中山大学计算机院本科生实验报告
（2024 学年春季学期）

课程名称：并行程序设计　　　　　　　　　　　　批改人：

实验	6-Pthreads 并行构造	专业（方向）	计算机科学与技术
学号	21307174	姓名	刘俊杰
Email	liujj255@mail2.sysu.edu.cn	完成日期	2024/5/3

1. 实验目的

parallel_for 并行应用

使用此前构造的 parallel_for 并行结构，将 heated_plate_openmp 改造为基于 Pthreads 的并行应用。

heated plate 问题描述：规则网格上的热传导模拟，其具体过程为每次循环中通过对邻域内热量平均模拟热传导过程，即：

$$\boldsymbol{w}_{i,j}^{t+1} = \frac{1}{4}(\boldsymbol{w}_{i-1,j-1}^{t} + \boldsymbol{w}_{i-1,j+1}^{t} + \boldsymbol{w}_{i+1,j-1}^{t} + \boldsymbol{w}_{i+1,j+1}^{t}),$$

其 OpenMP 实现见课程资料中的 heated_plate_openmp.c。

要求：使用此前构造的 parallel_for 并行结构，将 heated_plate_openmp 实现改造为基于 Pthreads 的并行应用。测试不同线程、调度方式下的程序并行性能，并与原始 heated_plate_openmp.c 实现对比。

2. 实验过程和核心代码

2.1 实验思路

①首先使用实验 5 实现的 parallel_for 来模拟实现 openmp 的加速功能。

②将原代码中的代码分为多个部分:，每个部分构造一个函数俩来实现，方便传入到 parallel_for 中多线程执行。

③按步骤将不同的函数传入到 parallel_for 中进行线程加速。

④输出迭代过程中的 diff 值和最终收敛需要的迭代次数和运行时间。

2.2 parallel.c

实验 5 实现的 parallel_for.c

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

// 定义结构体来传递参数给函数
struct parallel_args {
    void *functor_args; // 执行函数所需参数
    int start, end, inc;  // 开始位置 结束位置 增量
    pthread_mutex_t *mutex; // 互斥锁
};

// 打包成动态链接库的入口函数
void parallel_for(int start, int end, int inc,
                        void *(*functor)(void*), void *arg, int num_threads,pthread_mutex_t*mutex) {

    pthread_t threads[num_threads];
    struct parallel_args args_data[num_threads];

    int total_task = end-start;
    int per_task = total_task / num_threads;

    // 创建线程并执行并行for循环
    for (int i = 0; i < num_threads; ++i) {
        args_data[i].functor_args = arg;
        args_data[i].start = start + i * per_task;
        args_data[i].end = start + (i + 1) * per_task;
        args_data[i].inc = inc;
        args_data[i].mutex = mutex;
        pthread_create(&threads[i], NULL, functor, (void *)&args_data[i]);
    }

    // 等待所有线程结束
    for (int i = 0; i < num_threads; ++i) {
        pthread_join(threads[i], NULL);
    }
}

```

2.3 pthread 版本:heat_plate_pthread.c

①用到的传参数的结构体

```
//函数参数的结构体
struct functor_args{
    int m; // 维度M
    int n; // 维度N
    double *w; // 指向矩阵w
    double *mean; //指向平均值mean
    double *diff; // 指向判断收敛的diff
    double *u; //指向辅助矩阵u
};
// parallel_for参数结构体
struct parallel_args {
    void *functor_args;
    int start, end, inc;
    pthread_mutex_t *mutex; // 锁
};
```

②初始化矩阵 w,使用多线程,每个线程负责相应的位置,给其最左侧、最右侧、最上侧和最底部进行赋值来实现加速。

```c
// 初始化w矩阵
void *set_w(void *args){
    struct parallel_args *para_args = (struct parallel_args *)args;
    int start = para_args->start;
    int end = para_args->end;
    int inc = para_args->inc;
    pthread_mutex_t *mutex = para_args->mutex;

    struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
    int m = func_args->m;
    int n = func_args->n;
    double (*w)[n] = (double (*)[n])func_args->w;
      // 给w矩阵赋值
      for ( int i = start; i < end; i++ )
      {
        w[i][0] = 100.0;
      }

      for ( int i = start; i < end; i++ )
      {
        w[i][n-1] = 100.0;
      }

      for (int j = start; j < end; j++ )
      {
        w[m-1][j] = 100.0;
      }

      for (int j = start; j < end; j++ )
      {
        w[0][j] = 0.0;
      }

    return NULL;
}
```

③计算初始化后矩阵 w 中的元素和(方便后续计算出 mean)，结果存储到*mean 中(mean 指针指向主函数中的 mean)，计算过程中需要对互斥区实现加锁解锁操作。

