Virtualizing the CPU

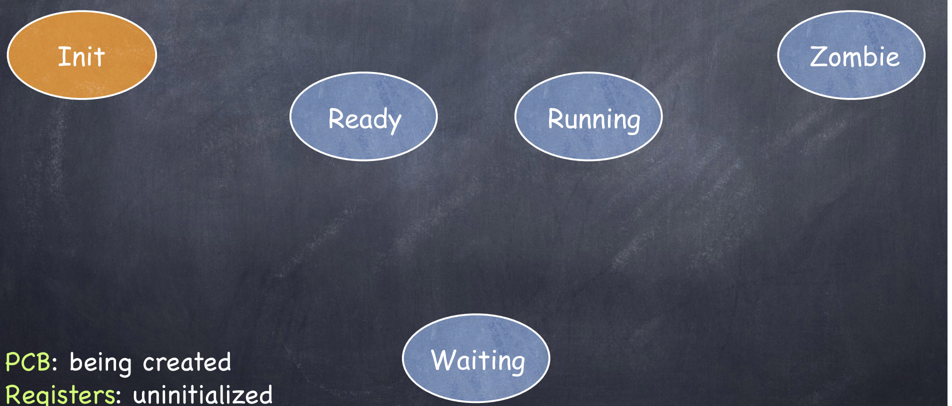
- OS keeps a PCB for each process
- It has space to hold a "frozen" version of the process's state
  - Program counter
  - Process status (ready, running, etc)
  - CPU registers
  - CPU scheduling info
  - Memory management info
  - Account info
  - I/O status info
- to be saved when the process relinquishes the CPU
- and reloaded when the process reacquires the CPU

Process Control Block

PC
Stack Ptr
Registers
PID
UID
Priority
List of open files
Process status
Kernel stack ptr
Location in Memory
Location of executable on disk
...

