Identifying Memory Allocation Patterns in HEP Software

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Introduction

• HEP Applications usually consume large amounts of memory

• Cost of memory per core is increasing

• Significant amount of this memory is due to temporary allocations

• Memory layout and access patterns are keys to performance
Introduction

- HEP Applications usually consume large amounts of memory
- Cost of memory per core is increasing
- Significant amount of this memory is due to temporary allocations
- Memory layout and access patterns are keys to performance

⇒ We need to understand how and why we allocate/deallocate memory
FOM-Tools

FOM-Tools provides a means to analyze memory allocation and utilization (https://gitlab.cern.ch/fom/FOM-tools.git)

- Identify unused memory allocations by making use of kernel features
- Intercept memory allocations/deallocations and record
  - time
  - address
  - size
  - type of allocation
  - stack trace
Performance

- Runtime overhead is 5-6x depending on profiled application and tool configuration

- Memory overhead is negligible ($\ll 100 \text{ MB}$)

- Typical output size, depending on the job and tool configuration is $O(10\text{GB})$ for compressed, $O(100\text{GB})$ for uncompressed
Key Metrics

Using data from FOM-Tools, we can calculate, globally or per class/stack

- **Density**: How many (de)-allocations per time unit
- **Variation**: How do consecutive allocations differ in size
- **Locality**: How close are allocations in address
- **Contention**: How many concurrent memory allocations
- **Lifetime**: How long does allocated memory live
Data Analysis

FOMTools output can be analyzed in various ways

- **ROOT**
  - Import
  - Convert
  - Export

- **FOM Output**
  - Import
  - Export

- **CSV File**
  - Your favorite BigData analysis

- **Bokeh**
  - Query subset and visualize

- **Hadoop**
  - Filter/Select
  - Create subsets and load into memory

- **Files**
  - Export

- **Zeppelin**
  - Export
Visualization

Results are visualized on browser with interactive bokeh plots
Visualization

Tooltips give stack-trace for the given point
Example-1: General Exploration

A Reconstruction job with 50 events:

- Generated roughly 870M records
- About 90 GB uncompressed binary output file (with 20 deep stack traces)

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Example-1: General Exploration

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Only data after start of event loop are considered
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![Graph showing Allocated Memory over Job duration](image-url)

Only data after start of event loop are considered.
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![Graph showing memory allocation patterns over job duration.](image-url)
Object Lifetimes

Looking at the lifetime of allocations

Object Lifetimes compared to the total number of allocations

- More than 65% of allocations have lifetimes \( \leq 10 \text{ ms} \), which is much smaller than the event processing time.
Object Lifetimes

Looking at the lifetime of allocations

More than 65% of allocations have lifetimes $\leq 10$ ms $\ll$ event processing time
Object Sizes

Looking at the size of allocations

Number of certain allocation sizes compared to the total number of malloc calls during the main loop

Size in Byte

Percentage

< 8 < 16 < 32 < 64 < 128 < 256 < 512 < 1k < 2k < 4k < 8k < 16k < 32k

Number of certain allocation sizes compared to the total number of malloc calls during the main loop
Object Sizes

Looking at the size of allocations

Number of certain allocation sizes compared to the total number of malloc calls during the main loop

- Pointer overhead

Size in Byte

- < 8
- < 16
- < 32
- < 64
- < 128
- < 256
- < 512
- < 1k
- < 2k
- < 4k
- < 8k
- < 16k
- < 32k

Percentage
Roughly 8.9% of the allocations happening during the main loop live between 100 $\mu$s and 1 ms and measure between 16 and 32 Bytes.
Object Size versus Object Lifetime

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Sort Based Analysis

Sort the records by allocation size

| Size in Bytes | Percentage |
|---------------|------------|
| 24            | 19.8%      |
| 8             | 11.2%      |
| 128           | 8.5%       |

Mostly std::list nodes. Opportunity to improve memory layout and utilization.

Mostly 1x1 Eigen matrices and pointers to them in tracking. A design issue?

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Sort Based Analysis

Check most common stack trace chains

| Size in Bytes | Percentage |
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| # | Stacktrace ID | Counts | Percentage | Bytes |
|---|---------------|--------|------------|-------|
| 1 | 350792 350790 350785 350975 350696 340149 340150 340151 340149 340150 340151 ... | 3,446,741 | 1.4% | 24 |
| 2 | 139508 350689 350671 340151 340149 340150 340151 340149 340150 340151 340147 ... | 2,610,367 | 1.1% | 8 |
| 3 | 340449 340445 340446 340437 340151 340149 340150 340151 340149 340150 340151 ... | 2,610,367 | 1.1% | 24 |
| 4 | 350690 350671 340149 340150 340151 340149 340150 340151 340147 340148 327958 ... | 2,610,367 | 1.1% | 96 |
| 5 | 350671 340151 340149 340150 340151 340149 340150 340151 340147 340148 327958 327736 ... | 2,610,367 | 1.1% | 8 |
| 6 | 350671 340151 340149 340150 340151 340149 340150 340151 340147 340148 327958 327736 ... | 2,610,367 | 1.1% | 24 |
| 7 | 350503 350691 350692 350671 340151 340149 340150 340151 340149 340150 340151 ... | 2,610,367 | 1.1% | 8 |
| 8 | 350793 350794 350795 350796 350975 350696 340149 340150 340151 340149 340150 ... | 1,854,205 | 0.8% | 24 |
| 9 | 351381 351620 340151 340149 340150 340151 340149 340150 340151 340147 340148 327958 ... | 1,699,944 | 0.7% | 48 |
| 10| 350792 350790 350785 350781 350696 340149 340150 340151 340149 340150 340151 ... | 1,638,489 | 0.6% | 24 |

