Using a JTAG in Linux Driver Debugging

Supporting New Hardware

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What We Will Talk About

- What are we trying to do?
- Hardware debuggers
- What is JTAG?
- How does it work?
- Board bring up
- The Linux boot sequence
- Debugging the kernel and device drivers

What are we trying to do?

- The board bring-up process is loaded with potential gotchas
    - Obtaining data sheets may be near impossible
    - The hardware may or may not be working
    - The boot firmware may have restrictive licensing issues
- There are two phases of device driver development that we’ll need to address
    - Getting the board to work at all
    - Adding features for peripherals

Porting Linux

- Bringing Linux up on a new board will require some knowledge of assembly language for your processor
    - There are several transitions from assembly to “C” and back if we’re using zImages
- Debugging at this level will require the use of JTAGs, or other hardware assistance
    - Never underestimate the power of an LED

Device Drivers in Linux

- Linux has several driver types
  - Character, block, network, etc.
- Linux uses a formal driver model
  - Drivers present a common API such as open(), release(), read(), write(), etc.
- User-mode device drivers are also possible
  - Via /dev/mem, /dev/ioports, etc.
  - Easier to debug using standard GDB

Statically Linked – Dynamically Loaded

- The typical kernel-mode driver can be statically linked into the kernel at kernel build time
  - Must be GPL
  - Initialized in start_kernel() sequence
- Dynamically-loaded drivers, a.k.a. kernel modules are loaded after the kernel is booted and init is running
  - Can be loaded from initramfs/initrd
  - Can have proprietary licenses

Driver Initialization Sequence

- Drivers must register themselves with the kernel
  - register_chrdev(), register_blkdev(), register_netdev(), etc.
- For block and character drivers you'll need to assign major/minor numbers
  - Can be done statically or dynamically
  - Coordinate with <linux>/Documentation/devices.txt
- You'll need to create device nodes as well
  - Statically or via UDEV

Loadable Module Example

```
#include <linux/module.h>
#include <linux/init.h>
#include <linux/kernel.h>

#define MODULE_NAME “celf"

int __init celf_init_module(void) {
     printk(“celf_init_module() called, ");
     return 0;
}

void __exit celf_cleanup_module(void) {
     printk(“celf_cleanup_module() called\n");
}

module_init(celf_init_module);
module_exit(celf_cleanup_module);
```

Old School Driver Registration

- Kernel is made aware of a character device driver when the driver registers itself
  - Typically in the __init function
- Registration makes the association between the major number and device driver

```
 int register_chrdev(unsigned int major,
const char *name, struct file_operations
*fops)
```

Old School Driver Registration #2

- Likewise, when a device driver removes itself from the system, it should unregister itself from the kernel to free up that major number
- Typically in the __exit function:

```
int unregister_chrdev(unsigned
   int major, const char *name);
```

New-School Driver Registration

- If you need to get beyond the 256 major limit, you'll need to use a different approach
  - This uses a different API, dev_t, cdev structures and a much more involved registration approach
- All of this is beyond scope for the current discussion, however

Giving Your Driver Something to do

- Character device driver exports services in file_operations structure
  - There are 26 supported operations in the 2.6 kernel
    - Up from 17 in the 2.4.kernel
- You only supply those calls that make sense for your device
- You can explicitly return error codes for unsupported functions or have the system return the default ENOTSUPP error
- Typically, the file_operations structure is statically initialized
  - Using C99 tagged initializer format

struct file_operations #1 of 2

```
struct file_operations {
  struct module *owner;
  loff_t  (*llseek) (struct file *, loff_t, int);
  ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
  ssize_t (*aio_read) (struct kiocb *, char __user *, size_t, loff_t);
  ssize_t (*write) (struct file *, const char __user *, size_t,
                loff_t *);
  ssize_t (*aio_write) (struct kiocb *, const char __user *,
                size_t, loff_t);
  int     (*readdir) (struct file *, void *, filldir_t);
  unsigned int (*poll) (struct file *, struct poll_table_struct *);
  int     (*ioctl) (struct inode *, struct file *, unsigned int,
                unsigned long);
  long    (*unlocked_ioctl) (struct file *, unsigned int, unsigned long);
  long    (*compat_ioctl) (struct file *, unsigned int, unsigned long);
  int     (*mmap) (struct file *, struct vm_area_struct *);
  int     (*open) (struct inode *, struct file *);
  int     (*flush) (struct file *);
```

struct file_operations #2 of 2

```
  int      (*release) (struct inode *, struct file *);
  int      (*fsync) (struct file *, struct dentry *, int datasync);
  int      (*aio_fsync) (struct kiocb *, int datasync);
  int      (*fasync) (int, struct file *, int);
  int      (*lock) (struct file *, int, struct file_lock *);
  ssize_t (*readv) (struct file *, const struct iovec *, unsigned long,
                loff_t *);
  ssize_t (*writev) (struct file *, const struct iovec *, unsigned long,
                loff_t *);
  ssize_t (*sendfile) (struct file *, loff_t *, size_t, read_actor_t, void *);
  ssize_t (*sendpage) (struct file *, struct page *, int, size_t,
                loff_t *, int);
  unsigned long (*get_unmapped_area)(struct file *, unsigned long,
                unsigned long, unsigned long, unsigned long);
  int      (*check_flags)(int);
  int      (*dir_notify)(struct file *filp, unsigned long arg);
  int      (*flock) (struct file *, int, struct file_lock *);
};
```

Which File Operations do I Need?

