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Postmortem Object Type Identification

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ABSTRACT

This paper presents a novel technique for the automatic type identification of arbitrary memory objects from a memory dump. Our motivating application is debugging memory corruption problems in optimized, production systems — a problem domain largely unserved by extant methodologies. We describe our algorithm as applicable to any typed language, and we discuss it with respect to the formidable obstacles posed by C. We describe the heuristics that we have developed to overcome these difficulties and achieve effective type identification on C-based systems. We further describe the implementation of our heuristics on one C-based system — the Solaris operating system kernel — and describe the extensions that we have added to the Solaris postmortem debugger to allow for postmortem type identification. We show that our implementation yields a sufficiently high rate of type identification to be useful for debugging memory corruption problems. Finally, we discuss some of the novel automated debugging mechanisms that can be layered upon postmortem type identification.

KEYWORDS: postmortem debugging; memory corruption; debugging production systems; debugging optimized systems; false sharing; lock detection; feedback-based debugging

1 Introduction

While there are a myriad of different techniques for automatically debugging memory corruption problems, they share one conspicuous trait: each induces a negative effect on run-time performance. In the least invasive techniques the effect is merely moderate, but in many it is substantial — and in none is the performance effect so slight as to allow the technique to be enabled at all times in production code. As such, the applicability of these techniques is limited to *reproducible* memory corruption problems in *development* environments. These techniques are ineffective for debugging the most virulent memory corruption problems: *non-reproducible* problems in *production* environments. The only data from such problems is the state of the system itself: when memory corruption induces a fatal failure in the system, a snapshot of state is typically taken and copied to stable storage. To be applicable to these memory corruption problems, automatic debugging techniques must assume an optimized system, and restrict themselves to making use only of *postmortem* state.

Memory corruption problems have several variants, but a particularly common pathology is a *buffer overrun*, in which a memory object is erroneously treated as a memory object of larger size[SC91]. Because the errant subsystem stores to the memory beyond the bounds of the object, this pathology can induce wildly varying manifestations: system failure is typically induced not by the corrupting subsystem, but rather by a disjoint (and otherwise correct) subsystem that happens to have a memory buffer adjacent to that of the errant subsystem. As Figure 1 shows, when debugging

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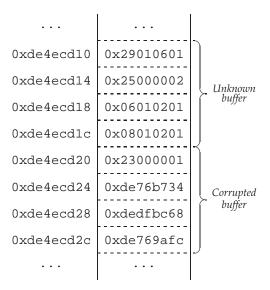


Figure 1: Example of buffer overrun memory corruption. The first word of the 16-byte buffer at address 0xde4ecd20 has been corrupted, inducing fatal error when the memory stored there (0x23000001) was interpreted as a pointer. The similarity between the corruption value and the contents of the buffer at address 0xde4ecd10 indicates that the code manipulating the unknown buffer is likely responsible for the corruption.

these problems postmortem it is often apparent based on buffer contents that one buffer has overrun the other. The subsystem associated with the victimized buffer is known by virtue of that subsystem having induced the fatal error; in order to make progress, the subsystem associated with the errant buffer must be determined. In a system that makes widespread use of derived types, determining the *type* of a buffer can often implicitly identify the subsystem — and at the very least, determining the type considerably focuses the search for errant code.

We have developed an automatic technique for determining the type of an arbitrary memory object from a memory dump of an optimized system. As many optimized systems are implemented in C, we have developed some specific heuristics to make our technique effective on C-based systems. We have implemented these heuristics on Solaris for use in debugging Solaris kernel crash dumps, and have in practice been able to achieve very high rates of type identification — typically better than 80 percent of all memory objects, and often better than 95 percent. This high rate of identification has allowed our technique to be used to successfully debug otherwise undebuggable kernel memory corruption problems.

The remainder of this paper is structured as follows: Section 2 discusses related work; Section 3 discusses our technique in general; Section 4 discusses the problems that a C-based system poses with our technique; Section 5 discusses the heuristics that we have developed to overcome the obstacles outlined in Section 4; Section 6 discusses the details of our implementation; Section 7 describes other applications of postmortem type identification; Section 8 outlines areas for future work.

2 Related work

There has been a substantial body of work devoted to debugging memory corruption problems in development, including Purify[HJ92], Sabre-C[KLP88], Kendall's bcc[Ken83], Steffen's rtcc[Ste92], and Jones and Kelly's bounds checking[JK97]. Many of these require recompilation, and all of them induce substantial performance impact, varying from as little as 130%[ABS94] to as much as 20,000%[KLP88]. None of these target production code explicitly, and Jones and Kelly even conclude

that it is "unlikely that we could ever achieve the 10-15% performance loss that would be acceptable if programs are to be distributed with bounds checks compiled in." [JK97]

The problem of debugging memory corruption problems in production was explicitly identified by Patil and Fischer in [PF95], in which they describe using idle processors to absorb their technique's substantial performance impact. Unfortunately, this is not practical in a general-purpose system: idle processors cannot be relied upon to be available for extraneous processing. Indeed, in performance critical systems *any* performance impact is often unacceptable.

