shouldn't casually mix them

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Mathematicians do this as it is convenient, but in CS we have to be more careful

Types

Exercise Consider the difference between:

- Converting an `int` to a `float` where we want to preserve the “meaning”, e.g., `1` becomes `1.0`
- Converting an `int` to a `float` where we want to preserve the bits, e.g.,
  `00000000 00000000 00000000 00000001` as an `int`
  becomes
  `00000000 00000000 00000000 00000001` as a `float`