OPERATING SYSTEMS: COMMUNICATION AND SYNCHRONIZATION AMONG PROCESSES

Concurrent server development

To remember…

Before classes

Class

After class

Prepare the prerequisites.

Study the material associated with the **bibliography**: slides alone are not enough.
Please ask questions (especially after study).

Exercising skills:

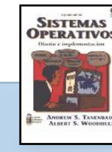
- Perform all **exercises**.
- Carrying out the **practice notebooks** and **the practical exercises** progressively.

Recommended reading

Base

1. Carretero 2020:
   1. Cap. 6
2. Carretero 2007:
   1. Cap. 6.1 and 6.2

Suggested



1. Tanenbaum 2006:
   1. (es) Chap. 5
   2. (en) Chap. 5
2. Stallings 2005:
   1. 5.1, 5.2 and 5.3
3. Silberschatz 2006:
   1. 6.1, 6.2, 6.5 and 6.6

Contents

- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization
  - Critical section and Race conditions
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- **Concurrent server development**
  - **Request servers.**
  - **Process-based solution.**
  - **On-demand thread-based solution.**
  - **Thread pool-based solution.**

Contents

- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization
  - Critical section and Race conditions
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- Concurrent server development
  - **Request servers.**
  - Process-based solution.
  - On-demand thread-based solution.
  - Thread pool-based solution.

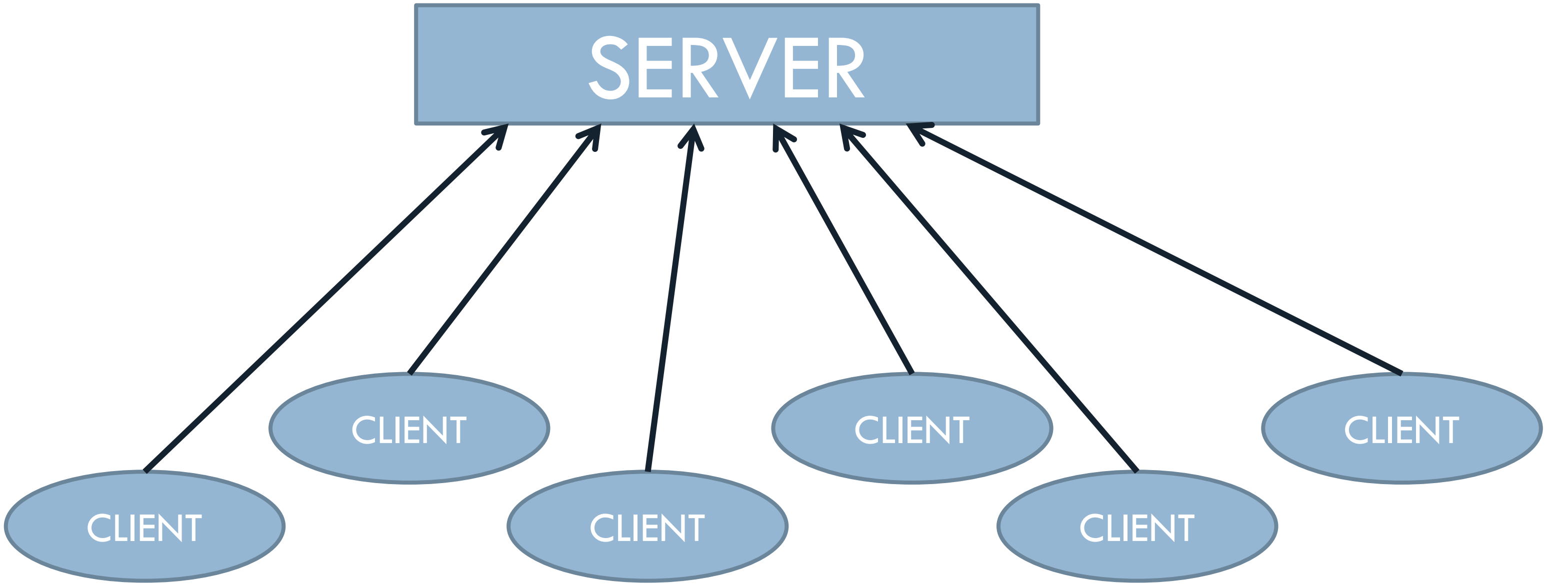
Request server

- A server receives requests that it must process.

- In many contexts, request servers are developed:
  - Web Server.
  - Database server.
  - Application server.
  - File server.
  - Messaging applications
  - …

Request server

- A server receives requests that it must process.

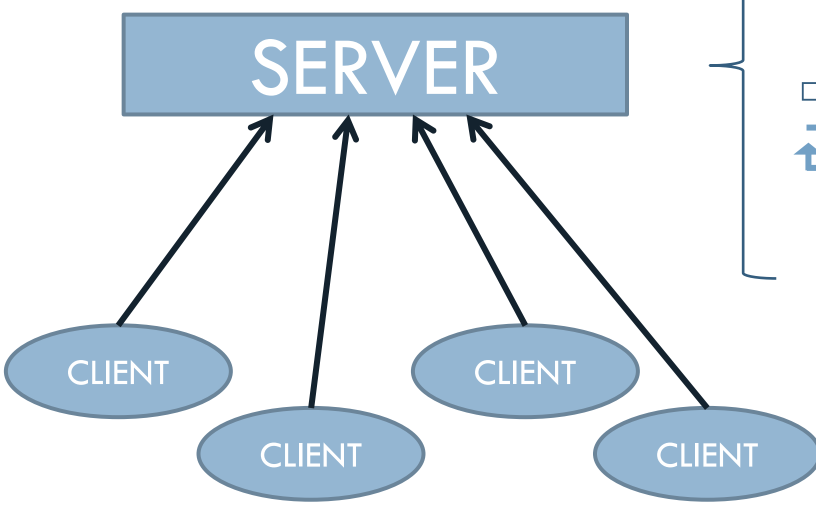


Request server

- A server receives requests that it must process.
- Structure of a generic server:
  - Receiving the request:
    - Each request requires a certain time in input/output operations to be received.
  - Request processing:
    - A certain CPU processing time.
  - Sending of the reply:
    - A certain input/output time for replying.

