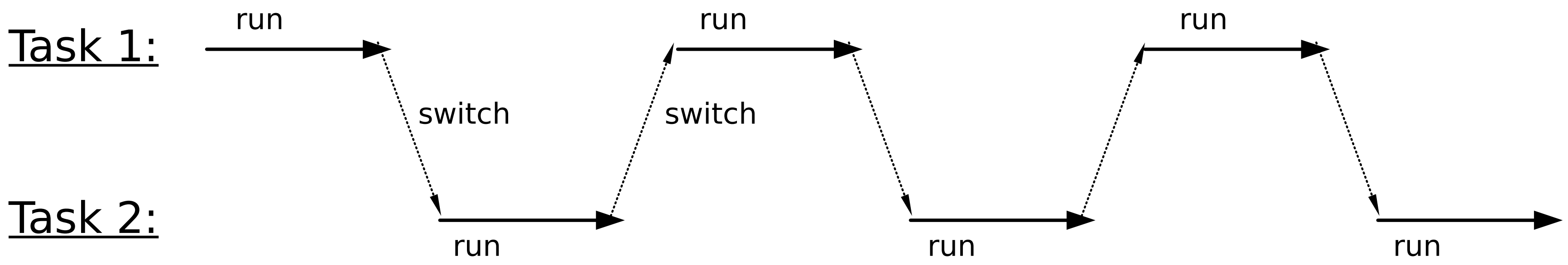
Concurrency

Concurreny

- Basic principles
- The Global Interpreter Lock
- Async and asyncio
- Threading
- Multiprocessing
- The future

Multitasking

- Multitasking with a single CPU means task switching



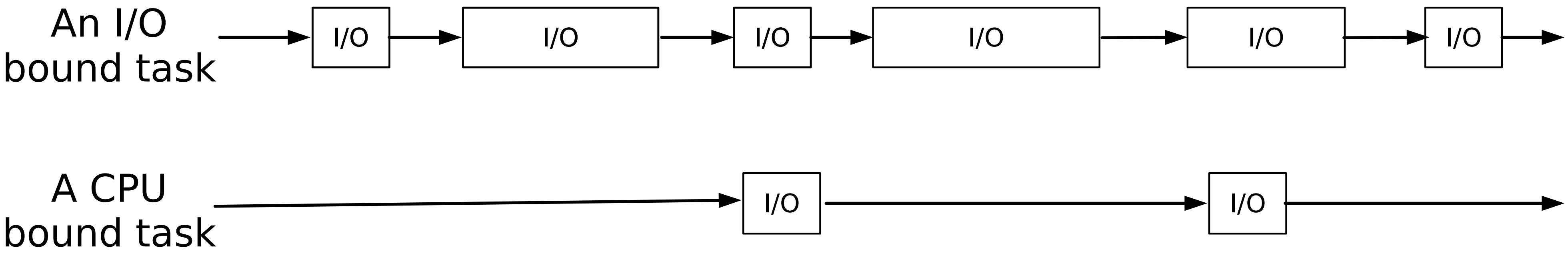
- The cost of task switching means running tasks concurrently is slower than running them consecutively

True Concurrency

With multiple cores and multiple CPUs, modern computers can do "parallel processing" and run multiple tasks simultaneously without the overhead of task switching.

Task Execution

- Tasks tend to be "I/O bound" (Input/Output) or "CPU bound"
- I/O means a network request, or accessing a file or a database which is much slower than the CPU, so the task spends a lot of time waiting
- CPU bound tasks do a lot of processing and will use as much processing power as you can give them



Task Execution

- A web crawler is an example of an I/O bound task
- Image processing is an example of a CPU bound task
- A single processor can run many I/O bound tasks concurrently as they spend most of their time waiting
- The basic unit for concurrent task execution is the "thread", an OS level unit of execution
- Multiple threads can run within a process
- Threads in Python are real system threads, the OS does the scheduling/thread switching
  - POSIX threads (pthreads) for Linux/Mac
  - Windows threads
- An alternative model for running multiple tasks concurrently is to use multiple processes

Processes

- Every program runs as a separate process
- Processes have "memory isolation"
- A process inherits an environment from the OS
- With multiple CPUs multiple processes can run concurrently
- Programs may launch "sub-processes", which inherit the same (or a modified) environment
- Sharing information between processes means "inter-process communication" of some kind (or shared memory)
- Both the subprocess and multiprocessing modules enable you to work with processes
- "Use processes not threads" is a common Python mantra

