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**Making DragonFly BSD operating system
compliant with the Multiboot specification**

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Aware of criminal liability for making untrue statements I declare that the following thesis was written personally by myself and that I did not use any sources but the ones mentioned in the dissertation itself.

I describe the Multiboot Specification which provides an interface between a bootloader and an operating system and how DragonFly BSD, a mature UNIX-derived operating system, can be modified to conform to that specification. I present an implementation for the Intel 386 architecture and sketch a solution for the x86-64 architecture. I demonstrate the changes made to GRUB, a bootloader implementing the specification, in order to allow it to boot DragonFly BSD. I also pinpoint certain issues in GRUB with respect to the x86-64 architecture.

Contents

1	Introduction	1
2	Booting a BSD system	2
2.1	BIOS	3
2.2	First stage: boot0	3
2.3	Second stage: boot2	3
2.4	Third stage: loader	4
2.5	x86 kernel	4
2.6	x86-64 kernel	4
3	The Multiboot Specification and GRUB	5
4	Booting DragonFly BSD with GRUB	5
4.1	State of the Art	5
4.2	Making GRUB understand disklabel64	6
4.2.1	GRUB source code organization	7
4.2.2	part_dfly GRUB module implementation	7
4.3	Booting DragonFly BSD with GRUB on x86	9
4.3.1	How does GRUB identify the kernel image?	10
4.3.2	Modifying the linker script	11
4.3.3	Booting the 32 bit kernel	14
4.3.4	Loading the image: dloader	15
4.3.5	Loading the image: GRUB	16
4.3.6	Adjusting the kernel entry point	17
4.3.7	Mounting the root file system	19
4.4	Booting DragonFly BSD with GRUB on x86-64	21
4.4.1	Embedding a 32 bit entry point into a 64 bit kernel	22
5	Tools of a Kernel Developer's Trade	23
6	Related Work	24
7	Conclusions and Future Work	25
8	References	26

1 Introduction

The concept of *bootstrapping*, or *booting* for short, is as old as computing itself. Bootstrapping relies on the machine being hardwired to read a simple program from a location known beforehand (e.g. a hard drive or a network interface) and running it. That program is called *the bootloader* and is responsible for loading the operating system.

Usually, a bootloader is crafted towards a particular operating system and hardware platform, as is the case with `loadlin`¹ or `LILO`² for Linux or `loader` for systems from the BSD family.

The multitude of problems involved in implementing a bootloader for each combination of an operating system and hardware platform as well as high coupling of the bootloader to the operating system were the reasons which led Okuji et al. (2006) to devise [the Multiboot Specification](#). The specification defines an interface between a universal bootloader and an operating system. One implementation of the specification is [GRUB](#) – the bootloader which came to existence thanks to the effort of FSF³, and is one of the most widely used bootloaders in the FOSS (Free and Open Source Software) world. Other motives behind the specification are:

- the reduction of effort put into crafting bootloaders for disparate hardware platforms (much of the code for advanced features⁴ will be platform independent),
- simplifying the boot process from the point of view of the OS programmer (who is not interested in the low level post-8086 cruft),
- introducing a well defined interface between a bootloader and an operating system (allowing the same bootloader to load different OSes).

GNU Hurd⁵, NetBSD⁶, NOVA⁷ and Xen hypervisors, L4 family microkernels, and VMware ESXi are examples of kernels supporting the Multiboot specification.

DragonFly BSD is an operating system based on FreeBSD, but with a number of different architectural and design decisions (scaling onto multi-core CPUs being one of them). GRUB is able to boot the system via *chain loading*, i.e. by loading the bootloader of DragonFly BSD. The same technique is used to make GRUB load a Microsoft Windows system.

¹`loadlin` was a bootloader common in the early days of Linux, when it was used to load the kernel from a DOS or pre-NT Windows environment; see Wikipedia (2014b) article on `loadlin`.

²`LILO` was another Linux-only bootloader, used in many distributions before GRUB came into popularity; see Wikipedia (2014a) article on `LILO`.

³Free Software Foundation (<http://www.fsf.org/>) is the entity behind GNU, the userland part of the majority of Linux distributions.

⁴E.g. a graphical user interface implementation most probably will not require platform specific adjustments; same goes for booting over a network (with the exception of a network interface driver, of course).

⁵See GNU Hurd contributors (2010).

⁶See Vidal (2007).

⁷See Steinberg and Kauer (2010).

This work describes the implementation of the Multiboot specification in DragonFly BSD, so that chain loading it is no longer necessary. The implementation was performed for x86 architecture and a sketch of how to perform a similar implementation for x86-64 is also presented. Special care had to be taken to ensure compatibility with the existing booting strategy, i.e. all changes done to the kernel had to be backwards compatible with `dloader` (the native DragonFly BSD bootloader) not to break the already existing boot path. The work also demonstrates changes necessary to make GRUB load the DragonFly BSD kernel, which are now part of official GRUB code. The following topics are elaborated on in the next sections:

- *2. Booting a BSD system* gives an approachable introduction to the boot process of a BSD-like operating system on the Intel x86 architecture. This section should also make the need for simplification of the boot process obvious.
- The rationale behind *the Multiboot Specification and GRUB* (section 3) which provide an abstraction over the hardware specifics an operating system programmer must overcome to bootstrap the system. This section shows how GRUB makes the boot process seem simpler than it really is.
- Section *4.3. Booting DragonFly BSD with GRUB on x86* provides a description of changes necessary to make the system conform to the version of the specification targeted at the 32bit Intel architecture. This is the core part of this work.

In fact, this section describes all the changes which were applied to the DragonFly BSD kernel in order to make it fully functional when booted by GRUB. These changes include, but are not limited to, adjusting the kernel linker script, modifying the existing entry point written in assembly language and finally enabling the system to interpret boot information passed by GRUB in order to mount the root file system.

This also includes extending the GRUB bootloader by writing a module for recognizing a new partition table type.

- *4.4. Booting DragonFly BSD with GRUB on x86-64* covers why the same approach can't be taken on the x86-64 architecture and how, even in the light of these differences, the system could be modified to work with GRUB on this architecture.

2 Booting a BSD system

The contents of this section are heavily (though not entirely) based on the outstanding work of the authors of the [FreeBSD Architecture Handbook](#) (The FreeBSD Documentation Project 2014); namely on chapter [1. Bootstrapping and Kernel Initialization](#) and on the analysis of FreeBSD and DragonFly BSD source code.

Though the description in this section is far from being simple, its every paragraph is only a simplification of what actually happens – a lot of details are omitted.

2.1 BIOS

The [BIOS Boot Specification](#) defines the behaviour of a PC (personal computer) just after power on when it is running in *real mode*. The real mode means that memory addresses are 20 bit wide which allows for addressing up to 1MiB of memory. This must be enough for all software running prior to the processor being switched to *protected mode*.

The value of *instruction pointer* register just after the boot up points to a memory region where BIOS and its POST (Power On Self Test) code is located. The last thing done by this code is the loading of 512 bytes from the MBR (Master Boot Record – usually the hard drive) and running the code contained within them.

2.2 First stage: boot0

The code contained in MBR is `boot0` - the first stage of the BSD bootloader. `boot0` does not know more than absolutely necessary to boot the next stage; it understands the partition table and can choose one of the four primary partitions to boot the later stage from. After the choice is done it just loads the first sector of that partition and runs it, i.e. it runs `boot2`⁸.

