Implementing SMB Direct for Linux SMB Client

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Agenda

- Introduce to SMB Direct and RDMA
- Implement SMB Direct
  - RDMA send/receive
  - RDMA read/write through memory registration
- Profiling and optimization
- Some benchmark data

Linux SMB kernel Client

CIFS.KO

/lib/moduels/`uname –r`/kernel/fs/cifs/cifs.ko

mount –t cifs

SMB Direct

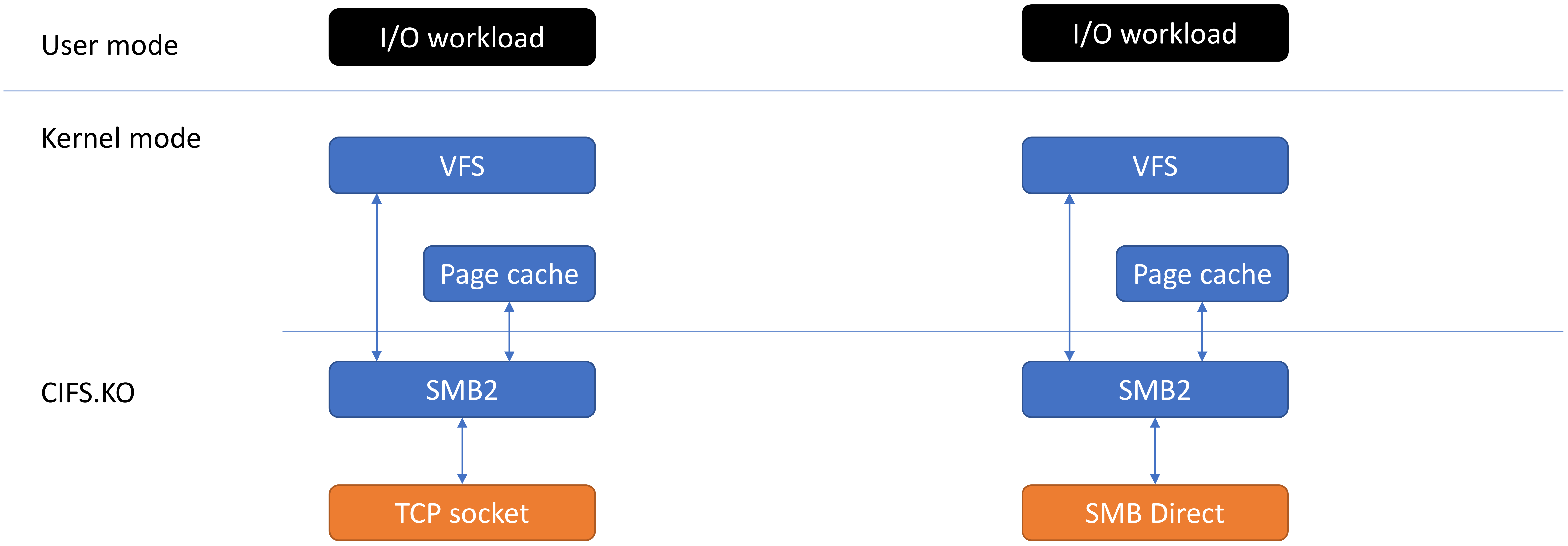
- Transferring SMB packets over RDMA
  - Infiniband
  - RoCE (RDMA over Converged Ethernet)
  - iWARP (IETF RDMA over TCP)
- Introduced in SMB 3.0 with Windows 2012

		New features
Windows Server 2012	SMB 3.0	SMB Direct
Windows Server 2012 R2	SMB 3.02	Remote invalidation
Windows Server 2016	SMB 3.1.1	

RDMA programming interface

- In kernel programming interface
  - drivers/infiniband/core
  - Verbs: ib_core
  - Connection Management: rdma_cm
- Works on all RDMA transport
  - Infiniband
  - RoCE
  - iWARP
- Avoid using verbs that are specific to Infiniband

SMB Direct as a transport



Transfer data with SMB Direct

- RDMA send and receive
  - Similar to TCP socket interface, but with no data copy in most cases
- RDMA read and write
  - Overlap local CPU and communication
  - Reduce CPU overhead on send sider
- Connection based
  - One RC (Reliable Connection) Queue Pair per connection
  - Completion Queue is used to signaling I/O complete

