OSH Lab 1

实验环境配置

本次实验所采用的操作环境

- Ubuntu 17.10 x64 (Linux version 4.13.0-32-generic (buildd@lgw01-amd64-016) (gcc version 7.2.0 (Ubuntu 7.2.0-8ubuntu3)))
- gdb 8.0.1
- gcc 7.2.0
- qemu 2.12.0-rc0
- busybox 1.28.1
  通过qemu模拟器+gdb追踪分析`linux-4.1.50`内核的启动过程。

环境搭建

内核编译

从kernel.org获取4.1.50版的Linux内核源码，并在本地编译。

```
sudo apt-get install libncurses5-dev libncursesw5-dev
make clean
make menuconfig
make x86_64_defconfig
make
```

在`make menuconfig`一步，进入内核配置菜单，选择`Kernel hacking->Compile-time checks and compiler options->`勾选`Compile the kernel with debug info`

qemu编译

之后从qemu.org获取qemu 2.12.0-rc0版，并编译anzhuna

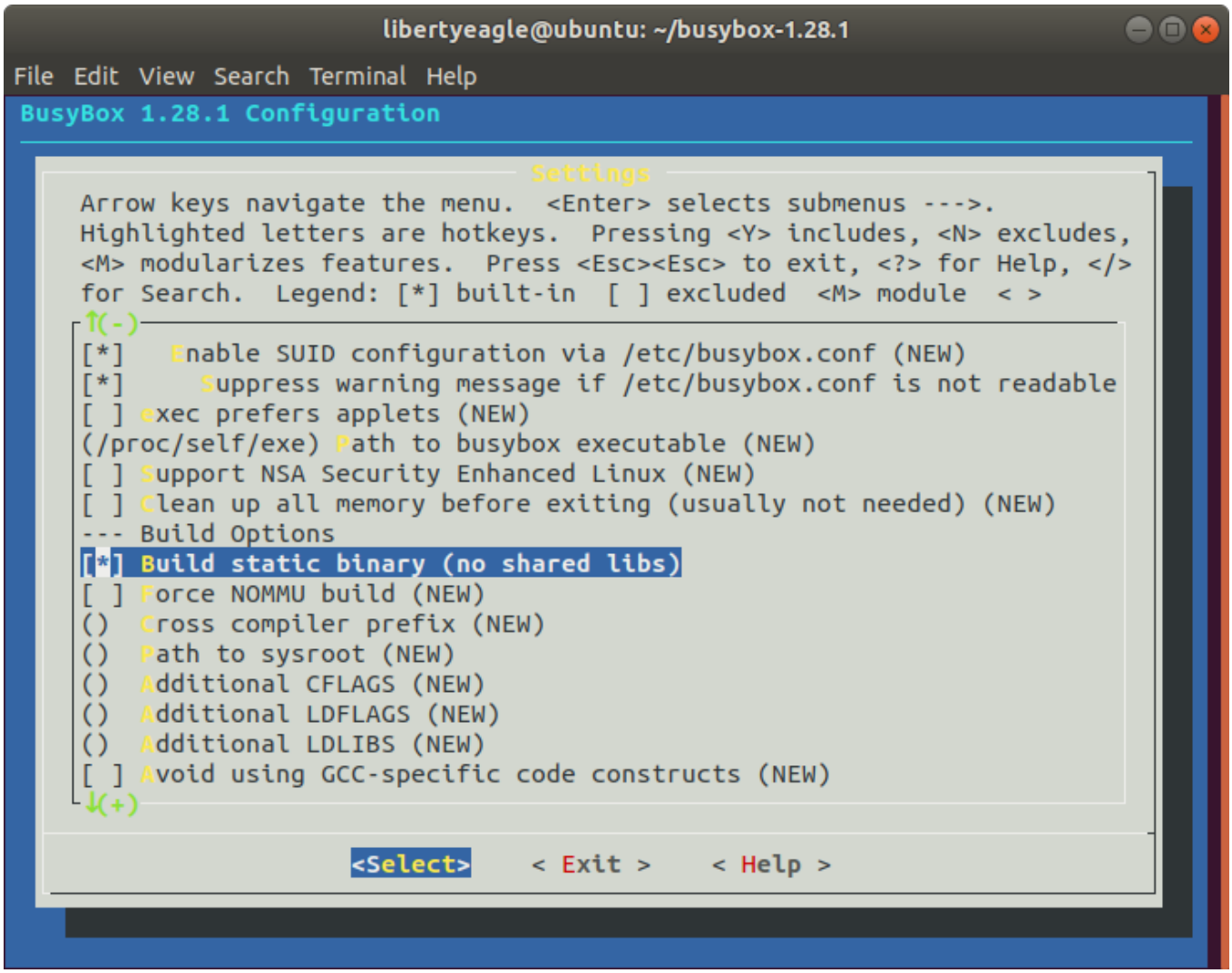
```
sudo apt-get install git libglib2.0-dev libfdt-dev libpixman-1-dev zlib1g-dev
make clean
./configure
make
make install
```

用busybox制作根文件系统（RootFS）

获取busybox 1.28.1版本
`wget http://busybox.net/downloads/busybox-1.28.1.tar.bz2`

```
make menuconfig
make
make install
```

其中menuconfig中勾选`Settings` -> `Build Options` -> `Build static binary (no shared libs)`



更新文件系统

```
cd _install
mkdir proc sys dev etc etc/init.d
touch _install/etc/init.d/rcS
```

然后编辑`rcS`文件，修改为以下内容

```
#!/bin/sh
mount -t proc none /proc
mount -t sysfs none /sys
/sbin/mdev -s
```

接下来修改`rcS`属性为可执行
`chmod +x _install/etc/init.d/rcS`
创建镜像

```
cd _install
find . | cpio -o --format=newc > ../rootfs.img
```