Some memory allocators have addressed debugging problems in production by allowing their behavior to be dynamically changed to provide greater debugging support[Bon94]. This allows optimal allocators to be deployed into production, while still allowing their debugging features to be later enabled should problems arise. A common way for these allocators to detect buffer overruns is to optionally place *red zones* around allocated memory. However, this only provides for immediate identification of the errant code if stores to the red zone induce a synchronous fault. Such faults are typically achieved by coopting the virtual memory system in some way — either by surrounding a buffer with unmapped regions, or by performing a check on each access. The first has enormous cost in terms of space, and the second in terms of time — neither can be acceptably enabled at all times. Thus, these approaches are still only useful for *reproducible* memory corruption problems.

If memory corruption cannot be acceptably prevented in production code, then the focus must shift to debugging the corruption postmortem. While the notion of postmortem debugging has existed since the earliest dawn of debugging[Gil51], there seems to have been very little work on postmortem debugging of memory corruption per se; such as it is, work on postmortem debugging has focused on race condition detection in parallel and distributed programs. The lack of work on postmortem debugging is surprising given its clear advantages for debugging production systems — advantages that were clearly elucidated by McGregor and Malone in [MM80]:

A major advantage of this method of obtaining information about a program's malfunction is that there is virtually no runtime overhead in either space or speed. No extra trace routines are necessary and the dump interpreting software is a separate system utility which is only used when required. This is a facility which remains effective when a program has passed into production use and is very effective in 'nailing' those occasional bugs in a production environment.

The only nod to postmortem debugging of memory corruption seems to come from memory allocators such as the slab allocator[Bon94] used by the Solaris kernel. This allocator can optionally log information with each allocation and deallocation; in the event of failure, these logs can be used to determine the subsystem allocating the overrun buffer. While this mechanism has proved to be enormously useful in debugging memory corruption problems in the Solaris kernel, it is still far too space- and time-intensive to be enabled at all times in production environments.

3 Object type identification

We seek to aid postmortem analysis by providing type identification for dynamically-allocated objects. In many systems, a memory dump due to fatal failure includes both compiler-supplied type information and a mapping of static memory objects to their type[Lin90]; we wish to use this information to develop type inferences for dynamically-allocated objects.

3.1 Initialization

We consume the memory dump, building a graph in which each node represents an allocated dynamic memory object and each edge represents a pointer from one memory object to another. (We determine the pointers contained within a memory object by scanning its aligned locations for values that correspond to other dynamically allocated objects.) For each node, we store the base address

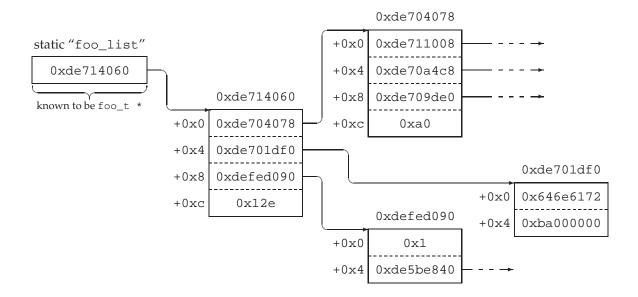


Figure 2: Initialization. Each dynamically allocated memory object is a node; each pointer between objects is an edge. Statically allocated objects such as foo_list are added to the graph as nodes. Pointers contained within them to dynamically allocated objects are added as edges, and the nodes themselves are marked with their type.

and size of the memory object, as well as type information (initially set to be *unknown*) and a list of outgoing and incoming edges. For each edge, we store the offset of the pointer in the pointed-from memory object (the *source offset*), and the offset pointed to in the pointed-to memory object (the *destination offset*). We then add to the graph a node for each static memory object, adding outgoing edges as appropriate for the pointers contained in the object. For these static objects, we can use the type information generated by the compiler to set the node's type. Figure 2 shows an example of such a graph construction.

3.2 Processing

We process the graph to propagate type information from nodes of known type (initially, the nodes representing the static memory objects) to nodes of unknown type. We begin this processing by marking and enqueuing all nodes of known type. While the queue is non-empty, we dequeue a node and process it. For each of the node's outgoing edges, we use the node's inferred type and the edge's source offset within the memory object to determine the pointer type of the edge. If the destination offset of the edge is zero (that is, if the represented pointer refers to the base of the pointed-to object), we set the type of the edge's destination node to be the dereferenced edge pointer type. If the (now-identified) destination node is unmarked, we mark and enqueue the destination node. Figure 3 shows how this processing would proceed on the graph from Figure 2.

As virtually all non-leaked dynamic memory objects are ultimately rooted in a static memory object, this process identifies type information for practically all dynamic memory objects.¹ Once processing has completed, the debugger may be queried for the type of any memory object by providing the object's address.

