Advanced I/O

Non-blocking I/O

- Many I/O Operations Are Slow or Blocked Forever
  - read from pipe, terminal devices, and network devices
  - write to a pipe (full buffer) and network devices (enable flow control)
  - open a pipe for write, but no reader is available
  - read or write of files that have mandatory record locking enabled
  - ioctl operations
  - some other IPC functions
- Non-blocking I/O
  - if an operation cannot be completed, an error is returned
  - it may return partial results
- Example

```
void set_fl(int fd, int flags) {
  int val;
  if ((val = fcntl(fd, F_GETFL, 0)) < 0) errquit("get flag");
  val |= flags;
  if (fcntl(fd, F_SETFL, val) < 0) errquit("set flag");
}

void clr_fl(int fd, int flags) {
  int val;
  if ((val = fcntl(fd, F_GETFL, 0)) < 0) errquit("get flag");
  val &= ~flags;
  if (fcntl(fd, F_SETFL, val) < 0) errquit("set flag");
}

int main(void) {
  int ntowrite, nwrite;
  char *ptr;
  ntowrite = read(STDIN_FILENO, buf, sizeof(buf));
  fprintf(stderr, "read %d bytes\n", ntowrite);
  set_fl(STDOUT_FILENO, O_NONBLOCK);
  ptr = buf;
  while (ntowrite > 0) {
    errno = 0;
    nwrite = write(STDOUT_FILENO, ptr, ntowrite);
    fprintf(stderr, "nwrite = %d, errno = %d\n", nwrite, errno);
    if (nwrite > 0) {
      ptr += nwrite;
      ntowrite -= nwrite;
    }
  }
```

```
  clr_fl(STDOUT_FILENO, O_NONBLOCK);
}
```

```
$ dd if=/dev/urandom bs=1k count=500 | hexdump -C > /tmp/data
500+0 records in
500+0 records out
512000 bytes (512 kB, 500 KiB) copied, 0.0962987 s, 5.3 MB/s
$ ls -la /tmp/data
-rw-rw-r-- 1 ee904 ee904 2528009  六  11 08:53 /tmp/data
$ ./a.out < /tmp/data > /tmp/output
read 500000 bytes
nwrite = 500000, errno = 0
$ ./a.out < /tmp/data | cat > /dev/null
read 500000 bytes
nwrite = 65536, errno = 0
nwrite = -1, errno = 11
nwrite = -1, errno = 11
nwrite = 65536, errno = 0
nwrite = 65536, errno = 0
nwrite = 65536, errno = 0
nwrite = 65536, errno = 0
nwrite = 65536, errno = 0
nwrite = 65536, errno = 0
nwrite = 41248, errno = 0
```

Record Locking

- Record Locking
  - prevent other processes from modifying a region of a file
  - byte-range locking
- `fcntl(2)`: `int fcntl(int fd, int cmd, ... /* arg */ );`
  - return: depend on `cmd` if OK, -1 error
- Lock with `fcntl(2)`
  - `arg` should be pointer to `struct flock`

```
struct flock {
  ...
  short l_type;    /* Type of lock: F_RDLCK, F_WRLCK, F_UNLCK */
  short l_whence;  /* How to interpret l_start: SEEK_SET,
SEEK_CUR, SEEK_END */
  off_t l_start;   /* Starting offset for lock */
  off_t l_len;     /* Number of bytes to lock, 0 means lock to
EOF */
  pid_t l_pid;     /* PID of process blocking our lock (set by
```

```
  F_GETLK and F_OFD_GETLK) */
    ...
};
```

- reader lock can be shared
- writer lock is exclusive
- lock the entire file: `l_start = 0; l_whence = SEEK_SET; l_len = 0;`
- to obtain a read lock, the descriptor must be open for reading
- to obtain a write lock, the descriptor must be open for writing
- `cmd`
  - `F_GETLK`: check if the lock described by `arg` is blocked by some other lock (`l_type`)
  - `F_SETLK`: set the lock described by `arg`, **has to follow the compatibility rules**
  - `F_SETLKW`: blocking version of `F_SETLK`, the process wakes up either when the lock becomes available or when interrupted by a signal

- Compatibility Rules

Region Current	Request Reader Lock	Request Writer lock
No locks	OK	OK
One or more reader locks	OK	Denied
One writer locks	Denied	Denied

  - this rule applies to lock requests made form **different processes**
  - if a process has an existing lock
    - subsequent attempts of place a lock on the same range by the same process
    - will replace the existing lock with the new one
    - example
      - a process has write lock on bytes 16-32
      - it attempts to place a read lock on bytes 16-32
      - the request succeeds, write lock is replace by read lock

