Making lazy mark scan a bit faster by avoiding scanning some objects based on their type

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Contents

1. Introduction

One major problem with reference counting is the fact that it cannot free objects that are involved in reference cycles. Lazy mark scan is a cyclic reference counting algorithm that aims to fix this issue, but it requires traversing all objects reachable from any potential cyclic roots [1]. This write-up describes a way to reduce the number of objects traversed by applying information about types known at compile-time. My project involved creating a language Fred and implementing a runtime for it that takes advantage of this optimization.

2. Background

Leo, you can probably skip/skim these first couple sections, they mostly just exist for future me.

2.1. Lazy mark scan

Lazy mark scan is a lazy version of an algorithm called local mark scan.

With local mark scan, every time an object's reference count is decremented, if its reference count does not hit 0, all of the objects reachable from that object are scanned recursively, and if it turns out that any of these objects were part of a cycle and are now no longer reachable, they will be freed [2].

Since this process is expensive, lazy mark scan merely adds each object to a list of **potential cyclic roots** (PCRs). Every once in a while, this list of PCRs is traversed and mark scan is performed on all of these PCRs at once. Note that each PCR is not simply scanned individually, in sequence, because this would essentially be the same as local mark scan. Rather, each phase of the mark scan algorithm is sequentially performed on all PCRs before moving on to the next phase.

This still requires scanning a bunch of objects. There are many things you can do to improve reference counting performance significantly, and I ran into a bunch of such articles. However, I only found a couple that make optimizations based on compile-time information. This is possibly because TODO

3. Algorithm

3.1. Avoiding scanning children based on type

In a statically typed language, some guarantees can be made about whether or not objects of one type can ever form cycles with objects of another type. At runtime, this lets us reduce the scanning we do.

Fewer guarantees can be made if the type system in question includes subtyping or something, but this project only looks at a very simple language, with no subtyping, polymorphism, dependent types, closures, or other bells and whistles.

Fred's user-defined types are only algebraic data types, I think they're called? They're tagged unions of product types. And rather than assume every field is mutable, fields need to be marked mutable explicitly. Immutability isn't central to my project, but it does give us some extra knowledge to avoid more scanning.

This makes it easy to represent all the types in a program as a directed graph where the nodes are types. The fields inside every type can be represented as edges going from that type to the type of the field.

Now that we have a graph of types, we can see that two objects `a` and `b` (not necessarily distinct) of types `A` and `B`, respectively, can only form a cycle if:

- `A` and `B` form a cycle,
- and somewhere along the path from `A` to `B` or `B` to `A`, there's a mutable field.

Although I may be lazy, Fred is not, and so there is currently no way to create cycles using only immutable fields. I don't feel like proving this or Googling for existing proofs of it.

Now that we know that certain objects cannot form cycles with certain other objects, we can apply this knowledge at runtime. When recursively scanning the objects reachable from a PCR, every time we come across some object, we can avoid scanning those of its children that can never form a cycle with that object (based on their types). We will also only add an object to the list of PCRs in the first place if it's possible for that object to be part of a cycle (note the two rules above).

3.2. Quadratic scanning problem

However, if done naively, this can result in not all garbage being collected in a single sweep of the list of PCRs [3]. A quick fix for this would be to go over the list of PCRs multiple times until all garbage is gone, but this makes cycle collection quadratic in the number of objects.

Below, I will give some example code that triggers this problem. Suppose you are creating a compiler and you have the following types. You can have `Context -> FileList -> Context` cycles, as well as `File -> ExprList -> Expr -> File` cycles.

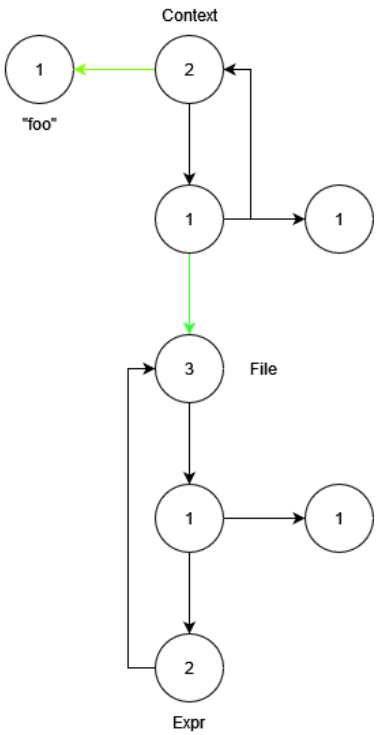
```
data Context = Context {
  name: str,
  mut files: FileList
}
data FileList
  = FileNil {}
  | FileCons {
    ctx: Context,
    head: File,
    tail: FileList,
  }
data File = File {
```

```
  mut exprs: ExprList
}
data ExprList
  = ExprNil {}
  | ExprCons {
    head: Expr,
    tail: ExprList
  }
data Expr = Expr {
  file: File,
  // other stuff here
}
```

