Redesigning Go’s Built-In Map to Support Concurrent Operations

March 14, 2017

Abstract

The Go programming language offers many features that simplify the creation of highly concurrent systems. However, it lacks built-in data structures that allow fine-grained concurrent access. In particular, its `map` data type, one of only two generic collections in Go, limits concurrency to the case where all operations are read-only; any mutation (insert, update, or remove) requires exclusive access to the entire map. The tight integration of this `map` into the Go language and runtime precludes its replacement with known scalable map implementations.

This paper introduces the Interlocked Hash Table (IHT). The IHT is the result of language-driven data structure design: it was designed to require minimal modifications to the existing Go `map` API, to support the full range of operations available on the sequential Go `map`, and also to provide a path for the language to evolve to become more amenable to scalable computation over shared data structures. The IHT employs a novel optimistic locking protocol, so that concurrent reads, writes, and iterations can make progress without risking deadlock. The IHT also allows large critical sections that access a single IHT element, and can easily support multi-key atomic operations. These features come at the cost of relaxed, though still straightforward, iteration semantics. In experimentation in both Java and Go, the IHT performs well, reaching up to 7$\times$ the performance of the state of the art in Go at 24 threads. In Java, the IHT performs on par with the best Java maps in the research literature, while providing iteration and other features absent from other maps.

1. Introduction

Safe, scalable, general-purpose concurrency support is an essential feature of modern programming languages [25]. This support typically includes a precisely-defined language-level memory model [2, 23], first-class support for threads and locks [28], and a standard library of highly concurrent data structures that facilitate the coordination of threads via shared memory [19, 16]. It may also include support for specific patterns, such as Communicating Sequential Processes (CSP) [13], Actors [1], and Transactional Memory [15].

As a modern programming language, Go offers many features that support concurrent programming. Its thread abstraction is a multi-CPU variant of Capriccio [30] that can multiplex hundreds of thousands of lightweight *goroutines* onto all the physical cores of a machine. Its *channel* abstraction provides first-class support for CSP, and scales to thousands of threads. Go also allows shared-memory synchronization, through the `sync` package’s `Mutex` and `RWMutex`. The `sync` package also provides atomic versions of primitive data types.

Unfortunately, Go does not provide any scalable concurrent data structures. In a language like Java, such a deficiency could be remedied through updates to a library, and indeed, the `java.util.concurrent` package is continually evolving [19]. However, the Go language does not allow user-defined generic collections. Go provides two built-in, generic, sequential collections, the `map` and `slice` (dynamic array). Both are highly optimized, and tightly integrated into the Go compiler and runtime. To create a scalable collection in a library, a programmer would need to use Go’s opaque `interface{}` type, which incurs an extra level of indirection, and would not be able to employ features that are exclusively available to Go’s sequential `map` and `slice`. For example, the Go compiler generates a suitable hash function for a `map` based on its key type (e.g., for multi-field `struct` keys, it will hash each field of the key), but the mechanisms for doing so are not available to library code.

Go offers an appealing mix of features for data structure design. Like Java, Go has garbage collection, which makes it easier for concurrent data structures to employ speculation: the memory accessed by a thread executing a doomed but incomplete speculation cannot be recycled while any thread retains a reference to it. Go is type-safe, and provides reflection and auto-boxing. Like C++, Go allows fine-grained control of the placement of hardware memory fences, and can avoid indirection by storing data, rather than references, in its built-in collections. Go also allows direct pointer access, through its `unsafe` package.

Because, Go’s `map` and `slice` are tightly coupled with the compiler and run-time system, it is not straightforward to use existing concurrent data structures efficiently. In the case of the `map`, the compiler selects a data layout based on the size of the key and value types, and the run-time interface to the `map` returns a pointer to a map element, rather than performing an insert or lookup directly. Go’s `range` keyword, used for iteration, must produce a randomized starting position. These properties prevent the use of state-of-the-art map implementations (e.g., those from JSR-166): nonblocking Java maps cannot support pointer-based access to map elements, and even the blocking Java maps struggle to guarantee termination if iteration begins from a random starting point.

Our solution is to create a new concurrent map data structure specifically for Go. Our Interlocked Hash Table (IHT) leverages Go’s garbage collection, `unsafe` pointer access, and unconventional iterator semantics, to deliver low latency and high scalability. The IHT is implemented in the Go compiler and runtime, supports concurrent insert, lookup, remove, update, and iteration, and also provides a facility through which programmers can write large critical sections over a single map element, or even multiple elements. In return for these features, the IHT offers weaker iteration guarantees than a sequential map: iteration will never return an item twice, or miss an item that was present for the duration of iteration, but it is not linearizable [12].

The remainder of this paper is organized as follows. In Section 2, we review background material in concurrent data structure design, and then discuss properties of Go that impact the design of the IHT. Section 3 introduces the IHT, and Section 4 discusses IHT implementation. In Section 5, we present performance evaluation, using stress-test microbenchmarks. Lastly, Section 6 summarizes our findings and suggests future work.

2. Background and Related Work

In this section, we briefly discuss the factors that have the most influence on high-performance concurrent data structure design, and also discuss the implementation of the default (sequential) Go map.

2.1. Concurrent Data Structure Design

The first obligation of concurrent data structures is to avoid unnecessary interaction among threads. For lock-based algorithms, using a plurality of fine-grained locks can prevent threads from attaining mutual exclusion over too large of a region of memory, but introduce extra latency for each lock acquire/release. For nonblocking algorithms [10], the state of any thread cannot impede the forward progress of other threads. Particularly appealing are lock-free data structures, which do not allow deadlock or livelock but may admit starvation under pathological interleavings. These are often the most scalable and performant concurrent data structures [6].

Not all data structures can be made lock-free and fast. When an operation must atomically modify multiple locations to achieve its desired change to a data structure, the use of a single atomic hardware instruction, such as compare-and-swap (CAS), may not be sufficient, necessitating the use of a software simulation of multi-word atomic operations (e.g., LLX/SCX [4] or multi-word CAS [22, 8]). The latency of multiple CAS instructions within these simulations, and the complex helping protocols needed to ensure forward progress, can reduce throughput and increase latency. Even when only one CAS instruction per operation is required, many lock-free data structures require atomic copying. For example, updating an element in a nonblocking set typically entails copying the element out of the set, modifying the copy, and then writing the new version back into the data structure. When the collection stores types larger than the machine word size, atomic copying becomes expensive.

Low-level techniques such as optimistic synchronization and laziness are often more important than nonblocking guarantees. A prime example is the lazy list [9]: it provides nonblocking list lookup operations, but uses locks when inserting and removing elements. The key techniques include avoiding lock acquisitions during traversal, validating the presence of a node in the list *after* locking it, leaving marked-but-invalid entries in the list for other threads to clean up at a later time, and leveraging garbage collection to ensure that data being accessed by concurrent "doomed" speculations is not reclaimed and re-allocated until after those speculations restart. The three most popular nonblocking maps also employ some of these techniques: the Split-Ordered List [26] and fixed-size nonblocking hashtable [24] use a nonblocking precursor to the lazy list as their fundamental data structure, and the lock-free resizable hashtable [20] lazily rehashes elements upon overflow of a bucket.

Concurrent data structures typically achieve a strong correctness guarantee, known as linearizability [12]. Linearizability guarantees that every operation appears to happen at a single instant in time, somewhere between when the operation was invoked, and when it provided a response to its caller. In nonblocking data structures, the point at which an operation linearizes is usually some CAS operation it issues. In lock-based data structures, the linearization point is usually some instruction within a lock-based critical section [11].

Linearizable iteration is particularly hard to achieve. The most straightforward approach, atomic snapshots, are complex and may not scale [3]. Worse, programmers wishing to perform modifications during iteration are poorly served by snapshots, which can return a stale copy of a large data structure. As a result, many concurrent data structures have relaxed iterator semantics. In JSR-166, iteration over a priority queue may not return elements in priority order, and iteration over a queue may "miss" elements in the queue. Still, these data structures guarantee that every element returned by the iterator was present in the data structure at the time when the iterator returned it. Several lock-based concurrent skiplists offer non-linearizable read-only iteration [21, 6, 11].

