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Enhancing Productivity on Heterogeneous Supercomputers with Task-based Programming Model

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SIAM CSE, Amsterdam
February 28, 2023
Most of the time, scientific applications are already parallelized for CPU (or partly for GPU).

To take advantage of GPUs, developers have to rewrite their codes (in part? in whole?)

**Goals:**
- Build a preliminary analysis to determine the potential of the application for a GPU port
- Port mini-application to heterogeneous architectures with this information
Contributions

**Goal**: Inform the user

- that there exists a test case of the application suitable for a GPU port
- about the strengths and weaknesses of the application for a GPU port

- We analyzed the variations of two metrics:
  - the degree of parallelism (→ saturate GPU cores)
  - and the working set (→ bounded GPU memory)

- Porting app. To GPU Computing
  - Using Task based prog. Model
    - MPI+OpenMP (tasks + target)

```c
int main(...)
{
    /* parallel CPU code */
}
```

- Relate the two metrics
- Extrapolate application behavior
- GPU Porting
Contents

1. Introduction

2. Application Characterization Method

3. Proxy Applications Analysis

4. Porting Proxy App to GPU: LULESH

5. Conclusion
2. Application Characterization Method
Maximizing FFMA throughput ("floating point fused multiple add")

$$RP = \#\text{cores} \cdot L$$

where

- $L$ : 32 bits FFMA instruction latency

### Targeted GPU Characterization

- **L2 Cache**
- **DRAM**
- **#cores**

Required Parallelism (RP)

- **RAM (GB)**

Characterization

Already known (GPU documentation)
Applications analyzed at Loop Granularity (already parallelized with OpenMP)

> L: for (i = 0; i < N; ++i) compute;

- Set of data necessary to run the loop
- Working Set measured at two Granularities, i.e., the size of smallest accessed memory element (using DynamoRIO)

- \( W_{\text{malloc}}(L) \)
- \( W_{\text{cache line}}(L) \)

- # independent Iterations (i.e., tripcount)
- Parallelism Degree \( P(L) \)
Extrapolation Methodology

For each loop

\[ \forall L \in S, n \in \{n_1, n_2, \ldots\} \rightarrow \text{measure} \]
- working set \( WS(L) \)
- parallelism degree \( P(L) \)

\[ WS(L) = f(P(L)) \]
\[ P(L) = g(n) \]

<table>
<thead>
<tr>
<th>loop</th>
<th>working set</th>
<th>parallelism degree</th>
<th>input size</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>( WS(L) )</td>
<td>( P(L) )</td>
<td>( n_1 )</td>
</tr>
<tr>
<td>L</td>
<td>( WS(L) )</td>
<td>( P(L) )</td>
<td>( n_2 )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Working set inference

Regression
Extrapolation Methodology

Extract most time-consuming loops

∀ \( L \in S \), \( n \in \{n1, n2, \ldots \} \)
→ measure
• working set \( WS(L) \)
• parallelism degree \( P(L) \)

inference
∀ \( L \in S \),
\( WS(L) = f(P(L)) \)
\( P(L) = g(n) \)

projection
Test cases fitting target GPU memory and exposing enough parallelism
3. Proxy Applications Analysis

LULESH, miniFE
Experimental Protocol

- Evaluation Machine

<table>
<thead>
<tr>
<th>processor</th>
<th>Intel Xeon E5-2680</th>
</tr>
</thead>
<tbody>
<tr>
<td>#sockets</td>
<td>2</td>
</tr>
<tr>
<td>#cores/socket</td>
<td>8</td>
</tr>
<tr>
<td>RAM (GB)</td>
<td>128</td>
</tr>
<tr>
<td>OS</td>
<td>Linux 3.10</td>
</tr>
<tr>
<td>Compiler</td>
<td>Intel 20.0.0</td>
</tr>
</tbody>
</table>

- Evaluated mini-applications

- LULESH (hydrodynamic simulation)
- MiniFE (finite element problem)
- Quicksilver (Monte Carlo particle transport)
- XSBench (Monte Carlo particle transport kernel)

All these applications have CPU OpenMP, GPU CUDA and HIP versions.

- Considered targeted GPUs

<table>
<thead>
<tr>
<th>GPU</th>
<th>RAM</th>
<th>#cores</th>
<th>minimal required parallelism RP</th>
</tr>
</thead>
<tbody>
<tr>
<td>V100</td>
<td>16 GB</td>
<td>5120</td>
<td>20480</td>
</tr>
<tr>
<td>A100 40GB</td>
<td>40 GB</td>
<td>6912</td>
<td>27648</td>
</tr>
<tr>
<td>A100 80GB</td>
<td>80 GB</td>
<td>6912</td>
<td>27648</td>
</tr>
<tr>
<td>MI100</td>
<td>32 GB</td>
<td>7680</td>
<td>30720</td>
</tr>
</tbody>
</table>
LULESH

Projection of dataset input size $s_{\text{max}}$ saturating GPU memory and corresponding $\rho$ ratio ($\rho(L) = \frac{P(L)}{RP}$)

- Sufficient exposed parallelism ($\rho \gg 1$)
- Limiting factor: memory size
- Advised data transfers granularity: malloc

