Device Drivers in Barrelfish

Barrelfish Technical Note 19

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Chapter 1

Introduction

This document describes the way we write device drivers in Barrelfish. It will walk you through the necessary steps to integrate your driver in the Barrelfish infrastructure and gives an overview of available APIs, libraries and tools to help you with the process.

In the next chapter, we will give a short overview and walkthrough of an existing driver in the Barrelfish code base, to introduce most of the common terms and concepts. In the following chapters, we will then go deeper and look into the hardware specific APIs available for all the different architectures that Barrelfish supports.

Unfortunately, at this point, there is no unified interface for drivers on ARM and x86. So, we will usually distinguish between these two architectures in the document.
Chapter 2

High-level overview: A first look at device drivers in BarreliSh

In a first step, we will look at the necessary bits and pieces to write a new driver in BarreliSh on the ARM platform, by using an existing, very simple driver as a walkthrough from the BarreliSh code base – the FDIF driver, a device used for face detection typically found on OMAP chips.

The relevant code for the driver resides in the tree at `usr/drivers/omap44xx/fdif/`. In order to get an idea of what the driver entails, we will look at its Hakefile. Hakefiles are the declarative description of how a program is built in BarreliSh and what its dependencies are. If you need more informations on our build system, you should have a look at the Hake technote [1], which provides a detailed description of Hake, the BarreliSh build system. We will look at the Hakefile for the FDIF driver in Listing 2.1 (a Haskell program, really) and explain what it means for the driver program. `cFiles` is a list of C source files that are compiled and linked for this driver. In our case, we use hake to just search for every file that has a "c" file extension in the current directory and return this as a list of files for `cFiles`. If you go and look at `usr/drivers/omap44xx/fdif` you will find that this will encompass only two files, `fdif.c` and `picture.c`.

The next attribute, `mackerelDevices`, contains a list Mackerel files, these are devices that we have specified in our domain specific language called Mackerel, and we would now like to use in our driver. If you do not know what Mackerel is, let me explain it to you: Mackerel is a DSL for describing device registers. You can find an abundance of Mackerel files in the `devices` directory inside the source tree. For example, the `omap44xx_fdif` device mentioned in the Hakefile at the third position is found in `devices/omap/omap44xx_fdif.dev`. They all, describe a particular device we use in BarreliSh to varying degrees of detail, ranging from ethernet cards to xAPIC or even descriptions of the file-allocation-table for the FAT file-system. Now, you might think, well, why can’t I just use a regular C struct or even integer types with bit operations for that? And in general you could. However, the Mackerel compiler gives you a lot of nice things on top of this description. For one thing, it will generate for you all the code you need to program the register with certain values, that means it takes care of all the bit-shifting and masking operations based on your description. On the other hand, it will generate functions that let you print the contents of the register in a human readable way, which is a very useful thing for debugging. For more information on Mackerel you should read the Mackerel Technote [3].
The `addLibraries` entry specifies the libraries your application needs in order to run. In this example, we add `driverkit`, a helper library for finding, and mapping our device registers in the virtual memory space of the application.

The last argument specifies the architectures we want to build this driver for. Since we are currently using this device on ARM/OMAP4 platforms, this is set to ARMv7 and ARMv7-M architectures.

```haskell
[ build application {
    target = "fdif",
    cFiles = (find withSuffices [".c"]),
    mackerelDevices = [
        "omap/omap44xx_cam_prm",
        "omap/omap44xx_cam_cm2",
        "omap/omap44xx_fdif",
        "omap/omap44xx_device_prm"
    ],
    addLibraries = ["driverkit"],
    architectures = ["armv7", "armv7-m"
}
]
```

Listing 2.1: A Hakefile for a simple device driver

Now let's have a look at `usr/drivers/omap44xx/fdif/fdif.c`, the device driver source code. If you open the file, aside from the comment header, you will see a bunch of included header files that are of interest to us (Listing 2.2).

```c
#include <dev/omap/omap44xx_cam_prm_dev.h>
#include <dev/omap/omap44xx_cam_cm2_dev.h>
#include <dev/omap/omap44xx_fdif_dev.h>
```

Listing 2.2: Mackerel includes in driver source code.

These look very familiar to our specified `mackerelDevices` in the Hakefile, and in fact, they are the generated header files based on our mackerel files. If you want to have a look at them, you can find these header files in your build directory in `<arch>/include/dev/omap`. In our code, we use various functions (the ones starting with `omap44xx`) that are defined in these header files and use them to access device registers.

