NOZOMI NETWORKS

C++ micro-problems

lock-free

C++ Micro-Problems

- Herb Sutter (2013) “My Favorite C++ 10-Liner” https://channel9.msdn.com/Events/GoingNative/2013/My-Favorite-Cpp-10-Liner
- Indeed some* problems can be solved in 10 lines
- We will show you three of them

(*) Not *all* problems unfortunately, but we are working on it

SLIDEWARE

WARNING

MAY CONTAIN TRACES OF
SIMPLIFIED CONTENTS

Highlights

1. Lock-free basics: the atomic_list
2. Micro-problems
3. The law of the instrument

Highlights

1. Lock-free basics: the atomic_list
2. Micro-problems
3. The law of the instrument

Lock-free basics

- User-space based synchronization algorithms
  - No mutex involved
  - Do not rely on the OS to serialize operations
  - Waste some CPU time instead
- Pros and Cons:
  - *Insanely* low overhead in the fast path
  - Poor scalability under high contention (for hardware reasons)
  - Did I mention they are hard to optimize?

The atomic linked list

The atomic linked list

The atomic linked list

- R. Kent Treiber (1986) *Systems Programming: Coping with Parallelism*
  - A lock-free linked list with front, push-front and pop-front
- DOES IT REALLY WORK IN C++?
  - Not as written
- A SUBSET of the original code is just perfect
  - Remove pop-front to get the *swiss knife of lock free programming*

The atomic linked list

atomic_list.hpp

```
template <typename T>
class atomic_list
{
        struct node_t
        {
                T value;
                node_t* next;
        };

        std::atomic<node_t*> head_{nullptr};
```

The atomic push-front

atomic_list.hpp

```
template <typename U>
void push_front(U&& u)
{
        node_t* const n = new node_t{ std::forward<U>(u), nullptr };
        node_t* h = head_.load();
        do
        {
                n->next = h;
        }
        while (!head_.compare_exchange_weak(h, n));
}
```

The atomic linked list

Scenario #1: push-front + front

atomic_list.hpp

```
const T* front() const
{
        if (node_t* h = head_.load())
                return &(h->value);
        else
                return nullptr;
}
```

Scenario #2: push-front + pop-all

atomic_list.hpp

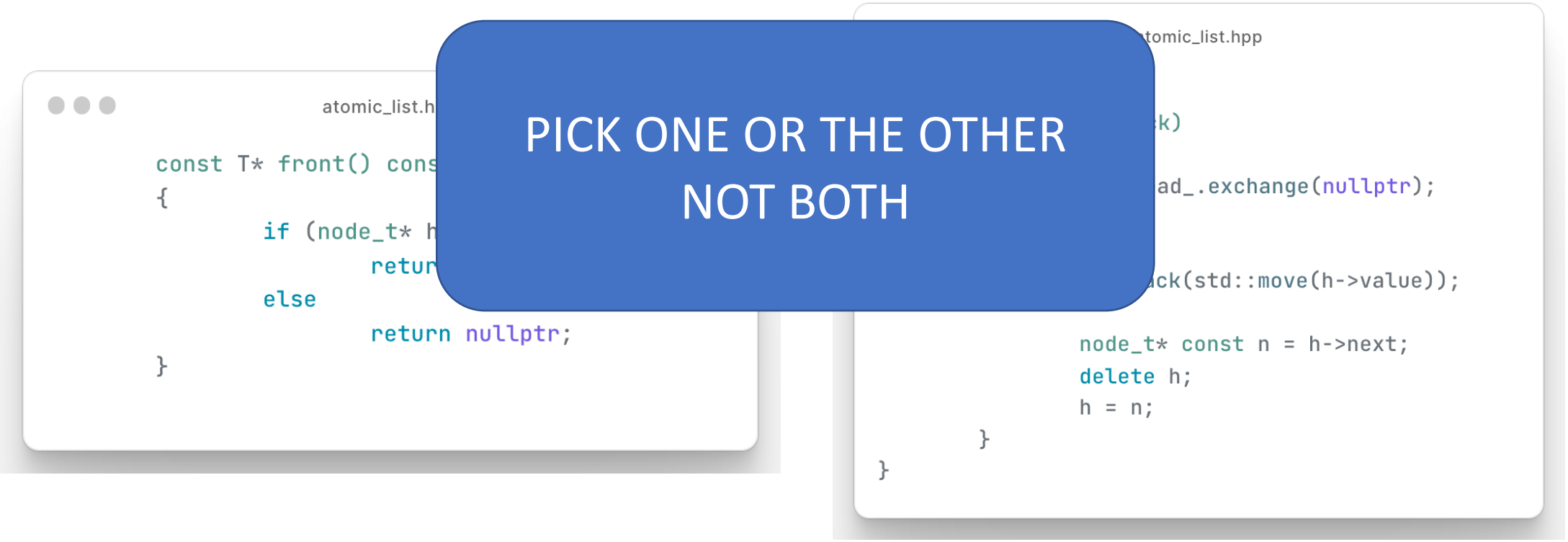
```
template <typename X>
void pop_all(X callback)
{
        node_t* h = head_.exchange(nullptr);
        while (h)
        {
                callback(std::move(h->value));

                node_t* const n = h->next;
                delete h;
                h = n;
        }
}
```

