Concurrency in Distributed Systems

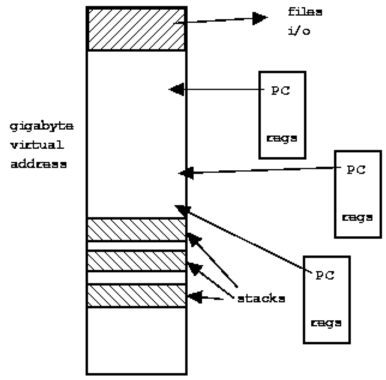
- Part 1: Threads
- Part 2: Concurrency Models
- Part 3: Thread Scheduling

Part 1: Threads and Concurrency

- Traditional process
  – One thread of control through a large, potentially sparse address space
  – Address space may be shared with other processes (shared mem)
  – Collection of systems resources (files, semaphores)
- Thread (light weight process)
  – A flow of control through an address space
  – Each address space can have multiple concurrent control flows
  – Each thread has access to entire address space
  – Potentially parallel execution, minimal state (low overheads)
  – May need synchronization to control access to shared variables

Threads

- Each thread has its own stack, PC, registers
  – Share address space, files,…



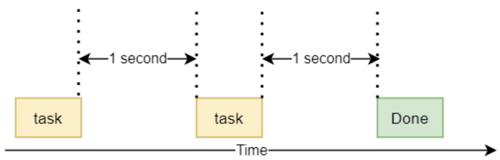
Why use Threads?

- Large multiprocessors/multi-core systems need many computing entities (one per CPU or core)
- Switching between processes incurs high overhead
- With threads, an application can avoid per-process overheads
  – Thread creation, deletion, switching cheaper than processes
- Threads have full access to address space (easy sharing)
- Threads can execute in parallel on multiprocessors

Threads Example

```python
from time import sleep, perf_counter

def task():
    print('Starting a task...')
    sleep(1)
    print('done')


start_time = perf_counter()

task()
task()

end_time = perf_counter()
```

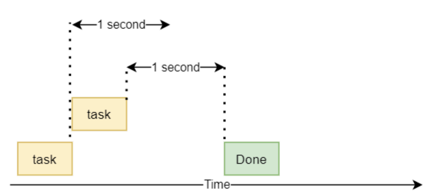
Single threaded program



Threads Example

```python
from threading import Thread


def task():
    print('Starting a task...')
    sleep(1)
    print('done')


start_time = perf_counter()

# create two new threads
t1 = Thread(target=task)
t2 = Thread(target=task)

# start the threads
t1.start()
t2.start()

# wait for the threads to complete
t1.join()
t2.join()
```

Multi-threaded version



https://www.pythontutorial.net/advanced-python/python-threading/

Why Threads?

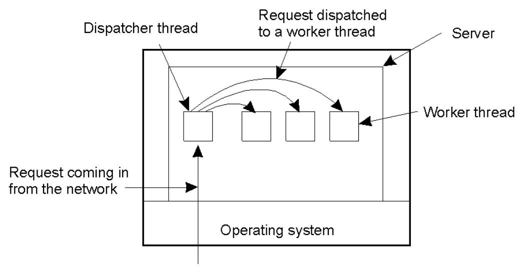
- *Single threaded process:* blocking system calls, no concurrency/parallelism
- *Finite-state machine* [event-based]: non-blocking with concurrency
- *Multi-threaded process:* blocking system calls with parallelism
- Threads retain the idea of sequential processes with blocking system calls, and yet achieve parallelism
- Software engineering perspective
  - Applications are easier to structure as a collection of threads
    - Each thread performs several [mostly independent] tasks

Multi-threaded Clients Example : Web Browsers

- Browsers such as IE are multi-threaded
- Such browsers can display data before entire document is downloaded: performs multiple simultaneous tasks
  - Fetch main HTML page, activate separate threads for other parts
  - Each thread sets up a separate connection with the server
    - Uses blocking calls
  - Each part (gif image) fetched separately and in parallel
  - Advantage: connections can be setup to different sources
    - Ad server, image server, web server…

