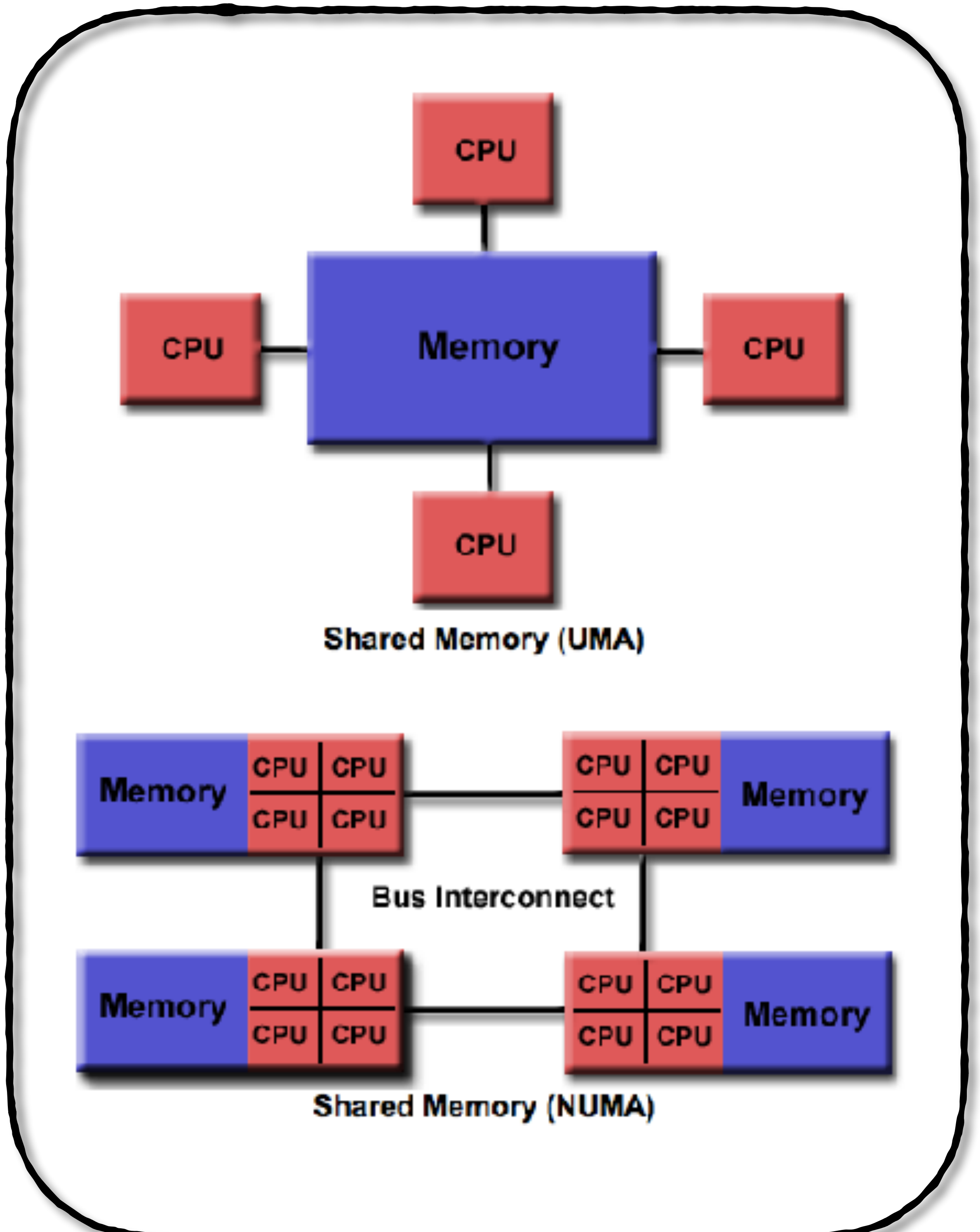
Shared memory parallelization

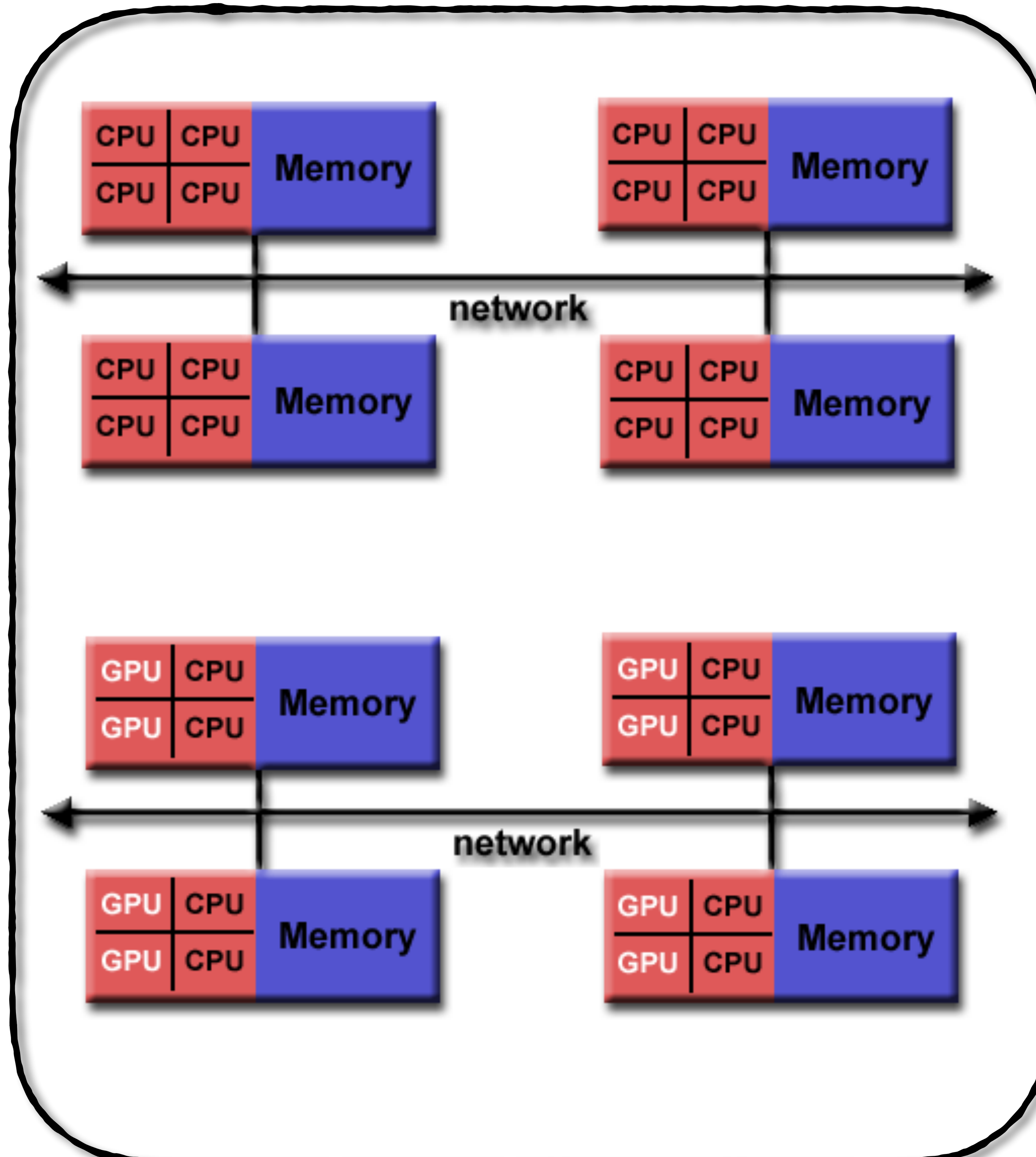
High Performance Scientific Computing 2018
Rio Yokota

