# rCUDA v16.11
# User's Guide

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The rCUDA Team

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# Notice:

rCUDA v16.11 provides support for the following versions of CUDA:

- CUDA 8.0
- CUDA 7.5
- CUDA 7.0

Support for other CUDA versions can be provided under request.

Please cite the following papers in any published work if you use the rCUDA software:

- C. Reaño, F. Silla, G. Shainer and S. Schultz, **"Local and Remote GPUs Perform Similar with EDR 100G InfiniBand"**, in proceedings of the International Middleware Conference, Vancouver, BC, Canada, December 2015.
- C. Reaño and F. Silla, **"A Performance Comparison of CUDA Remote GPU Virtualization Frameworks"**, in proceedings of the International Conference on Cluster Computing, Chicago, IL, USA, September 2015.

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# Contents

# Chapter 1

# Introduction

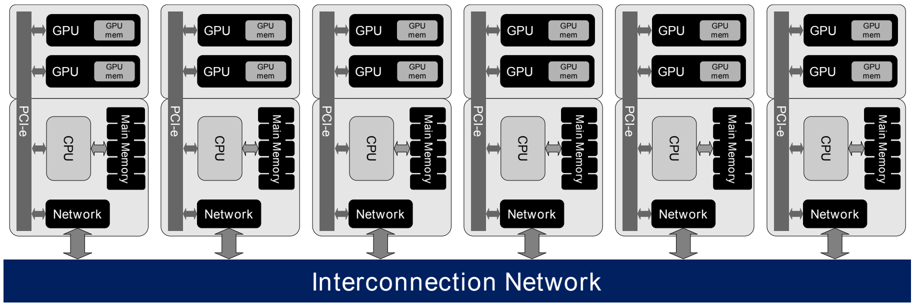
The rCUDA framework enables the usage of remote CUDA-compatible devices. To enable a remote GPU-based acceleration, this framework creates virtual CUDA-compatible devices on those machines without a local GPU. These virtual devices represent physical GPUs located in a remote host offering GPGPU services. By leveraging the remote GPU virtualization technique, rCUDA allows to decouple CUDA accelerators from the nodes where they are installed, so that GPUs across the cluster can be seamlessly accessed from any node. Furthermore, nodes in the cluster can concurrently access remote GPUs. Figure 1.1 graphically depicts the additional flexibility provided by rCUDA.

rCUDA can be useful in the following three different environments:

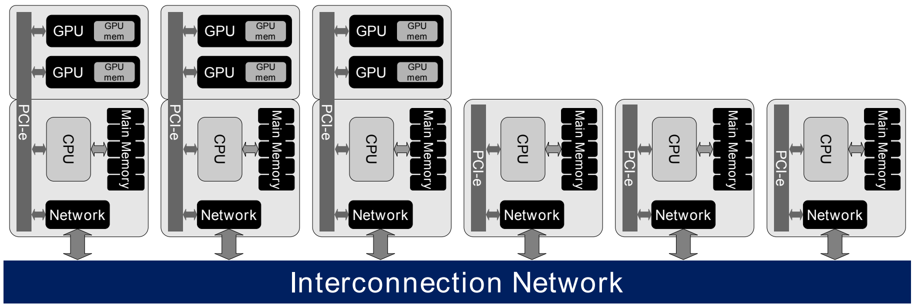
**HPC Clusters and datacenters.** In this context, rCUDA increases the flexibility of using the GPUs present in the cluster. Sharing a given GPU among several applications is made possible. In this way, when rCUDA is used along with the SLURM job scheduler, the time required to complete the execution of a job batch is noticeably reduced. This causes that waiting time for jobs is smaller. Furthermore, GPU utilization is increased at the same time that the overall energy required to execute the job batch is reduced.

**Virtual Machines.** In this scenario, rCUDA enables the access from the inside of the virtual machine to the CUDA accelerator(s) installed in the physical machine. In addition to allow accessing the accelerators installed in the real machine that hosts the virtual ones, it is also possible to access remote GPUs from the virtual domain.

