Shared Memory: Virtual Shared Memory, Threads & OpenMP

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    - Architectures of Memory Systems
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    - Memory Mapping
    - Separated Address Space
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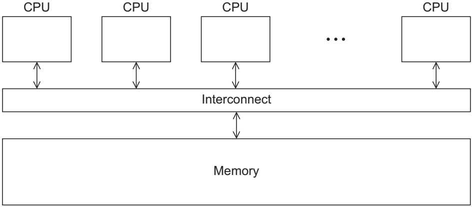
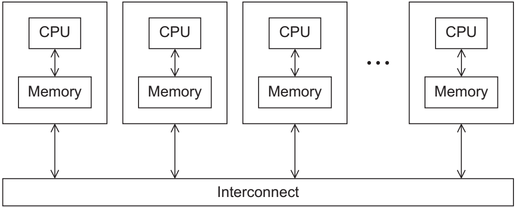
Shared Memory vs. Distributed Memory [1]

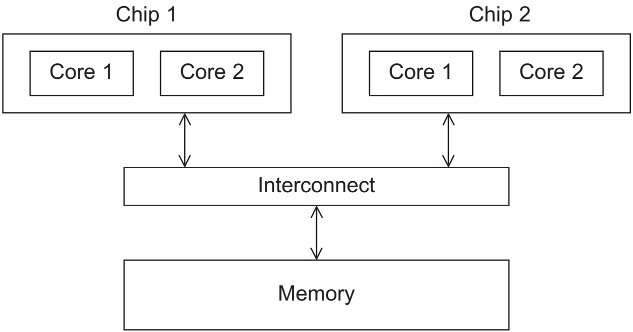
- Shared Memory



- Distributed Memory

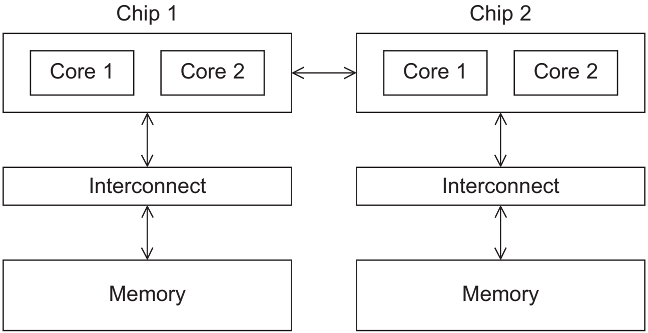


Shared Memory: Uniform Memory Access System



- Same access times for all the cores
- Direct connection to a block of memory
- Relative easy to program

Shared Memory: Nonuniform Memory Access System



- Different access times
- Different memory locations

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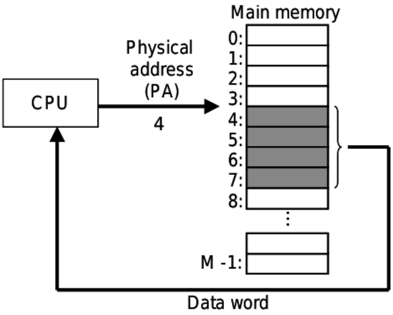
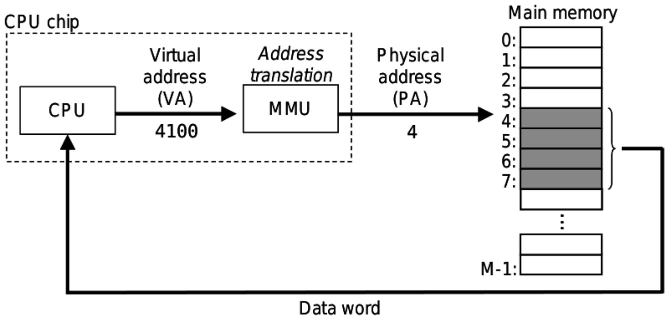
- A system that uses physical addressing

