Implementation of Xen PVHVM drivers in OpenBSD

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The goal

Produce a minimal well-written and well-understood code base to be able to run in Amazon EC2 and fix potential problems for our customers.

The challenge

Produce a minimal well-written and well-understood code base to be able to run in Amazon EC2 and **fix potential problems for our customers**.

Requirements

Need to be able to:

- boot

Requirements

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- boot: *already works!*

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- mount root partition

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- support SMP

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Need to be able to:

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- mount root partition: *already works!*
- support SMP: **didn't work on amd64**

Requirements

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- support SMP: *fixed shortly*

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- support SMP: *fixed shortly*
- perform "cloud init"

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- perform "cloud init": requires PV networking driver. *Snap!*

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- boot: *already works!*
- mount root partition: *already works!*
- support SMP: *fixed shortly*
- perform "cloud init": requires PV networking driver
- login into the system via SSH...

Requirements

Need to be able to:

- boot: *already works!*
- mount root partition: *already works!*
- support SMP: *fixed shortly*
- perform “cloud init”: requires PV networking driver
- login into the system via SSH... Same thing.

Outlook on the FreeBSD implementation

- Huge in size

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  “`du -csh`” reports 1.5MB *vs.* 124KB in OpenBSD as of 5.9

  35 C files and 83 header files *vs.* 4 C files and 2 headers

Outlook on the FreeBSD implementation

- Huge in size
- Needlessly complex

  Overblown XenStore API, interrupt handling, ...

  Guest initialization, while technically simple, makes you chase functions all over the place.

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- Clash of coding practices

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  Lots of code has been taken verbatim from Linux (where license allows)

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  Code-generating macros, e.g. `DEFINE_RING_TYPES`.

  Macros to "facilitate" simple producer/consumer arithmetics, e.g. `RING_PUSH_REQUESTS_AND_CHECK_NOTIFY` and friends.

  A whole bunch of things in the XenStore: `xs_directory` dealing with an array of strings, use of `sscanf` to parse single digit numbers, etc.

Porting plans...

...were scrapped in their infancy.

Single device driver model

In OpenBSD a pvbus(4) driver performs early hypervisor detection and can set up some parameters before attaching the guest nexus device:

```
xen0 at pvbus?
```

The xen(4) driver performs HVM guest initialization and serves as an attachment point for PVHVM device drivers, such as the Netfront, xnf(4):

```
xnf* at xen?
```

HVM guest initialization

- The hypercall interface

Hypercalls

Instead of defining a macro for every type of a hypercall we use a single function with variable arguments:

```
xen_hypercall(struct xen_softc *, int op,
    int argc, ...)
```

Xen provides an ABI for amd64, i386 and arm that we need to adhere to when preparing arguments for the hypercall.

The hypercall page

Statically allocated in the kernel code segment:

```
        .text
        .align  NBPG
        .globl  _C_LABEL(xen_hypercall_page)
_C_LABEL(xen_hypercall_page):
        .skip   0x1000, 0x90
```

The hypercall page

```
(gdb) disassemble xen_hypercall_page
<xen_hypercall_page+0>:      mov    $0x0,%eax
<xen_hypercall_page+5>:      sgdt
<xen_hypercall_page+6>:      add    %eax,%ecx
<xen_hypercall_page+8>:      retq
<xen_hypercall_page+9>:      int3
...
<xen_hypercall_page+32>:     mov    $0x1,%eax
<xen_hypercall_page+37>:     sgdt
<xen_hypercall_page+38>:     add    %eax,%ecx
<xen_hypercall_page+40>:     retq
<xen_hypercall_page+41>:     int3
...
```

HVM guest initialization

- The hypercall interface
- The shared info page

HVM guest initialization

- The hypercall interface
- The shared info page
- Interrupt subsystem

Interrupts

- Allocate an IDT slot

  Pre-defined value of 0x70 (start of an `IPL_NET` section) is used at the moment.

