An Extended Low Fat Allocator API and Applications

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Abstract
The primary function of memory allocators is to allocate and deallocate chunks of memory primarily through the malloc API. Many memory allocators also implement other API extensions, such as deriving the size of an allocated object from the object’s pointer, or calculating the base address of an allocation from an interior pointer. In this paper, we propose a general purpose extended allocator API built around these common extensions. We argue that such extended APIs have many applications and demonstrate several use cases, such as (manual) memory error detection, meta data storage, typed pointers and compact data-structures. Because most existing allocators were not designed for the extended API, traditional implementations are expensive or not possible.

Recently, the LowFat allocator for heap and stack objects has been developed. The LowFat allocator is an implementation of the idea of low-fat pointers, where object bounds information (size and base) are encoded into the native machine pointer representation itself. The “killer app” for low-fat pointers is automated bounds check instrumentation for program hardening and bug detection. However, the LowFat allocator can also be used to implement highly optimized version of the extended allocator API, which makes the new applications (listed above) possible. In this paper, we implement and evaluate several applications based efficient memory allocator API extensions using low-fat pointers. We also extend the LowFat allocator to cover global objects for the first time.

1 Introduction
Memory allocators are used heavily in languages without garbage collection, for example, in C/C++. Memory allocation (and deallocation), canonically this is through malloc/free (or C++’s new operators), is well understood and studied [18]. There are many widely used memory allocators, to name a few, the Lea [2], jemalloc [1], and TCMalloc [4]. Most allocators provide APIs for allocating (malloc and friends) and deallocation (free and friends). For brevity, we will simply call this the malloc API.

The nub of the malloc API has remained fairly static for a long time, focusing on the core functionality of allocation and deallocation of memory. However, there is other functionality which can be offered, separate from the main allocation and deallocation tasks. Indeed, some allocators provide some extended non-core functionality, and we argue that extensions, such as returning information about allocated objects, is both useful and can support a variety of applications. While some allocators have some non-core malloc API extensions, we propose a unifying set of malloc API extensions.

Our extensions leverage the LowFat allocator which has been recently developed for efficient bounds checking [8, 10]. The LowFat allocator allows for certain operations, such as calculating the allocation size/base/offset of pointers very efficiently, which forms the foundation of our API extensions. This is important for applications where the extended API is heavily used, e.g., in bounds checking potentially every read/write can make use of LowFat operations. Our API extension also allows for uniform treatment of all objects (globals, stack and heap), in contrast, traditional memory allocators only provide APIs for heap objects. Although some similar APIs already exist — e.g., the Boehm conservative garbage collector [6] also provides some similar functionality since the garbage collector also needs some of the operations we propose — by exploiting the properties of LowFat pointers, our implementation is very efficient, with many operations implementable in a few inlined low-latency instructions. While low-fat pointers have been implemented for heap [8] and stack [10] objects, in this paper we also extend low-fat pointers to also cover global objects, thereby covering all three main object kinds.

We show how to apply the extended malloc API to several applications, including: (manual) memory error checking, efficient and general meta data storage and retrieval, typed pointers, and compact data-structures. For each application we provide some (mini)benchmarks to support our claims. Berger et al. [5] propose the need for composable memory allocators, here, we argue the case for applications which leverage new functionality beyond memory allocation/deallocation.

In summary, the main contributions of this paper are the following:

• Low-fat Globals: In addition to heap and stack objects, we extend low-fat pointers to also cover global objects for the first time. This means that low-fat pointers are now applicable to all three main object kinds: heap, stack and globals.
• **An Extended LowFat Allocator API:** We present an extended version of the malloc API which gives additional operations outside the core allocation functionality. The extended API leverages low-fat pointers which allows for very efficient implementation of key operations.

• **Applications:** We present several novel applications, made possible by the extended malloc API, for non-traditional use cases, including: manual memory error checking; hidden meta-data; typed/tagged pointers; and compact vectors. We also evaluate the applications to show that they are efficient either from a time or space perspective.

The paper is organized as follows: Section 2 summarizes the existing LowFat allocator for heap and stack objects, and then we present a novel extension for low-fat global objects. We also evaluate the performance of the LowFat allocator against some more established competitors. Section 3 presents the LowFat allocator extended API, as well as details the efficient implementation of each operation. Finally, in Section 4, we present and evaluate several applications of the extended LowFat allocator API.

