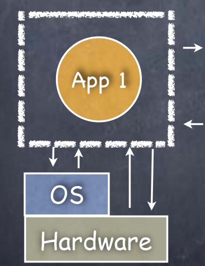
Threads

An abstraction for concurrency

Rethinking the process abstraction



- The Process, as we know it, serves two key purposes in the OS:
  - It defines the granularity at which the OS offers isolation
    - each process defines an address space that identifies what can be touched by the program
  - It defines the granularity at which the OS offers scheduling and can express concurrency
    - each process defines a stream of instructions executed sequentially

Thread: a new abstraction for concurrency

- A single-execution stream of instructions that represents a separately schedulable task
  - OS can run, suspend, resume a thread at any time
  - bound to a process (lives in an address space)
  - Finite Progress Axiom: execution proceeds at some unspecified, non-zero speed
- Virtualizes the processor
  - programs run on machine with an infinite number of processors (hint: not true)
- Allows to specify tasks that should be run concurrently…
  - …and lets us code each task sequentially

Why threads?

- To express a natural program structure
  - updating the screen, fetching new data, receiving user input — different tasks within the same address space
- To exploit multiple processors
  - different threads may be mapped to distinct processors
- To maintain responsiveness
  - splitting commands, spawn threads to do work in the background
- Masking long latency of I/O devices
  - do useful work while waiting

How can they help?

- Consider the following code segment:

  for (k = 0; k < n; k++)

  a[k] = b[k] × c[k] + d[k] × e[k]

- Is there a missed opportunity here?

```
thread_create(T1, fn, 0, n/2)
thread_create(T2, fn, n/2, n)

fn(l,m) {
   for (k = l; k < m; k++)
      a[k] = b[k] × c[k] + d[k] × e[k]
}
```


How can they help?

- Consider a Web server
  - get network message from client
  - get URL data from disk
  - compose response
  - send response

How can they help?

- Consider a Web server

  Create a number of threads, and for each do

  - get network message from client
  - get URL data from disk
  - compose response
  - send response

- What did we gain?

Overlapping I/O & Computation

Request 1
Thread 1

- get network message (URL) from client
- get URL from disk

(disk access latency)

- send data over network

Request 2
Thread 2

- get network message (URL) from client
- get URL from disk

(disk access latency)

- send data over network

Time

Total time is less than Request 1 + Request 2

All you need is Love

(and a stack)

- All threads within a process share
  - heap
  - global/static data
  - libraries
- Each thread has separate
  - program counter
  - registers
  - stack

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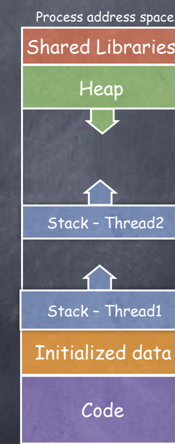
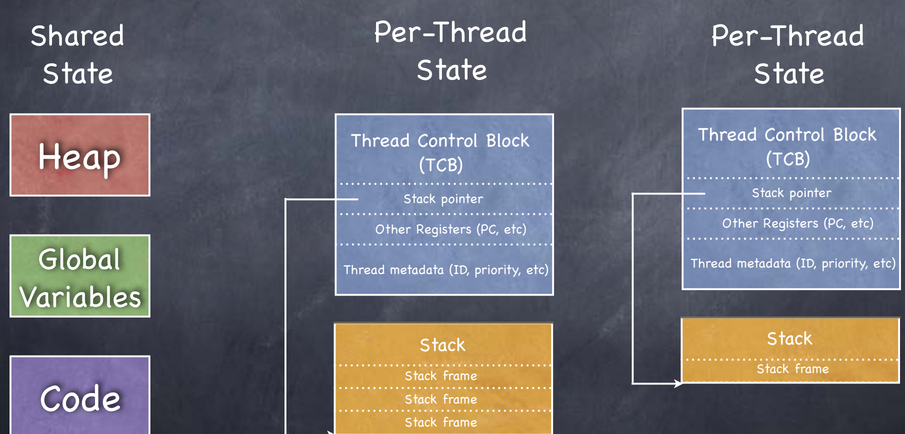
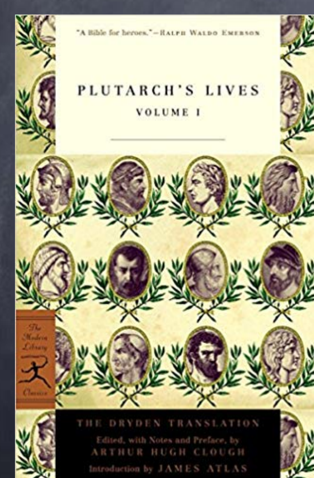


