Programming with Shared Memory PART I

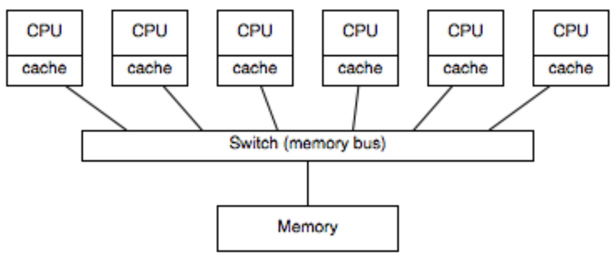
HPC Fall 2012

Prof. Robert van Engelen

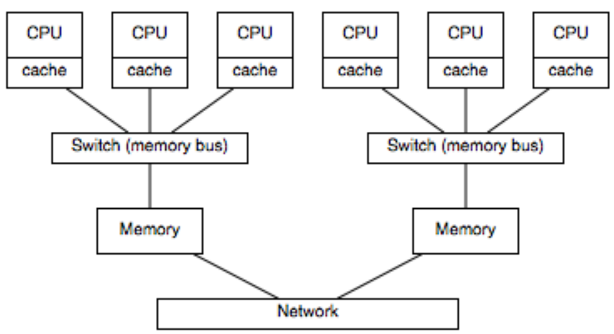
Overview

- Shared memory machines
- Programming strategies for shared memory machines
- Allocating shared data for IPC
- Processes and threads
- MT-safety issues
- Coordinated access to shared data
  - Locks
  - Semaphores
  - Condition variables
  - Barriers
- Further reading

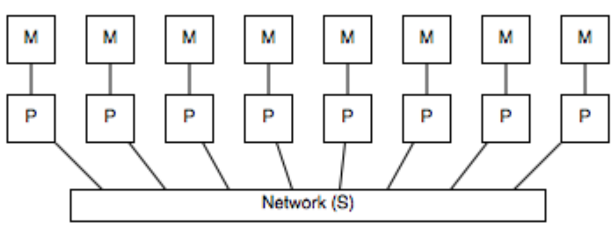
Shared Memory Machines



Shared memory UMA machine with a single bus

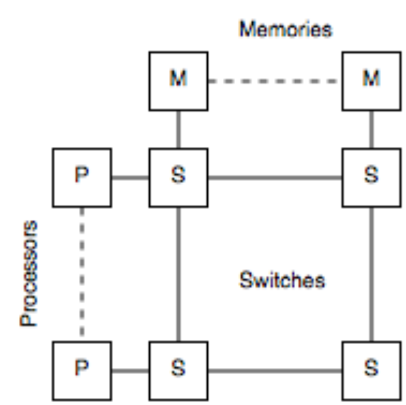


Shared memory NUMA machine with memory banks



DSM

- Single address space
- Shared memory
  - Single bus (UMA)
  - Interconnect with memory banks (NUMA)
  - Cross-bar switch
- Distributed shared memory (DSM)
  - Logically shared, physically distributed