Process Life Cycle

Process Life Cycle

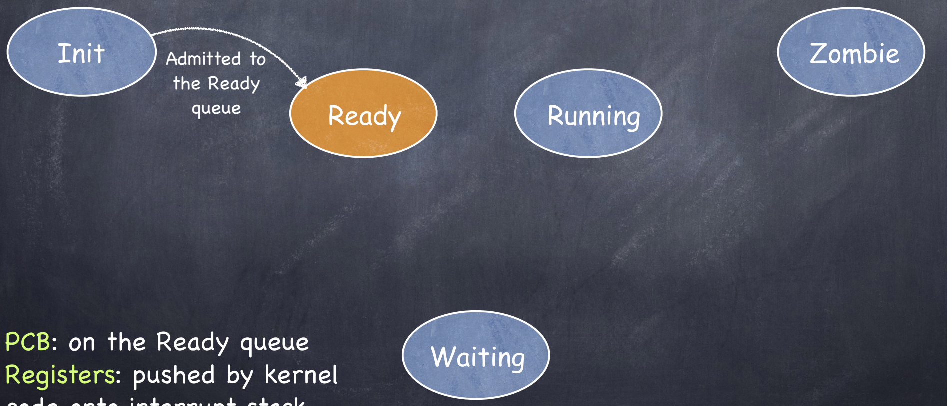


PCB: being created
Registers: uninitialized

Process Life Cycle

PCB: being created
Registers: uninitialized

Process Life Cycle

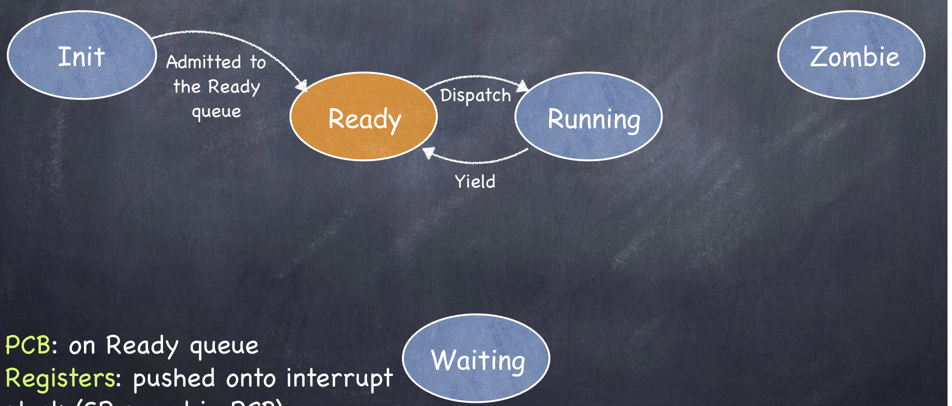


PCB: on the Ready queue
Registers: pushed by kernel code onto interrupt stack

