CSCI 4061: Inter-Process Communication

Chris Kauffman

Last Updated:
Wed Mar 24 03:26:48 PM CDT 2021

Exercise: Forms of IPC we've seen

- Identify as many forms of **inter-process communication** that we have studied as you can
- For each, identify **restrictions**
  - Must processes be related?
  - What must processes know about each other to communicate?
- You should be able to name at least 3-4 such mechanisms

Answers: Forms of IPC we've seen

- Pipes
- FIFOs
- Signals
- Files
- Maybe `mmap()`'ed files

Inter-Process Communication Libraries (IPC)

- Signals/FIFOs allow info transfer between unrelated processes
- Neither provides much
  - Communication synchronization between entities
  - Structure to data being communicated
  - Flexibility over access
- **Inter-Process Communication Libraries** (IPC) provide alternatives
  1. Semaphores: atomic counter + wait queue for coordination
  2. Message queues: direct-ish communication between processes
  3. Shared memory: array of bytes accessible to multiple processes

Two broad flavors of IPC that provide semaphores, message queues, shared memory...

Which Flavor of IPC?

System V IPC (XSI IPC)

- Most of systems have System V IPC but it's kind of strange, has its own *namespace* to identify shared things
- Part of Unix standards, referred to as **XSI IPC** and may be listed as optional
- Most textbooks/online sources discuss some System V IPC. Example:
  - Stevens/Rago 15.8 (semaphores)
  - Robbins/Robbins 15.2 (semaphore sets)
  - Beej's Guide to IPC

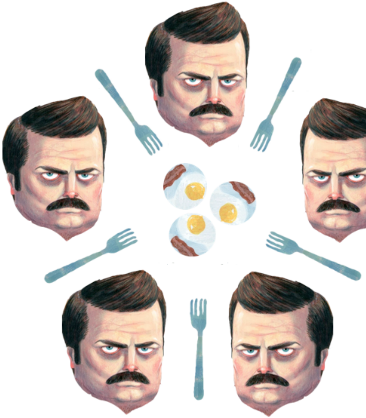
POSIX IPC

- POSIX IPC little more regular, uses filesystem to identify IPC objects
- Originated as optional POSIX/SUS extension, now required for compliant Unix
- Covered in our textbooks partially. Example:
  - Stevens/Rago 15.10 POSIX Semaphores
  - Robbins/Robbins 14.3-5 POSIX Semaphores
- Additional differences on StackOverflow

We will favor POSIX

Model Problem: Dining "Philosophers"

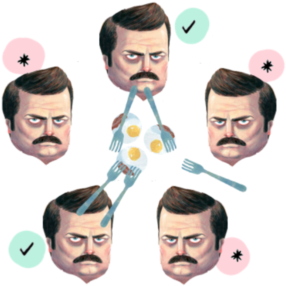
- Each Swansons will only eat with two forks
- JJ's only has 5 forks, must share
- After acquiring 2 forks, a Swanson eats an egg, then puts both forks back to consider how awesome he is
- Algorithms that don't share forks will lead to injury



Source: Aditya Y. Bhargava,
Originally: Dustin D'Arnault

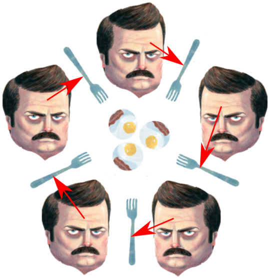
Exercise: Protocol for Dining "Philosophers"

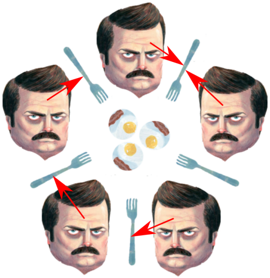
- Each Swansons will only eat with two forks
- JJ's only has 5 forks, must share
- Swanson's pick up one fork at a time
- After acquiring 2 forks, a Swanson eats an egg
- After eating an egg a Swanson puts both forks considers how awesome he is, repeats
- Swanson leaves after eating sufficient eggs
- Is there any potential for deadlock? How can this be avoided?
- Is there any chance for starvation?



Answers: Protocol for Dining “Philosophers”

Deadlock





Deadlock: All try for left fork first

- Each Swanson acquires left fork: cycle
- Each Waits forever for right fork

Dijkstra: One Swanson goes Right first

- Breaks the cycle so no deadlock possible
- Generalization establishes a **partial ordering** for each process to acquire resources, can prove lack of deadlocks

Starvation?

