VMware Paravirtual RDMA for High Performance Computing

PVRDMA Setup and Performance Study - November 29, 2021



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Introduction

High Performance Computing (HPC) workloads require ever-increasing demands for high throughput and low-latency networking. InfiniBand and Remote Direct Memory Access (RDMA) over Converged Ethernet (RoCE) have played a role in enabling these workloads to scale with superior performance to typical TCP-based solutions. Such devices can be configured to work with a virtual machine (VM) on ESXi through VMDirectPath I/O (passthrough) mode, but doing so disables certain features for the VM, such as vSphere HA, DRS, and vMotion.

Through VMware PVRDMA—the paravirtual RDMA device that takes advantage of any RoCEcapable hardware on an ESXi host—ESXi can support running workloads with high performance while still maintaining the flexibility offered by virtualization, including operational flexibility, better resilience, higher availability, and lifecycle management capabilities. This high performance is possible because PVRDMA allows for direct memory transfers (DMA) between guest memory to the RoCE-capable hardware without CPU intervention. Using the RDMA protocol enables the potential for memory-to-memory zero-copy transfers between guests on two different hosts.

In this paper, we first show you how to configure a PVRDMA device in a vSphere environment, including the ESXi host setup, VM setup, and guest operating system setup. We then demonstrate the performance benefits of PVRDMA over TCP and show close performance to RDMA-capable hardware used in passthrough mode, all while supporting vSphere HA, DRS, and vMotion.

PVRDMA Setup

PVRDMA is a virtual device that you can add to a VM. You need to set this up on both vCenter Server and the guest operating system. The instructions from VMware Docs have been replicated below with screenshots to follow along more easily. Please also see the KB article for supported operations and operating systems, limitations, and new features.

vCenter Server Setup

To create a distributed switch (DVS) with RoCE-capable NICs as uplinks:

 Go to the Networking tab in the menu on the left, right-click on your datacenter, and go to Distributed Switch > New Distributed Switch... and click on it:



 Datacenter RDMA Datacenter WM Network 	Actions - RDMA Datacenter		ä	Virtual Machines Clusters: Networks: Datastores:	: 1 0 1 11
	다 Add Host				
	New Folder Distributed Switch	•		age: Datastore us	-
	다 New Virtual Machine		Imp	ort Distributed Sw	[
	🔂 Deploy OVF Template		Attrib	utes	

Figure 1. Choose Datacenter > Distributed Switch > New Distributed Switch

2. After you create the distributed switch, right click on it, and then click on Add and Manage Hosts...:

∽ 📑 RDMA Datacenter		
🖉 VM Network		Ē
🗸 🔙 RDMA DSwitch 📊		_
🗥 DPortGroup 1	- Actions - RDMA DSwitch	-
🕮 RDMA DSwitch	Distributed Port Group	► S
	📳 Add and Manage Hosts	
	Edit Notes	N

Figure 2. Click the new switch and click on Add and Manage Hosts ...

- 3. Click on **Add hosts**, then go the next page.
- 4. Click on **New hosts...** and select the hosts you want to add to the distributed switch, then go to the next page.
- 5. Select the vmnic representing the RoCE-capable NIC you want to use as the uplink for the PVRDMA device.
 - a. if you are unsure of which uplink you need to select, you can click on the host in the Hosts and Clusters menu.
 - b. Click on the **Configure** tab.
 - c. Under Networking, look at Physical adapters.
 - By clicking on the listed vmnics, you can view under the RDMA tab if the vmnic supports RDMA. The vmnic needs to support either the RoCE v1 or RoCE v2 protocols.



e. Click on Assign uplink, select Uplink 1, then click on OK. The desired NIC should say (Assigned) and show Uplink 1 under the Uplink column.