- Typically, a driver will implement:
    - open()
    - release()
        - a.k.a., the user-space close()
    - read()
    - write()
    - ioctl()

- Additional features like mmap(), poll(), fasync(), and flush() are nice to haves
    - You can add them at any time during development
- Some methods like llseek() and readv()/writev() may not apply to your device
    - You decide what to support and errors to return

Initializing the file_operations

- C99 tagged initialization of the structures allows you to initialize the fields by name
  - No worry about the structure layout (which may change between kernel revisions)
- Un-initialized function entries in the structure shown below will be initialized to NULL

```
struct file_operations fops = {
                    .read    = my_read,
                    .write   = my_write,
                    .ioctl   = my_ioctl,
                    .open    = my_open,
                    .release = my_release
                    };
```

Debugging Device Drivers

- Statically-linked device drivers are notoriously difficult to debug
  - An error can cause a panic or oops before you can even get printk() to work
  - These will typically require a JTAG to debug them easily
- Dynamically-linked drivers are marginally easier because you can get more debugging infrastructure into place before loading them
  - The use of read_proc()/write_proc() functions and printk() are typical
  - JTAGs can help here too

Hardware Debugging Tools

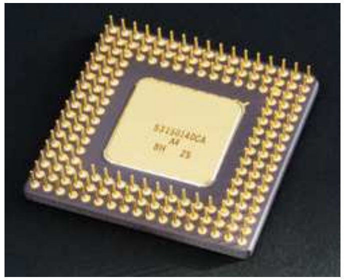
- The traditional hardware debug tool was the In-Circuit Emulator (ICE)
  - A device that plugged into the CPU socket and emulated the CPU itself
- These were rather expensive
  - $30K+ for the good ones
- Today, most devices that call themselves an ICE are actually JTAGs

Source: Avocet Systems

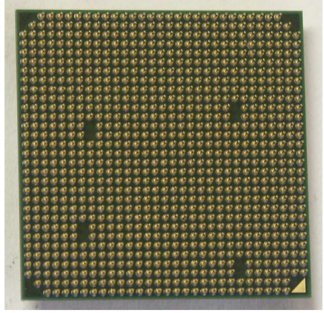
Source: Hitex Devel Tools

Why the Traditional ICE has Faded Away

- The biggest problem faced by the ICE concept was the increasing pin counts of processors
  - E.g., 939 pins for the Athlon-64
- Each pin required a wire to the ICE
  - Each wire started to become an antenna as frequencies increased
- Processors also started to move to Ball Grid Array (BGA) packages
  - No way to get to the pins in the center of the part because the part is soldered to the motherboard



Source: Intel



Source: AMD

Source: ESA

Enter the JTAG Port

- The Joint Test Action Group (JTAG) is the name associated with the IEEE 1149.1 standard entitled Standard Test Access Port and Boundary-Scan Architecture
  - Originally introduced in 1990 as a means to test printed circuit boards
  - An alternative to the bed of nails

Source: Test Electronics

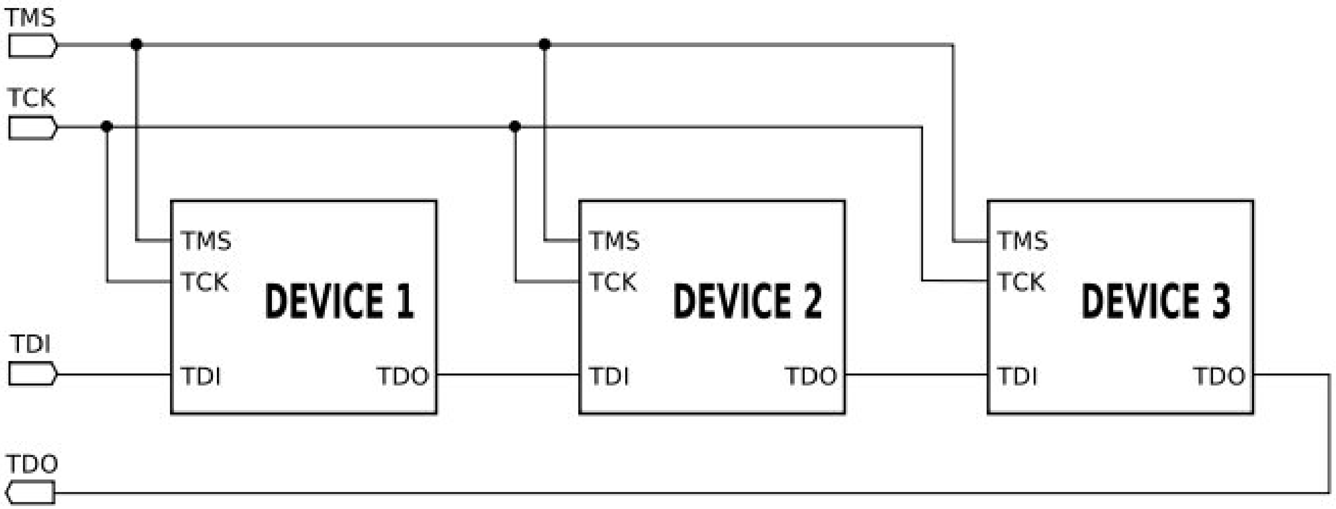
How JTAG Works

- JTAG is a boundary-scan device that allows the developer to sample the values of lines on the device
  - Allows you to change those values as well
- JTAG is built to allow chaining of multiple devices
  - Works for multi-core processors, too

