Concurrency and Threads

Thread: an abstraction for concurrency

- A single-execution stream of instructions that represents a separately schedulable task
  - OS can run, suspend resume thread at any time
  - Finite Progress Axiom: execution proceeds at some unspecified, non-zero speed
- Virtualizes the processor
  - programs run on machine with an infinite number of processors

- Allows to specify tasks that should be run concurrently...
  - ...and lets us code each task sequentially

Where threads are useful

- To express a natural program structure
  - updating the screen, fetching new data, receiving user input
- Exploiting multiple processors
  - different threads may be mapped to distinct processors
- Masking long latency of I/O devices
  - do useful work while waiting

A simple API

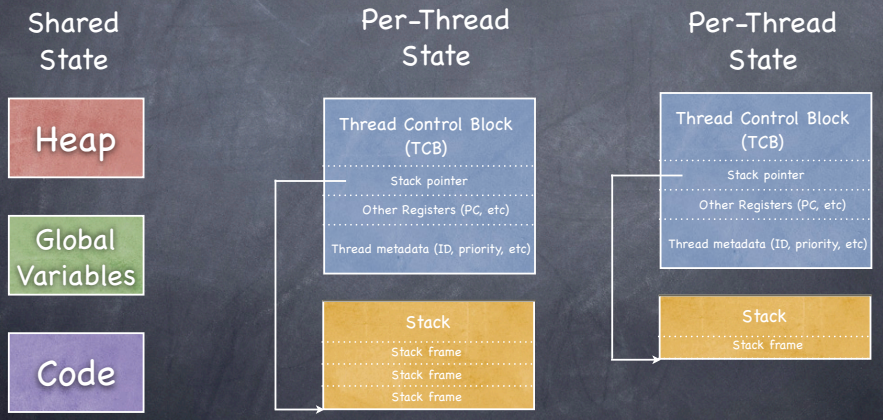
`void sthread_create(thread, func, arg)`
- creates a new thread in `thread`, which will execute function `func` with arguments `arg`

`void sthread_yield()`
- calling thread gives up the processor

`sthread_join(thread)`
- wait for `thread` to finish, then return the value `thread` passed to `sthread_exit`.

`sthread_exit(ret)`
- finish caller; store `ret` in caller's TCB and wake up any thread that invoked `sthread_join(caller)`

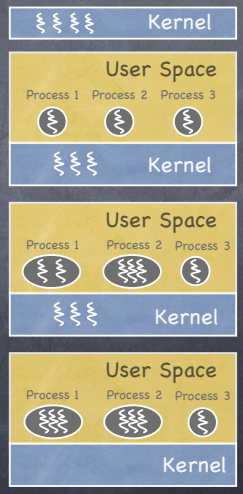
Implementing the thread abstraction: the state



Note: No protection enforced at the thread level!

One abstraction, many flavors

- In-kernel threads
- Single-threaded processes
  - add protection
- Multi-threaded processes with kernel supported thread
  - thread management through procedure calls & system calls
  - TCBs & PCBs on in kernel ready list
- User-level threads
  - thread management through procedure calls
  - TCBs in user space ready list



Threads Life Cycle

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

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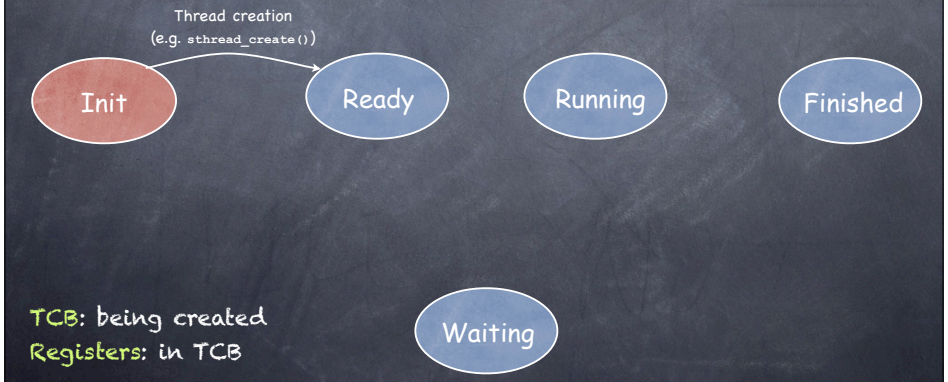