Interrupts

- Allocate an IDT slot
- Prepare interrupt, resume and recurse vectors

  Xen upcall interrupt is executing with an `IPL_NET` priority.

  `Xintr_xen_upcall` is hooked to the IDT gate.

  `Xrecurse_xen_upcall` and `Xresume_xen_upcall` are hooked to the interrupt source structure to handle *pending* Xen interrupts.

Interrupts

- Allocate an IDT slot
- Prepare interrupt, resume and recurse vectors
- Communicate the slot number with the hypervisor

A XenSource Platform PCI Device driver, xspd(4), serves as a backup option for delivering Xen upcall interrupts if setting up an IDT callback vector fails.

Interrupts

- Allocate an IDT slot
- Prepare interrupt, resume and recurse vectors
- Communicate the slot number with the hypervisor
- Implement API to (*dis*-)establish device interrupt handlers and mask/unmask associated event ports.

```
int  xen_intr_establish(evtchn_port_t,
     xen_intr_handle_t *, void (*handler)(void *),
     void *arg, char *name);
int  xen_intr_disestablish(xen_intr_handle_t);
void xen_intr_mask(xen_intr_handle_t);
int  xen_intr_unmask(xen_intr_handle_t);
```

Interrupts

- Allocate an IDT slot
- Prepare interrupt, resume and recurse vectors
- Communicate the slot number with the hypervisor
- Implement API to (*dis-*)establish device interrupt handlers and mask/unmask associated event ports.
- Implement events fan out

```
Xintr_xen_upcall(xen_intr()):
    while(pending_events?)
        xi = xen_lookup_intsrc(event_bitmask)
        xi->xi_handler(xi->xi_arg)
```

Almost there: XenStore

- Shared ring with a producer/consumer interface

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- Shared ring with a producer/consumer interface
- Driven by interrupts

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- Exposes a hierarchical filesystem-like structure

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- Driven by interrupts
- Exchanges ASCII NUL-terminated strings
- Exposes a hierarchical filesystem-like structure

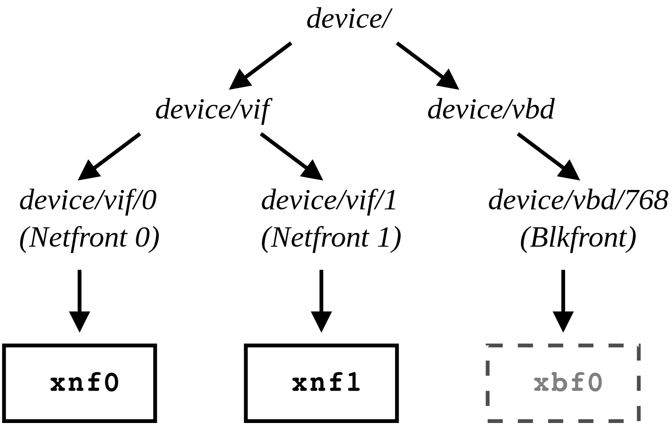
```
device/
device/vif
device/vif/0
device/vif/0/mac = "06:b1:98:b1:2c:6b"
device/vif/0/backend =
    "/local/domain/0/backend/vif/569/0"
```

Almost there: XenStore

References to other parts of the tree, for example, the backend `/local/domain/0/backend/vif/569/0`:

`domain`	`handle`	`uuid`
`script`	`state`	`frontend`
`mac`	`online`	`frontend-id`
`type`	`feature-sg`	`feature-gso-tcpv4`
`feature-rx-copy`	`feature-rx-flip`	`hotplug-status`

Almost there: Device discovery and attachment



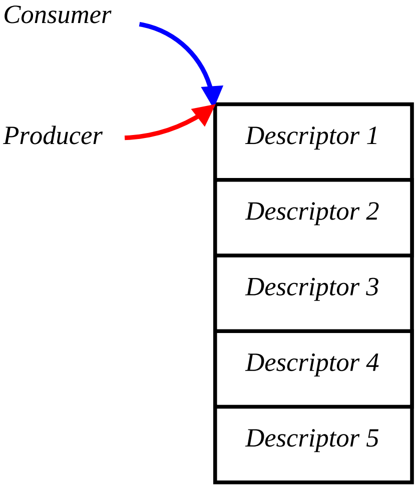
Enter Netfront

...or not!