shared memory vs. distributed memory

shared memory

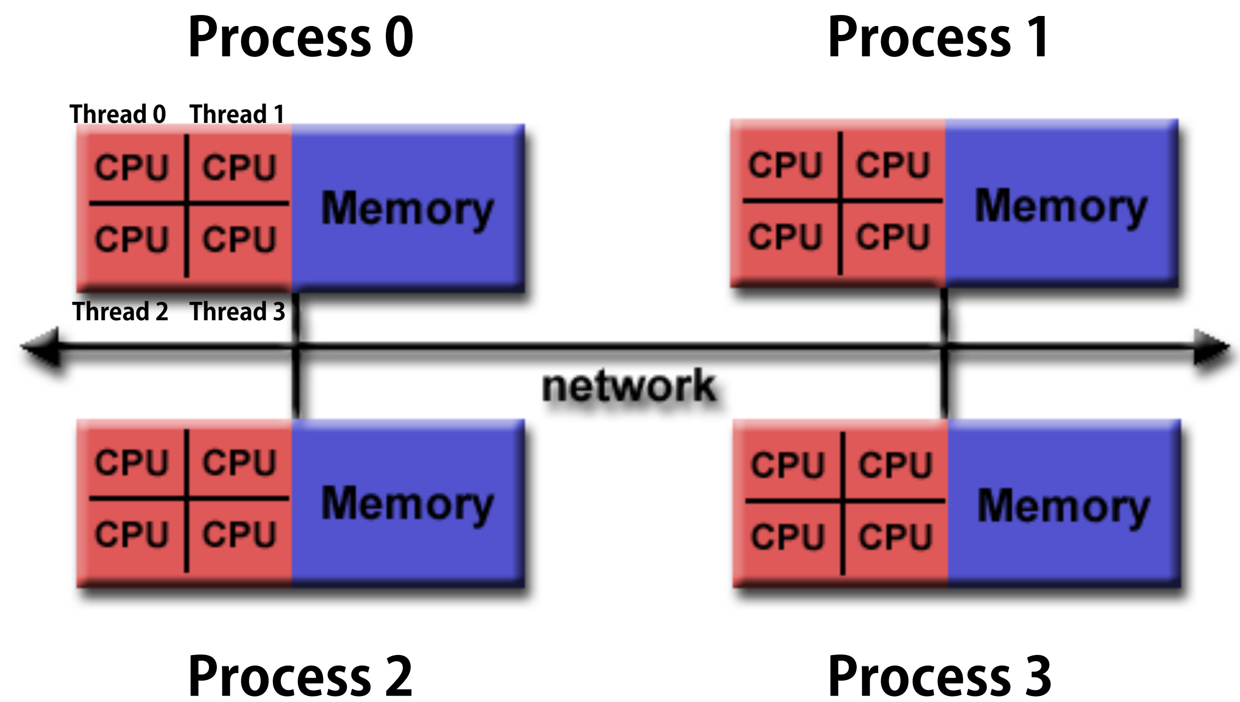


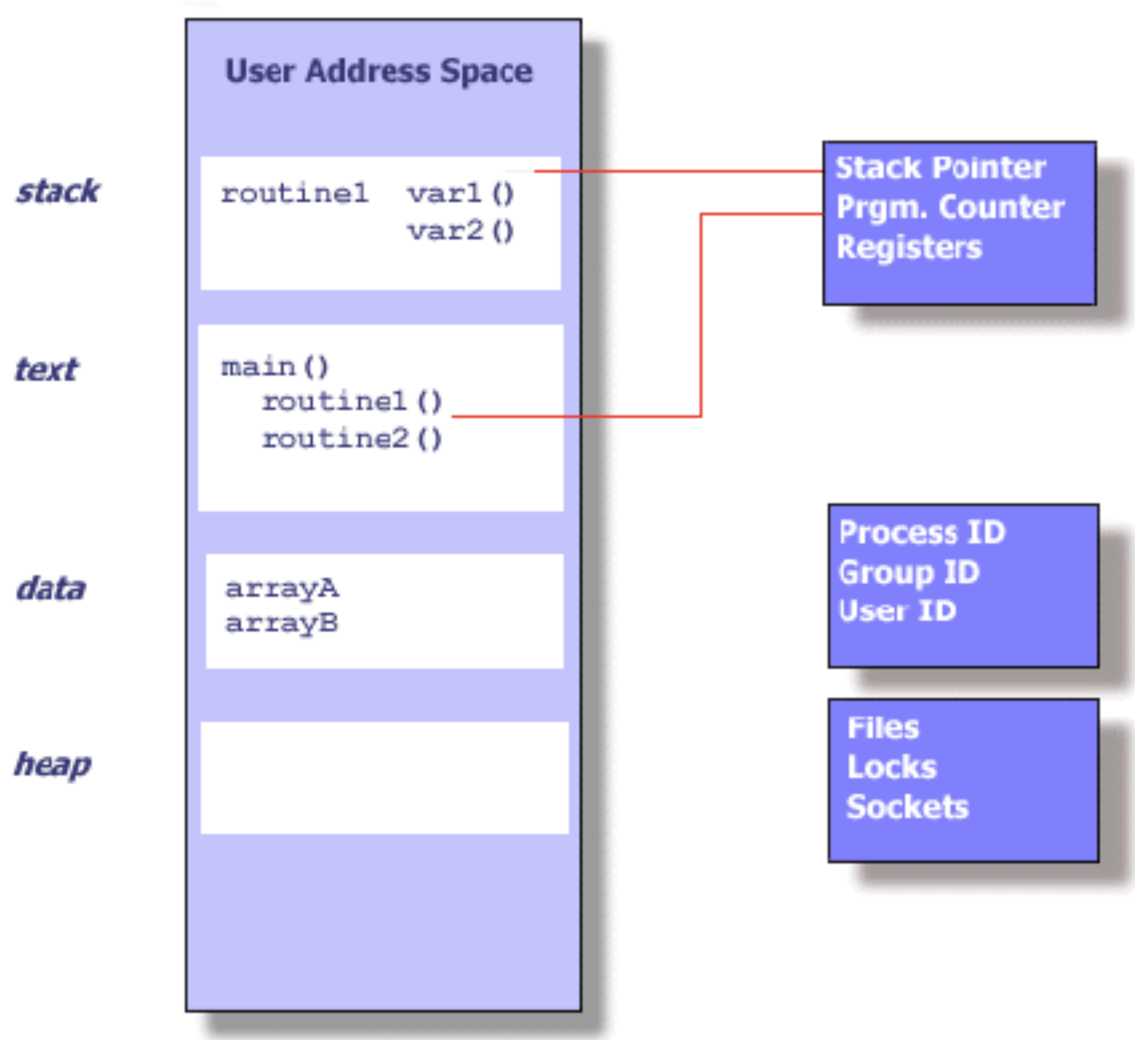
distributed memory



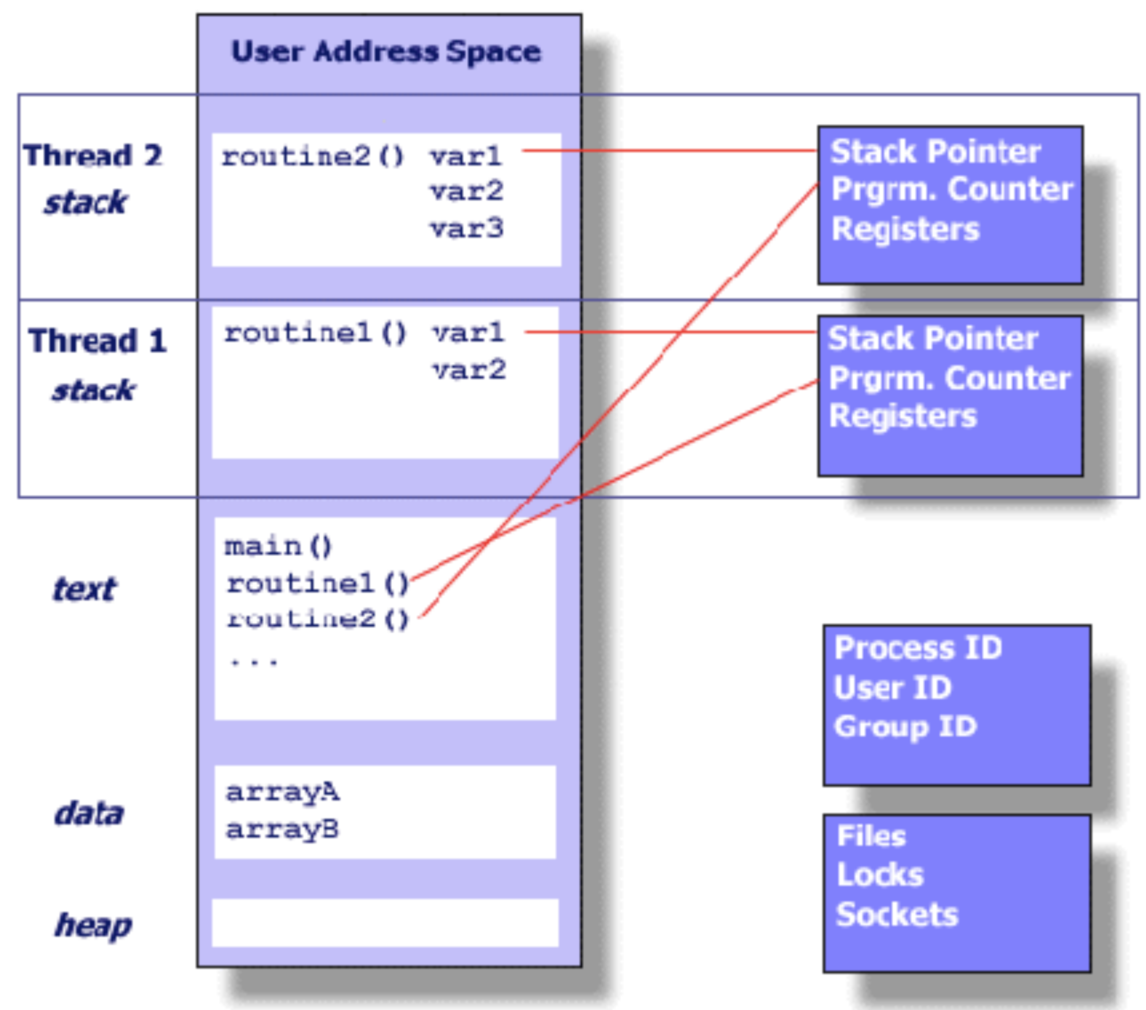
process vs. thread

```
Per process items             | Per thread items
------------------------------|-----------------
Address space                 | Program counter
Global variables              | Registers
Open files                    | Stack
Child processes               | State
Pending alarms                |
Signals and signal handlers   |
Accounting information        |
```





UNIX PROCESS



THREADS WITHIN A UNIX PROCESS

pthreads vs. OpenMP

pthreads

- POSIX standard
- Library functions
- Explicit fork and join
- Explicit synchronization
- Explicit locks

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

void* print(void*) {
  static int t=0;
  printf("%d\n", t++);
}

int main() {
  for(int i=0; i<10; i++) {
    pthread_t thread;
    pthread_create(&thread, NULL, print, NULL);
  }
  pthread_exit(NULL);
}
```

```
g++ -pthread example.cpp
```

OpenMP

- Industry standard
- Compiler directives
- Explicit fork and join
- Implicit synchronization
- Implicit locks

```
#include <stdio.h>

void print() {
  static int t=0;
  printf("%d\n", t++);
}

int main() {
#pragma omp parallel for
  for(int i=0; i<10; i++) {
    print();
  }
}
```

```
g++ -fopenmp example.cpp
```

pthreads (POSIX threads)

pthread APIs

thread management

```
pthread_create
pthread_join
pthread_exit
```

[examples]
00_serial.cpp
01_create.cpp
02_join.cpp

mutexes

```
pthread_mutex_t
pthread_mutex_lock
pthread_mutex_unlock
```

[examples]
03_mutex.cpp
04_range.cpp
05_array.cpp
06_timing.cpp

condition variables

```
pthread_cond_t
pthread_cond_wait
pthread_cond_signal
```

[examples]
07_producer_consumer.cpp
08_producer_loop.cpp
09_multiple.cpp
10_buffer.cpp

Thread management

00_serial.cpp