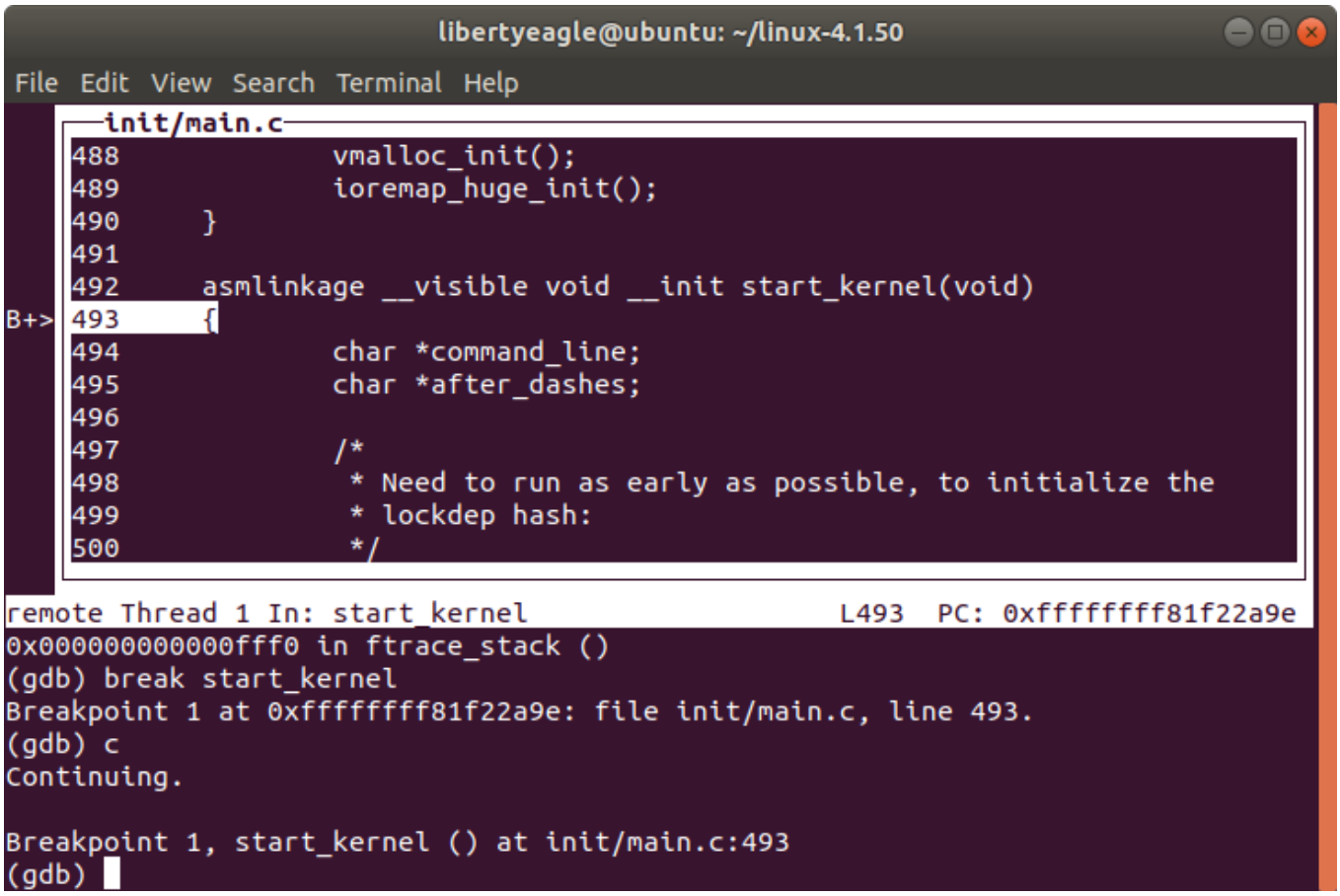
调试

我们使用下述命令启动qemu模拟器
`qemu-system-x86_64 -kernel ./arch/x86_64/boot/bzImage -initrd rootfs.img -append "console=tty1 root=/dev/ram rdinit=/sbin/init" -S -s`
然后使用gdb调试，为了方便，我们使用tui模式操作。将第一个断点设置在`start_kernel()`函数处

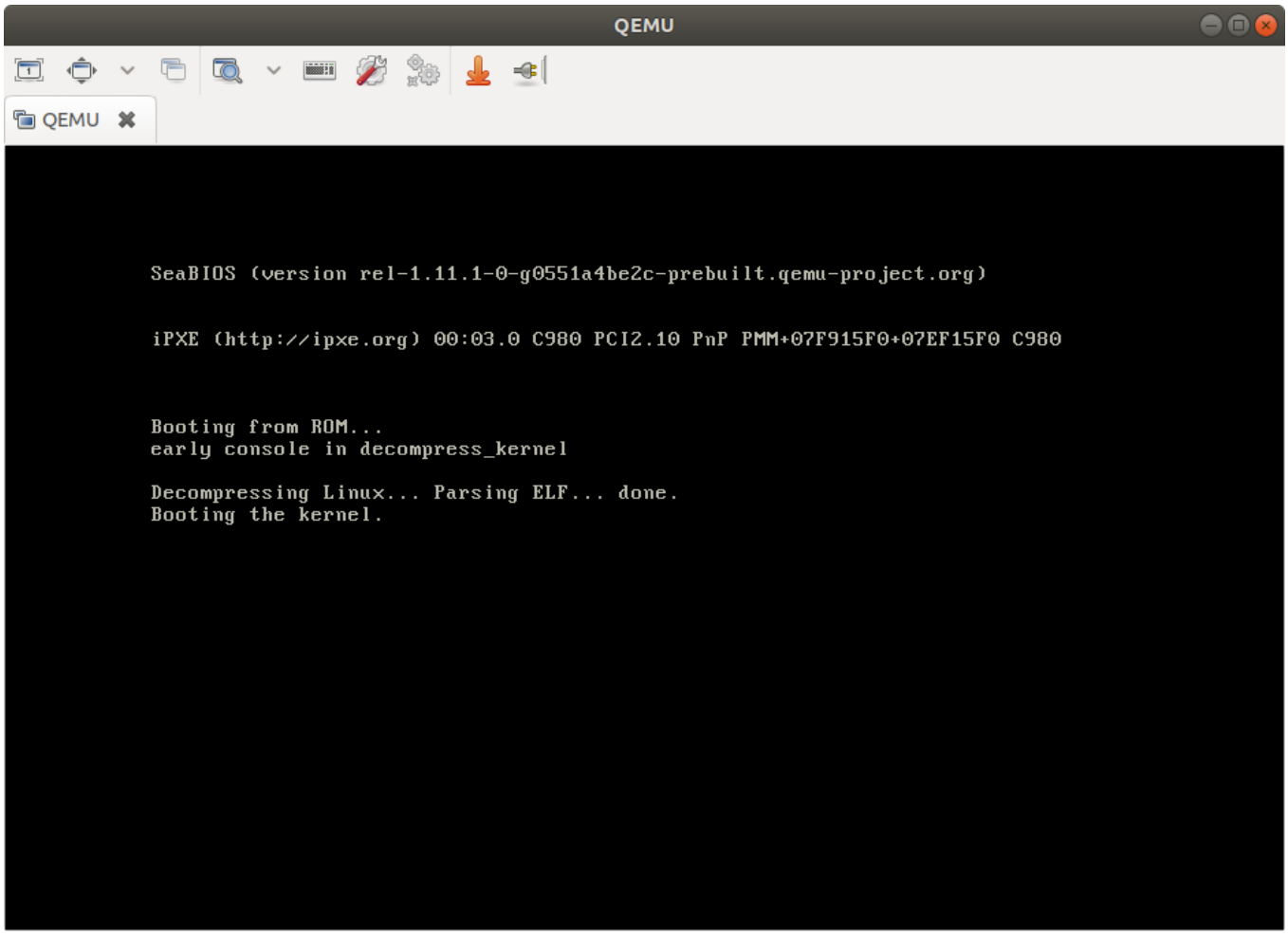
```
gdb -tui
```

```
(gdb) file vmlinux # 加载符号表
(gdb) target remote:1234 # 连接远程目标
(gdb) break start_point
(gdb) c # continue
```

之后我们可以看到，qemu停在了内核引导的位置



使用VNC连接远程桌面，可以看到



`start_kernel` - Linux内核的`main`函数

总揽

在完成内核初始化前的一系列预备工作后，`x86_64_start_reservations()`函数便会调用`start_kernel`。`start_kernel()`中调用了一系列初始化函数，以完成核心数据结构的初始化。它的主要目的是完成内核的初始化过程并且启动第一个`init`进程。
`start_kernel()`会调用一系列初始化函数来设置中断，执行进一步的内存配置，并加载初始 RAM 磁盘
`start_kernel`的主要流程