¹There may exist some (very small) number of dynamic memory objects that are rooted only in a thread stack or machine register; these objects cannot be identified by this process.

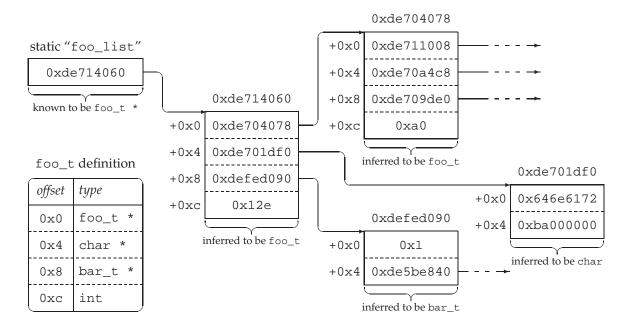


Figure 3: Processing. Based on the known type of foo_list, we infer that the node it points to (the dynamic memory object at 0xde714060) is a foo_t. Advancing to 0xde714060 and using the type definition for foo_t, we determine the type of each outgoing edge; dereferencing each type yields an inference for each pointed-to object. For example, the edge at offset zero is a pointer to a foo_t; we infer that the node pointed to by the memory at offset zero (0xde704078) is a foo_t. Likewise, we infer that the object pointed to by the memory at offset four is of type char and that pointed to by the memory at offset eight is of type bar_t.

4 Complexities due to C

The algorithm for postmortem type identification is straight-forward, but several complexities arise when applying it to the C programming language in particular.

C allows (and even encourages) type casting: nothing stops the programmer from storing a pointer to an object of one type as a pointer to a different type. If our algorithm encountered such a pointer, it would incorrectly assign the destination node to be the cast-to type. Worse, the node would be *propagated* as the incorrect type, potentially leading to more misidentifications and mispropagations. In theory, the presence of type casting in C merely prevents us from guaranteeing the correctness of type inference; in practice, its ubiquity reduces our algorithm to a series of heuristics.

One highly effective heuristic may be to *only* propagate type information when the size of the pointed-to type equals the size of the pointed-to object. This would limit incorrect behavior to cases where the programmer is storing a pointer to an object of one type as a pointer to a different type of *identical* size. However, this would also limit propagation unreasonably: even in well-written C, it is *often* the case that pointed-to objects are not the size of the pointing type. These objects can occur for many reasons, but several phenomena — discussed below — seem to be responsible for most examples in practice.

4.1 Array declaration syntax

Most ubiquitous of these phenomena is C's array declaration syntax. Unlike Pascal and other languages, C makes no distinction between the declaration of a pointer to a single object and a pointer

²C's union construct can be thought of as a slightly more sanctioned variant of type casting: instead of casting to arbitrary type, the compiler enforces that a given datum may only be interpreted as one of a specified list of types.

to an array of objects of like type. That is, in the declaration

```
struct foo *bar;
```

"bar" could be a pointer to a single foo structure, or it could point to an array of foo structures.

4.2 Flexible array members

C performs no bounds checking on array indexing, allowing declarations of structures that are implicitly followed by arrays of the type of the structure's last member. For example, in the declaration

```
typedef struct foo {
    int foo_bar;
    int foo_baz;
    mumble_t foo_mumble[1];
} foo_t;
```

when the programmer allocates a foo_t, the size of n-1 mumble_ts is added to the size of a foo_t to derive the total size of the allocation; this allows for the n trailing mumble_ts to be referenced from the allocated foo_t using C's convenient array syntax — and without requiring an additional memory dereference. This technique may seem arcane, but it is so widespread that ISO C99 has a name for the last member in such a structure: the "flexible array member" (FAM)[Int99].

4.3 Structure embedding

In object-oriented systems implemented in C, it is common for structures to contain embedded smaller structures and to pass pointers to these smaller structures to routines that track the structures only by the smaller, embedded type. This effects a crude polymorphism: the larger structure inherits the data of the smaller structure and methods can be called on that data by specifying a pointer to the embedded structure as a first argument. This technique has been described at some length by Siff et al.[SCB+99], and examples of it abound. In the Solaris kernel the most pervasive example is the virtual filesystem: file systems typically define their own file system node type that embeds the general system's virtual node type, "vnode_t"[Kle86]. The virtual file system contains data structures of vnode_ts, but each is actually the embedded vnode_t in a larger, file system-specific type.