```
#include <stdio.h>

void print() {
  static int t=0;
  printf("%d\n", t++);
}

int main() {
  for(int i=0; i<10; i++) {
    print();
  }
}
```

First let's review what a static variable is.

What will this code print?

01_create.cpp

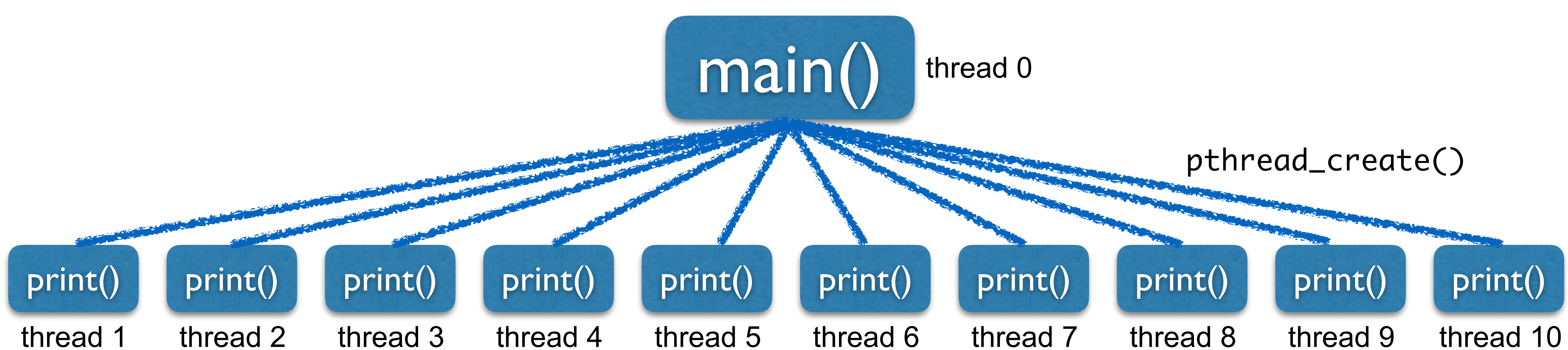
```
#include <pthread.h>
#include <stdio.h>

void* print(void*) {
  static int t=0;
  printf("%d\n", t++);
}

int main() {
  for(int i=0; i<10; i++) {
    pthread_t thread;
    pthread_create(&thread, NULL, print, NULL);
  }
  pthread_exit(NULL);
}
```

This code will create 10 threads and print from each of them.

Compile with "g++ -pthread 01_create.cpp"



Thread management

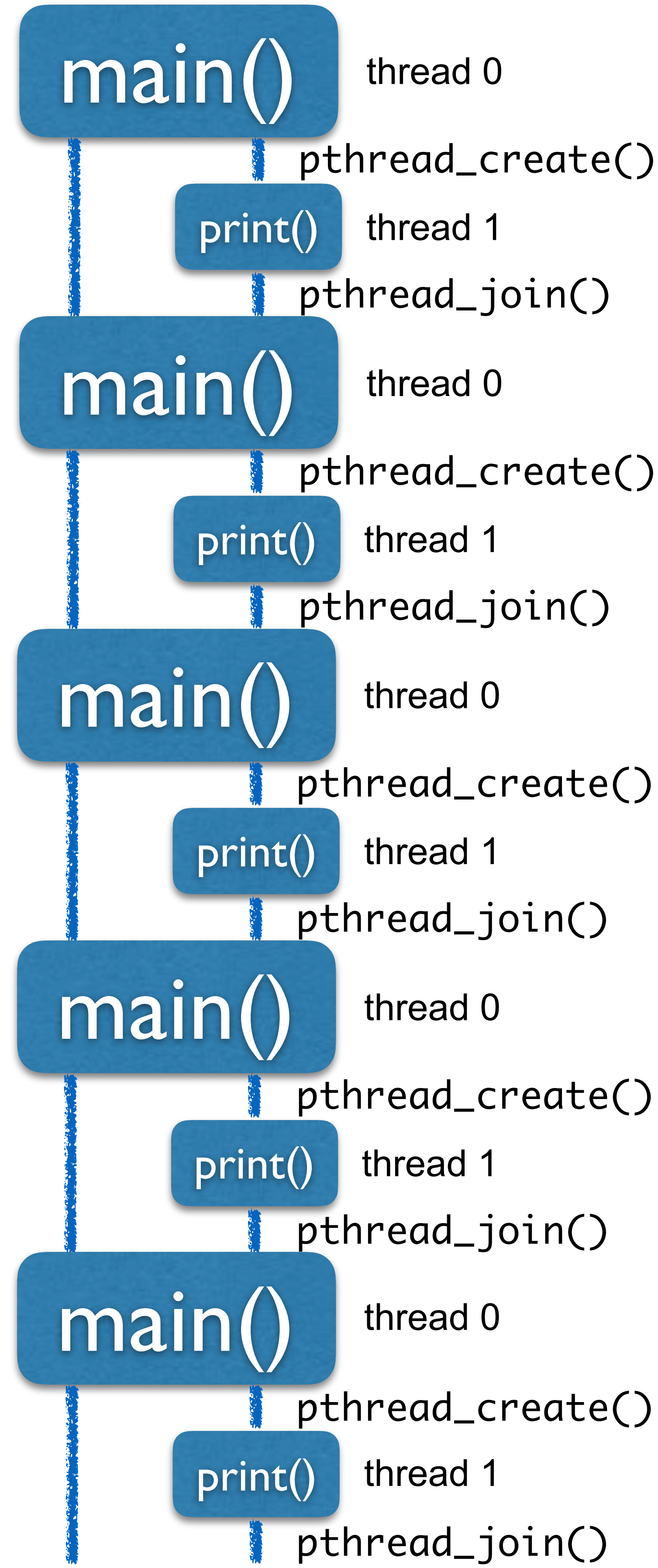
02_join.cpp

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

void* print(void*) {
  static int t=0;
  printf("%d\n", t++);
}

int main() {
  for(int i=0; i<10; i++) {
    pthread_t thread;
    pthread_create(&thread, NULL, print, NULL);
    pthread_join(thread, NULL);
  }
  pthread_exit(NULL);
}
```

What happens when we do a pthread_join in the loop?
Why is the output different from the previous code?