TCB: being created
Registers: in TCB

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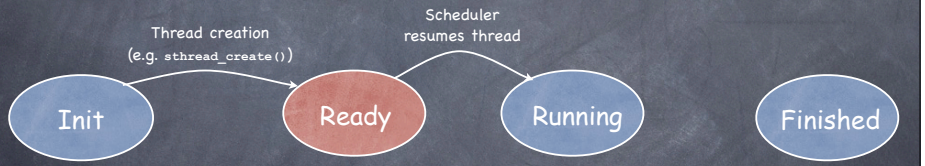

TCB: Ready list
Registers: in TCB

Waiting

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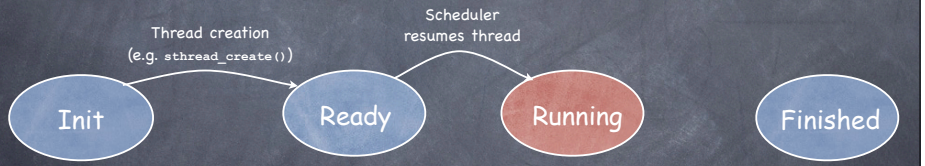

TCB: Running list
Registers: Processor

Waiting

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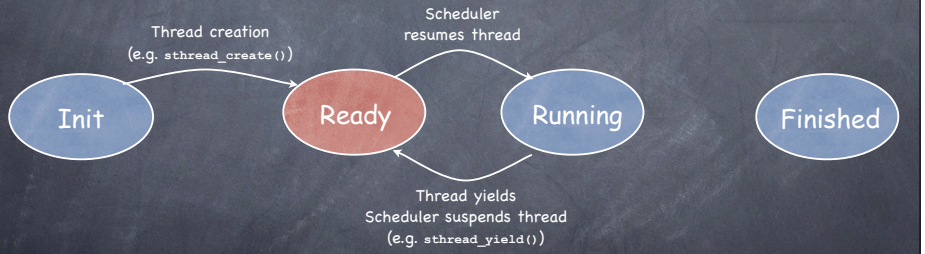

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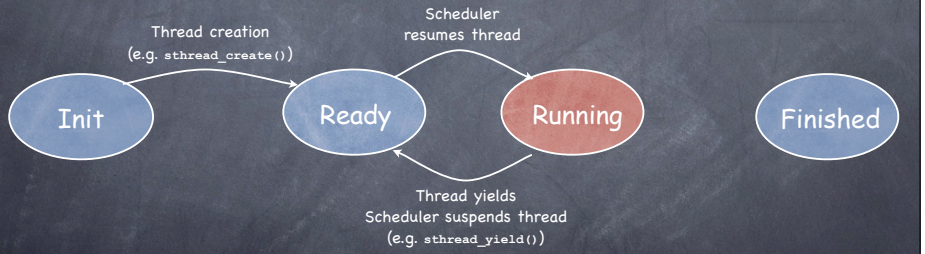

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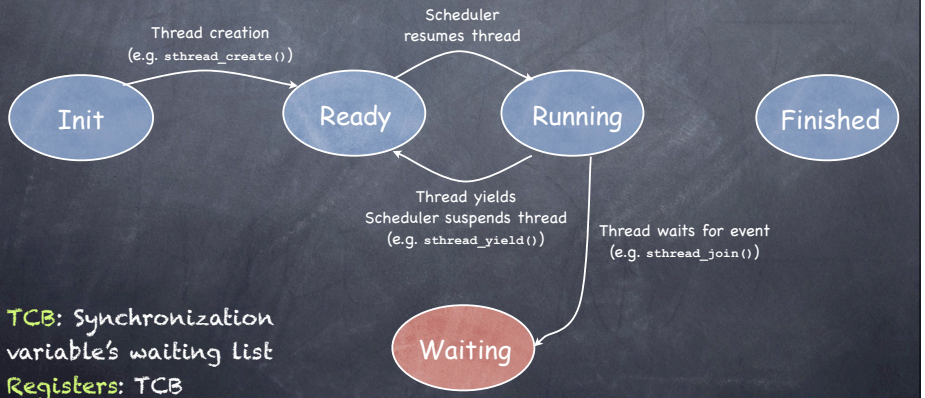

