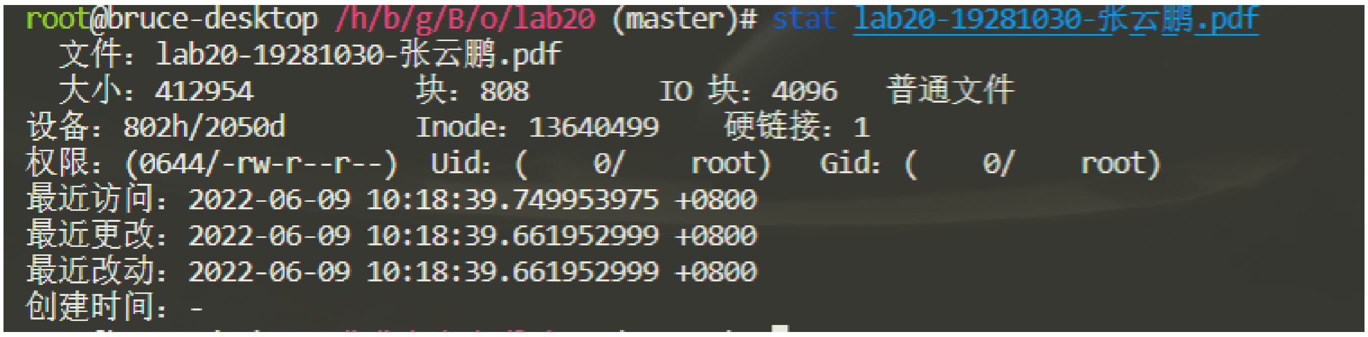
Linux 特定文件系统设计探析

19281030-张云鹏

实验截图



```
root@bruce-desktop /h/b/g/B/o/lab20 (master)# stat lab20-19281030-张云鹏.pdf
  文件：lab20-19281030-张云鹏.pdf
  大小：412954          块：808          IO 块：4096   普通文件
设备：802h/2050d        Inode：13640499    硬链接：1
权限：(0644/-rw-r--r--)  Uid：(    0/    root)   Gid：(    0/    root)
最近访问：2022-06-09 10:18:39.749953975 +0800
最近更改：2022-06-09 10:18:39.661952999 +0800
最近改动：2022-06-09 10:18:39.661952999 +0800
创建时间：-
```