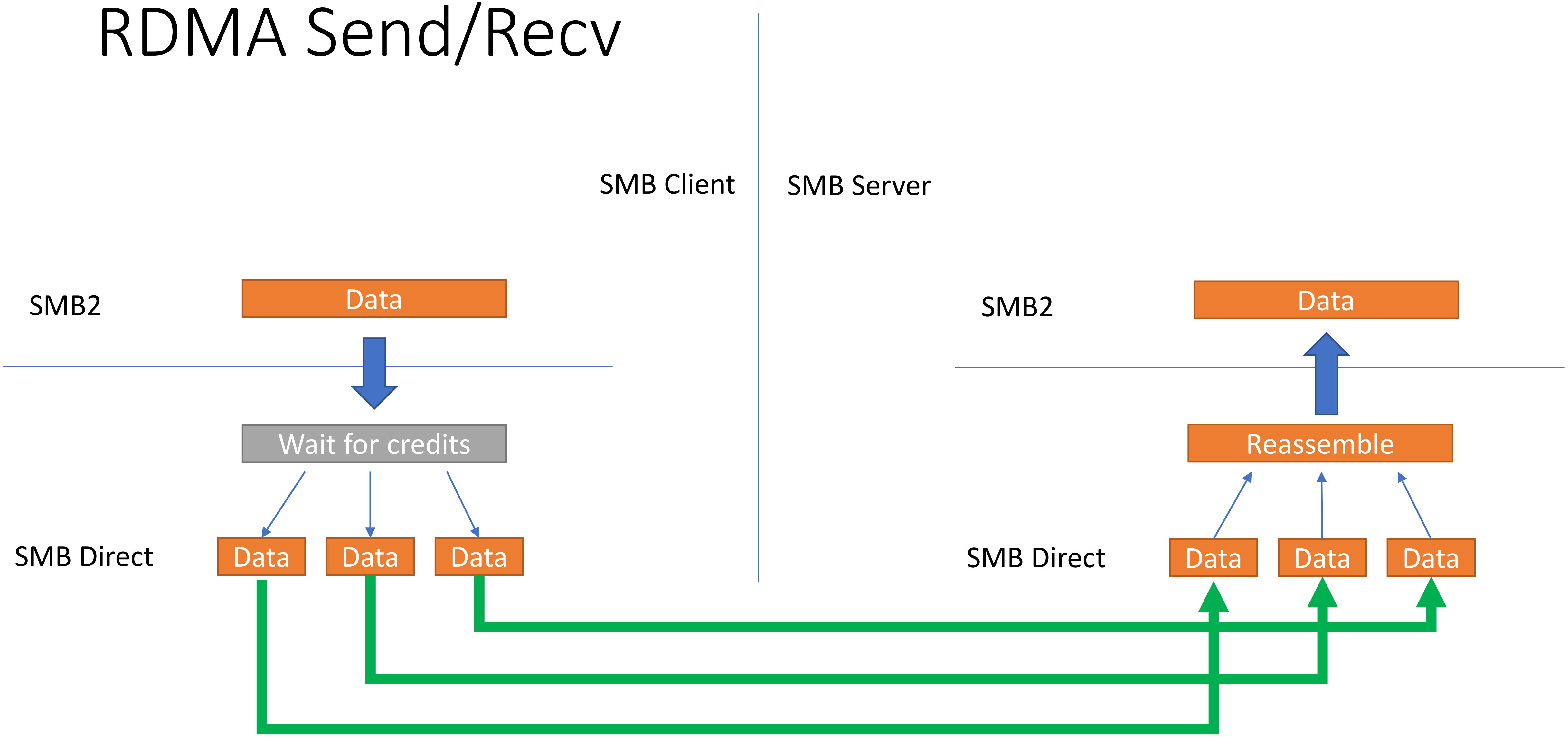
RDMA Send/Recv vs TCP

- Stream vs datagram
- Both have the option of establishing reliable connection
  - SMB Direct connection is a reliable connection
  - Port 445 for Infiniband and RoCE environments
  - Port 5445 for iWARP environments
- TCP works with stream
  - Send whatever you want and receive the way you want it
- RDMA works with datagram
  - Application figures out how to send them
  - May need to do segmentation on send
  - Reassemble data payloads on receive

RDMA Send/Recv vs TCP

- Memory management
- TCP socket
  - TCP maintains send and receive buffers and communicate with peer on flow control
- RDMA
  - Application manages its own buffers
    - Send -> no receive?
  - Application needs to do flow control
    - SMB Direct uses a credit system
    - No send-credits? Can’t send data.

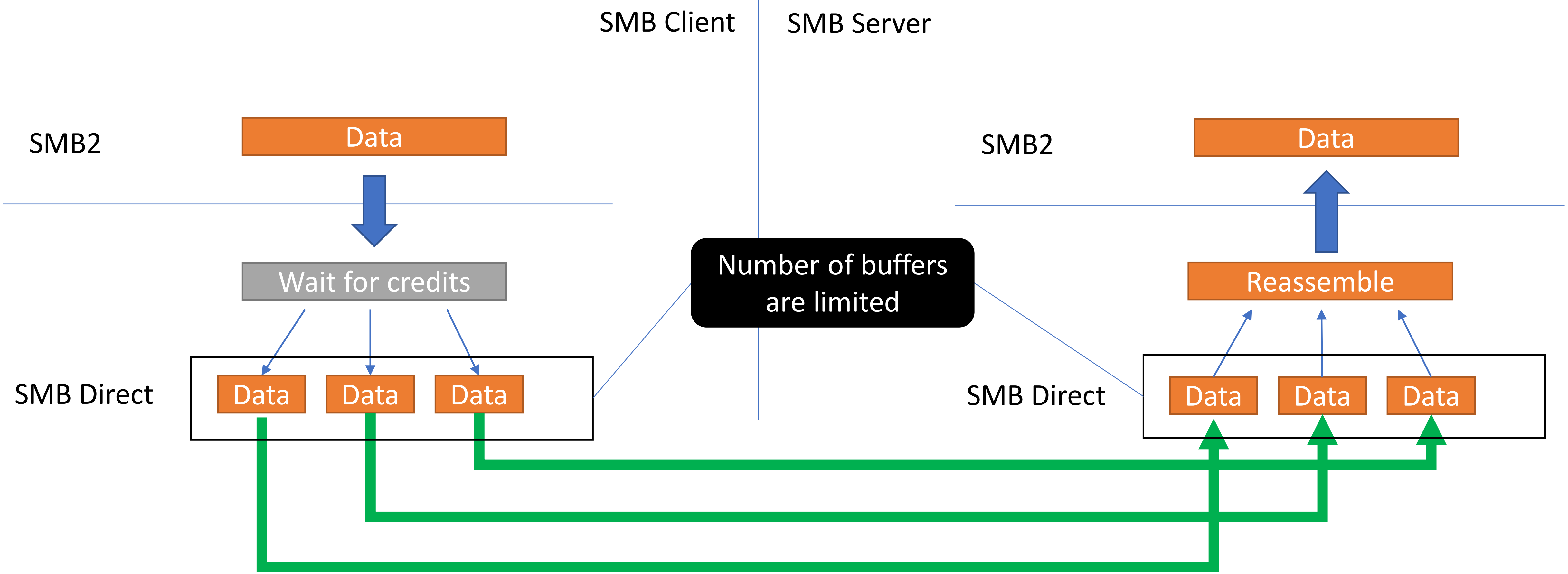
RDMA Send/Recv



RDMA Send/Recv

- CPU is doing all the hard work of packet segmentation and reassembly
- Not the best way to send or receive a large packet
  - Slower than most TCP hardware
  - Today most of TCP based NIC support hardware offloading
- SMB Direct uses RDMA send/recv for smaller packets
  - Default for packet size less than 4k bytes

SMB Direct credit system



SMB Direct credit system

- Send credits
  - Decreased on each RDMA send
  - Receiving peer guarantees a RDMA recv buffer is posted for this send
- Credits are requested and granted in SMB Direct packet

<table>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>1
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0</th><th>1</th></tr>
<tr><td colspan="16">CreditsRequested</td><td colspan="16">CreditsGranted</td></tr>
<tr><td colspan="16">Flags</td><td colspan="16">Reserved</td></tr>
<tr><td colspan="32">RemainingDataLength</td></tr>
<tr><td colspan="32">DataOffset</td></tr>
<tr><td colspan="32">DataLength</td></tr>
</table>