Enter Netfront

Grant Tables are required to implement receive and transmit rings.

What's in a ring?



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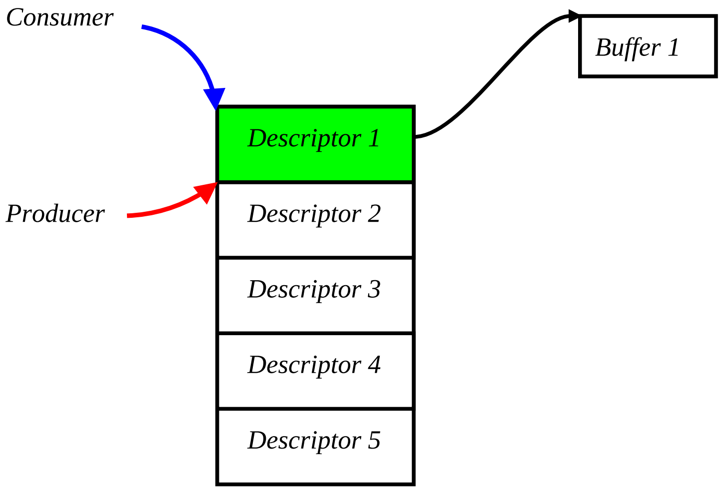

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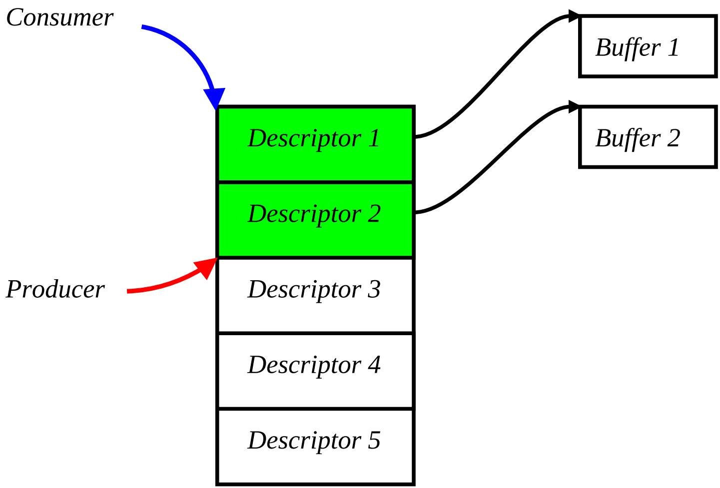

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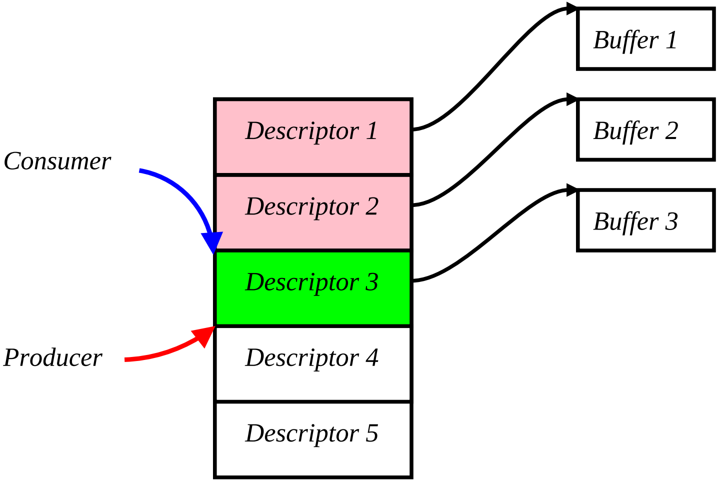