## 2 LowFat Allocation Design and Implementation

This section describes the LowFat allocator’s design and implementation. In a memory allocator, the precise system details can be important. Throughout this paper, we will tailor the implementation details for the x86_64 architecture and Linux operating system.

### 2.1 Background: Low-fat Pointers

Low-fat pointers [8, 10, 14] are a method for encoding object bounds information (object’s size and base) into the native machine pointer representation itself. For example, a highly simplified low-fat pointer encoding may be implemented as follows:

```c
union { void *ptr;
     struct {uintptr_t size:10; // MSB
               uintptr_t unused:54; } meta; } p;
```

Here the object size is represented explicitly as a field `size`, and the base address can be encoded implicitly by ensuring object’s are aligned to an address that is a multiple of `size`, thus `base(p) = p − (p mod p.size)`. Crucially we see that a low-fat pointer is the same size as a machine pointer, i.e., `(sizeof(p) == sizeof(void *))`. Low-fat pointers generally require a machine architecture with sufficient bit-width, i.e., 48 or 64bit pointers, such as the x86_64.

This simplified low-fat pointer encoding is difficult to implement in practice as it imposes strong constraints on the program’s virtual address space layout. Instead we focus on the flexible low-fat pointer encoding of [8, 10], which we shall refer to as LowFat. The general idea of LowFat is to partition the program’s virtual address space into several large equally-sized regions. There are two main types of regions: low-fat regions which contain objects managed by the LowFat allocator, and non-fat regions that contain everything else. In [8], region #0 is non-fat, and we will also follow that approach. The basic idea is that each low-fat region will service allocations of a given size range, as illustrated in Figure 1. For example, region #1 handle allocations of sizes 1-16 bytes, region #2 handles sizes 17-32 bytes, region #3 33-48 bytes, etc. The mapping between sizes and low-fat regions is called the size configuration [8], represented by a sequence Sizes. For example, the Sizes for [10] is as follows:

```plaintext
Sizes = ⟨16, 32, 48, 64, 80, 96, 112, 128, 144, ..⟩
```

Generally, the size configuration should have the following properties:

1. All sizes must be a multiple of 16 bytes;
2. Sizes must include a power-of-two sub-sequence, i.e.: Sizes ∪ {16, 32, 64, 128, 256, ..} = Sizes; and
3. Large multi-page sizes should be powers-of-two, i.e.: Sizes ∪ {16KB, 32KB, 64KB, ..} = Sizes;

Property 1 ensures the allocator obeys the default alignment of standard malloc for 64-bit systems. Property 2 is needed to support both the stack and global low-fat pointers (discussed below) as well as support for the malloc API. Property 3 keeps [Sizes] compact, since large multi-page objects can be “rounded-up” to the nearest power-of-two multiple without wasting memory (the “padding” will remain virtual). Note that properties 1, 2 and 3 are consistent with each other. The full low-fat allocator parameters used in this paper are listed in Appendix A.

During allocation, an object of size is rounded-up to the next allocation size (`allocSz ≥ size`) that fits, which some caveats discussed below. For the object O to qualify as low-fat, two main properties must be satisfied:

- **Region:** The object O is allocated from the sub-heap in region #I, where Sizes[I] = allocSz; and
- **Alignment:** The object O is allocSz-aligned.

These two properties ensure that the object’s size and base address can be quickly calculated from a (possibly interior) pointer to the object O. This will be elaborated on in Section 3.

Memory for the low-fat regions is created during program initialization, e.g., as a `preinit_array` callback. Regions do not grow or shrink during program execution, rather, the initial size is assumed to be large enough to accommodate all “reasonable” future memory requirements of the program. For example, the implementation of [10] assumes a region size of 32GB. The low-fat regions are initially `virtual_memory` reserved using `mmap` using the `MRESERVE` flag, and thus does not initially consume any RAM/swap resources. Memory resources are only consumed for the parts of each region that are actually allocated and used by the program. Finally,
within each region is left open. The implementation for Linux appends a 16-byte header (i.e., which region does the pointer point to?), and since there is no need to implement adjacent free object merging, the LowFat allocator also eliminates the need to store an explicit "malloc header", meaning that objects are tightly packed. In contrast, the standard \texttt{stdlib malloc} implementation for Linux appends a 16-byte header to every object. That said, we highlight that in this paper, the main aim of the LowFat allocator is to support an enriched LowFat allocator API presented in Section 3, rather than to design an allocator that directly competes with the current state-of-the-art on performance.

