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Chapter 4 – Threads & Concurrency

Spring 2023

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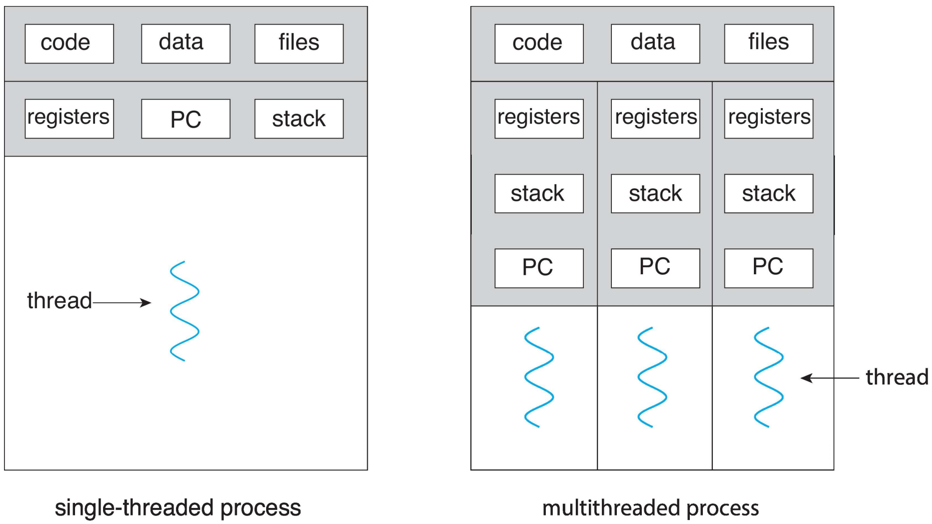
Threads & Concurrency

- Overview
- Multicore Programming
- Multithreading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Examples

Overview

- Most modern applications are multithreaded
- Threads run within application
- Multiple tasks with the application can be implemented by separate threads
  - E.g. Update display, Fetch data, Spell checking, Answer a network request
- Process creation is **heavy-weight** while thread creation is **light-weight**
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

Overview


code
data
files
registers
PC
stack
thread
single-threaded process
code
data
files
registers
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registers
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stack
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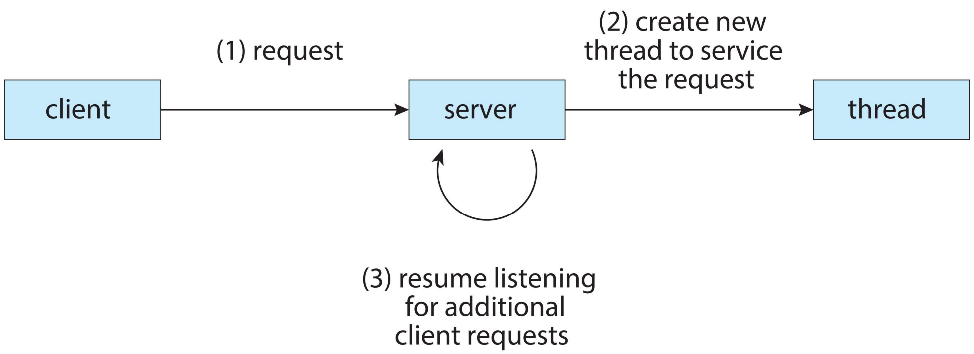
PC
PC
PC
thread
multithreaded process


client
(1) request
server
(2) create new thread to service the request
thread
(3) resume listening for additional client requests