1 Select task 2 Select hosts	Manage physical adapters Add or remove physical network adapters	s to this distributed sw	itch.	
3 Manage physical adapters 4 Manage VMkernel adapt	🖷 Assign uplink 🛛 🔀 Unassign adapter	(i) View settings		
5 Migrate VM networking	Host/Physical Network Adapters	In Use by Switch	Uplink	Uplink Port Group
6 Ready to complete	prmh-vrdma-009.eng.vmware.c			
	 On this switch 			
	🖭 vmnic4 (Assigned)		Uplink 1	RDMA DSwitch-DVU
	I On other switches/unclaimed			
	🖭 vmnic0			
	🖭 vmnic1			
	🖭 vmnic2	vSwitch0		
	🖭 vmnic3			
	🖭 vmnic5			
	🖭 vmnic6			
	🎹 vmnic7			
	🖭 vmnic8			

Figure 3. Add and Manage Hosts screen

6. Keep going to the next page until you finish creating a distributed switch.

Note: Adding more than one uplink to the distributed switch is not supported. Please have only a single uplink per host in the distributed switch.

ESXi Host Setup

PVRDMA needs to use a VMKernel network interface (vmknic) to send and receive control data with other PVRDMA devices. In order to do so, you need to set a vmknic for use by PVRDMA.

To set a vmknic that PVRDMA can use:

1. Select the host you need to configure the vmknic for PVRDMA on, go to the **Configure** tab, and select **Advanced System Settings**.



	🔋 prmh-vrdma-009.en	g.vmware.com	s 🗸	
() Þ = Ø	Summary Monitor Configur	e Permissions VMs Reso	urce Pools Datastores N	Networks Updates
 ✓ ⁽²⁾ sc2-10-187-131-69.nimbus.eng.vmware.com > ⁽¹⁾ Datacenter 	TCP/IP configuration Virtual Machines	Advanced System Set	tings	
Fill RDMA Datacenter Fill prmh-vrdma-009.eng.vmware.com	VM Startup/Shutdown	Кеу т	Value	T Summary
☐ rhel80_2	Agent VM Settings Default VM Compatibility	Annotations. Welcome Message		A welcome messag
	Swap File Location	BufferCache.FlushInterval	30000	Flush at this interva
	System V	BufferCache.HardMaxDirty	95	Block writers if this
	Licensing	BufferCache.PerFileHardMaxDirty	50	Block writers if this
	Host Profile	BufferCache.SoftMaxDirty	15	Flush immediately i
	Time Configuration	CBRC.DCacheMemReserved	400	Memory consumed
	Authentication Services	CBRC.Enable	false	Enable Content Ba
	Certificate	Config.Defaults.host.TAAworkaro	true	Enable mitigation c
	Power Management	Config.Defaults.monitor.if_pscha	false	Enable workaround
	Advanced System Settings	Config.Defaults.security.host.ruissl	true	Require SSL to be
	System Resource Reservation	Config.Defaults.vGPU.consolidati	false	Assignment policy
	Firewall	Confia Etc.issue		Contonte of Intelie

Figure 4. Advanced System Settings screen

Name	Value			
	Value			
▲ Modifying configuration parameters is unsupported and can cause instability. Continue only if you know what you are doing. ▼ Net.PVRDMA				
Edit Advanced System Settings prmh-vrdma-009.eng.vmware.com				

Figure 5. Edit Advanced System Settings screen

Note: The vmknics of hosts on which VMs with PVRDMA reside must be able to reach each other in order for the PVRDMA devices to communicate over the RDMA-capable NIC.

To edit firewall settings to allow PVRDMA control data traffic, follow these steps in the UI or enter the commands as shown at the end of the steps:

- 1. Select the host you need to edit the firewall settings on.
- 2. Go to the **Configure** tab.
- 3. Select System > Firewall
- 4. Click the **Edit...** button in the top right corner.
- 5. Filter for pvrdma.
- 6. Make sure the checkbox is checked.
- 7. Click OK.

vmware[®]

Edit Security Profile	prmh-vrdma-009.eng.vmware.	com ×
	e or client, check the corresponding b eir ports are opened, and stop when a	-
Groups		
UNGROUPED SECURE SHELL	SIMPLE NETWORK MANAGEMENT PROTOCOL	
		T pvrdma
Service name	Incoming Ports	Outgoing Ports
🛃 🗲 þvrdma	28250-28761 (TCP)	28250-28761 (TCP)
19		1 item
		CANCEL OK

Figure 6. Edit Security Profile screen

The above steps can be done using the ESXi shell instead. Just run the two commands below:

```
esxcli system settings advanced set -o /Net/PVRDMAVmknic -s vmk0
esxcli network firewall ruleset set -e true -r pvrdma
```

Virtual Machine Setup

PVRDMA devices are supported starting on virtual machine hardware version 13 and onwards. Make sure the VM you would like to add the PVRDMA device to is at least **HWv13 or higher**. If it is not:

- 1. Right click on the VM.
- 2. Go to Compatibility > Upgrade VM Compatibility...
- 3. Upgrade the VM to at least HWv13 (vSphere 6.5+).



