University of Glasgow

Garbage Collection

Advanced Systems Programming (M)
Lecture 5

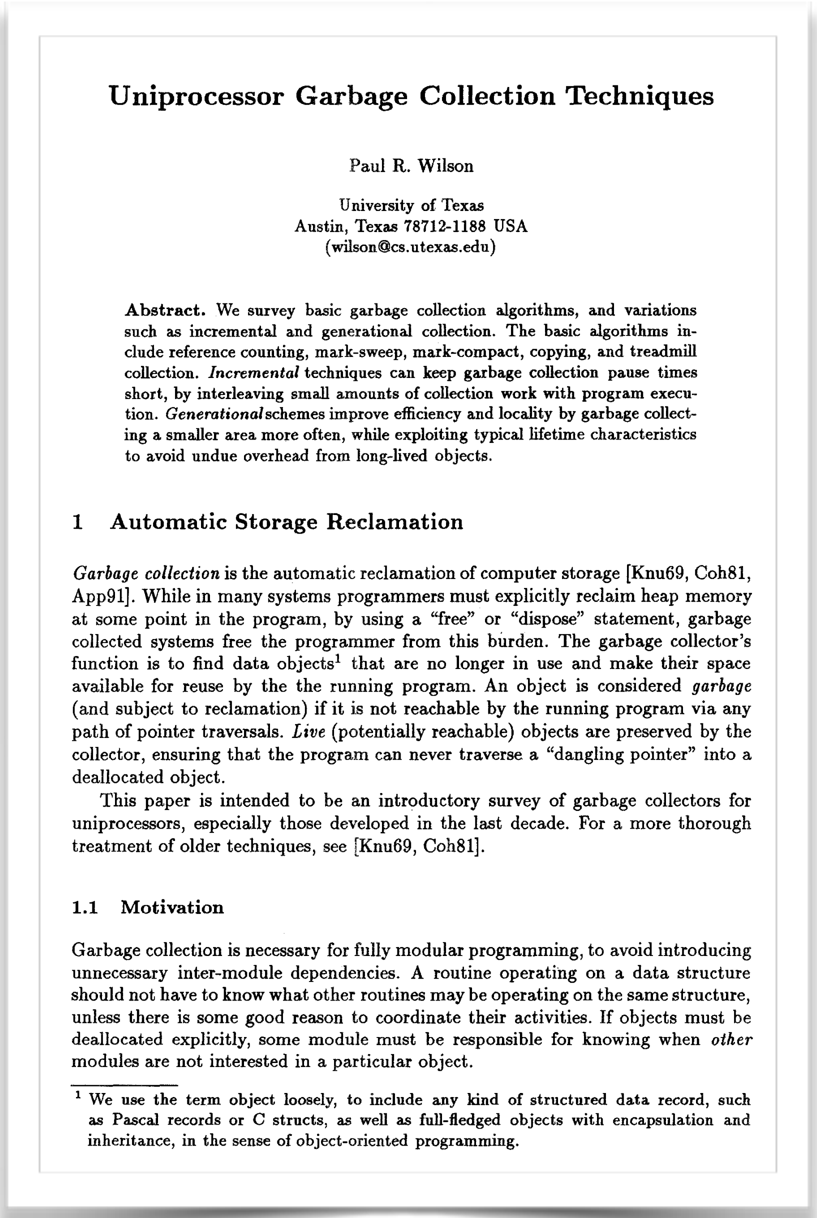
Rationale

- Region-based memory management (→ lecture 4) is novel, trades program complexity for predictable resource management
- Garbage collection widely implemented, but less predictable

- Need to understand garbage collector operation to understand the performance-complexity trade-off

Lecture Outline

- Garbage collection
  - Mark-sweep
  - Mark-compact
  - Copying collectors
  - Generational algorithms
  - Incremental algorithms
  - Real-time garbage collection
- Practical factors



Uniprocessor Garbage Collection Techniques

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Abstract. We survey basic garbage collection algorithms, and variations such as incremental and generational collection. The basic algorithms include reference counting, mark-sweep, mark-compact, copying, and treadmill collection. *Incremental* techniques can keep garbage collection pause times short, by interleaving small amounts of collection work with program execution. *Generational* schemes improve efficiency and locality by garbage collecting a smaller area more often, while exploiting typical lifetime characteristics to avoid undue overhead from long-lived objects.

1 Automatic Storage Reclamation

Garbage collection is the automatic reclamation of computer storage [Knu69, Coh81, App91]. While in many systems programmers must explicitly reclaim heap memory at some point in the program, by using a "free" or "dispose" statement, garbage collected systems free the programmer from this burden. The garbage collector's function is to find data objects[1] that are no longer in use and make their space available for reuse by the the running program. An object is considered *garbage* (and subject to reclamation) if it is not reachable by the running program via any path of pointer traversals. *Live* (potentially reachable) objects are preserved by the collector, ensuring that the program can never traverse a "dangling pointer" into a deallocated object.

This paper is intended to be an introductory survey of garbage collectors for uniprocessors, especially those developed in the last decade. For a more thorough treatment of older techniques, see [Knu69, Coh81].

1.1 Motivation

Garbage collection is necessary for fully modular programming, to avoid introducing unnecessary inter-module dependencies. A routine operating on a data structure should not have to know what other routines may be operating on the same structure, unless there is some good reason to coordinate their activities. If objects must be deallocated explicitly, some module must be responsible for knowing when *other* modules are not interested in a particular object.

[1] We use the term object loosely, to include any kind of structured data record, such as Pascal records or C structs, as well as full-fledged objects with encapsulation and inheritance, in the sense of object-oriented programming.