Overview

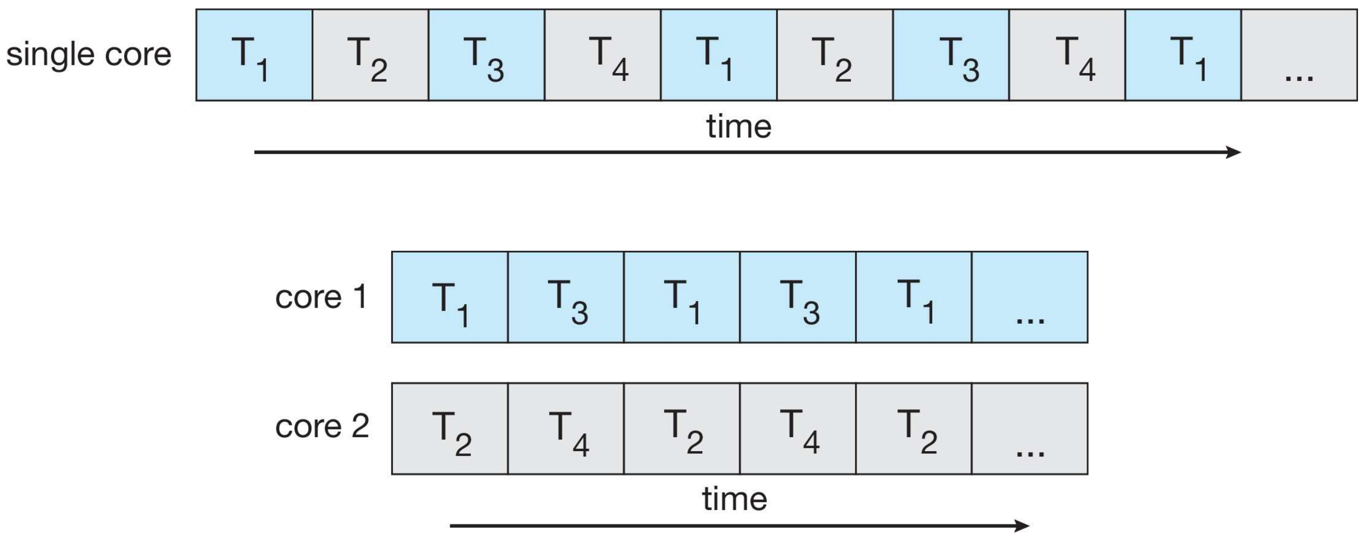
- Benefits
  - **Responsiveness** – may allow continued execution if part of process is blocked, especially important for user interfaces
  - **Resource Sharing** – threads share resources of process, easier than shared memory or message passing
  - **Economy** – cheaper than process creation, thread switching lower overhead than context switching
  - **Scalability** – process can take advantage of multicore architectures

Multicore Programming

- **Parallelism** implies a system can perform more than one task simultaneously
- **Concurrency** supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

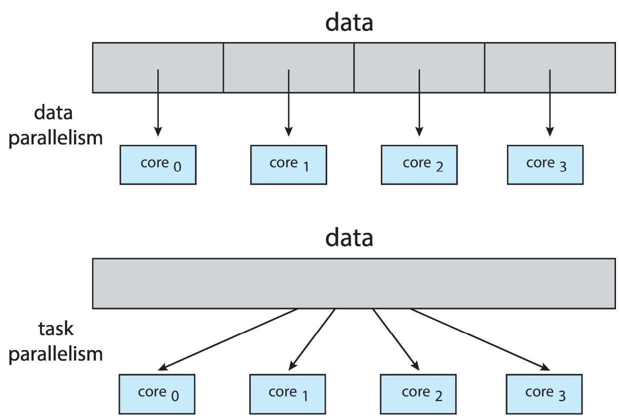
Multicore Programming

- Concurrent execution vs. Parallelism



Multicore Programming

- Types of parallelism
- **Data parallelism** – distributes subsets of the same data across multiple cores, same operation on each
- **Task parallelism** – distributing threads across cores, each thread performing unique operation



Multicore Programming

- Multicore or multiprocessor systems puts pressure on programmers, challenges include:
  - Dividing activities
  - Balance
  - Data splitting
  - Data dependency
  - Testing and debugging

Multicore Programming

- **Latency** – the amount of time it takes for a task to run from start to finish
- **Speed up in latency** – the calculated speedup of architecture 2 with respect to architecture 1

$$S_{\text{latency}} = \frac{L_1}{L_2}$$

Multicore Programming

- If a task can be done in 60 seconds when run in serial and 30 seconds when run in parallel, we say the task is run in "1/2 the time" or "2 times faster"
- If a task can be done in 50 seconds when run in serial and 10 seconds when run in parallel, we say the task is run in "1/5th the time" or "5 times faster"
- In general, if a task can be done in X seconds in scenario 1 and Y seconds in scenario 2, then scenario 2 accomplishes the task in 1/(X/Y) the time or (X/Y) times faster
- If we know what portion of a task must be run in serial and what portion of a task can be run in parallel, we can predict the speedup in latency when parallelizing the entire task

