Error-Free Garbage Collection Traces: How to Cheat and Not Get Caught

M. Hertz, S.M. Blackstone, K.S. McKinley,
J.E.B. Moss, & D. Stefanovic

CMPSCI TR 01-56

Error-Free Garbage Collection Traces: How to Cheat and Not Get Caught

Matthew Hertz[†] Stephen M Blackburn[†] Kathryn S. McKinley[‡]
J Eliot B Moss[†] Darko Stefanović[§]

[†] Dept. of Computer Science
University of Massachusetts
Amherst, MA 01003
{hertz,steveb,moss}@cs.umass.edu

[§] Dept. of Computer Science
University of New Mexico
Albuquerque, NM 87131
darko@cs.unm.edu

[‡] Dept. of Computer Science
University of Texas at Austin
Austin, TX, 78712
mckinley@cs.utexas.edu

ABSTRACT

Programmers are writing a large and rapidly growing number of programs in object-oriented languages such as Java that require garbage collection (GC). To explore the design and evaluation of GC algorithms quickly, researchers are using simulation based on traces of object allocation and lifetime behavior. The *brute force* method generates perfect traces using a whole-heap GC at every potential GC point in the program. Because this process is prohibitively expensive, researchers often use *granulated* traces by collecting only periodically, e.g., every 32K bytes of allocation.

We extend the state of the art for simulating GC algorithms in two ways. First, we present a systematic methodology and results on the effects of trace granularity for a variety of copying GC algorithms. We show that trace granularity often distorts GC performance results compared with perfect traces, and that some algorithms are more sensitive to this effect than others. Second, we introduce and measure the performance of a new precise algorithm for generating GC traces which is almost 100 times faster than the brute force method. Our algorithm, called Merlin, frequently timestamps objects and later uses the timestamps of dead objects to reconstruct precisely when they died. It performs only periodic garbage collections and achieves high accuracy at low cost, eliminating any reason to use granulated traces.

1. INTRODUCTION

While languages such as LISP and Smalltalk have always used garbage collection (GC), the recent explosion of people writing programs in Java and other modern languages has seen a corresponding surge in GC research. A number of studies use object lifetime traces and simulations to examine the effectiveness of new GC algorithms [11, 17]. Others use traces to tune garbage collection via profile feedback [3, 4, 10, 14]. The demand for traces is sufficient that the GC research community is discussing a standard file format to enable sharing traces [5].

Producing perfectly accurate traces is currently a very time consuming process; for many benchmarks (such as SPEC _202_jess, SPEC _213_javac, or SPEC _228_jack), the *brute force* method of producing traces can require over a month for each trace, since it performs a whole-heap collection at each allocation point. To reduce this cost, people often use *granulated* traces, which they generate by collecting after every k bytes of allocation. Unfortunately, researchers have not studied the effects of granularity on garbage collection simulations. While there has been research into better methods of approximating traces [16], the research did not study what effects these approximations have. We show here that granulated traces can produce *significantly* different results. Thus, past research based on the simulation of granulated traces may be problematic. This result also suggests a new requirement for any standard trace format: that it should include information recording the accuracy/granularity of the trace.

To address the efficiency problems of the brute force method and the accuracy problems of granulated traces, we propose the Merlin trace generation algorithm. The Merlin algorithm frequently timestamps live objects and later uses the timestamps to reconstruct the time at which the object died. Because it uses timestamps rather than collections to identify time of death, the new algorithm does not require frequent collections. Rather, it makes use of normal collections to identify *which* objects have died and then uses timestamps to identify *when* they died. Ordering the dead objects from the latest timestamp to the earliest, the algorithm works from the current time backwards. It thus determines when each object was last alive, saving it from having to process the object further. By avoiding frequent collections, the Merlin algorithm can run almost one hundred times faster than the brute force approach. It makes perfect tracing efficient and removes the need for granulated tracing.

The remainder of this paper analyzes the effects of trace granularity on GC simulation fidelity on a number of GC algorithms and then introduces the Merlin trace generation algorithm. Section 2 gives some background on garbage collection, GC traces, and trace granularity. Section 3 describes the experimental methodology we used to analyze the effects of trace granularity. Section 4 presents the results of our granularity analysis and Section 5 discusses these results. Section 6 then introduces our new trace generation algorithm and describes how it improves on the existing algorithm. Section 7 presents and analyzes results from the new tracing algorithm. Finally, Section 8 presents related studies and Section 9 summarizes

this study.

2. BACKGROUND

Three concepts are central for understanding this research: *garbage collection*, garbage collection *traces*, and garbage collection *trace granularity*.

2.1 Garbage Collection

Garbage collection automates reclamation of objects no longer needed from within the heap. While a wide variety of systems use garbage collectors, we assume a system that uses an implicit-free environment to make our explanations simpler, i.e., an explicit new command allocates objects, but there is no free command. Instead, an object is removed from the heap during a GC when the collector determines that the object is no longer reachable.

Since, without additional information, GCs cannot know which objects the program will use in the future, a garbage collector *conservatively* collects only objects it determines the program cannot reach and therefore cannot use. To determine reachability, GCs begin at a program's roots. The roots contain all the pointers into the heap, such as the program stack and static variables. Any objects in the heap not in the transitive closure of these pointers are unreachable. Since once an object becomes unreachable it is always unreachable (and cannot be updated or used), these objects can be safely removed from the heap.

In whole-heap collection, the collector determines the reachability of every object and removes all unreachable objects. Many collectors (e.g., generational collectors) often collect only part of the heap, limiting the work at each collection. Because the collector reclaims only unreachable objects, it must conservatively assume that the regions of the heap not examined contain only live objects. If objects in the unexamined region point to objects in the examined region, the target objects also remain in the heap. Since objects in the uncollected region are not even examined, collectors use *write barriers* to find pointers into the collected region. The write barriers are instrumentation invoked at every pointer store operation. A write barrier typically tests if the pointer source is in the uncollected region and the pointer target in the collected region and records such pointers in some data structure.

We assume that every pointer store is instrumented with a write barrier. In many systems this assumption is not true for root pointers, such as those in the stack. In this case, we enumerate the root pointers at each potential GC point, which is much less expensive than a whole-heap collection and can be further optimized using the techniques of Cheng et al. [4].

2.2 Copying Garbage Collection Algorithms

We use four copying garbage collection algorithms for our evaluation: a semi-space collector, a fixed-nursery generational collector [13], a variable-sized nursery generational collector [1], and an older-first collector [11]. We briefly describe each of these here for the reader who is unfamiliar with the GC literature.

A semi-space collector (SS) allocates into *to* space using a bump pointer. When it runs out of space, it collects this entire region by finding all reachable objects and copying them into a second *from* space. The collector then reverses *to* and *from* space and continues allocating. Since all objects in *to* space may be live, it must reserve half the total heap for the *from* space, as do the generational collectors that generalize this collector.

A fixed-nursery (FN) two generation collector divides the *to* space of the heap into a nursery and an older generation.[1] It allocates into the nursery. When the nursery is full, it collects the nursery and copies the live objects into the older generation. It repeats this process until the older generation is also full. It then collects the nursery together with the older generation and copies survivors into the *from* space.

A variable-size nursery collector (VN) also divides the *to* space into a nursery and an older generation, but does not fix their boundary. In steady state, the nursery is some fraction of *to* space and when it fills up, VN copies live objects into the older fraction. The new nursery size is reduced by the size of the survivors. When the nursery gets too small, VN collects all of *to* space.

The older-first collector (OF) organizes the heap in order of object age. It collects a fixed size window that it slides through the heap from older to younger objects. In the steady state and when the heap is full, OF collects the window, returns the free space to the nursery, compacts the survivors, and then positions the window for the next collection over objects just younger than those that survived. If the window bumps into the allocation point, it resets the window to the oldest end of the heap. It need only reserve space the size of a window for a collection.