It is less common (but by no means unheard of) for smaller structures to be used as place holders in data structures consisting of a larger structure. That is, instead of an instance of a larger structure being pointed to by the smaller structure pointer (as was the case with structures of vnode_ts, above), an instance of the smaller structure is pointed to by the larger structure pointer. This technique is somewhat dubious, but is most often used to implement hash tables in which a circular linked list of table elements is desired. In this implementation, the smaller structure might be declared this way:

```
typedef struct fooent {
    struct foo *foo_prev;
    struct foo *foo_next;
    int foo_flags;
} fooent_t;
```

The first members of the larger structure will be identical to that of the smaller structure, but the structure will contain additional data, e.g.:

```
typedef struct foo {
    struct foo *foo_prev;
    struct foo *foo_next;
    int foo_flags;
    struct bar foo_bar;
} foo_t;
```

The hash table itself will be a table of fooent_t instead of foo_t — thereby saving space in the table itself while still allowing circular lists of foo_t structures. This construct is critically important to identify: it often occurs in large, contiguous arrays of the smaller structure; mispropagating these as arrays of the larger structure would result in wide-spread misidentification.

5 Heuristics

We have developed a series of heuristics to implement the algorithm described in Section 3 while mitigating the inherent difficulties presented in Section 4. Wherever possible, these heuristics attempt to avoid mispropagation: no identification is preferred to misidentification.

5.1 Conservative propagation

We initialize the graph as described in Section 3.1, but instead of each node having a single type identifier, each stores a *list* of possible types. We propagate types out from the known nodes as described in Section 3.2, but proceeding as *conservatively* as possible. Specifically:

- We do not propagate an inferred type if the size of the type is less than twice the size of the object. These nodes may be examples of the phenomena described in Section 4; they are specifically addressed by other heuristics.
- We do not propagate if the inferred type is a union.
- If we discover a new type inference for a node, we add it to the node's type list but we only propagate through the node if it is unmarked. (The node is marked as we propagate through it.) This prevents any node from being propagated with multiple, different inferences.
- If the destination offset is something other than zero (that is, if the edge does not point to the base of an object), we propagate based on the destination type but we do *not* add the type to the destination node's type list. This allows us to conservatively propagate through embedded types.

5.2 Embedded type detection

Embedded types are largely dealt with by virtue of conservative propagation: because type inferences are only added when an edge points to the base of a structure, we can only potentially misinterpret a node to be its embedded type if the embedded type is the first member of the encapsulating structure. If this is the case, conservative propagation will hopefully yield *multiple inferences* for the node: because we refuse to perform further processing on any node that has multiple inferences, this will prevent a node with an embedded type as its first member from being misinterpreted as an array of the embedded type.

5.3 FAM detection

To detect FAMs, we visit each node for which we have exactly one inferred type, and for which the size of the object is greater than or equal to twice the size of the type. (These are nodes for which we made a type inference but through which we refused to propagate during conservative propagation.) To differentiate an array of the inferred type from a type with a flexible array member, we resort to an inelegant but effective technique: we check the last member of the inferred type; if the structure ends with an array of size one, it is deemed to have a flexible array member and processing advances to array propagation. This assumes that the *only* reason that one would have the last member of a structure be an array of size one is to use it as a flexible array member. While

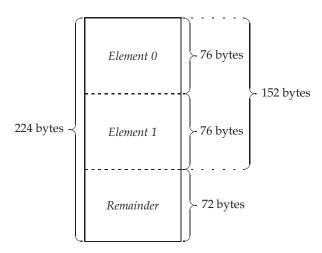


Figure 4: Evaluating a memory object as an array of an inferred type. In this example, the size of the inferred type is 76 bytes and the size of the memory object is 224 bytes. Were this an array of the inferred type, it would contain only two elements — there is not enough space in 224 bytes to fit a third. A two element array would be 152 bytes in size; if there exists a general-purpose object cache with objects smaller than 224 bytes but greater than or equal to 152 bytes, we will conclude that this is *not* an array of the inferred type.

one can clearly develop counterexamples, this technique works well in practice — and the cautious array propagation described in Section 5.5 prevents mispropagation should a counterexample be encountered in the wild.³

5.4 Array determination

If a node is deemed to not have a FAM, we must determine if it is an array of the inferred type. To do this, we make an important check that requires some explanation of the object-caching memory allocator used by the Solaris kernel[Bon94]. In this allocator, objects may be allocated either by specifying an object-specific cache, or they may be allocated by specifying the amount of memory desired. Because establishing an object-specific cache presents an additional complexity for the programmer, most objects are allocated by just specifying the object size. As all objects are allocated out of *some* cache, a number of general-purpose object caches are created by the allocator itself, with each cache corresponding to a fixed, common size. The allocator supports size-based allocations by allocating out of the general-purpose cache with the smallest object size that will satisfy the request.

Because all objects from a given cache are of fixed size, all dynamic arrays are allocated out of a general-purpose cache. We can use this implementation detail to perform an additional check on any potential array: we calculate the size of the object modulo the size of the inferred type and subtract it from the size of the object. If this value is less than or equal to the object size of the next-smaller general-purpose cache, we know that it is *not* an array of the inferred type — if it were an array of the inferred type, it would have been instead allocated out of the next-smaller cache. This determination is shown in Figure 4.

