Ch14. Threads
Concurrent Functions

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Doing Several Things at Once

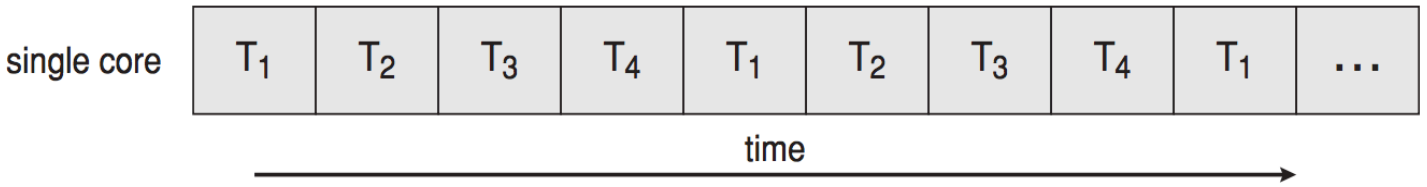
- **Using fork and exec**, we can **run several programs** at the same time.
- What if we want to **run several functions** at the same time or **several invocations of the same function**?
- In this chapter, we study **threads**.

What is in a process?

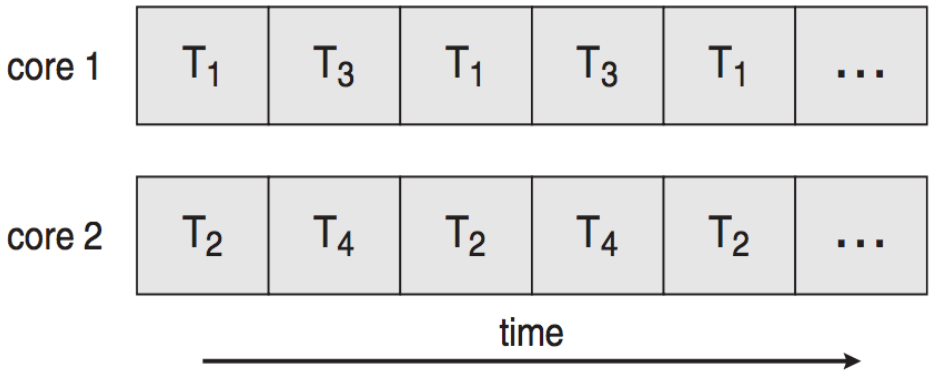
- A process consists of
  - An address space, containing
    - The code (instructions) for the running program
    - The data for the running program
  - Thread state, consisting of
    - The program counter (PC), indicating the next instruction
    - The stack pointer register
    - Other general purpose register values
  - A set of OS resources
    - Open files, network connections
- What if decompose …
  - Address space
  - Thread state (stack, stack pointer, program counter, registers)
  - OS resources

Thread: Concurrency vs. Parallelism

- Concurrent execution on single-core system:



- Parallelism on a multi-core systems:



Thread: Motivation

- One way to get concurrency and parallelism is to use multiple processes
  - The programs (code) of distinct processes are isolated from each other

- Threads are another way to get concurrency and parallelism
  - Threads share a process → same address space, same OS resources
  - Threads have private stack, CPU state, registers
    - So, threads are schedulable

What's needed?

- **In many cases**
  - Everybody wants to run the same code
  - Everybody wants to access the same data
  - Everybody has the same privileges
  - Everybody uses the same resources (open files, network connections, etc)

- **But, everybody would like to have multiple hardware execution states for concurrency and parallelism**
  - An execution stack and stack pointer (SP)
  - The program counter (PC), indicating the next instruction
  - A set of general-purpose processor registers and their values

Thread : Key Idea

- **Key idea:**
  - **Separate the concept of a process (address space, OS resources)** from that of a minimal “thread state” (execution state: stack, stack pointer, program counter, registers)
  - **This execution state is usually called a thread, or sometimes, a lightweight process**

