Thread

Pangfeng Liu
National Taiwan University

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Process and Threads

- A process is a program in execution.
- A computer may have multiple processes running simultaneously.
- A thread is an execution instance of a process.
- A process may have multiple threads running simultaneously.

UNIX Process

A UNIX process has the following information [1].

- Process ID, process group ID, user ID, and group ID
- Environment variables
- Working directory
- Program instructions
- Registers
- File descriptors
- Signal actions

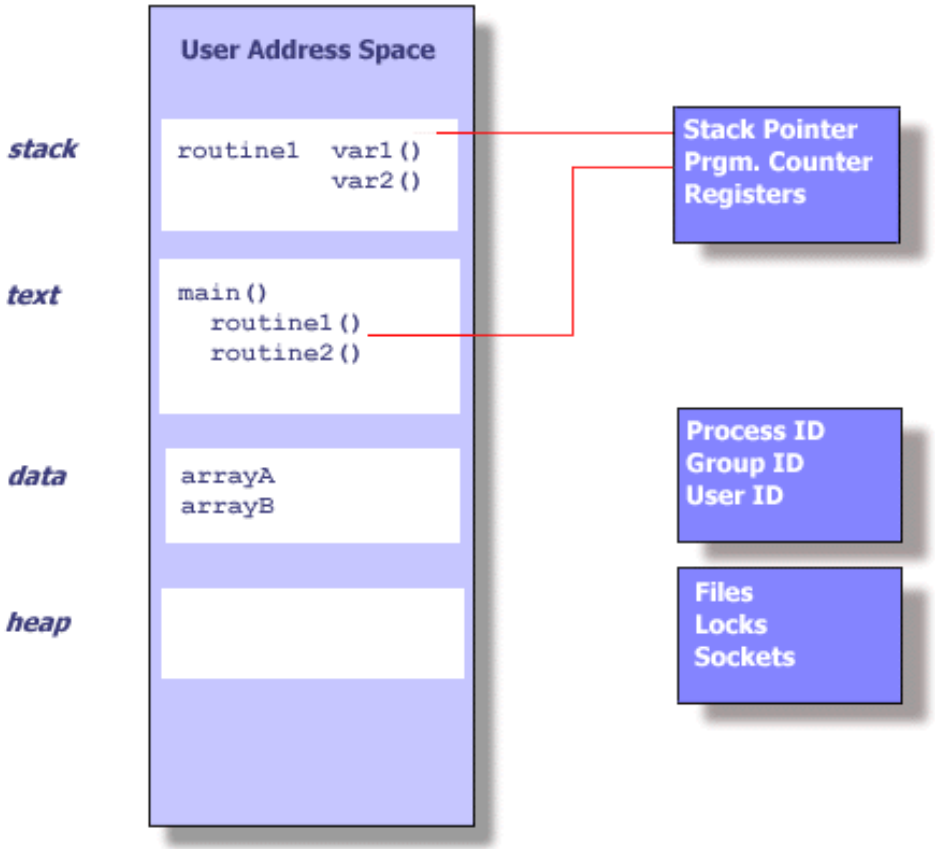
[1] https://computing.llnl.gov/tutorials/pthreads

UNIX Process

A UNIX process may place the data in the following sections.

- Stack
  - Variables declared within functions.
- Heap
  - Storage allocated dynamically (e.g., malloc).
- Data
  - Variables declared globally.

UNIX Process



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[2] https://computing.llnl.gov/tutorials/pthreads/images/process.gif

Discussion

- How to create a process in a UNIX environment?
- How to kill a process in a UNIX environment?

Thread

- A thread executes within a process, and has its own resources – program text, program counter, stack, private variables, etc.
- A thread runs on a core, and multiple threads can run on multiple cores simultaneously.
- We use threads to explore parallelism.

Parallelism

- We want to express parallelism with multi-threading on a multiprocessor because multiple threads can run on multiple cores simultaneously.
- We do *not* use processes since the communication among them require expensive inter-process-communication (IPC).
  - Threads within a process can easily share variables in a shared memory multiprocessor.
- We do *not* use processes since the process creation is expensive.
  - Thread creation is much cheaper.

Thread

- Threads exist within a process and share some of the process resources.
- Threads have their own independent flows of control.
- Threads die if the process dies.
- Threads are "lightweight" because most of the overhead has already been accomplished through the creation of its process.