2.2. The Go Map: Implementation and Interface

A simplified description of the interface to the Go map appears in Table 1.[1] The compiler translates map accesses into calls to five core functions. When a `map` is indexed as an `rvalue` (e.g.,`value := map[key]`), a call to `mapaccess` is generated. When a `map` is indexed as an `lvalue` (e.g., `map[key] := value`), a call to `mapassign` is generated. Calls to `delete` an element in the `map` (e.g., `delete(map, key)`) are replaced with a call to `mapdelete`. Finally, both `mapiterinit` and `mapiternext` are generated during a `for...range` iteration over a `map`.

[1]The Go runtime includes several versions of each of these functions, based on the size and type of the key.

`mapaccess(k)`	Returns an internal pointer to the `v` corresponding to `k`, if found.
`mapassign(k, v)`	Inserts `k` and `v` into the map, or updates them if k is already present.
`mapdelete(k)`	Removes `k` and its `v` from the map.
`mapiterinit(map, it)`	Initializes an iterator that iterates over `k`/`v` pairs in a randomized order.
`mapiternext(it)`	Yields a `k`/`v` pair from the map.

Table 1: Compiler API for map accesses. `k` and `v` refer to a key and its value, respectively.

The Go map API fundamentally differs from the interfaces that are common in nonblocking data structure research. The map allows keys with sizes greater than a machine word, and hence techniques that rely on atomic reads of keys, such as the lazy list's wait-free `contains` operation, become significantly more complex. For lookup operations, `mapaccess` explicitly returns an internal pointer to a value inside of the map. This behavior, which resembles barriers in garbage collectors [31], is not compatible with known nonblocking techniques, because the linearization point [12] of the read occurs after the response of the lookup function. In a naïve concurrent implementation of this interface, the internal pointer returned by `mapaccess` could be mutated while it is being accessed by a concurrent operation, yielding undefined behavior.

At the same time, the map interface and specification provide unique opportunities. Iteration is a fundamental feature of Go maps, and is required in order for certain runtime operations to interact with the map; this restricts the use of research concurrent data structures that do not provide iteration. However, the Go map is specified such that programmers cannot expect a map iteration to produce values in any particular order. For our purposes, this enables the use of randomization to prevent convoying when multiple threads iterate simultaneously. Additionally, the Go map is resizable (the implementation will grow, but never shrink, a map), and this is achieved via indirection. Thus concurrent maps need not incur overhead simply for introducing indirection: it is already inherent in the baseline.

3. Design of a Concurrent, Lock-based Map

We now present pseudocode and describe the behavior of the Interlocked Hash Table (IHT). While the presentation is not Go-specific, we assume certain Go features are present, such as garbage collection and simple atomic primitives (i.e., compare and swap (CAS), atomic loads and stores).

Whereas the Go sequential map is a flat array, which is resized by rehashing all elements in the array, our concurrent map is a fixed-depth tree. Figure 1 depicts the shape of the tree, and illustrates seven concurrent operations in-flight. Listing 1 introduces the two main data types used in the map construction: the `PointerList` and the `ElementList`.

The IHT consists of a root `PointerList` and three constants: `DEPTH`, the maximum depth of the tree; `EMAX`, the maximum number of elements in an `ElementList`, and `PINIT`, the capacity of the root `PointerList`. `PointerList` buckets

Listing 1: IHT types. Array sizes are known at construction time, so that arrays can be inlined into `PointerLists`. The `ParentStruct` type encapsulates information about the bucket within the parent `PointerList` that references an object.

```
Fields of PointerList Object:
  l        : CMLock          // spinlock + type identifier
  parent   : ParentStruct    // parent bucket
  size     : Integer         // size of buckets array
  hashkey  : Integer         // seed for hash function
  buckets  : ElementList[]   // pointers to ElementLists
Fields of ElementList Object:
  l        : CMLock          // spinlock + type identifier
  parent   : ParentStruct    // parent bucket
  count    : Integer         // number of active elements
  keys     : KeyType[]       // the keys stored in this ElementList
  values   : ValType[]       // the values stored in this ElementList
```

can be **nil**, reference `PointerLists`, or reference `ElementLists`. Once a bucket references a `PointerList`, it will never again be **nil** or reference an `ElementList`. Excluding the deepest level of the tree, once a bucket references a `PointerList`, it is immutable. At the last level, a bucket may reference a larger `PointerList` in the future.

The novelty of our algorithm draws, in part, from the lock type embedded in both list types. A `CMLock` couples mutual exclusion information with knowledge about the type of the object in which the lock is embedded. The `CMLock` is used as a spin lock, and releasing the lock can always be achieved by subtracting 1. The possible states appear below:

- e_{avail} – An unlocked `ElementList`.
- e_{lock} – A locked `ElementList`.
- p_{inner} – A `PointerList` at depth $< DEPTH$. Such `PointerLists` are always unlocked.
- p_{term} – An unlocked `PointerList` at $DEPTH$.
- p_{lock} – A locked `PointerList` at $DEPTH$.
- *GARBAGE* – A locked list undergoing rehashing.

Both `ElementLists` and `PointerLists` are organized so that their first word is a `CMLock` field. This enables us to reference either type from a `PointerList`: the lock state suffices to indicate the object type.

3.1. IHT Behavior

Figure 1 shows seven concurrent operations, which illustrate the key behaviors of the map. Each of these operations is represented by a number in a black circle, and is described below. In the figure, vertical stacks of rectangles indicate `PointerLists`, and horizontal stacks indicate `ElementLists`. White locks are unheld, gray locks are held, and black locks are *GARBAGE*. Gray boxes represent occupied positions in an `ElementList`, and striped boxes indicate the location where an action (lookup, insert, remove) takes place. Curved lines represent atomic stores; dashed lines represent `CAS` operations.

Operation 1 could be an insert, lookup, or remove. It hashes its key, using the hash function of the root `PointerList`, and finds an ElementList. If it can lock that `ElementList`, it can

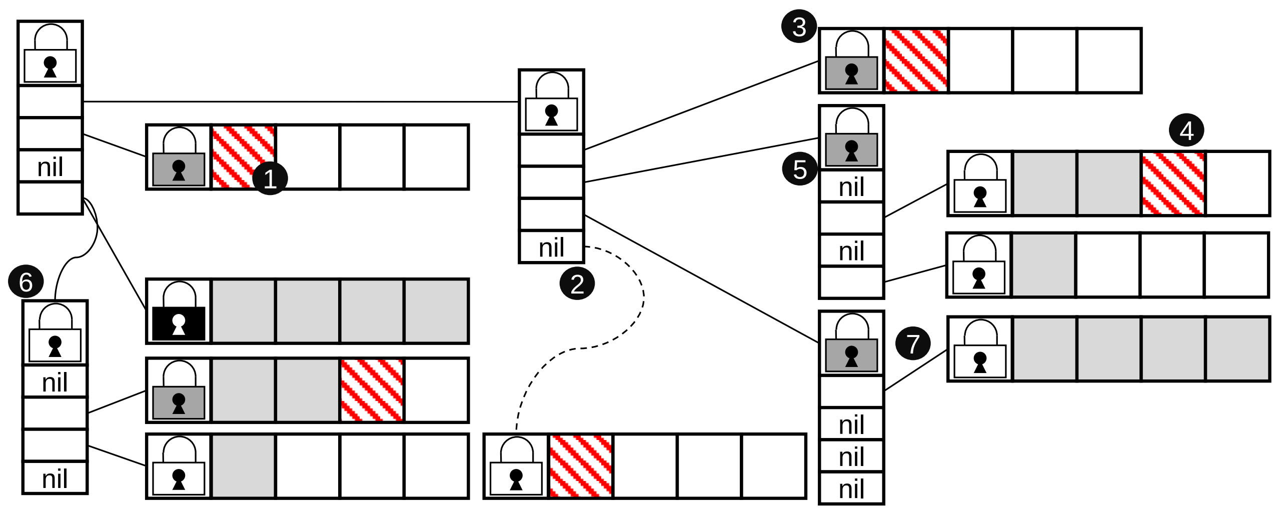


Figure 1: Concurrent hash shape and behavior. `PINIT` and `EMAX` are set to 4. `DEPTH` is set to 2. To avoid clutter in the figure, `PointerLists` at level $n, n < DEPTH$ are shown with size `PINIT`. In Section 5, these `PointerLists` will have a size of $n \times$`PINIT`

search through the list and decide whether the first element matches the provided key. If it matches, a lookup will return the value, whereas an insert will update it. A remove will remove the key/value pair from the `ElementList`. In this case, since the `ElementList` becomes empty, it will be marked as garbage, and its parent's pointer will be set to **nil**. If the key does not match, a lookup or remove will return an appropriate failure result, but an insert will add a new key/value pair to the `ElementList`.

