UNIX File Management (continued)

OS storage stack (recap)

Application

FD table

OF table

VFS

FS

Buffer cache

Disk scheduler

Device driver

Virtual File System (VFS)

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Older Systems only had a single file system

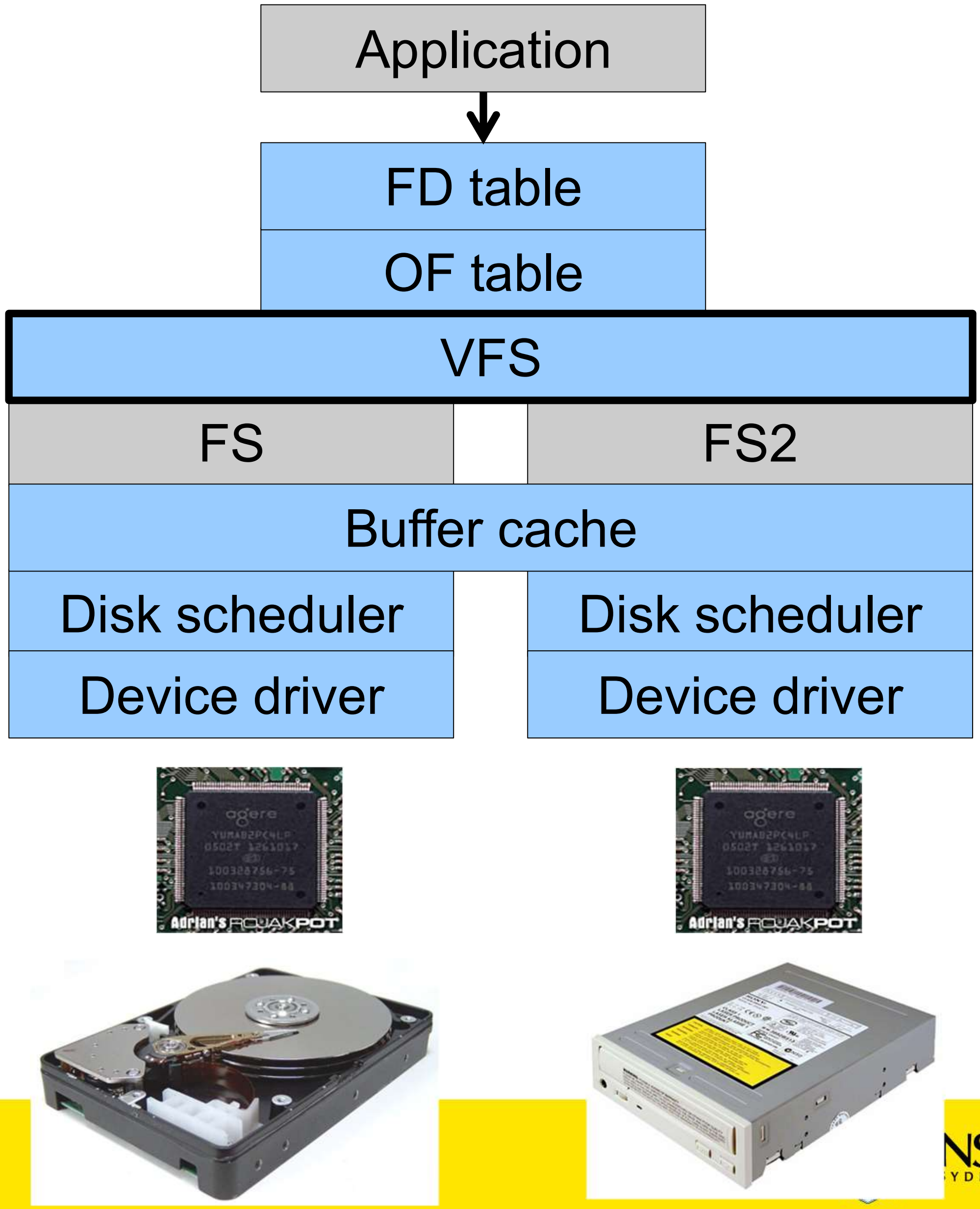
- They had file system specific open, close, read, write, … calls.
- However, modern systems need to support many file system types
  - ISO9660 (CDROM), MSDOS (floppy), ext2fs, tmpfs

Supporting Multiple File Systems

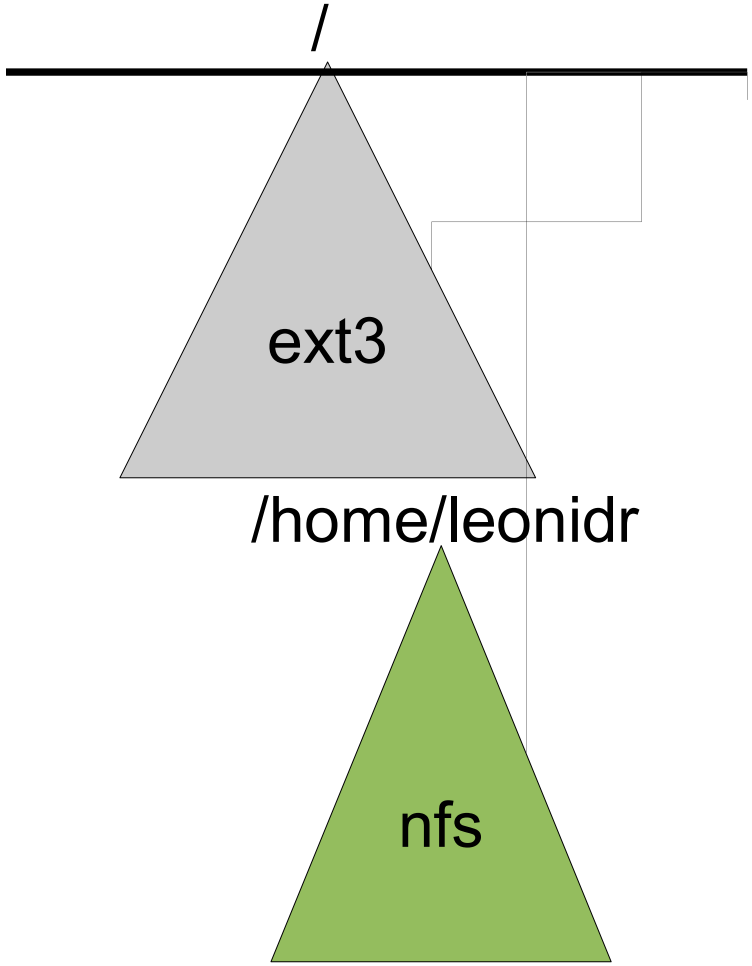
Alternatives

- Change the file system code to understand different file system types
  - Prone to code bloat, complex, non-solution
- Provide a framework that separates file system independent and file system dependent code.
  - Allows different file systems to be "plugged in"

Virtual File System (VFS)



Virtual file system (VFS)