The Global Interpreter Lock

- Python has a Global Interpreter Lock, the GIL
- Only one thread of Python code executes at a time
- The GIL simplifies the interpreter and means fewer locks internally (faster single threaded code, the common case)
- The GIL makes threads suitable for I/O bound tasks only
- CPU bound tasks will run slower!
- C extensions may release the GIL and run concurrently
- For parallel processing use processes
- For I/O bound tasks, event loops and coroutines (green threading) are another alternative (asyncio)

Async

- **Not true concurrency**, tasks are run sequentially with an "event loop", `asyncio` by default
- Tasks are non-blocking coroutines
- Defined with `async`, called with `await`
- `await` adds a new task to the loop
- Any blocking calls block the whole event loop
- Under the hood there are special non-blocking system calls used by the event loop (*see methods on loops*)
- Also called green threading
- Suitable for I/O bound concurrency
- Async generators use "`async for`"

Async Demo

```
>>> loop = asyncio.new_event_loop()
>>> async def first():
...  print("one")
...  print(await other())
...  print("three")
...
>>> async def other():
...  return "two"
...
>>> loop.run_until_complete(first())
one
two
three
```

Async Demo

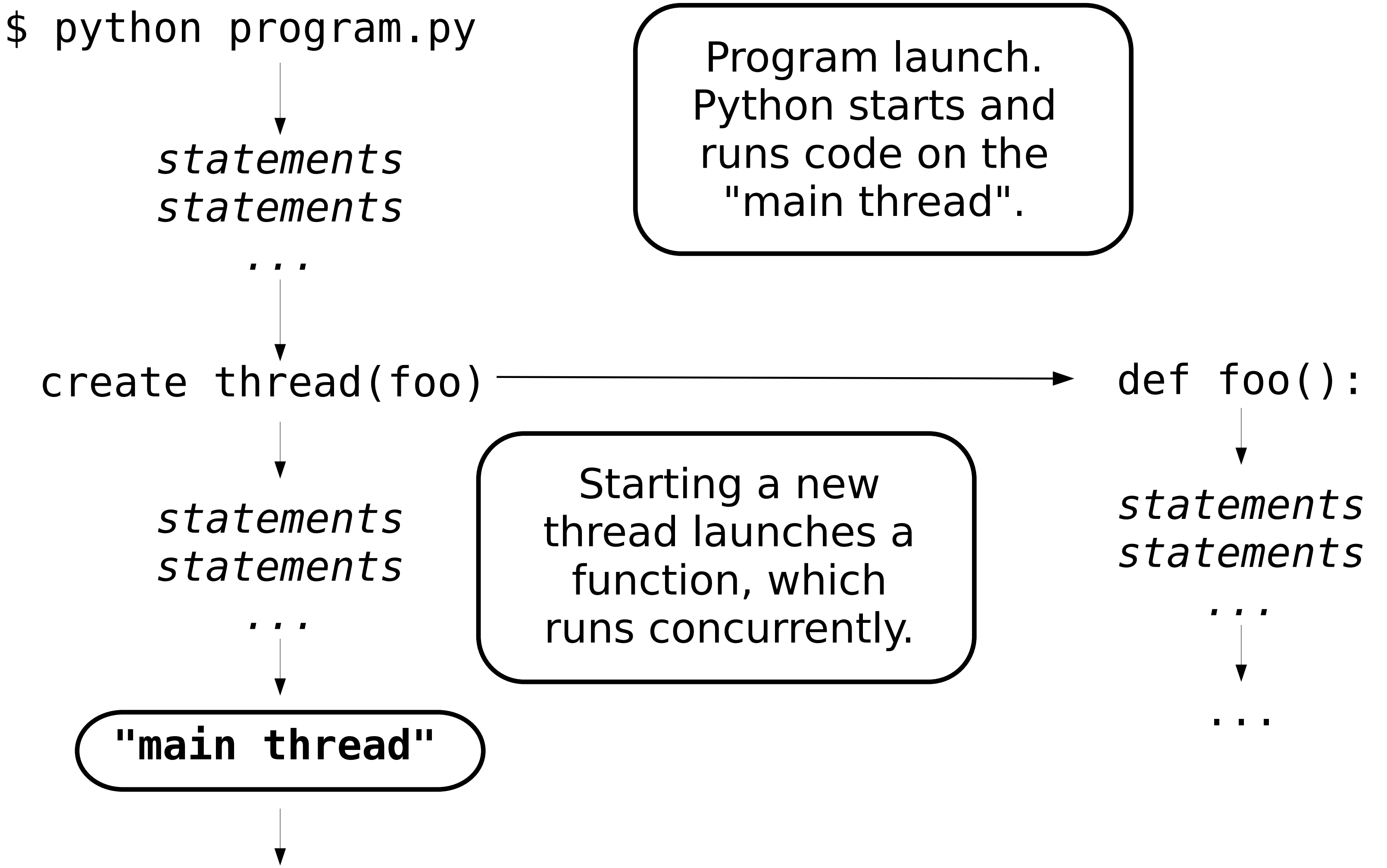
```
import asyncio

async def count():
    print("One")
    await asyncio.sleep(1)
    print("Two")

async def main():
    await asyncio.gather(count(), count(), count())

if __name__ == "__main__":
    import time
    s = time.perf_counter()
    asyncio.run(main())
    elapsed = time.perf_counter() - s
    print(f"Executed in {elapsed:0.2f} seconds.")
```

