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Making DragonFly BSD operating system compliant with the Multiboot specification

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The evolutionary development of processor architectures, requirement of maintaining backwards compatibility and design errors lead to a lot of complications for the operating system developer. Abstracting away the boot time peculiarities and legacy cruft allows for simple and fast implementation of novel operating system concept prototypes, new hypervisors for the purpose of virtualization and improvement of the structure and maintainability of existing systems. I describe the Multiboot Specification which provides such an abstraction and how DragonFly BSD, a mature UNIX-derived operating system, can be modified to conform to that specification along with an implementation for the Intel 386 architecture. I present the changes made to GRUB, a bootloader implementing the specification, in order to allow it to boot DragonFly BSD. I also pinpoint an issue with the modern x86-64 architecture and the negative impact a wrong CPU design decision may have on the whole boot process.

Contents

1 Introduction

Wikipedia states that *an operating system (OS) is a collection of software that manages computer hardware resources and provides common services for computer programs.* In other words, an operating system is a computer program which allows other programs to run. What, then, allows the operating system to run if itself it cannot rely on an operating system? Especially, what does start the operating system?

The problem at hand is as old as computing itself. So is the concept of *bootstrapping* or, to put it simply, starting the computer. Bootstrapping, *booting* for short, relies on the machine being hardwired to read a simple program from a known beforehand location (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. A more detailed description of the process is given in *2 Booting a BSD system*.

The multitude of problems involved in implementing a bootloader for each combination of an operating system and hardware platform in use 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 GNU and is one of the most widely used bootloaders in the FOSS (Free and Open Source Software) world. More on the specification and GRUB is available in *3 The Multiboot Specification and GRUB* section.

The contributions of this paper are following:

- *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.

  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.

This is the core part of this paper.

- *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` hardly knows 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`[1].

[1] Why 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.

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*[2].

One more thing `boot2` does before running `loader` is initializing the first few fields of the `struct bootinfo` structure which is passed to the `loader` and later to the kernel. This structure is the main interface between the BSD bootloader and the kernel and 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).

2.4 Third stage: `loader`

The `loader`, 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, 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*[3], 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 line from 8086. 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`.

[2]Flat 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.

[3]Long 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.

`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 slightly 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).

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.

Such high coupling of the bootloader to the operating system was one of the reasons behind the Multiboot Specification. Other motives behind the specification are:

- the reduction of effort put into crafting bootloaders for disparate hardware platforms (much of the code for advanced features[4] 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).

The bootloader implementing the Multiboot Specification is GNU GRUB. Thanks to the modular architecture and clever design, GRUB is able to run on multiple hardware platforms, support a range of devices, partition table schemes and file systems and load different operating systems. Is is also possible to use it as a Coreboot payload. GRUB also sports a modern graphical user interface for a seamless user experience from the boot to 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] E.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).

4 Booting DragonFly BSD with GRUB

The focus of this paper 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[5] loading and booting operating system kernels, GRUB is capable of so called *chain loading*. 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.

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 `disklabel64`

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 the files of the operating system are stored on.

Traditionally, systems of the BSD family (among 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 `disklabel64` which shares the basic concepts of `disklabel` but also introduces some incompatibilities:

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

- 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.

TODO: there could be an appendix on BSD partitioning-related parlance: slices, partitions, labels.

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 `disklabel64`. 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`.

The module responsible for reading `disklabel64` this section refers to is already included in GRUB. That is one of the main contributions of the project this paper is about.

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 paper, 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 sight, 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 as could be partially anticipated from the previous section. 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 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 GRUB partition recognition loop mentioned above works. Each partition type callback (e.g. `dfly_partition_map_iterate`, `grub_partition_msdos_iterate`, ...) is first run on the raw device to find a partition table. Then, consecutively, 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 deep partition nesting as in the `(hd0,msdos2,dfly1)` example.

The automatic partition table and file system discovery tests 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` not to break the already existing boot path.

The following sections describe in detail how the listed steps were performed, taking the above consideration into account, 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:

> An OS image must contain an additional header called Multiboot header, besides the headers of the format used by the OS image. The Multiboot header must be contained completely within the first 8192 bytes of the OS image, and must be longword (32-bit) aligned. In general, it should come as early as possible, and may be embedded in the beginning of the text segment after the real executable header.

Except the above requirements, there are really no constraints put onto the format of the kernel image file. Specifically, the requirements described above allow the kernel to 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.