P. R. Wilson, "Uniprocessor garbage collection techniques", Proceedings of the International Workshop on Memory Management, St. Malo, France, September 1992. DOI: 10.1007/BFb0017182

Basic Garbage Collection

- Mark-sweep
- Mark-compact
- Copying collectors

Garbage Collection

- Avoid problems of reference counting and complexity of compile-time ownership tracking via *tracing garbage collection*
  - Explicitly trace through the allocated objects, recording which are in use, rather than continually maintaining reference counts; dispose of unused objects
  - This moves garbage collection to be a separate phase of the program's execution, rather than an integrated part of an objects lifecycle
    - A garbage collector runs and disposes of objects
    - An object is reclaimed when its reference count becomes zero
- Many tracing garbage collection algorithms exist:
  - Mark-sweep, mark-compact, copying
  - Generational algorithms

Mark-Sweep Collectors

- Simplest automatic garbage collection scheme
- Two phase algorithm
  - Distinguish live objects from garbage (*mark*)
  - Reclaim the garbage (*sweep*)

- Non-incremental algorithm: program is paused to perform collection when memory becomes tight

- Will collect all garbage, whether or not there are cycles

Distinguishing Live Objects

- Find the *root* set of objects
    - Global and stack variables
- Traverse the object relationship graph staring at the root set to find all other reachable, live, objects
    - Breadth-first or depth-first search
    - Must read every pointer in every object in the system to systematically find all reachable objects
- Mark reachable objects
    - Stop traversal at previously seen objects to avoid following cycles
    - Either set a bit in the object header, or in some separate table of live objects

Reclaiming the Garbage

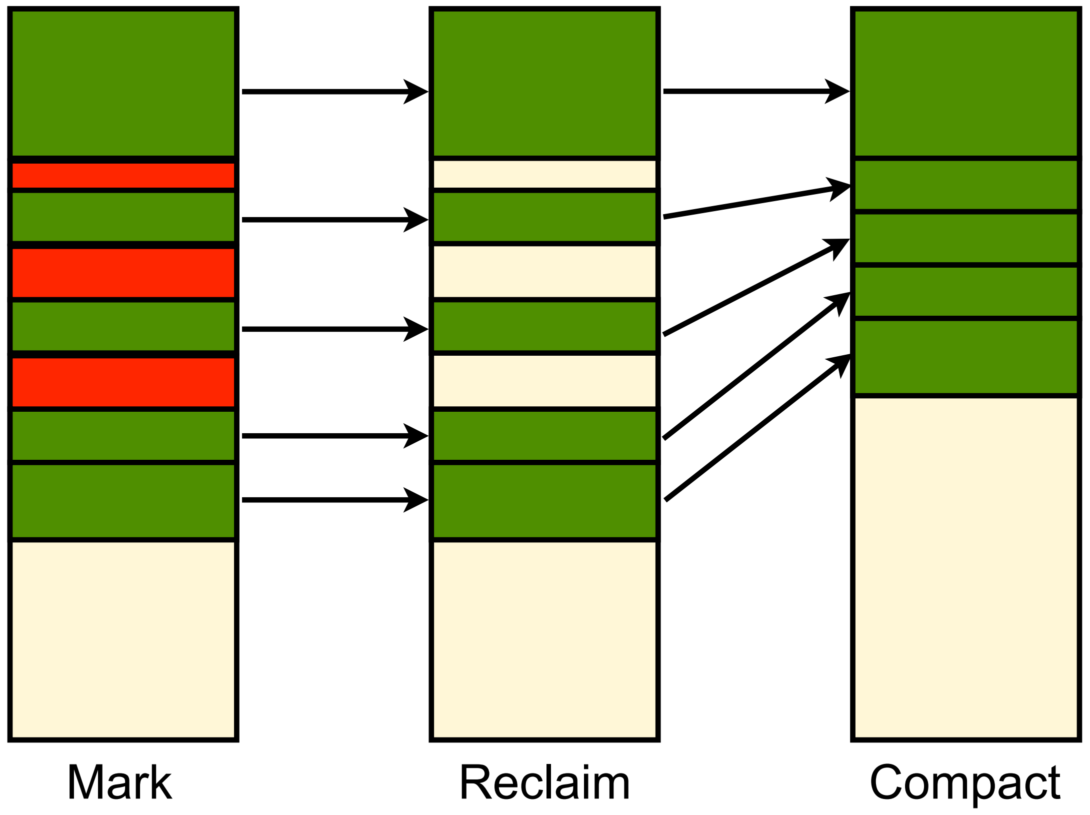
- Sweep through the entire heap, examining every object for liveness in turn
  - If marked as alive, keep it, otherwise reclaim the object's space
  - Space occupied by reclaimed objects is marked as free: the system must maintain one or more free lists to track available space
  - New objects are allocated in the space previously reclaimed
- No problem with collecting cycles, since the mark phase will not reach unreferenced cycles

Problems with Mark-Sweep Collectors

- Cost proportional to size of heap
  - Program is stopped with the collector runs; unpredictable collection time
  - All live objects must be marked, and all garbage must be reclaimed
  - Unlike reference counting, mark-sweep garbage collection is slower if the program has lots of memory allocated
- Fragmentation
  - Since objects are not moved, space may become fragmented, making it difficult to allocate large objects (even though space available overall)
- Locality of reference
  - Passing through the entire heap in unpredictable order disrupts operation of cache and virtual memory subsystem
  - Objects located where they fit (due to fragmentation), rather than where it makes sense from a locality of reference viewpoint