Process Life Cycle

PCB: currently executing
Registers: popped from interrupt stack into CPU

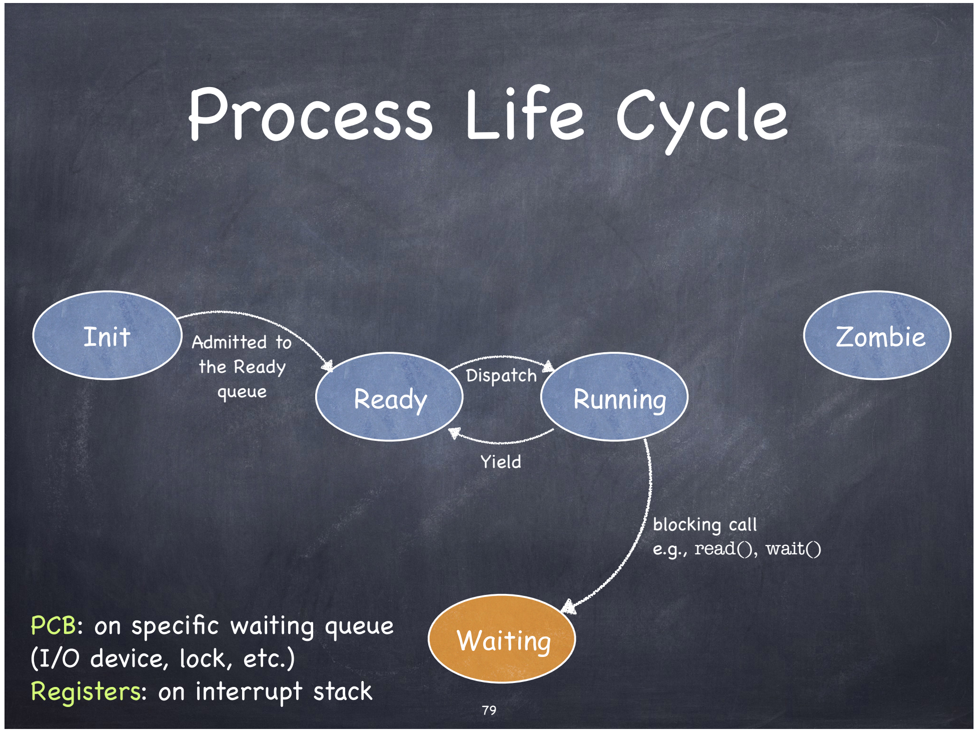
Process Life Cycle

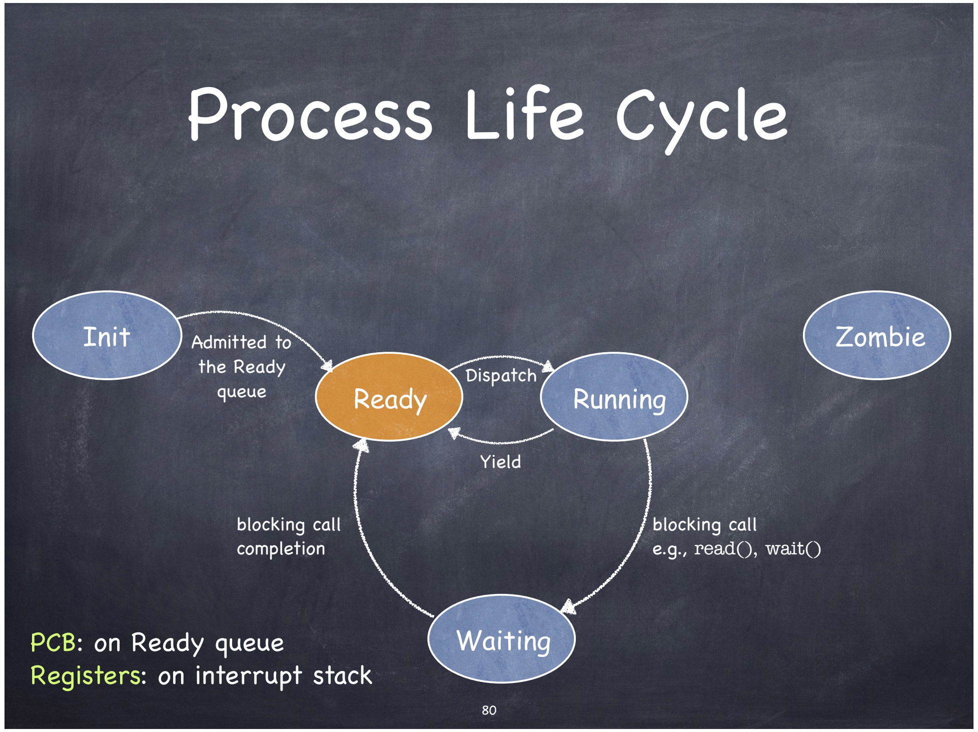


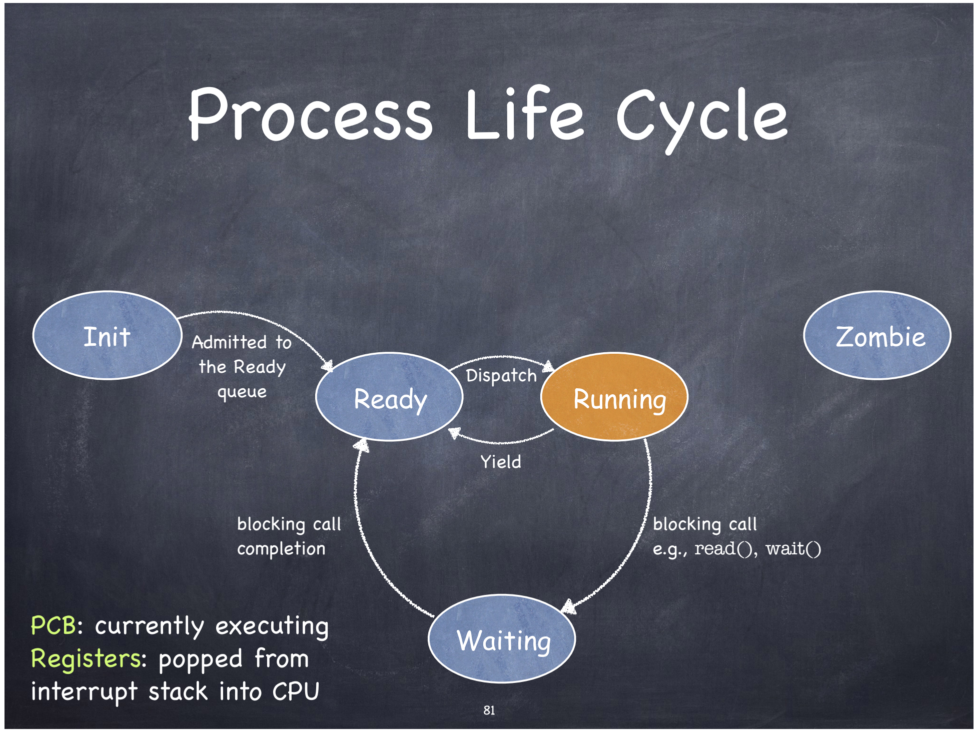
PCB: on Ready queue
Registers: pushed onto interrupt stack (SP saved in PCB)