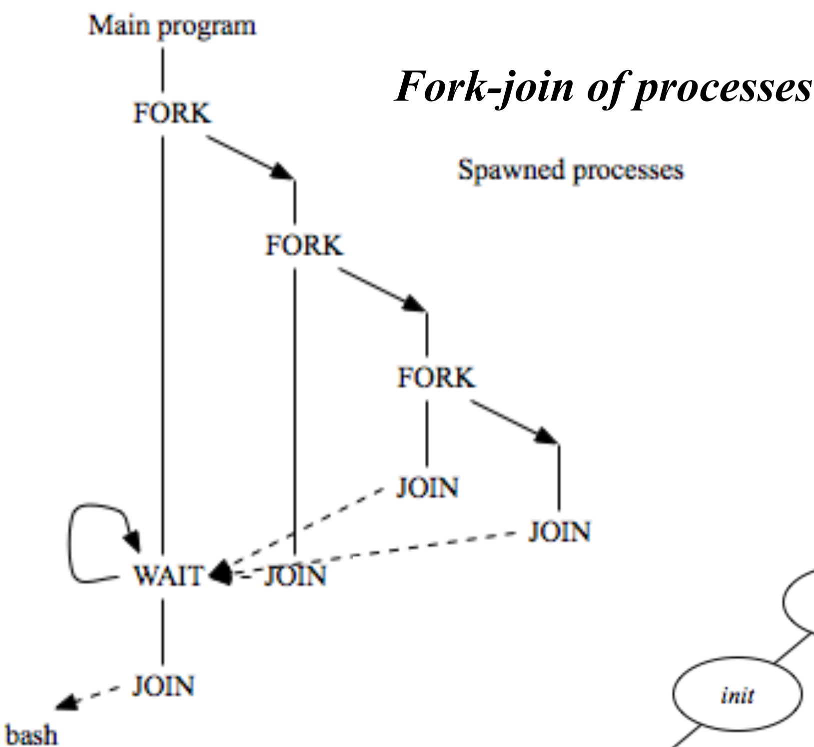


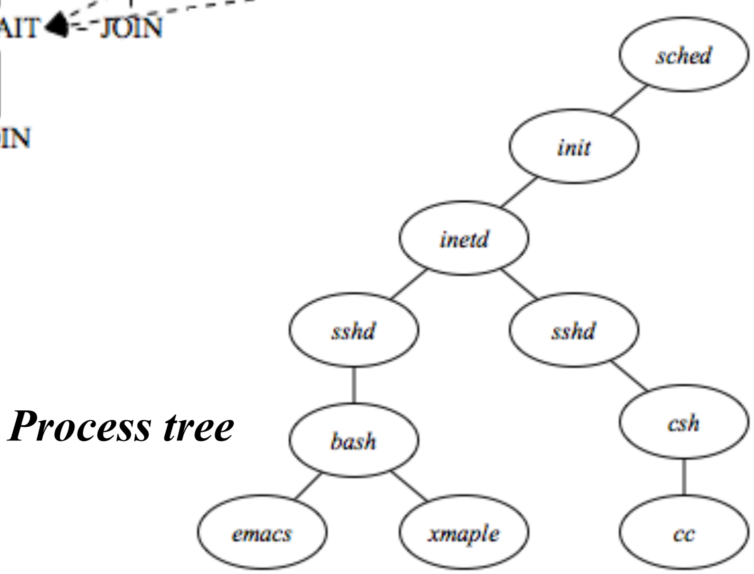
Shared memory multiprocessor with cross-bar switch

Programming Strategies for Shared Memory Machines

- Use a *specialized programming language* for parallel computing
  - For example: HPF, UPC
- Use *compiler directives* to supplement a sequential program with parallel directives
  - For example: OpenMP
- Use *libraries*
  - For example: ScaLapack (though ScaLapack is primarily designed for distributed memory)
- Use *heavyweight processes and a shared memory API*
- Use *threads*
- Use a *parallelizing compiler* to transform (part of) a sequential program into a parallel program

Heavyweight Processes





- The UNIX system call **`fork()`** creates a new process
  - **`fork()`** returns 0 to the child process
  - **`fork()`** returns process ID (pid) of child to parent
- System call **`exit(n)`** joins child process with parent and passes exit value **`n`** to it
- Parent executes **`wait(&n)`** to wait until one of its children joins, where **`n`** is set to the exit value
- System and user processes form a tree

Fork-Join

Process 1

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

SPMD program

Fork-Join

Process 1

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

SPMD program

Process 2

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

Copy of program, data, and file descriptors (operations by the processes on open files will be independent)

Fork-Join

Process 1

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

SPMD program

Process 2

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

Copy of program and data

Fork-Join

Process 1

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

SPMD program

Process 2

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

Copy of program and data

Fork-Join

Process 1

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

SPMD program

Process 2

```
…
…
pid = fork();
if (pid == 0)
{ … // code for child
  exit(0);
} else
{ … // parent code continues
  wait(&n); // join
}
… // parent code continues
…
```

Terminated

Creating Shared Data for IPC

`shmget()`
returns the shared memory identifier for a given key (key is for naming and locking)

`shmat()`
attaches the segment identified by a shared memory identifier and returns the address of the memory segment

`shmctl()`
deletes the segment with **`IPC_RMID`** argument

`mmap()`
returns the address of a mapped object described by the file id returned by **`open()`**

`munmap()`
deletes the mapping for a given address

- *Interprocess communication* (IPC) via shared data
- Processes do not automatically share data
- Use files to share data
  - Slow, but portable
- Unix system V **`shmget()`**
  - Allocates shared pages between two or more processes
- BSD Unix **`mmap()`**
  - Uses file-memory mapping to create shared data in memory
  - Based on the principle that files are shared between processes