Mark-Compact Collectors

- Traverse object graph, *mark* live objects
- Reclaim unreachable objects, then *compact* live objects, moving them to leave a contiguous free space
  - Reclaiming and compacting memory can be done in a single pass, but still touches the entire address space
- Advantages:
  - Solves fragmentation problems
  - Allocation is very quick (increment pointer to next free space, return previous value)
- Disadvantages:
  - Collection is slow, due to moving objects in memory, and time taken is unpredictable
  - Collection has poor locality of reference



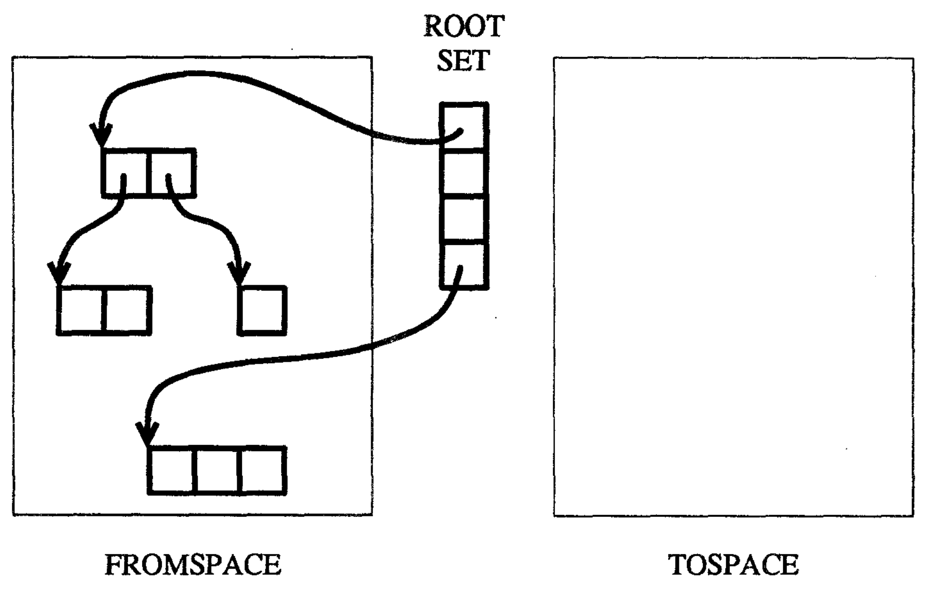
Copying Collectors

- Copying collectors integrate the traversal (marking) and copying phases into one pass
  - All the live data is copied into one region of memory
  - All the remaining memory contains garbage, or has not yet been used
- Similar to mark-compact, but more efficient
- Time taken to collect is proportional to the number of live objects

Stop-and-copy Using Semispaces (1)

- Standard approach: a semispace collector, that uses the Cheney algorithm for copying traversal
- Divide the heap into two halves, each one a contiguous block of memory
- Allocations made linearly from one half of the heap only
  - Memory is allocated contiguously, so allocation is fast (as in the mark-compact collector)
  - No problems with fragmentation due to allocating data of different sizes

- When an allocation is requested that won't fit into the active half of the heap, a collection is triggered



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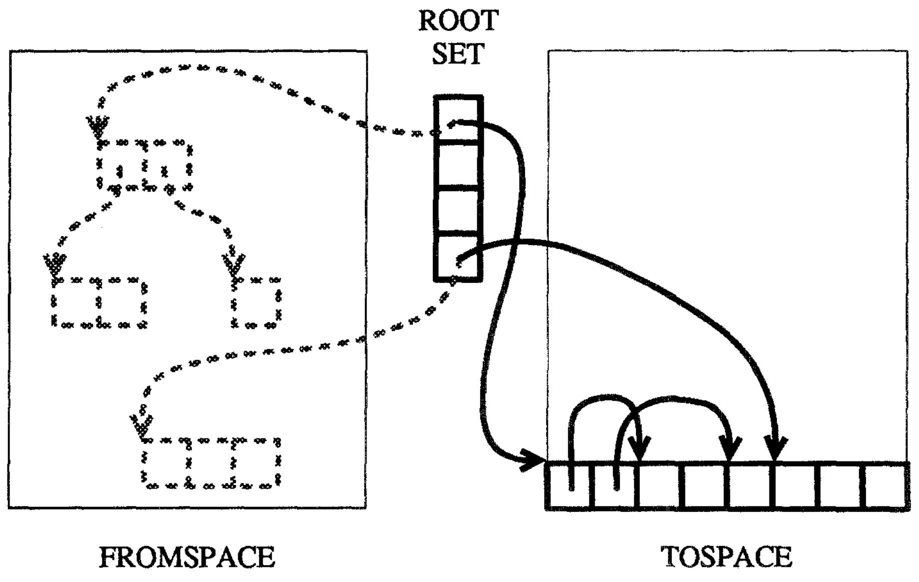
Stop-and-copy Using Semispaces (2)

- Collection stops execution of the program
- A pass is made through the active space, and all live objects are copied to the other half of the heap
  - The Cheney algorithm is commonly used to make the copy in a single pass
  - Anything not copied is unreachable, and is simply ignored (and will eventually be overwritten by a later allocation phase)
- The program is then restarted, using the other half of the heap as the active allocation region

- The role of the two parts of the heap (the two semispaces) reverses each time a collection is triggered