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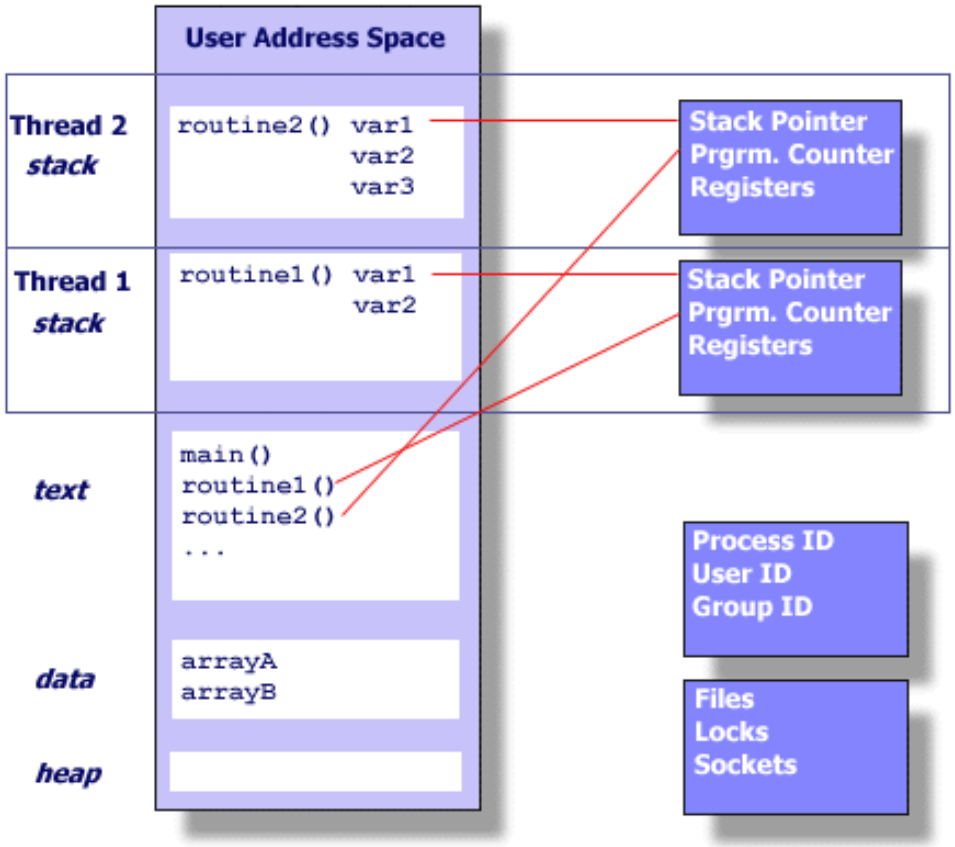
[3] https://computing.llnl.gov/tutorials/pthreads

Threads within a Process



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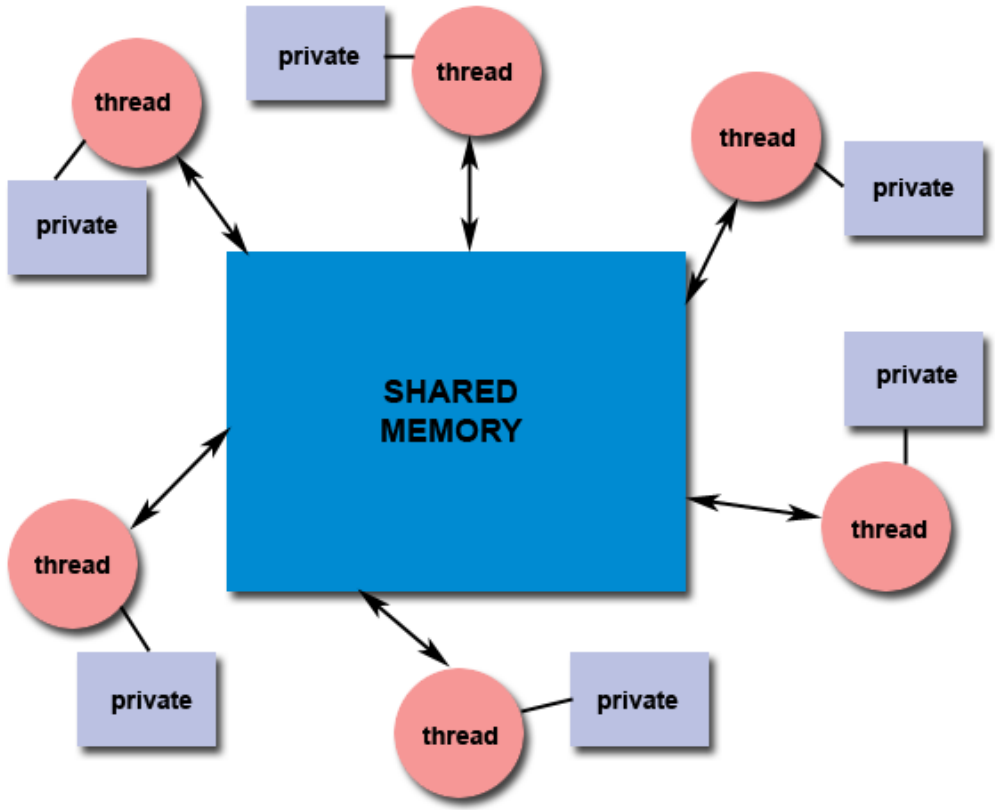
[4] https://computing.llnl.gov/tutorials/pthreads/images/thread.gif

Memory Model

- All threads have access to the same global shared memory and programmers are responsible for synchronizing access (protecting) them.
- Threads also have their own private data for their own private usage.