Multicore Programming

- Amdahl's Law
  - Identifies performance gains from adding additional cores to an application that has both serial and parallel components
    - S is serial portion
    - N processing cores

$$speedup \le \frac{1}{S + \frac{(1-S)}{N}}$$

Multicore Programming

- Amdahl's Law
  - That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times

$$\frac{1}{\frac{0.25}{1} + \frac{0.75}{2}}$$

  - What about 50% parallel / 50% serial on 2 cores? A speedup of ~1.3

$$\frac{1}{\frac{0.5}{1} + \frac{0.5}{2}}$$

  - What about 50% parallel / 50% serial on 1024 cores?

$$\frac{1}{\frac{0.5}{1} + \frac{0.5}{1024}}$$

Multicore Programming

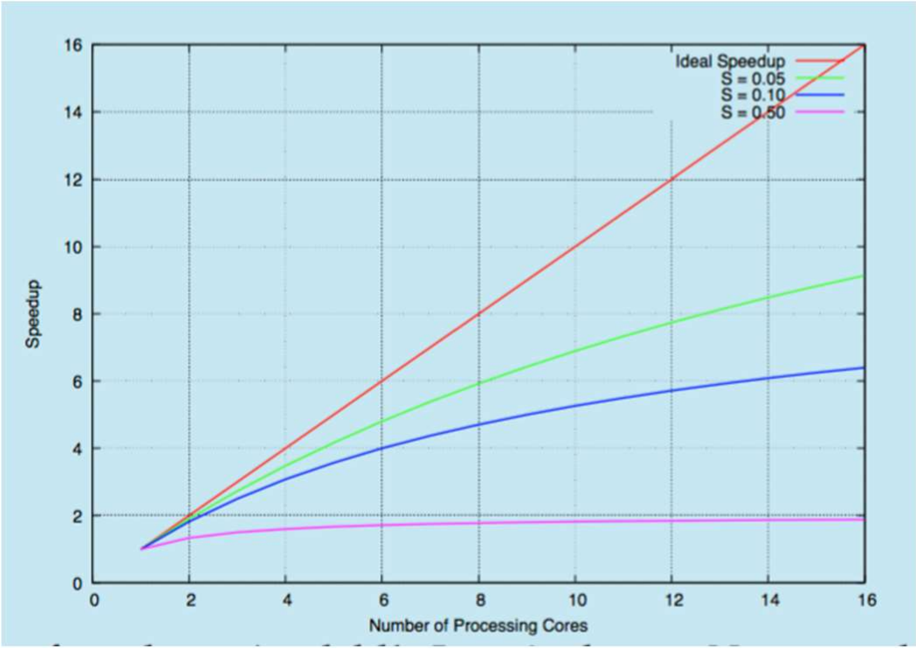
- Amdahl's Law
  - As N approaches infinity, speedup approaches 1 / S
    - Serial portion of an application has disproportionate effect on performance gained by adding additional cores
  - As S approaches 0, speedup approaches N

Multicore Programming

- Amdahl's Law applies to all parallel tasks, not just cores
  - What about a task where some parts are more parallel than others?
    - 11% must be done in serial
    - 18% can be done 5 times faster (1/5th the time)
    - 23% can be done 20 times faster (1/20th the time)
    - 48% can be done 1.6 times faster (1/1.6th the time)

