Verbs programming tutorial

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Mellanox Technologies
Connect. Accelerate. Outperform.™

About me

- A Senior Software Manager at Mellanox Technologies. I have more than 10 years experience in various roles such as:
  - a manager
  - a developer

- Was involved in several documentation projects in verbs programming
  - Man pages of libibverbs
  - Wrote the “RDMA Aware Networks Programming User Manual”
  - Wrote the chapter “InfiniBand” in the “Linux Kernel Networking – Implementation and Theory” book by Rami Rosen, 2013

- Wrote tens of applications over verbs
  - Over several verb(s) generations
  - In different OS’s

- Author of “RDMAmojo” - a blog on the RDMA technology

InfiniBand Advantages

- Features:
  - Remote Direct Memory Access (RDMA) – zero copy
  - Kernel bypass
  - Highly scalable (10K’s of nodes)
  - Message based transactions
  - Credit based flow control
- Performance
  - High BW (56 Gb/sec)
  - Low latency (700 nsec)
  - High message rate (137 Mpps)
  - The lower 4 OSI layers implemented in HW
- Other
  - Industry Standard
  - Developed as Open Source (in *NIX)
  - Inbox in several OS’s

InfiniBand Hardware Components

Channel Adapters

- Channel Adapters (CAs) are the end nodes in the subnet.
  - They create/consume packets
- There are two types of CAs:
  - HCA – CA which supports the verbs interface
  - TCA – “weak” CA, does not have to support many features

- xCAs are located in hosts/systems and they have a DMA engine that allows to initiate local and remote DMA operations.

- xCA has at least one port

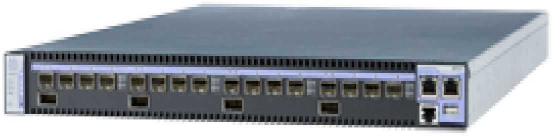
Switch

- Switches allow routing of a packet in a subnet according to the packet’s local destination addressing
  - Very fast routing (140-200 nsec)
  - Only Unicast packets are routed
  - Multicast packets may be duplicated across some/all ports

- A switch has at least three ports

Router and Gateway

- Routers allow routing of packets between different subnets according to the packet’s destination Global address
- Gateways allow encapsulation/de-capsulation of InfiniBand packets in other protocol packets
- Routers and Gateways have at least one port per subnet

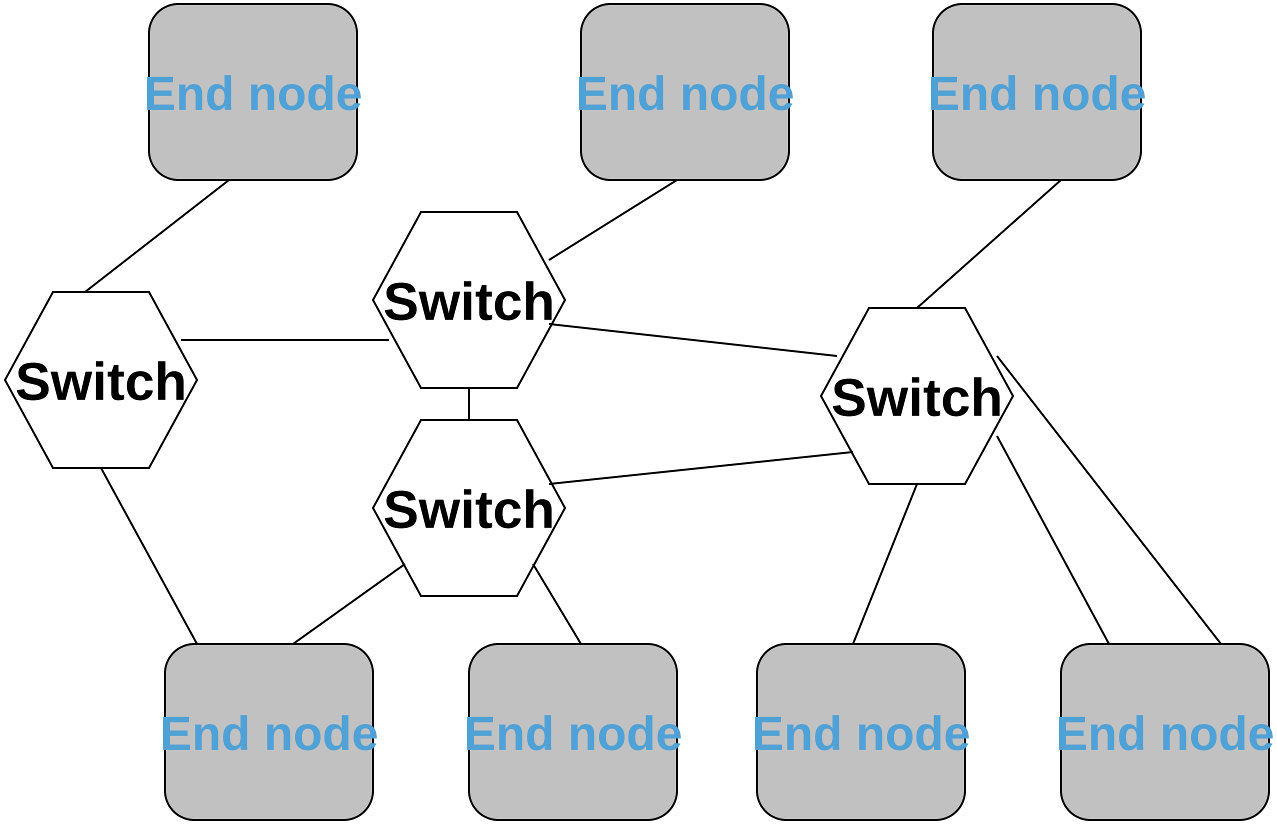


Links are Repeaters

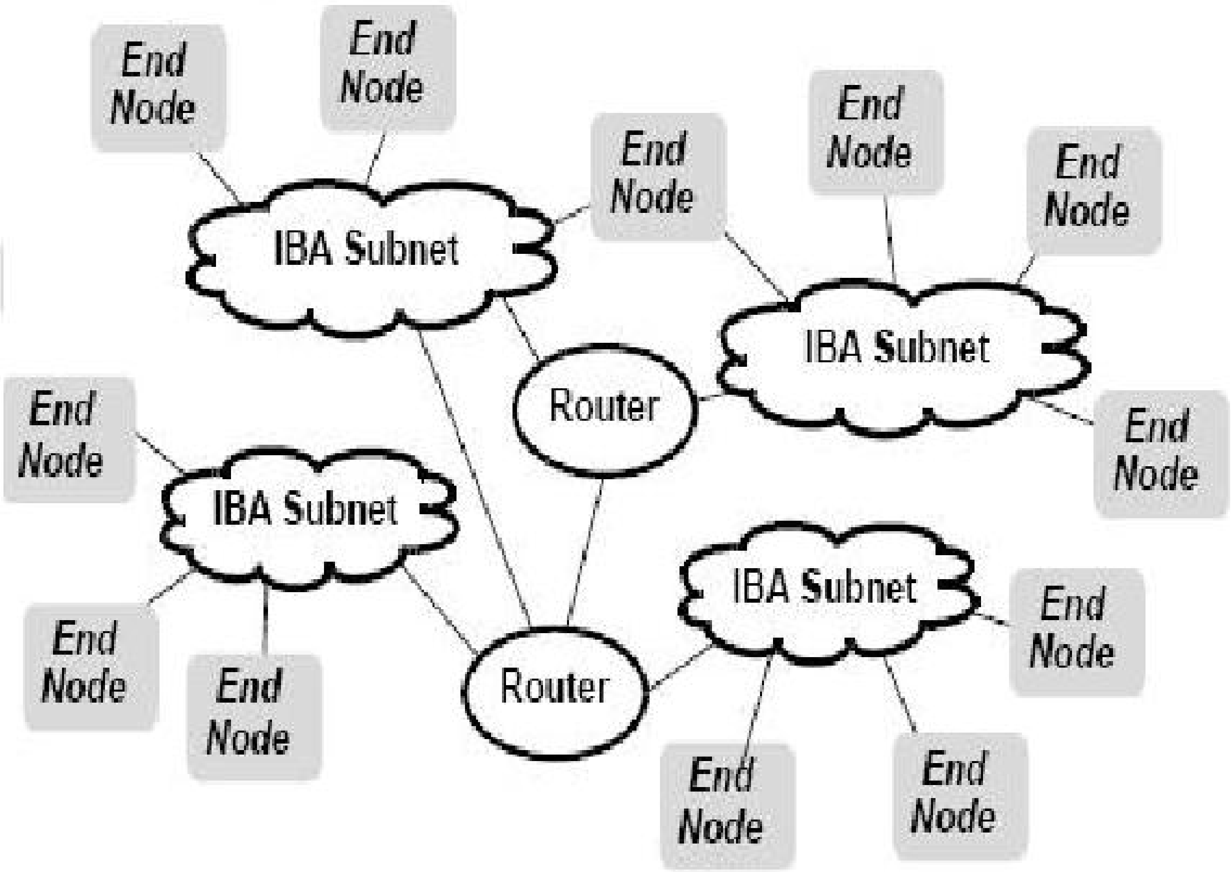
- Links connect xCAs, switches, routers, gateways together to create a subnet
  - Every link is full duplex
    - Lines(s) for TX
    - Lines(s) for RX
  - Link can be:
    - Copper cable
    - Optical cable
    - Printed circuit