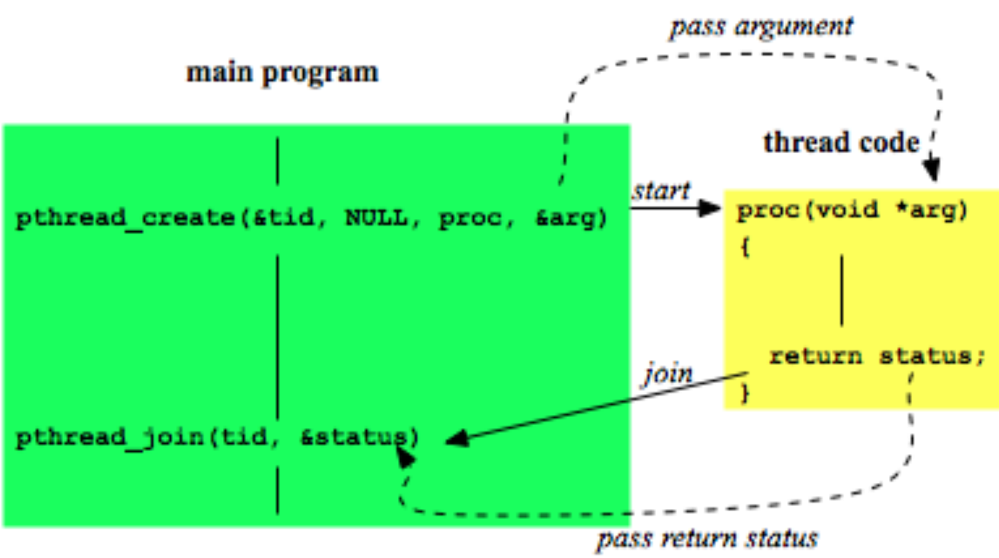
shmget vs mmap

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

size_t len; // size of data we want
void *buf; // to point to shared data
int shmid;
key_t key = 9876; // or IPC_PRIVATE
shmid = shmget(key,
               len,
               IPC_CREAT|0666);
if (shmid == -1) … // error
buf = shmat(shmid, NULL, 0);
if (buf == (void*)-1) … // error
…
fork(); // parent and child use buf
…
wait(&n);
shmctl(shmid, IPC_RMID, NULL);
```