```c
// 计算矩阵元素和,用mean记录
void *calculate_sum(void *args){
    struct parallel_args *para_args = (struct parallel_args *)args;
    int start = para_args->start;
    int end = para_args->end;
    int inc = para_args->inc;
    pthread_mutex_t *mutex = para_args->mutex;

    struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
    int m = func_args->m;
    int n = func_args->n;
    double (*w)[n] = (double (*)[n])func_args->w;
    double*mean = func_args->mean;

      for (int i = start ; i < end; i++ )
      {
        pthread_mutex_lock(mutex); // 上锁
        *mean = *mean + w[i][0] + w[i][n-1];
        pthread_mutex_unlock(mutex); // 解锁
      }

      for (int j = start; j < end; j++ )
      {
        pthread_mutex_lock(mutex); // 上锁
        *mean = *mean + w[m-1][j] + w[0][j];
        pthread_mutex_unlock(mutex);// 解锁
      }

    return NULL;
}
```

④计算出 mean 值后,使用多个线程对网格中间元素赋值 mean

```c
// 给矩阵w中间元素赋值平均值mean
void *set_mean(void *args){
    struct parallel_args *para_args = (struct parallel_args *)args;
    int start = para_args->start;
    int end = para_args->end;
    int inc = para_args->inc;
    pthread_mutex_t *mutex = para_args->mutex;

    struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
    int m = func_args->m;
    int n = func_args->n;
    double (*w)[n] = (double (*)[n])func_args->w;
    double*mean = func_args->mean;

      for (int i = start; i < end; i++ )
     {
       if(i == m - 1||i==0)continue;
       for (int j = 1; j < n - 1; j++ )
       {
         w[i][j] = *mean;
       }
     }

    return NULL;
}
```

⑤ 将 w 的值赋值给辅助矩阵 u

```c
// 将矩阵w的值赋值给u
void *w_to_u(void *args){
    struct parallel_args *para_args = (struct parallel_args *)args;
    int start = para_args->start;
    int end = para_args->end;
    int inc = para_args->inc;
    pthread_mutex_t *mutex = para_args->mutex;

    struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
    int m = func_args->m;
    int n = func_args->n;
    double (*w)[n] = (double (*)[n])func_args->w;
    double*mean = func_args->mean;

    double (*u)[n] = (double (*)[n])func_args->u;

      for (int i = start; i < end; i++ )
     {
       for (int j = 0; j < n ; j++ )
       {
         u[i][j] = w[i][j];
       }
     }

    return NULL;
}
```

⑥ 多线程模拟网格热传导

```c
// 模拟热传导
void *heat_transfer(void *args){
  struct parallel_args *para_args = (struct parallel_args *)args;
  int start = para_args->start;
  int end = para_args->end;
  int inc = para_args->inc;
  pthread_mutex_t *mutex = para_args->mutex;

  struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
  int m = func_args->m;
  int n = func_args->n;
   double (*w)[n] = (double (*)[n])func_args->w;
  double*mean = func_args->mean;

   double (*u)[n] = (double (*)[n])func_args->u;

     for (int i = start; i < end; i++ )
    {
      if(i == m - 1||i==0)continue;
      for (int j = 1; j < n - 1; j++ )
      {
        w[i][j] = ( u[i-1][j] + u[i+1][j] + u[i][j-1] + u[i][j+1] ) / 4.0;
      }
    }

  return NULL;
}
```

⑦多线程分区域计算 diff 值,使用锁来实现对 diff 的互斥访问

```c
//  计算diff
void *calculate_diff(void *args){
    struct parallel_args *para_args = (struct parallel_args *)args;
    int start = para_args->start;
    int end = para_args->end;
    int inc = para_args->inc;
    pthread_mutex_t *mutex = para_args->mutex;

    struct functor_args* func_args = (struct functor_args *)para_args->functor_args;
    int m = func_args->m;
    int n = func_args->n;
     double (*w)[n] = (double (*)[n])func_args->w;
     double (*u)[n] = (double (*)[n])func_args->u;
    double*mean = func_args->mean;

    double *diff = func_args->diff;


      for (int i = start; i < end; i++ )
      {
        if(i == m - 1||i==0)continue;
        for (int j = 1; j < n - 1; j++ )
        {
          if(*diff<fabs(w[i][j] - u[i][j])){
             pthread_mutex_lock(mutex);
            *diff = fabs(w[i][j] - u[i][j]);
             pthread_mutex_unlock(mutex);
        }
      }
      }
    return NULL;
}
```

3. 实验结果

3.1 head_plate_openmp.c

openmp 版本的实验结果:

针对 500X500 的网格,用 4 个线程的加速结果:

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ gcc -fopenmp heated_plate_openmp.c -o run
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run

HEATED_PLATE_OPENMP
  C/OpenMP version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of processors available = 4
  Number of threads =              4

  MEAN = 74.949900

 Iteration  Change

         1  18.737475
         2  9.368737
         4  4.098823
         8  2.289577
        16  1.136604
        32  0.568201
        64  0.282805
       128  0.141777
       256  0.070808
       512  0.035427
      1024  0.017707
      2048  0.008856
      4096  0.004428
      8192  0.002210
     16384  0.001043

     16955  0.001000

  Error tolerance achieved.
  Wallclock time = 20.713869

HEATED_PLATE_OPENMP:
  Normal end of execution.
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$
```