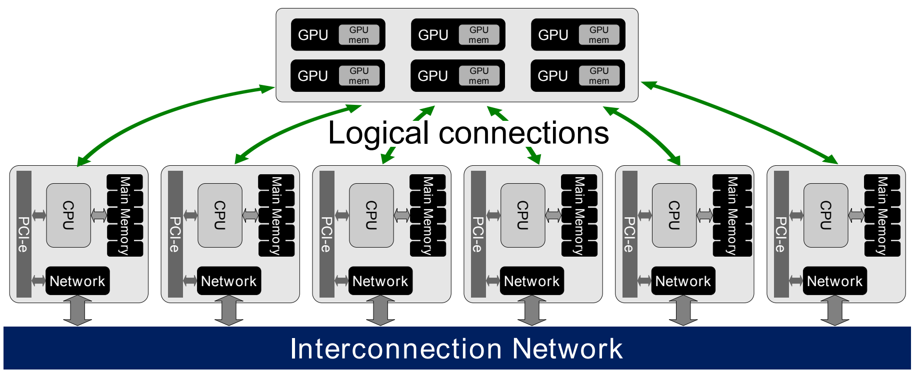
**Academia.** When using rCUDA in a teaching lab with a commodity network, our middleware offers concurrent access to a few high performance GPUs from the computers in the lab used by students as well as their laptops, or even virtual machines in the teaching lab. This reduces the acquisition costs of the lab infrastructure.




(a) When rCUDA is not deployed into the cluster, one or more GPUs must be installed in those nodes of the cluster intended for GPU computing. This usually leads to cluster configurations with one or more GPUs attached to all the nodes of the cluster. Nevertheless, GPU utilization may be lower than 100%, thus wasting hardware resources and delaying amortizing initial expenses.




(b) When rCUDA is leveraged in the cluster, only those GPUs actually needed to address overall workload must be installed in the cluster, thus reducing initial acquisition costs and overall energy consumption. rCUDA allows sharing the (reduced amount of) GPUs present in the cluster among all the nodes.




(c) From a logical point of view, GPUs in the cluster can be seen as a pool of GPUs detached from the nodes and accessible through the cluster interconnect, in the same way as networked storage (NAS) is shared among all the cluster nodes and concurrently accessed by them.

Figure 1.1: Different cluster configurations: (a) the traditional CUDA-based cluster deployment; (b) physical view of the cluster when leveraging rCUDA; (c) logical view of the cluster with rCUDA.

The current version of rCUDA (v16.11) implements all functions in the CUDA Runtime API and CUDA Driver API version 8.0, (as well as CUDA 7.5 and CUDA 7.0), excluding those related with graphics interoperability, Unified Memory Management and Module management. It also implements all the functions in the following libraries of CUDA Toolkit 8.0, 7.5, and 7.0: cuRAND, cuBLAS (excluding complex), cuSPARSE, and cuFFT (excluding complex). The cuDNN version 5.1 library is partially supported. Other libraries provided by NVIDIA will be supported in future rCUDA releases. rCUDA 16.11 targets the Linux operating system (for 64-bit x86-based configurations). It provides support for the same Linux distributions as CUDA does.

# Chapter 2

# Installation

The installation of the rCUDA software is very simple. The binaries of the rCUDA software are distributed whithin a tarball which has to be decompressed manually by the user. The steps to install rCUDA binaries are:

1. Decompress the rCUDA package.
2. Copy the rCUDA/lib folder to the client(s) node(s) (without GPU) as it is explained in Section 3.1.
3. Copy the rCUDA folder to the server node (with GPU) as it is explained in Section 3.2.

# Chapter 3

# Components and usage

rCUDA is organized following a client-server distributed architecture, as shown in Figure 3.1. The client middleware is contacted by the application demanding GPGPU services, both running in the same cluster node. The rCUDA client presents to the application the very same interface as the regular NVIDIA CUDA Runtime and Driver APIs. Upon reception of a request from the application, the client middleware processes it and forwards the corresponding requests to the rCUDA server middleware. In turn, the server interprets the requests and performs the required processing by accessing the real GPU to execute the corresponding request. Once the GPU has completed the execution of the requested command, results are gathered by the rCUDA server, which sends them back to the client middleware. There, the results are finally forwarded to the demanding application.

In order to optimize client/server data exchange, rCUDA employs a customized application-level communication protocol. Furthermore, rCUDA provides efficient support for several underlying network technologies. To do so, rCUDA supports runtime-loadable specific communication modules that currently target the InfiniBand network (using InfiniBand verbs) and the general TCP/IP protocol stack (see Figure 3.1). Additional network technologies may be supported in the future.