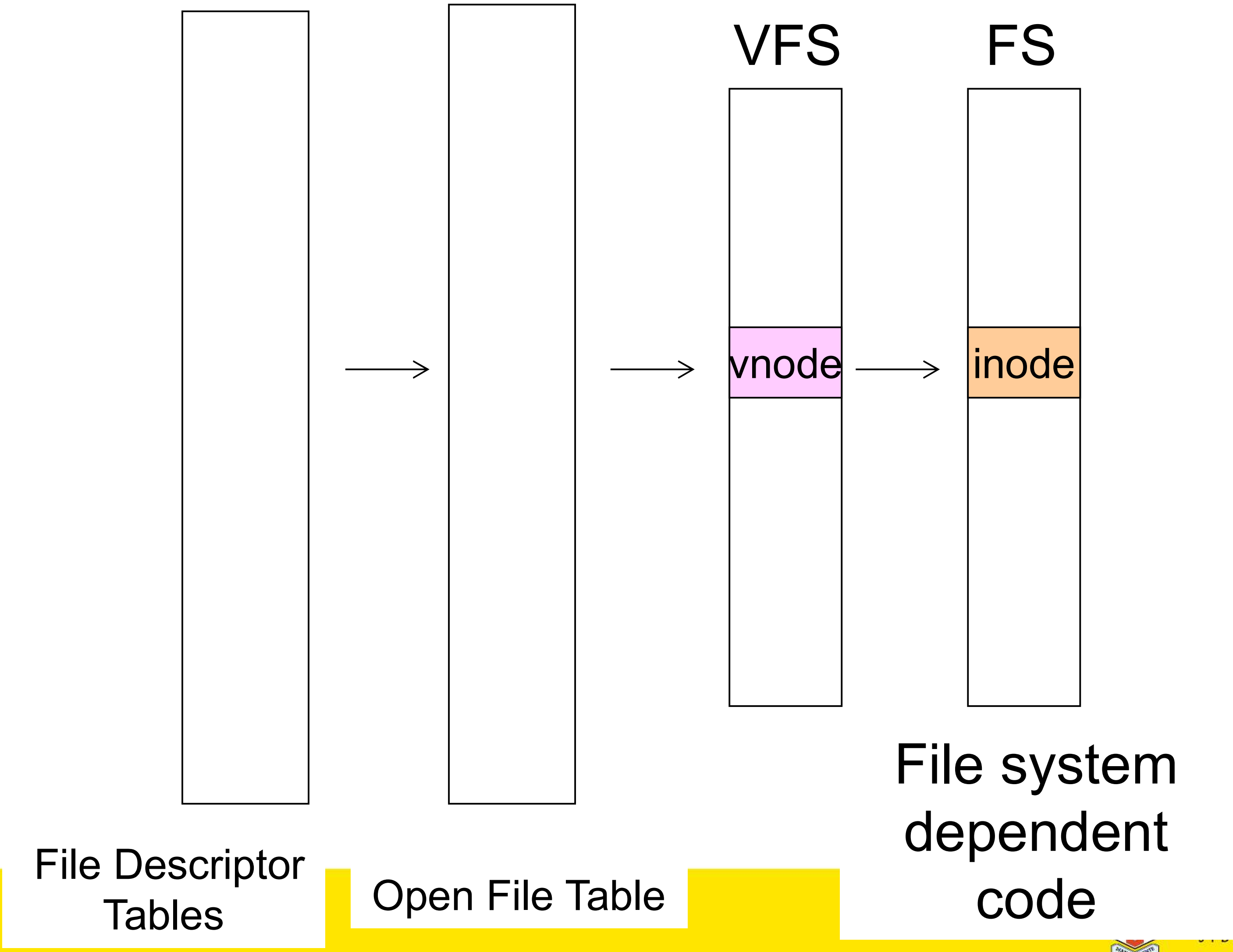
open("/home/leonidr/file", …);

Traversing the directory hierarchy may require VFS to issue requests to several underlying file systems

Virtual File System (VFS)

- Provides single system call interface for many file systems
  - E.g., UFS, Ext2, XFS, DOS, ISO9660,…
- Transparent handling of network file systems
  - E.g., NFS, AFS, CODA
- File-based interface to arbitrary device drivers (`/dev`)
- File-based interface to kernel data structures (`/proc`)
- Provides an indirection layer for system calls
  - File operation table set up at file open time
  - Points to actual handling code for particular type
  - Further file operations redirected to those functions

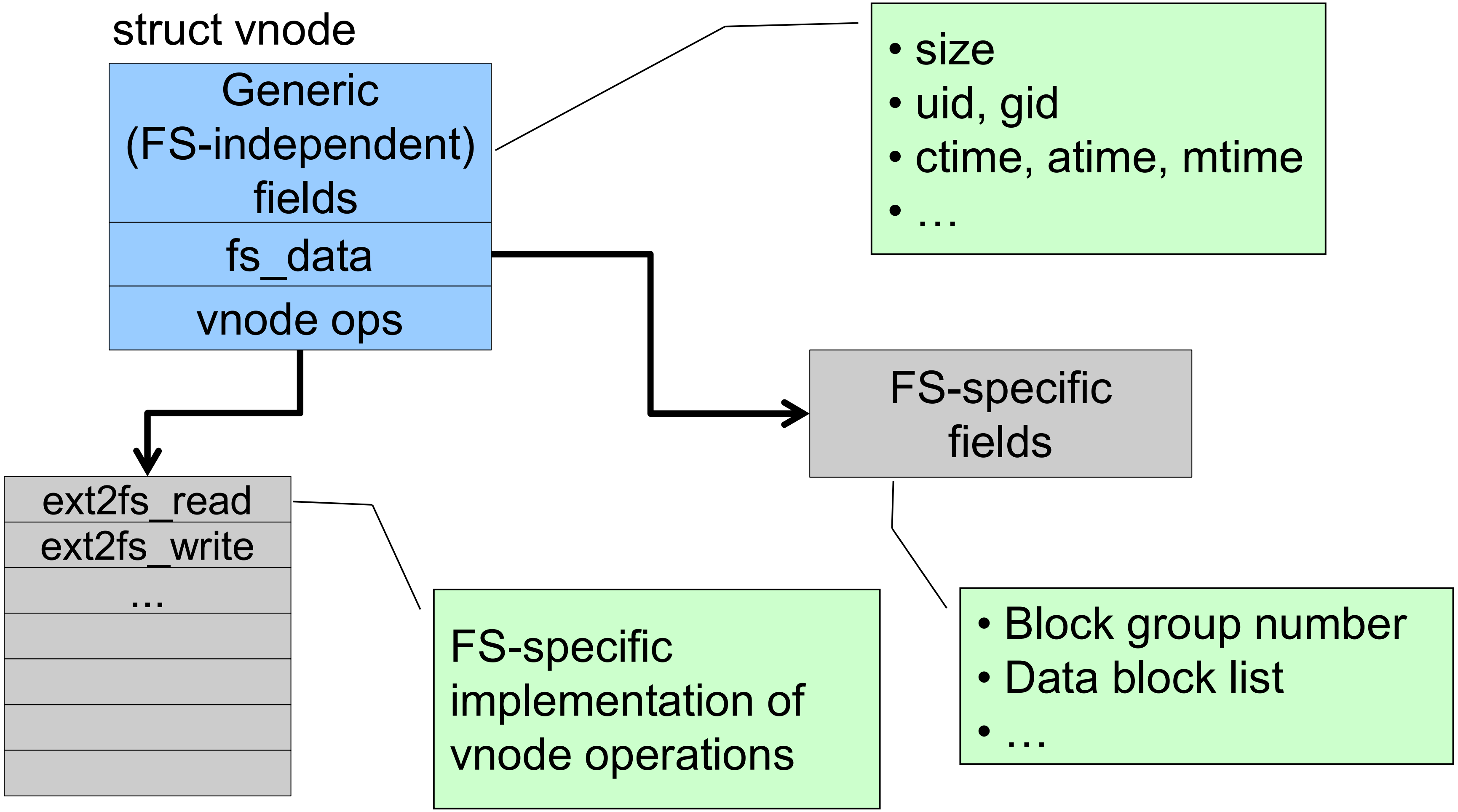
The file system independent code deals with vfs and vnodes