Concurrent request server?

- A server receives requests that it must process.



- Generic sequential server:
  - Receiving the request
  - Request processing
  - Sending of the reply
- Generic **concurrent** server:
  - Receiving the request
  - Create (process or thread) in charge of:
    - Request processing
    - Sending the reply

Test environment: test application

- Sequential
  - Generic sequential server:
    - Receiving the request
    - Request processing
    - Sending of the reply
- Concurrent with processes
  - Generic **concurrent** server:
    - Receiving the request
    - Create process in charge of:
      - Request processing
      - Sending of the reply
- Concurrent with threads on demand
  - Generic **concurrent** server:
    - Receiving the request
    - Create thread in charge of:
      - Request processing
      - Sending of the reply
- Concurrent with threads in a thread pool (pre-created)

Test environment: test application

- The following will be used to evaluate the solutions:
  - Program that:
    - Attends NPET requests:
      - Receiving request.
      - Sending of the reply.
    - Measures the time it takes to deal requests.
  - A library that will simulate:
    - Receiving requests.
    - The processing and sending of responses.

```c
#include "request.h“
#define NPET 20

 int main()
{
    request_t p;

    t1=measure_time();
    for (i=0; i<NPET; i++) {
        receive_request(&p);
        reply_request(&p);
    }
    t2=measure_time();

    printf(“Time: %d", t2-t1) ;
    return 0;
}
```

```c
#ifndef  REQUEST_H
#define REQUEST_H

 typedef struct request{
     /* ... */
 } request_t ;

 void receive_request  ( request_t * p );
 void reply_request     ( request_t * p );

#endif
```

Base library

requests.h

Alejandro Calderón Mateos

```c
#ifndef REQUEST_H
#define REQUEST_H

    #include <stdio.h>
    #include <stdlib.h>
    #include <string.h>
    #include <unistd.h>
    #include <sys/time.h>

    struct request{
       long id;
       /* Other required fields */
       int type;
       /* ... */
    };

    typedef struct request request_t;

    void receive_request  ( request_t * p );
    void reply_request    ( request_t * p );

#endif
```

Receiving requests

requests.c


```
static long petid = 0;

void receive_request (request_t * p)
{
   int delay;

   fprintf(stderr, "Receiving requests\n");
   p->id = petid++;

   /* I/O timing simulation*/
   delay = rand() % 5;
   sleep(delay);

   fprintf(stderr,"Request %d received after %d seconds\n",
            p->id, delay);
}
```

Receiving requests

requests.c


```
static long petid = 0;

void receive_request (request_t * p)
{
   int delay;

   fprintf(stderr, "Receiving requests\n");
   p->id = petid++;

   /* I/O timing simulation*/
   delay = rand() % 5;
   sleep(delay);

   fprintf(stderr,"Request %d received after %d seconds\n",
            p->id, delay);
}
```

Here would go some blocking call to receive the request (e.g. from the network).

Processing and sending of requests

requests.c


```
void reply_request (request_t * p)
{
  int delay, i;
  char * mz;

  fprintf(stderr, "Sending request %d\n", p->id);

  /* Simulation of processing time */
  mz = malloc(1000000);
  for (i=0; i<1000000; i++) { mz[i] = 0; }
  free(mz) ;

  /* I/O timing simulation*/
  delay = rand() % 20;
  sleep(delay);

  fprintf(stderr, "Request %d sent after %d seconds\n",
          p->id, delay);
}
```

Processing and sending of requests

requests.c


```
void reply_request (request_t * p)
{
  int delay, i;
  char * mz;

  fprintf(stderr, "Sending request %d\n", p->id);

  /* Simulation of processing time */
  mz = malloc(1000000);
  for (i=0; i<1000000; i++) { mz[i] = 0; }
  free(mz) ;

  /* I/O timing simulation*/
  delay = rand() % 20;
  sleep(delay);

  fprintf(stderr, "Request %d sent after %d seconds\n",
          p->id, delay);
}
```

The request would be processed here

Here would go a blocking call to reply to the request

Initial solution with metering

Alejandro Calderón Mateos

```
#include "request.h"

const int MAX_REQUESTS = 5;

int main ( int argc, char *argv[] )
{
    struct timeval ts;
    long t1, t2;
    request_t p;

    gettimeofday(&ts, NULL) ;
    t1 = (long)ts.tv_sec * 1000 +
     (long)ts.tv_usec / 1000 ;
    for (int i=0; i<MAX_REQUESTS; i++)   {
            receive_request(&p);
            reply_request(&p);
    }
    gettimeofday(&ts, NULL) ;
    t2 = (long)ts.tv_sec * 1000 +
     (long)ts.tv_usec / 1000 ;

    printf("Time: %lf\n", (t2-t1)/1000.0);
    return 0;
}
```

```
#include "request.h"

const int MAX_REQUESTS = 5;

int main ( int argc, char *argv[] )
{
   struct timeval ts;
   long t1, t2;
   request_t p;

   gettimeofday(&ts, NULL) ;
   t1 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;
   for (int i=0; i<MAX_REQUESTS; i++)  {
        receive_request(&p);
        reply_request(&p);
   }
   gettimeofday(&ts, NULL) ;
   t2 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;

   printf("Time: %lf\n", (t2-t1)/1000.0);
   return 0;
}
```

