rCUDA: a ready-to-use remote GPU virtualization framework

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Joint research effort
Outline

- GPU computing
- rCUDA framework
- Other GPU virtualization frameworks
- rCUDA SLURM integration
- SDK and real applications tests
Outline

- GPU computing
- rCUDA framework
- Other GPU virtualization frameworks
- rCUDA SLURM integration
- SDK and real applications tests
GPU computing: defines all the technological issues for using the GPU computational power for executing general purpose code.

GPU computing has experienced remarkable growth in the last years.
GPU computing

- GPU computing: defines all the technological issues for using the GPU computational power for executing general purpose code
- GPU computing has experienced remarkable growth in the last years

Top500
November 2012
- The basic building block is a node with 1 or more GPUs.
From the programming point of view:

- A set of nodes, each one with:
  - one or more CPUs (with several cores per CPU)
  - one or more GPUs (1-4)
  - disjoint memory spaces for each GPU and CPU
- An interconnection network
GPU computing

- Development tools have been introduced in order to ease the programming of the GPUs
- Two main approaches in GPU computing development environments:
  - CUDA → NVIDIA proprietary
  - OpenCL → open standard
Basically CUDA and OpenCL have the same working scheme:

- **Compilation**: Separate CPU code from GPU code (GPU kernel)
- **Execution**:
  - **Data transfers**: CPU and GPU memory spaces
    1. **Before** GPU kernel execution: data from CPU memory space to GPU memory space
    2. **Computation**: Kernel execution
    3. **After** GPU kernel execution: results from GPU memory space to CPU memory space
- Time spent on data transfers may not be negligible.
For the right kind of code the use of GPUs brings huge benefits in terms of performance and energy.

There must be data parallelism in the code: this is the only way to take benefit from the hundreds of processors in a GPU.

Different scenarios from the point of view of the application:
- Low level of data parallelism
- High level of data parallelism
- Moderate level of data parallelism
- Applications for multi-GPU computing
- GPU computing
- rCUDA framework
- Other GPU virtualization frameworks
- rCUDA SLURM integration
- SDK and real applications tests
rCUDA

A framework enabling that a CUDA-based application running in one node can access GPUs in other nodes

It is useful when you have:

- Moderate level of data parallelism
- Applications for multi GPU computing
Virtualized Remote GPUs

Interconnection network

Node

Node

Node

GPUs

Node

Node

Node

GPUs

Virtual GPUs
CUDA application

Application

CUDA libraries

CUDA device
rCUDA framework

Client side

Application

rCUDA library

Network device

CUDA application

rCUDA daemon

Network device

Server side

CUDA libraries

CUDA device
**rCUDA framework**

Client side

- Application
- rCUDA library
- Network device

CUDA application

- rCUDA daemon
- CUDA driver + runtime
- Network device

Server side

- CUDA device
rCUDA framework

Client side

CUDA application

Server side

Application

rCUDA library

Network device

rCUDA daemon

CUDA driver + runtime

CUDA device
rCUDA uses a proprietary communication protocol

Example:

1) initialization
2) memory allocation on the remote GPU
3) CPU to GPU memory transfer of the input data
4) kernel execution
5) GPU to CPU memory transfer of the results
6) GPU memory release
7) communication channel closing and server process finalization
rCUDA framework

Client side
- Application
  - Interception library
    - Communications
      - TCP
      - IB

Server side
- Server daemon
  - Communications
  - CUDA library
  - CUDA device
Optimized communications

- Use GPUDirect to avoid memory copies
- Pipeline to improve performance
- Preallocated pinned memory buffers
- Optimal pipeline block size
- Efficient pipeline implementation
  - Synchronous transfers → Pageable memory
rCUDA framework

- Efficient pipeline implementation
- Synchronous transfers → Pageable memory

[Diagram showing network request flow between client and server sides, with pinned memory highlighted]
- Efficient pipeline implementation
  - Synchronous transfers $\rightarrow$ Pageable memory

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**rCUDA framework**

![Diagram showing rCUDA framework with Client side, Network, and Server side connections between Main Memory and GPU Memory. The diagram highlights the process of request, send/receive, and pinned memory.]
Efficient pipeline implementation

- Synchronous transfers → Pageable memory

**rCUDA framework**
**Efficient pipeline implementation**
- Synchronous transfers $\rightarrow$ Pageable memory

### Diagram

**Client side**
- Main Memory
  - Pinned

**Server side**
- Main Memory
- Pinned
- GPU Memory

**Network**
- SEND / RECV

**rCUDA framework**
**rCUDA framework**

- Efficient pipeline implementation
  - Synchronous transfers → Pageable memory
Efficient pipeline implementation