- Repeaters are transparent physical entities that extend the range of a link

InfiniBand subnet



InfiniBand connected subnets

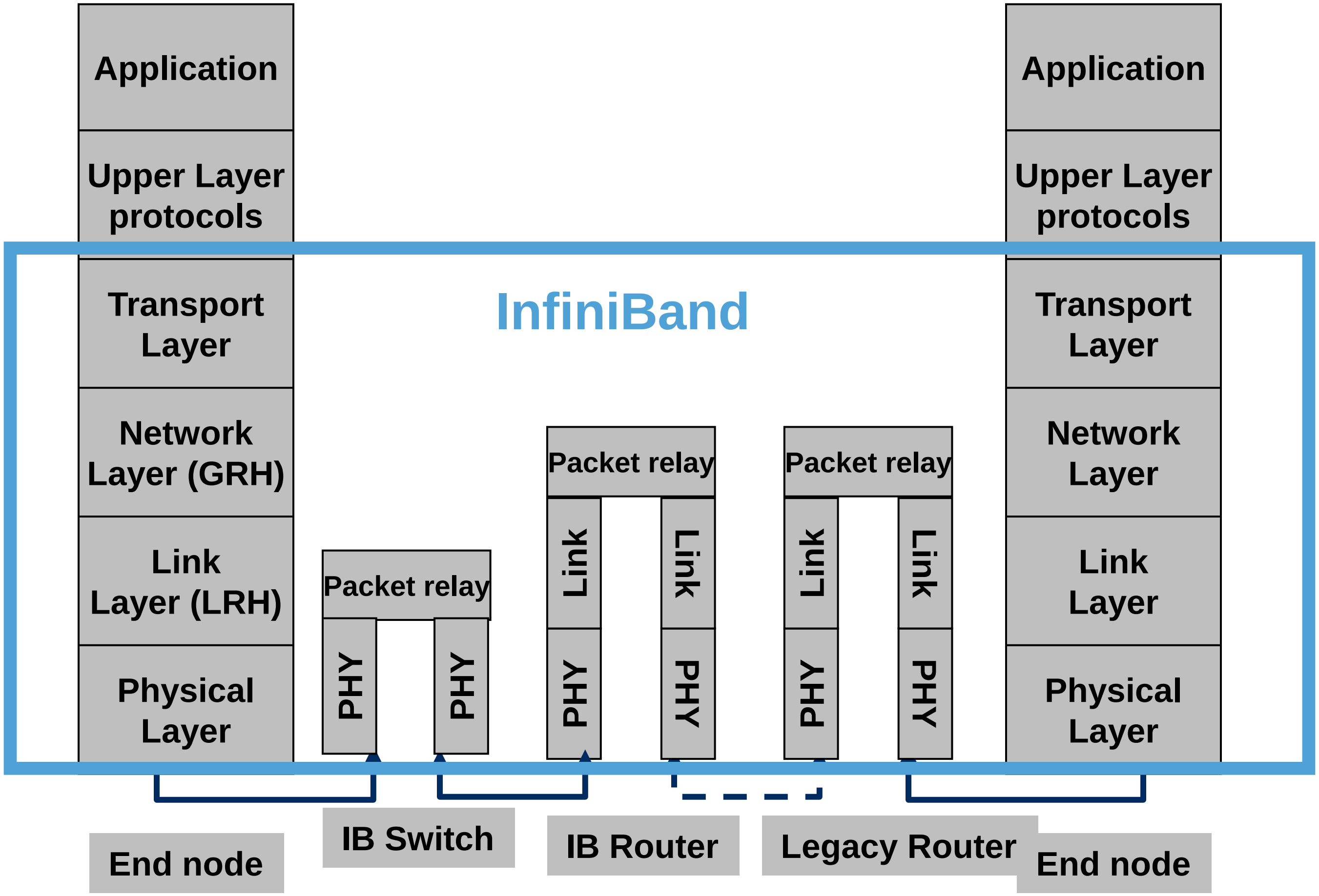


RDMA Data Model

InfiniBand Addressing

- Every node in InfiniBand has a Global Unique Identifier (GUID) – Node GUID
  - Persistent
  - World-wide unique 64 bits value (node GUID)
- Every port in a node has a port GUID
  - Ports can be identified using the port GUID
  - Every port can be configured with multiple additional GID (Global IDentifier) addresses in the port’s GID table
- A system, which contains several nodes, may have a System GUID configured in each node

InfiniBand Layers



Subnet Manager

- A subnet is configured and managed by a Subnet Manager (SM)
  - One centralized entity which configures and manages the subnet
    - Fills various tables in the node’s ports
    - Fills the forwarding tables and more switch tables
  - The SM assigns each port in an end-node a Local Identifier (LID)
    - 16 bits value
    - Unique in a specific subnet
    - Port may has one or range of LIDs
    - All switch ports have the same LID
  - One is active and the other if exists is in standby state
    - One of them becomes active if the active one cannot function

The Classic Data Transfer Model (Sockets)

- The receiver prepares the receive buffer(s)
- The sender prepares the send buffer(s)

- Points :
  - Network software stack involved
    - Usually part of the OS’s kernel
    - Consumes CPU
    - If needed, provides reliability
    - Caches the data
  - Order of operations does matter
    - Receive buffer(s) **should** be available before data is received

RDMA Data Transfer Model

- Send
  - Just like the classic model
  - Data is read in local side
    - Can be gathered from multiple buffers
  - Sent over the wire as a message
  - Remote side specify where the message will be stored
    - Can be scattered to multiple buffers

- RDMA
  - Local side can write data directly to remote side memory
    - Can be gathered locally from multiple buffers
  - Local side can read data directly from remote side memory
    - Can be scattered locally to multiple buffers
  - Remote side isn’t aware to any activity
    - No CPU involvement at remote side

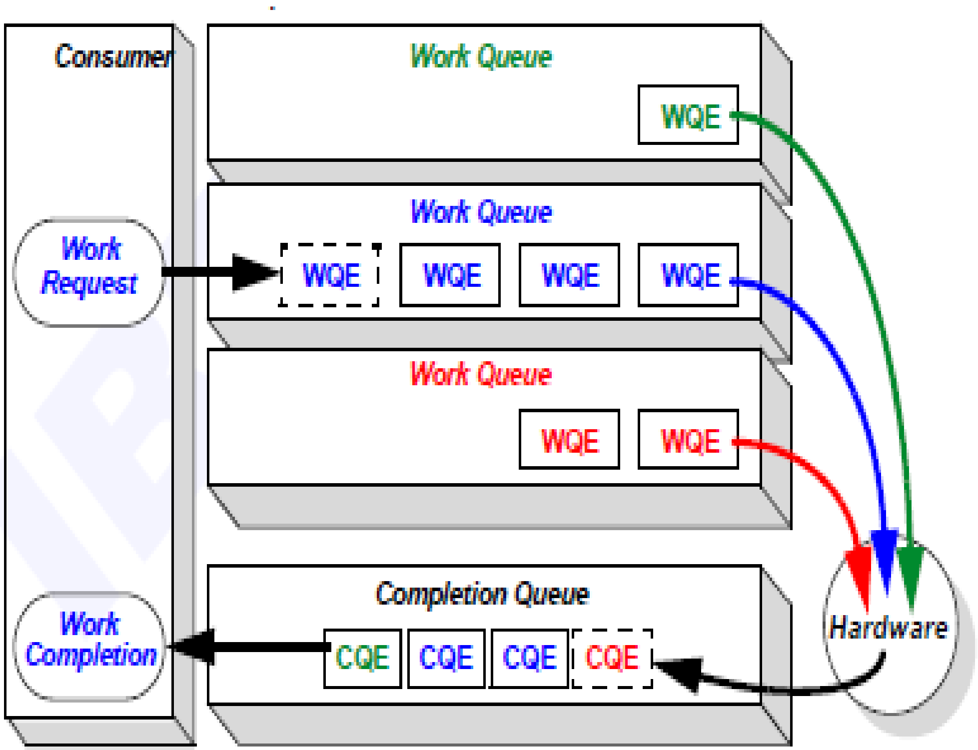
RDMA Data Transfer Model – Work Queues

- Work Request (WR)
  - Work items that the HW should perform

- Work Completion (completion)
  - When a WR is completed, it may create a Work Completion which provides information about the ended WR
    - Type, opcode, amount of data send/received, more

- Work Queue (WQ)
  - A queue which contains WRs
  - Scheduled by the HW
    - WR execution ordering is guaranteed within the same WQ – FIFO
    - There is no guarantee about the order between different Work Queues
  - Can be either Send or Receive Queue
  - Adding a WR to a WQ is called “posting a WR”
  - Every WR that was posted is considered “outstanding” until it ends with Work completion. While outstanding:
    - One cannot know if it was scheduled by the HW or not
    - Send buffer(s) cannot be (re)used/freed
    - Receive buffer(s) content is undetermined

RDMA data transfer model – Work Queues (cont.)



RDMA Data Transfer Model – Work Queues (cont.)

- Send Queue (SQ)
  - A Work Queue that handles sending messages
  - Every entry is called a Send Request (SR). It specifies:
    - How data is used
    - What memory buffers to use
      - To send or receive data – depends on the opcode
    - How much data is sent
    - More attributes
  - Adding a SR to an SQ is called “posting a Send Request”
  - SR may end with a Work Completion

- Receive Queue (RQ)
  - A Work Queue that handles incoming messages
  - Every entry is called a Receive Request (RR). It specifies:
    - Memory buffers to be used (If RR is consumed – depends on opcode)
  - Adding a RR is to the RQ called “posting a Receive Request”
  - An RR always ends with a Work Completion
  - This queue may send data as a response – depends on opcode

- Queue Pair (QP)
  - An object which unifies both Send and Receive Queues
  - Every Queue is independent
  - Every QP is associated with a Partition Key (P_Key)

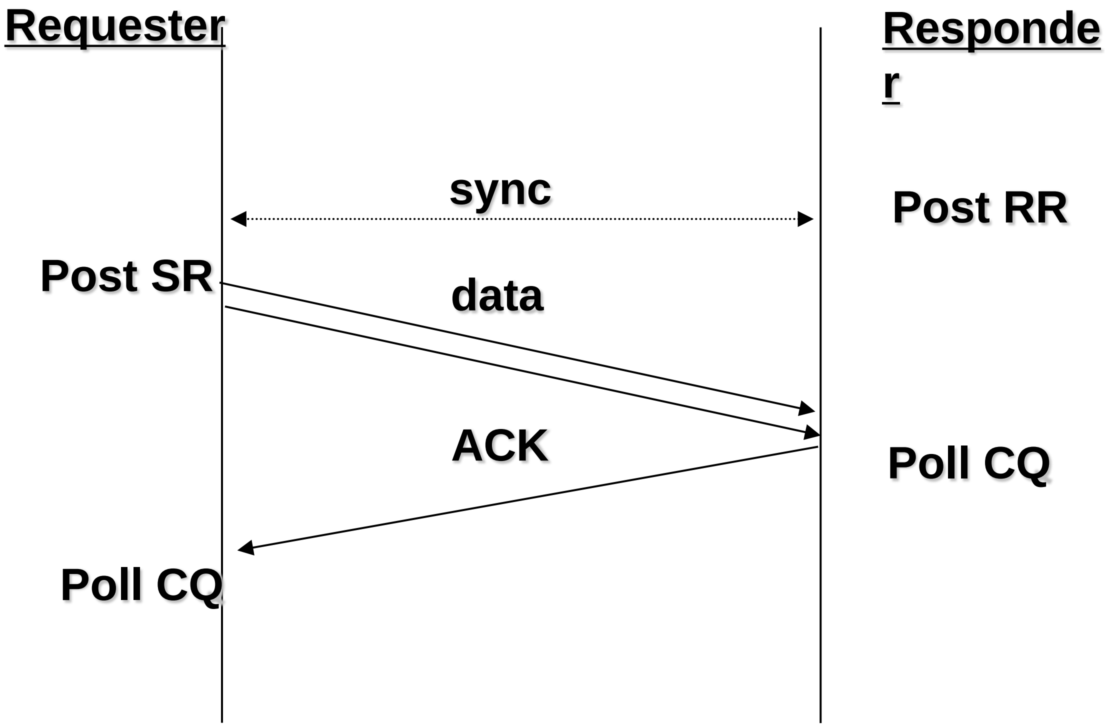
RDMA Data Transfer Model - Roles

- Requester
  - The active side
    - It initiates the data transfer
  - Post SR(s)