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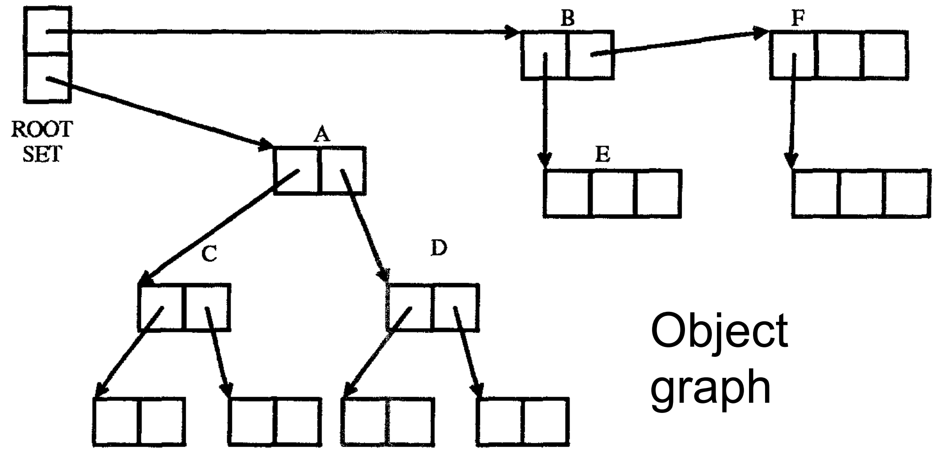
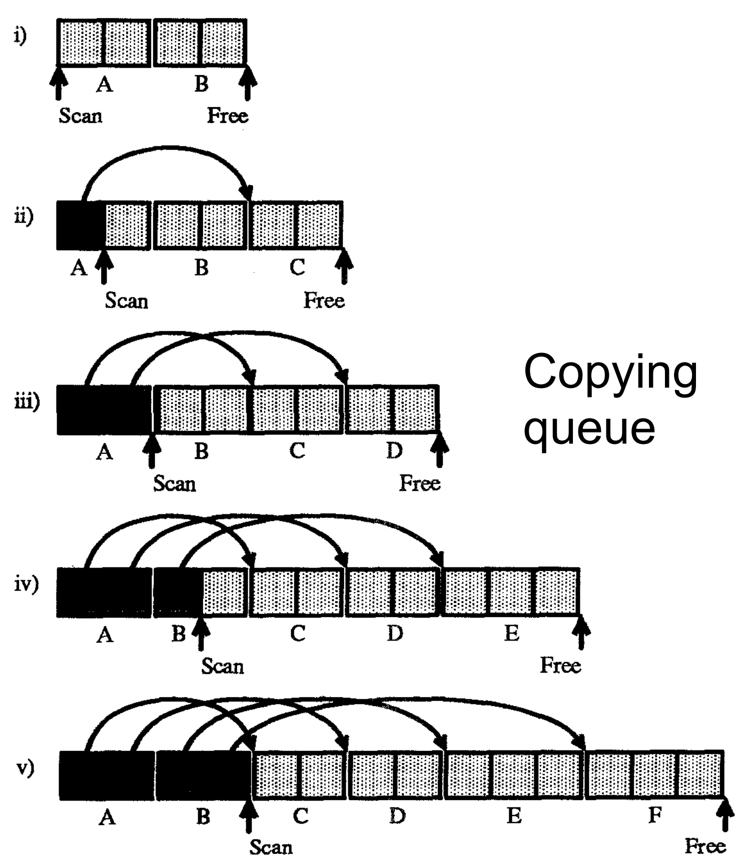
Breadth-first Copying: Cheney Algorithm



Object graph



Copying queue

Source: P. Wilson, "Uniprocessor garbage collection techniques", Proc IWMM'92, DOI 10.1007/BFb0017182

- The root set of objects is identified, forms initial queue of live objects to be copied
- Objects in the queue examined in turn:
  - Each unprocessed object directly referenced by the object in the queue is itself added to the end of the queue
  - The object in the queue is copied to the other space, and the original is marked as having been processed (pointers are updated as the copy is made)
- Once the end of the queue is reached, all live objects have been copied

Efficiency of Copying Collectors

- Time taken for collection depends on the amount of data copied, which depends on the number of live objects
- Collection only happens when the semispace is full

- *If most objects die young*, then can reduce the data to be copied by increasing the size of the heap
  - Increasing the size of the heap increases the age to which objects need to live in order to be copied; most don't live that long, and so aren't copied
  - Trade-off memory for collection time: more memory used, less fraction of time spent copying data

Summary: Basic Garbage Collection

- These approaches have broadly similar costs
  - But they move where the cost is paid: on allocation or collection; in terms of memory or processing time
  - Considering efficiency of copying collectors, and object lifetimes, leads to a possible optimisation: generational collectors (next lecture)
- Mark-sweep and reference counting don’t move data, and so can work with weakly-typed data
  - In languages like C and C++, with casting and pointer arithmetic, it’s hard to identify all possible pointers, but can usually identify values that might be pointers and be conservative in what’s collected
  - But – can’t move an object, if you can’t be sure all pointers to it have been updated