2.3 Garbage Collection Traces

A garbage collection trace is a chronological recording of every object allocation, heap pointer update, and object death (object becoming unreachable) over the execution of a program. These events include all the information that a memory manager needs for its processing. Processing an object allocation requires an identifier for the new object and how much memory it needs; pointer update records include the object and field being updated and the new value; object death records define which object became unreachable. These events comprise the minimum amount of information that GC simulations need.[2]

Simulators use a single trace file to analyze any number of different GC algorithms and optimizations applied to a single program run. The trace contains all the information to which a garbage collector would actually have access in a live execution and all of the events upon which the collector may be required to act, independent of any specific GC implementation. Traces do not record all aspects of program execution. Thus, researchers can simulate a single implementation of a garbage collector with traces from any number of different languages. For these reasons, GC simulators are useful when prototyping and evaluating new ideas. Since (non-concurrent) garbage collection is deterministic, simulations can return exact results for a number of metrics. When accurate trace files are used as input, results from a GC simulator can be relied upon, making simulation attractive and accurate traces critical.

Garbage collection trace generators must be integrated into the memory manager of the interpreter or virtual machine in which the program runs. If the program is compiled into a stand-alone executable, the compiler back end must generate code for trace gen-

[1] The obvious generalization to N generations applies.

[2] While some optimizations and collectors may need additional information, it can be added to the trace file so that the majority of simulations do not need to process it. Since most GC algorithms only use this minimum amount of information, and most traces, therefore, do not include additional data, here we assume only this minimal information.

eration instead of ordinary memory management code at each object allocation point and pointer update. The trace can log pointer updates by instrumenting pointer store operations; this instrumentation is particularly easy if the language and GC implementation use write barriers, since it then simply instruments those write barriers.

A reachability analysis of the heap from the program's root set determines object deaths. The common brute force method of trace generation determines reachability by performing a whole-heap garbage collection. Since the garbage collector marks and processes exactly the reachable objects, any objects unmarked (unprocessed) at the end of the collection must be unreachable and the trace generator produces object death records for them.

For a perfectly accurate trace, we must analyze the program at each point in the trace at which a garbage collection could be invoked. For most GC algorithms, collection may be needed whenever memory may need to be reclaimed: immediately before allocating each new object, assuming only object allocation triggers GC. Thus, brute force trace generators have the expense of collecting the *entire* heap prior to allocating *each* object. If the simulated GC algorithms allow more frequent garbage collection invocations, the reachability analyses must be undertaken more often, as well. These frequent reachability analyses are also difficult because of the stress they place on the system. These frequent collections expose any errors in the interpreter or virtual machine, making it impossible to perform tracing without having all of the garbage collection and related code perfect.

2.4 Garbage Collection Trace Granularity

Given the issues that generating perfect traces raises, a common alternative is to perform the reachability analysis only periodically. Limiting the analysis to every *n* bytes of allocation makes the trace generation process faster and easier. It also causes the trace to be guaranteed accurate only at those specific points; the rest of the time it may over-estimate the set of live objects. Any simulation should assume that objects become unreachable only at the accurate points. The *granularity* of a trace is the period between these moments of accurate death knowledge.

Although trace granularity is related to time, its most appropriate unit of measurement depends on how GC is triggered. Since most collectors perform garbage collection only when memory is exhausted, the most natural measure of granularity is the number of bytes allocated between accurate points in the trace. While other measures of granularity are possible (e.g., processor time or number of allocations), they would make it difficult later to correlate the granularity with information from the trace as the values would be expressed in different units.

3. EXPERIMENTAL DESIGN

This section describes our methodology for evaluating experimentally the effect of trace granularity on simulating the four copying garbage collectors. We start by describing our simulator and programs. We then describe how to deal with granularity in simulation.

3.1 Simulator Suite

For our trace granularity experiments, we used a GC simulator suite with a front-end for Smalltalk and Java traces. In our simulator, we implemented four different garbage collection algorithms: whole-heap/semi-space (SS), fixed-nursery (FN) generational, varying-size nursery (VN) generational, and Older-First (OF) collectors, as described in Section 2.2. The first three collectors are in widespread use. For each collector we simulated eight different *to* space sizes from 1.25 to 3 times the maximum size of the live objects within the heap at .25 increments. For FN and VN we simulated each heap size with five different nursery sizes and for OF with five window sizes. These latter parameters ranged from $\frac{1}{6}$ to $\frac{5}{6}$ of *to* space, in $\frac{1}{6}$ increments.

3.2 Granularity Schemes

We designed and implemented four different schemes to handle trace granularity. Each of these schemes works independently of the simulated GC algorithm. They explore the limits of trace granularity by affecting *when* the collections occur.

3.2.1 Unsynced

When we began this research, our simulator used this naive approach to handling trace granularity: it did nothing; we call this method *Unsynced*. Unsynced simulations allow a GC to occur at any time in the trace; collections are simulated at the natural collection points for the garbage collection algorithm (such as when the heap or nursery is full). This scheme allows the simulator to run the algorithm as it is designed and does not consider trace granularity when determining when to collect. Unsynced simulations may treat objects as reachable because the object death record was not reached in the trace, even though the object is unreachable. However, they allow a GC algorithm to perform collections at their natural point, unconstrained by the granularity of the input trace.

3.2.2 Synchronized Schemes

Three other schemes, which we call *Synced* (synchronized), simulate garbage collection invocations within the trace only at points with accurate knowledge of unreachable objects. The schemes check if a garbage collection is needed, or will be needed soon, only at the accurate points and perform a collection only at these points. Figure 1 shows how each of the Synced schemes makes collection decisions. In each of these figures, the solid line is the natural collection point for the algorithm. The triangles denote points with perfect knowledge. The shaded region is as large as one granule of the trace. Each scheme performs the collection at the point in the trace with perfect knowledge within the shaded region. This point is shown by the arrow labeled G.

3.2.2.1 SyncEarly

The first scheme we call *SyncEarly*. Figure 1(a) shows how SyncEarly decides when to collect. If, at a point with perfect knowledge, the simulator determines that the natural collection point will be reached within the following period equal to one granule of the trace, SyncEarly forces a GC invocation. SyncEarly always performs a collection *at or before* the natural point is reached. SyncEarly simulations may perform extra garbage collections, e.g., when the last natural collection point occurs between the end of the trace and what would be the next point with perfect knowledge. But, SyncEarly ensures that the simulated heap will never grow beyond the bounds it is given.

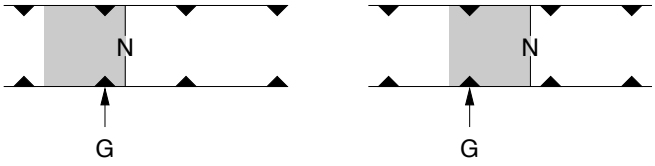
3.2.2.2 SyncLate

The second scheme is *SyncLate*. Figure 1(b) shows how SyncLate decides when to collect. At a point with perfect knowledge, if SyncLate computes that the natural collection point occurred within the preceding time of one granule of the trace, SyncLate invokes a garbage collection. SyncLate collects *at or after* the natural point is reached. SyncLate simulations may GC too few times,

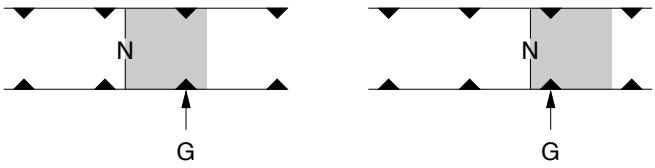
e.g., when the last natural collection point occurs between the last point with perfect knowledge and the end of the trace. SyncLate allows the heap and/or nursery to grow beyond their nominal bounds between points with perfect knowledge, but enforces the bounds whenever a collection is completed.

