A Practical Guide to Compute Express Link Memory Devices: Student Lab Guide

What you will learn

- An Introduction to CXL Memory Devices
- CXL Memory Benefits and Use Cases
- The CXL Architecture
- Hands-On Lab: Emulating CXL Devices in QEMU
- Continue Your Learning Path

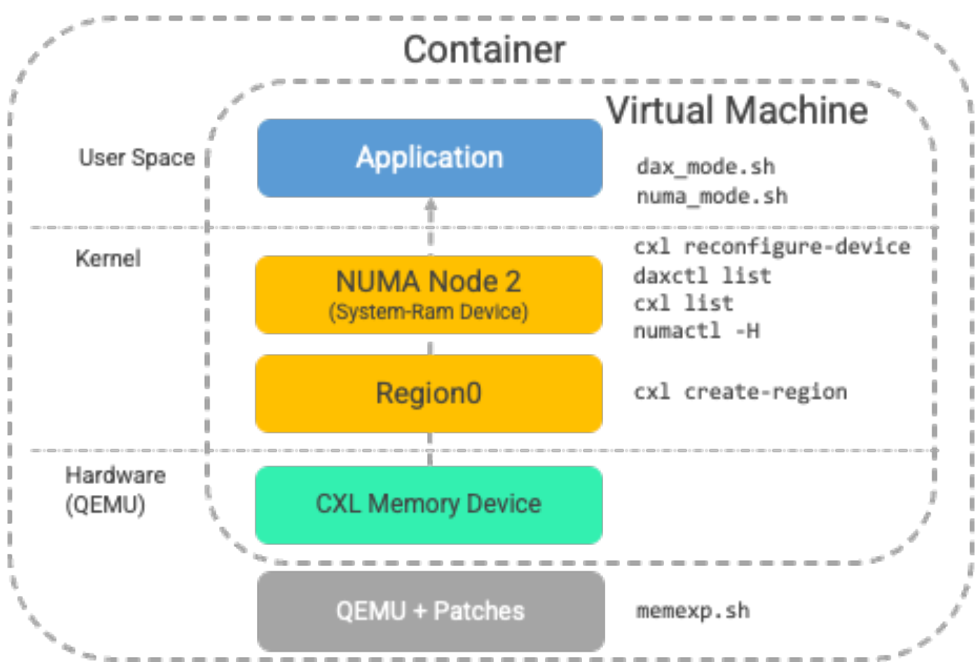
Lab Overview

1. ssh to your assigned lab host instance
2. Install podman
3. Pull the MemVerge CXL Expansion container image
4. Run the Container
5. Start a Guest VM with a single CXL Memory Expander
6. Login to the Guest VM

7. Create a Region
8. Explore the CXL Device using Linux tools
9. Start an Application using CXL and DRAM memory

Lab Environment

The lab software stack provides a ready-to-use QEMU binary and Virtual Machine image using features and functionality of QEMU and the Linux Kernel that are not currently upstreamed, but are available in development branches and patches.



Shell Prompts

The lab instructions predicate each command with the location is should be executed:

`[laptop]$` Run the command(s) on your desktop or laptop

`[container]$` Run the command(s) inside the container

`[vm]$` Run the commands(s) inside the virtual machine

Instructions

SSH to your assigned lab host. The hostname, ip address, username, and password will be provided separately.

```
[laptop]$ ssh user@hostname
Password:
```

Start the Container & Virtual Machine. The Virtual Machine automatically starts when the container starts.

```
// Pull the Container image
[host]$ podman pull docker.io/mvpool/qemu_cxl_memexp

// Start the container as a daemon
[host]$ podman run -d --name cxllab qemu_cxl_memexp

// Allow the Virtual Machine time to start. Wait 2-3mins before
continuing.

// Connect to the container
[host]$ podman exec -it cxllab bash
```

```
// Connect to the Virtual Machine (Please be patient! It may
take a few mins)
[container]$ ssh -p 2222 fedora@localhost
Password: password

// If you get the following error, wait another minute and try
again. The VM has not fully started.
[container]$ ssh -p 2222 fedora@localhost
ssh: connect to host localhost port 2222: Connection refused
```

Should the virtual machine fail to start, run `./memexp.sh`, located in the container's root, to start it.