- Responder
  - The passive side
    - It sends or receives data – depend on the used opcode
  - May Post RR(s)
  - Send ACK/NACK for reliable transport types

RDMA opcodes: Send

- The responder Post Receive Requests (before data is received)
- The requester Post Send Request
  - Only data is sent over the wire
- ACK is sent only in reliable transport types



Requester

Responder

sync

Post RR

Post SR

data

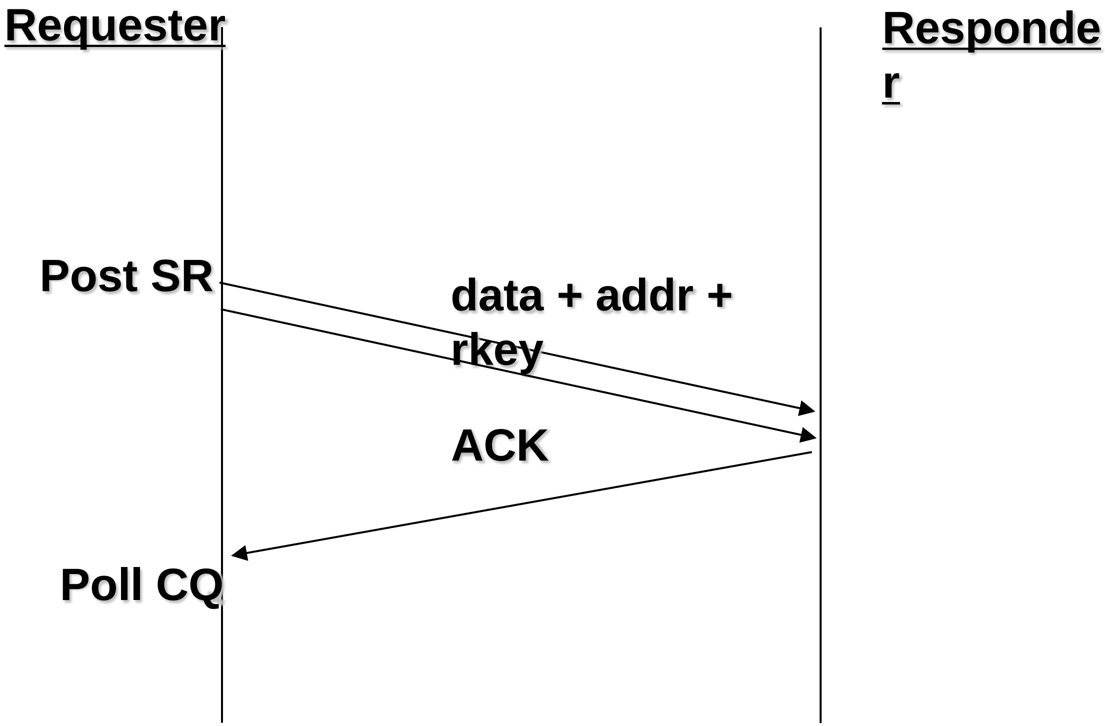
ACK

Poll CQ

Poll CQ

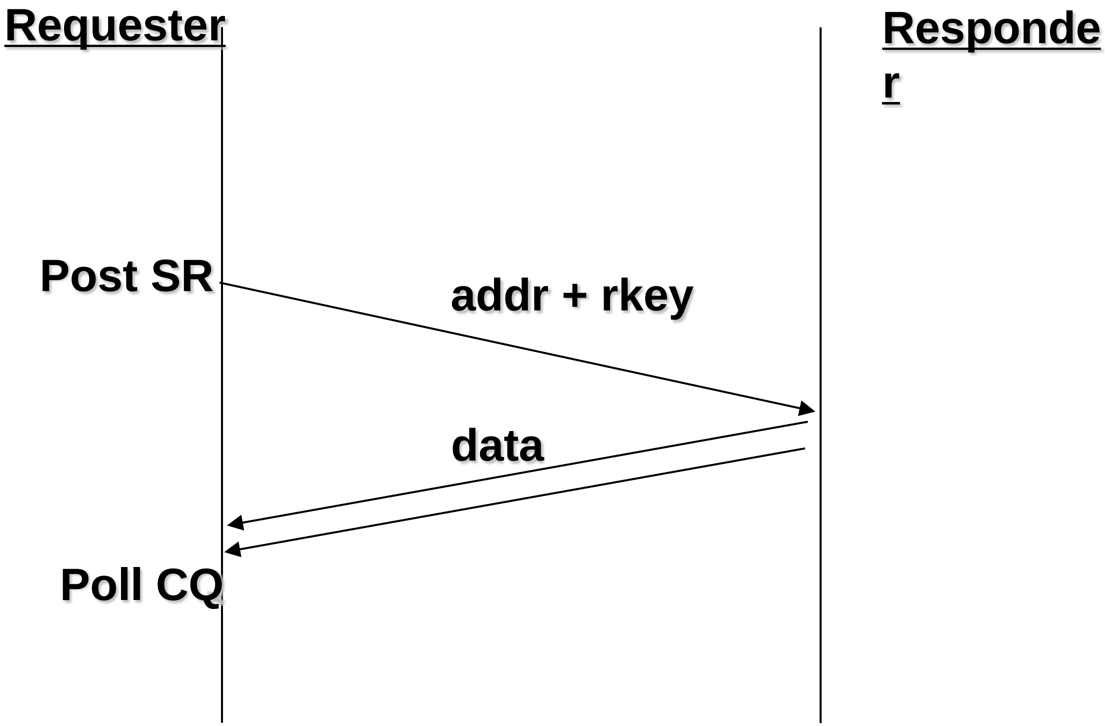
RDMA opcodes: RDMA Write

- The requester Post Send Request
  - Data and remote memory attributes are sent
  - Responder is passive
  - Immediate data can be used to consume RRs at the responder side
- ACK is sent only in reliable transport types



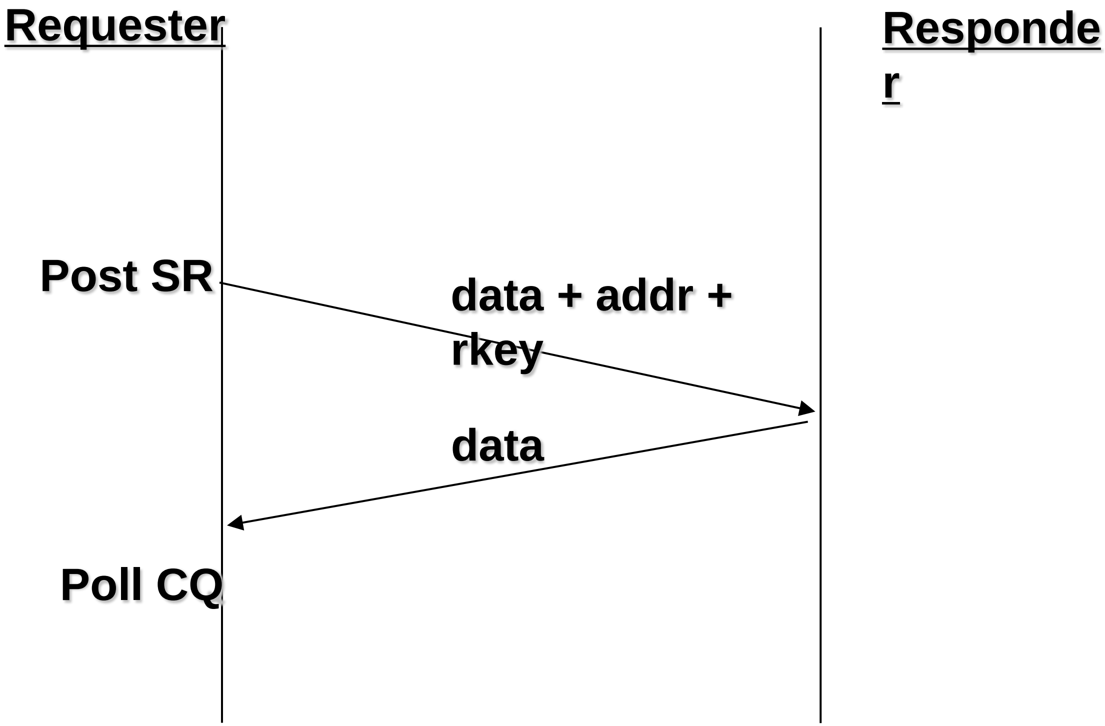
RDMA opcodes: RDMA Read

- The requester Post Send Request
  - Data and remote memory attributes are sent
  - Responder is passive
- Data is sent from the responder
  - Available only in reliable transport types



RDMA opcodes: Atomic

- The requester Post Send Request
  - Data and remote memory attributes are sent
  - Responder is passive
- Original data is sent from the responder
  - Read-modify-write is performed in responder’s memory
  - Available only in reliable transport types



Requester

Responder

Post SR

data + addr + rkey

data

Poll CQ

RDMA opcodes: Atomic (cont.)

- Fetch and Add
  - The following is done in atomic way for 64-bits numbers at responder’s memory:
    - Fetch data from memory
    - Add a value
    - Store the new number
  - Send the original value to the requester
- Compare and Swap
  - The following is done in atomic way for 64-bits numbers at responder’s memory :
    - Fetch data from memory
    - Compare the data with number1
      - If they are equal - store number2 in memory
  - Send the original value to the requester

RDMA opcodes summary

	Send	RDMA Write	RDMA Read	Atomic
Data direction	requester -> responder	requester -> responder	requester <- responder	requester <-> responder
Require RR at responder	Yes	Only in case of RDMA Write with immediate	No	No
Requester memory operations	Gather data (multiple buffers)	Gather data (multiple buffers)	Scatter data (multiple buffers)	Scatter data (multiple buffers)
Responder memory operation	Scatter data (multiple buffers)	Write data (contiguous block)	Write data (contiguous block)	Write data (contiguous block)
Atomicity	No	No	No	Yes

Verbs

Prerequisites

- Software
  - Linux distribution
  - RDMA stack installed
    - MLNX-OFED
    - Community's OFED
    - Native RDMA stack within the Linux distribution
    - Download manually the needed libraries and compile the Linux kernel

- Hardware
  - RDMA device
    - InfiniBand/RoCE is preferred
    - Connected in loopback or back-to-back/switch

What is the “verbs”?