The atomic linked list

Scenario #1: push-front + front

Scenario #2: push-front + pop-all



The atomic linked list

- Other combinations/variations are UNSAFE
  - There is no control on the lifetime of nodes
  - We solve the problem by *never deleting*
- Note in fact there's no destructor
  - Even destruction of the list may be problematic
  - But it would be: `pop_all` with an empty callback

The atomic linked list

- Whenever `front` is safe, we can add the const-equivalent of `pop_all`

atomic_list.hpp

```
template <typename X>
const T* find_if(X predicate) const
{
  for (node_t* h = head_.load(); h; h = h->next)
  {
    if (predicate(h->value))
      return &h->value;
  }
  return nullptr;
}

template <typename X>
void visit(X callback) const
{
  for (node_t* h = head_.load(); h; h = h->next)
    callback(h->value);
}
```

The atomic linked list

- Example 1: call `front` while a different thread runs `pop_all`

atomic_list.hpp

```
const T* front() const
{
        if (node_t* h = head_.load())
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The atomic linked list

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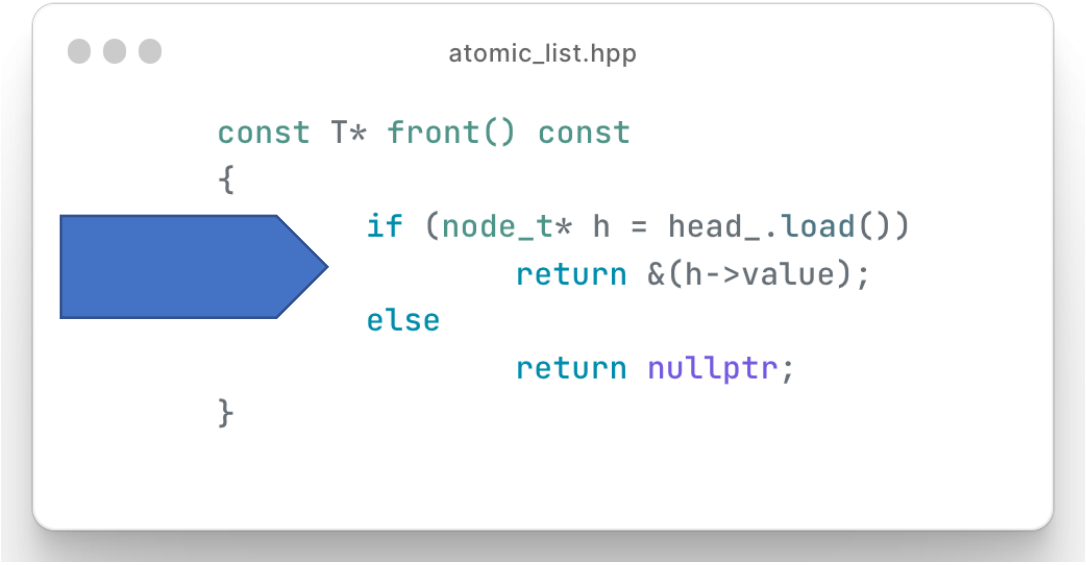

The atomic linked list

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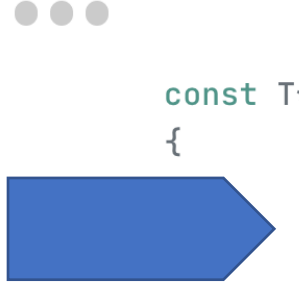

atomic_list.hpp

