61A Lecture 33

18th November, 2011

Last time

Why is parallel computation important?

What is parallel computation?

Some examples in Python

Some problems with parallel computation

Parallel computation terminology

Processor

- One of (possibly) many pieces of hardware responsible for executing instructions

Thread

- One of (possibly) many simultaneous sequences of instructions, being executed in a shared memory environment

Shared memory

- The environment in which threads are executed, containing variables that are accessible to all the threads.

Today: dealing with shared memory

"Vulnerable sections" of a program

- Critical Sections
- Atomicity

Correctness

- What does "correctness" mean for parallel computation?

Protecting vulnerable sections

- Locks
- Semaphores
- Conditions

Deadlock

Parallel computing example: bank balance

```
def make_withdraw(balance):
    def withdraw(amount):
        nonlocal balance
        if amount > balance:
            print('Insufficient funds')
        else:
            balance = balance - amount
            print(balance)
    return withdraw
```

w = make_withdraw(10)

balance = ~~10~~ 2 or 3

w(8)

w(7)

print('Insufficient funds')

Parallel computing example: bank balance

```
def make_withdraw(balance):
    def withdraw(amount):
        nonlocal balance
        if amount > balance:
            print('Insufficient funds')
        else:
            balance = balance - amount
            print(balance)
    return withdraw
```

`w = make_withdraw(10)`

`balance =` ~~10~~ ~~2~~ 3

`w(8)`

```
read balance: 10
read amount: 8
8 > 10: False
if False
10 - 8: 2
write balance -> 2
print 2
```

`w(7)`

```
read balance: 10
read amount: 7
7 > 10: False
if False
10 - 7: 3
write balance -> 3
print 3
```

$15 withdrawn from a $10 account?
With $3 left? Inconceivable!

Parallel computing example: bank balance

```
def make_withdraw(balance):
    def withdraw(amount):
        nonlocal balance
        if amount > balance:
            print('Insufficient funds')
        else:
            balance = balance - amount
            print(balance)
    return withdraw
```

w = make_withdraw(10)
balance = ~~10~~ 2 or 3

w(8)

w(7)

print('Insufficient funds')

Another problem: vector mathematics

```
A = B+C
V = MxA
```

$$A = B+C$$
$$V = M\text{x}A$$

Vector mathematics

$$A=\begin{pmatrix}2\\5\end{pmatrix} \quad V=\begin{pmatrix}12\\12\end{pmatrix} \quad B=\begin{pmatrix}2\\0\end{pmatrix} \quad C=\begin{pmatrix}0\\5\end{pmatrix} \quad M=\begin{pmatrix}1 & 2\\1 & 2\end{pmatrix} \quad A=\begin{pmatrix}2\\5\end{pmatrix}$$

$$A_1 = B_1+C_1$$
$$V_1 = M_1.A$$

$$A_2 = B_2+C_2$$
$$V_2 = M_2.A$$

P1

```
read B1: 2
read C1: 0
calculate 2+0: 2
write 2 -> A1
read M1: (1 2)
read A: (2 0)
calculate (1 2).(2 0): 2
write 2 -> V1
```

$$V=\begin{pmatrix}2\\12\end{pmatrix}$$

P2

```
read B2: 0
read C2: 5
calculate 5+0: 5
write 5 -> A2
read M2: (1 2)
read A: (2 5)
calculate (1 2).(2 5):12
write 12 -> V2
```

Vector mathematics

Step 1

$$A = B+C$$

Step 2

$$V = MxA$$

Threads must wait for each other.
Only move on when all have finished previous step.

Correctness

The outcome should *always* be equivalent to some serial ordering of individual steps.

serial ordering: if the threads were executed individually, from start to finish, one after the other instead of in parallel.

Problem 1: inconsistent values

Inconsistent values

- A thread reads a value and starts processing
- Another thread changes the value
- The first thread’s value is inconsistent and out of date

Problem 2: unsynchronized threads

Unsynchronized threads

- Operations is a series of steps
- Threads must wait until all have finished previous step

Need ways to make threads wait.