3.2 parallel_for 实验结果(针对 500X500 的网格)

①1 个线程加速:

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run 1

HEATED_PLATE_PTHREAD
  C/PTHREAD version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of threads =              1

  MEAN = 75.050100

 Iteration  Change

         1  18.762525
         2  9.381263
         4  4.104302
         8  2.292638
        16  1.138124
        32  0.568961
        64  0.283183
       128  0.141967
       256  0.070903
       512  0.035474
      1024  0.017731
      2048  0.008868
      4096  0.004434
      8192  0.002213
     16384  0.001044

     16978  0.001000

  Error tolerance achieved.
  Wallclock time = 59.589935

HEATED_PLATE_PTHREAD:
  Normal end of execution.
```

②2 个线程加速：

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run 2

HEATED_PLATE_PTHREAD
  C/PTHREAD version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of threads =              2

  MEAN = 75.050100

 Iteration  Change

         1  18.762525
         2  9.381263
         4  4.104302
         8  2.292638
        16  1.138124
        32  0.568961
        64  0.283183
       128  0.141967
       256  0.070903
       512  0.035474
      1024  0.017731
      2048  0.008868
      4096  0.004434
      8192  0.002213
     16384  0.001044

     16978  0.001000

  Error tolerance achieved.
  Wallclock time = 40.103887

HEATED_PLATE_PTHREAD:
  Normal end of execution.
```

③4 个线程加速：

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run 4

HEATED_PLATE_PTHREAD
  C/PTHREAD version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of threads =              4

  MEAN = 75.050100

 Iteration  Change

         1  18.762525
         2  9.381263
         4  4.104302
         8  2.292638
        16  1.138124
        32  0.568961
        64  0.283183
       128  0.141967
       256  0.070903
       512  0.035474
      1024  0.017731
      2048  0.008868
      4096  0.004434
      8192  0.002213

     14838  0.000595

  Error tolerance achieved.
  Wallclock time = 30.738437

HEATED_PLATE_PTHREAD:
  Normal end of execution.
```

④8 个线程加速

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run 8

HEATED_PLATE_PTHREAD
  C/PTHREAD version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of threads =               8

  MEAN = 74.498998

 Iteration  Change

         1  18.624749
         2  9.312375
         4  4.074164
         8  2.275803
        16  1.129766
        32  0.564783
        64  0.281103
       128  0.140924
       256  0.070382
       512  0.035214
      1024  0.017601
      2048  0.008802
      4096  0.004401
      8192  0.002197

     13515  0.000361

  Error tolerance achieved.
  Wallclock time = 39.187043

HEATED_PLATE_PTHREAD:
  Normal end of execution.
```

⑤16 个线程加速

```
ljj@ljj-virtual-machine:~/parrallel_programming/Lab6$ ./run 16

HEATED_PLATE_PTHREAD
  C/PTHREAD version
  A program to solve for the steady state temperature distribution
  over a rectangular plate.

  Spatial grid of 500 by 500 points.
  The iteration will be repeated until the change is <= 1.000000e-03
  Number of threads =               16

  MEAN = 74.498998

 Iteration  Change

         1  18.624749
         2  9.312375
         4  4.074164
         8  2.275803
        16  1.129766
        32  0.564783
        64  0.281103
       128  0.140924
       256  0.070382
       512  0.035214
      1024  0.017601
      2048  0.008802
      4096  0.004401
      8192  0.002197
     16384  0.001036

     16863  0.001000

  Error tolerance achieved.
  Wallclock time = 72.638829

HEATED_PLATE_PTHREAD:
  Normal end of execution.
```