Execution of the initial solution

Alejandro Calderón Mateos

```
$ time ./ej1
Receiving requests
Request 0 received after 3 seconds
Sending request 0
Request 0 sent after 6 seconds
Receiving requests
Request 1 received after 2 seconds
Sending request 1
Request 1 sent after 15 seconds
Receiving requests
Request 2 received after 3 seconds
Sending request 2
Request 2 sent after 15 seconds
Receiving requests
Request 3 received after 1 seconds
Sending request 3
Request 3 sent after 12 seconds
Receiving requests
Request 4 received after 4 seconds
Sending request 4
Request 4 sent after 1 seconds
Time: 62.110000

real    1m2.053s
user    0m0.047s
sys     0m0.000s
```

Problems

- Arrival of requests:
  - If two requests came at the same time…
  - If one request cames while another is being processed…
- Use of resources.
  - How will the CPU utilization be?

Comparison

Sequential	Process per req.	Thread per request	Pool of threads
62.11 sec.			

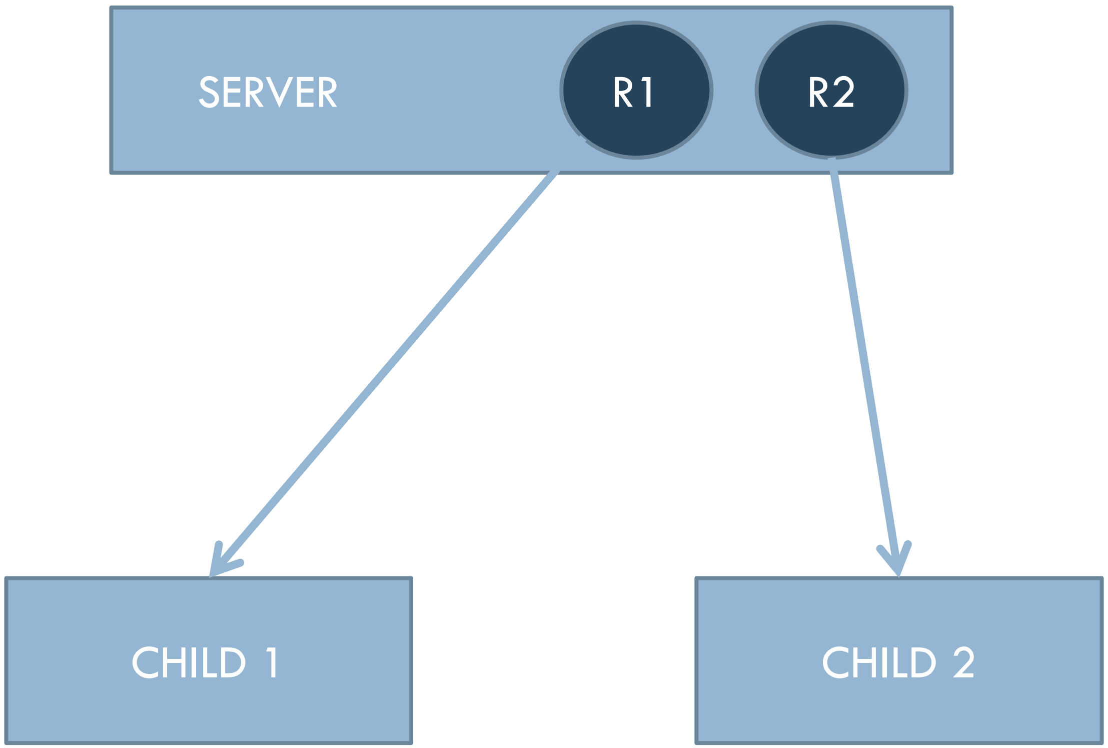
Contents

- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization
  - Critical section and Race conditions
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- Concurrent server development
  - Request servers.
  - **Process-based solution.**
  - On-demand thread-based solution.
  - Thread pool-based solution.

First idea

- Each time a request arrives, a child process is created (with fork system call):
  - The child process processes the request.
  - The parent process waits for the next request.

Process-based server



Implementation (1/2)


```c
#include <sys/types.h>
#include <sys/wait.h>
#include "request.h"

const int MAX_REQUESTS = 5;
void * receiver ( void ) ;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;
  receiver() ;
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}

void * receiver ( void )
{
  request_t p;
  int pid, nchilds=0;

  for (int i=0; i<MAX_REQUESTS; i++)
  {
     receive_request(&p);

     pid = fork();
     if (pid<0)  { perror("Error en la creación del hij");}
     if (pid==0) { reply_request(&p); exit(0); }   /* HIJO */
     if (pid!=0) { nchilds++; }                        /*
       PADRE */
  }

  fprintf(stderr, "Wait for %d nchilds\n", nchilds);
  while (nchilds > 0)
  {
       pid = waitpid(-1, NULL, WNOHANG);
       if (pid > 0) { nchilds--;  }
  } ;

  return NULL ;
}
```

```c
#include <sys/types.h>
#include <sys/wait.h>
#include "request.h"

const int MAX_REQUESTS = 5;
void * receiver ( void ) ;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;
  receiver() ;
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
```

