Inter-Process Communication

Science

Computer Science

CS 351: Systems Programming
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The OS kernel does a great job of *isolating* processes from each other

If not, programming would be *much harder*!

- all data accessible (read/write) to world
- memory integrity not guaranteed
- control flow unpredictable

But processes are more useful when they can *exchange data* & *interact dynamically*

The original data exchange unit: the *file*

see: BBS, FTP, Napster, BitTorrent

But what about *dynamic* data exchange?

e.g., instant messaging, VOIP, MMOGs

The kernel *enforces* isolation

… so to perform *inter-process communication* (IPC), must ask kernel for help/assistance

Another role for the kernel: errand boy

Select IPC mechanisms:

1. signals
2. (regular) files
3. shared memory
4. unnamed & named pipes
5. file locks & semaphores
6. sockets

§Common Issues

1. link/endpoint creation
   - naming
   - lookup / registry

2. data transmission

- unidirectional/bidirectional
- single/multi-sender/recipient
- speed/capacity
- message packetizing
- routing

3. data synchronization

- behavior with multiple senders and/or receivers
- control: implicit / explicit / none

4. access control
   - mechanism
   - granularity

§ Files

in general, regular files are a really lousy mechanism for *dynamic* IPC

- ultra-slow backing store (disk)
- coordinating file positions is tricky

```
int main() {
    int fd;
    if (fork() == 0) {
        fd = open("shared.txt", O_CREAT|O_TRUNC|O_WRONLY, 0644);
        dup2(fd, 1);
        execl("/bin/echo", "/bin/echo", "hello", NULL);
    }
    if (fork() == 0) {
        fd = open("shared.txt", O_RDONLY);
        dup2(fd, 0);
        execl("/usr/bin/wc", "/usr/bin/wc", "-c", NULL);
    }
}
```

Output?

… it depends …

we won't be considering regular files as a mechanism for (dynamic) IPC

§Shared Memory

simple idea: allow processes to share data stored in memory

i.e., sidestep memory protection

shm… APIs:

- file descriptor based
- memory mapped

FD-based API:

```
int shm_open(const char *name, int oflag, mode_t mode);
```

- returns FD for shared memory
- may be mapped to temp file (of name)
- persists until explicitly removed!

```
int shm_unlink(const char *name);
```

- explicitly remove shared memory

```
#define SHM_NAME "/myshm"  /* arbitrary shm identifier */


/* writing process */

int shmfd = shm_open(SHM_NAME, O_RDWR|O_CREAT, 0644);
write(shmfd, ...);
```

```
/* reading process */

int shmfd = shm_open(SHM_NAME, O_RDONLY, 0);
char buf[N];
read(shmfd, buf, N);
```

memory-mapped API:

```
int   shmget(key_t key, size_t size, int shmflg);
```

- returns ID for shm of size

```
void *shmat(int shmid, const void *shmaddr, int shmflg);
```

- returns (local) pointer to shm given ID

```
int   shmdt(const void *shmaddr);
```

- detach from shm (but still persists)

```
int   shmctl(int shmid, int cmd, struct shmid_ds *buf);
```

- manage existing shm object

```c
#define SHM_KEY  0xABCD
#define SHM_SIZE 1024

int shmid = shmget(SHM_KEY,                 /* unique system-wide shm key          */
                   SHM_SIZE,                /* size of shm (in bytes)              */
                   IPC_CREAT|0600);         /* IPC_CREAT not needed if already exists */

char *shm = shmat(shmid, NULL, 0);          /* map shm into my address space       */

strcpy(shm, "hello world!");                /* access shm (via pointer)            */

shmdt(shm);                                 /* detach from shm (i.e., unmap)       */

shmctl(shmid, IPC_RMID, NULL);              /* remove shm from system              */
```

shm is the *fastest* form of IPC;

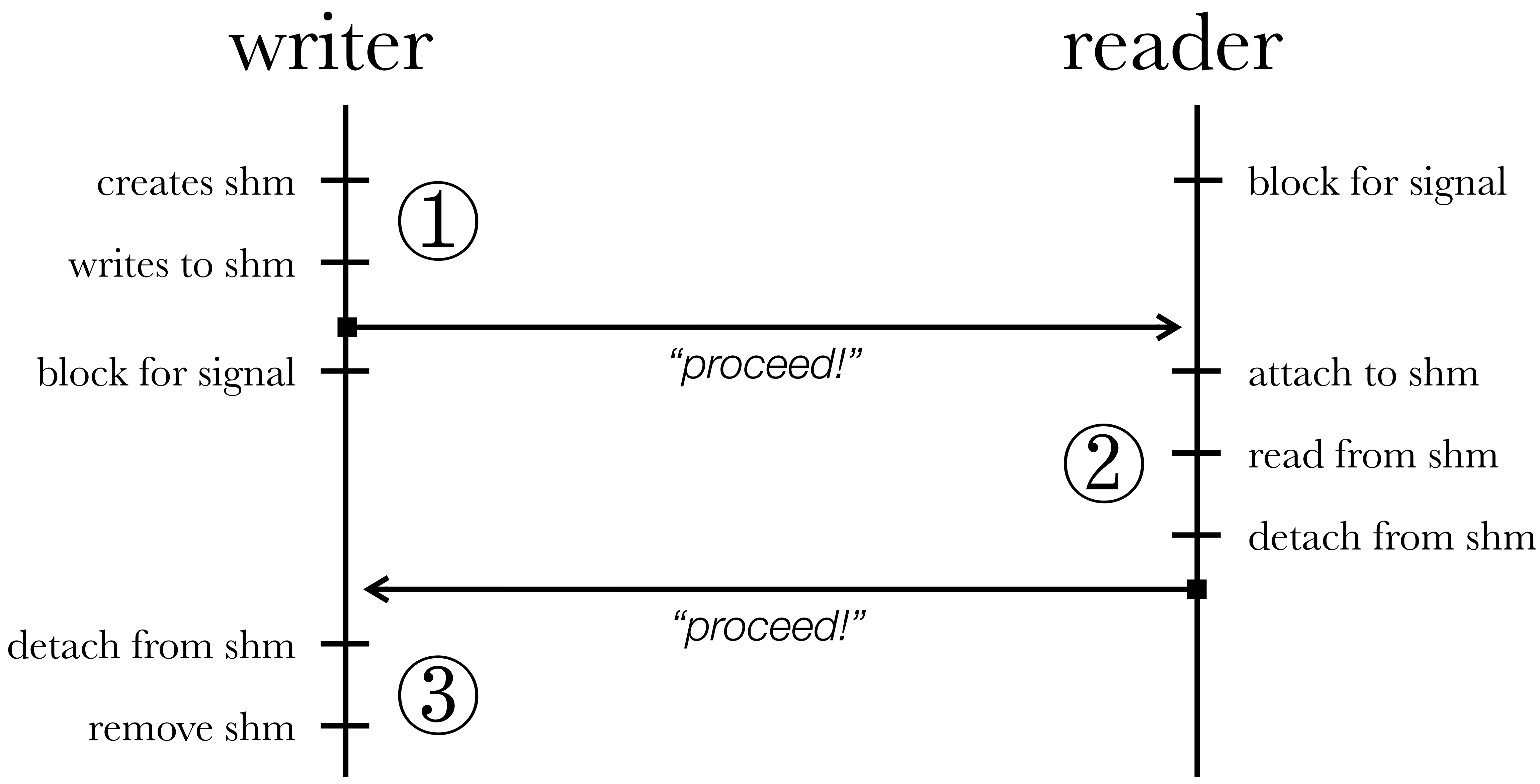
only overhead = process switch
(unavoidable anyway)

Problem: how do processes know when communication has occured?

To fix, we need processes using shared memory to communicate

… using another IPC mechanism!

one approach: signals



```c
int sig_recvd = 0;
void sighandler (int sig)
{
    if (sig == SIGUSR1)
        sig_recvd = 1;
}

int main (int argc, char *argv[])
{
    signal(SIGUSR1, sighandler);
```

```c
/* parent/writer process */
if ((pid = fork()) != 0) {
    shmid   = shmget(SHM_KEY, ..., IPC_CREAT|...);
    shm_arr = shmat(shmid, ...);

    for (i=0; i<SHM_SIZE; i++) {
        shm_arr[i] = i;
    }

    kill(pid, SIGUSR1); /* signal child */

    while (!sig_recvd) /* block for child signal */
        sleep(1);

    shmdt(shm_arr);
    shmctl(shmid, IPC_RMID, NULL);
}
```

①

③

```c
/* child/reader process */
else {
    while (!sig_recvd) /* block for parent signal */
        sleep(1);

    shmid = shmget(SHM_KEY, ...);

    shm_arr = shmat(shmid, ...);

    for (i=0; i<SHM_SIZE; i++) {
        printf("%d ", shm_arr[i]);
    }

    shmdt(shm_arr);
    kill(getppid(), SIGUSR1); /* signal parent */
}
```

②

```
0 1 2 3 4
```

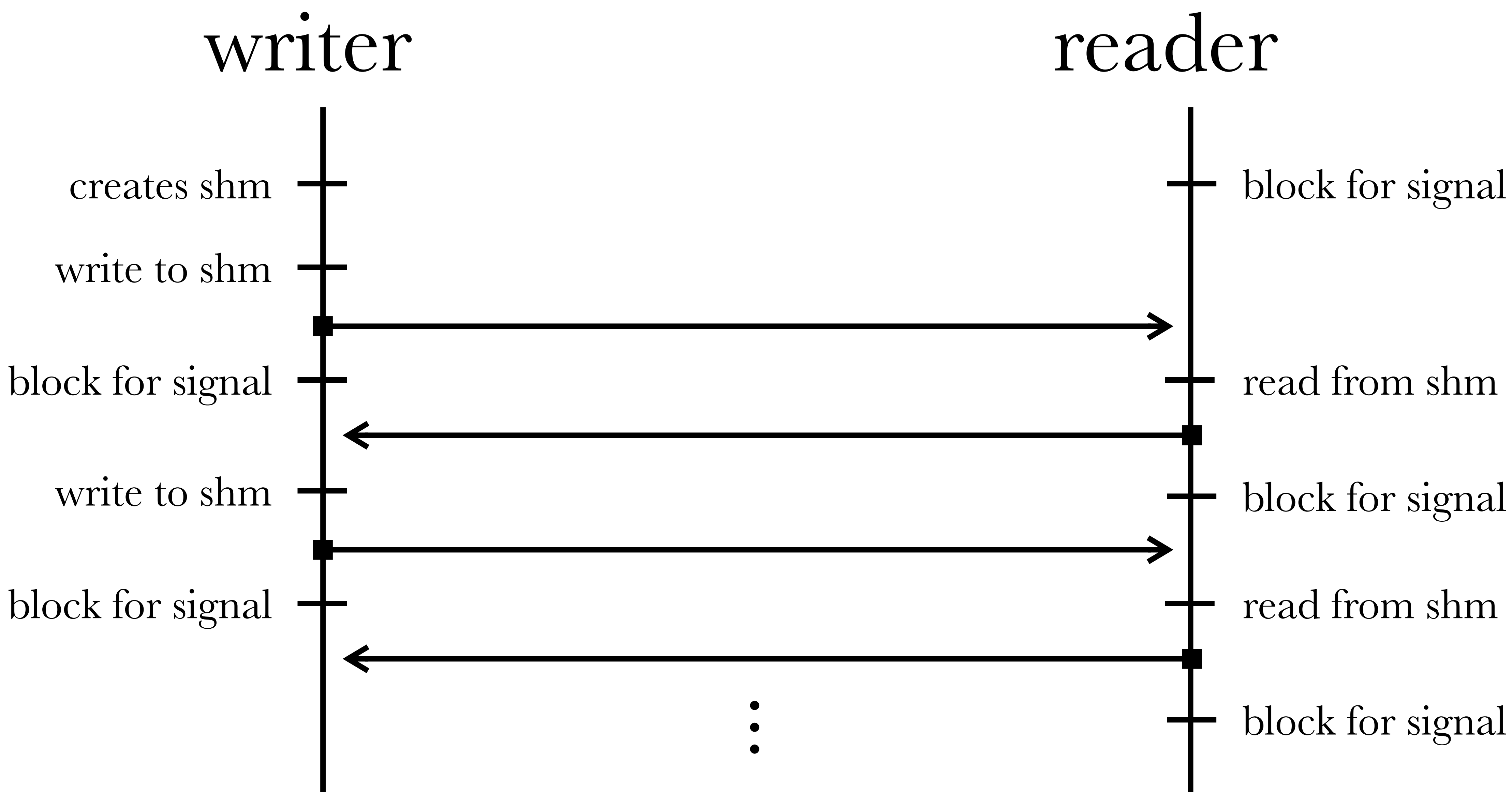
but wait …

```
/* parent/writer process */
if ((pid = fork()) != 0) {
    ...
    for (i=0; i<SHM_SIZE; i++) {
        shm_arr[i] = i;
    }

    kill(pid, SIGUSR1);

}
```

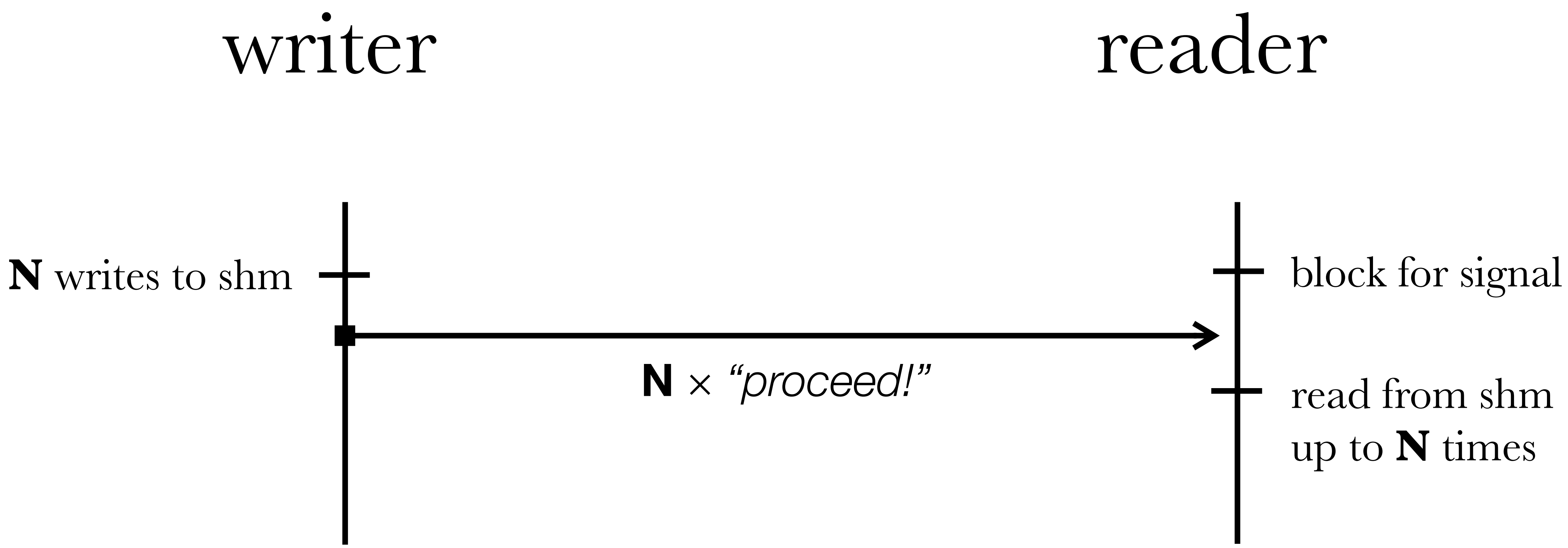
```
/* child/reader process */
else {
    while (!sig_recvd)
        pause();
    ...

    for (i=0; i<SHM_SIZE; i++) {
        printf("%d ", shm_arr[i]);
    }
}
```

we’ve eliminated concurrency!
(w.r.t. shm access)

how about:


writer
reader
creates shm
block for signal
write to shm
block for signal
read from shm
write to shm
block for signal
block for signal
read from shm
block for signal

how about:



