CSCI 4061: Inter-Process Communication

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Logistics

Reading

- Stevens/Rago Ch 15.6-12
- Wikip: Dining Philosophers

Goals

- Project Plans
- File Append Problem
- Semaphore Basics
- Shared Memory
- Message Queues
- Dining Philosphers

Date	Event
Wed 3/31	IPC ShMem IPC MsgQ
Mon 4/5	Spring Break No Class
Mon 4/12	Review
Wed 4/14	Exam 2

Lab 11

- Email lookup server/client
- Use of FIFO to communicate
- Difficult to write tests for it - sorry for any Gradescope problems
- How did it go?

Project Plans

- Don't have time for 3 projects anymore which is Kauffman's fault

  > *I apologize for this mistake. I have experienced some personal problems which have interfered with my ability to adequately prepare a solid Version Control project. I regret that I was not able to provide a project that puts the topics we have discussed into practical use.*

- P2: release after Exam 2
- Focus on Interprocess Communication: a local Chat Server/Client
- Same size as P1, Worth 20% of grade
- Opportunities for some Makeup Credit

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

Exercise: Concurrent Appends to a File

C code to append to a file some number of times.

```c
// append_loop.c
int main(int argc, char *argv[]){
  char *filename = argv[1];
  int count = atoi(argv[2]);
  int key = atoi(argv[3]);
  int fd = open(filename,
                O_CREAT | O_RDWR ,
                S_IRUSR | S_IWUSR);

  char line[128];
  sprintf(line,"%04d\n",key);
  int len = strlen(line);

  for(int i=0; i<count; i++){

    lseek(fd, 0, SEEK_END);
    write(fd, line, len);

  }
  close(fd);
  return 0;
}
```

Shell code demos its use. What's wrong with the last count?

```
> ./a.out
usage: ./a.out <filename> <count> <key>
> ./a.out thefile.txt 100 5555
> wc -l thefile.txt
100 thefile.txt
> ./a.out thefile.txt 100 7777
> wc -l thefile.txt
200 thefile.txt
> sort thefile.txt | uniq -c
    100 5555
    100 7777

> rm thefile.txt
> for i in $(seq 10); do
     ./a.out thefile.txt 100 $i &
  done
> wc -l thefile.txt
732 thefile.txt
```

Concurrency Principles

Atomic Action

- Cannot be divided; will run completely before any other action taken. Some system calls are atomic like ...
- `nbytes = write(fd, data, len);` is atomic: `nbytes` of `data` written in sequence, data from other `write()` calls before/after but NOT in the middle
- `lseek()` is atomic: modifies file position in kernel data structure

Race Condition

- Outcome depends on the ordering of unpredictable events such as the OS scheduler interrupting a process
- Race Conditions are **bad**: unlucky timing causes unpredictable behavior, bugs that only occasionally occur

Race Condition in append_loop.c 1 / 2

```
FILE          PROC1 key=5555              PROC2 key=7777

len=15
5555
5555          lseek(fd, 0, SEEK_END);
7777          // pos = 15
    <---------write(fd, line, len);

len=20
5555
5555
7777                                      lseek(fd, 0, SEEK_END);
5555                                      // pos = 20
    <-------------------------------------write(fd, line, len);
```

All appears well BUT cannot guarantee that `lseek() / write()` happen uninterrupted

- Individually atomic
- Combination is not

Race Condition in append_loop.c 1 / 2

```
FILE          PROC1 key=5555             PROC2 key=7777

len=25
5555                                     lseek(fd, 0, SEEK_END);
5555                                     // pos = 25
7777          lseek(fd, 0, SEEK_END);
7777          // pos = 25
    <---------write(fd, line, len);

len=30
5555
5555
7777
7777                                     // pos = 25
5555<------------------------------------write(fd, line, len);

len=30
5555
5555
7777
7777
7777 # Overwritten
```

Result: 1 line is lost as the `lseek()` between process is not coordinated

Exercise: Solve this with Current IPC

Suggest a way to solve this problem with current IPC mechanisms

> *Start an arbitrary number of processes. Each repeatedly appends a given key to a given file. All keys must be present at the end.*

- Describe new / old processes
- Describe new / old code and IPC to be used

Hint: where have we recently seen a bunch of entities that all want access to data? How were these requests coordinated?