TCB: Synchronization variable's waiting list
Registers: TCB

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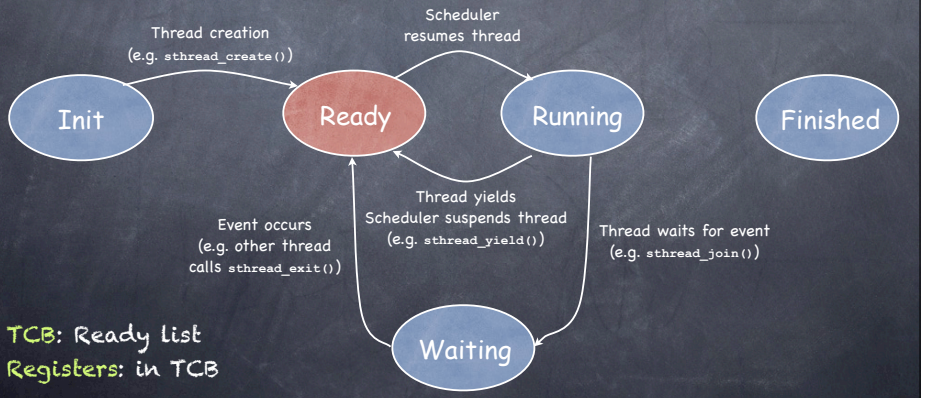

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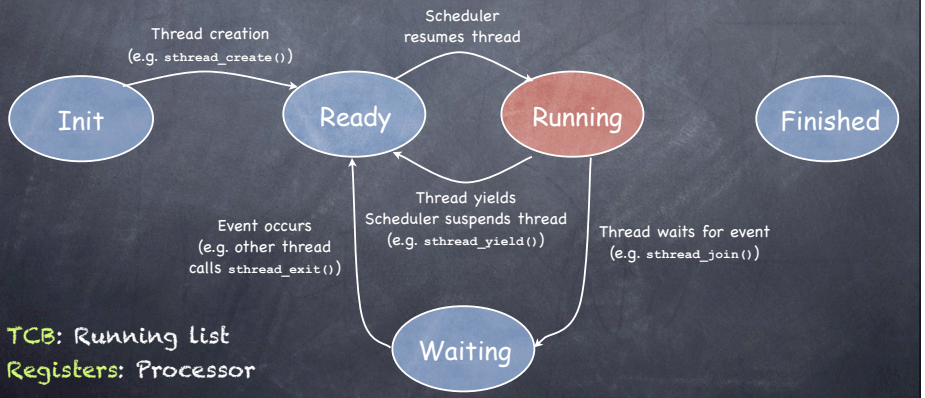

TCB: Running list
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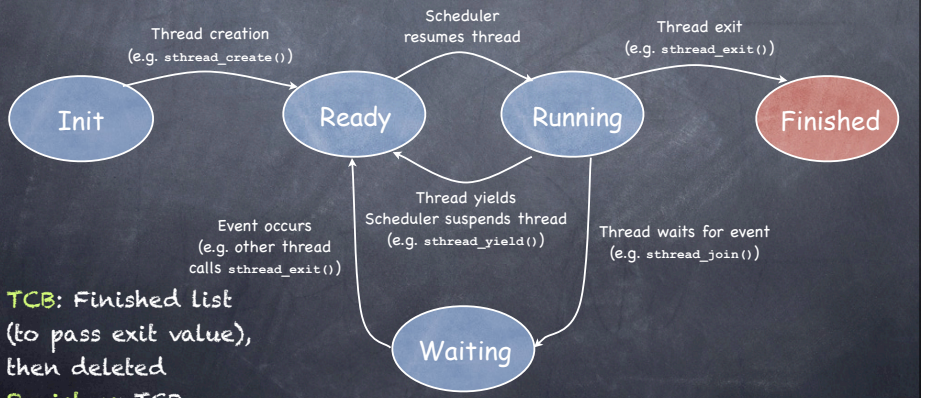

TCB: Finished list (to pass exit value), then deleted
Registers: TCB

Context switching in-kernel threads

- You know the drill:
  - Thread is running
  - Switch to kernel
  - Save thread state (to TCB)
  - Choose new thread to run
  - Load its state (from TCB)
  - Thread is running

Context switching in-kernel threads

- You know the drill:
  - Thread is running
  - Switch to kernel
  - Save thread state (to TCB)
  - Choose new thread to run { Policy decision left to the scheduler
  - Load its state (from TCB)
  - Thread is running

What triggers a context switch?