And for whatever reason, you have the following code that creates a context with a file that contains one expression:

```
let ctx = Context { name: "foo", files: FileNil {} } in
let file = File { exprs: ExprNil {} } in
let expr = Expr { file: file } in
ctx.files = FileCons { ctx: ctx, head: file, tail: ctx.files };
file.exprs = ExprCons { head: expr, tail: file.exprs }
```

After running that code, this is what the graph of objects looks like:



The green edges in the diagram above are references that are known not to introduce any cycles. Therefore, when doing mark-scan, we will not follow them (this is our modification from the previous section, not part of lazy mark scan). There are other references that don't cause cycles in there, but we can't know this at compile-time. I'm going to call these green edges "innocent", because I don't know what sort of terms are actually used for them by real researchers.

At some point, the variables `ctx`, `file`, and `expr` will go out of scope, so the `Context`, `File`, and `Expr` objects will all have their refcounts decremented before being added to the list of PCRs. All the objects in the diagram above have become garbage and are eagerly waiting to be freed, not knowing

that rather than nirvana, all they will get is an endless cycle of rebirth and deallocation, until your laptop finally stops working and you have to throw it away. Thankfully, planned obsolescence will eventually bring nirvana to these objects in a matter of years.

Let's trace what our naively modified lazy mark scan algorithm would do here:

- First, we go to every object reachable from the `Context`, `File`, and `Expr` objects (without traversing green edges) and mark it gray.
  - The reference count of every object reachable from these gray objects is decremented, as if the gray objects have been deleted.
  - After doing this, the `Context` and `FileList` objects have a refcount of 0. `File` has a refcount of 1, while the `Expr` and `ExprList` objects have a refcount of 0.
- TODO finish this

Now the stuff in the top cycle has been correctly marked as garbage, but not the stuff in the bottom cycle. `File` lives because it has a reference from the `FileCons` object, and it keeps the rest of the bottom cycle alive. All the scanning we did on the bottom cycle was in vain, because we'll have to go back and repeat it now.

Therefore, it is not enough to simply not traverse innocent edges. Fortunately, the solution to this is pretty simple.

3.3. Fixing the quadratic scanning problem

You may notice above that because we don't traverse innocent edges, processing the `Context` object happens completely separately from processing the `File` and `Expr` objects. We could have processed the `Context` object first, found it to be garbage, decremented the `File` object's reference count, and then processed the `File` and `Expr` objects together. This way, all of the objects would have been marked as garbage without processing any PCR multiple times.

In general, how do we determine which objects should be processed before which objects? We can do this based on which objects can reference which objects (directly or indirectly). A `Context` object can refer to `File` and `Expr` objects, so it must be processed before them. `File` and `Expr` objects can both refer to each other, so they must be processed together.

A simple way to determine this in practice is to take the graph of types and partition it into its **strongly-connected components** (**SCCs**). These SCCs have an ordering. Objects from the same SCC will all be processed together, but objects from earlier SCCs will be processed before objects from later SCCs.

To make this more concrete, let's return to the previous problematic example. There, you have the following SCCs:

1. `[Context, FileList]`
2. `[File, ExprList, Expr]`
3. `[str]`

I've listed them in the order they would be processed, although the second and third SCCs can be swapped, since they are unrelated.

This time, we would process only the `Context` PCR first, and we would find it and the two `FileList` objects to be garbage. This would cause the string `"foo"` and the `File` object to have their refcounts decremented. The string would be freed at this point.

Next, we would process the `File` and `Expr` PCRs together. This time, the refcount of `File` would be only 1, since it is being kept alive only by the cycle it's part of. After processing, the whole cycle would have refcount 0 and be freed.

As a bonus, grouping objects by SCC and processing them separately also lets us make cycle collection more incremental. If necessary, we can process PCRs from the first SCC, then continue on with the rest of the program rather than process all of the remaining PCRs too. I didn't explore this in my project, though.

4. Implementation

Fred was created to try out this algorithm. The implementation can be found at https://github.com/ysthakur/Fred. The language uses automatic reference counting and is compiled to C. Partly because it is compiled to C and partly because I made it, it involves copious amounts of jank. When I have time after finals, I will try to get rid of some of this awfulness, as well as document my code better, but in the meantime, Fred is mostly functional (functional as in alcoholic).

5. Benchmarks

I would like to preface this section by noting that it is complete bogus and that you can safely skip it. These benchmarks should not be taken as evidence of anything. Apologies in advance for that. Nevertheless, I have used these benchmarks to convince myself that my algorithm is vastly superior to the base lazy mark scan algorithm. Feel free to do the same.

I have two benchmarks at the moment. They can be found in the `benchmarks` folder.

The benchmarks work by running a piece of code a bunch of times, then looking at how much the processor's timestamp counter increased (using `rdtscp`) as well as the processor time (using `clock()`). Since within each benchmark, the code being timed is run lots of times, I only recorded the times after running each benchmark program once, rather than running each program multiple times and noting the mean and range.

