# Crossing the endianness bridge
## (or a foolish attempt at mixed-endian virtualization)

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KVM Forum '13

# Foreword

This is a (hopefully short) talk about mixed-endianness virtualization support on arm64. It is NOT about:

- Finding out whether Little Endian is better or worse than Big Endian
  - → We all know what the answer is, don't we?
- The big.LITTLE architecture
  - → One issue at a time, please...
- Claming we have nailed the problem for good
  - → If only...

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- Starting a discussion on how we can better support that kind of configuration

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Mandatory read:
Big and Little Endian Inside Out – Ben Herrenschmidt, LPC12

# ARM: to BE or not to BE?

So what about ARM and endianness?

- Endianness agnostic architecture
- Mostly used as LE with Linux
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Meanwhile, in Cambridge:

WD Too bad we can't really test this BE code...
MZ Wonder if we could stick something in KVM...
WD ...
MZ Profit!

# ARM: to BE or not to BE? (take #2)

Why this sudden surge in BE interest?

Isn't BE a dead horse anyway?

Well, maybe. But there's always a "But":

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- They are very interested in AArch64
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  - Unmaintained
  - Closed source
  - Certified
  - Not 64bit safe
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  - Did I say old and unmaintained?
- They either don't want to or simply cannot touch this code

# BE: Do the right thing!

Rewriting the BE code to be endianness agnostic.

- Solves the problem completely
- The perfect solution
- Why the hell are we here?

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## Not an option.

- It would take years to achieve
- Goes against all the reasons we have mentioned before

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## It's not fun at all anyway

# BE: Compiler magic to have endian-specific acccessors

```
struct bar {
        unsigned int foo;
};

void blah(struct bar *barp)
{
        barp->foo = 0xbe5afe;
}

blah:   mov     w1, #0x5afe
        movk    w1, #0xbe, lsl #16
        str     w1, [x0]
        ret
```

