Multi Producer, Multi Consumer, Lock Free, Atomic Queue

User API and Implementation

EREZ STRAUSS

Lockfree, MPMC Queue - Legal

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About me

- C++/C development for over 25 years
- Low Latency - Trading platforms
- Worked in both banks and hedge funds
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Lockfree, MPMC Queue - Agenda

1. Trading Platform, Latency
2. Queues Environment
3. Queues Requirement
4. Atomic hardware and C++ Atomic
5. Queues Classification
6. Queue creation, push, pop
7. Queue internals
8. Testing
9. Performance - Benchmarking

Lockfree, MPMC Queue - Background

- Trading platform - every message is tracked, at microseconds resolution
- Queues are essential data structure used to transfer messages from one component to another
- Business decisions depends on the message content and arrival time

Latency Fat Tail - Raw Data

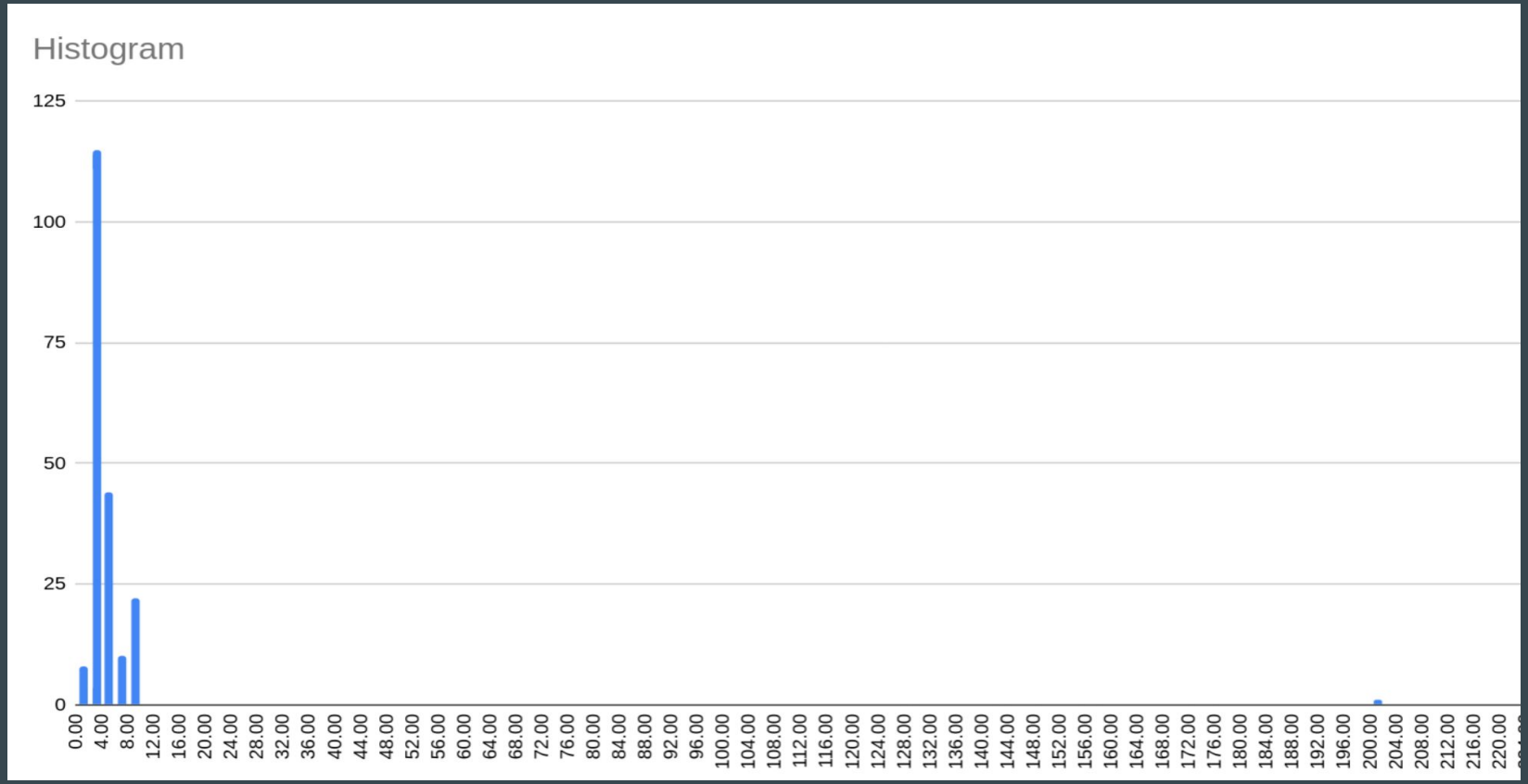
Response Time of a System

1. 200 samples
2. us - microseconds
3. %TT - % of the total time

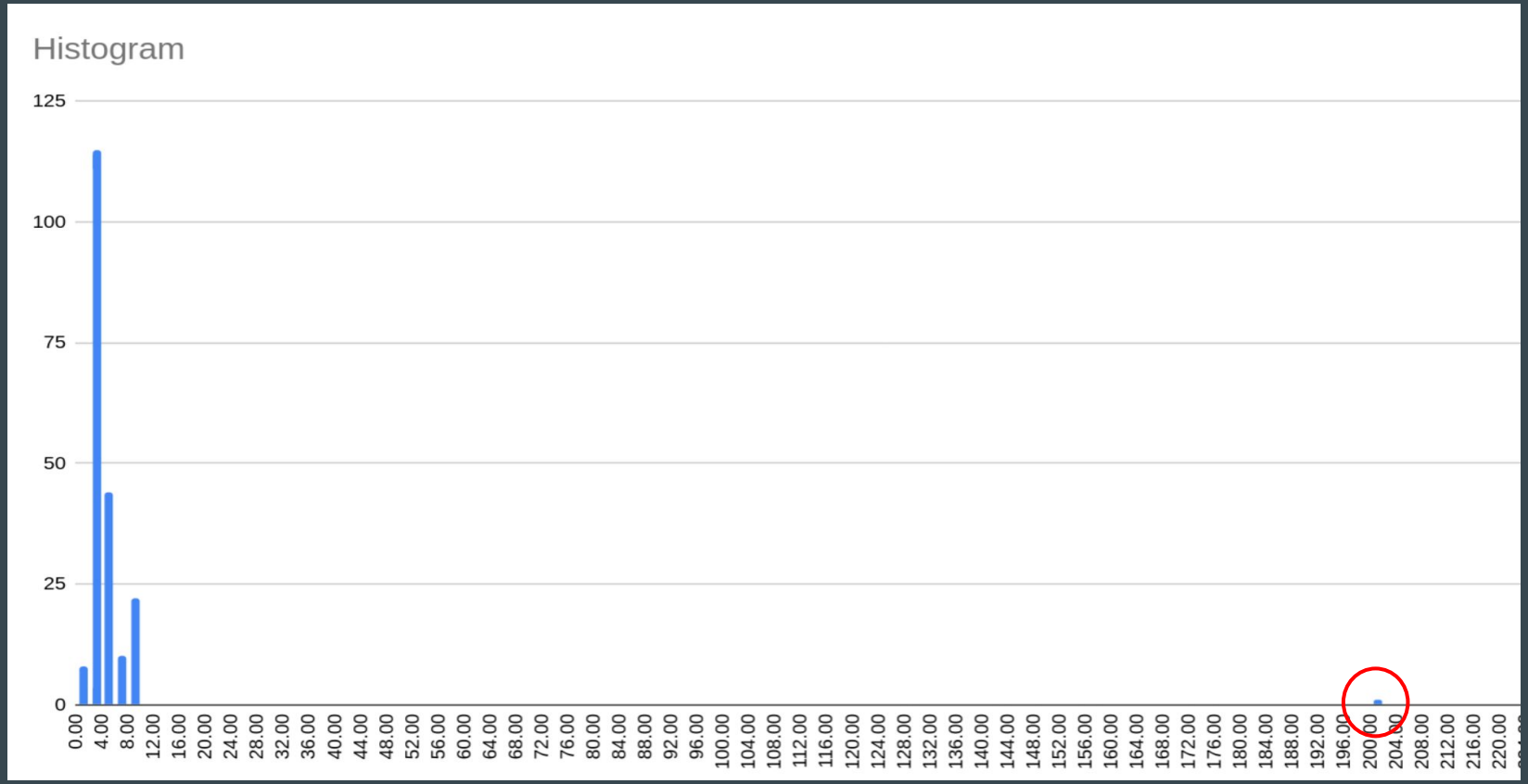
...