Multi-threaded Server Example

- Apache web server: pool of pre-spawned worker threads
  – Dispatcher thread waits for requests (“dispatcher-workers” architecture)
  – For each request, choose an idle worker thread
  – Worker thread uses blocking system calls to service web request



Part 2: Concurrency Models

- Concurrency for server-side applications

- All server-side applications involve using a loop to process incoming requests

```
while(1) {
  wait for incoming request;
  process incoming request;
 }
```

← called event loop

Sequential Server

- Simplest model: single process, single thread
  - Process incoming requests sequentially

```
while (queue.waitForMessage()) {
  queue.processNextMessage()
}
```

- Advantage: very simple
- Disadvantages:
  - Requests queue up while one request is being processed
  - Increases waiting time (queuing delay) and response time

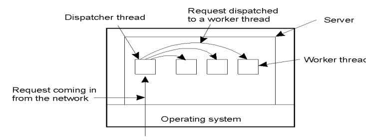
Multi-threaded Server

- Use threads for concurrent processing
- Simple model: **thread per request**
  - For each new request: start new thread, process request, kill thread

```
while(1){
req = waitForRequest();// get next request in queue
// wait until one arrives
thread = createThread(); // start a new thread
thread.process(req); // assign request to thread
}
```

- Advantage: Newly arriving requests don't need to wait
  - Assigned to a thread for concurrent processing
- Disadvantage: frequent creation and deletion of threads

Server with Thread Pool



- Use **Thread Pool**
  - Pre-spawn a pool of threads
  - One thread is dispatcher, others are worker threads
  - For each incoming request, find an idle worker thread and assign

```
CreateThreadPool(N);
while(1){
req = waitForRequest();
thread = getIdleThreadfromPool();
thread.process(req)
}
```

- Advantage: Avoids thread creation overhead for each request
- Disadvantages:
  - What happens when >N requests arrive at the same time?
  - How to choose the correct pool size N?

Dynamic Thread Pools

- Optimal size of thread pool depends on request rate
- Online services see dynamic workload
  - Request rate of a web server varies over time
- Dynamic thread pool: vary the number of threads in pool based on workload
  - Start with N threads and monitor number of idle threads
  - If # of idle threads < low threshold, start new threads and add to pool
  - If # < idle threads > high threshold, terminate some threads
- Many modern servers (e.g., apache) use dynamic thread pools to handle variable workloads
  - IT Admin need not worry about choosing optimal N for thread pool

Async Event Loop Model

- Async Event loop servers: single thread but need to process multiple requests
  - Use non-blocking (asynchronous) calls
  - **Asynchronous (aka, event-based) programming**
  - Provide concurrency similar to synchronous multi-threading but with single thread

```
import asyncio

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

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

Async version

```
def count():
    print("One")
    time.sleep(1)
    print("Two")

def main():
    for _ in range(3):
        count()
```

Synchronous version

Event Loop Model

- https://python.readthedocs.io/en/stable/library/asyncio-eventloop.html

```
import asyncio

def hello_world(loop):
    print('Hello World')
    loop.stop()

loop = asyncio.get_event_loop()

# Schedule a call to hello_world()
loop.call_soon(hello_world, loop)

# Blocking call interrupted by loop.stop()
loop.run_forever()
loop.close()
```

```
import asyncio

async def hello_world():
    print("Hello World!")

loop = asyncio.get_event_loop()
# Blocking call which returns when the
loop.run_until_complete(hello_world())
loop.close()
```

- async function in python: "coroutine"
- await/async pair