Shared Memory



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[5] https://computing.llnl.gov/tutorials/pthreads/images/sharedmemoryModel.gif

Pthread

- Historically, hardware vendors have implemented their own proprietary versions of threads.
- These implementations differed substantially from each other making it difficult for programmers to develop portable threaded applications.

Pthread

- In order to take full advantage of the capabilities provided by threads, a standardized programming interface was required[6].
- For UNIX systems, this interface has been specified by the IEEE POSIX 1003.1c standard (1995).
- Implementations adhering to this standard are referred to as POSIX threads, or Pthreads.
- Most hardware vendors now offer Pthreads in addition to their proprietary API's.

[6] https://computing.llnl.gov/tutorials/pthreads

Discussion

- Describe a "standard" in computer science, and why is it important.

Hello

Example 1: (hello.c) Main program

```
 8 #define NUM_ID 8
 9 int main(int argc, char *argv[])
10 {
11   for (int t = 0; t < NUM_ID; t++) {
12     printf("main: t = %d\n", t);
13     PrintHello(t);
14   }
15   return 0;
16 }
```

Hello

Example 2: (hello.c) Print

```
3 void PrintHello(int id)
4 {
5   printf("printHello: id = %d\n", id);
6 }
```

Demonstration

- Run the hello.c program.

Implementation

- Implement a program that prints 10 lines of "hello".

Discussion

- Describe the compiling environment you used.

Pthread Concepts

- Initially there is only one *main thread*.
- The main thread can spawn other threads. For ease of explanation we will refer to them as the *spawned* threads of the main thread.
- For ease of explanation we will also use *child* threads to refer to those threads spawned by the main thread.
- You have been programming the main thread *only*.

Pthread Steps

- Include the necessary header file `pthread.h`.
- Declare a variable of type `pthread_t` to store the identifier for the thread you will create.
- Call `pthread_create` creates a thread with the type `pthread_t` variable declared previously.
- Call `pthread_exit` when the main thread or the spawn thread wants to exit.

Hello

Example 3: (hello-pthread.c) Declaration

```
2 #include <pthread.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #define NUM_THREADS 8
```

- Must include `pthread.h`.

pthread_create

Example 4: pthread_create

```
1 int pthread_create(pthread_t *thread,
2   const pthread_attr_t *attr,
3   void *(*start_routine)(void*), void *arg);
```

pthread_create Parameters

`thread` A `pthread_t` pointer to the created thread.

`attr` A `pthread_type_t` pointer to the attribute of the thread.
We can set it to NULL for now.

pthread_create Parameters

`start_routinue` Thread starting routine. The routine must have `void *routine(void *)` prototype. i.e., it expects a pointer to `void` as the only parameter, and returns a pointer to `void`.

`arg` A pointer to an optional parameter to the spawned thread. We set it to the thread index `t` in our example.

`return value` Return 0 if success, and a non-zero error code on error.

pthread_exit

Example 5: pthread_exit

```
1 void pthread_exit(void *value);
```

`value` A thread can use this pointer to sent information back to its parent thread. We can set it to `NULL` for now because the threads will not send anything back to the main thread.

Discussion

- Name the functions that create and destroy pthreads respectively.

Hello with Pthread

Example 6: (hello-pthread.c) Main program

```
14 int main(int argc, char *argv[])
15 {
16     pthread_t threads[NUM_THREADS];
17     for(int t = 0; t < NUM_THREADS; t++) {
18         printf("main: create thread %d\n", t);
19         int rc =
20           pthread_create(&threads[t], NULL,
21                          printHello, (void *)(&t));
22         if (rc) {
23           printf("main: error code %d\n", rc);
24           exit(-1);
25         }
26     }
27     pthread_exit(NULL);
28     return 0;
29 }
```

Main Program

- We can use the argument `arg` to pass information to the spawned threads.
- In our example we pass the index `t` to the spawned thread as thread index.
- Note that the type of `arg` is `void *` since we do not know what kind of parameter will be passed into a thread.

Hello with Pthread

Example 7: (hello-pthread.c) Print

```
7  void *printHello(void *thread_id)
8  {
9    int tid = *((int *)thread_id);
10   printf("printHello: tid = %d\n", tid);
11   pthread_exit(NULL);
12 }
```

printHello

- This is the routine each spawned thread will run.
- Each thread receives a pointer to the thread index (`thread_id`) from the main thread, and prints it.
- We need to cast the type of the parameter back to `(int *)`, very much like the case of qsort.
- We do not have anything to send back to the main thread, so we use `NULL` in `pthread_exit(NULL)`.

Compile and Link

- You need to link your program with the pthread library.
- You can use gcc to compile and link you program with pthread library. Note that the library must be at the end of the gcc command.
  - `gcc program.c -o program -lpthread`

Demonstration

- Run the hello-pthread.c program.