Another interesting part is early on in the main function (Listing 2.3).

```c
err = map_device_register(0x4A10A000, 4096, &vbase);
```

Listing 2.3: Mapping device registers in virtual memory.

`map_device_register` is a function provided by the `driverkit` library. We will talk more about it later, but for now, here is what it does: It takes the physical address of a device register (0x4A10A000) the size of the register (4096) and will map this at a random virtual address in your address space (given back to you by `vbase`). Since our device drivers all run in user-space this function ensures that you can access the device in your address space. There is also the issue of how, and which programs we allow access to what device registers. We will discuss this in the next chapter.

For the FDIF device, we can receive an interrupt from the device in case the face processing is done. Since we run in user space, we have to invoke a system call to register for the interrupt in the kernel. Once the interrupt arrives, the kernel will use the message passing infrastructure of Barrelfish to forward the IRQ to us. Fortunately, `libbarrelfish` provides us with a high-level
interface to do just that. In the function `enable_irq_mode`, we register an interrupt for the
device by using `inhandler_setup_arm` (Listing 2.4). It takes as arguments a handler function
(`irq_handler`) that is executed in case the interrupt arrives, an additional state argument that
is passed to that function for this particular interrupt, in our case `NULL`, and the interrupt
number or vector we are interested in.

```c
err = inhandler_setup_arm(irq_handler, NULL, FDIF_IRQ);
```

Listing 2.4: Register to receive an Interrupt.

This concludes our walkthrough on the FDIF driver. So far, you have seen a glimpse of the
user-level side on writing device drivers for ARM. It consists of an interplay of the build sys-
tem, mackerel device descriptions, mapping device registers, interrupt registrations and your
actual driver code. In the next chapters we will have a closer look on what is actually happen-
ing behind the scenes and how to adapt the infrastructure for new architectures or boards.

Note that the FDIF driver is a very minimal example of a driver. We use it to teach students
about the basic concepts of device drivers. However, if you would want to write a real driver,
you also need to export a interface for clients. In Barreelfish, the typical way is to export a
message passing interface for the driver, so that applications can connect and communicate
with the driver using messages. There are many source code examples in the tree on how to
do this, as a starting point, have a look at `usr/examples/xmpl-call-response` in the source
tree and the tech-note on inter-dispatcher communication [2] to get started.
Chapter 3

System Knowledge Base (SKB)

Before we start looking at the internals of device management in Barrelfish, we have to introduce the system knowledge base (SKB). The goal of the SKB is to store all knowledge about a system and provide an interface for clients to query and reason about this knowledge.

3.1 x86, Octopus and the ECLiPSe Prolog engine

On x86 architectures, the SKB is implemented using the ECLiPSe logic and constraint programming (CLP) engine. The SKB was built as a part of Adrian Schüpbach's Phd thesis [], available on barrelfish.org. In this technote we briefly cover the main aspects. The SKB provides two different interfaces to clients. One of them is a direct way to access the Prolog query engine of the ECLiPSe runtime. This allows you to query for facts (i.e., knowledge) about the system in a very generic and flexible way. You can find an API to access the SKB in lib/skb. The other interface is a key–value storage engine, called Octopus, implemented in combination with the ECLiPSe engine. Octopus is used to provide various functionality in Barrelfish. The key–value store also offers as a publish–subscribe mechanism based for stored records. It allows subscribers to receive events in case of state changes in the system. We use Octopus to implement various functionality in the system such as a nameserver. The system also uses Octopus for device related events, if PCI devices are found in the system or CPUs are discovered for example. In most cases the device manager, which we will introduce in the next chapter, will handle these events for you. However, some subsystems such as USB, use Octopus directly to receive events about hotplugged devices. You can find the API to interact with the Octopus service in lib/octopus/client.

A documentation of the facts stored in the SKB is on the Barrelfish Wiki at http://wiki.barrelfish.org/.

3.2 ARM and the simple SKB

If you look in the source tree of the SKB (usr/skb/) you will find that there are currently two different versions of the SKB built. One is the SKB based on the ECLiPSe runtime engine for x86 systems, the other is the SKB simple for ARM. This is due to portability issues of the ECLiPSe runtime for ARM. So, what is the simple SKB? It is an implementation of the Octopus API. It is...
important to have at least a minimal implementation of Octopus for all architectures we run on. Because it provides essential system features such as the name-service which is used most for of the service look-ups.