```
#include <sys/types.h>
#include <sys/mman.h>

size_t len; // size of data we want
void *buf; // to point to shared data
buf = mmap(NULL,
           len,
           PROT_READ|PROT_WRITE,
           MAP_SHARED|MAP_ANON,
           -1, // fd=-1 is unnamed
           0);
if (buf == MAP_FAILED) … // error
…
fork(); // parent and child use buf
…
wait(&n);
munmap(buf, len);
…
```

Tip: use **`ipcs`** command to display IPC shared memory status of a system

Threads



Thread creation and join

- *Threads of control* operate in the same memory space, sharing code and data
  - Data is implicitly shared
  - Consider data on a thread's stack private
- Many OS-specific thread APIs
  - Windows threads, Linux threads, Java threads, …
- POSIX-compliant Pthreads:

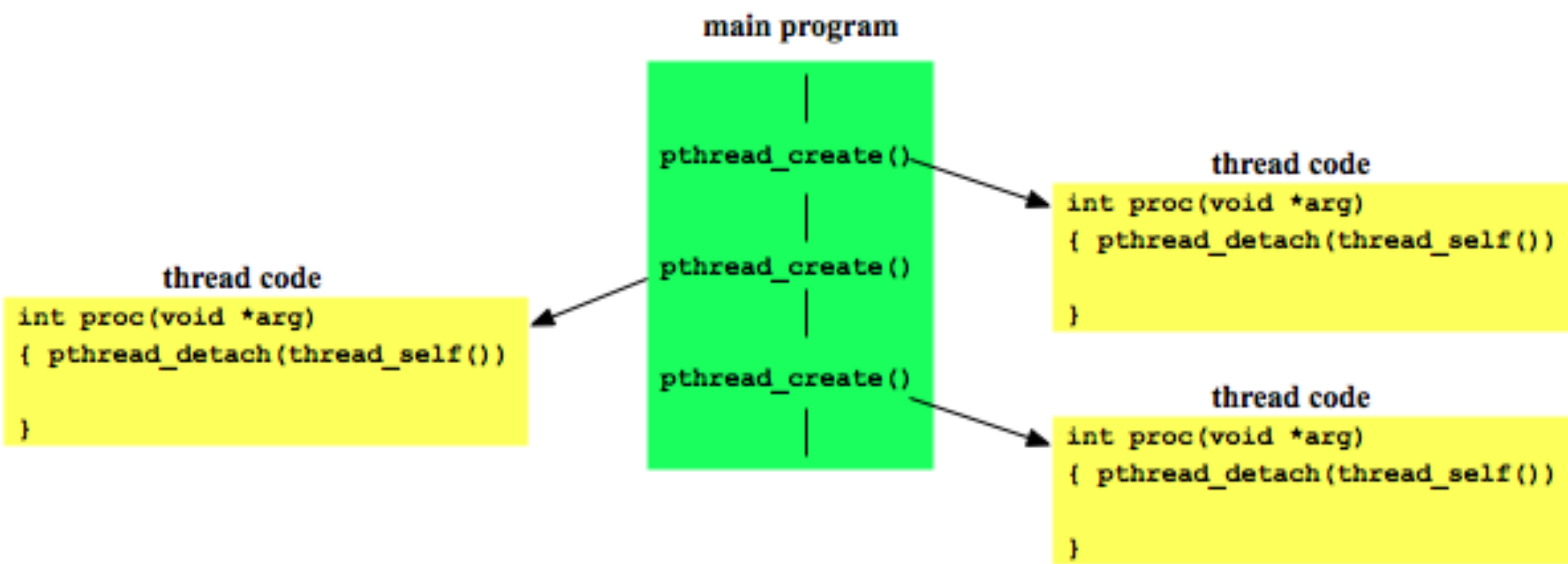
`pthread_create()`
start a new thread

`pthread_join()`
wait for child thread to join