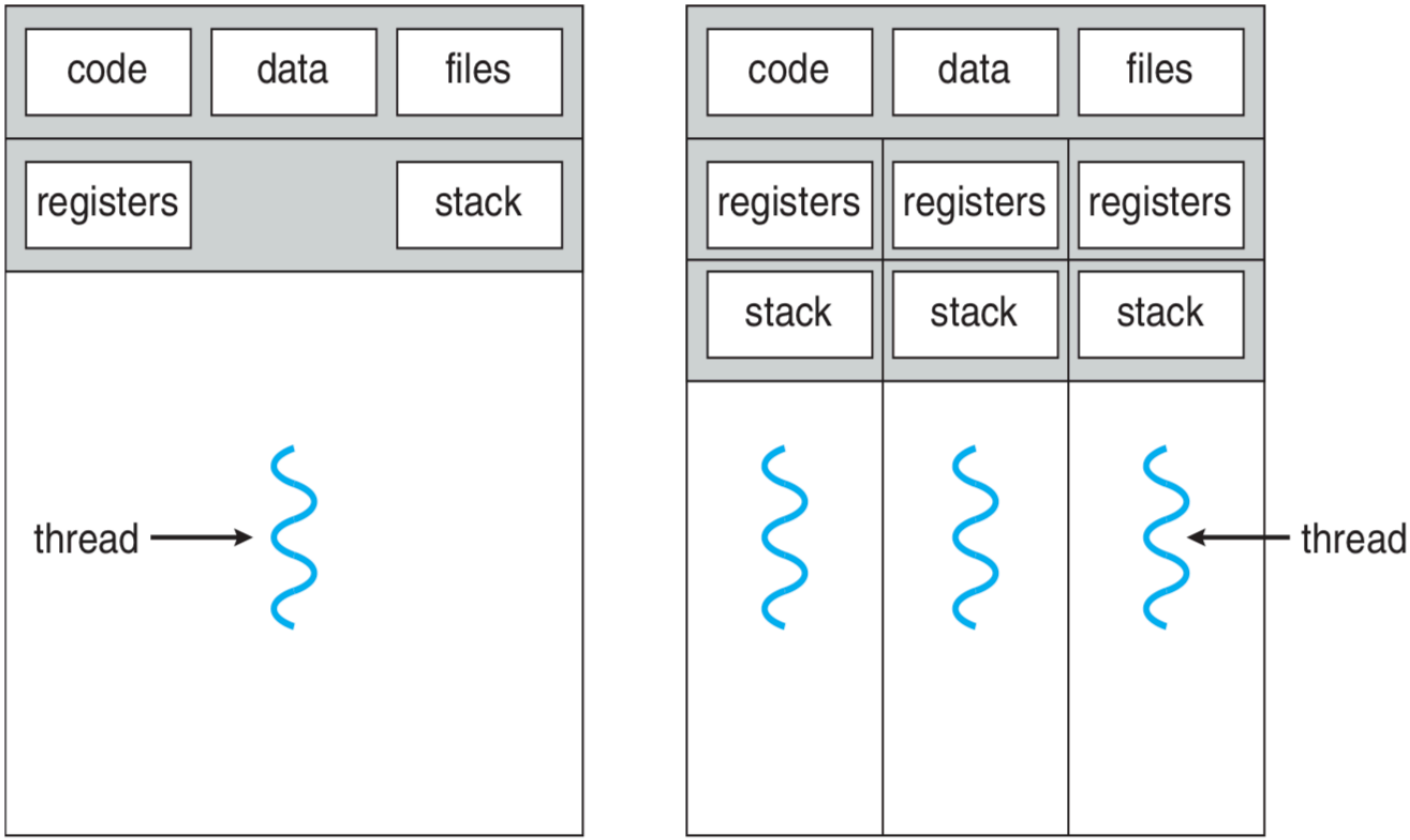
Thread vs Process

- **Most modern operating system support two entities**
  - **Process:** defines the address space and general process attributes (such as open files, etc)
  - **Thread :** defines a sequential execution stream within a process
- A thread is bound to a single process (address space)
  - Address spaces can have multiple threads executing within them
  - Sharing data between threads is cheap: all thread see the same address space.
  - Creating thread is cheap too!
- Threads become the unit of scheduling
  - Processes / address spaces are just containers in which threads execute

Thread vs Process

Process	Thread
Processes are heavyweight operations	Threads are lighter weight operations
Each process has its own memory space	Threads use the memory of the process they belong to
Inter-process communication is slow as processes have different memory addresses	Inter-thread communication can be faster than inter-process communication because threads of the same process share memory with the process they belong to
Context switching between processes is more expensive	Context switching between threads of the same process is less expensive
Processes don’t share memory with other processes	Threads share memory with other threads of the same process

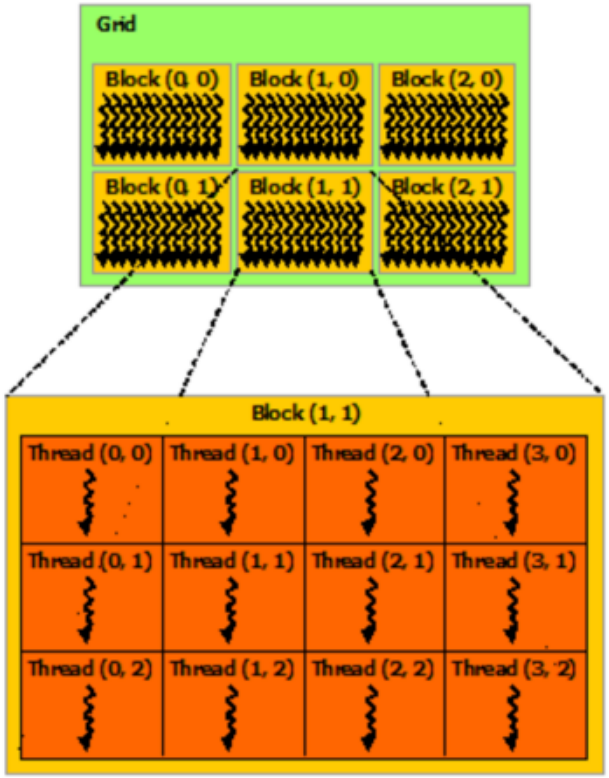
Single and multi-threaded processes

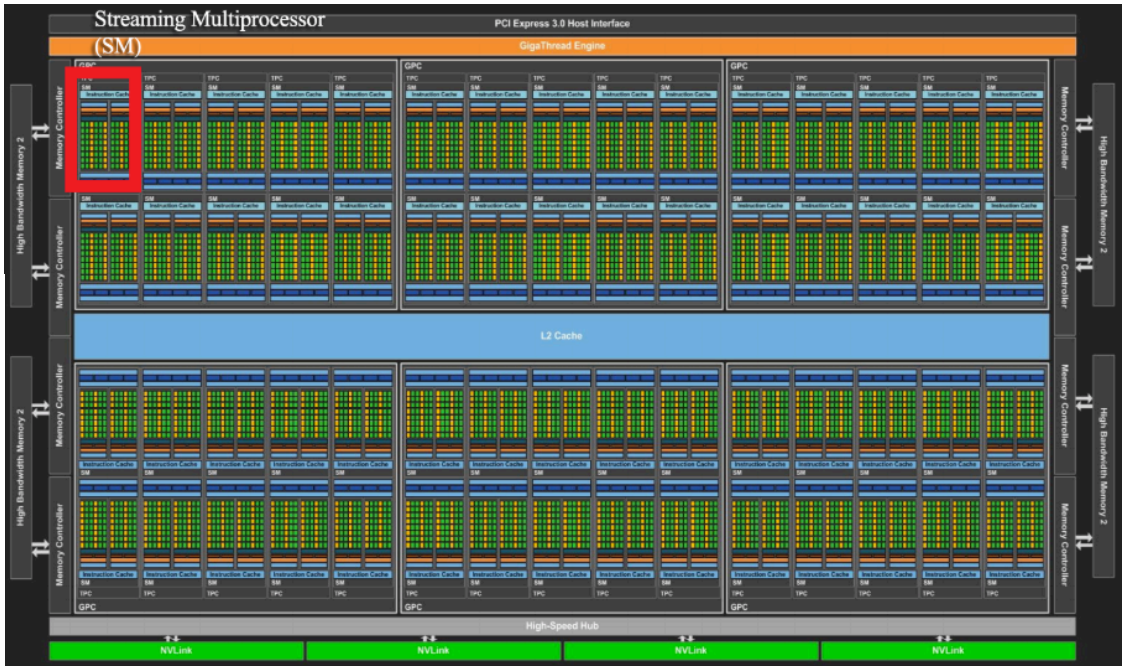


single-threaded process

multithreaded process

GPUs leverage massive Thread-level Parallelism (TLP)