Implementation (2/2)


```c
#include <sys/types.h>
#include <sys/wait.h>
#include "request.h"

const int MAX_REQUESTS = 5;
void * receiver ( void ) ;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;
  receiver() ;
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec * 1000 + (long)ts.tv_usec / 1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
void * receiver ( void )
{
  request_t p;
  int pid, nchilds=0;

  for (int i=0; i<MAX_REQUESTS; i++)
  {
     receive_request(&p);

     pid = fork();
     if (pid<0)  { perror("Error en la creación del hij");}
     if (pid==0) { reply_request(&p); exit(0); }    /* HIJO */
     if (pid!=0) { nchilds++; }                      /*
       PADRE */
  }

  fprintf(stderr, "Wait for %d nchilds\n", nchilds);
  while (nchilds > 0)
  {
      pid = waitpid(-1, NULL, WNOHANG);
      if (pid > 0) { nchilds--;  }
  } ;

  return NULL ;
}
```

```c
void * receiver ( void )
{
  request_t p;
  int pid, nchilds=0;

  for (int i=0; i<MAX_REQUESTS; i++)
  {
     receive_request(&p);

     pid = fork();
     if (pid<0)  { perror("Error in fork"); }
     if (pid==0) { reply_request(&p); exit(0); }
     if (pid!=0) { nchilds++; }
  }

  fprintf(stderr, "Wait for %d nchilds\n", nchilds);
  while (nchilds > 0)
  {
      pid = waitpid(-1, NULL, WNOHANG);
      if (pid > 0) { nchilds--;  }
  } ;

  return NULL ;
}
```

Execution

Alejandro Calderón Mateos

```
$ time ./ej2
Receiving requests
Request 0 received after 3 seconds
Receiving requests
Sending request 0
Request 1 received after 1 seconds
Receiving requests
Sending request 1
Request 2 received after 2 seconds
Receiving requests
Sending request 2
Request 3 received after 0 seconds
Receiving requests
Sending request 3
Request 4 received after 3 seconds
Wait for 5 nchilds
Request 0 sent after 6 seconds
Sending request 4
Request 3 sent after 13 seconds
Request 1 sent after 17 seconds
Request 2 sent after 15 seconds
Request 4 sent after 15 seconds
Time: 24.086000

real    0m24.012s
user    0m9.569s
sys     0m5.459s
```

Comparison

Alejandro Calderón Mateos

Sequential	Process per req.	Thread per request	Pool of threads
62.11 sec.	24.08 sec.		

Problems

Alejandro Calderón Mateos

- A process must be started (fork) for each incoming request.
- A process must be terminated (exit) for each request that terminates.
- Excessive consumption of system resources
- No admission control.
  - Quality of service problems.

Solutions with threads

Alejandro Calderón Mateos

- Thread on demand (per request).
  - Each time a request is received, a thread is created.

- Pool of threads.
  - You have a fixed number of threads created.
  - Each time a request is received, a free thread already created is searched for to handle the request.
    - Communication through a request queue.

Contents

- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization
  - Critical section and Race conditions
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- Concurrent server development
  - Request servers.
  - Process-based solution.
  - **On-demand thread-based solution.**
  - Thread pool-based solution.

On-demand (per request) threads

- There is a special thread in charge of receiving the requests.
- Each time a request arrives a thread is created, and **a copy of the request** is passed to the newly created thread.
  - It must be a copy of the request because the original request could be modified.

Implementation (1/3 main)


```c
#include <pthread.h>
#include <semaphore.h>
#include "request.h"

sem_t snchilds;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;
  pthread_t thr;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;
   sem_init(&snchilds, 0, 0);
   pthread_create(&thr, NULL, receiver, NULL);
   pthread_join(thr, NULL);
   sem_destroy(&snchilds);
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
void * service (void * p)
{
      request_t  pet;

      copy_request(&pet,(request_t*)p);
      fprintf(stderr, "Starting service\n");
      reply_request(&pet);
      sem_post(&snchilds);
      fprintf(stderr, "Completing service\n");
      pthread_exit(0);  return NULL;
}

void * receiver (void * param)
{
     const int MAX_REQUESTS = 5; int nservice = 0;  int i;
     request_t  p;  pthread_t  th_child;

     for (i=0;i<MAX_REQUESTS;i++)  {
         receive_request(&p);  nservice++;
         pthread_create(&th_child, NULL, service, &p);
     }


     for (i=0;i<nservice;i++)  {
          fprintf(stderr, "Doing wait\n");
          sem_wait(&snchilds);
          fprintf(stderr, "After wait\n");
    }

    pthread_exit(0);  return NULL;
}
```

```c
#include <pthread.h>
#include <semaphore.h>
#include "request.h"

sem_t snchilds;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;
  pthread_t thr;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;
   sem_init(&snchilds, 0, 0);
   pthread_create(&thr, NULL, receiver, NULL);
   pthread_join(thr, NULL);
   sem_destroy(&snchilds);
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
```

Implementation (2/3 receiver)