Not having the constraint logic programming interface unfortunately means we can currently not use the APIs in lib/skb on ARM. We are currently investigating alternatives for a constraint solver that will run on both platforms.
Chapter 4

Kaluga – The device manager

Kaluga is the device manager in Barrellfish. Its responsibility is to manage the peripherals of a system. That encompasses starting the correct drivers, once a device is discovered, in the right order and making sure that each driver has the permissions (capabilities) to access the device’s memory areas or I/O ports. In this chapter we will learn how Kaluga interacts with the rest of the system for device discovery and driver start-up.

For reasons stated in Section 3.2 we currently do not have the full system knowledge base on non-x86 platforms. Also, the ARM platforms we support right now, do not have an infrastructure like PCI that brings automatic device discovery – there are device trees, but we do not have support for them yet.

This means that right now, the way Kaluga finds the available devices differs quite a bit based on the platform we are running on. This ranges from automatic discovery using PCI, Octopus and the SKB on x86, to hardcoded information in Kaluga for the OMAP4 SoC. However, the general way of discovering what drivers are available and how we start them remains the same. We will briefly look at what operations Kaluga provides for finding binaries and how you can program it to start drivers the right way in your system.

If you look inside of the main function in Kaluga, you can see a call to the `init_boot_modules` function. We usually rely on multiboot to provide us with a set of ELF files at start-up. The `init_boot_modules` function parses the information provided by multiboot (your menu.lst file) to find a list of available binaries. It then looks at the arguments that are hardcoded next to those binaries and follows a simple policy for these, if a binary has the argument “auto” next to it, it considers this binary as a driver and will start it, if it finds a suitable device. How Kaluga finds a suitable device is explained in the following sections. Drivers are started in different ways, ranging from just starting one driver binary to a number of binaries or sending notifications to other subsystems and starting a driver. Kaluga supports custom start-up policies for different binaries in your system, you can set a start-up policy per driver binary using the `set_start_function`. The default start function, the one that is chosen if no special start-up function, is set for a binary, is defined in `usr/kaluga/driver_startup.c`. For example, on x86, this function will just spawn the binary and provide as arguments the PCI device identifiers (bus, class, function etc.) to the driver program.

As we mentioned before, a driver usually needs a special set of permissions to gain access to the device registers. For historical reasons, the way we provide this permissions currently differs between x86 and ARM. Unifying this interface is part of future work.
4.1 Starting PCI drivers on x86

On x86, peripherals are usually in the form of PCI or PCI express cards. PCI supports automatic discovery of peripherals using PCI bus enumeration. In Barrelish, the PCI related code lives in `usr/pci`. PCI is structured as a hierarchical tree with its leaves being devices. The root node, called PCI root bridge, forms the entry point to such a tree. PCI root bridges are found by reading the ACPI tables. ACPI, short for Advanced Configuration and Power Interface, is an open standard for device configuration and power management in operating systems. ACPI related code in Barrelish lives in `usr/acpi`.

The bootstrapping of an x86 machine in Barrelish works as follows: After parsing the boot script, Kaluga starts ACPI. ACPI will then add specific Octopus records for every PCI root bridge it finds. Meanwhile, Kaluga will receive notification for all the root bridges added to Octopus. If a root bridge is found, Kaluga will start the PCI domain which in turn will do a PCI bus enumeration. Devices found during PCI bus enumeration are again added to Octopus and propagated to Kaluga which will start individual device drivers to handle the peripherals. How does Kaluga know what driver to start for each device record? We already discussed how Kaluga uses different start functions for different types of devices. But how do we choose the right binary? Kaluga uses the SKB that stores a mapping from PCI identifiers to driver binaries. This mapping is retrieved from the SKB once Kaluga receives a Octopus record for a new device. You will find the mapping database in `usr/skb/programs/device_db.pl`. If you want to start your PCI driver with Kaluga, you will need to add it there and provide at least the corresponding device and vendor id.

Barrelish has a number of drivers for PCI cards. Mostly for network interfaces. Barrelish drivers, including the ones for PCI, are located in the source tree in `usr/drivers/`.

4.2 Writing PCI drivers

In order to write a PCI driver, one has to communicate with the PCI domain. There is a client library that provides a helpful API in `lib/pci` that helps doing that. One of the first steps is to initialize the client library by connecting to the PCI domain:

```c
err = pci_client_connect();
```

Listing 4.1: A client connects to the PCI subsystem.