5.1. `game.fred`

Here's the code. This program is supposed to be a game, except it does basically nothing. It demonstrates a case where normal lazy mark scan will unnecessarily scan a bunch of objects, but my algorithm won't.

It has the following types:

```
data Player
  = Player { store: Store }
  // This exists only to make the compiler think that Player can be involved in
cycles
  | PlayerCyclic {
    mut player: Player
  }
data Store = Store { datums: Data }
data Data
  = DataCons {
    value: int,
    // This is mut only so the compiler thinks there can be a cycle at runtime
    mut next: Data
  }
  | DataNil {}
```

`Store` represents some kind of shared state or resources or something that all `Player` objects have a reference to. This sort of thing is probably more common in Java than in a functional language, but whatever.

This is what `game.fred` does:

1. Create a ginormous `Store` object
2. Do the following 50,000 times:
    1. Create a `Player` object
    2. Increment and decrement its refcount so that it's added to the list of PCRs
    3. Invoke `processAllPCRs()`

The `processAllPCRs()` call above will cause the `Player` object to be scanned. When it's scanned, with my algorithm, the `Store` object won't be scanned, because it's in a separate SCC. But with base lazy mark scan, the `Store` object will have to be scanned, so it will be slower.

Here are the results:

Lazy mark scan only?	Timestamp counter	Clock (s)
No	74647376	0.028586
Yes	29478684752	11.289244

I'd go into how my algorithm is orders of magnitude faster than base lazy mark scan, but this benchmark means basically nothing. The only thing it really tells you is that there can be cases where my algorithm is faster than lazy mark scan, but even calculations on a blackboard would've told you that. This benchmark doesn't help one get a sense of how much faster my algorithm would be in general.

5.2. `stupid.fred`

If the previous benchmark wasn't artificial enough for you, this one definitely will be. I wanted to come up with something where my algorithm would perform worse than base lazy mark scan. This can happen if the overhead from inserting PCRs into the right bucket (sorted) is too high. You need to have a bunch of SCCs, and you need to often have objects from higher SCCs being added to the list of PCRs after objects from lower SCCs.

This is actually a situation that probably isn't uncommon in real codebases. If you have some long-lived object that's passed around everywhere, you probably have references to it being created all the time. I do believe escape analysis would help with/fix many, if not most of those cases, though. Removing a PCR every time its refcount is incremented could also help here, although that has tradeoffs.

I, unfortunately, couldn't come up with a decent example, so I wrote a script to do it for me. The script first generates 200 types. Each type T_{i+1} has a field of type T_i. The script then generates an object of type T_{199}. Then it goes from T_{199} down to T_0, adding objects to the list of PCRs. With base lazy mark scan, adding PCRs is a constant time operation, but with my algorithm, it's linear time, since an object of type T_i here would have to go through $199 - i$ objects first.

All of the stuff described above is then run 50,000 times. Here are the results:

Lazy mark scan only?	Timestamp counter	Clock (s)
No	27741037106	10.623692
Yes	11054113602	4.233204

Again, all this tells you is that there are some cases where my algorithm can do worse than lazy mark scan.

6. Conclusion

7. Future work

Bibliography

[1] R. D. Lins, “Cyclic Reference Counting With Lazy Mark-Scan,” *Information Processing Letters*, vol. 44, no. 4, pp. 215–220, Dec. 1992, Accessed: Sep. 18, 2024. [Online]. Available: http://dx.doi.org/10.1016/0020-0190(92)90088-D

[2] A. D. Martínez, R. Wachenchauzer, and R. D. Lins, “Cyclic reference counting with local mark-scan,” *Information Processing Letters*, vol. 34, no. 1, pp. 31–35, Feb. 1990, doi: 10.1016/0020-0190(90)90226-N.

[3] J. Morris Chang, W.-M. Chen, P. A. Griffin, and H.-Y. Cheng, “Cyclic reference counting by typed reference fields,” *Computer Languages, Systems & Structures*, vol. 38, no. 1, pp. 98–107, Apr. 2012, doi: 10.1016/j.cl.2011.09.001.

Why name it Fred?

I was going to name it Foo, but there’s already an esolang by that name that’s fairly well-known (by esolang standards). So I went to the Wikipedia page on metasyntactic variables and picked “fred.” I figured that if I needed to, I could pretend that it was something meaningful, like maybe an acronym or the name of a beloved childhood pet.

For example, I could say that when I was young, I had a cute little hamster called Freddie Krueger, so named because of the striped red sweater my grandmother had knitted for him, as well as his proclivity for murdering small children. In his spare time, Fred would exercise on his hamster wheel, or as he liked to call it, his Hamster Cycle.

But one day, I came home to find Fred lying on the hamster cycle, unresponsive. The vet said that he’d done too much running and had had a heart attack. I was devastated. It was then that I decided that, to exact my revenge on the cycle that killed Fred, I would kill all cycles.