```
template <typename X>
void pop_all(X callback)
{
        node_t* h = head_.exchange(nullptr);
        while (h)
        {
                callback(std::move(h->value));

                node_t* const n = h->next;
                delete h;
                h = n;
        }
}
```

The atomic linked list

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The atomic linked list

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        if (node_t* h = head_.load())
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        else
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}
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atomic_list.hpp

```
template <typename X>
void pop_all(X callback)
{
        node_t* h = head_.exchange(nullptr);
        while (h)
        {
                callback(std::move(h->value));

                node_t* const n = h->next;
                delete h;
                h = n;
        }
```

Delete object in use
(returning front by value does not fix)

The atomic linked list

- Example 2: Treiber's `pop_front`

The atomic linked list

- Example 2: Treiber's ... pop_front

atomic_list.hpp

```
template <typename U>
bool pop_front(U& result)
{
        node_t* h = head_.load();
        if (!h)
                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

        result = std::move(h->value);
        delete h;
        return true;
}
```

The atomic linked list

atomic_list.hpp

```
template <typename U>
bool pop_front(U& result)
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                node_t* h = head_.load();
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The atomic linked list

Thread#1

atomic_list.hpp

```
template <typename U>
bool pop_front(U& result)
{
                node_t* h = head_.load();
                if (!h)
                        return false;

                node_t* n = h->next;
                while (!head_.compare_exchange_weak(h, n))
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                result = std::move(h->value);
                delete h;
                return true;
}
```

atomic_list.hpp

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template <typename U>
bool pop_front(U& result)
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                node_t* h = head_.load();
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                node_t* n = h->next;
                while (!head_.compare_exchange_weak(h, n))
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                delete h;
                return true;
}
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The atomic linked list

Thread#1

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        if (!h)
                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

        result = std::move(h->value);
        delete h;
        return true;
}
```

atomic_list.hpp

```
template <typename U>
bool pop_front(U& result)
{
        node_t* h = head_.load();
        if (!h)
                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

        result = std::move(h->value);
        delete h;
        return true;
}
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The atomic linked list

Thread#1

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                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

        result = std::move(h->value);
        delete h;
        return true;
}
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The atomic linked list

Thread#1

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bool pop_front(U& result)
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                        return false;

                node_t* n = h->next;
                while (!head_.compare_exchange_weak(h, n))
                        n = h->next;

                result = std::move(h->value);
                delete h;
                return true;
}
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atomic_list.hpp

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template <typename U>
bool pop_front(U& result)
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                node_t* h = head_.load();
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                        return false;

                node_t* n = h->next;
                while (!head_.compare_exchange_weak(h, n))
                        n = h->next;

                result = std::move(h->value);
                delete h;
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```

The atomic linked list

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template <typename U>
bool pop_front(U& result)
{
        node_t* h = head_.load();
        if (!h)
                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

        result = std::move(h->value);
        delete h;
        return true;
}
```

Read from deleted memory

Thread#2

atomic_list.hpp

```
template <typename U>
bool pop_front(U& result)
{
        node_t* h = head_.load();
        if (!h)
                return false;

        node_t* n = h->next;
        while (!head_.compare_exchange_weak(h, n))
                n = h->next;