- Verbs is an abstract description of the functionality that is provided for applications for using RDMA.
  - Verbs is not an API
  - There are several implementations for it
- Verbs can be divided into two major groups
  - Control path – manage the resources and usually requires context switch
    - Create
    - Destroy
    - Modify
    - Query
    - Work with events
  - Data path – Use the resources to send/receive data and doesn’t require context switch
    - Post Send
    - Post Receive
    - Poll CQ
    - Request for completion event

Why use verbs?

- Verbs is a low level description for RDMA programming
  - Verbs are close to the “bear-metal” and provide best performance
    - Latency
    - BW
    - Message rate
  - Verbs can be used as building blocks for many applications
    - Sockets
    - Storage
    - Parallel computing
- Any other level of abstraction over verbs may harm the performance

- Once you know it, verbs are not so mysterious …

libibverbs

- libibverbs, developed and maintained by Roland Dreier since 2006, are de-facto the verbs API standard in *nix
  - Developed as an Open source
  - The kernel part of the verbs is integrated in the Linux kernel since 2005 – Kernel 2.6.11
  - Inbox in several *nix distributions
  - There are level low-level libraries from several HW vendors
- Same API for all RDMA-enabled transport protocols
  - **InfiniBand** – Networking architecture which supports RDMA
    - requires both NICs and switches that supports it.
  - **RDMA Over Converged Ethernet (RoCE)** – encapsulation of RDMA packets over Ethernet/IP frames
    - requires NICs which supports it and standard Ethernet switches
  - **Internet Wide Area RDMA Protocol (iWARP)** – provides RDMA over Stream Control Transmission Protocol (SCTP) and Transmission Control Protocol (TCP)
    - requires NICs which supports it and standard Ethernet switches

libibverbs: Thread Support

- libibverbs is completely thread safe
  - libibverbs itself is thread safe
  - The userspace low-level driver libraries are thread safe as well
  - Application can use RDMA resources in multiple threads

- Warning: libibverbs will not prevent you from getting into troubles
  - Destroying a resource in one thread and using it in another thread will end up with segmentation fault
    - This happens in non-thread code as well

libibverbs: fork() support

- When possible, avoid using fork()
  - fork() or other system calls that call fork(), for example: system(), popen(), etc.
- If fork() must be used, the next rules should be followed:
  - Prepare libibverbs to work with fork():
    - Call the verb ibv_fork_init()

      or

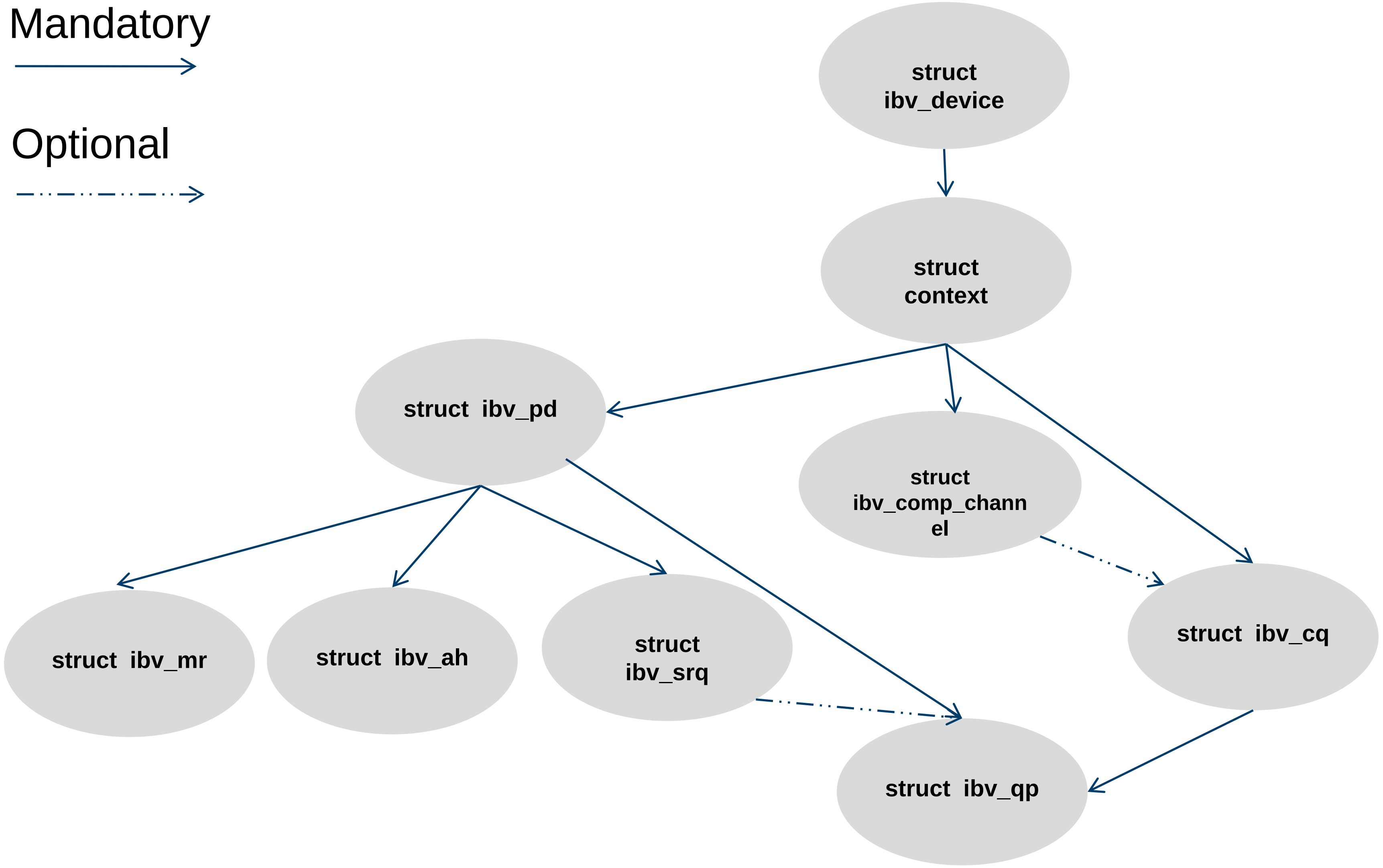
      Setting the environment variables **RDMAV_FORK_SAFE** or **IBV_FORK_SAFE**
    - This will allocate internal structures in way which is more “fork()”-friendly
  - RDMA should be used only in the parent process
  - Child process should call immediately exec*() or exit()
  - If huge pages are used, set the environment variable **RDMAV_HUGEPAGES_SAFE** as well

- Warning: Not following those rules may lead to data corruption or segmentation fault!

General tips on libibverbs

- Source code that uses libibverbs should include the header:
  - #include <infiniband/verbs.h>
- Executables/libraries that work with libibverbs should be linked with:
  - -libverbs
- All input structures should be zeroed
  - Using memset() or structure initialization
  - If the structure will be extended in the future, the value zero will keep the legacy behavior
- Most resource handles are pointers, so using bad handles may cause segmentation fault
- Verbs that return a pointer – return a valid value in case of a success and NULL incase of a failure
- Verbs that return an integer – return zero in case of a success and -1 or errno incase of a failure
  - For more information, read the documentation of each verb

RDMA resource creation hierarchy



Working with RDMA devices

- In every machine, there can be one or more RDMA devices
  - Each RDMA device is a PCI device
  - Multiple devices can be:
    - From the same or different vendors
    - From the same or different models
- One should check which devices are available, and open the requested device(s)
  - Every device has a unique name (at specific point in time) and a node GUID which is unique and persistent
  - GUID should be used to identify the device
- Every RDMA device is independent
  - Every resource exists in the scope of the RDMA device it was created in
  - Resources cannot be shared between different devices

Working with RDMA devices: API

- struct ibv_device **ibv_get_device_list(int *num_devices);
  - Return a NULL-terminated list of RDMA device that exist in the local host
  - num_devices is optional. NULL can be provided instead of a valid pointer.

  - Notice the following fields in struct ibv_device:
    - node_type - The node type of this device (xCA, switch, etc.)
    - transport_type – The transport type used by this device (IB, iWARP, etc.)
- void ibv_free_device_list(struct ibv_device **list);
  - Free the list of RDMA devices that was retuned from ibv_get_device_list()
    - This verb should be called after the required RDMA device was opened
- const char *ibv_get_device_name(struct ibv_device *device);
  - Return a string that describe the name of the RDMA device
- uint64_t ibv_get_device_guid(struct ibv_device *device);
  - Return the GUID of the RDMA device
    - This verb should be used to identify a device since the GUID is both unique and persistent

Working with RDMA devices: API (cont.)

- struct ibv_context *ibv_open_device(struct ibv_device *device);
  - Return a context from an RDMA device
    - This context will be used to create resources in this device

  - Notice the following fields in struct ibv_context:
    - num_comp_vectors – Number of completions vectors that this device supports
    - async_fd – File descriptor that will be used to report about asynchronic events from kernel

- int ibv_close_device(struct ibv_context *context);
  - Close the context of the RDMA device
    - This verb should be called after destroying all the resources that were created using this context
      - Not doing so will cause a memory leak

Working with RDMA devices: example

```
struct ibv_device **device_list;
int                num_devices;
int                i;

device_list = ibv_get_device_list(&num_devices);
if (!device_list) {
  fprintf(stderr, "Error, ibv_get_device_list() failed\n");
  exit(1);
}

for (i = 0; i < num_devices; ++ i)
  printf("RDMA device[%d]: name=%s\n", i, ibv_get_device_name(device_list[i]));

ibv_free_device_list(device_list);
```

Exercise 1:

Write a program that go over all the RDMA devices and print for every device its node type.

Tip: use ibv_node_type_str() to get a string from a node type enumerated value.

Context queries

- Every context supports several queries
  - Queries about the device attributes
  - Queries about a specific port properties
    - Or about tables within a port, such as GID and P_Key tables
- Some attributes are constant
  - Most of the device attributes are constant
- Some attributes are dynamic
  - Most of the port attributes are dynamic (LID, MTU, etc.)