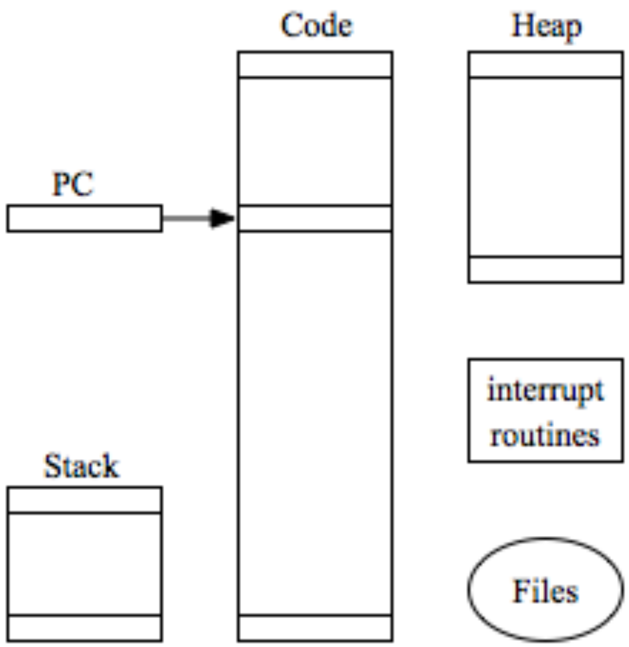
`pthread_exit()`
stop thread

Detached Threads

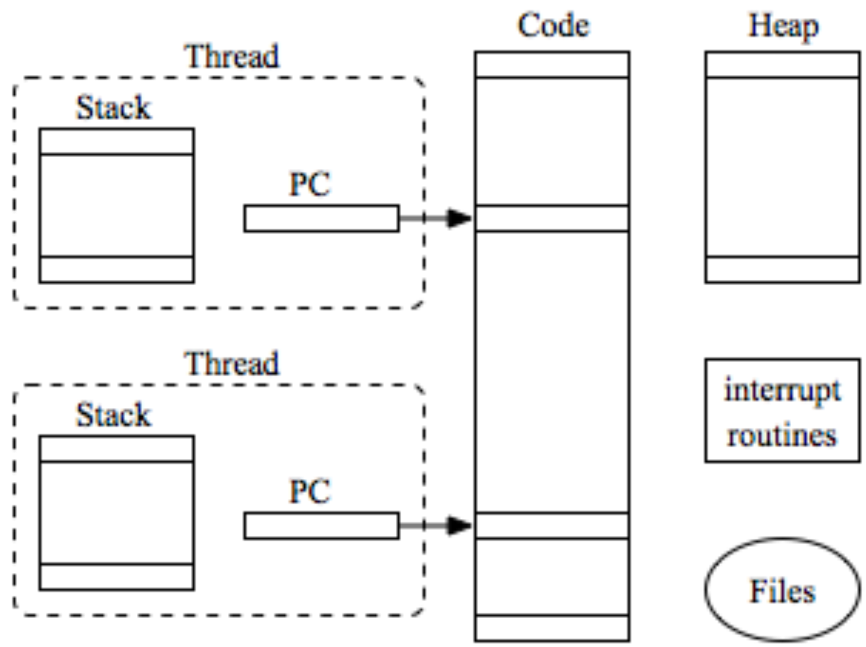
- Detached threads do not join
- Use **`pthread_detach(thread_id)`**
- Detached threads are more efficient
- Make sure that all detached threads terminate before program terminates



Process vs Threads



Process

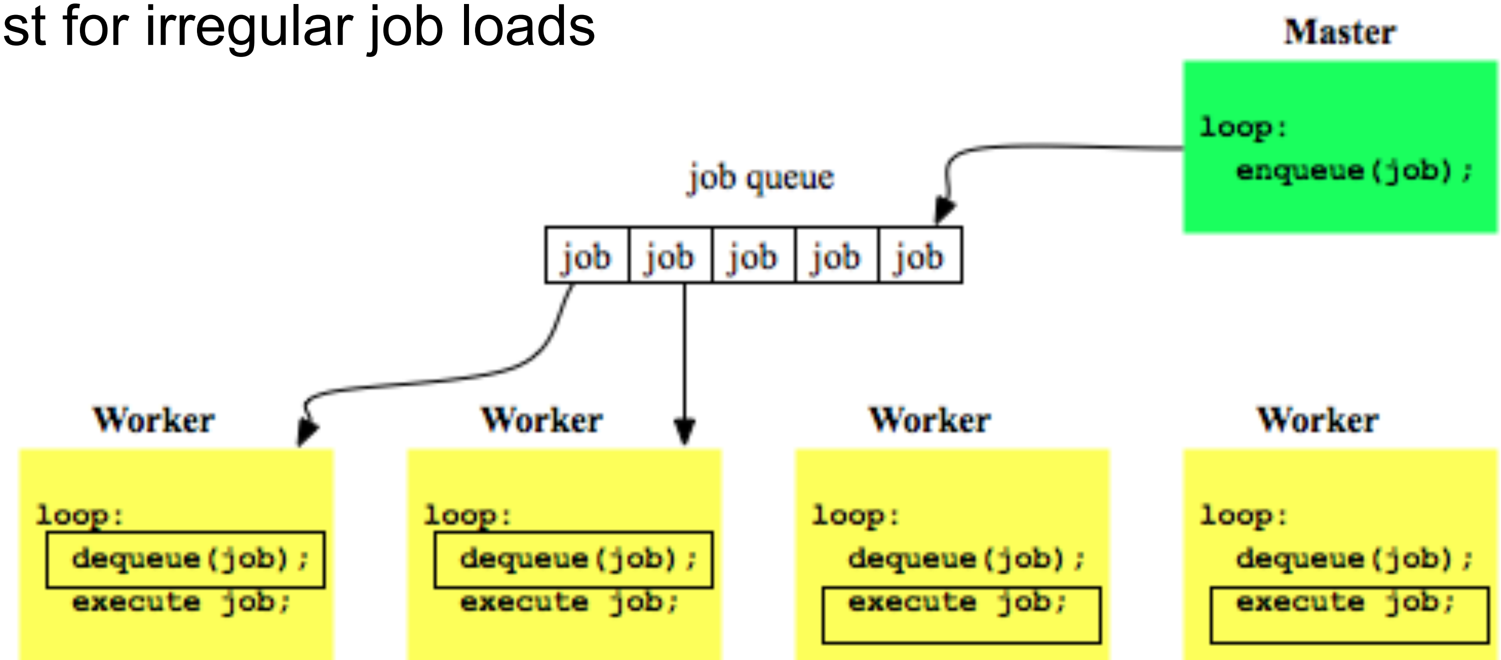


Process with two threads

What happens when we fork a process that executes multiple threads? Does fork duplicate only the calling thread or all threads?

Thread Pools

- *Thread pooling* (or *process pooling*) is an efficient mechanism
- One *master thread* dispatches jobs to worker threads
- *Worker threads* in pool never terminate and keep accepting new jobs when old job done
- Jobs are communicated to workers via a *shared job queue*
- Best for irregular job loads



MT-Safety