> 🗈 Datacenter	Actions - rhel80_2		
V 📑 RDMA Datacei	Power	>	
V 🗍 prmh-vrdma	Guest OS	>	Powered Off
िंगे rhel80_2	Snapshots	>	
	💆 Open Remote Console		AUNCH WEB CONSO
	급 Migrate		AUNCH REMOTE COM
	Clone	>	
	Fault Tolerance	>	VM Hardware
			> CPU
	VM Policies	>	> Memory
	Template	>	> Hard disk 1
	Compatibility	>	> Network adapte
	Export System Logs		CD/DVD drive 1
-			> Video card
	🖓 Edit Settings		PCI device 0

Figure 7. Actions screen

Now, you can add the PVRDMA device to the virtual machine:

- 1. Right-click on the VM and click on Edit Settings....
- 2. Click on Add New Device and under Network, select Network Adapter.



Edit Settings | rhel80_2

Virtual Hardware VM Options

		ADD NEW DEVICE Y
> CPU	2 ~	Disks, Drives and Storage
> Memory	4 ~ GB ~	Hard Disk
> Hard disk 1	40 GB ~	Existing Hard Disk
> SCSI controller 0	VMware Paravirtual	Host USB Device
> Network adapter 1	VM Network $$	NVDIMM
> CD/DVD drive 1	Client Device \checkmark	CD/DVD Drive Controllers
> USB controller	USB 2.0	NVMe Controller
> Video card	Specify custom settings $\ \ \lor$	SATA Controller
> Security Devices	Not Configured	USB Controller
VMCI device		Other Devices
SATA controller 0	AHCI	PCI Device Watchdog Timer
> Other	Additional Hardware	Precision Clock
		Serial Port
		Network
		Network Adapter
		CANCEL OK

Figure 8. Add a new network adapter

3. Change the adapter type to **PVRDMA** and click on the dropdown menu for **New Network**, and then click on **Browse**....

> SCSI controller 0	VMware Paravirtual	
> Network adapter 1	VM Network V	✓ Connect
✓ New Network *	✓ VM Network Browse	\otimes
Status	Connect At Power On	
Adapter Type	PVRDMA ~	
Device Protocol	RoCE v2 V	
MAC Address	Autom	natic V
> CD/DVD drive 1	Client Device V	Connect





4. Select the distributed port group corresponding to the distributed switch that you created and click **OK**. Then click **OK** again to finish editing the VM settings.

Select Networ	ſĸ		>
		T Filter	
Name	NSX Port Group ID	Distributed Swite	h
🗥 DPortGroup 1		RDMA DSwitch	
VM Network			
			2 items
		CANCEL	ок

Figure 10. Select Network screenshot

Guest Operating System Setup

PVRDMA requires driver support in the guest operating system. Below are the supported operating systems for the two different protocols supported by PVRDMA:

- In RoCEv1: PVRDMA supports CentOS 7.2 or later, RHEL 7.2 or later, SLES 12 SP1 or later, Oracle Linux 7 UEKR4 or later, Ubuntu LTS Releases 14.04 or later, and Photon OS 3.0 or later.
- In RoCEv2: PVRDMA supports CentOS 7.3 or later, RHEL 7.3 or later, SLES 12 SP3 or later, Oracle Linux 7 UEKR5 or later, Ubuntu LTS Releases 16.04.2 or later, and Photon OS 3.0 or later.

Userspace applications also require userspace libraries for PVRDMA. The easiest way to install this is to install rdma-core. You can also install rdma-core packages using your operating system's package manager.

Troubleshooting

To confirm that PVRDMA is using the underlying RoCE-capable NIC, you can check application performance from the VM or inspect the PVRDMA device backend settings from the ESXi shell.