Context queries: API

- int ibv_query_device(struct ibv_context *context, struct ibv_device_attr *device_attr);
  - Query for the device attributes
    - For number of objects, the mentioned values are the higher limit
    - Important properties: supported number of objects, number of physical ports
- int ibv_query_port(struct ibv_context *context, uint8_t port_num, struct ibv_port_attr *port_attr);
  - Query for specific port properties
    - First port number is: 1
    - Important properties: LID, MTU, supported VL, number of P_Keys, number of GIDs
- int ibv_query_pkey(struct ibv_context *context, uint8_t port_num, int index, uint16_t *pkey);
  - Query for the value in a specific index in a port's P_Key table
    - First index is: 0
    - Index 0 contains the default P_Key value (0xffff)
- int ibv_query_gid(struct ibv_context *context, uint8_t port_num, int index, union ibv_gid *gid);
  - Query for the value in a specific index in a port's GID table
    - First index is: 0
    - Index 0 is a special (constant) value – it contains the port GUID

Context queries: example

```
struct ibv_port_attr port_attr;
int port_num = 1;

rc = ibv_query_port(ctx, port_num, &port_attr);
if (rc) {
   fprintf(stderr, "Error, failed to query port %d attributes in device '%s'\n“,
                   port_num, ibv_get_device_name(ctx->device));
   return -1;
}
```

Exercise 2:

Write a program that go over all the RDMA devices and print for every port in each device the GID in entry 0 (i.e. Port GUID)

Protection Domain (PD)

- Protection Domain is a mechanism for associating Queue Pairs with other RDMA resources
  - Such as Memory Regions and Address Handles
- Not all resources have a PD
  - For example: Completion Queues
- Protection Domain as its name state is a mean of protection
  - Mixing resources that were associated with different PDs will result a Work Completion with error

- Every Protection Domain can be imagined as a different color
  - Resources that are associated with a Protection Domain get its color
  - Resources from different colors can’t work together

Protection Domain (PD): API

- struct ibv_pd *ibv_alloc_pd(struct ibv_context *context);
  - Create a Protection Domain
- int ibv_dealloc_pd(struct ibv_pd *pd);
  - Destroy a Protection Domain

  - This verb should be called after destroying all the resources that are associated with it

Protection Domain (PD): example

```
struct ibv_context *context;
struct ibv_pd *pd;

pd = ibv_alloc_pd(context);
if (!pd) {
    fprintf(stderr, "Error, ibv_alloc_pd() failed\n");
   return -1;
}

…

if (ibv_dealloc_pd(pd)) {
   fprintf(stderr, "Error, ibv_dealloc_pd() failed\n");
   return -1;
}
```

Memory Region (MR)

- Memory Region is a virtually contiguous memory block that was registered, i.e. prepared for work with RDMA.
  - Any memory buffer in the process' virtual space can be registered
  - Available permissions. One or more of the following permissions (Or'ed):
    - Local operations (Local Read is always supported)
      - IBV_ACCESS_LOCAL_WRITE
      - IBV_ACCESS_MW_BIND
    - Remote operations
      - IBV_ACCESS_REMOTE_WRITE
      - IBV_ACCESS_REMOTE_READ
      - IBV_ACCESS_REMOTE_ATOMIC
  - If Remote Write or Remote Atomic is enabled, local Write should be enabled too
  - The same memory buffer can be registered multiple times
    - even with different permissions
  - After a successful memory registration, two keys are being generated:
    - Local Key (lkey)
    - Remote Key (rkey)

    Those keys are used when referring to this MR in a Work Request

Memory Region (MR) (cont.)

- Memory pages pinning has advantages
  - Memory pages are always present in RAM
    - Never swapped out
    - Low latency
  - Address translation can be cached
- But Memory pages pinning decreases the available memory for the kernel
  - Only the process that registered it can use this memory
  - This may cause high use of the swap file
  - When too much memory is pinned, the kernel may start killing processes
    - Or machine may work very slow
- Creating the various queues register memory as well..

Memory Region (MR): API

- struct ibv_mr *ibv_reg_mr(struct ibv_pd *pd,
  void *addr, size_t length,
  enum ibv_access_flags access);
  - Register a memory buffer with specific permissions

  - Notice the following fields in struct ibv_mr:
    - lkey - The local key of this MR
    - rkey - The remote key of this MR
    - addr – The start address of the memory buffer that this MR registered
    - length – The size of the memory buffer that was registered

- int ibv_dereg_mr(struct ibv_mr *mr);
  - Deregister a Memory Region

  - This verb should be called if there is no outstanding Send Request or Receive Request that points to it

Memory Region (MR): example

```
struct ibv_pd *pd;
struct ibv_mr *mr;


mr = ibv_reg_mr(pd, buf, buf_size, IBV_ACCESS_LOCAL_WRITE);
if (!mr) {
    fprintf(stderr, "Error, ibv_reg_mr() failed\n");
   return -1;
}

…

if (ibv_dereg_mr(mr)) {
   fprintf(stderr, "Error, ibv_dereg_mr() failed\n");
   return -1;
}
```

Exercise 3:

Write a program that open a device, allocate a PD and register 3 MRs:

1) *One that allow local read*
2) *One that allow local write*
3) *One that allow remote write*

Completion Event Channel

- Completion Event channel is a mechanism for delivering notification about the creation of Work Completions in CQs that is attached to it.
  - Useful to reduce the CPU consumption
- This object will be used when creating new CQs
- One Completion Event channel can be used with multiple CQs

Completion Event channel: API

- struct ibv_comp_channel *ibv_create_comp_channel(struct ibv_context *context);
  - Create a new Completion Event channel

  - Notice the following fields in struct ibv_comp_channel:
    - fd – File descriptor that will be used to report about completion events from kernel

- int ibv_destroy_comp_channel(struct ibv_comp_channel *channel);
  - Destroy a Completion Event channel

  - This verb should be called after destroying all the CQs that are associated with it

Completion Event channel: example

```
struct ibv_context *context;
struct ibv_comp_channel *channel;


channel = ibv_create_comp_channel(context);
if (!channel) {
    fprintf(stderr, "Error, ibv_create_comp_channel() failed\n");
   return -1;
}

…

if (ibv_destroy_comp_channel(channel)) {
   fprintf(stderr, "Error, ibv_destroy_comp_channel() failed\n");
   return -1;
}
```

Completion Queue (CQ)

- Completion Queue is a Queue that holds information about completed Work Requests
  - Every Work Completion contains information about the corresponding completed Work Request
- A Completion Queue size is limited
  - If more Work Completions than its size are added, the CQ is overruled and all associated Work Queues are moved to the Error state
    - It is up to the user to make sure that the CQ size is enough
    - It is up to the user to empty the CQ in order to prevent CQ overrun
- One CQ can be shared with multiple queues
  - Several Queue Paris
  - Only Send Queues
  - Only Receive Queues
  - Mix of the above

Completion Queue (CQ): API

- struct ibv_cq *ibv_create_cq(struct ibv_context *context, int cqe, void *cq_context, struct ibv_comp_channel *channel, int comp_vector);
  - Create a new Completion Queue
  - Notice the following fields in struct ibv_cq:
    - cqe – The actual number of Work Completions that the CQ can hold
    - cq_context – The private context that the CQ is associated with
- int ibv_destroy_cq(struct ibv_cq *cq);
  - Destroy a Completion Queue
  - This verb should be called after destroying all the QPs that are associated with it
- int ibv_resize_cq(struct ibv_cq *cq, int cqe);
  - Resize an existing Completion Queue
  - The new size should be able to contain the Work Completions that currently populate the CQ

Completion Queue (CQ): example

```
struct ibv_context *context;
struct ibv_comp_channel *channel;
struct ibv_cq *cq;


cq = ibv_create_cq(context, cq_size, NULL, channel, 0);
       or
cq = ibv_create_cq(context, cq_size, NULL, NULL, 0);
if (!cq) {
    fprintf(stderr, "Error, ibv_create_cq() failed\n");
   return -1;
}

…

if (ibv_destroy_cq(cq)) {
   fprintf(stderr, "Error, ibv_destroy_cq() failed\n");
   return -1;
}
```

Exercise 4:

Write a program that open a device, create a Completion Event channel and create 2 CQs:

1) *One without any associated Completion Event channel*
2) *One with associated Completion Event channel*

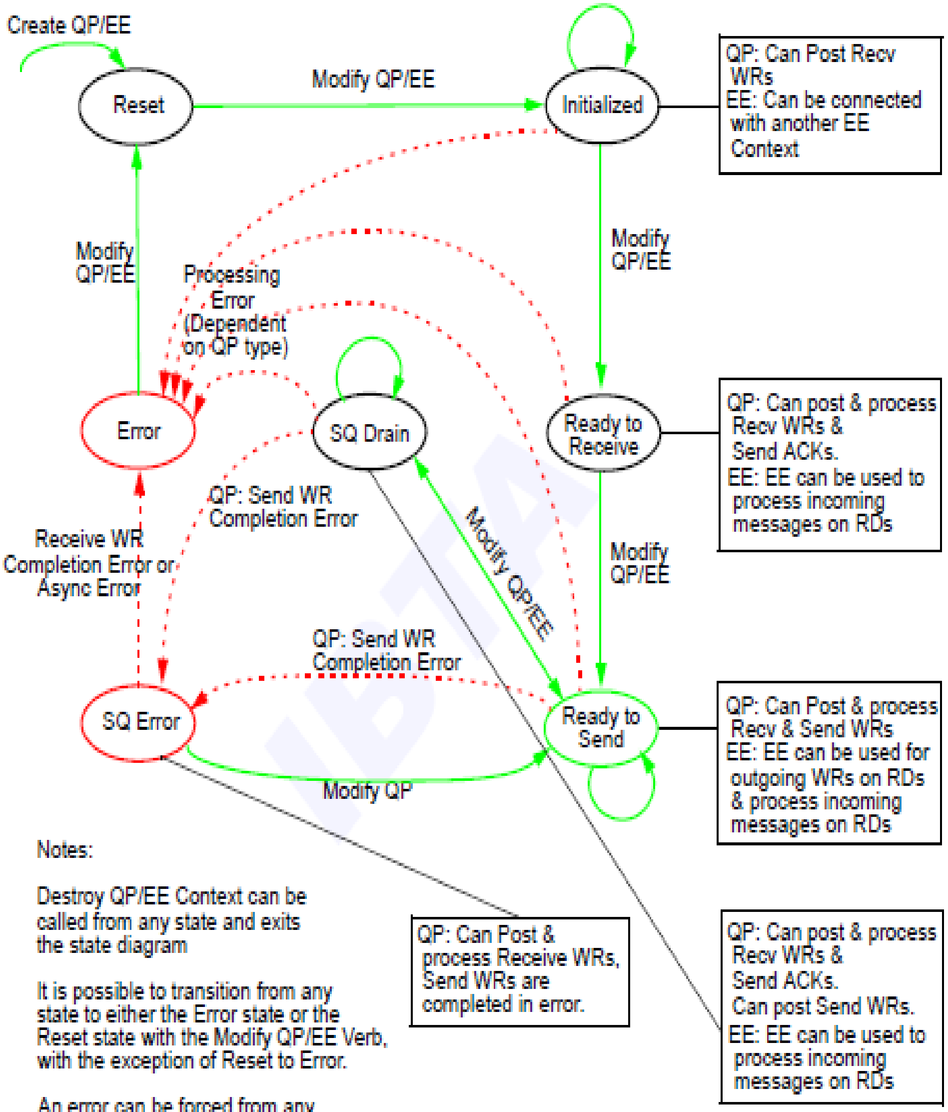
Queue Pair (QP)

- Queue Pair is the actual object that transfers data
  - It encapsulates both Send and Receive Queue
    - Each of them is completely independent
    - Send Queue can generate Work Completion for every Send Request or for specific Send Requests
    - Receive queue generates Work Completion for every completed Receive Request
  - Full duplex
  - A QP represent a real HW resource
- There are three major transport types
  - Reliable Connected (RC)
    - An RC QP is connected to a single RC QP
    - Reliability is guaranteed (ordering, integrity and arrival of all packets)
    - Supports operations that need ACK
  - Unreliable Connected (UC)
    - An UC QP connected to a single UC QP
    - Reliability is not guaranteed
  - Unreliable Datagram (UD)
    - An UD QP can send/receive messages to/from any UD QP
    - Reliability is not guaranteed
    - Multicast is supported
    - Each message is limited to one packet

Queue Pair (QP) (cont.)