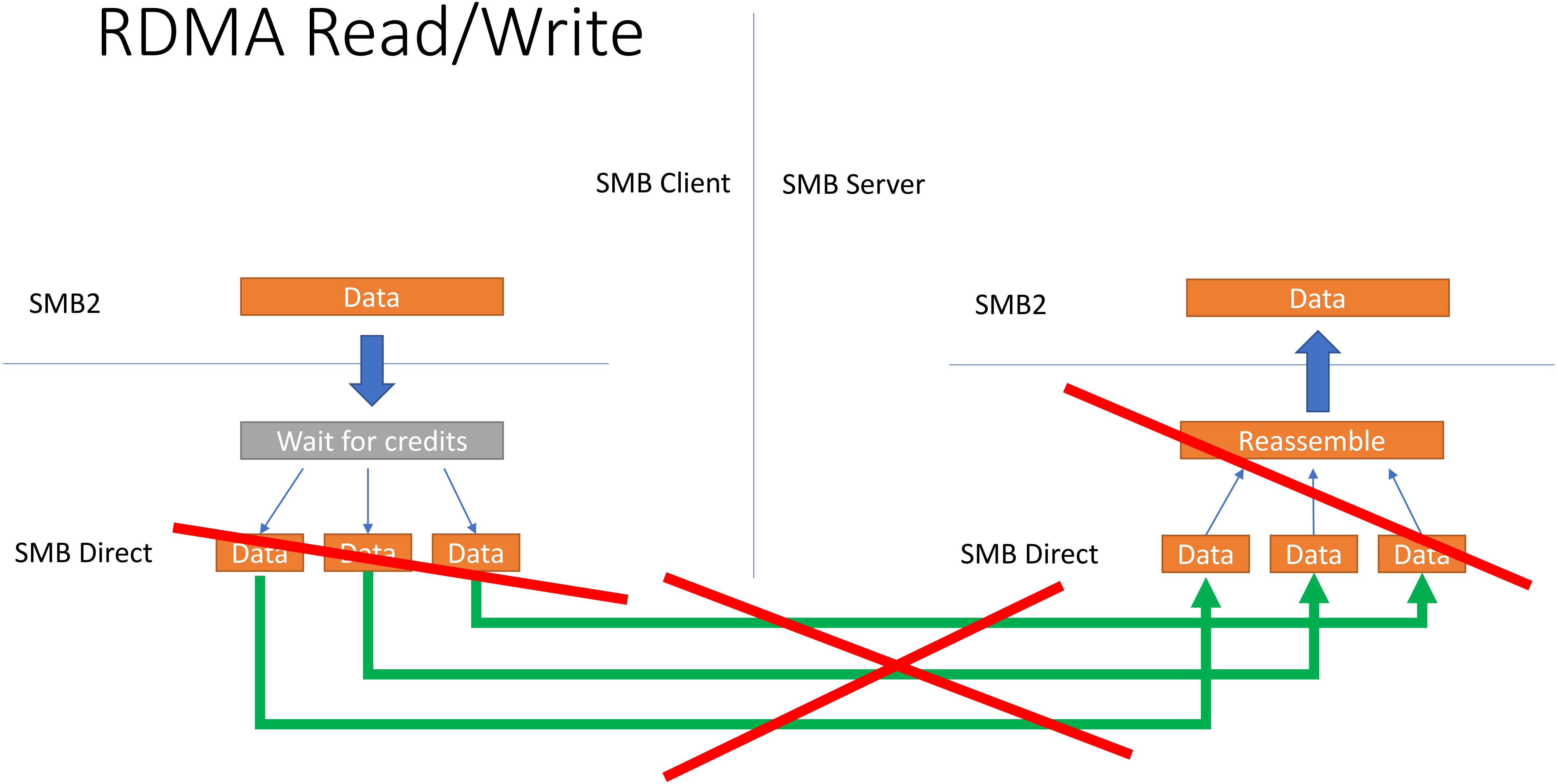
SMB Direct credit system

- Running out of credits?
  - Some SMB commands send or receive lots of packet
  - One side keeps sending to the other side, no response is needed
  - Eventually the send runs out of send credits
- SMB Direct packet without payload
  - Extend credits to peer
  - Keep transport flowing
  - Should send as soon as new buffers are make available to post receive

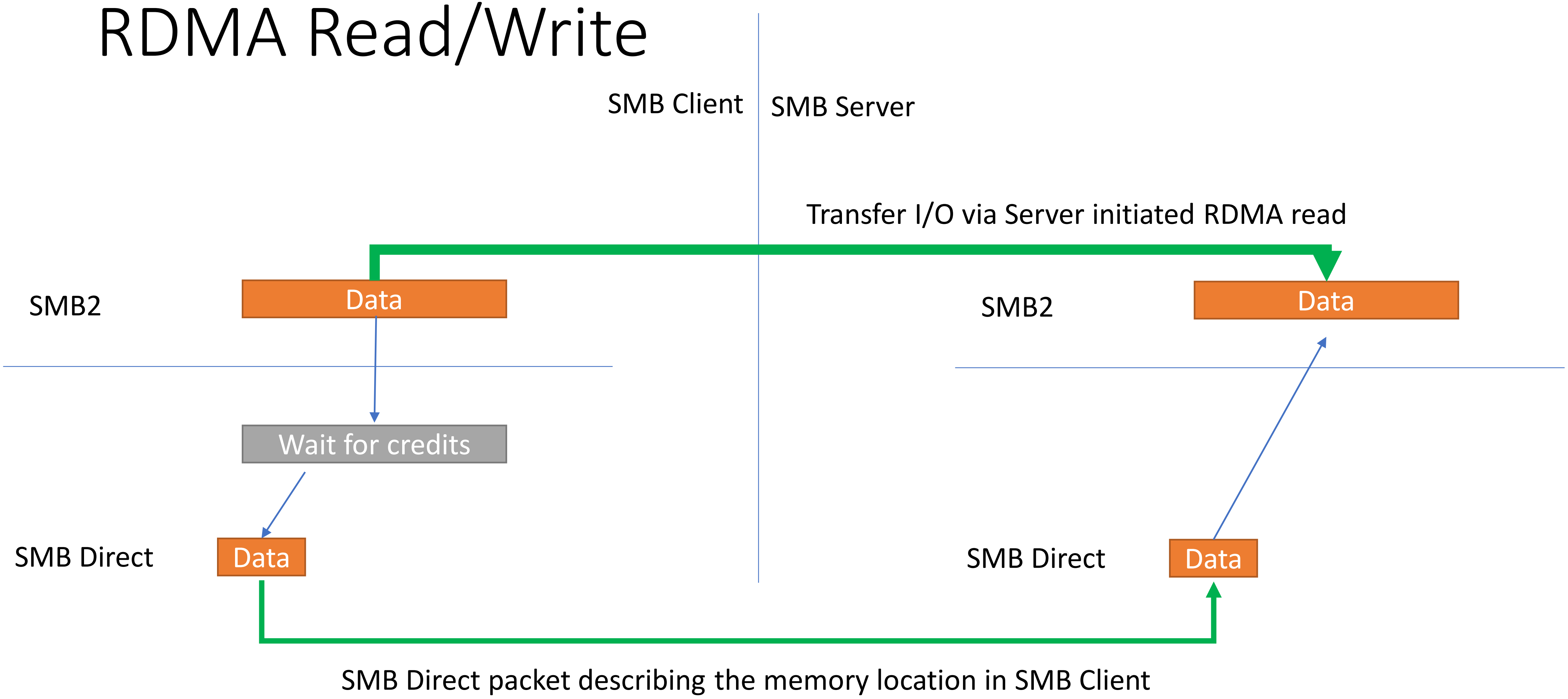
RDMA Send/Recv

- How about large packets for file I/O?
- Typically SMB negotiates with I/O size as large as 1MB