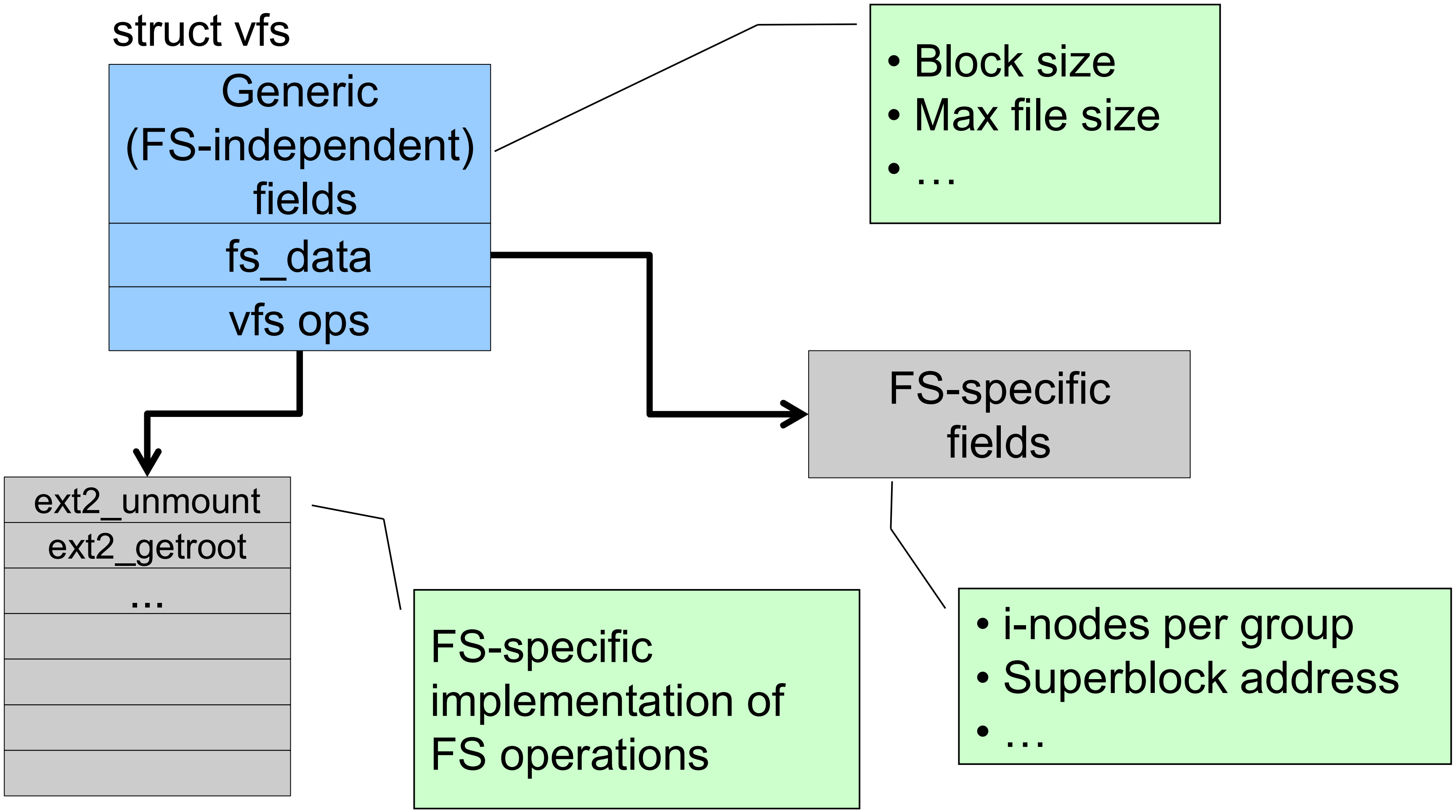
VFS Interface

- Reference
  - S.R. Kleiman., *"Vnodes: An Architecture for Multiple File System Types in Sun Unix,"* USENIX Association: Summer Conference Proceedings, Atlanta, 1986
  - Linux and OS/161 differ slightly, but the principles are the same
- Two major data types
  - VFS
    - Represents all file system types
    - Contains pointers to functions to manipulate each file system as a whole (e.g. mount, unmount)
      - Form a standard interface to the file system
  - Vnode
    - Represents a file (inode) in the underlying filesystem
    - Points to the real inode
    - Contains pointers to functions to manipulate files/inodes (e.g. open, close, read, write,…)

Vfs and Vnode Structures



Vfs and Vnode Structures



A look at OS/161's VFS

The OS161's file system type

Represents interface to a mounted filesystem

```
struct fs {
   int            (*fs_sync)(struct fs *);
   const char    *(*fs_getvolname)(struct fs *);
   struct vnode *(*fs_getroot)(struct fs *);
   int            (*fs_unmount)(struct fs *);

   void *fs_data;
};
```

Force the filesystem to flush its content to disk

Retrieve the volume name

Retrieve the vnode associated with the root of the filesystem

Unmount the filesystem
Note: mount called via function ptr passed to **`vfs_mount`**

Private file system specific data

Vnode

Count the number of “references” to this vnode

Lock for mutual exclusive access to counts

```
struct vnode {
  int vn_refcount;
  struct spinlock vn_countlock;k
  struct fs *vn_fs;
  void *vn_data;

  const struct vnode_ops *vn_ops;
};
```

Pointer to FS containing the vnode

Pointer to FS specific vnode data (e.g. in-memory copy of inode)

Array of pointers to functions operating on vnodes

Vnode Ops

```
struct vnode_ops {
   unsigned long vop_magic;       /* should always be VOP_MAGIC */

   int (*vop_eachopen)(struct vnode *object, int flags_from_open);
   int (*vop_reclaim)(struct vnode *vnode);


   int (*vop_read)(struct vnode *file, struct uio *uio);
   int (*vop_readlink)(struct vnode *link, struct uio *uio);
   int (*vop_getdirentry)(struct vnode *dir, struct uio *uio);
   int (*vop_write)(struct vnode *file, struct uio *uio);
   int (*vop_ioctl)(struct vnode *object, int op, userptr_t data);
   int (*vop_stat)(struct vnode *object, struct stat *statbuf);
   int (*vop_gettype)(struct vnode *object, int *result);
   int (*vop_isseekable)(struct vnode *object, off_t pos);
   int (*vop_fsync)(struct vnode *object);
   int (*vop_mmap)(struct vnode *file /* add stuff */);
   int (*vop_truncate)(struct vnode *file, off_t len);
   int (*vop_namefile)(struct vnode *file, struct uio *uio);
```

Vnode Ops

```
    int (*vop_creat)(struct vnode *dir,
                    const char *name, int excl,
                    struct vnode **result);
    int (*vop_symlink)(struct vnode *dir,
                      const char *contents, const char *name);
    int (*vop_mkdir)(struct vnode *parentdir,
                    const char *name);
    int (*vop_link)(struct vnode *dir,
                   const char *name, struct vnode *file);
    int (*vop_remove)(struct vnode *dir,
                     const char *name);
    int (*vop_rmdir)(struct vnode *dir,
                    const char *name);

    int (*vop_rename)(struct vnode *vn1, const char *name1,
                     struct vnode *vn2, const char *name2);


    int (*vop_lookup)(struct vnode *dir,
                     char *pathname, struct vnode **result);
    int (*vop_lookparent)(struct vnode *dir,
                         char *pathname, struct vnode **result,
                         char *buf, size_t len);
};
```

Vnode Ops

- Note that most operations are on vnodes. How do we operate on file names?
  - Higher level API on names that uses the internal VOP_* functions

```
int vfs_open(char *path, int openflags, mode_t mode, struct vnode **ret);
void vfs_close(struct vnode *vn);
int vfs_readlink(char *path, struct uio *data);
int vfs_symlink(const char *contents, char *path);
int vfs_mkdir(char *path);
int vfs_link(char *oldpath, char *newpath);
int vfs_remove(char *path);
int vfs_rmdir(char *path);
int vfs_rename(char *oldpath, char *newpath);

int vfs_chdir(char *path);
int vfs_getcwd(struct uio *buf);
```

Example: OS/161 emufs vnode ops

```
/*
 * Function table for emufs
   files.
 */
static const struct vnode_ops
   emufs_fileops = {
   VOP_MAGIC,  /* mark this a
   valid vnode ops table */

   emufs_eachopen,
   emufs_reclaim,

   emufs_read,
   NOTDIR,  /* readlink */
   NOTDIR,  /* getdirentry */
   emufs_write,
   emufs_ioctl,
   emufs_stat,
```

```
      emufs_file_gettype,
      emufs_tryseek,
      emufs_fsync,
      UNIMP,   /* mmap */
      emufs_truncate,
      NOTDIR,  /* namefile */

      NOTDIR,  /* creat */
      NOTDIR,  /* symlink */
      NOTDIR,  /* mkdir */
      NOTDIR,  /* link */
      NOTDIR,  /* remove */
      NOTDIR,  /* rmdir */
      NOTDIR,  /* rename */

      NOTDIR,  /* lookup */
      NOTDIR,  /* lookparent */
};
```

File Descriptor & Open File Tables

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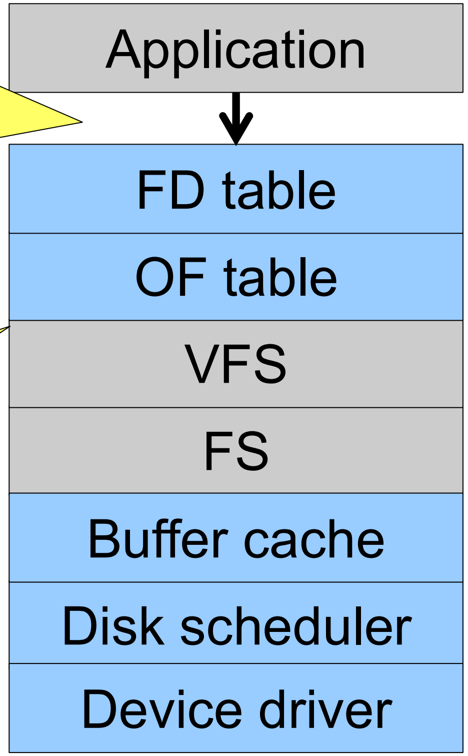
Motivation

