Reducing Memory Allocations In A Large C++ Application

Arnaud Desitter

CppOnSea Conference
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In memoriam

Hubert Matthews

RIP 2019

Bio

Arnaud Desitter

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Lives in Oxford, UK

25 years experience in working on scientific software

Developer for Schlumberger on a reservoir simulator

Opinions in this talk are my own, not my employer's.

Long standing ACCU member

And a cyclist !

Roadmap

- Motivations
- Methodology
- Part I: a case study
- Part II: solutions to address excessive memory allocations
  - Vocabulary types
  - Patterns and anti-patterns
- Part III: C++17 pmr allocators (briefly)
- Conclusions

Why optimise memory allocations ?

- Improve **performance** (usually speed)
- Decrease **memory footprint**

Performance may be of little importance.

Performance may not be a priority.

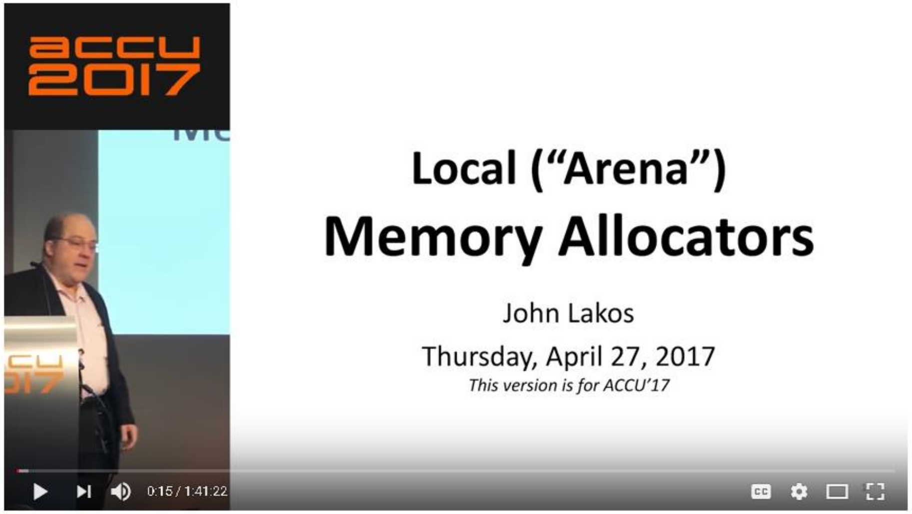
There may be better ways to improve performance:

find hot spot, use better algorithms, etc.

That said, large applications tend to have a rather flat profile and perform too many memory allocations.

Motivations

Custom allocators are a much discussed topic in the C++ industry.



Local (arena) Memory Allocators - John Lakos [ACCU 2017]

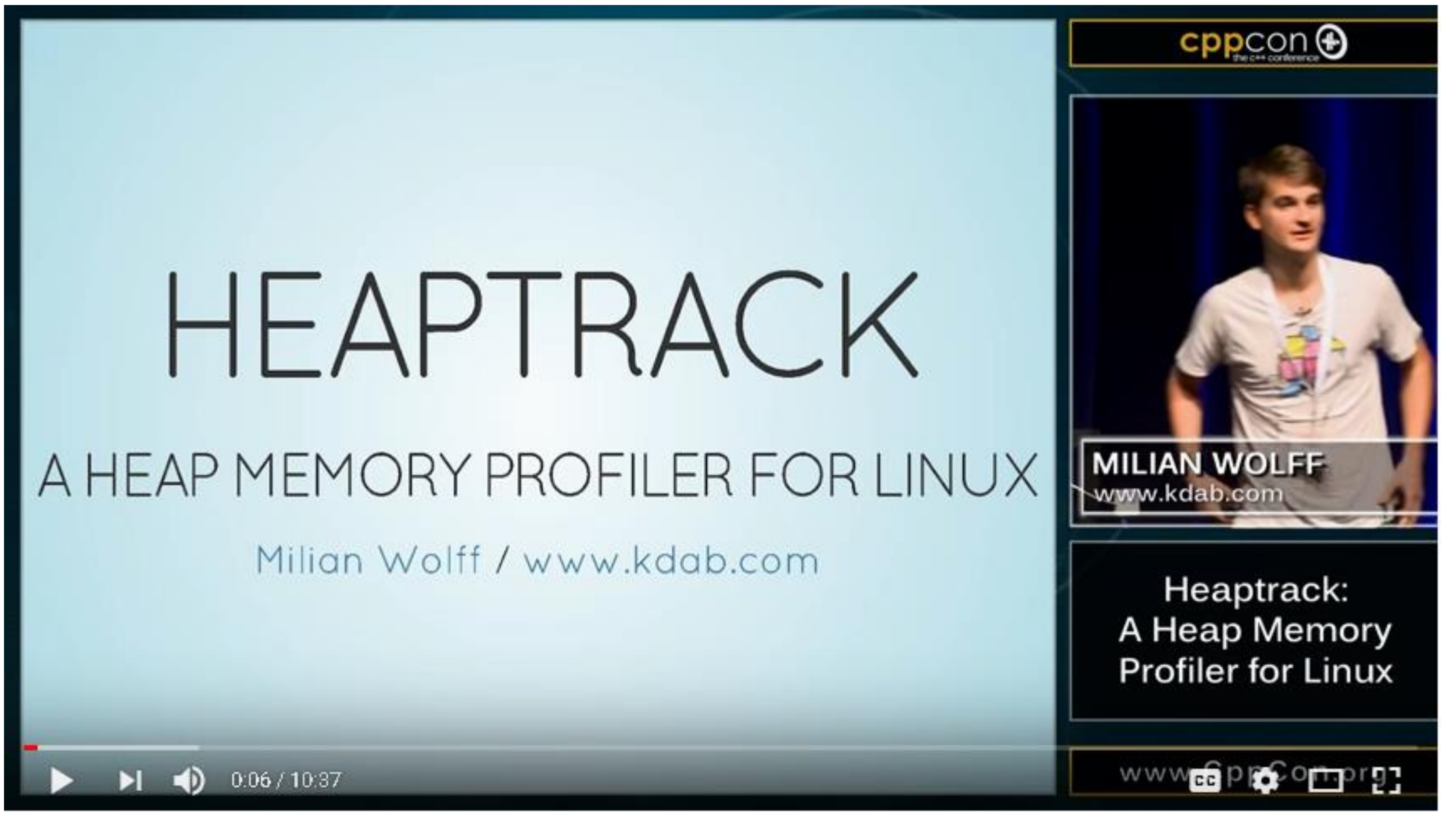
Motivations

Custom allocators are a much discussed topic in the C++ industry.

Local (arena) Memory Allocators - John Lakos [ACCU 2017]

How do I quantify the memory allocations of my application ?