- Internal events
  - system call
    - thread blocks for I/O
    - synchronization: thread wait for another thread to do something
    - thread explicitly gives up CPU (`sthread_yield()`)
  - exception
- External events
  - interrupt
    - I/O (type character, disk request finishes,...)
    - timer interrupt

One story, two perspectives

System calls: one story, two perspectives

In-kernel thread's viewpoint

Thread 1

```
while (true) {
  sthread_yield()
}
```

Thread 2

```
while (true) {
  sthread_yield()
}
```

System calls: one story, two perspectives

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System calls: one story, two perspectives

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while (true) {
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}
```

Thread 2

```
while (true) {
  sthread_yield()
}
```

```
call sthread_yield()
save state to stack
save state to TCB
choose to run T2
load T2's state
```

1. change SP to T2's
2. pop T2's general purpose registers
3. pop IP and execution flags

System calls: one story, two perspectives

In-kernel thread's viewpoint

Thread 1

```
while (true) {
  sthread_yield()
}
```

Thread 2

```
while (true) {
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```
call sthread_yield()
save state to stack
save state to TCB
choose to run T2
load T2's state
```

```
call sthread_yield()
save state to stack
save state to TCB
choose to run T1
load T1's state
```

System calls: one story, two perspectives

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```
while (true) {
  sthread_yield()
}
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Thread 2

```
while (true) {
  sthread_yield()
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```

In-kernel thread's viewpoint

```
call sthread_yield()
save state to stack
save state to TCB
choose to run T2
load T2's state

                    call sthread_yield()
                    save state to stack
                    save state to TCB
                    choose to run T1
                    load T1's state

return sthread_yield()
call sthread_yield
save state to stack
save state to TCB
choose to run T2
load T2's state
```


System calls: one story, two perspectives

Thread 1

```
while (true) {
  sthread_yield()
}
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Thread 2

```
while (true) {
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In-kernel thread's viewpoint


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call sthread_yield()
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return sthread_yield()
call sthread_yield
save state to stack
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choose to run T2
load T2's state

                    return sthread_yield()
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                    choose to run T1
                    load T1's state
```


System calls: one story, two perspectives

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while (true) {
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while (true) {
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```

In-kernel thread's viewpoint


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return sthread_yield()
call sthread_yield
save state to stack
save state to TCB
choose to run T2
load T2's state

                    return sthread_yield()
                    call sthread_yield
                    save state to stack
                    save state to TCB
                    choose to run T1
                    load T1's state

return sthread_yield()
```


System calls: one story, two perspectives

Thread 1

```
while (true) {
  sthread_yield()
}
```

Thread 2

```
while (true) {
  sthread_yield()
}
```

In-kernel thread's viewpoint

Processor's viewpoint

```
call sthread_yield()
save state to stack
save state to TCB
choose to run T2
load T2's state

                    call sthread_yield()
                    save state to stack
                    save state to TCB
                    choose to run T1
                    load T1's state

return sthread_yield()
call sthread_yield
save state to stack
save state to TCB
choose to run T2
load T2's state

                    return sthread_yield()
                    call sthread_yield
                    save state to stack
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                    choose to run T1
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return sthread_yield()
```

```
call sthread_yield()
save state to stack
save state to TCB
choose to run T2
load T2's state
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load T2's state
return sthread_yield()
call sthread_yield
save state to stack
save state to TCB
choose to run T1
load T1s state
return sthread_yield()
```
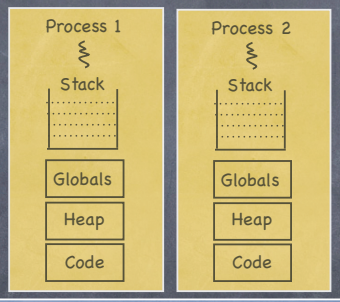

Multi-threaded kernel, single-threaded processes

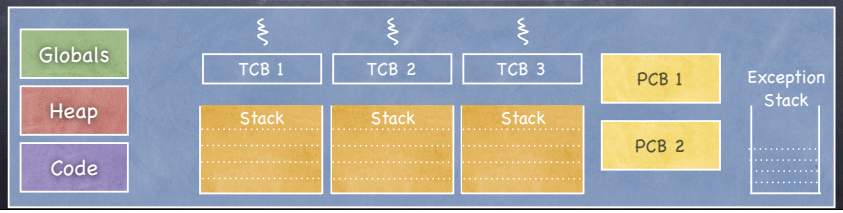
Per Process	Per Thread
Address space	Program counter
Global variables	Registers
Open Files	Stack
Child processes	State
Pending alarms	
Signals and their handlers	
Accounting info	



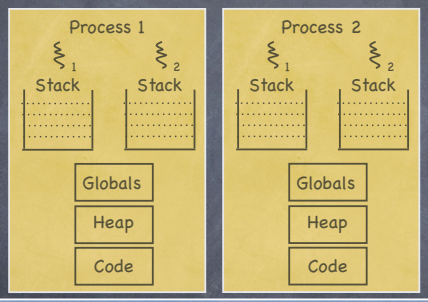
In-kernel ready list includes both TCBs and PCBs