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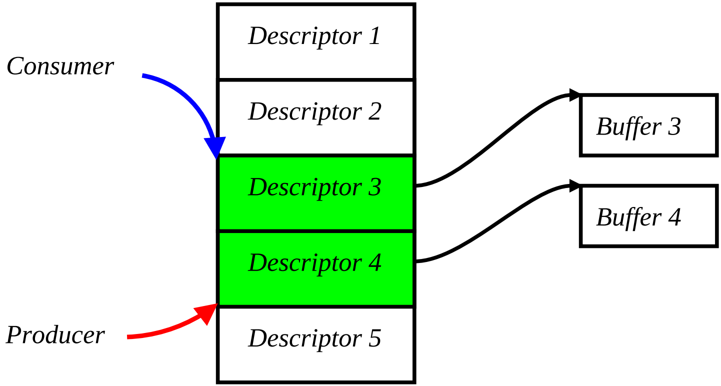

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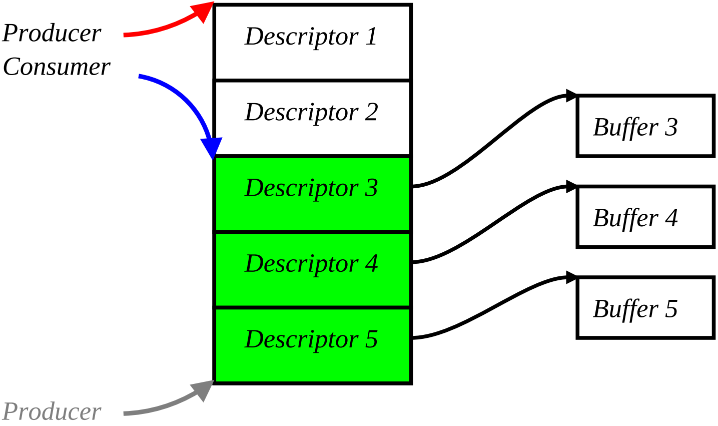

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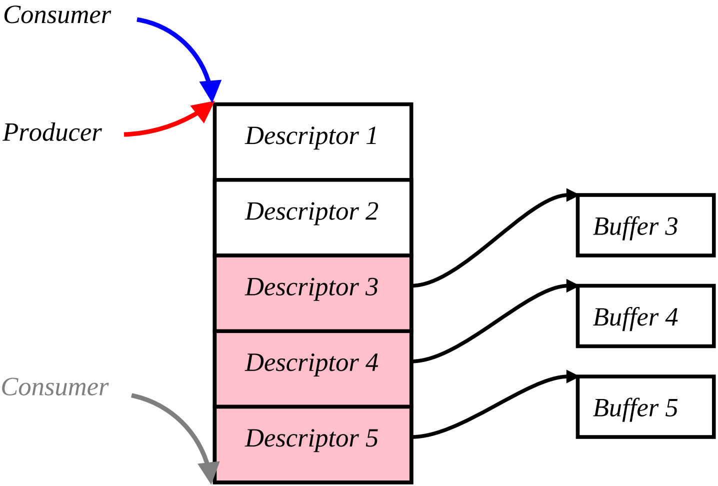

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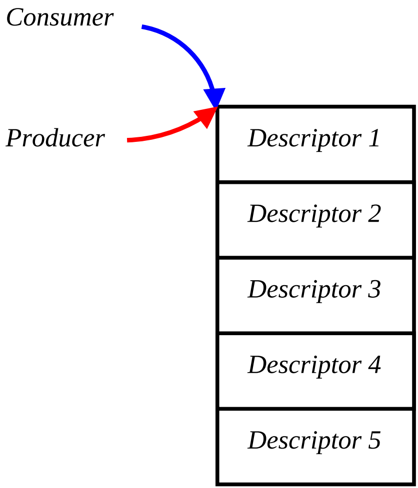