1. Running a simple server-client bandwidth test can tell you if the PVRDMA device is operating as expected. One set of microbenchmarks for RDMA is perftests. If *ib_send_bw* gives a



bandwidth close to line rate on larger packet sizes, the PVRDMA device should be configured correctly. For example, see the output of **ib_send_bw** on a 40G RoCE-capable NIC:

[root@prmh-	lab-net3-dhcp232	-029 ~]# ib_send_	bw -x 1 192.168.51.31	
	Send BW	Test		
Dual-port	: OFF	Device	: vmw_p∨rdma0	
Number of	qps : 1	Transport ty	pe : IB	
Connection	type : RC	Using SRQ	: OFF	
PCIe relax	order: ON			
ibv_wr* AP	I : OFF			
TX depth	: 128			
CQ Moderat	ion : 1			
Mtu	: 1024[B]			
Link type	: Ethernet			
GID index	: 1			
Max inline	data : 0[B]			
rdma_cm QP	s : OFF			
Data ex. m	ethod : Ethernet			
local addr	ess: LID 0000 QP	N 0x2a61 PSN 0x24	4ed6	
GID: 00:00	:00:00:00:00:00:00:	00:00:00:255:255:	192:168:51:32	
remote add	ress: LID 0000 Q	PN 0x0002 PSN 0x9	a7160	
GID: 00:00	:00:00:00:00:00:00:	00:00:00:255:255:	192:168:51:31	
#bvtes	#iterations	BW peak[MB/sec]	BW average[MB/sec]	MsaRate[Mpps]
			4395.71	

Figure 11. Output of ib_send_bw on a 40G ROCE-capable NIC

2. If you have access to the ESXi shell, you can use the **vsish** command to check if the PVRDMA device is correctly configured to use the RDMA-capable NIC. The command to do so is:

vsish -e cat /vmkModules/vrdma/pvrdmaDevices/<VM World ID>_<Adapter Index>/properties with <VM World ID> found by running esxcli vm process list, and <Adapter Index> likely to be 0, unless there are multiple PVRDMA devices added to the virtual machine. If Physical HCA available is 1 in the output, that means the RDMA-capable NIC is in use by the PVRDMA device.



[root@sc2-cpbu2-b0710:/vmfs/volumes/abd78922-9b6e495c/bryantan/scripts] esxcli vm process list
rhel80_1
World ID: 1001474360
Process ID: 0
VMX Cartel ID: 1001474359
UUID: 42 31 0d 66 62 8c b0 5d-46 6f 24 42 52 c6 95 8f
Display Name: rhel80_1
Config File: /vmfs/volumes/abd78922-9b6e495c/bryantan/rhel80_1/rhel80_1.vmx
[root@sc2-cpbu2-b0710:/vmfs/volumes/abd78922-9b6e495c/bryantan/scripts] vsish -e cat /vmkModules/vrdma/pvrdmaDevices/1001474360_0/properties
PVRDMA Device Properties {
VMM leader ID of VM:1001474360
adapter index:0
MAC address:00:50:56:8a:9f:c2
Physical HCA available:1
Namespace allocated:0
Hardware S/R available:0
MR tracing available:0
SRQ support enabled:1
MR Key extension enabled:1
Phys handles enabled:1
Native endpoints supported:0
Native vmotion supported:0
DMA accelerator enabled:0
DMA accelerator transfer threshold:32768
Prefer RoCE v1 over v2:0
RoCE version:2
Active MTU:1024

Figure 12. Output of vsish command

Through the ESXi shell, you can also view the available RDMA devices using esxcli rdma device list and view device stats of each RDMA device using esxcli rdma device stats get -d vmrdmaX. RDMA device stats only works on PCI device physical functions and may not work with certain RDMA or PVRDMA configurations.

Performance Testing with HPC Application OpenFOAM

OpenFOAM is a popular open-source software used for solving computational fluid dynamics (CFD) problems, including aerodynamics, simulation of industrial flows, combustion systems, and electronic design automation. CFD is the largest user of HPC infrastructures in engineering. OpenFOAM uses MPI for parallel distributed workloads.

Message passing interface (MPI) is a standard for multiple processor programming of HPC code that runs on a variety of machines: from small clusters to giant supercomputers. Numerous scientific applications that run in a distributed way use the MPI library and take advantage of its communication operations.

By demonstrating PVRDMA performance and utility in OpenFOAM with MPI, we show that it is possible to achieve good performance with virtualization in applications commonly used in the HPC space.