Motivations



CppCon 2015: Milian Wolff "Heaptrack: A Heap Memory Profiler for Linux"

Installing Milian Wolff's heaptrack

- Build it from source
  `search for "heaptrack build ubuntu"`

- Use pre-built AppImage
  - https://download.kde.org/stable/heaptrack/1.1.0/heaptrack-v1.1.0-x86_64.AppImage.mirrorlist
  - `https://travis-ci.org/KDAB/heaptrack` for recent snapshots

```
wget …/heaptrack-v1.1.0-x86_64.AppImage
chmod +x heaptrack-v1.1.0-x86_64.AppImage
```

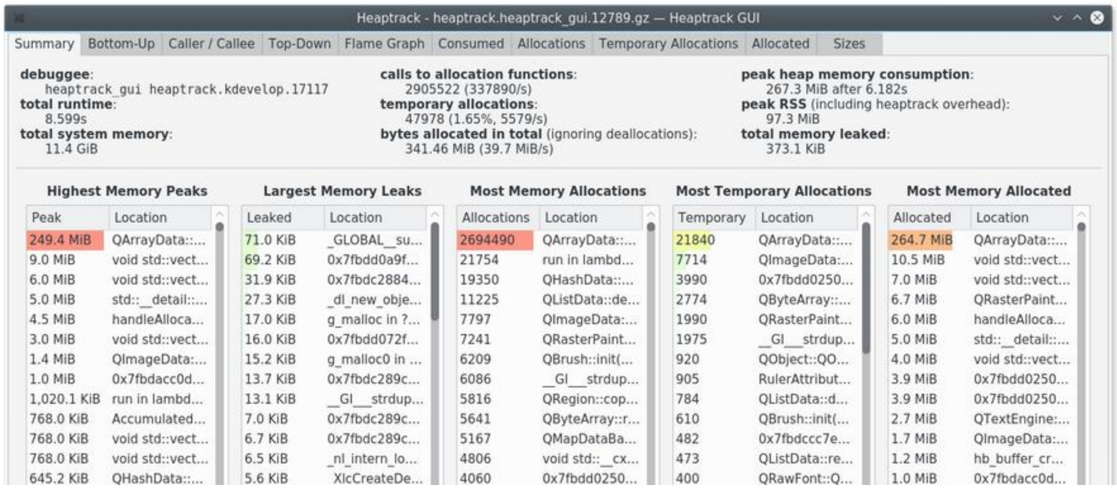
Running Milian Wolff's heaptrack

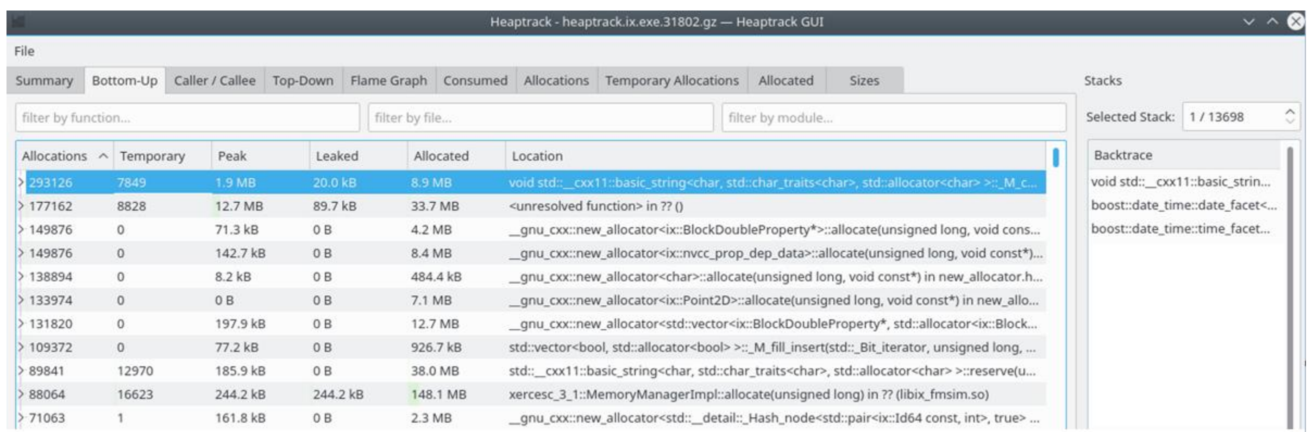
```
# heaptrack operates on any executable.
# Stack traces available only with debugging symbols (compile with "-g")
> ./heaptrack-v1.1.0-x86_64.AppImage /bin/ls
heaptrack output will be written to "heaptrack.ls.1877.zst"
starting application, this might take some time...
heaptrack.ls.1877.zst  heaptrack-v1.1.0-x86_64.AppImage
heaptrack stats:
        allocations:            44
        leaked allocations:     38
        temporary allocations:  2
Heaptrack finished! Now run the following to investigate the data:

  heaptrack --analyze "heaptrack.ls.1877.zst"
>./heaptrack-v1.1.0-x86_64.AppImage --analyze heaptrack.ls.1877.zst
```