Async Generators

```
>>> async def thing():
...     return "thing"
...
>>> async def asyncgen():
...     yield await thing() # await allowed!
...     yield "two"
...
>>> async def function():
...     async for value in asyncgen():
...         print(value)
...
>>> import asyncio
>>> asyncio.run(function())
thing
two
```

Threads

- With threads we have multiple tasks running together within a program, each thread is independent but with access to shared resources



Threads

- Threads run independently until they terminate on return or program exit
- Many "thread primitives" (locks, events, queues, etc) allow them to communicate and synchronise
- No shared resources (the "actor model"/CSP) is a way to minimise locking and maximise sanity
- The GIL ensures only one thread is actually running Python code at any time
- The GIL is released/acquired every hundred interpreter "ticks" or so (around bytecode boundaries)
- We use the threading module to access threads

Functions as Threads

- How to launch a function in a thread

```
import threading
import time

def countdown(count):
    while count > 0:
        print("Counting down", count)
        count -= 1
        time.sleep(5)

>>> t1 = threading.Thread(target=countdown, args=(10,))
>>> t1.start()
Counting down 10
>>> Counting down 9
Counting down 8
Counting down 7
```

- countdown runs in a thread. We can still execute code in the interactive interpreter ("main thread") whilst it runs

Joining a Thread

- Once you start a thread it runs independently until it returns or the program exits
- Threads don't return a value, use a queue
- Use t.join() to wait for a thread to exit

```
t.start()        # Launch a thread
...
# Do other work
...
# Wait for thread to finish
t.join()         # blocks until t exits
```

- This only works from *another* thread
- A thread can't join itself!

Thread Termination

- Python has no built in support for thread cancellation
- Sometimes programs with threads can only be force killed! (kill -9)
- The normal solution is periodic polling and a terminate flag
- You can cancel threads at the OS level using the ctypes library and this solution (but it isn't recommended):

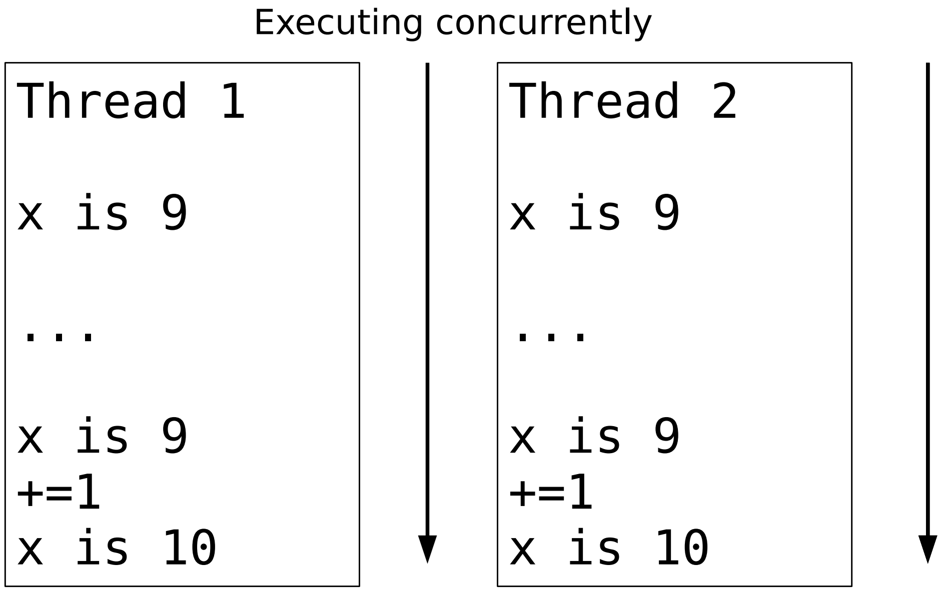
  https://stackoverflow.com/questions/323972/is-there-any-way-to-kill-a-thread-in-python