Operation 2 encounters an inner `PointerList`, but when it hashes its key at that list, it finds a **nil** bucket. If it is an insert, it constructs a new `ElementList`, inserts its element into the list (as a striped block), and then replaces the **nil** bucket with a reference to the new `ElementList`, via a `CAS`.

Operation 3 is identical to Operation 1, except the operation is on an `ElementList` at the maximum depth; It locks this `ElementList`. In contrast, when Operation 4 reaches a `PointerList` at the same level, it acquires the `PointerList`'s lock, traverses once more, locates its desired `ElementList`, but does not acquire another lock, since it already acquired the lock of its parent.

Operation 5 is blocked attempting to acquire the lock on the `PointerList` owned by Operation 4. This is a necessary consequence of the fixed depth of the map: even if the operation would hash to a different bucket than Operation 4, it cannot run concurrently with Operation 4.

Operation 6 is a common-case resize: an insertion encounters a full `ElementList` that is not at *DEPTH*. It marks the `ElementList` as *GARBAGE*, which does not release the lock, creates a new `PointerList`, and rehashes both the `ElementList`'s elements, and the key/value pair it is adding, into it. Finally, it installs the `PointerList` by atomically overwriting the reference to the now-defunct `ElementList`. Note that if Operation 3 encountered a full `ElementList`, it would operate in the same manner.

Operation 7 is a resize at maximum depth. The figure does not show the completed state, only the point where the `ElementList` is found to be full. From there, the thread would create a new locked `PointerList` with more capacity than the old locked `PointerList`, copy all elements from all child `ElementLists` of the old `PointerList` into children of the new `PointerList`, and then perform its operation on a child of the new list. Finally, it would install the new `PointerList`, using an atomic store.

3.2. Algorithm Correctness and Key Properties

Having sketched the key behaviors of the concurrent map, we now present pseudocode and discuss the key invariants to ensure the correctness of the synchronization mechanisms. To simplify the discussion, we encapsulate the traversal and expansion behaviors of the map in a single function, `GetEList` (Algorithm 1). Specific insert, lookup, and remove operations are then presented in Algorithm 2

The algorithm for finding an ElementList carries a few simplifications: it does not backoff when encountering a held lock, and sometimes inserts an `ElementList` or rehashes into a new `PointerList` during a lookup or remove for a key not present in the map. While these inefficiencies are not present in our implementation, they simplify the discussion below. We also use the shorthand of `EToP` and `PToBiggerP` to represent the sequential operations of hashing an `ElementList`'s elements into a new `PointerList`, and rehashing a `PointerList`'s elements into a larger `PointerList`, respectively.

As a lock-based algorithm, the correctness arguments are substantially simpler than in the case of non-blocking data structures. In particular, note that an operation never requires

Algorithm 1: Concurrent map expanding traversal

```
// Given a map and key, this function returns a locked ElementList within that
// map, representing the sole place where that key may exist
function GetEList ($map, key$)
    $curr \leftarrow map$ // The search path and its top
    $(found, l) \leftarrow (nil, nil)$ // The ElementList and its lock
    loop
        $idx \leftarrow curr.hash(key)\%curr.size$
        $next \leftarrow curr.buckets[idx]$
        // on nil bucket, insert new ElementList; ensure one lock is held
        if $next = nil$ then
            $found \leftarrow$ new ElementList$(0, e_{avail})$
            if $l = nil$ then
                $found.lock \leftarrow e_{lock}$
                $l \leftarrow found$
            if $cas(\&curr.buckets[idx], nil, found)$ then
                return $\langle found, l \rangle$
        // if bucket is a terminal PointerList, lock it and traverse
        else if $next.lock = p_{term}$ then
            if $cas(\&next.lock, p_{term}, p_{lock})$ then
                $l \leftarrow curr \leftarrow next$
        // on inner PointerList, traverse
        else if $next.lock = p_{inner}$ then
            $curr \leftarrow next$
        // if ElementList, we may need to resize
        else if $next.lock = e_{avail}$ then
            // Ensure one lock held and stored in l
            if $l \neq nil \vee cas(\&next.lock, e_{avail}, e_{lock})$ then
                if $l = nil$ then $l \leftarrow next$
                // if bucket not full, return it
                if $next.count < EMAX$ then
                    return $\langle next, l \rangle$
                // if key in bucket, return it
                if $next.bucket.contains(key)$ then
                    return $\langle next, l \rangle$
                // Need to resize. Invalidate the ElementList
                $next.lock \leftarrow GARBAGE$
                // Simple case: no locked PointerList
                if $curr.lock = p_{inner}$ then
                    // Create PointerList from ElementList
                    $p \leftarrow EToP(next, p_{inner})$
                    if $backPath(p, map) = DEPTH$ then
                        $p.lock \leftarrow p_{lock}$
                        $l \leftarrow p$
                    // atomically install new PointerList
                    atomic $curr[idx] \leftarrow p$
                // Tricky case: need to resize locked PointerList
                else
                    // Create larger PointerList from old PointerList
                    $p \leftarrow PToBiggerP(curr)$
                    $p.lock \leftarrow p_{lock}$
                    $curr.lock \leftarrow GARBAGE$
                    $l \leftarrow p$
                    // replace curr with p in curr's parent
                    atomic $curr.parent.setTo(p)$
                    // prepare for next iteration, with p replacing curr
                    $curr \leftarrow p$
```

Algorithm 2: Insert, lookup, and removal operations

```
function Lookup ($map, key$)
    $res \leftarrow NOTFOUND$
    $(elist, lock) \leftarrow$ GetEList$(map, key)$
    for $i \in 0 \dots elist.count - 1$ do
        if $elist.keys[i] = key$ then
            $res \leftarrow \langle elist.keys[i], elist.values[i] \rangle$
            break
    $lock.release$
    return $res$

function Insert ($map, key, value$)
    $(elist, lock) \leftarrow$ GetEList$(map, key)$
    for $i \in 0 \dots elist.count - 1$ do
        if $elist.keys[i] = key$ then
            $elist.values[i] \leftarrow value$
            $lock.release$
            return
    $elist.keys[count] \leftarrow key$
    $elist.values[count] \leftarrow value$
    $elist.count \leftarrow elist.count + 1$
    $lock.release$

function Remove ($map, key$)
    $(elist, lock) \leftarrow$ GetEList$(map, key)$
    for $i \in 0 \dots elist.count - 1$ do
        if $elist.keys[i] = key$ then
            $elist.keys[i] \leftarrow elist.keys[elist.count - 1]$
            $elist.values[i] \leftarrow elist.values[elist.count - 1]$
            $elist.count \leftarrow elist.count - 1$
            break
    $lock.release$
```

more than one lock, and hence deadlock is not possible. The ability to avoid multiple lock acquisitions is a direct consequence of the state transition mentioned above: if a bucket points to an inner `PointerList`, then the bucket is immutable, and the enclosing object need not be locked in order to read that bucket's value. This sort of inductive, speculative object access is inspired by RCU [5], sequence locks [18], and Software Transactional Memory [27].