# BE: Compiler magic to have endian-specific acccessors

```
struct bar {
        unsigned int foo;
} __struct_layout_be;

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```

Lovely idea, but requires the data structure to be annotated, which defeats the whole idea of *not touching the code*.

# BE: hacking the kernel to run mixed-endian userspace

Allow the kernel to deal with both LE and BE userspaces *at the same time*, by doing the neccessary marshalling at the syscall level (*à la compat-layer*).
Seems like an ideal solution:

- No source code change
- No userspace change
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Unfortunately yes. It is perfect until you consider:

- Futexes
- Shared memory
- Most IPCs, actually

## But we seem to get closer...

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Let's move all our BE code (including the kernel) into a VM:

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Let's investigate...

# ARM: The art of BEing

ARM BE support started off with something called BE-32:

- 32bit word invariant
  - → Words have the same ordering, no matter the endianness
- Byte (and 16bit) addressing differs between BE and LE
- Just a hack on the bus
- Affects both data and intructions
- Switching from one mode to another is a nightmare
  - → The best path to insanity

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Thankfully, we can now forget about this.

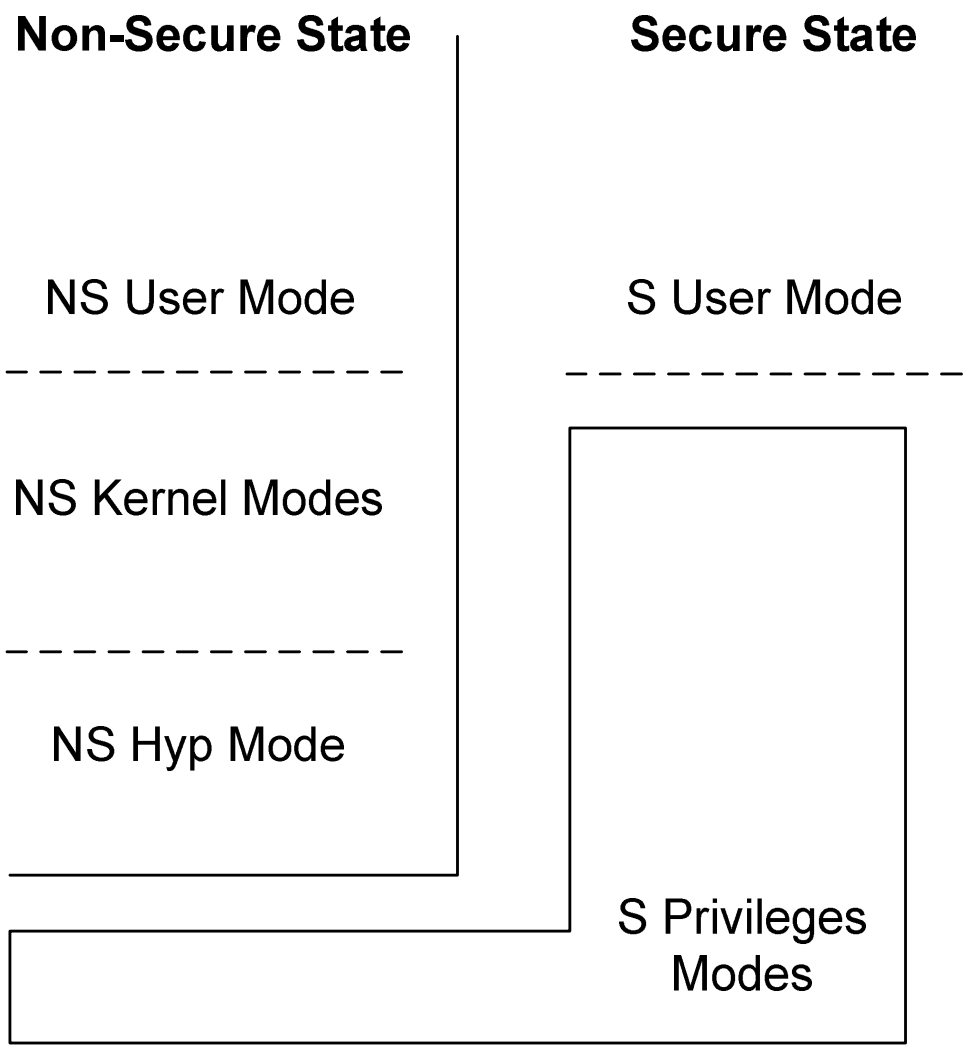
# ARM: The art of BEing

Starting with ARMv6, BE support is implemented as BE-8:

- Byte invariant
  - → Bytes are located at the same address, no matter the endianness
- 16bit, 32bit addressing differs between BE and LE
  - → Just like on any other sane architecture...
- Instructions and data have distinct endianness
  - Instructions are always little endian
  - Data endianness is configurable

This is what to want to support.

# ARM: Exception levels and endianness



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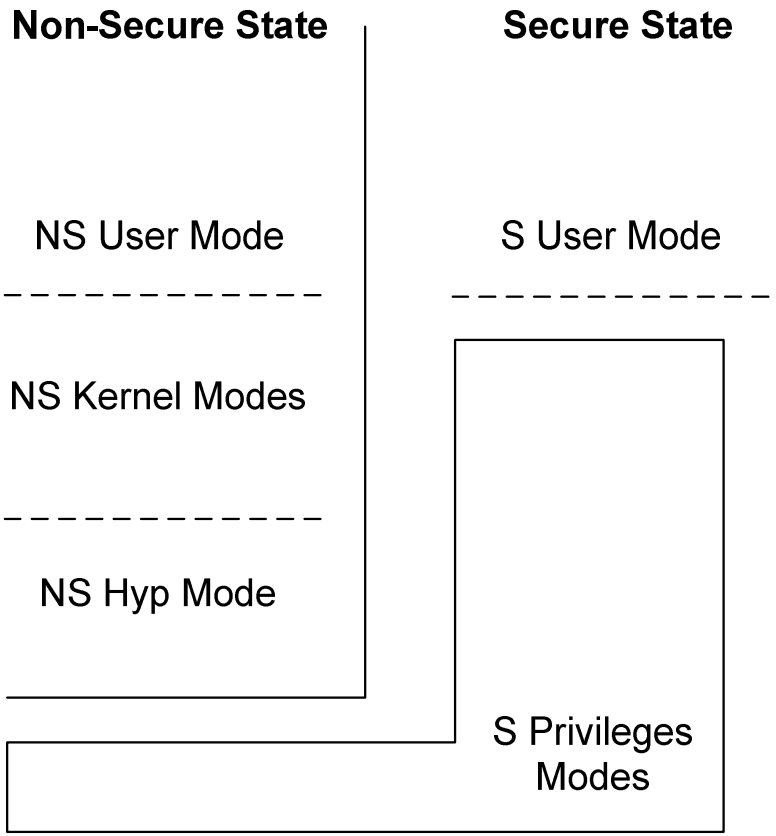


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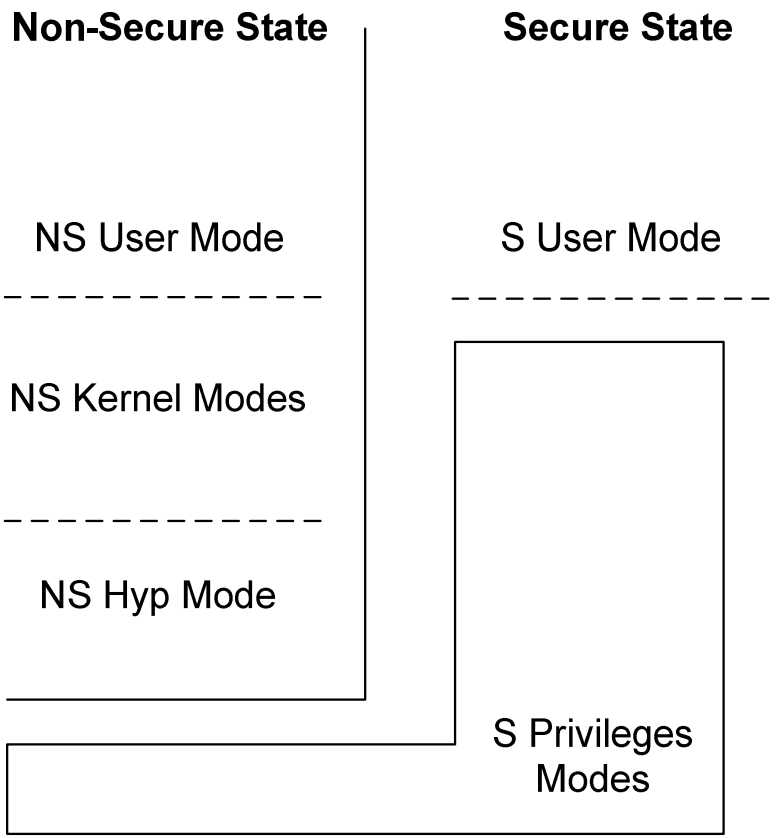


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- Let the guest deal with its own endianness
- Switch back to LE when trapping into the hypervisor.

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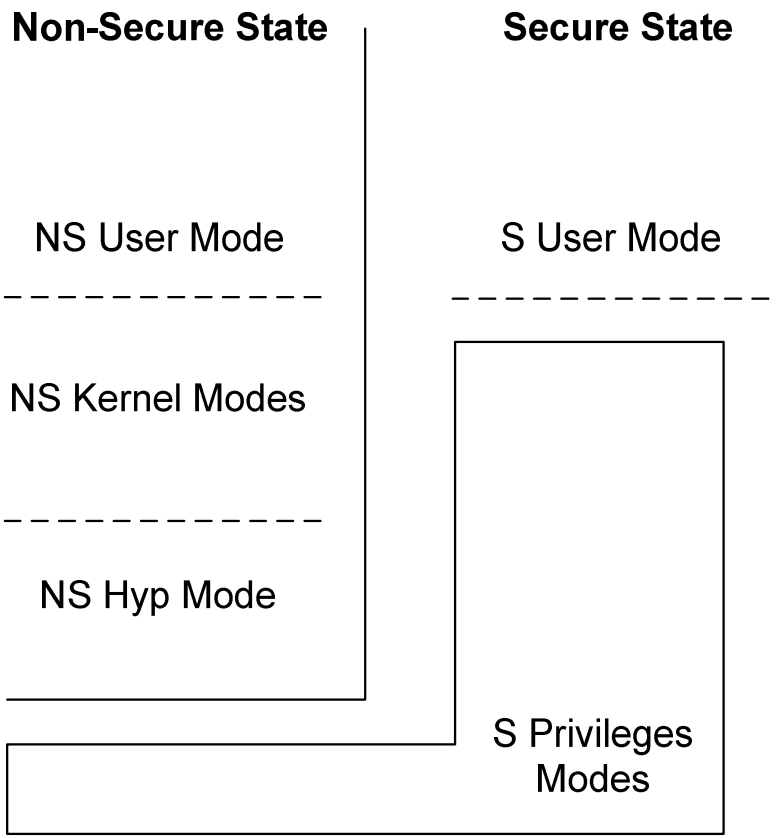


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Job done! Well, almost...

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- Emulated devices should also be OK
- Let's look a bit closer

