IEMS 5780 / IERG 4080
Building and Deploying Scalable Machine Learning Services

Lecture 9 - Concurrent Programming (II)

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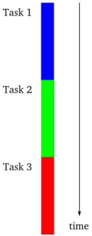
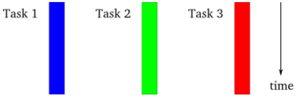
Asychronous Programming

Asynchronous Programming

- Consider the two models of programming we have came across so far
- Ref: http://krondo.com/in-which-we-begin-at-the-beginning/



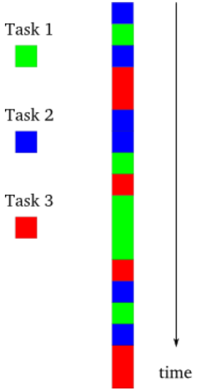
- The single thread synchronous model
- Everything is executed sequentially
- Latter tasks can consume output of earlier tasks that have completed



- The multi-thread or multi-process parallel model
- Tasks are executed in parallel
- If tasks need to communicate with each other they need shared objects

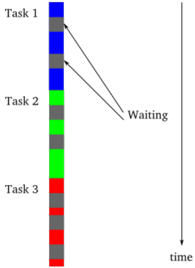
Asynchronous Programming

- There is also a model called **asynchronous programming**
- All tasks run in a single thread, but their execution can be **interleaved**
- NO two tasks will be executed at exactly the same time
- **The programmer would decide** when to switch from one task to another task (in contrast to the multi-thread model)
- **Why** do we need such a model?



Asynchronous Programming

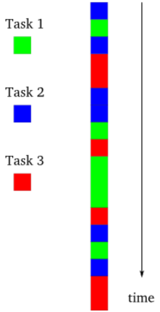
- Both **computation** and **I/O** operations will be involved in many tasks (e.g. sorting a list of numbers vs. loading data from a DB)
- For a **single-threaded synchronous model**
  - One task has to wait until another task has finished, even when the previous task is blocking
- For a **multi-threading model**
  - Different threads must either carry out independent tasks, or use some sophisticated way to communicate among each other



- A task may invoke quite a lot of blocking function calls during with the CPU is idling

Asynchronous Programming

- An asynchronous program will **switch** to perform another task when one task is blocked by some I/O operations
- Such a program will only **block** when no tasks at hand can make any progress (e.g. all tasks are waiting for downloading something from the Internet)
- Thus, an asynchronous program is also called a **non-blocking** program



The asynchronous model

Asynchronous Programming

When should we use asynchronous programming?

1. The number of tasks to execute is **large**, so it is likely that there is always at least one task that can make progress
2. The tasks perform a lot of **I/O** operations (thus using a synchronous model will waste a lot of time)
3. The tasks are **independent** from one another, no or little inter-task communication is needed

- Sounds like what a **server** needs to do when facing a lot of **clients**!

Revisit the TCP server

```python
import socket

server_socket = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server_socket.bind((socket.gethostname(), 50001))
server_socket.listen(10)

while True:
    (client_socket, address) = server_socket.accept()
    data = client_socket.recv(1024)
    client_socket.sendall(data)
    client_socket.close()
```

- We have discussed how to use multi-threading or multi-processing to implement the TCP server
- How about using the **asynchronous model**?

Non-blocking Socket Operations

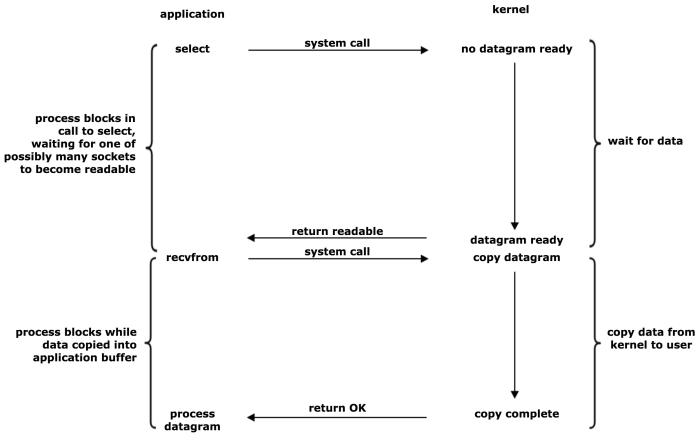
- By default, all socket methods are **blocking** (e.g. `accept()`, `recv()`, `send()`)
- We can switch to use sockets **asynchronously** by using the `setblocking()` method
- Then all socket methods will return **immediately** (!?)

```
# Create a TCP/IP socket
server = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server.setblocking(0)
...
```