Another key feature of the algorithm is that (excluding max-depth `PointerLists`), the lock protecting an `ElementList` is embedded in the list itself, not in its parent. This improves locality, since common-case insert and remove operations only perform writes to a single object. Furthermore, since locks protecting references are in the payload `ElementLists`, instead of the parent `PointerLists`, we do not require padding of the pointers in the `PointerList`: they are read-shared in the cache.

Armed with the `GetEList` function, Algorithm 2 presents lookup, insert, and remove operations. They employ the same pattern: they use `GetEList` to get a locked `ElementList` in which their operations can occur. They perform their operation, and then unlock the `ElementList`.

3.3. Iteration

Go requires its map to support iteration, with a caveat: the iteration order is not guaranteed to be the same, even if the map is unchanged from the previous iteration. While this feature was not designed with concurrency in mind, it is an essential enabler for our iteration algorithm.

A sketch of the iteration algorithm appears Algorithm 3. To iterate through the map, we begin by selecting a random bucket in the root `PointerList`. From that point, we iterate over the entire set of buckets in the root, via a linear traversal. For each bucket, we follow roughly the behavior of `GetEList`: If the bucket is `nil`, it is skipped. If it is an `ElementList`, we lock it and then iterate over its elements. If it is an inner `PointerList`, we recurse into it, select a random starting point, and repeat the process. During the recursion, if we en-

Algorithm 3: Simplified pseudocode for iteration. For clarity of presentation, we do not limit *DEPTH*.

```
// Perform a function ($\lambda$) on every element of the map
function StartIteration ($map, \lambda$)
       // Keep track of passed-over buckets
1      $deferred \leftarrow$ new $set\langle PointerList, Integer\rangle()$
2      EnterPList ($map, \lambda, deferred$) // Recall: the map is a PointerList
3      HandleDeferred ($\lambda, deferred$) // Visit passed-over buckets

// Visit each bucket of a PointerList, starting at a random position
function EnterPList ($plist, \lambda, deferred$)
1      $start \leftarrow random(plist.size)$
2      for $i \in 1 \ldots plist.size$ do
3          ProcessPList ($plist, (start + idx)\%plist.size, \lambda, deferred$)

// Within a bucket, decide whether to recurse or process an ElementList
function ProcessPList ($plist, i_p, \lambda, deferred$)
1      if $plist[i_p] = nil$ then
2          return // no data to pass to $\lambda$ from this bucket
3      else if $plist[i_p].lock = p_{inner}$ then
           // Recurse into child PointerList
4          EnterPList ($plist[i_p], \lambda, deferred$)
5      else if $plist[i_p].lock = e_{avail} \wedge cas(\&plist[i_p], e_{avail}, e_{lock})$ then
           // Iterate over entries in locked ElementList
6          for $i \in 1 \ldots plist[i_p].count$ do
7              $\lambda(plist[i_p].keys[i], plist[i_p].values[i])$
8          $plist[i_p].lock = e_{avail}$
9      else
           // Bucket is garbage, locked, or being resized... defer processing
10         $deferred \leftarrow deferred \cup \langle plist, i_p\rangle$

// Handle PointerList elements that were deferred
function HandleDeferred ($\lambda, deferred$)
1      for $\langle plist, i_p\rangle \in deferred$ do
2          if $plist[i_p].lock = p_{inner}$ then
               // Bucket was rehashed, so recurse into it
3              $deferred \leftarrow deferred - \langle plist, i_p\rangle$
4              EnterPList ($plist[i_p], \lambda, deferred$)
5          else if $plist[i_p].lock = e_{avail} \wedge cas(\&plist[i_p], e_{avail}, e_{lock})$ then
               // Iterate over entries in locked ElementList
6              $deferred \leftarrow deferred - \langle plist, i_p\rangle$
7              for $i \in 1 \ldots plist[i_p].count$ do
8                  $\lambda(plist[i_p].keys[i], plist[i_p].values[i])$
9              $plist[i_p].lock = e_{avail}$
10     if $deferred \neq \{\}$ then
11         $optionalBackoff()$
12         goto 1
```

counter a terminal `PointerList`, we lock it, and then recurse into it, taking care not to lock its `ElementLists`. To reduce convoying, we maintain per-iteration lists of "busy" objects. Whenever an iteration encounters a locked `ElementList` or `PointerList`, we save the address of its parent's reference to it, and defer visiting it until later in the execution.

There are several benefits to this algorithm. Only one lock is held at a time, and hence iteration cannot deadlock with other iterations, or with concurrent lookup/insert/remove operations. Second, Go's requirement of an unpredictable iteration order is enhanced: rather than pick a random starting point in a single flat array, we randomize at the level of each `PointerList`. Third, the fact that randomization is built into the language provides a guard against convoy effects: iterators do not start at the same point, and hence are unlikely to visit `ElementLists` in the same order. The guaranteed variation in order also allows us to maintain the busy object list, without presenting unexpected behavior to the programmer. In essence, Go's desire to prevent programmers from relying on implementation artifacts transforms into a language-level semantics that enables concurrent iteration with minimal waiting. However, as discussed in Section 4.3, the iterator's guarantees are weaker than Go's sequential map.

4. Implementation

The IHT provides the same API as the sequential map. As we shall see in Section 5, this does not hold for library-based concurrent maps for Go. In this section, we describe the IHT implementation, and discuss the guarantees it provides.

4.1. Compiler Integration and Transformations

As discussed in Section 2.2, the default Go map implementation is tightly coupled with the compiler and runtime. To provide the same syntax for the IHT, it must be implemented by the compiler as well. However, the existing compiler infrastructure is insufficient: a `mapaccess` does not return a value, but instead returns a live, internal pointer into the map. While we can acquire the lock protecting the referenced data before `mapaccess` returns, it is unreasonable to delegate lock release to the programmer.

When the compiler generates a `mapaccess` call, the returned pointer is live for a short duration. The next instruction dereferences the pointer, either to `memcpy` the (large) value to memory, or to copy the (machine word-sized or smaller) value to a register. Immediately thereafter, the pointer is not live; consequently, the lock can be released. In our lock implementation, the same function releases the lock, regardless of whether it protects an `ElementList` or a `PointerList`. However, the lock may be hard to locate, if the returned value is in an `ElementList` reached from a maximum-depth `PointerList`.

Our solution is for `mapaccess` to return references to both the lock and the value. This increases the coupling between the IHT and the compiler, but saves overhead, as the tree need not be re-traversed to find the lock. An additional complication is that multiple calls to `mapaccess` could occur in a single statement (e.g., `a = m[b] + m[c]`). The current Go implementation performs the accesses sequentially, and thus we only hold one lock at a time. In the interests of remaining future-proof, we observe that the keys could hash to the same `ElementList`. If the Go compiler were to allow both pointers to be live simultaneously, in addition to needing deadlock avoidance we would need to make our spin locks reentrant.

4.2. The sync.Interlocked Interface

The above mechanism provides atomicity for individual map accesses, but not atomicity for multiple statements accessing the same map element. For complex individual statements, we could automatically defer all lock releases until the end of the statement, but doing so would introduce the possibility of deadlock when multiple map accesses, with different keys, are performed in a single statement.

Instead, we provide a means for exposing the map's locks to the programmer. The `sync.Interlocked(map, key)` library function acquires the lock associated with a particular key in a particular map, and `sync.Release(map)` releases that key's lock. Between the calls, a thread can make multiple accesses to a map element, without intermediate results being visible to other goroutines. Exposing these operations as functions, instead of as a keyword and lexical scope, supports the Go idiom in which the `defer` keyword can be used to ensure that locks are released upon error.