	A	B
1	943	Total Samples' Time [us]
2	4.715	Average Sample Time[us]
3	14.01054072	StdDev
4	200	number of samples
5	**[us]**	**%TT**
6	2	0.2120891
7	3	0.3181336
8	5	0.5302227
9	3	0.3181336
10	2	0.2120891
11	1	0.1060445
12	9	0.9544008
13	3	0.3181336
14	4	0.4241782
15	6	0.6362672
16	4	0.4241782
17	200	21.2089077
18	2	0.2120891
19	2	0.2120891
20	3	0.3181336
21	5	0.5302227
22	3	0.3181336

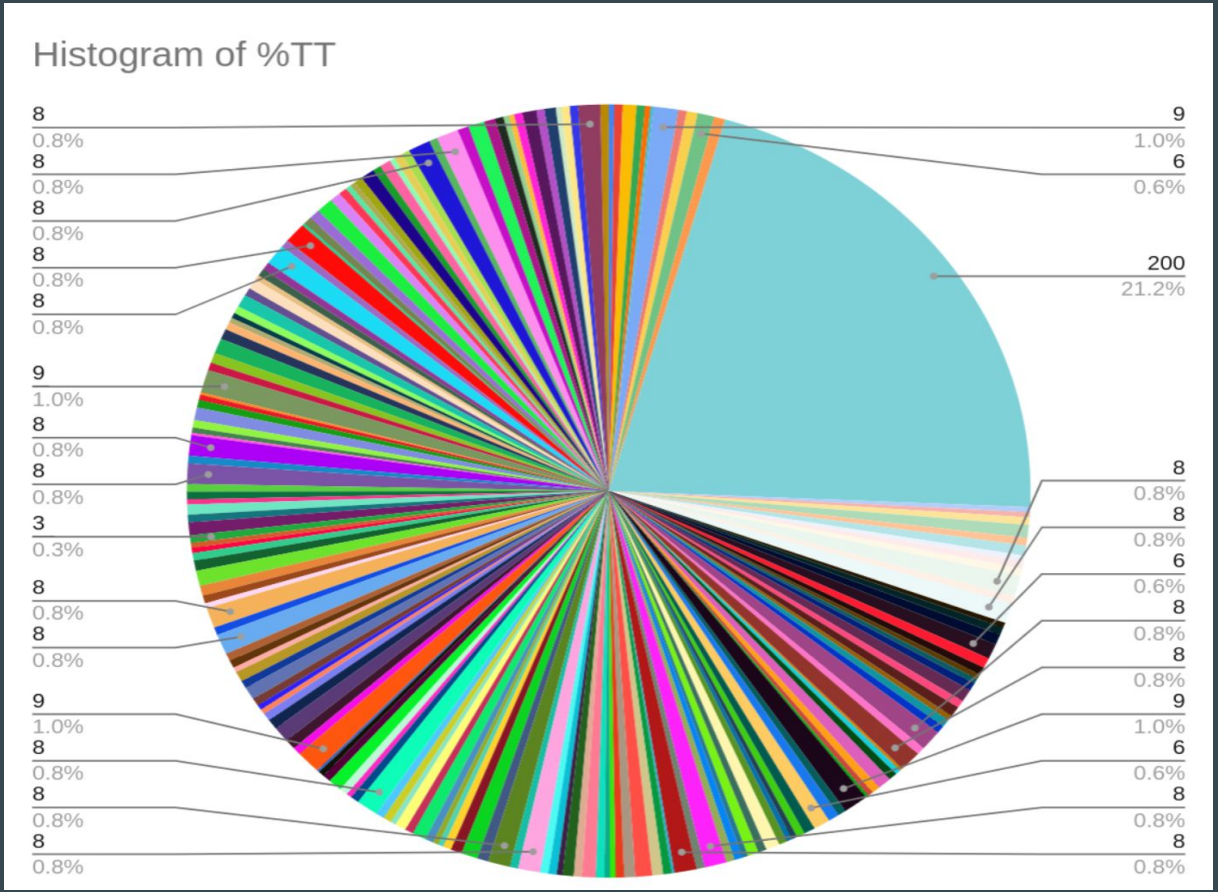
Latency Fat Tail - Simple Histogram



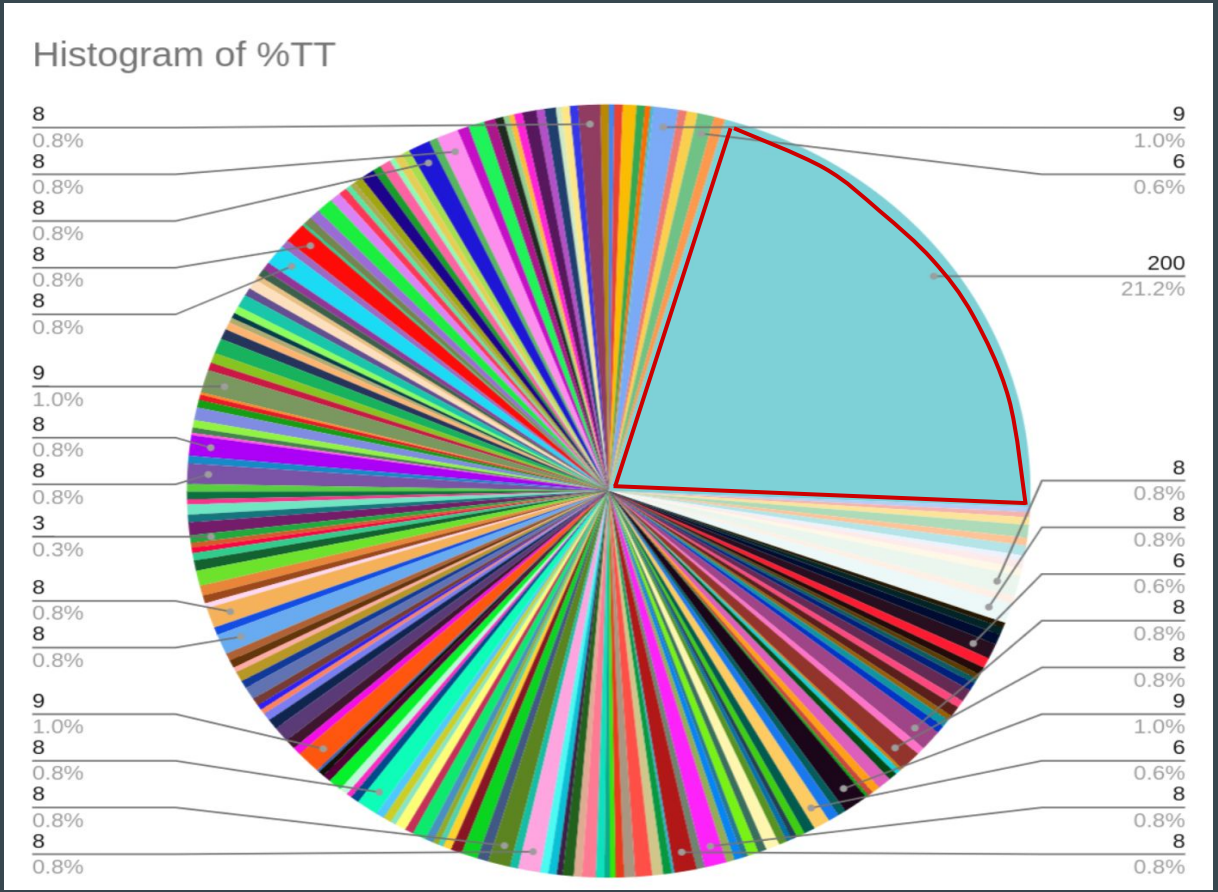
Latency Fat Tail - Simple Histogram



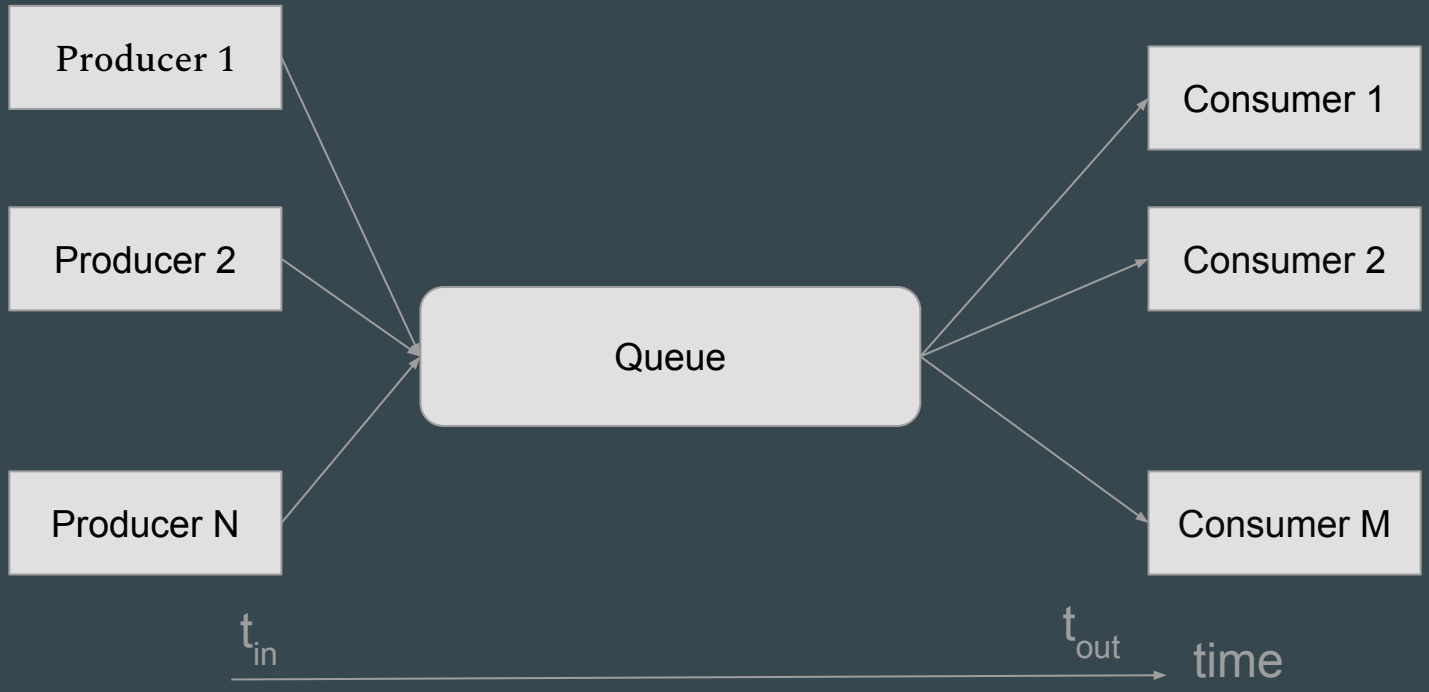
Latency Fat Tail - Pie Chart



Latency Fat Tail - Pie Chart



Queue - Message and time flow



Lockfree, MPMC Queue - Connecting Application Components

Queues transfer messages and synchronize thread

- A message source to thread pools
- A buffer to handle bursts of incoming messages
- A pool of objects to be used by multiple threads
- A message queue between processes - IPC

Lockfree, MPMC Queue - Queues classification

- Number of producers / consumers: SPSC, SPMC, MPSC, **MPMC**
- Capacity: **Bounded** / dynamic & memory allocation
- Serialization: **Strict global order** or relaxed per producer order
- API: **single item** / multiple items, **atomicity-ready** or not
- Message size: **fixed** / dynamic
- **Queue** - push(back / tail), pop(front / head)
- **Busy** polling on full / empty vs. sync using system calls
- Blocking / **non blocking** / wait-free
- Data ownership or just **value propagation**

Lockfree, MPMC Queue - Scheduler Interaction

```
template<typename T>
class QueueSchedulerIssue {
   std::atomic<unsigned>  writeIndex;
   std::atomic<unsigned>  readIndex;
   std::unique_ptr<std::pair<unsigned, T>>
elements;

   bool try_push(T&& value) {
      auto my_entry = writeIndex.fetch_add(1);
      elements[my_entry].first = std::move(value);
      // No code, does not mean no-time.
      // scheduler will hit here, and
      // block the queue progress.
      elements[my_entry].second = my_entry;
      return true;
   }
};
```

```
template<typename T>
class QueueSchedulerIssue {
   // …
   bool try_pop(T& value) {

      auto my_entry = readIndex.fetch_add(1);
      while (elements[my_entry].second != my_entry)
            ; // spin and wait, maybe with pause();
      value = std::move(elements[my_entry].first);
      return true;
   }
};
```

pseudo code!

Lockfree, MPMC Queue - The requirements

- Minimal latency for all message, not just good average
- Worst case scenario, as close as possible to average
- Multi producers threads - on multiple cpu-cores
- Multi consumers threads - on multiple cpu-cores
- C++17 - no need to support C++14
- No system calls during critical path
- No locking - no interaction with the scheduler
- Non blocking - is full, returns with a full-status, on empty the same
- No need of C++ object transfers, simple data types (*)

Lockfree, MPMC Queue - Unique Requirements

- Strict ordering: prevents the use queues with relaxed ordering - multiple send queues (spmc)
- Guaranteed progress: no blocking due to scheduler interruption between two operations, like placing data and increment index

C++ Atomic Operations / CPU instructions

- std::atomic<T> - provides load / store / compare_exchange
- std::atomic<T>::is_always_lock_free
- **Load** and **Store** of aligned 8 bytes
- **CAS** (old-expected, new-value) - atomic **C**ompare **A**nd **S**wap