## 3.1 Client Side

The client side of the rCUDA middleware is a library of wrappers that replaces the CUDA Toolkit dynamic libraries mentioned at the end of Chapter 1. In this way, CUDA applications that use rCUDA are not aware of being accessing an external device. Also, they do not need any source code modification.

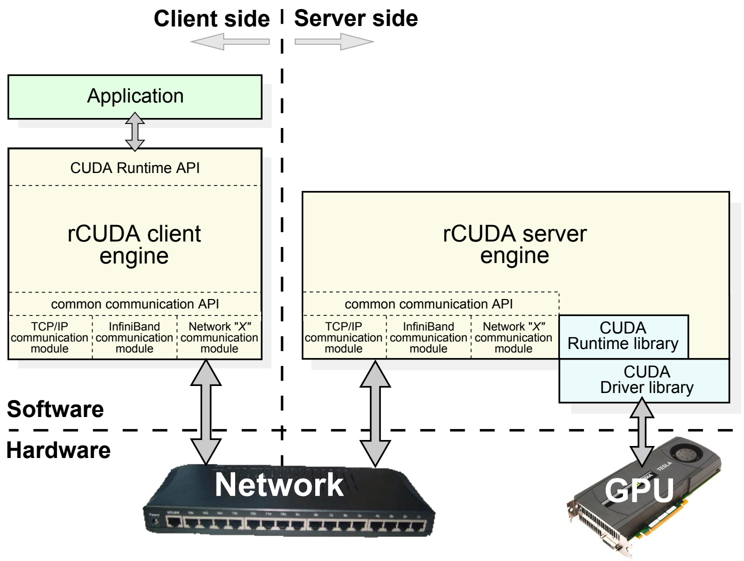



Figure 3.1: rCUDA architecture, showing also the runtime-loadable specific communication modules.

The rCUDA client is distributed in a set of files: "libcuda.so.$m.n$[1], libcudart.so.$x.y$[2], libcublas.so.$x.y$, libcufft.so.$x.y$, libcusparse.so.$x.y$, libcurand.so.$x.y$ and libcudnn.so.$x.y$. These shared libraries should be placed in those machines accessing remote GPGPU services. Set the LD_LIBRARY_PATH environment variable according to the final location of these files (typically "`/opt/rCUDA/lib`", "`/usr/local/rCUDA/lib`", or "`$HOME/rCUDA/lib`", for instance).

In order to properly execute the applications using the rCUDA library, set the following environment variables:

- RCUDA_DEVICE_COUNT: indicates the number of GPUs which are accessible from the current node.
  Usage: "RCUDA_DEVICE_COUNT=<number_of_GPUs>"
  For example, if the current node will access two remote GPUs:
  "RCUDA_DEVICE_COUNT=2"
- RCUDA_DEVICE_X: indicates where GPU X, for the client being configured, is located.
  Usage: "RCUDA_DEVICE_X=<server[@<port>]>[:GPUnumber]"
  For example, if GPUs 0 and 1 assigned to the current client are located at server "192.168.0.1" using the default rCUDA port (8308):
  "RCUDA_DEVICE_0=192.168.0.1"
  "RCUDA_DEVICE_1=192.168.0.1:1"

[1] $m.n$ are based on the exact version of the CUDA driver.
[2] $x.y$ refer to the exact version of CUDA supported by the provided rCUDA package.

Furthermore, as the nvcc compiler links with CUDA static libraries by default, a compilation using CUDA dynamic libraries is needed to allow the use of the rCUDA software. This step can be done by the user in two different ways:

- If nvcc compiler is used, the flag -cudart=shared is needed.
- If gcc/++ compiler is used, the -lcudart flag is needed.

In case the user of rCUDA is compiling the NVIDIA CUDA Samples, he/she should notice that NVIDIA CUDA Samples must be compiled after the EXTRA_NVCCFLAGS environment variable has been set to --cudart=shared.