2.3 Second stage: boot2

`boot2` is aware of the possibility of multiple hard drives in the PC; it also understands the file system structures. Its aim is to locate and run the `loader` – the third stage of the bootloader which is responsible for loading the kernel. `boot2` also switches the CPU to the aforementioned protected mode. The main characteristics of this mode are 32 bit memory addresses and a *flat memory model*⁹.

One more thing `boot2` does before running `loader` is initializing the first few fields of the `struct bootinfo` structure. The structure is passed to the `loader` and later to the kernel and is the main interface between the BSD bootloader and the kernel. It contains basic information about the kernel (its location), the hardware (disk geometry as detected by the BIOS), available memory, preloaded modules and the environment (variables configuring the kernel and the modules).

⁸Why not `boot1`? `boot1` actually exists. It is used when booting from a floppy disk, which is rarely the case nowadays. It performs the role equivalent to `boot0`, i.e. finding and loading `boot2`, with the difference of being run from a floppy.

⁹Flat memory model essentially means that the whole available memory is addressable in a linear space. All segment registers may be reset to 0 – the whole memory may be viewed as one huge segment.

2.4 Third stage: loader

The `loader` (known as `dloader` in DragonFly BSD), already running in the protected mode, is actually quite a capable piece of software. It allows for choosing which kernel to boot, whether to load any extra modules, configuring the environment, and booting from encrypted disks. It is an ELF binary as is the kernel itself. In case of a 64 bit system, the `loader` is capable of entering the *long mode*¹⁰, turning on paging and setting up the initial page tables (the complete setup of the virtual memory management is done later in the kernel).

2.5 x86 kernel

Once loaded, the kernel must perform some initialization. After the basic register setup there are three operations it performs: `recover_bootinfo`, `identify_cpu`, `create_pagetables`.

On the Intel x86 architecture the `identify_cpu` procedure is especially hairy as it must differentiate between all the possible CPUs in the x86 line. The first processors did not support precise self-identification instructions, so the identification is a trial and error process. Discriminating between versions of the same chip manufactured by different vendors is in fact done by checking for known vendor-specific defects in the chip.

`create_pagetables` sets up the page table and after that enables paging. After doing that a fake return address is pushed onto the stack and return to that address is performed – this is done to switch from running at low linear addresses and continue running in the virtualized address space. Then, two more functions are called: `init386` and `mi_startup`. `init386` does further platform dependent initialization of the chip. `mi_startup` is the machine independent startup routine of the kernel which never returns – it finalizes the boot process.

2.6 x86-64 kernel

On x86-64 initialization of the kernel is performed a bit differently and in fact is less of a hassle. As `loader` has already enabled paging as a requirement to enter the long mode the CPU is already running in that mode and the jump to the kernel code is performed in the virtual address space. The kernel does the platform dependent setup and calls `mi_startup` (the machine independent startup).

¹⁰Long mode is the mode of execution where the processor and the programmer are at last allowed to use the full width of the address bus. In theory. In practice, at most 48 bits of the address are actually used as there is simply no need to use more with today's amounts of available memory.

3 The Multiboot Specification and GRUB

The described boot procedure and software is battle proven and works well for FreeBSD as well as, with minor changes, DragonFly BSD. However, no matter how fantastic software the BSD bootloader is there is one problem with it – it is **the BSD** bootloader.

In other words, the bootloader is crafted towards a particular operating system and hardware platform. It will not boot Linux or any other operating system which significantly differs from FreeBSD.

The bootloader implementing the Multiboot Specification is GNU GRUB. Apart from the points already mentioned in *1. Introduction*, GRUB, thanks to the modular architecture and clever design, is able to run on multiple hardware platforms, support a range of devices, partition table schemes and file systems and load different operating systems. It is also possible to use it as a Coreboot payload¹¹. GRUB also sports a modern graphical user interface for a seamless user experience from as early as the boot menu to as far as the desktop environment login screen.

The availability of GRUB is a major step towards simplification of the boot process from the OS programmer point of view.

4 Booting DragonFly BSD with GRUB

The focus of this work is to describe all changes necessary to the DragonFly BSD kernel and the GRUB bootloader to make both interoperate as described in the Multiboot specification. In other words, all the changes necessary to make GRUB load and boot DragonFly BSD using the Multiboot protocol. This might lead to the question – can GRUB boot DragonFly BSD using any other protocol? It turns out that it can.

4.1 State of the Art

Besides loading and booting operating system kernels, GRUB is capable of so called *chain loading*¹². This is a technique of substituting the memory contents of the running program with a new program and passing it the control flow. The UNIX `exec(2)` system call is an application of the same technique.

By chain loading GRUB is able to load other bootloaders which in turn might boot operating systems that GRUB itself can't (e.g. Microsoft Windows) or perform specific configuration of the environment before running some exotic kernel with unusual requirements.

¹¹Coreboot is a BIOS firmware replacement. Payloads are standalone ELF executables that Coreboot can use in order to support some desired functionality.

¹²In fact it's not true that GRUB can chain load besides booting OS kernels. Chain loading is *how* it boots both these kernels and loads other bootloaders.

That is the approach commonly used with many BSD flavours (of which only NetBSD supports the Multiboot protocol) and DragonFly BSD is not an exception. That is, the only way to boot DragonFly BSD using GRUB before starting this project was to make it load `dloader` and delegate to it the rest of the boot process.

However, this defeats the purpose of Multiboot and a uniform OS-kernel interface. The hypothetical gain of decreased maintenance effort thanks to one universal bootloader doesn't apply anymore due to the reliance on `dloader`. Neither the seamless graphical transition from power-on to useful desktop is achievable when relying on chain loading. Therefore, chain loading is unsatisfactory.

4.2 Making GRUB understand disklabel164

The module for reading `disklabel164` described in this section [is already included in GRUB](#). That is one of the main contributions of this work.

One of the things a bootloader does is understanding the disk layout of the machine it is written for – the partition table and file system on which the files of the operating system are stored.

Traditionally, systems of the BSD family (along with Solaris, back in the day called SunOS) used the `disklabel` partitioning layout. Unfortunately, DragonFly BSD has diverged in this area from the main tree. It introduced a new partition table layout called `disklabel164` which shares the basic concepts of `disklabel` but also introduces some incompatibilities:

- partitions are identified using Globally Unique Identifiers (GUIDs),
- fields describing sizes and offsets are 64 bit wide to accommodate the respective parameters of modern hardware.

GRUB is extensible with regard to the partition tables and file systems it is able to understand. Although the variants of `disklabel` used by disparate BSD flavours differ, all of them have already been supported by GRUB before this project was started. Unfortunately, that wasn't the case for DragonFly BSD's `disklabel164`. It is very important, because one piece of the puzzle is booting the kernel but another one is finding and loading it from the disk.

Fortunately, the main file system used by DragonFly BSD is UFS (the Unix file system) which is one of the core traditional Unix technologies and is already supported by GRUB. Alas, to get to the file system we must first understand the partition table.

Extending GRUB to support a new partition table or file system type is essentially a matter of writing a module in the C language. Depending on the module type (file system, partition table, system loader, etc) it must implement a specific interface.

The module is compiled as a standalone object (`.o`) file and depending on the build configuration options either statically linked with the GRUB image or loaded on demand during the boot up sequence from a preconfigured location.

As the `disklabel64` format is not described anywhere in the form of written documentation the GRUB implementation was closely based on the original header file found in the DragonFly BSD source tree (`sys/disklabel64.h`) and the behaviour of the userspace utility program `disklabel64`.