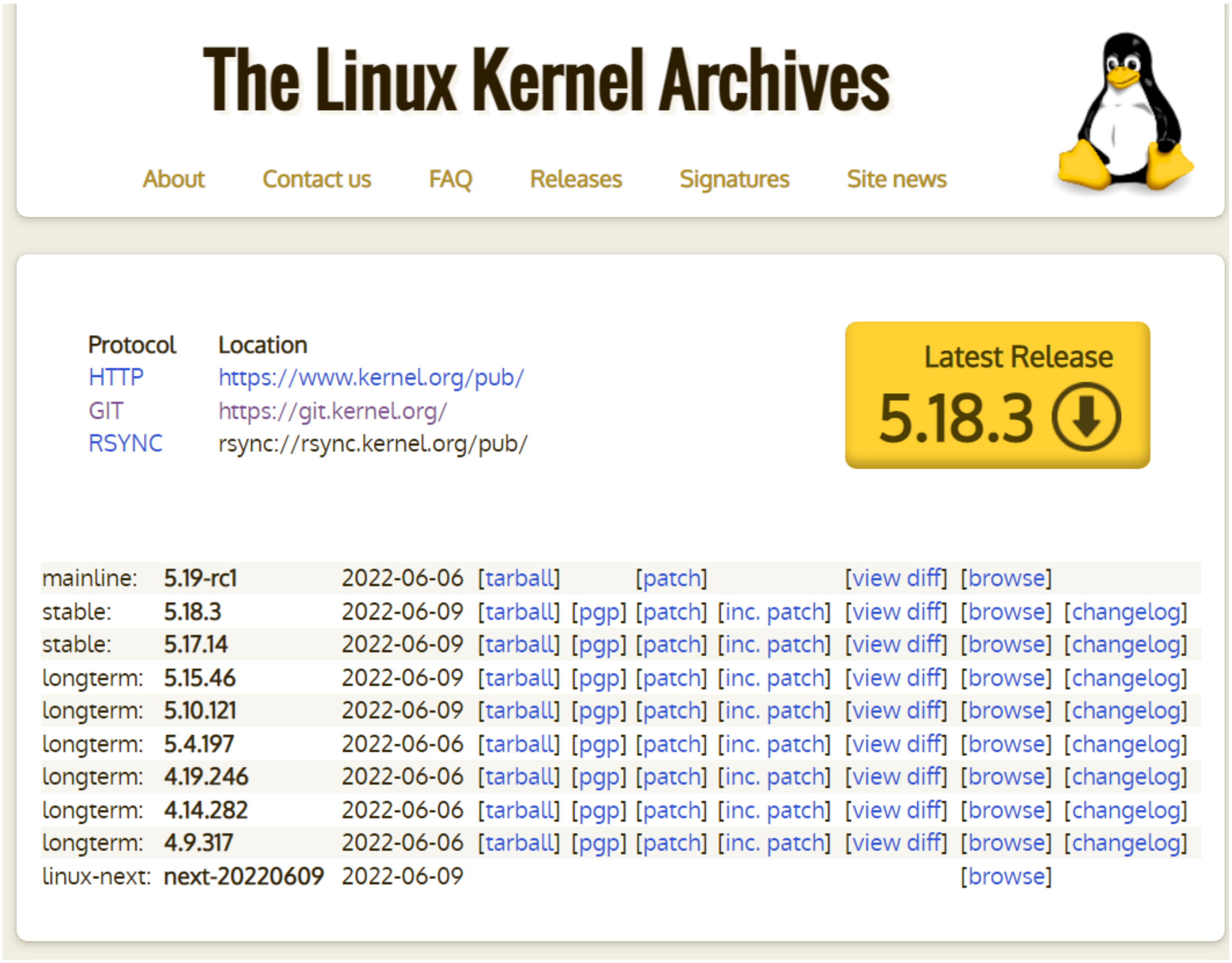
实验环境

- Ubuntu20.04 LTS

Linux源码分析

内核源码下载

下载内核最新版本源码



Protocol	Location
HTTP	https://www.kernel.org/pub/
GIT	https://git.kernel.org/
RSYNC	rsync://rsync.kernel.org/pub/

mainline:	5.19-rc1	2022-06-06	[tarball]		[patch]		[view diff]	[browse]	
stable:	5.18.3	2022-06-09	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
stable:	5.17.14	2022-06-09	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	5.15.46	2022-06-09	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	5.10.121	2022-06-09	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	5.4.197	2022-06-06	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	4.19.246	2022-06-06	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	4.14.282	2022-06-06	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
longterm:	4.9.317	2022-06-06	[tarball]	[pgp]	[patch]	[inc. patch]	[view diff]	[browse]	[changelog]
linux-next:	next-20220609	2022-06-09						[browse]	