- **CAS16** (old-128bits-reference, new-128b-value)
- The building blocks the atomic mpmc queue

```
std::atomic<uint64_t> u8{45};
uint64_t a_get() { return u8.load();    }
void a_set(uint64_t v) { u8.store(v);  }
void a_cas(uint64_t& old, uint64_t value) {
    u8.compare_exchange_strong(old, value);
}
```

Compiler explorer example: https://godbolt.org/z/54jGq3q4f
https://godbolt.org/z/en3e79arT
https://godbolt.org/z/oqc9PTYcz – with gcc & clang Arm

Lockfree, MPMC Queue - C++ std::atomic<>

std::atomic<T> - atomic access not interrupted, if T is too large the std::atomic<> will use internal lock to provide atomic access to type T.

if T is small enough and the atomic<> implementation supports atomicity by the CPU platform, than **std::atomic<uint8_t>::is_always_lockfree** will be true.

The queue requires hardware atomicity, if it is not available from the compile atomic<> implementation, the queue will use the compiler intrinsic functions that will use the cmpxchg16b assembly instruction

Lockfree, MPMC Queue - Hardware interaction

- C++17 provides atomic<>::is_always_lockfree
- padding and alignment - avoid false sharing
- CAS (Compare and Swap) on consecutive 16 bytes, using 16 bytes integers
- Alignment requirements, for Entries of 16 bytes, and for other data types
- gcc / clang -mcx16 – avoid calling the atomic library
- Numa consideration: – entries array on reader side

Lockfree, MPMC Queue - Design

- Fixed size array with atomic entries [1 ... 2^N], atomic entries are 8 or 16 bytes, aligned to cachline.
- Each Entry contains: 1. Sequence/Index, 2. data-flag, 3. data-value
- Entries in the array are modified only using CAS operations (Compare and Swap)
- A successful CAS operation on an entry completes the push/pop operation.
- Indexes are also modified using CAS operations
- Atomic indexes for read and write

Lockfree, MPMC Queue - API

```
template<typename DataT,              // Data Type: 1 - 12 bytes.
        size_t N = 0,                 // 0 - set at constructor
        typename IndexT = uint32_t,   // index type: 4 or 8 bytes
        bool lazy_push = false,       // delay write index increment
        bool lazy_pop = false>        // delay read index increment
class mpmc_queue {

    explicit mpmc_queue(uint64_t n = N);
    bool push(value_type d);  // try to push, fail iff the queue is full
    bool pop(value_type& d);  // try to pop, fail iff the queue is empty.
    bool push(value_type d, index_type& i);  // Same as above, update i
    bool pop(value_type& d, index_type& i);  //  with op. sequence number
    bool exchange(index_type& i, value_type old_value, value_type new_value);
    bool push_keep_n(value_type d);
    bool push_keep_n(value_type d, index_type& i);
};
```

Lockfree, MPMC Queue - Internal data members

```
template<typename DataT,              // Data Type: 1 - 12 bytes.
        size_t N = 0,                 // 0 - set at constructor
        typename IndexT = uint32_t, // index type: 4 or 8 bytes
        bool lazy_push = false,       // delay write index increment
        bool lazy_pop = false>        // delay read index increment
class mpmc_queue {
    // ...
private:

    std::atomic<index_type> _write_index alignas(2 * cachelinesize);

    std::atomic<index_type> _read_index alignas(2 * cachelinesize);

    array_t                 _array; // array of entries.

};
```