While we have couched our array determination technique in terms of the Solaris kernel memory allocator, it is actually applicable to *any* memory allocator. The efficacy of the technique will vary depending on the degree to which the size of an allocated buffer matches the size of the allocation request: the technique will be most effective on allocators that exactly match allocated buffer size to requested buffer size, or otherwise track requested buffer size on a per-buffer basis.

³ISO C99 defines an alternate syntax to denote a FAM: instead of declaring foo_mumble[1], one may declare foo_mumble[]. Assuming that this information percolates into the compiler-supplied type information, this will allow for reliable FAM detection.

5.5 Array propagation

In the case that an array or a FAM is detected, the type of each element of the array must be propagated. Because the array and FAM determination heuristics are imperfect, array propagation runs the risk of propagating incorrect types. To mitigate this risk, we perform an additional check before propagating an array: we iterate through each element of the hypothesized array, checking that each pointer member points to either NULL or valid memory. If pointer members do not satisfy these criteria, it is assumed that we have not accurately determined that the given object is an array of the inferred type, and we abort processing of the node. Note that uninitialized pointers can potentially prevent an otherwise valid array from being interpreted as such. Array misinterpretation can induce substantial cascading type misinterpretation; it is preferred to be conservative and accurate in such cases — even if it means a lower type recognition rate. An array is propagated by propagating the type of each array element using conservative propagation.

6 Implementation

We have implemented postmortem type identification as a debugger command in Solaris's modular debugger, MDB[Sun02]. MDB provides an API that allows for the rapid development of pluggable debugging components, and includes a specific API for the processing of the type information present in all Solaris kernel memory dumps. MDB's architecture allows new components to easily build on extant ones, trivializing otherwise complex tasks such as iterating over all allocated memory objects.

Type identification is performed by using the "::typegraph" debugger command. To avoid propagating incorrect type information if at all possible, ::typegraph applies our heuristics in a series of passes, with more aggressive heuristics applied to only those nodes for which more conservative heuristics have failed to make a type identification.

6.1 Initial pass

The initial pass uses the internal data structures of the Solaris kernel memory allocator to iterate over all allocated dynamic memory objects and build the graph as described in Sections 3.1 and 5.1. Our implementation adds an important additional step to the initialization: because the Solaris kernel uses an object-based allocator, we can iterate over nodes from kernel memory caches of known type and set their type accordingly. (For example, the objects allocated from the "process_cache" are known to be of type "proc_t.") This technique requires very little encoded knowledge of the system, but allows for substantial preprocessing identification: our current implementation contains a table consisting of only nine cache/type pairs, but it leads to a priori identification of up to a third of all dynamic memory objects.

6.2 Processing passes

Our heuristics vary in the assumptions they make. To avoid mispropagation, we process the graph as a series of passes, applying more aggressive heuristics only to those nodes for which conservative heuristics have failed to make an identification.

6.2.1 Conservative propagation

Conservative propagation is the first processing pass, proceeding exactly as described in Section 5.1.

6.2.2 Array determination

The array determination pass processes all nodes through which we did not propagate in the first pass, proceeding exactly as described in Section 5.4. If a node is determined to be an array or is determined to have a FAM, the array is conservatively propagated as described in Section 5.5. Because this propagation can lead to previously unidentified nodes being identified as potential arrays, this pass is repeated until no improvements are made.

6.2.3 Type coalescence

The type coalescence pass processes all nodes that have multiple type inferences. If a node has one inference that is a structure and others that are not a structure, the non-structure inferences are eliminated. For example if an object is inferred to be either of type "char" (pointed to by a "char *") or type "struct frotz," the possibilities will be coalesced into just "struct frotz."

```
pass => initial
typegraph:
typegraph:
                          maximum nodes => 1401799
                           actual nodes => 824313
typegraph:
                         anchored nodes => 4992
typegraph:
              time elapsed, this pass => 1526 seconds
typegraph:
typegraph:
                  time elapsed, total => 1526 seconds
typegraph:
typegraph:
                                  pass => 1
                                 nodes => 824313
typegraph:
                               unmarked => 576829
                                                      (69.9%)
typegraph:
                                known => 255955
                                                       (31.0%)
typegraph:
typegraph:
                            conjectured => 242699
                                                        (29.4%)
                conjectured fragments => 3737
typegraph:
                                                        ( 0.4%)
typegraph:
                  known or conjectured => 502391
                                                       (60.9%)
typegraph:
                             conflicts => 35878
typegraph:
                             candidates => 172816
typegraph:
                time elapsed, this pass => 44 seconds
                    time elapsed, total => 1570 seconds
typegraph:
typegraph:
typegraph:
                                  pass => 2
                                  nodes => 824313
typegraph:
                               unmarked => 275390
                                                        (33.4%)
typegraph:
                                known => 255955
                                                       (31.0%)
typegraph:
                            conjectured => 535919
                                                       (65.0%)
typegraph:
               conjectured fragments => 4049
typegraph:
                                                       ( 0.4%)
                  known or conjectured => 795923
typegraph:
                                                       (96.5%)
                              conflicts => 39132
typegraph:
                             candidates => 15597
typegraph:
                time elapsed, this pass => 81 seconds
typegraph:
typegraph:
                    time elapsed, total => 1652 seconds
typegraph:
```