(1) Execution with heaptrack data collection

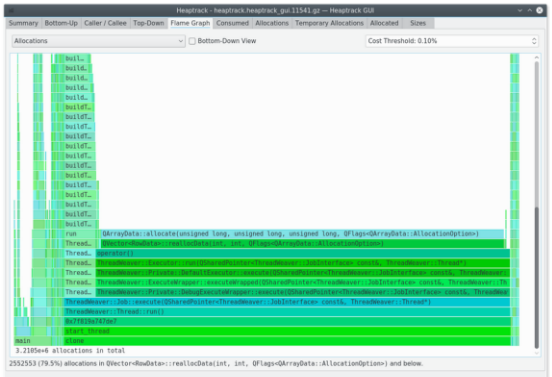
(2) Data visualisation

Heaptrack

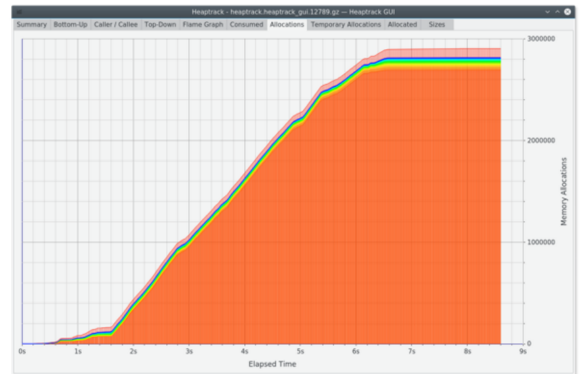

Heaptrack - heaptrack.heaptrack_gui.12789.gz — Heaptrack GUI
Summary Bottom-Up Caller / Callee Top-Down Flame Graph Consumed Allocations Temporary Allocations Allocated Sizes
debuggee: heaptrack_gui heaptrack.kdevelop.17117
total runtime: 8.599s
total system memory: 11.4 GiB
calls to allocation functions: 2905522 (337890/s)
temporary allocations: 47978 (1.65%, 5579/s)
bytes allocated in total (ignoring deallocations): 341.46 MiB (39.7 MiB/s)
peak heap memory consumption: 267.3 MiB after 6.182s
peak RSS (including heaptrack overhead): 97.3 MiB
total memory leaked: 373.1 KiB
Highest Memory Peaks
Largest Memory Leaks
Most Memory Allocations
Most Temporary Allocations
Most Memory Allocated
Peak Location
249.4 MiB QArrayData::...
9.0 MiB void std::vect...
6.0 MiB void std::vect...
5.0 MiB std::__detail::...
4.5 MiB handleAlloca...
3.0 MiB void std::vect...
1.4 MiB QImageData:...
1.0 MiB 0x7fbdacc0d...
1,020.1 KiB run in lambd...
768.0 KiB Accumulated...
768.0 KiB void std::vect...
768.0 KiB void std::vect...
645.2 KiB QHashData::...
Leaked Location
71.0 KiB _GLOBAL__su...
69.2 KiB 0x7fbdd0a9f...
31.9 KiB 0x7fbdc2884...
27.3 KiB _dl_new_obje...
17.0 KiB g_malloc in ?...
16.0 KiB 0x7fbdd072f...
15.2 KiB g_malloc0 in ...
13.7 KiB 0x7fbdc289c...
13.1 KiB __GI___strdup...
7.0 KiB 0x7fbdc289c...
6.7 KiB 0x7fbdc289c...
6.5 KiB _nl_intern_lo...
5.6 KiB XlcCreateDe...
Allocations Location
2694490 QArrayData::...
21754 run in lambd...
19350 QHashData::...
11225 QListData::de...
7797 QImageData:...
7241 QRasterPaint...
6209 QBrush::init(...
6086 __GI___strdup...
5816 QRegion::cop...
5641 QByteArray::r...
5167 QMapDataBa...
4806 void std::__cx...
4060 0x7fbdd0250...
Temporary Location
21840 QArrayData::...
7714 QImageData:...
3990 0x7fbdd0250...
2774 QByteArray::...
1990 QRasterPaint...
1975 __GI___strdup...
920 QObject::QO...
905 RulerAttribut...
784 QListData::d...
610 QBrush::init(...
482 0x7fbdccc7e...
473 QListData::re...
400 QRawFont::Q...
Allocated Location
264.7 MiB QArrayData::...
10.5 MiB void std::vect...
7.0 MiB void std::vect...
6.7 MiB QRasterPaint...
6.0 MiB handleAlloca...
5.0 MiB std::__detail::...
4.0 MiB void std::vect...
3.9 MiB 0x7fbdd0250...
3.9 MiB 0x7fbdd0250...
2.7 MiB QTextEngine:...
1.7 MiB QImageData:...
1.2 MiB hb_buffer_cr...
1.0 MiB 0x7fbdacc0d...


Heaptrack - heaptrack.ix.exe.31802.gz — Heaptrack GUI
File
Summary Bottom-Up Caller / Callee Top-Down Flame Graph Consumed Allocations Temporary Allocations Allocated Sizes
Stacks
filter by function...
filter by file...
filter by module...
Selected Stack: 1 / 13698
Allocations Temporary Peak Leaked Allocated Location
293126 7849 1.9 MB 20.0 kB 8.9 MB void std::__cxx11::basic_string<char, std::char_traits<char>, std::allocator<char> >::_M_c...
177162 8828 12.7 MB 89.7 kB 33.7 MB <unresolved function> in ?? ()
149876 0 71.3 kB 0 B 4.2 MB __gnu_cxx::new_allocator<ix::BlockDoubleProperty*>::allocate(unsigned long, void cons...
149876 0 142.7 kB 0 B 8.4 MB __gnu_cxx::new_allocator<ix::nvcc_prop_dep_data>::allocate(unsigned long, void const*)...
138894 0 8.2 kB 0 B 484.4 kB __gnu_cxx::new_allocator<char>::allocate(unsigned long, void const*) in new_allocator.h...
133974 0 0 B 0 B 7.1 MB __gnu_cxx::new_allocator<ix::Point2D>::allocate(unsigned long, void const*) in new_allo...
131820 0 197.9 kB 0 B 12.7 MB __gnu_cxx::new_allocator<std::vector<ix::BlockDoubleProperty*, std::allocator<ix::Block...
109372 0 77.2 kB 0 B 926.7 kB std::vector<bool, std::allocator<bool> >::_M_fill_insert(std::_Bit_iterator, unsigned long, ...
89841 12970 185.9 kB 0 B 38.0 MB std::__cxx11::basic_string<char, std::char_traits<char>, std::allocator<char> >::reserve(u...
88064 16623 244.2 kB 244.2 kB 148.1 MB xercesc_3_1::MemoryManagerImpl::allocate(unsigned long) in ?? (libix_fmsim.so)
71063 1 161.8 kB 0 B 2.3 MB __gnu_cxx::new_allocator<std::__detail::_Hash_node<std::pair<ix::Id64 const, int>, true> ...
Backtrace
void std::__cxx11::basic_strin...
boost::date_time::date_facet<...
boost::date_time::time_facet...

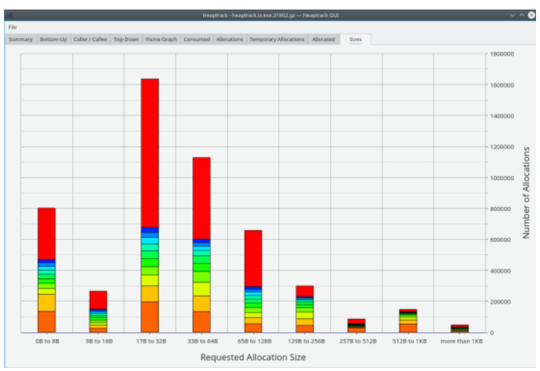
Heaptrack



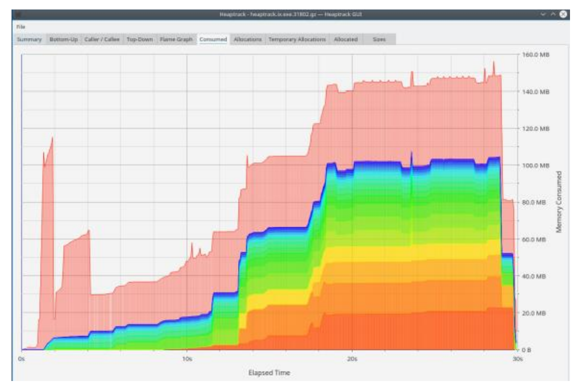
Flamecharts



Cumulated allocations



Sizes



Consumed

Demo time

Profiling: a methodology

- Choose a case.
- Run it under a profiler.
- Spot a problem.
- Try to fix it.
- Profile again with the fix.
  - Discard fix if it does not work.
  - Submit if it does.
- Iterate until there are no more opportunities for change.
- Choose another case and iterate.