# Interlude: Second stage translation

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- A second set of page tables (Stage-2 translation)
- Converts IPA to PA
  - → Allows mapping of what the guest sees as physical memory with the real thing
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MMIO devices do not have a Stage-2 translation, allowing access to be trapped.

# The journey of a (wana)BE write

Let's have a look at what happens when a BE guest writes to an emulated LE device:

- Guest loads the value to write in a register
- Guest byteswaps the value in the register
  - → The bus is LE, so the value has to be swapped
- Guest performs the write
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At that point, we have the following information:

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But the register now contains a byteswapped value, that we'll *have to byteswap again* before passing it to the device emulation.

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BE guest reads from a LE device are quite similar:

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Once the device has emulated the read access, we have to:

- Byteswap the value
  → The guest thinks it reads from a LE bus...
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- Resume the guest
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Because device emulation completely bypasses the bus (and registers have no endianness), we end up byteswapping data twice.

# The aftermath

So what have we found so far:

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Are we there yet? Not quite.

# The case of virtio/MMIO

What is virtio?

- A framework for paravirtualized devices
- Uses shared memory between host and guest
- High performance, low overhead

What is virtio/MMIO?

- The sick brainchild of Paweł Moll <pawel.moll@arm.com>
- Allows a virtio device to be exposed to a PCI-less system
- Exposes the configuration registers as an MMIO range
- Extensively used on ARM systems ("PCI? WTF?")
- The only way kvmtool can provide a useful device to a KVM/arm[64] guest

So what is the problem with virtio/MMIO?

# The case of `virtio/MMIO` #2

The spec is quite unclear when it comes to endianness.

- Config space (recently) declared as LE only
- Endianness in the `virtio-ring` unspecified
  - $\rightarrow$ Assumed to be identical between host and guest

The challenge here is to introduce mixed-endian support without breaking existing users.

# virtio/MMIO: Fixing the config space

As we said above, the virtio/MMIO configuration space is strictly LE. However, the Linux driver code accessing it looks like this:

```
static void vm_get(struct virtio_device *vdev, unsigned offset,
                   void *buf, unsigned len)
{
        struct virtio_mmio_device *vm_dev = to_virtio_mmio_device(vdev);
        u8 *ptr = buf;
        int i;

        for (i = 0; i < len; i++)
                ptr[i] = readb(vm_dev->base + VIRTIO_MMIO_CONFIG + offset + i);
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}
```

While the above code works for LE guests on LE hosts, it is unlikely to give any meaningful result on a BE guest (no matter the endianness of the host)...

# virtio/MMIO: Fixing the config space

Let's change the function prototype, providing an access size:

```
static void vm_get(struct virtio_device *vdev, unsigned offset,
                   void *buf, unsigned len, unsigned access_size)
{
        struct virtio_mmio_device *vm_dev = to_virtio_mmio_device(vdev);
        int i;

        switch (access_size) {
        [...]
        case 2: {
                u16 *ptr = buf;
                for (i = 0; i < len; i++)
                        ptr[i] = readw(vm_dev->base + VIRTIO_MMIO_CONFIG + offset + i);
                break;
        }
        case 4: {
                u32 *ptr = buf;
                for (i = 0; i < len; i++)
                        ptr[i] = readl(vm_dev->base + VIRTIO_MMIO_CONFIG + offset + i);
                break;
        }
        [...]
}
```

Using the proper accessors (which are LE) solves the problem.

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        [...]
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```

Using the proper accessors (which are LE) solves the problem.

At the expense of quite a few changes across **all** `virtio` drivers...

# virtio/MMIO: One ring to BEnd them all

The virtio-ring can contain pure data, but also:

- Structures that are part of the virtio protocol
  - → vring_desc, vring_avail...
- Data Directly parsed by the device backend
  - → Depend on the device protocol itself
- When guest and host don't agree on endianness, things get a bit ugly

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So what do we do?

- One possibility would be to declare all data to be LE
  - → Breaks existing BE users
  - → Could be an option for long term future, though
- Another is to add an endianness negotiation phase to the setup protocol
  - → We have to make sure this gracefully falls back to the existing behaviour with unsuspecting guests

# virtio/MMIO: One ring to BEnd them all

When a guest initializes a virtio device, it engages in a "feature negotiation" phase

For each virtio queue the guest initializes:

- Guest reads "feature flags" from the host
- Guest clears flags it doesn't support (or doesn't understand)
- Guest writes the flags it has selected back to the host

We can leverage this negotiation phase to our benefit:

- Let's define two new flags
  - → VIRTIO_RING_F_GUEST_LE: LE guest
  - → VIRTIO_RING_F_GUEST_BE: BE guest
- The host can set either or both, depending on the endianness it supports
- The guest can keep the one corresponding to its endianness, or clear both.
  - → It can't keep them both on!

# virtio/MMIO: One ring to BEnd them all

So how does this work in practice:

- Host can expose whatever endianness it supports, or none
- Guest can expose the one it uses, or none
- "none" is the current behaviour...
- Very finely grained – done on a per-queue basis

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- "none" is the current behaviour...
- Very finely grained – done on a per-queue basis

Added bonus:

- Selected at run time
  - → No need for a endian-specific platform emulation
- No overhead at init time
  - → Part of the feature negotiation phase
- Minimal overhead at run time
  - → Platform emulation locally tests the queue flag
  - → No need to trap into the kernel to find out
  - → No hardcoded behaviour
- Architecture independant
  - → Assuming your platform is bi-endian

# virtio/MMIO: One ring to BEnd them all

And the guest side patch for that is incredibly small:

```
diff --git a/drivers/virtio/virtio_ring.c b/drivers/virtio/virtio_ring.c
index 6b4a4db..efff20a 100644
--- a/drivers/virtio/virtio_ring.c
+++ b/drivers/virtio/virtio_ring.c
@@ -813,6 +813,14 @@ void vring_transport_features(struct virtio_device *vdev)
                        break;
                case VIRTIO_RING_F_EVENT_IDX:
                        break;
+#ifdef __LITTLE_ENDIAN
+               case VIRTIO_RING_F_GUEST_LE:
+#endif
+#ifdef __BIG_ENDIAN
+               case VIRTIO_RING_F_GUEST_BE:
+#endif
+                       break;
                default:
                        /* We don't understand this bit. */
                        clear_bit(i, vdev->features);
```

# kvmtool: Handling mixed-endianness

kvmtool is the primary tool for KVM/arm64 development, as it makes a wonderful prototyping platform:

- Implements the queue endianness extension
- Extensive changes in the queue management
  - `virt_queue__available()`
  - `virt_queue__pop()`
  - `virt_queue__get_head_iov()`
  - ...
  - most of `tools/kvm/virtio/core.c`, actually
- A number of backends
  - console
  - block
  - 9p
  - net (uip)

# kvmtool: let there BE...

## The result:

```
root@genericarmv7ab:~# cat /proc/cpuinfo
processor : 0
model name : ARMv7 Processor rev 0 (v7b)
Features : swp half thumb fastmult vfp edsp neon vfpv3 tls vfpv4 idiva idivt vfpd32 lpae
CPU implementer : 0x41
CPU architecture: 7
CPU variant : 0x0
CPU part : 0xd0f
CPU revision : 0

processor : 1
model name : ARMv7 Processor rev 0 (v7b)
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CPU implementer : 0x41
CPU architecture: 7
CPU variant : 0x0
CPU part : 0xd0f
CPU revision : 0