```
async def foo():       await: suspend execution of foo
    await bar()               and wait for bar
```

- https://python.plainenglish.io/build-your-own-event-loop-from-scratch-in-python-da77ef1e3c39
- https://docs.python.org/3.9/library/asyncio-task.html

Process Pool Servers

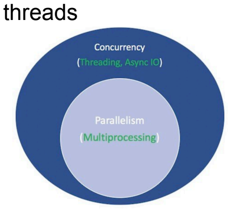
- Multi-process server
  - Use a separate process to handle each request
  - Process Pool: dispatcher process and worker processes
  - Assign each incoming request to an idle process
- Apache web server supports process pools
- Dynamic Process Pools: vary pool size based on workload
- Advantages
  - Worker process crashes only impact the request, not application
  - Address space isolation across workers
- Disadvantages
  - Process switching is more heavy weight than thread switching

Server Architecture

- Sequential
  - Serve one request at a time
  - Can service multiple requests by employing events and asynchronous communication
- Concurrent
  - Server spawns a process or thread to service each request
  - Can also use a pre-spawned pool of threads/processes (apache)
- Thus servers could be
  - Pure-sequential, event-based, thread-based, process-based
- Discussion: which architecture is most efficient?

Parallelism versus Concurrency

- **Concurrency** enables handling of multiple requests
  - Request processing does not block other requests
  - Achieved using threads or async (non-blocking) calls
  - Concurrency can be achieved on single core/processor
- **Parallelism** enable simultaneous processing of requests
  - Does not block other requests; requests processed in parallel
  - Needs multiple threads or multiple processes
    - Threads/processes simultaneously run on multiple cores
    - Async event loops? Will need multiple threads



Part 3: Thread Scheduling

- *Key issues:*

- Cost of thread management
  – More efficient in user space
- Ease of scheduling
- Flexibility: many parallel programming models and schedulers
- Process blocking – a potential problem

User-level Threads

- Threads managed by a threads library
  - Kernel is unaware of presence of threads
- Advantages:
  - No kernel modifications needed to support threads
  - Efficient: creation/deletion/switches don't need system calls
  - Flexibility in scheduling: library can use different scheduling algorithms, can be application dependent
- Disadvantages