Metric	UD	UC	RC
Reliability			☺
Send (with immediate)	☺	☺	☺
RDMA Write (with immediate)		☺	☺
RDMA Read			☺
Atomic operations			☺
Multicast	☺		
Max message size	MTU	2GB	2GB
CRC	☺	☺	☺

QP state machine



QP: Can Post Recv WRs
EE: Can be connected with another EE Context

QP: Can post & process Recv WRs & Send ACKs.
EE: EE can be used to process incoming messages on RDs

QP: Can Post & process Recv & Send WRs
EE: EE can be used for outgoing WRs on RDs & process incoming messages on RDs

QP: Can Post & process Receive WRs, Send WRs are completed in error.

QP: Can post & process Recv WRs & Send ACKs. Can post Send WRs.
EE: EE can be used to process incoming messages on RDs

Notes:

Destroy QP/EE Context can be called from any state and exits the state diagram

It is possible to transition from any state to either the Error state or the Reset state with the Modify QP/EE Verb, with the exception of Reset to Error.

An error can be forced from any state, except Reset, with the Modify QP/EE Verb.

QP state machine (cont.)

	Reset	Init	RTR	RTS	SQD	SQE	Error
Post RR	Disallowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed
Post SR	Disallowed	Disallowed	Disallowed	Allowed	Allowed	Allowed	Allowed
RR processing	Not processed	Not processed	Processed	Processed	Processed	Processed	Flushed with error
SR processing	Not processed	Not processed	Not processed	Processed	New WRs aren’t processed	Flushed with error	Flushed with error
Incoming packets	Silently dropped	Silently dropped	Handled	Handled	Handled	Handled	Silently dropped
Outgoing packets	None	None	None	Initiated	Initiated	None	None

Connecting QPs

- Communication should be established between the connected QPs
  - Each side needs to know who is the other side
  - Each side needs to have information about the other side and the path to it
  - Each side needs to configure attributes that describe the send attributes

- Problem: How to connect QP X with QP Y?
  - We cannot transfer the needed information to establish the connection until the connection has already been established between them …

- Solutions:

1. Exchange information Out Of Band
   - For example: over sockets
2. Use Communication Manager (CM) ← **this is the right way to connect QPs**

Connecting QPs (cont.)

- The following information needs to be exchanged when connecting QPs
  - QP number
  - LID number
  - RQ Packet Serial Number (PSN)
  - GID (if GRH is used)

- Path MTU must be equal on both sides
- If RDMA opcodes are used, the permissions of QP and MR should be configured to support them

- In each QP state transition, the relevant attributes to enable the state functionality needs to be configured
  - There are different attributes for every transport type
    - For RC QPs: retransmission count and timers
    - For RC/UC QPs: Primary path and alternate path (optional)

Queue Pair (QP): API

- struct ibv_qp *ibv_create_qp(struct ibv_pd *pd,
  struct ibv_qp_init_attr *qp_init_attr);
  - Create a new Queue Pair

  - Notice the following fields in struct ibv_qp:
    - qp_num – The physical QP number
    - qp_context – The private context that the QP is associated with

- int ibv_destroy_qp(struct ibv_qp *qp);
  - Destroy a Queue Pair

  - This verb should be called after detach is from all multicast groups
- int ibv_modify_qp(struct ibv_qp *qp, struct ibv_qp_attr *attr,
  enum ibv_qp_attr_mask attr_mask);
  - Modify the QP attributes

- int ibv_query_qp(struct ibv_qp *qp, struct ibv_qp_attr *attr,
  enum ibv_qp_attr_mask attr_mask,
  struct ibv_qp_init_attr *init_attr);

  - Query the attributes of a QP

Queue Pair (QP): API (cont.)

```
struct ibv_qp_cap {
   uint32_t max_send_wr;     - The number of Send Requests that can be outstanding in the QP
   uint32_t max_recv_wr;     - The number of Receive Requests that can be outstanding in the QP
   uint32_t max_send_sge;    - The number of S/G entries that each Send Request may hold
   uint32_t max_recv_sge;    - The number of S/G entries that each Receive Request may hold
   uint32_t max_inline_data; - The requested inline data (in bytes) to be sent
};

struct ibv_qp_init_attr {
   void *qp_context;              - A private context that the QP will be associated with
   struct ibv_cq *send_cq;        - The CQ to be associated with the QP’s Send Queue
   struct ibv_cq *recv_cq;        - The CQ to be associated with the QP’s Receive Queue
   struct ibv_srq *srq;           - Optional: if not NULL,  the SRQ to be associated with
   struct ibv_qp_cap cap;         - The QP attributes to be created
   enum ibv_qp_type qp_type; - The QP transport type
   int sq_sig_all;                - Indication if every completed Send Request will generate a Work
   Completion
};
```

Queue Pair (QP): example

```
struct ibv_pd *pd;
struct ibv_cq *cq;
struct ibv_qp *qp;
struct ibv_qp_init_attr init_attr = {
     send_cq = cq,
    .recv_cq = cq,
    .cap = {
                            .max_send_wr = 1,
                            .max_recv_wr = rx_depth,
                             .max_send_sge = 1,
                             .max_recv_sge = 1
     },
      .qp_type = IBV_QPT_RC
 };

qp = ibv_create_qp(pd, &init_attr);
if (!qp) {
      fprintf(stderr, "Error, ibv_create_qp() failed\n");
     return -1;
}

…

if (ibv_destroy_qp(qp)) {
     fprintf(stderr, "Error, ibv_destroy_qp() failed\n");
     return -1;
}
```

Data Transfer verbs

Scatter/Gather (S/G) elements

- Every Work Request contains usually one or more S/G entries
  - Every S/G entry refers to a Memory Region or part of it
  - No S/G entries means zero-byte message
  - Gather – when local data is read and sent over the wire
  - Scatter – when data is received and written locally

```
struct ibv_sge {
   uint64_t addr;                 - Start address of the memory buffer (usually registered memory)
   uint32_t length;               - Size (in bytes) of the memory buffer
   uint32_t lkey;                              - lkey of Memory Region that is associated with this
   memory buffer
};
```

- Warning: The value zero in ‘length’ is special – it means 2 GB

Post Send Request

- Add a Send Request to the Send Queue
  - No context switch will occur
  - The HW will process it according to its scheduling algorithm
- Specify the attributes of the data transfer
  - How data will be sent (opcode, attributes)
  - How much data will be sent
  - Which local memory buffer(s) to read/write to
    - Depends on the opcode
  - If RDMA: the remote memory buffer attributes
  - If atomic: the remote memory buffer attributes and needed operands
  - If UD QP: information on how to reach to remote side
- Every Send Request is considered outstanding until a work Completion was generated for it or for other Send Request that followed it
  - While a Send Request is outstanding, the resources that this Send Request use must not be destroyed/(re)used
    - The content of memory buffers that their content will be filled is undefined
    - The memory buffers that their content is sent must be available
    - For UD QPs: Address Handles must be available

Post Send Request: API

- int ibv_post_send(struct ibv_qp *qp, struct ibv_send_wr *wr, struct ibv_send_wr **bad_wr);
  - Add a linked list of Send Requests to the Send Queue
  - Warning: bad_wr is mandatory; It will be assigned with the address of the Send Request that its posting failed

struct ibv_send_wr {
uint64_t wr_id; - Private context that will be available in the corresponding Work Completion
struct ibv_send_wr *next; - Address of the next Send Request. Should be NULL in the last Send Request
struct ibv_sge *sg_list; - Array of scatter/gather elements
int num_sge; - Number of elements in sg_list
enum ibv_wr_opcode opcode; - The opcode to be used
int send_flags; - Send flags. Or of the following flags:
IBV_SEND_FENCE – Prevent process this Send Request until the processing of previous RDMA Read and Atomic operations were completed.
IBV_SEND_SIGNALED – Generate a Work Completion after processing of this Send Request ends
IBV_SEND_SOLICITED – Generate Solicited event for this message in remote side
IBV_SEND_INLINE - allow the low-level driver to read the gather buffers

uint32_t imm_data; - Send message with immediate data (for supported opcodes); extra 32 bits, in network order, that will be available in remote's Work Completion

Post Send Request: API (cont.)

```
  union {
          struct {                                - Attributes for RDMA Read and write opcodes
                      uint64_t remote_addr;       - Remote start address (the message size is according to the S/G entries)
                      uint32_t rkey;              - rkey of Memory Region that is associated with remote memory buffer
          } rdma;
          struct {                                - Attributes for Atomic opcodes
                      uint64_t remote_addr;       - Remote start address (the message size is according to the S/G entries)
                      uint64_t compare_add;       - Value to compare/add (depends on opcode)
                      uint64_t swap;              - Value to swap if the comparison passed
                      uint32_t rkey;              - rkey of Memory Region that is associated with remote memory buffer
          } atomic;
          struct {                                - Attributes for UD QP
                      struct ibv_ah *ah;          - Address Handle to get to remote side
                      uint32_t remote_qpn;        - Remote QP number (of 0xffffff for multicast message)
                      uint32_t remote_qkey;       - Remote Q_Key value
          } ud;
  } wr;
};
```

Post Send Request: example (for RC/UC QPs)

```
struct ibv_qp *qp;

struct ibv_sge sg_list = {
   .addr    = (uintptr_t)buf,
   .length = buf_size,
   .lkey     = mr->lkey
};
struct ibv_send_wr wr = {
    .next         = NULL,
   .sg_list       = &sg_list,
   .num_sge  = 1,
   .opcode     = IBV_WR_SEND
};
struct ibv_send_wr *bad_wr;

If (ibv_post_send(qp, &wr, &bad_wr)) {
    fprintf(stderr, "Error, ibv_post_send() failed\n");
   return -1;
}
```