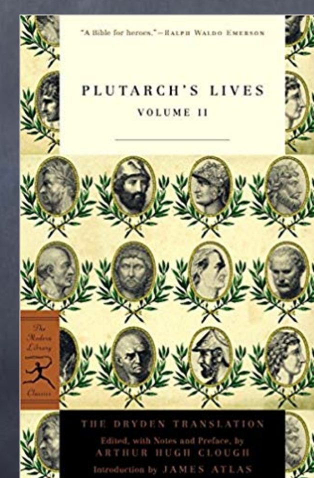
Implementing the thread abstraction: the state



Note: No protection enforced at the thread level!

Processes vs. Threads: Parallel lives





Processes vs. Threads: Parallel lives

Processes

- Have data/code/heap and other segments
- Include at least one thread
- If a process dies, its resources are reclaimed and its threads die
- Interprocess communication via OS and data copying
- Have own address space, isolated from other processes'
- Each process can run on a different processor
- Expensive creation and context switch

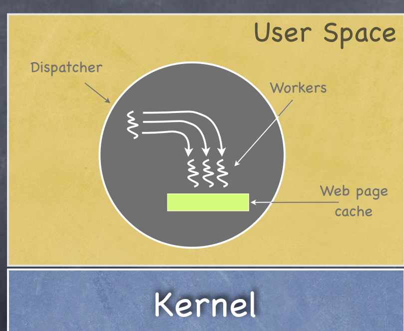
Threads

- No data segment or heap
- Needs to live in a process
- More than one can be in a process. First calls main.
- If a thread dies, its stack is reclaimed
- Inter-thread communication via memory
- Have own stack and registers, but no isolation from other threads in the same process
- Each thread can run on a different processor
- Inexpensive creation and context switch

A simple API

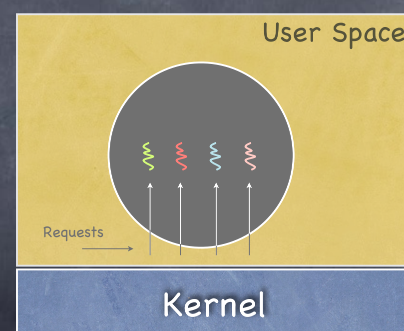
Syscall	Description
void thread_create (thread, func, arg)	Creates a new thread in thread, which will execute function func with arguments arg.
void thread_yield()	Calling thread gives up processor. Scheduler can resume running this thread at any time
int thread_join (thread)	Wait for thread to finish, then return the value thread passed to thread_exit. May be called only once for each thread.
void thread_exit (ret)	Finish caller; store ret in caller's TCB and wake up any thread that invoked thread_join(caller).