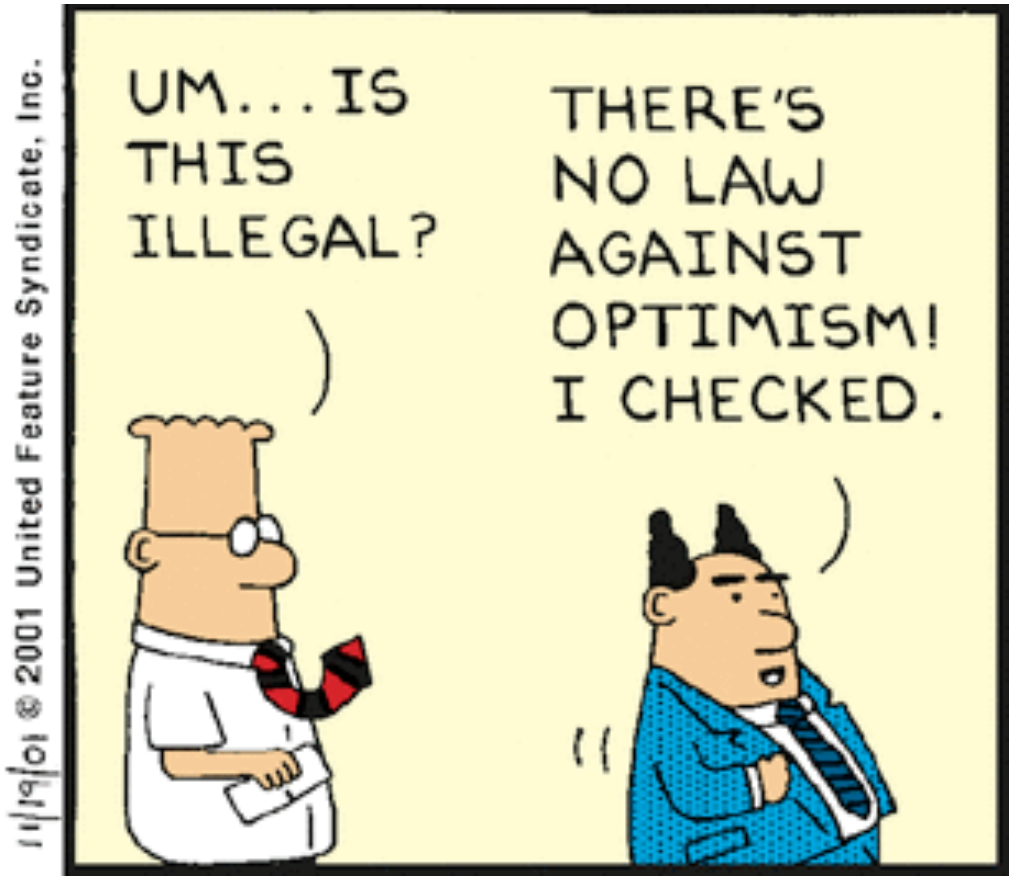
        result = std::move(h->value);
        delete h;
        return true;
```

How to (not) optimize

- Relax atomic memory order ❌
  - On average, low performance gain
  - Operations that are not «sequentially consistent» may not be sequenced
  - Intel processors are special
  - Testing is hard
- Pay attention to reduce sharing ✅
  - Often not usable in practice

https://www.1024cores.net/home/lock-free-algorithms/false-sharing---false

That’s enough for the pessimistic part…



Highlights

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Highlights

1. Lock-free basics: the atomic_list
2. Micro-problems
    1. Read often, write rarely
    2. MP queue
    3. Thread notifications
3. The law of the instrument

Problem #1: read often, write rarely

- We have a global variable that is
  - Not a trivial type (say T := std::string)
  - Read very often (by N threads)
  - Rarely updated (by any thread)
- The variable is accessed via two free/static functions
  - T GetGlobalValue()
  - SetGlobalValue(T newVal)
- Bonus points if you can make it
  - const T& GetGlobalValue()

Problem #1: read often, write rarely

- Naïve solution:

Problem #1: read often, write rarely

- Naïve solution:

Options.cpp

```
using T = std::string;

std::mutex myMutex; // global
T myName; // global

void SetMyName(const T& newVal)
{
  std::lock_guard g(myMutex);
  myName = newVal;
}

T GetMyName()
{
  std::lock_guard g(myMutex);
  return myName;
}
```

Problem #1: read often, write rarely

- Naïve solution:

Options.cpp

```
using T = std::string;