Discussion

- Is the answer correct? If not what is the reason?

Hello with Pthread

Example 8: (hello-pthread-correct.c) main

```
14  int main(int argc, char *argv[])
15  {
16      pthread_t threads[NUM_THREADS];
17      int threadIndex[NUM_THREADS];
18      for(int t = 0; t < NUM_THREADS; t++) {
19          printf("main: create thread %d\n", t);
20          threadIndex[t] = t;
21          int rc =
22            pthread_create(&threads[t], NULL,
23                           printHello,
24                           (void *)(threadIndex + t));
25          if (rc) {
26            printf("main: error code %d\n", rc);
27            exit(-1);
28          }
29      }
30      pthread_exit(NULL);
31      return 0;
32  }
```

Main Thread Variables

- We use an array `threadIndex` to keep the thread index for all threads.
- We then pass the address of the index to the spawned threads. This prevents the threads from accessing the same memory address in the previous example.
- From this example we know that the spawned threads can access the memory of the main thread.

Demonstration

- Run the hello-pthread-correct.c program.
- Is the answer correct?
- Is there timing constraints between these threads?

Implementation

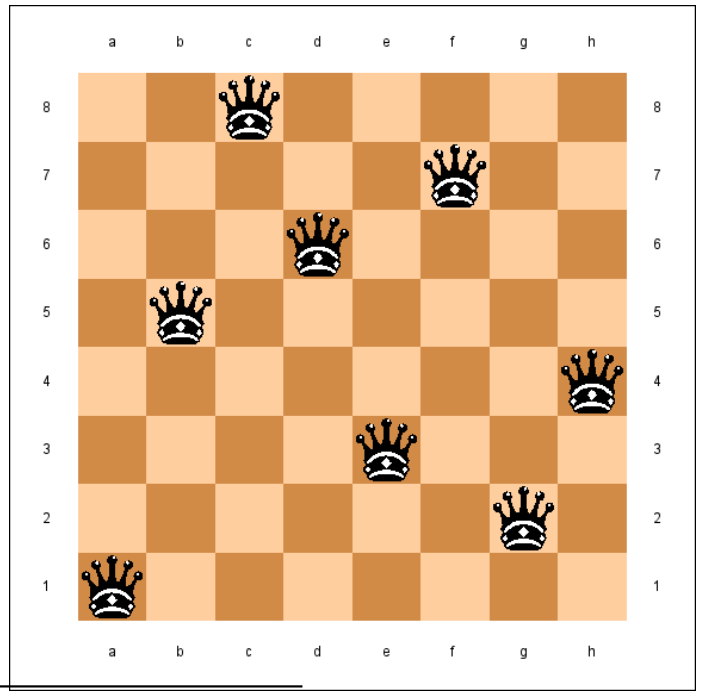
- Implement a pthread program that prints 10 lines of "hello". You should use `pthread_create` to create 10 threads to do this, where each thread prints an index from 0 to 9.

Discussion

- Does your program function properly if you remove the `pthread_exit` from the main program? Explain the reason if it does not.

Eight Queen

- Place eight queen on a chessboard so that no queen can attack any other queen.[7]
- We would like to know the number of such solutions.



[7] http://support.sas.com/documentation/cdl/en/orcpug/59630/HTML/default/images/queens.png

Solution

- Use an array `position` to store the positions of n queens.
- The i-th element of the array stores the row index of the queen at the i-column.
- Receive the size of the board n as the second command line argument.
- Use a recursive function `queen` to compute the number of solutions.

Headers

Example 9: (queen.c) Headers

```
2 #include <stdio.h>
3 #include <stdlib.h>
4 #include <assert.h>
5 #define MAXN 20
```

Headers

- `stdlib.h` for `atoi`.
- `MAXN` is the maximum size of the board.

Eight Queen

Example 10: (queen.c) Main program

```
30 int main(int argc, char *argv[])
31 {
32   int position[MAXN];
33   assert(argc == 2);
34   int n = atoi(argv[1]);
35   assert(n <= MAXN);
36   printf("%d\n", queen(position, 0, n));
37   return 0;
38 }
```

main

- `position` for queen positions.
- `n` is the size of the board.
- `queen` will return the number of solutions.

Eight Queen

Example 11: (queen.c) queen

```
17 int queen(int position[], int next, int n)
18 {
19   if (next >= n)
20     return 1;
21   int sum = 0;
22   for (int test = 0; test < n; test++)
23     if (ok(position, next, test)) {
24       position[next] = test;
25       sum += queen(position, next + 1, n);
26     }
27   return sum;
28 }
```

queen

- The `queen` function computes the number of solutions.
- The `queen` uses a parameter `next` to keep track of the column number it wishes to place a queen next.
- If `next` is already n then we have placed all n queens.
- Otherwise we try all rows and sum up the number of solutions from all possible row placements.