3.2.2.3 SyncMid

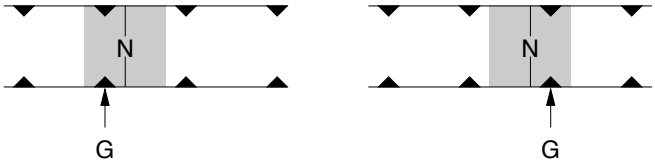
The last Synced scheme is *SyncMid*. Figure 1(c) shows how SyncMid decides when to collect. SyncMid forces a GC invocation at a point with perfect knowledge if a natural collection point is within half of the trace granularity in the past or future. SyncMid requires a collection at the point with perfect knowledge *closest* to the natural collection point. Doing this, SyncMid simulations try to balance the times they invoke collections too early and invoke collections too late to achieve results close to the average. SyncMid simulations may perform more or fewer garbage collections just like SyncEarly or SyncLate. Between points with perfect knowledge, SyncMid simulations may also require the heap and/or nursery to grow beyond their nominal bounds. However, heap bounds are still enforced immediately following a collection.



(a) SyncEarly



(b) SyncLate



(c) SyncMid

Figure 1: When Each of the Sync Schemes Decides to Collect. The triangles denote points in the trace with perfect knowledge. The natural collection point is shown as the solid line labeled N. The shaded region is as large as one granule of the trace and shows the region in which garbage collection is allowed. A GC is forced at the point in the trace with perfect knowledge within the shaded region, shown by the arrow labeled G.

4. TRACE GRANULARITY RESULTS

In this section, we present our data analysis and results.

4.1 GC Simulation Metrics

During a garbage collection simulation we measure a number of metrics: the number of collections invoked, the mark/cons ratio, the number of interesting stores, and the space-time product. Since the metrics we consider are deterministic, simulators can quite accurately return these results.

The mark/cons ratio is the number of bytes that the collector copied divided by the number of bytes allocated. The ratio serves as a measure of the amount of work done by a copying collector. Higher mark/cons ratios suggests an algorithm will need more time, because it must process and copy more objects.

Another metric we report is the number of interesting stores for a program run. Since many garbage collectors do not collect the entire heap, they use a write barrier to find pointers into the region currently collected (as we mentioned in Section 2.1). The write barrier instruments pointer store operations to determine if the pointer is one of which the garbage collector needs knowledge. The number of pointer stores, and the cost to instrument each of these, does not vary in a program run, but the number of pointer stores that must be remembered varies between GC algorithms at run time and will affect their performance.

We also measure the space-time product. While this is not directly related to the time required by an algorithm, it measures another important resource: space. This metric is the sum of the number of bytes used by objects within the heap at each time interval (allocation point) over the program run. Since the number of bytes allocated does not vary between different algorithms, this metric measures how well an algorithm manages the size of the heap throughout the program execution.

None of these metrics is necessarily sufficient in itself to determine how well an algorithm performs. Algorithms can perform better in one or more of the metrics at the expense of another. The importance of considering the totality of the data can be seen in the models developed that combine the data to determine the total time each algorithm needs [11].

4.2 GC Traces

We used 15 GC traces in this study. Nine of the traces are from a compiler and run-time system for Java in which we implemented our trace generator. The nine Java traces are: bloat-bloat (bloat [9] using its own source code as input), two different configurations of Olden health (5 256 and 4 512), and SPEC compress, jess, raytrace, db, javac, and jack. We also have six GC traces from a bytecode-interpreted virtual machine for Smalltalk. The Smalltalk traces are: lambda-fact5, lambda-fact6, tomcatv, heapsim, tree-replace-random, and tree-replace-binary. More information about the traces appears in Table 1.

We implemented a filter that takes perfect traces and a target value and outputs traces with the targeted level of granularity. We first generated perfectly accurate traces for each of the programs and then our filter generated 10 versions of each trace with granularity ranging from 1KB to 64KB and 512KB to 2048KB. Then our simulator used the perfect and granulated traces as input.

4.3 Analysis

We began by simulating all combinations of program trace, trace granularity, granularity scheme, GC algorithm, *to* space and nursery (window) size. We record the four metrics from above for each

Program	Description	Max. Live (in bytes)	Total Alloc (in bytes)
bloat-bloat	Bytecode-Level Optimization and Analysis Tool 98 using its own source code as input	3 207 176	164 094 868
Olden Health (5 256)	Columbian health market simulator from the Olden benchmark suite, recoded in Java	2 337 284	14 953 944
(4 512)		1 650 444	9 230 756
SPEC _201_compress	Repeatedly compresses and decompresses 20MB of data using the Lempel-Ziv method. From SPECJVM98.	8 144 188	120 057 332
SPEC _202_jess	Expert shell system using NASA CLIPS. From SPECJVM98.	3 792 856	321 981 032
SPEC _205_raytrace	Raytraces a scene into a memory buffer. From SPECJVM98.	5 733 464	154 028 396
SPEC _209_db	Performs series of database functions on a memory resident database. From SPECJVM98.	10 047 216	85 169 104
SPEC _213_javac	Sun's JDK 1.0.4 compiler. From SPECJVM98.	11 742 640	274 573 404
SPEC _228_jack	Generates a parser for Java programs. From SPECJVM98.	3 813 624	322 274 664
lambda-fact5	Untyped lambda calculus interpreter evaluating expression 5! in the standard Church numerals encoding	25 180	1 111 760
lambda-fact6	Untyped lambda calculus interpreter evaluating expression 6! in the standard Church numerals encoding	54 700	4 864 988
tomcatv	Vectorized mesh generator	126 096	42 085 496
heapsim	Garbage collected heap simulator	549 504	9 949 848
tree-replace-random	Builds a binary tree then replaces random subtrees at a fixed height with newly built subtrees	49 052	2 341 388
tree-replace-binary	Builds a binary tree then replaces random subtrees with newly built subtrees	39 148	818 080

Table 1: Traces Used in the Experiment

gc num	alloc b	alloc o	copy b	copy o	xcopy b	xcopy o	garbge b	garbge o	mark/con	xcp/cp	mut. i/s	gc i/s
6	5 221 236	148 532	1 098 480	27 504	268 088	5 558	3 770 048	121 022	0.210 387	0.244 054	14 243	0
10	9 230 756	353 094	1 552 152	48 481	284 404	6 379	6 622 732	278 931	0.168 150	0.183 232	40 675	0

(a) Perfect Trace

gc num	alloc b	alloc o	copy b	copy o	xcopy b	xcopy o	garbge b	garbge o	mark/con	xcp/cp	mut. i/s	gc i/s
6	4 787 328	125 037	1 443 608	32 306	355 768	7 173	2 824 328	92 722	0.301 548	0.246 444	11 644	0
11	9 230 756	353 094	200 7252	58 368	375 464	8 164	6 392 528	290 239	0.217 453	0.187 054	41 949	0

(b) SyncMid With 1KB Granularity

Figure 2: Simulator Output From A Fixed-Sized Nursery Simulation of Health (4, 512). The top lines are the metrics after six collections, when the differences first become more clear; the bottom lines are the final results of the simulation.

combination. Figure 2 shows an example of the simulator output. With this large population of data (approximately 600 simulations for each GC/granularity scheme combination), we perform a detailed statistical analysis of the results. For this analysis, we remove any simulation that required fewer than 10 garbage collections. In simulations with few GCs, the addition or removal of a single collection can create dramatically different effects and furthermore the garbage collector would rarely make a difference in the actual time required for these actual program runs. For these reasons, these results would rarely be included in an actual implementation study either. We also remove any simulation where the trace granularity equaled 50% or more of the simulated *to* space size, since trace granularity would obviously impact these results. We felt secure in pruning these cases, as the data would only bolster our claims that granularity is important. In addition, we only include simulations where both the perfect trace and the granulated trace completed. Occasionally, simulations of the granulated trace would complete merely because the simulator expanded the heap and delayed collection until an accurate point. There were also simulations of granulated traces that were not able to finish because garbage collection was invoked earlier than normal, causing too many objects to be promoted. Because any metrics generated from simulations that did not finish would be incomplete, we did not include them in our analysis. The number of experiments we used is listed in Table 2.