Lockfree, MPMC Queue - transfer simple values

```
#include <mpmc_queue.h>
int main()
{
    es::lockfree::mpmc_queue<unsigned> q{32};

    constexpr unsigned N{1000000};
    constexpr unsigned P{2};
    std::atomic<uint64_t> prod_sum{0};
    std::atomic<uint64_t> cons_sum{0};

    auto producer = [&]() {
        for (unsigned x = 0; x < N; ++x) {
            while (!q.push(x))
                ;
            prod_sum += x;
        }
    };
    std::vector<std::thread> producers;
    producers.resize(P);
    for (auto& p : producers) p =
std::thread{producer};
```

```
    auto consumer = [&]() {
        unsigned v{0};
        for (unsigned x = 0; x < N; ++x) {
            while (!q.pop(v))
                ;
            cons_sum += v;
        }
    };
    std::vector<std::thread> consumers;
    consumers.resize(P);
    for (auto& c : consumers) c =
std::thread{consumer};

    for (auto& p : producers) p.join();
    for (auto& c : consumers) c.join();
    std::cout << (cons_sum && cons_sum ==
prod_sum ? "OK" : "ERROR") << " " << cons_sum
<< '\n';
    return 0;
}
```

Large message transfer - using std::unique_ptr

```
#include <pointer_mpmc_queue.h>
struct DataRecord {
    std::array<uint64_t, 64> _sample;
};
using queue_type =
   es::lockfree::pointer_mpmc_queue<es::lockfree::mpmc_queue,
DataRecord>;

int main()
{
    queue_type                          q0{1024};
    constexpr unsigned                  N{10000};
    constexpr unsigned                  PCPC{2};
    std::atomic<uint64_t>               prod_sum{0};
    std::atomic<uint64_t>               cons_sum{0};

    auto producer = [&](queue_type* const q) {
        uint64_t m{0};
        for (unsigned x = 0; x < N; ++x)
        {
            auto p = std::make_unique<DataRecord>();
            p->_sample[0] = x; //Prepare message
            while (!q->push(std::move(p)))
                ;
            m += x;
        }
        prod_sum += m;
    };
```

```
        auto consumer = [&](queue_type* const q) {
         uint64_t m{0};
         for (unsigned x = 0; x < N; ++x)
         {
             std::unique_ptr<DataRecord> p{};
             while (!q->pop(p))
                 ;
             m += p->_sample[0];  //  process message
         }
         cons_sum += m;
     };

    std::vector<std::thread> consumers;
    consumers.resize(PCPC);
    for (auto& c : consumers) c = std::thread{consumer, &q0};
    std::vector<std::thread> producers;
    producers.resize(PCPC);
    for (auto& p : producers) p = std::thread{producer, &q0};

    for (auto& p : producers) p.join();
    for (auto& c : consumers) c.join();
    std::cout << (cons_sum && cons_sum == prod_sum ? "OK" :
"ERROR")
      << " " << cons_sum << '\n';
}
```

Lockfree, MPMC Queue - Internal algorithm

- Entries hold data value and sequence & data-present flag bit (lsb)
- The seq is 32 or 64 bits
- Data is 4 to 12 bytes, and can contain pointer / unique_ptr<> (simple one)
- Write_Index - where should be the next write/push operation
- Read_Index - where would be the next read/pop operation
- The relation between the content of the cell and the index defines the state of the index
- Cell & Entry content and Indices content are updated using CAS only
- There is no need that the push-data and write-index-increment will be done by the same thread
- There is no need that the pop-data and read-index-increment will be done by same thread - that way we achieve collaboration

Lockfree, MPMC Queue - Internal Queue Entry

```
class alignas(sizeof(helper_entry)) entry
{
   union entry_union
   {
       mutable entry_as_value _value;
       struct entry_data
       {
           value_type _data;
           index_type _seq;
       } _x;
       entry_union() { _value = 0; }
   } _u;

   index_type get_seq() noexcept { return _u._x._seq; }
   value_type get_data() noexcept { return _u._x._data; }
   bool is_empty() const { return !(_u._x._seq & 1U); }
   bool is_full() const { return !is_empty(); }
};
```

Lockfree, MPMC Queue - Queue States

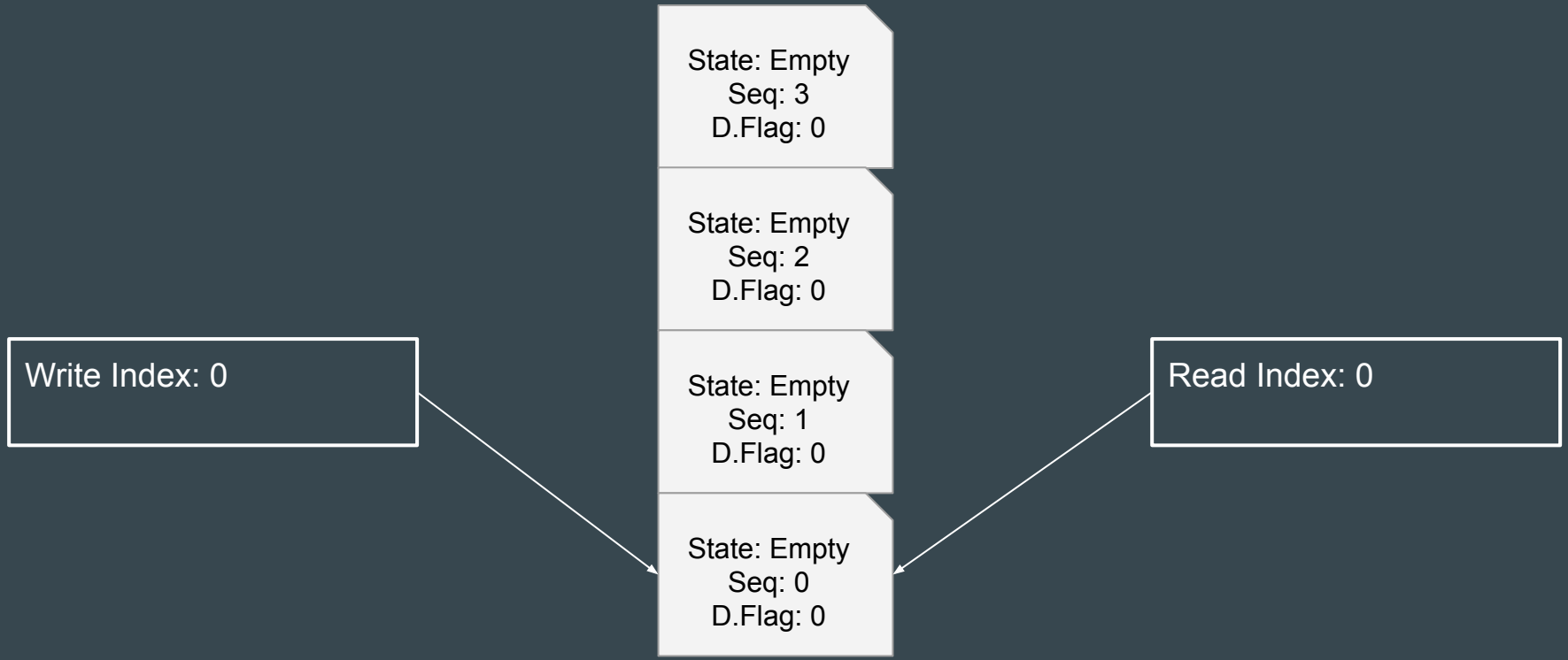
Queue is empty: read index refers to a cell with false data_flag and the sequence number in the entry is equal to the read index.