```
time_t clk = clock();
char *txt = ctime(&clk);
printf("Current time: %s\n", txt);
```

Use of a non-MT-safe routine

```
time_t clk = clock();
char txt[32];
ctime_r(&clk, txt);
printf("Current time: %s\n", txt);
```

Use of the reentrant version of ctime

```
static int counter = 0;
int count_events()
{ return counter++;
}
```

Is this routine MT-safe?

What can go wrong?

- Routines must be *multi-thread safe* (MT-safe) when invoked by more than one thread
- Non-MT-safe routines must be placed in a critical section, e.g. using a mutex lock (see later)
- Many C libraries are not MT-safe
  - Use *libroutine*`_r`() versions that are "reentrant"
  - When building your own MT-safe library, use `#define _REENTRANT`
- Always make your routines MT-safe for reuse in a threaded application
- Use locks when necessary (see next slides)

Coordinated Access to Shared Data (Such as Job Queues)

- Reading and writing shared data by more than one thread or process requires coordination with *locking*
- Cannot update shared variables simultaneously by more than one thread

```
static int counter = 0;
int count_events()
{ return counter++;
}
```

```
reg1 = M[counter]     = 3
reg2 = reg1 + 1       = 4
M[counter] = reg2     = 4
return reg1           = 3
```

Thread 1

```
reg1 = M[counter]     = 3
reg2 = reg1 + 1       = 4
M[counter] = reg2     = 4
return reg1           = 3
```

Thread 2

```
static int counter = 0;
int count_events()
{ pthread_mutex_lock(&lock);
  counter++;
  pthread_mutex_unlock(&lock);
  return counter-1;
}
```

```
acquire lock
reg1 = M[counter]     = 3
reg2 = reg1 + 1       = 4
M[counter] = reg2     = 4
release lock
```

Thread 1

```
acquire lock
…
… wait
…
…
reg1 = M[counter]     = 4
reg2 = reg1 + 1       = 5
M[counter] = reg2     = 5
release lock
```

Thread 2

Spinlocks

- *Spin locks* use *busy waiting* until a condition is met
- Naïve implementations are almost always incorrect

```
// initially lock = 0

while (lock == 1)
   ; // do nothing
lock = 1;
   … critical section …
lock = 0;
```

Acquire lock

Release lock

Two or more threads want to enter the critical section, what can go wrong?

Spinlocks

- *Spin locks* use *busy waiting* until a condition is met
- Naïve implementations are almost always incorrect

Thread 1

```
while (lock == 1)
  ; // do nothing
lock = 1;
  … critical section …
lock = 0;
```

Thread 2

```
while (lock == 1)
  …
  …
lock = 1;
  … critical section …
lock = 0;
```

This ordering works

Spinlocks

- *Spin locks* use *busy waiting* until a condition is met
- Naïve implementations are almost always incorrect

Thread 1

```
while (lock == 1)
  ; // do nothing
lock = 1;
  … critical section …
lock = 0;
```

Not set in time before read

Thread 2

```
while (lock == 1)
  …
lock = 1;
  … critical section …
lock = 0;
```

This statement interleaving leads to failure

Both threads end up executing the critical section!

Spinlocks

- *Spin locks* use *busy waiting* until a condition is met
- Naïve implementations are almost always incorrect

Thread 1

```
while (lock == 1)
  ; // do nothing
~~lock = 1;~~
  … critical section …
lock = 0;
```

Useless assignment removed

Assignment can be moved by compiler

Thread 2

```
while (lock == 1)
  …
lock = 1;
  … critical section …
lock = 0;
```

Compiler optimizes the code!

Atomic operations such as atomic "test-and-set" instructions must be used (these instructions are not reordered or removed by compiler)

Spinlocks

- Advantage of spinlocks is that the kernel is not involved
- Better performance when acquisition waiting time is short
- Dangerous to use in a uniprocessor system, because of *priority inversion*
- No guarantee of *fairness* and a thread may wait indefinitely in the worst case, leading to *starvation*

```
void spinlock_lock(spinlock *s)
{ while (TestAndSet(s))
    while (*s == 1)
      ;
}
```

```
void spinlock_unlock(spinlock *s)
{ *s = 0;
}
```

Correct and efficient spinlock operations using atomic **`TestAndSet`** *assuming hardware supports cache coherence protocol*

Note: **`TestAndSet(int *n)`** sets **`n`** to 1 and returns old value of **`n`**

Semaphores

- A semaphore is an integer-valued *counter*
- The counter is *incremented* and *decremented* by two operations *signal* (or *post*) and *wait*, respectively
  - Traditionally called *V* and *P* (Dutch “verhogen” and “probeer te verlagen”)
- When the counter $\leq$ 0 the *wait* operation blocks and waits until the counter > 0

```
sem_post(sem_t *s)
{ (*s)++;
}
```

```
sem_wait(sem_t *s)
{ while (*s <= 0)
      ; // do nothing
   (*s)--;
}
```

Note: actual implementations of POSIX semaphores use atomic operations and a queue of waiting processes to ensure fairness

Semaphores

- A two-valued (= binary) semaphore provides a mechanism to *implement mutual exclusion* (mutex)
- POSIX semaphores are *named* and have *permissions*, allowing use across a set processes

Unique name *Permissions* *Initial value*

```
#include "semaphore.h"

sem_t *mutex = sem_open("lock371", O_CREAT, 0600, 1);
…
sem_wait(mutex);        // sem_trywait() to poll state
…
… critical section …
…
sem_post(mutex);
…
sem_close(mutex);
```

Tip: use **`ipcs`** command to display IPC semaphore status of a system

Pthread Mutex Locks