Problem 1: inconsistent values

Inconsistent values

- A thread reads a value and starts processing
- Another thread changes the value
- The first thread’s value is inconsistent and out of date

P1

```
harmless code
harmless code
modify shared variable
.............
.............
.............
.............
write shared variable
harmless code
harmless code
```

P2

Critical Section

Should not be interrupted by other threads that access same variable

Terminology

“Critical section”

- A section of code that should not be interrupted
- Should be executed as if it is a single statement

“Atomic” and “Atomicity”

- Atomic: cannot be broken down into further pieces
- Atomic (when applied to code): cannot be interrupted, like a single hardware instruction.
- Atomicity: a guarantee that the code will not be interrupted.

Critical sections need to have atomicity.

Protecting shared state *with shared state*

Use shared state to store signals

Signals can indicate:

- A variable is in use
- A step is complete (or not)
- How many threads are using a resource
- Whether or not a condition is true

Signals:

- Locks or mutexes (mutual exclusions)
- Semaphores
- Conditions

Don’t physically protect shared state

Convention and shared rules for signals protect shared state.

- Like traffic signals “protect” an intersection

Locks

Implemented using real atomic hardware instructions.

Used to signal that a shared resource is in use.

acquire()

- “set” the signal.
- No other threads will be able to acquire()
- They will automatically wait until ...

release()

- “unset” a signal.
- Any one thread that was waiting for acquire() will now succeed

Using locks: bank balance example

```python
def make_withdraw(balance):
    def withdraw(amount):
        nonlocal balance
        if amount > balance:
            print('Insufficient funds')
        else:
            balance = balance - amount
            print(balance)
    return withdraw
```

critical section

`w = make_withdraw(10)`

balance = ~~10~~ ~~2~~ 3

```
w(8)

read balance: 10
read amount: 8
8 > 10: False
if False
10 - 8: 2
write balance -> 2
print 2
```

```
w(7)

read balance: 10
read amount: 7
7 > 10: False
if False
10 - 7: 3
write balance -> 3
print 3
```

Using locks: bank balance example

```
def make_withdraw(balance):
    def withdraw(amount):
        nonlocal balance
        if amount > balance:
            print('Insufficient funds')
        else:
            balance = balance - amount
            print(balance)
    return withdraw
```

critical section

New code

```
def make_withdraw(balance)
        balance_lock = Lock()
        def withdraw(amount):
            nonlocal balance
            # try to acquire the lock
            balance_lock.acquire()
            # once successful, enter the critical section
            if amount > balance:
                print("Insufficient funds")
            else:
                balance = balance - amount
                print(balance)
            # upon exiting the critical section, release the lock
            balance_lock.release()
```

Using locks: bank balance example

```
w = make_withdraw(10)
balance = 10
balance_lock = Lock()   acquired by p2
```

```
w(8)
```

```
w(7)
```

P1

```
acquire balance_lock: ok
read balance: 10
read amount: 8
8 > 10: False
if False
10 - 8: 2
write balance -> 2
print 2
release balance_lock
```

P2

```
acquire balance_lock: wait
wait
wait
wait
wait
wait
wait
wait
acquire balance_lock:ok
read balance: 2
read amount: 7
7 > 2: True
if True
print 'Insufficient funds'
release balance_lock
```

Quiz: does this solution enforce correctness?

```python
def make_withdraw(balance)
        balance_lock = Lock()
        def withdraw(amount):
            nonlocal balance
            # try to acquire the lock
            balance_lock.acquire()
            # once successful, enter the critical section
            if amount > balance:
                print("Insufficient funds")
            else:
                balance = balance - amount
                print(balance)
            # upon exiting the critical section, release the lock
            balance_lock.release()
```

remember: always
release your locks.

Answer: yes

```
def make_withdraw(balance)
        balance_lock = Lock()
        def withdraw(amount):
            nonlocal balance
            # try to acquire the lock
            balance_lock.acquire()
            # once successful, enter the critical section
            if amount > balance:
                print("Insufficient funds")
            else:
                balance = balance - amount
                print(balance)
            # upon exiting the critical section, release the lock
            balance_lock.release()
```

important, allows others
to proceed

No two processes can be in the critical section at the same time.