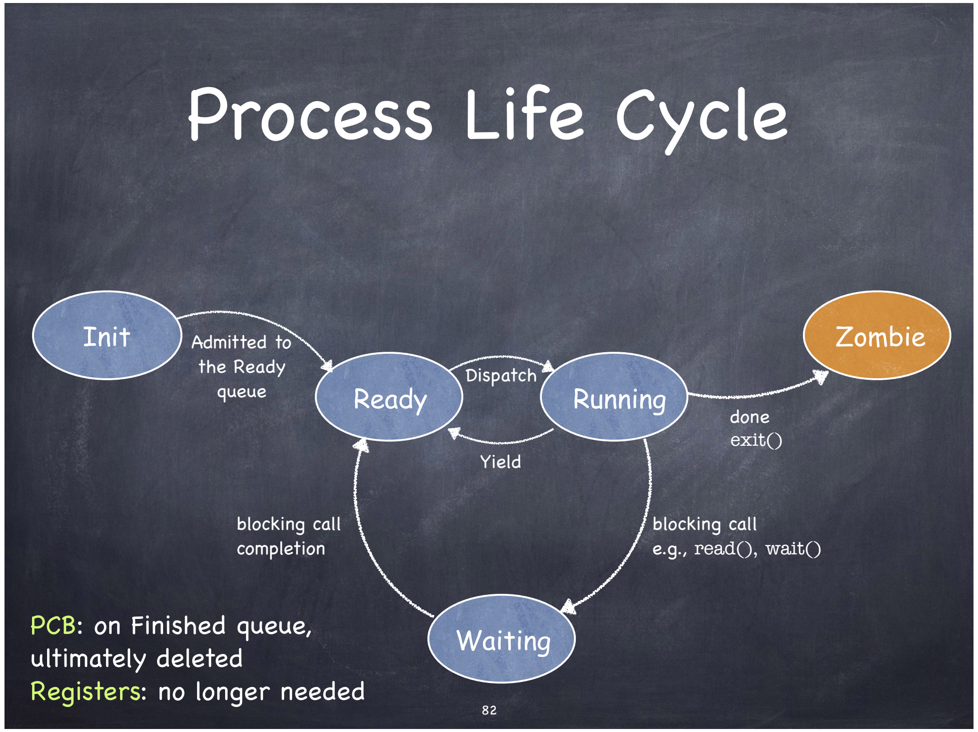
Process Life Cycle

PCB: currently executing
Registers: popped from interrupt stack into CPU


Process Life Cycle
Init
Admitted to the Ready queue
Ready
Dispatch
Running
Yield
Zombie
blocking call
e.g., read(), wait()
Waiting
PCB: on specific waiting queue (I/O device, lock, etc.)
Registers: on interrupt stack
79


Process Life Cycle
Init
Admitted to the Ready queue
Ready
Dispatch
Running
Yield
Zombie
blocking call completion
blocking call
e.g., read(), wait()
Waiting
PCB: on Ready queue
Registers: on interrupt stack
80


Process Life Cycle
Init
Admitted to the Ready queue
Ready
Dispatch
Running
Yield
Zombie
blocking call completion
blocking call
e.g., read(), wait()
Waiting
PCB: currently executing
Registers: popped from interrupt stack into CPU
81


Process Life Cycle
Init
Admitted to the Ready queue
Ready
Dispatch
Running
Yield
Zombie
done
exit()
blocking call completion
blocking call
e.g., read(), wait()
Waiting
PCB: on Finished queue, ultimately deleted
Registers: no longer needed
82