Part I: a case study

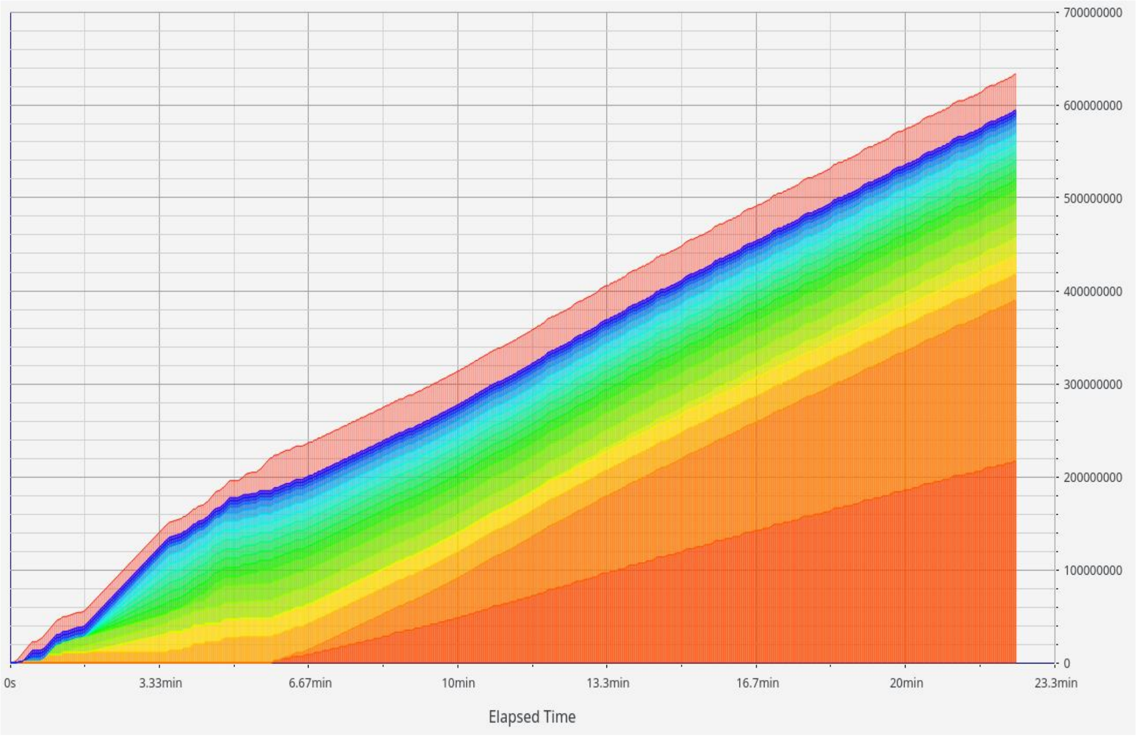
A numerical simulation

- Reasonably large synthetic problem
  … but shortened to a single day of simulation
- Dominated by floating point computation
- Run **without** any concurrency for the sake of this example

Reservoir simulator

- Considered amongst the most advanced of its type
- Constantly developed for more than 15 years
- Multi-millions lines C++ code base
- No memory leaks

