Implementation of Xen PVHVM drivers in OpenBSD

Mike Belopuhov
Esdenera Networks GmbH
mikeb@openbsd.org

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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

Need to be able to:

- boot: *already works!*
Requirements

Need to be able to:

- boot: *already works!*
- mount root partition
Requirements

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► boot: *already works!*

► mount root partition: *already works!*
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- boot: *already works!*
- mount root partition: *already works!*
- support SMP
Requirements

Need to be able to:

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

Need to be able to:

- boot: *already works!*
- mount root partition: *already works!*
- support SMP: *fixed shortly*
Requirements

Need to be able to:

- boot: already works!
- mount root partition: already works!
- support SMP: fixed shortly
- perform “cloud init”
Requirements

Need to be able to:

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- mount root partition: already works!
- support SMP: fixed shortly
- perform “cloud init”: requires PV networking driver. Snap!
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...
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
Outlook on the FreeBSD implementation

▶ Huge in size

“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.
Outlook on the FreeBSD implementation

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- Needlessly complex
- Clash of coding practices
Outlook on the FreeBSD implementation

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Lots of code has been taken verbatim from Linux (where license allows)
Outlook on the FreeBSD implementation

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- Questionable abstractions
Outlook on the FreeBSD implementation

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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.
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:

```c
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:

```assembly
.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.

```c
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

```c
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
Almost there: XenStore

- Shared ring with a producer/consumer interface
- Driven by interrupts
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- Shared ring with a producer/consumer interface
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- Exchanges ASCII NUL-terminated strings
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- Shared ring with a producer/consumer interface
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- Exchanges ASCII NUL-terminated strings
- Exposes a hierarchical filesystem-like structure
Almost there: XenStore

- Shared ring with a producer/consumer interface
- 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:

<table>
<thead>
<tr>
<th>domain</th>
<th>handle</th>
<th>uuid</th>
</tr>
</thead>
<tbody>
<tr>
<td>script</td>
<td>state</td>
<td>frontend</td>
</tr>
<tr>
<td>mac</td>
<td>online</td>
<td>frontend-id</td>
</tr>
<tr>
<td>type</td>
<td>feature-sg</td>
<td>feature-gso-tcpv4</td>
</tr>
<tr>
<td>feature-rx-copy</td>
<td>feature-rx-flip</td>
<td>hotplug-status</td>
</tr>
</tbody>
</table>
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?

Producer ➔ Consumer

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5
What’s in a ring?

Producer

Consumer

Buffer 1

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5
What’s in a ring?
What’s in a ring?

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5
Producer
Consumer
Buffer 1
Buffer 2
Buffer 3
What’s in a ring?

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5
Producer
Consumer
Buffer 3
Buffer 4
What’s in a ring?
What’s in a ring?
What’s in a ring?

Producer

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5
Consumer
What’s in a ring?

Descriptor 1
Descriptor 2
Descriptor 3
Descriptor 4
Descriptor 5

Buffer

Physical memory

Descriptor 1
0x4000
0x5000

Descriptor 2

Virtual memory

Descriptor 3
0xffff3000
0xffff4000
0xffff5000

Descriptor 4

Descriptor 5

memcpy
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

```c
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

- `bus_dmamap_create` to specify DMA memory layout
- `bus_dmamem_alloc` to allocate physical memory
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
An example of buffer spanning multiple pages

Page 1

Page 2

Physical memory

0xFFFF5000
0xFFFF4000
0xFFFF3000
...

Virtual memory

Buffer
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

Segments of a DMA map

Segment 1
Segment 2

Physical memory

0x5000
0x4000
0x3000

Virtual memory

0xffff5000
0xffff4000
0xffff3000

Buffer
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
bus_dma(9): Transfer completion

- `bus_dmamap_unload` to disconnect the memory
- `bus_dmamem_unmap` to unmap the memory from the KVA
- `bus_dmamem_free` to give the memory back to the system
bus_dma(9): Transfer completion

- `bus_dmamap_unload` to disconnect the memory
- `bus_dmamem_unmap` to unmmap 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.

```c
#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:

```c
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_dmamap_create` a single entry segment map
- `bus_dmamemAlloc` a single page of memory for descriptors
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_dmmem_alloc a single page of memory for descriptors
- bus_dmmem_map the page and obtain a VA
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_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 page 0 (0-511)
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.
Grant Table entry

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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:

```c
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_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.
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

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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.

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!

xnfd0: 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
Future work

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

- Support for the PVCLOCK timecounter
- 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!

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Question Time

Questions?
Thank you for attending the talk!