Eight Queen

Example 12: (queen.c) ok

```
 8 int ok(int position[], int next, int test)
 9 {
10   for (int i = 0; i < next; i++)
11     if (position[i] == test ||
12         (abs(test - position[i]) == next - i))
13       return 0;
14   return 1;
15 }
```

ok

- The `queen` function determines if we could place a queen at the end of `position`.
- The newly added queen is at row `position[next]`, column `next`.
- if any previously placed queen is at the same row or at the diagonal of the newly placed queen, the function returns 0. Otherwise it return 1.

Demonstration

- Run and time the queen.c program.

Implementation

- Implement a sequential program that solves the eight queen problem.

Discussion

- Can you think of any simple optimization that will speed up your program?

n Queen with pthread

Now we want to parallelize the previous program with pthread.

- We create *n* threads, and use one thread to search each of the *n* subtrees when we place the first queen at all *n* possible cells in the first column.
- All threads can run in parallel.
- Right now we just let each thread report the number of answers it finds, and do not sum them.

Issues

- How do all thread know the size of the board?
  - We declare a global `n`.
- How does a thread know which subtree it should solve?
  - We pass this information to the spawned threads by the `arg` parameter in `pthread_create`.
- Can these threads share a board?
  - No, they need their own `position`.
- Do these threads need to communicate with each other?
  - No, because right now we do not sum the numbers of solutions.

Headers

Example 13: (queen-pthread.c) Headers

```
2 #include <pthread.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #include <assert.h>
6
7 #define MAXN 20
8 int n;   /* a global n */
```

Headers

- `pthread.h` for pthread functions.
- `stdlib.h` for `atoi`.
- `MAXN` is the maximum size of the board.
- A global `n` for all threads.

Eight Queen with Pthread

Example 14: (queen-pthread.c) Main program

```
40 int main (int argc, char *argv[])
41 {
42   assert(argc == 2);
43   n = atoi(argv[1]);
44   assert(n <= MAXN);
45   int *position;
46   pthread_t threads[MAXN];
47   for(int i = 0; i < n; i++) {
48     position = (int *)calloc(n, sizeof(int));
49     assert(position != NULL);
50     position[0] = i;
51     int error = pthread_create(&threads[i], NULL, goQueen,
52                                (void *)position);
53     assert(error == 0);
54   }
55   pthread_exit(NULL);
56 }
```

main

- We call `calloc` to allocate an array and keep the starting address in `position`.
- We set the first element of `position` according to the thread index, so that each thread searches its own subtree.
- We pass the `position` to `pthread_create` so that the threads can access their own arrays.
- From this example we know that all threads share the global variables and heap space.

goQueen

Example 15: (queen-pthread.c) goqueen

```
32 void *goQueen(void *pos)
33 {
34   int *position = (int *)pos;
35   printf("goQueen: thread %d, # of solution = %d\n",
36          position[0], queen(position, 1));
37   pthread_exit(NULL);
38 }
```

goQueen

- goQueen is the starting function of spawned threads.
- goQueen uses its own pointer petition to point to the array in the heap. Some casting is required.
- goQueen calls queen with next set to 1.
- All threads can get the board size from the global variable n.

Demonstration

- Run and time the queen-pthread.c program.

Implementation

- Implement a parallel program that solves the n queen problem with pthread. Each thread only reports the number of solutions it finds and no summation is required.
- Measure the speedup and efficiency.

Discussion

- Why do we call queen with 1?
- What are the speedup and efficiency you are getting?
- Is the workload evenly distributed?

Total Number

- Now we want to compute the total number of solutions, instead of individual number of solution from each thread.
- We use a global variable `numSolution` to store the sum of the numbers of solutions from all threads. This variable is initialized to 0 automatically.

Headers

Example 16: (queen-pthread-sum.c) Headers

```
2 #include <pthread.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #include <assert.h>
6
7 #define MAXN 20
8 int n;     /* a global n */
9 int numSolution;
```

Headers

- `pthread.h` for pthread functions.
- `stdlib.h` for `atoi`.
- `MAXN` is the maximum size of the board.
- A global `n` for all threads.
- A global `numSolution` for the total number of solutions.

Eight Queen with Pthread

Example 17: (queen-pthread-sum.c) Main program

```
43 int main (int argc, char *argv[])
44 {
45   assert(argc == 2);
46   n = atoi(argv[1]);
47   assert(n <= MAXN);
48   int *position;
49   pthread_t threads[MAXN];
50   for(int i = 0; i < n; i++) {
51     position = (int *)calloc(n, sizeof(int));
52     assert(position != NULL);
53     position[0] = i;
54     int error = pthread_create(&threads[i], NULL, goQueen,
55                                (void *)position);
56     assert(error == 0);
57   }
58   printf("total # of solution %d\n", numSolution);
59   pthread_exit(NULL);
60   return 0;
61 }
```

main

- We print the number of solutions `numSolution` before we call `pthread_exit`.
- If we place the `printf` after `pthread_exit`, it will not be executed.

goQueen

Example 18: (queen-pthread-sum.c) goqueen

```
33 void *goQueen(void *pos)
34 {
35   int *position = (int *)pos;
36   int num = queen(position, 1);
37   printf("goQueen: thread %d, # of solution = %d\n",
38          position[0], num);
39   numSolution += num;
40   pthread_exit(NULL);
41 }
```

goQueen

- goQueen reports the number of solution queen finds.
- goQueen also adds the number of solutions computed by queen to the global variable numSolution.