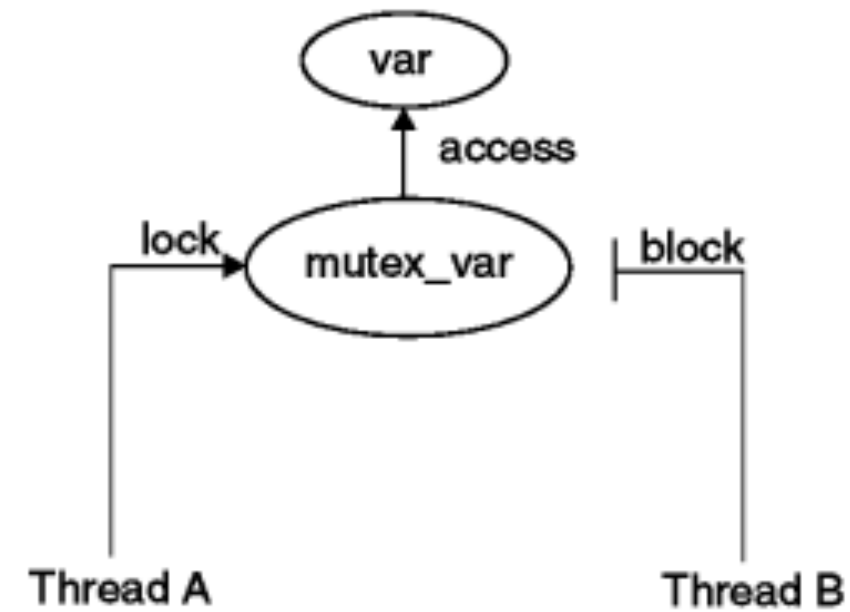
Mutexes

03_mutex.cpp

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

void* print(void*) {
  static int t=0;
  static pthread_mutex_t mutex=PTHREAD_MUTEX_INITIALIZER;
  pthread_mutex_lock(&mutex);
  t++;
  pthread_mutex_unlock(&mutex);
  printf("%d\n", t-1);
}

int main() {
  for(int i=0; i<10; i++) {
    pthread_t thread;
    pthread_create(&thread, NULL, print, NULL);
  }
  pthread_exit(NULL);
}
```



A mutex can be used for mutually exclusive updates of t++.

This means only one thread can read/write at any given time.

Why is the output always in order?

Mutexes

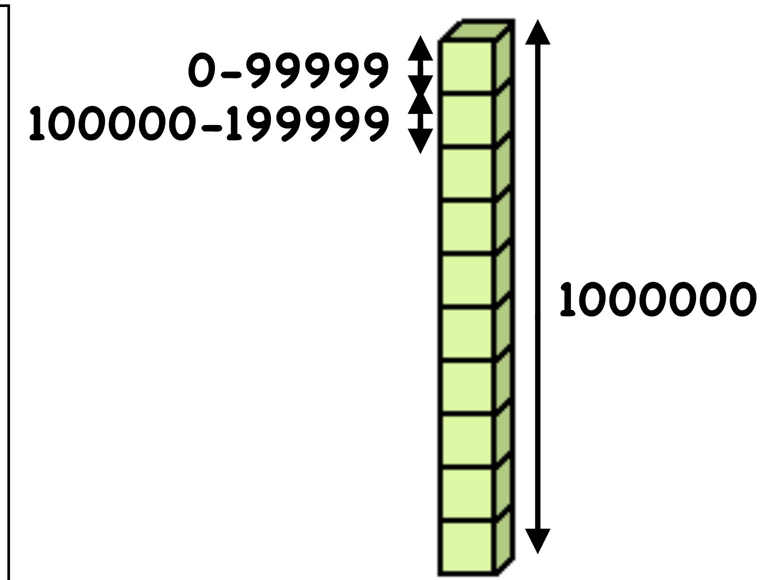
04_range.cpp

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

const int size=1000000;

void* print(void*) {
  static int t=0;
  static pthread_mutex_t mutex=PTHREAD_MUTEX_INITIALIZER;
  pthread_mutex_lock(&mutex);
  t++;
  pthread_mutex_unlock(&mutex);
  int ibegin = (t-1)*size/10;
  int iend = t*size/10;
  printf("thread %d, range %d - %d\n", t-1, ibegin, iend-1);
}

int main() {
  for(int i=0; i<10; i++) {
    pthread_t thread;
    pthread_create(&thread, NULL, print, NULL);
  }
  pthread_exit(NULL);
}
```



Now let us calculate a range of numbers for each thread.

This will be used in the next example to loop over subsets of an array.

Mutexes

05_array.cpp

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

const size_t size=1000000;
static size_t sum=0;

void* print(void* arg) {
  static int t=0;
  static pthread_mutex_t mutex=PTHREAD_MUTEX_INITIALIZER;
  pthread_mutex_lock(&mutex);
  t++;
  pthread_mutex_unlock(&mutex);
  size_t ibegin = (t-1)*size/10;
  size_t iend = t*size/10;
  printf("thread %d, range %ld - %ld\n", t-1, ibegin, iend-1);
  size_t *a = (size_t*)arg;
  pthread_mutex_lock(&mutex);
  for (int i=ibegin; i<iend; i++) sum+=a[i];
  pthread_mutex_unlock(&mutex);
}

int main() {
  size_t *a = new size_t [size];
  for (size_t i=0; i<size; i++) a[i] = 1;
  pthread_t thread[10];
  for(int i=0; i<10; i++) {
    pthread_create(&thread[i], NULL, print, (void*)a);
  }
  printf("sum = %ld\n", sum);
  for(int i=0; i<10; i++) {
    pthread_join(thread[i], NULL);
  }
  printf("sum = %ld\n", sum);
  delete[] a;
  pthread_exit(NULL);
}
```

This code calculates the sum of all elements of an array.
See how the sum is only correct after all the threads are joined.

06_timing.cpp

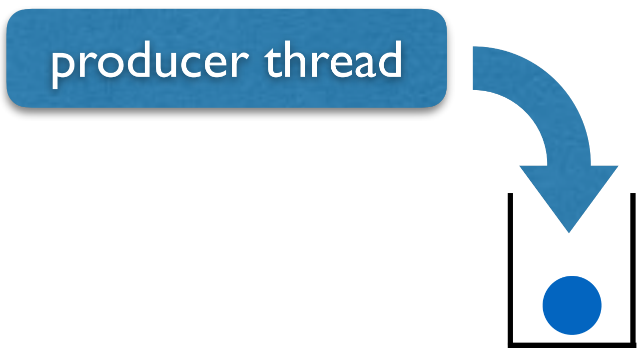
```
Not showing the code here because it's too large.
```

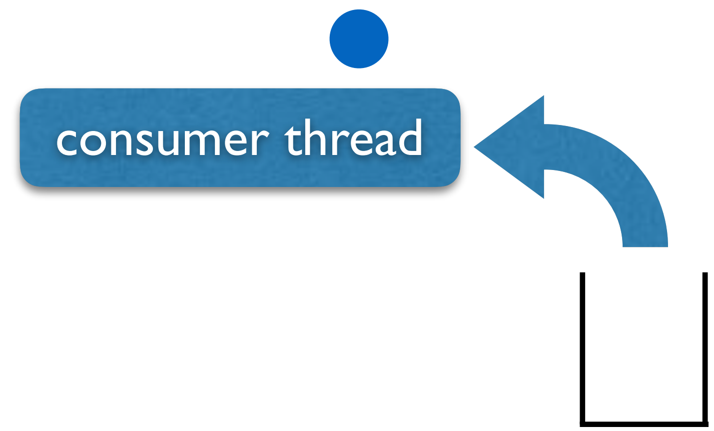
This code measures the execution time of the multi-threaded array summation.

Change the parameter "nthreads" and see how the execution time changes.

Producer consumer model

07_producer_consumer.cpp



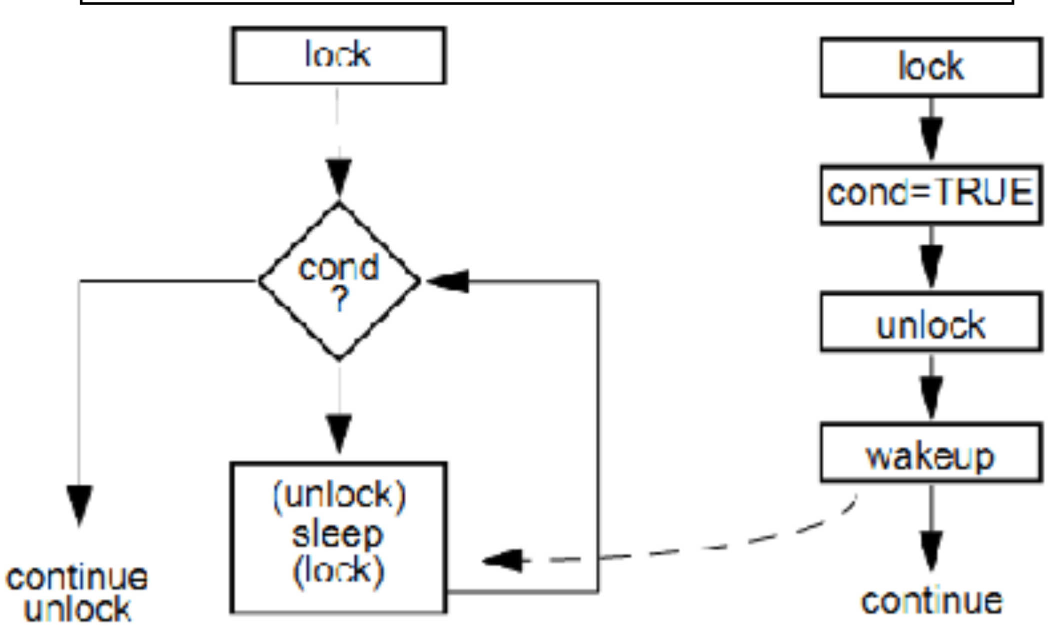