- Sample Functions and Macros to Lock and Unlock a Region

```
int lock_reg(int fd, int cmd, int type, off_t offset, int whence,
off_t len) {
  struct flock lock;
  lock.l_type = type;     /* F_RDLCK, F_WRLCK, F_UNLCK */
  lock.l_start = offset;  /* byte offset, relative to l_whence */
  lock.l_whence = whence; /* SEEK_SET, SEEK_CUR, SEEK_END */
  lock.l_len = len;       /* #bytes (0 means to EOF) */
  return (fcntl(fd, cmd, &lock));
}
```

```
#define read_lock(fd, offset, whence, len) \
  lock_reg((fd), F_SETLK, F_RDLCK, (offset), (whence), (len))
#define readw_lock(fd, offset, whence, len) \
  lock_reg((fd), F_SETLKW, F_RDLCK, (offset), (whence), (len))
#define write_lock(fd, offset, whence, len) \
  lock_reg((fd), F_SETLK, F_WRLCK, (offset), (whence), (len))
#define writew_lock(fd, offset, whence, len) \
  lock_reg((fd), F_SETLKW, F_WRLCK, (offset), (whence), (len))
#define un_lock(fd, offset, whence, len) \
  lock_reg((fd), F_SETLK, F_UNLCK, (offset), (whence), (len))
```

- Sample Functions and Macros to Test Locking Condition

```
pid_t lock_test(int fd, int type, off_t offset, int whence, off_t len)
{
  struct flock lock;
  lock.l_type = type;     /* F_RDLCK or F_WRLCK */
  lock.l_start = offset;  /* byte offset, relative to l_whence */
  lock.l_whence = whence; /* SEEK_SET, SEEK_CUR, SEEK_END */
  lock.l_len = len;       /* #bytes (0 means to EOF) */
  if (fcntl(fd, F_GETLK, &lock) < 0) errquit("fcntl error");
  if (lock.l_type == F_UNLCK)
    return 0;         /* false, region isn't locked by another proc */
  return lock.l_pid; /* true, return pid of lock owner */
}

#define is_read_lockable(fd, offset, whence, len) \
  (lock_test((fd), F_RDLCK, (offset), (whence), (len)) == 0)
#define is_write_lockable(fd, offset, whence, len) \
  (lock_test((fd), F_WRLCK, (offset), (whence), (len)) == 0)
```

- Deadlock Example

```
void lockabyte(const char *name, int fd, off_t offset) {
  if (writew_lock(fd, offset, SEEK_SET, 1) < 0) {
    char str[256];
    snprintf(str, sizeof(str), "%s: writew_lock error", name);
    errquit(str);
  }
  printf("%s: got the lock, byte %ld\n", name, offset);
}

int main(void) {
  int fd;
  pid_t pid;

  if ((fd = creat("templock", S_IRUSR | S_IWUSR | S_IRGRP | S_IROTH))
< 0)
    errquit("creat error");
```