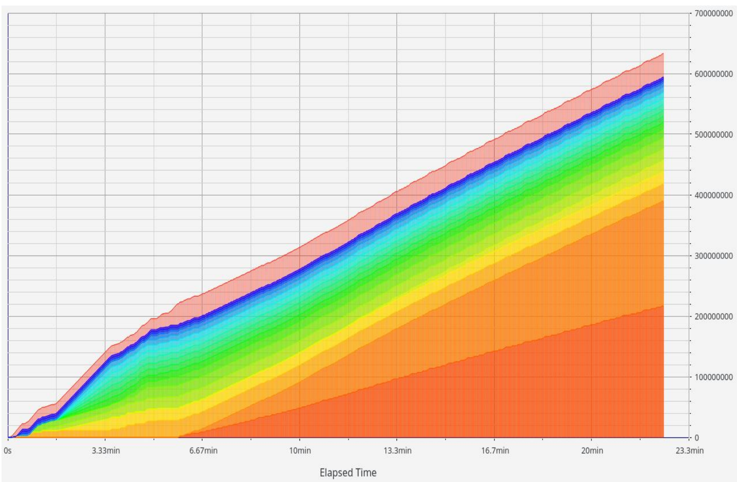
A case study



~630e6

Cumulative number of allocations

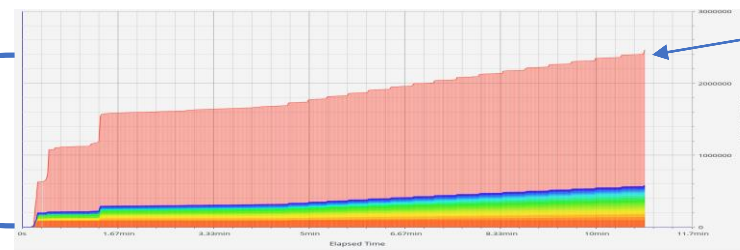
A case study



~630e6

Number of allocations reduced by x250

~2.5e6



Before

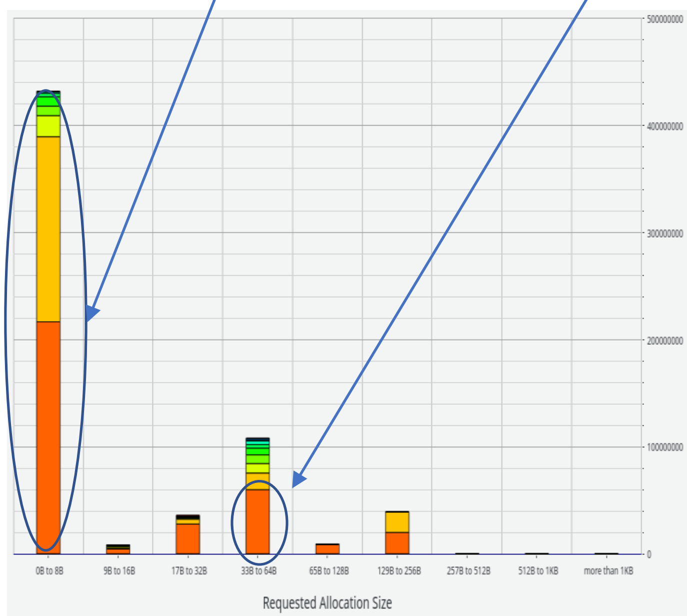
After

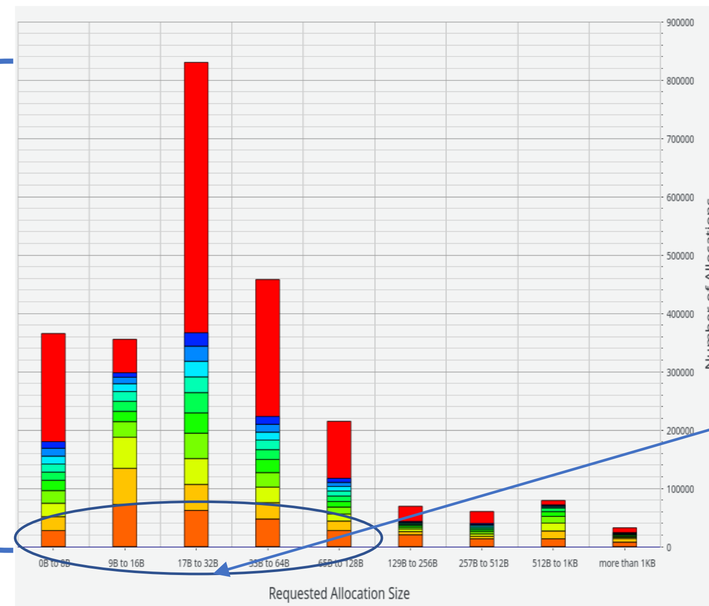
A case study

Most allocations were for 8 bytes or less.

Map nodes

450e6





0.8e6

Largest contributors

Before

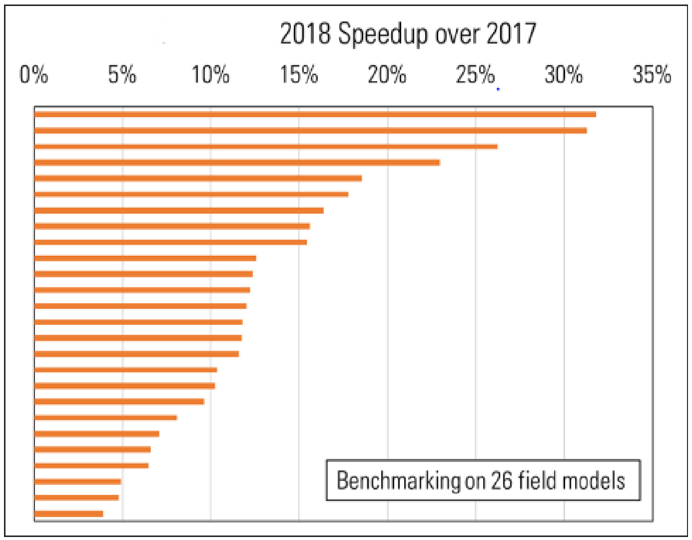
After

Costs of allocations are hard to predict

- Before: **5.5%** time was spent in malloc/free.
- After: **1.5%.**
- But we have a speed up well above 10%.

Reported time spent in allocator is an **under-estimate** of possible gain, as excessive memory allocations can be a source of cache-misses.

Continuous performance improvement



[redacted] 2018 delivers continuous improvement in performance by better memory management and optimization in the linear solver. Benchmarking over a wide range of field models confirm an average performance improvement of 15% over 2017 release.

Memory growth: a case study

A large numerical simulation

- Real world case. Very large grid.
- 128 processes. About 15 Gb per process.
- ~18 h

As the current version of the simulator calls the memory allocator infrequently, using heaptrack is possible.

Memory growth: a case study - before

~ 18 h, 128 processes using about 15 Gb each

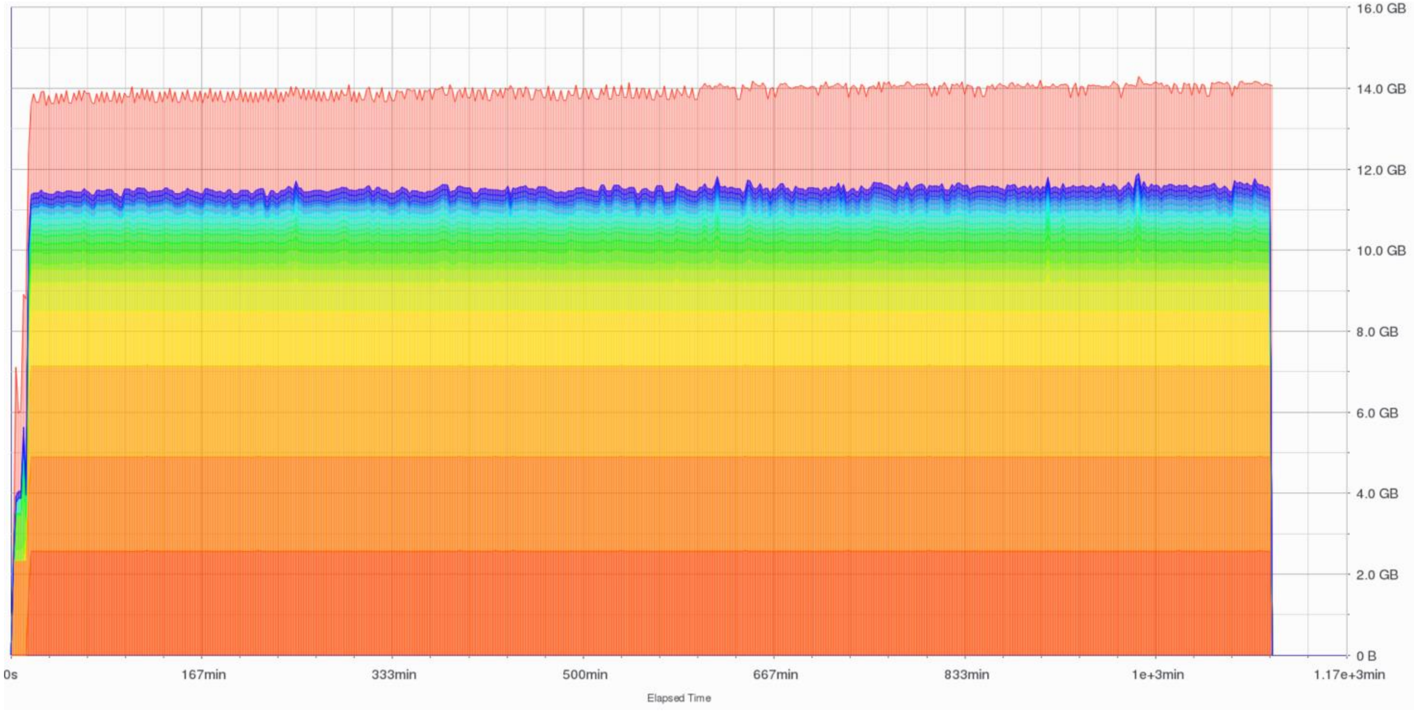
Peaks

Growth

Due to retaining vector capacity for too long

Due to a very pessimistic vector<>::reserve() on a long living object

Memory growth: a case study - after



Conclusions so far

- Heaptrack works really well.
    - Uses **debug information** provided by gcc and clang (“-g”).
    - **Small overhead** once the number of allocations is under control.
    - Compatible with **threads** and inter-process communication.