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A Single-Threaded Program

```
 /* hello_single.c  -- a single threaded hello
world program*/

#include <unistd.h>
#include <stdio.h>
#define NUM 5

void print_msg(char*);

main()
{

     print_msg("hello");
     print_msg("world\n");

 }

 void print_msg(char *m)
 {
      int i;

     for(i=0; i<NUM;  i++)
        {
          printf("%s", m);
          fflush(stdout);
          sleep(1);
        }

}
```

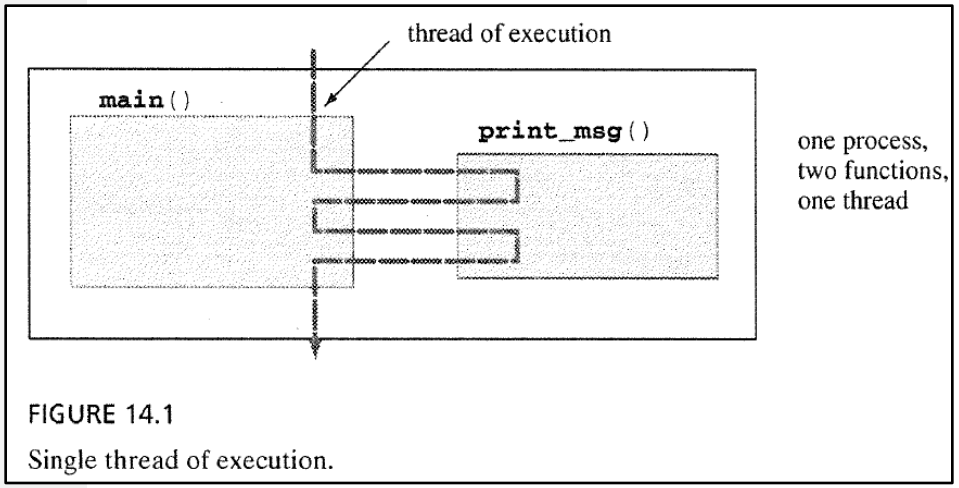


FIGURE 14.1

Single thread of execution.

A Multi-threaded Program

pthread_create

PURPOSE Create a new thread

INCLUDE
```
#include <pthread.h>
```

USAGE
```
int  pthread_create(pthread_t        *thread,
                    pthread_attr_t   *attr,
                    void             *(*func)(void *),
                    void             *arg);
```

ARGS

thread	a pointer to a variable of type pthread_t
attr	a pointer to a variable of type pthead_attr_t or NULL. ※ indicates default thread attributes
func	the function this new thread will run
arg	the argument to be passed to func

RETURNS

0	if successful
errcode	if not successful

A Multi-threaded Program (Cont'd)

pthread_join		
PURPOSE	Wait for termination of a thread	
INCLUDE	#include <pthread.h>	
USAGE	int pthread_join(pthread_t thread, void **retval)	
ARGS	thread	the thread to wait for
	retval	points to a variable to receive the return value from the thread
RETURNS	0	if thread terminates
	errcode	if an error

※ **`pthread_join`** blocks the calling thread until the specified thread terminates.

A Multi-threaded Program (Cont'd)

```
 /* hello_multi.c  -- a multi-threaded  hello world  program*/

#include <unistd.h>
#include <stdio.h>
#include <pthread.h>
#define NUM 5


void *print_msg(void*);

main()
{
     pthread_t  t1, t2;   /* two threads*/


     pthread_create(&t1,  NULL, print_msg,  (void *) "hello");
     pthread_create(&t2,  NULL, print_msg,  (void *) "world\n");
     pthread_join(t1,  NULL);
     pthread_join(t2,  NULL);

 }

 void  *print_msg(void  *m)
 {
   int i;
   for(i=0; i<NUM;  i++)
   {
     printf("%s", m);
     fflush(stdout);
     sleep(1);
   }
}
```

```
$ cc hello_multi.c -lpthread -o hello_multi
$ ./hello_multi
helloworld
helloworld
helloworld
helloworld
helloworld
$
```

A Multi-threaded Program (Cont'd)

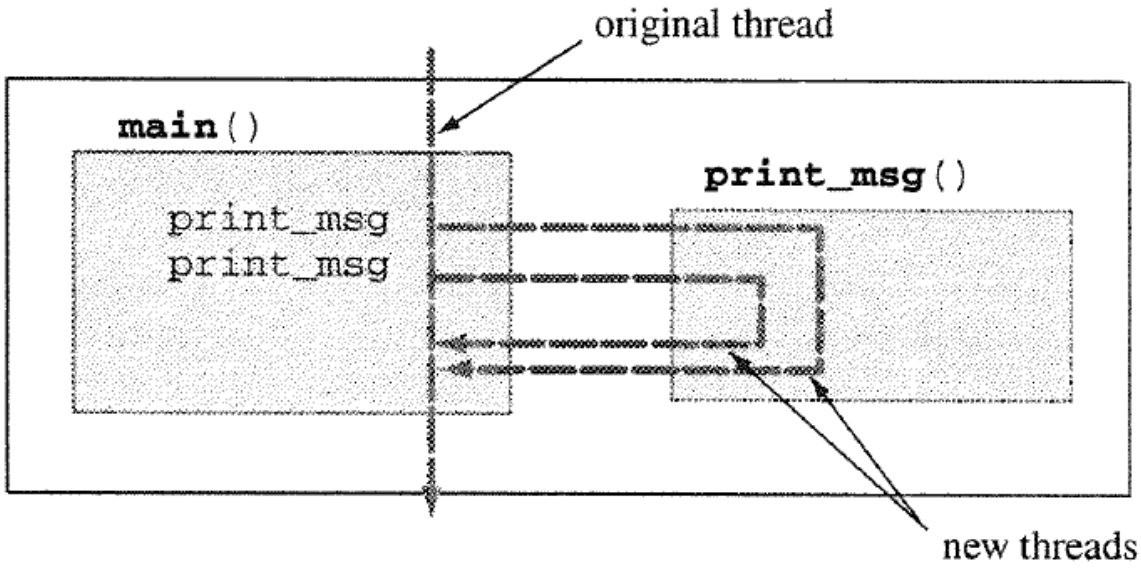


FIGURE 14.2

Multiple Threads of Execution.