If an InfiniBand network is available and the rCUDA user prefers to use the high performance InfiniBand Verbs APIs instead of the lower performance TCP/IP socket API, then the following environment variables should be considered:

- RCUDAPROTO: This environment variable must be set to "IB" in order to make use of the InfiniBand Verbs API. If this variable is not set, or if it is set to "TCP", then the TCP/IP sockets API will be used even if an InfiniBand network is available. For example:
  "RCUDAPROTO=IB" will use the InfiniBand Verbs API
  "RCUDAPROTO=TCP" will use the TCP/IP sockets API even if an InfiniBand network is used
- RCUDAIBDEVNO: (Optional. Default value is 1). In case the computer where rCUDA is being used has two or more InfiniBand network adapters, then the user may instruct rCUDA what adapter to use by appropriately setting this environment variable to the number of the selected InfiniBand adapter. For example:
  "RCUDAIBDEVNO=1" will use the first InfiniBand network adapter
  "RCUDAIBDEVNO=2" will use the second InfiniBand network card
- RCUDAIBPORTNO and RCUDAIBPORTNO2: (Optional. By default only port 1 is used). In case the computer executing rCUDA makes use of a dual-port InfiniBand card, then the rCUDA user may select to use the first port, the second port, or both. In case the rCUDA user decides to use only one of the two ports, then the port to be used may be selected by setting the environment variable "RCUDAIBPORTNO" to "1" or to "2". In case the rCUDA user decides to concurrently use both ports, then the environment variables "RCUDAIBPORTNO" and "RCUDAIBPORTNO2" should be set to "1" and "2", respectively. Notice that using both ports means that every single data transfer between the rCUDA client and server will be split among both ports, which will be concurrently used, thus aggregating their individual performance. For example:
  "RCUDAIBPORTNO=1" will use the first port of the InfiniBand network adapter
  "RCUDAIBPORTNO=2" will use the second port of the InfiniBand network card
  "RCUDAIBPORTNO=1" and "RCUDAIBPORTNO2=2" will concurrently use both ports of the InfiniBand network adapter

It is important to remark that the RCUDAPROTO variable must be set both in the client and server sides with the same value. In addition, when using two ports, the RCUDAIBPORTNO and RCUDAIBPORTNO2 variables must be set both in the client and server sides.

## 3.2 Server Side

The rCUDA server is configured as a daemon (rCUDAd) that runs in those nodes offering GPGPU acceleration services.

Set the LD_LIBRARY_PATH environment variable according to the location of the CUDA libraries (typically "`/usr/local/cuda/lib64`"). Notice that this is the path to the original CUDA libraries, not the rCUDA ones. Add also to the LD_LIBRARY_PATH environment variable the path to rCUDA cuDNN library (typically "`$HOME/rCUDA/lib/cudnn`"). See Section 3.2.1 for further information on the use of the cuDNN library.

Set the "RCUDAPROTO" environment variable to IB if an InfiniBand network is available and the InfiniBand Verbs API is to be used. The rest of environment variables related to the use of the InfiniBand Verbs API detailed in the previous section (such as RCUDAIBDEVNO, RCUDAIBPORTNO, and RCUDAIBPORTNO2) should also be considered.

This daemon offers the following command-line options:

**-i** : Do not daemonize. Instead, run in interactive mode.

**-l** : Local mode using AF_UNIX sockets (TCP only).

**-n <number>** : Number of concurrent servers allowed. 0 stands for unlimited (default).

**-p <port>** : Specify the port to listen to (default: 8308).

**-v** Verbose mode.

**-h** Print usage information.

### 3.2.1 cuDNN Users

If you are not going to use the NVIDIA CUDA Deep Neural Network library (cuDNN), you can ignore this section.

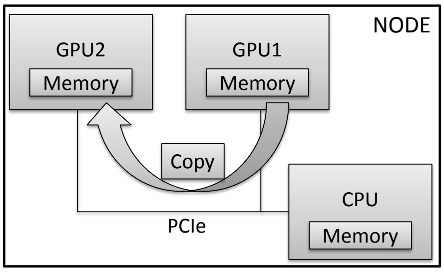
If, on the contrary, you plan to use this library, please, notice that in order to use the cuDNN library, the LD_LIBRARY_PATH environment variable in the server node must contain the location of the NVIDIA cuDNN libraries (typically "`/usr/local/cudnn/lib`"), instead of the rCUDA ones (typically "`$HOME/rCUDA/lib/cudnn`").