if entry.seqnum == read_index + size, then, just increase the read index

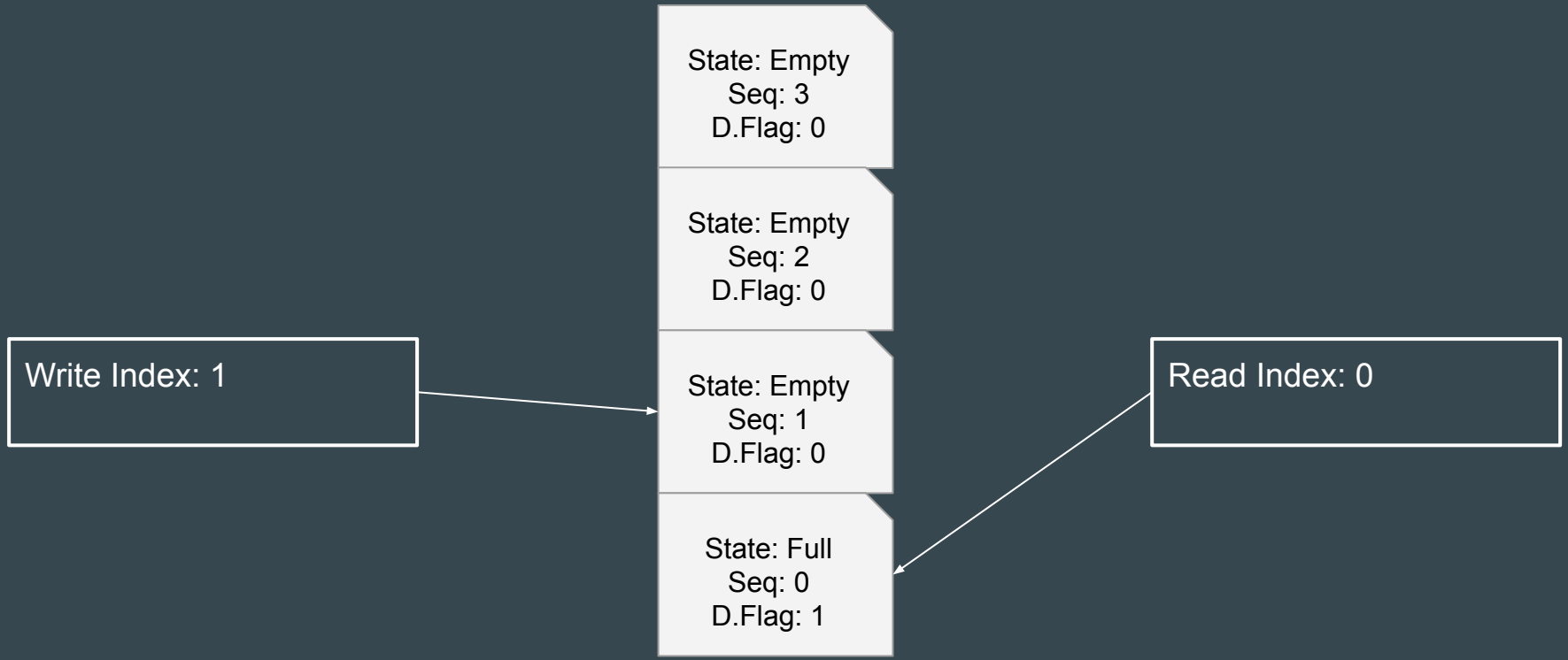
if (entry.seqnum == read_index && entry.data_flag)

{ replace the entry with an empty one with seqnum + size }

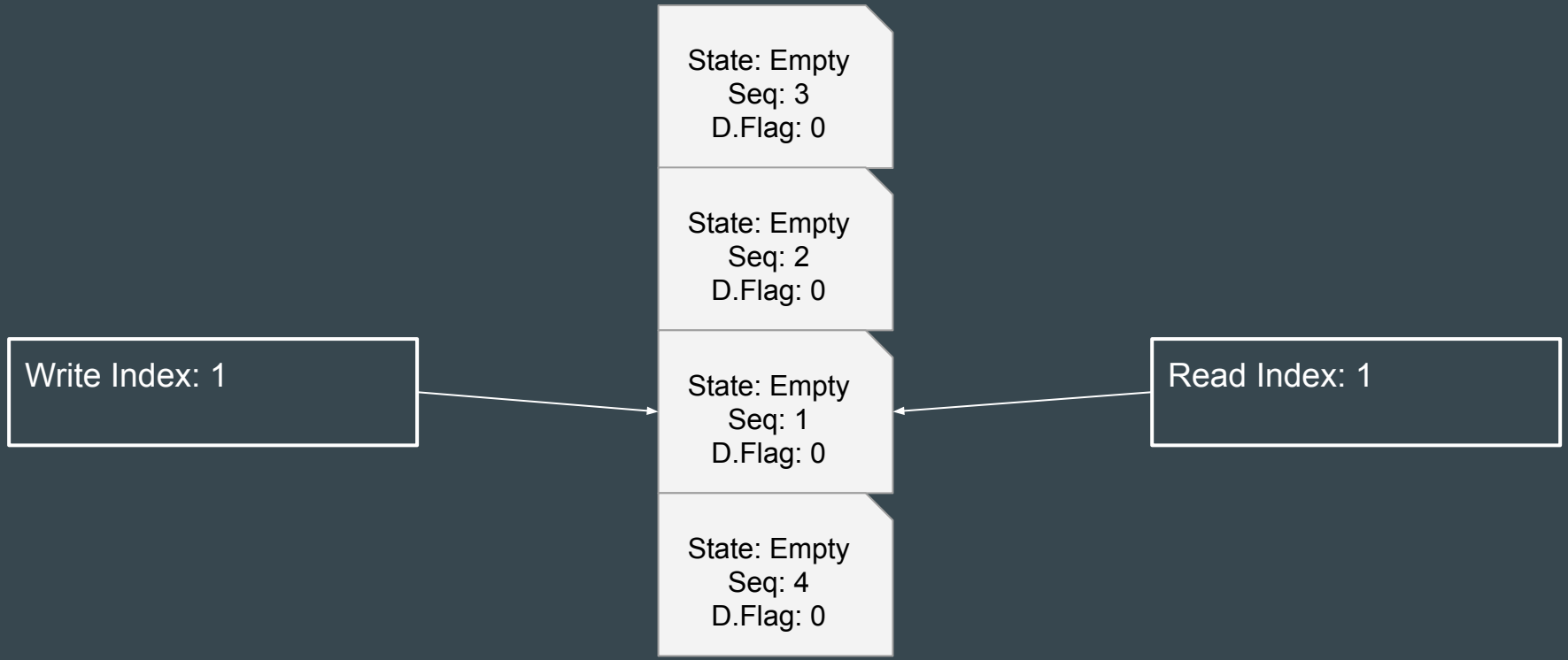
Lockfree, MPMC Queue - Depth Capacity 4 - S_0 - Empty



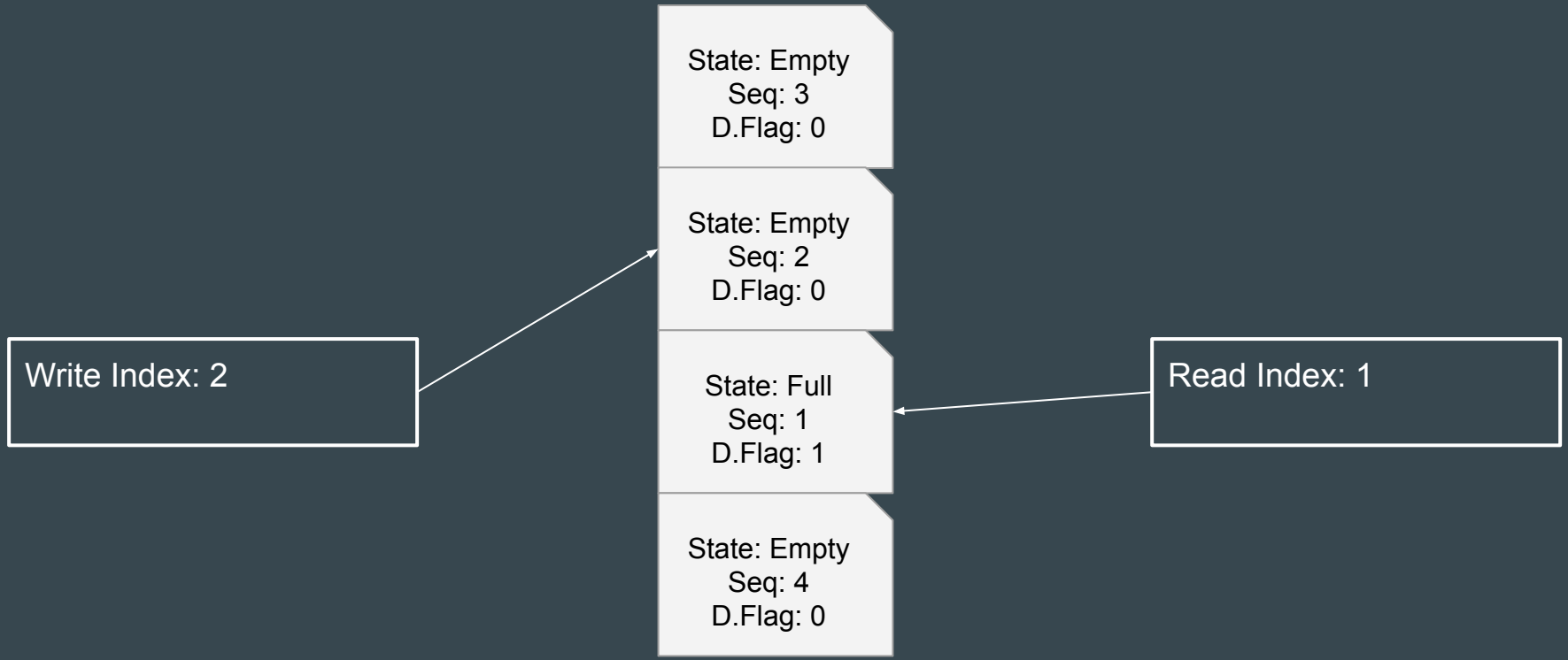
Lockfree, MPMC Queue - Depth Capacity 4 - S_1 - One data item