System call interface:

```
fd = open("file",…);
read(fd,…);write(fd,…);lseek(fd,…);
close(fd);
```

VFS interface:

```
vnode = vfs_open("file",…);
vop_read(vnode,uio);
vop_write(vnode,uio);
vop_close(vnode);
```



File Descriptors

- File descriptors
  - Each open file has a file descriptor
  - Read/Write/lseek/…. use them to specify which file to operate on.
- State associated with a file descriptor
  - File pointer
    - Determines where in the file the next read or write is performed
  - Mode
    - Was the file opened read-only, etc.…

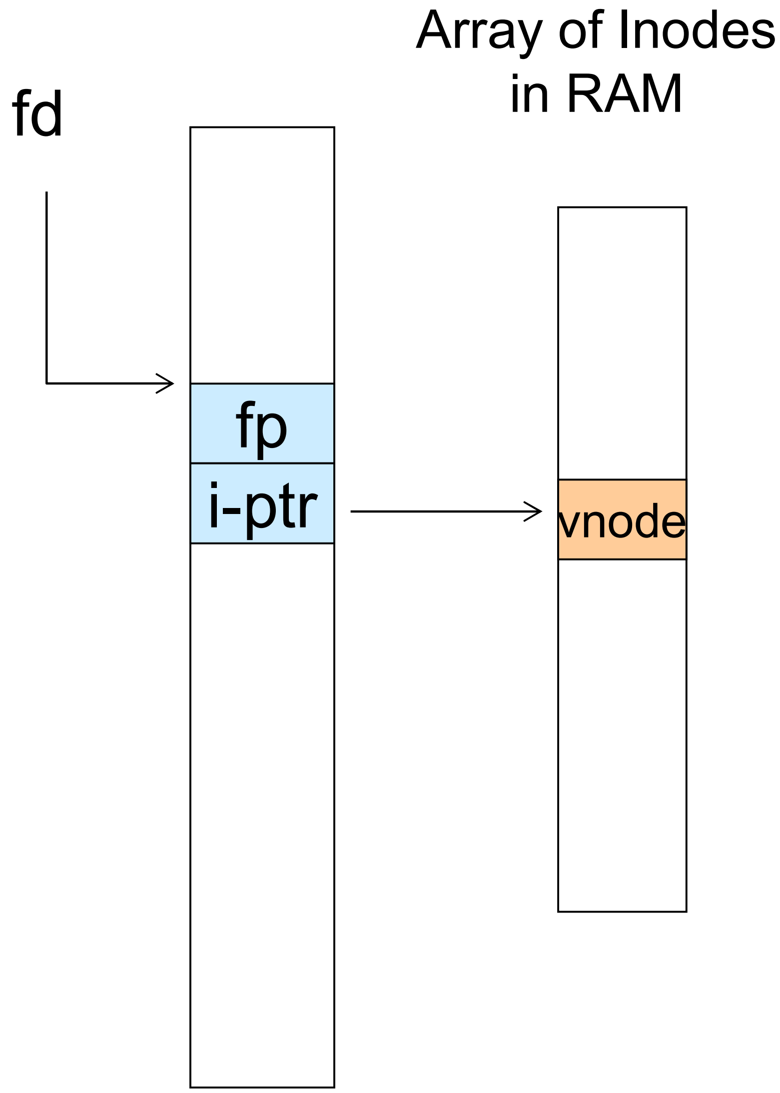
An Option?

- Use vnode numbers as file descriptors and add a file pointer to the vnode

- Problems
  - What happens when we concurrently open the same file twice?
    - We should get two separate file descriptors and file pointers….

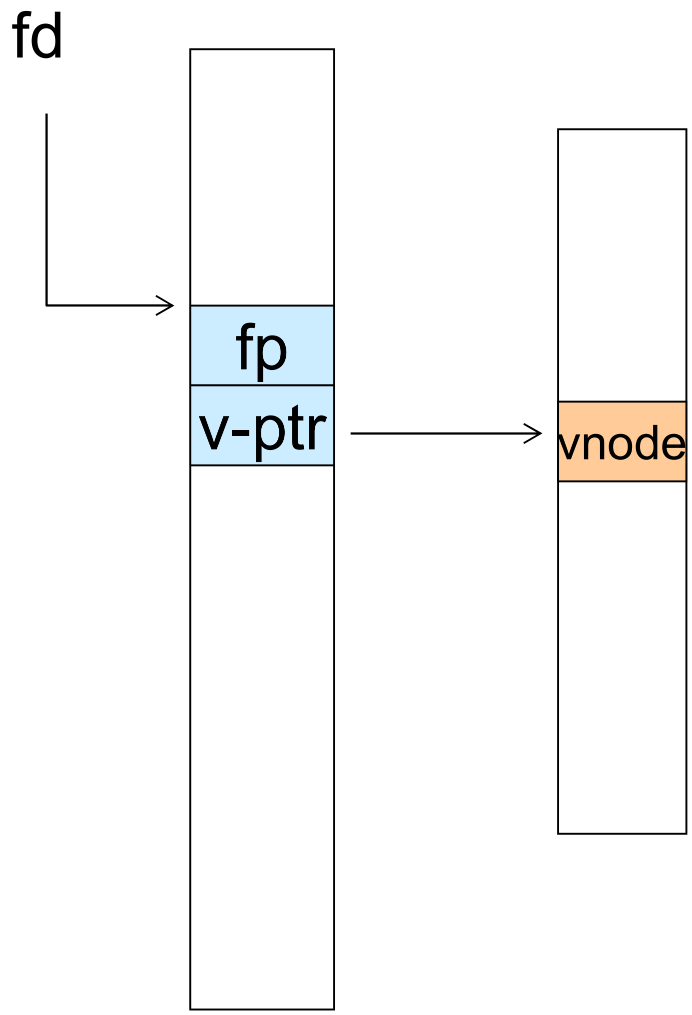
An Option?

- Single global open file array
  - *fd* is an index into the array
  - Entries contain file pointer and pointer to a vnode



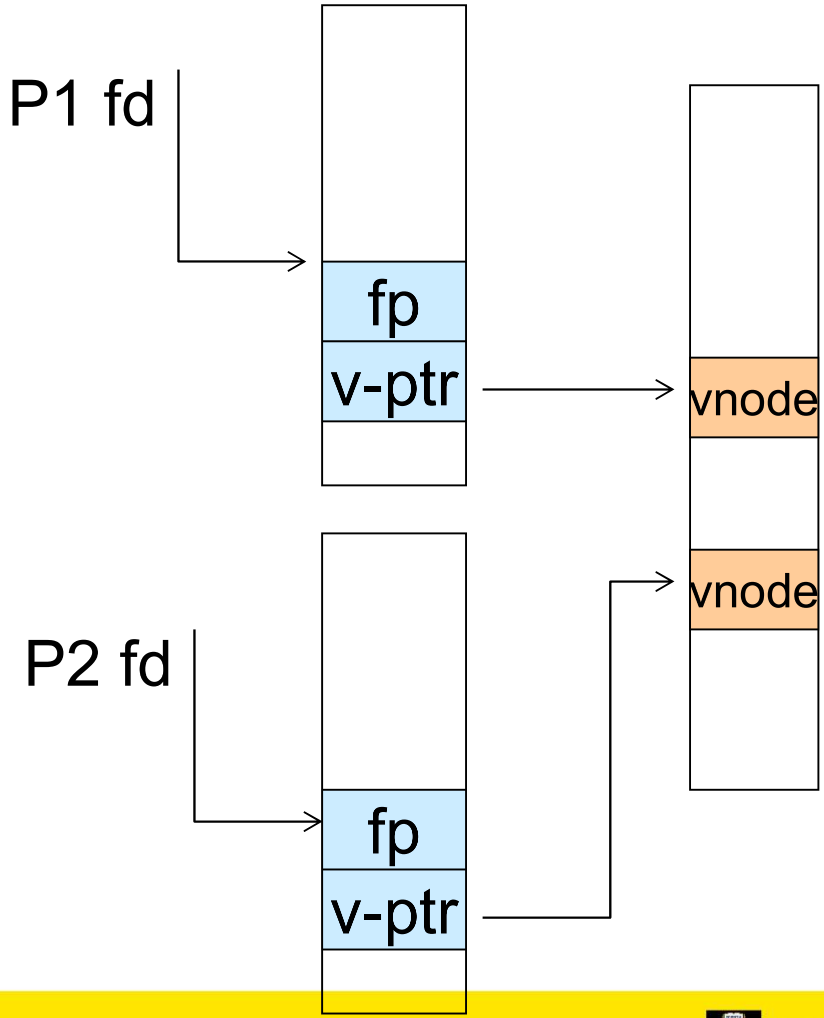
Issues

- File descriptor 1 is stdout
  - Stdout is
    - console for some processes
    - A file for others
- Entry 1 needs to be different per process!