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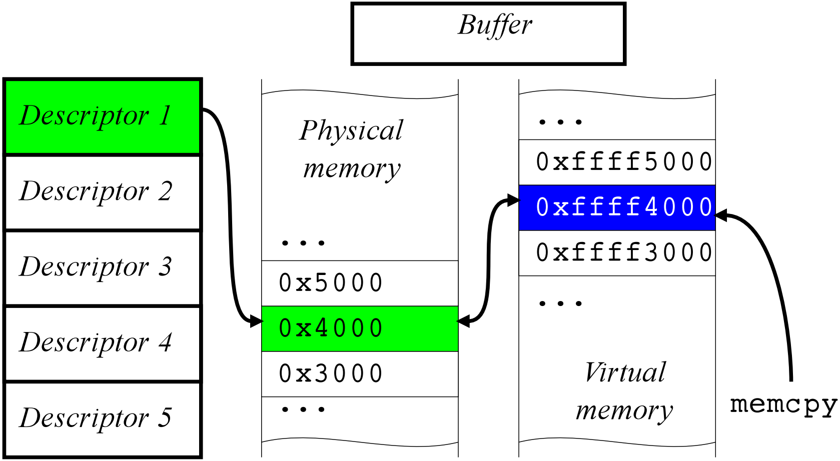

bus_dma(9)

Since its inception, bus_dma(9) interface has unified different approaches to DMA memory management across different architectures.

bus_dma(9): Preparing a transfer

- bus_dmamap_create to specify DMA memory layout

```
struct bus_dmamap {
    ...
    void                 *_dm_cookie;  // <-- cookie!
    bus_size_t             dm_mapsize;
    int                    dm_nsegs;
    bus_dmamap_segment_t dm_segs[1];
};
typedef struct bus_dmamap_segment {
    bus_addr_t             ds_addr;
    bus_size_t             ds_len;
    ...
} bus_dmamap_segment_t;
```

bus_dma(9): Preparing a transfer

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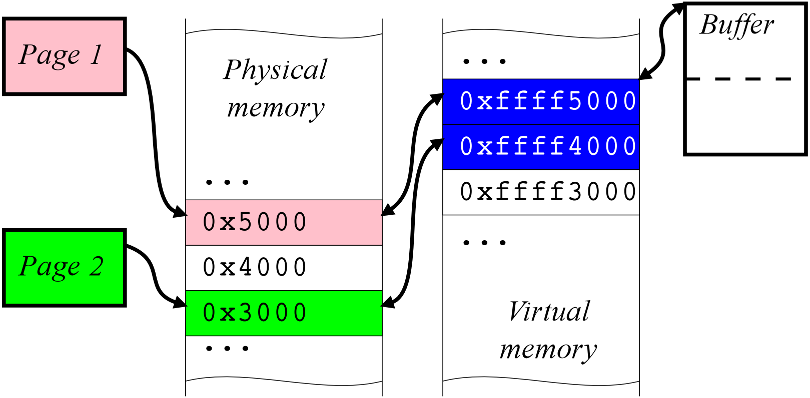
- `bus_dmamap_create` to specify DMA memory layout
- `bus_dmamem_alloc` to allocate physical memory
- `bus_dmamem_map` to map it into the KVA

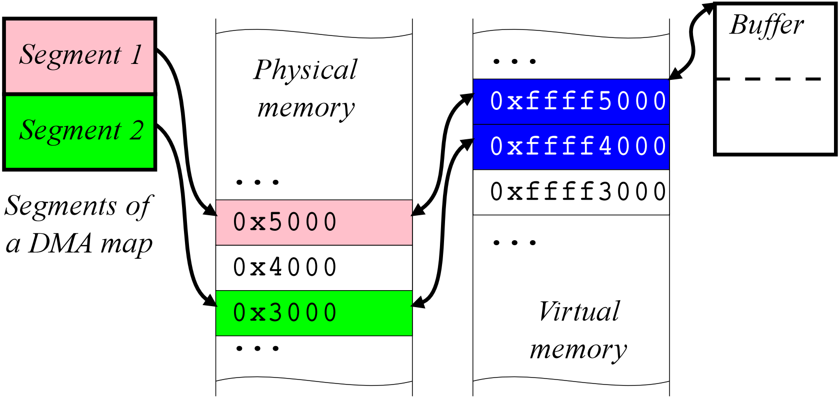
An example of buffer spanning multiple pages



bus_dma(9): Preparing a transfer

- `bus_dmamap_create` to specify DMA memory layout
- `bus_dmamem_alloc` to allocate physical memory
- `bus_dmamem_map` to map it into the KVA
- `bus_dmamap_load` to connect allocated memory to the layout