Figure 5: ::typegraph output from the first two passes (conservative propagation and array determination) for a dump with 824,313 dynamic memory objects. First, note that a relatively large number of objects (31.0%) are known after the initial pass. This is due to the known kernel object caches. Second, note that while conservative propagation identifies a large number of objects (29.4%), there are still many objects (39.1%) unidentified after the first pass. The array determination pass is critical for identifying these objects; after this pass, types are known or conjectured for 96.5% of objects. These results are typical. Finally, note that much more time is spent in the initial pass than in either of the subsequent passes. This is because the initial pass includes the time to read the crash dump from disk into memory — and the crash dump is over two gigabytes in this example.

```
> 33a31007088::whattype
33a31007088 is 33a31007088+0, struct seg
> 3039b042370::whattype
3039b042370 is 3039b042370+0, possibly struct dcentry
> 30062034c3c::whattype
30062034c3c is 30062034c38+4, possibly char (struct rnode.r_path)
> 329642d7878::whattype
329642d7878 is 329642d7878+0, possibly one of the following:
    struct sonode (from 15925e0+8, type struct socklist)
    struct vnode (from 30985f1d038+10, type struct stdata)
> 3020a383880::whattype
3020a383880 is 3020a383880+0, possibly one of the following:
    struct filock (from 33cf55b2a80+80, type struct tmpnode)
    struct lock_descriptor (from 4823ff82a00+8, type struct lock_descriptor)
```

Figure 6: Example ::whattype output for several different objects. In the first example, the object in question is from a cache of known type. In the second example, the type of the object has been inferred (and ::whattype softens its language accordingly by only claiming that this is "possibly" the type). In the third example, the type is inferred to be a base type, so ::whattype provides the referring type name and member. In the final two examples, the objects have a type conflict. The first of these is an example of the idiom discussed in Section 4.3: the embedded type ("struct vnode") is the first member of its encapsulating type ("struct sonode"). The second is simply a result of sloppy programming: an explicit cast has been used to store a "struct lock_descriptor" object in a pointer to "struct filock" — despite the fact that the two structures have nothing to do with one another! Fortunately, such conflicts are rare; typically fewer than 0.1% of objects are identified as having type conflicts.

6.2.4 Non-array type inference

The non-array type inference pass is the least conservative. It processes those objects that meet the following conditions:

- The object has a single type inference.
- The size of the type inference is less than half the object size.
- The object was not identified as an array.

These objects — which are not propagated by earlier passes — are propagated in this pass as being a non-array of the inferred type. This pass is necessary to propagate objects that have embedded types as their first member, but for which only the embedded type was inferred.

6.3 Type identification

Once processing is complete, the type of an arbitrary object may be queried by specifying its address to the "::whattype" debugger command. If an inference has been drawn for the specified object, its type is displayed. If the type has been identified to be a base type (e.g., char, int, void, etc.), the type and member of the referring object is displayed. If multiple inferences have been drawn for the object, all of the conflicting types are displayed, along with the nodes that led to each inference. Figure 6 shows some example output from ::whattype.

6.4 Manual intervention

If recognition rate is low (or, from a more practical perspective, if the object of interest is not automatically identified), it can be useful to know which node is the greatest impediment to further

recognition. If the user can — by hook or by crook — determine the true type of this node, more type identification should be possible. To facilitate this, we therefore define the *reach* of a node to be the number of unknown nodes that could potentially be identified were the node's type known. We determine the reach by performing a depth-first pass through the graph. The node of greatest reach (along with the number of reachable unknown nodes) is reported upon completion of a post-processing pass. We added an additional debugger command, ::istype, to allow the type to be set manually. When a type is set manually, the graph is immediately reprocessed.

Manual intervention in the presence of imperfect heuristics allows for a paradigm of *feedback-based* postmortem debugging, where automatic inferences by the debugger about the system lead to further inferences by the user about the system — which in turn lead to more automatic inferences and so on. While this is intriguing in principle, we have found that the high rate of type recognition has not necessitated its use in practice.

7 Other applications

While debugging buffer overrun corruption was our original motivating application for postmortem type identification, we have discovered it to have a wide range of applications to postmortem debugging.