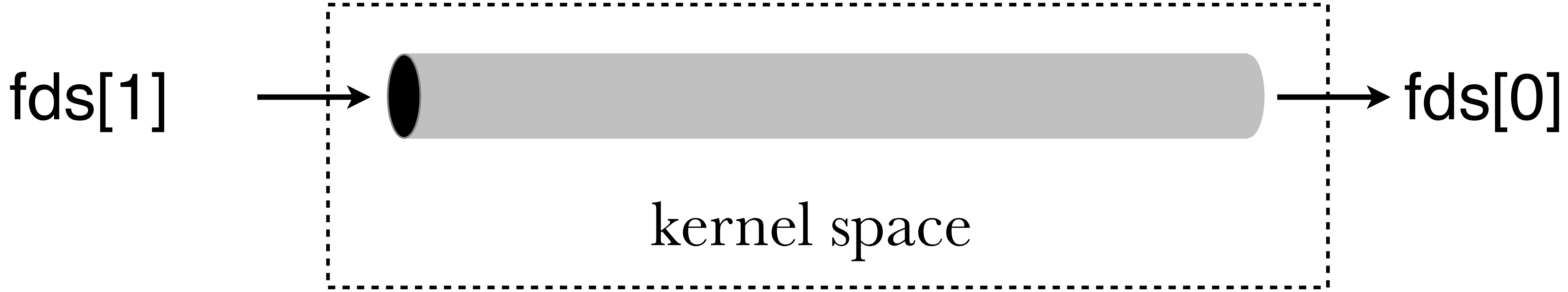
recall: signals aren't queued! :-(

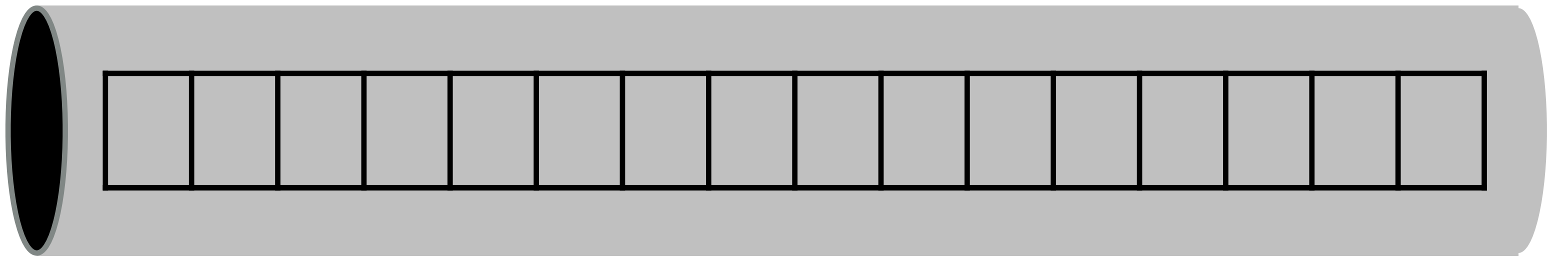
also, with all this sync overhead,
shm isn't looking so hot anymore

§Unnamed Pipes

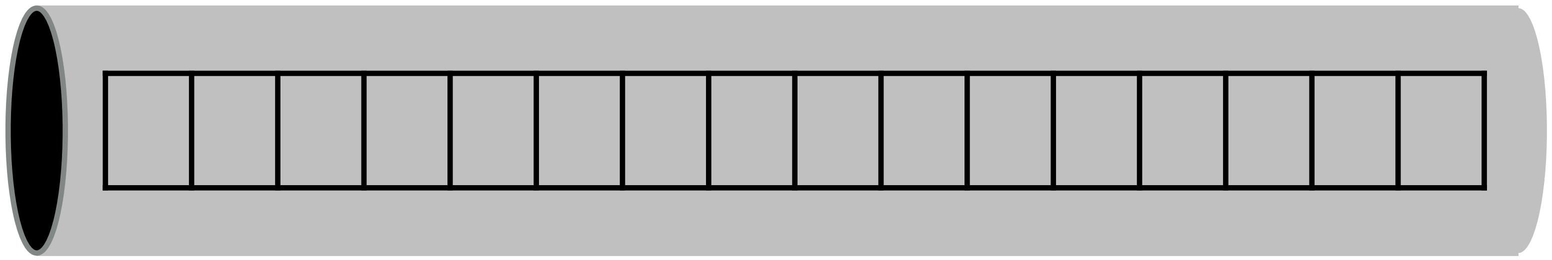
```c
int pipe(int fds[2]);
```

fds[0] is the "reading end"
fds[1] is the "writing end"

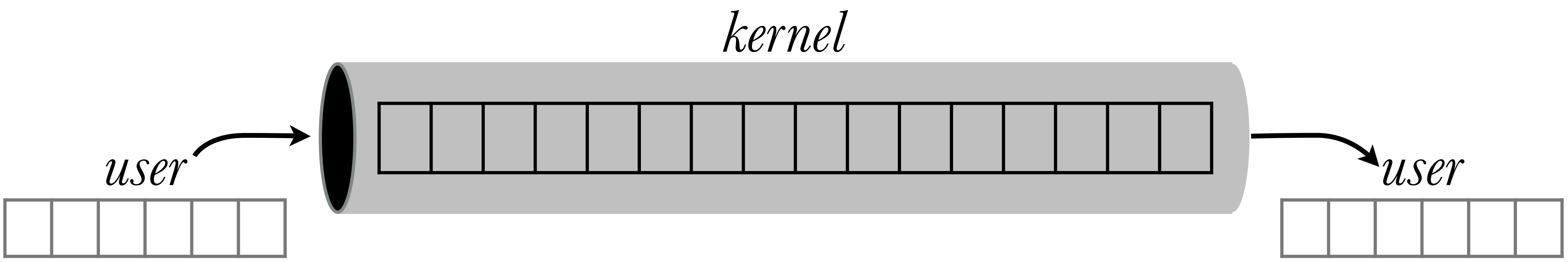




- buffer of finite size = PIPE_BUF
    - defined in <limits.h>
- on fourier = 4096 bytes



- read blocks for min of 1 byte
- write blocks until complete
- writes ≤ PIPE_BUF are **atomic**
  - can't be interrupted by other writes



- speed can't compare to shm!
- requires copy from user to kernel buffer, then back to a user buffer

```c
int i, j, fds[2];

pipe(fds); /* create pipe */

if (fork() != 0) {
    /* parent writes */
    for (i=0; i<10; i++) {
        write(fds[1], &i, sizeof(int));
    }
} else {
    /* child reads */
    for (i=0; i<10; i++) {
        read(fds[0], &j, sizeof(int));
        printf("%d ", j);
    }
}
```

```
0 1 2 3 4 5 6 7 8 9
```

```
int i, n, fds[2];
char buf[80];
char *strings[] = {"the", "quick", "brown", "fox", "jumps",
                   "over", "the", "lazy", "dog"};

pipe(fds);
for (i=0; i<9; i++) { /* 9 child processes! */
    if (fork() == 0) {
        write(fds[1], strings[i], strlen(strings[i]));
        exit(0);
    }
}

while ((n = read(fds[0], buf, sizeof(buf))) > 0) {
    write(1, buf, n);
    printf("\n");
}
```

```
the
quick
foxoverbrown
jumpslazythe
dog
```

kernel takes care of buffering & synchronization! (yippee!)

back to shell pipes:

```
$ echo hello | wc
       1       1       6
```

```
int fds[2];
pid_t pid1, pid2;
pipe(fds);

if ((pid1 = fork()) == 0) {
    dup2(fds[1], 1);
    execlp("echo", "echo", "hello", NULL);
}

if ((pid2 = fork()) == 0) {
    dup2(fds[0], 0);
    execlp("wc", "wc", NULL);
}
waitpid(pid2, NULL, 0);
```

```
(hangs)
```

Read on pipe will *always block* for ≥ 1 byte until writing ends are all closed

```
int fds[2];
pid_t pid1, pid2;
pipe(fds);
if ((pid1 = fork()) == 0) {
    dup2(fds[1], 1);
    execlp("echo", ...);
}
if ((pid2 = fork()) == 0) {
    dup2(fds[0], 0);
    execlp("wc", ...);
}
waitpid(pid2, NULL, 0);
```

← never sees EOF!

```
if ((pid1 = fork()) == 0) {
    dup2(fds[1], 1);
    close(fds[1]);
    execlp("echo", "echo", "hello", NULL);
}
close(fds[1]);
if ((pid2 = fork()) == 0) {
    dup2(fds[0], 0);
    execlp("wc", "wc", NULL);
}
```

```
    1    1    6
```

so … why "**unnamed**" pipes?

```
int fds[2];

if (fork() == 0) {
    /* proc 1 */
    pipe(fds);
    write(fds[1], ...);
}

if (fork() == 0) {
    /* proc 2 */
    read(?, ...);
}
```

- no way for proc 1 and proc 2 to talk over pipe!
- identified solely by FDs – process local

§Named Pipes (FIFOs)

```
int mkfifo (const char* path,
            mode_t perms)
```

- creates a *FIFO special file* at path in file system
- open(s) then read & write
- exhibits pipe semantics!

let's talk a bit more about
synchronization

why?

so **concurrent** systems can be made **predictable** how?

so far:

- wait (limited)
- kill & signal (lousy)
- pipe (implicit)

some UNIX IPC mechanisms are *purpose-built* for synchronization

§File Locks

motivation:

- process virtual worlds don't extend to the file system
- concurrently modifying files can have ugly consequences
- but files are the most widely used form of IPC!

a process can acquire a **lock** on a file, preventing other processes from using it

important: locks are *not* preserved across forks! (i.e., a child doesn't inherit its parent's locks) problem: most file systems only support **advisory** locking

i.e., locks are not enforced!

in Linux, mandatory locking is *possible*, but requires filesystem to support it

The implementation of mandatory locking in all known versions of Linux is **subject to race conditions** which render it **unreliable**: a write(2) call that overlaps with a lock may modify data after the mandatory lock is acquired; a read(2) call that overlaps with a lock may detect changes to data that were made only after a write lock was acquired. Similar races exist between mandatory locks and mmap(2). It is therefore **inadvisable to rely on mandatory locking**.

also, file locks are not designed for *general-purpose synchronization* e.g., what if we want to:

- allow only 1 of N processes to access an *arbitrary* resource?
- allow M of N processes to access a resource?
- control the order in which processes run?

§Semaphores

semaphore = synchronization primitive

- object with associated counter
- usually init to count ≥ 0

```
sem_t *sem_open(const char *name, int oflag,
                mode_t mode, unsigned int value);
```

- creates semaphore initialized to `value`

```
sem_t *sem_open(const char *name, int oflag);
```