### 2.2 LowFat Heap Allocation

The exact memory allocation algorithm used for heap objects within each region is left open. The implementation uses a simple free-list allocator design that partitions the heap sub-region into \textit{used} and \textit{unused} space. Objects in the \textit{used} space are either allocated and in use by the program, or have been freed and placed on a "free list" awaiting reallocation. When a call to \texttt{lowfat\_malloc(s)} occurs, the LowFat allocator:

1. Determines which region \#i corresponding to size \(s\) should be allocated and serviced from; and
2. Pops an entry from the free-list for region \#i if non-empty; else
3. Allocate a new object from the \textit{unused} space otherwise.

Calls to \texttt{free(p)} are handled by pushing the allocated space pointed to by \(p\) onto the corresponding free-list. For large objects, it is sometimes necessary to return free-ed memory back to the operating system, which is done using the \texttt{madvise} system call with the \texttt{DONTNEED} flag.

Since all allocations of a particular size class are serviced from a single region, this has the side-effect of simplifying the overall allocator design. For example, merging of adjacent free objects is disallowed, thus the corresponding logic to do so is not needed by the allocator. The trade-off is that this may lead to more fragmented memory since free-ed objects can only be reallocated as objects within the same size class. On the other hand, since the allocation size can be determined from the pointer (i.e., which region does the pointer point to?), and since there is no need to implement adjacent free object merging, the LowFat allocator also eliminates the need to store an explicit "malloc header", meaning that objects are tightly packed. In contrast, the standard \texttt{stdlib malloc} implementation for Linux appends a 16-byte header to every object. That said, we highlight that in this paper, the main aim of the LowFat allocator is to support an enriched LowFat allocator API presented in Section 3, rather than to design an allocator that directly competes with the current state-of-the-art on performance.

### Benchmarking the LowFat Heap Allocator

We present some benchmarks to evaluate the performance of the LowFat allocator against some more established alternatives. All experiments (including in later sections) are run on a Xeon E5-2630v4 processor (clocked at 2.20GHz) with 32GB of RAM on Linux. The compiler used is LLVM 4.0.0 at -O2, and we evaluate against the SPEC2006 benchmark suite. We compare the LowFat implementation of [3] against \texttt{stdlib malloc}, \texttt{jemalloc} [1], and the Boehm \texttt{malloc} (in manual memory management mode) [6]. The results on the SPEC2006 benchmark suite are shown in Figure 2. The geometric mean for \texttt{stdlib malloc} is 277.8 (100%), LowFat is 280.9 (101.1%), \texttt{jemalloc} is 266.8 (96.0%), and Boehm is 283.6 (102.1%).

Overall we see that the LowFat allocator is competitive against the alternatives. The LowFat allocator described in this paper is intended to be a basic prototype without the many optimizations used in mature memory allocators, so we expect higher overheads compared to more optimized memory allocators such as jemalloc. Furthermore, the LowFat allocator is a relatively young system, meaning that further optimizations may be implemented in the future. We also highlight that only the LowFat allocator supports the optimized LowFat API, which is the main focus of this paper. The memory overhead for the LowFat allocator is \(\sim 3\%\) compared to \texttt{stdlib malloc} [8, 10].

### 2.3 LowFat Stack Allocation

A LowFat allocator for stack memory is presented in [10], which we briefly summarize here. The low-fat stack allocator works by maintaining a linear mapping between the stack sub-regions (Figure 1) and the main program stack. When the program requests a stack allocation of size \(\text{size}\), the LowFat stack allocator performs the following steps:

1. Round-up size to the nearest power-of-two allocation size (\texttt{allocSize}) that fits;
2. Mask the stack pointer \(\%\text{rsp}\) with \(\texttt{allocSize} - 1\). This \(\texttt{allocSize}\)-aligns \(\%\text{rsp}\);
3. Decrement \(\%\text{rsp}\) by \(\texttt{allocSize}\), allocating space;
4. Map \(\%\text{rsp}\) to a pointer \(\texttt{ptr}\) to the stack sub-region corresponding to \(\texttt{allocSize}\) using the linear mapping. The \(\texttt{ptr}\) now points to the newly allocated low-fat stack object.

This mapping is implemented as a compiler transformation [3]. Power-of-two sizes are used since this simplifies object alignment at the cost of increased space overheads. Stack deallocation is handled the same as before, i.e., by restoring \(\%\text{rsp}\) to some previous value. The LowFat stack allocation method is similar to the notion of parallel shadow stacks [7], but with multiple shadow stacks (one for each sub-region) and some additional steps \(\texttt{allocSize}\)-aligning objects. Having multiple shadow stacks may waste memory, however, this can be mitigated by mapping each shadow
stack to the same physical memory. See the memory aliasing optimization from [10].

