Shared-Memory Programming

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Programming Shared Memory Systems

In a shared-memory system, a single address space exists, *i.e.* each memory location is given a unique address, and any memory location is accessible by any of the processors.

Shared-memory systems are typically used in two ways:

- *Executing multiple unrelated programs concurrently* (*aka* "multi-programming")
  - This is a feature of OS, and will not be discussed further.
- *Executing a single application by multiple threads* (*aka* "multi-threading")
  - We'll look into the different approaches for this.

Multi-Threaded Execution

Once multiple threads are created, their execution order will depend upon the system — they may be assigned to different processors, or they may be executed on a single processor in a time-shared fashion. In either case, the statements of individual threads might be *interleaved* in time.

Example:

Thread 1: A; B; C

Thread 2: X; Y; Z

Any interleaving execution order of these two statement sequences is a legal execution, *e.g.*

Scenario 1: A; B; C; X; Y; Z

Scenario 2: A; B; X; C; Y; Z

Scenario 3: X; A; Y; B; Z; C

...

Implication: For practical applications, synchronizations are likely needed.

Multi-Threaded Programming

Issues:

- *Thread control and management* — for expressing parallelism.
  - create, terminate, suspend, resume, sleep, wake up
- *Thread synchronization* — for synchronizing shared data access and coordinating computation.
  - locks, semaphores, condition variables, barriers, monitors

Approaches:

1. Explicit control through thread libraries (*e.g.* Pthreads)
2. Implicit control through compiler directives (*e.g.* OpenMP)
3. Implicit control through language support (*e.g.* Algol68, Chapel)

Thread Libraries

Thread libraries provide direct control over all aspects of threads, giving the programmer full programming power.

Example:

- Pthreads — POSIX threads, supported by all versions of Unix/Linux.
- Other libraries exist, *e.g.* Win32 threads, OS/2 Threads, and Java threads.

```
void grandson() {
  printf("grandson\n");
}
void son(int *ip) {
  pthread_t t3;
  pthread_create(&t3, NULL, grandson, NULL);
  printf("son %d\n", *ip);
  pthread_join(t3, NULL);
}
int main() {
  int i=1, j=2;
  pthread_t t1, t2;
  pthread_create(&t1, NULL, son, &i);
  pthread_create(&t2, NULL, son, &j);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  printf("Work done\n");
}
```


Compiler Directives

Compiler directives provide a *non-intrusive* approach for shared-memory programming. In this approach, the parallelism information is presented in the form of compiler directives embedded in the user program.

Example:

- OpenMP

```
void Hello() {
  #pragma omp parallel num_threads(4)
  printf("Hello world!\n");
}
```

- These directives do not change a program's sequential semantics.
- The information carried by the directives is picked up by special parallelizing compilers.
- The directives can be easily adapted to different host languages.

Third approach (Preffered). Built in parallelization support!

Similar idea was tried for Fortran, (but was too coplicated, Algol is very simple.

Language Support (old Idea)

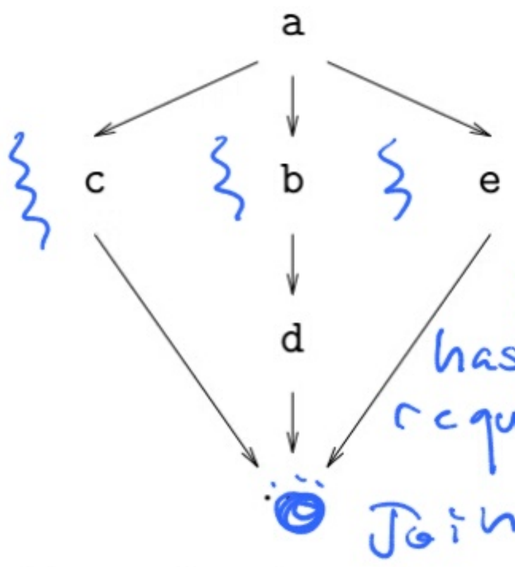
Language support means that the expression of parallelism is through programming languages' constructs.

One of the earlier ones, Constrained (no order of threads etc...)

Example: Algol 68 supports a parallel construct, *parbegin*/*parend*, for creating multiple threads to be executed concurrently.

Each of the statements executed by individual thread

```
a;
parbegin
  c,
  begin
    b; d
  end,
  e
parend
```



← Concurrently

in Contrast Fortran has ForAll Loop which requires 12 pages configuration

Parbegin/parend can be nested within each other. However, there are restrictions on the parallel threads created by parbegin/parend, for instance, they must share a common stack frame.