- retrieves existing semaphore

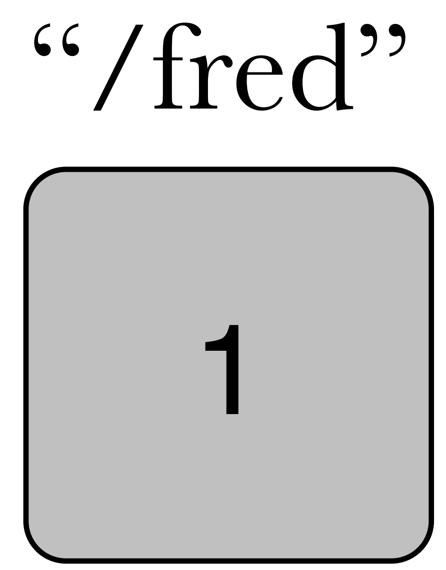
```
int sem_wait(sem_t *sem);
```

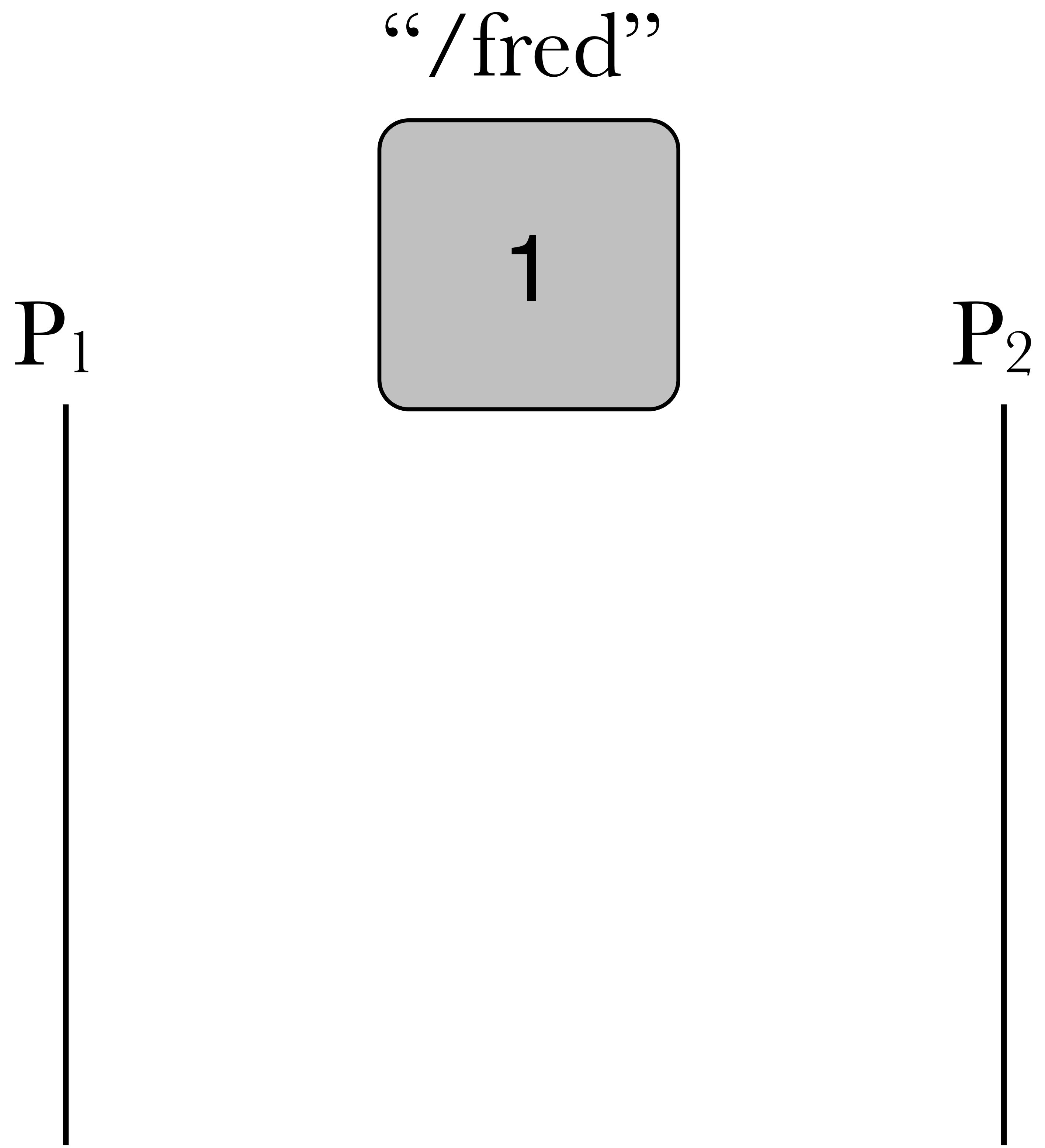
- **decrements** value; **blocks** if new value < 0
- returns 0 on success
- returns -1 if interrupted without decrementing

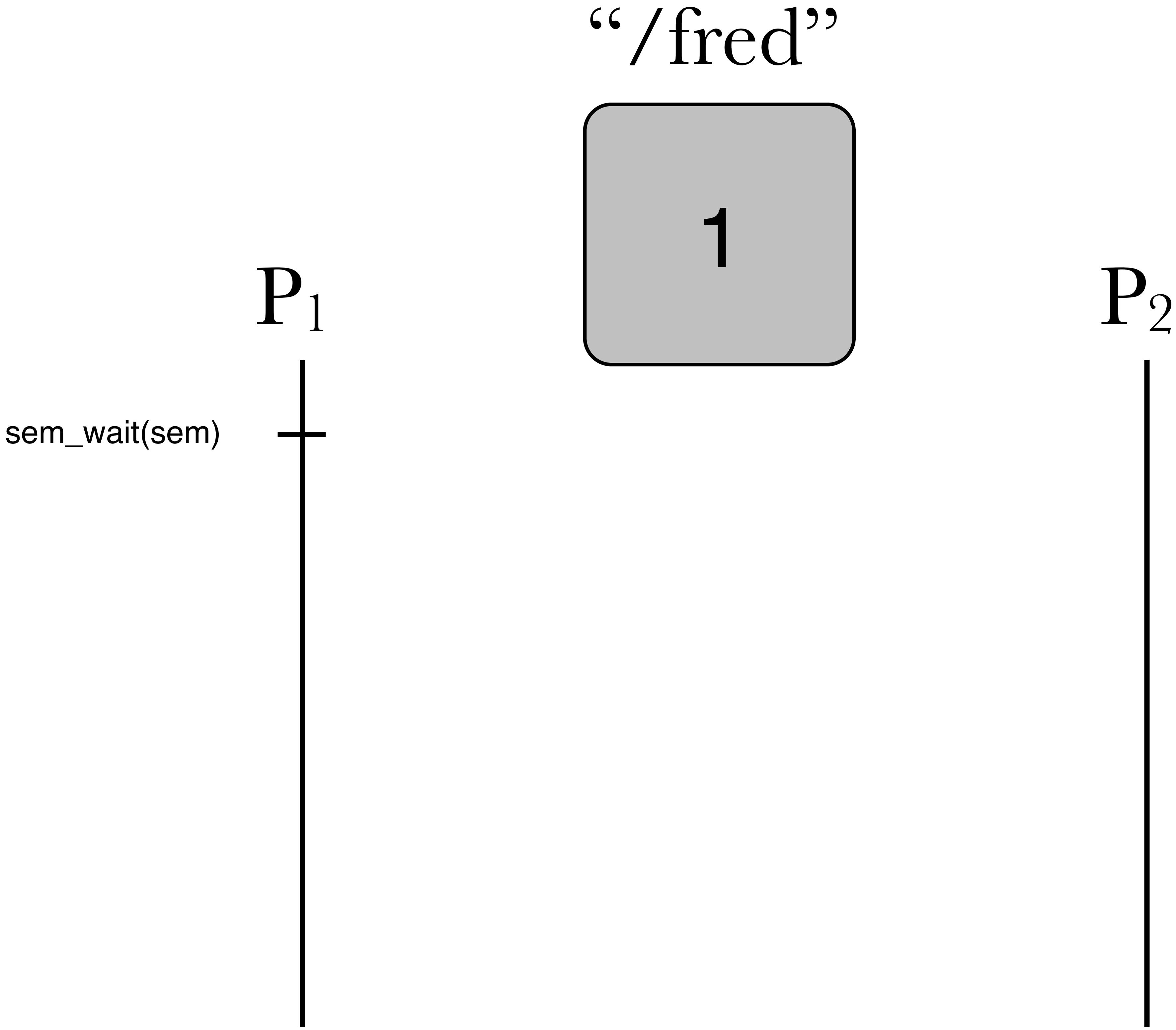
```
int sem_post(sem_t *sem);
```

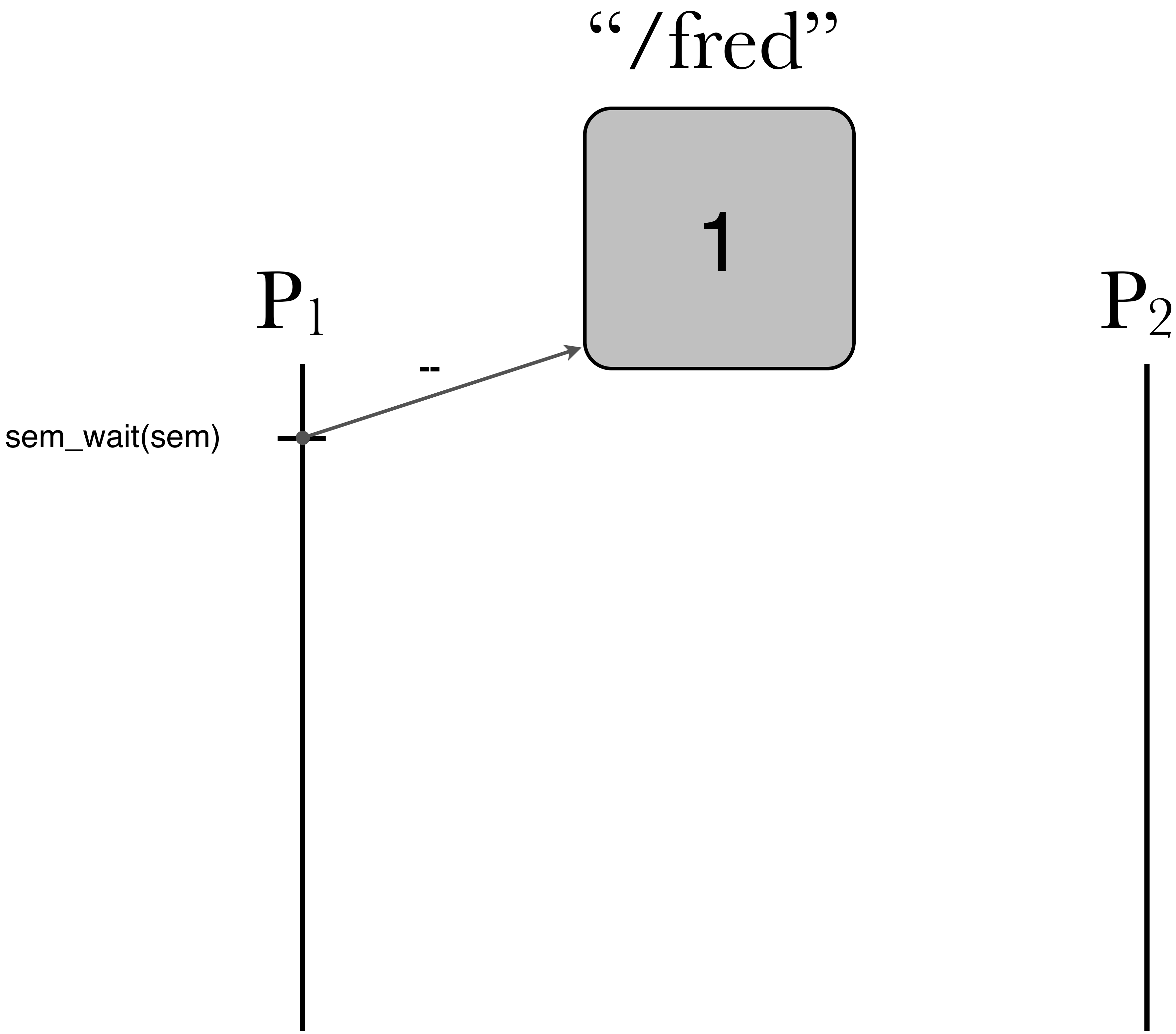
- **increments** value; **unblocks 1** process (if any)
- returns 0 on success

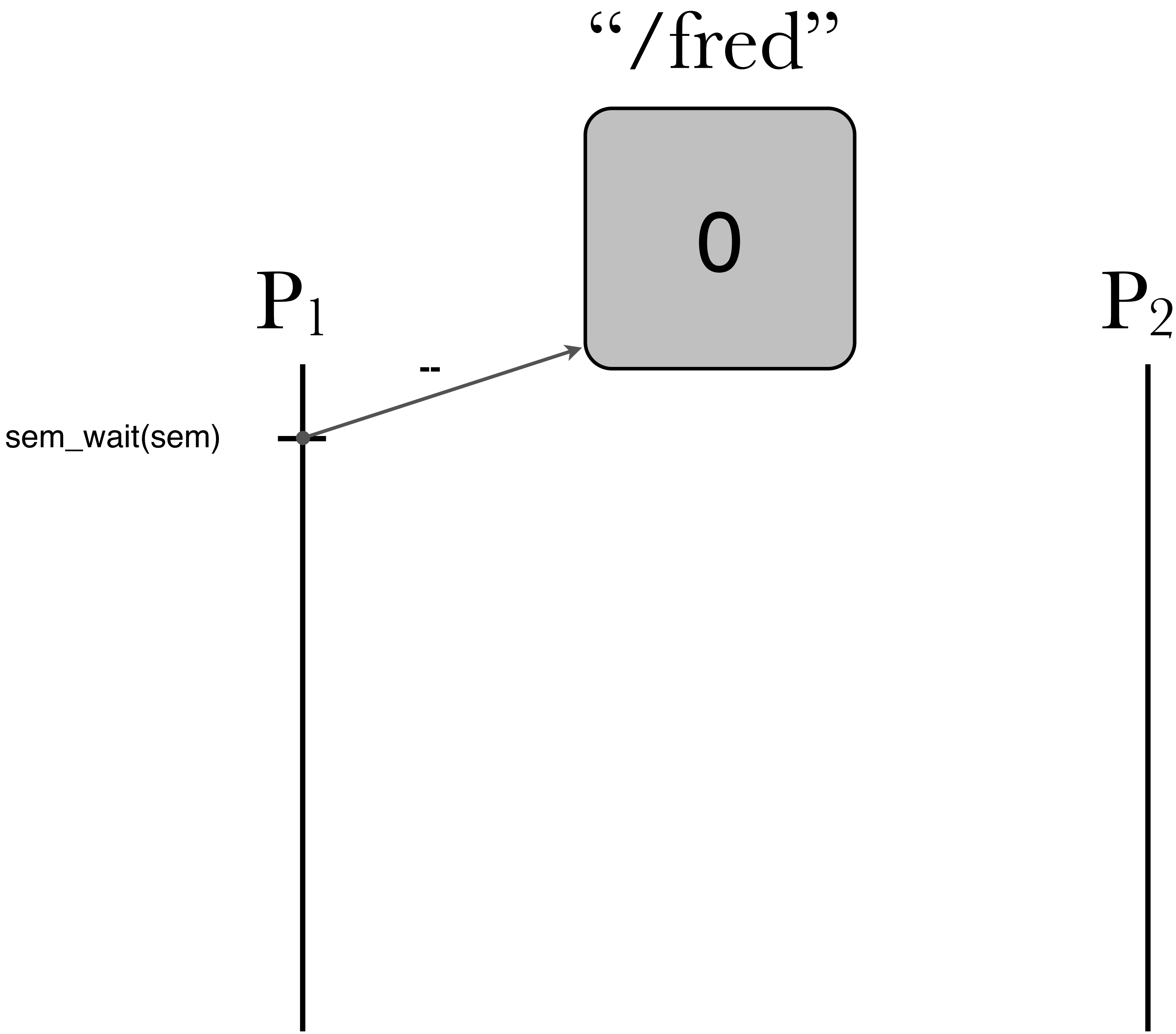
```
sem_t *sem = sem_open("/fred", O_CREAT, 0600, 1);
```