4.2.1 GRUB source code organization

During this project, the revision control system of GNU GRUB changed from [Bazaar](#) to [Git](#). As of writing this work, the code is located at <http://git.savannah.gnu.org/grub.git>.

GRUB uses, as one might expect, GNU Autotools as its build system. Since the source tree, while well organized, might be intimidating at first glance, a short overview of its contents follows.

The project comes with a set of helper utilities meant to be run from a fully functional operating system. These are, among others, `grub-file`, `grub-install`, `grub-mkrescue`. The last one is particularly useful for creating file system images containing a configured and installed GRUB with a set of arbitrary files, e.g. a development kernel. Use of this command greatly simplifies and speeds up the development process. All the code meant to be run from an operating system is located in the main project directory.

Code intended to be run at boot time is located under `grub-core/`. In general, the structure follows the `grub-core/SUBSYSTEM/ARCH/` pattern, where `grub-core/SUBSYSTEM/` contains generic code of a given subsystem, while each `grub-core/SUBSYSTEM/ARCH/` subdirectory contains platform specific details. Some of the subsystems are:

- `boot/` – boot support of GRUB itself, e.g. the code which runs just after GRUB is loaded by BIOS on an x86 machine,
- `commands/` – implementation of commands available in the GRUB shell,
- `fs/` – file system support, e.g. `btrfs`, `ext2`, `fat`, `ufs`, `xfs`,
- `gfxmenu/` – graphical menu for choosing from the available boot options,
- `loader/` – loaders for different kernels and boot protocols, e.g. Mach, Multiboot, XNU (i.e. the Darwin / MacOS X kernel),
- `partmap/` – partition table support, e.g. `apple`, `bsdlabel`, `gpt`, `msdos`,
- `term/` – support for a textual interface through a serial line or in a graphical mode,
- `video/` – graphical mode support for different platforms and devices.

It is worth noting that GRUB deliberately contains almost no code for writing data to file systems – that’s a guarantee that it can’t be responsible for any file system corruption.

4.2.2 `part_dfly` GRUB module implementation

The newly added support for `disklabel64` partitioning scheme was located in `grub-core/partmap/dfly.c` file. In order to make the new module build along with the rest of GRUB a few changes had to be introduced:

- modification of `Makefile.util.def` to include a reference to `grub-core/partmap/dfly.c`,
- modification of `grub-core/Makefile.core.def` to include a reference to `grub-core/partmap/dfly.c` and indicate that the name of the loadable GRUB module is `part_dfly` (this is the name usable from GRUB shell),
- addition of `grub-core/partmap/dfly.c` with `disklabel64` read support,
- addition of automatic tests of the new code and auxiliary files in `tests/`.

`grub-core/partmap/dfly.c` contains the definitions of `disklabel64` on-disk structures, a single callback function called by GRUB from outside the module and some initialization and finalization boilerplate code.

The first structure actually is *the disklabel*, i.e. a header containing some meta information about the disk, along with a table of entries describing the consecutive partitions:

```
/* Full entry is 200 bytes however we really care only
   about magic and number of partitions which are in first 16 bytes.
   Avoid using too much stack. */
struct grub_partition_disklabel64
{
    grub_uint32_t    magic;
#define GRUB_DISKLABEL64_MAGIC          ((grub_uint32_t)0xc4464c59)
    grub_uint32_t    crc;
    grub_uint32_t    unused;
    grub_uint32_t    npartitions;
};
```

As can be seen from the above listing, only fields strictly necessary to enable read support of the disklabel are included in the structure definition. This is due to two guides – the limitations of the embedded environment that GRUB is running in, and the design decision that GRUB ought not to have write support of any on-disk data for safety and security reasons.

The second structure is a disklabel entry, i.e. a description of a single partition:

```
/* Full entry is 64 bytes however we really care only
   about offset and size which are in first 16 bytes.
   Avoid using too much stack. */
#define GRUB_PARTITION_DISKLABEL64_ENTRY_SIZE 64
struct grub_partition_disklabel64_entry
{
    grub_uint64_t    boffset;
    grub_uint64_t    bsize;
};
```

Again, full read-write support would require full details of the structure to be present.

Signature of the callback function defined in `dfly.c` is as follows:

```
static grub_err_t
dfly_partition_map_iterate (grub_disk_t disk,
                           grub_partition_iterate_hook_t hook,
                           void *hook_data)
```

This function is called in a loop implemented in GRUB framework code.

In general, GRUB is able to handle nested partition tables, which are quite common on the personal computer (PC) x86 architecture. It's customary, that a PC drive is partitioned using an MS-DOS partition table, which supports up to 4 primary partitions and significantly more logical partitions on an extended partition.

A bare disk would be referred to as (hd0) by GRUB; the second MS-DOS partition on a disk as (hd0,msdos2) (please note that disks are counted from 0 while partitions from 1), while the first DragonFly BSD subpartition of that MS-DOS partition as (hd0,msdos2,dfly1).

In this light, it should be clearer how the partition recognition loop of GRUB (mentioned above) works. First, each partition type callback (e.g. `dfly_partition_map_iterate`, `grub_partition_msdos_iterate`, ...) is run on the raw device to find a partition table. Then, it is run on each partition found in the table (by using the `grub_partition_iterate_hook_t hook` parameter). Such a discovery procedure leads to at most two-level partition nesting, as in the (hd0,msdos2,dfly1) example.

The tests for automatic partition table and file system discovery, located in `tests/` directory of GRUB source tree, rely on GNU Parted. Being a partitioning utility, Parted, unlike GRUB, supports full read and write access to a number of partition table and file system formats. Unfortunately, `disklabel64` is not one of them. In order to enable automatic tests of the `part_dfly` module it was necessary to supply a predefined disk image containing the relevant disklabel. Two such images were prepared: one with an MS-DOS partition table and one with a DragonFly BSD `disklabel64`.

4.3 Booting DragonFly BSD with GRUB on x86

Conceptually, enabling GRUB to boot DragonFly BSD is relatively simple and involves the following steps:

- enabling GRUB to identify the kernel image as Multiboot compliant,
- adding an entry point to which GRUB will perform a jump when the kernel image is loaded and the environment is set up,
- once in the kernel, interpreting the information passed in by GRUB and performing any relevant setup to successfully start up the system.

However, things get hairy when we get to the details. The foremost issue is compatibility with the existing booting strategy. In other words, all changes done to the kernel must be backwards compatible with `dloader`, so as not to break the already existing boot path.

The following sections describe in detail how the steps listed above were implemented for the pc32 variant of DragonFly BSD kernel, i.e. for the Intel x86 platform.

4.3.1 How does GRUB identify the kernel image?

The Multiboot specification (Okuji et al. 2006, sec. 3.1) states that besides the usual headers of the format used by an OS image, the image must contain a 32-bit aligned Multiboot header. This header must not exceed past 8KiB from the beginning of the image and generally should come as early as possible.

Except this requirement, there are really no constraints put onto the format of the kernel image file. Specifically, the kernel may be stored in ELF format, which is a widely accepted standard for object file storage. However, ELF requires the ELF header to be placed at the immediate beginning of a file (see TIS Committee and others 1995, sec. 1–2).

If not for the aforementioned flexibility of Multiboot, this ELF requirement would lead to a serious problem for booting DragonFly BSD with GRUB, because of the kernel being natively stored as an ELF file.