Generational Garbage Collection

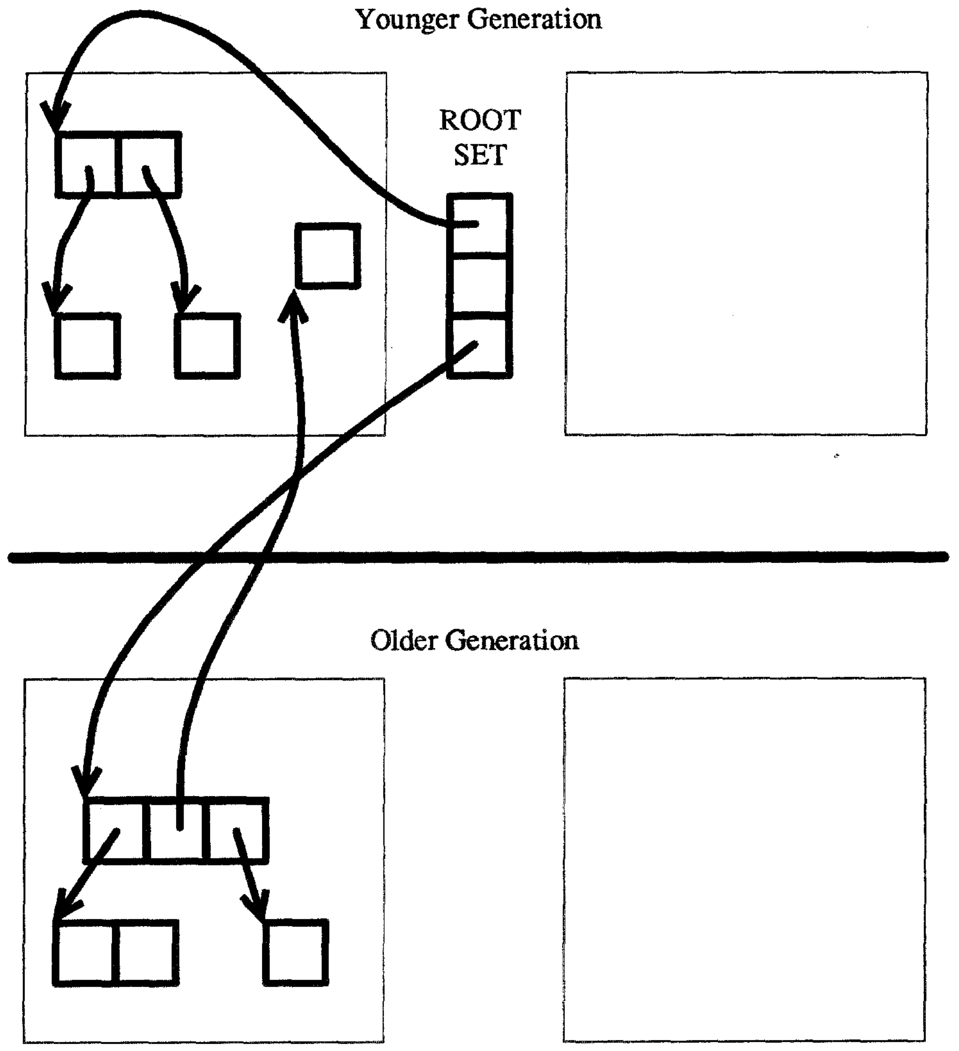
Object Lifetimes

- Studies have shown that most objects live a very short time, while a small percentage of them live much longer
  - This seems to be generally true, no matter what programming language is considered, across numerous studies
  - Although, obviously, different programs and different languages produce varying amount of garbage

- Implication: when the garbage collector runs, live objects will be in a minority
  - Statistically, the longer an object has lived, the longer it is likely to live
  - Can we design a garbage collector to take advantage?

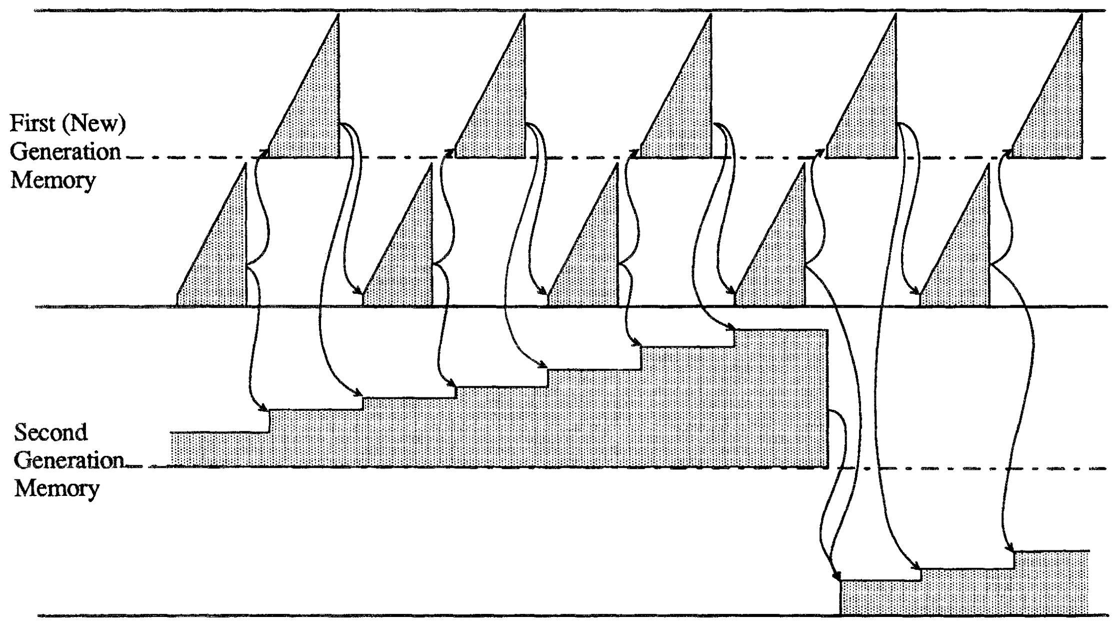
A Copying Generational Collector (1)