Create a Region

```
[vm]$ ./create_region.sh
```

The `create_region.sh` script automatically provisions the memory in the 'system-ram' mode so it appears as another memory NUMA Node in the operating system.

CXL Device Discovery

The following commands allow you to discover CXL devices installed or attached to a host.

```
// List the CXL devices
[vm]$ cxl list
[vm]$ cxl list -vvv

// List the DAX devices
[vm]$ daxctl list

// Check the PCI device(s)
[vm]$ lspci | grep -i cxl
35:00.0 CXL: Intel Corporation Device 0d93 (rev 01)

// Get more info about the PCI/CXL device
[vm]$ lspci -s 35:00.0 -vvv
```

If the `lspci` command is not installed, run:

```
[vm]$ sudo dnf install -y pciutils
```

Note: The output from `lspci` is limited inside Virtual Machines. For example, your virtual machine will return something similar to the following:

```
[vm]$ lspci -s 35:00.0 -vvv
35:00.0 CXL: Intel Corporation Device 0d93 (rev 01) (prog-if 10
[CXL Memory Device (CXL 2.x)])
  Subsystem: Red Hat, Inc. Device 1100
  Physical Slot: 0
  Control: I/O+ Mem+ BusMaster+ SpecCycle- MemWINV- VGASnoop-
ParErr- Stepping- SERR+ FastB2B- DisINTx+
  Status: Cap+ 66MHz- UDF- FastB2B- ParErr- DEVSEL=fast >TAbort-
<TAbort- <MAbort- >SERR- <PERR- INTx-
  Latency: 0
  Region 0: Memory at fe840000 (64-bit, non-prefetchable)
[size=64K]
  Region 2: Memory at fe800000 (64-bit, non-prefetchable)
[size=256K]
  Region 4: Memory at fe850000 (32-bit, non-prefetchable)
[size=4K]
  Capabilities: <access denied>
  Kernel driver in use: cxl_pci
  Kernel modules: cxl_pci
```

Use `lstopo-no-graphics` to display the system topology:

```
[vm]$ /opt/hwloc/bin/lstopo-no-graphics --no-caches --no-icaches
--no-smt --no-useless-caches --verbose
```