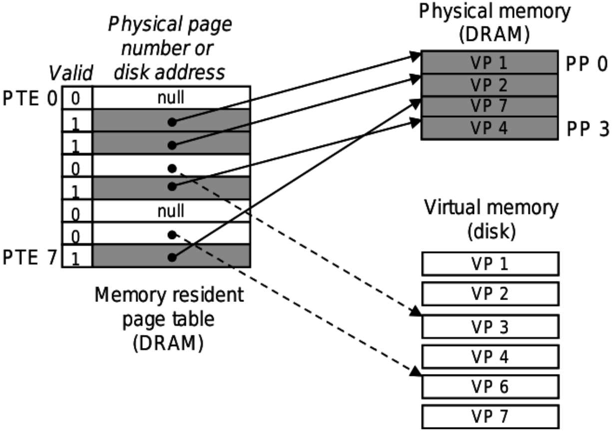


Virtual Memory: Mapping I

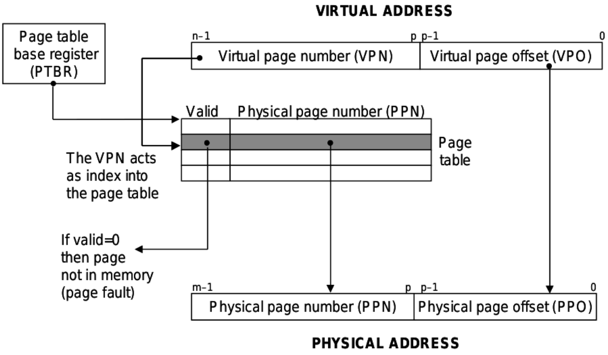
- A system that uses virtual addressing
- MMU - Memory Management Unit



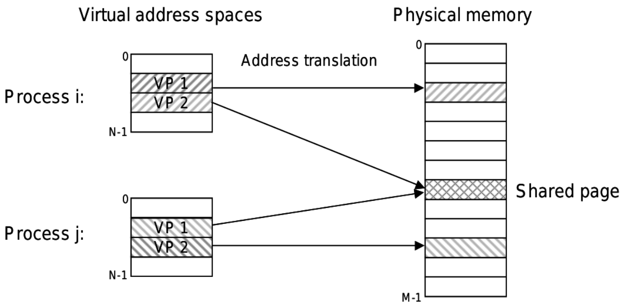
Virtual Memory: Mapping II



Virtual Memory: Mapping III



Virtual Shared Memory: Separated Address Space I

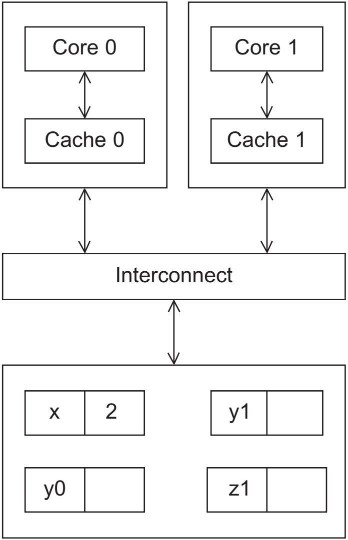


- Each process has its own Virtual Address Space

Virtual Shared Memory: Separated Address Space II

- Simplifying linking
  - Allows a linker to produce fully linked executables that are independent of the ultimate location of the code and data in the physical memory
- Simplifying loading
  - Easy to load executable and shared objects into memory
- Simplifying sharing
  - Mapping to the same physical page
- Simplifying memory allocation
  - Allocation of contiguous space

Cache Coherence



Example

x is initialized to 2
y0 is private and owned by core 0
y1, z1 are private and owned by core 1

Time	Thread 0	Thread 1
0	`y0 = x;`	`y1 = 3 * x;`
1	`x = 7;`	
2		`z1 = 4 * x;`

What is the value of z1?
`z1 = 4 * 7 = 28`
or
`z1 = 4 * 2 = 8`

Problem: Cache Coherence

Snooping cache coherence

Cores share a bus. When core 0 updates the copy of `x` stored in its cache, it broadcasts this information across the bus. Core 1 is "snooping" the bus and it will see that `x` has been updated. He marks his copy of `x` as invalid.

Directory-based cache coherence

A directory stores the status of each cache line. A directory is typically distributed and each CPU/Memory pair is responsible to update the status of its own local memory. If core 0 reads a cache line in its own local cache, it writes in the directory, that he has a copy of this cache line in his local cache. When an other core modifies a variable, that lies in that cache line, the cache controller invalidates the copies in corresponding local caches.