RDMA Read/Write



RDMA Read/Write

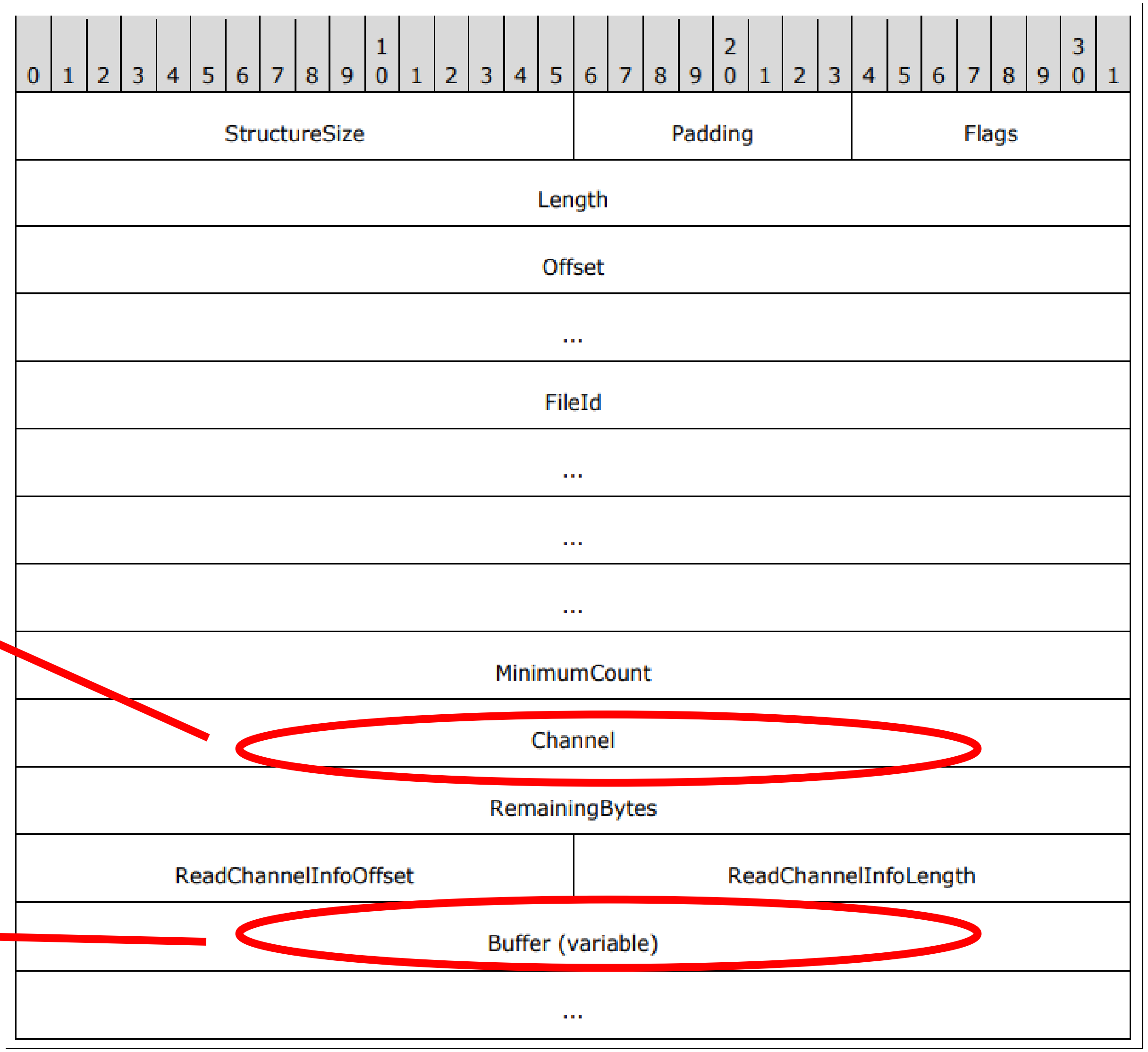


Memory registration

- Client needs to tell Server where to write or read the data from its memory
- Memory is registered for RDMA
  - May not always be mapped to virtual address
  - I/O data are described as pages
- Correct permission is set on the memory registration
- SMB Client asks the SMB Server to do a RDMA I/O on this memory registration

Memory registration in SMB2 READ

- Specifying channel
  - SMB2_CHANNEL_NONE
  - SMB2_CHANNEL_RDMA_V1
  - SMB2_CHANNEL_RDMA_V1_INVALIDATE
- SMB_DIRECT_BUFFER_DESCRIPTOR_1
  - Offset 8 bytes
  - Token 4 bytes
  - Length 4 bytes



Memory registration in Linux

Each memory registration is represented by ib_mr

```
struct ib_mr {
	struct ib_device  *device;
	struct ib_pd      *pd;
	u32               lkey;
	u32               rkey;
	u64               iova;
	u32               length;
	unsigned int      page_size;
	bool              need_inval;
	union {
		struct ib_uobject     *uobject;    /* user */
		struct list_head      qp_entry;    /* FR */
	};
};
```

Memory registration in Linux

Translate Linux memory registration to SMB format

```
struct ib_mr {
	struct ib_device  *device;
	struct ib_pd      *pd;
	u32               lkey;
	u32               rkey;
	u64               iova;
	u32               length;
	unsigned int      page_size;
	bool              need_inval;
	union {
		struct ib_uobject     *uobject;     /* user */
		struct list_head      qp_entry;     /* FR */
	};
};
```

SMB_DIRECT_BUFFER_DESCRIPTOR_1

- Offset 8 bytes (← iova)
- Token 4 bytes (← rkey)
- Length 4 bytes (← length)