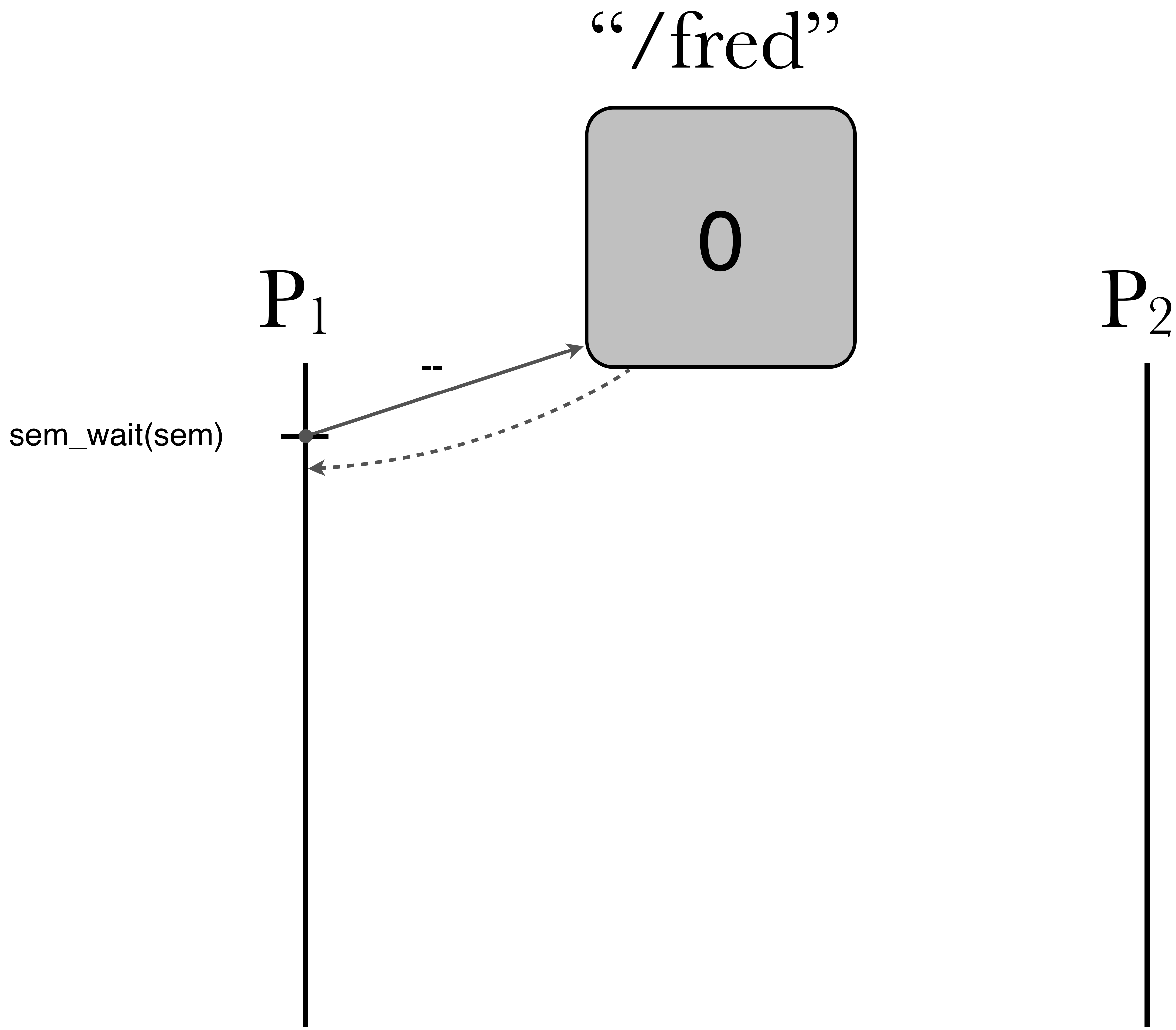


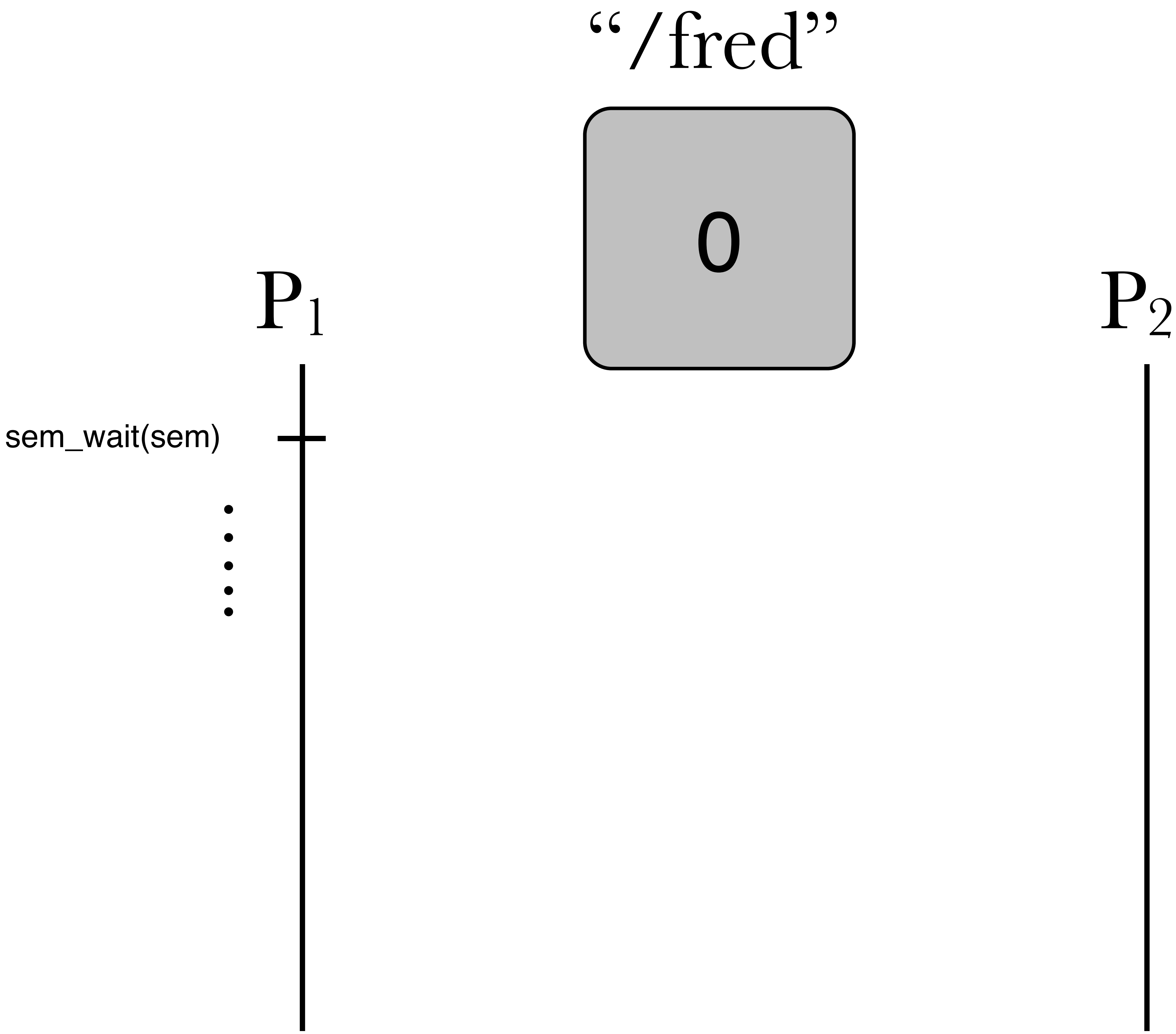

“/fred”
1
P1
P2

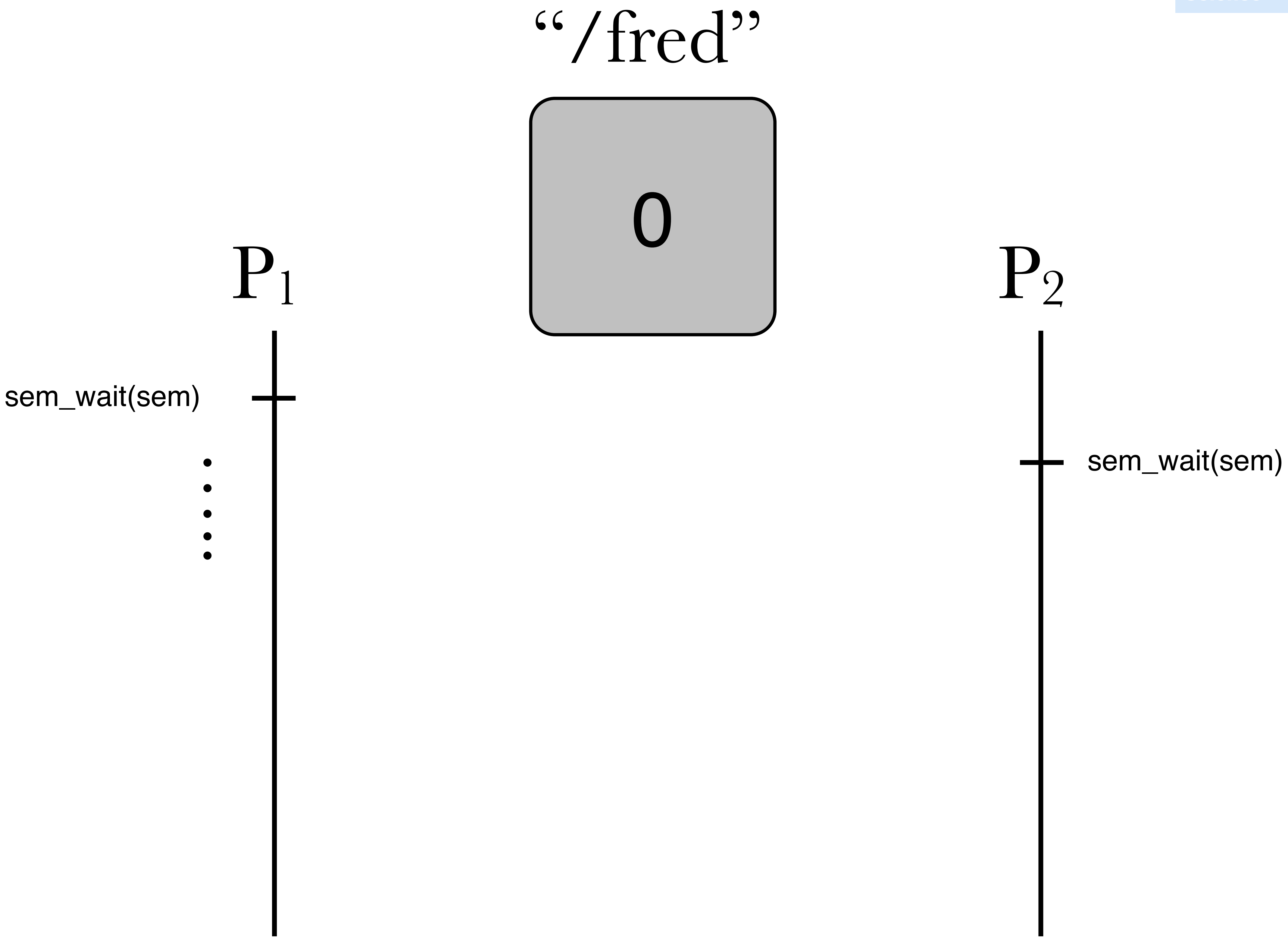

"/fred"
1
P1
P2
sem_wait(sem)

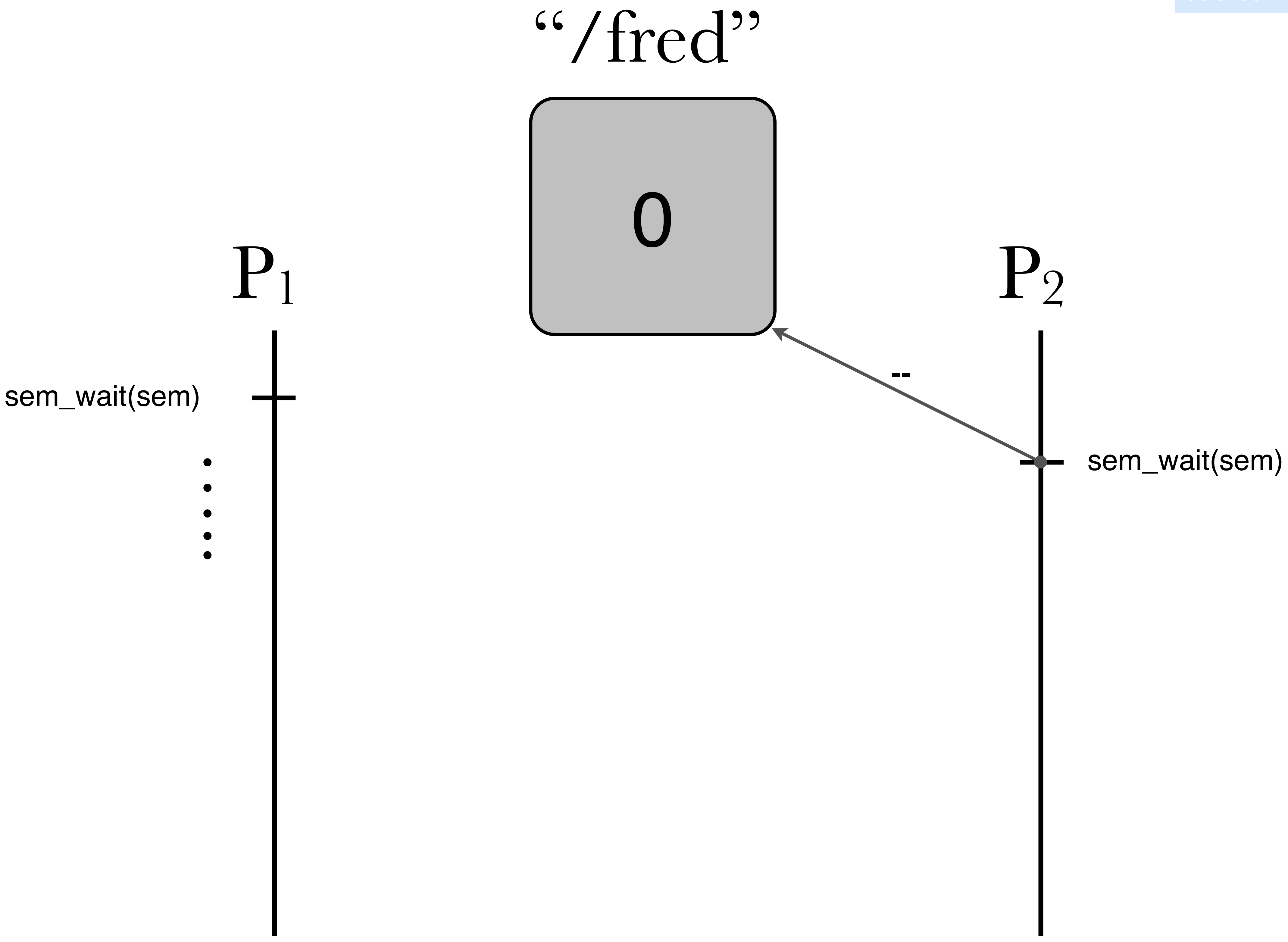

"/fred"
1
P1
P2
--
sem_wait(sem)