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  return myName;
}
```

copy

Problem #1: read often, write rarely

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  return myName;
}
```

Problem #1: read often, write rarely

- Naïve solution:

Options.cpp

```
using T = std::string;

std::mutex myMutex; // global
T myN

void

  std
  myN
}

T GetMyName()
{
  std::lock_guard g(myMutex);
  return myName;
}
```

SIDE NOTE

To see a good lock-free solution,
you may have to question something
{hypotheses, properties, …}
that *superficially* looks fundamental

Problem #1: read often, write rarely

- Naïve solution:

SIDE NOTE

To see a good lock-free solution,
you may have to question something
{hypotheses, properties, …}
that *superficially* looks fundamental

- Do I really need to keep a single value in memory?

Problem #1: read often, write rarely

- Solution:
  - *Never delete old values*
  - Use a global `atomic_list<T>` with front/push_front

- Optional:
  - Clear the list in the destructor (it may be acceptable to leak)
  - Wrap `front` to return a default instead of `nullptr`

Problem #1: read often, write rarely

Options.cpp

```cpp
#include "atomic_list.h"

struct NameList
{
   atomic_list<std::string> data;

   ~NameList()
   {
     data.pop_all([](auto&&){});
   }
} myName;

const std::string& GetMyName()
{
  static const std::string empty{};
  if (auto ptr = myName.data.front())
    return *ptr;
  else
    return empty;
}

void SetMyName(std::string name)
{
  myName.data.push_front(std::move(name));
}
```

Problem #1: read often, write rarely

reference

Options.cpp

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}

void SetMyName(std::string name)
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}
```

Problem #2: MP queue

- Producers and consumers (threads)
- An object of type T represents some «work» to do
- Producers create T's and *move* them in a «shared list»
  - Order is not relevant
- Consumer(s) remove T's from the «shared list»
  - Work items are «consumed»

Problem #2: MP queue

- ACTIVE LOGGING
  - Many threads produce strings that must be appended to a log file
  - One thread gathers them, adds a timestamp, etc. and writes

- Solution: use an atomic_list<T> with push_front / pop_all

Problem #2: MP queue

ActiveLog.h

```
#include <...>

using LogLine = std::tuple<time_t, const char*, std::string, long>;

atomic_list<LogLine>& LogQueue();

#define LOG_D(...)  \
    LogQueue().push_front(LogLine{now(), "DEBUG", fmt::format(__VA_ARGS__), __LINE__})
```

Problem #2: MP queue

ActiveLog.cpp

```
#include <...>

struct ActiveLog
{
  atomic_list<LogLine> logLines;
  std::atomic<bool> logExit = false;

  std::ofstream logFile;
  std::thread logWriter;

  void Flush();
  ActiveLog(const char* file);
  ~ActiveLog();
}

// ...

ActiveLog theLog("/var/log/async.log");

atomic_list<LogLine>& LogQueue()
{
  return theLog.logLines;
}
```

Problem #2: MP queue

Let's zoom here…

ActiveLog.cpp

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Problem #2: MP queue

ActiveLog.cpp

```
ActiveLog::ActiveLog(const char* file) : logFile(file)
{
  logWriter = std::thread([this]{
    while (!logExit)
    {
      std::this_thread::sleep_for(2_s);
      Flush();
    }
  });
}

ActiveLog::~ActiveLog()
{
  logExit = true;
  logWriter.join();
  Flush();
}
```

ActiveLog.cpp

```
void ActiveLog::Flush()
{
  std::vector<std::string> tmp;
  logLines.pop_all([&tmp](auto&& t) {
    auto& [time, label, msg, line] = t;
    tmp.push_back(fmt::format(...));
  });

  std::sort(tmp.begin(), tmp.end());
  for (auto& line : tmp)
    logFile << line << '\n';

  logFile << std::flush;
}
```

Problem #2: MP queue

ActiveLog.cpp

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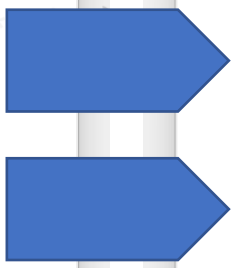

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}
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Problem #2: MP queue

ActiveLog.cpp

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ActiveLog::~ActiveLog()
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  Flush();
}
```