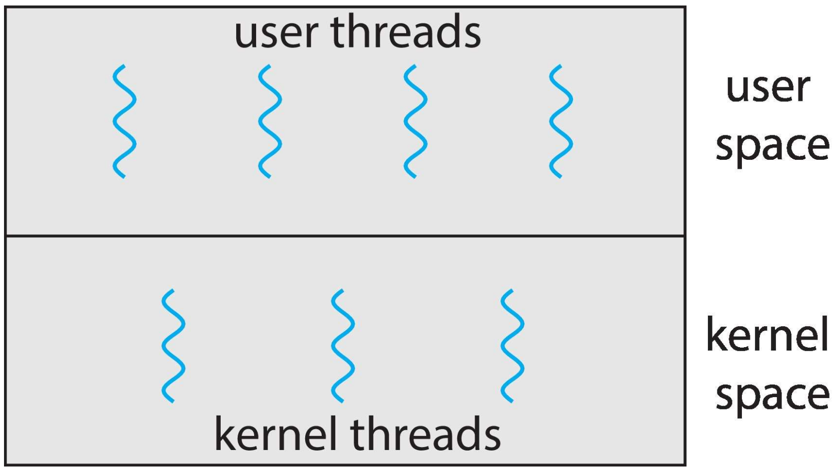
$$S_{\text{latency}} = \frac{1}{\frac{p1}{s1} + \frac{p2}{s2} + \frac{p3}{s3} + \frac{p4}{s4}} = \frac{1}{\frac{0.11}{1} + \frac{0.18}{5} + \frac{0.23}{20} + \frac{0.48}{1.6}} = 2.19.$$

Multicore Programming



Multithreading Models

- User threads - management done by user-level threads library (see the next section)
- Kernel threads - Supported by the Kernel
- Some relationship must exist between user threads and kernel threads

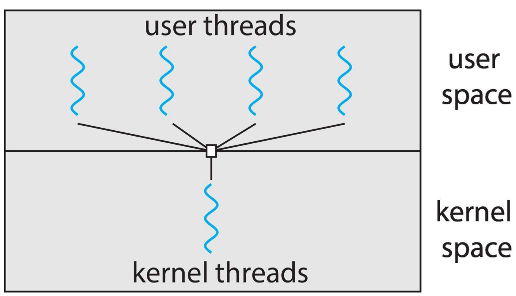


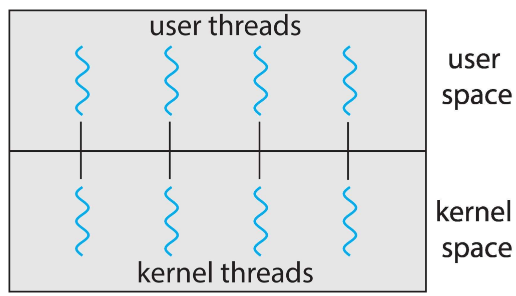
Multithreading Models

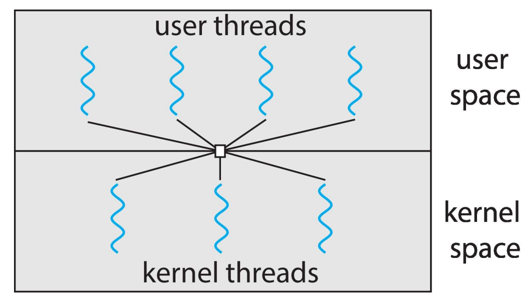
- Many-to-One
  - The developer can create as many threads as they wish, but the kernel is limiting parallelism
- One-to-One
  - The developer can create as many threads as they wish, but the kernel may limit or run out of resources
- Many-to-Many
  - The developer can create as many threads as they wish, but the kernel needs to manage threads

Multithreading Models

- Since computers have more cores these days, one-to-one is used in Linux and Windows and is the most common approach
- Many-to-One vs. One-to-One vs. Many-to-Many







Thread Libraries

- POSIX Pthreads
  - Must include `pthread.h`
  - See the manpage: `man pthreads`
  - On Linux, both `fork()` and `pthread_create()` use the system call `clone()`
    - Fork shares nothing. Threads share, for example, file-system information (`CLONE_FS`), memory space (`CLONE_VM`), signal handlers (`CLONE_SIGHAND`) and open files (`CLONE_FILES`).
- Windows threads
- Java threads

Implicit Threading

- Some compilers and run-time libraries will insert threading for developers rather than asking the developer to handle threading explicitly

- The general idea is to just "label" a task (e.g. a function) as "able to be run in parallel in a thread". The compiler or run-time library does the rest.