Invariants to keep in mind

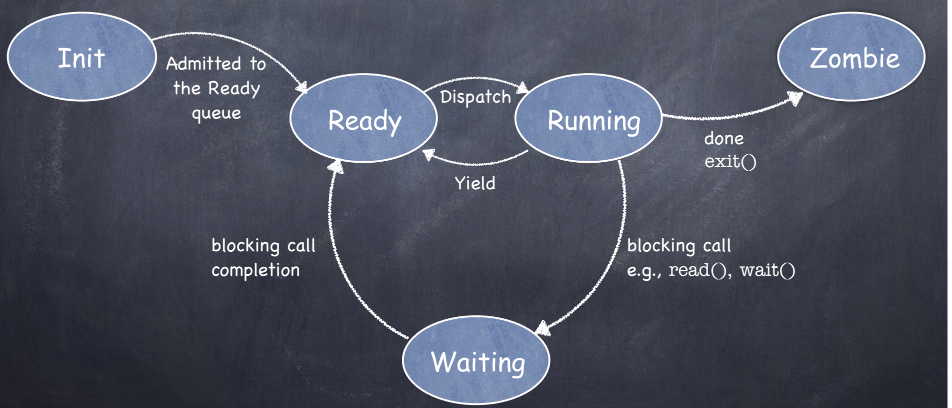
- At most one process/core running at any time
- When CPU in user mode, current process is RUNNING and its interrupt stack is empty
- If process is RUNNING
  - its PCB not on any queue
  - it is not necessarily in USER mode
- If process is RUNNABLE or WAITING
  - its registers are saved at the top of its interrupt stack
  - its PCB is either
    - on the READY queue (if RUNNABLE)
    - on some WAIT queue (if WAITING)
- If process is a ZOMBIE
  - its PCB is on FINISHED queue

Cleaning up Zombies

- Process cannot clean up itself (why?)
- Process can be cleaned up
  - by some other process, checking for zombies before returning to RUNNING state
  - or by parent which waits for it
    - but what if parent turns into a zombie first?
  - or by a dedicated "reaper" process

- Linux uses a combination
  - if alive, parent cleans up child that it is waiting for
  - if parent is dead, child process is inherited by the initial process, which is continually waiting

Process Life Cycle



How to Yield/Wait?

- Must switch from executing the current process to executing some other READY process
  - Current process: RUNNING → READY
  - Next process: READY → RUNNING

1. Save kernel registers of Current on its interrupt stack
2. Save kernel SP of Current in its PCB
3. Restore kernel SP of Next from its PCB
4. Restore kernel registers of Next from its interrupt stack

Yielding

```
ctx_switch: //ip already pushed
    pushq  %rbp
    pushq  %rbx
    pushq  %r15
    pushq  %r14
    pushq  %r13
    pushq  %r12
    pushq  %r11
    pushq  %r10
    pushq  %r9
    pushq  %r8
    movq   %rsp, (%rdi)
    movq   %rsi, %rsp
    popq   %rbp
    popq   %rbx
    popq   %r15
    popq   %r14
    popq   %r13
    popq   %r12
    popq   %r11
    popq   %r10
    popq   %r9
    popq   %r8
    retq
```

```
struct pcb *current, *next;

void yield(){
    assert(current->state == RUNNING);
    current->state = RUNNABLE;
    readyQueue.add(current);
    next = scheduler();
    next->state = RUNNING;
    ctx_switch(&current->sp, next->sp)
    current = next;
}
```

Starting a New Process

```
ctx_start:
    pushq  %rbp
    pushq  %rbx
    pushq  %r15
    pushq  %r14
    pushq  %r13
    pushq  %r12
    pushq  %r11
    pushq  %r10
    pushq  %r9
    pushq  %r8
    movq   %rsp, (%rdi)
    movq   %rsi, %rsp
    retq
```

```
void createProcess( func ){
    void *SP;
    current->state = READY;
    readyQueue.add(current);
    struct pcb *next = malloc(...);
    next->func = func;
    next->state = RUNNING;
    SP = next->top_of_stack;
    *- - SP = PSW;
    * - - SP = USP;
    * - - SP = UPC;
    ctx_start(&current->sp, SP)
}
```

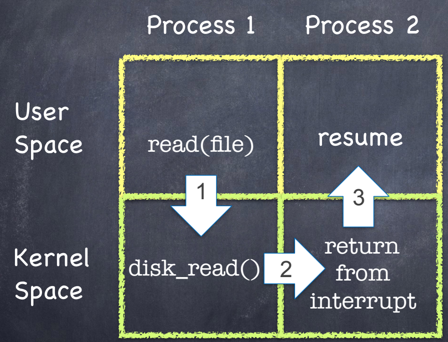
Anybody there?