Non-blocking Socket Operations

- What happen after we set sockets to non-blocking?
- `accept()`, `recv()`, `send()` may return **without having done anything**!
- We need a way to know whether calling that method will result in something done
  - Only call `accept()` when a client is trying to connect
  - Only call `recv()` when some data is ready to be read
  - Only call `send()` when we have successfully connected
- **Soluton 1:** using the `select()` function in the `select` module
- Ref: https://docs.python.org/3.6/library/select.html

Using `select`



(From W. Richard Stevens. Unix Network Programming. 1990)

- `select()` is a function that you should use when you want to do **I/O multiplexing**
- **I/O multiplexing**: switching between different I/O tasks when they are ready for reading or writing

Using `select`

- To use select, you need to prepare **three** lists
  - A list of sockets you want to **read from**
  - A list of sockets you want to **write to**
  - A list of sockets you want to **check for errors**
- It also returns three lists:
  - A list of sockets you can read from
  - A list of sockets you can write to
  - A list of sockets with errors

```
readables, writables, w_errors = select(inputs, outputs, [], 60)
# 60 is timeout in seconds, empty lists will be returned upon timeout
```

- Note: on Unix/Linux systems, `select()` works on file handlers too (because everything is a file)

Using **select**

```
import socket
from select import select

server = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server.setblocking(0)
server.bind(('localhost', 56789))
server.listen(10)

inputs = [server]   # we want to accept (read) from this socket
outputs = []        # nothing we want to write to so far

while True:
    readables, writables, w_errors = select(inputs, outputs, [], 60)
    ...
```

Using **select**

```
while True:
    readables, writables, w_errors = select(inputs, outputs, [], 60)

    for soc in readables:

        if soc is server:  # server socket is readable, someone is connecting
            client_socket, address = soc.accept()
            client_socket.setblocking(0)  # also set to non-blocking
            inputs.append(client_socket)  # a socket that we want to read from

        else:
            # It is a client socket, let's read from it
            data = soc.recv(1024)
            if data:
                # Handle the data
            else:
                # Empty string, client has disconnected
                # Close this socket, remove it from all lists
```

Using **select**

- Continue...

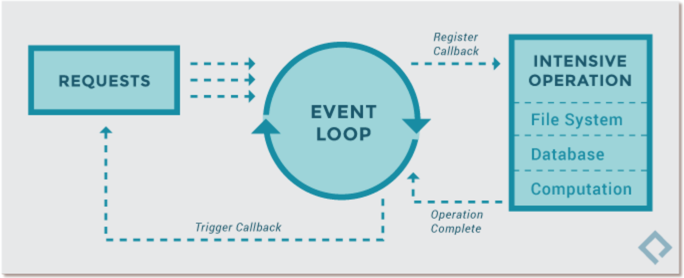
```
    for soc in writables:
        # This should be a client socket
        # Send something to it if you want to
        soc.send("Hello from Server")

    for soc in w_errors:
        # Socket has error
        # We should close the socket and remove it from all lists
        ...
```

- See complete example at https://pymotw.com/3/select/

Asynchronous I/O

Introduction

- `asyncio` is included in the standard library starting from Python 3.4
- A single-thread asynchronous model of programming
- `asyncio` allows you to switch between different **coroutines** when there are blocking calls
- Before diving into `asyncio`, let's learn about **generators** and **coroutines**



(Ref: https://eng.paxos.com/python-3s-killer-feature-asyncio)

Iterators

- In Python, we can use a for loop to loop over:
  - a list (e.g. `[1, 2, 3, 4, 5]`)
  - a dictionary (e.g. `{1: "a", 2: "b"}`)
  - a file (e.g. `for line in infile: ...`)
- Things that can be iterated over are called **iterable objects**
- We can turn iterable objects into **iterators** using the `iter()` function

```
>>> l = iter([1, 2, 3, 4])
>>> l
<list_iterator object at ...>
>>> next(l)
1
>>> next(l)
2
>>> next(l)
3
>>> next(l)
4
```

Generators

Generator functions provide a simplified way to create iterators

- Generator returns a sequence of values, one at a time
- It *generates* a new value **on-the-fly**, without the need to store all values in memory
- Consider the `range()` function. How would you implement that?