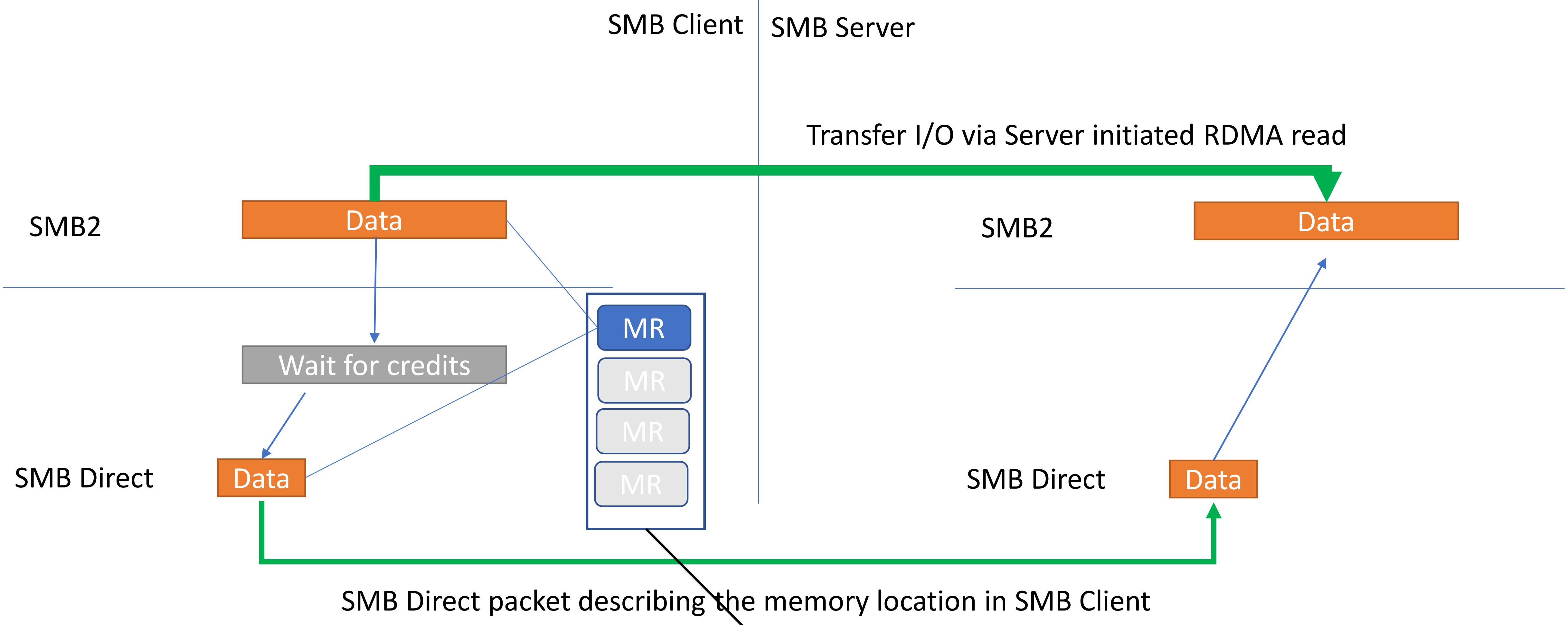
Memory registration in Linux

- Need to make sure memory is registered before posting the request for SMB server to initiate RDMA I/O
- FRWR (Fast Registration Work Requests)
  - Send IB_WR_REG_MR through ib_post_send
  - No need to wait for completion
  - Acts like a barrier in QP, guarantees it finishes before the following WR
  - Supported by almost all the modern RDMA hardware

Memory registration invalidation

- What to do when I/O is finished
  - Make sure SMB server no long has access to the memory region
  - Otherwise it can be messy since this is a hardware address and can be potentially changed by the server without client knowing it
- Client invalidates memory registration after I/O is done
  - IB_WR_LOCAL_INV
  - After it completes, server no longer has access to this memory
  - Client has to wait for completion before buffer is consumed by upper layer
- Starting with SMB 3.02, SMB server supports remote invalidation
  - SMB2_CHANNEL_RDMA_V1_INVALIDATE

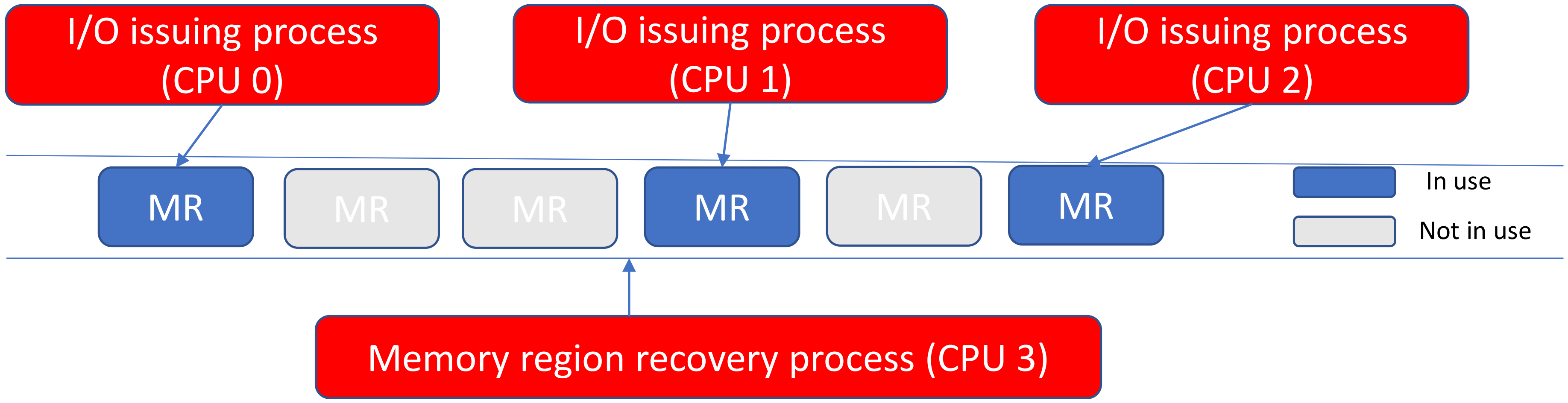
Memory registration



Limited number of memory registration pending I/O available per QP – determined by responder resources in CM

Memory deregistration

- Need to deregister memory registration after it's used
  - It is a slow process
  - Can slow down I/O significantly if doing it synchronously
- Maintain a list of pre-allocated memory registration slots
- Defer to background process to recover MR while other I/Os are in progress
  - Return I/O as soon as the MR is invalidated
  - How about recovery process being blocked?
  - No lock needed since there is one only recovery process modifying the list