Answers: Solve this with Current IPC

Use a FIFO to coordinate multiple writers

Manager Process

- Only the manager writes to `thefile.txt`
- Starting the manager creates a FIFO; manager `read()`'s from the FIFO, appends text to the end of the file

Writer Processes

- Writer processes `write()` into the FIFO (not `thefile.txt`)
- FIFOs automatically serialize data: no chance for loss as OS controls the singular read/write positions

Familiar but Unsatisfactory

- Similar to `em_server / em_client` from Lab/HW
- Works and requires now new IPC mechanisms BUT...
- Dissatisfying: **must split code into manager/writer**. Would like a solution without a central manager.

Locking the Critical Region

Critical Region

- Code sequence `lseek(); write()` is a **Critical Region**: not atomic, unsafe to have multiple entities in it at the same time
- Typically protect these with a coordination mechanism, a **lock** for the critical region

OS Locking Mechanisms

- **Semaphore**: general purpose locking mechanism associated with multi-process programming
- **Mutex**: locking mechanism associated with threaded programming
- **File Locks**: lock all or portions of a file, alway

Semaphore History

Source: Wikipedia Railway Sempahore Signal

Semaphore: ***noun***
A system of sending messages by holding the arms or two flags or poles in certain positions...
– Oxford Dictionary

Semaphore: ***(computing)***
In computer science, a semaphore is a variable or abstract data type used to control access to a common resource by multiple processes and avoid critical section problems in a concurrent system such as a multitasking operating system.

The semaphore concept was invented by Dutch computer scientist Edsger Dijkstra...
– Wikipedia

Semaphore Basics: 3 Parts

Counter Variable variable

Semaphores have an integer value indicating how much of a resource is available

- S=0: none left
- S>0: some available

Most common case is S=1 (available) or S=0 (in-use)

Atomic Operations

- **Acquire**: If S>0, decrement; Else, enter wait-queue and block
- **Release**: Increment S, notify wait-queue of avialability

Wait Queue

Modern semaphores include a wait-queue. If S==0, **Acquire** will cause an entity (process) to enter the wait-queue and **block**.

Posix Implementation of Semaphores

```
sem_t *sem =
  sem_open("/the_sem", O_CREAT, S_IRUSR | S_IWUSR);
// abstract type sem_t representing semaphores
// file-like semantics with open, semaphore name, flags, permissions

// Note: "the_sem" may or may not appear in the file system somewhere
// Under Linux, will be at /dev/shm/the_sem

sem_init(sem, 1, 1);   // Initialize the semaphore value
//            |  +------> Initial counter value = 1
//            +---------> Share among Processes (1: Processes, 0: Threads)

sem_wait(sem);
// ACQUIRE the semaphore; block and queue up if not available

// CRITICAL REGION

sem_post(sem);
// RELEASE the semaphore; notifies any queued processes of availability

sem_close(sem);
// file-like semantics: close when process is finished using it

sem_unlink("/the_sem");
// POSIX named semaphores have kernel persistence: if not removed by
// sem_unlink(), a semaphore will exist until the system is shut down.
```

Examine: append_file_sem.c

Examine and experiment with append_file_sem.c which solves coordinates appends using a POSIX semaphore.

Look for use of semaphore functions like

- Opening
- Unlinking, initializing
- Acquiring / Releasing
- How the critical region is protected

```
> gcc -g append_loop_sem.c -lpthread
> ./a.out -init 1 1
initializing

> for i in $(seq 10); do
    ./a.out thefile.txt 100 $i &
  done

> wc -l thefile.txt
1000 thefile.txt     # ALL THERE!

> sort thefile.txt |uniq -c
    100 0001         # ALL KEYS
    100 0002         # FROM ALL
    100 0003         # PROCESSES
    100 0004
    100 0005
    100 0006
    100 0007
    100 0008
    100 0009
    100 0010

> ./a.out -unlink 1 1
unlinking
```

File Append Alternatives

Semaphores give general purpose coordination but the special case of coordinating file appends have several other simpler solutions.