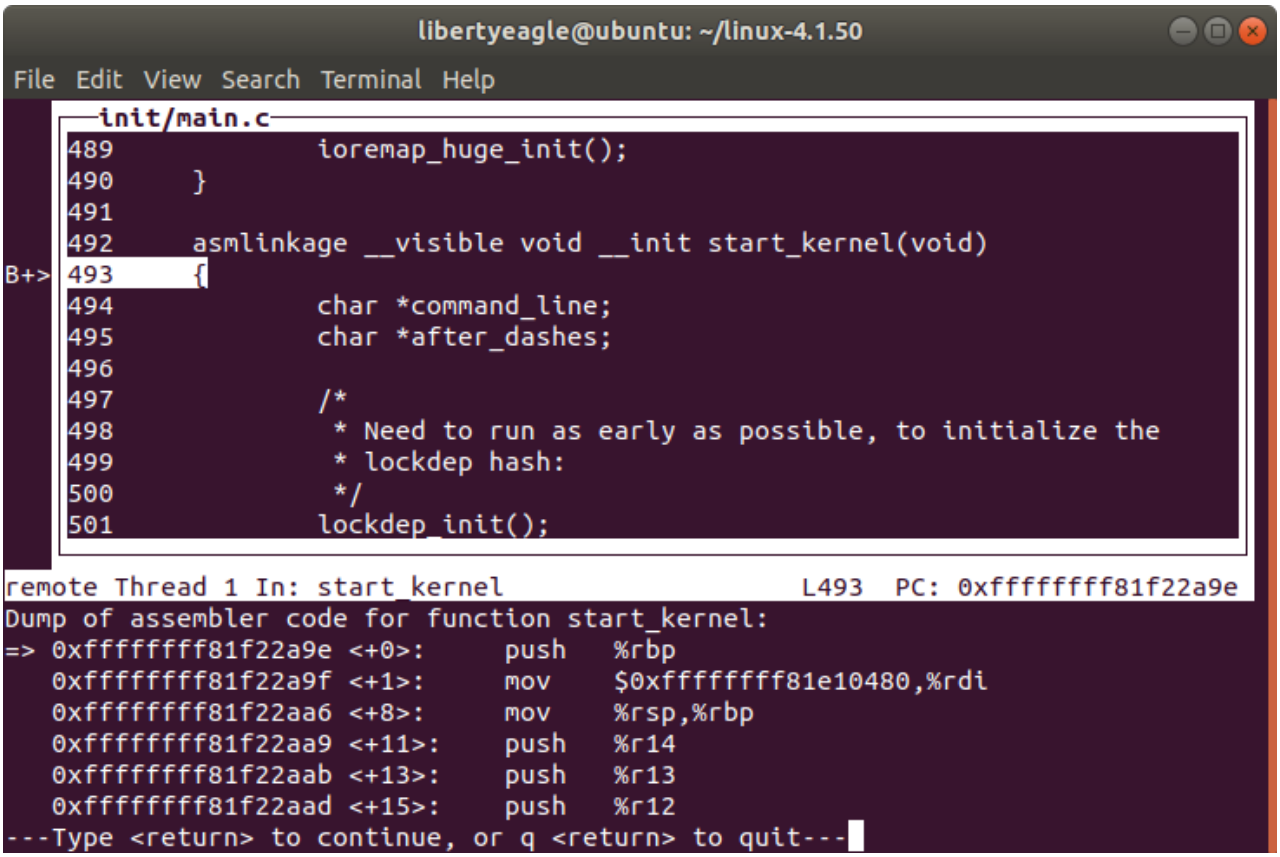
- 初始化lock validator (lockdep_init)
- 设置操作系统的第一个进程init (set_task_stack_end_magic)
- 设置`obj_hash`, `obj_static_pool`两个全局变量
- 设定不确定的stack canary，阻止buffer overflow攻击 (boot_init_stack_canary)
- 初始化control groups (cgroup_init_early)
- 关闭中断操作 (local_irq_disable)
- 完成页地址的初始化 (page_address_init)
- 打印linux_banner (pr_notice)
- 内核架构相关初始化函数，包含处理器相关参数的初始化、内核启动参数的获取和前期处理、内存子系统的早期初始化 (setup_arch)
- 为SMP系统里引导CPU进行准备工作 (smp_prepare_boot_cpu)
- 设置内存页分配通知器 (page_alloc_init)
- 中断描述符号表初始化 (trap_init)
- 初始化内存管理器 (mm_init)

- 对进程调度器的数据结构进行初始化 (sched_init)
- 初始化直接读拷贝更新的锁机制 (rcu_init)
- 中断管理系统的早期初始化 (early_irq_init)
- 初始化软件中断 (softirq_init)
- 初始化系统时钟，开启一个硬件定时器 (time_init)
- 启用中断操作 (local_irq_enable)
- 控制台初始化 (console_init)
- 完成剩余部分 (rest_init)

  在刚开始我们可以看到两个字符串变量`command_line`和`after_dashes`，我们可以用gdb看到他们的值

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
   init/main.c
   491
   492     asmlinkage __visible void __init start_kernel(void)
B+ 493     {
   494             char *command_line;
   495             char *after_dashes;
   496
   497             /*
   498              * Need to run as early as possible, to initialize the
   499              * lockdep hash:
   500              */
   501             lockdep_init();
B+> 502             set_task_stack_end_magic(&init_task);
   503             smp_setup_processor_id();
remote Thread 1 In: start_kernel                    L502  PC: 0xffffffff81f22a9f

Breakpoint 2, start_kernel () at init/main.c:502
(gdb) display command_line
1: command_line = 0xffffffff81f85c8f <memblock_reserve+76> "[A\\]\303UH\211\345A
WAVAUATSH\211\363H\367\323H\203\354\020H9\323", <incomplete sequence \307>
(gdb) display after_dashes
2: after_dashes = <optimized out>
(gdb)
```

  可以看到该部分的一些汇编代码



在`start_kernel()`，我们看到其调用的第一个函数是`lockdep_init()`，这个函数会初始化内核死锁检测机制的哈希表。接下来，会调用`set_task_stack_end_magic(&init_task)`函数

`set_task_stack_end_magic()`

用gdb设置断点，我们可以看到这部分的代码