- What if no process is READY?
  - scheduler() would return NULL — aargh!
- No panic on the Titanic:
  - OS always runs a low priority process, in an infinite loop executing the HLT instruction
    - halts CPU until next interrupt
  - Interrupt handler executes yield() if some other process is put on the Ready queue

Three Flavors of Context Switching

- Interrupt: from user to kernel space
  - on system call, exception, or interrupt
  - Px user stack → Px interrupt stack
- Yield: between two processes, inside kernel
  - from one PCB/interrupt stack to another
  - Px interrupt stack → Py interrupt stack
- Return from interrupt: from kernel to user space
  - with the homonymous instruction
  - Px interrupt stack → Px user stack

Switching between Processes



1. Save Process 1 user registers
2. Save Process 1 kernel registers and restore Process 2 kernel registers
3. Restore Process 2 user registers

System Calls to Create a New Process

- Windows
  - CreateProcess(...);
- Unix (Linux)
  - fork() + exec(...)

CreateProcess (Simplified)

```
if (!CreateProcess(
    NULL,          // No module name (use command line)
    argv[1],       // Command line
    NULL,          // Process handle not inheritable
    NULL,          // Thread handle not inheritable
    FALSE,         // Set handle inheritance to FALSE
    0,             // No creation flags
    NULL,          // Use parent's environment block
    NULL,          // Use parent's starting directory
    &si,           // Pointer to STARTUPINFO structure
    &pi )          // Ptr to PROCESS_INFORMATION structure
)
```

[Windows]

fork (actual form)

process identifier

```
int pid = fork();
```

..but needs exec(...)

[Unix]

Kernel Actions to Create a Process

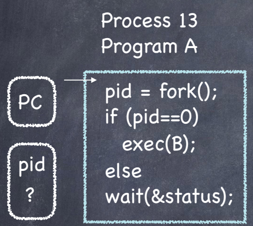
- fork()
  - allocate ProcessID
  - initialize PCB
  - create and initialize new address space
  - inform scheduler new process is READY
- exec(program, arguments)
  - load program into address space
  - copy arguments into address space's memory
  - initialize h/w context to start execution at ``start"
- CreateProcess(...) does both

Creating and managing processes

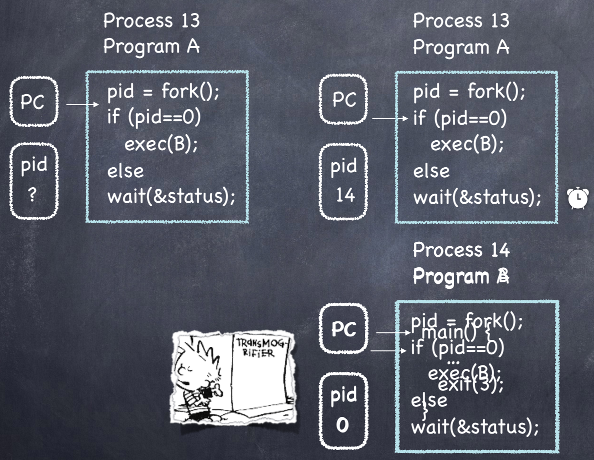
Syscall	Description
fork()	Create a child process as a clone of the current process. Return to both parent and child. Return child's pid to parent process; return 0 to child
exec (prog, args)	Run application prog in the current process with the specified args (replacing any code and data that was present in process)
wait (&status)	Pause until a child process has exited
exit (status)	Tell kernel current process is complete and its data structures (stack, heap, code) should be garbage collected. May keep PCB.
kill (pid, type)	Send an interrupt of a specified type to a process (a bit of an overdramatic misnomer...)

[Unix]

In action



In action



In action

Process 13
Program A

PC

pid
?

```
pid = fork();
if (pid==0)
  exec(B);
else
wait(&status);
```

Process 13
Program A

PC

pid
14

```
pid = fork();
if (pid==0)
  exec(B);
else
wait(&status);
```

Status
3

Process 14
Program B

PC

```
main() {
  ...
  exit(3);
}
```