Inter-thread Cooperation

- Processes communicate with each other using pipes, sockets, signals, exit/wait, and the environment.
- **Threads** execute functions **in a single process**, so **threads share global variables.**
- **Threads** can **communicate** by setting and reading **these global variables.**
- **Simultaneous access to memory** is a **powerful**, but **dangerous**.

Inter-thread Cooperation, Ex1 : incprint.c

```c
// incprint.c - one thread increments, the other prints
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>
#define NUM 5

int counter = 0;
void    *print_count(void*);  // its function

void main(){
    pthread_t t1;            // one thread
     int i;

    // create a thread
    pthread_create(&t1, NULL, print_count, NULL);
   for(i = 0;i<NUM;i++){
      counter++;
      sleep(1);
   }
    // wait for a thread to be completed
    pthread_join(t1, NULL);
  return 0;
}

void *print_count(void* m){
   int i;
   for(i = 0;i < NUM;i++){
      printf("count = %d\n", counter);
      sleep(1);
   }
   return NULL;
}
```

Inter-thread Cooperation, Ex1 : `incprint.c`

```
// incprint.c - one thread increments, the other prints
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>
#define NUM 5

int counter = 0;
void    *print_count(void*);  // its function

void main(){
    pthread_t  t1;            // one thread
     int i;

    // create a thread
    pthread_create(&t1, NULL, print_count, NULL);
   for(i = 0;i<NUM;i++){
      counter++;
      sleep(2);
   }
    // wait for a thread to be completed
    pthread_join(t1, NULL);
  return 0;
}

void *print_count(void* m){
    int i;
    for(i = 0;i < NUM;i++){
       printf("count = %d\n", counter);
       sleep(1);
    }
    return NULL;
}
```

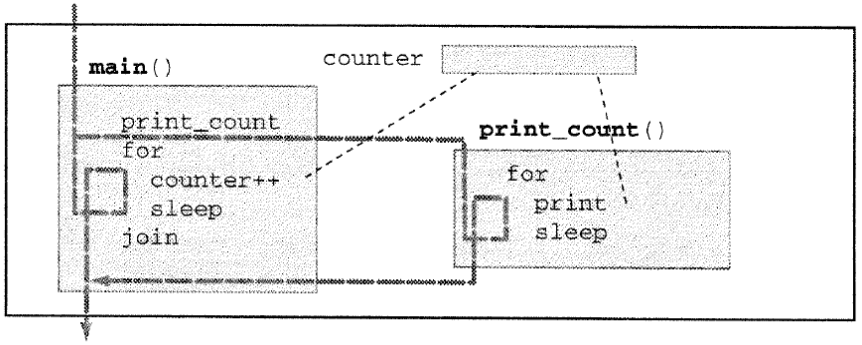


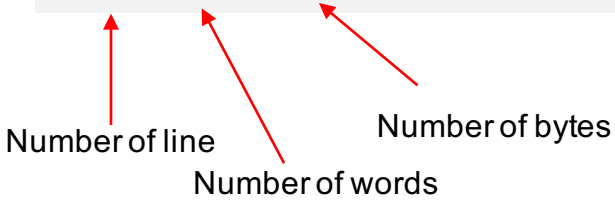
FIGURE 14.3

Two threads share a global variable.

Inter-thread Cooperation, Ex2 : twordcount1.c

- Unix wc program : …

```
seokin@compasslab1  $ wc twordcount1.c  incprint.c
  45  132   992 twordcount1.c
  33   80   572  incprint.c
  78  212  1564 total
```



- How can we design a **multithreaded** program to count and print the total number of words in two files?

Inter-thread Cooperation, Ex2 : twordcount1.c

- Version 1: Two Threads, One Counter

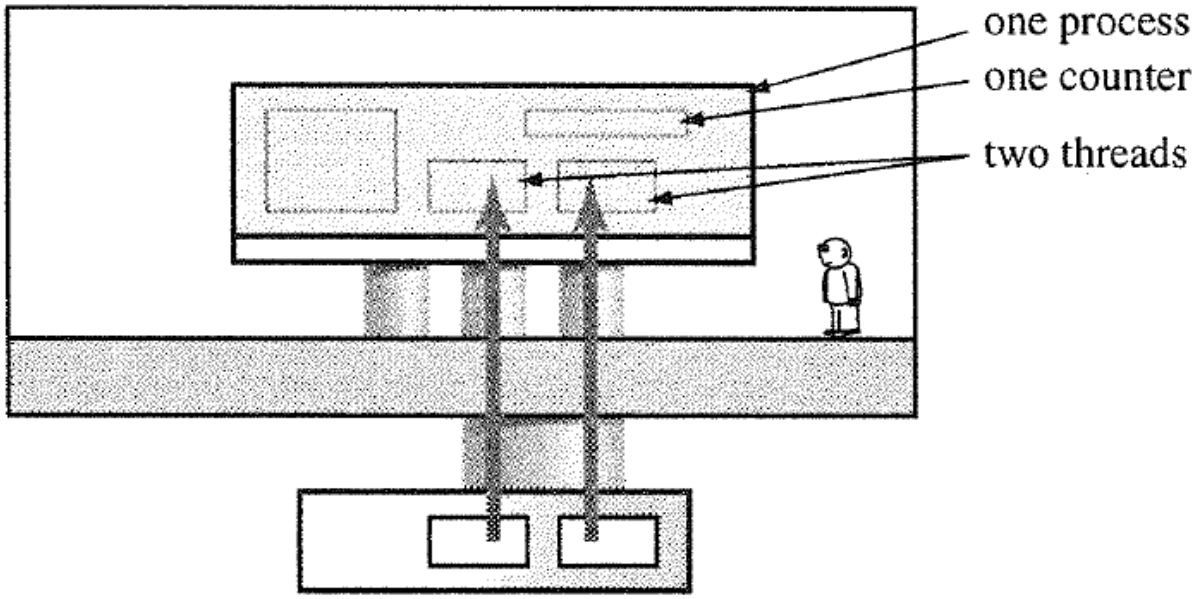


FIGURE 14.4

A common counter for two threads.

```c
/* twordcount1.c  - threaded word counter for two files. Ver1.0 */

#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <ctype.h>

int total_words;

main(int ac, char *av[])
{
    pthread_t t1, t2;
    void *count_words(void*);

     if(ac !=3)
     {
       printf("usage: %s file1 file2\n", av[0]);
       exit(1);
     }

     total_words=0;
    pthread_create(&t1, NULL, count_words, (void*)av[1]);
    pthread_create(&t2, NULL, count_words, (void*)av[2]);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("%5d: total words\n", total_words);
}
```

```
void *count_words(void *f)
 {
    char *filename = (char *) f;
    FILE *fp;
    int c, prevc = '\0';

    if((fp=fopen(filename, "r"))!=NULL)
    {
       while((c=getc(fp))!=EOF)
       {
          if(!isalnum(c) && isalnum(prevc))
             total_words++;
          prevc = c;
       }
       fclose(fp);
    }
    else
       perror(filename);

    return NULL;
 }
```