The most natural way of embedding the Multiboot header into the kernel is defining it in the assembly language. Given the heritage of DragonFly BSD it should not make one wonder that the kernel uses the AT&T assembler syntax¹³.

The low level architecture dependent parts of the kernel are in `sys/platform/pc32` and `sys/platform/pc64` subdirectories of the system source tree.

`sys/platform/pc32/i386/locore.s` is an assembly file defining the entry point to the x86 kernel. It's format may seem a bit strange at first, since it's the AT&T syntax assembly mixed with C preprocessor directives. Deciphering some definitions and rules from `sys/conf/kern.pre.mk` leads to the general command the file is processed with:

```
gcc -x assembler-with-cpp -c sys/platform/pc32/i386/locore.s
```

The command handles generating an object file from such a C preprocessed assembly file. Thanks to this setup, the Multiboot header definition can use meaningfully named macros instead of obscure numbers defined by the specification:

```
/*
 * Multiboot definitions
 */
#define MULTIBOOT_HEADER_MAGIC      0x1BADB002
#define MULTIBOOT_BOOTLOADER_MAGIC 0x2BADB002
#define MULTIBOOT_PAGE_ALIGN       0x00000001
#define MULTIBOOT_MEMORY_INFO      0x00000002
#define MULTIBOOT_HEADER_FLAGS     MULTIBOOT_PAGE_ALIGN \
```

¹³Ritchie and Thompson (1974) developed UNIX when working at AT&T Bell Laboratories.

```

| MULTIBOOT_MEMORY_INFO
#define MULTIBOOT_CMDLINE_MAX    0x1000
#define MI_CMDLINE_FLAG          (1 << 2)
#define MI_CMDLINE               0x10

/* ... snip ... */

.section .mbheader
.align 4
multiboot_header:
.long    MULTIBOOT_HEADER_MAGIC
.long    MULTIBOOT_HEADER_FLAGS
.long    -(MULTIBOOT_HEADER_MAGIC + MULTIBOOT_HEADER_FLAGS)

```

The header itself consists of 3 fields, each 4 bytes wide:

- the Multiboot header magic number: 0x1BADB002,
- flags which state what the kernel expects from the bootloader,
- a checksum which when added to the other header fields, must have a 32-bit unsigned sum of zero.

These values are sufficient for GRUB to recognize the kernel image as Multiboot compliant. Please refer to Okuji et al. (2006) for more details.

However, it's not sufficient just to place the header in `locore.s`. Please note that the header is declared in its own `.mbheader` section of the object file. This is necessary, but not enough, to comply with the requirement of placing it in the first 8KiB of the kernel image.

4.3.2 Modifying the linker script

Executable and Linking Format Specification (TIS Committee and others 1995) describes the format of an object file – e.g. the DragonFly BSD kernel executable. While ELF and its specification is a product of the post-UNIX age of computing history, the process of composing programs from reusable parts in its rawest form, or *linking*, is probably as old as computing itself.

What is the responsibility of a linker? Levine (1999) in *Linkers & Loaders* gives an answer that a linker assigns numeric locations to symbols, determines the sizes and location of the segments in the output address space, and, what is crucial in our case, figures out where everything goes in the output file. Chamberlain and Taylor (2003) in *Using ld, the GNU linker* point at a different aspect – that a linker maps sections of the input files into the output file and that most linker scripts do nothing more than this. The same authors also inform that GNU `ld` accepts Linker Command Language files written in a superset of AT&T's Link Editor Command Language syntax, which ought to provide explicit and total control over the linking process.

In the light of this *total control* which decides *where everything goes in the output file*, one might think that making the linker place the Multiboot header at the beginning of the output file is a simple matter. The experience gained from this project is exactly the opposite.

The behaviour of GNU `ld`, the linker used by DragonFly BSD, may either be driven by an explicitly specified linker script or by one embedded in the linker executable itself.

In case of userspace applications, the programmer doesn't have to worry about specifying the linker script, as `ld` will in almost all cases *just do the right thing*. Unfortunately, that's not the case for kernel development. There are several reasons for using a custom linker script for the kernel.

One of them is portability among different architectures and compiler vendors which is needed for bootstrapping. In order to be able to build the kernel on a different OS, the linker script must be compatible with the platform's compiler which might emit different output than the native compiler of DragonFly BSD. In other words, before we have *any* running DragonFly BSD system, we can't build DragonFly BSD on DragonFly BSD, hence the need of supporting different architectures.

Another reason is that by using the linker script it's possible to define symbols in the program namespace, whose values couldn't be otherwise determined in the code. Examples of such symbols are `edata` or `end` meaning, respectively, the end of the `.data` section and of the kernel binary. In a userspace program there's no (or little) use for such symbols, but the kernel uses them for calculating the offset and size of the `.bss`¹⁴ section which the it must initialize itself.

The language accepted by `ld` has constructs for setting symbol/section virtual addresses, overriding their linear (or load) addresses, specifying regions of accessible memory and their access modes and assigning input sections to output sections placed in particular program segments. None of these constructs could be used to precisely specify the place of the Multiboot header in the output kernel binary.

The following is a description of tried methods.

Placing the `.mbheader` section before the `.text` section:

```
diff --git a/sys/platform/pc32/conf/ldscript.i386 \
        b/sys/platform/pc32/conf/ldscript.i386
index a0db817..1068ba5 100644
--- a/sys/platform/pc32/conf/ldscript.i386
+++ b/sys/platform/pc32/conf/ldscript.i386
@@ -21,6 +21,7 @@ SECTIONS
    kernmxps = CONSTANT (MAXPAGESIZE);
    kernpage = CONSTANT (COMMONPAGESIZE);
```

¹⁴ `.bss` is a traditional name of a section in the object file containing uninitialized data; since this data has no explicit value, there's no point in assigning storage space for this section in an object file. The name stands for *block started by symbol*.


```

    . = kernbase + kernphys + SIZEOF_HEADERS;
+  .mbheader      : { *(.mbheader) }
    .interp       : { *(.interp) } :text :interp
    .note.gnu.build-id : { *(.note.gnu.build-id) } :text
    .hash         : { *(.hash) }

```

On the contrary to what one might expect, this had the effect of placing the `.mbheader` input section in the `.data` output section, which is placed *after* the `.text` output section. That's definitely far from the initial 8KiB of the kernel binary.

Inserting the `.mbheader` section at the beginning of the `.text` section succeeded in the sense that the header was in fact placed before all other program code. Alas, the `.text` section itself begins far in the file, after the program headers, the `.interp` section and a number of sections containing relocation information.

Analysis of `readelf` and `objdump` output showed that symbol offsets from the beginning of the kernel image were equal to the virtual addresses decreased by a constant value. In fact, the binary was linked to use the same values for virtual and load addresses. The constant offset was equal to the value of symbol `kernbase`, which specifies a page aligned base address at which the kernel is loaded.

This led to an attempt at forcing the position in the output binary by modifying the load address of the whole `text` output segment through adjusting it in the PHDRS section of the linker script. This segment contained all consecutive sections up to the `.data` section, i.e. `.interp`, sections with relocation and symbol information and finally the `.text` section. An arbitrary address close to the beginning of the file was picked, but to no avail. As it became obvious later (when figuring out how to make GRUB understand what address to load the kernel at) this couldn't have worked.

Another, still unsuccessful, approach was putting the `.mbheader` section into the `headers` output segment. Introducing a completely new program header (a.k.a. segment) was also tried with no success. This is probably explained by the message of commit e19c755¹⁵ from the DragonFly BSD repository from which we can infer that `dloader` expects a kernel with exactly 2 loadable program segments. An image with more can be generated easily, but it won't be bootable by `dloader`.