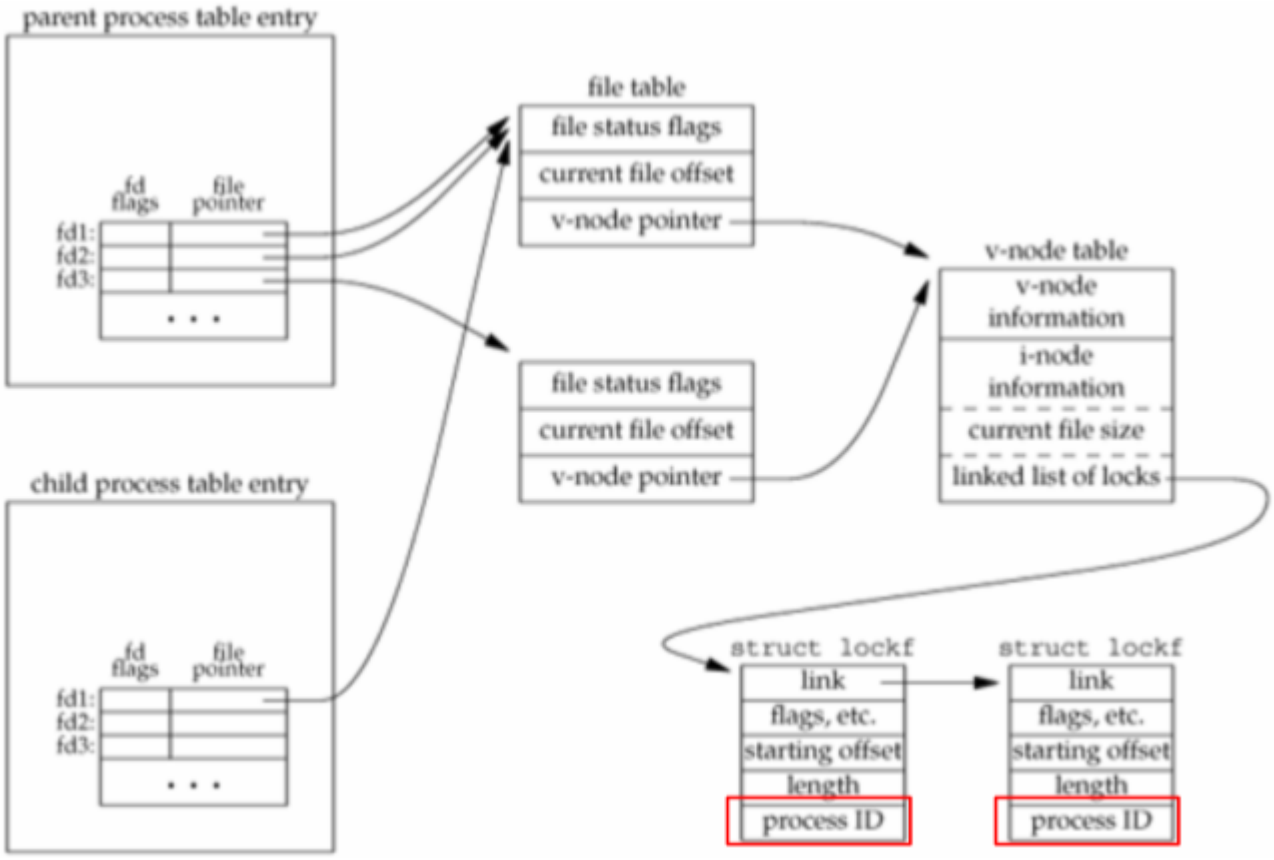
```
  if (write(fd, "ab", 2) != 2) errquit("write error");

  TELL_WAIT();
  if ((pid = fork()) < 0) {
    errquit("fork error");
  } else if (pid == 0) {
    lockabyte("child", fd, 0);
    TELL_PARENT(getppid());
    WAIT_PARENT();
    lockabyte("child", fd, 1);
  } else {
    lockabyte("parent", fd, 1);
    TELL_CHILD(pid);
    WAIT_CHILD();
    lockabyte("parent", fd, 0);
  }
  exit(0);
}
```

```
$ ./a.out
parent: got the lock, byte 1
child: got the lock, byte 0
parent: writew_lock error: Resource deadlock avoided
child: got the lock, byte 1
```

- Three Rules

1. locks are associated with a process and a file
    - lock release when a process terminates or the file descriptor is closed
2. locks are never inherited by the child across a `fork(2)`
3. locks are inherited by a new program across an `exec(2)`



- Lock on Entire File Example

```
int lockfile(int fd) {
  struct flock fl;
  fl.l_type = F_WRLCK;
  fl.l_start = 0;
  fl.l_whence = SEEK_SET;
  fl.l_len = 0;
  return fcntl(fd, F_SETLK, &fl);
}
```

- Lock at End of File
  - most implementations convert `l_whence` value of `SEEK_CUR` or `SEEK_END` into **absolute file offset**
  - erroneous example

```
writew_lock(fd, 0, SEEK_END, 0);
write(fd, buf, 1);
un_lock(fd, 0, SEEK_END);  // not unlock one byte before current
SEEK_END
write(fd, buf, 1);
```

- Advisory vs. Mandatory Locks

    - advisory locks
        - all processes should follow **lock -> read/write -> unlock**
        - if a process does not follow the procedure, it could break the protection
        - most systems implement this
    - mandatory locks
        - once a process lock a file, other read/write access to the file may be not granted
        - some systems enable mandatory lock is a file has enabled `SGID` but disabled group-execute bits
        - mount with `mand` option
        - effect of mandatory locks
            - `bd`: blocking descriptor tries to
            - `nbd`: nonblocking descriptor tries to

Already held	bd read	bd write	nbd read	nbd write
read lock	OK	blocks	OK	EAGAIN
write lock	blocks	blocks	EAGAIN	EAGAIN

        - open usually succeeds even if a file is locked
        - however, if a file is opened with `O_TRUNC` or `O_CREAT`, open returns `EAGAIN`

- Alternative of `fcntl`
    - `flock(2)`: `int flock(int fd, int operation);`
        - return: 0 OK, -1 error
        - lock a file descriptor
        - `LOCK_SH`: place a shared lock
        - `LOCK_EX`: place a exclusive lock
        - `LOCK_UN`: remove an existing lock
    - `lockf(3)`: `int lockf(int fd, int cmd, off_t len);`
        - return: 0 OK, -1 error
        - lock starting from the current file position
        - `F_LOCK`: set an exclusive lock, could be blocked
        - `F_TLOCK`: same as `F_LOCK`, but never blocks (return error if failed)
        - `F_UNLOCK`: unlock
        - `F_TEST`: test if a region is locked or not