- A Swanson may wait indefinitely to get both forks, resource **starvation**
- Requires introduction of **priority** and communication to fix (Chandy/Misra Solution)

Semaphore

Source: Wikipedia Railway Sempahore Signal

- A counter variable with atomic operations
- **Atomic operation**: not divisible, all or none, no partial completion possible
- Used to coordinate access to shared resources such as shared memory, files, connections
- Typically allocate one semaphore per resource and acquire all that are needed

Activity: Dining “Philosophers” with Semaphores

Examine the dining philosophers code here:

http://www.cs.umn.edu/~kauffman/4061/philosophers_posix.c

Use the Man Pages here:

http://man7.org/linux/man-pages/man7/sem_overview.7.html

Find out how the following are done:

1. What does a POSIX semaphore look like?
2. How does one create a POSIX semaphore?
3. What calls are used to “acquire” and “release” a POSIX semaphore?
4. What happens when multiple processes modify the same semaphore?
5. How are semaphores used to coordinate use of forks?
6. How is deadlock avoided in the code?

Lessons Learned from `philosophers_posix.c` (1/2)

Posix Semaphores

- POSIX semaphores are single integer values with atomic operations
- Semaphore operations are guaranteed to be **atomic**: only one process can increment/decrement at a time, function as efficient **locks**
- `sem_t *sem = sem_open(name,...);` is used to obtain a semaphore from the operating system. Uses *named semaphores* which are managed by OS, shared between processes
- `sem_wait(sem);` wait until semaphore is non-zero, then atomically decrement/lock it
- `sem_post(sem);` increment/unlock a semaphore and schedule a process waiting on it to run
- `sem_close(sem);` to stop using a semaphore

Lessons Learned from `philosophers_posix.c` (2/2)

Dining Philosophers

- In Dining Philosophers, one semaphore per utensil
- Philosophers acquire both adjacent utensils to eat
- Circular Deadlock avoided via one Philsopher acquiring in a different order
  - Philosopher N: Get right utensil, then left utensil
  - Other Philosopher: Get left utensil, the right utensil

Alternative: System V Semaphores

- File `philosophers_sysv.c` implements same problem with System V semaphores which look stranger than POSIX
  - Always come in an array of multiple semaphores
  - Operate atomically on the array: can incr/decr multiple semaphores at once
  - Requires use of structs to perform operations
  - Provide some other forms of synchronization such as waiting until a semaphore reaches 0
  - C calls such as `semget()`, `semctl()`, `semop()`
- Net effect is the same: each Philosopher locks a utensil by atomically decrementing and incrementing semaphores

The Nature of a Semaphore

- As seen, semaphores have several component parts that the OS manages
  1. An integer, usually quantity of resources available, often 1 or 0
  2. A locking mechanism allowing atomic operations on the value
  3. A **wait queue** of processes (or threads) that are blocked until the semaphore becomes non-zero
- Semaphores typically used to **lock** a resource or protect a critical region in code, efficiently blocks competing processes
- Later will discuss each component separately in context of threads
  - Locks are **Mutexes**
  - Wait queues are **Condition variables**
  - Integers can be any variable in memory
  - Can build our own semaphores as with these
  - SO: cucufrog on Condition Variables vs Semaphores

Linux shows Posix IPC objects under /dev/shm

```
> gcc -o philosophers philosophers_posix.c -lpthread
> ./philosophers
Swanson 0: wants utensils 0 and 1
Swanson 2: wants utensils 2 and 3
Swanson 1: wants utensils 1 and 2
...
Swanson 3 (egg 10/10): leaving the diner
pausing prior to cleanup/exit (press enter to continue)
while you're waiting, have a look in /dev/shm
  C-z
[1]+  Stopped                 ./philosophers

> ls -l /dev/shm
total 20K
-rw------- 1 kauffman kauffman 32 Apr  1 21:36 sem.utensil_0
-rw------- 1 kauffman kauffman 32 Apr  1 21:36 sem.utensil_1
-rw------- 1 kauffman kauffman 32 Apr  1 21:36 sem.utensil_2
-rw------- 1 kauffman kauffman 32 Apr  1 21:36 sem.utensil_3
-rw------- 1 kauffman kauffman 32 Apr  1 21:36 sem.utensil_4

> fg
./philosophers

> ls -l /dev/shm
total 0
```

`/dev/shm` is a Linux convention, shard memory under as well, message queues under `/dev/mqueue`

Exercise: Concurrent Appends to a File

- C code to the right appends a string to `the_file.txt`
- Shell code below launches 100 processes to append
- What's with the results of `wc`?

```
> gcc -o append_clobber append_clobber.c
> for i in $(seq 100); do
    append_clobber $i &
  done
[3] 18724
[4] 18725
...
[99]-  Done append_clobber $i
[100]+  Done append_clobber $i
> wc the_file.txt
 97  96 281 the_file.txt
```

```c
// append_clobber.c
int main(int argc, char *argv[]){
  if(argc < 2){
    printf("usage: %s <word>\n");
    return 1;
  }

  char *word = argv[1];
  char *filename = "the_file.txt";

  int fd = open(filename,
                O_CREAT | O_RDWR ,
                S_IRUSR | S_IWUSR);
  lseek(fd, 0, SEEK_END);

  int n = strlen(word);
  word[n] = '\n';
  write(fd, word,n+1);
  close(fd);

  return 0;
}
```