The output will look similar to the following. Look for the 'CXL' entry:

```
Machine (P#0 total=7997MiB DMIProductName="Standard PC (Q35 +
ICH9, 2009)" DMIProductVersion=pc-q35-8.1 DMIChassisVendor=QEMU
DMIChassisType=1 DMIChassisVersion=pc-q35-8.1
DMIChassisAssetTag= DMIBIOSVendor=SeaBIOS DMIBIOSVersion=rel-
1.16.2-0-gea1b7a073390-prebuilt.qemu.org DMIBIOSDate=04/01/2014
DMISysVendor=QEMU)
  Package L#0 (P#0 total=3901MiB CPUVendor=AuthenticAMD
CPUFamilyNumber=15 CPUModelNumber=107 CPUModel="QEMU Virtual CPU
version 2.5+" CPUStepping=1)
    NUMANode L#0 (P#0 local=3901MiB total=3901MiB)
    Core L#0 (P#0)
    Core L#1 (P#1)
    Core L#2 (P#2)
    Core L#3 (P#3)
  Group0 L#0 (total=4096MiB)
    NUMANode(SPM) L#1 (P#1 local=4096MiB total=4096MiB
DAXDevice=dax0.0 DAXType=SPM CXLDevice=0000:35:00.0
DAXParent=ACPI0017:00/root0/decoder0.0/region0/dax_region0)
  HostBridge L#0 (buses=0000:[00-00])
    PCI L#0 (busid=0000:00:01.0 id=1234:1111 class=0300(VGA))
    PCI L#1 (busid=0000:00:02.0 id=8086:10d3
class=0200(Ethernet) PCIVendor="Intel Corporation"
PCIDevice="82574L Gigabit Network Connection")
      OSDev[Network] L#0 (Address=52:54:00:12:34:56) "eth0"
    PCI L#2 (busid=0000:00:1f.2 id=8086:2922 class=0106(SATA)
PCIVendor="Intel Corporation" PCIDevice="82801IR/IO/IH
(ICH9R/DO/DH) 6 port SATA Controller [AHCI mode]")
      OSDev[Storage](Removable Media Device) L#1 (Size=2
SectorSize=2048 LinuxDeviceID=11:0 Model=QEMU_DVD-ROM
Revision=2.5+ SerialNumber=QM00005) "sr0"
```

```
      OSDev[Storage](Disk) L#2 (Size=41943040 SectorSize=512 LinuxDeviceID=8:0 Model=QEMU_HARDDISK Revision=2.5+ SerialNumber=QM00001) "sda"
  HostBridge L#1 (buses=0000:[34-35])
    PCIBridge L#2 (busid=0000:34:00.0 id=8086:7075 class=0604(PCIBridge) link=0.25GB/s buses=0000:[35-35] PCIVendor="Intel Corporation")
      PCI L#3 (busid=0000:35:00.0 id=8086:0d93 class=0502(CXLMem) link=0.25GB/s PCISlot=0 PCIVendor="Intel Corporation")
        OSDev[Memory,Storage](CXLMem) L#3 (CXLRAMSize=4194304 SerialNumber=0x0) "mem0"
depth 0:           1 Machine (type #0)
 depth 1:          1 Package (type #1)
  depth 2:         4 Core (type #2)
   depth 3:        1 Group0 (type #12)
    depth 4:       4 PU (type #3)
Special depth -3:  2 NUMANode (type #13)
Special depth -4:  3 Bridge (type #14)
Special depth -5:  4 PCIDev (type #15)
Special depth -6:  4 OSDev (type #16)
Relative latency matrix (name NUMALatency kind 5) between 2 NUMANodes (depth -3) by logical indexes:
 index     0     1
     0    10    20
     1    20    10
Topology infos: LinuxCgroup=/ Backend=Linux OSName=Linux OSRelease=6.3.7-200.fc38.x86_64 OSVersion="#1 SMP PREEMPT_DYNAMIC Mon Jun 12 22:37:21 PDT 2023" HostName=localhost Architecture=x86_64 hwlocVersion=3.0.0a1-git ProcessName=lstopo-no-graphics
```

Understanding the Memory Layout

Now that you have configured and provisioned an emulated CXL device inside a virtual machine, you will learn what it looks like from the operating system and how applications can use it.

List the NUMA nodes. Notice how there is a NUMA node with no CPUs and some memory. This is because CXL Type 3 Memory Devices have no CPUs. Run:

```
[vm]$ numactl -H
```

In the following example, Node 1 is the CXL device.

```
[vm]$ numactl -H
available: 2 nodes (0-1)
node 0 cpus: 0 1 2 3
node 0 size: 3901 MB
node 0 free: 3062 MB
node 1 cpus:             <-- A CXL.mem Device has no CPUs
node 1 size: 4096 MB
node 1 free: 4096 MB
node distances:
node   0   1
  0:  10  20
  1:  20  10 <-- CXL Device
```

Each NUMA node is broken into memory blocks by the Kernel. The default size is 2GiB blocks. To see the memory layout, use the following commands

```
[vm]$ lsmem
```

You will see an output similar to the following:

```
[vm]$ lsmem
RANGE                                 SIZE  STATE REMOVABLE
BLOCK
0x0000000000000000-0x000000007fffffff   2G online       yes
0-15
0x0000000100000000-0x000000017fffffff   2G online       yes
32-47
0x0000000390000000-0x000000048fffffff   4G online       yes 114-
145

Memory block size:       128M
Total online memory:       8G
Total offline memory:      0B
```

To see the ZONE mode and which NUMA node the memory is assigned to, use:

```
[vm]$ lsmem -o+ZONES,NODE
```