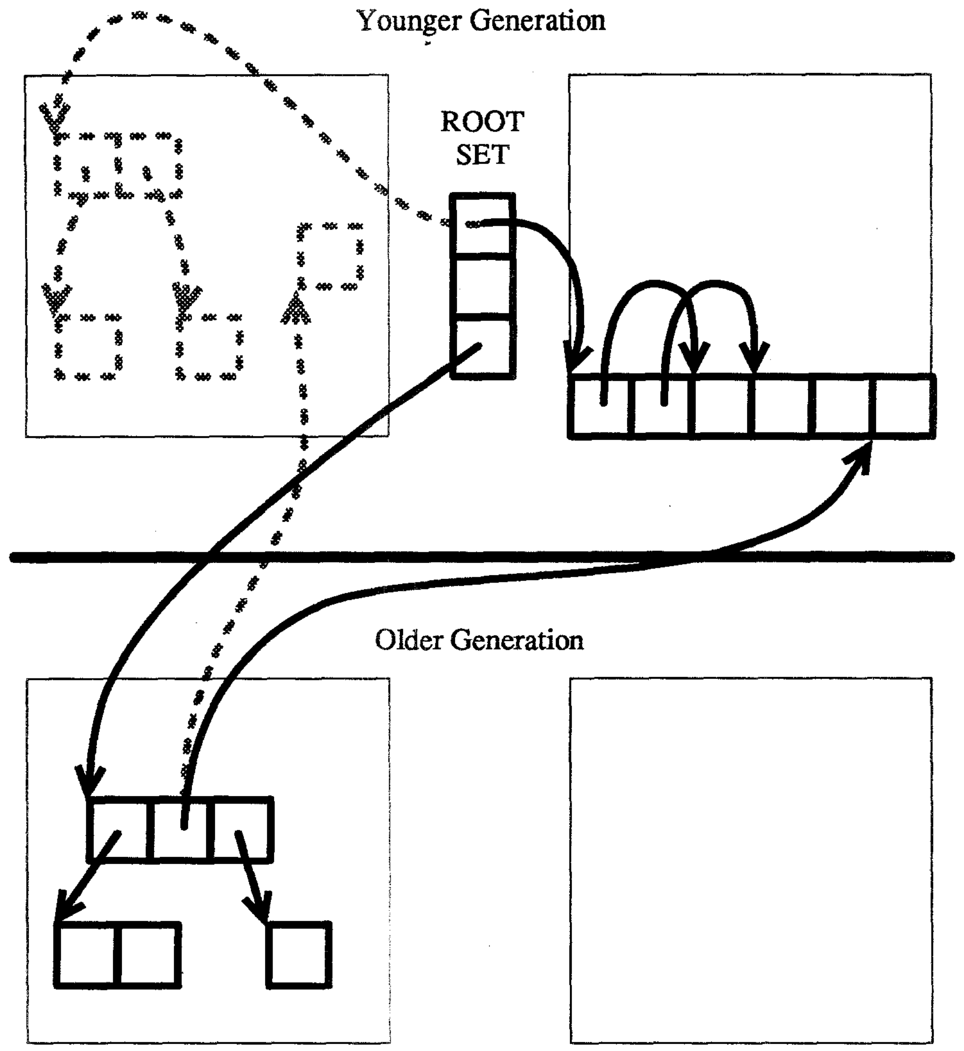
- In a generational garbage collector, the heap is split into regions for long-lived and young objects
    - Regions holding young objects are garbage collected more frequently
    - Objects are moved to the region for long-lived objects if they're still alive after several collections
    - More sophisticated approaches may have multiple generations, although the gains diminish rapidly with increasing numbers of generations
- Example: stop-and-copy using semispaces with two generations
    - All allocations occurs in the younger generation's region of the heap
    - When that region is full, collection occurs as normal
    - …



A Copying Generational Collector (2)

- …
- Objects are tagged with the number of collections of the younger generation they have survived; if they're alive after some threshold, they're copied to the older generation's space during collection
- Eventually, the older generation's space is full, and is collected as normal





- Note: not to scale: older generations are generally much larger than the younger, as they're collected much less often

Detecting Intergenerational References

- In generational collectors, younger generation must collected independent of the long-lived generation
  - But – there may be object references between the generations
  - Young objects referencing long-lived objects common but straight-forward since most young objects die before the long-lived objects are collected
    - Treat the younger generation objects as part of the root set for the older generation, if collection of the older generation is needed
  - Direct pointers from old-to-young generation are problematic, since they require a scan of the old generation to detect
  - May be appropriate to use an indirection table (“pointers-to-pointers”) for old-to-young generation references
    - The indirection table forms part of the root set of the younger generation
    - Movement on objects in the younger generation requires an update to the indirection table, but not to long-lived objects
    - Note: this is conservative: the death of a long-lived object isn’t observed until that generation is collected, but that may be several collections of the younger generation, in which time the younger object appears to be referenced

Generational Garbage Collection

- Variations on this concept are widely used
  - E.g., the HotSpot JVM uses a generational garbage collector

- Generational collectors achieve good efficiency:
  - Cost of collection is generally proportional to number of live objects
  - Most objects don't live long enough to be collected; those that do are moved to a more rarely collected generation
  - But – eventually the longer-lived generation must be collected; this can be very slow