Post Receive Request

- Add a Receive Request to the Receive Queue
  - No context switch will occur
  - The HW will process it according to its scheduling algorithm
- Specify where incoming message that needs Receive Request will be saved
  - The local memory buffer(s) to write to
  - Each incoming message will consume one Receive Request
  - The S/G list must be able to hold the incoming message
  - If the message was received on a UD QP
    - Extra 40 bytes should be added to the scatter list (for the Global Routing Header (GRH))
    - The message data will start at offset 40
- Every Receive Request is considered outstanding until a work Completion was generated to it
  - While a Receive Request is outstanding, the resources that this Receive Request use mustn't be destroyed/(re)used
    - The content of memory buffers that their content will be filled is undefined

Post Receive Request: API

- int ibv_post_recv(struct ibv_qp *qp, struct ibv_recv_wr *wr,
  struct ibv_recv_wr **bad_wr);
  - Add a linked list of Receive Requests to the Receive Queue
  - Warning: bad_wr is mandatory; It will be assigned with the address of the Receive Request that its posting failed

struct ibv_recv_wr {

uint64_t wr_id; - Private context that will be available in the corresponding Work Completion

struct ibv_recv_wr *next; - Address of the next Receive Request. Should be NULL in the last Receive Request

struct ibv_sge *sg_list; - Array of scatter elements

int num_sge; - Number of elements in sg_list

};

Post Receive Request: example

```
struct ibv_qp *qp;

struct ibv_sge sg_list = {
   .addr    = (uintptr_t)buf,
   .length = buf_size,
   .lkey     = mr->lkey
};
struct ibv_recv_wr wr = {
    .next         = NULL,
   .sg_list       = &sg_list,
   .num_sge  = 1
};
struct ibv_recv_wr *bad_wr;

If (ibv_post_recv(qp, &wr, &bad_wr)) {
    fprintf(stderr, "Error, ibv_post_recv() failed\n");
   return -1;
}
```

Polling for Work Completion

- Polling for Work Completion checks if the processing of a Work Request has ended
- A Work Completion holds information about a completed Work Request
  - Every Work Completion contains information about the corresponding completed Work Request
- Every Work Completion contain several attributes
  - The following fields are always valid (even if the Work Completion was ended with error)
    - *wr_id*
    - *status*
    - *qp_num*
    - *vendor_err*
  - The rest of the fields depend on the QP's transport type, opcode and status
- Work Completion of Send Requests:
  - Mark that a Send Request was performed and its memory buffers can be (re)used
    - For reliable transport QP: this means that the message was written in the buffers (if status is successful)
    - For unreliable transport QP: this means that the message was sent from the local port
- Work Completion of Receive Requests:
  - Mark that an incoming message was completed and its memory buffers can be (re)used
  - Contains some attributes about the incoming message, such as size, origin, etc.

Polling for Work Completion: API

- int ibv_poll_cq(struct ibv_cq *cq, int num_entries, struct ibv_wc *wc);
  - Read one or more Work Completions from a CQ and remove them from the CQ

  - If the return value is non-negative – this is the number of polled Work Completions
  - If the return value is negative – error occurred

```
struct ibv_wc {
    uint64_t wr_id;                  - Private context that was posted in the corresponding Work Request
    enum ibv_wc_status status;       - The status of the Work Completion
    enum ibv_wc_opcode opcode;       - The opcode of the Work Completion
    uint32_t vendor_err;             - Vendor specific error syndrome
    uint32_t byte_len;               - Number of bytes that were received
    uint32_t imm_data;               - Immediate data, in network order, if the flags indicate that such exists
    uint32_t qp_num;                 - The local QP number that this Work Completion ended in
    uint32_t src_qp;                 - The remote QP number
    int wc_flags;                    - Work Completion flags. Or of the following flags:
                          IBV_WC_GRH – Indicator that the first 40 bytes of the receive buffer(s) contain a valid
    GRH
                          IBV_WC_WITH_IMM – Indicator that the received message contains immediate data
    uint16_t pkey_index;
    uint16_t slid;                   - For UD QP: the source LID
    uint8_t sl;                      - For UD QP: the source Service Level
    uint8_t dlid_path_bits;          - For UD QP: the destination LID path bits
};
```

Polling for Work Completion: API (cont.)

- Typical Work Completion status:
  - IBV_WC_SUCCESS – Operation completed successfully
  - IBV_WC_LOC_LEN_ERR – Local length error when processing SR or RR
  - IBV_WC_LOC_PROT_ERR – Local Protection error; S/G entries doesn’t point to a valid MR
  - IBV_WC_WR_FLUSH_ERR – Work Request flush error; it was processed when the QP was in Error state
  - IBV_WC_RETRY_EXC_ERR – Retry exceeded; the remote QP didn’t send any ACK/NACK, even after message retransmission
  - IBV_WC_RNR_RETRY_EXC_ERR – Receiver Not Ready; a message that requires a Receive Request was sent, but isn’t any RR in the remote QP, even after message retransmission

Polling for Work Completion: example

```
struct ibv_cq *cq;
struct ibv_wc wc;
int num_comp;

do {
   num_comp = ibv_poll_cq(cq, 1, &wc);
} while (num_comp == 0);

if (num_comp < 0) {
   fprintf(stderr, "ibv_poll_cq() failed\n");
   return -1;
}

if (wc.status != IBV_WC_SUCCESS) {
   fprintf(stderr, "Failed status %s (%d) for wr_id %d\n", ibv_wc_status_str(wc.status),
   wc.status, (int)wc.wr_id);
   return -1;
}
```

Full data flow

<u>Requester</u>

Open device
Allocate PD
Register MR
Create CQ
Create QP
Connect QPs

Post SR
Poll CQ
Check completion status

CM

<u>Responder</u>

Open device
Allocate PD
Register MR
Create CQ
Create QP
Connect QPs + post RR

Post Send Request
Poll CQ
Check completion status

Exercise 5:

Write a program that will open all the needed resources and transfer data for RC QP for every Send opcode.

Optional:

1. *Extend it to support RDMA Write operation.*
2. *Change the QP transport type to UC.*

Additional Control Operations

Asynchronous events

- Asynchronous event is a mechanism to report about an event that occurred to a specific process’ resource (CQ, QP, SRQ) or for global resource (port, device)
  - Sometimes there is no other way to update about this scenario
- It is advised to create a dedicated threat that will handle the asynchronous events

Asynchronous events: API

- int ibv_get_async_event(struct ibv_context *context,
  struct ibv_async_event *event);
  - Read an asynchronous event for this context
  - Default behavior: Blocking. Can be changed to be non-blocking
- void ibv_ack_async_event(struct ibv_async_event *event);
  - Acknowledge an incoming asynchronous event
  - Every asynchronous event must be acknowledged. Not doing this may cause destruction of RDMA resources to be blocked forever.

```
struct ibv_async_event {
   union {                                        - The element that got the asynchronous event;
   depends on the event type
            struct ibv_cq *cq;
             struct ibv_qp *qp;
             struct ibv_srq *srq;
             int port_num;
    } element;
   enum ibv_event_type event_type;     - The asynchronous event type
};
```

Asynchronous events: API (cont.)

- CQ events
  - IBV_EVENT_CQ_ERR – Error occurred to the CQ

- QP events
  - IBV_EVENT_COMM_EST – incoming message received while the QP in RTR state
  - IBV_EVENT_SQ_DRAINED – The processing of all Send Requests was ended
  - IBV_EVENT_PATH_MIG – The alternative path of the QP was loaded (for connected QPs)
  - IBV_EVENT_QP_LAST_WQE_REACHED – Receive Request won't be read from SRQ anymore
  - IBV_EVENT_QP_FATAL - Error occurred to the CQ
  - IBV_EVENT_QP_REQ_ERR – Transport errors detected in responder side
  - IBV_EVENT_QP_ACCESS_ERR – Violation detected in responder side
  - IBV_EVENT_PATH_MIG_ERR – Failed to load the alternative path of the QP (for connected QPs)

- SRQ events
  - IBV_EVENT_SRQ_LIMIT_REACHED – SRQ limit was reached
  - IBV_EVENT_SRQ_ERR – Error occurred to the SRQ

Asynchronous events: API (cont.)

- Port events
  - IBV_EVENT_PORT_ACTIVE – Port’s logical state become active
  - IBV_EVENT_LID_CHANGE – Port’s LID changed
  - IBV_EVENT_PKEY_CHANGE – Port’s P_Key table was changed
  - IBV_EVENT_GID_CHANGE - Port’s GID table was changed
  - IBV_EVENT_SM_CHANGE – New SM started to manage the subnet
  - IBV_EVENT_CLIENT_REREGISTER - New SM started to manage the subnet
  - IBV_EVENT_PORT_ERR – Port’s logical state is not active anymore

- Device events
  - IBV_EVENT_DEVICE_FATAL – Something really bad happened to the device

Asynchronous events: example

```
struct ibv_context *context;
struct ibv_async_event event;

if (ibv_get_async_event(context, &event)) {
    fprintf(stderr, "Error, ibv_get_async_event() failed\n");
   return -1;
}

…

ibv_ack_async_event(&event);
```

Exercise 6:

Write a program that open a device, and listen for asynchronous events in a loop and print them.

Completion Events

- Working with completion events help reducing the CPU usage
- Once the application requests to get a notification on a specific CQ, it can be block until the next Work Completion be enqueued to this CQ

- The following pseudo-code example demonstrates one possible way to work with completion events. It performs the following steps:

- Stage I: Preparation
  1. Creates a CQ
  2. Request for notification upon a new (first) completion event
- Stage II: Completion Handling Routine
  3. Wait for the completion event and ack it
  4. Request for notification upon the next completion event
  5. Empty the CQ

- Note that an extra event may be triggered without having a corresponding completion entry in the CQ. This occurs if a completion entry is added to the CQ between Step 4 and Step 5, and the CQ is then emptied (polled) in Step 5.