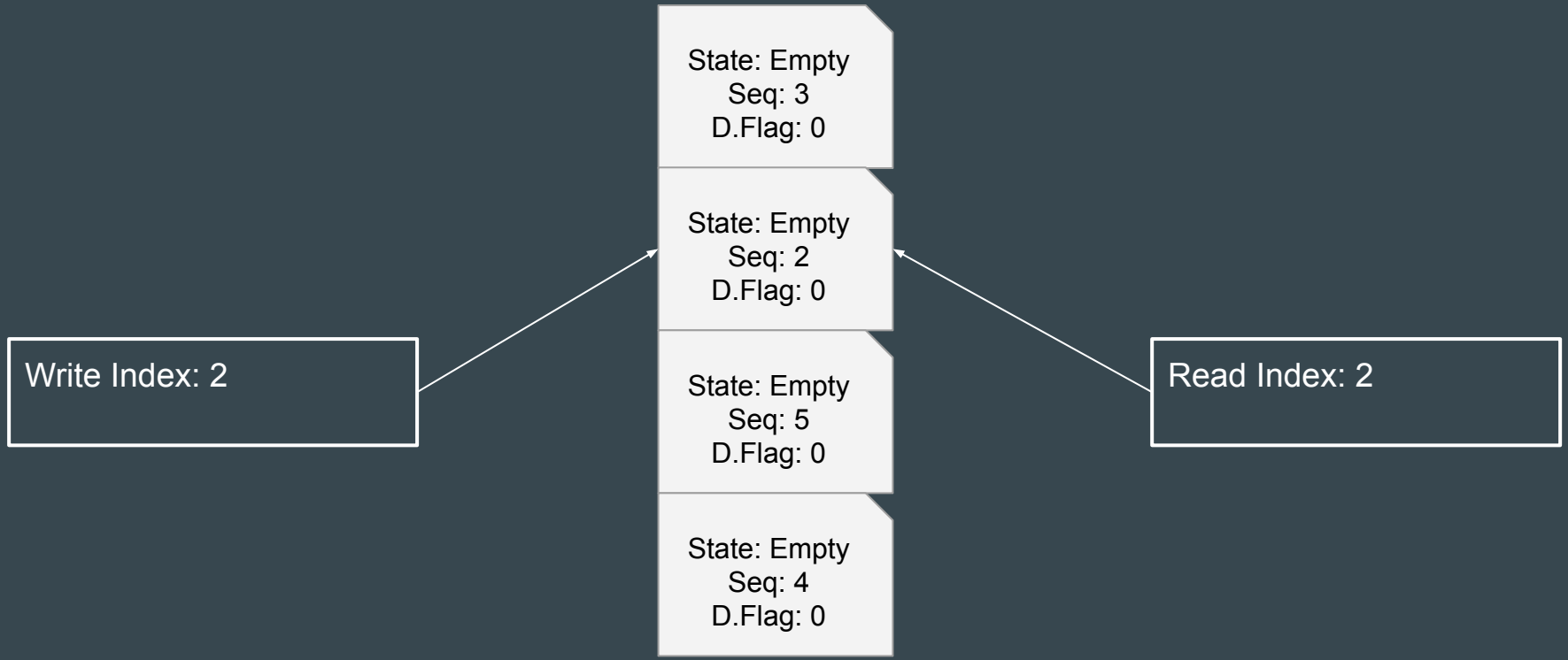
Lockfree, MPMC Queue - Depth Capacity 4 - S_2 - 1 in, 1 out



Lockfree, MPMC Queue - Depth Capacity 4 - S_3 - 2 in, 1 out



Lockfree, MPMC Queue - Depth Capacity 4 - S_4 - 2 in, 2 out



Lockfree, MPMC Queue - push / try_push

bool push(T value) - executes two CAS operations, after verifying the write_index points to an empty entry

1. CAS operation on Entry in the array, sets:
   sequence - same as before
   data_present_flag - 1 - data available, and
   data - the new value
2. CAS operation on the Write Index,
   progress to next entry

If write index refers to a full entry, from previous round, queue is full, return false.

Lockfree, MPMC Queue - push() code

```
[[using gnu: hot, flatten]] bool push(value_type d) noexcept
{
   while (true) {
       index type wr index =  write index.load();
       index_type seq = _array[wr_index].get_seq();

       if (seq == static cast<index type>(wr index << 1)) {
           entry e{static cast<index type>(wr index << 1)};
           entry data_entry{static_cast<index_type>((wr_index << 1) | 1U), d};

           if ( array[wr_index].compare_exchange(e, data_entry)) { // <=== DWCAS atomic instruction
               if constexpr (!lazy_push) {
                   _write_index.compare_exchange_strong(wr_index, wr_index + 1);
               }
               return true;
           }
       }
       else if ((seq == static cast<index type>((wr index << 1) | 1U)) ||
                (static cast<index type>(seq) == static cast<index type>((wr_index + _array.size()) << 1))){
           _write_index.compare_exchange_strong(wr_index, wr_index + 1);
       }
       else if (static cast<index type>(seq + ( array.size() << 1)) ==
                static cast<index_type>((wr_index << 1) | 1U)){
           return false;
       }
   }
}
```

Lockfree, MPMC Queue - pop / try_pop

try_pop(T& value) - executes two CAS operations:

1. CAS operation on Entry in the array, sets:
   sequence = sequence + size - make it ready for next write operation
   data_present_flag - 0 - clear that entry, and
   data - zero value
   The Swap operation gets the old value into the value–reference
2. CAS operation on the Read Index,
   progress to next entry

Lockfree, MPMC Queue - pop() code

```
bool pop(value_type& d) noexcept {
   while (true) {
       index_type rd_index = _read_index.load();
       entry e{_array[rd_index].load()};
       if (e.get_seq() == static_cast<index_type>((rd_index << 1) | 1U)) {
           entry empty_entry{static_cast<index_type>((rd_index + _array.size()) << 1U)};
           if (_array[rd_index].compare_exchange(e, empty_entry)) {   // <=== DWCAS atomic instruction
               d = e.get_data();
               if constexpr (!lazy_pop) {
                   _read_index.compare_exchange_strong(rd_index, rd_index + 1);
               }
               return true;
           }
       } else if (static_cast<index_type>(e.get_seq() | 1U) ==
                  static_cast<index_type>(((rd_index + _array.size()) << 1) | 1U)) {
           _read_index.compare_exchange_strong(rd_index, rd_index + 1);
       } else if (e.get_seq() == static_cast<index_type>(rd_index << 1)) {
           return false;
       }
   } }
```

Lockfree, MPMC Queue - exchange() code

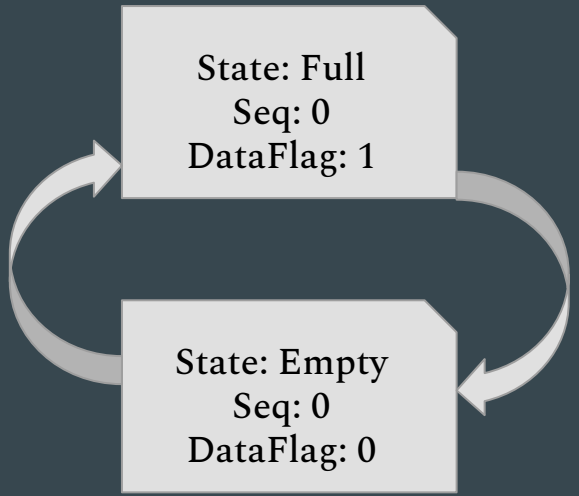
```
// replace old value with a new one

bool exchange(index_type& i, value_type old_value, value_type new_value) noexcept
{
        entry old_entry{static_cast<index_type>((i << 1) | 1U), old_value};
        entry new_entry{static_cast<index_type>((i << 1) | 1U), new_value};

        return _array[i].compare_exchange(old_entry, new_entry);
}
```