```
void *producer(void *arg) {
  pthread_mutex_lock(&mutex);
  put();
  pthread_cond_signal(&fill);
  pthread_mutex_unlock(&mutex);
  return NULL;
}

void put() {
  value=1;
}
```

```
void *consumer(void *arg) {
  int tmp=0;
  pthread_mutex_lock(&mutex);
  while (value == 0) {
    pthread_cond_wait(&fill, &mutex);
  }
  get();
  pthread_mutex_unlock(&mutex);
  return NULL;
}

void get() {
  value=0;
}
```



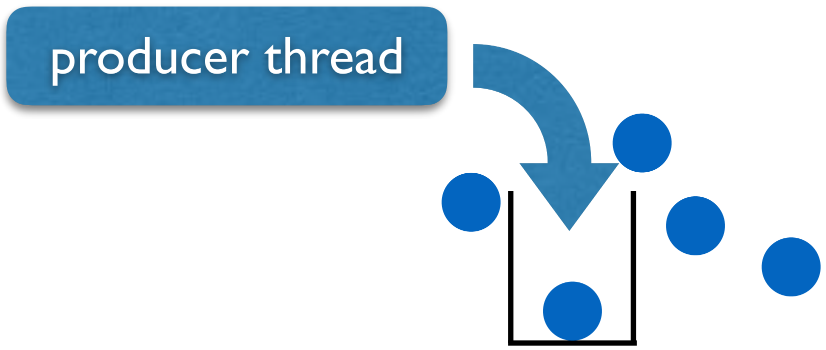
Using a Condition Variable

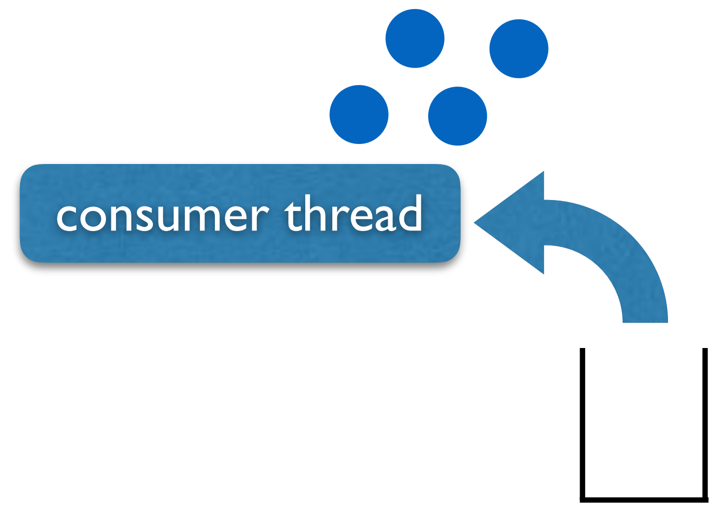
What happens if the value is empty?

This is where we need condition variables.

Producer consumer model

08_producer_loop.cpp