More flexible than Algol 68:

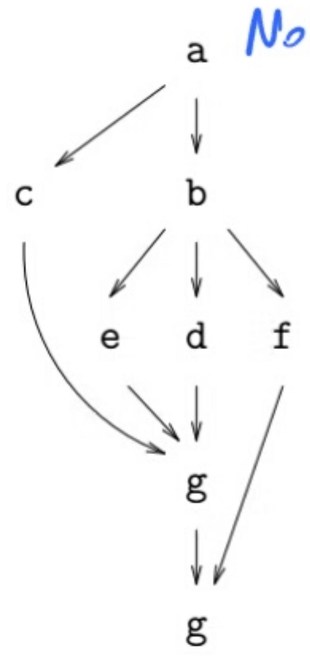
Language Support (cont.) Pascal language family.

Several languages (e.g. Modular-3) support explicit creation and management of full-scale threads with *fork* and *join* constructs.

Uses fork and Join, which is the most flexible way to create threads

Threads don't need to be properly nested

```
      a;
      fork L1;
      b;
      fork L2, L3;
      d;
      join L4;
L1:   c; join L4;
L2:   e; join L4;
L3:   f; join L5;
L4:   g; join L5;
L5:   h;
      quit
```



No nesting scopes (Very flexible)

With fork and join, a thread can start at any point and end at any point.

Each language has very similar set of issues, with often significant differences.

Newer languages cleaned up older languages issues.
Like "fork", "join" — very powerfull, but messy like GOTO

New generation of parallel languages. Tried to simplify parallelism

Language Support (cont.)

Chapel has several constructs for supporting thread-based programming:

- The *begin* statement (threads may execute sequentially)

```
begin writeln("hello 1");   // thread 1
begin writeln("hello 2");   // thread 2
writeln("good bye!");       // parent thread (won't wait)
```

to threads are created and doesn't join.

- The *cobegin* statement (threads must execute concurrently)

```
cobegin {
  writeln("hello 1");   // thread 1
  writeln("hello 2");   // thread 2
}
writeln("good bye!");   // parent thread (will wait)
```

forces parallelization, 1st case can run sequentially.

One allows sequential, another does not

The other side of shared memory → synchronization (how to avoid deadlocks or memory corruption)

Thread Synchronizations

Two main purposes.

Thread synchronizations are needed for two situations:

- *Resolving competition (or achieving mutual exclusion)* —
  When multiple threads try to access the same shared data or execute the same section of code (*i.e.* a critical section), synchronization can ensure that they access the data or enter the critical section one at a time. Multiple threads updating the same variable. (Example)

  ← locks

- *Facilitating cooperation* —
  When one thread needs the data produced by another thread (*e.g.* a consumer-producer pair), synchronization can provide ways for the producer to inform the consumer that data is ready; and for the consumer to tell the producer that more data is needed.

Ordering Constraint. Typical example — "producer, consumer" problem.
It is possible to use locks for this purpose (with special flags).

Simplest mechanism for MUTEX problem.

Locks

Boolean value as single atomic bit.

Locks are the simplest mechanism for ensuring mutual exclusion of critical sections.

- A lock is just a 1-bit variable — the two values 1 and 0 represent the "locked" and "unlocked" states, respectively.
- A thread can only enter a critical section when lock is unlocked, and it locks the lock before entering.

Typical usage:

```
while (lock==1)      // check the lock; if not available,
  wait;              // wait for the lock to open
lock = 1;            // lock; enter critical section
<critical section>
lock = 0;            // leave critical section; unlock
```

someone else is using it => wait.

looks like a single 1 line instruction, however when translated to machine code becomes multiline code.

The key to supporting locks is atomicity!

Locks (cont.)

Note that the lock-checking statement and the actual-locking statement in the previous code must be implemented as one inseparable *atomic* operation. Otherwise, the lock may fail.

In other words, what we need is

```
Lock(lock);          // atomic operation: check and lock
                     // the lock; wait if not available
<critical section>
Unlock(lock);        // unlock
```

Question: How to implement an atomic operation?

Answer:

1. Use normal loads and stores — complicated and expensive // bottleneck.
2. Use special synchronization primitives — simple and efficient

later impl.

read-modify-write

How to support locking/unlocking? (multicore).
locking can be very expensive.

