Faster persistent data structures through hashing

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2011-09-23

Motivating problem: Twitter data analysis

I'm computing a communication graph from Twitter data and then scan it daily to allocate social capital to nodes behaving in a good karmic manner. The graph is culled from 100 million tweets and has about 3 million nodes.

We need a data structure that is

- fast when used with string keys, and
- doesn't use too much memory.

Persistent maps in Haskell

- `Data.Map` is the most commonly used map type.
- It's implemented using size balanced trees and is representative of the performance of other binary tree implementations.
- Keys can be of any type, as long as values of the type can be ordered.

Real world performance of Data.Map

- Good in theory: no more than $O(\log n)$ comparisons.
- Not great in practice: up to $O(\log n)$ comparisons!
- Many common types are expensive to compare e.g `String`, `ByteString`, and `Text`.
- Given a string of length k, we need $O(k * \log n)$ comparisons to look up an entry.

Hash tables

- Hash tables perform well with string keys: $O(k)$ amortized lookup time for strings of length k.
- However, we want persistent maps, not mutable hash tables.

Milan Straka's idea: IntMaps as arrays

- We can use hashing without using hash tables!
- `Data.IntMap` implements a persistent array and is much faster than `Data.Map`.
- Use hashing to derive an `Int` from an arbitrary key.

```
class Hashable a where
  hash :: a -> Int
```

Collisions are easy to deal with

- `IntMap` implements a sparse, persistent array of size 2^{32} (or 2^{64}).
- Hashing using this many buckets makes collisions rare: for 2^{24} entries we expect about 32,000 single collisions.
- Implication: We can use any old collision handling strategy (e.g. chaining using linked lists).

HashMap implemented using an IntMap

Naive implementation:

```
newtype HashMap k v = HashMap (IntMap [(k, v)])
```

By inlining (``unpacking'') the list and pair constructors we can save 2 words of memory per key/value pair.

Benchmark: Map vs HashMap

Keys: 2^{12} random 8-byte `ByteString`s

	Runtime (μs)		Runtime
	Map	HashMap	% increase
lookup	1956	916	-53%
insert	3543	1855	-48%
delete	3791	1838	-52%

Can we do better?

- Imperative hash tables still perform better, perhaps there's room for improvement.
- We still need to perform $O(min(W, \log n))$ `Int` comparisons, where W is the number of bits in a word.
- The memory overhead per key/value pair is still high, about 9 words per key/value pair.

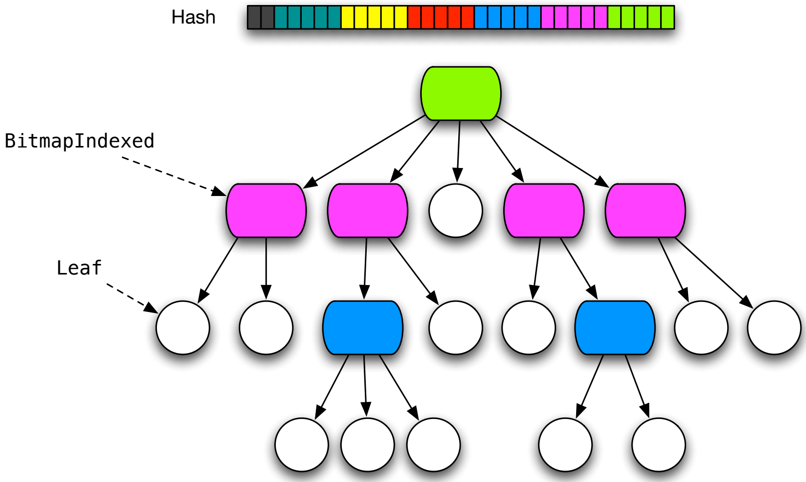
Borrowing from our neighbours

- Clojure uses a *hash-array mapped trie* (HAMT) data structure to implement persistent maps.
- Described in the paper ``Ideal Hash Trees'' by Bagwell (2001).
- Originally a mutable data structure implemented in C++.
- Clojure's persistent version was created by Rich Hickey.