When `sync.Interlocked` is passed a key not present in the map, room for the key/value pair is created in the map. We extended the runtime to track uses of the pair; if an automatically-created pair is never assigned, it is deleted during `sync.Release`. Similarly, if a key is deleted from the map during `sync.Interlocked` execution, the space is not reclaimed until `sync.Release`.

Each goroutine has a private context, which is visible only to the runtime. This context can be used in scenarios where runtime features require thread-local storage. In our implementation, interlocked access exploits this space to optimize map accesses: in the IHT's `mapaccess`, `mapassign`, and `mapdelete` functions, as well as the lock release functions we insert during compilation, we check if an interlocked operation over the map/key combination is active. If so, all traversal required to locate the key/value pair can be elided, as can any locking/unlocking.

Go includes run-time facilities for detecting races and dangerous behaviors. In the case of `sync.Interlocked`, we track its use during execution, and ensure that multiple keys from the same map are never simultaneously interlocked by one goroutine. Since the mapping of keys to `ElementLists` is invisible to the programmer, this ensures that deadlocks will not occur when the run-time choice of hash function leads to two goroutines issuing conflicting interlocking accesses while holding locks. (Note that when atomicity can be ensured through other means, the programmer can use a new goroutine to concurrently access other keys in the map. If the goroutine conflicts with the parent, it will block until the parent's interlocked execution completes.) Leveraging goroutine-local storage, ensures there is little overhead for dynamic checks to detect and prevent acquisition of multiple locks during interlocked execution. We do, however, allow overlapping interlocked accesses to *different* maps, since it ought to be possible for programmers desiring this ability to design a safe locking order.

It is trivial to add support for multi-key interlocked execution, if the keys are known statically. Deadlock is not possible because the locks can be acquired in an order that is equivalent to in-order traversal of the IHT: all that is required is to hash all keys before acquiring any locks. To handle keys that map to the same `ElementList`, and to continue to support race detection, requires overhead linear in the number of keys.

4.3. Iteration

Existing approaches to iteration in concurrent collections take one of two approaches. On the one hand, an atomic snapshot provides a copy of the collection, such that there existed a point in time when the contents of the collection were identical to those presented in the snapshot. On the other hand, non-atomic iteration provides weaker guarantees, but is typically less costly. For example, in Java, an iteration through a concurrent collection is not linearizable: it can "miss" items that were concurrently added by other threads.

Despite the appeal of atomic snapshots, we deemed them impractical for the IHT. If we were to provide snapshots without copying, then an iteration would continually grow its lock set, until it held locks over the entire map. Such a technique would strangle concurrency, and forbid concurrent iteration. Indeed, since Go specifies iteration returns keys in a random order, we would need to eagerly serialize all iterations, since concurrent iterations would otherwise start at different parts of the map and then deadlock. If, instead, we created a snapshot by copying all map contents to a temporary location, we would incur space overhead proportional to the number of concurrent iterations. This could cause out-of-memory errors for large maps. Furthermore, a copy-based atomic snapshot offers weak guarantees to programmers: a key in the snapshot may no longer be present in the map, necessitating additional error handling.

Our approach is more like that in Java. Our iterator holds one lock at a time, and generates values from one locked subtree at a time. Since resizing is localized to a subtree of a `PointerList`, we can safely release one lock before acquiring the next: once an element is visited during iteration, it cannot be moved such that the iterator encounters it again. This simplifies reasoning about correctness: since only one lock is held by an iterator at any time, two iterations cannot deadlock. At the same time, while some key/value pairs can be missed, every pair returned by the iterator is guaranteed to be present in the map at the time it is returned. Furthermore, the pair is present in a locked subtree, owned by the thread performing the iteration. Consequently, the iterating thread can safely modify or remove the pair without racing with concurrent map operations that attempt to use the same key.

5. Performance Evaluation

In this section, we explore two performance criteria. First, we evaluate the performance of the IHT algorithm against state-of-the-art. We perform this evaluation in Java, so that all algorithms can be on the same footing. The experiments focus on the common set of operations available to the IHT and its competitors: insertion, removal, and lookups of a single element. Second, we look at the behavior of the IHT when implemented in Go, and compare against the best concurrent map implementations for Go. The experiments consider both elemental operations and iteration.

Both sets of experiments were conducted on a machine with two Xeon X5650 CPUs (6 cores/12 threads per CPU), 12 GB of RAM, Ubuntu Linux 16.04.1 (kernel version 4.4.0), and the Go 1.6 compiler. We used the 64-bit Server JVM version 1.8.0_11-b12. We conducted additional experiments (not presented in this manuscript) on a single-chip Core i7-4770, and observed the same performance trends.

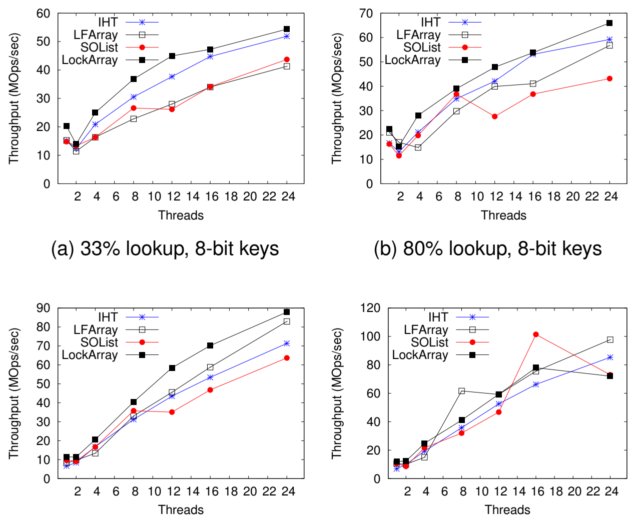
5.1. Raw IHT Performance Evaluation in Java

The two most scalable known hash table implementations [6] are the Split Ordered List (SOList) [26] and the resizable non-blocking hash set (LFArray) [20]. Both are lock-free data structures with highly optimized implementations in Java. Based on these data structures, we consider three comparison points:

- The SOList uses a sorted lock-free list [7, 24] to store key/value pairs, and employs an auxiliary fixed-depth "directory" of hash values to rapidly jump to the position within the list where an insert, remove, or lookup should take place. To iterate over the SOList, a thread accesses the underlying list directly. As a nonblocking data structure, operations are achieved by using a CAS to insert or remove a list node. Update operations, which replace a key's value with a new value, are not supported, and the most common benchmark of the SOList is as a nonblocking integer set. The SOList can expand while preserving $O(1)$ overhead, but like the IHT, can not shrink in response to a significant decrease in the number of items it holds.
- The LFArray uses one level of indirection to reach an array of pointers to "freezable sets", or "FSets". An FSet resembles our `ElementList`, in that it includes an array of keys. Like the SOList, a lookup does not require any CAS, and reaches the appropriate FSet in $O(1)$ time. However, to insert or remove an element, the LFArray uses copy-on-write of an FSet, and then uses a CAS to install the copy. The LFArray resizes (both expanding and shrinking) by creating a new array, and then lazily moving elements into it.
- The LockArray is a lock-based version of the LFArray. The use of locks within FSets avoids copying. However, lookups must lock an FSet before performing a lookup, which can create more overhead in read-dominated workloads.

In all three cases, the data structure places constraints on the hash function, in order to ensure the correctness of resizing. For consistency, we use the same hash function for the SOList, LFArray, LockArray, and our Java IHT implementation.

Strictly speaking, the available Java implementations of LFArray. LockArray, and SOList are not maps, but rather hash sets. We emulate a set in our Java IHT implementation by making the value equal the key. Figure 2 compares the four algorithms with two different key ranges (8-bit and 16-bit), and two different operation mixes: On the left, inserts, lookups, and removes are selected with equal probability. On



(a) 33% lookup, 8-bit keys (b) 80% lookup, 8-bit keys

(c) 33% lookup, 16-bit keys (d) 80% lookup, 16-bit keys

Figure 2: Microbenchmark performance in Java

the right, 80% of operations are lookups, with the remainder split between inserts and removes. Note that a slowdown at 2 threads is expected, due to cross-chip communication.