```
set_task_stack_end_magic(struct task_struct *tsk)
{
    unsigned long *stackend;
  stackend = end_of_stack(tsk);
  *stackend = STACK_END_MAGIC;  /* for overflow detection */
}
```

`set_task_stack_end_magic()`函数将栈底地址设置为`STACK_END_MAGIC`，作为溢出的标记（canary）
`init_task`代表下面的初始任务结构
`struct task_struct init_task = INIT_TASK(init_task);`
其中，`task_struct`存储了关于一个进程的所有信息。这个结构在`include/linux/init_task.h`中定义。`init_task`被`INIT_TASK`宏初始化，以完成第一个进程的配置

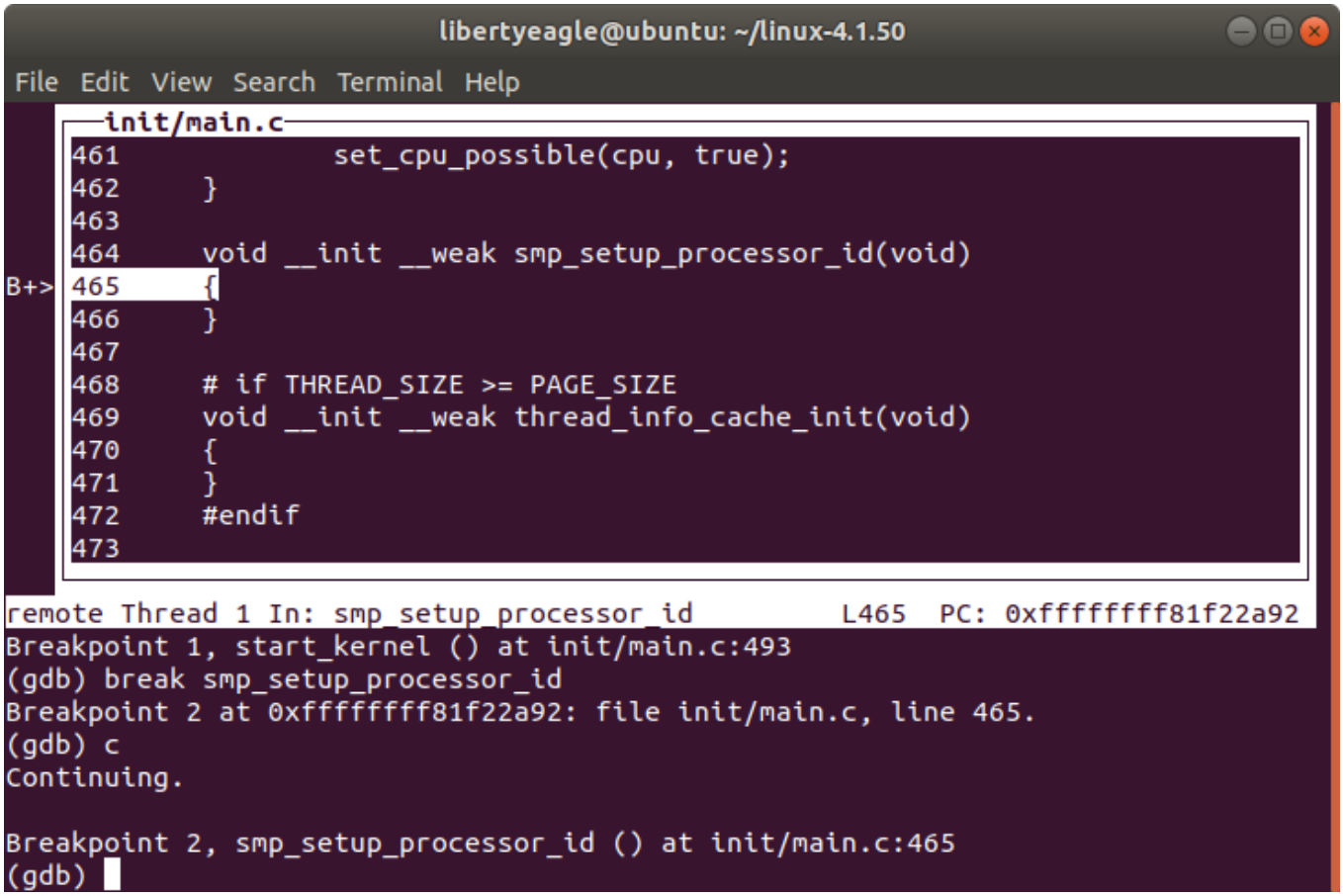
- 将进程的状态置为`runnable`
- 将进程的标记置为`PF_KTHREAD` (kernel thread)
- 配置一个`runnable`的task list
- 配置进程的地址空间
  之后会初始化进程的内核态堆栈，由`thread_union`结构表示

```
union thread_union {
#ifndef CONFIG_THREAD_INFO_IN_TASK
    struct thread_info thread_info;
#endif
    unsigned long stack[THREAD_SIZE/sizeof(long)];
};
```

在`include/linux/sched.h`中可以找到
其中`thread_info`的定义在`arch/x86/arch/x86/include/asm/thread_info.h`中

```
struct thread_info {
    struct task_struct  *task;      /* main task structure */
    struct exec_domain  *exec_domain;   /* execution domain */
    __u32           flags;      /* low level flags */
    __u32           status;     /* thread synchronous flags */
    __u32           cpu;        /* current CPU */
    int         saved_preempt_count;
    mm_segment_t        addr_limit;
    struct restart_block    restart_block;
    void __user     *sysenter_return;
    unsigned int        sig_on_uaccess_error:1;
    unsigned int        uaccess_err:1;  /* uaccess failed */
};
```

`smp_setup_processor_id()`



`smp_setup_process_id()`中`smp`指的是symmetric multi-processor，与之对应的是NUMA和MPP。用以设置SMP模型的CPU ID

```
# if THREAD_SIZE >= PAGE_SIZE
void __init __weak thread_info_cache_init(void)
{
}
#endif
```

`cgroup_init_early()`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
kernel/cgroup.c
5023     */
5024    int __init cgroup_init_early(void)
> 5025    {
5026            static struct cgroup_sb_opts __initdata opts;
5027            struct cgroup_subsys *ss;
5028            int i;
5029
5030            init_cgroup_root(&cgrp_dfl_root, &opts);
5031            cgrp_dfl_root.cgrp.self.flags |= CSS_NO_REF;
5032
5033            RCU_INIT_POINTER(init_task.cgroups, &init_css_set);
5034
5035            for_each_subsys(ss, i) {
remote Thread 1 In: cgroup_init_early              L5025 PC: 0xffffffff81f3f826
Breakpoint 3 at 0xffffffff81f22abb: file init/main.c, line 504.
(gdb) c
Continuing.

Breakpoint 3, start_kernel () at init/main.c:511
(gdb) stepi
cgroup_init_early () at kernel/cgroup.c:5025
(gdb)
```

该函数定义在`kernel/cgroup.c`中，在系统启动时初始化control groups，并且初始化任何需要early init的子系统其中`cgroup_subsys`结构的定义可以在`include/linux/cgroup-defs.h`中找到