Finally, the trial and error process led to inserting the `.mbheader` section at the end of the `.interp` section. Section `.interp` contains a path to the program interpreter, i.e. a program which is run in place of the loaded binary and prepares it for execution¹⁶. In

¹⁵The verbatim message is: *The gold linker changed its ELF program header handling defaults for version 2.22, and this resulted in an extra LOAD segment reserved only for the program headers. The DragonFly loader wasn't expecting that and instantly rebooted when trying to load a gold kernel.*

¹⁶On x86-64 Linux this is typically `/lib64/ld-linux-x86-64.so.2` while on DragonFly BSD `/usr/libexec/ld-elf.so.2`. The majority of software nowadays is dynamically linked. This means that an executable doesn't contain all the code the program needs to run successfully and relies on shared libraries commonly available on the target system. In case of userspace programs, the interpreter handles symbol relocations and lazy loads these dynamically linked shared libraries finalizing the linking of the program during its execution.

case of a kernel, the path to the interpreter is just a stub (*/red/herring* to be exact). The `.interp` section is the first in the kernel image. Placing the `.mbheader` section after the null-terminated string in the `.interp` section causes no issues with accessing the interpreter path (if it is ever necessary) while still leading to placement of the Multiboot header in the first 8KiB of the kernel binary:

```
diff --git a/sys/platform/pc32/conf/ldscript.i386 \
        b/sys/platform/pc32/conf/ldscript.i386
index dc1242e..24081c9 100644
--- a/sys/platform/pc32/conf/ldscript.i386
+++ b/sys/platform/pc32/conf/ldscript.i386
@@ -21,8 +21,8 @@ SECTIONS
    kernmxps = CONSTANT (MAXPAGESIZE);
    kernpage = CONSTANT (COMMONPAGESIZE);
    . = kernbase + kernphys + SIZEOF_HEADERS;
-   .interp          : { *(.interp) } :text :interp
+   .interp          : { *(.interp)
+   +               *(.mbheader) } :text :interp
    .note.gnu.build-id : { *(.note.gnu.build-id) } :text
    .hash             : { *(.hash) }
    .gnu.hash         : { *(.gnu.hash) }
```

This approach hasn't caused any issues with the resulting binaries so far, but can't be considered *the proper way* of embedding the Multiboot header.

4.3.3 Booting the 32 bit kernel

Once the kernel is identifiable by GRUB what's left is making it bootable. This requires making GRUB load the image to a reasonable memory address, using a valid entry address and modifying the kernel entry point to handle entry from GRUB. All of that must be done in a way which maintains bootability by `dloader`.

The kernel, once booted by GRUB, instead of expecting the `struct bootinfo` structure must be able to interpret the structure passed from GRUB, which the Multiboot specification describes in detail. This is required at least for setting the root filesystem, but adjusting the kernel environment may be used for multiple other purposes.

No matter what bootloader booted the kernel, the entry will happen at the same address. However, just after entry from the bootloader the code must branch taking the points stated above into account. The branching should converge before calling the platform dependent `init386` initialization procedure. The rest of the system should not need to be aware of what bootloader loaded the kernel.

4.3.4 Loading the image: dloader

By default, the DragonFly BSD kernel image is linked with virtual and physical addresses being the same. Moreover, the kernel has only two loadable program segments (marked LOAD in the listing below). This information can be read from the kernel image using `readelf`:

```
$ readelf -l /boot/kernel.generic/kernel

Elf file type is EXEC (Executable file)
Entry point 0xc016c450
There are 5 program headers, starting at offset 52

Program Headers:
  Type           Offset       VirtAddr    PhysAddr    FileSiz MemSiz  Flg Align
  PHDR           0x000034    0xc0100034  0xc0100034  0x000a0 0x000a0 R   0x4
  INTERP         0x0000d4    0xc01000d4  0xc01000d4  0x0000d 0x0000d R   0x1
      [Requesting program interpreter: /red/herring]
  LOAD           0x000000    0xc0100000  0xc0100000  0x85a6ec 0x85a6ec R E 0x1000
  LOAD           0x85a6ec    0xc095b6ec  0xc095b6ec  0x9d313 0x50b454 RW 0x1000
  DYNAMIC        0x85a6ec    0xc095b6ec  0xc095b6ec  0x00068 0x00068 RW 0x4
  ...
```

The `-l` flag tells `readelf` to list just the program headers (a.k.a. segments).

`dloader` can load such a kernel just fine, thanks to its algorithm for reading ELF images. First, it ignores the physical addresses embedded in the ELF image. Second, it calculates the load address based on the entry address stored in the image.

The entry address is read from the ELF header¹⁷ and then passed to an architecture word size aware function that will read the ELF image. The signature of this function is automatically generated using the `__elfN(loadimage)`¹⁸ macro, so that the same definition, written with appropriate care, can be reused for both ELF32 and ELF64 formats. For ELF32 a call to this function expands to `elf32_loadimage(fp, &ef, dest)`.¹⁹ The load address is adjusted depending on the architecture²⁰. For ELF32 and an initial entry address equal to `0xc016c450` calculation of the offset evaluates to `0xffffffff40000000`. An example program header virtual address of `0xc0100000` offset by `0xffffffff40000000` gives `0x100000`, i.e. 1MiB – a convenient low physical address to load the kernel at.

The insight from the above analysis is that the load addresses the kernel is linked with aren't important from the perspective of `dloader`. They can be freely adjusted in any way that is convenient.

¹⁷See DragonFly BSD: `sys/boot/common/load_elf.c:174`

¹⁸See DragonFly BSD: `sys/boot/common/load_elf.c:258`

¹⁹See DragonFly BSD: `sys/boot/common/load_elf.c:233`

²⁰See DragonFly BSD: `sys/boot/common/load_elf.c:289`

4.3.5 Loading the image: GRUB

The ending remark of the previous section is very fortunate, as GRUB is much stricter than `dloader` in following the ELF specification. It relies solely on the segment load addresses for loading an ELF kernel. Thanks to `dloader`'s ambivalence as to the values of these addresses, we can safely adjust them in any way required by GRUB. One thing to keep in mind, though, is not to introduce extra program headers, as `dloader` won't be able to handle it.

The only thing required to adjust the load addresses is overriding the load address of the first output section in the linker script. The following sections will be just laid out linearly after the adjusted one. The first section is the already mentioned `.interp`. The introduced change is presented below:

```
kernmxps = CONSTANT (MAXPAGESIZE);
kernpage = CONSTANT (COMMONPAGESIZE);
. = kernbase + kernphys + SIZEOF_HEADERS;
- .interp          : { *(.interp)
-                  *(.mbheader) } :text :interp
+ .interp          : AT (ADDR(.interp) - kernbase)
+ {
+   *(.interp)
+   *(.mbheader)
+ } :text :interp
.note.gnu.build-id : { *(.note.gnu.build-id) } :text
.hash              : { *(.hash) }
.gnu.hash          : { *(.gnu.hash) }
```

The `AT (<expression>)` keyword sets the load address of an output section. As already mentioned, following sections will be laid out linearly after this one, so their load addresses will be modified accordingly. The `ADDR (<section>)` keyword returns the virtual address of `<section>`.