With the remaining data, we normalize the results of each granulated trace simulation to the results from the same simulation configuration using a perfect trace. Because we are concerned with the percentage difference, we use the logarithm of this ratio. If granulated traces have no effect, we would expect all results to equal 0. For each metric and combination of garbage collector and granularity scheme we performed two-tailed t-tests to see if the results from perfect and granulated traces were different. The two tailed t-test determines the confidence that the population mean of a metric from granulated simulations is different than the population mean of the metric from simulations using perfect data, assuming the populations are normally distributed [8]. We considered differences to be significant only when they existed at the 95% confidence level or higher (p=0.05). Table 3 shows the smallest granularity, in kilobytes, at which we were able to observe a statistically significant difference.

Programs with smaller *to* space and nursery (window) sizes, will obviously be less able to handle trace granularity. Just as we removed simulations where the granularity was over half of *to* space size, we also re-ran our analysis using only those traces that, at some point, had enough live objects to equal the largest trace granularity. The excluded programs are small enough that the brute force algorithm can generate perfect traces in under 8 hours. The

	Unsynced				SyncLate				SyncEarly				SyncMid			
Granularity	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF
1 024	89	244	196	415	89	255	205	433	89	254	205	434	89	255	205	434
2 048	88	240	192	414	89	254	205	434	89	254	205	434	89	254	205	436
4 096	88	241	195	406	89	254	205	431	89	254	205	432	89	255	202	435
8 192	88	246	197	400	89	256	205	433	89	255	204	433	89	256	205	431
16 384	85	217	173	390	89	254	205	429	89	255	204	426	89	255	204	432
32 768	76	198	149	353	81	246	197	405	81	246	197	397	81	246	197	404
65 536	62	175	130	298	64	210	161	331	64	211	162	325	64	211	162	331
524 288	46	130	98	206	46	158	117	228	46	152	116	218	46	159	118	228
1 048 576	43	120	89	182	46	159	118	229	45	155	117	217	46	160	118	228
2 097 152	39	102	72	156	45	151	115	205	45	147	112	197	45	150	115	207

Table 2: Number of Usable Simulations By Granularity, Simulation Method, And Granularity

	Unsynced				SyncLate				SyncEarly				SyncMid			
	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF
Mark/Cons	1	1	1	1	1	8	16	4	1	1	4	4	none	1	none	1
Space-Time	1	1	1	1	1	1	1	2	1	1	1	1	none	1	2	1
Num. of GCs	1	1	16	1	1	1	1	1	1	1	4	4	none	1	16	1
Int. Stores	n/a	16	16	1	n/a	2	4	8	n/a	2	8	4	n/a	32	16	none

Table 3: Earliest Granularity (in KB) At Which Each Metric Becomes Significantly Different, By Simulation Method And Collector.

	Unsynced				SyncLate				SyncEarly				SyncMid			
Granularity	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF
1 024	46	141	110	200	46	151	117	219	46	151	117	218	46	151	117	220
2 048	46	141	110	198	46	151	117	220	46	151	117	218	46	151	117	220
4 096	46	140	110	197	46	151	117	220	46	151	117	218	46	151	117	220
8 192	46	141	109	197	46	151	117	220	46	151	116	218	46	151	117	218
16 384	46	140	108	197	46	150	117	219	46	151	116	214	46	151	116	220
32 768	46	137	105	197	46	151	117	220	46	151	117	214	46	151	117	220
65 536	46	135	105	197	46	150	116	220	46	151	117	214	46	151	117	220
524 288	46	123	98	197	46	149	116	219	46	143	115	209	46	150	117	219
1 048 576	43	113	89	177	46	150	117	220	45	146	116	208	46	151	117	219
2 097 152	39	98	72	155	45	147	115	204	45	143	112	196	45	146	115	206

Table 4: Number of Usable Simulations From Traces With A Maximum Live Size of 2MB Or More, By Granularity, Simulation Method and Collector

	Unsynced				SyncLate				SyncEarly				SyncMid			
	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF	SS	FN	VN	OF
Mark/Cons	1	1	4	32	32	1	1024	16	8	512	none	8	none	512	none	64
Space-Time	4	1	512	1	16	1	512	512	1	1	512	2	1	1	512	32
Num. of GCs	32	1	512	16	16	1	64	8	64	1	512	8	none	1	512	1024
Int. Stores	n/a	512	2098	512	n/a	16	1024	16	n/a	32	1	8	n/a	16	1	none

Table 5: Earliest Granularity (in KB) At Which Each Metric Becomes Significantly Different, By Simulation Method And Collector. This table only considers data from traces with a maximum live size of of 2MB or more

traces remaining in this analysis are those for which brute force tracing would need to generate granulated traces. The number of remaining simulations can be seen in Table 4. The results of this analysis are shown in Table 5.

5. TRACE GRANULARITY DISCUSSION

The data in Table 3 are quite revealing about the effects of trace granularity and the usefulness of the different schemes in handling granulated traces. From this data it is clear that the use of granulated traces distorts GC performance results, compared with perfect traces. For a majority of the metrics, a granularity of only one kilobyte is enough to cause this distortion! Clearly, trace granularity significantly affects the simulator results.

5.1 Unsynced Results

Unsynced collections dramatically distort the simulation results. In Table 3, two collectors (semi-space and older-first) have statistically significant differences for every metric at the 1KB granularity. In both cases, the granulated traces copied more bytes, needed more GCs, and used more space. For both collectors the differences were actually significant at the 99.9% confidence level or higher. The generational collectors did not fare much better. Both collectors saw granulated traces producing significantly higher mark/cons ratios than the perfect traces. As one would expect, these distortions grew with the trace granularity. In Unsynced simulations, collections may come at inaccurate points in the trace; the garbage collector must process and copy objects that are reachable only because the trace has not reached the next set of death records. Once copied, these objects increase the space-time product and cause the heap to be full sooner, thus require more frequent GCs. This process quickly snowballs, so that even small granularities produce significant differences. Only the number of interesting stores for the generational collectors and the number of collections required for the variable-sized nursery collector are not immediately affected. As There are not significantly more pointers from the older generation to the nursery because Unsynced collections tend to promote objects that are truly unreachable and, therefore, do not have any pointer updates.

We expect simulations using larger heaps to be less affected by these issues. The results in Table 5 show that this is true. The space-time product and mark/cons results for the semi-space collector show that objects are staying in the heap longer. For variable-sized nursery simulations, however, we do not see a significant increase in the number of collections; the extra objects require the collector to perform more whole-heap collections and not just nursery collections. Therefore each collection does more work: the number of collections remains similar to results with perfect traces by producing a significantly higher mark/cons ratio. No matter the collection algorithm, Unsynced simulations clearly distort the results. This result suggests a new requirement for the trace file format: it should clearly label the points in the trace with perfect knowledge.

5.2 Synced Results

Synced simulations tend to require slightly higher granularities than Unsynced before producing significant distortions. However, every Synced scheme significantly distorts the results for each metric for at least one collector. Examining the results from Table 3 and Table 5, reveals a few patterns. Considering all the traces, SyncEarly and SyncLate still produce differences from simulations using perfect traces, but slightly larger trace granularities may be required before the differences become statistically significant. SyncMid has several cases where significant distortions do not appear, but this result is both collector- and metric-dependent. In addition, there are still statistically significant distortions at traces with granularities as small as 1KB. In Table 5, when only considering traces with larger maximum live sizes, Synced simulations provide better estimates of the results from simulating perfect traces. But, there still exist significant differences at fairly small granularities.

Because Synced simulations only affect when the collections occur, they do not copy unreachable objects because the object deletion record has not been reached. Instead, adjusting the collection point causes other problems. Objects that are allocated and those whose death records should occur between the natural collection point and the Synced collection point are initially affected. Depending on the Synced scheme, these objects may be removed from the heap or processed and copied earlier than in a simulation using perfect traces. Once the heap is in error (containing too many or too few objects), it is possible for the differences to be compounded as the Synced simulation may collect at points even further away (and make different collection decisions) than the simulation using perfect traces. Just as with Unsynced simulations, small initial differences can snowball.