Whichever gets to balance_lock.acquire() first gets to finish.

All others have to wait until it’s finished.

Semaphores

Used to protect access to limited resources

Each has a limit, N

Can be acquire()’d N times

After that, processes trying to acquire() automatically wait

Until another process release()’s

Semaphores example: database

A database that can only support 2 connections at a time.

```
# set up the semaphore
db_semaphore = Semaphore(2)

def insert(data):
    # try to acquire the semaphore
    db_semaphore.acquire()
    # if successful, proceed
    database.insert(data)
    #release the semaphore
    db_semaphore.release()
```

Example: database

```
db_semaphore = Semaphore(2)

def insert(data):
    db_semaphore.acquire()
    database.insert(data)
    db_semaphore.release()
```

insert(7)	insert(8)	insert(9)
P1	P2	P3
acquire db_semaphore: ok	acquire db_semaphore: wait	acquire db_semaphore: ok
read data: 7	wait	read data: 9
read global database	wait	
insert 7 into database	wait	read global database
release db_semaphore: ok	acquire db_semaphore: ok	insert 9 into database
	read data: 8	release db_semaphore: ok
	read global database	
	insert 8 into database	
	release db_semaphore: ok	

Conditions

Conditions are signals used to coordinate multiple processes

Processes can wait() on a condition

Other processes can notify() processes waiting for a condition.

Conditions example: vector mathematics

A = B+C

V = MxA

```
step1_finished = 0
start_step2 = Condition()

def do_step_1(index):
  A[index] = B[index] + C[index]
  start_step2.acquire()
  step1_finished += 1
  if(step1_finished == 2):
        start_step2.notifyAll()
  start_step2.release()

def do_step_2(index):
        start_step2.wait()
        V[index] = M[index] . A
```

Conditions example: vector mathematics

```
step1_finished=2
start_step2 = Condition()
```

$$B=\begin{pmatrix}2\\0\end{pmatrix} \quad C=\begin{pmatrix}0\\5\end{pmatrix} \quad M=\begin{pmatrix}1 & 2\\1 & 2\end{pmatrix} \quad A=\begin{pmatrix}2\\5\end{pmatrix}$$

$$A_1 = B_1+C_1$$
$$V_1 = M_1.A$$

$$A_2 = B_2+C_2$$
$$V_2 = M_2.A$$

P1	P2
read B1: 2	
read C1: 0	
calculate 2+0: 2	
write 2 -> A1	read B2: 0
acquire start_step2: ok	read C2: 0
write 1 -> step1_finished	calculate 5+0: 5
step1_finished == 2: false	write 5-> A2
release start_step2: ok	acquire start_step2: ok
start_step2: wait	write 2-> step1_finished
start_step2: wait	step1_finished == 2: true
start_step_2: wait	notifyAll start_step_2: ok
read M1: (1 2)	
read A:(2 5)	read M2(1 2)
calculate (1 2). (2 5): 12	read A: (2 5)

Deadlock

A condition in which threads are stuck waiting for each other forever

Deadlock example

```
>>> x_lock = Lock()
>>> y_lock = Lock()
>>> x = 1
>>> y = 0
>>> def compute():
        x_lock.acquire()
        y_lock.acquire()
        y = x + y
        x = x * x
        y_lock.release()
        x_lock.release()
>>> def anti_compute():
        y_lock.acquire()
        x_lock.acquire()
        y = y - x
        x = sqrt(x)
        x_lock.release()
        y_lock.release()
```

Deadlock: example

```
def compute():
     x_lock.acquire()
     y_lock.acquire()
     y = x + y
     x = x * x
     y_lock.release()
     x_lock.release()
```

```
def anti_compute():
     y_lock.acquire()
     x_lock.acquire()
     y = y - x
     x = sqrt(x)
     x_lock.release()
     y_lock.release()
```