Inspecting a kernel built with the adjusted linker script shows that the segment load addresses are in fact offset from the virtual addresses by a value of `0xc0000000`, i.e. the `kernbase` location.

```
$ readelf -l /boot/kernel/kernel
```

```
Elf file type is EXEC (Executable file)
```

```
Entry point 0xc013b040
```

```
There are 5 program headers, starting at offset 52
```

```
Program Headers:
```

Type	Offset	VirtAddr	PhysAddr	FileSiz	MemSiz	Flg	Align
PHDR	0x000034	0xc0100034	0x00100034	0x000a0	0x000a0	R	0x4

```

INTERP 0x0000d4 0xc01000d4 0x001000d4 0x00019 0x00019 R 0x4
        [Requesting program interpreter: /red/herring]
LOAD   0x000000 0xc0100000 0x00100000 0x310134 0x310134 R E 0x1000
LOAD   0x310134 0xc0411134 0x00411134 0x2b875 0x4662ac RW 0x1000
DYNAMIC 0x310134 0xc0411134 0x00411134 0x00068 0x00068 RW 0x4
...

```

Also, it is worth noting how GRUB treats the entry address present in the ELF headers of the kernel image:

```

$ readelf -h /boot/kernel/kernel
ELF Header:
...
Entry point address:          0xc013b040
...

```

As can be seen above, the entry point (0xc013b040) is specified as a virtual address positioned high in the memory. Fortunately, GRUB is capable of adjusting this value by the difference between the virtual and physical addresses of the segment the entry point is contained in (i.e. by `kernbase`)²¹.

This is sufficient for GRUB to be able to properly load the kernel image and jump to the entry point address. The next step is to make the entry point expect entry from GRUB, i.e. to adjust the low level assembly routine controlling the kernel just after it's jumped to.

4.3.6 Adjusting the kernel entry point

Output of `readelf` in the previous section tells us that the entry address of the kernel is 0xc013b040 (more or less, depending on the exact version of the code). The top of the linker script, on the other hand, tells us what code actually resides at that address:

```

/* Default linker script, for normal executables */
OUTPUT_FORMAT("elf32-i386", "elf32-i386",
              "elf32-i386")
OUTPUT_ARCH(i386)
ENTRY(btext)
SEARCH_DIR(/usr/lib);
...

```

`btext` is an assembly procedure defined in `sys/platform/pc32/i386/locore.s`, the same file where the definition of the Multiboot header was placed.

There's no use quoting the verbatim contents of the file, but I'll describe the changes introduced in order to perform an entry from GRUB.

²¹See GRUB: `grub-core/loader/multiboot_elfxx.c:131`

Just after entering the kernel we check whether the bootloader that booted us is Multiboot compliant by comparing the value stored in `eax` register with `MULTIBOOT_BOOTLOADER_MAGIC` macro, whose value is a magic number defined in the Multiboot specification.

```

@@ -208,6 +232,17 @@ NON_GPROF_ENTRY(btext)
    /* Tell the bios to warmboot next time */
    movw    $0x1234,0x472

+/* Are we booted by a Multiboot compliant bootloader? */
+    cml    $MULTIBOOT_BOOTLOADER_MAGIC,%eax
+    jne    1f
+    /* We won't be using the traditional bootinfo,
+     * so mark the relevant fields as undefined. */
+    movl    $0, R(bootinfo+BI_ESYMTAB)
+    movl    $0, R(bootinfo+BI_KERNEND)
+    movl    %ebx, R(multiboot_info)
+    jmp     2f
+1:

```

Unless the kernel is booted by a Multiboot compliant bootloader, we skip the newly added code block and continue booting along the old path (i.e. `jne 1f` – *if not equal jump forward to local label 1*).

If it is Multiboot compliant, we mark the relevant fields of the `bootinfo` global variable as unused by assigning to them the value of zero. There are two interesting constructs used in these assignments. The first is a C structure field access done in assembly language:

```
bootinfo+BI_ESYMTAB
```

`bootinfo` is of course the address of the structure itself, while `bi_esymtab` is one of the structure fields²². `BI_ESYMTAB` is a macro defined in `assym.s`, equal to the offset of field `bi_esymtab` in structure `struct bootinfo`. `assym.s` is a file automatically generated by `genassym.sh`. `genassym.sh(8)` FreeBSD 9.2 manpage says that the generated file is used by kernel sources written in assembler to gain access to information (e.g. structure offsets and sizes) normally only known to the C compiler. The second interesting thing in the above diff is the `R` macro:

```
movl    $0, R(bootinfo+BI_ESYMTAB)
```

whose definition is:

```
#define R(foo) ((foo)-KERNBASE)
```

The above definition tells us that each memory access via a virtual address should be done to a location specified by that virtual address decreased by the value of `KERNBASE`. It makes perfect sense when we realize that:

²²See DragonFly BSD: `sys/platform/pc32/include/bootinfo.h:48`

- the kernel is linked to run at a high virtual address (0xc0000000),
- the kernel is loaded at a low physical address (0x100000).

In fact, most of code in `locore.s` is running from a low memory location because that's where the bootloader puts the kernel. The MMU (memory management unit) is not setup yet to perform translation from low physical to high virtual addresses. Appropriately setting up the page tables (which drive the MMU translation) is one of the tasks performed in `locore.s`. Since the MMU isn't ready yet, some other mechanism of translation must be used to access the memory at the proper physical location – that's the purpose of the `R` macro. Code intended to run after relocation²³ does not use the macro anymore.

We're done with `struct bootinfo` once its fields are marked as unused. The next line:

```
movl    %ebx, R(multiboot_info)
```

saves the pointer to the Multiboot info structure passed in by GRUB. Later, the kernel command line is extracted from the structure by the `recover_multiboot_info` procedure and stored in a preallocated static page of kernel memory. Copying the whole command line buffer is done because of two reasons:

- the buffer is allocated by GRUB and its location is arbitrary; sooner or later the operating system will reuse the memory where it's stored, so it's safer to copy the contents to kernel memory,
- since the location of the buffer is not known beforehand (i.e. can't be foreseen at kernel compile time) it's not obvious how to access it after relocation.

Once the changes of the entry point described in this section were carried out the system was able to boot. The boot process at this moment was interactive, i.e. since the `struct bootinfo` fields were zeroed, the kernel was unable to find a root device and mount the root filesystem at `/`. This led to a prompt being displayed at boot time, requiring to specify the device to be mounted as root. Except for that, the system turned out to be fully functional.

4.3.7 Mounting the root file system

`dloader` is capable of preparing the kernel environment before booting the kernel. In fact, it's got a Forth interpreter built in, what makes it capable of performing some complicated tasks. Most of the time, though, `dloader` is simply used for parameterizing the functioning of some kernel subsystem, device driver or network stack. Setup of the kernel might also involve basic things like choosing the root device. However, the kernel

²³Relocation is the switch from executing code at physical addresses to executing at virtual addresses. It's done by setting up a virtual to physical memory mapping through appropriately populating the page tables. Once the MMU uses the proper page tables, a "fake return" virtual address is pushed onto the stack and a "return" to that address is performed using the `ret` instruction. See `sys/platform/pc32/i386/locore.s:335` for an example.

environment is essentially just a simple key-value storage space, where keys and values are zero-terminated strings whose meaning is left for interpretation to particular kernel subsystems.

GRUB is neither aware nor capable of adjusting this kind of BSD specific kernel environment. However, the Multiboot specification defines that the kernel may be passed a command line. It's simple to simulate a key-value kernel environment with a command line formatted according to the below scheme:

```
kernel key1=val1 key2=val2 ...
```

Interpreting such a command line, however, requires some logic in the kernel aware of the convention. The logic could populate the kernel environment just as `dloader` would do.