Delegate some work to the writer thread

ActiveLog.cpp

```
void ActiveLog::Flush()
{
  std::vector<std::string> tmp;
  logLines.pop_all([&tmp](auto&& t) {
    auto& [time, label, msg, line] = t;
    tmp.push_back(fmt::format(...));
  });

  std::sort(tmp.begin(), tmp.end());
  for (auto& line : tmp)
    logFile << line << '\n';

  logFile << std::flush;
}
```

Problem #3: Thread notifications

- Suppose we have a thread-safe global «map» where multiple threads execute concurrent lookups
- Assume for simplicity that the global map is read-only and is occasionally reloaded
  - Think anti-virus signatures…

Lookup.cpp

```
// this is expensive
return GlobalMap().Lookup(myKey);
```

Problem #3: Thread notifications

- As lookups are expensive, we decide to add a thread-local cache

Problem #3: Thread notifications

Lookup.cpp

```
struct LazyValue
{
        K& myKey;

        operator V() const
        { return GlobalMap().Lookup(myKey); }
};

thread_local unordered_map<K, V> myCache;
auto [iter, added] = myCache.try_emplace(myKey, LazyValue{myKey});
return iter->second;
```

Problem #3: Thread notifications

- As lookups are expensive, we decide to add a thread-local cache
- But how do we *clear* the local caches?

Lookup.cpp

```
struct LazyValue
{
        K& myKey;

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```

Problem #3: Thread notifications

- As lookups are expensive, we decide to add a thread-local cache
- But how do we *clear* the local caches?

Problem #3: Thread notifications

- Solution: a global «hub» that can broadcast a boolean
- A thread-local message is connected to the hub on construction

a_different_thread.cpp

```
{
  // ...
  h.broadcast(true);
}
```

Lookup.cpp

```
notification_hub<bool> h;

V SomeFunc(K myKey)
{
        thread_local unordered_map<K, V> myCache;

        thread_local notification_hub<bool>::message msg(h);
        if (msg.get_and_clear())
                myCache.clear();

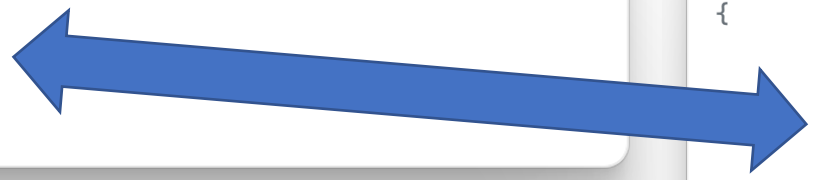
        auto [iter, added] = myCache.try_emplace(myKey, LazyValue{myKey});
        // ...
}
```

Problem #3: Thread notifications

- Solution: a global «hub» that can broadcast a boolean
- A thread-local message is connected to the hub on construction

a_different_thread.cpp

```
{
  // ...
  h.broadcast(true);
}
```



Lookup.cpp

```
notification_hub<bool> h;

V SomeFunc(K myKey)
{
        thread_local unordered_map<K, V> myCache;

        thread_local notification_hub<bool>::message msg(h);
        if (msg.get_and_clear())
                myCache.clear();

        auto [iter, added] = myCache.try_emplace(myKey, LazyValue{myKey});
        // ...
}
```

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- The ”hub” is a linked list of reference-counted nodes
- A thread_local message
  - pushes a node in the hub on creation
  - …and keeps a reference to it
  - So the reference count is 2 (1 for the hub, 1 for the thread)

- `hub.broadcast` walks the list and stores `true` in every node
  - then it’s up to each thread to pick up the message

Problem #3: Thread notifications

notification_hub.h

```
template <typename T>
class notification_hub
{
    struct node_t
    {
        std::atomic<T> value{T()};
        std::atomic<int> ref_count{2};
        node_t* next{nullptr};

        static void push_front(std::atomic<node_t*>& head, node_t* const n);
        static void release(node_t* const n);
    };

    std::atomic<node_t*> head_ { nullptr };

    template <typename X> void on_nodes(X action);
    template <typename X> void on_messages(X action);

  public:

    void broadcast(T value)
    {
        on_messages([value](auto& msg) { msg.store(value); });
    }