isalnum(): returns non-zero value if c is a digit or a letter, else it returns 0

```
seokin@compasslab1  $ ./twordcount  singthr.c  twordcount.c
  160: total words
seokin@compasslab1$  ./twordcount  singthr.c  twordcount.c
  158: total words
seokin@compasslab1$  ./twordcount  singthr.c  twordcount.c
  161: total words
seokin@compasslab1$  ./twordcount  singthr.c  twordcount.c
  161: total words
seokin@compasslab1$  ./twordcount  singthr.c  twordcount.c
  159: total words
seokin@compasslab1$  ./twordcount  singthr.c  twordcount.c
  156: total words
```

Different results ! Why?

```
total_words++;
→ total_words = total_words + 1;
```

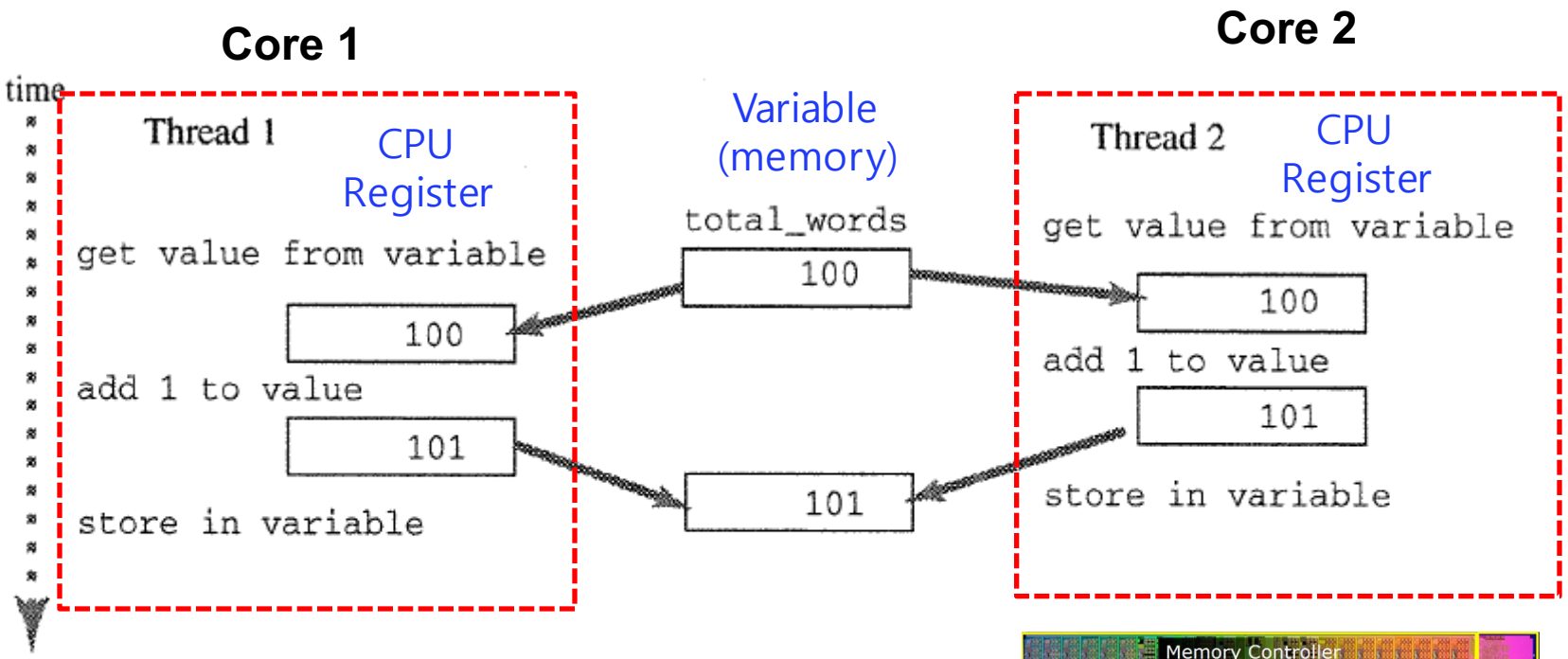
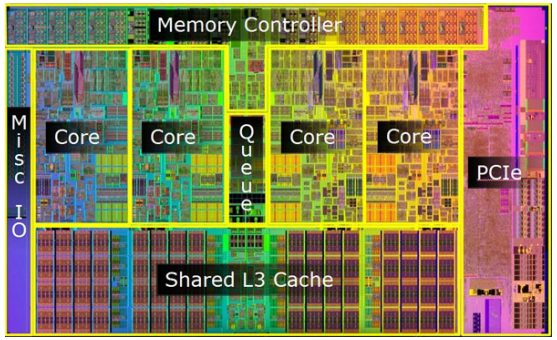


FIGURE 14.5

Two threads increment the same counter.



```
total_words++;
→ total_words = total_words + 1;
```