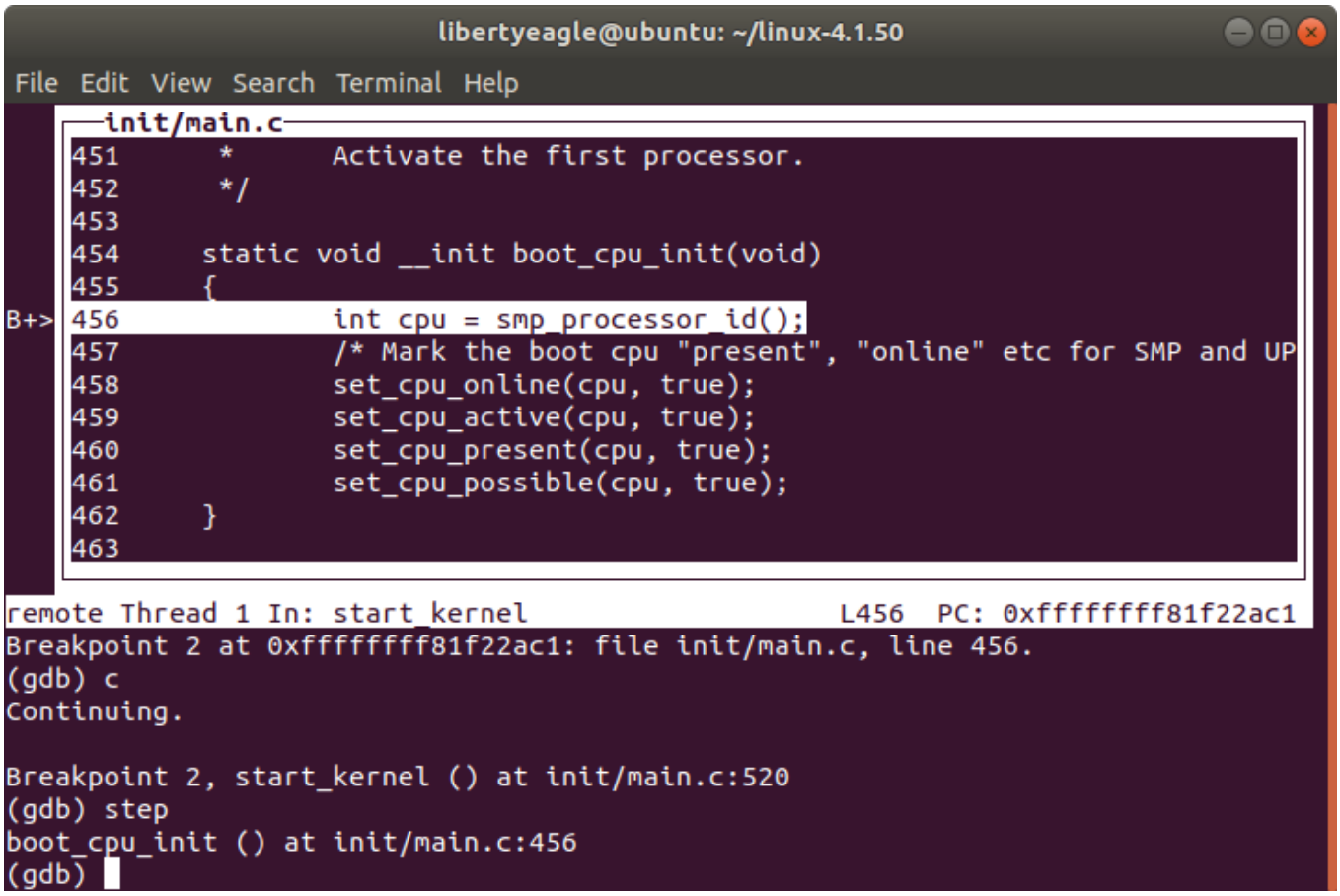
```c
struct cgroup_subsys {
    struct cgroup_subsys_state *(*css_alloc)(struct cgroup_subsys_state *parent_css);
    int (*css_online)(struct cgroup_subsys_state *css);
    void (*css_offline)(struct cgroup_subsys_state *css);
    void (*css_released)(struct cgroup_subsys_state *css);
    void (*css_free)(struct cgroup_subsys_state *css);
    void (*css_reset)(struct cgroup_subsys_state *css);
    void (*css_e_css_changed)(struct cgroup_subsys_state *css);

    int (*can_attach)(struct cgroup_subsys_state *css,
            struct cgroup_taskset *tset);
    void (*cancel_attach)(struct cgroup_subsys_state *css,
            struct cgroup_taskset *tset);
    void (*attach)(struct cgroup_subsys_state *css,
            struct cgroup_taskset *tset);
    void (*fork)(struct task_struct *task);
    void (*exit)(struct cgroup_subsys_state *css,
            struct cgroup_subsys_state *old_css,
            struct task_struct *task);
    void (*bind)(struct cgroup_subsys_state *root_css);

    int disabled;
    int early_init;

    /*
     * If %false, this subsystem is properly hierarchical -
     * configuration, resource accounting and restriction on a parent
     * cgroup cover those of its children.  If %true, hierarchy support
     * is broken in some ways - some subsystems ignore hierarchy
```

```
     * completely while others are only implemented half-way.
     *
     * It's now disallowed to create nested cgroups if the subsystem is
     * broken and cgroup core will emit a warning message on such
     * cases.  Eventually, all subsystems will be made properly
     * hierarchical and this will go away.
     */
    bool broken_hierarchy;
    bool warned_broken_hierarchy;

    /* the following two fields are initialized automtically during boot */
    int id;
    const char *name;

    /* link to parent, protected by cgroup_lock() */
    struct cgroup_root *root;

    /* idr for css->id */
    struct idr css_idr;

    /*
     * List of cftypes.  Each entry is the first entry of an array
     * terminated by zero length name.
     */
    struct list_head cfts;

    /*
     * Base cftypes which are automatically registered.  The two can
     * point to the same array.
     */
    struct cftype *dfl_cftypes; /* for the default hierarchy */
    struct cftype *legacy_cftypes;  /* for the legacy hierarchies */

    /*
     * A subsystem may depend on other subsystems.  When such subsystem
     * is enabled on a cgroup, the depended-upon subsystems are enabled
     * together if available.  Subsystems enabled due to dependency are
     * not visible to userland until explicitly enabled.  The following
     * specifies the mask of subsystems that this one depends on.
     */
    unsigned int depends_on;
};
```

`cgroup_sb_opts`则在同一文件(`cgroup.c`)中

```
struct cgroup_sb_opts {
    unsigned int subsys_mask;
    unsigned int flags;
    char *release_agent;
    bool cpuset_clone_children;
    char *name;
    /* User explicitly requested empty subsystem */
    bool none;
};
```

`boot_cpu_init()`



该函数激活第一个CPU，先取得CPU的ID，然后将该CPU标记为`online`, `active`, `present`, `possible`

```
static void __init boot_cpu_init(void)
{
    int cpu = smp_processor_id();
    /* Mark the boot cpu "present", "online" etc for SMP and UP case */
    set_cpu_online(cpu, true);
    set_cpu_active(cpu, true);
    set_cpu_present(cpu, true);
    set_cpu_possible(cpu, true);
}
```