Multithreaded Processing Paradigms



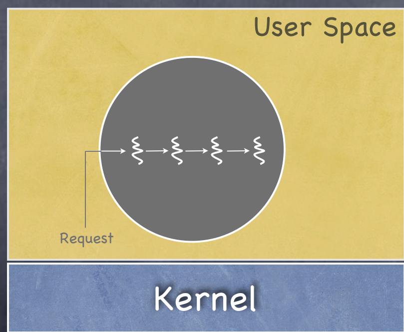
Dispatcher/Workers

Multithreaded Processing Paradigms



Specialists

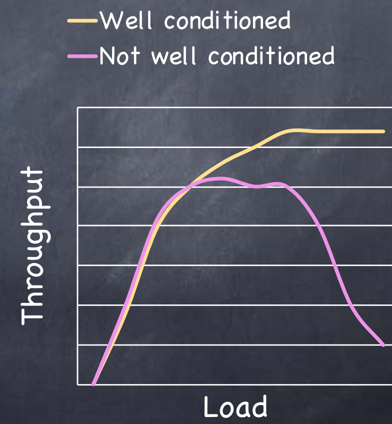
Multithreaded Processing Paradigms



Pipelining

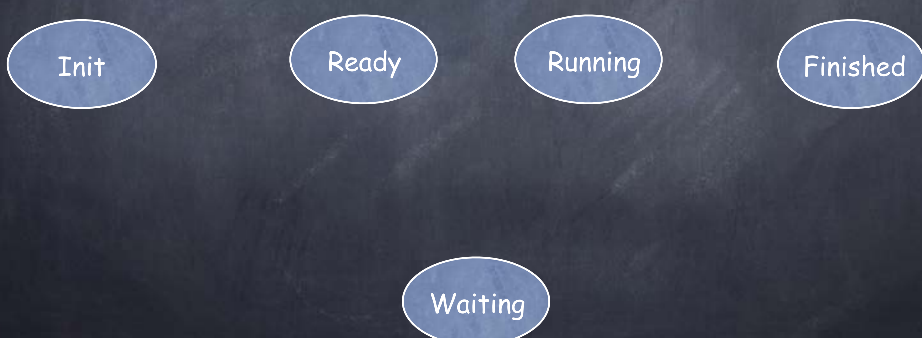
Threads considered harmful

- Creating a thread or process for each unit of work (e.g., user request) is dangerous
  - High overhead to create & delete thread/process
  - Can exhaust CPU & memory resource
- Thread/process pool controls resource use
  - Allows service to be well conditioned
    - output rate scales to input rate
    - excessive demand does not degrade pipeline throughput



Threads Life Cycle

- Threads (just like processes) go through a sequence of Init, Ready, Running, Waiting, and Finished states



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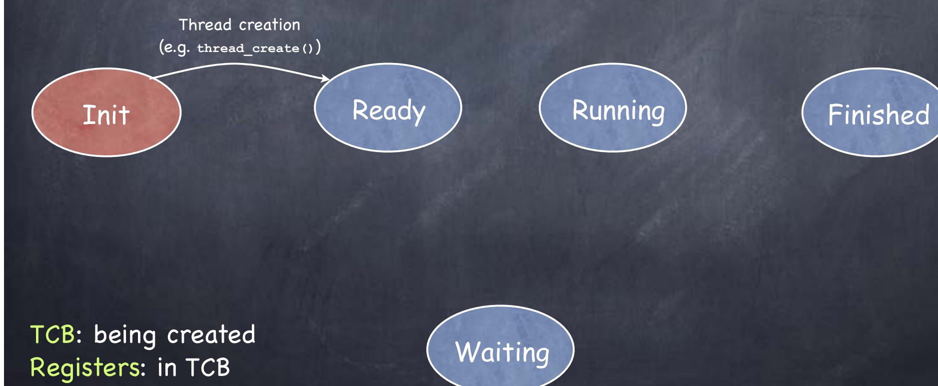
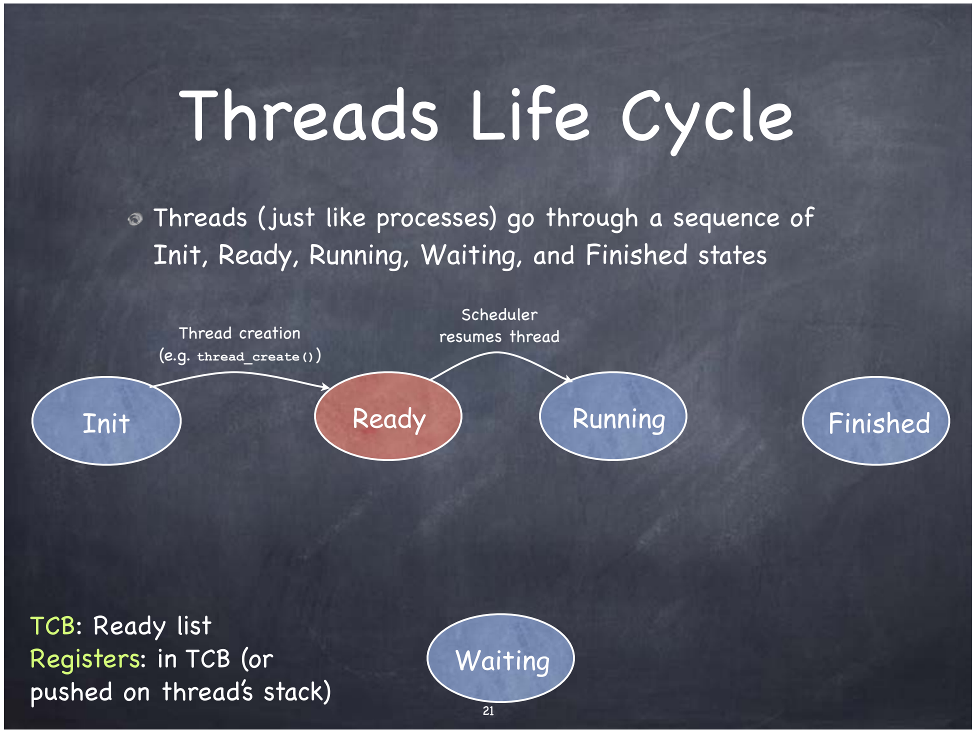