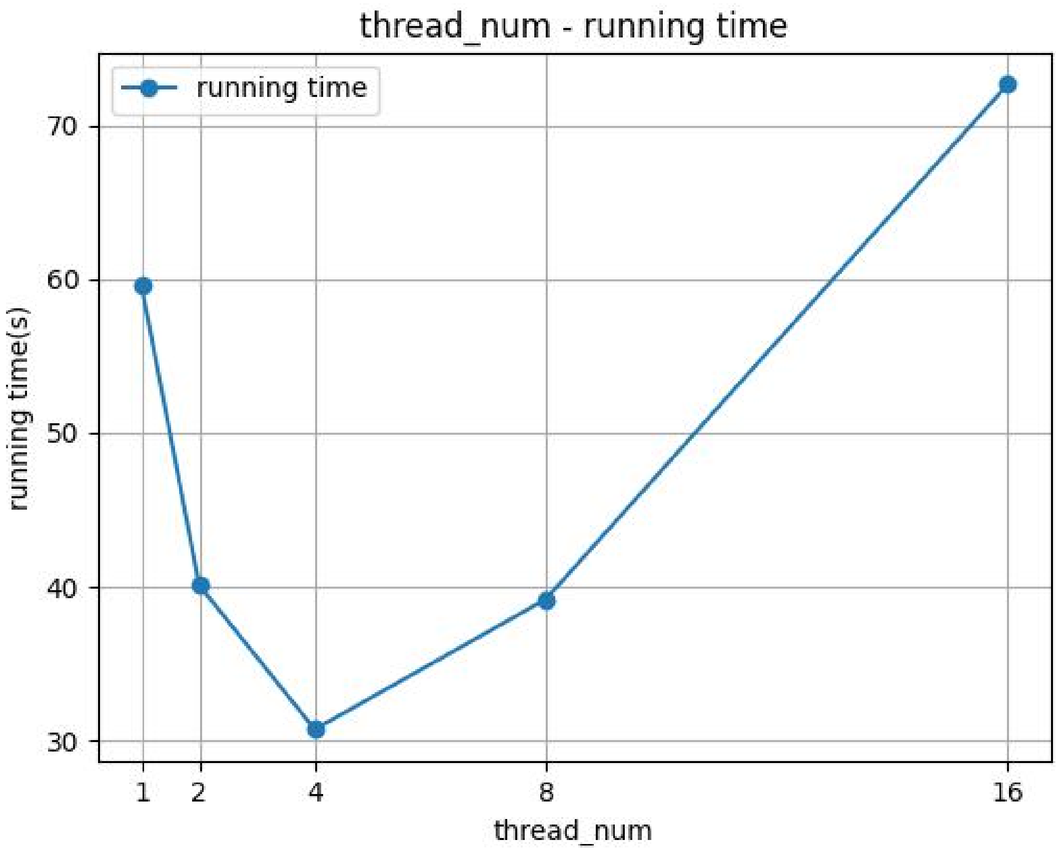
3.3 综合对比

openmp:

线程数	迭代次数	运行时间
4	16955	20.713869s

parallel_for:

线程数	迭代次数	运行时间
1	16978	59.589935s
2	16978	40.103887s
4	14838	30.738437s
8	13515	39.187043s
16	16863	72.638829s



由于虚拟机资源数有限,不足以支持 8 线程和 16 线程的运行,所以其运行时间反而增长了。

看从 1 个线程到 4 个线程的运行时间的减少,可以看出 parallel_for 成功实现了对热传导模拟的多线程加速。

但是与 openmp 的 4 个线程加速的效果来看，parallel_for 的效果相对来说没有那么好,应该是 parallel_for 只有静态调度，没有实现其他的线程调度,可能导致有部分线程资源浪费，同时 openmp 库中可能有一些优化操作。

4. 实验感想

4.1 问题

①程序运行过程中出现段错误

原因及解决办法：

自己存储函数参数的结构体是指针，并没有为其分配内存空间。

最后为其开辟空间后解决。

②出现线程越多,运行时间越长的结果

原因及解决办法：

出现这种情况的原因是因为我在一开始的计时过程中使用了 clock 函数计时。

clock()函数的功能: 这个函数返回从“开启这个程序进程”到“程序中调用 C++ clock()函数”时之间的 CPU 时钟计时单元（clock tick）数当程序单线程或者单核心机器运行时，这种时间的统计方法是正确的。但是如果要执行的代码多个线程并发执行时就会出问题,因为最终 end-begin 将会是多个核心总共执行的时钟嘀嗒数，因此造成时间偏大。

最后使用 clock_gettime()来计时,解决了这个问题。

4.2 感悟

学会了使用自己构造的 parallel_for.c 对特定的问题进行加速，同时在不同问题中注意到了对共享变量的保护，会使用锁来形成互斥去来避免竞争访问。

同时注意到了多线程程序中使用 clock 计时的不可靠性,因为 clock 中的时钟会受到多个线程核心的影响而造成时间增加。

之后的改进可以为 parallel_for.c 实现可选择的不同的线程调度方式(如实现一个线程池来实现动态调度,给每个空闲的线程分配一个任务,避免有的线程执行完自身的任务而闲置造成资源浪费)，避免一些线程资源的浪费来进一步实现加速。