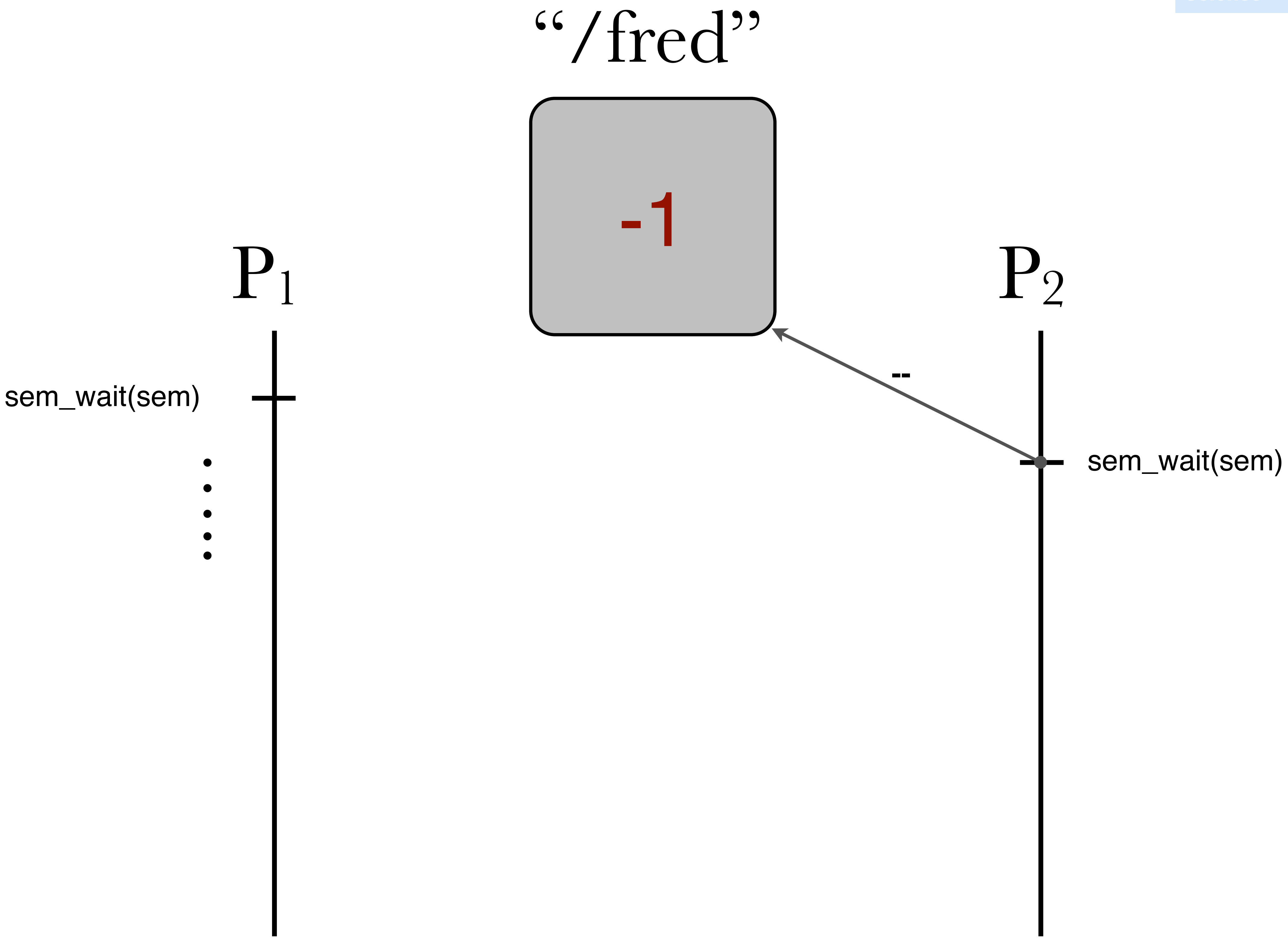

"/fred"
0
P1
P2
--
sem_wait(sem)

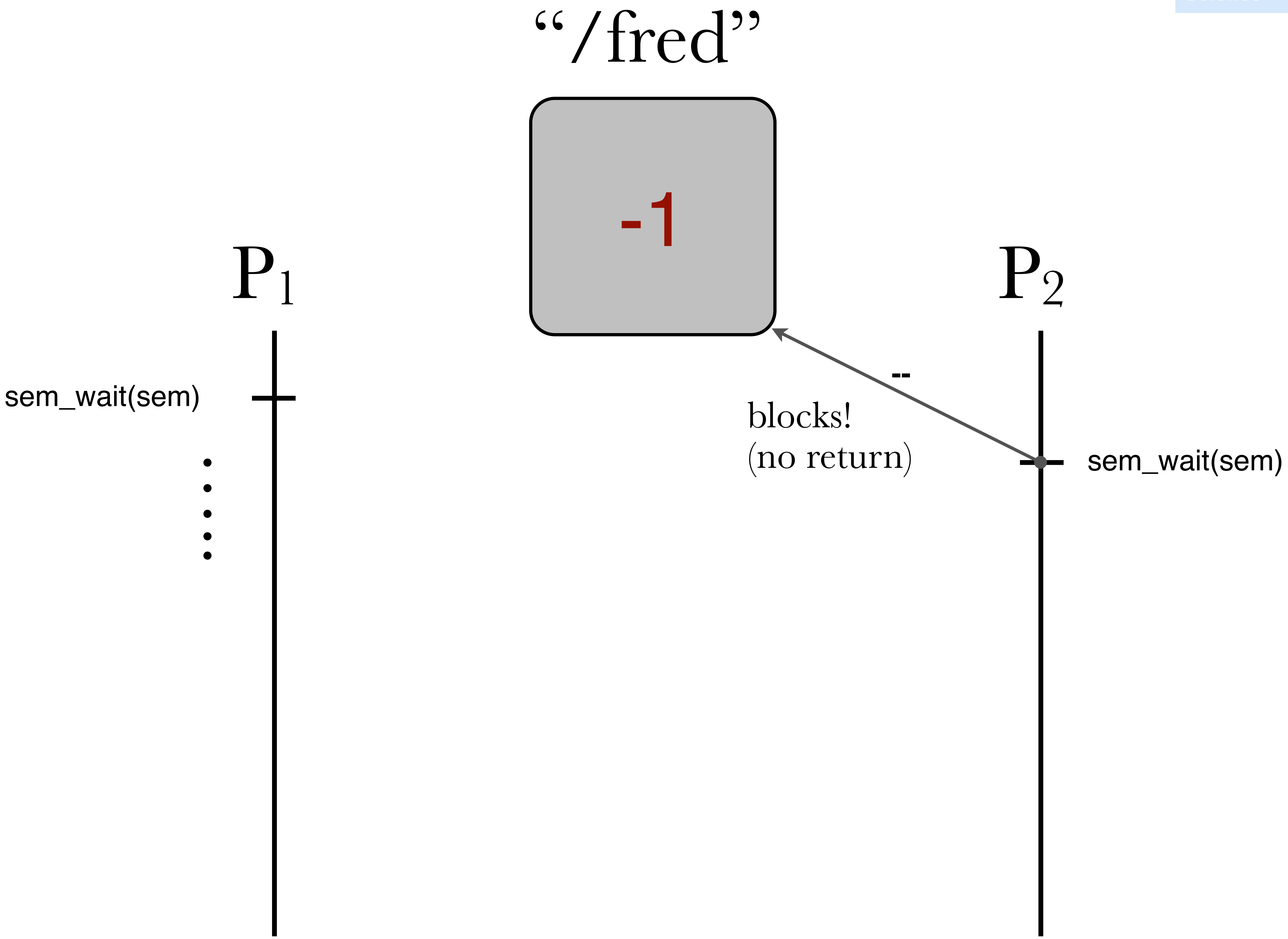

"/fred"
0
P_1
P_2
--
sem_wait(sem)

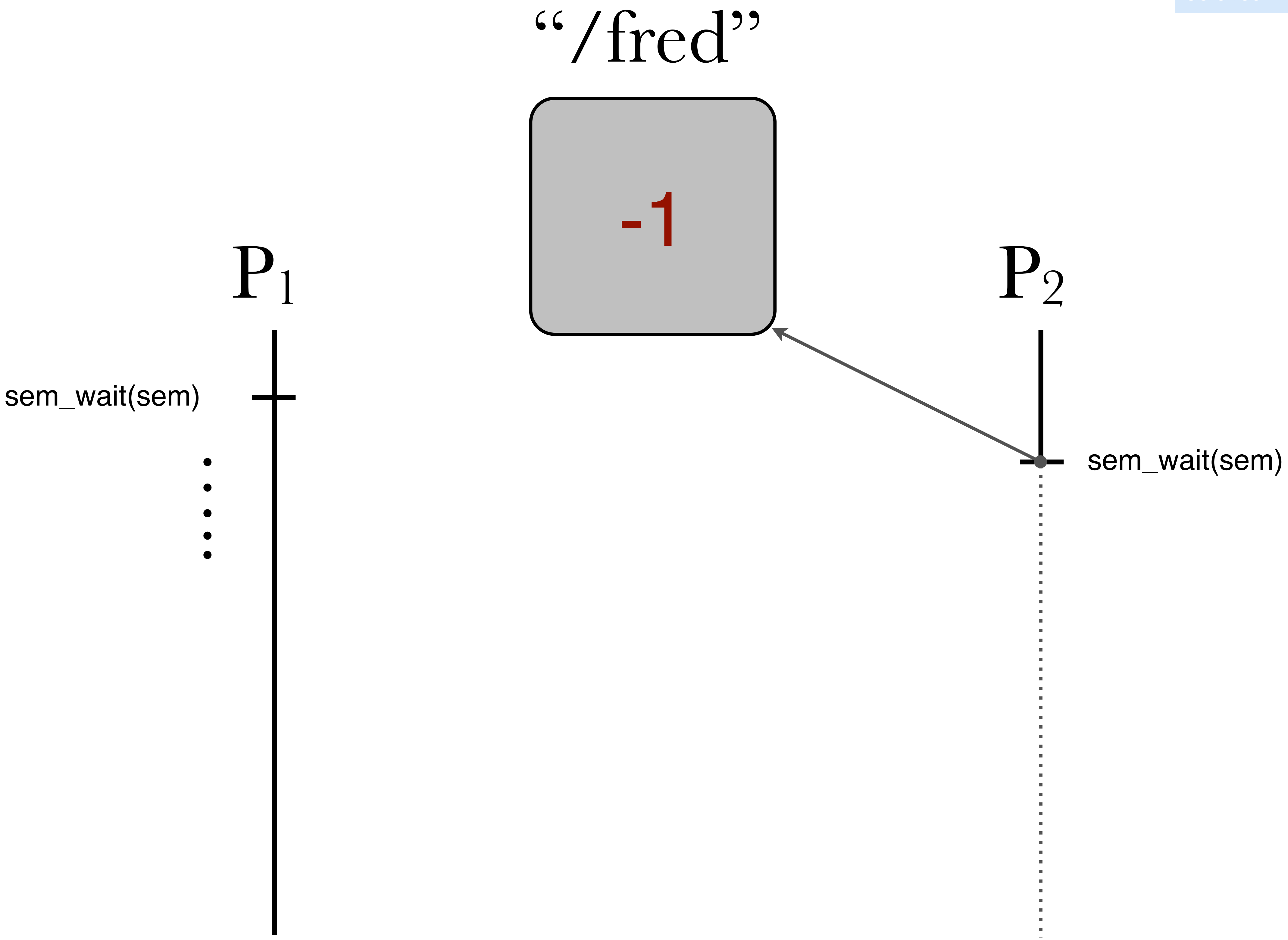

“/fred”
0
P1
P2
sem_wait(sem)


"/fred"
0
P_1
P_2
sem_wait(sem)
sem_wait(sem)

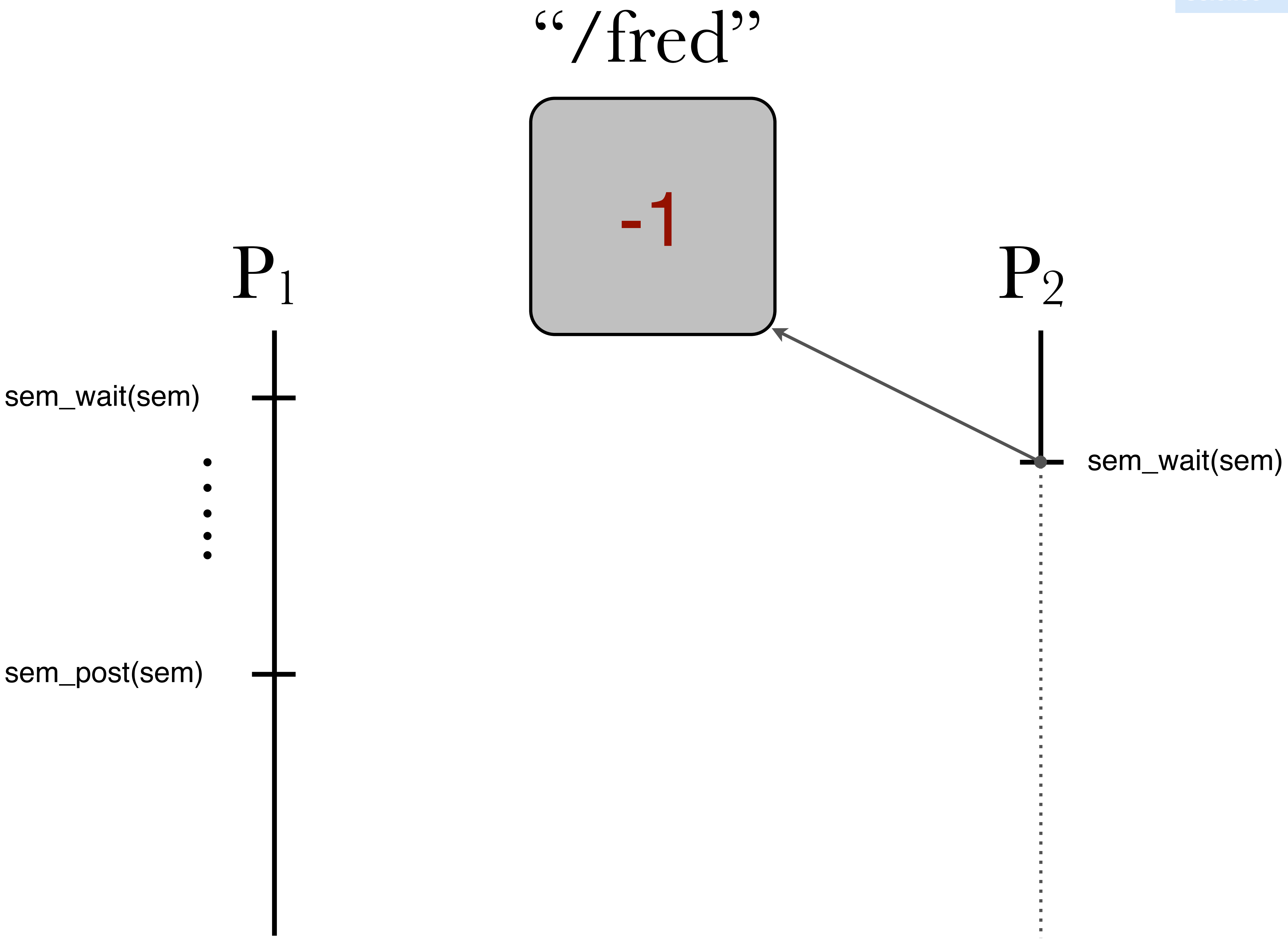

"/fred"
0
P_1
P_2
sem_wait(sem)
--
sem_wait(sem)