Problem: False Sharing I

Example (Serial program)

As an example, suppose we want to repeatedly call a function **f(i,j)** and add the computed values into a vector.

```
int i, j, m, n;
double y[m];
/* Assign y = 0 */
...
for (i = 0; i < m; i++)
        for (j = 0; i < n; i++)
                y[i] += f(i,j);
```

Problem: False Sharing II

Example (Parallel program)

```
/* Private variable */
int i, j, iter_count;
/* Shared variables initialized by one core */
int m, n, core_count;
double y[m];

iter_count = m/core_count;

/* Core 0 does this */
for (i = 0; i < iter_count; i++)
        for (j = 0; i < n; i++)
                y[i] += f(i,j);

/* Core 1 does this */
for (i = iter_count + 1; i < 2 * iter_count; i++)
        for (j = 0; i < n; i++)
                y[i] += f(i,j);
```

- $m = 8$
- doubles are 8 bytes
- cache line can store eight doubles (64 bytes)
- y takes one full cache line

What happens?

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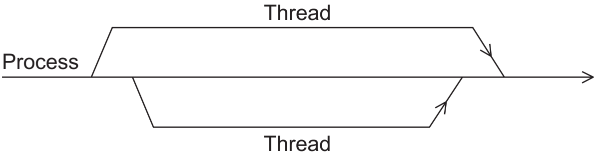
Pthreads

- Pthreads - POSIX threads
- Specifies a library for Unix-like systems
- It exists other specifications like: Java threads, Windows threads, Solaris threads. All of the specifications support the same basic ideas.

Pthreads: Forking and Joining



- Threads are often called light-weight processes
- Master thread forks slave threads
- Slave threads joins to the master thread
- Typical approaches to thread startup:
  - Static threads: all threads are created before computation
    - Example: Computation of scalar product
  - Dynamic threads: threads are created at demand
    - Example: Web server applications, that responds to client requests

Pthreads: Example I

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

/* Global variable:  accessible to all threads */
int thread_count;

void *Hello(void* rank);  /* Thread function */
```

Pthreads: Example II

```
int main(int argc, char* argv[]) {
   long       thread;  /* Use long in case of a 64-bit system */
   pthread_t* thread_handles;

   /* Get number of threads from command line */
   thread_count = strtol(argv[1], NULL, 10);

   thread_handles = malloc (thread_count*sizeof(pthread_t));

   for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL, Hello, (void*) thread);

   printf("Hello␣from␣the␣main␣thread\n");

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   free(thread_handles);
   return 0;
}  /* main */
```

Pthreads: Example III

```
void *Hello(void* rank) {
   long my_rank = (long) rank;  /* Use long in case of 64-bit system */

   printf("Hello from thread %ld of %d\n", my_rank, thread_count);

   return NULL;
}  /* Hello */
```

Pthreads: Forking and Joining functions

- Starting/forking threads

```
int pthread_create(
        pthread_t* thread_p,
        const pthread_attr_t* attr_p,
        void* (*start_routine)(void*),
        void* arg_p);
```

- Thread function

```
void* thread_function(void* args_p);
```

- Stopping/joining threads

```
int pthread_join(
        pthread_t thread,
        void** ret_val_p);
```

Pthreads: Example execution

- Compilation

```
gcc -g -Wall -o pth_hello pth_hello.c -lpthreads
```

- Execution with 1 thread

```
./pth_hello 1
```

```
Hello from the main thread
Hello from thread 0 of 1
```

- Execution with 4 threads results in a non-deterministic output

```
./pth_hello 4
```

```
Hello from the main thread
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
```

```
Hello from thread 0 of 4
Hello from thread 2 of 4
Hello from thread 1 of 4
Hello from the main thread
Hello from thread 3 of 4
```

Pthreads: Race conditions and critical sections

Race condition

When several threads attempt to access a shared resource such as a shared variable or a shared file, at least one of the accesses is an update, and the access can result in an error, we have a race condition.

Pthreads: Example of Race Condition

Example

Suppose that we have two threads. Each thread computes a value and stores it in a private variable y. We want add these both values to the shared variable x.

```
y = Compute(my_rank);
x = x + y;
```

Time	Thread 0	Thread 1
1	Started by main thread	
2	Call Compute()	Started by main thread
3	Assign y = 1	Call Compute()
4	Put x = 0 and y = 1 into registers	Assign y = 2
5	Add 0 and 1	Put x = 0 and y = 2 into registers
6	Store 1 in memory location x	Add 0 and 2
7		Store 2 in memory location x

The "winner" result will be overwritten by the "loser".

Pthreads: Locks

- Locks
  - busy-waiting
  - mutexes (mutual exclusions)
  - semaphores
  - read-write locks

Pthreads: Example of Critical Section

Formula for computing π

$$\pi = 4\left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots + (-1)^n \frac{1}{2n+1} + \cdots\right) \quad (1)$$

- Serial computation of π