Hardware : Dummy Virtual Machine
Revision : 0000
Serial : 0000000000000000
```

ARMv7 BE VM running on top of an ARMv8 LE host. A lot of headache for a very unspectacular result.

# What we end up with

- A `virtio` extention that is:
  - → architecture independant
  - → `virtio`-centric
  - → easily implemented
  - → efficient
  - → optional
- A `kvmtool` implementation that is:
  - → minimal
  - → mostly made of bug-fixes
- A KVM/arm implementation that is 100% bug-fixes

# What got fixed so far

Doing this work was an interesting opportunity to revisit some areas of the code:

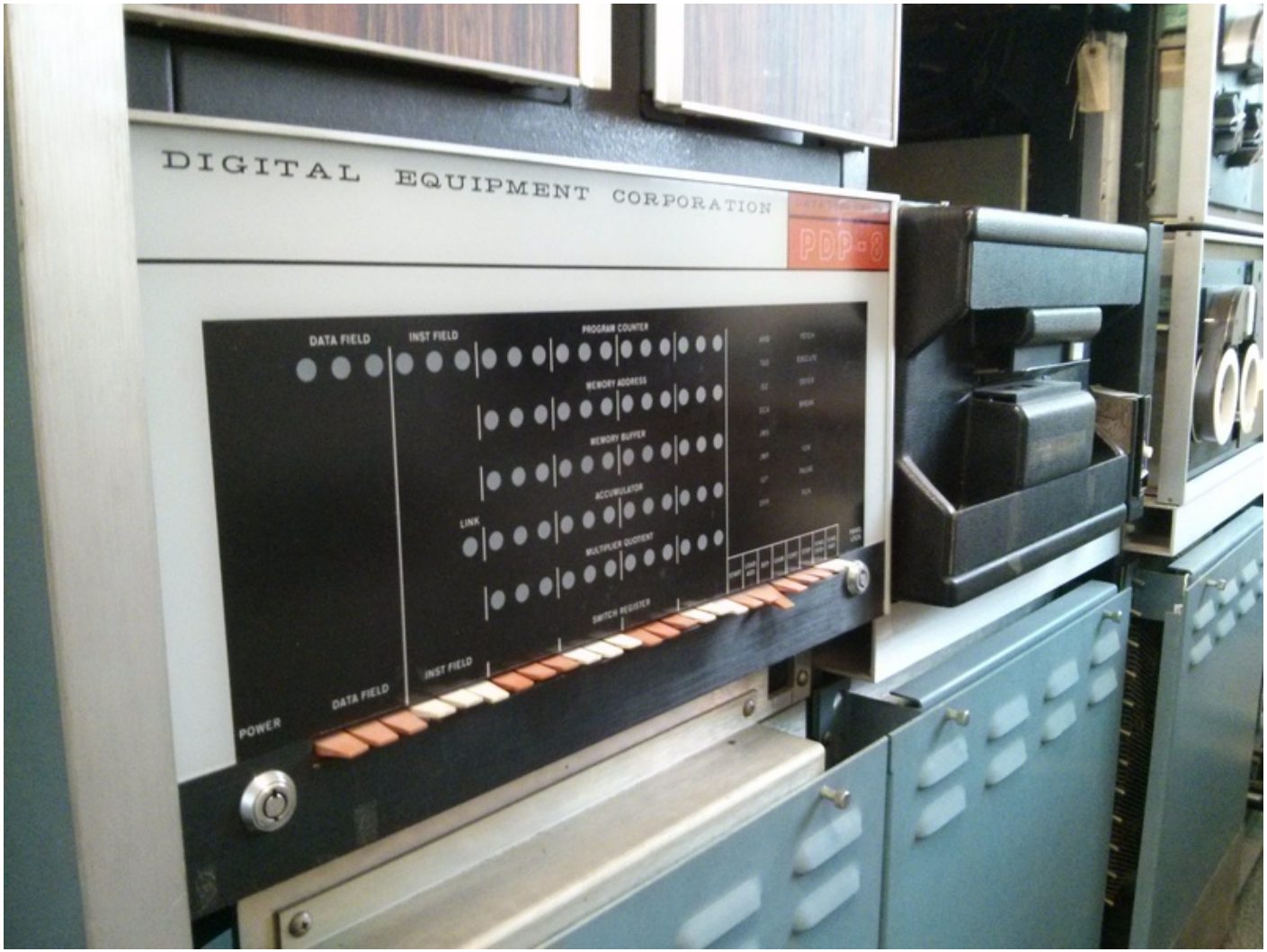
- Assumptions about the endianness in the KVM/arm code
  - → MMIO handling code has been substantially rewritten
  - → More to come...
- Configuration register access from the guest kernel
  - → Introduction of size-based accessors
  - → Signature check fix
- Endianness independance of the kvmtool virtio implementation
  - → virtio queue rework
  - → device implementation fixes

# What is left to fix

We're not quite done yet:

- A bunch of virtio devices are still left unloved
  - → `scsi`
  - → `rng`
  - → and probably more...
- Running LE guests on BE host
  - → Just in case you didn't have enough
  - → Requires more fixes in KVM/arm code
  - → Probably some more in `kvmtool`
  - → Linux driver code should hopefully be in a decent shape

# The future




Middle-endian is the way!

# The future, more seriously

In parallel, work is being done on the virtio front to solve the endianness problem for good (among others).
This virtio 1.0 specification would change:

- Everything is Little-Endian
  - → Native endianness has been forcefully eliminated
  - → Solves the problem in the long run

# The future, more seriously

In parallel, work is being done on the virtio front to solve the endianness problem for good (among others).
This virtio 1.0 specification would change:

- Everything is Little-Endian
  - → Native endianness has been forcefully eliminated
  - → Solves the problem in the long run

But this also brings its own set of problems:

- Two different driver implementations
- Two different device implementations
- Some kind of (transitionnal) compatibility mode between them
- Nothing is available now

This presentation is more about a short term solution.

# The end

Questions?