Hardware Synchronization Primitives

Most modern computer architectures provide a variant of the `read-modify-write` (`RMW`) operation as a synchronization primitive:

- `get-and-set(v)` — read and return the old value, and set the new value v // Simple - provide new independent value.
- `get-and-increment()` — read and return the old value, and set the incremented value // do not provide independent new value, read, increment return
- `test-and-set(v)` — test the old value, and set the new value v if the old value passes the test; return a boolean read old value, and create new value depending on the previous.
- `load-linked()/store-conditional()` — like `test-and-set()`, but with two separate read and write instructions; still guarantees atomicity Separate load and store is good when supported by hardware.

The common theme: A non-interruptible instruction or instruction sequence capable of atomically retrieving and changing a value. // The base for implementing locks

Different versions all good for creating locks

Common Types of Locks

Based on strategies for handling waiting, locks can be categorized as:

- *Spin Locks:* What should we do if lock is locked.
  - If the lock is locked, the thread repeatedly tests the lock status, until it becomes unlocked. (Busy waiting).
- *Blocking Locks:* (Yeilding) go to sleep. Must be woken up
  - If the lock is locked, the requesting thread gets blocked and goes into sleep. (This strategy requires a waking-up mechanism.)
- *Combination:* Block for some time and wake up, or spin for sometime and block.
  - If the lock is locked, the thread spins for a specified period, then block. (This is useful if the thread knows that the thread holding the lock is about to release it.) Or something more complicated

There are also

- *Readers/Writer Locks:* Multiple readers / single writes.
  - Multiple threads can *concurrently read* the data protected by an RW lock; but any thread to write to the data must have exclusive access.

Consumes resources (expensive) VS Context switch (expensive)

Default implementation is usually spin lock since critical sections are usually small.

Support User-Level Spin Locks

Supporting user-level spin locks is not a trivial task.

First try: Using the synchronization primitives directly at the user level.

```
void Lock(boolean lock) {
  while (get-and-set(lock,true)) {}
}
void Unlock(boolean lock) {
  set(lock, false);
}
```

Problem:

- Excessive memory accesses. Each `get-and-set()` call translates to a memory read and a memory write. When number of competing threads increases, the situation worsens quickly.
- It can take exponential (or more) number of memory accesses for n competing threads to each get the lock. // Reading, Writing, Updating Cache.

Support Spin Locks, Take Two

Taking advantage of the cache coherence mechanism.

```
void Lock(boolean lock) {
  while (true) {
    while (get(lock)) {}          // spin on a cache copy
    if (!get-and-set(lock,true)) // one memory access
      return;
  }
}
```

Remaining Problem:

- When the lock is released, every waiting thread will issue a `get-and-set()` call, even though only one will succeed.
- It can take $O(n^2)$ number of memory accesses for n competing threads to each get the lock.

Support Spin Locks, Take Three

Using the "exponential back-off" strategy — if a `get-and-set()` call fails, double the waiting time.

```
void Lock(boolean lock) {
  int delta = <a small-random-init-value>;
  while (true) {
    while (get(lock)) {}          // spin on a cache copy
    pause delta; // So all threads don't jump to the memory at
    if (!get-and-set(lock,true)) // one memory access the same time -
      return;
    delta = delta * 2; // double every time to avoid collisions.
  } works very well
}
```


Fair waiting system.

Support Spin Locks, Take Four

Issue a tick with line numbers (much more complex).
Some hardware supports it out of the box..

Using a queue to organize the waiting threads; letting only one thread to call `get-and-set()` when the lock is released.

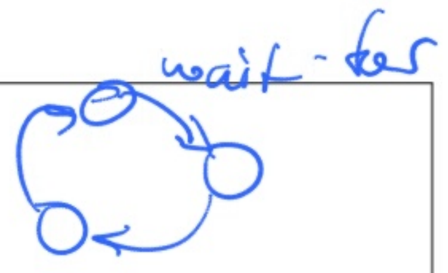
The queue can be implemented either in software or in hardware.

- In software — with the use of an array
- In hardware — with queuing functionality added to directory controller on directory-based multiple processors

Implementation of spin lock is getting of lot harder on multithreading machines.

Deadlock

Cycling holding pattern



- Deadlock can occur with two threads when each requires a resource held by the other. For example,

  Thread 1: requests A; requests B; uses A and B
  Thread 2: requests B; requests A; uses A and B

  Deadlock occurs when thread 1 holds A, thread 2 holds B, and each wants to get another resource.

Simple cycling.