Buffer loaded into the segment map



bus_dma(9): Preparing a transfer

- `bus_dmamap_create` to specify DMA memory layout
- `bus_dmamem_alloc` to allocate physical memory
- `bus_dmamem_map` to map it into the KVA
- `bus_dmamap_load` to connect allocated memory to the layout
- signal *the other side* to start the DMA transfer

bus_dma(9): Transfer completion

- `bus_dmamap_unload` to disconnect the memory

bus_dma(9): Transfer completion

- `bus_dmamap_unload` to disconnect the memory
- `bus_dmamem_unmap` to unmap the memory from the KVA

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bus_dma(9): Transfer completion

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- `bus_dmamem_unmap` to unmap the memory from the KVA
- `bus_dmamem_free` to give the memory back to the system
- `bus_dmamap_destroy` to destroy the DMA layout

Netfront RX ring

Consists of a 64 byte header and a power-of-2 number of 8 byte descriptors that fit in one page of memory.

```
#define XNF_RX_DESC    256
struct xnf_rx_ring {
    uint32_t           rxr_prod;
    uint32_t           rxr_prod_event;
    uint32_t           rxr_cons;
    uint32_t           rxr_cons_event;
    uint32_t           rxr_reserved[12];
    union xnf_rx_desc  rxr_desc[XNF_RX_DESC];
} __packed;
```

Netfront RX ring

Each descriptor can be a “request” (when announced to the backend) or a “response” (when receive is completed):

```
union xnf_rx_desc {
    struct xnf_rx_req rxd_req;
    struct xnf_rx_rsp rxd_rsp;
} __packed;
```

Netfront RX ring

Descriptor contains a *reference* (`rxq_ref`) of a *page sized* memory buffer:

```
struct xnf_rx_req {
    uint16_t rxq_id;
    uint16_t rxq_pad;
    uint32_t rxq_ref;
} __packed;
```

bus_dma(9) usage for the Netfront RX ring

Create a shared page of memory for the ring data:

- `bus_dmamap_create` a single entry segment map

bus_dma(9) usage for the Netfront RX ring

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bus_dma(9) usage for the Netfront RX ring

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- `bus_dmamem_alloc` a single page of memory for descriptors
- `bus_dmamem_map` the page and obtain a VA
- `bus_dmamap_load` the page into the segment map

bus_dma(9) usage for the Netfront RX ring

Now we can *communicate* the location of this page with a backend, but first we need to create packet maps for each descriptor (256 in total) so that we can connect memory buffers (mbuf clusters) with references in the descriptor.

We don't need to allocate memory for buffers since they're coming from the mbuf cluster pool.

bus_dma(9) usage for the Netfront RX ring

Whenever we need to put the cluster on the ring we just need to perform a `bus_dmamap_load` operation on an associated DMA map and then set the descriptor reference to the value stored in the DMA map segment...

Right?