- Supported

System	Advisory	Mandatory	fcntl	lockf	flock
SUS	•		•	XSI	
FreeBSD 8.0	•		•	•	•
Linux 3.2.0	•	•	•	•	•

System	Advisory	Mandatory	`fcntl`	`lockf`	`flock`
Mac OS X 10.6.8	•		•	•	•
Solaris 10	•	•	•	•	•

- SUS: Single UNIX Specification
- XSI: X/Open System Interfaces

I/O Multiplexing

- multi-way communication

- Solutions
  - work with two process
    - each process handle one-way communication
    - child received `EOF`: it terminates, parent receives `SIGCHLD`
    - parent received `EOF`: notify child to stop, use `SIGUSR1`
  - work with two threads
  - work with polling
    - polling in a busy loop
    - set the descriptors to non-blocking
    - perform reads on both descriptors and forward when data is available
  - asynchronous I/O
    - kernel notify with a signal when a descriptor is ready for I/O
    - but not all systems support this feature
    - may work only on descriptors that refer to terminal devices or networks
    - only one `SIGIO` or `SIGPOLL` per process
      - how to differentiate multiple descriptors?
    - have to check each (non-blocking) descriptors
  - I/O multiplexing
    - work with `select(2)` and poll
    - highly compatibility, usually O(n) complexity
  - modern UNIX systems supports event multiplexing
    - kqueue for BSD and epoll for Linux
    - O(1), faster than traditional I/O multiplexing

- `select(2)`: `int select(int nfds, fd_set *readfds, fd_set *writefds, fd_set *exceptfds, struct timeval *timeout);`
  - return: number of ready file descriptors, 0 timeout, -1 error
  - `ndfs`: highest number of file descriptor + 1

    - `readfds`, `writefds`, `exceptfds`: interested descriptors
    - `timeout`
        - `NULL` -> wait infinitely
        - `tv_sec` is zero and `tv_usec` is zero -> no wait
        - wait given time
    - manipulate descriptor sets
        - `void FD_CLR(int fd, fd_set *set);`
        - `int FD_ISSET(int fd, fd_set *set);`
        - `void FD_SET(int fd, fd_set *set);`
        - `void FD_ZERO(fd_set *set);`
    - change `readfds`, `writefds`, `exceptfds` to set ready bits
        - `readfds`: if a read from that descriptor will not block
        - `writefds`: if a write to that descriptor will not block
        - `exceptfds`: if an exception condition is pending on that descriptor, it depends on the type of a descriptor
    - may change `timeout` depends on system
    - descriptors do not affect whether `select(2)` blocks, only `timeout` can make it to block

- `pselect(2)`: `int pselect(int nfds, fd_set *readfds, fd_set *writefds, fd_set *exceptfds, const struct timespec *timeout, const sigset_t *sigmask);`
    - return: number of ready file descriptors, 0 timeout, -1 error
    - two additional benefits

        1. `struct timespec`: nanoseconds instead of microseconds

        ```
        struct timeval {
          long int tv_sec;
          long int tv_usec;
        };

        struct timespec {
          long int tv_sec;
          long int tv_nsec;
        };
        ```

        2. signal mask: atomic operation for `sigprocmask(2)` and `select(2)`
            - setup `sigmask` -> run `select` -> restore `sigmask`

- `poll(2)`: `int poll(struct pollfd *fds, nfds_t nfds, int timeout);`
    - return: number of ready file descriptors, 0 timeout, -1 error
    - similar to `select(2)`, but pass an array of descriptors
    - `events` and `revents` flags

Name	Input	Result	Description
`POLLIN`	•	•	Equivalent to `POLLRDNORM | POLLRDBAND`

Name	Input	Result	Description
`POLLRDNORM`	•	•	Normal data (priority 0) can be read without blocking
`POLLRDBAND`	•	•	Data from a nonzero priority band can be read without blocking
`POLLPRI`	•	•	High-priority data can be read without blocking
`POLLOUT`	•	•	Normal data can be written without blocking
`POLLWRNORM`	•	•	Same as `POLLOUT`
`POLLWRBAND`	•	•	Data for a nonzero priority band can be written without blocking
`POLLERR`		•	An error has occurred
`POLLHUP`		•	A hangup has occurred
`POLLNVAL`		•	The descriptor does not reference an open file

```
struct pollfd {
  int fd;          /* file desrriptor */
  short events;    /* requested events */
  short revents;   /* returned events */
}
```

    - `timeout`
        - -1: wait infinitely
        - 0: no wait
        - > 0: wait for `timeout` milliseconds

- `ppoll(2)`: `int ppoll(struct pollfd *fds, nfds_t nfds, const struct timespec *tmo_p, const sigset_t *sigmask);`
    - changes as same as `select(2)` to `pselect(2)`

Asynchronous I/O

`readv` and `writev` Functions

`readn` and `writen` Functions

Memory-mapped I/O