- It helped us to identify and then obtain significant speedup
    - Biggest gains come from **removing allocations within loops**.
    - Biased towards small size allocations.

Part II: solutions

- Do not copy if you can.
- Avoid allocations.
- Re-use allocated memory.
- Use contiguous containers.

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector.
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

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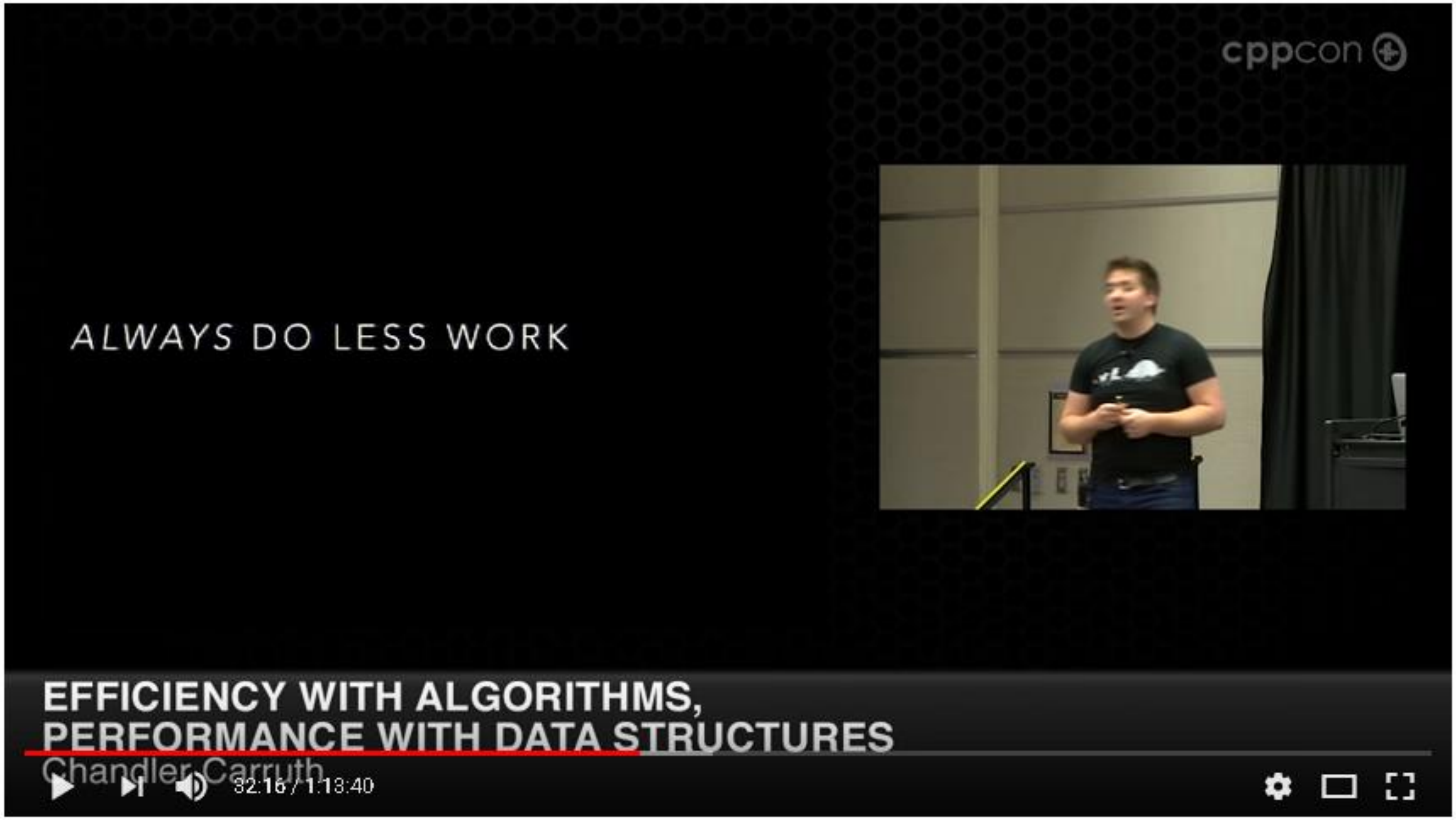
Case study – problem #1 – Avoid unnecessary copies

Some leftovers of a debugging experiment: 210e6 allocations

```
std::vector<double> average_m(m.size());
for (int ic = 0; ic < m.size(); ic++)
  average_m[ic] = m[ic];
```

```
auto const& average_m = m;
```



CppCon 2014: Chandler Carruth "Efficiency with Algorithms, Performance with Data Structures"

Part II: solutions

- Do not copy if you can.
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  - Make use of std::vector capacity.
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Do not copy – “auto const& x = f()”

```
for (…) { for (…) {
  std::vector<int> bs =
    the_sizes[…]->get_sizes();
```

Returns “std::vector<int> const&”

```
for (…) { for (…) {
  // See GotW #88: A Candidate For the “Most Important const”
  auto const& bs = the_sizes[…]->get_sizes();
```

Do not copy arguments

```
// copy !
void add_res_from_buffer(std::vector<double> dbuffer);
```

```
void add_res_from_buffer
      (std::vector<double> const& dbuffer);
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - **Use views (tcb::span, std::string_view).**
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector.
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Vocabulary types - views

- Views are non-owning **pointers**.
  - They can dangle.
  - They are cheap to copy.
- C++17 std::string_view
  - A read-only view to a **contiguous** sequence of “char”.
  - May **not** have a trailing ‘\0’.
- C++20 std::span<T>
  - Implemented by Tristan Brindle as tcb::span<T>
  - A view to a **contiguous** sequence of T.
  - tcb::span<**T**>: read-write
  - tcb::span<**const T**>: read-only

Vocabulary types – std::string_view

- Avoid allocating a string when referring to a substring

- Avoid creating temporary std::string when passing a literal (“A very long string”).

  “std::string **const &**” -> “std::string_view” can be beneficial.

Use std::string_view

```
int size = 0;
const std::unique_ptr<char[]> pchar = block->get_char(size);
std::string str(pchar.get(), size - 1); // Copy!
```

```
int size = 0;
const std::unique_ptr<char[]> pchar = block->get_char(size);
const std::string_view str{ pchar.get(), size - 1 };
```

string_view and std::map

```
struct Map {
  std::map<std::string, int> m_map;
  bool contain(std::string const& key) const
  { return m_map.find(key) != m_map.end(); }
};
Map m; m.contain("a very long string");
```

Temporary std::string created