2.4 LowFat Global Allocation

Previous work on low-fat pointers are restricted to heap [8] and stack [10] objects only. In this paper, we present an extension of LowFat to also cover global objects. The basic idea is to statically allocate global objects from the global sub-region for the corresponding allocation size. To achieve this, we use a program transformation which annotates global objects using a section attribute and then uses a special linker script to control the location of objects. Namely, objects of given size are annotated with a

\[
\text{attribute(\text{section(\"lowfat_region_idx\")})}
\]

section attribute, where idx corresponds to the region index for the global object’s size. The static location of the objects can then be controlled via an appropriate linker script (ld), e.g.:

\[
\ldots = (\text{global sub-region #1 address})
\]

\[
\text{lowfat_region_1 :}
\]

\[
\text{KEEP(* \text{(lowfat_region_1)})}
\]

\[
\ldots
\]

In addition to location, alignment of global objects is controlled using the aligned attribute. Due to the power-of-two limitation of the aligned attribute, global objects are placed into the nearest power-of-two sized region that fits (as is the case with stack objects).

There are some (compiler tool-chain) caveats for generating global low-fat pointers. Firstly, the dynamic linker does not support the section directive meaning that dynamically linked globals (e.g., from shared objects) will not be low-fat pointers. This does not affect program behavior but limits the applicability of the LowFat API for such objects. The second caveat is that the compiler may assume all global objects occupy the first 4GB of the virtual address space. This allows the compiler to generate slightly faster code for the x86_64 architecture. This assumption is violated by global low-fat pointers, meaning that the program must be compiled using the (-mcmodel=large) option which disables the assumption. The final caveat this that, like the LowFat stack allocator, global objects are not low-fat by default unless the compiler transformations described in this section are employed.

3 LowFat Allocator API

The core motivation for the allocator design is to support the LowFat memory API, as summarized in Figure 3. It is divided into three classes. Class I refers to the (traditional) malloc API. The focus of this paper will be on classes II and III detailed below.

3.1 Standard allocator functionality

Our LowFat allocator supports standard replacements for libc’s memory allocation functions (Figure 3 class I), such as,
malloct, free, realloc, memalign, etc. The LowFat replacements are also aliased to versions prefixed by “lowfat_”, e.g., lowfat_malloct, etc.

Stack and global objects can be transformed automatically as a compiler pass (e.g., as used by [10]). As such, stack and global support is optional, and programmers may opt not to use it.

3.2 Core LowFat functionality

The motivation behind LowFat allocation is that allows for some key pointer operations to be implemented efficiently, namely, calculating the size, base, offset, etc., of a pointer p with respect to the original allocation. We highlight that the operations take only a few machine instructions making them suitable for inlining which helps efficiency and compiler optimizations. Since these operations are not traditionally supported by the malloc API, we refer to these operations as the extended memory allocation API.

By design, unlike the malloc API, these operations work uniformly, regardless of whether the pointer is for a heap, stack, global, interior or exterior, just as long as the pointer is lowfat as per Section 2. In Section 4, we will describe some applications of the API.

Given the memory layout of Figure 1, we can define a fundamental operation, lowfat_index, that maps a pointer ptr to the region index to which ptr belongs, as follows:

\[
\text{lowfat_index}(\text{ptr}) = \frac{\text{ptr}}{\text{LOWFAT_REGION_SIZE}}
\]

Here LOWFAT_REGION_SIZE is the region size and is assumed to be a power-of-two. For example, our reference implementation assumes LOWFAT_REGION_SIZE is 32GB. Crucially, the lowfat_index is fast, compiling down into a single x86_64 shift instruction with this default:

\[
\text{shrq } 35, \%rax \quad /\!\!/ 2^35 = 320B *
\]

Size (lowfat_size)

One common memory allocator API operation is to determine the size of the allocation based on a pointer to an object. This exists in the form of malloc_usable_size for stdlib’s malloc, HeapSize for the Window’s HeapAlloc, and GC_size for the Boehm collector, amongst others. Note that all of these functions assume a pointer to the base of the allocated object. Furthermore, such extensions typically differ on whether the size returned accounts for any additional bytes of padding that may have been added by the allocator. For example, malloc_usable_size returns the size including the padding, whereas HeapSize returns the original requested allocation size, depending on the version of Windows.

