rCUDA v20.07alpha
User’s Guide

July, 2020

The rCUDA Team

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Disclaimer:

This is an alpha release and therefore unexpected errors may occur. Additionally, the performance of this release has not been assessed yet. Thus, please consider that performance might not be optimum when using this release of rCUDA. As a consequence, this release is not intended to be used in performance measurements.

Important information:

We will be very happy to receive your feedback and comments. Notice, however, that we are a small team and thus we are not able to provide immediate support for the rCUDA technology. Actually, your feedback and comments will likely be incorporated into the next rCUDA release. Thank you for your patience and understanding.
Changelog:

The most important changes in this version of rCUDA with respect to version v18.10beta are:

- A completely new and disruptive internal architecture has been designed and implemented for the core of rCUDA. The new internal architecture is aimed at provide much better support to more CUDA applications and also better performance. Notice, however, that we have not checked yet the amount of applications supported neither their performance when using rCUDA.

- A completely new communications layer has been implemented, which has been architected to provide much easier maintenance of the code and also much better performance than previous versions of rCUDA.

- Multi-tenancy is supported. That is, a real GPU can be virtualized into multiple GPUs, which can be concurrently provided to several applications.

- The rCUDA server can simultaneously provide service across TCP and InfiniBand networks. That is, the rCUDA server can provide support to some applications by using TCP/IP at the same time that other applications are served using the InfiniBand network.

- Support for functions in the Driver API has been noticeably improved.

- The use of P2P data copies has been noticeably simplified, making it fully transparent to the user.

- GPU memory can be safely partitioned among different applications. In next releases of rCUDA we will disclose the public API to do so.

- Next releases of rCUDA will include the rCUDA-smi tool, which is similar to the nvidia-smi tool except that remote GPUs are monitored.

- Next releases of rCUDA will include the rCUDA GPU scheduler, intended to provide efficient integration of rCUDA with Slurm and other job schedulers.

- Next releases of rCUDA will include the sbatch and srun commands required to integrate rCUDA with Slurm. Other job schedulers, such as PBSpro, could also be supported.

The rCUDA Team hopes that you enjoy this new version of the rCUDA technology!
The most important changes in recent versions of rCUDA (v18.03beta and v18.10beta) were:

- The NCCL library was supported
- A license server was introduced into the rCUDA suite. In order to use rCUDA, you need first to set the license server in your cluster. Please refer to the installation chapter later in this guide for more information
- The architecture of the rCUDA server was renewed from scratch in order to provide full support to multi-threaded applications
- The rCUDA daemon was improved in order to make a better usage of the GPU memory, allowing more memory for applications
- Support for functions in the Driver API was improved
- Management module was supported
- Support for Deep Learning frameworks such as TensorFlow or Caffe2 was introduced
- Support for the cuSOLVER, cuBLAS-XT and NVGRAPH libraries was introduced
- The NPP library was partially supported
- Version 7.0 of the cuDNN library was supported
- The rCUDA server used a single TCP port to provide service to all clients. The need for shutting down the firewall at the server node was therefore removed
- The RCUDAPROTO environment variable was replaced by the RCUDA_NETWORK environment variable. Please update the scripts you used with previous versions of rCUDA
Notice:

rCUDA v20.07alpha provides support for the following versions of CUDA:

- CUDA 9.0

Support for other CUDA versions will be provided in future releases.
Please cite the following papers in any published work if you use the rCUDA software:


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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 shared access from the inside of the virtual machine to the CUDA accelerators 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 (v20.07alpha) implements all functions in the CUDA Runtime API and CUDA Driver API version 9.0 excluding those related with graphics interoperability and Unified Memory Management. It also implements most of the functions in the following libraries of CUDA Toolkit 9.0: cuRAND, cuBLAS, cuSPARSE, cuFFT, cuSOLVER, cuBLAS-XT, NCCL and NVGRAPH. The NPP library is partially supported. Additionally, version 7.0 of the cuDNN library is supported. Other libraries provided by NVIDIA will be supported in future rCUDA releases. rCUDA 20.07alpha targets the Linux operating system for 64-bit x86-based configurations. Future releases will provide support for the ARM and POWER systems. It provides support for the same Linux distributions as CUDA does.
Chapter 2

Fixing Most Common Errors with rCUDA

2.1 Error 1: "mlock error: Cannot allocate memory"

While using rCUDA you may get the error message "mlock error: Cannot allocate memory".