When the key range is 8-bits, `LockArray` has the best performance, and IHT performs second best. In these cases, SOList suffers from the overhead of its directory, and LFArray suffers from wasted work: if two operations are simultaneously copying the same bucket, one will eventually fail and retry its operation. In such cases, throughput is better when one of those threads waits on the other, via a spinlock, and then modifies an object without performing a copy. In the 8-bit experiment, the shape of the LockArray and IHT are virtually the same, with the main difference being the cost of lock acquisition: in LockArray there are simple spinlocks, whereas IHT must use the slightly more complex `CMLock`.

With 16-bit keys, the IHT has additional levels of indirection versus the LFArray and LockArray. Thus while all algorithms scale roughly equivalently, the IHT pays a penalty. In addition, we see that at 80% lookup, the lock-free algorithms are more likely to outperform the lock-based ones: when conflicts are rare, the lock-free techniques avoid any CAS overheads on 80% of their operations. This more than compensates for the cost of copying in the LFArray, and for the cost of pointer chasing in the SOList. However, the IHT provides stable, scalable performance that remains competitive. In particular, the high rate of memory allocation in the SOList leads to unstable performance.

These experiments are tipped slightly in favor of prior work, since the IHT uses a key and value, while the other data structures only manage a key. Nonetheless, the IHT always shows good scalability. Furthermore, the IHT supports features that are not available in those data structures, such as iteration (not present in the LFArray and LockArray) and a map interface (not present in the SOList and LFArray). We now turn our attention to the Go language, where we can assess the importance of our tight integration into the Go `map` API.

5.2. The Benefit of Integrating Into Go

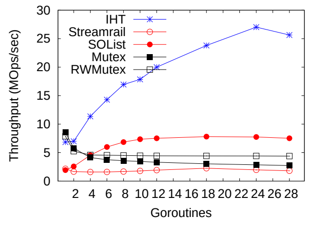
We now evaluate IHT performance in Go. Integration of the IHT into Go was not trivial, requiring several thousands of lines of changes to the Go compiler and run-time libraries. However, doing so made it possible to leverage the same features as are available to the sequential Go `map`.

The LFArray and LockArray algorithms do not support iteration: if a resize occurs, it is possible for an item to be visited twice, or missed entirely. Thus we only carry forward the SOList and IHT evaluation from the prior section. In this case, we use the open-source SOList implementation, available in the `gotomic` [32] package. Note that it supports a map interface, instead of the set interface of the Java SOList implementation. We add three more comparison points:

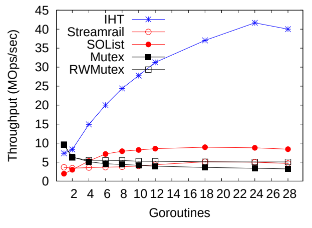
- Streamrail – A lock-based map, implemented as a fixed-size array of RWMutex-protected Go maps [14].
- RWMutex – A RWMutex-protected default Go map.
- Mutex – A Mutex-protected default Go map.

Of these implementations, SOList and Streamrail are library-based. Since neither is integrated into the Go run-time, each must provide its own hashing strategy. SOList allows arbitrary key types, but the programmer must provide an appropriate hash function. Streamrail requires keys to be strings, and values to be `interface{}` (Go's opaque type), and then uses its own hash function. We used the default configuration for each map: in Streamrail, there are 32 buckets in the top-level map. In SOList, there is no bound on the maximum depth of the directory tree that indexes into the underlying lock-free list.

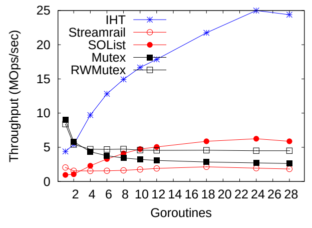
We configured the IHT with 8-entry `ElementLists` and variable `PointerList` sizes: the root `PointerList` was 32 elements, with a doubling of `PointerList` capacity at each subsequent level. With this configuration, and a default *DEPTH* of 4, the IHT can grow to hold up to 53M elements without resizing a last-level `PointerList`. When configured to store 64-bit integer key and 64-bit integer value pairs, the IHT grew to require roughly 2GB of RAM when 10M random elements were inserted, whereas the default Go map consumed 600MB to hold the same data. We ran the same test with Streamrail's Concurrent Map, which is backed by 32 Go maps. Each of Streamrail's maps holds fewer elements, but must be resized independently, resulting in 1.1GB of memory consumption. The SOList, which uses a linked list as its underlying data structure, requires many small allocations. Even though it is free of internal fragmentation, the cost of individual list nodes results in a total space overhead of 2.6GB. When elements are removed from the SOList, marker nodes in the list, and all nodes of the directory, must remain. However, nodes holding data can be reclaimed. Similarly, in the IHT, removals result in `ElementLists` being reclaimed, but not `PointerLists`. The IHT shrinks to about 500MB when filled



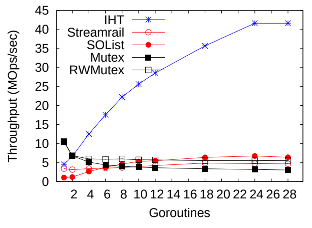
(a) 33% lookup, 8-bit keys



(b) 80% lookup, 8-bit keys



(c) 33% lookup, 16-bit keys



(d) 80% lookup, 16-bit keys

Figure 3: Microbenchmark performance in Go

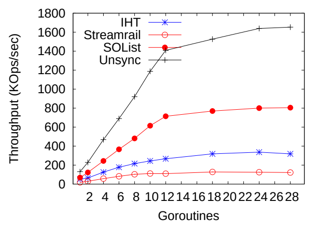
with 10M elements and then emptied. The Go map, and the set of maps in Streamrail, never shrink.

Microbenchmark Performance Figure 3 repeats the experiments from Section 5.1. However, now integer keys are 64 bits, and each implementation stores a byte-sized value at each key. As before, we consider 8-bit and 16-bit keys, and 33% and 80% lookup ratios. Again, each data point is the average of 10 trials.

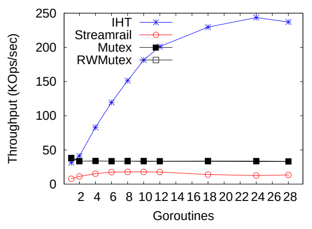
Surprisingly, the IHT's raw performance is worse in Go than in Java. Some of this is attributable to a different testing harness. The remainder is due to differences between the Go compiler's static inlining policy, and the ability of the JVM to inline at run time, based on a program profile. We suspect that differences in garbage collection algorithms could also explain part of this gap. In all cases, these are overheads that are common to all of the Go map implementations we considered, and do not affect relative performance.

As expected, the IHT has more latency than a lock-protected default map. At one thread, Go's `mutex` implementation is very efficient, and its map is highly optimized for sequential code. There is only one level of indirection in the common case, all hashing is performed in the runtime, and the use of a single flat array to store all data results in good locality. While the IHT also has good locality and an efficient lock implementation, it has more indirection: in the 8-bit case, some ElementLists are reached directly from the root PointerList, but since we use the built-in Go hash function, collisions cause some elements to have two PointerLists before the ElementList is reached. For the 16-bit case, the cost goes up to three PointerLists for some keys, or four levels of indirection.

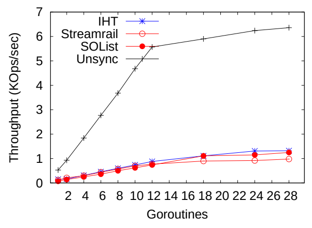
The IHT outperforms the SOList and Streamrail at one goroutine. In the case of SOList, the implementation keeps the depth of the directory low, but each key/value pair is in



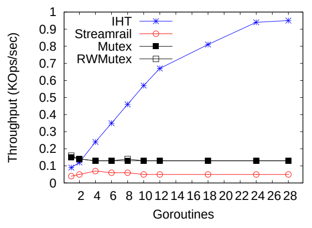
(a) Read-Only, 8-bit keys



(b) Read/Write, 8-bit keys



(c) Read-Only, 16-bit keys



(d) Read/Write, 16-bit keys

Figure 4: Iteration microbenchmark

its own list node, leading to little locality. In Streamrail, the overhead of string types for the keys, and one additional level of indirection for the sub-maps, create less latency than SOList, but more than IHT.