We define lowfat_size to return the allocation size of a pointer including any padding, similar to malloc_usable_size:

\[
\text{lowfat_size}(\text{ptr}) = \text{LOWFAT_SIZES}[\text{lowfat_index}(\text{ptr})]
\]

Here, LOWFAT_SIZES is a constant lookup table mapping region indices to the allocation sizes according to the size configuration defined in Section 2. For region indices i that are not associated with LowFat allocation, we define:

\[
\text{LOWFAT_SIZES}[i] = \text{SIZE_MAX}
\]

This definition simplifies some applications relating to bounds checking.

Note that, unlike related allocators, the lowfat_size works for any interior pointer and does not assume the base address. The other advantage is that the lowfat_size compiles down into two x86_64 instructions, one shift for lowfat_index followed by a memory read:

\[
\text{movq } \text{LOWFAT_SIZES}(,%rax,8),\%rbx
\]

Base (lowfat_base) and offset (lowfat_offset)

Given a pointer ptr to an allocated object O of size, then

\[
(ptr + 1, \ldots, ptr + \text{size})
\]

are the interior pointers of O, and ptr is the base pointer (a.k.a. exterior pointer) of O. We can map any (possibly interior) pointer ptr’ ∈ I to object O to the base pointer ptr using the following operation:

\[
\text{lowfat_base}(\text{ptr}) = (\text{ptr} / \text{lowfat_size}(\text{ptr})) * \text{lowfat_size}(\text{ptr})
\]

This assumes 64bit integer arithmetic, and is also equivalent to ptr − ptr % lowfat_size(ptr). This also relies on the LowFat allocator ensuring that all allocated objects are size-aligned. Assuming the pointer is stored in register %rax (and is an implicit argument), and the allocation size in %rbx, then the lowfat_base operation reduces to two instructions:

\[
\text{divq } \%rbx \\
\text{imulq } \%rbx
\]

As noted in [8], the 64bit divq operation is relatively slow (high throughput and latency [13]), which may not be desirable. There are two main approaches to optimizing lowfat_base, namely:

1. Use a power-of-two-only size configuration; or
2. Use fixed-point or floating-point arithmetic.

The first allows for the slow division to be replaced by a fast bitmask operation, for example:

\[
\text{lowfat_base}(\text{ptr}) = \text{ptr} & \text{LOWFAT_MASKS}[\text{lowfat_index}(\text{ptr})]
\]

where LOWFAT_MASKS[i] is defined to be (LOWFAT_SIZES[i]−1) for low-fat region #i, or 0 otherwise. The main disadvantage with this approach is that object sizes are rounded to the nearest power-of-two, which leads to increased space overheads. An alternative approach is to use fixed-point arithmetic by defining:

\[
\text{LOWFAT_MAGICS}[i] = (1 << R) / \text{LOWFAT_SIZES}[i] + 1
\]

for low-fat region #i, or 0 otherwise. The (+1) term is for error control, see [8] Section 5.1.1. Here R defines the position of
Figure 4. Two bounds-check instrumented variants of (simple) memcpy. The instrumentation is highlighted.
4 Applications

The LowFat allocator implementation supports efficient implementations of some operations. This enables some applications that would otherwise be too slow for other memory management systems. In this section we explore examples of such applications, including: manual bounds checking, hidden meta-data, typed pointers and compact data-structure representations.

4.1 Detecting Memory Errors

Automated bounds check instrumentation is the “killer app” for low-fat pointers, and this idea has been explored by previous literature [8, 10]. The basic idea is to instrument all pointer arithmetic and memory access with an explicit bounds check (isOOB) defined as follows:

\[(p < \text{base}) \lor (p > \text{base}+\text{size}-\text{sizeof}(\ast p)) \quad \text{(isOOB)}\]

Automatic bounds instrumentation follows the schema introduced in [8]. The basic idea is as follows: for all input pointers \(q\) (function arguments, return values, or pointer values read from memory), we calculate the bounds meta information by calling the \text{lowfat_size}/\text{lowfat_base} operations. For example:

```c
void f(int *q) {
    void *q_base = lowfat_base(q);
    size_t q_size = lowfat_size(q); ... 
}
```

Next, for all pointers \(p\) derived from an input pointer \(q\) through pointer arithmetic \((p = q+k)\) or field access \((p = &q->\text{field})\), we instrument any access to \(p\) with an (isOOB) check. For example:

```c
int *p = q + k;
if (isOOB(p, q_base, q_size)) error();
x = *p; or *p = x;
```

Such bounds-check instrumentation is implemented as a LLVM [16] compiler pass, see [3].