Exercise 2: Concurrent Appends to a File

- `append_clobber.c` does not coordinate writes to the end of `the_file.txt` leading to some data to be overwritten and lost
- Fix this using **semaphores**
- Research alternatives that also allow safe appends to files

```c
// append_clobber.c
int main(int argc, char *argv[]){
  if(argc < 2){
    printf("usage: %s <word>\n");
    return 1;
  }

  char *word = argv[1];
  char *filename = "the_file.txt";

  int fd = open(filename,
                O_CREAT | O_RDWR ,
                S_IRUSR | S_IWUSR);
  lseek(fd, 0, SEEK_END);

  int n = strlen(word);
  word[n] = '\n';
  write(fd, word,n+1);
  close(fd);

  return 0;
}
```

Answers: Concurrent Appends to a File

Semaphore Solution

- `append_sem.c` uses a POSIX semaphore named `/the_lock` to lock `the_file.txt` prior to working on it
- Must lock prior to the `lseek()`, unlock after the `write()`

Alternatives

- `append_lockf.c`: Use the `lockf()` function to get an exclusive lock on the file, identical to semaphore solution but tied to individual files
- `append_os.c`: Open with `O_APPEND`, OS guarantees all `write()`'s are appended to the end

```c
// append_sem.c
int main(int argc, char *argv[]){
  if(argc < 2){
    printf("usage: %s <word>\n");
    return 1;
  }

  char *word = argv[1];
  char *sem_name = "/the_lock";
  char *filename = "the_file.txt";

  int fd = open(filename,
                O_CREAT | O_RDWR ,
                S_IRUSR | S_IWUSR);
  sem_t *sem = sem_open(sem_name,
                        O_CREAT,
                        S_IRUSR | S_IWUSR);
  sem_wait(sem);    // wait/lock semaphore
  lseek(fd, 0, SEEK_END);

  int n = strlen(word);
  word[n] = '\n';
  write(fd, word,n+1);
  close(fd);

  sem_post(sem);    // unlock semaphore
  sem_close(sem);   // done with sempahore

  return 0;
}
```

Semaphore Application in Lab

This week's Lab will illustrate a more useful application of semaphores to coordinate multiple unrelated processes

- Process a "jobs" file with a list of shell commands to run

```
- seq 100000
- gcc --version
- du . -h
- ls
- ls -l
- date
...
```

- Start multiple 'runners' which execute lines from the jobs file

```
> runner jobs.txt & runner jobs.txt &
# starts 2 runners to work on jobs.txt
```

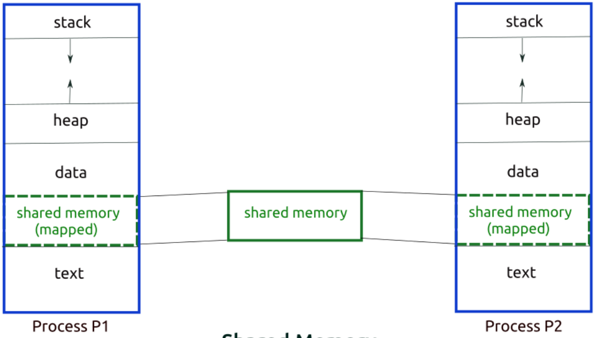
- Runners read file lines, execute jobs, mark as done

```
D seq 100000
D gcc --version
R du . -h
D ls
R ls -l
- date
...
```

- To prevent duplication of job running, use a Semaphore to lock the file while making changes

Shared Memory Segments

- The ultimate in flexibility is to get a segment of raw bytes that can be shared between processes
- POSIX shared memory outlives a process
- **Examine** `shmdemo_posix.c` to see how this looks
- Importantly, this program creates shared memory that outlives the program: must clean it up at some point