Cell / Entry State Diagram - Empty & Full

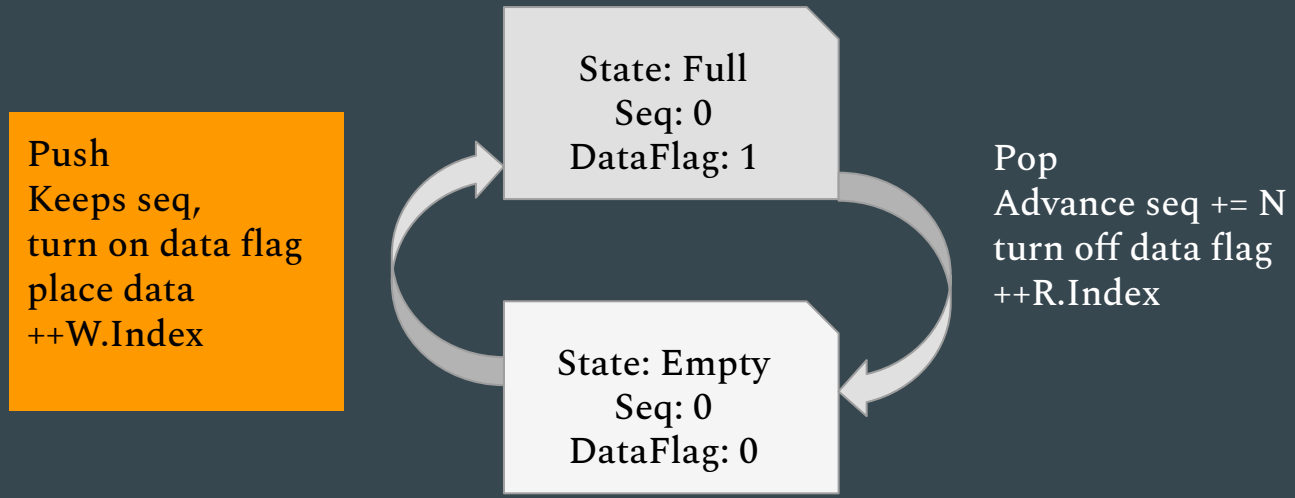
Push
Keeps seq,
turn on data flag
place data
++W.Index



Pop
Advance seq += N
turn off data flag
++R.Index

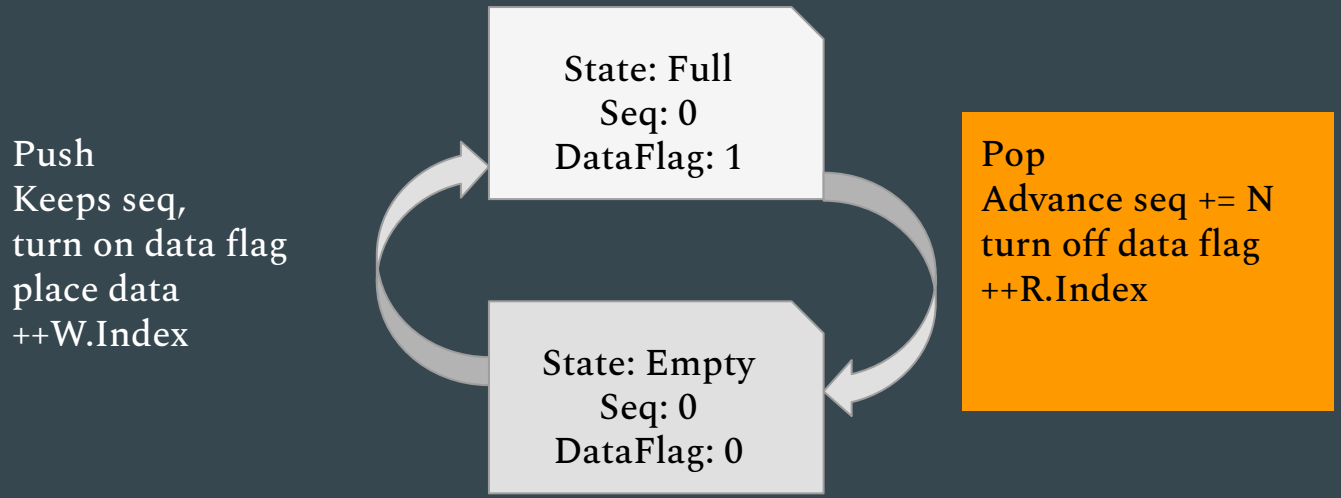
Cell / Entry State Diagram - Empty & Full

Cell index 0, Start, empty - Round



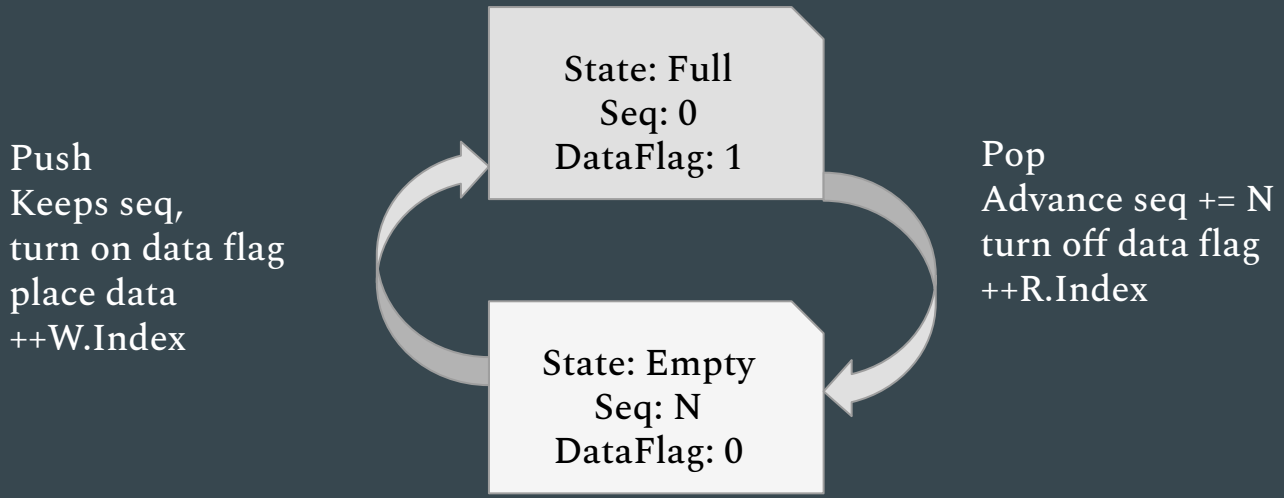
Cell / Entry State Diagram - Empty & Full

Cell index 0, push1, full, round 0



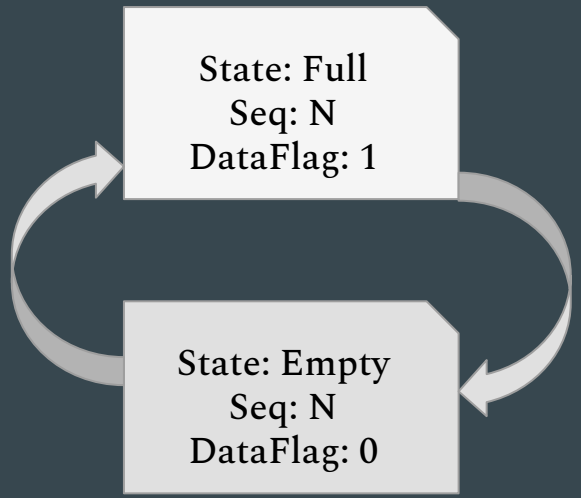
Cell / Entry State Diagram - Empty & Full