```
struct Map {
  std::map<std::string, int, std::less<>> m_map;
  bool contain(std::string_view key) const
  { return m_map.find(key) != m_map.end(); }
};
Map m; m.contain("a very long string"sv);
```

C++14 transparent comparator

string_view and std::unordered_map

C++20 makes it easy: P0919.
Possible in C++17 using:
Marc Mutz, *StringViews, StringViews everywhere!*, Meeting C++ 2017

```
std::unordered_map<std::string, int> map;
```

```
std::unordered_map<
     std::string_view, std::pair<std::string, int>> map;
```

Vocabulary types – tcb::span

- Usually used as function parameters
  - “std::vector<double> **&**”
    -> tcb::span<double> (if std::vector is not resized)
  - “std::vector<double> **const&**”
    -> tcb::span<**const** double>
- Allow passing any contiguous sequences such as:
  - std::vector,
  - std::array,
  - boost small_vector, static_vector,
  - a sub-section of a contiguous sequence,
  - etc.

Use tcb::span

```cpp
class TwoDTable { ...
  void lookup(double x, std::vector<double>& y) const;
};
std::vector<double> val(2);
m_table->lookup(x, val);
```

```cpp
class TwoDTable { ...
    void lookup(double x, tcb::span<double> y) const;
};
std::array<double,2> val = {};
m_table->lookup(x, val);
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - **Use moves.**
- Avoid allocation.
  - Use std::array, boost::container::small_vector.
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Use “move”

```
{
  std::vector<std::int64_t> vertex_ids_for_this_cell;
  ...
  cell_vertex_ids.push_back(vertex_ids_for_this_cell); // Copy!
}
```

```
{
  std::vector<std::int64_t> vertex_ids_for_this_cell;
  ...
  cell_vertex_ids.push_back(std::move(vertex_ids_for_this_cell));
}
```

Use “move”: rule of zero

```cpp
class X {
  ~X() = default; // Disable move operations generation
  std::string m_s;
};
std::vector<X> v = ...;
std::reverse(begin(v), end(v)); // temporary copies are created
```

```cpp
class X {
  std::string m_s; // Rule of zero
};
static_assert(std::is_nothrow_move_constructible_v<X>);
std::vector<X> v = ...;
std::reverse(begin(v), end(v));  // Move operations are used.
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - **Use std::array,** boost::container::small_vector.
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Use std::array

```
void calc(...) { ...
  std::vector<double> COF(15, 0.0);
  COF[0] = ...
  ...
  COF[14] = ...
```

```
void calc(...) {
  std::array<double, 15> COF = {
    ...
  };
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array**, boost::container::small_vector.**
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Vocabulary types: small_vector

- Implements the **small buffer optimisation** using the std::vector API
- small_vector<T, N>
  - Will handle any size.
  - Will not allocate any memory as long as the size never exceeds N.
  - Is larger than vector<T>.

- Popularised by LLVM.

  CppCon 2016: Chandler Carruth “High Performance Code 201: Hybrid Data Structures"

CppCon 2016: Chandler Carruth "High Performance Code 201: Hybrid Data Structures"

Boost small_vector

Implemented as **boost::container::small_vector** (by Ion Gaztanaga)

- Header only, exception safe, no specialisation for bool

```
// Propagation of noexcept requires boost 1.71 or later
#define BOOST_MOVE_HAS_NOTHROW_MOVE_ASSIGN(T) \
   std::is_nothrow_move_assignable_v<T>
#include <boost/container/small_vector.hpp>
```

Case study – problem #2 – small_vector

170e6 allocations

```
std::vector<int> js(n);
```

```
namespace bc = boost::container;
bc::small_vector<int, 16> js(n);
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector.
  - **Avoid pimpl when necessary.** Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
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- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Avoid Pimpl when too expensive

- Pimpl are about data hiding.
- Not worth it for internal code that is in the critical path.

Avoid Pimpl when necessary

```
class NodeContainerIterator {
  struct IIterator;
  std::shared_ptr<IIterator> m_pimpl;
```

Flagged as an excessive source of allocations

```
class NodeContainerIterator {
  std::vector<Node*>::const_iterator
     m_iterator;
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector.
  - Avoid pimpl when necessary. **Use std::optional.**
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Use std::optional to delay initialisation

```
class ExecutorCommand {
  // “Context” not default initialisable.
  // Initialised in pre_execution().
  std::unique_ptr<Context> m_ctx;
  bool pre_execution(...);
```

```
class ExecutorCommand {
  std::optional<Context> m_ctx; // Avoid memory allocation
  bool pre_execution(...);
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Re-use vector capacity

```
for (…) {
  std::vector<int> bsz;
  for (…)
    bsz.push_back(…);
```

```
std::vector<int> bsz;  // hoisted to re-use capacity
for (…) {
  bsz.clear();         // clear it
  bsz.reserve(…);      // “reserve” safe after a clear()
  for (…)
    bsz.push_back(…);
```

The same technique can be used with std::string and std::stringstream.

Do **not** use reserve() in a loop

```
for (…) {
  auto const& blocks = received();
  if (blocks.empty())
    break;
  buffer.reserve(buffer.size() +
                 blocks.size());
  for (auto const& block : blocks)
    buffer.push_back(block);
```

Performance killer

Replace push_backs by insert

```
for (…) {
  auto const& blocks = received();
  if (blocks.empty())
    break;
 for (auto const& block : blocks)
    buffer.push_back(block);
 buffer.insert(end(buffer),
      begin(blocks), end(blocks));
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Avoid node-based containers

```
void process(std::vector<int> const&
                recvIndexSet)
{
  std::unordered_set<int> receivedNodes;
  for (int i : recvIndexSet) {
    // Avoid duplicates in recvIndexSet
    if (receivedNodes.insert(i).second) {
      …
```

Flagged as a source of allocations

Avoid node-based containers

```
std::sort(begin(recv_ind), end(recv_ind));
process(recv_ind);

void process(std::vector<int> const&
                recvIndexSet)
{
  …
```

Call site

Avoid node-based containers

```
// Sort and remove duplicates
std::sort(begin(recv_ind),end(recv_ind));
recv_ind.erase(std::unique(begin(recv_ind),
                           end(recv_ind)),
               end(recv_ind));
process(recv_ind);

void process(std::vector<int> const& recvIndexSet)
// Expect: recvIndexSet is sorted and contains no
//         duplicates
{
```

Part II: solutions

- Do not copy if you can.
  - Avoid unused objects.
  - Use references.
  - Use views (tcb::span, std::string_view).
  - Use moves.
- Avoid allocation.
  - Use std::array, boost::container::small_vector
  - Avoid pimpl when necessary. Use std::optional.
- Re-use allocated memory.
  - Use std::vector::reserve().
  - Make use of std::vector capacity.
- Use contiguous containers.
  - Avoid if possible std::map, std::set and std::list in critical code.

Part III: C++17 “pmr” allocators

C++17 introduces the “polymorphic memory resources”.