Testbed Setup

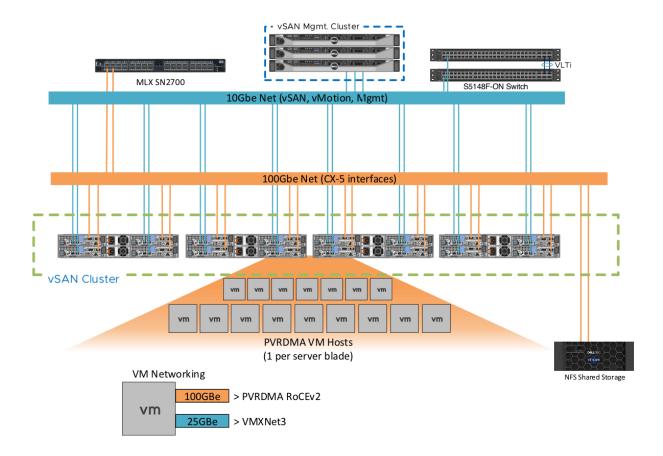


Figure 13. Cluster and OpenFOAM setup

The testbed consisted of:

- 8 ESXi 7.0 hosts on PowerEdge C6420 with Intel Xeon Gold 6148 CPU (20 core/40 thread), 200GB RAM, NVIDIA Mellanox ConnectX-5 Ex 100GbE NIC for RDMA
- NVIDIA Mellanox ConnectX-5 Ex NICs connected using a 100GbE NVIDIA Mellanox switch
- CentOS 7.6, 20 vCPUs, 100GB RAM, VM on VSAN datastore, one VM per ESXi host
- OpenMPI version 4.1.0, using openib BTL for RDMA transport
- OpenFOAM version 8, running the cavityFine experiment from the OpenFOAM user guide

The cavityFine test runs a fluid dynamics simulation with the given parameters. The simulated case is a two-dimensional square with stationary walls on 3 sides and a moving wall on the fourth.



Results

We ran the case for the cavityFine experiment with a start time of 0.5 seconds and an end time of 0.50003 seconds. We aimed to keep the amount of work done per node equal as we scaled up the number of nodes, a method known as *weak scaling*, similar to what customers do by running larger problems or the same problem with higher resolution when scaling up on larger clusters. To do so, we had to double the mesh size to be solved and halved the time delta for the solver when the number of processes was doubled. We ran a single VM on each ESXi host, with each VM running 20 MPI processes, and tested with 1, 2, 4, and 8 VMs ranging from 20 MPI processes to 160 MPI processes.

The below table and graphs show the performance of PVRDMA, and its comparison with passthrough (using NVIDIA Mellanox ConnectX-5 Ex NIC with SR-IOV virtual function) and TCP. The PVRDMA device is configured to use RDMA over the NVIDIA Mellanox ConnectX-5 Ex NIC, and TCP was run over the NVIDIA Mellanox ConnectX-5 Ex NIC as well, without RDMA but still taking advantage of the NIC's higher performance. Case names encode the number of hosts used for the test (n) and the number of MPI processes run per host (np).

Note: The 1 node, 20 MPI processes run does not use the underlying transport and had an average run time of 119.61 seconds.

Cases	Mesh Size	Time Delta (s)	PVRDMA (s)	Passthrough (s)	TCP (s)
n2np40	(2000 2000 1)	0.0000012	336.49	279.78	501.19
n4np80	(4000 2000 1)	0.0000006	768.74	601.52	1014.25
n8np160	(4000 4000 1)	0.0000003	1583.22	1307.51	2878.94

Table 1. OpenFOAM weak scaling performance on different transports, measured in seconds (s)

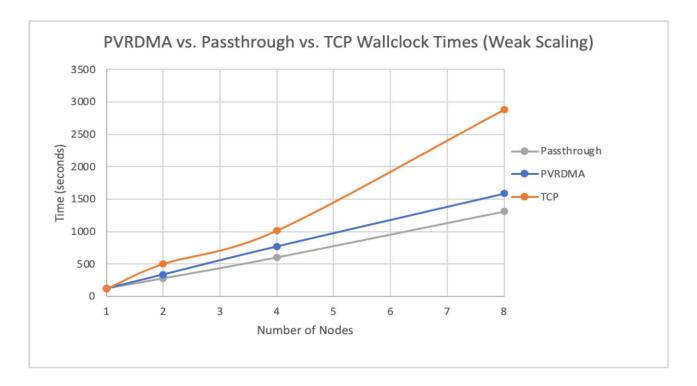


Figure 14. Weak scaling performance comparison between passthrough, PVRDMA, and TCP (lower is better)