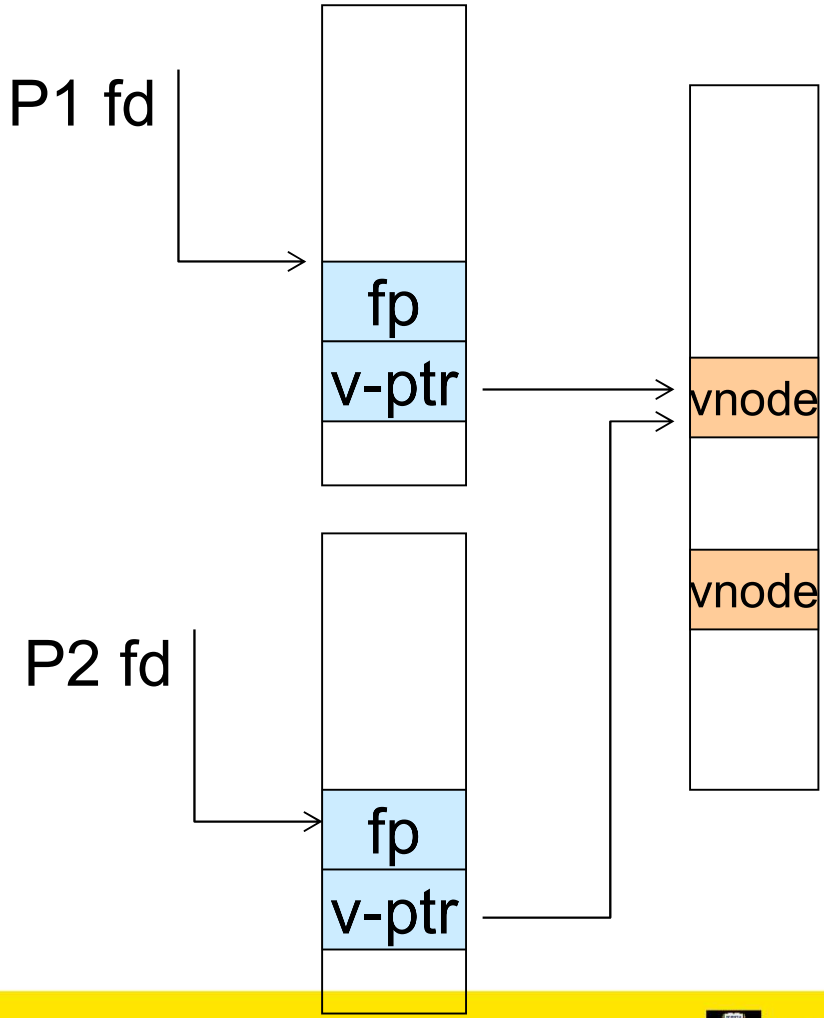
Per-process File Descriptor Array

- Each process has its own open file array
  - Contains fp, v-ptr etc.
  - *Fd* 1 can point to any vnode for each process (console, log file).



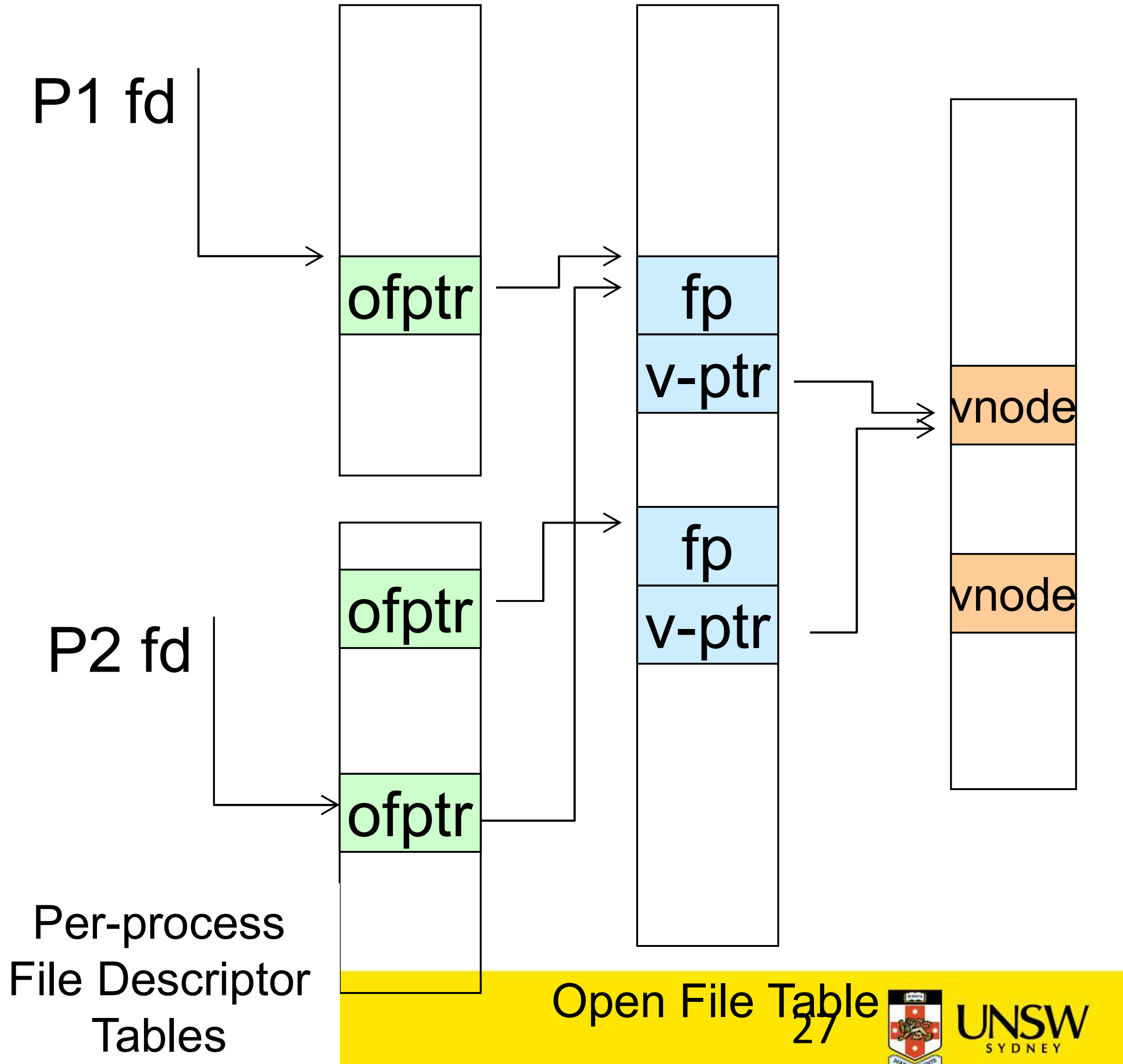
Issue

- Fork
  - Fork defines that the child shares the file pointer with the parent
- Dup2
  - Also defines the file descriptors share the file pointer
- With per-process table, we can only have independent file pointers
  - Even when accessing the same file