JTAG Details

- JTAG is a simple serial protocol
- Configuration is done by manipulating the state machine of the device via the TMS line

1. TDI (Test Data In)
2. TDO (Test Data Out)
3. TCK (Test Clock)
4. TMS (Test Mode Select)
5. TRST (Test ReSeT) optional.



JTAG-Aware Processors

- Most embedded processors today support JTAG or one of its relatives like BDM
  - E.g., ARM/XScale, PPC, MIPS
- Even the x86 has a JTAG port although it is rarely wired out
  - Grandma can barely send e-mail, let alone know what to do with a JTAG port
- Some processors like MIPS come in different versions
  - Some with JTAG ports for development, some without in order to save $$$

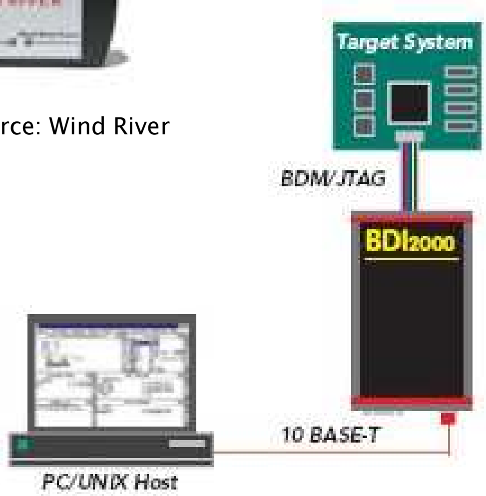
JTAG Vendors

- Several different vendors sell JTAG port interface hardware
  - JTAG is also referred to as On-Chip Debugging (OCD)
- Here are a few of the vendors:
  - Wind River Systems (http://www.windriver.com)
  - Abatron AG (http://www.abatron.ch)
  - American Arium (http://www.arium.com)
  - Mentor Graphics (http://www.epitools.com)
- Some vendors do certain processors better than others
  - MIPS will usually have a more custom EJTAG interface

JTAG Connections

- The maximum speed of JTAG is 100 MHz
  - A ribbon cable is usually sufficient to connect to the target
- Connection to the development host is accomplished via
  - Parallel port
  - USB
  - Serial port
  - Ethernet

Source: Wind River

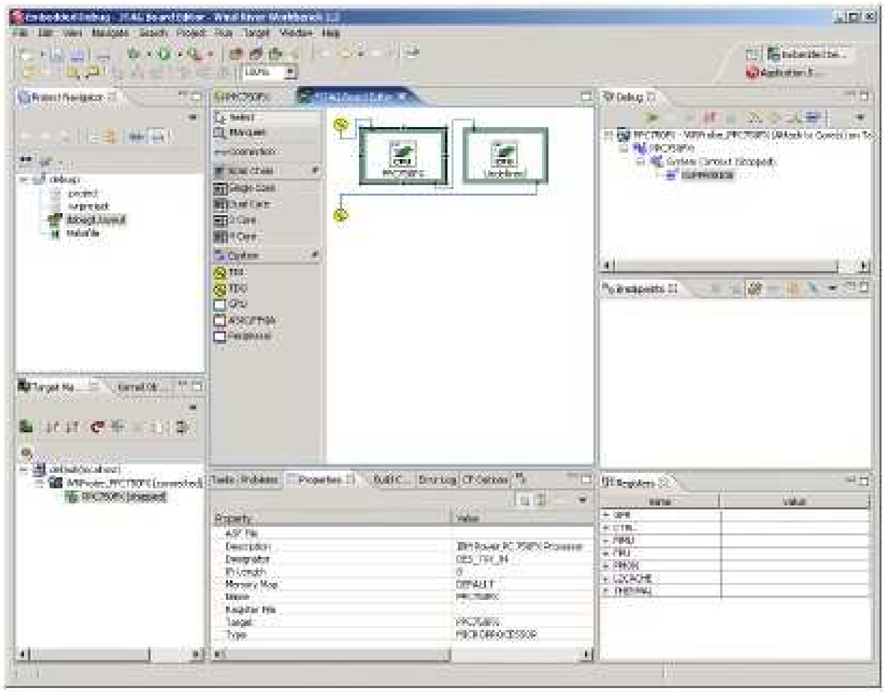


Source: Olimex

Source: Abatron

JTAG User Interface

- Some JTAG interfaces use a GDB-style software interface
  - Any GDB-aware front end will work
- Others have Eclipse plug-ins to access the JTAG via an IDE
- Some still use a command line interface



Source: Wind River

What can you do with a JTAG?