In addition, note that the cuDNN library is distributed separately from the CUDA package and, therefore, must be explicitly downloaded and installed. Furthermore, notice that the cuDNN library is not supported by the rCUDA framework for CUDA versions earlier than 6.5.

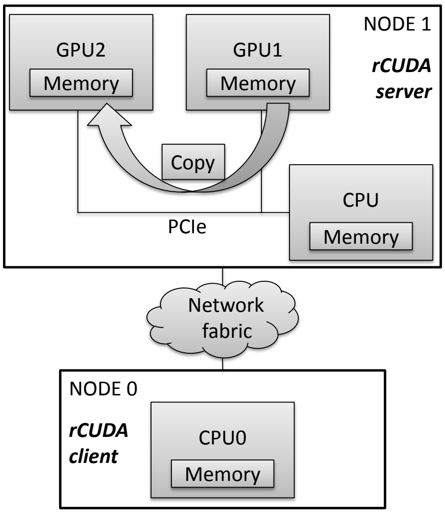
## 3.3 Support for P2P Memory Copies between Remote GPUs

Figure 3.2 presents the possible scenarios when making peer-to-peer (P2P) memory copies with CUDA and rCUDA. As we can see, with CUDA there is only one possible scenario, depicted in Figure 3.2a, where the GPUs are located in the same cluster node and are interconnected by the PCIe link. On the contrary, when using rCUDA there are two possible scenarios for making copies between remote GPUs: (i) the remote GPUs are located in the same remote node and are interconnected by the PCIe link as shown in Figure 3.2b, and (ii) the remote GPUs are located in different remote nodes in the cluster and therefore they are interconnected by the network fabric, as depicted in Figure 3.2c.

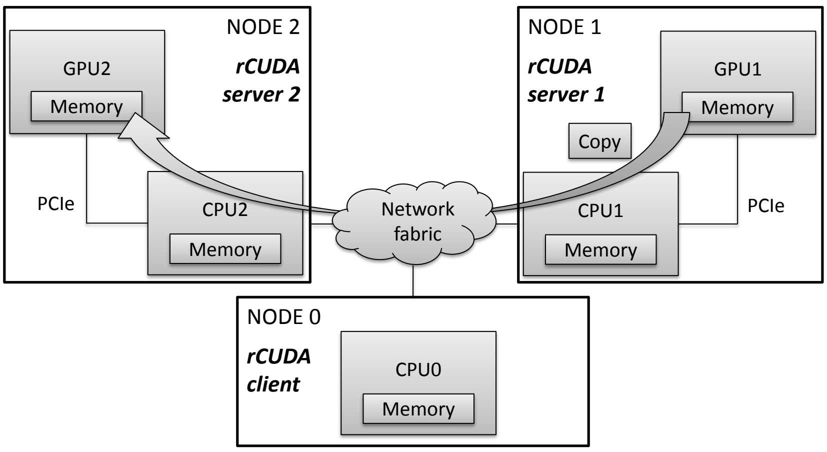
By default, rCUDA supports the first scenario exposed in Figure 3.2b. In this manner, it is possible to perform memory copies between remote GPUs located in the same server node. However, the second scenario presented in Figure 3.2c is only supported for InfiniBand networks. The TCP port for setting up the connection for P2P memory copies between remote GPUs could be indicated in the environment variable "RCUDAP2P_TCP_PORT". If it is not set, port number 18515 is used by default.




(a) CUDA scenario.




(b) rCUDA scenario 1.




(c) rCUDA scenario 2.

Figure 3.2: Possible scenarios for P2P memory copies with CUDA and rCUDA.

# Chapter 4

# Current limitations

The current implementation of rCUDA features the following limitations:

- Graphics interoperability is not implemented. Missing modules: OpenGL, Direct3D 9, Direct3D 10, Direct3D 11, VDPAU, Graphics
- The Profiler Control module is not supported.
- Unified Memory Management is not supported.
- Module management is not supported
- Timing with the event management functions might be inaccurate, since these timings will discard network delays. Using standard Posix timing procedures such as "*clock_gettime*" is recommended.

# Chapter 5

# Further Information

For further information, please refer to [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. Also, do not hesitate to contact support@rcuda.net for any questions or bug reports.

# Chapter 6

# Credits

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