After that, you are able to invoke the library functions in Listing 4.2 to initialize devices. The functions allow to gain control for a specific PCI device. The device is identified by using the numerous PCI identifiers (subclass, prog_if, vendor et. al.). The caller provides a callback function (`init_func`) that gets called by the library once it has registered the device with the PCI domain. `init_func` takes as an argument an array of `struct device_mem`. A description of the basic address registers (BAR) for this PCI device and also permissions (capabilities) to map these address registers in the drivers address space. You can use the defined in helper functions in `include/pci/mem.h` to map these BARs into the address space of the client. For legacy devices (such as a serial driver for example) that live in the I/O address space and do not use memory mapped registers you can use the `pci_register_legacy_driver_noirq` function.

```c
e rval_t pci_register_driver_noirq(pci_driver_init_fn init_func, uint32_t class,
    uint32_t subclass, uint32_t prog_if,
```

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Listing 4.2: A driver uses one of the following functions to register for PCI devices.

Note that the discussed PCI API is rather low-level and provides a lot of freedom in who can register for PCI devices. In the future the plan is for x86 to push more of that complexity in Kaluga. The device registration with PCI should be done by Kaluga before the driver is started, the driver then only receives a list of capabilities for a particular device which it can map in its address space. That means a driver no longer has the need to call these functions.

4.3 Writing drivers for ARM and System-on-Chip platforms

You have already encountered most of the provided functionality for ARM drivers in the overview in Chapter 2. This section will focus on how we currently support the OMAP platform to start drivers in Kaluga.

On ARM the situation differs compared to x86. There is currently no established standard like PCI for x86. That means that the way we have to integrate ARM differs from platform to platform. We also have no support for device trees at the moment. Therefore, if you look at the main function in Kaluga, you will find that we currently look-up the binaries using the find_module function and hardwire the start-up of these drivers for the pandaboard platform. In omap_startup.c we define the start function for these binaries. If you look at the code in the file you’ll also see that we use the function spawn_program_with_caps to start the driver and pass the driver a list of memory capabilities to access the device memory. This is the service part of the driverkit library we have seen in Chapter 2, it makes sure the capabilities are actually given to the driver in a way that driverkit can map them. What capabilities we give to a driver for the OMAP chip is also hardcoded at the moment, you can find a series of struct allowed_registers in the same file that defines for a given driver, what memory ranges it is allowed to access. The situation is not solved sufficiently right now, in the future, we would like to store this information in a SKB like system that also runs on ARM and lets us query for information about various platforms.

If you go on and read the capability technote [4] you’ll learn that capabilities can only be created in the kernel, and the representation we have in user-space, are references to capabilities. So, a valid question here is how Kaluga gets the capabilities for these devices in the first place. For that we have to look at the device_caps.c file inside Kaluga. The file contains the capability manager or memory manager for Kaluga, it is an instance of the memory management library found in lib/mm. The memory manager (libmm) manages capabilities for you, in reality it is a B+-tree structure that will manage a certain range of memory, in our case device
memory. It allows you to request a smaller range from this usually very large range that we initialze our memory manager with and, libmm will split up the initial capability we gave to the instance at the beginning into smaller pieces and hand them out to you, giving you a way to have fine grained, page level access control on memory. In practice, because capabilities can only be created and split in half in the kernel, it has to invoke system calls to do that.

As a note aside, there are three important memory managers in the system. The one found in memserv (usr/memserv), it manages all physical memory, the one in ACPI (usr/acpi), it handles all device memory on x86 and should really be merged with the third one in Kaluga that we use for ARM.

If you look at the function `init_cap_manager` in usr/kaluga/device_caps.c you will find a call to the monitor to request the I/O capability:

```c
err = cl->vtbl.get_io_cap(cl, &requested_cap, &error_code);
```

Listing 4.3: RPC call to receive the I/O capability from the monitor.

In the case of the ARM Pandaboard, the requested capability allows one to access the whole space of the device memory. We pass this capability on to the device manager in the `mm_add` call further down. Now, we are free to use the `get_device_cap` function, also defined in this file to create fine grained capabilities for this entire memory range. If you go back and look at code in usr/kaluga/omap_startup.c you will find it actually uses `get_device_cap` to create the capabilities it needs to pass on to the device drivers.