Generators

Our first attempt to implement the `range()` function

```
def my_range_1(n):
    nums = []
    i = 0
    while i < n:
        nums.append(i)
        i += 1
    return nums
```

- **Problem**: if `n` is large (say 1,000,000), you end up creating a huge list of integers that eats up a lot of memory

Generators

A better approach

```
def my_range_2(n):
    i = 0
    while i < n:
        yield i
        i += 1
```

- `yield` is used in place of `return`, now the function becomes a **generator**
- When the line `yield i` is reached, the function will return the value of `i`, and **pause**, until we call its `next()` function again

Generators

```
nums = my_range_2(100)

print(nums)
# Prints something like <generator object my_range_2 at 0x7f4f480c4410>

next(nums)   # returns 0
next(nums)   # returns 1
...
```

- Your function becomes an **iterator**, which can be iterated over to return a new value at a time
- The function is **NOT terminated**, because it remembers its current state
- Now, you notice that a `for` loop is just a loop that helps you to call the `next()` function automatically if given a generator

Generators

Another example:

```python
def get_odds(n):
    """Return odd numbers up to n"""
    i = 0
    while i < n:
        i += 1
        if i % 2 == 0:
            continue
        yield i

o = get_odds(100)
next(o)  # returns 1
next(o)  # returns 3
...
```

Generators

- You can also chain iterators:

```
def get_every_two_odds(odds):
    i = 0
    for o in odds:
        if i % 2 == 0:
            yield o
        i += 1

nums = get_every_two_odds(get_odds(100))
next(nums)  # returns 1
next(nums)  # returns 5
next(nums)  # returns 9
```

From Generators to Coroutines

- For generators, we use the `yield` keyword to specify where the function should return a value and stop, waiting for the next call of `next()`
- What if we want something the other way round: we want a function to pause and wait for something to **be sent** to it?
- Consider an example: we would like to write function that returns whether a given number `x` is a divsor of a given number `n` (e.g. if n = 10, x = 2, then this function returns `True`)

```
def is_divisor(x, n):
    return n % x == 0

is_divisor(2, 10)  # returns True
is_divisor(3, 32)  # returns False
is_divisor(5, 55)  # returns True
```

From Generators to Coroutines

- We can also re-write this in the form of a **coroutine**, one that would **wait for an input** to be sent into it

```python
def is_divisor(n):
    while True:
        x = yield
        yield n % x == 0

d = is_divisor(55)
next(d)
d.send(2)  # returns False
next(d)
d.send(5)  # returns True
next(d)
d.send(11) # returns True
```

Coroutines

```
def is_divisor(n):
    while True:
        x = yield
        yield n % x == 0

d = is_divisor(55)
next(d)
d.send(2)  # returns False
next(d)
d.send(5)  # returns True
next(d)
d.send(11) # returns True
```

- The first **`yield`** is for waiting input to be sent into the function
- The second **`yield`** is for emitting a value
- We need to call **`next()`** to make the function arrives at the line **`x = yield`** again.

Coroutines

- Another way to implement the **`is_divisor`** coroutine

```
def is_divisor(n):
    x = 1
    while True:
        divisible = False
        if n % x == 0:
            divisible = True
        x = yield divisible

d = is_divisor(55)
next(d)    # this would return True
d.send(2)  # returns False
d.send(5)  # returns True
d.send(11) # returns True
```

Coroutines

```python
def is_divisor(n):
    cnt = -1
    x = 1
    while True:
        divisible = False
        if n % x == 0:
            cnt += 1
            divisible = True
        x = yield (divisible, cnt)

d = is_divisor(55)
next(d)     # this would return True
d.send(2)  # returns (False, 0)
d.send(5)  # returns (True, 1)
d.send(11) # returns (True, 2)
```

- A coroutine stores its internal **state**
- For example, we can count how many times we see a divisor of `n`