Alejandro Calderón Mateos

```
#include <pthread.h>
#include <semaphore.h>
#include "request.h"

sem_t snchilds;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;
  pthread_t thr;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;
   sem_init(&snchilds, 0, 0);
   pthread_create(&thr, NULL, receiver, NULL);
   pthread_join(thr, NULL);
   sem_destroy(&snchilds);
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}

void * service (void * p)
{
      request_t  pet;

      copy_request(&pet,(request_t*)p);
      fprintf(stderr, "Starting service\n");
      reply_request(&pet);
      sem_post(&snchilds);
      fprintf(stderr, "Completing service\n");
      pthread_exit(0);  return NULL;
}

void * receiver (void * param)
{
     const int MAX_REQUESTS = 5; int nservice = 0;  int i;
     request_t  p;  pthread_t  th_child;

     for (i=0;i<MAX_REQUESTS;i++)  {
         receive_request(&p);  nservice++;
         pthread_create(&th_child, NULL, service, &p);
     }


     for (i=0;i<nservice;i++)  {
          fprintf(stderr, "Doing wait\n");
          sem_wait(&snchilds);
          fprintf(stderr, "After wait\n");
    }

    pthread_exit(0);  return NULL;
}
```

```
const int MAX_REQUESTS = 5;

void * receiver ( void * param )
{
      int nservice = 0;
      request_t  p;
      pthread_t  th_child;

      for (int i=0; i<MAX_REQUESTS; i++) {
          receive_request(&p);
          nservice++;
          pthread_create(&th_child, NULL, service, &p);
      }

      for (int i=0; i<nservice; i++)  {
           fprintf(stderr, "Doing wait\n");
           sem_wait(&snchilds);
           fprintf(stderr, "After wait\n");
     }

     pthread_exit(0);
     return NULL;
}
```

Implementation (3/3 service)


```c
#include <pthread.h>
#include <semaphore.h>
#include "request.h"

sem_t snchilds;

int main ( int argc, char *argv[] )
{
  struct timeval ts;
  long t1, t2;
  pthread_t thr;

  gettimeofday(&ts, NULL) ;
  t1 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;
   sem_init(&snchilds, 0, 0);
   pthread_create(&thr, NULL, receiver, NULL);
   pthread_join(thr, NULL);
   sem_destroy(&snchilds);
  gettimeofday(&ts, NULL) ;
  t2 = (long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
void * service (void * p)
{
      request_t  pet;

      copy_request(&pet,(request_t*)p);
      fprintf(stderr, "Starting service\n");
      reply_request(&pet);
      sem_post(&snchilds);
      fprintf(stderr, "Completing service\n");
      pthread_exit(0);  return NULL;
}
void * receiver (void * param)
{
     const int MAX_REQUESTS = 5; int nservice = 0;  int i;
     request_t  p;  pthread_t  th_child;

     for (i=0;i<MAX_REQUESTS;i++)  {
         receive_request(&p);  nservice++;
         pthread_create(&th_child, NULL, service, &p);
     }


     for (i=0;i<nservice;i++)  {
          fprintf(stderr, "Doing wait\n");
          sem_wait(&snchilds);
          fprintf(stderr, "After wait\n");
    }

    pthread_exit(0);  return NULL;
}
```

```c
void * service ( void * p )
{
     request_t  pet;

     memmove(&pet, (request_t *)p, sizeof(pet));
     fprintf(stderr, "Starting service\n");
     reply_request(&pet);
     sem_post(&snchilds);

     fprintf(stderr, "Completing service\n");
     pthread_exit(0);
     return NULL;
}
```

Thoughts

- Can a race condition occur?

```
void * receiver ( void * param )
{
     const int MAX_REQUESTS = 5;
     int nservice = 0;
     request_t  p;
     pthread_t  th_child;

     for (int i=0; i<MAX_REQUESTS; i++) {
         receive_request(&p);
         nservice++;
         pthread_create(&th_child, NULL, service, &p);
     }
     for (int i=0; i<nservice; i++)  {
          fprintf(stderr, "Doing wait\n");
          sem_wait(&snchilds);
          fprintf(stderr, "After wait\n");
    }
    pthread_exit(0);
    return NULL;
}
```

```
void * service ( void * p )
{
     request_t  pet;

     memmove(&pet, (request_t *)p, sizeof(pet));
     fprintf(stderr, "Starting service\n");
     reply_request(&pet);
     sem_post(&snchilds);

     fprintf(stderr, "Completing service\n");
     pthread_exit(0);
     return NULL;
}
```

Execution


```
$ time ./ej3
Receiving requests
Request 0 received after 3 seconds
Receiving requests
Starting service
Sending request 0
Request 1 received after 1 seconds
Receiving requests
Starting service
Sending request 1
Request 2 received after 0 seconds
Receiving requests
Starting service
Sending request 3
Request 3 received after 3 seconds
Receiving requests
Starting service
Sending request 4
Request 4 received after 2 seconds
Doing wait
...
After wait
Doing wait
Request 1 sent after 15 seconds
Completing service
After wait
Doing wait
Request 0 sent after 17 seconds
Completing service
After wait
Time: 20.012000

real	0m20.012s
user	0m0.033s
sys	0m0.000s
```

Comparison

Sequential	Process per req.	Thread per request	Pool of threads
62.11 sec.	24.08 sec.	20.01 sec.	

Problem

- Thread creation and termination has a lower cost than process creation and termination, but it is still a cost.

- There is no admission control:
  - What happens if too many requests arrive or the requests received are not completed?

Thoughts

Alejandro Calderón Mateos

- Can a race condition occur?