Demonstration

- Run and time the queen-pthread-sum.c program.

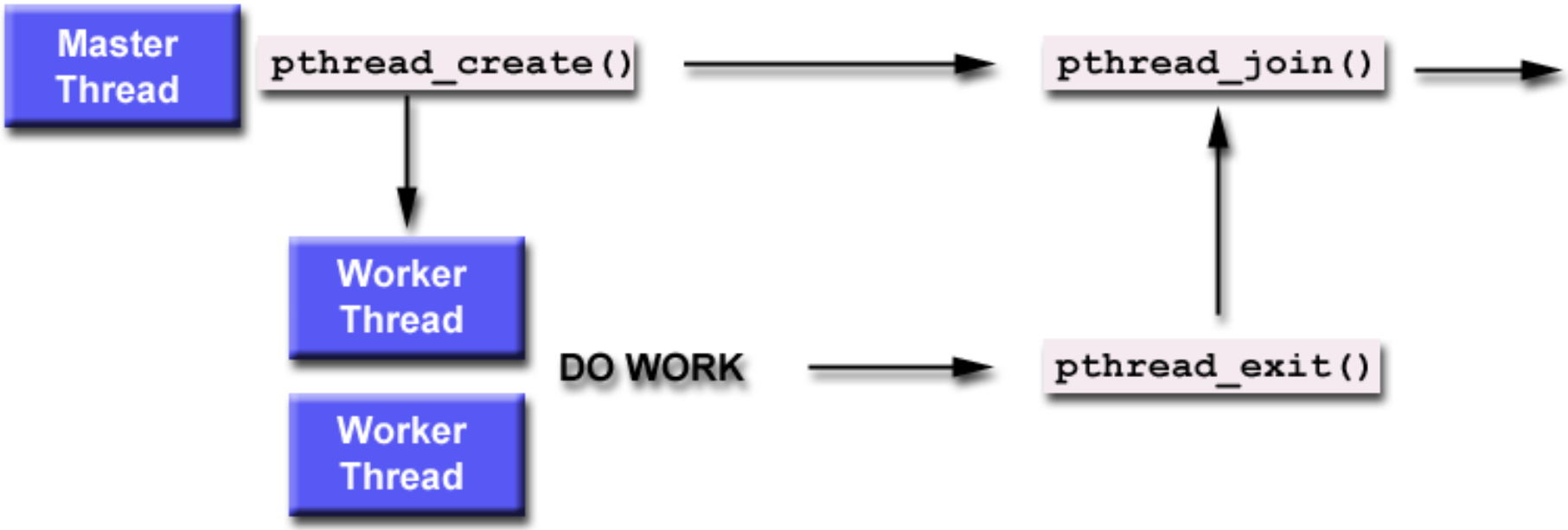
Discussion

- Does the program produce correct output?

Synchronization

- The problem of the previous program is that the main thread did *not* wait for all spawned threads to complete.
- We need a *barrier synchronization*, and after that the main thread can get the correct total number of solutions in `numSolution`.
- The main thread can wait for its spawned threads by calling `pthread_join`.

Join a Pthread



Pthread Attribute

Steps to set threads as joinable.[8].

- Declare a pthread attribute variable of type `pthread_attr_t`.
- Initialize the attribute variable with `pthread_attr_init()`.
- Set the attribute detached status with `pthread_attr_setdetachstate()`.
- When done, free library resources used by the attribute with `pthread_attr_destroy()`.

[8] `https://computing.llnl.gov/tutorials/pthreads/`

pthread_attr_init

Example 19: (pthread-attr-init.c) Initialize/destroy attributes

```
1 int  pthread_attr_init(pthread_attr_t *attr);
2 int  pthread_attr_destroy(pthread_attr_t *attr);
```

- Initialize and destroy the attribute of a thread.

pthread_attr_setdetachstate

Example 20: (pthread-attr-setdetachstate.c) Set the attribute

```
1 int pthread_attr_setdetachstate(pthread_attr_t *attr,
2                                 int detachstate);
```

- Set the attribute of a thread.
- In our example we want to set the threads so that they can join with the main thread, so we will set PTHREAD_CREATE_JOINABLE.