5.2.1 SyncEarly

SyncEarly simulations *tend* to decrease the space-time products and increase the number of GCs, interesting stores, and mark/cons ratios versus simulations using perfect traces. At smaller granularities, the fixed-nursery generational collector produces higher space-time products. Normally, this collector copies objects from the nursery because they have not had time to die before collection. SyncEarly exacerbates this situation, collecting even earlier and copying more objects into the older generation than similar simulations using perfect traces. As trace granularity grows, however, this result disappears (the simulations still show significant distortions, but in the expected direction) because the number of points in the trace with perfect knowledge limits the number of possible GCs.

5.2.2 SyncLate

In a similar, but opposite manner, SyncLate simulations *tend* to decrease the mark/cons ratio and number of collections. As trace granularity increases, these distortions become more pronounced as the number of potential collection points begins to limit the collectors as well. Not every collector produces the same distortion on the same metric, however. The fixed-nursery generational collector produces significantly higher mark/cons ratios and more garbage collections at small granularities. While SyncLate simulations allow it to copy fewer objects early on, copying fewer objects causes the collector to delay whole-heap collections. The whole-heap collections remove unreachable objects from the older generation and prevent them from forcing the copying of other unreachable objects in the nursery. The collector eventually promotes more and more unreachable objects, so that it often must perform whole-heap collections soon after nursery collection, boosting both the mark/cons ratio and the number of GCs.

5.2.3 SyncMid

The best results we found are for SyncMid. From Table 5, the larger *to* space sizes produce similar results for SyncMid simulations and simulations using perfect traces at even large granularities. The design of SyncMid tries to balance the times that it collects too early with those times it collects too late. As a result, it tends to balance

collections distorting the results in one direction and collections distorting results in the other. While this is a benefit, it also makes the affects of trace granularity hard to predict. Both SyncEarly and SyncLate showed collector-dependent behavior. While we showed that it would not be sound to base conclusions for a new or unknown collector from their results, one could make an assumption about their effect on the metrics. SyncMid simulations, by comparison, produced biases that were dependent upon both the metric and collector. When significant differences occur, it is not clear in which way the metric will be skewed. While the results were very good on the whole, there is still not a single metric for which every collector returned results without statistically significant distortions.

5.3 Trace Granularity Conclusion

From this research, it is clear that trace granularity has a significant impact on the simulated results of garbage collection algorithms. While Unsynced simulations clearly caused distortions, the SyncMid scheme allowed the use of traces with small granularities to be simulated without significant differences. However, all of the Synced simulations suffer from statistically significant deviations and there are no clear patterns that predict when and how each metric will be distorted. When using traces to compare and measure new GC algorithms and optimizations, there is not a clear way to use granulated traces and have confidence that the results are valid.

6. MERLIN TRACE GENERATION

Life can only be understood backwards; but it must be lived forwards.

—Søren Kierkegaard We present our new *Merlin Trace Generation Algorithm* which generates perfect traces up to one hundred times faster than the dominant brute force method of trace generation. Given the speed with which it can generate perfect traces, the Merlin algorithm removes the need to use granulated traces and avoids the issues that their use can cause.

The Merlin algorithm has other advantages over brute force trace generation. As discussed in Section 2.4, implementing the latter algorithm is difficult. For brute force to work, all GC and GC-affecting code must be *completely* error-free and the system must support semi-space garbage collection. Our new trace generator can work with almost any garbage collection algorithm and stresses the system less.

According to Arthurian legend, the wizard Merlin began life as an old man. He then lived backwards in time, dying at the time of his birth. Merlin's knowledge of the present was based on what he had already experienced in the future. The Merlin tracing algorithm works in a similar manner. Because it computes when each object died backwards in time, the first time the Merlin trace generation algorithm encounters an object in this calculation is the time of the object's death; any other possible death times would be earlier in the running of the program (but later in Merlin's processing), and need not be considered. Merlin, both the mythical character and our trace generator, works in reverse chronological order so that each decision, once made, never has to be revisited.

This section describes the Merlin trace generation algorithm in more detail. It begins by explaining how objects become unreachable and how this information can be used to compute object death times. We then give the pseudo-code for Merlin's death time computations. The method of finding object allocations and pointer updates does not change much, but we describe how this works with the Merlin algorithm.

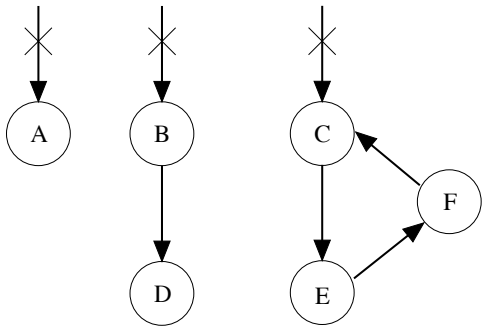


Figure 3: Objects A and B each become unreachable when their last incoming reference is removed. Object C becomes unreachable when a pointer update removes an incoming reference, even though it has others. Objects D, E, and F become unreachable without losing an incoming reference.

6.1 Object Deaths

The advantage of working backward in time is that object deaths are easier to discover. As discussed in Section 2.3, finding which objects are dead requires computing a reachability analysis. Our new algorithm cannot change this requirement. Instead, it improves on the previous brute force method by doing only a small amount of work at each point where the trace must be accurate and allowing less frequent GCs during trace generation. As we will see, it still determines object deaths and death times in periodic batches, but the death times that it computes are accurate.

6.1.1 How Objects Become Unreachable

To understand how the Merlin algorithm is able to delay death time computation, it is important to understand how objects become unreachable. Table 6 is a series of generalizations about how objects within the heap become unreachable.

1. An object transitions from one to zero incoming references via a pointer update. Objects A and B in Figure 3 are examples of this case.
2. An object transitions from n to $n-1$ incoming references via a pointer update, where all $n-1$ references are from unreachable objects. An example of this case is object C in Figure 3.
3. An object's number of incoming references does not change, but all the reachable objects pointing to it become unreachable. The objects labeled D, E, and F in Figure 3 are examples of this case.

Table 6: How Objects Become Unreachable

Entries 1 and 2 of this table describe an object becoming unreachable due to an action involving that object; entry 3 describes an object becoming unreachable without it being involved in an action, but because the objects that point to it become unreachable. These objects may in turn have become unreachable by this third method. At the beginning of this process though, an object must become unreachable because of a pointer store. Clearly, not all pointer stores

lead to the death of an object; any object that does become unreachable because of a pointer store must be in the transitive closure set of the object that lost an incoming reference.

6.1.2 Object Death Time

Using knowledge of how objects become unreachable allows trace generators to separate finding *when* objects become unreachable from *whether* an object is unreachable. This division potentially saves trace generators substantial amounts of work, but requires the introduction of *time* into trace generation. In brute force trace generation, a death record is appended to the trace when an object is found to be unreachable. Therefore whenever objects could be dead, the trace generator must find which objects are unreachable. Separating object death time from finding which objects are unreachable removes the need for this constant processing. It also means that objects' death times often will not be the current point in the trace. Where in the trace to add these death records is specified by the object's death time. Time is related to trace granularity; time must advance wherever object death records are expected: at the points in the trace with perfect knowledge.

6.1.3 Finding Potential Object Death Times

Knowing how objects become unreachable and using the concept of time, is is now possible to find object death times. Since it is not always clear if a pointer store leaves an object unreachable (if a pointer update leaves an object with no incoming references, it is clear the object is unreachable; if an update leaves an object with n remaining incoming references, it may not be clear if the object is unreachable), we devise an algorithm that finds death times without knowing which event actually causes an object to become unreachable. We consider below the different methods by which objects become unreachable.

6.1.3.1 Instrumented Pointer Stores

Most pointer stores will be instrumented by a write barrier. Objects may become unreachable when a pointer store, caught by a write barrier, removes an incoming reference. To find these object death times, the pointer store instrumentation must know which object is losing an incoming reference (the old target of the pointer). The Merlin trace generator stamps the old target object with the current time. Time increases monotonically; each object will therefore be stamped with the final time it loses an incoming reference. If the last incoming reference is removed by an instrumented pointer store, the code shown in Figure 4 stamps the object with its death time.