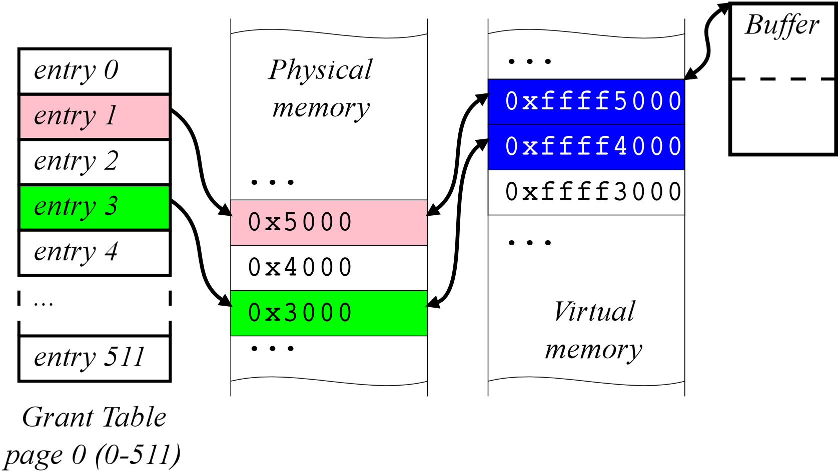
bus_dma(9) usage for the Netfront RX ring

Whenever we need to put the cluster on the ring we just need to perform a `bus_dmamap_load` operation on an associated DMA map and then set the descriptor reference to the value stored in the DMA map segment...

Right? ***Wrong!***

RX and TX descriptors use **references**, not physical addresses!

Grant Table reference



Grant Table entry

Grant Table entry *version 1* contains a *frame number*, flags (including permissions) and a domain number to which the access to the *frame* is provided.

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If only we could add a translation layer to the bus_dma(9) interface to convert between physical address and a frame number.

bus_dma(9) and Grant Tables

Luckily bus_dma(9) interface allows us to use custom methods:

```
struct bus_dmamap_tag xen_bus_dmamap_tag = {
    NULL,  // <-- another cookie!
    xen_bus_dmamap_create,  xen_bus_dmamap_destroy,
    xen_bus_dmamap_load,    xen_bus_dmamap_load_mbuf,
    NULL,  NULL,            xen_bus_dmamap_unload,
    xen_bus_dmamap_sync,    _bus_dmamem_alloc,
    NULL,                   _bus_dmamem_free,
    _bus_dmamem_map,        _bus_dmamem_unmap,
};
```

Xen bus_dma(9) interface

After creation of the DMA segment map structure via `_bus_dmamap_create`, we can create an additional array for the purpose of mapping Grant Table references to physical addresses of memory segments loaded via `bus_dmamap_load` and set it to be a DMA map cookie!

Xen bus_dma(9) interface

After creation of the DMA segment map structure via `_bus_dmamap_create`, we can create an additional array for the purpose of mapping Grant Table references to physical addresses of memory segments loaded via `bus_dmamap_load` and set it to be a DMA map cookie!

We have to preallocate Grant Table references at this point so that we can perform `bus_dmamap_load` and `bus_dmamap_unload` sequences fast. Since we create DMA maps in advance, `xen_grant_table_alloc` can take time to increase the number of Grant Table pages if we're running low on available references.

Xen bus_dma(9) interface

When we're ready to put the buffer on the ring we call `bus_dmamap_load` that populates the DMA map segment array with physical addresses of buffer segments.

Xen bus_dma(9) interface

When we're ready to put the buffer on the ring we call `bus_dmamap_load` that populates the DMA map segment array with physical addresses of buffer segments.

Once it's done we can punch those addresses into Grant Table entries that we have preallocated and set appropriate permission flags via `xen_grant_table_enter`.

Xen bus_dma(9) interface

When we're ready to put the buffer on the ring we call `bus_dmamap_load` that populates the DMA map segment array with physical addresses of buffer segments.

Once it's done we can punch those addresses into Grant Table entries that we have preallocated and set appropriate permission flags via `xen_grant_table_enter`.

We record physical addresses in our reference mapping array and swap values in the DMA map segment array to Grant Table references. This allows the Netfront driver to simply use these values when setting up ring descriptors.

Xen bus_dma(9) interface

During `bus_dmamap_unload` we perform the same operations backwards: `xen_grant_table_remove` clears the Grant Table entry, we swap physical addresses back and call into the system to finish unloading the map.

If we wish to destroy the map, `bus_dmamap_destroy` will deallocate Grant Table entries via `xen_grant_table_free` and then destroy the map itself.