An automatically instrumented version of a (simple) implementation of \text{memcpy} is shown in Figure 4a (based off [10] Figure 2). Here the instrumented lines are highlighted, including the bounds meta data calculation using \text{lowfat_size}/\text{lowfat_base} shown in lines 3–6. Automated bounds checking has an overhead of 64% for heap/stack/global objects [3], although lower overheads are possible depending on what optimizations are enabled (generally trading error coverage for speed).

Manual Bounds Checking

Automatic bounds instrumentation has the advantage in that it requires minimal intervention on behalf of the programmer (e.g., changing the compiler’s flags). However, the automatically generated instrumentation is generally sub-optimal. For example, in the code from Figure 4a, there are two instrumented bounds checks for each iteration of the loop (one for the read and one for the write). A more “natural”/optimal approach is to check the bounds once for each pointer outside of the loop, as shown in Figure 4b. Here we use \text{lowfat_usable_size} to determine the number of bytes available in the src and dst buffers, and verify that this is consistent with the parameter \(n\). Such instrumentation can be added manually by the programmer, assuming that objects are allocated using the LowFat allocator.

In principle, the automatic instrumentation could be further optimized, e.g., by using program analysis to automatically transform Figure 4a into 4b. However, program analysis generally has limitations, and cannot optimize all cases. Furthermore, in some applications the programmer needs fine grained control over what to instrument, in order to achieve an acceptable overhead versus security ratio. Thus, the programmer can restrict instrumentation to specific operations (e.g., \text{memcpy} or specific pointers to sensitive data.

The overheads of manual bounds checking depend on how much is instrumented.

Bonus: Finding free API errors

The LowFat API can be also be used to find some memory errors relating to free. For example, a stack or global object should not be free’ed:

```c
if (lowfat_is_heap_ptr(ptr)) lowfat_free(ptr); else error();
```

In a similar vein, a pointer which is not the base of a heap object, e.g. an interior heap pointer, should not be free’ed:

```c
if (lowfat_is_heap_ptr(ptr) && !lowfat_offset(ptr)) lowfat_free(ptr);
else error();
```

We remark that general use-after-free checking is beyond the scope of the LowFat API. Testing if a pointer is free or not is known to suffer from races (test versus usage) in multi-threaded environments.

4.2 Conservative Garbage Collection

Another application of the LowFat allocator is for marking in conservative garbage collection for C/C++. Under this idea, the LowFat heap allocator itself is modified to automatically invoke a mark-sweep collection phase eliminating the need to manually free objects. As is the standard approach, the “mark” phase scans for all objects reachable from some root set of pointers, typically global and stack memory. Any reachable object is “marked” using internal meta-data associated with each object. Next, a “sweep” frees all unmarked (unreachable) objects since these are no longer referenced by the program. The garbage collector is conservative meaning that it does not rely on C/C++ type information — rather any bit pattern that could be a pointer is assumed to be a pointer. The trade-offs for conservative collection are well known, e.g., see [6].
The LowFat API can also be used to associate arbitrary meta-
data to allocated objects. The basic idea is to store the meta-
data at the base of the object, as illustrated in Figure 6. Here $p$ is a (possibly interior) pointer to a LowFat allocated (object), and the meta-data (meta) is stored at the base of the allocation. The meta-data can be transparently bound to an object by wrapping memory allocation, such as the following:

```c
void *meta_malloc(size_t size, META m) {
    META *ptr = lowfat_malloc(size + sizeof(META));
    *ptr = m;
    return (ptr + 1);
}
```

Note the function returns ($ptr + 1$), meaning that the meta-
data is hidden from the program, analogous to a hidden malloc header that occupies the memory immediately before the allocated object. However, a crucial difference with malloc headers is that in malloc accessing the header is restricted through a base pointer, here, we have no restrictions. Later, the meta-data can be retrieved via a call to lowfat_base, as follows:

```c
m = *(META *)lowfat_base(p);
```

The same basic idea can be extended to both stack and global objects, but requires a compiler transformation. Stack allocation is transformed in a similar way to malloc, where

```c
ptr = alloca(size);
```

is transformed into:

```c
*META *mptr = lowfat_alloca(size + sizeof(META));
*mptr = m;
p = (mptr + 1);
```

Here, lowfat_alloca is itself expanded via program transformation, as per [10]. We note that the usage of alloca is just for the sake of an example, and the transform is applicable to all forms of stack allocation. In particular, the use of alloca can be internal to the compiler as is the case with LLVM.