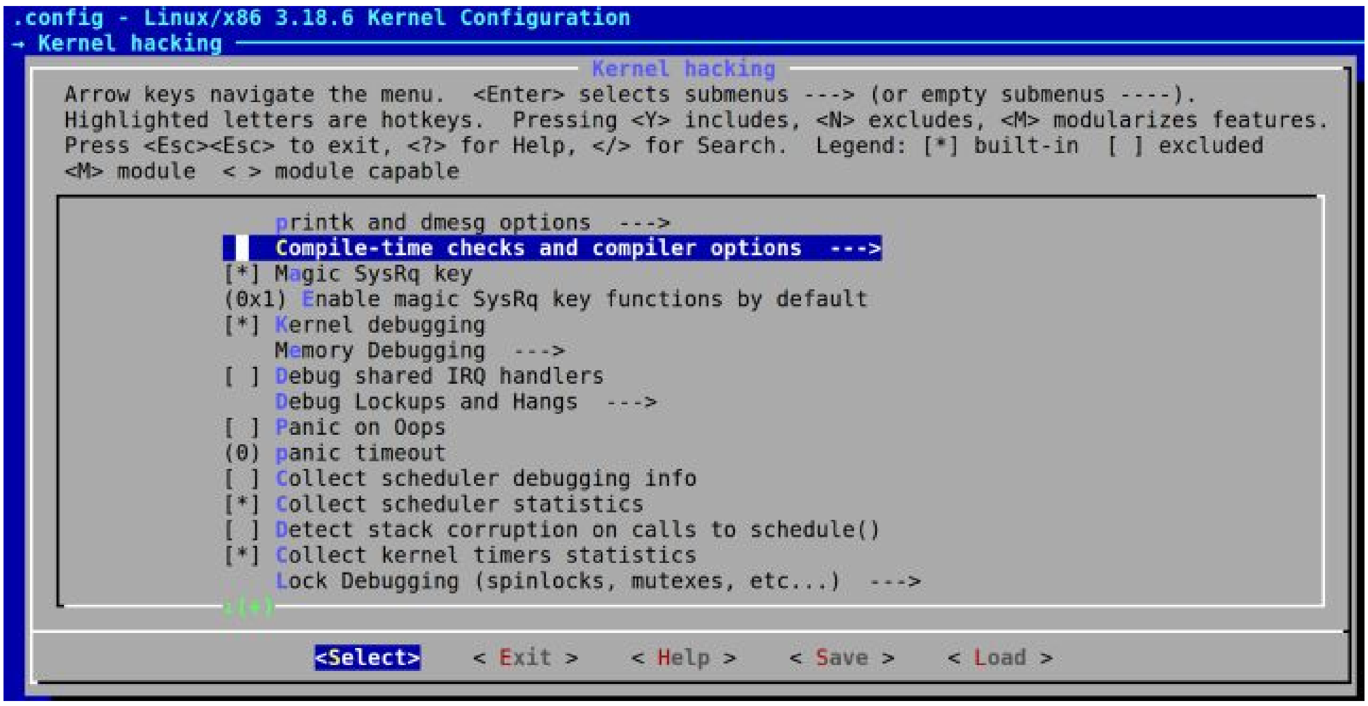
```
wget https://cdn.kernel.org/pub/linux/kernel/v5.x/linux-5.18.3.tar.xz
```

解压源码

```
xz -d linux-5.18.3.tar.xz
tar xvf linux-5.18.3.tar
```

编译源码

```
cd linux-5.18.3
make i386_defconfig
cd ~/19281030zyp/    $设置文件系统根目录
mkdir rootfs
cd menu
gcc -o init linktable.c menu.c test.c -m32 -static -lpthread
cd ../rootfs
cp ../menu/init ./
find . | cpio -o -H newc |gzip -9 > ../rootfs.img
```



```
.config - Linux/x86 3.18.6 Kernel Configuration
→ Kernel hacking
                              Kernel hacking
  Arrow keys navigate the menu.  <Enter> selects submenus ---> (or empty 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  < > module capable

            printk and dmesg options  --->
            Compile-time checks and compiler options  --->
        [*] Magic SysRq key
        (0x1) Enable magic SysRq key functions by default
        [*] Kernel debugging
            Memory Debugging  --->
        [ ] Debug shared IRQ handlers
            Debug Lockups and Hangs  --->
        [ ] Panic on Oops
        (0) panic timeout
        [ ] Collect scheduler debugging info
        [*] Collect scheduler statistics
        [ ] Detect stack corruption on calls to schedule()
        [*] Collect kernel timers statistics
            Lock Debugging (spinlocks, mutexes, etc...)  --->
        ↓(+)

        <Select>    < Exit >    < Help >    < Save >    < Load >
```

源码分析

进程与文件系统

```
truct task_struct {
    ……
    /* filesystem information */
    struct fs_struct *fs;
    /* open file information */
    struct files_struct *files;
    /* namespaces */
    struct nsproxy *nsproxy;
    ……
}
```