This code, though still coupled to the particulars of the bootloader which booted the kernel, is definitely out of scope of `locore.s`. Moreover, it would be unwise to write it in assembly, when C is easily available just a little later in the boot process.

As described in the previous section, the contents of the command line passed by GRUB are stored safely into kernel memory in `locore.s`. However, the command line contents aren't interpreted until later in the boot process. Choosing the exact moment is a bit tricky. On the one hand, the support mechanism of the dynamic kernel environment must be setup already, on the other hand, the interpretation must be performed as early as possible, since other initializing subsystems might depend on the information passed on the command line.

Fortunately, there exists a subsystem initialization mechanism with sophisticated priority management in the DragonFly BSD kernel already. Below is a glimpse of the priority setting definitions:

```
// sys/sys/kernel.h:90
/*
 * Enumerated types for known system startup interfaces.
 *
 * Startup occurs in ascending numeric order; the list entries are
 * sorted prior to attempting startup to guarantee order.
 * ...
 */
enum sysinit_sub_id {
    ...
    SI_BOOT1_POST      = 0x1800000,    /* post boot1 inits */
    ...
    SI_SUB_ROOT_CONF   = 0xb000000,    /* Find root devices */
    ...
};
```

As seen in the example listing above, the priorities are defined in wide intervals in order to leave room for introducing new subsystems in between the existing ones. Kernel

subsystems, defined in multiple files around the source code tree, define the points at which they expect to be initialized. Using a declaration instead of direct control flow passing from one subsystem to the next guarantees loose coupling between the components, but still maintains the proper relative order of their initialization. Subsystems loaded dynamically as kernel modules are also taken into account when determining the subsystem initialization order.

Given the above-described initialization mechanism, the following listing presents how the code interpreting the command line passed by GRUB²⁴ declares its required moment of initialization:

```
SYSINIT(multiboot_setup_kenv, SI_SUB_ROOT_CONF, SI_ORDER_MIDDLE,  
        multiboot_setup_kenv, NULL)
```

The `SYSINIT` macro is used to define the subsystem name (`multiboot_setup_kenv`), initialization order (`SI_SUB_ROOT_CONF` and `SI_ORDER_MIDDLE`) and initialization function (again `multiboot_setup_kenv`). Please note that this initialization step must be done between `SI_BOOT1_POST` and `SI_SUB_MOUNT_ROOT`.

At `SI_BOOT1_POST` the static kernel environment (inherited from the bootloader in case of `dloader`) is copied into the dynamic kernel environment, accessible via a kernel API. Before this operation, the dynamic kernel environment is not initialized yet and not accessible programmatically.

At `SI_SUB_MOUNT_ROOT` the kernel mounts the root device and expects any hints as to what device to use to already be present in the dynamic environment. `SI_SUB_ROOT_CONF` seems to be a reasonable step at which to perform the GRUB command line interpretation.

The initialization function uses `strsep()` implemented in the kernel C library (`sys/libkern.h`) to parse the command line and set a `kenv` for each `key=val` entry on the command line. Malformed entries (i.e. not containing an equal sign `=`) are ignored.

This way, given GRUB passes a valid value for `vfs.root.mountfrom` (e.g. `vfs.root.mountfrom=ufs:/dev/ad0s1a`) the code responsible for mounting the root file system in `sys/kern/vfs_conf.c` is aware of the device to be used for that purpose. This makes the boot process using GRUB fully automatic and seamless from the GRUB prompt straight to the login shell.

4.4 Booting DragonFly BSD with GRUB on x86-64

In case of the x86-64 architecture the problem of loading the kernel by GRUB is more complicated. The Multiboot Specification only defines an interface for loading 32 bit operating systems. This is due to two reasons.

First, when the specification was defined in 1995, the x86-64 was still to be unknown for the next 5 years.²⁵ Second, the AMD64 (the standard describing the x86-64 instruction

²⁴See DragonFly BSD: `sys/platform/pc32/i386/autoconf.c:500`

²⁵According to Wikipedia: [AMD64](#) was announced in 1999 with a full specification in August 2000.

set) requires the entry to the long mode be preceded by enabling paging and setting a logical to physical address mapping. Choosing any scheme for this mapping limits the freedom with respect to the operating system design. In other words, the mapping initialized by the bootloader would be forced onto the to-be-loaded kernel. The kernel programmer would have two choices: either leave the mapping as is or write some custom code to reinitialize the page table hierarchy upon entry into the kernel. The former is limiting. The latter is feasible: after all, the kernel manipulates the memory management settings as part of usual process context switching.

An alternative approach, however, would be to allow the processor to enter *real long mode* in which the addresses would be 64 bit wide and physical. That way the bootloader would be freed from setting up memory management on behalf of the OS. The kernel would be responsible for setting up memory management from the ground up in the most sensible way. This approach would also require the kernel to use the relocation macro technique (see the `R` macro description in section 4.3.6. *Adjusting the kernel entry point*) in order to make the code linked for high logical addresses function properly before setting up the page table hierarchy and relocating.

Since GRUB doesn't enter long mode and can't make use of 64 bit addressing, no matter whether the architecture allows for that with or without paging, the only way to boot a 64 bit operating system by GRUB is by embedding a piece of 32 bit code into the 64 bit kernel image.

4.4.1 Embedding a 32 bit entry point into a 64 bit kernel

Given the aforementioned limitations of GRUB and the CPU the cleanest possible way of loading a 64 bit kernel is by embedding some 32 bit code into the 64 bit kernel. This limits the choice of kernel load location to the 32 bit addressable space.

In case of DragonFly BSD this 32 bit code would realize roughly the same functionality as `sys/boot/pc32/libi386/x86_64_trampoline.S` which is part of the native `dloder`:

- It would set a preliminary memory mapping. Each (without loss of generality 1GiB in size) block of logical memory would point to the first block of physical memory (see figure 1). That way the kernel could be loaded to low physical memory but still be linked to use high logical addresses. Both the prerelocation and postrelocation code would run without requiring tricks such as the `R` prerelocation macro.
- It would enable paging, enter long mode and jump to the 64 bit entry point of the kernel.

One problem with this approach is that there would be two distinct entry points to the kernel: one for `dloder`, which is capable of booting the kernel straight into long mode, and another for protected mode only GRUB. That would require using the *a.out kludge*, i.e. apart from embedding the Multiboot header into the kernel image, embedding some extra fields which would override the meta information already stored in the ELF headers.