```
pthread_mutex_t mylock;

pthread_mutex_init(&mylock, NULL);
…
pthread_mutex_lock(&mylock);
…
… critical section …
…
pthread_mutex_unlock(&mylock);
…
pthread_mutex_destroy(&mylock);
```

- POSIX mutex locks for thread synchronization
  - Threads share user space, processes do not
- Pthreads is available for Unix/Linux and Windows ports

`pthread_mutex_init()`
initialize lock

`pthread_mutex_lock()`
lock

`pthread_mutex_unlock()`
unlock

`pthread_mutex_trylock()`
check if lock can be acquired

Using Mutex Locks

- Locks are used to synchronize shared data access from any part of a program, not just the same routine executed by multiple threads
- Multiple locks should be used, each for a set of shared data items that is disjoint from another set of shared data items (no single lock for everything)

```
pthread_mutex_lock(&array_A_lck);
… A[i] = A[i] + 1 …
pthread_mutex_unlock(&array_A_lck);

pthread_mutex_lock(&array_A_lck);
… A[i] = A[i] + B[i]
pthread_mutex_unlock(&array_A_lck);
```

Lock operations on array A

```
pthread_mutex_lock(&queue_lck);
… add element to shared queue …
pthread_mutex_unlock(&queue_lck);

pthread_mutex_lock(&queue_lck);
… remove element from shared queue …
pthread_mutex_unlock(&queue_lck);
```

Lock operations on a queue

*What if threads may or may not update some of the same elements of an array, should we use a lock for **every** array element?*

Condition Variables

- *Condition variables* are associated with mutex locks
- Provide signal and wait operations *within* critical sections

Process 1

```
lock(mutex)
if (cannot continue)
  wait(mutex, event)
…
unlock(mutex)
```

Process 2

```
lock(mutex)
…
signal(mutex, event)
…
unlock(mutex)
```

Can't use semaphore wait and signal here: what can go wrong when using semaphores?

Condition Variables

`signal` *releases one waiting thread (if any)*

Process 1

```
lock(mutex)
if (cannot continue)
  wait(mutex, event)
…
unlock(mutex)
```

Process 2

```
lock(mutex)
…
signal(mutex, event)
…
unlock(mutex)
```

`wait` *blocks until a signal is received*
When blocked, it releases the mutex lock, and reacquires the lock when wait is over

Producer-Consumer Example

- Producer adds items to a shared container, when not full
- Consumer picks an item from a shared container, when not empty

A consumer

```
while (true)
{ lock(mutex)
  if (container is empty)
    wait(mutex, notempty)
  get item from container
  signal(mutex, notfull)
  unlock(mutex)
}
```

A producer

```
while (true)
{ lock(mutex)
  if (container is full)
    wait(mutex, notfull)
  add item to container
  signal(mutex, notempty)
  unlock(mutex)
}
```

Condition variables associated with mutex

Semaphores versus Condition Variables

- Semaphores:
  - Semaphores must have matching signal-wait pairs, that is, the semaphore counter must stay balanced
  - One too many waits: one waiting thread is indefinitely blocked
  - One too many signals: two threads may enter critical section that is guarded by semaphore locks
- Condition variables:
  - A signal can be executed at any time
  - When there is no wait, signal does nothing
  - If there are multiple threads waiting, signal will release one
- Both provide:
  - Fairness: waiting threads will be released with equal probability
  - Absence of starvation: no thread will wait indefinitely

Pthreads Condition Variables

- Pthreads supports condition variables
- A condition variable is always used in combination with a lock, based on the principle of "*monitors*"

Declarations