- Similar conclusions for miniFE

<table>
<thead>
<tr>
<th>target GPU</th>
<th>$s_{\text{max}}$</th>
<th>$\rho$ (loop 1773)</th>
<th>$\rho$ (other loops)</th>
<th>$s_{\text{max}}$</th>
<th>$\rho$ (loop 1773)</th>
<th>$\rho$ (other loops)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V100 16 GB</td>
<td>285</td>
<td>19.2</td>
<td>1130.3</td>
<td>289</td>
<td>19.4</td>
<td>1178.6</td>
</tr>
<tr>
<td>A100 40GB</td>
<td>387</td>
<td>19.3</td>
<td>2099.4</td>
<td>393</td>
<td>19.6</td>
<td>2195.4</td>
</tr>
<tr>
<td>A100 80GB</td>
<td>487</td>
<td>24.3</td>
<td>4198.7</td>
<td>495</td>
<td>24.7</td>
<td>4386.8</td>
</tr>
<tr>
<td>MI100 32GB</td>
<td>359</td>
<td>16.1</td>
<td>1511.5</td>
<td>365</td>
<td>16.4</td>
<td>1586.6</td>
</tr>
</tbody>
</table>

Working set of LULESH selected loops as a function of their tripcount
Porting Proxy App to GPU: LULESH
Porting LULESH to MPI+OpenMP (tasks)

- **LULESH**
  - Hydrodynamic problems solver - Iterative simulation
  - Original code express loop-based parallelism (parallel-for)

- **Porting to MPI+OpenMP (tasks)**
  - Loops splitted into tasks with dependencies
  - Single producer/multi-consumer scheme
  - MPI communications nested within OpenMP tasks
    - Overlap communications by computations

```c
for (int j = 0 ; j < n_nodes; j += BS)
{
    # pragma omp task depend(out : mesh->nodes[j])
    {
        for (int i = j ; i < j + BS ; ++i)
            work_on_nodes(mesh->nodes[i]);
    }
}

for (int j = 0 ; j < n_cells; j += BS)
{
    # pragma omp task depend(in : [...])
    {
        for (int i = j ; i < j + BS ; ++i)
            work_on_cells(mesh->cells[i]);
    }
}
```
Concept Generalization for Heterogeneous Architectures with OpenMP Target

- Porting to MPI+OpenMP (tasks + GPU target)
  - GPU « super-tasks » merging several CPU tasks
  - From CPU tasks to GPU offloading while enhancing asynchronism
    - Sending/Retrieving data to/from GPU with ‘update’ clause
    - Executing GPU kernels through ‘nowait’ clause
  - Offloading 6 loops given by application characterization
    - IntegrateStressForElems, CalcKinematicsForElems, CalcAccelerationForNodes, CalcFBHourglassForceForElems1, CalcHourglassControlForElems, CalcMonotonicQGradientsForElems
- Use of cudaMallocHost for the GPU buffers
  - Pinned memory to enable asynchronous execution

```c
for (int j = 0 ; j < n_nodes; j += BS)
{
    # pragma omp task depend(out: mesh->nodes[j])
    
    for (int i = j; i < j + BS; ++i)
        work_on_nodes(mesh->nodes[i], buffer[i]);
}
```

1 buffer = cudaMallocHost(…); 

[…]

2 for (int j = 0 ; j < n_nodes; j += BS)
3 {
    # pragma omp target update to(buffer[j:BS]) \ 
    depend(out: mesh->nodes[j])
4    
    # pragma omp target \ 
    teams distribute parallel for nowait \ 
    depend(iterator(i=0:N_BS), out: mesh->nodes[j+i*BS])
8    {
9        for (int i = j; i < j + N_BS * BS ; ++i)
10           work_on_nodes(mesh->nodes[i], buffer[i]);
11    }
12    # pragma omp target update from(buffer[j:BS]) \ 
13    depend(out: mesh->nodes[j])
14}
```
Experimental Protocol

<table>
<thead>
<tr>
<th>Processor</th>
<th>AMD EPYC 7H12</th>
</tr>
</thead>
<tbody>
<tr>
<td>#sockets</td>
<td>2</td>
</tr>
<tr>
<td>#cores/socket</td>
<td>64</td>
</tr>
<tr>
<td>GPU</td>
<td>NVIDIA A100</td>
</tr>
<tr>
<td>#GPU/socket</td>
<td>2</td>
</tr>
<tr>
<td>RAM (GB)</td>
<td>256</td>
</tr>
</tbody>
</table>

- MPC-OpenMP (No Offloaded part) 4.1.0
- LLVM (Offloaded part) 16.x
- Open MPI 4.0.5
LULESH Performance Evaluation

- Problem size
  - $264^3$ elements
    - 80% of the NUMA domain memory capacity
    - 20% of the GPU memory capacity
  - 128 iterations

- Placement
  - Per MPI Process:
    - 16 threads (on 16 cores)
    - + 1 GPU

- Weak scaling
  - Median runtime of 10 runs
  - Each version scale very well
  - OpenMP tasks version significantly improves performances due to cache reuse
  - Significant performance gain with GPU offloading

<table>
<thead>
<tr>
<th>Number of MPI ranks</th>
<th>Median Time (s)</th>
<th>parallel-for</th>
<th>no-offloading</th>
<th>offloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>565.84</td>
<td>325.02</td>
<td>209.31</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>572.45</td>
<td>331.09</td>
<td>209.43</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>581.26</td>
<td>333.98</td>
<td>212.78</td>
<td></td>
</tr>
</tbody>
</table>
5. Conclusion
Conclusion

- An **approach**: (int main(...){
  ...
}) \rightarrow \{ test cases such that int main(...){
  ...
} fit on RAM and do not lack parallelism }

- **complementary** to existing work (analysis of several application runs \(\rightarrow\) extrapolation)

- We have **evaluated** our approach and shown that we can **qualitatively guide developer** in their GPU porting

- We have **ported** LULESH on heterogeneous machine with a **task-based programming model**
  - Significant gains are observed
Thank you!

Questions?