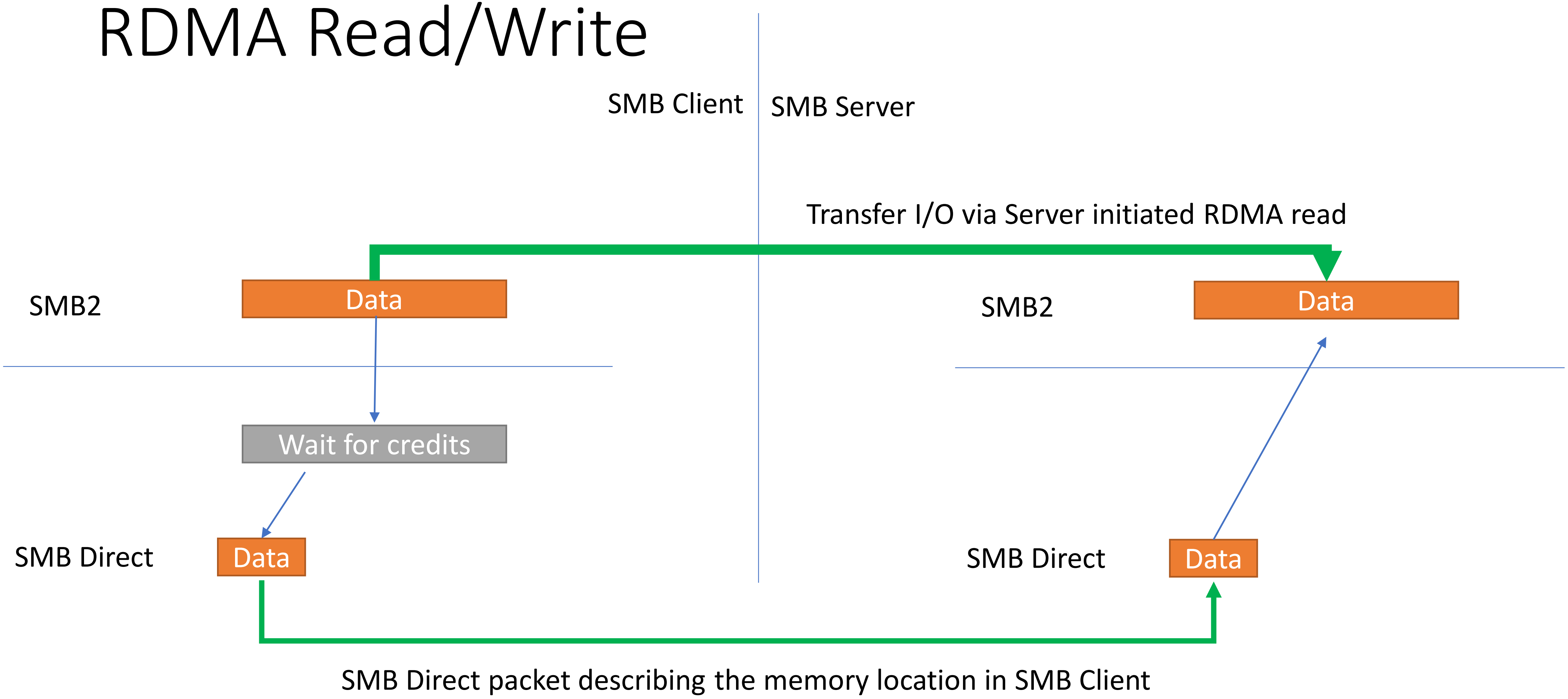
RDMA read/write

- Overlap local CPU and communication
  - Client can proceed with other activities after memory is registered and SMB requests sent to server
  - The actually data transfer is done by RDMA hardware without CPU intervention
- Hardware figures out the best way to transfer data and handle all the I/O details. e.g. segmentation and reassembly if needed
- Reduce CPU overhead on send sider
- There is a cost for doing memory registration and invalidation
  - Suitable for larger packet
  - The default threshold is 4k bytes
    - Packets < 4k Send/Recv
    - Packets >=4k Read/Write

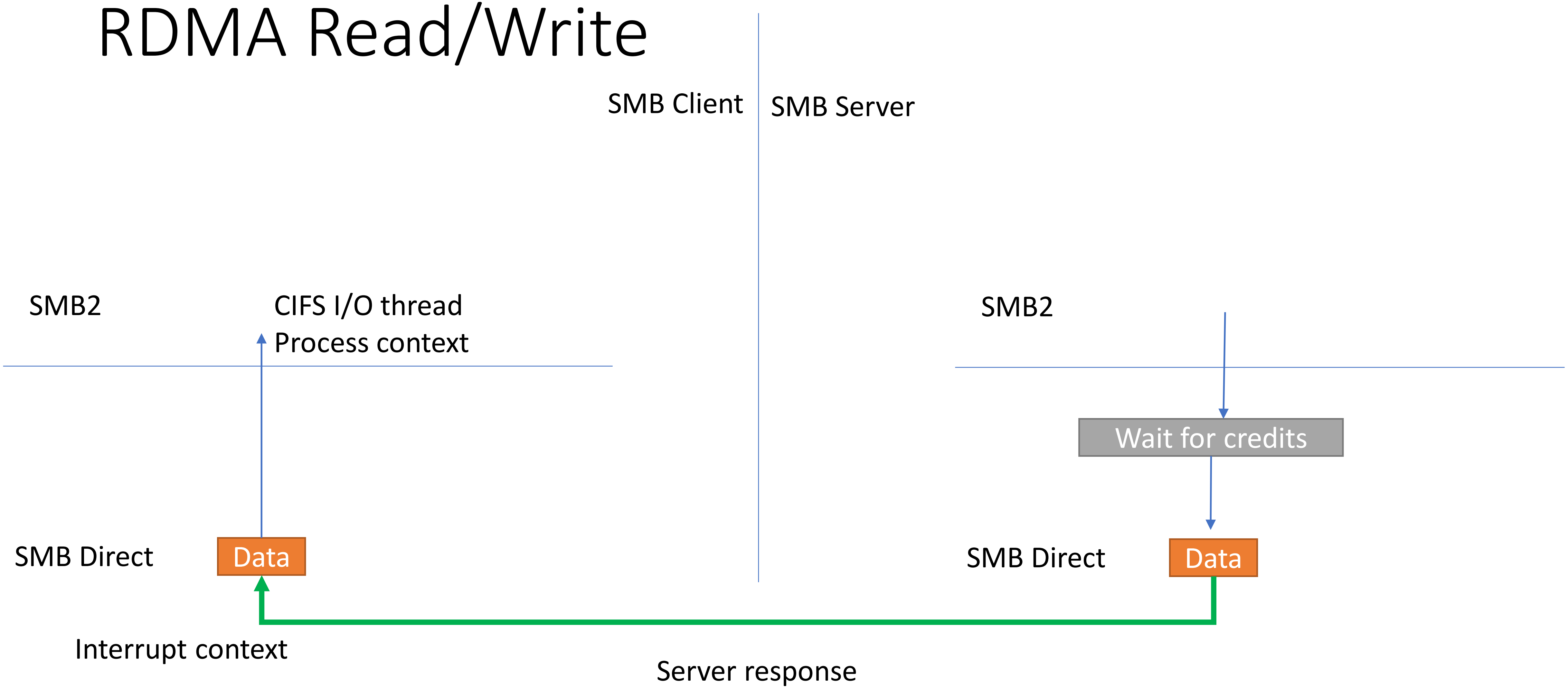
Profiling

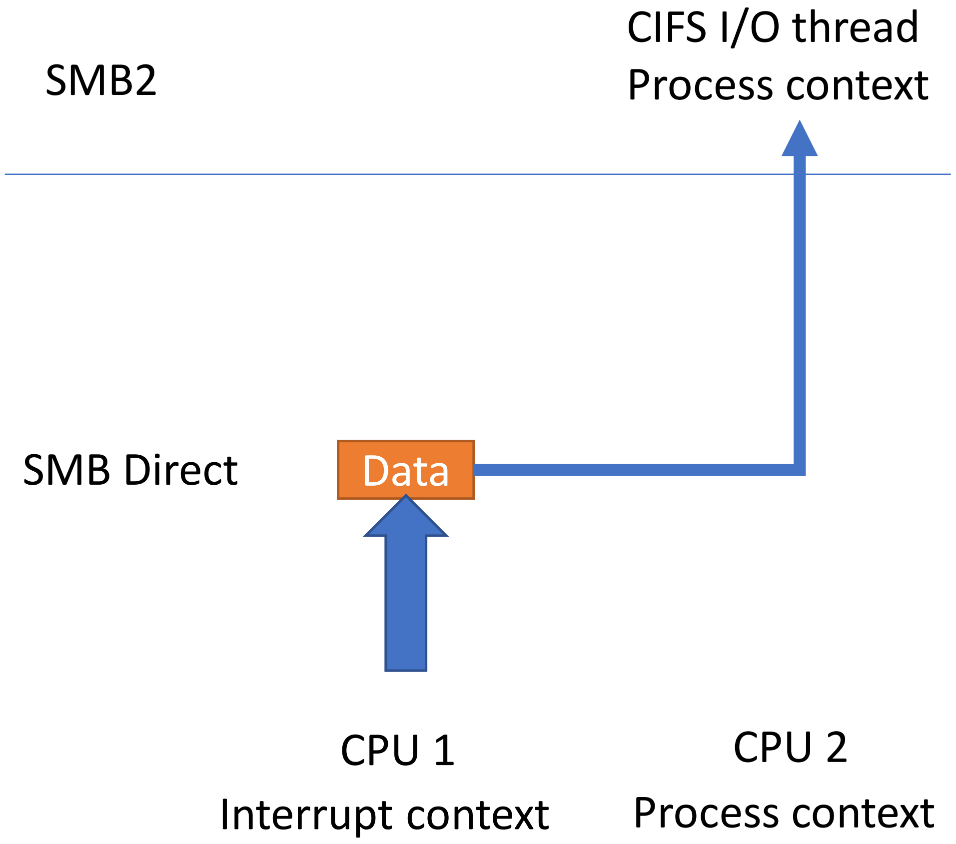
- Need to figure out the where is slow in the I/O path
- Light-weight profling
- TSC (Time Stamp Counter)
  - Common in X86
  - BIOS for C-states
  - rdtsc()
- Store cycles in a histogram
  - Number of leading zeros in TSC cycles
  - __builtin_clzll()