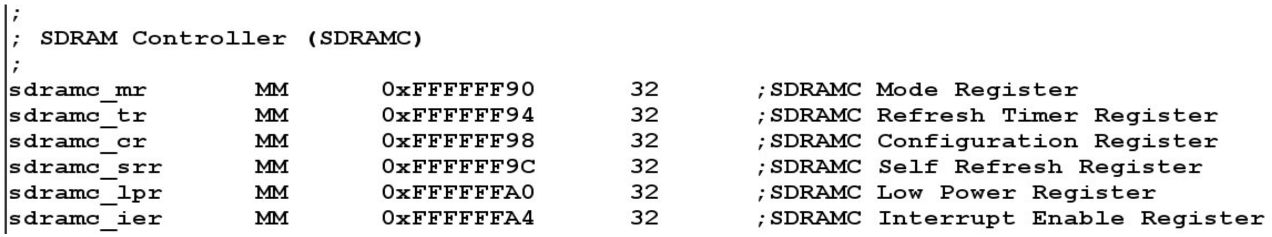
- Typical JTAG usage includes reflashing boot firmware
  - Even the really cheap JTAG units can do this
- However, it is in the use as a debugging aid that JTAG comes into its own
  - You can set hardware or software breakpoints and debug in source code
  - Sophisticated breakpoint strategies and multi-core debugging usually require the more expensive units
- JTAG units can also be used to exercise the address bus and peripherals
  - This is what JTAG was originally designed for

Hardware Configuration Files

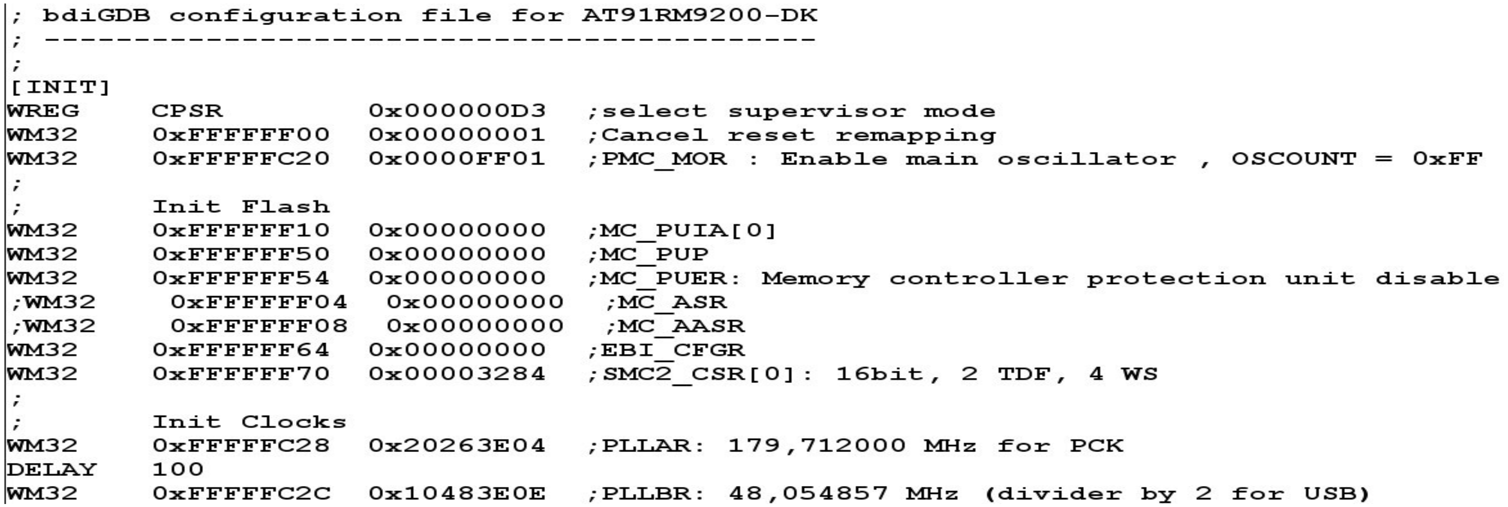
- Most JTAG units require you to describe the hardware registers in a configuration file
  - This is also how you describe what processor architecture you are using
- All of that information about register maps that you collected earlier now goes into the configuration file
- Unfortunately, there is no standard format for these configuration files
  - Each JTAG vendor uses different syntax