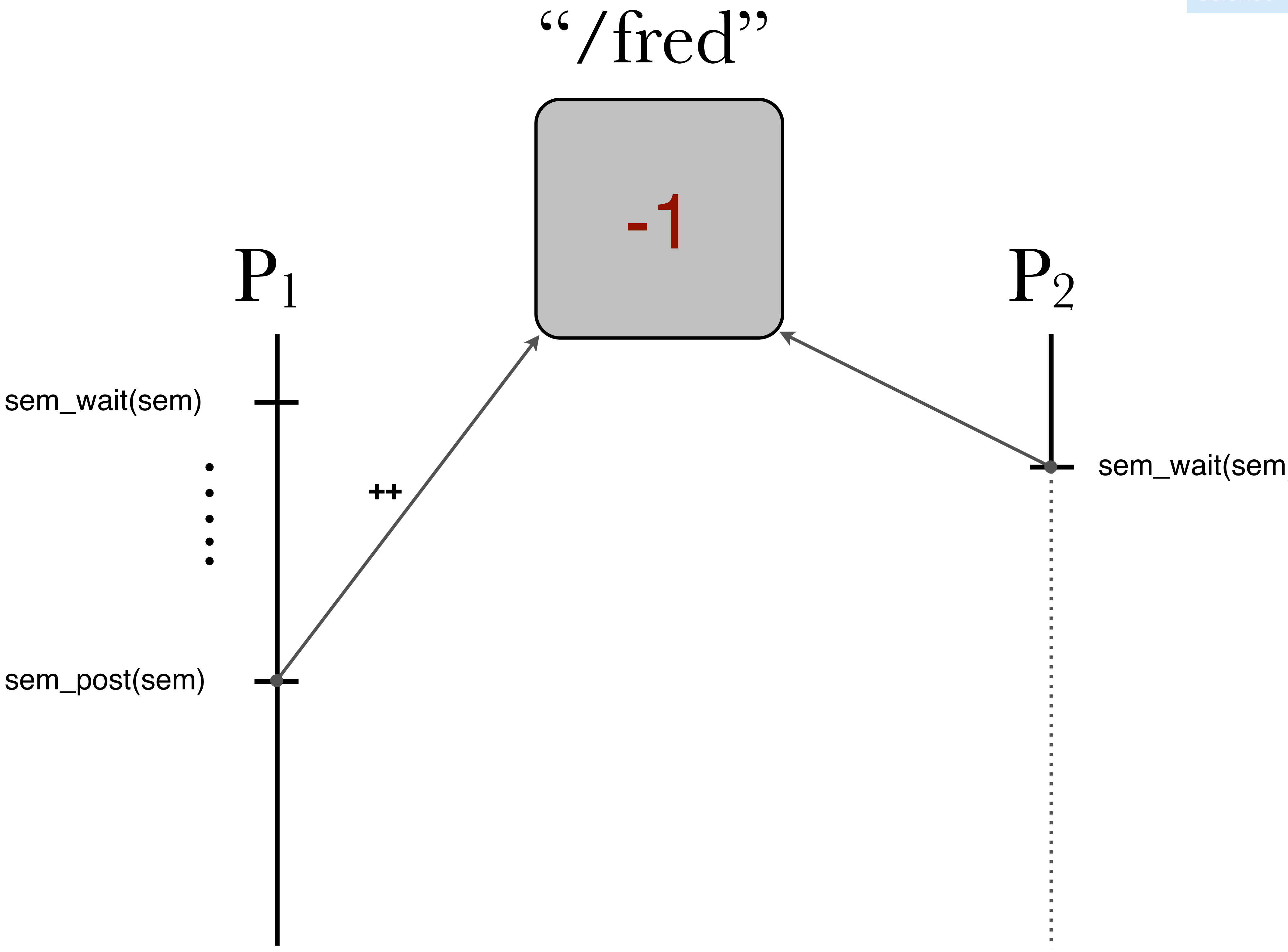

"/fred"
-1
P1
P2
--
sem_wait(sem)
sem_wait(sem)


"/fred"
-1
P_1
P_2
sem_wait(sem)
--
blocks!
(no return)
sem_wait(sem)

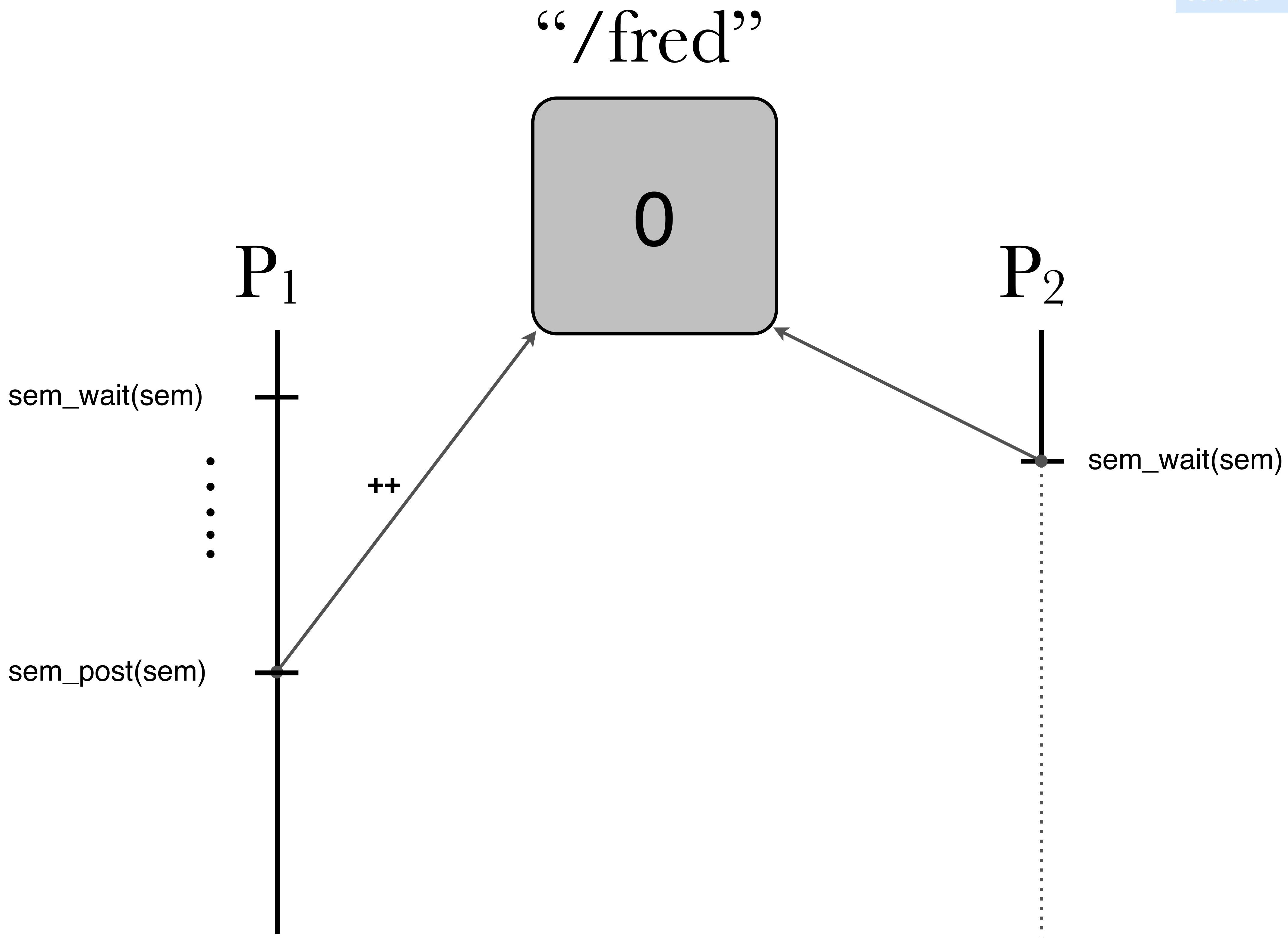


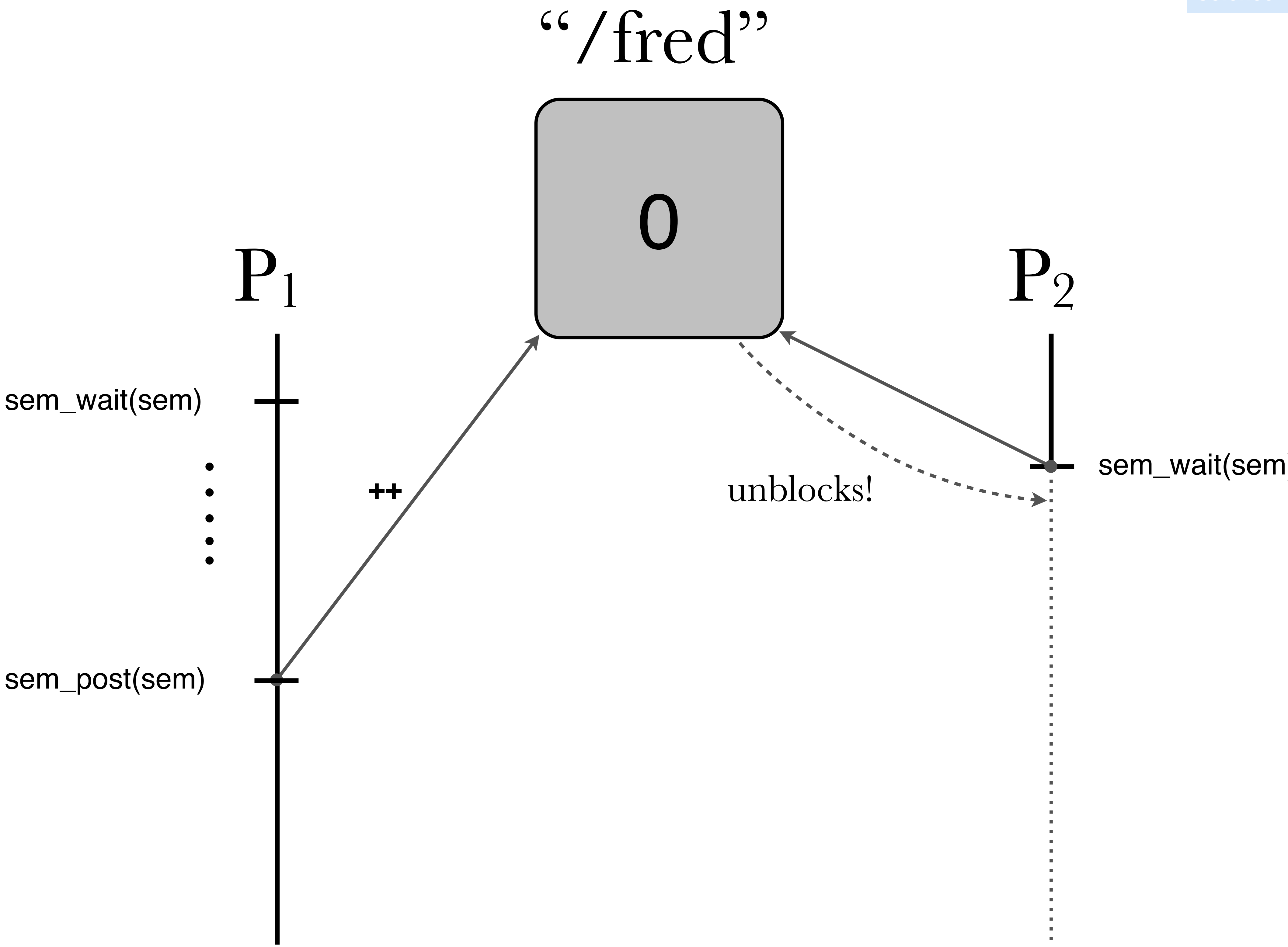
"/fred"
-1
P_1
P_2
sem_wait(sem)
sem_wait(sem)