RDMA Read/Write



RDMA Read/Write

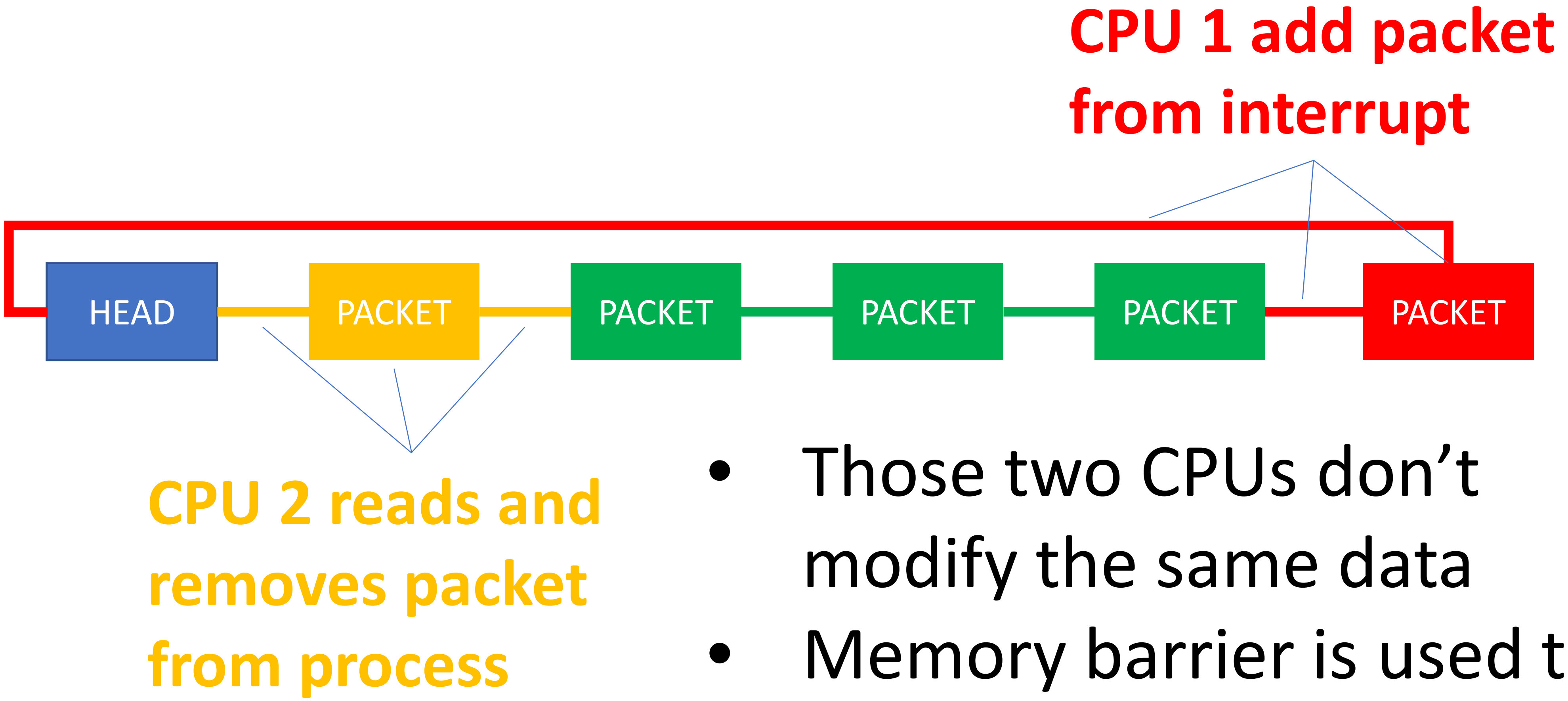




- RDMA is completed from SOFTIRQ
- Completion Queue is polled one by one on the same CPU

- Upper layer reads I/O in a kernel thread on another CPU
- Reassembly queue is used to pass data from CPU1 to CPU2

Reduce lock contention in receive queue



- Those two CPUs don't modify the same data
- Memory barrier is used to reduce lock contention
- Ring buffer?

RDMA send path

- Send path is about 6 - 10 times slower than receive path

CIFS code to send data:

1. allocate buffer

2. call transport to send buffer

3. release buffer

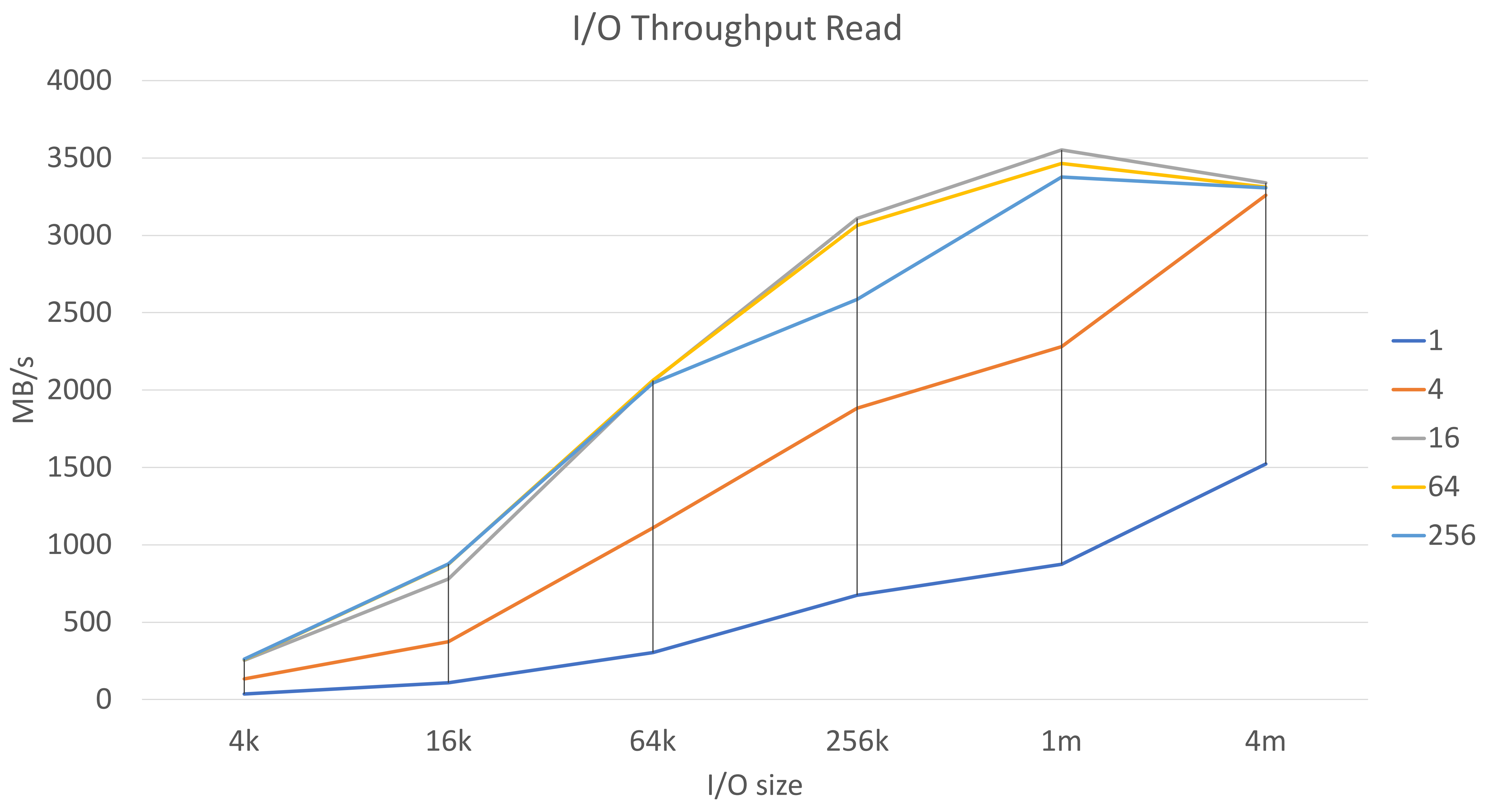
- RDMA doesn’t do buffers, so step 2 has to wait until I/O is finished
  - wait_for_completion involves calling schedule
- Solution: move CIFS buffer allocation code to SMB Direct layer
  - Estimated improvement: 5 – 20% on high queue depth