The IHT quickly scales past the default Go maps. At 2 goroutines, the IHT matches the 2-goroutine performance of the Go map, and at 4 goroutines, the IHT outperforms the Go map's peak performance. It then scales up to the full size of the machine (24 hardware threads), with a slight bend at 12 goroutines (where simultaneous multithreading (SMT) [29] begins). While the RWMutex provides better performance than a simple Mutex, cache contention for the lock is a significant impediment to scalability even when 80% of operations are read-only.

Neither the SOList nor Streamrail scales as well as the IHT. This is even true in SOList with 80% lookups, where SOList lookup operations do not use any `CAS` instructions. We identified three main causes for the superior scaling of IHT. First, the Go SOList implementation relies on shared counters to manage the maximum depth of its directory, and these counters can become a bottleneck, especially on multi-chip machines. Second, Streamrail's use of a lock table, instead of locks embedded with data, means that concurrent lock acquisitions can cause cache invalidations in concurrent hardware threads. Lastly, the SOList provides less locality than IHT, since each key/value pair is its own list element. With 16-bit keys, the cost is especially great, since the key range causes an increase in the depth of the SOList directory, and directory nodes also have little locality.

5.3. Iteration Performance

One of the essential features of the IHT is its support for iteration. We created a microbenchmark with a 100% mix of iterations by each goroutine. The map is pre-filled with either 256 or 64K elements, but now we consider two iteration approaches: read-only, in which no operation changes a value or inserts/removes elements, and read-write, in which all operations change the value of each key they encounter. We count a complete iteration through the data structure as a single operation.

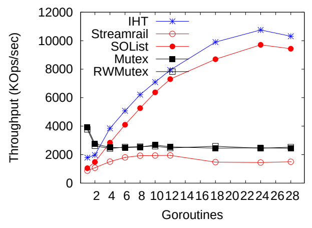
For read-only iteration, no concurrency control is required. In this case, Go allows concurrent access to the default map. Thus in Figure 4, we compare IHT, Streamrail, SOList, and an unsynchronized map. When there is no Mutex to acquire, the unsynchronized map scales perfectly up to 12 goroutines, and then continues to scale, at a slower rate, as SMT results in hardware threads sharing cores.

For small maps, the SOList also outperforms the IHT under read-only iteration. The SOList's nonblocking implementation can avoid any `CAS` instructions during an iteration, and the lack of insert and remove operations avoids the need for any accesses to the shared counters used by the SOList to manage directory height. Thus the SOList enjoys disjoint-access parallelism [17]. In contrast, the IHT is unaware of the read-only nature of the workload, because it uses the Go map interface (in which reads and updates use the same API call). Thus each iteration acquires many locks. With 16-bit keys, however, the cost of locking in IHT is roughly equal to the indirection overheads and lack of locality in SOList, and the two maps perform equivalently.

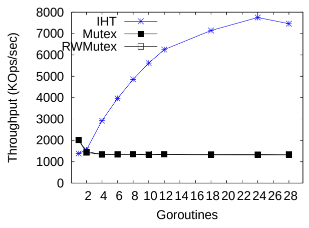
Both SOList and IHT outperform Streamrail. For a single iteration operation, Streamrail creates one goroutine per bucket, and then each of the 32 goroutines executes in parallel. While the locks protecting the buckets are acquired for reading, and hence goroutines can make progress, each tick along the X axis corresponds to an additional 32 goroutines launching and coordinating with their parent, each time the parent performs an iteration. These goroutines communicate with the parent goroutine via channels, and the aggregate overhead is greater than the gain in concurrency.

Unfortunately, SOList does not support mutating iteration, because the nonblocking implementation cannot guarantee that, upon returning a key/value pair, that pair remains in the map. Streamrail provides mutating iteration, so long as there are not concurrent insert/remove/lookup operations. As with read-only iteration, the heavy use of goroutines creates high latency. In addition, the per-bucket locks must now be acquired exclusively, rather than in read mode. With only 32 buckets, and 32 goroutines per thread, most goroutines are blocked at any time on our 24-thread machine.

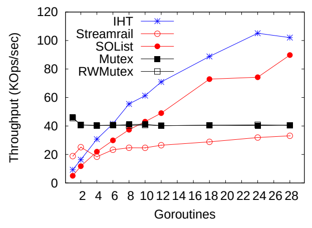
Comparison of IHT to mutating iteration in a mutex-protected default Go map shows equivalent performance at 2 threads, with IHT outperforming the peak Go map performance at 4 threads and above. With 8-bit keys, our convoy avoidance plays an essential role. As concurrency increases, goroutines scatter through the IHT as they choose random starting points. However, with such a shallow tree, goroutines quickly collide as concurrency passes 8 goroutines. By defer-



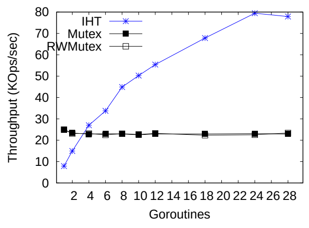
(a) Read-Only iteration, 8-bit keys



(b) Read/Write iteration, 8-bit keys



(c) Read-Only iteration, 16-bit keys



(d) Read/Write iteration, 16-bit keys

Figure 5: Mixed workload with 2.5% iteration, and remaining operations split evenly among lookups, inserts, and removes.

ring processing of locked ElementLists, and revisiting them later, the average iteration avoids spin-waiting entirely.

We observe that Streamrail, SOList, and IHT all provide weak iteration guarantees. In Streamrail, one sub-map is locked at a time, and thus each element returned by the iterator is present in the map, but the set of returned elements is not an atomic snapshot. In SOList, one element is returned at a time, without preventing concurrent mutations throughout the remainder of the underlying list. SOList cannot handle mutation during iteration. IHT's behavior is like Streamrail: every element that is present in the map for the duration of an iteration is returned by the iterator, but the entire set of returned items is not an atomic snapshot.

5.4. Combined Performance

Lastly, we consider workloads in which iteration is concurrent with inserts, lookups, and removals of key/value pairs. As above, we count each iteration across the map as a single operation. However, threads now have a 2.5% chance of performing an iteration, with the remaining operations split evenly among inserts, lookups, and removes. We consider read-only iteration and read-write iteration. In the case of read-only iteration, the possibility of concurrent accesses necessitates that the default Go map be protected by a Mutex. Again, SOList does not allow read/write iteration, and is not presented. Additionally, Streamrail deadlocks for the read/write workload, because of a race when the number of elements in a sub-map changes after an iterator creates the channels used by its spawned goroutines.

The results in Figure 5 represent a composition of the prior two sets of experiments. In both SOList and IHT, neither iteration nor elemental operations impedes the expected performance of the other, and both scale well. These experiments also represent the first time that SOList's peak performance is greater than the default Go map's peak. In the 8-bit test with read-only iteration, where SOList's iteration greatly outperformed IHT before, we now see equivalent performance, tipping slightly in favor of IHT. In the 16-bit case, where SOList and IHT had equivalent iteration performance, the higher performance of IHT's elemental accesses gives it a slight edge. As in Figure 4, adding goroutines does not lead to contention in the IHT, despite long-running iteration. The invariant that operations only hold one lock at a time, coupled with randomized start points for iteration, result in steady scaling. In contrast, read-only iterations, which reduce the rate at which shared counters are modified, reduce the significance of a bottleneck in SOList, and help it to recover performance relative to its scaling in Figure 3.