Globals are more difficult to transform, since a global is also a symbol that may be referenced externally, possibly by code not subject to the automatic program transformation. Thus, we cannot rely on solutions that change the Application Binary Interface (ABI). To fix this, we use a simple symbol-within-a-symbol trick. The basic idea is as follows: given the original global variable definition:

```c
T global = definition;
```

We first define a `wrapper` type of the form:

```c
struct wrapper { META m; T data; };
```

We also ensure that the structure is packed (e.g. by using the GCC packed attribute), meaning that there will be no gap between the $m$ and $data$ fields. Next, we replace the original global with the wrapped version

```c
struct wrapper wrappedGlobal = { m, definition };
```

The program (including external modules) may still reference the original `global` symbol. To fix this we define `global` to point to the data field inside `wrappedGlobal`. The most direct way to do this is via (module-level) inline assembly:

```assembler
asm (".*global global
    .set global, wrappedGlobal+size*");
```

where `size=sizeof(META)`. By using this symbol-within-a-symbol trick, the global variable (global) can be used as normal by the program, including by external untransformed modules.

A form of the hidden meta-data approach is used by EffectiveSan [9] to store object dynamic type information, a.k.a., the effective type of allocated objects, in order to support dynamic type checking for C/C++. However, there is no limit on the kinds of meta-data that can be stored. Like other generic...
4.4 Typed Pointers

A typed pointer is one of various methods for associating dynamic type information with pointers. There are several existing methods [11] for associating a type \( t \) to a pointer \( p \) to form a typed-pointer \( q \). These include:

- Headers: store \( t \) within the object pointed to by \( p \) (Figure 7a);
- Tagged: fold \( t \) into the representation of \( p \) itself (Figure 7b);
- Partitioned: allocate \( p \) from different regions based on \( t \) (Figure 7c).

Each approach as its own advantages/disadvantages: header pointers is portable but consumes memory to store \( t \); tagged pointers and partitioned pointers do not consume more memory, but rely on knowledge about the underlying memory management system.

In this section we explore some alternatives/extensions based on the LowFat API, namely: size-typed pointers and extended tagged pointers.

Size-typed pointers

One idea is to distinguish pointer types based on the allocation size, a.k.a. size-typed pointers. The size can be determined very quickly via the `lowfat_index` API call, however, this approach is only applicable to objects where each supported dynamic type happens to correspond to a different allocation size. That said, real-world applications exist, as illustrated by the following example:

**Example 1 (2-3-4 Trees).** To illustrate size-typed pointers we consider an implementation of 2-3-4 trees [17]. A 2-3-4 tree is a self-balancing tree data-structure that can be used to implement associative arrays mapping keys to values. For example, the following

```
  5 1 2 8 9
```

is a 2-3-4 tree consisting of a root 2-node, a left child 3-node, and a right child 4-node. The name "2-3-4" represents the three node types: 2-nodes, 3-nodes, and 4-nodes, which are of sizes (in 8-byte words) of 3, 5, and 7 respectively. This means the nodes will be allocated from different region \#2, \#3, and \#5 respectively, assuming the standard size configuration. Thus, given a pointer \( \text{ptr} \) to a (undetermined) 2-3-4 node, we can efficiently determine the dynamic type by using the `lowfat_index` operation.

Size-typed pointers are essentially a special case of partitioned pointers. The main advantage is that the LowFat allocator supports the functionality directly, rather than requiring the programmer to implement a specialized allocator.

Extended Tagged Pointers

Sized-typed pointers have limited applicability, since the mapping from types to allocation sizes must be one-to-one. Tagged pointers are more general, but the number of tag bits can be limited. For this, we introduce the notion of extended tagged pointers which are a generalization of standard tagged pointers using the unused lower \( N \)-bits (typically \( N=4 \)) of allocated objects. Assuming \( N=4 \) allows for 16 distinct types, whereas extended tagged pointers can store up to \( N \times \text{size} \) distinct types, where \( \text{size} \) is the allocation size of the object. Normally, for standard tagged pointers, the type (tag) can be retrieved via a simple bitmask operation, e.g.,

\[
\text{tag} = \text{ptr} \& 0xF
\]

However, using the LowFat API, we can generalize this as follows:

\[
\text{tag} = \text{lowfat_offset}(<\text{ptr}>)
\]

This supports all possible tag values within the range \([0..\text{size}]\). Alternatively, tagged pointers may use the unused high bits (typically 16 bits for x86_64). Extended tagged pointers may replace or be used in conjunction with high tag bits, depending the application.