- fs成员指向进程当前工作目录的文件系统信息。files成员指向了进程打开的文件的信息。nsproxy指向了进程所在的命名空间，其中包含了虚拟文件系统命名空间。
- fs中包含了文件系统的挂载点和挂载点的dentry信息。而files指向了一系列的struct file结构，其中struct path结构用于将struct file和vfsmount以及dentry联系起来。struct file保存了内核所看到的文件的特征信息，进程打开的文件列表就存放在task_struct->files->fd_array[]数组以及fdtable中。
- task_struct结构还存放了其打开文件的文件描述符fd的信息，这是用户进程需要用到的，用户进程在通过文件名打开一个文件后，文件名就没有用处了，之后的操作都是对文件描述符fd的，在内核中，fget_light()函数用于通过整数fd来查找对应的struct file对象。由于每个进程都维护了自己的fd列表，所以不同进程维护的fd的值可以重复，例如标准输入、标准输出和标准错误对应的fd分别为0、1、2
- struct file的mapping成员指向属于文件相关的inode实例的地址空间映射，通常它设置为inode->i_mapping。在读写一个文件时，每次都从物理设备上获取文件的话，速度会很慢，在内核中对每个文

件分配一个地址空间，实际上是这个文件的数据缓存区域，在读写文件时只是操作这块缓存，通过内核有相应的同步机制将脏的页写回物理设备。super_block中维护了一个脏的inode的链表。

```
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 (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long,
loff_t);
    ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long,
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 *, fl_owner_t id);
    int (*release) (struct inode *, struct file *);
    int (*fsync) (struct file *, struct dentry *, int datasync);
    ……
};
```

文件系统打包

在制作好了文件系统的目录之后，可通过特定于文件系统类型的工具对目录进行打包，即制作文件系统。例如squashfs文件系统的打包工具为mksquashfs。除了打包之外，打包工具还针对特定文件系统生成超级块和inode节点信息，最终生成的文件系统镜像可以被内核解释并挂载。

VFS相关数据结构

```
struct inode {
    /* 全局的散列表 */
    struct hlist_node   i_hash;
    /* 根据inode的状态可能处理不同的链表中 (inode_unused/inode_in_use/super_block-
>dirty)  */
    struct list_head    i_list;
    /* super_block->s_inodes链表的节点 */
    struct list_head    i_sb_list;
    /* inode对应的dentry链表，可能多个dentry指向同一个文件 */
    struct list_head    i_dentry;
    /* inode编号 */
    unsigned long       i_ino;
    /* 访问该inode的进程数目 */
    atomic_t        i_count;
    /* inode的硬链接数 */
    unsigned int        i_nlink;
    uid_t           i_uid;
    gid_t           i_gid;
    /* inode表示设备文件时的设备号 */
    dev_t           i_rdev;
    u64         i_version;
    /* 文件的大小，以字节为单位 */
    loff_t          i_size;
#ifdef __NEED_I_SIZE_ORDERED
    seqcount_t      i_size_seqcount;
#endif
    /* 最后访问时间 */
    struct timespec     i_atime;
    /* 最后修改inode数据的时间 */
    struct timespec     i_mtime;
    /* 最后修改inode自身的时间 */
    struct timespec     i_ctime;
    /* 以block为单位的inode的大小 */
    blkcnt_t        i_blocks;
    unsigned int        i_blkbits;
    unsigned short          i_bytes;
    /* 文件属性，低12位为文件访问权限，同chmod参数含义，其余位为文件类型，如普通文件、目
录、socket、设备文件等 */
    umode_t         i_mode;
    spinlock_t      i_lock; /* i_blocks, i_bytes, maybe i_size */
    struct mutex        i_mutex;
    struct rw_semaphore i_alloc_sem;
    /* inode操作 */
    const struct inode_operations   *i_op;
    /* file操作 */
    const struct file_operations    *i_fop;
    /* inode所属的super_block */
    struct super_block  *i_sb;
    struct file_lock    *i_flock;
    /* inode的地址空间映射 */
    struct address_space    *i_mapping;
    struct address_space    i_data;
#ifdef CONFIG_QUOTA
    struct dquot        *i_dquot[MAXQUOTAS];
#endif
    struct list_head    i_devices; /* 若为设备文件的inode，则为设备的打开文件列表节点
*/
    union {
        struct pipe_inode_info  *i_pipe;
        struct block_device *i_bdev; /* 若为块设备的inode，则指向该设备实例 */
        struct cdev     *i_cdev; /* 若为字符设备的inode，则指向该设备实例 */
    };
    __u32           i_generation;
#ifdef CONFIG_FSNOTIFY
    __u32           i_fsnotify_mask; /* all events this inode cares about */
    struct hlist_head   i_fsnotify_mark_entries; /* fsnotify mark entries */
#endif
#ifdef CONFIG_INOTIFY
    struct list_head    inotify_watches; /* watches on this inode */
    struct mutex        inotify_mutex;  /* protects the watches list */
```

```
#endif
    unsigned long       i_state;
    unsigned long       dirtied_when;   /* jiffies of first dirtying */
    unsigned int        i_flags; /* 文件打开标记，如noatime */
    atomic_t        i_writecount;
#ifdef CONFIG_SECURITY
    void            *i_security;
#endif
#ifdef CONFIG_FS_POSIX_ACL
    struct posix_acl    *i_acl;
    struct posix_acl    *i_default_acl;
#endif
    void            *i_private; /* fs or device private pointer */
};
```