6.1.3.2 Uninstrumented Pointer Stores

For objects that become unreachable in other ways more work is required. Pointer stores within the heap need to be instrumented (e.g., using a write barrier) for accurate tracing. As discussed in Section 2.1, root pointers may not have their pointer stores instrumented in write barriers, and an object may become unreachable in a manner the prior method could not discover. Just as a normal GC begins with a root scan, each time the trace must be accurate, our trace generator performs a modified root scan. This modified root scan still enumerates the root pointers, but merely stamps the root-referenced object with the current time. While root-referenced, objects are always stamped with the current time; when the object is no longer root-referenced, the timestamp will hold the last time it had an incoming reference from the root set. If the last incoming reference is removed by an uninstrumented pointer store, the object will be stamped with its death time. Figure 5 shows Merlin's pseudo-code executed whenever the root scan finds a pointer.

6.1.3.3 Referring Objects Become Unreachable

Even more work is required to determine the death time of an object that becomes unreachable when the objects pointing to it become unreachable (entry 3 of Table 6). This case requires us to know when each of the objects holding pointers to it became unreachable. The possibility that these other objects became unreachable by the same means exacerbates this difficulty. Since there could exist cycles of these objects, updating the death time for one object can require recomputing the death times of objects to which it points. By computing the transitive closure set for each object, we can find the object with the latest death time pointing to each of these objects.

Because the Merlin algorithm is concerned with *when* an object became unreachable and cannot always determine *how* the object became unreachable, the issue is to find a single method that computes every object's death time. The methods from Paragraphs 6.1.3.1 and 6.1.3.2 will stamp objects that become unreachable as described in entries 1 and 2 of Table 6 with their death time. As each object is a member of its own transitive closure set, Merlin can determine the death time of every object by combining the two timestamping methods with computing death times by membership in transitive closure sets.

No object points to an object that became unreachable as described by entry 1 of Table 6 when the latter object becomes unreachable. Thus, the latter object will only be a member of its own transitive closure set and the death time is its timestamp. The death time computed for an object that becomes unreachable via entry 2 of Table 6 will also be the time with which it is stamped. Immediately after its timestamp was last updated, the object was unreachable. Since any object that pointed to the initial object must also have been unreachable, the pointing objects could not have later death times. Thus, the transitive closure computation will determine the object died at the time with which it is already stamped. Since we shown above that this combined method computes death times for objects that become unreachable by entry 3 of Table 6, Merlin can compute every object death time and need not know how each object becomes unreachable.

6.1.4 Computing When Objects Become Unreachable

Computing the full transitive closure is a time consuming process, requiring $O(n^2)$ time. But finding an object's death time requires knowing only the *latest* object containing the former object in its transitive closure set. Rather than formally computing the transitive closure sets, Merlin performs a depth-first search from each object, propagating the death time forward to the objects visited in the search. To save time, Merlin begins by ordering the objects from the earliest timestamp to the latest and then pushing them onto search's stack. Figure 6(a) shows this initialization. Upon removing an object from the stack, the Merlin algorithm analyzes its fields to find pointers to other objects. If a pointed-to object could be unreachable and is stamped with an earlier time than the referring object, then the pointed-to object is stamped with this later time and pushed onto the stack (e.g., Figure 6(b) and 6(c)). If a pointed-to object's time were equal to that of the referring object, then either we have found a cycle (e.g., Figure 6(d)) or the pointed-to object is already on the stack to propagate this time. Either way, the pointed-to object does not need to be pushed on the stack. If a pointed-to object's time were later, then the object remained reachable after

```
void PointerStoreInstrumentation(ADDRESS source, ADDRESS newTarget) {
  ADDRESS oldTarget = getMemoryWord(source);
  if (oldTarget ≠ null) {
    oldTarget.timeStamp = currentTime;
  }
  addToTrace(pointerUpdate, source, newTarget);
}
```

Figure 4: Code for Merlin's Pointer Store Instrumentation

```
void ProcessRootPointer(ADDRESS rootAddr) {
  ADDRESS rootTarget = getMemoryWord(rootAddr);
  if (rootTarget ≠ null) {
    rootTarget.timeStamp = currentTime);
  }
}
```

Figure 5: Code for Merlin's Root Pointer Processing

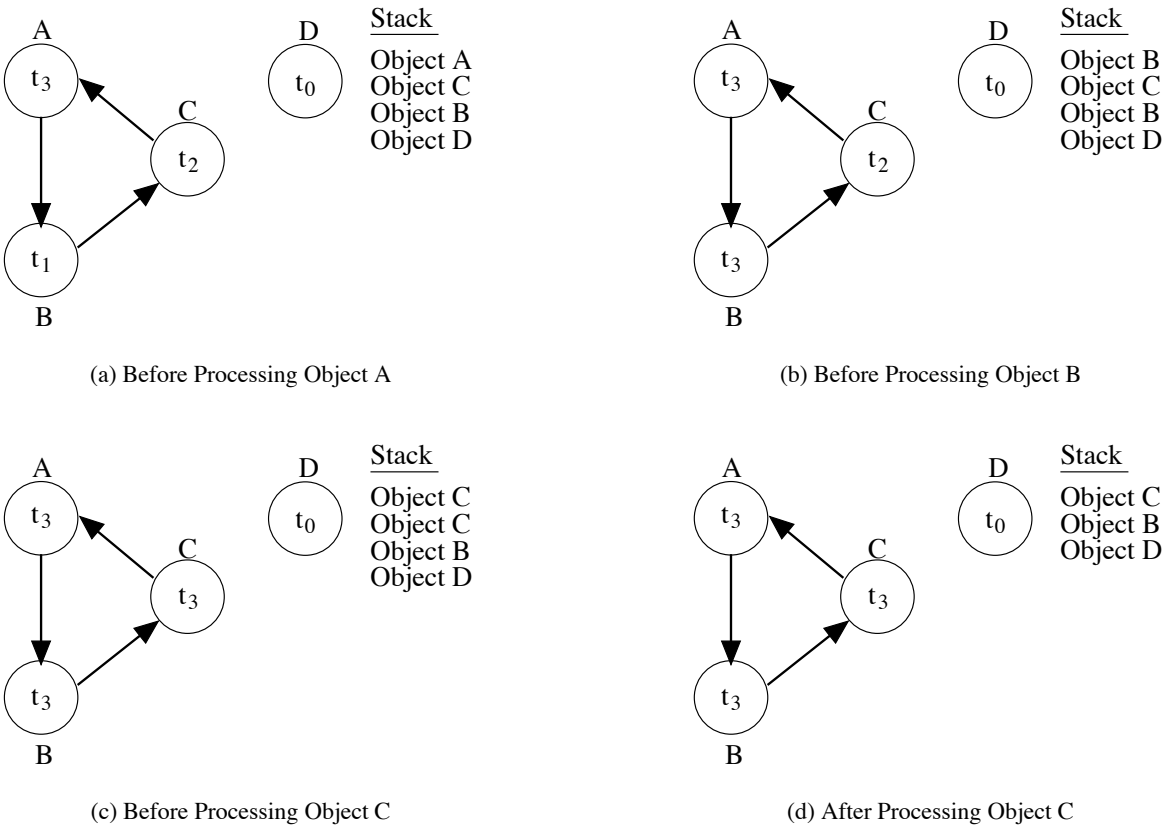


Figure 6: Computing Object Death Times, where $t_i < t_{i+1}$. Since Object D doesn't have any incoming references, Merlin's computation cannot change its timestamp. Although Object A became unreachable at its timestamp, case is needed not to change this incorrectly via its incoming reference. In (a), Object A is processed finding the pointer to Object B. Object B's timestamp is earlier, so Object B is added to the stack and death time set. We process Object B and find the pointer to Object C in (b). Object C has an earlier timestamp, so it is added to the stack and timestamp updated. In (c), Object C is processed. Object A is pointed to, but it does not have an earlier timestamp and is not added to the stack. In (d), the cycle has finished being processed. The remaining objects in the stack will be examined, but no further processing is needed.

```
void ComputeObjectDeathTimes() {
  Time lastTime = ∞
  sort unreachable objects from the earliest timestamp to the latest;
  push each unreachable object onto a stack in sorted order;
  while (!stack.empty()) {
    Object obj = stack.pop();
    Time objTime = obj.timeStamp;
    if (objTime <= lastTime) {
      lastTime = objTime; {
      for each (field in obj) {
        if (isPointer(field) && obj.field ≠ null) {
          Object target = getMemoryWord(obj.field);
          Time targetTime = target.timeStamp;
          if (isUnreachable(target) && targetTime < lastTime) {
            target.timeStamp = lastTime;
            stack.push(target);
          }
        }
      }
    }
  }
}
```