- Deadlock can also occur in a circular fashion with several threads:

  Thread 1: holds A_1; requests A_2
  Thread 2: holds A_2; requests A_3
  ...
  Thread k: holds A_k; requests A_1

Live Lock / waiting forever due to low priority.

- Deadlock can be avoid if all threads request resources in the same order.

Simple solution

How can deadlocks be detected? Some try to implement it.

Semaphores

Semaphores are an extension to locks. A semaphore, s, is a non-negative integer operated upon by two operations:

- *P(s)* — waits until s is > 0 and then decrements s by one and allows the thread to continue.
- *V(s)* — increments s by one to release one of the waiting threads (if any).

The P and V operations are performed atomically. A mechanism for activating waiting threads is also implicit in the operations.

Threads delayed by $P(s)$ are kept in sleep until released by a $V(s)$ on the same semaphore.

Typical -> Semaphore defined one integer
P - pass/wait wait until semaphore is greater than >0, then decrement it
V - increment value by one
There is no spin waiting thread goes to sleep by P and woken up by V.

A Semaphore Example

Semaphore can be used to solve the producer-consumer problem:

```
// a global task queue
queue_t *queue = ...;

void producer() {
  task_t *task;
  while (true) {
    task = create_task();
    add_task(queue, task);
    V(queue.len);
  }
}
```

```
void consumer() {
  task_t *task;
  while (true) {
    P(queue.len);
    task = remove_task(queue);
    compute(task);
  }
}
```


Condition Variables

Pthread doesn't support semaphores, since it is possible to implement everything with locks. Linux/Unix has limit in semaphores. Do not limit condition to counting integers → it can be anything. as long as condition is satisfied go ahead.

Condition variables are a further extension to semaphores.

Often, a critical section is to be executed if a specific global condition exists; for example, if a certain value of a variable has been reached.

- With locks, the global variable would need to be examined at frequent intervals ("polled") within the critical section. This is a very time-consuming and unproductive exercise.
- Semaphores, on the other hand, can only handle a limited form of conditions, *e.g.* a counter reaching 0.

This problem can be overcome by using condition variables.

Three operations are defined for a condition variable:

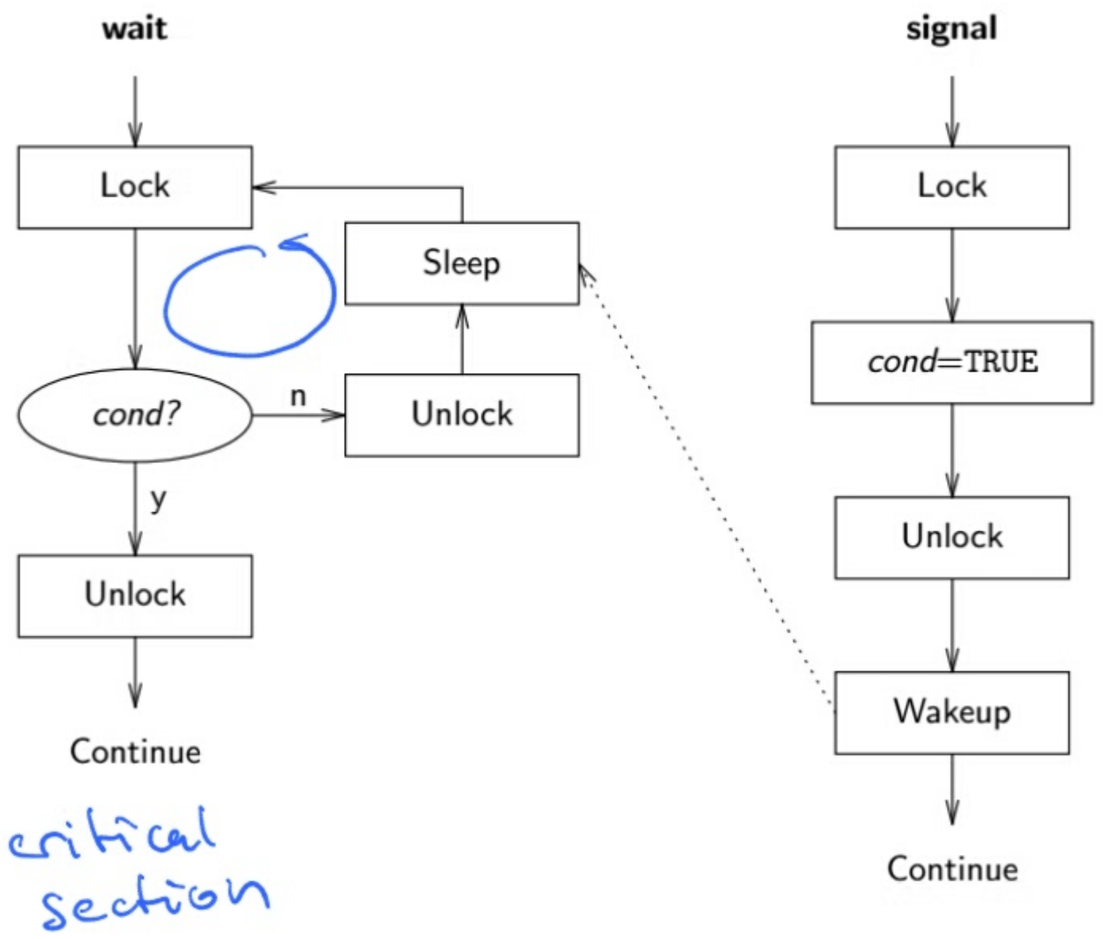
`Wait(cond)` — wait for a condition to occur = P condition not satisfied