Hash-array mapped tries

- Shallow tree with high branching factor.
- Each node, except the leaf nodes, contains an array of up to 32 elements.
- 5 bits of the hash are used to index the array at each level.
- A clever trick, using bit population count, is used to represent sparse arrays.

HAMT



The Haskell definition of a HAMT

```
data HashMap k v
    = Empty
    | BitmapIndexed !Bitmap !(Array (HashMap k v))
    | Leaf !Hash !k v
    | Full !(Array (HashMap k v))
    | Collision !Hash !(Array (Leaf k v))

type Bitmap = Word
type Hash = Int
data Array a = Array (Array# a)
```

High performance Haskell programming

Optimized implementation using standard techniques:

- constructor unpacking,
- GHC's new `INLINABLE` pragma, and
- paying careful attention to strictness.

`insert` performance still bad (e.g compare to hash tables).

Optimizing insertion

- Most time in `insert` is spent copying small arrays.
- Array copying is implemented in Haskell and GHC doesn't apply enough loop optimizations to make it run fast.
- When allocating arrays GHC fills the array with dummy elements, which are immediately overwritten.

Optimizing insertion: copy less

- Bagwell's original formulation used a fanout of 32.
- A fanout of 16 seems to provide a better trade-off between `lookup` and `insert` performance in our setting.
- Improved performance by 14%

Optimizing insertion: copy faster

- Daniel Peebles and I have implemented a set of new primops for copying arrays in GHC.
- The implementation generates straight-line code for copies of statically known small size, and uses a fast `memcpy` otherwise.
- Improved performance by 20%

Optimizing insertion: common patterns

- In many cases maps are created in one go from a sequence of key/value pairs.
- We can optimize for this case by repeatedly mutating the HAMT and freezing it when we're done.

Keys: 2^{12} random 8-byte `ByteString`s

	Runtime (%)
fromList/pure	100
fromList/mutating	50

Optimizing lookup: Faster population count

- Tried several bit population count implementations.
- Best speed/memory-use trade-off is a lookup table based approach.
- Using the `POPCNT` SSE 4.2 instructions improves the performance of `lookup` by 12%.

Benchmark: IntMap-based vs HAMT

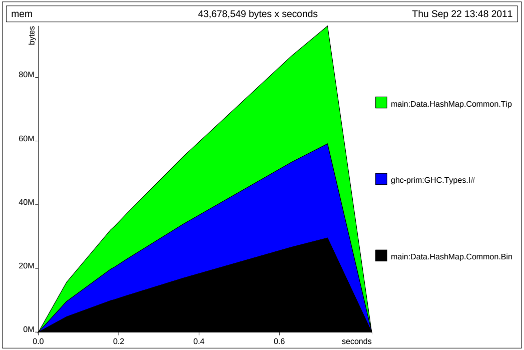
Keys: 2^{12} random 8-byte `ByteString`s

	Runtime (μs)		Runtime
	IntMap	HAMT	% increase
lookup	916	477	-48%
insert	1855	1998	8%
delete	1838	2303	25%

The benchmarks don't include the `POPCNT` optimization, due to it not being available on many architectures.

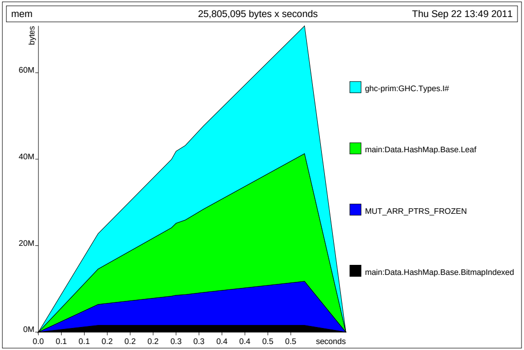
Memory usage: IntMap-based

Total: 96 MB, tree: 66MB (2^{20} `Int` entries)



Memory usage: HAMT

Total: 71MB, tree: 41MB (2^{20} `Int` entries)



Summary

Keys: 2^{12} random 8-byte `ByteString`s

	Runtime (μs)		Runtime
	Map	HAMT	% increase
lookup	1956	477	-76%
insert	3543	1998	-44%
delete	3791	2303	-39%