Figure 7: Code of Merlin Trace Generation Object Death Computation

the time being propagated and this possible death is unimportant. Pushing objects onto the stack from the earliest stamped time to the latest means each object is processed only once. The search proceeds from the latest stamped time to the earliest; a repeat visit to an object is computing an earlier death time! This method of finding death times requires only $\Theta(n \log n)$ time, the sorting of the objects now being the limiting factor. Figure 7 shows the code the Merlin algorithm uses for this modified depth-first search.

6.2 The Merlin Trace Generator

As described so far, Merlin is able to reconstruct *when* objects become unreachable. However, it is unable to determine *which* objects are unreachable; it still needs a reachability analysis. The Merlin algorithm uses two simple solutions to overcome this. Whenever possible, it delays computation until immediately after garbage collection. Before any memory is cleared, the trace generation algorithm has access to objects within the heap *and* the garbage collector's reachability analysis. This piggy-backing saves a lot of duplicative analyses. At other times (e.g., when a program terminates), garbage collection may not be invoked but the algorithm needs a reachability analysis. We first stamp the root-referenced objects with the current time and then compute the death times of every object in the heap. Objects with a death time equal to the current time must be reachable from the program roots and therefore are still alive. All other objects are unreachable and their death records are added to the trace. This method of finding unreachable objects enables the Merlin algorithm to work with any garbage collector. Even if the garbage collector cannot guarantee that it will collect all unreachable objects, when the program terminates Merlin performs the combined object reachability/death time analysis to find any remaining unreachable objects and their death times.

As stated in Section 2.1, we rely upon a couple of assumptions about the host GC. First, that any unreachable object the GC is treating as live will have the objects it points to treated as live, as is common among many GC algorithms. Thus no object is removed from the heap until all objects pointing to it are removed. Second, the Merlin algorithm assumes that there are no pointer stores involving an unreachable object. Therefore, we assume that once an object becomes unreachable, its incoming and outgoing references are constant. Both of these preconditions are important for our transitive closure computation, and languages such as Java and Smalltalk satisfy them.

The order in which the Merlin trace generator adds information to the trace is an issue. As discussed in Section 6.1.2, our trace generator needs the concept of time to determine where in the trace each object death record should be placed. The object death records either must be added back into chronological order before writing the trace to disk or can be appended to the trace and a post-processing step places the trace into proper order. Holding all the trace records in memory until all object deaths are found is a difficult challenge; with larger traces holding these records can require significant amounts of memory. Our implementation of the Merlin algorithm uses a post-processing step that sorts and integrates the object death records. This solution creates a different problem, that of splitting and recreating the trace, but this latter problem is much easier to solve. Either way of handling this issue has advantages and disadvantages, but adds very little time to trace generation.

6.3 Object Allocations and Pointer Updates

Trace generation is already efficient at finding and reporting object allocations and pointer updates. As discussed in Section 2.3, even the brute force method of trace generation can find and record these actions in linear time. Our new algorithm, like those before it, instruments the host system's memory manager to determine when memory is allocated for new objects. At those times, Merlin records the ongoing object allocation.

Finding and reporting pointer updates also does not change. Like brute force trace generation, the Merlin algorithm instruments the heap pointer store operations (preferably by augmenting existing

write barriers). Our new trace generation algorithm does add an additional requirement, the reasons for which are explained in Section 6.1.3. Unlike brute force, our trace generator requires access to the object being updated, the new value of the pointer, and the old value of the pointer. As many write barriers are already implemented to access these values (e.g., a write barrier capable of reference counting), this additional requirement is not a hardship. Allowing our trace generator to work with almost any garbage collector (rather than requiring a semi-space collector) makes the instrumentation to record pointer updates easier to add. While a semi-space collector does not require a write barrier (although different languages/systems may), many algorithms (e.g., generational and OF collectors) do. Combining our trace generator with these algorithms allows the use of the preexisting write barriers, enabling the Merlin trace generator to leverage already existing code.

7. EVALUATION OF THE MERLIN TRACE ALGORITHM

We implemented both Merlin and the brute force trace algorithm within a Java virtual machine. We then performed some initial timing runs on a Macintosh Power Mac G4, with two 533 MHz processors, 32KB on-chip L1 data and instruction caches, 256KB unified L2 cache, 1MB L3 off-chip cache and 384MB of memory, running PPC Linux 2.4.3. We used only one processor for our experiments, which were run in single-user mode with the network card disabled. We built two versions of the JVM, one for each of the algorithms. Whenever possible we used identical code for the two JVMs, so Merlin used a semi-space collector.

We generated traces at different granularities across a small range of programs. Because of the time required for brute force trace generation, we limited some traces to only the initial few megabytes of data allocation. Working with common benchmarks and generating traces of identical granularity, Merlin achieved speedup factors of up to 94. In the time that brute force needed to generate traces with 4 to 16KB of granularity, Merlin generated perfect traces. Figure 8 shows the speedup Merlin, generating perfect traces, achieves over the brute force algorithm generating traces at different levels of granularity.

Clearly, Merlin can greatly reduce the time needed to generate a trace. However, as seen in Figure 8, the speedup is less as granularity increases. The time required depends on the time needed to generate object death records and, therefore, on trace granularity. Brute force limits object death time processing to only when the trace must be accurate; as the granularity increases the time needed greatly diminishes. While Merlin needs to perform only periodic collections, it also must perform a small set of actions at each pointer update and location in the trace with perfect knowledge. Even with brute force performing more frequent GCs, the cost of Merlin's frequent root enumerations and updating timestamps becomes too great.

These results are promising, but we can speed up performance of the Merlin tracing algorithm even more. As program's memory footprint grows, and as more accurate points are needed, the Merlin algorithm is far less affected than brute force. Using larger traces would better show these differences. We also have not implemented several known GC optimizations. Because Java only allows functions to access their own stack frame, repeated scanning within the same method always enumerates the same objects below this method's frame. Using a write barrier that is called when frames are popped off the stack would enable Merlin to scan the stack less and further reduce the time needed for Merlin tracing [4].

8. RELATED WORK

We do not know of any previous research into the effects of trace granularity or different methods of generating garbage collection traces. In this section, we discuss the research from which this study draws its roots.

Using Knowledge of the Future

Belady's [2] optimal virtual memory page replacement policy, MIN, decided which blocks should not be paged to disk by analyzing future events. At each decision point, the MIN algorithm considers future memory accesses, stored within an available file, until it determines the single block to evict. Because the algorithm did not cache results, at each decision point the MIN algorithm begins a new analysis. While Belady's algorithm used knowledge of future events to perform optimally, it processes events in chronological order. Each time it is invoked, the MIN algorithm only looks far enough into the future as is necessary to make the current decision.

Cyclic Reference Counting

One of the earliest methods of garbage collection was to use reference counts: each object has a count of its incoming references so, when the count reaches 0, the object can be freed [6]. McBeth was the first to appreciate that this approach cannot collect cycles of objects, since the reference counts would never reach zero [7]. Many different schemes have been developed to deal with cycles. Trial deletions [15] collects cycles of objects by removing a pointer thought to be within a cycle. After removing the pointer, trial deletion updates the reference counts. If, in updating the reference counts, the source object for the removed pointer is found unreachable, then a cycle exists and the objects are dead. Otherwise a dead cycle may not exist, the deleted pointer is reestablished and the original reference counts restored. This method can handle and detect cycles, but it may incorrectly guess that some objects are in a cycle and cannot take advantage of other object reachability analyses.