Race Conditions

- Threads can introduce great complexity
- Race conditions deadlocks, livelocks, resource contention, etc…
- You will need locks to access shared resources to avoid race conditions

```
x = 9

statements
statements
...
x += 1
```

race condition



- If two threads read x as 9 at the same time and both add 1 then x will be 10 when it should be 11

Mutex Locks

- Thread safe concurrent access to resources with locks

```python
import threading

m = threading.Lock()
with m:          # Acquires the lock (or blocks)
    statements
    statements
    ...
                 # Lock is released
statements
```

- Only one thread can acquire the lock at a time
- Others will block waiting for it to be released
- with automatically acquires and releases the lock
- All access to shared resources must be protected with locks

Coordinating Threads

- Synchronising threads or communicating between them can be done with an **Event**
  - Events have an internal flag that can be **set/clear** and other threads can **wait** on it being set
- Other useful thread specific primitives:
  - Re-entrant locks
  - Queues (useful for implementing the actor model)
  - Conditions
  - Semaphores
  - Thread local variables

See also: `concurrent.futures.ThreadPoolExecutor` is a high level interface to push tasks to a background thread.

Processes

- For concurrent task execution with processes we use the multiprocessing module
- Provides a similar API and primitives to threading
- Uses fork on Linux
- On Windows tasks and their environment are pickled and sent to the new process (so higher startup cost)
- Using processes bypasses the problem of the GIL (one GIL per process)
- Can send (copy) objects between processes using queues, but use the actor model (CSP)
- New (Python 3.11) shared memory constructs (low level – bytes and numpy arrays)

Multiprocessing

- Creating a process and sending it a task is easy
- The task must be "importable" by the new process
- Processes have useful methods like join/kill/is_alive, etc

```python
import multiprocessing

def worker(i):
    print(f'Worker {i}')

if __name__ == '__main__':
    for i in range(3):
        p = multiprocessing.Process(target=worker, args=(i,))
        p.start()
```

```
$ python workerprocesses.py
Worker 0
Worker 1
Worker 2
```

Higher Level API: ProcessPool

- A process based worker pool

```
p = multiprocessing.Pool([num_processes])
```

- It executes functions in a subprocess
- It maintains a pool of workers to divide tasks between
- A high level API, no need to worry about the details
- Core pool operations:

```
p.apply(func [, args [, kwargs]])

p.apply_async(func [, args [, kwargs [,callback]]])
```

- apply blocks and waits for a result
- apply_async returns a result object you can poll for the result or wait on

Pool: apply()

- Running a function in another process

```
import multiprocessing

def add(x, y):
    return x + y

if __name__ == '__main__':
    p = multiprocessing.Pool()
    r = p.apply(add, (3, 4))
    print(r)

$ python processingpool.py
7
```

- apply() runs the function in one of the subprocesses and waits for the result

Pool: apply_async()

- Running a function in another process without blocking
- Provides a handle (an ApplyResult) to fetch the result

```
import multiprocessing
import time

def add(x, y):
    return x + y

if __name__ == '__main__':
    p = multiprocessing.Pool()
    r = p.apply_async(add, (3, 4)) # r is an ApplyResult object

    # We could call r.wait([timeout])
    while not r.ready():
        time.sleep(0.1)

    print(r.ready())
    print(r.successful())
    print(r.get())        # get has an optional timeout param
```

The Future: PEP 703

- Python 3.13: The GIL is optional.
- It's a compile time choice, extensions must be compiled against this version `--disable-gil`
- 5-8% slower for single threaded code
- Uses deferred reference counting (etc)

The Future: Subinterpreters

- Python 3.12: Subinterpeters in C (PEP 684)
- Python 3.13: Subinterpreters in Python (PEP 554)
- A new `interpreters` module
- One GIL per subinterpreter
- Inspired by the PythonEngine from IronPython
- Adds an `InterpreterPoolExecutor` and an `Interpreter` class
- Objects copied between interpreters not shared
- Some limits on extension modules for sharing between interpreters (requires a "multi-phase init")