7.1 Use-after-free corruption

Postmortem type identification may be of help in debugging other variants of memory corruption. In particular, it may help root-cause *use-after-free* corruption, in which a memory object is used after it is deallocated. After buffer overrun corruption, use-after-free corruption has been found to be the most common type of memory corruption[SC91]. This pathology can be difficult to diagnose: it manifests itself as "random" corruption. If the object as reallocated is of different type than the object as erroneously used after being freed — and if the freed object is still present in its original data structure — postmortem type identification will explicitly identify the object as a type conflict. By providing the two types in conflict, postmortem type identification considerably focuses the search for errant code.

7.2 Postmortem lock detection

When debugging parallel software systems postmortem, it is often useful to know which mutually exclusive regions a given thread of control has access to. Such regions are entered by acquiring a mutual exclusion lock ("mutex"); the problem distills to determining which mutexes are owned in the system and by whom. Knowing the regions that a thread of control has exclusive access to sheds light on the state of the system at the time of the failure, and therefore aids analysis into the failure's root cause.

The simplest way to solve this problem is to log each entry to and exit from a mutually exclusive region. However, in parallel software systems with fine-grained locking, mutexes are acquired and released far too frequently to allow for any sort of logging without inducing an unacceptable impact on performance.

If mutexes are implemented with a single C type (as they are in the Solaris kernel — a "kmutex_t") we can build on postmortem type identification to find all held locks: after type identification has completed, we iterate over all nodes of inferred type, and look for any embedded mutex types. Adding the offset of the embedded mutex type to the base address of the node yields the address of the mutex. Because parallel systems must be able to determine the owning thread of a mutex given its address (to correctly implement priority inheritance, guard against recursive entry, allow for adaptive blocking behavior, etc.), we can build a system-specific way to get from the mutex to the owning thread.

```
> ::findlocks
300182d9a78 (struct segkp_data.kp_lock) is owned by 140a000
3001c69ca80 (struct anon_map.serial_lock) is owned by 3008de45a40
3000d2c46f0 is owned by 3008de45a40
3000c43b658 (struct anon_map.serial_lock) is owned by 30018a7bce0
3001aabdca8 (struct anon_map.serial_lock) is owned by 30018a7a2a0
3001b8c390 (struct anon_map.serial_lock) is owned by 3001lbb6d20
3001lb8c898 (struct anon_map.serial_lock) is owned by 30018a73d00
3001lb8c940 (struct anon_map.serial_lock) is owned by 30018a7dd00
3008423e740 (struct anon_map.serial_lock) is owned by 30078e06d20
30320df6118 (struct anon_map.serial_lock) is owned by 30078e06d20
30320df6118 (struct anon_map.serial_lock) is owned by 30084296800
30320f5dcf0 (struct anon_map.serial_lock) is owned by 3001ccfd260
30320f5dcf0 (struct anon_map.serial_lock) is owned by 3000c442fe0
14b4a18 (pageout_mutex) is owned by 2a100527d40
14cc7a8 (ufs_scan_lock) is owned by 3000c4437c0
```

Figure 7: Example ::findlocks output. The address of the lock is shown on the left; the address of the owning thread structure is shown on the right. For static locks (such as "pageout_mutex" and "ufs_scan_lock" in the above), the symbol name is provided. For locks embedded in dynamic objects, the structure type of the object and member name of the embedded lock are provided. ::findlocks output should be taken only to be advisory; if type recognition is anything less than 100%, it will not find all held locks.

We have implemented an additional MDB command, "::findlocks," that implements this for the Solaris kernel; its output is shown in Figure 7.

7.3 False sharing detection

In caching SMP systems, memory is kept coherent through a variety of different protocols. Typically, these protocols dictate that only a single cache may have a given line of memory in a dirty state. If a different cache wishes to write to the dirty line, the new cache must first read-to-own the dirty line from the owning cache. The size of the line used for coherence (the coherence granularity) has an immediate ramification for parallel software: because only one cache may own a line at a given time, one wishes to avoid a situation where two or more small, disjoint data structures are both contained within a single line *and* accessed in parallel on disjoint CPUs. This situation — so-called *false sharing*[DSR+93] — can induce suboptimal scalability in otherwise scalable software.

Historically, one has been able to find false sharing only with some combination of keen intuition and good luck. Building on postmortem type information we can — from a system crash dump — detect the potentially most egregious cases of false sharing. This pushes postmortem analysis into an entirely new domain: analyzing a system crash dump for potential (but as of yet unknown) performance problems.

We can detect false sharing by iterating over all nodes, looking for nodes that satisfy the following criteria:

- The node is an array. That is, the node was either determined to be of a C type that is an array type, or the node was inferred to be an array in the array determination pass of type identification.
- Each element of the array is a structure that is smaller than the coherence granularity.
- The total size of the array is greater than the coherence granularity.
- Each element of the array is a structure that contains within it a synchronization primitive (mutex, readers/writer lock, condition variable or semaphore). We use the presence of a synchronization primitive as a crude indicator that the disjoint elements of the array are accessed in parallel.