Lifetime Approximation

To cope with the cost of producing GC traces, there has been previous research into approximating the lifetimes of objects. These approximations model the object allocation and object death behavior of actual programs. One described mathematical functions that model object lifetime characteristics based upon the actual lifetime characteristics of 58 Smalltalk and Java programs [12]. Zorn and Grunwald compare several different models one can use to approximate object allocation and object death records of actual programs [16]. Neither study attempted to generate actual traces, nor does either study consider the effects of pointer updates; rather, these studies attempted to find ways other than trace generation to produce input for memory management simulations.

9. SUMMARY

The use of granulated traces for garbage collection simulation raises a number of issues. We first develop a method by which any variable that affects garbage collection simulations can be statistically tested. We then use this method to show that over a wide range of variables, granulated traces produce results that are significantly different from those produced by perfect traces. Additionally, we show that there are ways of simulating granulated traces that are better at minimizing these issues. With these results, we propose several changes to the trace format standard.

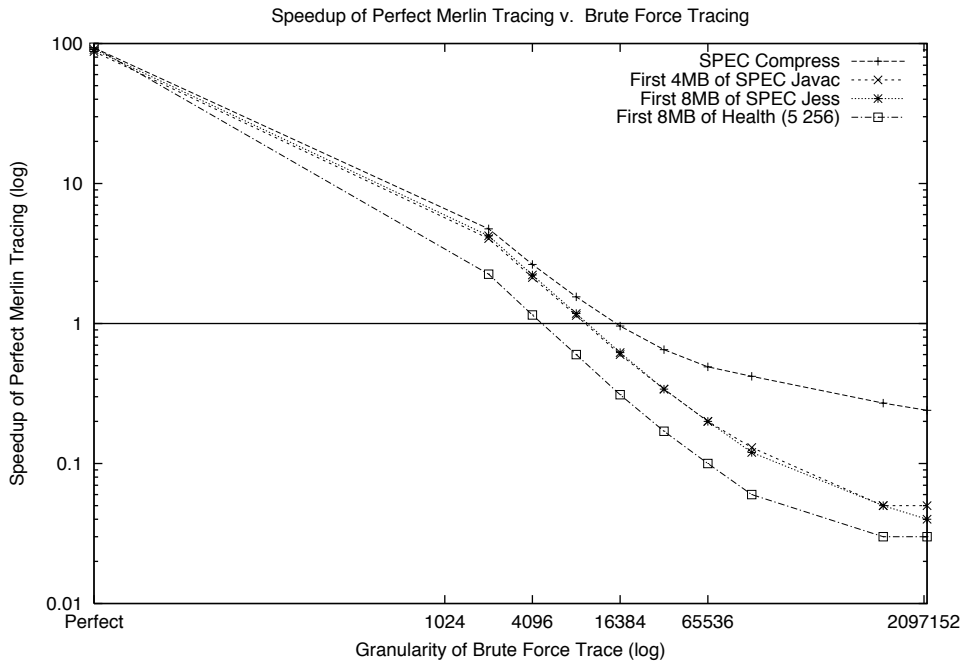


Figure 8: The speedup of Merlin versus Brute Force trace generation. Note the log-log scale.

Finally, we introduce and describe the Merlin Trace Generation Algorithm. We show that the Merlin algorithm can produce traces almost one hundred times as fast as the common brute force method of trace generation. By generating traces with Merlin, we can generate perfect traces in less time than previously required for granulated traces. Thus, the Merlin algorithm makes trace generation quick and easy and eliminates the need for granulated traces.

10. REFERENCES

[1] APPEL, A. W. Simple generational garbage collection and fast allocation. *Software Practice and Experience 19(2)* (1989), 171–183.

[2] BELADY, L. A. A study of replacement algorithms for a virtual-storage computer. *IBM Systems Journal 5(2)* (1966), 78–101.

[3] BLACKBURN, S. M., SINGHAI, S., HERTZ, M., MCKINLEY, K. S., AND MOSS, J. E. B. Pretenuring for Java. In *Proceedings of SIGPLAN 2001 Conference on Object-Oriented Programming, Languages, & Applications* (Tampa, FL, Oct. 2001), vol. 36(10) of *ACM SIGPLAN Notices*, ACM Press, pp. 342–352.

[4] CHENG, P., HARPER, R., AND LEE, P. Generational stack collection and profile-driven pretenuring. In *Proceedings of SIGPLAN 1998 Conference on Programming Language Design and Implementation* (Montreal, Canada, June 1998), vol. 33(5) of *ACM SIGPLAN Notices*, ACM Press, pp. 162–173.

[5] CHILIMBI, T., JONES, R. E., AND ZORN, B. Designing a trace format for heap allocation events. In *ISMM 2000 Proceedings of the Second International Symposium on Memory Management* (Minneapolis, MN, Oct. 2000), vol. 36(1) of *ACM SIGPLAN Notices*, ACM Press, pp. 35–49.

[6] COLLINS, G. E. A method for overlapping and erasure of lists. *Communications of the ACM 3(12)* (Dec. 1960), 655–657.

[7] MCBETH, J. H. On the reference counter method. *Communications of the ACM 6(9)* (Sept. 1963), 575.

[8] NATRELLA, M. G. *Experimental Statistics*. US Department of Commerce, Washington, DC, 1963.

[9] NYSTROM, N. Bytecode-level analysis and optimization of Java classfiles. Master's thesis, Purdue University, West Lafayette, IN, May 1998.

[10] SHAHAM, R., KOLODNER, E. K., AND SAGIV, M. On the effectiveness of GC in Java. In *ISMM 2000 Proceedings of the Second International Symposium on Memory Management* (Minneapolis, MN, Oct. 2000), vol. 36(1) of *ACM SIGPLAN Notices*, ACM Press, pp. 12–17.

[11] STEFANOVIĆ, D., MCKINLEY, K. S., AND MOSS, J. E. B. Age-based garbage collection. In *Proceedings of SIGPLAN 1999 Conference on Object-Oriented Programming, Languages, & Applications* (Denver, CO, Oct. 1999), vol. 34(10) of *ACM SIGPLAN Notices*, ACM Press, pp. 379–381.

[12] STEFANOVIĆ, D., MCKINLEY, K. S., AND MOSS, J. E. B. On models for object lifetimes. In *ISMM 2000 Proceedings of the Second International Symposium on Memory Management* (Minneapolis, MN, Oct. 2000), vol. 36(1) of *ACM SIGPLAN Notices*, ACM Press, pp. 137–142.

[13] UNGAR, D. M. Generation scavenging: A non-disruptive high-performance storage reclamation algorithm. In *Proceedings of the ACM SIGSOFT/SIGPLAN Software Engineering Symposium on Practical Software Development*

Environments (Pittsburgh, PA, Apr. 1984), vol. 19(5) of *ACM SIGPLAN Notices*, ACM Press, pp. 157–167.

[14] UNGAR, D. M., AND JACKSON, F. An adaptive tenuring policy for generational scavengers. *ACM Transaction of Programming Languages and Systems 14(1)* (Jan. 1992), 1–27.

[15] VESTAL, S. C. *Garbage Collection: An Exercise in Distributed, Fault-Tolerant Programming*. PhD thesis, University of Washington, Seattle, WA, Jan. 1987.

[16] ZORN, B., AND GRUNWALD, D. Evaluating models of memory allocation. Tech. Rep. CU-CS-603-92, University of Colorado at Boulder, Boulder, CO, July 1992.

[17] ZORN, B. G. *Comparative Performance Evaluation of Garbage Collection Algorithms*. PhD thesis, University of California at Berkeley, Berkeley, CA, Mar. 1989.