`compute()`

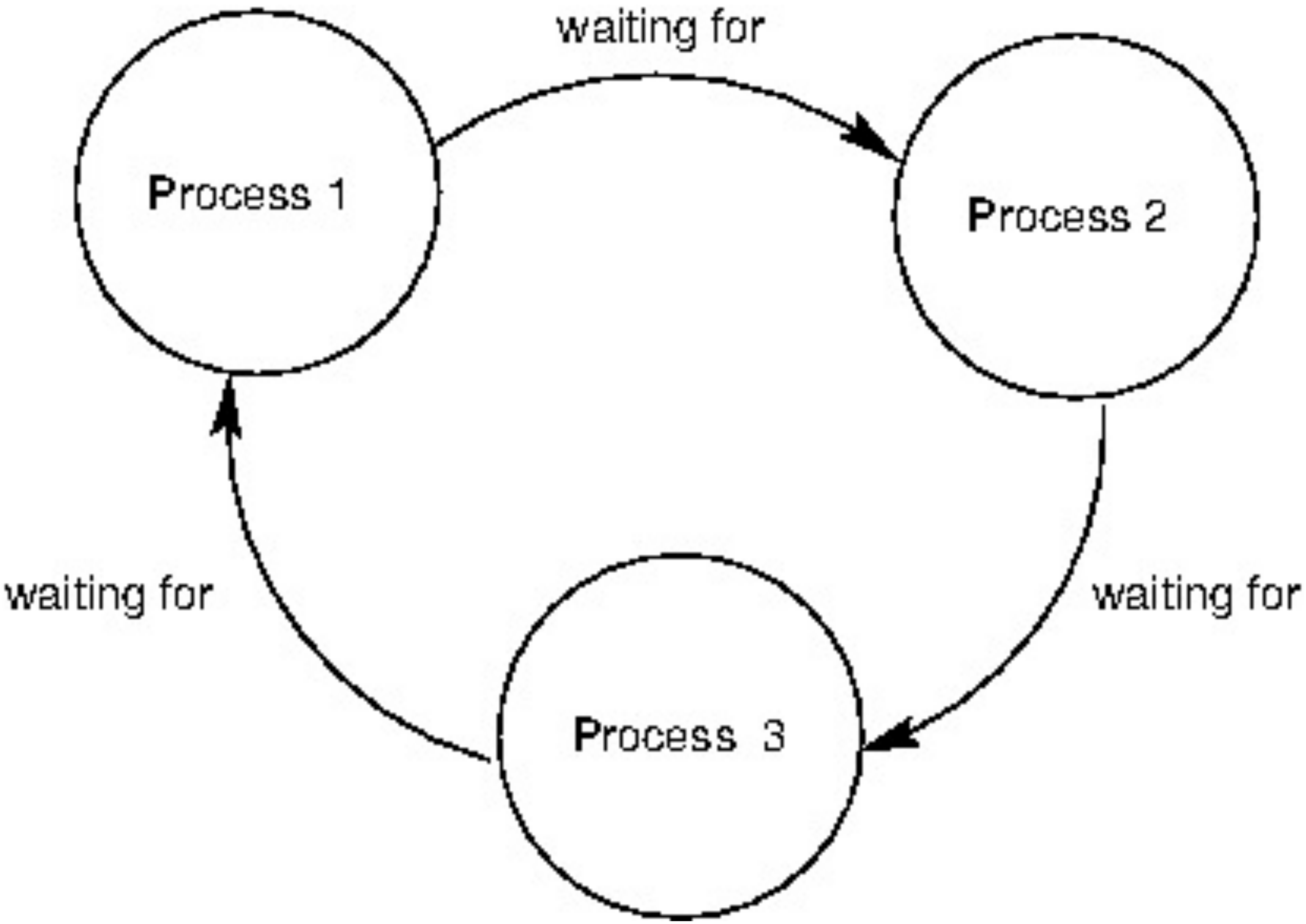
```
P1
acquire x_lock: ok
acquire y_lock: wait
wait
wait
wait
wait
...
```

`anti_compute()`

```
P2
acquire y_lock: ok
acquire x_lock:

wait
wait
wait
...
```

Deadlock


waiting for
Process 1
Process 2
waiting for
waiting for
Process 3

Next time

Sequences and Streams