If it is known

Not known

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;   2

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t p; 2

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;   2

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

```
void * service (void * p)

request_t  pet;

copy_request(&pet, p);
reply_request(&pet);
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;   2

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

```
void * service (void * p)

request_t  pet;
-------------------------------------
copy_request(&pet, p);
reply_request(&pet);
```

Thoughts

Alejandro Calderón Mateos

- Can a race condition occur?

void * receiver (void * param)

```
request_t  p;   2

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

void * service (void * p)

```
request_t  pet;
-----------------------------
copy_request(&pet, p);
reply_request(&pet);
```

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;  3

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```

```
void * service (void * p)

request_t  pet;
copy_request(&pet, p);
reply_request(&pet);
```

STOP

Thoughts

- Can a race condition occur?

```
void * receiver (void * param)

request_t  p;   3

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

receive_request(&p);
nservice++;
pthread_create(&child, NULL, service, &p);

...
```


```
void * service (void * p)

request_t  pet;

copy_request(&pet, p);
reply_request(&pet);
```

Possible solution (mutex + condition)

- Parent thread

```
 lock(mutex);   /* access to the resource */
while (request is not copied)
        wait(condition, mutex);
mark request as no copied;
unlock(mutex);
```

- Child thread

```
 lock(mutex);
copy request
mark request as copied;
signal(condition);
unlock(mutex);
```

Contents

- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization
  - Critical section and Race conditions
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- Concurrent server development
  - Request servers.
  - Process-based solution.
  - On-demand thread-based solution.
  - **Thread pool-based solution.**

Threads pool

- A thread pool is a set of threads that you have created at the beginning to run a service:
  - Each time a request arrives, it is placed in a queue of pending requests.
  - All threads wait until there is a request in the queue and remove it for processing.

Implementation: main (1/3)

```c
#include "request.h"
#include <pthread.h>
#include <semaphore.h>

#define MAX_BUFFER 128
request_t  buffer[MAX_BUFFER];

int  n_elements  = 0;
int  pos_service = 0;
int  fin=0;

pthread_mutex_t  mutex;
pthread_cond_t    not_full;
pthread_cond_t    no_empty;

void * receiver (void * param) ;
void * service  (void * param) ;
```

Implementation: main (2/3)

Alejandro Calderón Mateos

```
#include "request.h"
#include <pthread.h>
#include <semaphore.h>

#define MAX_BUFFER 128
request_t  buffer[MAX_BUFFER];

int  n_elements  = 0;
int  pos_service = 0;
int  fin = 0;
pthread_mutex_t  mutex;
pthread_cond_t     not_full;
pthread_cond_t     no_empty;

void * receiver (void * param) ;
void * service (void * param) ;

int main()
{
   struct timeval ts;
   long t1, t2;
   pthread_t thr;
   pthread_t ths[MAX_SERVICE];
   const int MAX_SERVICE = 5;

   pthread_mutex_init(&mutex,NULL);
   pthread_cond_init(&not_full,NULL);
   pthread_cond_init(&no_empty,NULL);

   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_create(&ths[i],NULL,service,NULL);
   }
   sleep(1);
   gettimeofday(&ts, NULL) ;
   t1 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000;
   pthread_create(&thr,NULL,receiver,NULL);
   pthread_join(thr, NULL);
   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_join(ths[i],NULL);
   }
   gettimeofday(&ts, NULL) ;
   t2 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

   pthread_mutex_destroy(&mutex);
   pthread_cond_destroy(&not_full);
   pthread_cond_destroy(&no_empty);

   printf("Time: %lf\n", (t2-t1)/1000.0);
   return 0;
}

void * receiver (void * param)
{
    const int MAX_REQUESTS = 5;
    request_t p; int pos=0;

    for (int i=0; i<MAX_REQUESTS; i++)
    {
        receive_request(&p);
        pthread_mutex_lock(&mutex);
        while (n_elements == MAX_BUFFER)
               pthread_cond_wait(&not_full, &mutex);
        buffer[pos] = p;
        pos = (pos+1) % MAX_BUFFER;
        n_elements++;
        pthread_cond_signal(&no_empty);
        pthread_mutex_unlock(&mutex);
    }
    fprintf(stderr,"Closing receiver\n");

    pthread_mutex_lock(&mutex);
    fin=1;
    pthread_cond_broadcast(&no_empty);
    pthread_mutex_unlock(&mutex);

    fprintf(stderr, "Receiver closed\n");
    pthread_exit(0);
    return NULL;
}

void * service (void * param)
{
    request_t p;

    for (;;)
    {
       pthread_mutex_lock(&mutex);
       while (n_elements == 0)
       {
          if (fin==1) {
              fprintf(stderr, "Finalizing service\n");
              pthread_mutex_unlock(&mutex);
              pthread_exit(0);
          }
          pthread_cond_wait(&no_empty, &mutex);
       } // while
       printf(stderr,"Serving pos. %d\n",pos_service);
       p = buffer[pos_service];
       pos_service = (pos_service + 1) % MAX_BUFFER;
       n_elements --;
       pthread_cond_signal(&not_full);
       pthread_mutex_unlock(&mutex);
       reply_request(&p);
    }
    pthread_exit(0);
    return NULL;
}
```

```
int main()
{
    struct timeval ts;
    long t1, t2;
    pthread_t thr;
    pthread_t ths[MAX_SERVICE];
    const int MAX_SERVICE = 5;

    pthread_mutex_init(&mutex,NULL);
    pthread_cond_init(&not_full,NULL);
    pthread_cond_init(&no_empty,NULL);

    for (int i=0;i<MAX_SERVICE;i++) {
         pthread_create(&ths[i],NULL,service,NULL);
    }
    sleep(1);
```

Implementation: main (3/3)