> ::findfalse					
ADDR	SYMBOL	TYPE		SZ	TOTSIZE
7839fc30	fx_list_lock	struct	mutex	8	128
7839f6b0	fx_cb_list_lock	struct	mutex	8	128
78360448	t_hashmutex	struct	mutex	8	512
782e2418	kcpc_ctx_llock	struct	mutex	8	512
14c3438	tcp_bind_fanout	struct	tbf_s	16	8192
14c2438	tcp_listen_fanout	struct	tf_s	16	4096
14c1428	tcp_acceptor_fanout	struct	tf_s	16	4096
14bd2e8	ipc_tcp_listen_fanout_v6	struct	icf_s	16	4096
14bb628	tbftable	struct	tbf	56	1792
30000c07e80	-	struct	fifolock	32	288
30000c07d60	-	struct	fifolock	32	288
30000c07c40	_	struct	fifolock	32	288
30000b70000	-	struct	icf_s	16	8192
30000b6c000	-	struct	icf_s	16	8192
30000b62000	_	struct	tbf_s	16	8192
300008d1000	-	struct	mutex	8	4096
30004153530	-	struct	uf_entry	40	2688
3000284eaa8	-	struct	uf_entry	40	2688
3000284e028	-	struct	uf_entry	40	2688
30004149538	-	struct	uf_entry	40	2688
30004148038	-	struct	uf_entry	40	2688
30006cc7540	-	struct	uf_entry	40	2688
30000c01520	-	struct	uf_entry	40	2688
30000c00aa0	-	struct	uf_entry	40	2688
30000c00020	-	struct	uf_entry	40	2688
3000256f9c0	-	struct	uf_entry	40	1312
3000256f4a0	-	struct	uf_entry	40	1312
30000061988	-	struct	smfree	24	192
30000ca0000	-	struct	irb	32	65536
30000ae6000		struct		8	262144
30000920000	-	struct	plock	8	124624
30000916000	-	struct	_kcondvar	2	31156

Figure 8: Example of ::findfalse output. All the above structures can potentially suffer from false sharing. One of these ("struct uf_entry") was deemed important enough to fix immediately. Others are either under investigation or are in data structures that are not sufficiently parallel to merit eliminating the false sharing.

Any node satisfying these criteria is identified as an object that could potentially suffer from false sharing, and the node's address, type, type size, and total size are provided as output. We have implemented this as a "::findfalse" debugger command; its output is shown in Figure 8.

While there are some instances of false sharing that do not meet the above criteria (e.g., if the synchronization for each element is handled in a separate structure, or if the elements are only manipulated with atomic memory operations), these criteria yield many examples of false sharing without swamping the user with false positives. (As a proof of concept, ::findfalse has found several known instances of false sharing in the Solaris kernel, and further revealed two serious — and hitherto unknown — instances of false sharing.)

8 Future work

8.1 Better recognition

In our experience, the greatest impediments to type recognition are data structures that are stored *only* with pointers to base types that are subsequently cast before every use. This may seem arcane, but it comes up frequently in the Solaris kernel: device driver instances register an object that represents their state with a framework that stores it as a "void *," handing it back to the device driver as needed. Because these objects are never stored with a pointer to the true type, we cannot identify

their type. We would ideally like to extend postmortem type identification to be able to identify these structures, perhaps by extending the interfaces that create such state to explicitly specify type.

8.2 User-level core files

Postmortem type identification has proved very useful for debugging Solaris kernel crash dumps; a logical extension is to allow for type identification in user-level core files. The work required to do this is relatively small: MDB can already process user-level core files and the slab allocator used in the Solaris kernel has recently been made available to user-level processes[BA01]. The only impediment is the addition of the type information consumed by MDB to user-level core files; this work is currently underway. Furthermore, because multithreaded applications on Solaris are forced to use well-defined types for synchronization primitives, we expect to be able to provide ::findlocks and ::findfalse for user-level core files as well.

9 Conclusions

We have described a mechanism to provide automatic postmortem identification of arbitrary memory objects. While the technique can in principle be applied to any typed language, we have focused on the specific issues presented by C. We have described heuristics to overcome the obstacles inherent in postmortem type identification for C-based systems, and have described our implementation on one such system, the Solaris kernel. We have found postmortem type identification to be very useful in debugging buffer overrun memory corruption in optimized systems — problems that were practically undebuggable prior to this work. Moreover, we have found that our heuristics yield a sufficiently high recognition rate to allow for additional novel applications, including postmortem identification of held locks and postmortem identification of structures that may induce false sharing. There will certainly be more applications of postmortem object type identification, some of which will presumably rely on near-perfect type recognition; there is therefore great incentive to develop further heuristics to improve the object recognition rate as much as possible.

Availability

The debugger commands described in this work — ::typegraph, ::whattype, ::istype, ::findlocks and ::findfalse — have been integrated into Solaris, and will be available in the October 2003 update of Solaris 9. More information on the availability of Solaris can be found at http://www.sun.com/software/solaris/.

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