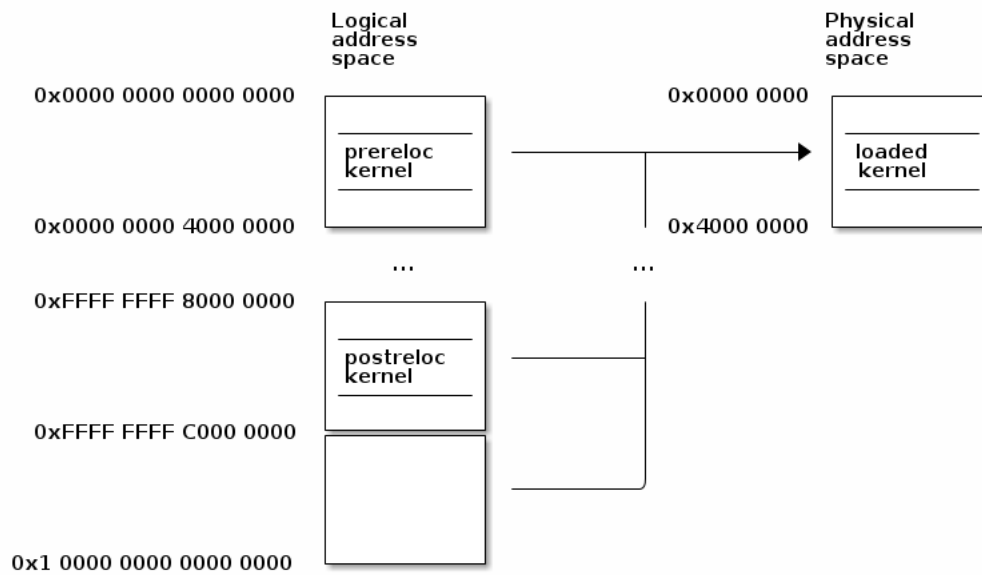


Figure 1: Each 1GiB block of logical memory is mapped to the first 1GiB block of physical memory (64 bit address space). Before relocation the code executes from *prereloc kernel*, after relocation from *postreloc kernel*.

As the names suggests, the technique is hardly elegant, but in case of two possible entry points might be unavoidable. In other words, the *a.out kludge* is another way apart from ELF headers GRUB is able to use to read the metadata from the loaded file.

Implementation of this approach was tried during the project, but due to the involved complexity and limited amount of time was not successful. This path is open for pursuing in the future.

5 Tools of a Kernel Developer's Trade

So, you want to write a kernel module. You know C, you've written a few normal programs to run as processes, and now you want to get to where the real action is, to where a single wild pointer can wipe out your file system and a core dump means a reboot.

– Salzman, Burian, and Pomerantz (2001), The Linux Kernel Module Programming Guide

Well... not really. Thankfully, the days when kernel debugging was done using a serial printer plugged into a spare headless PC and a core dump meant a reboot are gone now thanks to virtualization.

The tools I used for virtualization are VirtualBox and QEMU with Linux KVM (Kernel-based Virtual Machine). Although the work was started using a VirtualBox virtual machine I had to switch to QEMU/KVM in the middle of the project because of VirtualBox not supporting debugging with GNU gdb. Moreover, the 32 bit and 64 bit systems had to use separate virtual machines, so all the work with virtual machine management and system installation and setup had to be done twice.

As already mentioned, GNU gdb was used for GRUB and kernel debugging. Since the kernel image is linked to use high logical addresses and before relocation (just after being loaded by the bootloader) the kernel operates from a physical address, most of the debugging had to be done by setting breakpoints at manually calculated physical addresses instead of using symbol names. The process was arduous, very error prone and consumed a lot of time.

The main piece of software worked on during the project was DragonFly BSD. Hsu (2004) introduces the system well and points out some of its differences from the parent FreeBSD. Just to name a few features which stand out:

- DragonFly BSD tries to scale linearly on modern multi-core CPUs by multiplication of certain subsystems and data structures (e.g. the scheduler, memory allocator, ...) onto all cores and using non-blocking algorithms where possible, what allows for mostly asynchronous operation of all cores,
- HAMMER (and upcoming HAMMER2) filesystem, whose feature list is too long to quote here, but the most prominent are the built-in historical access and master-to-multiple-slaves streaming,
- Swapcache, which is an extension to the well-known swap partition mechanism; the feature allows an SSD swap partition to cache any filesystem operation(s) in order to speed up file systems stored on non-SSD devices.

All the operations on the kernel image and verification of changes in the linker script had to be checked by inspecting the resulting file. The utilities for these tasks are `readelf` and `objdump` which come from the GNU binutils package.

Of course, parts of the code written during this project are 64 bit assembly. The book by Seyfarth (2011) was a great help in putting these down.

The 6.828: Operating System Engineering course material from MIT (Cates et al. 2012), as well as the source code and its commentary of the Xv6 teaching operating system (Cox, Kaashoek, and Morris) were also of considerable help.

6 Related Work

There is a number of projects revolving around the issue of bootstrapping.

Coreboot is a BIOS firmware replacement. It is based on the concept of *payloads* (standalone ELF executables) which it loads in order to offer a specific set of functionality required by the software which is to run later. The usual payload is Linux, but there is a number of others available: SeaBIOS (offering traditional BIOS services), iPXE/gPXE/Etherboot (for booting over a network) or GNU GRUB. Thanks to the number of payloads Coreboot is able to load most PC operating systems.

Coreboot has a broad range of capabilities but as a firmware replacement it is intended for use by hardware manufacturers in their products (motherboards or systems-on-chip) in contrast to GRUB which is installable on a personal computer by a power-user.

UEFI (Unified Extensible Firmware Interface) is a specification of an interface between an operating system and a platform firmware. The initial version was created in 1998 as *Intel Boot Initiative*, later renamed to *Extensible Firmware Interface*. Since 2005 the specification is officially owned by the *Unified EFI Forum* which leads its development. The latest version is 2.4 approved in July 2013.

UEFI introduces processor architecture independence, meaning that the firmware may run on a number of different processor types: 32 or 64 bit alike. However, the OS system must size-match the firmware of the platform, i.e. a 32 bit UEFI firmware can only load a 32 bit OS image.

GPT (GUID Partition Table) is the new partitioning scheme used by UEFI. GPT is free of the MBR limitations such as number of primary partitions or their sizes still maintaining backwards compatibility with legacy systems understanding only MBR. The maximum number of partitions on a GPT partitioned volume is 128 with the maximum size of a partition (and the whole disk) of 8ZiB (2^{70} bytes).

In essence, UEFI is similar to the Multiboot Specification addressing the same limitations of the BIOS and conventional bootloaders. However, the Multiboot Specification was intended to provide a solution which could be retrofitted onto already existent and commonly used hardware, while UEFI is aimed at deployment on newly manufactured hardware. The Multiboot Specification is also a product of the Free Software community in contrast to the UEFI which was commercially backed from the beginning. The earliest version of the Multiboot Specification also predates the earliest version of UEFI (then known as Intel Boot Initiative) by 3 years.

7 Conclusions and Future Work

The evolutionary development of processor architectures, requirement of maintaining backwards compatibility and design errors lead to a lot of complications for the operating system developers.

However, with clever software design it is possible to abstract away most of the boot time peculiarities and cruft from the OS while initiatives like the Multiboot Specification and UEFI provide a clean interface for new and existing OS implementations.

Implementation of the GRUB and DragonFly BSD interoperability described herein was done for the x86 platform of DragonFly BSD. Based on the finding by Tigeot (2013) that *80.15% of downloaded packages are for the amd64/x86_64 architecture* it was decided that the x86 platform will be dropped in near future, though the exact release when that will happen hasn't been decided yet.

In this light, implementing the GRUB – DragonFly BSD interoperability, either according to the scenario described in one of the previous sections or by extending Multiboot and GRUB to allow loading ELF64 kernels natively, is an open field for future work.

The current implementation is only capable of loading the DragonFly BSD kernel from a UFS filesystem, but the hallmark feature of DragonFly BSD is the HAMMER filesystem. Enabling GRUB to read HAMMER and boot from a HAMMER volume would be a major step forward. HAMMER2 design is described by Dillon (2011), while more written word on the initial version of the filesystem is available from Lorch (2009) and Oppegaard (2009).

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