Alejandro Calderón Mateos

```c
#include "request.h"
#include <pthread.h>
#include <semaphore.h>

#define MAX_BUFFER 128
request_t  buffer[MAX_BUFFER];

int  n_elements  = 0;
int  pos_service = 0;
int  fin = 0;
pthread_mutex_t  mutex;
pthread_cond_t     not_full;
pthread_cond_t     no_empty;

void * receiver (void * param) ;
void * service (void * param) ;

int main()
{
   struct timeval ts;
   long t1, t2;
   pthread_t thr;
   pthread_t ths[MAX_SERVICE];
   const int MAX_SERVICE = 5;

   pthread_mutex_init(&mutex,NULL);
   pthread_cond_init(&not_full,NULL);
   pthread_cond_init(&no_empty,NULL);

   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_create(&ths[i],NULL,service,NULL);
   }
   sleep(1);

   gettimeofday(&ts, NULL) ;
   t1 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000;
   pthread_create(&thr,NULL,receiver,NULL);
   pthread_join(thr, NULL);
   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_join(ths[i],NULL);
   }
   gettimeofday(&ts, NULL) ;
   t2 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

   pthread_mutex_destroy(&mutex);
   pthread_cond_destroy(&not_full);
   pthread_cond_destroy(&no_empty);

   printf("Time: %lf\n", (t2-t1)/1000.0);
   return 0;
}
void * receiver (void * param)
{
    const int MAX_REQUESTS = 5;
    request_t p; int pos=0;

    for (int i=0; i<MAX_REQUESTS; i++)
    {
        receive_request(&p);
        pthread_mutex_lock(&mutex);
        while (n_elements == MAX_BUFFER)
               pthread_cond_wait(&not_full, &mutex);
        buffer[pos] = p;
        pos = (pos+1) % MAX_BUFFER;
        n_elements++;
        pthread_cond_signal(&no_empty);
        pthread_mutex_unlock(&mutex);
    }
    fprintf(stderr,"Closing receiver\n");

    pthread_mutex_lock(&mutex);
    fin=1;
    pthread_cond_broadcast(&no_empty);
    pthread_mutex_unlock(&mutex);

    fprintf(stderr, "Receiver closed\n");
    pthread_exit(0);
    return NULL;
}

void * service (void * param)
{
    request_t p;

    for (;;)
    {
       pthread_mutex_lock(&mutex);
       while (n_elements == 0)
       {
          if (fin==1) {
              fprintf(stderr, "Finalizing service\n");
              pthread_mutex_unlock(&mutex);
              pthread_exit(0);
          }
          pthread_cond_wait(&no_empty, &mutex);
       } // while
       printf(stderr,"Serving pos. %d\n",pos_service);
       p = buffer[pos_service];
       pos_service = (pos_service + 1) % MAX_BUFFER;
       n_elements --;
       pthread_cond_signal(&not_full);
       pthread_mutex_unlock(&mutex);
       reply_request(&p);
    }
    pthread_exit(0);
    return NULL;
}
```

```c
  gettimeofday(&ts, NULL) ;
  t1 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000;

   pthread_create(&thr,NULL,receiver,NULL);
   pthread_join(thr, NULL);
   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_join(ths[i],NULL);
   }

  gettimeofday(&ts, NULL) ;
  t2 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

   pthread_mutex_destroy(&mutex);
   pthread_cond_destroy(&not_full);
   pthread_cond_destroy(&no_empty);

  printf("Time: %lf\n", (t2-t1)/1000.0);
  return 0;
}
```

Implementation: receiver

Alejandro Calderón Mateos

```c
#include "request.h"
#include <pthread.h>
#include <semaphore.h>

#define MAX_BUFFER 128
request_t  buffer[MAX_BUFFER];

int  n_elements  = 0;
int  pos_service = 0;
int  fin = 0;
pthread_mutex_t  mutex;
pthread_cond_t     not_full;
pthread_cond_t     no_empty;

void * receiver (void * param) ;
void * service (void * param) ;

int main()
{
   struct timeval ts;
   long t1, t2;
   pthread_t thr;
   pthread_t ths[MAX_SERVICE];
   const int MAX_SERVICE = 5;

   pthread_mutex_init(&mutex,NULL);
   pthread_cond_init(&not_full,NULL);
   pthread_cond_init(&no_empty,NULL);

   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_create(&ths[i],NULL,service,NULL);
   }
   sleep(1);

   gettimeofday(&ts, NULL) ;
   t1 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000;
   pthread_create(&thr,NULL,receiver,NULL);
   pthread_join(thr, NULL);
   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_join(ths[i],NULL);
   }
   gettimeofday(&ts, NULL) ;
   t2 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

   pthread_mutex_destroy(&mutex);
   pthread_cond_destroy(&not_full);
   pthread_cond_destroy(&no_empty);

   printf("Time: %lf\n", (t2-t1)/1000.0);
   return 0;
}
void * receiver (void * param)
{
    const int MAX_REQUESTS = 5;
    request_t p; int pos=0;

    for (int i=0; i<MAX_REQUESTS; i++)
    {
        receive_request(&p);
        pthread_mutex_lock(&mutex);
        while (n_elements == MAX_BUFFER)
               pthread_cond_wait(&not_full, &mutex);
        buffer[pos] = p;
        pos = (pos+1) % MAX_BUFFER;
        n_elements++;
        pthread_cond_signal(&no_empty);
        pthread_mutex_unlock(&mutex);
    }
    fprintf(stderr,"Closing receiver\n");

    pthread_mutex_lock(&mutex);
    fin=1;
    pthread_cond_broadcast(&no_empty);
    pthread_mutex_unlock(&mutex);

    fprintf(stderr, "Receiver closed\n");
    pthread_exit(0);
    return NULL;
}
void * service (void * param)
{
    request_t p;

    for (;;)
    {
       pthread_mutex_lock(&mutex);
       while (n_elements == 0)
       {
          if (fin==1) {
               fprintf(stderr, "Finalizing service\n");
               pthread_mutex_unlock(&mutex);
               pthread_exit(0);
          }
          pthread_cond_wait(&no_empty, &mutex);
       } // while
       printf(stderr,"Serving pos. %d\n",pos_service);
       p = buffer[pos_service];
       pos_service = (pos_service + 1) % MAX_BUFFER;
       n_elements --;
       pthread_cond_signal(&not_full);
       pthread_mutex_unlock(&mutex);
       reply_request(&p);
    }
    pthread_exit(0);
    return NULL;
}
```

```c
void * receiver (void * param)
{
    const int MAX_REQUESTS = 5;
    request_t p; int pos=0;

    for (int i=0; i<MAX_REQUESTS; i++)
    {
        receive_request(&p);
        pthread_mutex_lock(&mutex);
        while (n_elements == MAX_BUFFER)
                pthread_cond_wait(&not_full, &mutex);
        buffer[pos] = p;
        pos = (pos+1) % MAX_BUFFER;
        n_elements++;
        pthread_cond_signal(&no_empty);
        pthread_mutex_unlock(&mutex);
    }
    fprintf(stderr,"Closing receiver\n");
    pthread_mutex_lock(&mutex);
    fin=1;
    pthread_cond_broadcast(&no_empty);
    pthread_mutex_unlock(&mutex);
    fprintf(stderr, "Receiver closed\n");
    pthread_exit(0);
    return NULL;
}
```