Incremental Garbage Collection

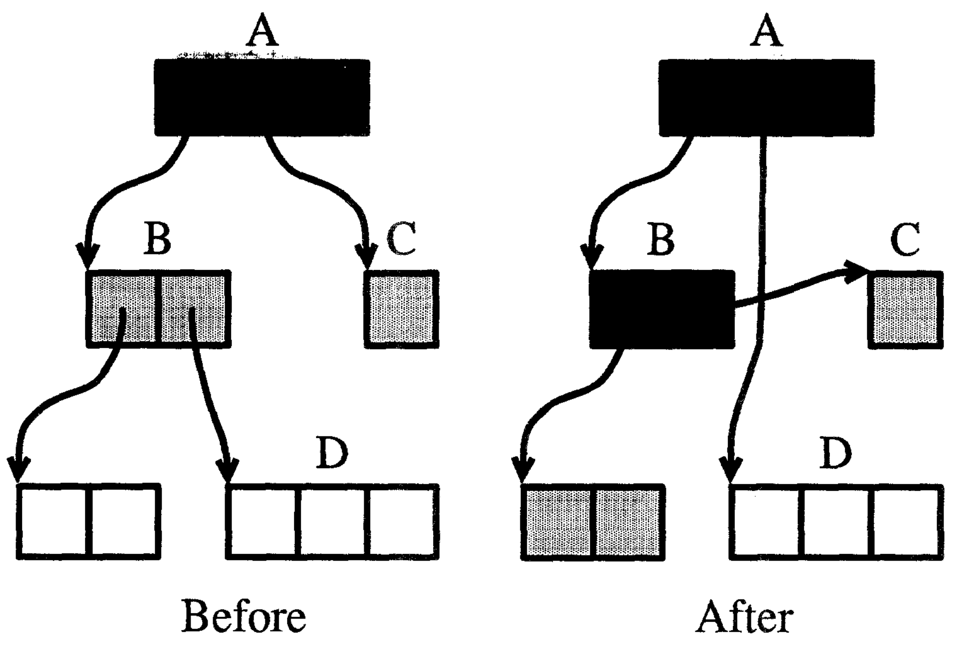
- Preceding discussion has assumed the collector “stops-the-world” when it runs
  - Clearly problematic for interactive or real-time applications
- Desire a collector that can operate incrementally
  - Interleave small amounts of garbage collection with small runs of program execution
  - Implication: the garbage collector can’t scan the entire heap when it runs; must scan a fragment of the heap each time
  - Problem: the program (the “mutator”) can change the heap between runs of the garbage collector
  - Need to track changes made to the heap between garbage collector runs; be conservative and don’t collect objects that might be referenced – can always collect on the next complete scan

Tricolour Marking

- For each complete collection cycle, each object is labelled with a colour:
  - White – not yet checked
  - Grey – live, but some direct children not yet checked
  - Black – live
- Basic incremental collector operation:
  - Garbage collection proceeds with a wavefront of grey objects, where the collector is checking them, or objects they reference, for liveness
  - Black objects behind are behind the wavefront, and are known to be live
  - Objects ahead of the wavefront, not yet reached by the collection, are white; anything still white once all objects have been traced is garbage
  - No direct pointers from black objects to white – any program operation that will create such a pointer requires coordination with the collector

Tricolour Marking: Need for Coordination

- Garbage collector runs
  - Object A scanned, known to be live → black
  - Objects B and C are reachable via A, and are live, but some of their children have not been scanned → grey
  - Object D not checked → white
- Program runs, and swaps the pointers from A→C and B→D such that A→D and B→C
- This creates a pointer from black to white
  - Program must now coordinate with the collector, else collection will continue, marking object B black and its children grey, but D will not be reached since children of A have already been scanned



Coordination Strategies

- Read barrier: trap attempts by the program to read pointers to white objects, colour those objects grey, and let the program continue
    - Makes it impossible for the program to get a pointer to a white object, so it cannot make a black object point to a white
- Write barrier: trap attempts to change pointers from black objects to point to white objects
    - Either then re-colour the black object as grey, or re-colour the white object being referenced as grey
    - The object coloured grey is moved onto the list of objects whose children must be checked

Incremental Collection

- Many variants on read- and write-barrier tricolour algorithms
  - Performance trade-off differs depending on hardware characteristics, and on the way pointers are represented
  - Write barrier generally cheaper to implement than read barrier, as writes are less common in most code
- There is a balance between collector operation and program operation
  - If the program tries to create too many new references from black to white objects, requiring coordination with the collector, the collection may never complete
  - Resolve by forcing a complete stop-the-world collection if free memory is exhausted, or after a certain amount of time

Real-time Garbage Collection

- Real-time collectors build incremental collectors
  - Two basic approaches:
    - Work based: every request to allocate an object or assign an object reference does some garbage collection; amortise collection cost with allocation cost
    - Time based: schedule an incremental collector as a periodic task
  - Obtain timing guarantees by limiting amount of garbage that can be created in a given interval to less than that which can be collected
  - The amount of garbage that can be collected can be measured: how fast can the collector scan memory (and copy objects, if a copying collector)
    - Cannot collect garbage faster than the collector can scan memory to determine if objects are free to be collected
    - This must be a worse-case collection rate, if the collector has varying runtime
  - The programmer must bound the amount of garbage generated to within the capacity of the collector

A Real-time Garbage Collector with Low Overhead and Consistent Utilization

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ABSTRACT

Now that the use of garbage collection in languages like Java is becoming widely accepted due to the safety and software engineering benefits it provides, there is significant interest in applying garbage collection to hard real-time systems. Past approaches have generally suffered from one of two major flaws: either they were not provably real-time, or they imposed large space overheads to meet the real-time bounds. We present a mostly non-moving, dynamically defragmenting collector that overcomes both of these limitations: by avoiding copying in most cases, space requirements are kept low; and by fully incrementalizing the collector we are able to meet real-time bounds. We implemented our algorithm in the Jikes RVM and show that at real-time resolution we are able to obtain mutator utilization rates of 45% with only 1.6–2.5 times the actual space required by the application, a factor of 4 improvement in utilization over the best previously published results. Defragmentation causes no more than 4% of the traced data to be copied.

General Terms

Algorithms, Languages, Measurement, Performance

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems; D.3.2 [**Programming Languages**]: Java; D.3.4 [**Programming Languages**]: Processors—*Memory management (garbage collection)*

Keywords

Read barrier, defragmentation, real-time scheduling, utilization

1. INTRODUCTION

Garbage collected languages like Java are making significant inroads into domains with hard real-time concerns, such as automotive command-and-control systems. However, the engineering and product life-cycle advantages consequent from the simplicity of programming with garbage collection remain unavailable for use in the core functionality of such systems, where hard real-time constraints must be met. As a result, real-time programming requires the use of multiple languages, or at least (in the case of the Real-Time Specification for Java [9]) two programming models within the same language. Therefore, there is a pressing practical need for a system that can provide real-time guarantees for Java without imposing major penalties in space or time.