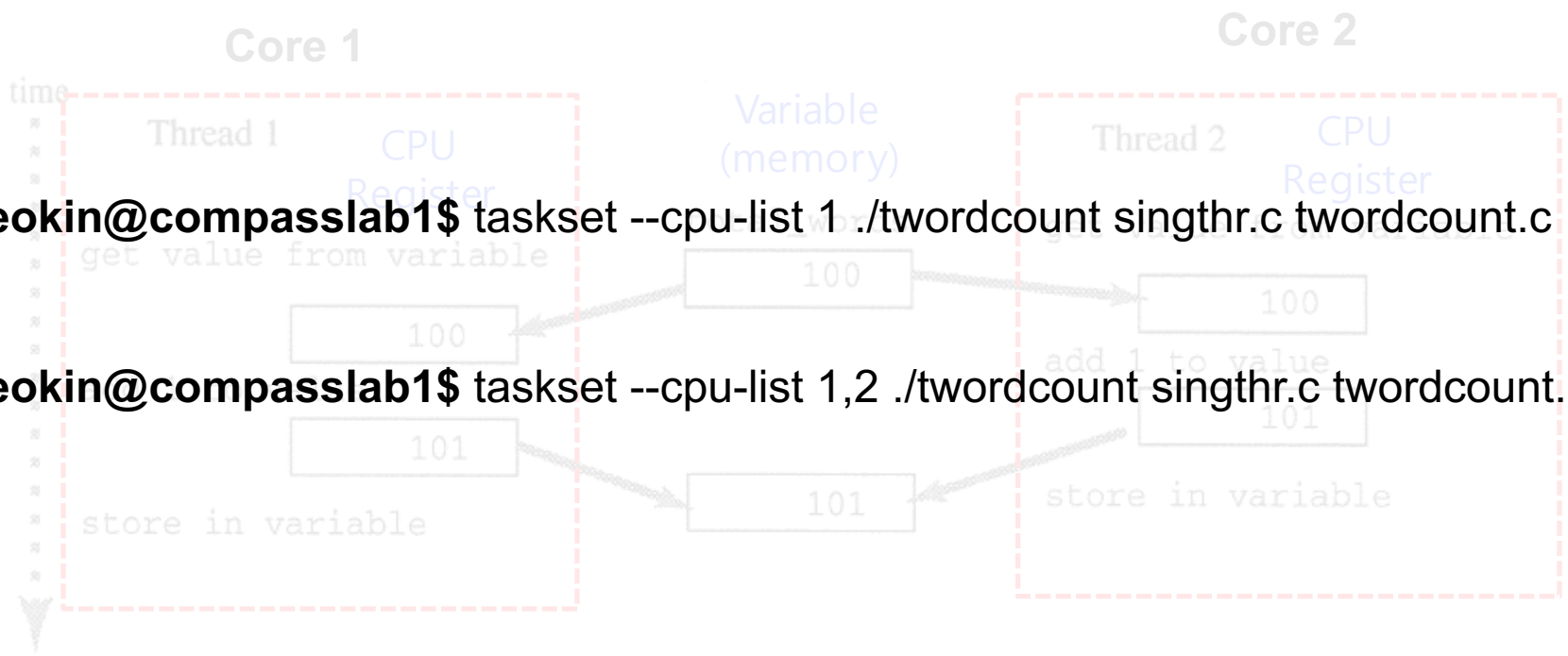


FIGURE 14.5

Two threads increment the same counter.

seokin@compasslab1$ taskset --cpu-list 1 ./twordcount singthr.c twordcount.c

seokin@compasslab1$ taskset --cpu-list 1,2 ./twordcount singthr.c twordcount.c

- How can we prevent threads from interfering with each other?

- **Two solutions :**
  - Version 2: Two Threads, One Counter, One Mutex
  - Version 3: Two Threads, Two Counters, Multiple Arguments to Threads

Inter-thread Cooperation, Ex3 : twordcount2.c

- Version 2 : Two Threads, One Counter, One Mutex
  - The threads system uses variables called **mutual exclusion lock** to prevent simultaneous access to any variable, function, or other resource

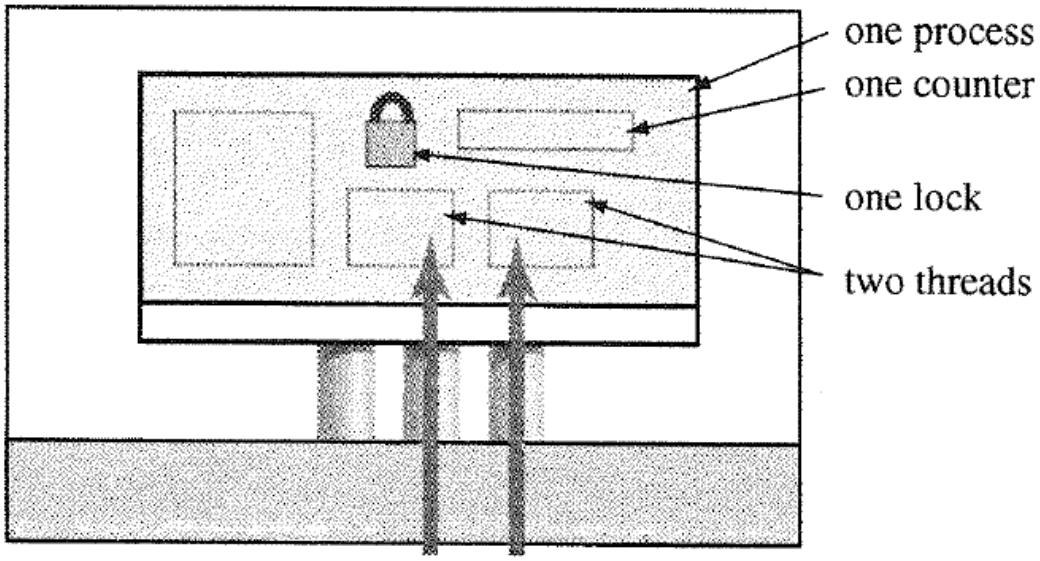
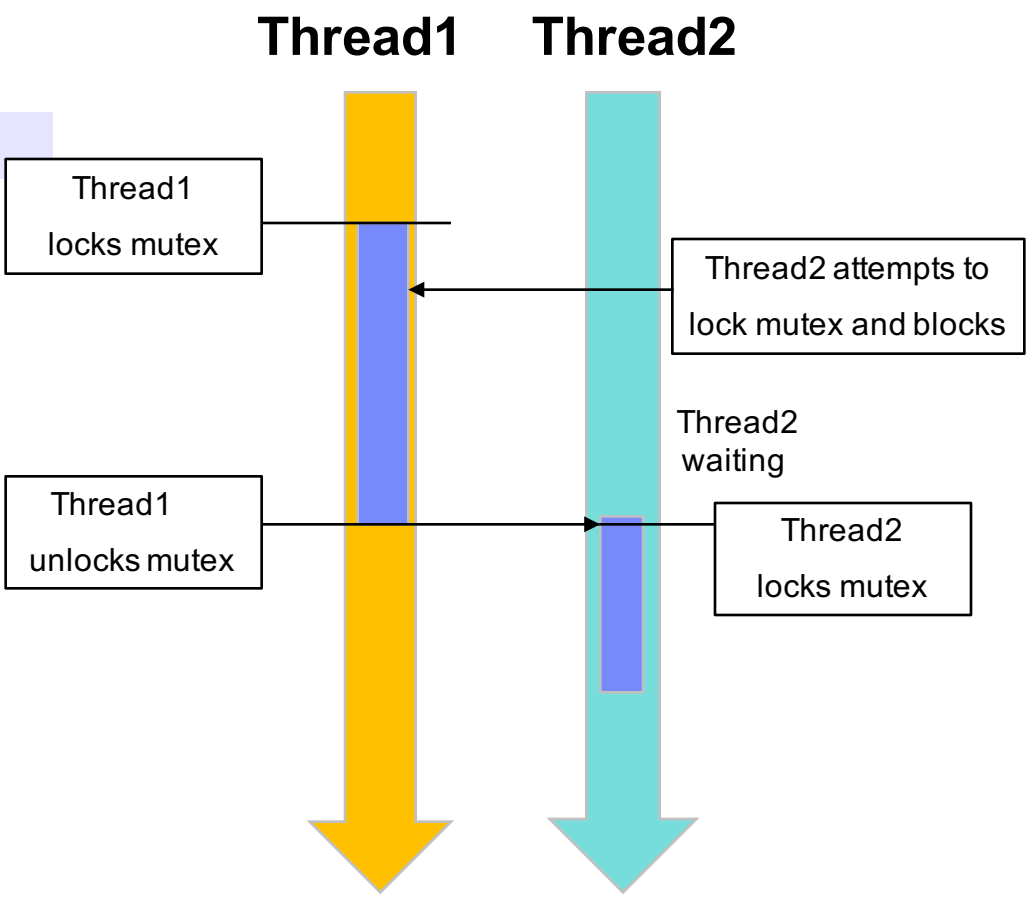