```
void *producer(void *arg) {
  for (int i=0; i<loops; i++) {
    pthread_mutex_lock(&mutex);
    while (value != 0) {
      pthread_cond_wait(&empty, &mutex);
    }
    put(i);
    pthread_cond_signal(&fill);
    pthread_mutex_unlock(&mutex);
  }
  return NULL;
}
```

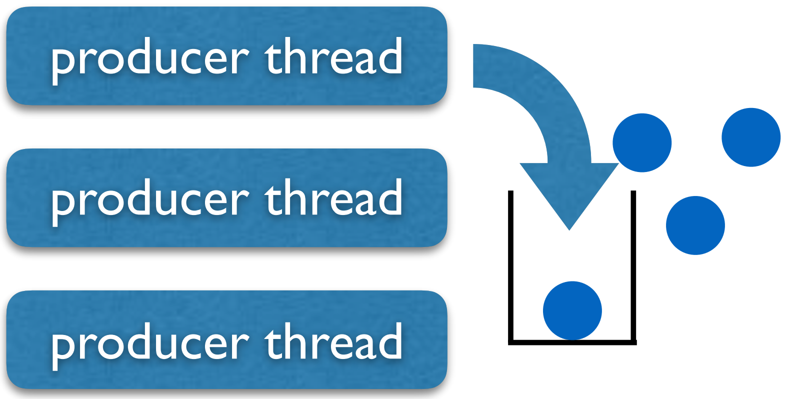
```
void *consumer(void *arg) {
  int tmp=0;
  while (tmp != end) {
    pthread_mutex_lock(&mutex);
    while (value == 0) {
      pthread_cond_wait(&fill, &mutex);
    }
    tmp=get();
    pthread_cond_signal(&empty);
    pthread_mutex_unlock(&mutex);
  }
  return NULL;
}
```

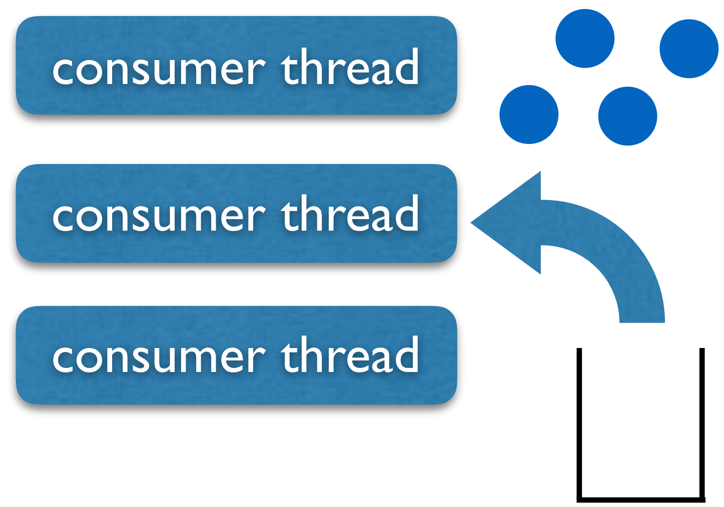
Now let us consider the case where the producer puts multiple values.
This requires an “end” flag to indicate the last value.
We use a conditional variable to signal if full.

The consumer loops until it reaches the “end” value.
We use a conditional variable to signal if empty.

Producer consumer model

09_multiple.cpp






```
for (int i=0; i<producers; i++) {
  pthread_create(&pid[i], NULL, producer, (void *) thread_id);
  thread_id++;
}
for (int i=0; i<consumers; i++) {
  pthread_create(&cid[i], NULL, consumer, (void *) thread_id);
  thread_id++;
}
for (int i=0; i<producers; i++) {
  pthread_join(pid[i], NULL);
}
for (int i=0; i<consumers; i++) {
  pthread_mutex_lock(&mutex);
  while (value != 0)
    pthread_cond_wait(&empty, &mutex);
  put(end);
  pthread_cond_signal(&full);
  pthread_mutex_unlock(&mutex);
}
for (int i=0; i<consumers; i++) {
  pthread_join(cid[i], NULL);
}
```

Many threads are created for the producer and consumer.

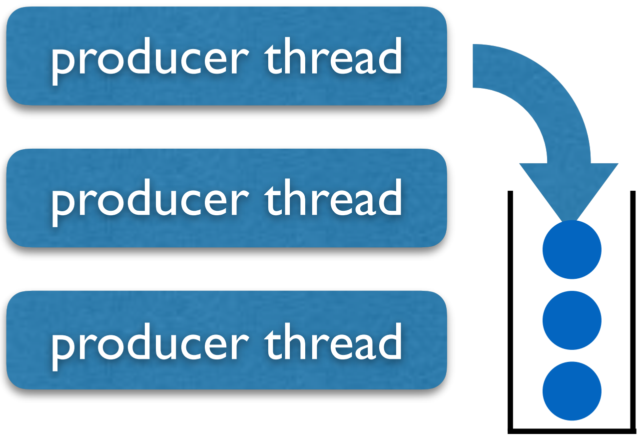
Since only one value can fit in the buffer conditional variables are used to check for full or empty buffers.

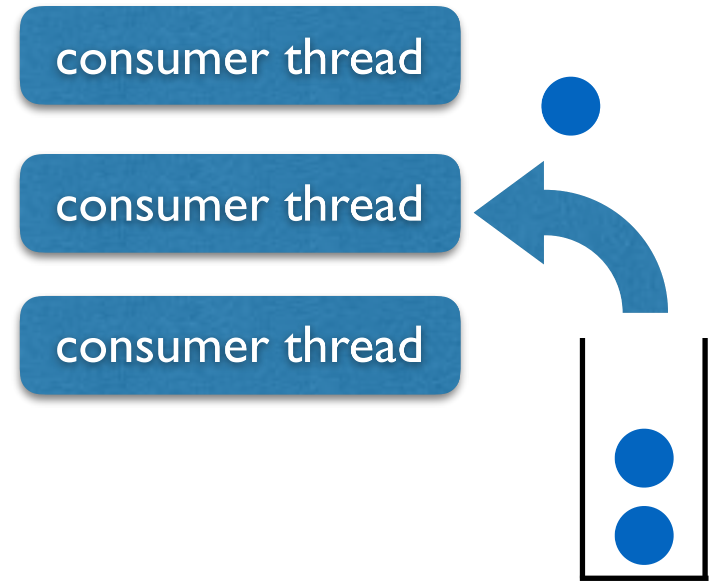
If all the producer threads have been joined and the value is not empty, then the "end" flag is inserted.

Finally the consumer threads are joined.

Producer consumer model

10_queue.cpp






```
void put(int value) {
  queue[end_p]=value;
  end_p=(end_p + 1) % max_queue;
  count++;
}