```
pthread_mutex_t mutex;
pthread_cond_t notempty, notfull;
```

Initialization

```
pthread_mutex_init(&mutex, NULL);
pthread_cond_init(&notempty, NULL);
pthread_cond_init(&notfull, NULL);
```

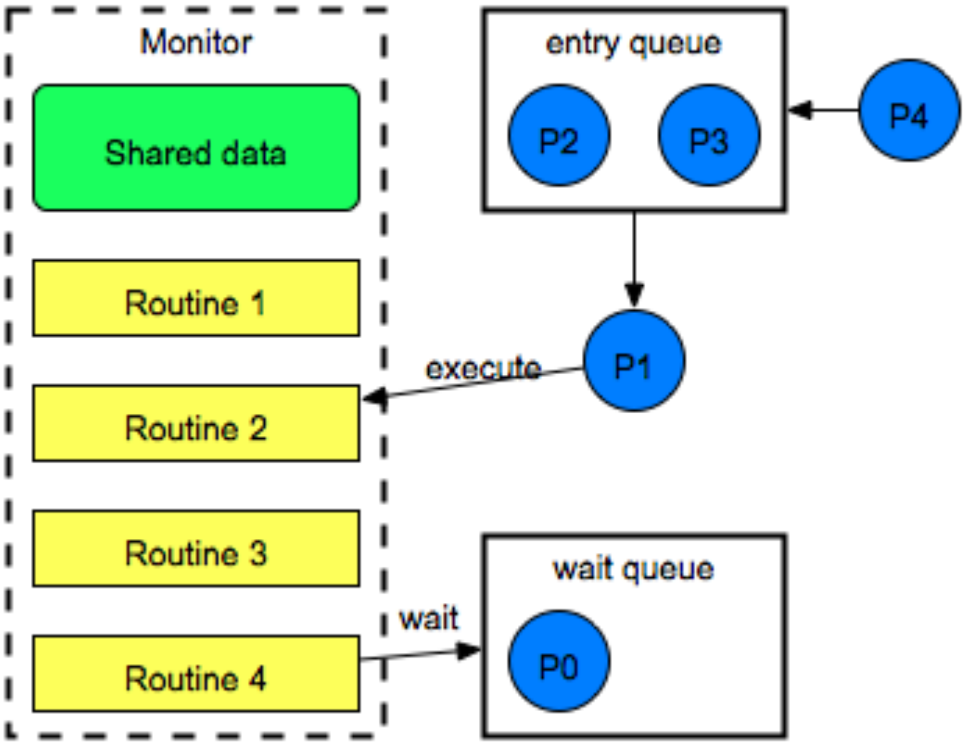
A consumer

```
while (1)
{ pthread_mutex_lock(&mutex);
  if (container is empty)
    pthread_cond_wait(&mutex, &notempty);
  get item from container
  pthread_cond_signal(&mutex, &notfull);
  pthread_mutex_unlock(&mutex);
}
```

A producer

```
while (1)
{ pthread_mutex_lock(&mutex);
  if (container is full)
    pthread_cond_wait(&mutex, &notfull);
  add item to container
  pthread_cond_signal(&mutex, &notempty);
  pthread_mutex_unlock(&mutex);
}
```

Monitor with Condition Variables



Only P1 executes a routine, P0 waits on a signal, and P2, P3 are in the entry queue to execute next when P1 is done (or moved to the wait queue)

- A *monitor* is a concept
- A monitor combines a set of shared variables and a set of routines that operate on the variables
- Only one process may be active in a monitor at a time
  - All routines a synchronized by implicit locks (like an entry queue)
  - Shared variables are safely modified under mutex
- Condition variables are used for signal and wait within the monitor routines
  - Like a wait queue

Barriers

- A *barrier* synchronization statement in a program blocks processes until all processes have arrived at the barrier
- Frequently used in data parallel programming (implicit or explicit) and an essential part of BSP

Each process produces part of shared data X
barrier
Processes use shared data X

Two-Phase Barrier with Semaphores for *P* Processes

```
sem_t *mutex = sem_open("mutex-492", O_CREAT, 0600, 1);
sem_t *turnstile1 = sem_open("ts1-492", O_CREAT, 0600, 0);
sem_t *turnstile2 = sem_open("ts2-492", O_CREAT, 0600, 1);
int count = 0;
…
sem_wait(mutex);
  if (++count == P)
  { sem_wait(turnstile2);
    sem_signal(turnstile1);
  }
sem_signal(mutex);
sem_wait(turnstile1);
sem_signal(turnstile1);
sem_wait(mutex);
  if (--count == 0)
  { sem_wait(turnstile1);
    sem_signal(turnstile2);
  }
sem_signal(mutex);
sem_wait(turnstile2);
sem_signal(turnstile2);
```

Rendezvous

Critical point

Barrier sequence

Pthread Barriers

```
pthread_barrier_t barrier;

pthread_barrier_init(
  barrier,
  NULL,   // attributes
  count); // number of threads
…
pthread_barrier_wait(barrier);
…
```

- Barrier using POSIX pthreads (advanced realtime threads)
- Specify number of threads involved in barrier syncs in initialization

---

`pthread_barrier_init()`
initialize barrier with thread count

`pthread_barrier_wait()`
barrier synchronization

Further Reading

- [PP2] pages 230-247
- [HPC] pages 191-218
- Optional:
  - [HPC] pages 219-240
  - Pthread manuals (many online)
  - "*The Little Book of Semaphores*" by Allen Downey
    `http://www.greenteapress.com/semaphores/downey05semaphores.pdf`