super_block

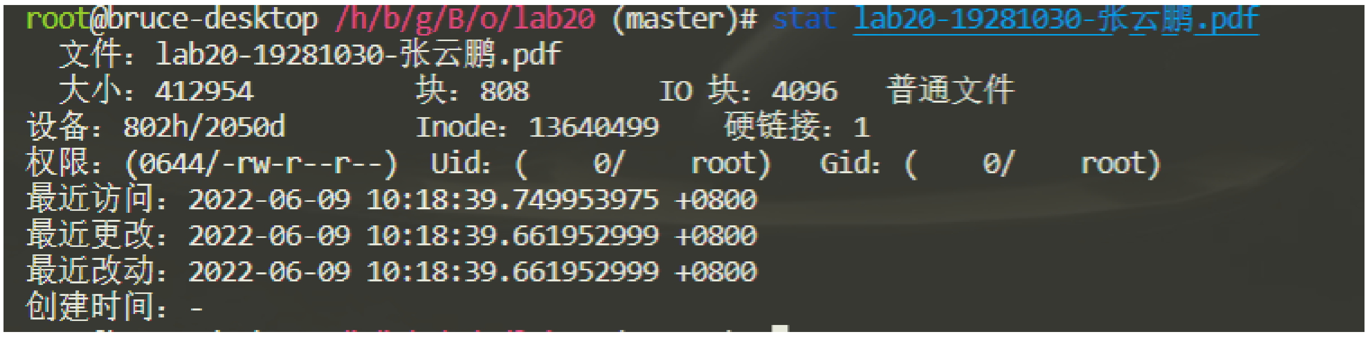
```


super_block {
    /* 全局链表元素 */
    struct list_head    s_list;
    /* 底层文件系统所在的设备 */
    dev_t           s_dev;
    /* 文件系统中每一块的长度 */
    unsigned long       s_blocksize;
    /* 文件系统中每一块的长度（以2为底的对数） */
    unsigned char       s_blocksize_bits;
    /* 是否需要向磁盘回写 */
    unsigned char       s_dirt;
    unsigned long long  s_maxbytes; /* Max file size */
    /* 文件系统类型 */
    struct file_system_type *s_type;
    /* 超级块操作方法 */
    const struct super_operations   *s_op;
    struct dquot_operations *dq_op;
    struct quotactl_ops *s_qcop;
    const struct export_operations *s_export_op;
    unsigned long       s_flags;
    unsigned long       s_magic;
    /* 全局根目录的dentry */
    struct dentry       *s_root;
    struct rw_semaphore s_umount;
    struct mutex        s_lock;
    int         s_count;
    int         s_need_sync;
    atomic_t        s_active;
#ifdef CONFIG_SECURITY
    void                    *s_security;
#endif
    struct xattr_handler    **s_xattr;
    /* 超级块管理的所有inode的链表 */
    struct list_head    s_inodes;   /* all inodes */
    /* 脏的inode的链表 */
    struct list_head    s_dirty;    /* dirty inodes */
    struct list_head    s_io;       /* parked for writeback */
    struct list_head    s_more_io;  /* parked for more writeback */
    struct hlist_head   s_anon;     /* anonymous dentries for (nfs) exporting */
    /* file结构的链表，该超级块上所有打开的文件 */
    struct list_head    s_files;
    /* s_dentry_lru and s_nr_dentry_unused are protected by dcache_lock */
    /* 不再使用的dentry的LRU链表 */
    struct list_head    s_dentry_lru;   /* unused dentry lru */
    int         s_nr_dentry_unused; /* # of dentry on lru */
    struct block_device *s_bdev;
    struct mtd_info     *s_mtd;
    /* 相同文件系统类型的超级块链表的节点 */
    struct list_head    s_instances;
    struct quota_info   s_dquot;    /* Diskquota specific options */
    int         s_frozen;
    wait_queue_head_t   s_wait_unfrozen;
    char s_id[32];              /* Informational name */
    void            *s_fs_info; /* Filesystem private info */