Example Configuration Files

- Many JTAG units split the configuration files into a CPU register file and a board configuration file



```
;
; SDRAM Controller (SDRAMC)
;
sdramc_mr        MM      0xFFFFFF90      32      ;SDRAMC Mode Register
sdramc_tr        MM      0xFFFFFF94      32      ;SDRAMC Refresh Timer Register
sdramc_cr        MM      0xFFFFFF98      32      ;SDRAMC Configuration Register
sdramc_srr       MM      0xFFFFFF9C      32      ;SDRAMC Self Refresh Register
sdramc_lpr       MM      0xFFFFFFA0      32      ;SDRAMC Low Power Register
sdramc_ier       MM      0xFFFFFFA4      32      ;SDRAMC Interrupt Enable Register
```



```
; bdiGDB configuration file for AT91RM9200-DK
; --------------------------------------------
;
[INIT]
WREG     CPSR          0x000000D3   ;select supervisor mode
WM32     0xFFFFFF00    0x00000001   ;Cancel reset remapping
WM32     0xFFFFFC20    0x0000FF01   ;PMC_MOR : Enable main oscillator , OSCOUNT = 0xFF
;
;        Init Flash
WM32     0xFFFFFF10    0x00000000   ;MC_PUIA[0]
WM32     0xFFFFFF50    0x00000000   ;MC_PUP
WM32     0xFFFFFF54    0x00000000   ;MC_PUER: Memory controller protection unit disable
;WM32     0xFFFFFF04    0x00000000   ;MC_ASR
;WM32     0xFFFFFF08    0x00000000   ;MC_AASR
WM32     0xFFFFFF64    0x00000000   ;EBI_CFGR
WM32     0xFFFFFF70    0x00003284   ;SMC2_CSR[0]: 16bit, 2 TDF, 4 WS
;
;        Init Clocks
WM32     0xFFFFFC28    0x20263E04   ;PLLAR: 179,712000 MHz for PCK
DELAY    100
WM32     0xFFFFFC2C    0x10483E0E   ;PLLBR: 48,054857 MHz (divider by 2 for USB)
```

Source: Abatron

Developing the Configuration File

- The JTAG vendor will likely already have a register file for the processor
  - ARM920, PPC8241, etc.
- Your task will be to develop the board configuration file
  - There may be a configuration file for the reference board that you can use as a starting point
- The configuration file is essentially a script of commands to initialize the target board
  - You keep working on it until you can initialize memory
  - Once memory is on-line, you should then be able to write values into memory via the JTAG that can be read back
  - Then, enhance the configuration to initialize other peripherals

Linux-Aware JTAGs

- There are several rather tricky transitions during the Linux booting process
  - Transitioning from flash to RAM
  - Transitioning from physical addresses to kernel virtual addresses
  - These transitions require the use of hardware breakpoints
- Make sure that your JTAG is “Linux aware”
  - It must understand Linux’s use of the MMU to be of much use for driver debugging

The Linux Boot Sequence

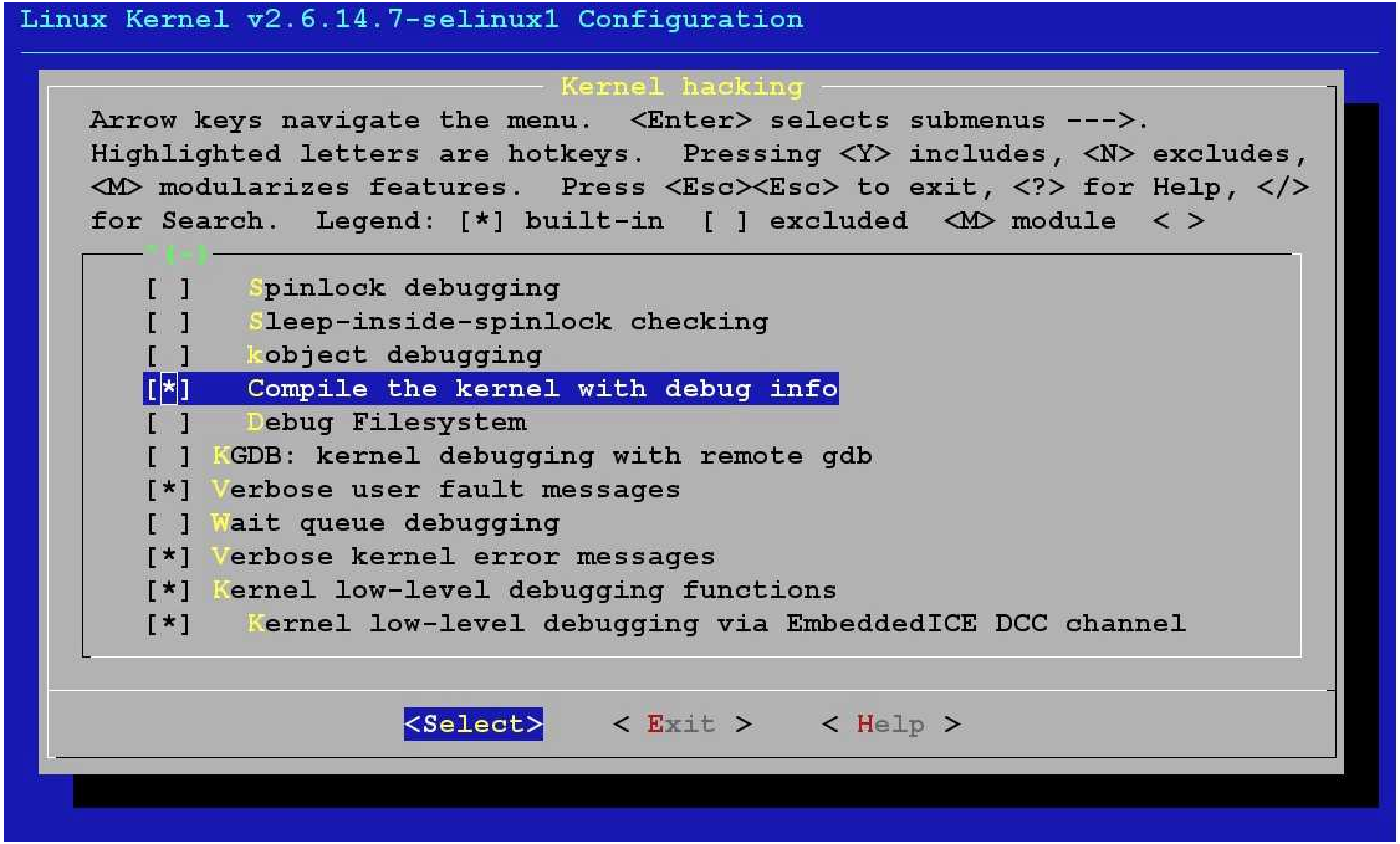
- Like the boot firmware, the Linux kernel starts in assembly language
  - Sets up the caches, initializes some MMU page table entries, configures a “C” stack and jumps to a C entry point called start_kernel() (init/main.c)
- start_kernel() is then responsible for:
  - Architecture and machine-specific hardware initialization
  - Initializing virtual memory
  - Starting the system clock tick
  - Initializing kernel subsystems and device drivers
- Finally, a system console is started and the init process is created
  - The init process (PID 1) is then the start of all user-space processing