Interrupts/exceptions
- hw & sw cooperate
  - ... but no need to save SP when within kernel

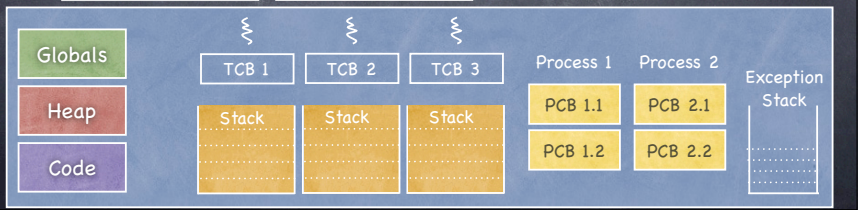
Library calls vs System calls
- in kernel, use simple procedure call
- in user mode, needs system call to access PCB in kernel



Multi-threaded kernel, multi-threaded processes



Process creates threads via system call
- thread's PCB in kernel
- stack in user space



User-level Threads

- No OS support
  - TCBs, ready list, finished list, waiting list — in user space
  - thread library calls are just procedure calls!
- Use upcalls to virtualize interrupts and exceptions
  - use system call to register a signal handler
  - on interrupt, save state of process P and run kernel handler; when done:
    - copy P's saved state in signal stack in P's address space
    - load state with PC = &signal_handler; SP -> state on stack
    - signal handler moves state from stack to TCB
    - restores state of some other TCB on ready list

Pros and Cons of User-level Threads

Pros

- Better than nothing!
  - use to be only game in town
- More portable
  - Java's green threads
- Low context switch cost

Cons

- OS is unaware of user-level threads
  - can't use for parallel processing
  - can't use to mask I/O latency

Processes and Threads

- The process abstraction combines two concepts
  - Concurrency: each process is a sequential execution stream of instructions
  - Protection: Each process defines an address space that identifies what can be touched by the program
- Threads
  - Key idea: decouple concurrency from protection
  - A thread represents a sequential execution stream of instructions
  - A process defines the address space that may be shared by multiple threads

Threads vs. Processes

Threads

- No data segment or heap
- Multiple can coexist in a process
- Share code, data, heap and I/O
- Have own stack and registers, but no isolation from other threads in the same process
- Inexpensive to create
- Inexpensive context switching

Processes

- Have data/code/heap and other segments
- Include at least one thread
- Have own address space, isolated from other processes'
- Expensive to create
- Expensive context switching

Concurrency is great …

```
int a = 1, b = 2;
main() {
    CreateThread(fn1, 4);
    CreateThread(fn2, 5);
}
fn1(int arg1) {
    if(a) b++;
}
fn2(int arg1) {
    a = arg1;
}
```

What are the value of a and b at the end of execution?

…but can be problematic

```
int a = 1, b = 2;
main() {
    CreateThread(fn1, 4);
    CreateThread(fn2, 5);
}
fn1(int arg1) {
    if(a) b++;
}
fn2(int arg1) {
    a = 0;
}
```

What are the values of a & b at the end of execution?

Some More Examples

- What are the possible values of x in these cases?

Thread1: x = 1;	Thread2: x = 2;

Initially y = 10;	
Thread1: x = y + 1;	Thread2: y = y * 2;

Initially x = 0;	
Thread1: x = x + 1;	Thread2: x = x + 2;

Everyone's a winner (?)

Thread A

```
i = 0;
while (i < 10) {
  i = i+1;
}
print "A wins"
```

Thread B

```
i = 0;
while (i > - 10) {
  i = i-1;
}
print "B wins"
```

- Who wins?
- Is a winner guaranteed?
- What if they proceed in lockstep?

This is because ...

- Order of process/thread execution is non-deterministic
  - A system may contain multiple processors and cooperating threads/ processes can execute simultaneously
  - Thread/process execution can be interleaved because of time-slicing
- Operations are often not atomic
  - An atomic operation is one that executes to completion without any interruption or failure---it is "all or nothing"
  - x := x+1 is not atomic
    - read x from memory into a register
    - increment register
    - store register back into memory
  - even loads and stores on 64 bit machines are not atomic
- Goal: Ensure correctness under ALL possible interleaving

We have a problem...

- Enumerating all cases is impractical
- We need to
  - define constructs to help with synchronization and coordination
  - develop a programming style that eases the construction of concurrent programs
    - restore modularity
  - more fundamentally, we need to know what we are talking about we we mention "synchronization" or "coordination"...