- Synchronous transfers → Pageable memory
rCUDA framework

- Efficient pipeline implementation
  - Synchronous transfers → Pageable memory
- Efficient pipeline implementation
  - Synchronous transfers → Pageable memory
Efficient pipeline implementation

- Asynchronous transfers $\rightarrow$ Pinned memory
Efficient pipeline implementation

- Asynchronous transfers → Pinned memory
- Efficient pipeline implementation
  - Asynchronous transfers → Pinned memory
Efficient pipeline implementation
- Asynchronous transfers \(\rightarrow\) Pinned memory
**rCUDA framework**

- Efficient pipeline implementation
  - Asynchronous transfers → Pinned memory
- Efficient pipeline implementation
  - Asynchronous transfers → Pinned memory

```
Client side
  Main Memory
  | REQUEST |
  
  | Network |
  
  | SEND / RECV |
  
  | REQUEST |
  
Server side
  Main Memory
  | RDMA READ |
  
  | GPU Memory |
```
- Efficient pipeline implementation
  - Asynchronous transfers → Pinned memory

```
  +-----------------+     +-----------------+     +-----------------+
  | REQUEST         |     | NETWORK          |     | REQUEST         |
  +-----------------+     +-----------------+     +-----------------+    
  | SEND / RECV     |     | RDMA READ        |     |                 |
  +-----------------+     +-----------------+     +-----------------+    
  | CLIENT SIDE     |     | SERVER SIDE      |     |                 |
  +-----------------+     +-----------------+     +-----------------+    
  | MAIN MEMORY     |     | GPU MEMORY       |     |                 |
  +-----------------+     +-----------------+     +-----------------+    
```

rCUDA framework
Efficient pipeline implementation

- Asynchronous transfers ➔ Pinned memory
- Efficient pipeline implementation
- Asynchronous transfers → Pinned memory
Pipeline block size for Infiniband FDR

- NVIDIA Tesla K20
- Mellanox ConnectX-3 + SX6025 Mellanox switch
**rCUDA framework**

- Host to device copy with pinned memory
Host to device copy with pageable memory
**rCUDA framework**

- Copy a small dataset for latency study (64 bytes)
Outline

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Several efforts have been done regarding to GPU virtualization in the recent years.

- rCUDA (CUDA 5.0)
- GVirtuS (CUDA 3.2)
- DS-CUDA (CUDA 4.1)
- vCUDA (CUDA 1.1)
- GViM (CUDA 1.1)
- GridCUDA (CUDA 2.3)
- V-GPU (CUDA 4.0)
GPU virtualization

- Comparison of virtualization solutions.
  - Latency (transfer 64 bytes)
    - Intel Xeon E5-2620 (6 cores) 2.0GHz
    - GPU NVIDIA Tesla K20
    - Mellanox ConnectX-3 single-port InfiniBand Adapter (FDR)
    - CentOS 6.3 + Mellanox OFED 1.5.3

<table>
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<th>Pinned H2D</th>
<th>Pageable D2H</th>
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</table>
GPU virtualization

- Bandwidth host to device using pageable memory
GPU virtualization

- Bandwidth device to host using pageable memory
• Bandwidth host to device using pinned memory
GPU virtualization

- Bandwidth device to host using pinned memory
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SLURM integration

- SLURM job scheduler.
- Does not understand about virtualized GPUs.
- Add a new GRES (general resource) in order to manage the virtualized GPUs.
- Where the GPUs are in the system is completely transparent to the user.
- In the job script or in the submission command, the user specifies the number of rGPUS for the job.
SLURM integration

```plaintext
slurm.cof

ClusterName=rcu
...
GresTypes=gpu,rgpu
...
NodeName=rcu16 NodeAddr=rcu16 CPUs=8 Sockets=1
    CoresPerSocket=4 ThreadsPerCore=2
RealMemory=7990  Gres=rgpu:4,gpu:4
```
**SLURM integration**

`scontrol show node`

NodeName=rcu16  Arch=x86_64  CoresPerSocket=4
CPUAlloc=0  CPUErr=0  CPUSys=0  CPULastSubsysErr=0  CPULastSysErr=0  CPUTot=8
Features=(null)
Gres=rgpu:4,gpu:4
NodeAddr=rcu16  NodeHostName=rcu16
OS=Linux  RealMemory=7682  Sockets=1
State=IDLE  ThreadsPerCore=2  TmpDisk=0  Weight=1
BootTime=2013-04-24T18:45:35
SlurmdStartTime=2013-04-30T10:02:04
SLURM integration