n Queen with Pthread

Example 21: (queen-pthread-sum-join.c) Main program

```
45 int main (int argc, char *argv[])
46 {
47   assert(argc == 2);
48   n = atoi(argv[1]);
49   assert(n <= MAXN);
50   int *position;
51   pthread_t threads[MAXN];
52   pthread_attr_t attr;
53   pthread_attr_init(&attr);
54   pthread_attr_setdetachstate(&attr,
55     PTHREAD_CREATE_JOINABLE);
```

Steps

- Declare a variable `attr` of type `pthread_attr_t` and initialize it with `pthread_attr_init()`.
- Set the attribute to `PTHREAD_CREATE_JOINABLE` with `pthread_attr_setdetachstate()`.
- Use the address of `attr` as the second argument in `pthread_create` while creating threads.
- Destroy `attr`.

n Queen with Pthread

Example 22: (queen-pthread-sum-join.c) Main program

```
57    for (int i = 0; i < n; i++) {
58      position = (int *)calloc(n, sizeof(int));
59      assert(position != NULL);
60      position[0] = i;
61      int error = pthread_create(&threads[i], &attr, goQueen,
62                                 (void *)position);
63      assert(error == 0);
64    }
65    pthread_attr_destroy(&attr);
```

n Queen with Pthread

Example 23: (queen-pthread-sum-join.c) Main program

```
67    for (int i = 0; i < n; i++) {
68      pthread_join(threads[i], NULL);
69  #ifdef VERBOSE
70    printf("main: thread %d done\n", i);
71  #endif
72    }
73    printf("total # of solution %d\n", numSolution);
74    pthread_exit(NULL);
75    return 0;
76  }
```

Join a Pthread

Example 24: pthread_join

```
1 int pthread_join(pthread_t thread,
2                   void **value_ptr);
```

`thread` The thread you want to wait for. This is the variable you used to call `pthread_create`.

`value_ptr` A pointer to a pointer to the return value from the spawned thread. We do not return anything from the spawned thread so we set it to `NULL`.

Demonstration

- Run and time the queen-pthread-sum-join.c program.

Discussion

- Does this program produce correct results?
- Does this program *always* produce correct results?

A Global Counter

- The previous program uses a recursive function `queen` to compute the number of solutions.
- We will change the program so that `queen` does not return the number of solutions it finds – instead whenever it finds a solution it adds 1 to the global counter `numSolution`.

Example 25: (queen-pthread-sum-join-race.c) queen

```
20 void queen(int position[], int next)
21 {
22   if (next >= n)
23     numSolution++;
24   else
25     for (int test = 0; test < n; test++)
26       if (ok(position, next, test)) {
27         position[next] = test;
28         queen(position, next + 1);
29       }
30 }
```

Changes

- The return type of `queen` is changed to `void` since it does not return the number of solutions anymore.
- The program structure is simplified since we do not keep track of the number of solutions found.

Example 26: (queen-pthread-sum-join-race.c) goQueen

```
32 void *goQueen(void *pos)
33 {
34   int *position = (int *)pos;
35   queen(position, 1);
36   pthread_exit(NULL);
37 }
```

Demonstration

- Run the queen-pthread-sum-join-race.c program.

Discussion

- Is the answer correct? If not what is the reason?
- Does the previous program queen-pthread-sum-join.c have the same problem? If yes why it did not show up?

Race

- In fact the race condition exists in queen-pthread-sum-join.c. It doe not show up because there are only a few additions to `numSolution`.
- When we increase the number of additions to `numSolution`, it becomes much easier for the race condition to occur.
- The solution is to use the return value of `pthread_exit` to return the number of solutions found in a thread.

pthread_exit

Example 27: pthread_exit

```
1 void pthread_exit(void *value);
```

Example 28: pthread_join

```
1 int pthread_join(pthread_t thread,
2                   void **value_ptr);
```

Return value

- We will find a place for the spawned thread to store the number of solutions it finds, and return the address by `pthread_exit` to the main thread.
- The main thread will use the second parameter of `pthread_join` to retrieve the number of solutions a thread found.

No Global

Example 29: (queen-pthread-sum-join-correct.c) Headers

```
2 #include <pthread.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #include <assert.h>
6
7 #define MAXN 20
8 int n; /* a global n */
```

No Global

- We remove the global variable `numSolution`, which causes the race condition.

goQueen

Example 30: (queen-pthread-sum-join-correct.c) goQueen

```
32 void *goQueen(void *pos)
33 {
34   int *position = (int *)pos;
35   int *num = (int *)malloc(sizeof(int));
36   *num = queen(position, 1);
37 #ifdef VERBOSE
38   printf("goQueen: thread %d, # of solution = %d\n",
39          position[0], *num);
40 #endif
41   pthread_exit(num);
42 }
```

Heap

- We decide to put the number of solutions a spawned thread found in the heap, with the address stored in `num`.
- Recall that all threads share the heap.
- This address, i.e., the value of num, is passed back with `pthread_exit`.

main

Example 31: (queen-pthread-sum-join-correct.c) main

```
66    int numSolution = 0;
67    for (int i = 0; i < n; i++) {
68      int *num;
69      pthread_join(threads[i], (void **)&num);
70      numSolution += *num;
71  #ifdef VERBOSE
72    printf("main: thread %d done\n", i);
73  #endif
74    }
75    printf("total # of solution %d\n", numSolution);
76    pthread_exit(NULL);
77    return 0;
78  }
```

Return Value

- Note that the API requires that we pass the address of a pointer into `pthread_join`.
- The value returned by `pthread_join` is then added into `numSolution`, which is now a local variable.