- Available in VS 2017 and GCC 9
  (be aware of https://gcc.gnu.org/PR94906, fixed in gcc 9.4)

- Nicely explained in:
  Nicolai Josuttis, *C++17 - The Complete Guide*, chapter 29

Howard Hinnant’s stack_alloc is still handy.

(https://howardhinnant.github.io/stack_alloc.html)

C++17 “pmr” allocators

- pmr and vector
  - A use case
- pmr and node based containers
  - A use case
  - An anti-pattern

C++17 pmr allocators - vector

```
// Allocated and never resized
std::vector<double>
 f1(num_1), f2(num_1*num_1),
 f3(num_2), f4(num_2*num_2);
```

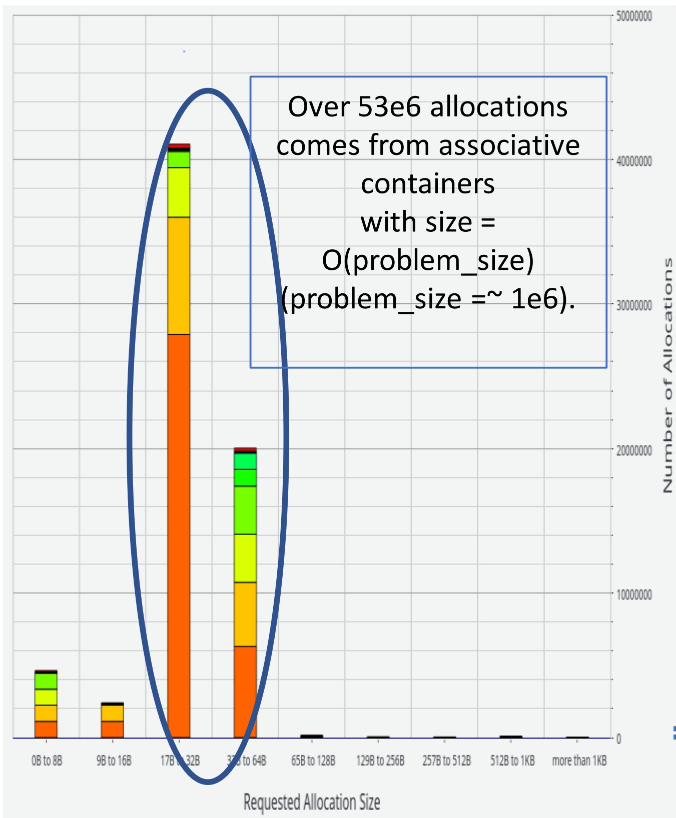
```
std::array<std::byte, 256> stack_buffer;
std::pmr::monotonic_buffer_resource mem_res
    {std::data(stack_buffer), std::size(stack_buffer)};
std::pmr::vector<double>
 f1(num_1, 0., &mem_res), f2(num_1*num_1, 0., &mem_res),
 f3(num_2, 0., &mem_res), f4(num_2*num_2, 0., &mem_res);
```

C++17 pmr allocators - map

```
class X {
  // No individual erase operations
  std::unordered_map<std::int64_t, std::size_t> m_id_to_index;
public:
  X() = default;
};
```

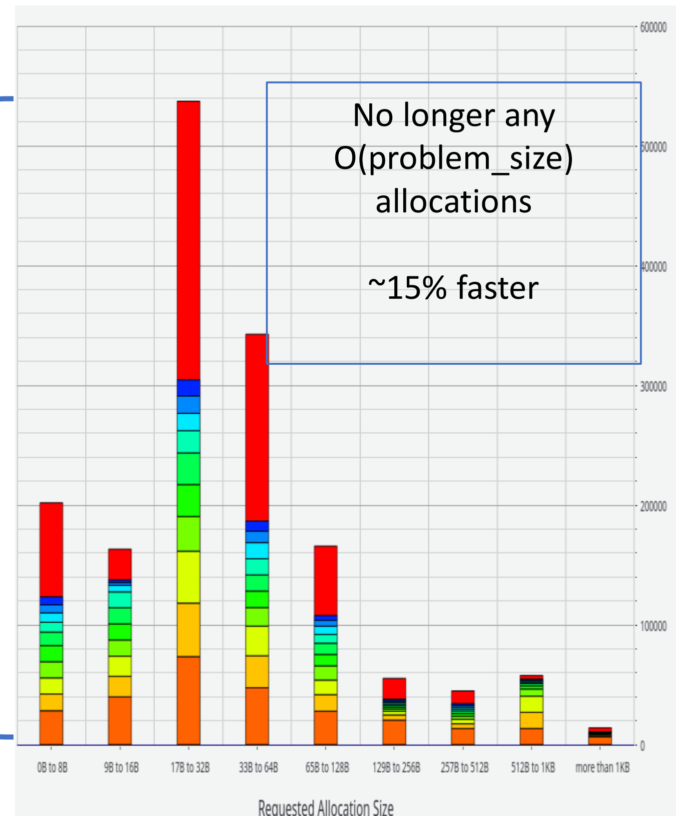
```
class X {
 std::pmr::monotonic_buffer_resource m_res;
 std::pmr::unordered_map<std::int64_t, std::size_t> m_id_to_index{&m_res};
public:
  X() = default;
  X(X const&) = delete; X& operator=(X const&) = delete;
};
```

~50e6



Before

~0.6e6



After

Anti-pattern: monotonic_buffer_resource and emplace/insert

```
class Cache {
  std::pmr::monotonic_buffer_resource m_res;
  std::pmr::unordered_map<std::size_t, int> m_cache{&m_res};
public:
  int get_index(std::size_t key) {
    // A temporary node is created resulting in slow memory growth.
    const auto [it, inserted] = m_cache.emplace(key,-1);
    if (!inserted)
      it->second = get_new_index(...);
    return it->second;
  }
};
```

Slow memory growth

Pattern: monotonic_buffer_resource and try_emplace

```
class Cache {
  std::pmr::monotonic_buffer_resource m_res;
  std::pmr::unordered_map<std::size_t, int> m_cache{&m_res};
public:
  int get_index(std::size_t key) {
    // C++17 try_emplace does not create any temporary node.
    const auto [it, inserted] = m_cache.try_emplace(key,-1);
    if (!inserted)
      it->second = get_new_index(...);
    return it->second;
  }
};
```

Conclusions

- Memory allocations can be surprisingly expensive.
- Heaptrack rocks.
- Top tips
  - Do not copy unnecessarily.
  - Learn about views (string_view, span) and small_vector.

Appendix

C++17 std::string_view

Supported by VS 2017, gcc 7.1 and later

For older compilers:

- boost's "boost/utility/string_view.hpp"
- https://github.com/tcbrindle/cpp17_headers
- std::string compatible std::hash support missing but easy to implement

tcb:span, gsl::span, C++20 std::span

- https://github.com/tcbrindle/span
- https://github.com/microsoft/GSL
- https://github.com/martinmoene/span-lite