POSIX File Locks

- See `append_loop_lockf.c`
- `lockf()`: apply, test or remove a POSIX lock on an open file
- Protect critical region via

```
lockf(fd, F_LOCK, 0);
lseek(fd, 0, SEEK_END);
write(fd, line, len);
lockf(fd, F_ULOCK, 0);
```

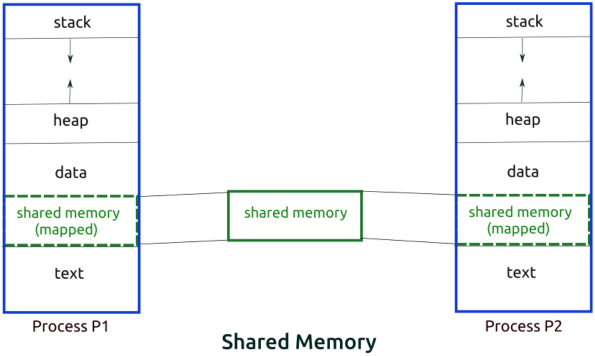
- Major Plus: no Init/Unlink funny business
- Drawback: Lock is tied to a file, Semaphores are independent

`O_APPEND` Flag

- See `append_loop_oappend.c`
- `open(..., O_APPEND, ...)` opens a file in append mode:
- "The file offset shall be set to the end of the file prior to each `write()`." – `man open(3)`
- Major Plus: no locks, semaphores, or other funny business
- Major Drawback: only works for appending to the end of files; Not Applicable to coordinating any other activity

Shared Memory Segments

- An memory area that can be shared by multiple processes
- POSIX shared memory outlives a process like a file BUT with no permanent storage
  - Must clean up / unlink Shared Mem manually
  - Shared Mem Contents unreliable across power off/on
- **Examine** `shmdemo_posix.c` to see how that works much like a memory mapped file



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 file to lock so `flock()` wouldn't work
- Not appending so `O_APPEND` won't cut it
- A **semaphore** allows coordination of bit flipping through `sem_wait() / sem_post()` to protect the critical region

```
// 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

Practice Problem: A Semaphore Application

- 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
...
```

- Will provide initial version of this
- To prevent duplication of job running, add coordination to prevent duplicate jobs

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 $\sim$ 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

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

More Resources IPC

System V IPC

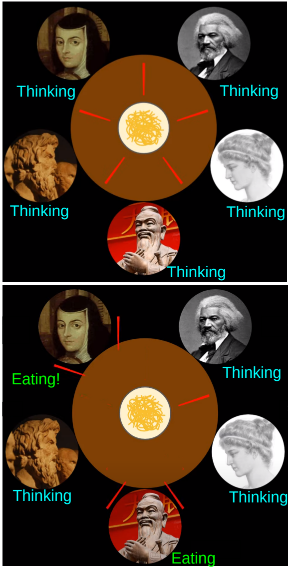
- http://beej.us/guide/bgipc/
- http://www.tldp.org/LDP/tlk/ipc/ipc.html

General Overview

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

Model Problem: Dining Philosophers

- N Philosophers with N Chopsticks between them
- Philosophers "Algorithm"
  - Think for a while
  - Get adjacent chopsticks
  - Eat for a while
  - Replace Chopsticks
  - Repeat
- Models concurrent processes/thread acquiring multiple resources



Source: Introduction to RTOS Part 10 - Deadlock and Starvation | Digi-Key Electronics

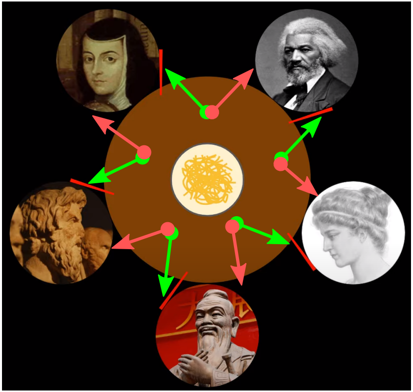
Exercise: Coding Dining Philosophers

Central philosopher algorithm is

- Think for a while
- Get adjacent chopsticks
- Eat for a while
- Replace Chopsticks
- Repeat

Questions:

1. What can be used to model "chopsticks"?
2. How does one avoid deadlock?



Deadlocked Table

Answers: Coding Dining Philosophers

1. Model chopsticks with **semaphores**: only one process can acquire them at a time; the other blocks.
2. All philosophers get right chopstick (lower number) first EXCEPT last philosopher: go left first
   - Breaks the cycle that would create deadlock

See `philosphers_posix.c` for demonstration code