Completion Events: API

- int ibv_req_notify_cq(struct ibv_cq *cq, int solicited_only);
  - Request for a notification about the next Work Completion to be added to the Completion Queue event for this context
  - Request for any Work Completion or only for Work Completion of completed Receive Requests that their requester send them with the solicited event indicator on
- int ibv_get_cq_event(struct ibv_comp_channel *channel,
  struct ibv_cq **cq, void **cq_context);
  - Read a Completion event
  - Default behavior: Blocking. Can be changed to be non-blocking
- void ibv_ack_cq_events(struct ibv_cq *cq, unsigned int nevents);
  - Acknowledge Completion event(s)
  - Multiple completion events can be acknowledge in one time

Completion Events: example

```
struct ibv_cq *cq, *en_cq;
ibv_comp_channel *channel;
void *ev_ctx;

if (ibv_req_notify_cq(cq, 0)) {
     fprintf(stderr, "Error, ibv_req_notify_cq() failed\n");
    return -1;
}
 . . .
if (ibv_get_cq_event(channel, &ev_cq, &ev_ctx)) {
     fprintf(stderr, "Error, ibv_get_cq_event() failed\n");
    return -1;
}

ibv_ack_cq_events(ev_cq, 1);

if (ibv_req_notify_cq(ev_cq, 0)) {
     fprintf(stderr, "Error, ibv_req_notify_cq() failed\n");
    return -1;
}
TODO - Need to empty the CQ here …
```

Shared Receive Queue (SRQ)

- Shared Receive Queue is an object that provides better scalability
  - One Receive Queue to multiple QPs
    - When there is a need for a Receive Request, it is being fetched, in atomic way, from the SRQ
  - If there are N QPs, each of them may get M incoming messages at any random time
    - Without SRQ: there is a need to post N * M RRs
    - With SRQ: we can post K * M RRs (where K << N)
- SRQ provides mechanism for the application to be notified when a number of RRs is dropped bellow a limit
  - Using the SRQ limit event
- RRs will be posted to the SRQ
  - And not to the QP

Shared Receive Queue (SRQ): API

- struct ibv_srq *ibv_create_srq(struct ibv_pd *pd,
  struct ibv_srq_init_attr *srq_init_attr);
  - Create a new Shared Receive Queue
- int ibv_destroy_srq(struct ibv_srq *srq);
  - Destroy a Shared Receive Queue
  - This verb should be called after destroying all the QPs that are associated with it
- int ibv_modify_srq(struct ibv_srq *srq,
  struct ibv_srq_attr *srq_attr,
  enum ibv_srq_attr_mask srq_attr_mask);
  - Resize or modify the Shared Receive Queue attributes
- int ibv_query_srq(struct ibv_srq *srq, struct ibv_srq_attr *srq_attr);
  - Query the attributes of a Shared Receive Queue
  - The limit value may change
- int ibv_post_srq_recv(struct ibv_srq *srq, struct ibv_recv_wr *recv_wr,
  struct ibv_recv_wr **bad_recv_wr);
  - Add a linked list of Receive Requests to a Shared Receive Queue

Shared Receive Queue (SRQ): API (cont.)

```
struct ibv_srq_attr {
   uint32_t max_wr;            - The number of Receive Requests that can be outstanding in the SRQ
   uint32_t max_sge;           - The number of scatter entries that each Receive Request may hold
   uint32_t srq_limit;         - The SRQ watermark value (only relevant in modify_srq)
};

struct ibv_srq_init_attr {
   void *srq_context;            - A private context that the SRQ will be associated with
   struct ibv_srq_attr attr;     - The SRQ attributes to be created
};
```

Shared Receive Queue (SRQ): example

```
struct ibv_pd *pd;
struct ibv_srq *srq;
struct ibv_srq_init_attr attr = {
   .attr = {
                 .max_wr = rx_depth,
                 .max_sge = 1
    }
};

srq = ibv_create_srq(pd, &attr);
if (!srq) {
    fprintf(stderr, "Error, ibv_create_srq() failed\n");
   return -1;
}

…

if (ibv_destroy_srq(srq)) {
   fprintf(stderr, "Error, ibv_destroy_srq() failed\n");
   return -1;
}
```

Shared Receive Queue (SRQ): example2

```
struct ibv_srq *srq;
struct ibv_srq_attr srq_attr;

memset(&srq_attr, 0, sizeof(srq_attr));

srq_attr.srq_limit = 10;

if (ibv_modify_srq(srq, &srq_attr, IBV_SRQ_LIMIT)) {
   fprintf(stderr, "Error, ibv_modify_srq() failed when arming an SRQ\n");
   return -1;
}
```

Exercise 7:

Use the program from exercise 5 and add an SRQ support.

Tips:

- *Add the SRQ handle when creating the QP*
- *Post the RR to the SRQ and not to the QP*

Address Handle (AH)

- Every UD QP can send message to any other UD QP
- Address Handle describes the path from local to remote ports
  - Same AH can be used by multiple QPs
- The Address Handle will be used when posting a Send Request to an UD QP

Address Handle (AH): API

- struct ibv_ah *ibv_create_ah(struct ibv_pd *pd, struct ibv_ah_attr *attr);
  - Create a new Address Handle
- int ibv_init_ah_from_wc(struct ibv_context *context, uint8_t port_num,
  struct ibv_wc *wc, struct ibv_grh *grh,
  struct ibv_ah_attr *ah_attr);

  - Initialize an ibv_ah_attr structure according to a Work Completion and a GRH buffer
- struct ibv_ah *ibv_create_ah_from_wc(struct ibv_pd *pd, struct ibv_wc *wc,
  struct ibv_grh *grh, uint8_t port_num);
  - Create an Address Handle according to a Work Completion and a GRH buffer
- int ibv_destroy_ah(struct ibv_ah *ah);
  - Destroy an Address Handle

  - This verb should be called if there isn't any outstanding Send Request that points to it

Address Handle (AH): API (cont.)

```
struct ibv_global_route {
   union ibv_gid dgid;               - Destination GID address
   uint32_t flow_label;              - Flow label which is a hint for switches and routers which path to
   take
   uint8_t sgid_index;               - The index in the port’s GID table of the source GID
   uint8_t hop_limit;                - The number of hops to take before dropping the message
   uint8_t traffic_class;            - Traffic class of the message (priority)
};

struct ibv_ah_attr {
   struct ibv_global_route grh;   -  Description of the Global Routing Header
   uint16_t dlid;                    - The Destination LID (can be unicast or multicast)
   uint8_t sl;                       - The Service Level value of the message
   uint8_t src_path_bits;            - The source path bits used when the port has a range of LIDs
   uint8_t static_rate;              - The static rate between local and remote port speeds
   uint8_t is_global;                - Indication that the message will be sent with GRH
   uint8_t port_num;                 - The local port number to send the message from
};
```

Address Handle (AH): example

```
struct ibv_pd *pd;
struct ibv_ah *ah;
struct ibv_ah_attr ah_attr = {
    .is_global = 0,
    .dlid = dlid,
    .sl = sl,
    .src_path_bits = 0,
    .port_num = port
};

ah = ibv_create_ah(pd, &ah_attr);
if (!ah) {
    fprintf(stderr, "Error, ibv_create_ah() failed\n");
    return -1;
}
…

if (ibv_destroy_ah(ah)) {
    fprintf(stderr, "Error, ibv_destroy_ah() failed\n");
    return -1;
}
```

Exercise 8:

Use the program from exercise 5 and add an UD support.

Tips:

- *AH should be used when posting in the SR*
- *Remote side attributes should be added to the SR as well*
- *The data in the receive buffer starts at address 40*

Tips and Tricks

Performance tips

- General tips
  - Avoid using control operations in data path
    - They will perform context switch
    - They may allocate/free dynamic resources
  - Set affinity for process/task
  - Work with local NUMA node
  - Use MTU which provide best performance
  - Register physical contiguous memory
  - UD is more scalable than RC

- Posting
  - Post multiple Work Request in one call
  - Avoid using many scatter/gather elements
  - Atomic operations are performance killers
  - Work with big messages
  - Use selective signaling to reduce number of Work Completions
  - Inline data will provide better latency

- Polling
  - Read multiple Work Completion in one call
  - Use polling to get low latency and Completion events to get lower CPU usage
  - When working with events: acknowledge multiple events at once

When packets are “lost” – check the counters

- /sys/class/infiniband/<device name>/diag_counters

- rq_num_lle - Responder - number of local length errors
- rq_num_lqpoe - Responder - number local QP operation error
- rq_num_leeoe - Responder - number local EE operation error
- rq_num_lpe - Responder - number of local protection errors
- rq_num_wrfe - Responder - number of WR flushed errors
- rq_num_lae - Responder - number of local access errors
- rq_num_rire - Responder - number of remote invalid request errors
- rq_num_rae - Responder - number of remote access errors
- rq_num_roe - Responder - number of remote operation errors
- rq_num_rnr - Responder - number of RNR Naks sends
- rq_num_oos - Responder - number of out of sequence requests received
- rq_num_dup - Responder - number of duplicate requests received
- rq_num_rirdre - Responder - number of remote invalid RD request errors
- rq_num_mce - Responder - number of bad multicast packets received
- rq_num_rsync - Responder - number of RESYNC operations
- num_cqovf - Number of CQ overflows
- num_eqovf - Number of EQ overflows

When packets are “lost” – check the counters (cont.)

- sq_num_lle - Requester - number of local length errors
- sq_num_lqpoe - Requester - number local QP operation error
- sq_num_leeoe - Requester - number local EE operation error
- sq_num_lpe - Requester - number of local protection errors
- sq_num_wrfe - Requester - number of WR flushed errors
- sq_num_mwbe - Requester - number of memory window bind errors
- sq_num_bre - Requester - number of bad response errors
- sq_num_rire - Requester - number of remote invalid request errors
- sq_num_rae - Requester - number of remote access errors
- sq_num_roe - Requester - number of remote operation errors
- sq_num_rnr - Responder - number of RNR Naks received
- sq_num_oos - Requester - number of out of sequence Naks received
- sq_num_to - Requester - number of time out received
- sq_num_tree - Requester - number of transport retries exceeded errors
- sq_num_rree - Requester - number of RNR Nak retries exceeded errors
- sq_num_lrdve - Requester - number of local RDD violation errors
- sq_num_rabrte - Requester - number of remote aborted errors
- sq_num_ieecne - Requester - number of invalid EE context number errors
- sq_num_ieecse - Requester - invalid EE context state errors
- sq_num_rsync - Requester - number of RESYNC operations

More Information is Available

- InfiniBand specifications
- RDMAmojo (my blog) ☺
- The document “RDMA Aware Networks Programming User Manual”
- The man pages
- Code samples that comes with libibverbs and librdmacm

Advanced Features and Enhancements

eXtended Reliable Connection (XRC)

- Each two nodes can use the same XRC QP
  - No matter how many cores they have
- Provide reliable transport type
  - Like RC
- Increase the scalability
  - Reduce the number of QPs between each two nodes
  - Reduce the memory usage

Dynamically Connected Transport (DCT)

- Allow dynamically (re)connect QPs when needed
- Provide reliable transport type
  - Like RC
- Provide very high scalability
  - Reduce the number of opened QPs in each node
    - One QP per core
  - Reduce the memory usage

GPUDirect RDMA

- Allow registration of GPU memory
- Data can be send and received using RDMA devices directly to the GPU memory
  - Avoiding unnecessary memory copy
- Working with NVIDIA’s CUDA toolkit

CORE-direct (Collective Offload Resource Engine)

- Provide offload for collective operations
  - Perform collective operations in wire speed
  - Floating point operation
  - Support blocking and non-blocking operations
- Increase the scalability
- Decrease the CPU usage

Thank You

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