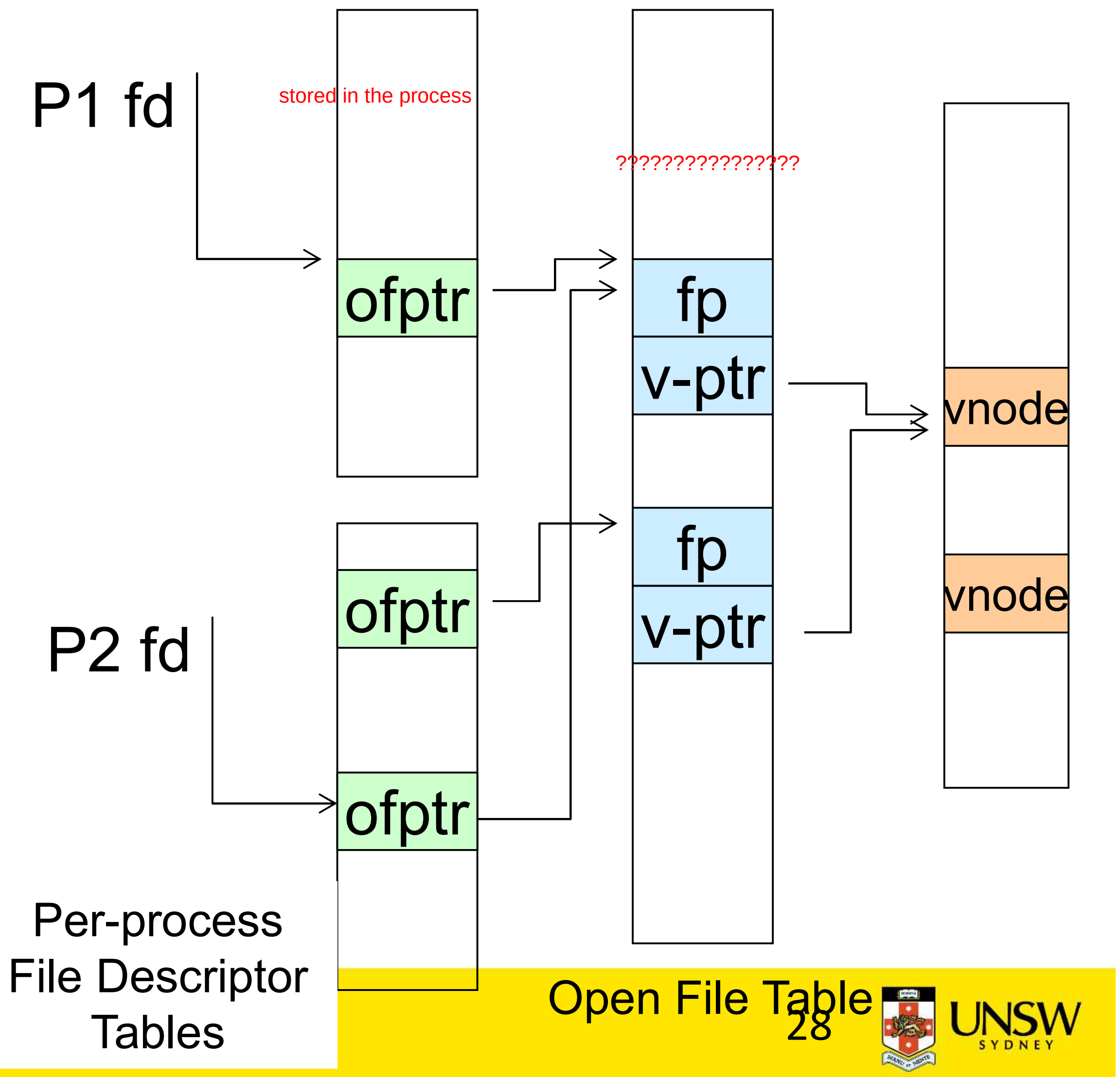
Per-Process *fd* table with global open file table

- Per-process file descriptor array
  - Contains pointers to *open file table entry*
- Open file table array
  - Contain entries with a fp and pointer to an vnode.
- Provides
  - Shared file pointers if required
  - Independent file pointers if required
- Example:
  - All three *fds* refer to the same file, two share a file pointer, one has an independent file pointer



Per-Process *fd* table with global open file table

- Used by Linux and most other Unix operating systems



Buffer Cache

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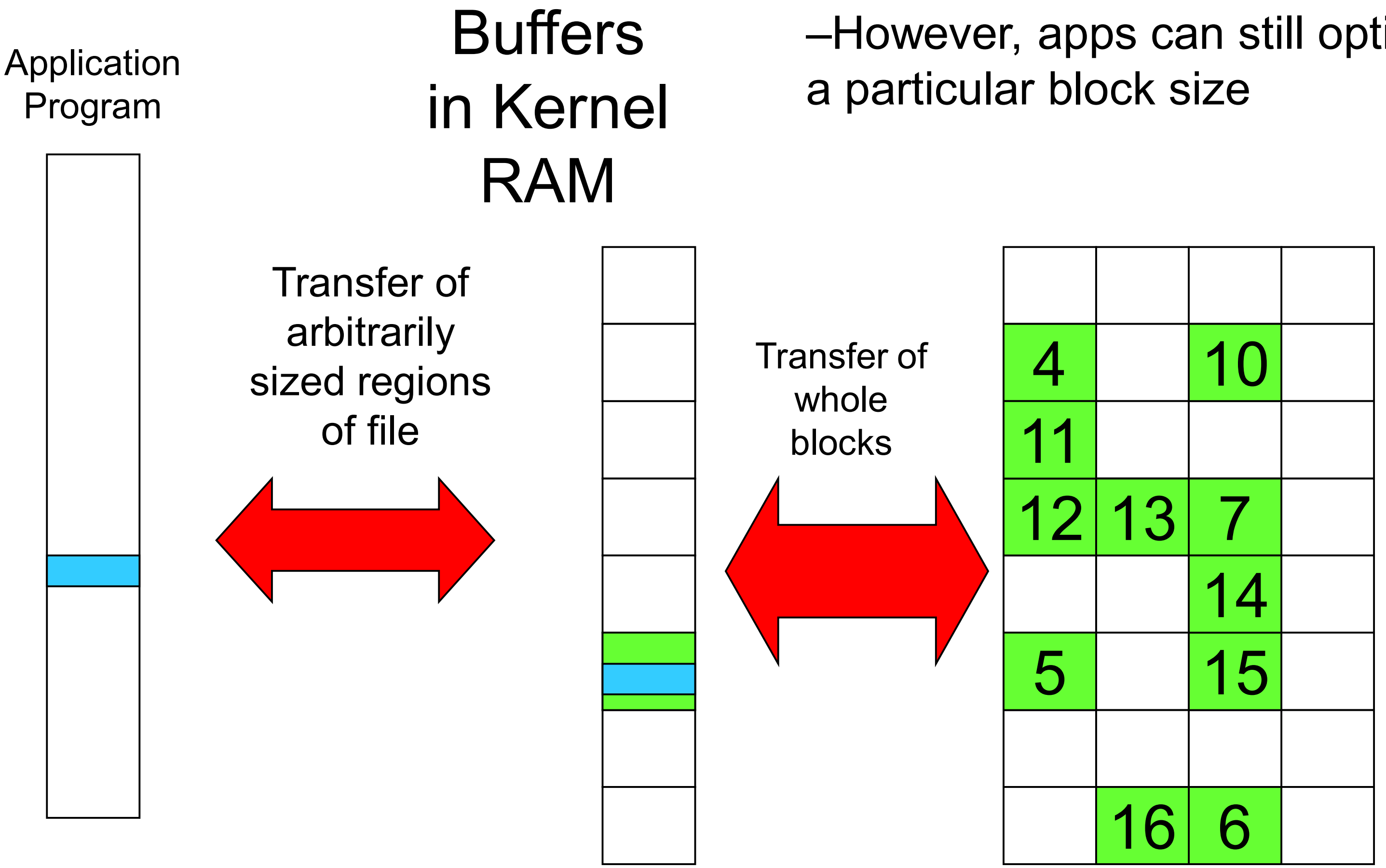
Buffer

- Buffer:
  - Temporary storage used when transferring data between two entities
    - Especially when the entities work at different rates
    - Or when the unit of transfer is incompatible
    - Example: between application program and disk