TCB: being created
Registers: in TCB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(e.g. thread_create())
Scheduler
resumes thread
Init
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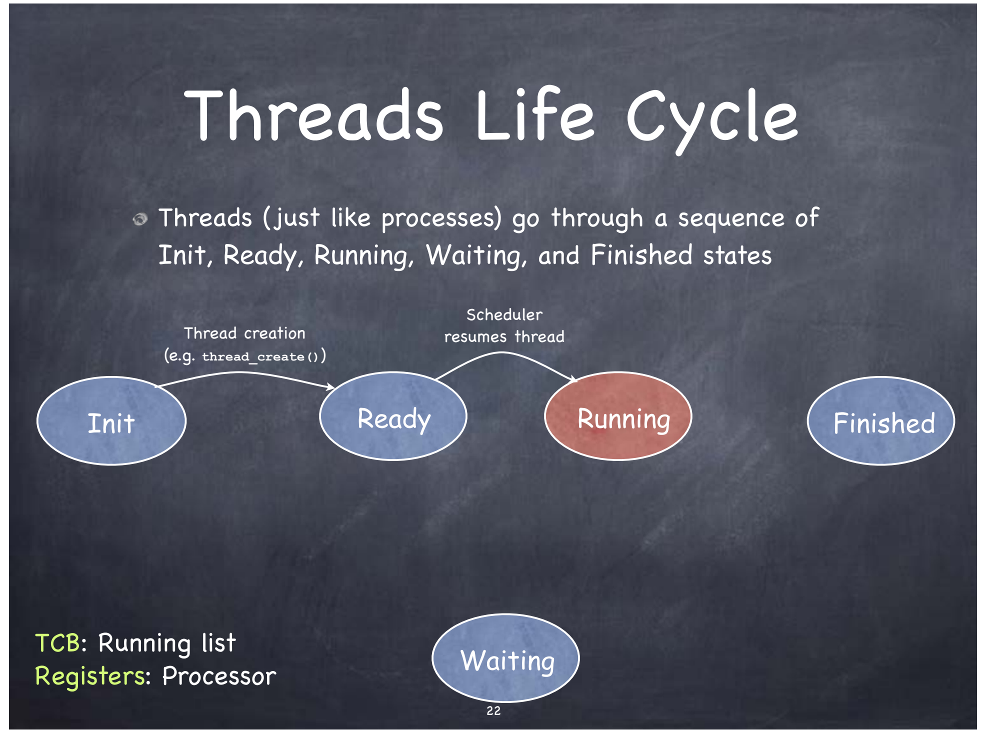
Waiting
TCB: Ready list
Registers: in TCB (or pushed on thread's stack)