FIGURE 14.6

Two threads use a mutex to share a counter.

```
int  total_words ;
pthread_mutex_t counter_lock = PTHREAD_MUTEX_INITIALIZER;
```

```
pthread_mutex_lock(&counter_lock);
total_words++;
pthread_mutex_unlock(&counter_lock);
```



```c
/*twordcounter2.c  -- threaded word counter for two files */
 /*      version 2: uses mutex to lock counter           */

 #include <stdio.h>
 #include <pthread.h>
 #include <ctype.h>
 #include <stdlib.h>

 int total_words;  /* the counter */
 pthread_mutex_t  counter_lock  = PTHREAD_MUTEX_INITIALIZER;  /* lock*/

 void * count_words(void*);

main(int ac, char *av[])
{
    pthread_t  t1, t2;        /* two threads */
    if(ac!=3){
        printf("usage: %s file1  file2\n", av[0]);
        exit(1);
    }

   total_words = 0;
   pthread_create(&t1,  NULL, count_words,  (void*) av[1]);
   pthread_create(&t2,  NULL, count_words,  (void*) av[2]);
   pthread_join(t1,  NULL);
   pthread_join(t2,  NULL);
   printf("%d:  total words\n",  total_words);
 }
```

```
void *count_words(void *f)
{
     char *filename = (char *) f;
     FILE *fp;
     int c, prevc = '\0';
     if((fp=fopen(filename, "r"))!=NULL){
          while((c=getc(fp))!=EOF){
               if(!isalnum(c) && isalnum(prevc)){
                    pthread_mutex_lock(&counter_lock);
                    total_words++;
                    pthread_mutex_unlock(&counter_lock);
               }
               prevc = c;
          }
          fclose(fp);
     }else
          perror(filename);

  return NULL;
}
```

```
pthread_mutex_lock(&counter_lock);
total_words++;
pthread_mutex_unlock(&counter_lock);
```

pthread_mutex_lock

PURPOSE	Wait for and lock a mutex
INCLUDE	#include <pthread.h>
USAGE	int pthread_mutex_lock(pthread_mutex_t *mutex)
ARGS	mutex a pointer to a mutual exclusion object
RETURNS	0 for success errcode for errors

```
pthread_mutex_lock(&counter_lock);
total_words++;
pthread_mutex_unlock(&counter_lock);
```

pthread_mutex_unlock

PURPOSE	Unlock a mutex
INCLUDE	#include <pthread.h>
USAGE	int pthread_mutex_unlock(pthread_mutex_t *mutex)
ARGS	mutex — a pointer to a mutual exclusion object
RETURNS	0 — for success errcode — for errors

Do We Need a Mutex?

- If both threads might try to modify the same variable at the same time, they have to use a mutex to prevent interference.
  - Mutex ensures that the both threads have a proper view of the memory.

- Using a mutex makes the program run slower.
  - Checking the lock, setting the lock, and releasing the lock for every word in both files adds up to a lot of operations

Inter-thread Cooperation, Ex4 : twordcount3.c

- Version 3: Two Threads, Two Counters, Multiple Arguments to Threads
  - **Give each thread its own counter**

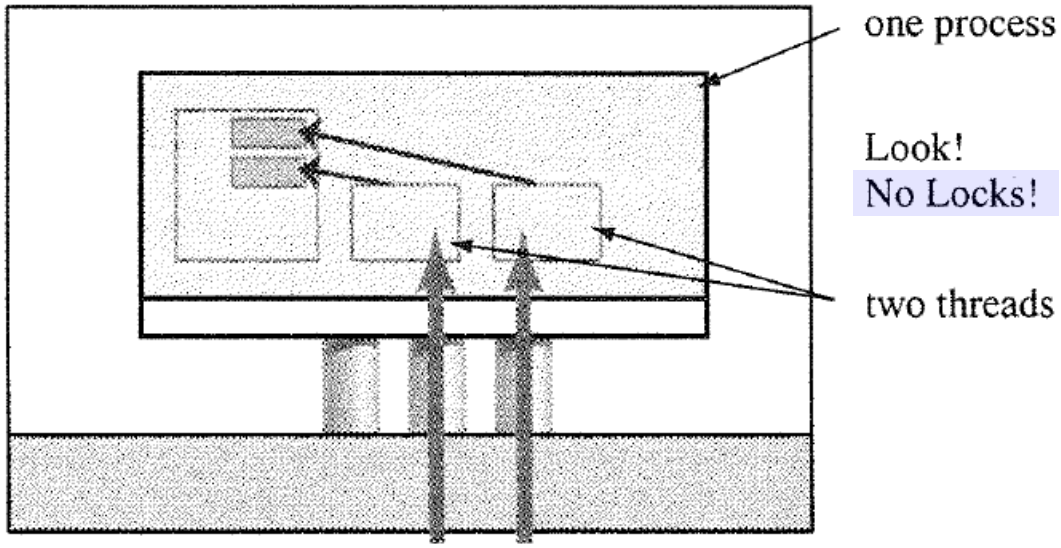


FIGURE 14.7

Each thread has a pointer to its own struct.

```
/* twordcount3.c  - threaded word counter for two files
 *                - version 3: one counter per file
 */

#include <stdio.h>
#include <pthread.h>
#include <ctype.h>
#include <stdlib.h>

struct arg_set {
    char *fname;   /* file to examine   */
    int count;     /* number of words */
};
```

* **`pthread_create`** only lets us pass a single argument. Thus, we need to use a structure data type to pass multiple argument to the thread.