6. Conclusions and Future Work

In this paper, we introduced the Interlocked Hash Table (IHT), a highly concurrent lock-based map designed specifically for the Go programming language. The IHT employs a speculative traversal of a fixed-max-depth tree of intermediate nodes, which enables it to acquire exactly one lock per insert/remove/update/lookup operation. By co-locating locks with data, the net result is negligible contention even when 24 hardware threads are performing simultaneous random accesses to a small map. The scalability of the IHT, and its optimized implementation inside of the Go compiler and runtime, enable it to outperform all known alternatives in Go, to include lock-free and lock-based open-source maps. In microbenchmarks, we observed performance up to 7× the performance of the default map at high thread counts, and a peak throughput more than 4*times* the peak achieved speedup by the default (typically at one thread). Furthermore, even in Java, where the IHT cannot benefit from tight integration with the run-time libraries, the IHT is competitive with the best known map implementations.

The IHT exploits Go's randomized iteration requirement. This allows concurrent IHT iterators to begin at random locations within the data structure, and to delay processing of any locked regions they encounter during iteration. Our experiments show an absence of convoying effects, which enables both read-only and read/write iteration to scale to the full size of the machine.

Through a minor addition to the `sync` package, we provide support for large critical sections over a single map element, which can easily be extended to multi-element critical sections. Because the hash functions within the IHT vary from one execution to the next, the programmer cannot infer a safe locking order to prevent deadlock cycles. However, the runtime can determine this information, and for operations over a set of map locations known at the beginning of the critical section, we believe it will be possible possible to guarantee atomicity and deadlock-freedom.

References

[1] Gul Agha and Carl Hewitt. Actors: A Conceptual Foundation for Concurrent Object-Oriented Programming. In *Research Directions in Object-Oriented Programming*, pages 49–74. MIT Press, 1987.

[2] Mark Batty, Scott Owens, Susmit Sarkar, Peter Sewell, and Tjark Weber. Mathematizing C++ Concurrency. In *Proceedings of the 28th ACM Symposium on Principles of Programming Languages*, Austin, TX, January 2011.

[3] Anastasia Braginsky and Erez Petrank. A Lock-Free B+tree. In *Proceedings of the 24th ACM Symposium on Parallelism in Algorithms and Architectures*, Pittsburgh, PA, June 2012.

[4] Trevor Brown, Faith Ellen, and Eric Ruppert. Pragmatic Primitives for Non-blocking Data Structures. In *Proceedings of the 32nd ACM Symposium on Principles of Distributed Computing*, Montreal, Quebec, July 2013.

[5] Mathieu Desnoyers, Paul McKenney, Alan Stern, Michel Dagenais, and Jonathan Walpole. User-Level Implementations of Read-Copy Update. *IEEE Transactions on Parallel and Distributed Systems*, 23(2):375–382, 2012.

[6] Vincent Gramoli. More Than You Ever Wanted to Know about Synchronization. In *Proceedings of the 20th ACM Symposium on Principles and Practice of Parallel Programming*, San Francisco, CA, February 2015.

[7] Tim Harris. A Pragmatic Implementation of Non-Blocking Linked Lists. In *Proceedings of the 15th International Symposium on Distributed Computing*, Lisbon, Portugal, October 2001.

[8] Tim Harris, Keir Fraser, and Ian Pratt. A Practical Multi-word Compare-and-Swap Operation. In *Proceedings of the 16th International Conference on Distributed Computing*, Toulouse, France, October 2002.

[9] Steve Heller, Maurice Herlihy, Victor Luchangco, Mark Moir, William Scherer, and Nir Shavit. A Lazy Concurrent List-Based Set Algorithm. In *Proceedings of the 9th international conference on Principles of Distributed Systems*, Pisa, Italy, December 2006.

[10] Maurice Herlihy. A Methodology for Implementing Highly Concurrent Data Structures. In *Proceedings of the Second ACM Symposium on Principles and Practice of Parallel Programming*, Seattle, WA, March 1990.

[11] Maurice Herlihy and Nir Shavit. *The Art of Multiprocessor Programming*. Morgan Kaufmann, 2008.

[12] Maurice P. Herlihy and Jeannette M. Wing. Linearizability: a Correctness Condition for Concurrent Objects. *ACM Transactions on Programming Languages and Systems*, 12(3):463–492, 1990.

[13] C. A. R Hoare. Communicating Sequential Processes. *Communications of the ACM*, 21(8):666–677, 1978.

[14] IronSource Neon. A thread-safe concurrent map for go, 2016. https://github.com/streamrail/concurrent-map/.

[15] ISO/IEC JTC 1/SC 22/WG 21. Technical Specification for C++ Extensions for Transactional Memory, May 2015.

[16] ISO/IEC TS 19570:2015. Technical Specification for C++ Extensions for Parallelism, 2015.

[17] Amos Israeli and Lihu Rappoport. Disjoint-Access-Parallel Implementations of Strong Shared Memory Primitives. In *Proceedings of the 13th ACM Symposium on Principles of Distributed Computing*, 1994.

[18] Christoph Lameter. Effective Synchronization on Linux/NUMA Systems. In *Proceedings of the May 2005 Gelato Federation Meeting*, San Jose, CA, May 2005.

[19] Doug Lea. JSR-166 Interest Site, 2017. http://gee.cs.oswego.edu/dl/concurrency-interest/.

[20] Yujie Liu, Kunlong Zhang, and Michael Spear. Dynamic-Sized Nonblocking Hash Tables. In *Proceedings of the 33rd ACM Symposium on Principles of Distributed Computing*, Paris, France, July 2014.

[21] Itay Lotan and Nir Shavit. Skiplist-Based Concurrent Priority Queues. In *Proceedings of the 14th International Parallel and Distributed Processing Symposium*, Cancun, Mexico, May 2000.

[22] Victor Luchangco, Mark Moir, and Nir Shavit. Nonblocking k-compare-single-swap. In *Proceedings of the 15th ACM Symposium on Parallel Algorithms and Architectures*, San Diego, CA, June 2003.

[23] Jeremy Manson, William Pugh, and Sarita Adve. The Java Memory Model. In *Proceedings of the 35th ACM Symposium on Principles of Programming Languages*, Long Beach, CA, January 2005.

[24] Maged Michael. High Performance Dynamic Lock-Free Hash Tables and List-Based Sets. In *Proceedings of the 14th ACM Symposium on Parallel Algorithms and Architectures*, Winnipeg, Manitoba, Canada, August 2002.

[25] Michael Scott. *Programming Language Pragmatics*. Morgan Kaufmann, 2009.

[26] Ori Shalev and Nir Shavit. Split-ordered lists: Lock-free extensible hash tables. *Journal of the ACM*, 53(3):379–405, 2006.

[27] Nir Shavit and Dan Touitou. Software Transactional Memory. In *Proceedings of the 14th ACM Symposium on Principles of Distributed Computing*, Ottawa, ON, Canada, August 1995.

[28] Standard C++ Foundation. C++11 Overview, 2017. https://isocpp.org/wiki/faq/cpp11.

[29] Dean Tullsen, Susan Eggers, and Henry Levy. Simultaneous Multithreading: Maximizing On-Chip Parallelism. In *Proceedings of the 22nd International Symposium on Computer Architecture*, Santa Margherita Ligure, Italy, June 1995.

[30] Rob von Behren, Jeremy Condit, Feng Zhou, George Necula, and Eric Brewer. Capriccio: Scalable Threads for Internet Services. In *Proceedings of the 19th ACM Symposium on Operating Systems Principles*, Bolton Landing, NY, October 2003.

[31] Xi Yang, Daniel Frampton, Steve Blackburn, and Antony Hosking. Barriers Reconsidered, Friendlier Still! In *Proceedings of the International Symposium on Memory Management*, Beijing, China, June 2012.

[32] Zond. Non blocking data structures for Go, 2016. https://github.com/zond/gotomic/.