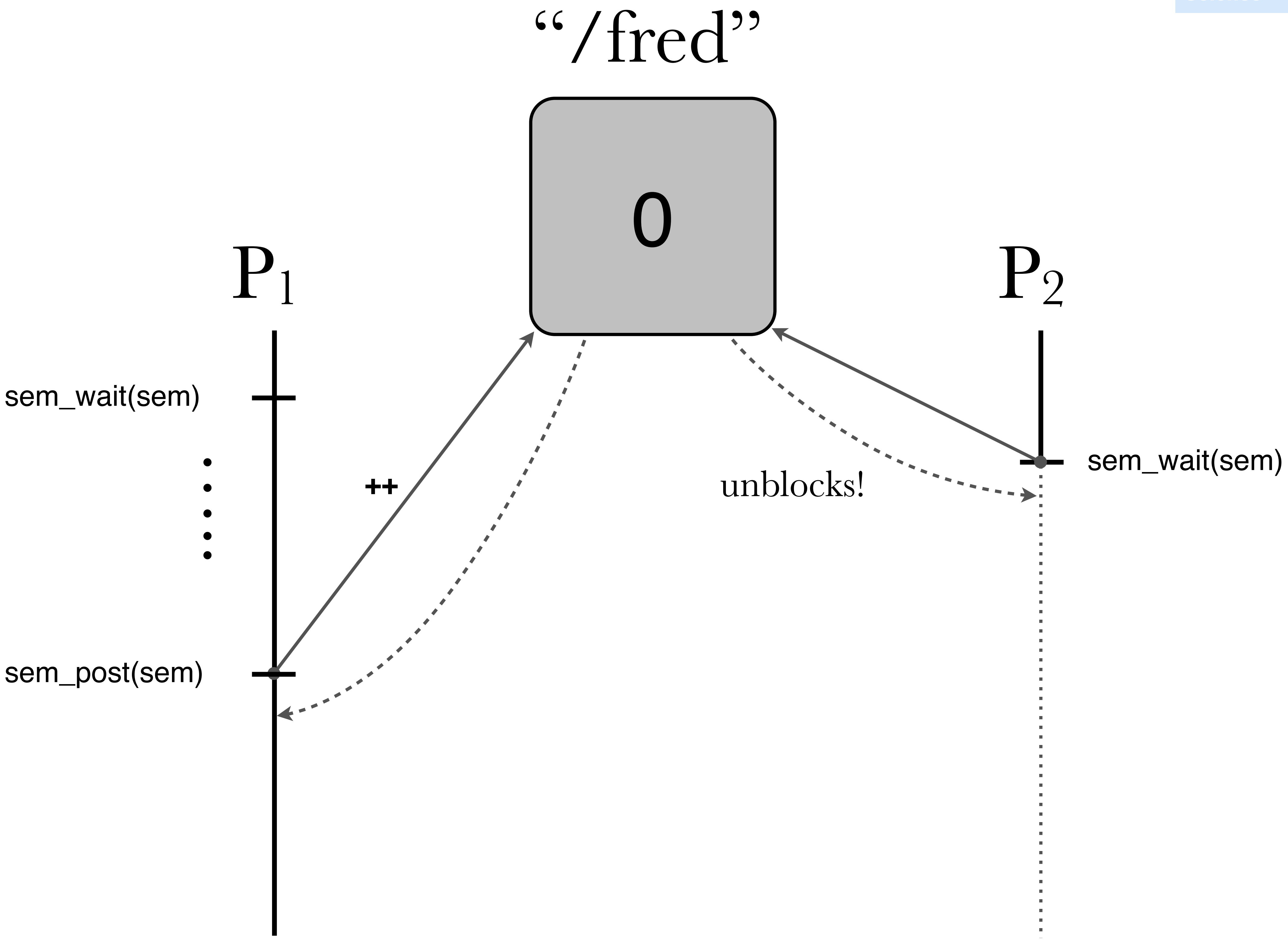

"/fred"
-1
P_1
P_2
sem_wait(sem)
sem_post(sem)
sem_wait(sem)

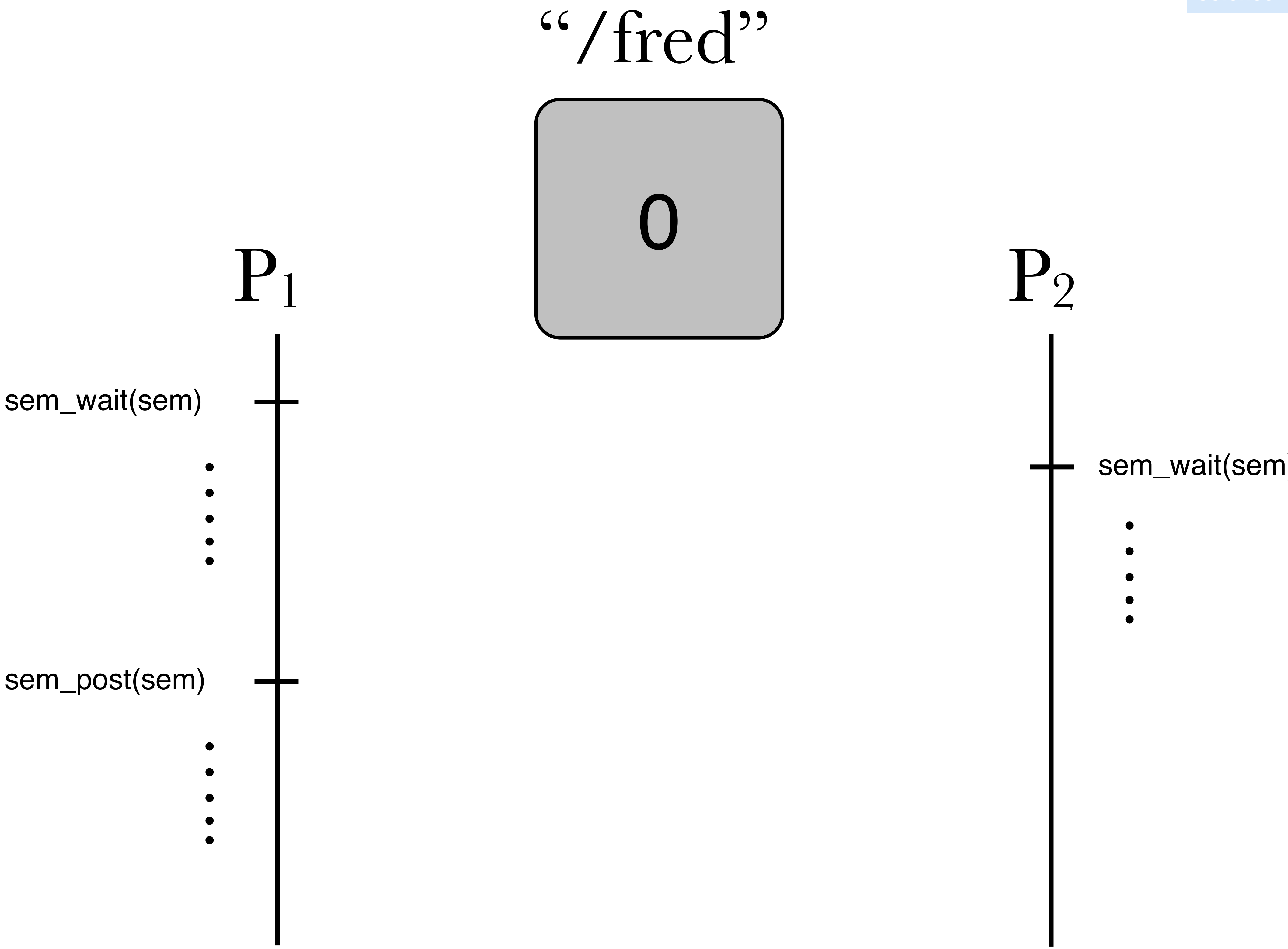


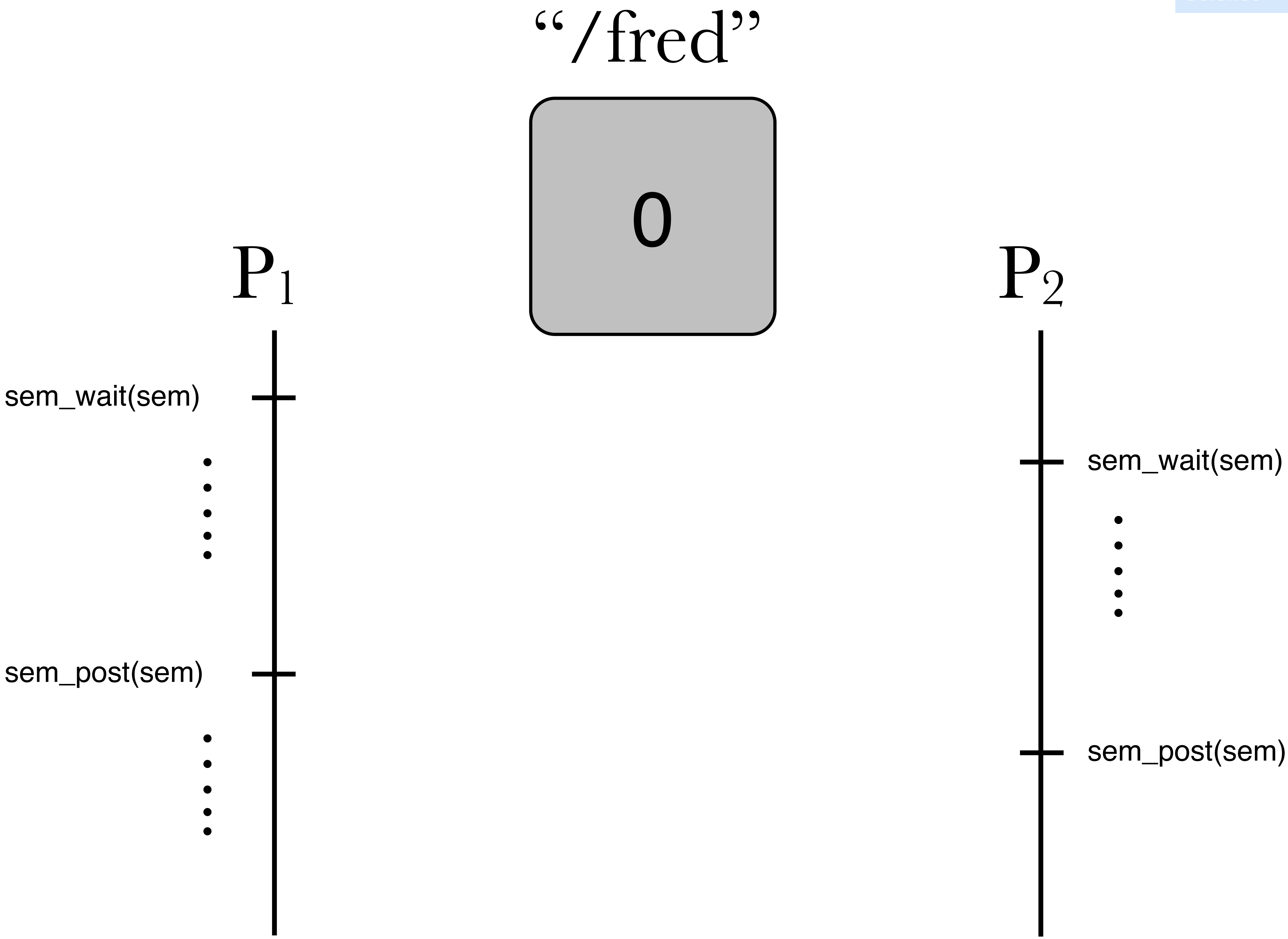
"/fred"
-1
P_1
P_2
sem_wait(sem)
++
sem_post(sem)
sem_wait(sem)

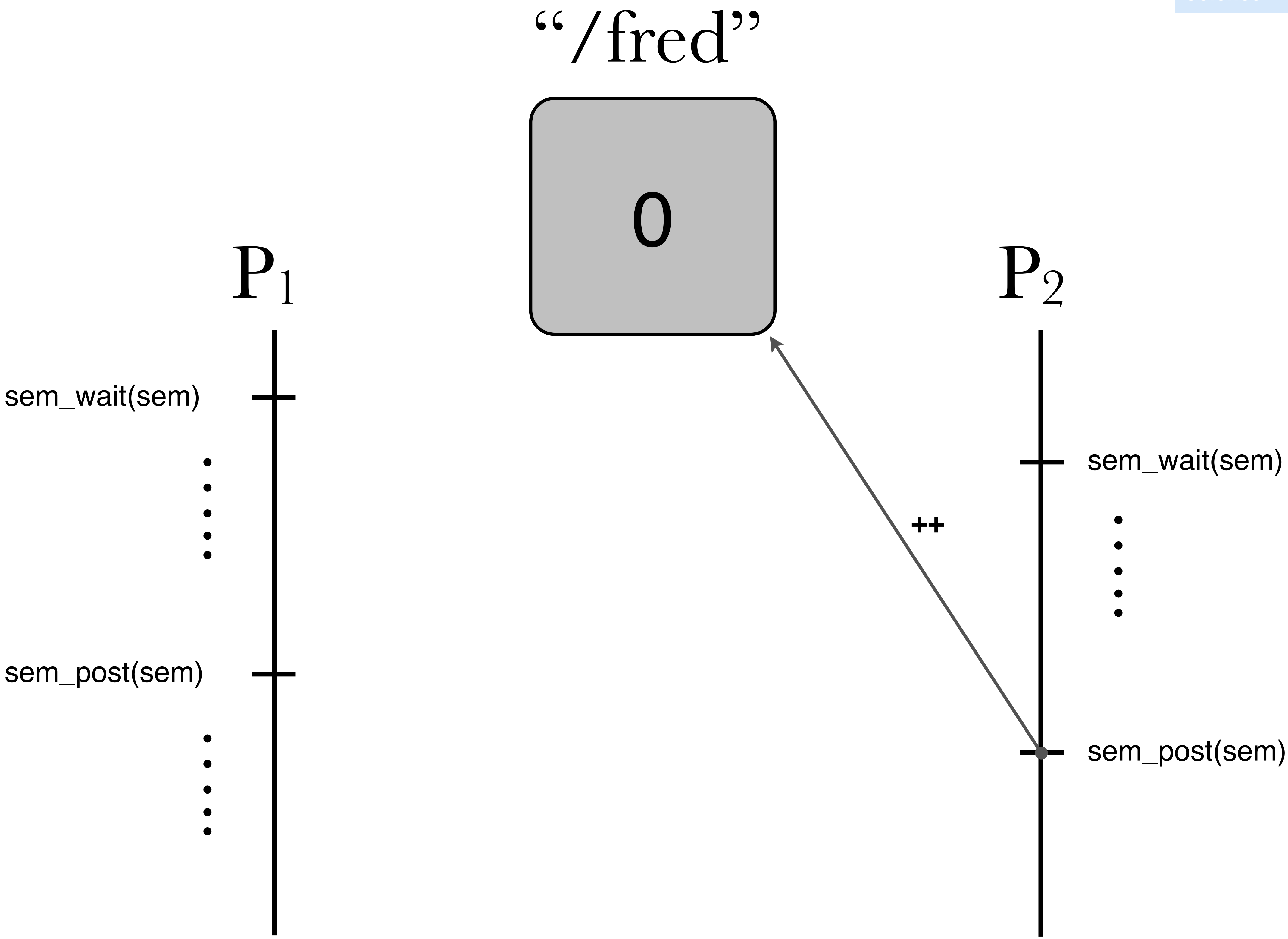

"/fred"
0
P1
P2
sem_wait(sem)
++
sem_post(sem)
sem_wait(sem)