Cell index 0, push1, pop1, empty - round 1



Cell / Entry State Diagram - Empty & Full

Cell index 0, push1, pop1, push2, full - Round 1

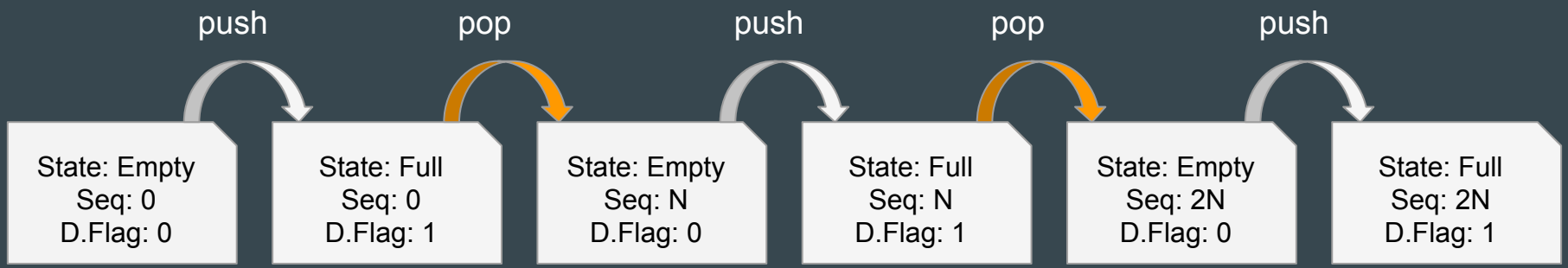


Push
Keeps seq,
turn on data flag
place data
++W.Index

Pop
Advance seq += N
turn off data flag
++R.Index

Cell 0, seq#: 0, N, 2N, 3N, 4N .... 0, N, 2N, ...
Cell 1, seq#: 1, N+1, 2N+1, 3N+1, 4N+1 .... 1, N+1, 2N+1, ...
Cell 2, seq#: 2, N+2, 2N+2, 3N+2, 4N+2 .... 2, N+2, 2N+2, ...

Lockfree, MPMC Queue - Push / pop - one entry



Lockfree, MPMC Queue - Special features

1. Works between threads and between processes - two or more address space

2. Supports atomic conflation - writer can replace atomically a value if not read by any reader

Lockfree, MPMC Queue - Testing

No message drop

No message duplication

No messages reordering

No starvation of reader or writers?

On Intel and AMD platforms

Lockfree, MPMC Queue - Benchmark

What to measure:

- number of messages per second:
  - different Arch (Intel , AMD)
  - data size - 4, 8, 12 bytes
  - number of producers, consumers 1-1,2-2,3-3,... 1-2,1-3, 2-3, 3-3, 2-1, 3-2 3-3
  - Lazy increment operation in the push / pop - default not lazy
- Time inside the queue per message - need to assume reader is faster than writer
- Half RTT - using echo server - using two queues

Lockfree, MPMC Queue - Performance

CPU overhead in read, write

RTT with echo server

Bandwidth - how many messages per second - depends on data-size, index-size

Benchmark Inputs: data-size, producers-count, consumer-count, lazy read, lazy write

Worst case - maximum time in the queue when sending from producer to consumer

Lockfree, MPMC Queue - Bandwidth Performance

1-1 data width 4:

$ ./q_bandwidth -W4 -p1 -c1

Q BW: data size: 4 index size: 4 capacity: 32 producers: 1 consumers: 1 for: 1000ms mpmc_queue<ff> push: **73842434** pop: 73842434 tsc: 2470341002 tsc/op: 33 push/pop per sec: **73120193**

Q BW: data size: 4 index size: 4 capacity: 32 producers: 1 consumers: 1 for: 1000ms mpmc_queue<ft> push: **78907377** pop: 78907377 tsc: 2445654794 tsc/op: 30 push/pop per sec: **78924290**

Q BW: data size: 4 index size: 4 capacity: 32 producers: 1 consumers: 1 for: 1000ms mpmc_queue<tf> push: 85094559 pop: 85094559 tsc: 2445654223 tsc/op: 28 push/pop per sec: **85112818**

Q BW: data size: 4 index size: 4 capacity: 32 producers: 1 consumers: 1 for: 1000ms mpmc_queue<tt> push: 75885964 pop: 75885964 tsc: 2445682659 tsc/op: 32 push/pop per sec: **75901364**

Lockfree, MPMC Queue - Bandwidth Performance

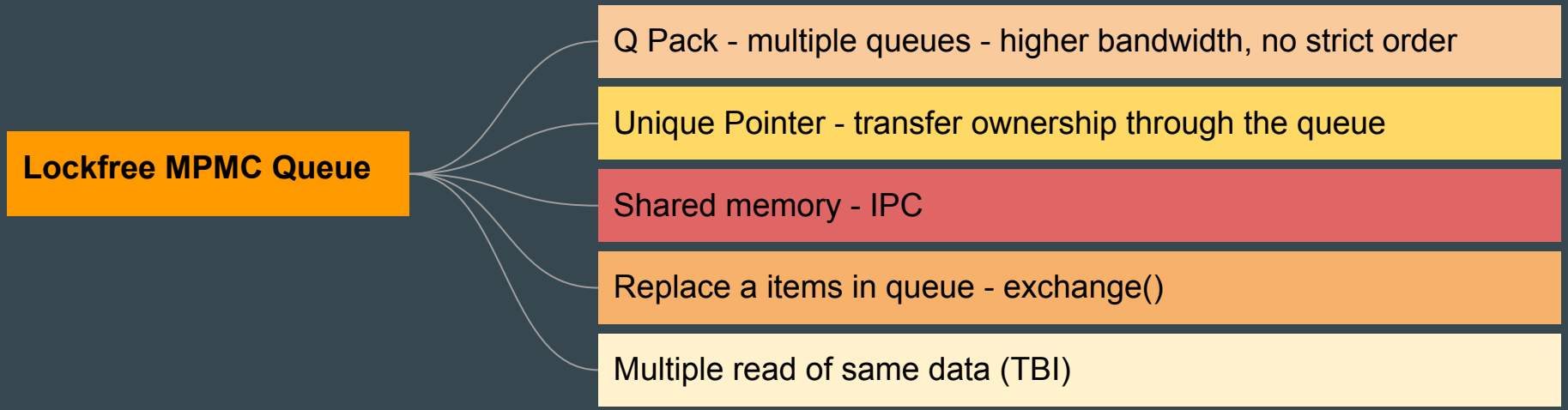
2-2 data width 4:

$ ./q_bandwidth -W4 -p2 -c2 -d 1024

Q BW: data size: 4 index size: 4 capacity: 1024 producers: 2 consumers: 2 for: 1000ms mpmc_queue<ff> push: **11958731** pop: 11958731 tsc: 2470260104 tsc/op: 206 push/pop per sec: **11841101**
Q BW: data size: 4 index size: 4 capacity: 1024 producers: 2 consumers: 2 for: 1000ms mpmc_queue<ft> push: **8372482** pop: 8372482 tsc: 2445914533 tsc/op: 292 push/pop per sec: **8372644**
Q BW: data size: 4 index size: 4 capacity: 1024 producers: 2 consumers: 2 for: 1000ms mpmc_queue<tf> push: 8245603 pop: 8245603 tsc: 2445644652 tsc/op: 296 push/pop per sec: **8246672**
Q BW: data size: 4 index size: 4 capacity: 1024 producers: 2 consumers: 2 for: 1000ms mpmc_queue<tt> push: 9377623 pop: 9377623 tsc: 2445890844 tsc/op: 260 push/pop per sec: **9377895**

$ ./cbuild/q_bandwidth -W4 -p4 -c4 -d 2048
Q BW: data size: 4 index size: 4 capacity: 2048 producers: 4 consumers: 4 for: 1000ms mpmc_queue<ff> push: 7372234 pop: 7372234 tsc: 2230384516 tsc/op: 302 push/pop per sec: 7304356

Lockfree, MPMC Queue - Derived work



Lockfree, MPMC Queue - Next steps:

1. Benchmarks - compare with similar queues / disruptor
2. Blocking using conditional variable - non-busy wait on empty or full
3. Unify API, according to the WG21 concurrent queue paper
4. Multiple read of the same entry - reads count
5. Porting to other platforms Windows, RISC-V, Arm
6. Performance improvement

Lockfree, MPMC Queue - Summary

Header only queue

- low latency queue - using atomic operations, no system calls
- lockfree - no interaction with scheduler
- collaborative - between publishers and consumers
- bounded - no memory allocation, other than init time
- Multi producer, multi consumer
- Limited data size - up 12 bytes
- Ownership transfer using unique_ptr<T> wrapper
- Between threads or processes - for simple types
- We need this queue - for these requirements

Lockfree, MPMC Queue - References

- https://github.com/erez-strauss/lockfree_mpmc_queue
- https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2020/p0260r4.html
- moodycamel::ConcurrentQueue: https://github.com/cameron314/concurrentqueue
- Intel: https://github.com/oneapi-src/oneTBB/blob/master/include/oneapi/tbb/concurrent_queue.h
- Rigtorp's Queue https://github.com/rigtorp/MPMCQueue

Lockfree, MPMC Queue

Thank You!