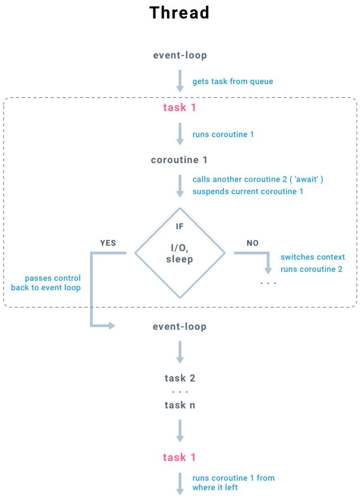
More on Coroutines

- **Coroutines** can be considered as generalized **subroutines** (a sequence of instructions that carry out some tasks)
- Coroutines have **multiple entry points** for suspending and resuming execution (unlike subroutines)
- Coroutines allows a programmer to **explicitly** handle context changes (when to switch from one task to another task)
- (Compare this with multi-threading or multi-processing)

Event Loop

- We will discuss more about **`asyncio`** in the next lecture, but let's get to know about the **event loop** first
- Event loop: *"a programming construct that waits for and dispatches events or messages in a program"*
- It keeps on waiting for events to happen, and execute different tasks depending on what event happens

Ref: [A guide to asynchronous programming in Python with asyncio]



`asyncio`

`asyncio`

- A framework for asynchronous programming in Python
- For writing **single-threaded** concurrent code using coroutines
- Some important concepts:
    1. Event Loop
    2. Coroutines
    3. Futures / Tasks

Event Loop

- An event loop is the **central execution device** in `asyncio`
- It is a program construct that waits for something (**events**) to happen, and then act on them
- It can register **tasks** to be executed, execute them, deplay or cancel them
- It allows two or more functions to run together **co-operatively**
- Example of **events**:
  - A client has connected to the server
  - A client has sent a certain request
  - Finished downloading a file from a remote server
- Each event may be associated with some functions (**callbacks**), which will be invoked when the event is triggered

Futures / Tasks

A **future** is an object that is supposed to have a **result** in the future

- **Task** is a scheduler, it schedule the execution of a coroutine
  - Responsible for executing a coroutine object in an event loop
  - A task will suspend a coroutine if the it has to wait for some futures to be completed
- The event loop only runs **one** task at a time
- When a task waits for the completion of a future, the event loop executes a new task (if available)

Example

```python
import asyncio

async def fake_io_operation():  # simulate some long I/O operations
    print("Perform I/O now...")
    await asyncio.sleep(1)
    print("I/O completed")

async def compute_square(x):
    print("Compute square of %d" % x)
    await fake_io_operation()
    print("Square of %d is %d" % (x, x*x))

tasks = []
for i in [4, 5, 6, 7]:
    tasks.append(asyncio.ensure_future(compute_square(i)))

loop = asyncio.get_event_loop()
loop.run_until_complete(asyncio.wait(tasks))
loop.close()
```

Example (continue)

```
import asyncio

async def fake_io_operation():
    print("Perform I/O now...")
    await asyncio.sleep(1)
    print("I/O completed")

async def compute_square(x):
    print("Compute square of %d" % x)
    await fake_io_operation()
    print("Square of %d is %d" % (x, x*x))

...
```

- The **`async`** keyword changes a function into a **coroutine** (a *native coroutine*)
- **`await something`** will suspect the coroutine at that point, until that *something* is completed
- Calling a **coroutine function** does not start it, it will just return a **coroutine object**

Example (continue)

```
...

tasks = []
for i in [4, 5, 6, 7]:
    tasks.append(
        asyncio.ensure_future(
            compute_square(i)))

loop = asyncio.get_event_loop()
loop.run_until_complete(
    asyncio.wait(tasks))
loop.close()
```

- `ensure_future` creates a task that wraps a **coroutine** (in this case the `computer_square()` function)
- `asyncio.wait(tasks)` wraps all tasks in a **coroutine** so that they can be passed to the event loop
- `run_until_complete` will run all the **tasks** passed to it until everything is completed

Example (continue)

- What would happen if we execute the above script?
- Observations:
  - When one task reaches the `asyncio.sleep(1)` line, **another** task is executed
  - When all tasks reaches that line, the whole program is **blocked** (why?)
  - The program terminates when all tasks are completed