Implementation: service


```
#include "request.h"
#include <pthread.h>
#include <semaphore.h>

#define MAX_BUFFER 128
request_t  buffer[MAX_BUFFER];

int  n_elements  = 0;
int  pos_service = 0;
int  fin = 0;
pthread_mutex_t  mutex;
pthread_cond_t     not_full;
pthread_cond_t     no_empty;

void * receiver (void * param) ;
void * service (void * param) ;

int main()
{
   struct timeval ts;
   long t1, t2;
   pthread_t thr;
   pthread_t ths[MAX_SERVICE];
   const int MAX_SERVICE = 5;

   pthread_mutex_init(&mutex,NULL);
   pthread_cond_init(&not_full,NULL);
   pthread_cond_init(&no_empty,NULL);

   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_create(&ths[i],NULL,service,NULL);
   }
   sleep(1);

   gettimeofday(&ts, NULL) ;
   t1 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000;
   pthread_create(&thr,NULL,receiver,NULL);
   pthread_join(thr, NULL);
   for (int i=0;i<MAX_SERVICE;i++) {
        pthread_join(ths[i],NULL);
   }
   gettimeofday(&ts, NULL) ;
   t2 =(long)ts.tv_sec*1000+(long)ts.tv_usec/1000 ;

   pthread_mutex_destroy(&mutex);
   pthread_cond_destroy(&not_full);
   pthread_cond_destroy(&no_empty);

   printf("Time: %lf\n", (t2-t1)/1000.0);
   return 0;
}

void * receiver (void * param)
{
    const int MAX_REQUESTS = 5;
    request_t p; int pos=0;

    for (int i=0; i<MAX_REQUESTS; i++)
    {
        receive_request(&p);
        pthread_mutex_lock(&mutex);
        while (n_elements == MAX_BUFFER)
               pthread_cond_wait(&not_full, &mutex);
        buffer[pos] = p;
        pos = (pos+1) % MAX_BUFFER;
        n_elements++;
        pthread_cond_signal(&no_empty);
        pthread_mutex_unlock(&mutex);
    }
    fprintf(stderr,"Closing receiver\n");

    pthread_mutex_lock(&mutex);
    fin=1;
    pthread_cond_broadcast(&no_empty);
    pthread_mutex_unlock(&mutex);

    fprintf(stderr, "Receiver closed\n");
    pthread_exit(0);
    return NULL;
}
void * service (void * param)
{
    request_t p;

    for (;;)
    {
       pthread_mutex_lock(&mutex);
       while (n_elements == 0)
       {
          if (fin==1) {
               fprintf(stderr, "Finalizing service\n");
               pthread_mutex_unlock(&mutex);
               pthread_exit(0);
          }
          pthread_cond_wait(&no_empty, &mutex);
       } // while
       printf(stderr,"Serving pos. %d\n",pos_service);
       p = buffer[pos_service];
       pos_service = (pos_service + 1) % MAX_BUFFER;
       n_elements --;
       pthread_cond_signal(&not_full);
       pthread_mutex_unlock(&mutex);
       reply_request(&p);
    }
    pthread_exit(0);
    return NULL;
}
```

```
void * service (void * param)
{
    request_t p;

    for (;;)
    {
       pthread_mutex_lock(&mutex);
       while (n_elements == 0)
       {
          if (fin==1) {
               fprintf(stderr, "Finalizing service\n");
               pthread_mutex_unlock(&mutex);
               pthread_exit(0);
          }
          pthread_cond_wait(&no_empty, &mutex);
       } // while
       printf(stderr,"Serving pos. %d\n", pos_service);
       p = buffer[pos_service];
       pos_service = (pos_service + 1) % MAX_BUFFER;
       n_elements --;
       pthread_cond_signal(&not_full);
       pthread_mutex_unlock(&mutex);
       reply_request(&p);
    }
    pthread_exit(0);
    return NULL;
}
```

Comparison

Sequential	Process per req.	Thread per request	Pool of threads
62.11 sec.	24.08 sec.	20.01 sec.	?

OPERATING SYSTEMS: COMMUNICATION AND SYNCHRONIZATION AMONG PROCESSES

Concurrent server development