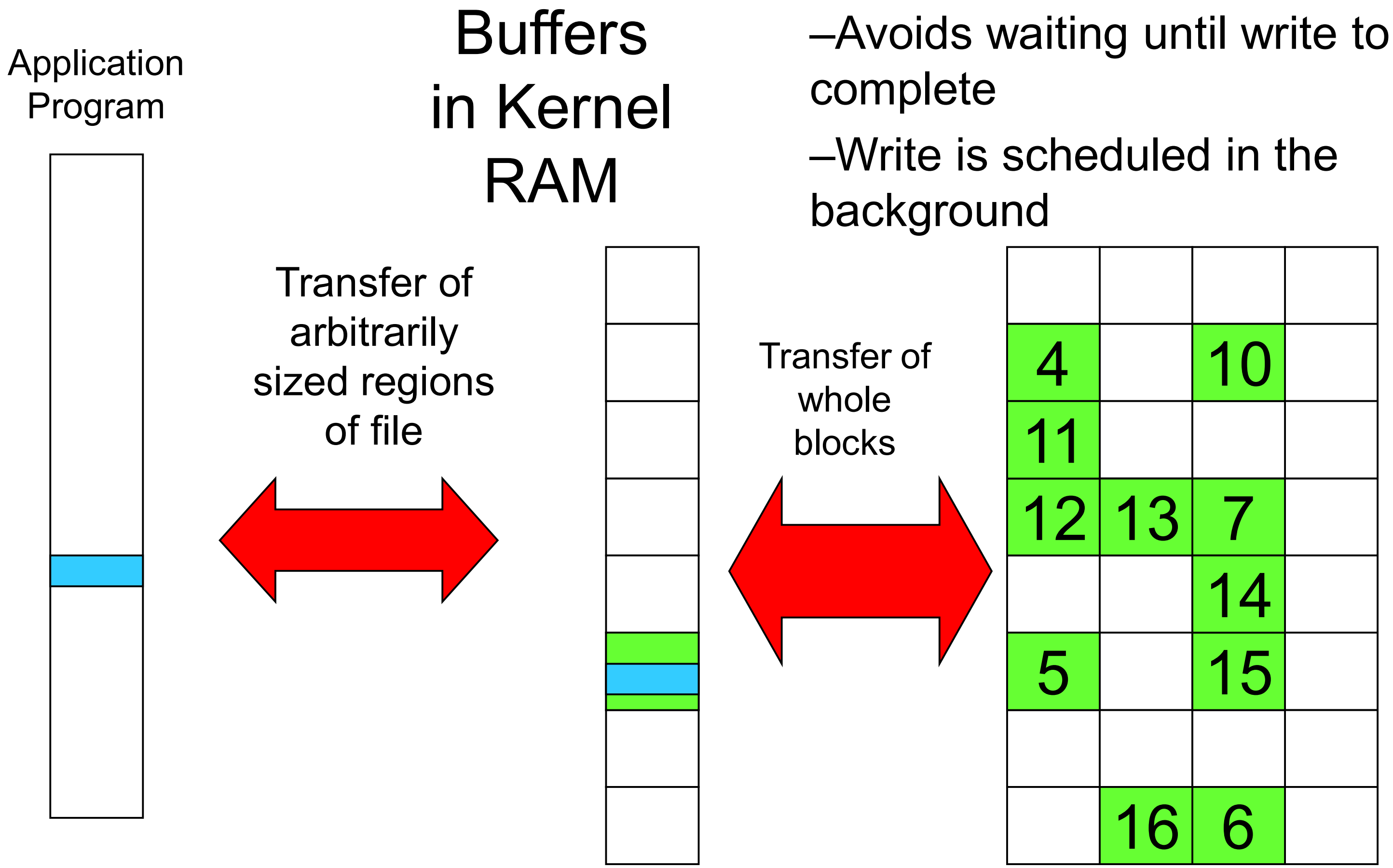
Buffering Disk Blocks

- Allow applications to work with arbitrarily sized region of a file
  - However, apps can still optimise for a particular block size



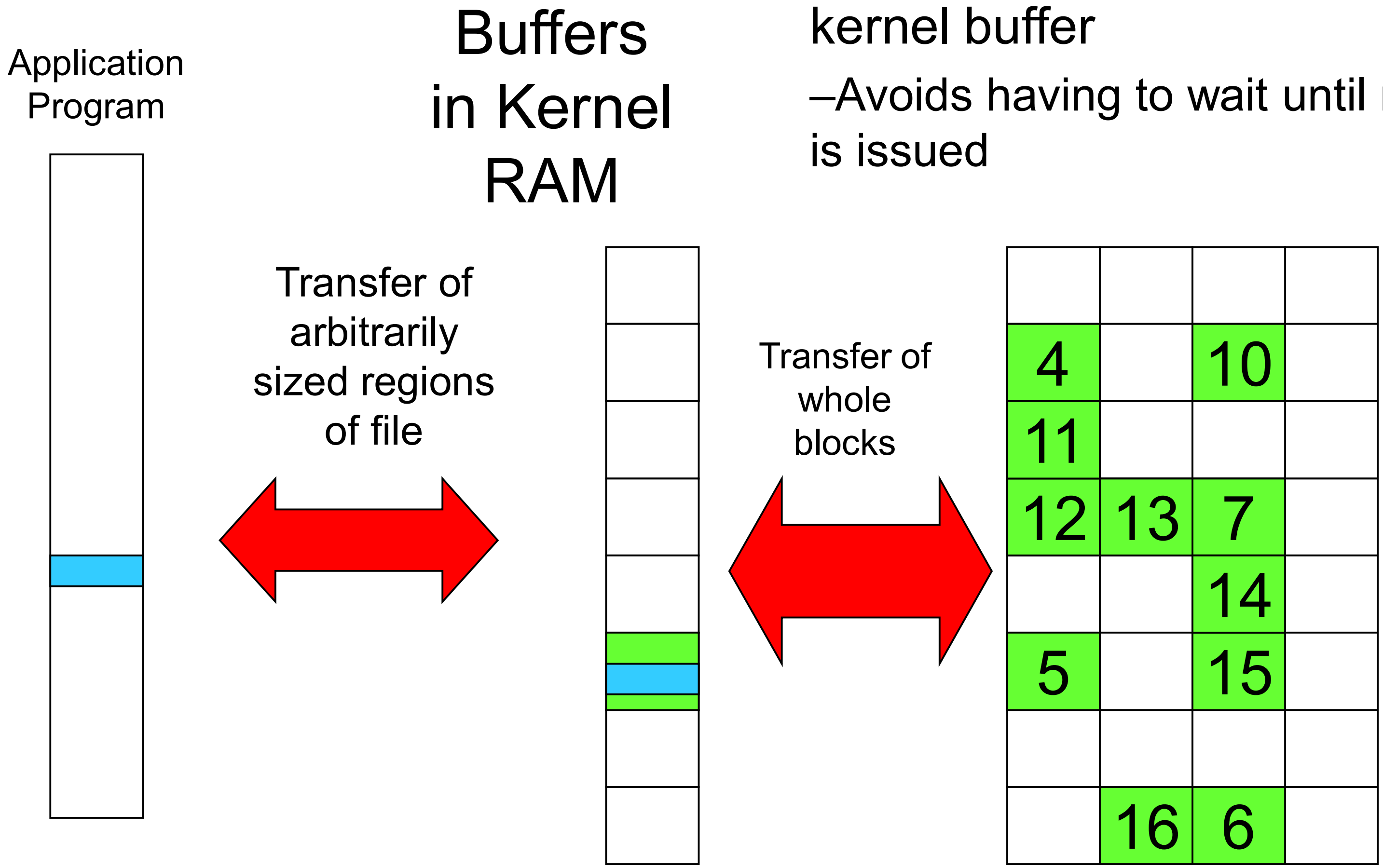
Buffering Disk Blocks

- Writes can return immediately after copying to kernel buffer
  - Avoids waiting until write to disk is complete
  - Write is scheduled in the background



Buffering Disk Blocks

- Can implement read-ahead by pre-loading next block on disk into kernel buffer
  - Avoids having to wait until next read is issued