`pr_notice("%s", linux_banner)`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
kernel/printk/printk.c
1850    asmlinkage __visible int printk(const char *fmt, ...)
1851    {
1852            printk_func_t vprintk_func;
1853            va_list args;
1854            int r;
1855
> 1856          va_start(args, fmt);
1857
1858            /*
1859             * If a caller overrides the per_cpu printk_func, then it n
1860             * to disable preemption when calling printk(). Otherwise
1861             * the printk_func should be set to the default. No need to
1862             * disable preemption here.
remote Thread 1 In: printk                          L1856 PC: 0xffffffff8189897a
Type "help" followed by command name for full documentation.
Type "apropos word" to search for commands related to "word".
Command name abbreviations are allowed if unambiguous.
(gdb) display linux_banner
2: linux_banner = 0xffffffff81a00080 <linux_banner> "Linux version 4.1.50 (liber
tyeagle@ubuntu) (gcc version 7.2.0 (Ubuntu 7.2.0-8ubuntu3.2) ) #1 SMP Mon Mar 26
 08:03:29 PDT 2018\n"
(gdb)
```

这一步会调用`printk()`打印`linux_banner`

printk函数在`kernel/printk/printk.c`中

我们用gdb可以看出其内容是

`Linux version 4.1.50 (libertyeagle@ubuntu) (gcc version 7.2.0 (Ubuntu 7.2.0-8ubuntu3.2) ) #1 SMP Mon Mar 26 08:03:29 PDT 2018\n`

`setup_arch(&command_line)`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
arch/x86/kernel/setup.c
     *
     * Note: On x86_64, fixmaps are ready for use even before this is c
     */

    void __init setup_arch(char **cmdline_p)
B+> {
            memblock_reserve(__pa_symbol(_text),
                             (unsigned long)__bss_stop - (unsigned long

            early_reserve_initrd();

            /*
             * At this point everything still needed from the boot load
remote Thread 1 In: setup_arch                    L862  PC: 0xffffffff81f257e6
Breakpoint 7 at 0xffffffff81f25580: file arch/x86/kernel/time.c, line 95.
(gdb) c
Continuing.

Breakpoint 3, setup_arch (
    cmdline_p=0xffffffff81e03f78 <init_thread_union+16248>)
    at arch/x86/kernel/setup.c:862
(gdb)
```

这一部分为体系结构的初始化函数，定义在`arch/x86/kernel/setup.c`中，接受`command_line`为参数

`trap_init`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
arch/x86/kernel/traps.c
            set_intr_gate(X86_TRAP_PF, page_fault);
    #endif
    }

    void __init trap_init(void)
B+> {
            int i;

    #ifdef CONFIG_EISA
            void __iomem *p = early_ioremap(0x0FFFD9, 4);

            if (readl(p) == 'E' + ('I'<<8) + ('S'<<16) + ('A'<<24))
                    EISA_bus = 1;
remote Thread 1 In: trap_init                     L954  PC: 0xffffffff81f2502e
Breakpoint 2 at 0xffffffff81f2502e: file arch/x86/kernel/traps.c, line 954.
(gdb) break mm_init
Breakpoint 3 at 0xffffffff8104f450: mm_init. (2 locations)
(gdb) c
Continuing.

Breakpoint 2, trap_init () at arch/x86/kernel/traps.c:954
(gdb)
```

这一部分定义在`arch/x86/kernel.tarps.c`中，用来构建中断描述符号表

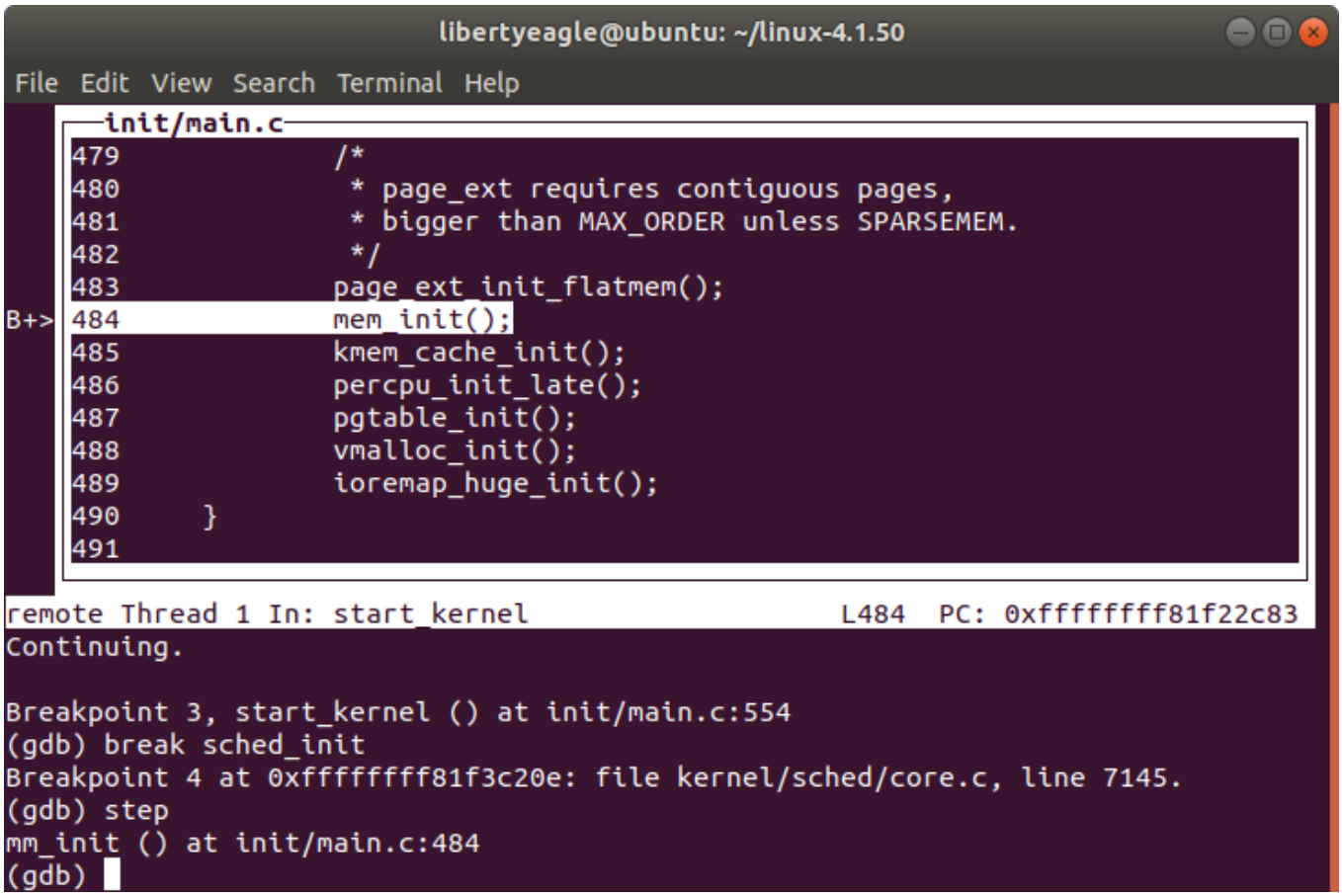
可以观察出一些关键部分