    fmode_t         s_mode;
    /*
     * The next field is for VFS *only*. No filesystems have any business
     * even looking at it. You had been warned.
     */
    struct mutex s_vfs_rename_mutex;    /* Kludge */
    /* Granularity of c/m/atime in ns.
       Cannot be worse than a second */
    u32        s_time_gran;
    /*
     * Filesystem subtype.  If non-empty the filesystem type field
     * in /proc/mounts will be "type.subtype"
     */
    char *s_subtype;
    /*
     * Saved mount options for lazy filesystems using
     * generic_show_options()
     */
    char *s_options;
};
dentry:
struct dentry {
    atomic_t d_count;
    unsigned int d_flags;       /* protected by d_lock */
    spinlock_t d_lock;      /* per dentry lock */
    /* 该dentry是否是一个装载点 */
    int d_mounted;
    /* 文件所属的inode */
    struct inode *d_inode;
    /*
     * The next three fields are touched by __d_lookup.  Place them here so they
all fit in a cache line.
     */
    /* 全局的dentry散列表 */
    struct hlist_node d_hash;   /* lookup hash list */
    /* 父目录的dentry */
    struct dentry *d_parent;    /* parent directory */
    /* 文件的名称，例如对/tmp/a.sh，文件名即为a.sh */
    struct qstr d_name;
    /* 脏的dentry链表的节点 */
    struct list_head d_lru;     /* LRU list */
    /*
     * d_child and d_rcu can share memory
     */
    union {
        struct list_head d_child;   /* child of parent list */
        struct rcu_head d_rcu;
    } d_u;
    /* 该dentry子目录中的dentry的节点链表 */
    struct list_head d_subdirs; /* our children */
    /* 硬链接使用几个不同名称表示同一个文件时，用于连接各个dentry */
    struct list_head d_alias;   /* inode alias list */
    unsigned long d_time;       /* used by d_revalidate */
    const struct dentry_operations *d_op;
    /* 所属的super_block */
    struct super_block *d_sb;   /* The root of the dentry tree */
    void *d_fsdata;         /* fs-specific data */
    /* 如果文件名由少量字符组成，在保存在这里，加速访问 */
    unsigned char d_iname[DNAME_INLINE_LEN_MIN];    /* small names */
};
```

文件系统测试与验证

测试命令

```
stat lab20-19281030-张云鹏.pdf
```



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