In order to fix this error, you can add the following lines at the end of file "/etc/security/limits.conf" in both client and server nodes:

* hard memlock unlimited
* soft memlock unlimited

After rebooting the system, you can run the following command to verify that the limits have been changed:

$ ulimit -a | grep "max locked memory"

You should get an output similar to "max locked memory (kbytes, -l) unlimited".
2.2 Error 2: ”rCUDA error: function cuGetExportTable not supported”

This error is caused because the application was compiled to used static libraries (in particular, the CUDA library). Notice that rCUDA needs applications to be compiled to use CUDA as a dynamic library. That is, 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.
Chapter 3

Installation

Notice that prior to use the rCUDA middleware, you MUST have a license key and appropriately configure the rCUDA license server in your cluster.

Typically, if you are reading this document, you should already received a license key from the rCUDA Team. If not, please ask the rCUDA Team for a license key at support@rcuda.net

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

1. Decompress the rCUDA package.
2. Install and configure the rCUDA license server as it is explained in Section 3.1 (you should already have a license key).
3. Copy the rCUDA/lib folder to the client(s) node(s) (without GPU) as it is explained in Section 4.1.
4. Copy the rCUDA folder to the server node (with GPU) as it is explained in Section 4.2.

3.1 Setting up the rCUDA License Server

The rCUDA license server is a daemon that must be in execution in one of the nodes of the cluster before the rCUDA server is executed. It is important to know that a license key is required by the rCUDA license server.
In order to get a license key, the user was previously provided by the rCUDA Team with a program that gathers some information of the node that will run the license server. This information comprises, among other parameters, the MAC address of the Ethernet adapter of the node. Other pieces of information are also gathered. Because of this, the license key received from the rCUDA Team can only be used in the same node where the information was initially gathered.

After receiving the license key from the rCUDA Team, the user must store it in the config/rCUDA.conf file. In this way, the user must include a new line in that file, similar to:

```
RCUDA_LICENSE_KEY=3232145765453730306042551...
```

You should include in the config/rCUDA.conf file a line with the IP address of the node where the license server is being run, such as

```
RCUDA_LICENSE_SERVER=192.168.0.34
```

Now the license server can be executed. To that end please launch the rCUDAils program located in the bin folder. It is helpful to execute the license server in interactive and verbose mode by using the -iv options. That is, you should type:

```
./rCUDAils -iv
```

You should get an output similar to:

```
rCUDAils v1.0
Copyright 2009-2018 UNIVERSITAT POLITECNICA DE VALENCIA. All rights reserved.
rCUDAils[16812]: License Features:
- Expiration date: 31 Dec 2021
- Max rCUDA server(s): 2
- Max remote GPU(s): 4
- Max virtual GPU(s): 1 per remote GPU
- Allow Migration: no
rCUDAils[16812]: License server daemon successfully started.
```

Once you have checked that the rCUDA license server is properly configured and running, you might decide to run it in non-interactive and non-verbose mode if desired. To that end, just do not use the -iv options.

Finally, notice that the rCUDA license server listens in the TCP port number 8309. Therefore, if a firewall is in execution in the node running the rCUDA license server, then it must be configured to allow incoming connections to TCP port 8309.
Chapter 4

Components and usage

rCUDA is organized following a client-server distributed architecture, as shown in Figure 4.1. 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 that end, rCUDA currently targets the InfiniBand network (using InfiniBand verbs), the RoCE network (using RDMA) and the general TCP/IP protocol stack (see Figure 4.1). Additional network technologies may be supported in the future.

4.1 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.
The rCUDA client is distributed in a set of files: “libcuda.so.m.n\textsuperscript{1}, libcudart.so.x.y\textsuperscript{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).
Notice that you do not need to be root in order to use the rCUDA middleware.

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_GPLUs>”
  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 con-
  figured, 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”

\textsuperscript{1}m.n are based on the exact version of the CUDA driver.
\textsuperscript{2}x.y refer to the exact version of CUDA supported by the provided rCUDA package.

