MemProf: a Memory Profiler for NUMA Multicore Systems

Renaud Lachaize, Baptiste Lepers, Vivien Quema
Machines are NUMA

Node 1

Node 2

Node 3

Memory

CPU0

CPU2

CPU1

CPU3

8GB/s 160 cycles

3GB/s 300 cycles
Applications ignore NUMA
That is problematic

<table>
<thead>
<tr>
<th>Application</th>
<th>% remote memory accesses in default version</th>
</tr>
</thead>
<tbody>
<tr>
<td>FaceRec (ALPBench)</td>
<td>63%</td>
</tr>
<tr>
<td>Streamcluster (Parsec)</td>
<td>75%</td>
</tr>
<tr>
<td>Psearchy (Mosbench)</td>
<td>13%</td>
</tr>
<tr>
<td>Apache</td>
<td>75%</td>
</tr>
</tbody>
</table>
That is problematic

<table>
<thead>
<tr>
<th>Application</th>
<th>% remote memory accesses in default version</th>
<th>% performance improvement provided by an adequate NUMA optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>FaceRec (ALPBench)</td>
<td>63%</td>
<td>42%</td>
</tr>
<tr>
<td>Streamcluster (Parsec)</td>
<td>75%</td>
<td>161%</td>
</tr>
<tr>
<td>Psearchy (Mosbench)</td>
<td>13%</td>
<td>8.2%</td>
</tr>
<tr>
<td>Apache</td>
<td>75%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Application-Agnostic Heuristics exist

• Thread scheduling and page migration (*USENIX ATC’11*)

• Thread Clustering (*EuroSys’07*)

• Page replication (*ASPLOS’96*)

• Etc.
... But they do not always improve performance

Example: Apache

<table>
<thead>
<tr>
<th>% remote memory accesses</th>
<th>% performance impact over default version</th>
</tr>
</thead>
<tbody>
<tr>
<td>On default Linux</td>
<td>75%</td>
</tr>
<tr>
<td>With thread scheduling and migration (USENIX’11)</td>
<td>75%</td>
</tr>
</tbody>
</table>
We want to understand the causes of remote memory accesses
... In order to select an adequate optimization

- Custom allocation policy
- Memory replication
- Memory migration
- Memory interleaving
- Custom thread scheduling policy
Can we understand the causes of remote memory accesses using existing profilers?
Let’s take an example
FaceRec

• Facial recognition engine

• 63% of DRAM accesses are remote

• 42% gain when modified based on MemProf output
Existing profilers point out

- The functions that perform remote accesses
- The memory pages that are remotely accessed
- The global static objects that are remotely accessed
Existing profilers point out (FaceRec)

- The functions that perform remote accesses
  - $\text{transposeMultiplyMatrixL} = 98\%$

- The memory pages that are remotely accessed
  - 1/3 of the allocated pages

- The global static objects that are remotely accessed
  - No such object
What can we conclude?

• Should we change the allocation policy?
  – No idea

• Should we migrate memory pages?
  – No idea

• Should we replicate memory pages?
  – No idea

• Etc.
So... We need a new profiler!
We designed MemProf, a profiler that points out:

- Remotely accessed objects
- Thread-Object interaction patterns
Objects

• Global statically allocated objects
• Dynamically allocated objects
• Memory-mapped files
• Code sections mapped by the OS
• Thread stacks
Thread-Object interaction patterns

Object Event Flow (OEF)
- size
- code location of allocation
- node of allocation
- TEF of the allocator thread

Thread Event Flow (TEF)
- process id
- application name

thread access
- accessing node
- accessed node
- accessing thread
- latency
- read/write
- callchain

object access
- accessing node
- accessed node
- accessed object
- latency
- read/write
- callchain
What can we do with MemProf?
We can detect that an object is simultaneously read by several remote threads…
And thus decide to replicate this object on several nodes.
This is the pattern observed in FaceRec

- 193 matrices
- 1 matrix induces 98% of the remote accesses
- This matrix is first written and then read by all threads

- We replicate the matrix (10 lines of code)
- Performance improvement: 42%
We can detect that an object is simultaneously read and written by several threads with a high latency.

Thread T0 (node N0)
Allocate Obj1 on node N0

Thread T1 (node N1)
Read/Write Obj1 (remotely) *High latency*

Thread T2 (node N2)
Read/Write Obj1 (remotely) *High latency*

Read/Write Obj1 (remotely) *High latency*
And thus decide to interleave this object

Thread T0 (node N0)
- Allocate Obj1 with memory interleaved

Thread T1 (node N1)
- Use Obj1 (locally/remotely)
  - Low latency

Thread T2 (node N2)
- Use Obj1 (locally/remotely)
  - Low latency
This is the pattern observed in Streamcluster

- 1000 objects allocated
- 1 represents 80% of remote memory accesses
- It is accessed read/write by all threads

- We interleave this object (1 line of code)
- Performance improvement: 161%
We can detect that threads do not share objects

Thread T0 (node N0)
- Allocate Obj1-4 on node N0

Thread T1 (node N1)
- Use Obj1 (remotely)
- Use Obj2 (remotely)

Thread T2 (node N2)
- Use Obj3 (remotely)
- Use Obj4 (remotely)
And thus decide to change the allocation policy
This is the pattern observed in Psearchy

- Remote accesses are done on private variables
- We forced local allocations (2 lines of code)
- Performance improvement: 8.2%
As a summary

- MemProf allows finding memory access patterns

- Knowing memory access patterns allows designing simple and efficient optimizations
A word on the implementation
MemProf – Online Profiling

- Memory access tracking
  - IBS samples

- Object lifecycle tracking
  - Overloading of allocation functions
  - Kernel hooks

- Threads lifecycle tracking
  - Kernel hooks
MemProf – Offline Analysis

- Sort samples by time
- Match memory addresses with objects
  - Leverages object lifecycle tracking
  - Leverages thread lifecycle tracking
- Create object-thread interaction flows
  - Leverages thread lifecycle tracking
Overhead

• 5% slowdown

• 2 sources of overhead:
  – IBS sampling collection: one interrupt every 20K cycles
  – Object lifecycle tracking
Conclusion

• Remote memory accesses are a major source of inefficiency

• Existing profilers do not pinpoint the causes of remote memory accesses

• We propose MemProf, a memory profiler that allows:
  – Finding which objects are accessed remotely
  – Understanding the memory access patterns to these objects

• Using MemProf, we profiled and optimized 4 applications on 3 machines
  – Optimizations are simple: less than 10 lines of code
  – Optimizations are efficient: up to 161% improvement
QUESTIONS?