`Signal(cond)` — signal that the condition has occurred = V condition changes

`Status(cond)` — return the number of waiting threads → See what is these (optional)

Requires lock to support it.

A Graphic View of Condition Variables



Version of a blocking lock

critical section

Condition Variable Example

Consider one or more threads designed to take action whenever a counter, x, reaches a value that is a multiple of 5. (A separate thread is responsible for incrementing the counter.)

Produce — consumer

```
void action() {
  lock();
  while (x % 5 == 0)
    wait(s);
  unlock();
  take_action();
}
```

```
void counter() {
  lock();
  x++;
  if (x % 5 == 0)
    signal(s);
  unlock();
}
```

can be any condition

// loop unlocks automat.

Critical Section

// if no waiting threads signal is lost.

- The `wait` operation will automatically release the lock, to allow another thread to alter the condition.
- The `signal` operation will automatically wake up any or all waiting threads (implementation dependent).
- The waking-up threads will try to lock the lock again, and one of them will succeed.

Pthread has some unique characteristics.

We are not dealing with data items in OOP data is protected by a class, which restricts access to the data?

Maybe we can provide sync with access methods.

Monitors - Different way of providing synchonization.

Monitors are introduced for providing object-oriented style of access control — Essentially the protected data and the operations (*monitor procedures*) that can operate upon it are encapsulated inside a structure. Reading and writing to the data can only be done by using monitor procedures, and only one thread can use a monitor procedure at any instant.

A monitor procedure could be implemented using a semaphore to protect its entry; i.e.,

```
void monitor_procedure() {
  P(monitor_semaphore);
  <monitor body>
  V(monitor_semaphore);
  return;
}
```

→ Special method. exclusive access mode only one thread can be in this mode.

Monitor Example

The concept of monitor exists in Java. The keyword `synchronized` in Java makes a method thread safe, preventing more than one thread executing the method at the same time.

```
public class Adder {
  public int[] array;
  private int sum=0, i=0;
  public Adder() { ... } // constructor

  public synchronized int nextIndex() {
    return (i < 1000) ? i++ : -1;
  }

  public synchronized void addSum(int psum) {
    sum += psum;
  }
}
```

makes it exclusive only one thread is allowed.

locking/unlocking included.

Con: Can't make size of these methods large, it is equal to serializing the code.

Monitor Example (cont.)

```
class AdderThread extends Thread {
  Adder adder;
  public AdderThread(Adder adder) { this.adder = adder; }

  public void run() {
    int i, psum;
    while ((i=adder.nextIndex()) != -1)
      psum = psum + adder.array[i];
    adder.addSum(psum);
  }
}

public static class Driver {
  public static void main(String args[]) {
    Adder adder = new Adder();
    for (int i=0; i<10; i++)
      new AdderThread(adder, i).run();
  }
}
```


Desirable Synchronization Properties

The above synchronization mechanisms provide basic access control on shared data. For many applications, stronger policies are required on top of them, such as

Different runs produce the same result.

- *Safe* — A safe policy is one that enforces deterministic results, i.e. access order is always the same no matter how many times the program run.
- *Fair* — A fair policy guarantees access to all tasks that have requested access, before second or third accesses are granted to any pending tasks.
- *Deadlock-Free* — A deadlock-free policy guarantees that no deadlock can ever happen no matter what order or speed the requests are generated.