  - Need to avoid blocking system calls [all threads block]
  - Threads compete for one another
  - Does not take advantage of multiprocessors [no real parallelism]

User-level threads

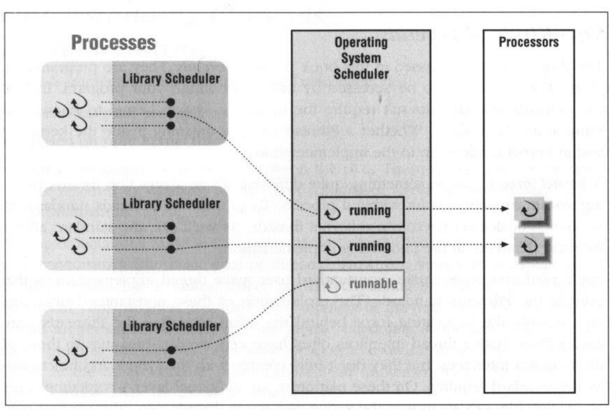


Figure 6-1: User-space thread implementations

Kernel-level threads

- Kernel aware of the presence of threads
  - Better scheduling decisions, more expensive
  - Better for multiprocessors, more overheads for uniprocessors

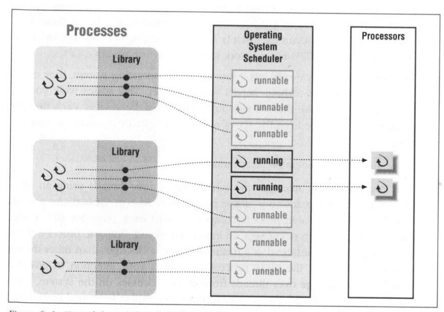
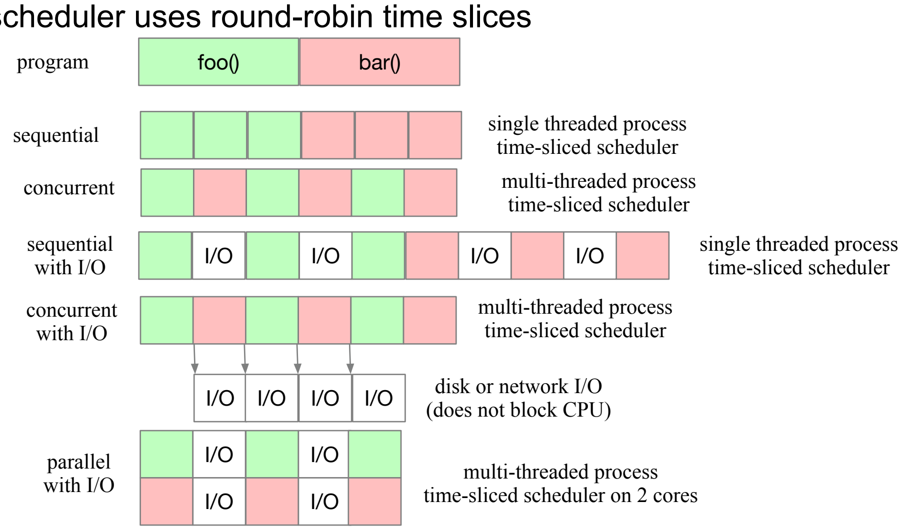


Figure 6–2: Kernel thread–based implementations

Thread Scheduling Example

- CPU scheduler uses round-robin time slices



Scheduler Activation

- User-level threads: scheduling both at user and kernel levels
  - user thread system call: process blocks
  - kernel may context switch thread during important tasks
- Need mechanism for passing information back and forth
- Scheduler activation: OS mechanism for user level threads
  - Notifies user-level library of kernel events
  - Provides data structures for saving thread context
- Kernel makes up-calls : CPU available, I/O is done etc.
- Library informs kernel: create/delete threads
  - N:M mapping: n user-level threads onto M kernel entities
- Performance of user-level threads with behavior of kernel threads

Light-weight Processes

- Several LWPs per heavy-weight process
- User-level threads package
  – Create/destroy threads and synchronization primitives
- Multithreaded applications – create multiple threads, assign threads to LWPs (one-one, many-one, many-many)
- Each LWP, when scheduled, searches for a runnable thread *[two-level scheduling]*
  – Shared thread table: no kernel support needed
- When a LWP thread block on system call, switch to kernel mode and OS context switches to another LWP

LWP Example

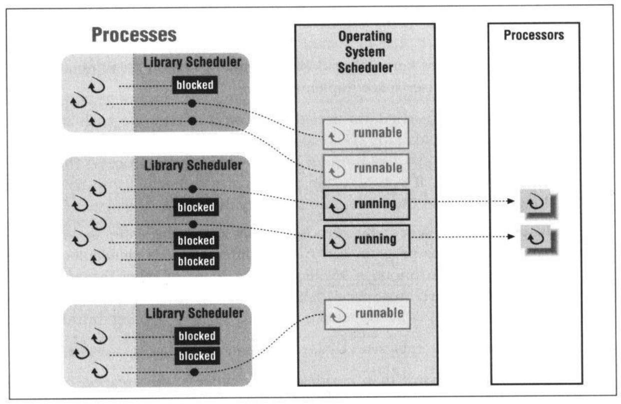


Figure 6–3: Two-level scheduler implementations

Process Scheduling

- Priority queues: multiples queues, each with a different priority
  - Use strict priority scheduling
  - Example: page swapper, kernel tasks, real-time tasks, user tasks
- Multi-level feedback queue
  - Multiple queues with priority
  - Processes dynamically move from one queue to another
    - Depending on priority/CPU characteristics
  - Gives higher priority to I/O bound or interactive tasks
  - Lower priority to CPU bound tasks
  - Round robin at each level