int get() {
  int tmp=queue[begin_p];
  queue[begin_p]=0;
  begin_p=(begin_p + 1) % max_queue;
  count--;
  return tmp;
}
```

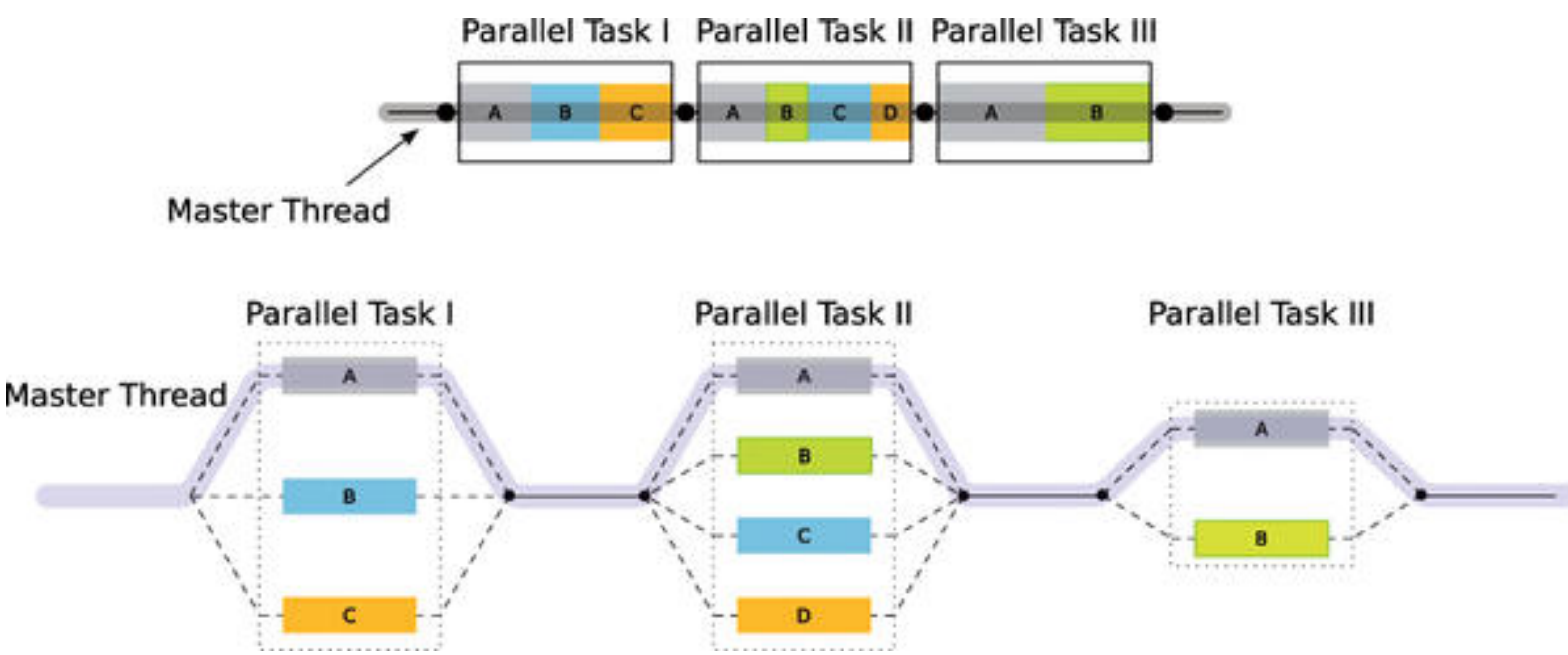
Finally, we enlarge the queue to hold many variables.

The producer and consumer put and get the data by FIFO.

We need both "begin" and "end" pointers for the queue.

We also introduce a "count" for the queue
and signal "full" if count == max_queue
and signal "empty" if count == 0.

OpenMP




```
#pragma omp parallel for
for (int i=0; i<n; i++) {
  b[i] = -a[i];
}
#pragma omp parallel for
for (int i=0; i<n; i++) {
  c[i] = 2*b[i]+a[i];
}
```

OpenMP: parallel for

```
void print() {
  static int t=0;
  printf("%d\n", t);
  t++;
}

int main() {
#pragma omp parallel for
  for(int i=0; i<10; i++) {
    print();
  }
}
```

```
>g++ -fopenmp step01.cpp
```

OpenMP: barrier

```
#include <cstdio>
#include <omp.h>
int main() {
  int x = 2;
#pragma omp parallel shared(x)
  {
    if (omp_get_thread_num() == 0) {
      x = 5;
    } else {
      printf("1: Thread# %d: x = %d\n", omp_get_thread_num(),x );
    }
#pragma omp barrier
    if (omp_get_thread_num() == 0) {
      printf("2: Thread# %d: x = %d\n", omp_get_thread_num(),x );
    } else {
      printf("3: Thread# %d: x = %d\n", omp_get_thread_num(),x );
    }
  }
}
```

OpenMP: nowait

```
#include <cmath>
#include <cstdlib>
#include <cstdio>
#include <sys/time.h>
int main(int argc, char ** argv) {
  struct timeval tic, toc;
  int n = atoi(argv[1]);
  double * a = new double [n];
  double * b = new double [n];
  double * y = new double [n];
  double * z = new double [n];
  gettimeofday(&tic, NULL);
#pragma omp parallel
  {
#pragma omp for nowait
    for (int i=1; i<n; i++)
      b[i] = (a[i] + a[i-1]) / 2.0;
#pragma omp for nowait
    for (int i=0; i<n; i++)
      y[i] = sqrt(z[i]);
  }
  gettimeofday(&toc, NULL);
  printf("%lf s\n",toc.tv_sec-tic.tv_sec+(toc.tv_usec-tic.tv_usec)*1e-6);
  delete[] a;
  delete[] b;
  delete[] y;
  delete[] z;
}
```

OpenMP: lastprivate

```
#include <cstdio>
#include <omp.h>
int main() {
  int jlast, klast;
#pragma omp parallel
  {
#pragma omp for collapse(2) lastprivate(jlast, klast)
    for (int k=1; k<=2; k++) {
      for (int j=1; j<=3; j++) {
        jlast = j;
        klast = k;
      }
    }
#pragma omp single
    printf("%d %d\n", klast, jlast);
  }
}
```

OpenMP: sections

```
#include <cstdio>
#include <omp.h>
int main() {
  int section_count = 0;
  omp_set_dynamic(0);
  omp_set_num_threads(2);
#pragma omp parallel
#pragma omp sections
  {
#pragma omp section
    {
      section_count++;
      printf("section_count %d\n",section_count);
    }
#pragma omp section
    {
      section_count++;
      printf("section_count %d\n",section_count);
    }
  }
}
```

OpenMP: Fibonacci

```
#include <cstdlib>
#include <cstdio>
int fib(int n) {
  int i,j;
  if (n<2) return n;
#pragma omp task shared(i)
  i = fib(n-1);
#pragma omp task shared(j)
  j = fib(n-2);
#pragma omp taskwait
  return i+j;
}

int main(int argc, char ** argv) {
  int n = atoi(argv[1]);
  printf("%d\n",fib(n));
}
```

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, …

OpenMP: depend

```
#include <cstdio>
int main() {
  int x = 1;
#pragma omp task shared(x) depend(out: x)
  x = 2;
#pragma omp task shared(x) depend(in: x)
  printf("x + 1 = %d\n", x+1);
#pragma omp task shared(x) depend(in: x)
  printf("x + 2 = %d\n", x+2);
}
```

OpenMP: atomic

```
#include <cstdio>
int main() {
  float x[10];
  int index[1000];
  for (int i=0; i<1000; i++) {
    index[i] = i % 10;
  }
  for (int i=0; i<10; i++)
    x[i] = 0.0;
#pragma omp parallel for shared(x, index)
  for (int i=0; i<1000; i++) {
#pragma omp atomic update
    x[index[i]]++;
  }
  for (int i=0; i<10; i++)
    printf("%d %f\n",i, x[i]);
}
```

OpenMP: ordered

```
#include <cstdio>
int main() {
#pragma omp parallel for ordered schedule(dynamic)
  for (int i=0; i<100; i+=5) {
#pragma omp ordered
    printf("%d\n",i);
  }
}
```

OpenMP: threadprivate

```
#include <cstdio>
int counter = 0;
#pragma omp threadprivate(counter)

int main() {
#pragma omp parallel for
  for (int i=0; i<100; i++) {
    counter++;
  }
  printf("%d\n",counter);
}
```