※ Passing pointers to local structs
not only eliminates the need for a mutex,
but also gets rid of global variables.

```
void *count_words(void *);
main(int ac, char *av[])
{
     pthread_t t1, t2;              /*two threads */
     struct arg_set args1, args2;   /*two argsets */

    if(ac !=3){
       printf("usuage: %s file1 file2\n", av[0]);
       exit(1);
     }
     args1.fname = av[1];
     args1.count = 0;
     pthread_create(&t1, NULL, count_words, (void*)&args1);

     args2.fname = av[2];
     args2.count = 0;
     pthread_create(&t2, NULL, count_words, (void *)&args2);

     pthread_join(t1, NULL);
     pthread_join(t2, NULL);
     printf("%5d: %s\n", args1.count, av[1]);
     printf("%5d: %s\n",args2.count, av[2]);
     printf("%5d: total words\n", args1.count+args2.count);
 }
```

```
void *count_words(void *a)
{
     struct arg_set *args = a;
     FILE *fp;
      int c, prevc = '\0';

     if((fp=fopen(args->fname, "r"))!=NULL){
     while((c=getc(fp)) != EOF){
        if(!isalnum(c)&& isalnum(prevc))
            args->count++;
        prevc = c;
    }
    fclose(fp);
  }else
    perror(args->fname);

     return NULL;
}
```

Contents

Inter-thread Notification

- How can one thread notify another thread?
  - When a counting thread finishes its work, how can it notify the original thread that its results are ready?
  - Ex)
    - $ twordcount really-big-file tiny-file

Functions for Condition Variables

pthread_cond_wait	
PURPOSE	Blocks a thread on a condition variable
INCLUDE	`#include <pthread.h>`
USAGE	`int pthread_cond_wait(pthread_cond_t *cond,` `pthread_mutex_t *mutex);`
ARGS	cond — pointer to a condition variable mutex — pointer to a mutex
RETURNS	0 — if successful errcode — if not successful

Functions for Condition Variables

- ***pthread_cond_wait()***
  - This function is used to block on a condition variable
    - It allows a set of threads to sleep until tickled!
    - This makes processor time available to the other threads!
  - called with *mutex* locked by the calling thread
  - atomically release *mutex* and cause the calling thread to block on the condition variable *cond*
  - upon successful return, the mutex has been locked and is owned by the calling thread.
  - The mutex is used to protect *the condition variable itself*

Functions for Condition Variables

pthread_cond_signal	
PURPOSE	Unblocks a thread waiting on a condition variable
INCLUDE	`#include <pthread.h>`
USAGE	`int pthread_cond_signal(pthread_cond_t *cond);`
ARGS	cond pointer to a condition variable
RETURNS	0 if successful errcode if not successful

```
/*twordcount4.c - threaded word counter for two files.
*               - Version4: condition variable allows counter
*                           functions to report results early
*/

 #include <stdio.h>
 #include <pthread.h>
 #include <ctype.h>
 #include <stdlib.h>
 struct arg_set{
     char *fname;
     int count;
};

 struct arg_set *mailbox = NULL;
 pthread_mutex_t lock    = PTHREAD_MUTEX_INITIALIZER;
 pthread_cond_t flag     = PTHREAD_COND_INITIALIZER;
```

```
void *count_words(void*);
 main(int ac, char* av[])
 {
    pthread_t t1, t2;
    struct arg_set args1, args2;

    int reports_in = 0;
    int total_words = 0;

    if(ac!=3)
    {
       printf("usage: %s file1 file2\n",av[0]);
       exit(1);
    }

    pthread_mutex_lock(&lock);  /*lock the mail box now*/
    args1.fname = av[1];
    args1.count = 0;
    pthread_create(&t1, NULL, count_words, (void *)&args1);
    args2.fname = av[2];
    args2.count = 0;
    pthread_create(&t2, NULL, count_words, (void *)&args2);
```

```
  while(reports_in<2){
      printf("MAIN: waiting for flag to go up\n");
      pthread_cond_wait(&flag, &lock);              /*wait for notification*/
      printf("MAIN: Wow! flag was raised, I have the lock\n");
      printf("%7d: %s\n", mailbox->count, mailbox->fname);
      total_words += mailbox->count;

      if(mailbox == &args1)
         pthread_join(t1,NULL);
      if(mailbox == &args2)
         pthread_join(t2,NULL);

      mailbox = NULL;
      pthread_cond_signal(&flag);
      reports_in++;
   }
   printf("%7d: total words\n", total_words);

}
```

```
void *count_words(void *a)
{
    struct arg_set *args = a;
    FILE *fp;
    int c, prevc = '\0';

    if((fp=fopen(args->fname, "r"))!=NULL){
        while((c=getc(fp))!=EOF)
        {
            if((!isalnum(c) && isalnum(prevc)))
                args->count++;
            prevc = c;
        }
        fclose(fp);
    }else
        perror(args->fname);

    printf("COUNT: waiting to get lock\n");
    pthread_mutex_lock(&lock);        /*get the mailbox*/
    printf("COUNT: have lock, storing data\n");
    if (mailbox !=NULL)
        pthread_cond_wait(&flag, &lock);

    mailbox = args;                   /*put ptr to our args there */
    printf("COUNT: raising flag\n");
    pthread_cond_signal(&flag);       /*raise the flag*/
    printf("COUNT: unlocking box\n");
    pthread_mutex_unlock(&lock);      /*release the mailbox */
    return NULL;
}
```