    ~notification_hub()
    {
        on_nodes([](node_t* n) { node_t::release(n); });
    }
```

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notification_hub.h

```
    class message
    {
        node_t* const self_;

      public:
        message(notification_hub& h)
        : self_{new node_t}
        {
            node_t::push_front(h.head_, self_);
        }

        ~message() {
            node_t::release(self_);
        }

        T get_and_clear() {
            return self_->value.exchange(T{});
        }

        bool connected() const {
            return self_->ref_count == 2;
        }
    };
```

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Problem #3: Thread notifications

notification_hub.h

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void node_t::push_front(std::atomic<node_t*>& head, node_t* const n)
{
    node_t* h = head.load();
    do
    {
        n->next = h;
    }
    while (!head.compare_exchange_weak(h, n));
}

void node_t::release(node_t* const n)
{
    if (!(--n->ref_count))
        delete n;
}
```

notification_hub.h

```
template <typename X>
void on_nodes(X action)
{
    node_t* n = head_.load();
    while (n) {
        node_t* const next = n->next;
        action(n);
        n = next;
    }
}

template <typename X>
void on_messages(X action)
{
    on_nodes([&](node_t* n) {
        if (n->ref_count == 2) action(n->value);
    });
}
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Highlights

1. Lock-free basics: the atomic_list
2. Micro-problems
3. The law of the instrument

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1. Lock-free basics: the atomic_list
2. Micro-problems
3. The law of the instrument

The law of the instrument

- To a man with a hammer, everything looks like a nail
- To a man with an atomic_list, everything looks like a push_front

- When you have an apparently unrelated problem, consider solving it with an atomic_list

The law of the instrument

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Thank You!

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Bonus slide: an atomic hashtable

- Assume atomic_list is written as:

atomic_list.hpp

```
template <typename U>
void push_front(U&& u)
{
  push_front(new node_t { std::forward<U>(u), nullptr });
}

void push_front(node_t* n)
{
  // as before...
```

Bonus slide: an atomic hashtable

- Using T= std::tuple<std::atomic<size_t>, const K, V>
- Create an array of atomic_list<T>
  - Reserve is mandatory
- Find scans the appropriate bucket
- Insert is a push_front in the appropriate bucket
  - Yes, we have duplicated elements…
  - …But find will stop on the first (i.e. the last insert)
  - Erase just flips the bits of the hash

Bonus slide: an atomic hashtable

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atomic_hashtable.hpp

```
template <typename K, typename V>
class atomic_hashtable
{
  enum { HASH, KEY, VALUE };
  using tuple_t = std::tuple<std::atomic<size_t>, const K, V>;
  using list_t = atomic<list<tuple_t>>;

  std::unique_ptr<list_t []> bucket_;
  const unsigned size_;

 public:
    atomic_hashtable(unsigned n) // reserve is mandatory
    : bucket_(new list_t[n]), size_(n)
    {
    }

    const V* find(const K& key) const;
    void insert(const K& key, const V& value);
    void erase(const K& key);
};
```

Bonus slide: an atomic hashtable

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};
```

atomic_hashtable.hpp

```
const V* find(const K& key) const
{
  const auto hash = std::hash<K>{}(key);
  auto elem = bucket_[hash % size_].find_if([&](const tuple_t& t)
  {
    return std::get<HASH>(t) == hash && std::get<KEY>(t) == key;
  });

  return elem ? &std::get<VALUE>(*elem) : nullptr;
}

void insert(const K& key, const V& value)
{
  const auto hash = std::hash<K>{}(key);
  bucket_[hash % size_].push_front(new tuple_t { hash, key, value });
}

void erase(const K& key)
{
  const auto hash = std::hash<K>{}(key);
  bucket_[hash % size_].visit([&](tuple_t& t)
  {
    if (std::get<HASH>(t) == hash && std::get<KEY>(t) == key)
      std::get<HASH>(t) ^= ~0ull;
  });
}
```