JTAG and Early Kernel Debug

- An odd thing happens when the MMU is enabled
  - All of the physical addresses suddenly get translated into virtual addresses
- The kernel’s debug symbols are all built assuming a virtual address space
  - You’ll need to turn debugging symbols on in the kernel
- Consequently, while you can step through the early code by using a hardware breakpoint address, software breakpoint on symbols will only work after the MMU is enabled
  - Fortunately, this happens fairly early in the kernel initialization
- You can typically tell the JTAG to step so many instructions and then stop again
  - Step past the MMU initialization, stop and then set additional breakpoints

Configure Kernel for Debugging

- Enable debugging info and rebuild the kernel



```
Linux Kernel v2.6.14.7-selinux1 Configuration

                         Kernel hacking
  Arrow keys navigate the menu.  <Enter> selects submenus --->.
  Highlighted letters are hotkeys.  Pressing <Y> includes, <N> excludes,
  <M> modularizes features.  Press <Esc><Esc> to exit, <?> for Help, </>
  for Search.  Legend: [*] built-in  [ ] excluded  <M> module  < >

     ^(-)
      [ ]     Spinlock debugging
      [ ]     Sleep-inside-spinlock checking
      [ ]     kobject debugging
      [*]     Compile the kernel with debug info
      [ ]     Debug Filesystem
      [ ]   KGDB: kernel debugging with remote gdb
      [*]   Verbose user fault messages
      [ ]   Wait queue debugging
      [*]   Verbose kernel error messages
      [*]   Kernel low-level debugging functions
      [*]     Kernel low-level debugging via EmbeddedICE DCC channel

                 <Select>    < Exit >    < Help >
```

Loading Symbols into the JTAG UI

- Depending on the JTAG UI, you may simply have to load the kernel's vmlinux image to be able to access the symbols by name
    - The techniques for doing this vary by JTAG vendor
- Attach the JTAG to the hardware
    - Reset the board via JTAG and hold in reset
    - Set H/W breakpoint using the JTAG
    - Load the vmlinux via the JTAG (this loads the symbols)
    - Command the JTAG to tell the hardware to "go"
- Once you encounter the hardware breakpoint, you can step in assembly until the MMU is enabled
    - The MMU will translate physical addresses to virtual addresses
    - Once virtual addressing is on, set breakpoints as normal

Using JTAG to Dump printk Buffer

- If you kernel hangs right after displaying "Uncompressing Kernel Image … OK" message…
  - You probably have printk() output, but the serial console isn't initialized yet
- We can dump the printk buffer using the JTAG!
  - Look in the kernel's System.map file for something like "__log_buf"

```
$ grep __log_buf /boot/System.map
   c0445980 b __log_buf
```