- Example strategies: Thread pools, Fork-join model, OpenMP, Grand Central Dispatch, Intel Thread Building Blocks

Threading Issues

- Semantics of fork() and exec() system calls
- Signal handling
  - Synchronous and asynchronous
- Thread cancellation of target thread
  - Asynchronous or deferred

Threading Issues

- Semantics of fork() and exec() system calls
  - Does fork() duplicate only the calling thread or all threads?
    - On Linux, only the calling thread is duplicated. Therefore, the child process starts single threaded
    - Some UNIXes have two versions of fork
  - exec() usually works as normal – replace the running process including all threads

Threading Issues

- Signal handling
  - Signals are used in UNIX systems to notify a process that a particular event has occurred.
    - When a signal is sent to a process, its normal execution is interrupted
  - Such events can arise due to internal or external sources:
    - Internal: Manual (intentional) signals, Illegal instruction (e.g. divide by zero)
    - External: e.g. `CTRL+C` or `kill` command
  - Upon receipt of a signal, the process takes some action (the "handler")

Threading Issues

- Signal handling
  - A signal handler is used to process signals
    - Signal is generated by particular event
    - Signal is delivered to a process
    - Signal is handled by one of two signal handlers: default or user-defined

Threading Issues

- Signal handling
  - Important signals. See `man 7 signal`
    - SIGALRM – Timer signal. call with `alarm()` or `raise(SIGALRM)`
    - SIGINT – Interrupt from keyboard (e.g. CTRL+C)
    - SIGTERM – Termination signal (e.g. `kill <pid>`)
    - SIGKILL – CANNOT be caught. No user-defined option (e.g. `kill -9 <pid>`)

Threading Issues

- Signal handling. For single-threaded, signal delivered to process
  - Where should a signal be delivered for multi-threaded? Depends on the signal
    - Deliver the signal to the thread to which the signal applies
    - Deliver the signal to every thread in the process (e.g. SIGKILL)
    - Deliver the signal to certain threads in the process
    - Assign a specific thread to receive all signals for the process
  - `kill(pid_t pid, int signal)` vs. `pthread_kill(pthread_t tid, int signal)`

Threading Issues

- Signal handling
  - Every signal has a default handler that the kernel runs when handling signal
    - User-defined signal handler can override default
      - ```
        #include <signal.h>
        int alarmflag=0;
        void alarmHandler (){
            printf("An alarm clock signal was received\n");
            alarmflag = 1;
        }
        ```
        ```

Threading Issues

```
void main() {
    signal(SIGALRM, alarmHandler);
    alarm(3);
    printf("Alarm has been set\n");
    while (alarmflag==0);
    printf("Back from alarmHandler function\n");
}
```

Threading Issues

- Thread cancellation of target thread
  - Terminating a thread before it has finished
  - Thread to be canceled is **target thread**
  - Two general approaches:
    - **Asynchronous cancellation** terminates the target thread immediately
    - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled

Threading Issues

- Thread cancellation of target thread
  - Use `pthread_cancel()` – but this is only a **request**
  - Use `pthread_setcanceltype()` to set it. Use `pthread_testcancel()` to check for cancellation requests

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

 . . .

/* cancel the thread */
pthread_cancel(tid);

/* wait for the thread to terminate */
pthread_join(tid,NULL);
```

Examples

- Create a thread
  - `int pthread_create(pthread_t* thread, pthread_attr_t* attr, void * (start_routine), void *arg);`
    - Returns 0 to indicate success, otherwise returns error code
    - `thread` – name of the new thread
    - `attr` – argument that specifies the attributes of the thread to be created (NULL = default attributes)
    - `start_routine` – function to use as the start of the new thread
    - `arg` – argument to pass to the new thread routine

Examples

- Waiting for a thread to complete
  - `int pthread_join(pthread_t thread, void **retval);`
    - Returns 0 to indicate success, otherwise returns error code
    - `thread` – name of the new thread
    - `retval` – copy the return value of pthread_exit() into the address of retval
  - If you do not wait for a thread to complete, the parent process may get cleaned up before the thread can do its work

Examples