21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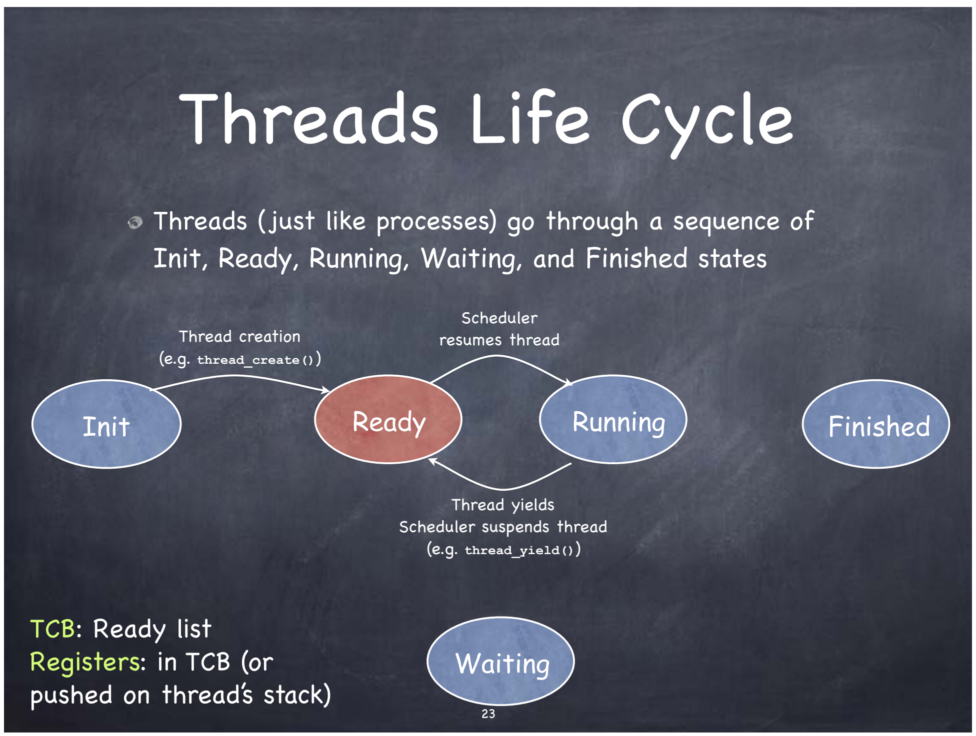
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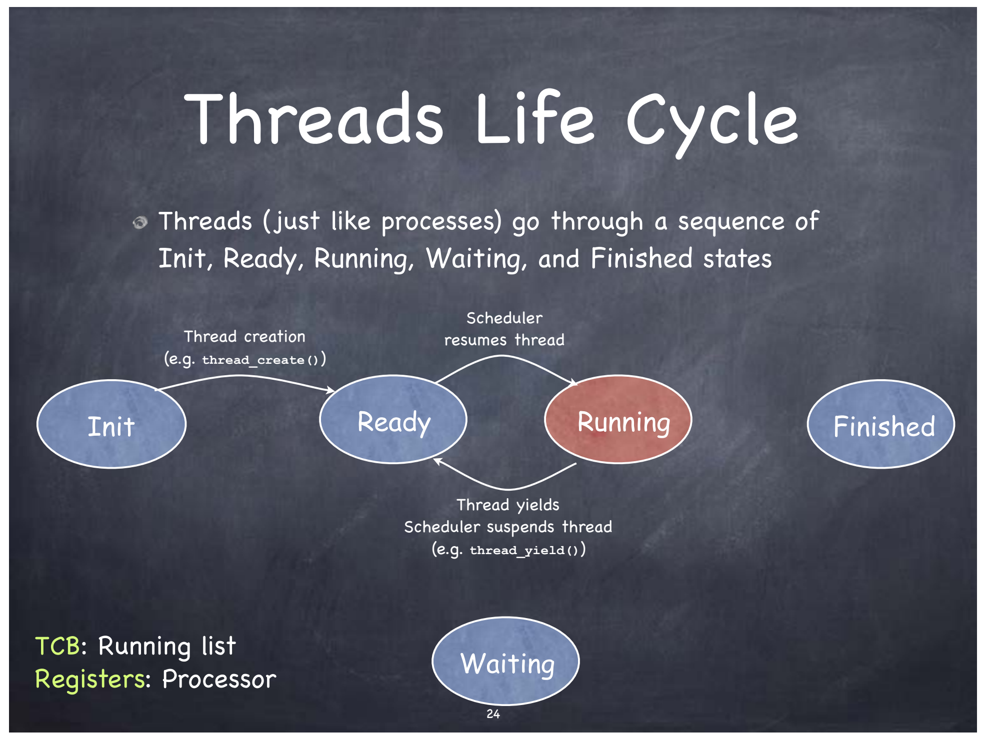
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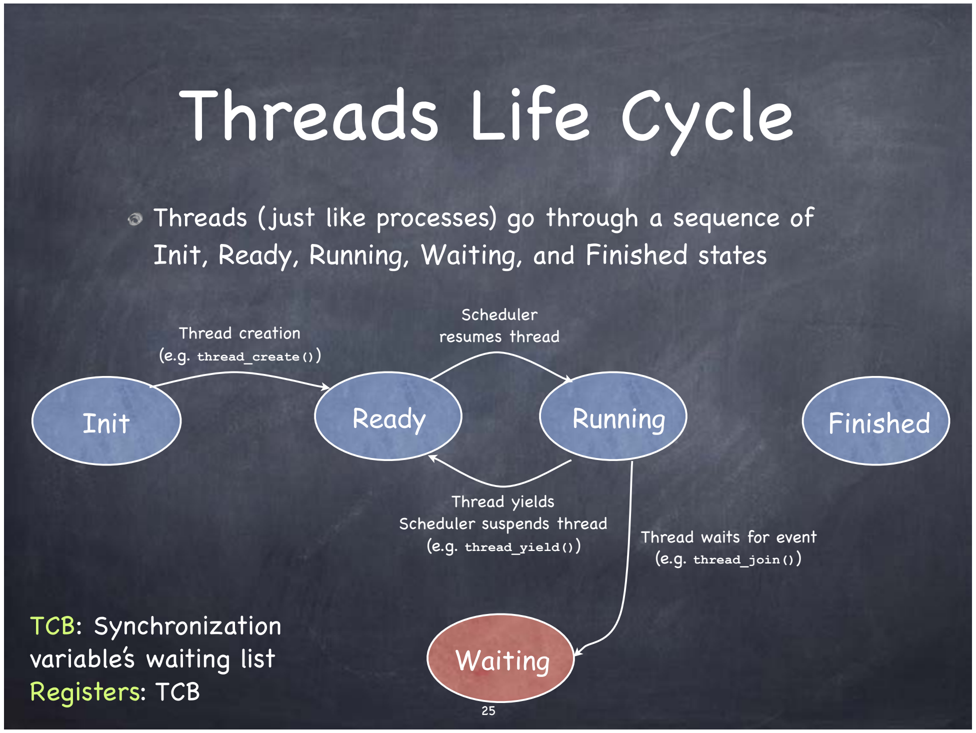
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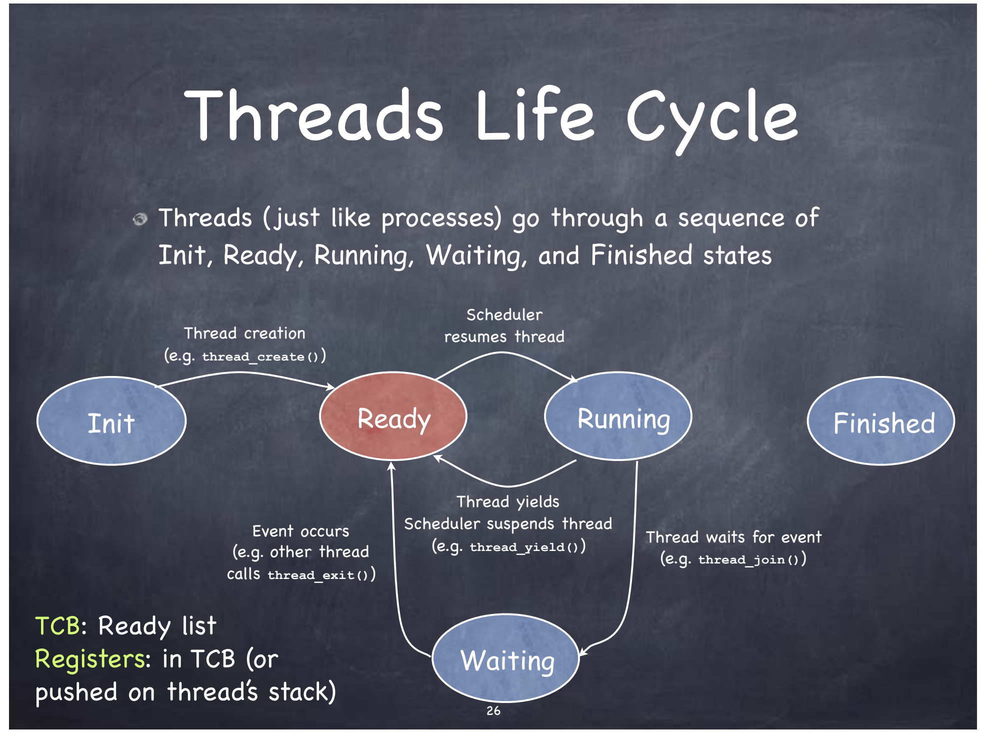