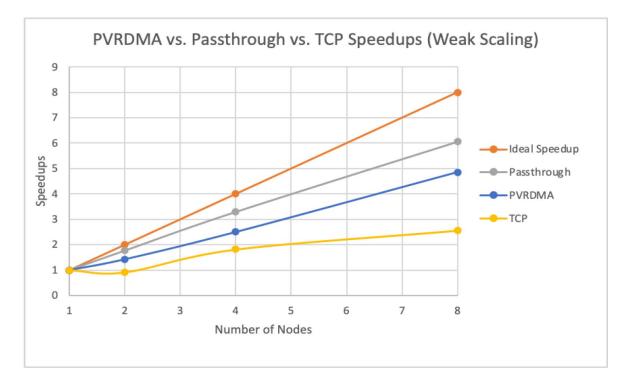
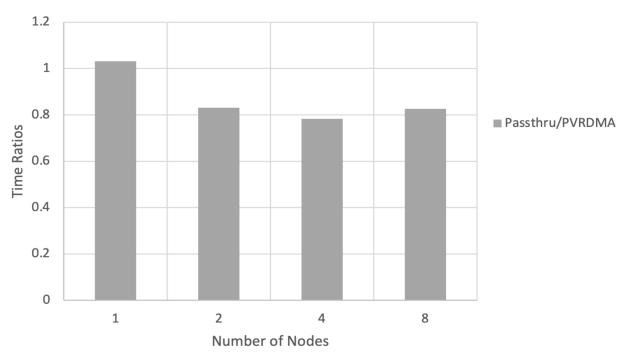


Figure 15. Weak scaling speedup comparison between passthrough, PVRDMA, TCP, and the ideal case (higher is better)

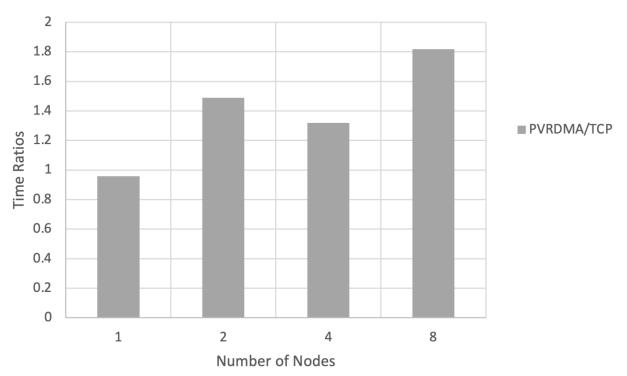


In figures 14 and 15 we can see that PVRDMA runs closely to passthrough, and even though there is some cost for virtualization, it offers vSphere features like consolidation, HA, vMotion, and more.



PVRDMA vs. Passthru Time Ratios (Weak Scaling)

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TCP vs. PVRDMA Time Ratios (Weak Scaling)

From figure 16, we can see that PVRDMA performance is approximately 80% of the passthrough performance using the same RoCE-capable NIC, and from figure 17 the PVRDMA performance is 30%-80% better than the TCP performance. While using an RoCE-capable NIC in passthrough mode is still the most performant, PVRDMA bridges the gap between TCP and passthrough, while still providing the benefits of virtualization.

Conclusion

Through the experiments with OpenFOAM, PVRDMA is shown to achieve good performance on an HPC application. The performance of PVRDMA exceeds that of TCP, and while using an RDMA-capable NIC in passthrough mode allows better performance, PVRDMA can take full advantage of virtualization benefits, such as vSphere HA, DRS, and vMotion. In the future, we also plan to demonstrate the performance and functionality benefits of using PVRDMA for machine learning/deep learning workloads.



About the Authors

Bryan Tan is a senior member of technical staff working on virtualized Remote Direct Memory Access (RDMA) and other virtual devices within VMware vSphere.

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