```
double Serial_pi(long long n) {
   double sum = 0.0;
   long long i;
   double factor = 1.0;

   for (i = 0; i < n; i++, factor = -factor) {
      sum += factor/(2*i+1);
   }
   return 4.0*sum;
}  /* Serial_pi */
```

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;

   for (i = my_first_i; i < my_last_i; i++, factor = -factor) {
      sum += factor/(2*i+1); // Critical Section
   }

   return NULL;
}  /* Thread_sum */
```

Pthreads: Busy-Waiting

"Concept of Busy-Waiting"

```
y = Compute(my_rank);
while = (flag != my_rank);
x = x + y;
flag++;
```

- Thread keep re-executing the test until the test is false
- Simple implementation with a busy-wait loop
- Programmer can control the order of execution of threads
- Consumes CPU cycles
- Can seriously degrade performance

Pthreads: Example of Busy-Waiting

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor, my_sum = 0.0;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;

   for (i = my_first_i; i < my_last_i; i++, factor = -factor)
      my_sum += factor(2*i+1);

   while (flag != my_rank);
   sum += my_sum;
   flag = (flag+1) % thread_count;

   return NULL;
}  /* Thread_sum */
```

Pthreads: Mutexes

- Abbreviation of mutual exclusions
- A mutex is a special type of a variable

Pthreads: Mutexes

A variable of type `pthread_mutex_t` needs to be initialized before it (a mutex) can be used.

- Initialization of a mutex

```
int pthread_mutex_init(
        pthread_mutex_t* mutex_p,
        const pthread_mutexattr_t* attr_p);
```

- Destruction of a mutex

```
int pthread_mutex_destroy(pthread_mutex_t* mutex_p);
```

- Gain access to a critical section

```
int pthread_mutex_lock(pthread_mutex_t* mutex_p);
```

- Unlock critical section

```
int pthread_mutex_unlock(pthread_mutex_t* mutex_p);
```

Pthreads: Semaphores

- Semaphores can be thought as a special type of `unsigned int`
  - They can take values `0, 1, 2, ...`
  - Binary semaphore takes `0` and `1` as values
  - Value `0` means “locked” and `1` means “unlocked”
- Semaphores are not a part of Pthreads and it’s necessary to add the following preprocessor directive:

```
#include <semaphore.h>
```

- It’s possible to control the order in which the threads execute the critical section

Pthreads: Semaphores in C-Language

A variable of type sem_t needs to be initialized before it (a semaphore) can be used.

- Initialization of a semaphore

```
int sem_init(
        sem_t* semaphore_p,
        int shared,
        unsigned initial_val);
```

- Destruction of a mutex

```
int sem_destroy(sem_t* semaphore_p);
```

- Increment semaphore

```
int sem_post(sem_t* semaphore_p);
```

- Decrement semaphore

```
int sem_wait(sem_t* semaphore_p);
```

Pthreads: Read-Write Locks

- Low-level locking
- Provides two lock-functions
  - One lock function locks the read-write lock for reading
  - The other lock function locks the read-write lock for writing

Pthreads: Read-Write Locks in C-Language

A variable of type `pthread_rwlock_t` needs to be initialized before it (a rwlock) can be used.

- Initialization of rwlock

```
int pthread_rwlock_init(
        pthread_rwlock_t* rwlock_p,
        const pthread_rwlockattr_t*);
```

- Destruction of rwlock

```
int pthread_rwlock_destroy(pthread_rwlock_t* rwlock_p);
```

- Read-write lock for reading

```
int pthread_rwlock_rdlock(pthread_rwlock_t* rwlock_p);
```

- Read-write lock for writing

```
int pthread_rwlock_rwlock(pthread_rwlock_t* rwlock_p);
```

- Unlock

```
int pthread_rwlock_unlock(pthread_rwlock_t* rwlock_p);
```

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OpenMP (OpenMultiProcessing)

- Standard for programming shared memory systems
- Uses library functions and preprocessor directives (pragmas)
- Requires compiler support
- Developers could incrementally parallelize existing serial programs
- Higher-level than Pthreads

OpenMP: Example I

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

void Hello(void);  /* Thread function */

int main(int argc, char* argv[]) {
   int thread_count = strtol(argv[1], NULL, 10);

# pragma omp parallel num_threads(thread_count)
   Hello();

   return 0;
}  /* main */

void Hello(void) {
   int my_rank = omp_get_thread_num();
   int thread_count = omp_get_num_threads();

   printf("Hello from thread %d of %d\n", my_rank, thread_count);

}  /* Hello */
```