```
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>

void *do_work() {
    printf("Hello, World!...I am a thread\n");
}
int main(int argc, char **argv) {
    pthread_t worker_thread;
    if (!pthread_create(&worker_thread, NULL, do_work, NULL)) {
        printf("Error while creating thread\n");
    }
    pthread_join(worker_thread, NULL);
}
```

name of the new thread.

if join is not here,

Examples

- ```
  //3 threads
  #include <stdio.h>
  #include <unistd.h>
  #include <pthread.h>

  ...
  int main(int argc, char **argv) {
      pthread_t worker_thread[3];
      for (int i = 0; i<3; i++){
          if (!pthread_create(&worker_thread[i], NULL, do_work, NULL)) {
              printf("Error while creating thread\n");
          }
      }
      for (int i = 0; i<3; i++){
          if (!pthread_join(worker_thread[i], NULL)){
              printf("Error joining with thread");
          }
      }
  }
  ```
  ```

Examples

- Passing data to threads
  - Typically, you want to create threads that work independently, so passing data back and forth is unusual
  - However, there are a few ways to copy data between the parent and its threads or between threads themselves
    - Global variables (Remember, threads, **unlike** forked processes, can share global variables. This can be useful but be careful about updating them. Solutions in chapter 6) If we're using forking, this cannot be used.
    - Arguments to pthread_create, pthread_exit, pthread_join
      - We could use a pipe as an argument

Examples

the return type have to be the same as accept type.

casting the input as string.

```
//Pass in a message
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>
void *thread_prints_msg(void *msg) {
    printf("From thread_prints_msg: %s\n", (char *) msg);
}
int main(int argc, char **argv){
    pthread_t thread_1;
    printf("From main: Going to create Thread...\n");
    pthread_create(&thread_1, NULL, thread_prints_msg, "Hello, World!");
    pthread_join(thread_1, NULL);
    printf("thread terminates...\n");
    return 0
}
```

passing str

Examples

- ```
  //3 threads. Pass data in only
  #include <stdio.h>
  #include <unistd.h>
  #include <pthread.h>

  void *do_work(void * args) {
      int threadNumber = *(int *) args;
      printf("Hello, World!...I am thread %d\n", threadNumber);
  }
  int main(int argc, char **argv) {
      pthread_t worker_thread[3];
      int threadNumber[3];
      for (int i = 0; i<3; i++){
          threadNumber[i] = i; //Each thread needs to use its own variable
          if (!pthread_create(&worker_thread[i], NULL, do_work, &threadNumber[i])) {
              printf("Error while creating thread\n");
          }
      }
      ...
  ```

this place is not updated in future for loops
  ```

Examples

- ```
  //15 threads. Pass data in and get data out
  #include <stdio.h>
  #include <unistd.h>
  #include <pthread.h>

  #define MAX_NUMBER 15
  void *do_work(void * args) {
      int *square = (int *)args;
      *square *= *square;
  }
  ```
  ```

Examples

```
• int main(int argc, char **argv) {
      pthread_t worker_thread[MAX_NUMBER];
      int squareNumber[MAX_NUMBER];
      for (int i = 0; i<MAX_NUMBER; i++){
          squareNumber[i] = i;
          if (!pthread_create(&worker_thread[i], NULL, do_work, &squareNumber[i])) {
              printf("Error while creating thread\n");
          }
      }
      for (int i = 0; i<MAX_NUMBER; i++){
          if (!pthread_join(worker_thread[i], NULL)){
              printf("Error joining with thread");
      }
      printf("%d squared is %d\n", i, squareNumber[i]);
  }
  }
```

Examples

- ```
  //Use a pipe
  #include <stdio.h>
  #include <unistd.h>
  #include <pthread.h>

  void * dowork(void* args){
      int *port = (int *) args;
      char s[4];
      read(port[0],&s,sizeof(s));
      printf("Thread finds %s\n", s);
  }
  ```
  ```

Examples

- ```
  int main(int argc, char **argv) {
      int port[2];
      if (pipe(port) < 0){
          perror("pipe error");
          exit(1);
      }
      char s[4] = "ABC"; //Note: sizeof(s) == 4
      write(port[1],s,sizeof(s)); // write string
  ...
      pthread_create(&tid, NULL, dowork, port);
  ...
  ```
  ```

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