Embedding the Multiboot header

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 syntax[6].

The low level architecture dependent parts of the kernel are to be found 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 sight 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 such a 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 \
                                    | MULTIBOOT_MEMORY_INFO
#define MULTIBOOT_CMDLINE_MAX       0x1000
#define MI_CMDLINE_FLAG             (1 << 2)
#define MI_CMDLINE                  0x10

/* ... snip ... */
```

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

```
    .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.

What is a 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 a succinct answer to that question:

> [A] linker assigns numeric locations to symbols, determines the sizes and location of the segments in the output address space, and figures out where everything goes in the output file.

The last part of this sentence is crucial.

Chamberlain and Taylor (2003) in *Using ld, the GNU linker* specify:

> The main purpose of the linker script is to describe how the sections in the input files should be mapped into the output file, and to control the memory layout of the output file. Most linker scripts do nothing more than this.

Again Chamberlain and Taylor (2003) also inform what language GNU `ld` accepts:

> `ld` accepts Linker Command Language files written in a superset of AT&T's Link Editor Command Language syntax, to provide explicit and total control over the linking process.

In the light of the above, especially the *total control over the linking process* 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 determined in the code otherwise. 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` section which the it must initialize itself.

Modifying the linker script

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);
   . = 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. 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.

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 e19c755 from the DragonFly BSD repository:

> 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.

From this message 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 execution[7]. In case of a kernel, the path

[7] On x86-64 Linux this is typically `/lib64/ld-linux-x86-64.so.2` while on DragonFly BSD

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.

4.3.2 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 that the code must branch taking the points stated above into account. The branching should converge before calling the platform dependent `init386`

`/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 those dynamically linked shared libraries finalizing the linking of the program during its execution.

initialization procedure. The rest of the system should not need to be aware of what bootloader loaded the kernel.

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. Firstly, it ignores the physical addresses embedded in the ELF image. Secondly, it calculates the load address based on the entry address stored in the image.

The entry address is read from the ELF header:

```
// sys/boot/common/load_elf.c:174
/*
* Calculate destination address based on kernel entrypoint
*/
dest = ehdr->e_entry;
```

The entry address is passed to an architecture word size aware function that will read the ELF image. For ELF32 the macro call `__elfN(loadimage)` expands to `elf32_loadimage(fp, &ef, dest)`.

```
// sys/boot/common/load_elf.c:233
__elfN(loadimage)(fp, &ef, dest);
```

The following is the commented signature of `elf32_loadimage()`. Note that variable `dest` is known as `off` inside the function.

```
// sys/boot/common/load_elf.c:258
/*
 * With the file (fd) open on the image, and (ehdr) containing
 * the Elf header, load the image at (off)
 */
static int
__elfN(loadimage)(struct preloaded_file *fp,
                  elf_file_t ef,
                  u_int64_t off);
```

Below, the load address is adjusted depending on the architecture. For ELF32 and the initial entry address equal to `0xc016c450` this calculation 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.

```
// sys/boot/common/load_elf.c:289
if (ef->kernel) {
#ifdef __i386__
#if __ELF_WORD_SIZE == 64
    /* x86_64 relocates after locore */
    off = - (off & 0xffffffffff000000ull);
#else
    /* i386 relocates after locore */
    off = - (off & 0xff000000u);
#endif
```

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

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 that `dloader` won't be able to handle.

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) }
```

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
...
```

At last, 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:
  Magic:   7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF32
  Data:                              2's complement, little endian
  Version:                           1 (current)
```

```
OS/ABI:                            UNIX - System V
ABI Version:                       0
Type:                              EXEC (Executable file)
Machine:                           Intel 80386
Version:                           0x1
Entry point address:               0xc013b040
Start of program headers:          52 (bytes into file)
Start of section headers:          21377500 (bytes into file)
Flags:                             0x0
Size of this header:               52 (bytes)
Size of program headers:           32 (bytes)
Number of program headers:         5
Size of section headers:           40 (bytes)
Number of section headers:         34
Section header string table index: 31
```

As 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`) as seen in the code below:

```
// grub-core/loader/multiboot_elfxx.c:131
if (phdr(i)->p_vaddr <= ehdr->e_entry
    && phdr(i)->p_vaddr + phdr(i)->p_memsz > ehdr->e_entry)
  {
    grub_multiboot_payload_eip = (ehdr->e_entry - phdr(i)->p_vaddr)
      + phdr(i)->p_paddr;
    ...
  }
```

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.

Adjusting the 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.

Just after entering the kernel we check whether the bootloader that booted us is Multiboot compliant:

```
@@ -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? */
+       cmpl    $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 it is Multiboot compliant, we mark the relevant fields of the `struct bootinfo` global variable `bootinfo` 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. Let's look at its definition:

```
// sys/platform/pc32/include/bootinfo.h:48
/*
 * A zero bootinfo field often means that there is no info available.
 * Flags are used to indicate the validity of fields where zero is a
 * normal value.
 */
struct bootinfo {
```

```
    u_int32_t   bi_version;
    u_int32_t   bi_kernelname;      /* represents a char * */
    u_int32_t   bi_nfs_diskless;    /* struct nfs_diskless * */
                /* End of fields that are always present. */
#define bi_endcommon    bi_n_bios_used
    u_int32_t   bi_n_bios_used;
    u_int32_t   bi_bios_geom[N_BIOS_GEOM];
    u_int32_t   bi_size;
    u_int8_t    bi_memsizes_valid;
    u_int8_t    bi_bios_dev;        /* bootdev BIOS unit number */
    u_int8_t    bi_pad[2];
    u_int32_t   bi_basemem;
    u_int32_t   bi_extmem;
    u_int32_t   bi_symtab;      /* struct symtab * */
    u_int32_t   bi_esymtab;     /* struct symtab * */
                /* Items below only from advanced bootloader */
    u_int32_t   bi_kernend;     /* end of kernel space */
    u_int32_t   bi_envp;        /* environment */
    u_int32_t   bi_modulep;     /* preloaded modules */
};
```

As seen above, `bi_esymtab` is one of the structure fields. `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:

> 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:

- 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 relocation[8] 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.

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. Setup of the kernel might involve basic things like choosing the root device or much more specific ones like fine tuning particular device driver or network stack parameters. However, the kernel 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:

[8] Relocation 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 pagle 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.

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

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

This logic, 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 this logic in assembly if C is easily available just a little later in the boot process.

TODO: subsystem initialization mechanisms, adding multiboot_setup_kenv initializer, finally booting non-interactively

4.4 Booting DragonFly BSD with GRUB on x86-64

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

Firstly, when the specification was defined in 1995, the x86-64 was still to be unknown for the next 5 years.[9]

Secondly, the AMD64 (the standard describing the x86-64 instruction 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 would defeat the initial purpose of the specification, i.e. to make the OS startup procedure as simple as possible.

Given the above, from the point of view of creating a universal bootloader **the CPU design decision to require enabling of the virtual addressing before entering the long mode is a flaw.** The CPU should be able to enter the long mode with a simple one-to-one logical-to-physical address mapping; the bootloader would then be able to load the 64 bit kernel anywhere into the 64 bit addressable memory and run it; the kernel itself would be responsible for setting up the memory mapping scheme according to its own requirements.

4.4.1 The workaround

Given the aforementioned limitations of GRUB and the CPU the cleanest possible way of loading the 64 bit kernel is out of reach. It does not mean, however, that adapting the x86-64 DragonFly BSD kernel to the Multiboot Specification is impossible.

[9] According to Wikipedia: AMD64 was *announced in 1999 with a full specification in August 2000.*

The idea is to embed a portion of 32 bit code inside the 64 bit kernel executable and only for the sake of the bootloader pretend to be a 32 bit binary.

This code logic would be similar to the code found in the 64 bit extension of the BSD `loader`, i.e. it would set up paging, enter the long mode and jump to the 64 bit kernel entry point.

Implementation of this approach is yet to be carried out.

5 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.

6 Conclusions

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.

Even the newest architecture designs are not free of flaws such as the x86-64 CPU's requirement of enabling virtual memory addressing before entering the long mode.

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.

The extension of the Multiboot Specification to cover loading of 64 bit operating systems might be an interesting path of research. This might be achieved by constructing a generally acceptable logical to physical memory mapping for at least the size of the kernel (contained inside the ELF binary) and spanning the whole range of addresses the kernel is linked to use. However, the concept needs thorough evaluation.

7 Literature

TODO: embed bibtex or whatever makes sense, for now it's just copy-n-paste

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TODO: clean up the references/citations stuff up

(see Hsu 2004)

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8 References

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