You will see something similar to this:

```
[vm]$ lsmem -o+ZONES,NODE
RANGE                                  SIZE  STATE REMOVABLE
BLOCK   ZONES NODE
0x0000000000000000-0x0000000007ffffff  128M online       yes
  0    None    0
0x0000000008000000-0x000000007fffffff  1.9G online       yes
1-15   DMA32    0
0x0000000100000000-0x000000017fffffff    2G online       yes
32-47  Normal    0
0x0000000390000000-0x000000048fffffff    4G online       yes
114-145 Movable    1

Memory block size:       128M
Total online memory:       8G
Total offline memory:      0B
```

Use the `--all` option to see each individual memory block. ie: `lsmem -o+ZONES,NODE --all`

Start an Application

For this lab, we use the `memhog` utility, which allocates and then frees memory. When an application is run with `numactl` , we can control which memory NUMA nodes are used for memory allocations.

Allocate memory from DRAM and CXL using a 50:50 Interleave policy:

```
$ numactl --interleave=0,1 memhog 1g
```

Run `memhog` again, using memory allocated entirely from CXL

```
$ numactl --membind 1 memhog 1g
```

Run `numastat` to confirm memory has been touched in the CXL NUMA Node (Node 1), for example:

```
[vm]$ numastat
                           node0           node1
numa_hit                 1154086          262175
numa_miss                      0               0
numa_foreign                   0               0
interleave_hit               980               0
local_node               1154086               0
other_node                     0          262175
```

Explore the Kernel

If you are interested in learning how the Kernel works and how CXL is surfaced through the Kernel, explore the following directories and files within them to learn more.

Investigate `/dev`

```
[vm]$ ls /dev/dax*
[vm]$ ls /dev/cxl/
```

`sysfs` has a lot of useful information. Explore and have fun.

```
[vm]$ ls /sys/bus/node/devices/node1/
[vm]$ ls /sys/bus/cxl/devices/
[vm]$ ls /sys/bus/acpi/devices/
```

Understanding DeviceDAX and System-RAM Namespace Modes

A Region is the Linux term for what APCI and UEFI call a system physical address range that may belong to a single memory device or interleaved amongst many. This is a similar concept to a concat-stripe amongst one or more disks.

Depending upon the physical device characteristics - SLD, MLD, DCD, etc, a Region may be partitioned using Namespaces, similar to how disks can be partitioned.

A Namespace can be provisioned to operate in one of four modes - `fsdax`, `devdax`, `sector`, and `raw`. The supported modes depend on the physical device. CXL Type 3 Memory Devices currently support `devdax` only.

The DeviceDAX (devdax) namespace mode creates a single character device file (`/dex/dax{X.Y}`). Applications can directly `mmap()` the device and perform load/store operations, just like any other memory mapped address range.

A more useful mode for applications that use a `malloc()` approach to allocating memory is to convert the devdax namespace to a `system-ram` mode. In system-ram mode, the memory is surfaced through the Kernel as a new NUMA Node, which any application can use.

Two scripts in the container's root allow you to change between `devdax` and `system-ram` modes.

```
// Convert the 'System-Ram' device to a 'devdax'
[vm]$ cd
[vm]$ ./dax_mode.sh

// Convert the 'devdax' device to a 'System-Ram' node
[vm]$ cd
[vm]$ ./numa_mode.sh
```

Read the relevant man pages and visit https://pmem.io/ to learn more about thishttps://pmem.io). The same concepts for persistent memory can be applied to CXL Memory devices.

Continue Your Learning Path

We encourage you to continue learning and exploring. The Container and Virtual Machine images provided in this lab can be run on your laptop, desktop, or server. Here are some additional resources you will find useful to learn more. You will find several growing and enthusiastic communities.

- CXL Consortium: https://www.computeexpresslink.org/
- Linux Kernel CXL Mailing List: https://lore.kernel.org/linux-cxl/
- Linux Kernel CXL Driver: https://github.com/torvalds/linux/tree/master/drivers/cxl
- NDCTL Linux Tools: https://github.com/pmem/ndctl
  - Includes `cxl` & `daxctl`
- QEMU: https://www.qemu.org/
  - Join the Community: https://www.qemu.org/contribute
- Intel Performance Counter Monitor (PCM) https://github.com/intel/pcm