Figure 4.1: rCUDA architecture, showing also the runtime-loadable specific communication modules.
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, the user 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:

- RCUDA_NETWORK: 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:
  “RCUDA_NETWORK=IB” will use the InfiniBand Verbs API
  “RCUDA_NETWORK=TCP” will use the TCP/IP sockets API even if an InfiniBand network is used

- RCUDA_NETWORK_DEV_NAME: 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 name of the selected InfiniBand adapter. For example:
  “RCUDA_NETWORK_DEV_NAME=mlx4_0” will use the InfiniBand network adapter named as mlx4_0
  “RCUDA_NETWORK_DEV_NAME=mlx5_0” will use the InfiniBand network card named as mlx5_0

It is important to remark that the RCUDA_NETWORK variable must only be set in the client side. This variable is not used in the server side because the rCUDA server automatically uses TCP/IP or InfiniBand depending on the configuration of the incoming client.

4.2 Server Side

The rCUDA server is configured as a daemon (rCUDAd) that runs in those nodes offering GPGPU acceleration services. Notice that you do not need to be root in order to use the rCUDA middleware. The rCUDA server contacts the rCUDA license server in order to check that its execution is allowed. To that
end, the rCUDA server needs to know the IP address of the node executing the rCUDA license server. A line with the license key should also be included. The way to achieve this is to include two new lines in the config/rCUDA.conf file such as

```
RCUDA_LICENSE_KEY=3232145765453730306042551...
RCUDA_LICENSE_SERVER=192.168.0.34
```

The IP address 192.168.0.34 is just an example. The actual IP address of the node running the rCUDA license server in your cluster should be used instead. Notice that every rCUDA server in the cluster must be configured to know the IP address of the rCUDA license server. Moreover, notice that the rCUDA License Server and the rCUDA Server can share the same config/rCUDA.conf. In this way, setting these two lines in such file once will satisfy both servers. Also, in case different rCUDA servers running in different cluster nodes share a common file system, a single config/rCUDA.conf will satisfy all the servers.

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 4.2.1 for further information on the use of the cuDNN library.

Notice that the “RCUDA_NETWORK” environment variable is not required in the server side because the rCUDA server automatically uses TCP/IP or InfiniBand depending on the configuration of the incoming client. In any case, if the node hosting the rCUDA server presents more than one InfiniBand adapter, the environment variable `RCUDA_NETWORK_DEV_NAME` should be set in order to select which adapter to use in case an incoming client is using the InfiniBand network.

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.

We suggest you to use the -iv options the first time you execute the rCUDA server in order to check that it properly works. Once you have verified that the rCUDA server can connect to the license server, you might stop using the interactive and verbose modes if desired.
4.2.1 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.

4.3 Support for P2P Memory Copies between Remote GPUs

Figure 4.2 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 4.2a, where the GPUs are located in the same cluster node and are interconnected by the PCIe link or NVlink. 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 of NVlink as shown in Figure 4.2b, 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 4.2c.

By default, rCUDA automatically supports both scenarios exposed in Figures 4.2b and 4.2c. In this manner, it is possible to perform memory copies between remote GPUs located in the same server node as well as between GPUs located in different server nodes. The use of P2P data copies is completely transparent to the rCUDA user.
Figure 4.2: Possible scenarios for P2P memory copies with CUDA and rCUDA.
Chapter 5

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.
- Thrust library 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.
- Please, notice that this is an alpha release and therefore unexpected errors may occur. Additionally, the performance of this release has not been assessed yet. Thus, this release is not intended to be used in performance measurements.
Chapter 6

Further Information

For further information, please refer to [11, 8, 10, 12, 9, 17, 15, 18, 14, 13, 7, 3, 4, 5, 2, 1, 6, 44, 43, 41, 42, 40, 39, 38, 35, 37, 36, 34, 28, 27, 32, 26, 33, 30, 31, 29, 21, 19, 23, 22, 24, 20, 16, 25]. Also, do not hesitate to contact support@rcuda.net for any questions or bug reports.
Chapter 7

Credits

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Bibliography