Now you should understand how the user-space side works if you want to write user-space drivers for your own platform. We have not covered yet how we actually create a capability in the kernel and how it ends up in the monitor, but we will cover that shortly in Section 5.2.
Chapter 5

Kernel support for user-space drivers

In this chapter, we will look at the necessary support in the kernel, if we want to write user-level device drivers on a new, unsupported platform. We cover the main parts that are needed in this case: How do we forward interrupts to user-space and how we create capabilities for device memory.

5.1 Interrupts

In Chapter 2 we have already seen how we can register to receive interrupts using the message passing architecture in Barrelfish. In this section we will look at what the kernel does in order to forward the interrupt to you. It all starts with having a driver for your interrupt controller. We have support for a number of interrupt controllers already in Barrelfish, like the xAPIC on x86 (kernel/x86/apic.c) or the GIC in ARMv7 (kernel/arch/armv7/gic.c). If there is currently no interrupt controller for your architecture, you’ll have to write one yourself. In any case, if you want to forward interrupts to user-space, you can rely on the send_user_interrupt function provided by the architecture independent part of the CPU driver. It allows you to forward interrupts from the kernel to a domain running on its core using the message passing infrastructure of Barrelfish [2].

5.2 Device Memory

In Section 4.3 we talked about how Kaluga constructs a series of smaller capabilities for device drivers from an initial, huge capability it receives from the monitor. We also mention that capabilities are created in the kernel. In this Section we look at what is necessary to create capabilities for device memory and how we can pass it on to user-space.

First you need to know what memory areas your devices are in. On x86 we usually ask the BIOS to get a list of memory regions for RAM and device memory. In Barrelfish, we construct capabilities for these regions and we hand the device regions to ACPI which is the domain that initializes the ACPI subsystem and does the memory book keeping for PCI drivers. On an ARM platform, the device memory usually lives in a statically pre-defined range. In kernel/arch/omap44xx/startup_arch.c in spawn_init_common we can see how we construct
a capability for the device memory range of the OMAP4 platform. The relevant parts are given in Listing 5.1.

```c
struct cte *iocap = caps_locate_slot(CNODE(spawn_state.taskcn), TASKCN_SLOT_IO);
errval_t err = caps_create_new(ObjType_DevFrame, 0x40000000, 30, 30, iocap);
```

Listing 5.1: Creating a capability in the kernel and placing it in the I/O slot in a task cnode.

spawn_init_common is setting up a new dispatcher control block, for the first user-space program called init, in the system. Similar to a UNIX based OS, all subsequent programs are children of init. The call to caps_create_new creates a new capability of type ObjType_DevFrame, a special type for device memory that makes sure the pages are not zeroed before mapping it for the first time. The next two arguments are the physical base of the address range and the size (in bits) of the range. This particular capability covers a memory range of $2^{30}$ bytes, or one GiB, starting from address 0x40000000 – the device memory region of the OMAP4 chip. The last argument specifies where this new capability is stored. The location is defined by the preceding caps_locate_slot function call. You can think of the caps_locate_slot function as an array look-up. We use the task CNode (a table of capabilities) of spawn_state, a struct representing the kernel state for the init domain. We use TASKCN_SLOT_IO as an index to the cnode table. Once init is started, it can refer to this capability by using the TASKCN_SLOT_IO offset to find it. If you look inside usr/init/spawn.c you will find the code (Listing 5.2) doing just that to propagate the capability on to the monitors task cnode. Notice that cap_copy is now a system call. The monitor then can use the I/O capability in his task cnode if somebody requests it (for example by using get_io_cap, seen in Listing 4.3).

```c
/* Give monitor I/O */
dest.cnode = si->taskcn;
dest.slot = TASKCN_SLOT_IO;
src.cnode = cnode_task;
src.slot = TASKCN_SLOT_IO;
err = cap_copy(dest, src);
if (err_is_fail(err)) {
    return err_push(err, INIT_ERR_COPY_IO_CAP);
}
```

Listing 5.2: Copy of the I/O capability from src to dest.
Chapter 6

Limitations & Work in Progress

Although we currently have the necessary support for user-space drivers on both major platforms Barrelfish runs on we do not yet have an unified interface between ARM and x86 architectures. In this technote we have seen both approaches explained to varying levels of details and we mentioned briefly where the two approaches differ. In the future we will most likely unify both platforms under a standardized API which will have the best of both worlds.
References