The `lowfat_offset` operation is generally slower than the constant bitmask operation required standard tagged pointers, especially if fixed-point arithmetic is used. Thus, there exists trade-off between performance and number of types, meaning the usefulness is application dependent. We provide one such application in Section 4.5.
We evaluate both size-typed and extended tagged pointers for 2-3-4 trees. Our benchmark consists of a searching for every key in a 2-3-4 tree of size $N$, measured in seconds. We compare six different versions: a standard tagged pointer implementation (tag) using the lower 4 tag bits, an implementation using size-typed pointers (size), and an implementation using extended tagged pointers (extended). Although extended tagged pointers are overkill for 2-3-4 trees, it is nevertheless a useful test for performance evaluation. We compare each version implemented either the LowFat API, or using the similar Boehm GC API. For the Boehm tests, we use manual memory management mode.

The results are shown in Figure 8. Unsurprisingly, the (tag) tests (which do not use any special API calls) show little difference in performance between the two versions. For LowFat, size-typed pointers (size) are even faster than traditional tagged pointers by ~27%. This shows that size-typed pointers are a good alternative for performance critical code, under the caveat that size-typing is applicable to target data-structure. Extended tagged pointers (extended) are slower than traditional tagged pointers by ~27%, so should only be used for applications that require extra tag bits. Also unsurprisingly, the Boehm variants of size-typed and extended tagged pointers were much slower than the LowFat version, e.g. $\times 2$ for extended tagged pointers. This is because the LowFat API is highly optimized and inlined for the size/base operations, whereas the Boehm API requires library calls.

### Evaluation: 2-3-4 trees

### Evaluation: Low-fat vectors

The main advantage of low-fat vectors is that they eliminate the need to explicitly store the len, pos and data fields. Assuming that len, pos, (item *) and item are all 1-word in size, then if a fat vector consumes $n$ words, the corresponding low-fat vector will consume $(n - 3)$ words. The trade-off is that (re)calculating fields incurs additional overheads compared to storing the values directly. To evaluate the performance of low-fat vectors, we benchmark constructing a single vector of integers using the push_back operation. Next, we evaluate the time taken to calculate the sum of all elements of the vector. The results are shown in Figure 9 illustrating the classic space-time tradeoff. We see that constructing low-fat vectors is $\sim 2\times$ overhead for non-power-of-two sizes, $\sim 1.33\times$ overhead for power-of-two sizes. Reading from low-fat vector incurs a $\sim 1.2\times$ overhead for both versions. Thus, low-fat vectors are best suited for programs that create large numbers of small vectors and where optimizing memory overheads are the priority.
5 Conclusions
In this paper we presented an extended LowFat memory allocation API. The main advantage of the LowFat API extensions is that some operations, namely, finding the size/base/offset of pointers, relative to the original allocation, are very fast operations (typically can be implemented in a few in-lined instructions). We argue that these properties enable several applications for the LowFat allocator that are not feasible with existing allocators, such as bounds checking, generic meta-data storage, typed pointers and compact data-structures. We evaluated several of these ideas, with promising results. The malloc API has been essentially unchanged for a long time, we believe that the idea of memory allocation API extensions going beyond the core allocator function is a genuinely useful and practical addition.

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A Low-fat Parameters
\[
\text{LOWFAT\_REGION\_SIZE} = 32 \text{GB}
\]
\[
M = |\text{Sizes}| = 61
\]
\[
16, 32, 48, 64, 80, 96, 112, 128, 144, 160, 192, 224, 256, 272, 320, 384, 448, 512, 528, 640, 768, 896, 1024, 1040, 1280, 1536, 1792, 2048, 2064, 2560, 3072, 3584, 4096, 4112, 5120, 6144, 7168, 8192, 8208, 10240, 12288, 16KB, 32KB, 64KB, 128KB, 256KB, 512KB, 1MB, 2MB, 4MB, 8MB, 16MB, 32MB, 64MB, 128MB, 256MB, 512MB, 1GB, 2GB, 4GB, 8GB
\]