Shared Memory

Source: SoftPrayog System V IPC

Exercise: Shared Memory Coordination

- Creating shared memory is relatively easy
- Like files, Coordinating shared memory is not automatic
- Consider `shared_flip.c`
  - Shared memory of all "00000" or "1111"
  - `shared_flip -flip` flips all characters ($0 \rightarrow 1$, $1 \rightarrow 0$)
- What happens if multiple programs simultaneously try to flip bits?
- How does one prevent "corruption" of that data?
- Experiment noting that a command like

  ```
  for i in $(seq 100); do ./shared_flip -flip & done
  ```

  will start 100 identical processes as background jobs

Answers: Shared Memory Coordination

```
// No Coordination: Errors



printf("flipping bits\n");
for(int i=0; i<SHM_SIZE-1; i++){
  if(shared_bytes[i] == '0'){
    shared_bytes[i] = '1';
  }
  else if(shared_bytes[i] == '1'){
    shared_bytes[i] = '0';
  }
}
```

```
// Coordinate via Semaphore
sem_t *sem =
  sem_open(sem_name,O_CREAT,S_IRUSR|S_IWUSR);
sem_wait(sem);                    // lock semaphore
printf("flipping bits\n");
for(int i=0; i<SHM_SIZE-1; i++){
  if(shared_bytes[i] == '0'){
    shared_bytes[i] = '1';
  }
  else if(shared_bytes[i] == '1'){
    shared_bytes[i] = '0';
  }
}
sem_post(sem);                    // unlock sem
sem_close(sem);
```

Shared Memory vs mmap'd Files

- Recall Memory Mapped files give direct access of OS buffer for disk files
- Changes to file are done in RAM and occasionally `sync()`'d to disk (permanent storage)
- POSIX Shared Memory segment cut out the disk entirely: an OS buffer that looks like a file but has no permanent backing storage
- Which to pick?
  - Shared Memory when data does not need to be saved permanently and/or syncing would costly
  - Memory Mapped File when data should be saved permanently
- Related concept: RAM Disk, a main memory file system, high performance with no permanence

Exercise: Email lookup with Shared Memory

- In HW, worked on a simple email lookup "server" or database
- Clients connected to server, server gave back emails based on name
- Shared memory makes server/client less relevant
- Propose how to use shared memory for email lookups AND alterations
- How might multiple processes coordinate use of shared memory?

```
// structure to store a lookup_t of
// name-to-email association
typedef struct {
  char name [STRSIZE];
  char email[STRSIZE];
} lookup_t;

lookup_t original_data[NRECS] = {
  {"Chris Kauffman"       ,"kauffman@umn.edu"},
  {"Christopher Jonathan" ,"jonat003@umn.edu"},
  {"Amy Larson"           ,"larson@cs.umn.edu"},
  {"Chris Dovolis"        ,"dovolis@cs.umn.edu"},
  {"Dan Knights"          ,"knights@cs.umn.edu"},
  {"George Karypis"       ,"karypis@cs.umn.edu"},
  ...
```

```
# Sample of potential use
> email_db lookup 'Chris Kauffman'
Looking up Chris Kauffman
Found: kauffman@umn.edu
> email_db lookup 'Rick Sanchez'
Looking up Rick Sanchez
Not found
> email_db change 'Chris Kauffman' 'kman@kauffmoney.co
Changing Chris Kauffman to kman@kauffmoney.com
Alteration complete
> email_db lookup 'Chris Kauffman'
Looking up Chris Kauffman
Found: kman@kauffmoney.com
```

Answer: Email lookup with Shared Memory

- Store entire array of name/email in a piece of shared memory with a known name/file
- Likely want database of saved so a **memory mapped file** is probably best
- Processes open shared memory/file, scan through looking
- Updates can be done by altering the shared memory
- **Danger** multiple processes writing may corrupt the data
- Use semaphores to control access for reading/writing, would need to establish a **protocol** for this
  - Lock entire database: easy but only one lookup at a time
  - Lock individual name/emails: more complex but potential for more throughput
  - Differentiate reading locks and writing locks

Posix Message Queues

- Implements basic send/receive functionality through shared memory
- Message Queues share much with FIFOs
  - `mq_send()` is similar to `write()` to a FIFO
  - `mq_receive()` is similar to `read()` from a FIFO
  - Known global name of a message queue ~ name of FIFO file
- Differences from FIFOs
  - FIFOs/Pipes have a fixed total size (64K)
  - FIFOs allow `read()/write()` of arbitrary # of bytes
  - Message Queues limit #messages and max size of messages on queue
  - Message Queues send/receive individual messages

Kirk and Spock: Talking Across Interprocess Space

- Demo the following pair of simple communication codes which use Posix Message Queues.
- Examine source code to figure out how they work.

See `msg_kirk_posix.c` and `msg_spock_posix.c`

Email Lookup with Message Queues

- Recent HWs build an email lookup server using FIFOs
- Another HW compare it to an approach that uses Message Queues
- Worth of study to see the many similarities between FIFOs/Message Queues and a few of the differences between them
- Such contrast between IPC mechanisms make for good Exam questions

More Resources IPC

System V IPC

- http://beej.us/guide/bgipc/
- http://www.tldp.org/LDP/tlk/ipc/ipc.html

General Overview

- http://man7.org/conf/lca2013/IPC_Overview-LCA-2013-printable.pdf