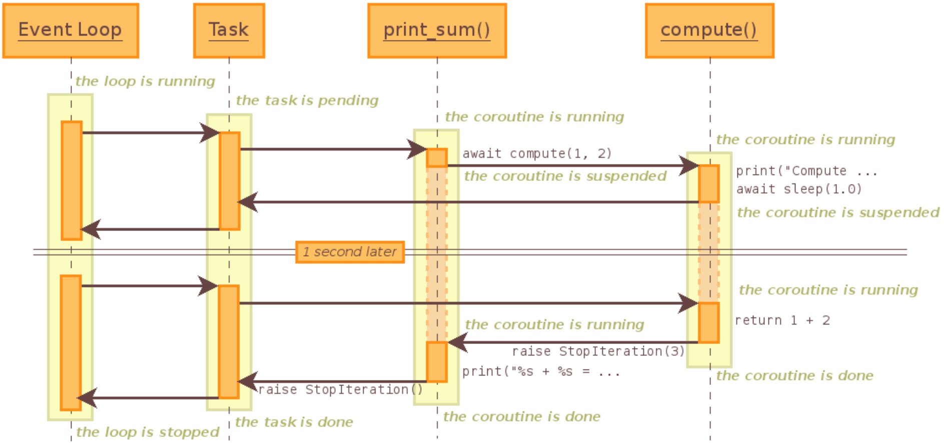
```
Compute square of 4
Perform I/O now...
Compute square of 5
Perform I/O now...
Compute square of 6
Perform I/O now...
Compute square of 7
Perform I/O now...
I/O completed
16
I/O completed
25
I/O completed
36
I/O completed
49
```

Another Example

- Consider another example (from https://docs.python.org/3/library/asyncio-task.html)

```
import asyncio

async def compute(x, y):
    print("Compute %s + %s ..." % (x, y))
    await asyncio.sleep(1.0)
    return x + y

async def print_sum(x, y):
    result = await compute(x, y)
    print("%s + %s = %s" % (x, y, result))

loop = asyncio.get_event_loop()
loop.run_until_complete(print_sum(1, 2))
loop.close()
```

Another Example (continue)



Getting the Result of a Coroutine

- What if you want to get back the results of the coroutines?

```
...
tasks = []
for i in [4, 5, 6, 7]:
    tasks.append(
        asyncio.ensure_future(compute_square(i)))

loop = asyncio.get_event_loop()
results, _ = loop.run_until_complete(
    asyncio.wait(tasks))
loop.close()

for f in results:
    print(f.result())
```

```
Compute square of 4
Perform I/O now...
Compute square of 5
Perform I/O now...
Compute square of 6
Perform I/O now...
Compute square of 7
Perform I/O now...
I/O completed
I/O completed
I/O completed
I/O completed
16
25
49
36
```

Using `asyncio.gather()`

- `asyncio.gather()` focuses on gathering all results for you
- It may not run the coroutines in order, but the results will be in order as the input

```
...
loop = asyncio.get_event_loop()
coros = [compute_square(i) for i in range(5)]
all_futures = asyncio.gather(*coros)

loop = asyncio.get_event_loop()
results = loop.run_until_complete(several_futures)
loop.close()

# results is a list: [0, 1, 4, 9, 16]
```

Event Loop

- Notice that we must use `run_until_complete()` to make sure that all tasks have been completed
- `ensure_future()` creates a future from the coroutine function, it also tries to execute the task
- What if we do not wait for the completion of the task(s) (try removing the line with `run_until_complete()`)?

```
Task was destroyed but it is pending!
task: <Task pending coro=<compute_square() running at example2.py:8>>
Task was destroyed but it is pending!
task: <Task pending coro=<compute_square() running at example2.py:8>>
Task was destroyed but it is pending!
task: <Task pending coro=<compute_square() running at example2.py:8>>
Task was destroyed but it is pending!
task: <Task pending coro=<compute_square() running at example2.py:8>>
sys:1: RuntimeWarning: coroutine 'compute_square' was never awaited
```

Concurrent Execution of Many Tasks

- Do we get speed up using **asyncio**? Let's try a test

```
import asyncio

async def long_task(x):
    print("Wait for 1/{:d} seconds...".format(x))
    await asyncio.sleep(1.0 / x)
    return 1.0 / x

coroutines = [long_task(i) for i in range(1, 101)]

loop = asyncio.get_event_loop()
all_futures = asyncio.gather(*coroutines)
loop.run_until_complete(all_futures)
loop.close()
```

Concurrent Execution of Many Tasks

- We can measure the time of the execution of the script by:

```
$ time python3 example.py
...
real    0m1.099s
user    0m0.100s
sys     0m0.004s
```

- If the tasks are executed sequentially, it would require 1 + 1/2 + 1/3 + ... + 1/100 = **5.187 seconds**
- When a task has to wait, the event loop will start to execute another task, thus almost all tasks are started at the same time.

End of Lecture 9