Announcing Netfront rings

In order to announce locations of RX and TX rings, Netfront driver needs to set a few properties in its “device” subtree via XenStore API.

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A Grant Table reference for the RX ring data needs to be converted to an ASCII string and set as a value for the “rx-ring-ref” property.

Announcing Netfront rings

In order to announce locations of RX and TX rings, Netfront driver needs to set a few properties in its “device” subtree via XenStore API.

A Grant Table reference for the RX ring data needs to be converted to an ASCII string and set as a value for the “rx-ring-ref” property.

TX ring location is identified by the backend with the “tx-ring-ref” property.

Operation in the Amazon EC2

Amazon Machine Image (AMI) is required to contain some knowledge of the EC2 cloud to be able to obtain an SSH key during the instance creation.

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Since the information is provided by the EC2 via an internal HTTP server, it's required that the first networking interface comes up on startup with a DHCP configuration and fetches the SSH key.

Operation in the Amazon EC2

Amazon Machine Image (AMI) is required to contain some knowledge of the EC2 cloud to be able to obtain an SSH key during the instance creation.

Since the information is provided by the EC2 via an internal HTTP server, it's required that the first networking interface comes up on startup with a DHCP configuration and fetches the SSH key.

This procedure is called "cloud-init" and obviously requires some additions and adjustments to the OpenBSD boot procedure.

Operation in the Amazon EC2

- Public images of 5.8-current snapshots were provided regularly by Reyk Flöter (reyk@) and Antoine Jacoutot (ajacoutot@) in several “availability zones”.

Operation in the Amazon EC2

- Public images of 5.8-current snapshots were provided regularly by Reyk Flöter (reyk@) and Antoine Jacoutot (ajacoutot@) in several "availability zones".
- Antoine has created a few scripts to automate creation and upload of OpenBSD images to the EC2 using ec2-api-tools as well as perform minimal "cloud-init" on the VM itself.

Running under Qubes OS

- Booted fine but the network didn't work

Running under Qubes OS

- Booted fine but the network didn't work
- Turned out that Qubes "chains" VMs

```
/local/domain/3/device/vif/0/backend-id = "2"
```

Running under Qubes OS

- Need to pass down the backend domain number to the `xen_grant_table_enter`

Running under Qubes OS

- Need to pass down the backend domain number to the `xen_grant_table_enter`
- Need to bind the event channel to the correct remote domain

Running under Qubes OS

Grant Table entries are not given back to us!

```
xnf0: grant table reference 9 is held by domain 2
```

Running under Qubes OS

Grant Table entries are not given back to us!

`xnf0: grant table reference 9 is held by domain 2`

Fixed by taking Domain ID field in account when doing CAS

Running under Qubes OS

- VM configuration is done through shared memory setup accessed via libxc and libs.

Running under Qubes OS

- VM configuration is done through shared memory setup accessed via libxc and libs.
- libxc and libs issue hypercalls via a device node accessible by the root user.

Future work

- Support for the PVCLOCK timecounter

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- Support for the PVCLOCK timecounter
- Support for suspend and resume

Future work

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- Support for suspend and resume
- Driver for the Blkfront interface

Future work

- Support for the PVCLOCK timecounter
- Support for suspend and resume
- Driver for the Blkfront interface
- Support for the PCI pass-through

Thank you!

I'd like to thank Reyk Flöter and Esdenera Networks GmbH for coming up with this amazing project, support and letting me have a freedom in technical decisions.

I'd also like to thank OpenBSD developers, especially Reyk Flöter, Mark Kettenis, Martin Pieuchot, Antoine Jacoutot, Mike Larkin and Theo de Raadt for productive discussions and code reviews.

Huge thanks to all our users who took their time to test, report bugs, submit patches and encourage development.

Special thanks to Wei Liu and Roger Pau Monné from Citrix for being open to questions and providing valuable feedback as well as other present and past contributors to the FreeBSD port. Without it, this work might not have been possible.

Question Time

Questions?

Thank you for attending the talk!