```
    set_intr_gate(X86_TRAP_DE, divide_error);
    set_intr_gate_ist(X86_TRAP_NMI, &nmi, NMI_STACK);
    /* int4 can be called from all */
    set_system_intr_gate(X86_TRAP_OF, &overflow);
    set_intr_gate(X86_TRAP_BR, bounds);
    set_intr_gate(X86_TRAP_UD, invalid_op);
    set_intr_gate(X86_TRAP_NM, device_not_available);
    set_intr_gate_ist(X86_TRAP_DF, &double_fault, DOUBLEFAULT_STACK);
    set_intr_gate(X86_TRAP_OLD_MF, coprocessor_segment_overrun);
    set_intr_gate(X86_TRAP_TS, invalid_TSS);
    set_intr_gate(X86_TRAP_NP, segment_not_present);
    set_intr_gate(X86_TRAP_SS, stack_segment);
    set_intr_gate(X86_TRAP_GP, general_protection);
    set_intr_gate(X86_TRAP_SPURIOUS, spurious_interrupt_bug);
    set_intr_gate(X86_TRAP_MF, coprocessor_error);
    set_intr_gate(X86_TRAP_AC, alignment_check);
```

可以看出来这部分代码定义了各种exception，例如

- `#DE` -> 被0除
- `#NMI` -> 不可屏蔽中断（Non-maskable Interrupt）
- `#0F` -> 溢出
- `#BR` -> 边界检查错误
- `#UD` -> 无效指令（Invalid Opcode）
- `#NM` -> 设备不可用

`mm_init()`



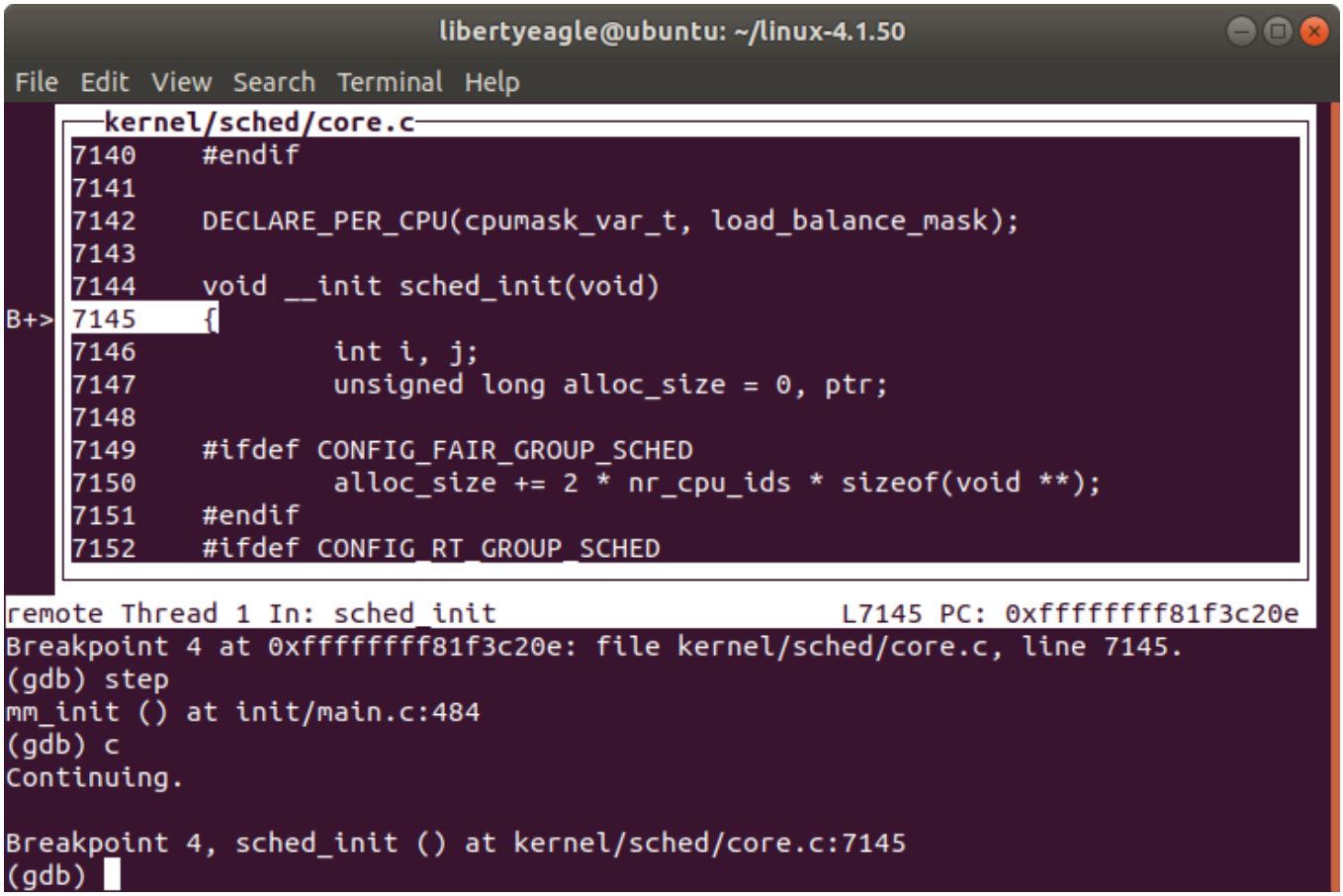
该函数就在`init/main.c`中，内容如下

```
static void __init mm_init(void)
```

```
{
    /*
     * page_ext requires contiguous pages,
     * bigger than MAX_ORDER unless SPARSEMEM.
     */
    page_ext_init_flatmem();
    mem_initp();
    kmem_cache_init();
    percpu_init_late();
    pgtable_init();
    vmalloc_init();
    ioremap_huge_init();
}
```

其中`page_ext_init_flatmem`与`CONFIG_SPARSEMEM`有关，`mem_init`释放所有`bootmem`，`kmem_cahce_init`初始化内核缓存，`vmalloc_init`初始化`vmalloc`

`sched_init()`



定义在`kernel/sched/core.c`中，主要目的是

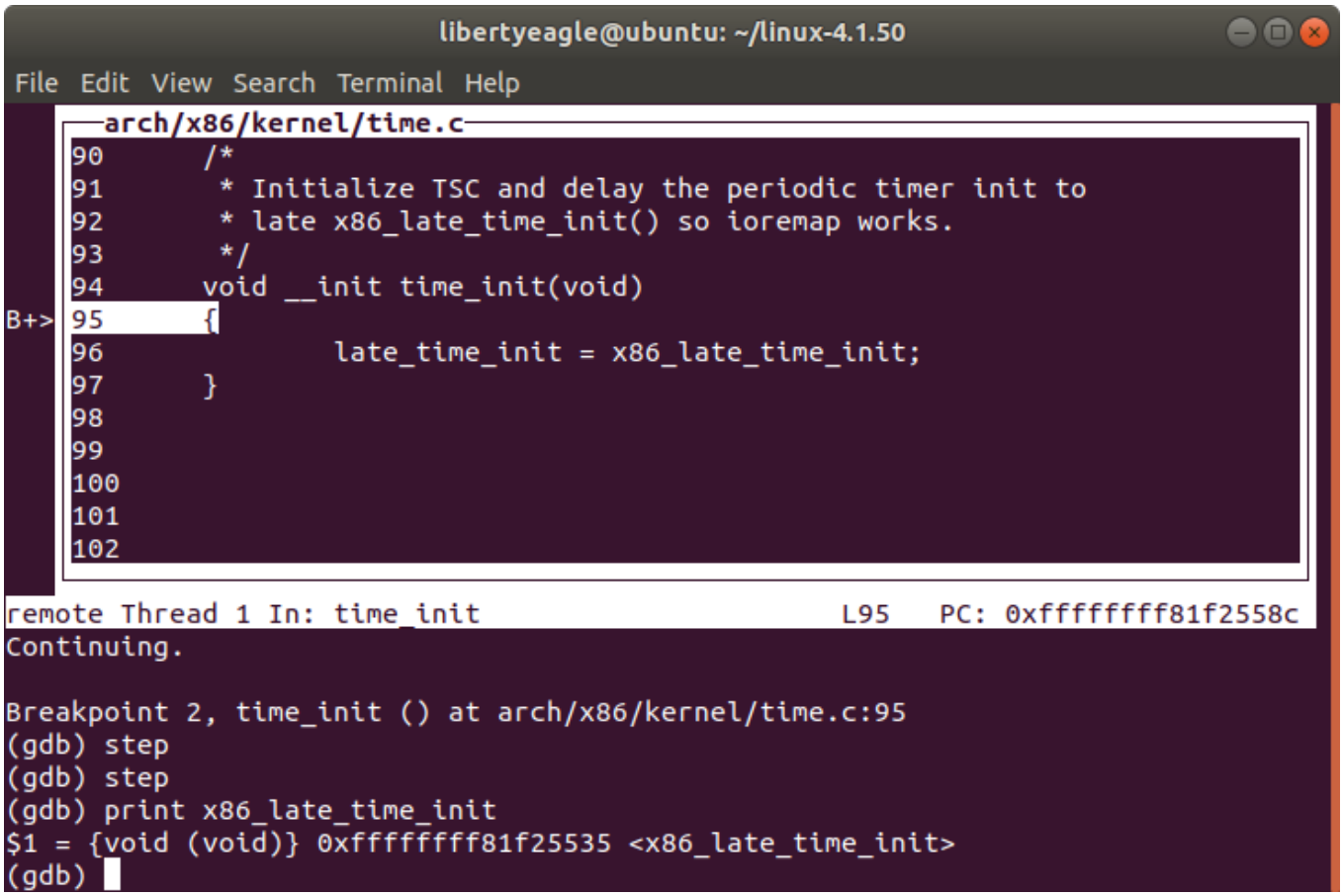
- 对相关数据结构分配内存
- 初始化root_task_group
- 初始化每个CPU的rq队列(包括其中的cfs队列和实时进程队列)
- 将init_task进程转变为idle进程
  其中我们可以看到