Demonstration

- Run and time the queen-pthread-sum-join-correct.c program.

Implementation

- Implement a parallel program that solves the n queen problem with pthread. You need to sum up the number of solutions from all threads correctly.
- Measure the speedup and efficiency.

Discussion

- Does this program produce correct results?
- Compare the timing from queen-pthread-sum-join-correct.c and queen-pthread-sum-join-race.c

Mutex

- We can prevent the race condition by allowing only thread to access the shared variable `numSolution`.
- Pthread library provide a *mutex* (mutual exclusion) mechanism that allows only one thread to proceed in execution. This effectively provide a way to implement a critical section.

Steps

- Declare a mutex variable of type `pthread_mutex_t`. This variable must be global because every thread will use it.
- Initialize the mutex with `pthread_mutex_init`.
- Lock the mutex with `pthread_mutex_lock`.
- Unlock the mutex with `pthread_mutex_unlock`.

Declaration

Example 32: (queen-pthread-sum-join-race-mutex.c) Declaration

```
2  #include <pthread.h>
3  #include <stdio.h>
4  #include <stdlib.h>
5  #include <assert.h>
6
7  #define MAXN 20
8  int n;                                  /* a global n */
9  int numSolution;
10 pthread_mutex_t numSolutionLock;
```

Mutex Variable

- Declare a global mutex variable `numSolutionLock`.
- We will use this mutex variable to synchronize the access to the global counter `numSolution`.

main

Example 33: (queen-pthread-sum-join-race-mutex.c) queen

```
42 int main (int argc, char *argv[])
43 {
44   assert(argc == 2);
45   n = atoi(argv[1]);
46   assert(n <= MAXN);
47   int *position;
48   pthread_t threads[MAXN];
49   pthread_attr_t attr;
50   pthread_attr_init(&attr);
51   pthread_attr_setdetachstate(&attr,
52     PTHREAD_CREATE_JOINABLE);
53   pthread_mutex_init(&numSolutionLock, NULL);
```

pthread_mutex_init

Example 34: (pthread-mutex-init.c) Initialize a mutex

```
1 int pthread_mutex_init(pthread_mutex_t *mutex,
2                        const pthread_mutexattr_t *attr);
```

`mutex` The mutex to initialize.

`attr` The attribute of the mutex to set. Set to `NULL` for the default.

main

- Initialize `numSolutionLock` with `pthread_mutex_init`.
- Use `NULL` for the default mutex attribute value.

pthread_mutex_lock

Example 35: (pthread-mutex-lock.c) Lock/Unlock a mutex

```
1 int pthread_mutex_lock(pthread_mutex_t *mutex);
2 int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

`mutex` The mutex to lock/unlock.

queen

Example 36: (queen-pthread-sum-join-race-mutex.c) queen

```
21 void queen(int position[], int next)
22 {
23   if (next >= n) {
24     pthread_mutex_lock(&numSolutionLock);
25     numSolution++;
26     pthread_mutex_unlock(&numSolutionLock);
27   } else
28     for (int test = 0; test < n; test++)
29       if (ok(position, next, test)) {
30         position[next] = test;
31         queen(position, next + 1);
32       }
33 }
```

queen

- Whenever the function queen finds a solution, it needs to lock numSolution with mutex numSolutionLock by calling pthread_mutex_lock.
- If it cannot acquire the lock it will have to wait.
- After adding 1 to numSolution, queen releases the lock by calling pthread_mutex_unlock.

main

Example 37: (queen-pthread-sum-join-race-mutex.c) queen

```
65    for (int i = 0; i < n; i++) {
66      pthread_join(threads[i], NULL);
67  #ifdef VERBOSE
68      printf("main: thread %d done\n", i);
69  #endif
70    }
71    printf("total # of solution %d\n", numSolution);
72    pthread_mutex_destroy(&numSolutionLock);
73    pthread_exit(NULL);
74    return 0;
75  }
```

pthread_mutex_destroy

Example 38: (pthread-mutex-destroy.c) pthread_destroy

```
1 int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

main

- After all spawned threads finish, we release the mutex by calling `pthread_mutex_destroy`.

Demonstration

- Run and time the queen-pthread-sum-join-race-mutex.c program.

Discussion

- Does this program produce correct results?
- Compare the timing from queen-pthread-sum-join-race-mutex.c with that from queen-pthread-sum-join-correct.c.