Thread waits for event (e.g. thread_join())
Waiting
TCB: Synchronization variable's waiting list
Registers: TCB
25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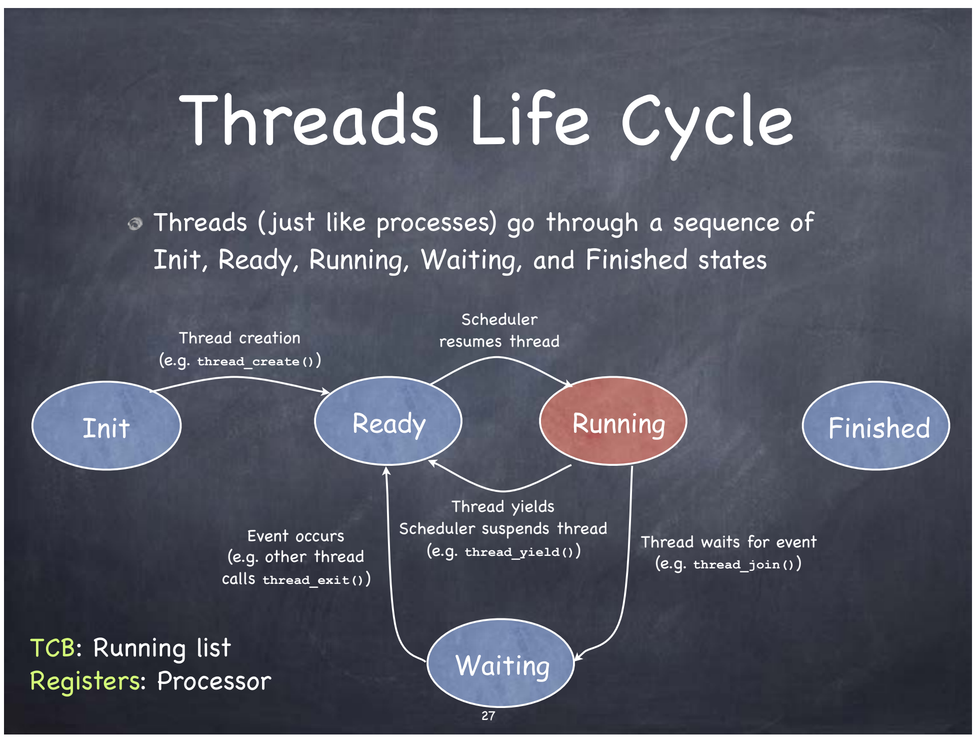
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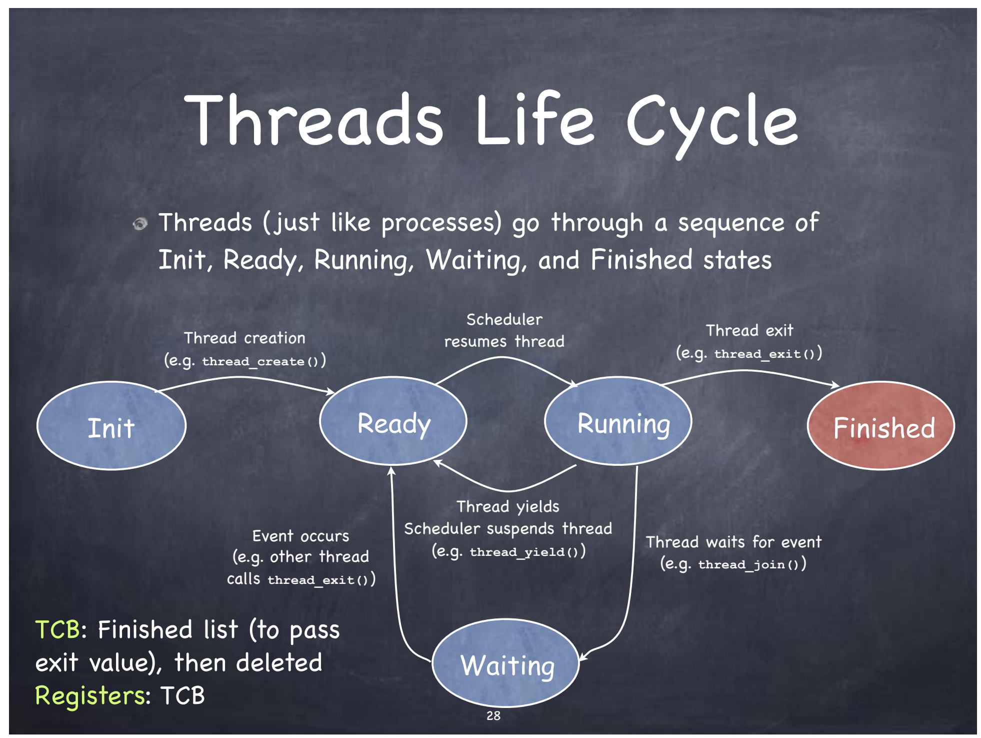
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Thread yields Scheduler suspends thread (e.g. thread_yield())
Thread waits for event (e.g. thread_join())
Waiting
TCB: Finished list (to pass exit value), then deleted
Registers: TCB
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Kernel thread context switches