Cache

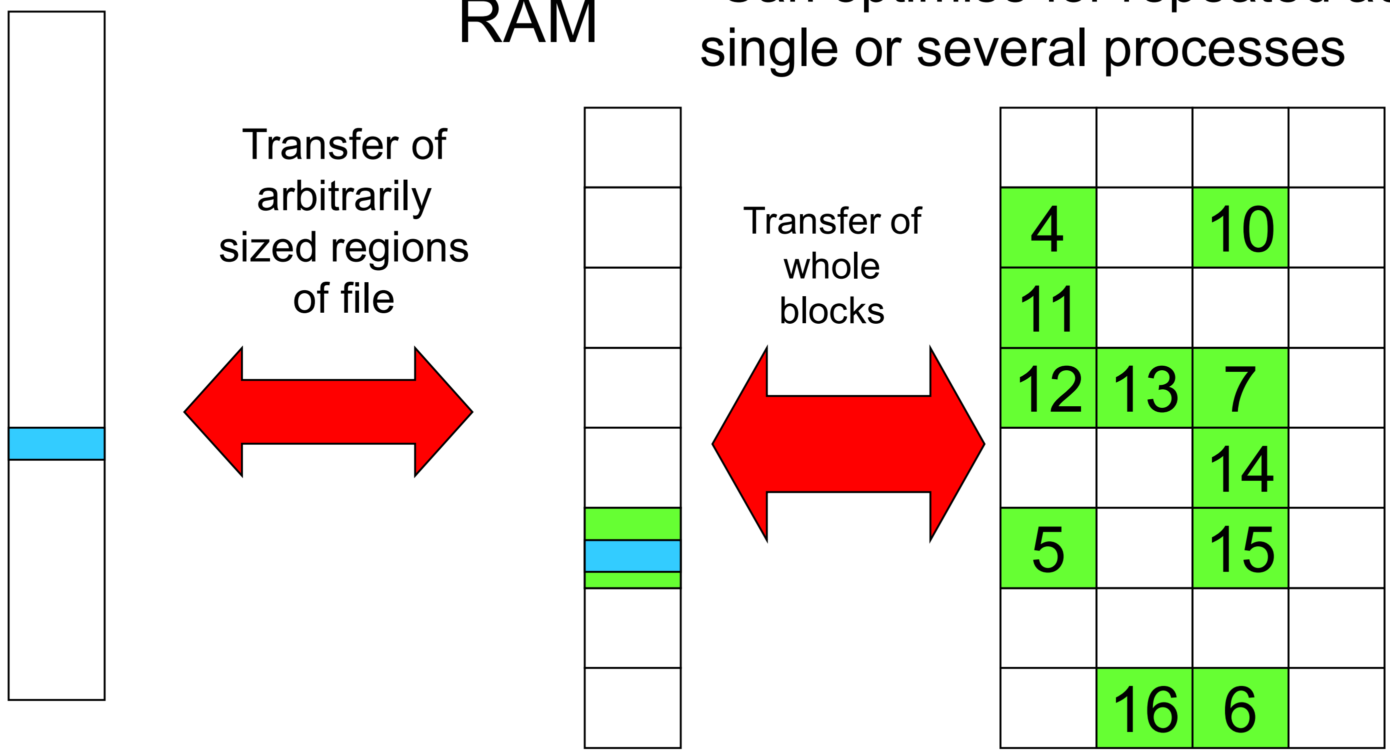
- Cache:
  - Fast storage used to temporarily hold data to speed up repeated access to the data
- Example: Main memory can cache disk blocks

Caching Disk Blocks

Application Program

Cached blocks in Kernel RAM

- On access
  - Before loading block from disk, check if it is in cache first
    - Avoids disk accesses
- Can optimise for repeated access for single or several processes



Buffering and caching are related

- Data is read into buffer; an extra independent cache copy would be wasteful
- After use, block should be cached
- Future access may hit cached copy
- Cache utilises unused kernel memory space;
  - may have to shrink, depending on memory demand

Unix Buffer Cache

On read

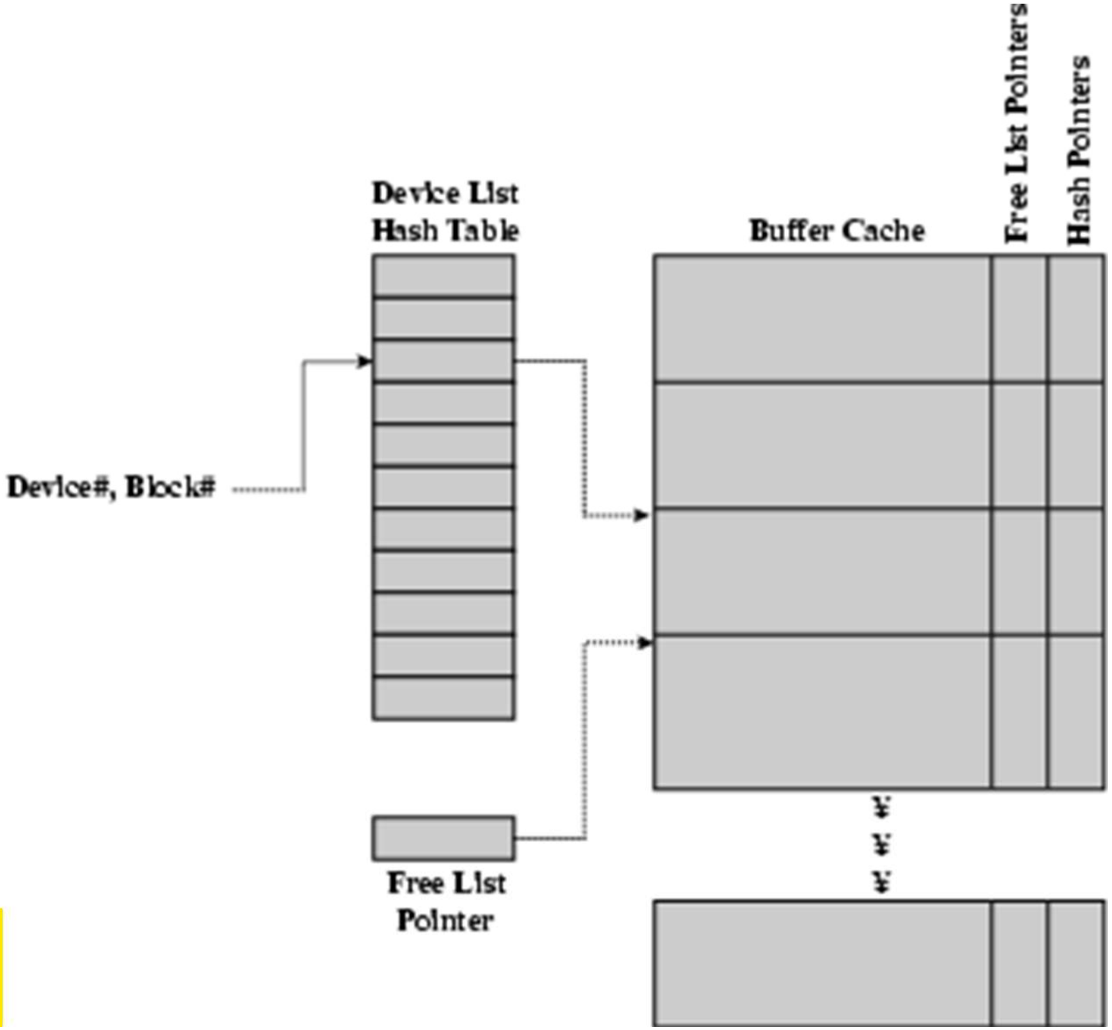
–Hash the device#, block#

–Check if match in buffer cache

–Yes, simply use in-memory copy

–No, follow the collision chain

–If not found, we load block from disk into buffer cache



Replacement

- What happens when the buffer cache is full and we need to read another block into memory?
  - We must choose an existing entry to replace
  - Need a policy to choose a victim
    - Can use First-in First-out
    - Least Recently Used, or others.
      - Timestamps required for LRU implementation
    - However, is strict LRU what we want?

File System Consistency

- File data is expected to survive
- Strict LRU could keep modified critical data in memory forever if it is frequently used.

File System Consistency

- Generally, cached disk blocks are prioritised in terms of how critical they are to file system consistency
  - Directory blocks, inode blocks if lost can corrupt entire filesystem
    - E.g. imagine losing the root directory
    - These blocks are usually scheduled for immediate write to disk
  - Data blocks if lost corrupt only the file that they are associated with
    - These blocks are only scheduled for write back to disk periodically
    - In UNIX, flushd (*flush daemon*) flushes all modified blocks to disk every 30 seconds

File System Consistency

- Alternatively, use a write-through cache
  - All modified blocks are written immediately to disk
  - Generates much more disk traffic
    - Temporary files written back
    - Multiple updates not combined
  - Used by DOS
- Gave okay consistency when
  - »Floppies were removed from drives
  - »Users were constantly resetting (or crashing) their machines
  - Still used, e.g. USB storage devices