Dumping printk Buffer #2

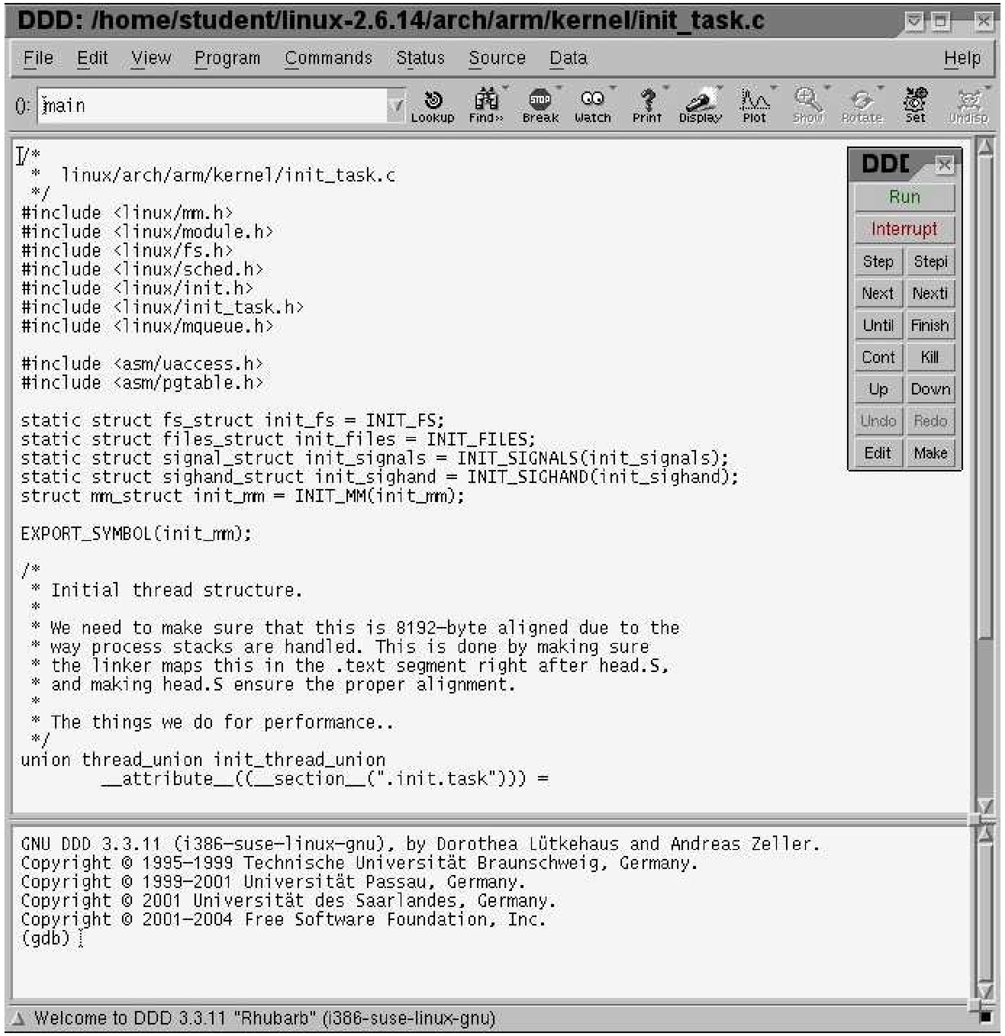
- The address of the buffer is a translated kernel address
  - Strip off the 0xC0000000 portion of the address to get (typically) the physical address on processors like the X86
  - i.e., 0xc0445980 would typically be at physical address 0x445980
  - You must understand your processor to do the translations correctly
- Now, use the JTAG to dump that address
  - Raw printk output, but you can get an idea of what it was doing when it crashed
  - Data is still there even after reset (but not power-off)

GDB-Aware JTAGs

- If the JTAG is GDB-aware, then you will be able to control it using normal GDB commands
  - Attach to the JTAG via “target remote xx” command where “xx” is via Ethernet, serial or other connection between your JTAG and the host
- Use the GDB “mon” command to pass commands directly to the JTAG

DDD GUI Front-End Example

- Invoked from command line with vmlinux compiled for debugging
- Then attach to JTAG using “target remote” command



```
/*
 *  linux/arch/arm/kernel/init_task.c
 */
#include <linux/mm.h>
#include <linux/module.h>
#include <linux/fs.h>
#include <linux/sched.h>
#include <linux/init.h>
#include <linux/init_task.h>
#include <linux/mqueue.h>

#include <asm/uaccess.h>
#include <asm/pgtable.h>

static struct fs_struct init_fs = INIT_FS;
static struct files_struct init_files = INIT_FILES;
static struct signal_struct init_signals = INIT_SIGNALS(init_signals);
static struct sighand_struct init_sighand = INIT_SIGHAND(init_sighand);
struct mm_struct init_mm = INIT_MM(init_mm);

EXPORT_SYMBOL(init_mm);

/*
 * Initial thread structure.
 *
 * We need to make sure that this is 8192-byte aligned due to the
 * way process stacks are handled. This is done by making sure
 * the linker maps this in the .text segment right after head.S,
 * and making head.S ensure the proper alignment.
 *
 * The things we do for performance..
 */
union thread_union init_thread_union
	__attribute__((__section__(".init.task"))) =
```

```
GNU DDD 3.3.11 (i386-suse-linux-gnu), by Dorothea Lütkehaus and Andreas Zeller.
Copyright © 1995-1999 Technische Universität Braunschweig, Germany.
Copyright © 1999-2001 Universität Passau, Germany.
Copyright © 2001 Universität des Saarlandes, Germany.
Copyright © 2001-2004 Free Software Foundation, Inc.
(gdb) 
```

Welcome to DDD 3.3.11 "Rhubarb" (i386-suse-linux-gnu)

Debugging Device Drivers

- Statically linked driver symbols are already built into the kernel’s symbol table
  - Simply set break points on the driver methods themselves
- Dynamically loaded drivers require additional steps
  - We need to find the addresses used by the driver
- The next few charts assume a GDB-aware JTAG