OpenMP: Example II

- Compilation

```
gcc -g -Wall -fopenmp -o omp_hello omp_hello.c
```

- Execution with 4 threads

```
./omp_hello 4
```

- Output is non-deterministic

```
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
```

```
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
```

OpenMP: Pragmas

OpenMP pragmas always begin with **# pragma omp**. They are followed by a directive. Strings after a directive are called clauses. Clauses provide additional information for the directive.

Example

```
#  pragma omp parallel num_threads(thread_count)
   Hello();
```

- The **parallel** directive specifies, that the structured block of code that follows should be executed by multiple threads
- The clause **num_threads(thread_count)** specifies how many threads of the structured block below should be created

OpenMP: Library

- `#include <omp.h>` provides predefined constants and OpenMP functions
  - `int omp_get_thread_num(void);` returns the ID of the current thread
  - `int omp_get_num_threads(void);` returns the number of threads in the team
- `#include omp.h` is only needed, if we use predefined constants or call OpenMP functions

Race Conditions and Critical Sections

Race Condition: multiple threads are attempting to access a shared resource, at least one of the accesses is an update, and the accesses can result in an error.

Example

Time	Thread 0	Thread 1
0	`global_result = 0` to register	finish `my_result`
1	`my_result = 1` to register	`global_result = 0` to register
2	add `my_result` to `global_result`	`my_result = 2` to register
3	store `global_result = 1`	add `my_result` to `global_result`
4		store `global_result = 2`

```
# pragma omp critical
        global_result = my_result;
```

- Only one thread can execute after **`# pragma omp critical`** following structured block of code.
- No other thread can start execute this code until the first thread has finished.

OpenMP: Locks

- `# pragma omp critical`
- `# pragma omp atomic`
- Lock-functions in `omp.h`

OpenMP: **critical** Directive

```
# pragma omp critical(name)
        <structured block>
```

- Blocks protected with **critical** directives with different names can be executed simultaneously.

OpenMP: atomic Directive

```
# pragma omp atomic
        <single C assignment statement>
```

- Can only protect critical sections that consist of a single C assignment statement.
- Statement must ave one of the following form:
  - `x <op> = <expression>;`
  - `x++;`
  - `++x;`
  - `x--;`
  - `--x;`
- `<op>` can be one of the binary operators:
  - `+, *, -, /, &, ^, |, <<, >>`
- `<expression>` must not reference `x`

OpenMP: Lock Functions

A variable of type omp_lock_t needs to be initialized before it (a lock) can be used.

- Initialization

```
void omp_init_lock(omp_lock_t* lock_p);
```

- Set lock

```
void omp_set_lock(omp_lock_t* lock_p);
```

- Unset lock

```
void omp_unset_lock(omp_lock_t* lock_p);
```

- Destroy lock

```
void omp_destroy_lock(omp_lock_t* lock_p);
```

OpenMP: **reduction** Clause

```
reduction(<operator>: <variable list>)
```

- **<operator>** can be **+, *, -, &, |, ^, &&, ||**
- OpenMP creates for each variable in **variable list** a private variable and stores there the result of computation
- OpenMP creates a critical section, where the results from the private variables are computed with the corresponding variable

OpenMP: Reduction Clause in C-Language

Example

Code without reduction clause:

```
#       global_result = 0.0;
#       pragma omp parallel num_threads(thread_count)
        {
                double my_result = 0.0 /* private */
                my_result += Local_trap(double a, double b, int n);
#               pragma omp critical
                global_result += my_result;
        }
```

Equivalent code with reduction clause:

```
        global_result = 0.0
#       pragma omp parallel num_threads(thread_count) \
                reduction(+: global_result)
        global_result += Local_trap(double a, double b, int n);
```

OpenMP

OpenMP provides many more other directives, clauses and library functions.

- Parallelization of `for`-loops
- Barriers and condition variables

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Summary

- Memory Systems
  - Shared and distributed systems
  - Uniform and non-uniform memory systems
- Virtual shared memory
  - Virtual addressing
  - Problems: cache coherence and false sharing
- Pthreads and OpenMP
  - Example
  - Race conditions
  - Locks

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