Use SMB Direct with Linux SMB Client

- mount -t -o rdma,vers=3.02
- Problems?
  - Kernel messages
  - /proc/fs/cifs/DebugData
  - /sys/module/cifs/parameters/smbd_logging_class

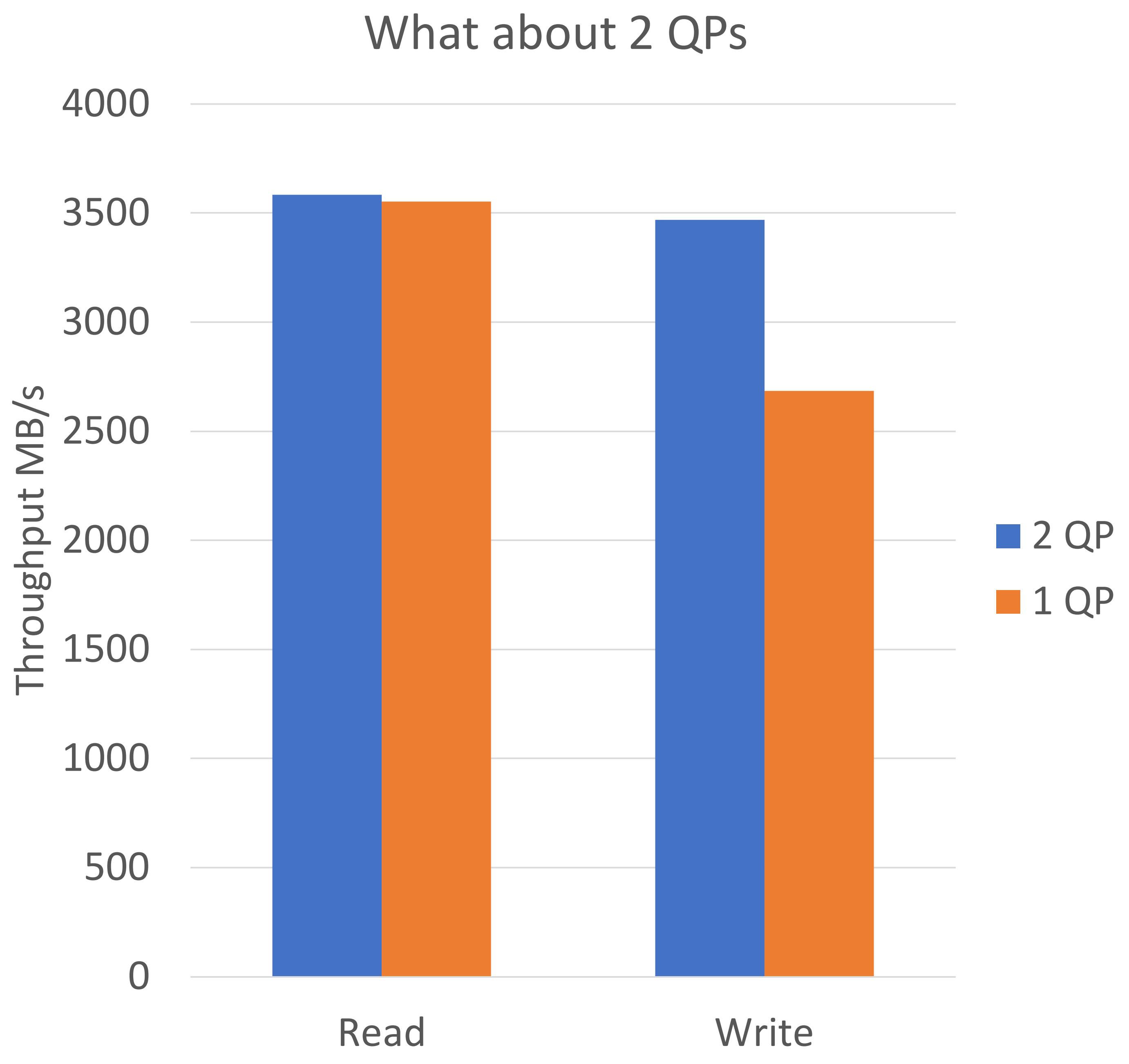
Test setup

- Linux SMB Client
  - 2 x Intel E5-2650 v3 @ 2.30GHz
  - 128 GB RAM
  - Mellanox ConnectX-3 Pro 40G Infiniband
- Windows 2106 SMB Server
  - 2 x Intel E5-2695 v2 @ 2.40GHz
  - 128 GB RAM
  - SMB share on RAM disk
  - Mellanox ConnectX-3 Pro 40G Infiniband
- Switch
  - Mellanox SX6036 in Infiniband mode
- SMB dialect 3.02



I/O Throughput Read
MB/s
4000
3500
3000
2500
2000
1500
1000
500
0
4k
16k
64k
256k
1m
4m
I/O size
1
4
16
64
256

I/O Throughput Write
3000
2500
2000
1500
1000
500
0
MB/s
4k
16k
64k
256k
1m
4m
I/O size
1
4
16
64
256



If we have multiple connections
2 QPs vs 1 QP

I/O size: 1m
queue depth: 16

30% increase for WRITE
Unchanged for READ

Future work

- Upper layer uses SMB Direct layer to allocate buffers
- Support multiple channel
  - Multiple QPs

Questions

Thank you