Debugging Loadable Modules

- In order to debug a loaded module, we need to tell the debugger where the module is in memory
  - The module's information is not in the vmlinux image because that shows only statically linked drivers
- How we proceed depends on where we need to debug
  - If we need to debug the __init code, we need to set a breakpoint in the sys_init_module() function

Debugging Loadable Modules #2

- We’ll need to breakpoint just before the control is transferred to the module’s __init
  - Somewhere around line 1907 of module.c
- Once the breakpoint is encountered, we can walk the module address list to find the assigned address for the module
  - We then use the add-symbol-file GDB command to add the debug symbols for the driver at the address for the loaded module
  - E.g.,

```
add-symbol-file ./mydriver.ko 0x<addr> -e .init.text
```

Debugging Loadable Modules #3

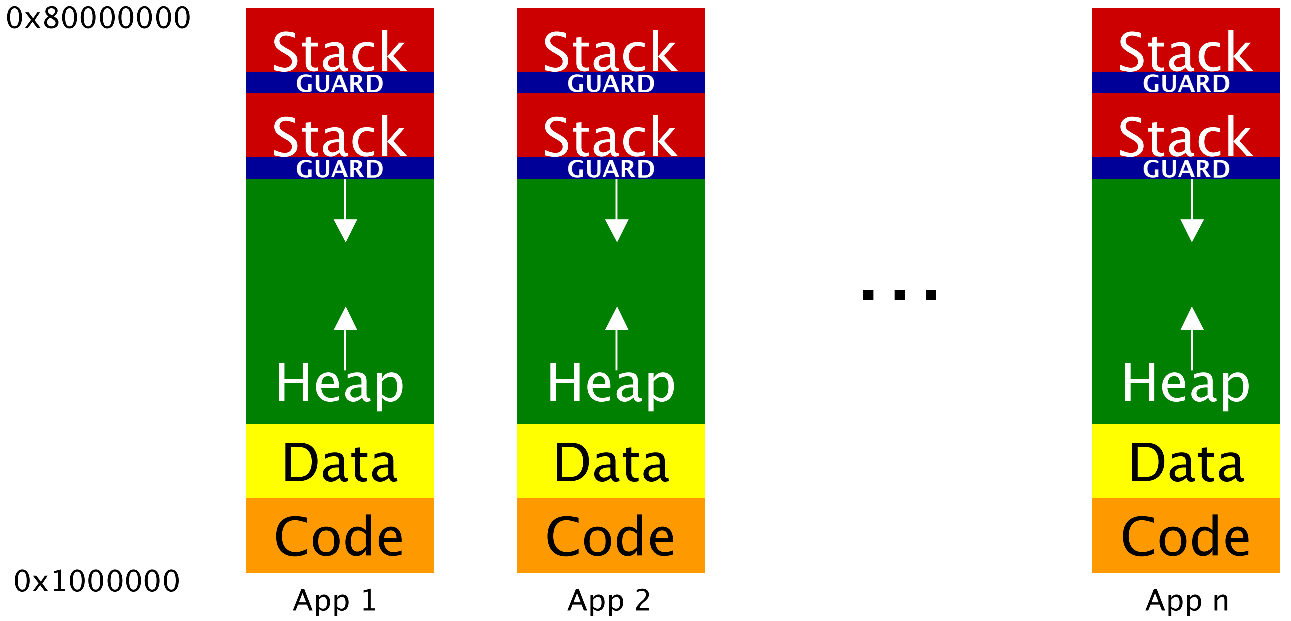
- Now, you can set breakpoints via the GDB commands to the JTAG and tell the system to continue until a breakpoint in encountered

What if the __init is Working?

- If you do not need to debug the __init code, then load the driver and look in the /sys/modules/<module name>/sections/.text for the address of the text segment
- Next, use the add-symbol-file command again, but use the .text address and omit the “-e .init.text”
  - Set your breakpoints and continue

User-Space Addresses

- Within Linux, each user-space application occupy the same virtual address space
  - The address spaces are physically different, but the addresses overlap



JTAG Confusion

- JTAGs normally run in what is called halt mode debugging
  - The entire processor is stopped when a given breakpoint address is accessed
- This works reasonably well in kernel space
  - Only one kernel address space
- While it is possible to debug user applications with the JTAG, the JTAG can get confused by seeing the same virtual address in different applications due to context switches
  - This requires run mode support for the JTAG

Run–Mode Support

- Using a debugging agent in user space and register support like the ARM's Debug Communications Channel (DCC) we can associate a virtual address to a particular context
  - This allows the breakpoint to only stop the one application instead of any application that matches the address
- Only a few JTAGs support this run mode debugging mechanism
  - Otherwise, we are left with normal GDB process trace (ptrace) debugging control via an application like gdbserver
- Naturally, GDB already does a reasonable job for user–space debugging
  - The need to use JTAG for user–space debug is rare

Summary

- Hardware debuggers such as JTAG are invaluable for exercising new hardware
  - They let us test address lines and registers
- Once we can configure the board via the JTAG, we then take that info and use it to port the boot firmware
  - We can usually burn the boot firmware into flash via the JTAG as well
- Once the boot firmware is loading Linux, the JTAG can then help again in early kernel debugging and device driver debugging
- Don’t start your next bring-up project without one!
- Demo time…