We present a design for a real-time garbage collector for Java, an analysis of its real-time properties, and implementation results that show that we are able to run applications with high mutator utilization and low variance in pause times.

The target is uniprocessor embedded systems. The collector is therefore concurrent, but not parallel. This choice both complicates and simplifies the design: the design is complicated by the fact that the collector must be interleaved with the mutators, instead of being able to run on a separate processor; the design is simplified since the programming model is sequentially consistent.

Previous incremental collectors either attempt to avoid overhead and complexity by using a non-copying approach (and are therefore subject to potentially unbounded fragmentation), or attempt to prevent fragmentation by performing concurrent copying (and therefore require a minimum of a factor of two overhead in space, as well as requiring barriers on reads and/or writes, which are costly and tend to make response time unpredictable).

Our collector is unique in that it occupies an under-explored portion of the design space for real-time incremental collectors: it is a *mostly non-copying* hybrid. As long as space is available, it acts like a non-copying collector, with the consequent advantages. When space becomes scarce, it performs defragmentation with limited copying of objects. We show experimentally that such a design is able to achieve low space and time overhead, and high and consistent mutator CPU utilization.

In order to achieve high performance with a copying collector, we have developed optimization techniques for the Brooks-style read barrier [10] using an "eager invariant" that keeps read barrier overhead to 4%, an order of magnitude faster than previous software read barriers.

Our collector can use either time- or work-based scheduling. Most previous work on real-time garbage collection, starting with Baker's algorithm [5], has used work-based scheduling. We show both analytically and experimentally that time-based scheduling is superior, particularly at the short intervals that are typically of interest in real-time systems. Work-based algorithms may achieve short individual pause times, but are unable to achieve consistent utilization.

The paper is organized as follows: Section 2 describes previ-

POPL'03, January 15–17, 2003, New Orleans, Louisiana, USA.
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Bacon *et al.*, "A real-time garbage collector with low overhead and consistent utilization". ACM Symposium on Principles of Programming Languages, New Orleans, LA, USA, January 2003. DOI: 10.1145/604131.604155

Practical Factors

- Interaction with Virtual Memory
- Garbage Collection for Weakly-Typed Languages

Practical Factors

- Two significant limitations:
  - Interaction with virtual memory
  - Garbage collection for C-like languages

- In general, garbage collected programs will use significantly more memory than (correct) programs with manual memory management
  - E.g., many of the copying collectors must maintain two regions, and so a naïve implementation doubles memory usage

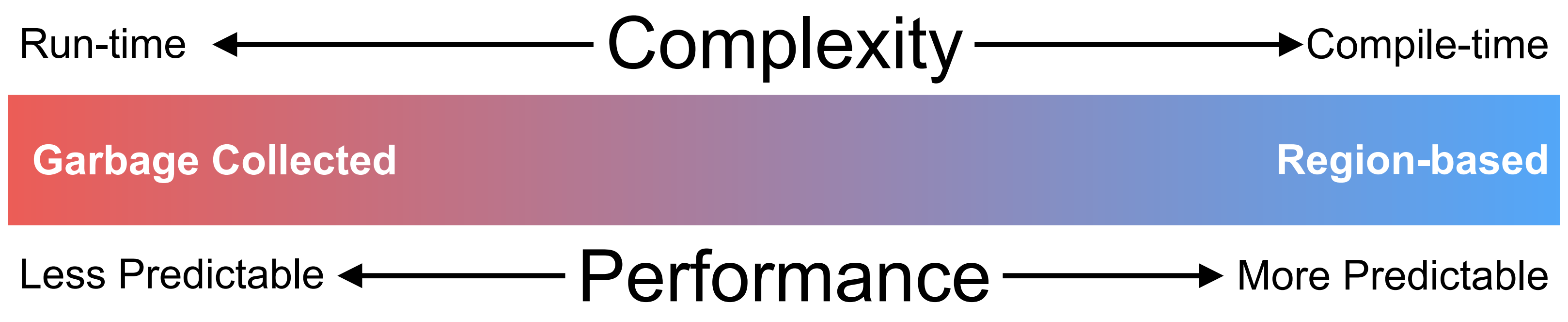
Interaction with Virtual Memory

- Virtual memory subsystems page out unused data in an LRU manner
- Garbage collector scans objects, paging data back into memory
- Leads to thrashing if the working set of the garbage collector larger than memory
    - Open research issue: combining virtual memory with garbage collector

Garbage Collection for Weakly-typed Languages

- Collectors rely on being able to identify and follow pointers, to determine what is a live object
- Weakly typed, such as C, can cast any integer to a pointer, and perform pointer arithmetic
  - Implementation-defined behaviour, since pointers and integers are not guaranteed to be the same size
- Greatly complicates garbage collection:
  - Need to be conservative: any memory that might be a pointer must be treated as one
  - The Boehm-Demers-Weiser garbage collector can be used for C and C++ (http://www.hboehm.info/gc/) – this works for strictly conforming ANSI C code, but beware that much code is not conforming

Memory Management Trade-offs



- Rust pushes memory management complexity onto the programmer
  - Predictable run-time performance, low run-time overheads
  - Uniform resource management framework, including memory
  - Limits the programs that may be expressed – matches common patterns in good C code
- Garbage collection imposes run-time costs and complexity, but simpler for the programmer

Summary

- Garbage collection
  - Mark-sweep
  - Mark-compact
  - Copying collectors
  - Generational algorithms
  - Incremental algorithms
- Real-time garbage collection
- Practical factors