Stack trace id mapping to source-line
Sort Based Analysis

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Stack trace id mapping to source-line
Investigation lifetime plots with bokeh

Possible causes for patterns:

1. Curves: Accelerating loops
   - E.g. A lot of track candidates in the beginning and towards the end of the track more and more candidates are removed

2. Straight line: Linear loop that creates and deletes objects at similar timesteps

3. Ascending line: Objects (e.g. vector of elements with reserved size) created at the same time and then deleted element by element in a loop

4. Descending line: Objects (e.g. empty vector) extended step by step and then deleted in one go

Figure: Pattern 1  Figure: Pattern 2  Figure: Pattern 3  Figure: Pattern 4
An Interesting Pattern in Lifetime Plots

![Lifetime Plots Graph]

- Two repeating patterns
- Output Container generation
- TString creation and TMap rebalancing

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An Interesting Pattern in Lifetime Plots

Two repeating patterns

Lifetime in ns

Two repeating patterns

10^3

10^4

10^5

10^6
An Interesting Pattern in Lifetime Plots

Two repeating patterns

Output Container generation

TString creation and TMap rebalancing

Lifetime in ns

$10^3$ $10^4$ $10^5$ $10^6$
Origin of patterns

// In pseudo code
Root::TAccept selectionPassed;
for (itr in tracks) {
    if (some criteria)
    {
        selectionPassed = m_trkFilter->accept(**itr,.....);
    }
    if (selectionPassed)
    {
        // add track to output container
    }
}
Origin of patterns

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// accept() signature
Root::TAccept& TrkFilter::accept(...){/*...*/} 

FOM identified line. No apparent allocations

Returns reference, no allocations. OK
Origin of patterns

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    }
    if (selectionPassed) {
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    }
}

// accept() signature
Root::TAccept& TrkFilter::accept(....)++){/*...*/} // FOM identified line. No apparent allocations

namespace Root{
    class TAccept{
        // Class methods
        //....
        private:
            TString m_memberString; // OK
    }
}
Origin of patterns

// In pseudo code
Root::TAccept selectionPassed;
for (itr in tracks) {
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        selectionPassed = m_trkFilter->accept(**itr,....);
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Example-2: Targeted Analysis

A simulation job of 50 events

- Generated roughly 746M records

- About 9GB compressed binary output file (with 50 deep stack traces)

- Targeting `std::string(stream)` related allocations
  - About 27.6M allocations related with strings (3.6% of total)
  - 385374 unique allocation traces
  - 530690 unique traces and sizes

Especially if you consider log file contains 412132 characters in 50403 words in 6042 lines.
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- Especially if you consider log file contains 412132 characters in 50403 words in 6042 lines.
String Hotspots

| # | Stacktrace ID | Counts |
|---|---------------|--------|
| 1 | 1078 1493 1494 3487 3488 123384 123297 123298 123239 123218 122997 ... | 4687515 |
| 2 | 1078 1493 1494 3487 3488 123385 123297 123298 123239 123218 122997 ... | 4687515 |
| 3 | 1078 1079 1080 102889 102890 102884 10807 33149 102885 | 787187 |
| 4 | 1078 3559 3560 30120 102891 102890 102884 10807 33149 102885 | 787187 |
| 5 | 1078 1079 1080 124549 124547 123297 123298 123239 123218 122997 ... | 584465 |

2 string constructions + forgotten code?
String Hotspots

2 string constructions
+ forgotten code?

```
//pseudo code
for(ll:i4NavigationHistoryDepth){
  G4PhysicalVolume* vl = g4navigation->GetVolume(ll);
  // do some stuff...
  if (vl->GetName()==G4String(m_detectorName+"SomeSubDetName")) dep=ll;
  if (vl->GetName()==G4String(m_detectorName+"AnotherSubDetName")) testbeam=true;
  // do more stuff ..
}
```

| #  | Stacktrace ID                                                                 | Counts   |
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String Hotspots

2 string constructions + forgotten code?

```cpp
//pseudo code
for(ii: g4NavigationHistoryDepth){
    G4PhysicalVolume* vl = g4navigation->GetVolume(ii);
    // do some stuff...
    if(vl->GetName()==G4String(m_detectorName+"SomeSubDetName")) idep=ii;
    if(vl->GetName()==G4String(m_detectorName+"AnotherSubDetName")) testbeam=true;
    // do more stuff ..
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```

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Geometry Construction
String Hotspots

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//pseudo code
for(ii=0;ii<gNavigationHistoryDepth){
    G4PhysicalVolume* vl = gNavigation->GetVolume(ii);
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    if(vl->GetName()==G4String(m_detectorName+"SomeSubDetName")) idep=ii;
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    // do more stuff ..
}

2 string constructions + forgotten code?

String construction from const char*

Geometry Construction
Summary

• FOM-Tools provides detailed view of an applications allocation patterns

• Data can be analyzed in various ways

• Even simplest of analysis can reveal issues not apparent from source code

• Detailed analysis of the data can provide design hints and optimization opportunities
Thank you for your attention