<table>
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<th>gres.conf</th>
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<tr>
<td>Name=rgpu File=/dev/nvidia0 Cuda=2.1 Mem=1535m</td>
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<td>Name=rgpu File=/dev/nvidia1 Cuda=3.5 Mem=1535m</td>
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<tr>
<td>Name=rgpu File=/dev/nvidia2 Cuda=1.2 Mem=1535m</td>
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<tr>
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<td>Name=gpu File=/dev/nvidia1</td>
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<td>Name=gpu File=/dev/nvidia2</td>
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<tr>
<td>Name=gpu File=/dev/nvidia3</td>
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</table>
SLURM integration

Submit a job

```
$ srun -N1 --gres=rgpu:4:512M script.sh...
```

- Environment variables are initialized by SLURM and used by rCUDA client (transparently to the user)

```
RCUDADEVICE_COUNT=4

RCUDADEVICE_0=rcu16:0
RCUDADEVICE_1=rcu16:1
RCUDADEVICE_2=rcu16:2
RCUDADEVICE_3=rcu16:3
```

Server name/IP address : GPU
**SLURM integration**

Resources per job:
- 1: 2 nodes 3 GPUs
- 2: 3 nodes 1 GPU
- 3: 1 node 0 GPUs
- 4: 2 nodes 1 GPUs
- 5: 2 node 1 GPUs

Time slots:
- t0: Job 1
- t1: Job 2
- t2: Job 3
- t3: Job 4
- t4: Job 5
- t5: Job 5
- t6: Job 5
- t7: Job 5
- t8: Job 5

Error message:
```
srun: error: Unable to allocate resources
```
SLURM integration

Resources per job:
- 1: 2 nodes 3 GPUs
- 2: 3 nodes 1 GPU
- 3: 1 node 0 GPUs
- 4: 2 nodes 1 GPUs
- 5: 2 node 1 GPUs

GPUs are decoupled from nodes:

<table>
<thead>
<tr>
<th>GPU 0</th>
<th>GPU 1</th>
<th>GPU 2</th>
<th>NODE 0</th>
<th>NODE 1</th>
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<td>5</td>
</tr>
</tbody>
</table>

Job Queue:
- t0: 1
- t1: 2
- t2: 2
- t3: 4
- t4: 4
- t5: 3
- t6: 5
- t7: 5
• GPU computing
• rCUDA framework
• Other GPU virtualization frameworks
• rCUDA SLURM integration
• SDK and real applications tests
Test system

- Intel Xeon E5-2620 (6 cores) 2,0GHz
- GPU NVIDIA Tesla K20
- Mellanox ConnectX-3 single-port InfiniBand Adapter (FDR)
- Mellanox switch SX6025 (FDR)
- Cisco switch SLM2014 (1Gpbs Ethernet)
- CentOS 6.3 + Mellanox OFED 1.5.3
Test CUDA SDK examples
• CUDASW++

Bioinformatics software for Smith-Waterman protein database searches

Please, don’t ask me about this
• CUDABLAST

accelerated version of the NCBI-BLAST. Basic Local Alignment Search Tool, a widely used bioinformatics tool.
Test system for MultiGPU

- For CUDA tests one node with:
  - 2 Quad-Core Intel Xeon E5440 processors
  - Tesla S2050 (4 Tesla GPUs)
  - Each thread (1-4) uses one GPU

- For rCUDA tests 8 nodes with:
  - 2 Quad-Core Intel Xeon E5520 processors
  - 1 NVIDIA Tesla C2050
  - Infiniband QDR
  - Test running in one node and using up to all the GPUs of the others
  - Each thread (1-8) uses one GPU
- MonteCarlo MultiGPU (from NVIDIA SDK)
- GEMM MultiGPU
  - using **libflame**: high performance dense linear algebra library
    http://www.cs.utexas.edu/~flame/web/
rCUDA work in progress

- Scheduling in SLURM taking into account the actual GPU utilization
- Test in ARM platforms
  - CARMA board as client and rCUDA daemon on Intel Platform equipped with NVIDIA Tesla Fermi
  - Functional test with NVIDIA SDK and LAMMPS
  - Limited performance due to 1Gbps ethernet network
- Test more applications from
  “Popular GPU-accelerated Applications”
- Support to CUDA 5.5 (release candidate)
Thanks to Mellanox for its support to this work

rCUDA people

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