```
    for_each_possible_cpu(i) {
        struct rq *rq;

        rq = cpu_rq(i);
```

```
        raw_spin_lock_init(&rq->lock);
        rq->nr_running = 0;
        rq->calc_load_active = 0;
        rq->calc_load_update = jiffies + LOAD_FREQ;
        init_cfs_rq(&rq->cfs);
        init_rt_rq(&rq->rt);
        init_dl_rq(&rq->dl);
```

这部分代码遍历设置每一个处在`possible`状态的CPU，为其中的每一个CPU初始化一个`runqueue`队列

`time_init()`



用`x86_late_time_init`初始化event timer，该代码在`arch/x86/kernel/time.c`中

`console_init()`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
drivers/tty/tty_io.c
3566     * we can't necessarily depend on lots of kernel help here.
3567     * Just do some early initializations, and do the complex setup
3568     * later.
3569     */
3570    void __init console_init(void)
B+> 3571    {
3572            initcall_t *call;
3573
3574            /* Setup the default TTY line discipline. */
3575            tty_ldisc_begin();
3576
3577            /*
3578             * set up the console device so that later boot sequences c
remote Thread 1 In: console_init                    L3571 PC: 0xffffffff81f5d619
Continuing.

Breakpoint 7, time_init () at arch/x86/kernel/time.c:95
(gdb) c
Continuing.

Breakpoint 2, console_init () at drivers/tty/tty_io.c:3571
(gdb)
```

在`drivers/tty/tty_io.c`中，用于初始化控制台，在这里仅完成一些early initializations

`rest_init()`

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
init/main.c
382
383     static noinline void __init_refok rest_init(void)
B+> 384     {
385             int pid;
386
387             rcu_scheduler_starting();
388             smpboot_thread_init();
389             /*
390              * We need to spawn init first so that it obtains pid 1, ho
391              * the init task will end up wanting to create kthreads, wh
392              * we schedule it before we create kthreadd, will OOPS.
393              */
394             kernel_thread(kernel_init, NULL, CLONE_FS);
remote Thread 1 In: rest_init                       L384  PC: 0xffffffff81896000
do_raw_spin_unlock (lock=<optimized out>) at kernel/locking/spinlock.c:191
(gdb) break rest_init
Breakpoint 6 at 0xffffffff81896000: file init/main.c, line 384.
(gdb) c
Continuing.

Breakpoint 6, rest_init () at init/main.c:384
(gdb)
```

这是`start_kernel()`最后调用的函数，进一步完成内核的初始化

```
static noinline void __init_refok rest_init(void)
```

```c
{
    int pid;

    rcu_scheduler_starting();
    smpboot_thread_init();
    /*
     * We need to spawn init first so that it obtains pid 1, however
     * the init task will end up wanting to create kthreads, which, if
     * we schedule it before we create kthreadd, will OOPS.
     */
    kernel_thread(kernel_init, NULL, CLONE_FS);
    numa_default_policy();
    pid = kernel_thread(kthreadd, NULL, CLONE_FS | CLONE_FILES);
    rcu_read_lock();
    kthreadd_task = find_task_by_pid_ns(pid, &init_pid_ns);
    rcu_read_unlock();
    complete(&kthreadd_done);

    /*
     * The boot idle thread must execute schedule()
     * at least once to get things moving:
     */
    init_idle_bootup_task(current);
    schedule_preempt_disabled();
    /* Call into cpu_idle with preempt disabled */
    cpu_startup_entry(CPUHP_ONLINE);
}
```

例如，`rest_init()`首先会完成RCU调度器的启动

```
libertyeagle@ubuntu: ~/linux-4.1.50
File  Edit  View  Search  Terminal  Help
kernel/rcu/tree.c
3915     * idle tasks are prohibited from containing RCU read-side critical
3916     * sections.  This function also enables RCU lockdep checking.
3917     */
3918    void rcu_scheduler_starting(void)
3919    {
> 3920            WARN_ON(num_online_cpus() != 1);
3921            WARN_ON(nr_context_switches() > 0);
3922            rcu_scheduler_active = 1;
3923    }
3924
3925    /*
3926     * Compute the per-level fanout, either using the exact fanout spec
3927     * or balancing the tree, depending on CONFIG_RCU_FANOUT_EXACT.
remote Thread 1 In: rcu_scheduler_starting          L3920 PC: 0xffffffff810a5d30
(gdb) c
Continuing.

Breakpoint 6, rest_init () at init/main.c:384
(gdb) step
(gdb) step
rcu_scheduler_starting () at kernel/rcu/tree.c:3920
(gdb)
```

```c
void rcu_scheduler_starting(void)
{
```

```
    WARN_ON(num_online_cpus() != 1);
    WARN_ON(nr_context_switches() > 0);
    rcu_scheduler_active = 1;
}
```

首先会确保当前只有一个CPU在线，且没有上下文切换，之后会将RCU使能

启动完成