- Voluntary event
  - via a call to the thread library: `thread_yield(), thread_wait(), thread_exit()`
- Involuntary event
  - e.g., timer or I/O interrupt; processor exception

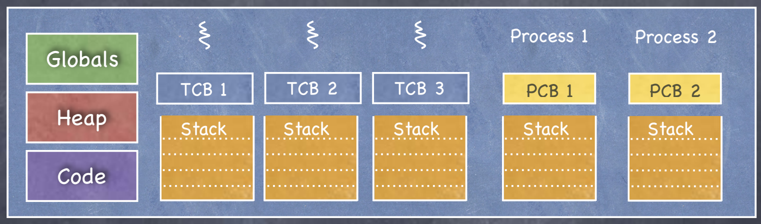
Voluntary Kernel thread context switch

- Defer interrupts
- Choose next thread to run from ready list
- Switch!
  - save register and stack of current thread in TCB
  - add current thread to ready list
  - switch to new thread's stack
  - slurp in new thread's state from <u>its</u> TCB
  - change state of new thread to RUNNING
- Enable interrupts

Involuntary Kernel thread context switch

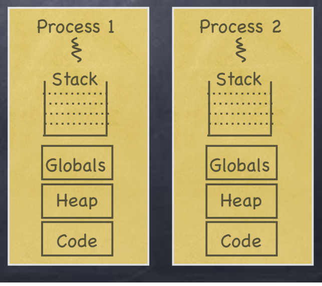
- Save the thread's state in the TCB
  - through a combination of hardware and software
- Run kernel handler
  - can use stack of kernel thread to push variables used by handler
- Restore next ready thread

Single-threaded processes + kernel threads

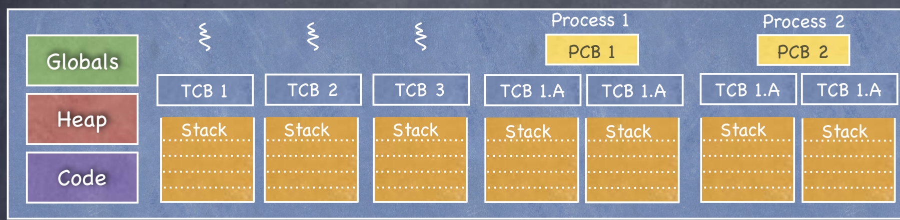


Each kernel thread has its own TCB and its own stack.

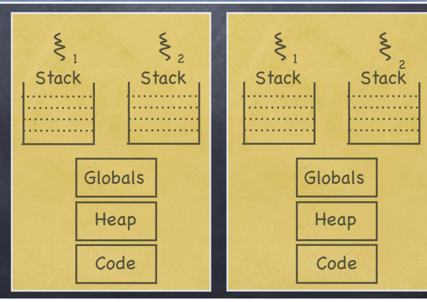
Each user process has a stack at user-level for executing user code and a kernel interrupt stack for executing interrupts and system calls.



Multi-threaded processes: kernel threads



Each user-level thread has a user-level stack and an interrupt stack in the kernel for executing interrupts and system calls.



User-level Threads

- Motivation
  - Threads are a useful programming abstraction
  - Calling OS to manage threads is expensive.
  - Implement thread creation/scheduling using procedure calls to a user-level library rather than system calls
- User-level threads
  - User-level library implementations of thread_create(), thread_yield(), etc.
  - UL library performs same set of actions as corresponding system calls, but thread management is controlled by user-level library
  - What happens if a user-level thread makes a system call?

User-level Threads: Pros and Cons

- Benefits:
  - Small context for switching between threads of a process
  - Thread scheduling is more flexible
    - Can use application-specific scheduling policy
    - Each process can use a different scheduling algorithm
    - Threads voluntarily give up CPU
- Drawbacks:
  - OS is unaware of the existence of user-level threads
    - Poor scheduling decisions
    - If a user-level thread waits for I/O - entire process waits
  - OS schedules processes independent of number of threads within a process

Can we do better?

- Why not a user level thread scheduler that spawns a kernel thread for blocking operations?
  - Forget spawning, use a pool of kernel threads!
  - But how do we know if an operation will block?
    - `read` might block, or data might be in page cache.
    - Any memory reference might cause a page fault to disk!

Scheduler Activations (best of both worlds)

- Kernel assigns to process k "virtual processors" (initially, k=1), implemented as kernel threads.
  - Usel-level thread scheduler can run m user-level thread on top of its k virtual processors
- Kernel notifies (activates) via an upcall the user-level thread scheduler for any kernel event that migh affect user-level threads
  - e.g., if a thread calls a blocking system call, kernel notifies user-level scheduler to schedule a different thread.
- Kernel notifies user-level scheduler whenever it adds or reclaims a virtual processor assigned to the process