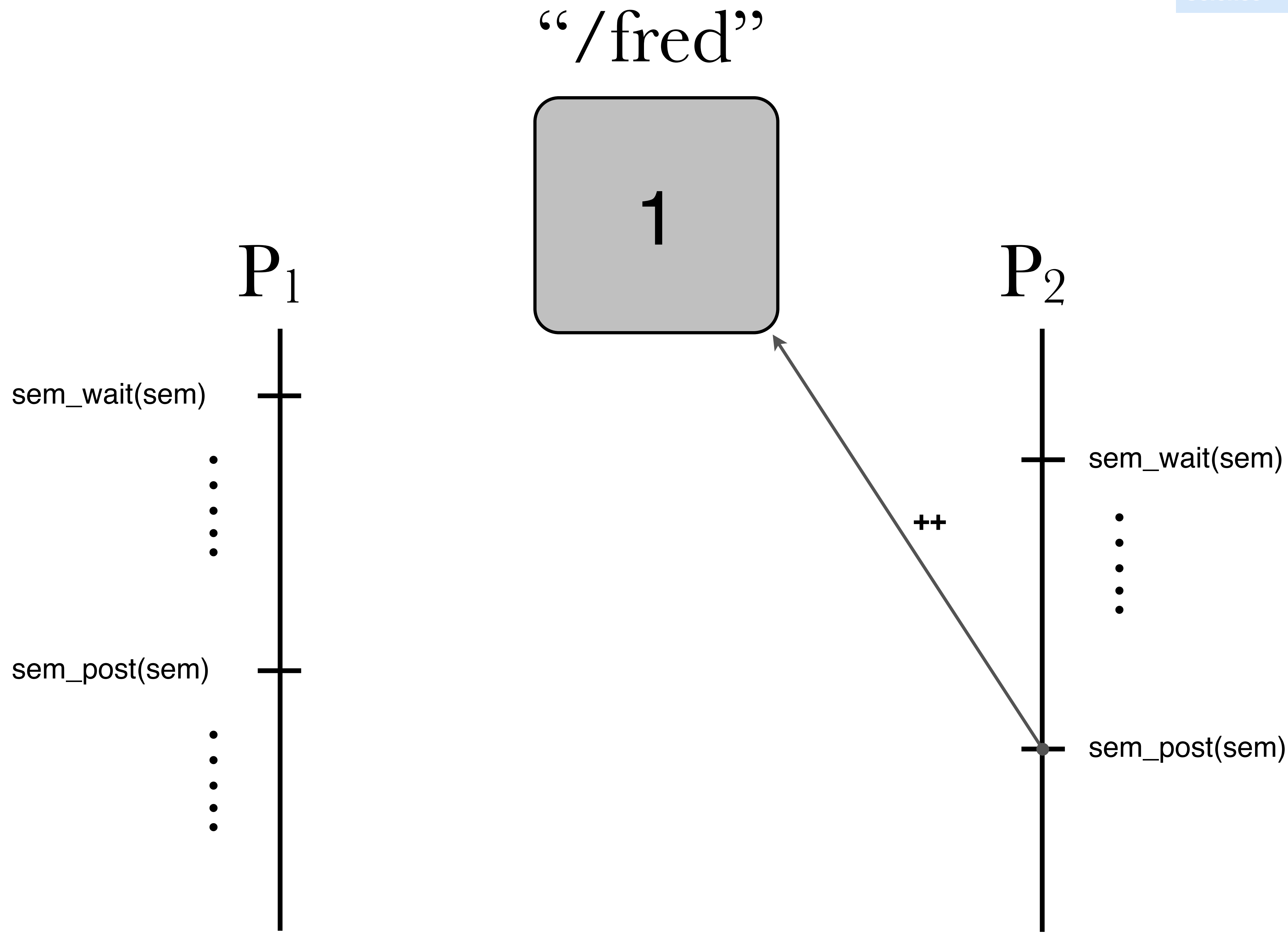

"/fred"
0
P1
P2
sem_wait(sem)
++
sem_post(sem)
sem_wait(sem)
unblocks!


"/fred"
0
P1
P2
sem_wait(sem)
++
sem_post(sem)
unblocks!
sem_wait(sem)

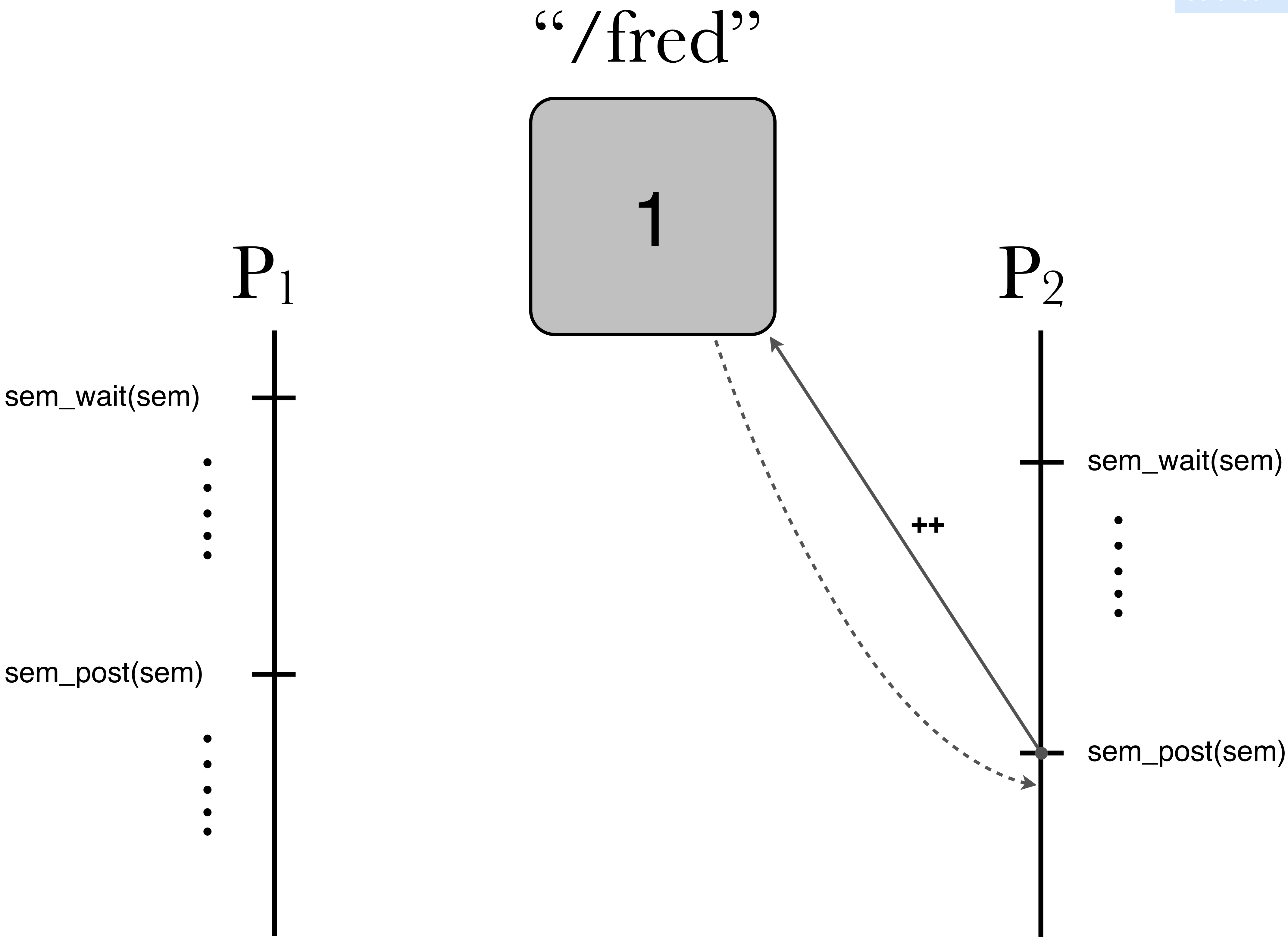

"/fred"
0
P1
P2
sem_wait(sem)
sem_post(sem)
sem_wait(sem)

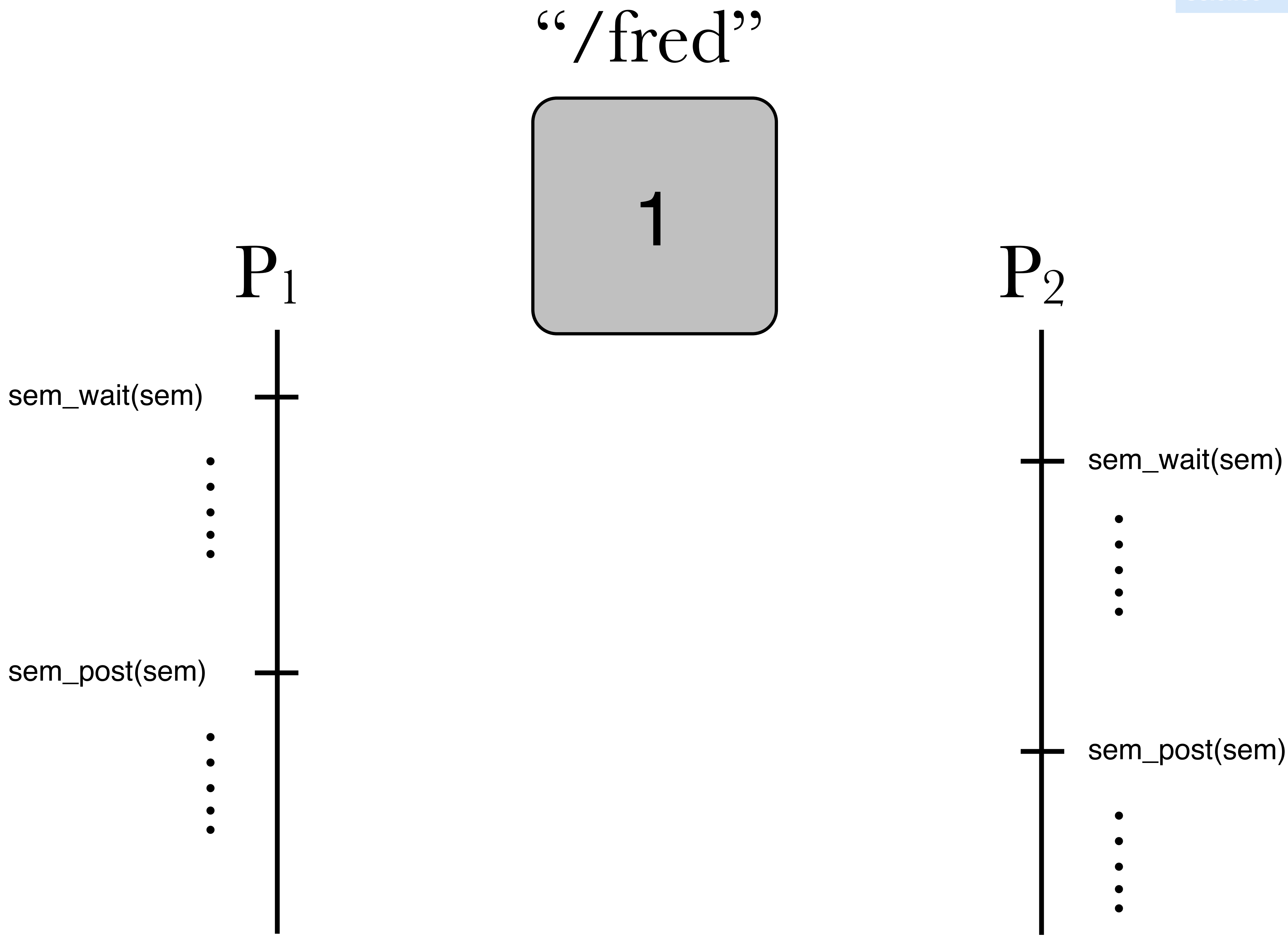

“/fred”
0
P_1
P_2
sem_wait(sem)
sem_post(sem)
sem_wait(sem)
sem_post(sem)


"/fred"
0
P1
P2
sem_wait(sem)
sem_post(sem)
++
sem_wait(sem)
sem_post(sem)



"/fred"
1
P1
P2
sem_wait(sem)
sem_post(sem)
++
sem_wait(sem)
sem_post(sem)


"/fred"
1
P1
P2
sem_wait(sem)
sem_post(sem)
sem_wait(sem)
++
sem_post(sem)


"/fred"
1
P1
P2
sem_wait(sem)
sem_post(sem)
sem_wait(sem)
sem_post(sem)

```c
/* unsynchronized file writers */
int i, j, fd;
fd = open("shared.txt", O_CREATIO_WRONLY, 0600);
for (i=0; i<5; i++) {
    if (fork() == 0) {
        for (j='0'; j<='9'; j++) {
            write(fd, &j, 1);
            sleep(random() % 3);
        }
        exit(0);
    }
}
```

```
$ cat shared.txt
01000011223411234532356765475968764798789529869789
```

```
/* synchronized file writers */
int i, j, fd;
sem_t *mutex = sem_open("/mutex", O_CREAT, 0600, 1);
fd = open("shared.txt", O_CREATIO_WRONLY, 0600);
for (i=0; i<5; i++) {
    if (fork() == 0) {
        while (sem_wait(mutex) < 0) ;
        for (j='0'; j<='9'; j++) {
            write(fd, &j, 1);
            sleep(random() % 3);
        }
        sem_post(mutex);
        exit(0);
    }
}
```

```
$ cat shared.txt
01234567890123456789012345678901234567890123456789
```

just as with shared memory, semaphores *persist* when process exits … must *unlink*

```
sem_t *mutex = sem_open("/mutex", O_CREAT, 0600, 1);
for (i=0; i<5; i++) {
    if (fork() == 0) {
        while (sem_wait(mutex) < 0) ;
        ...
        sem_post(mutex);
        exit(0);
    }
}
while (wait(NULL) >= 0);
sem_close(mutex);
sem_unlink("/mutex");
```

there is much, much more to synchronization & concurrency …

(coming in CS 450!)

§IPC Recap

Select IPC mechanisms:

1. signals
2. (regular) files
3. shared memory
4. unnamed & named pipes
5. file locks & semaphores
6. sockets

one motive: *data communication*

- at one end: shm — fast but no synchronization
- at other end: pipes — slower but implicitly synchronized

another motive: *synchronization*

- signals: system events
- file locks (advisory!)
- semaphores: simple but surprisingly versatile!

so far, just **intra**-system IPC.

coming later, network sockets for **inter**-system IPC!