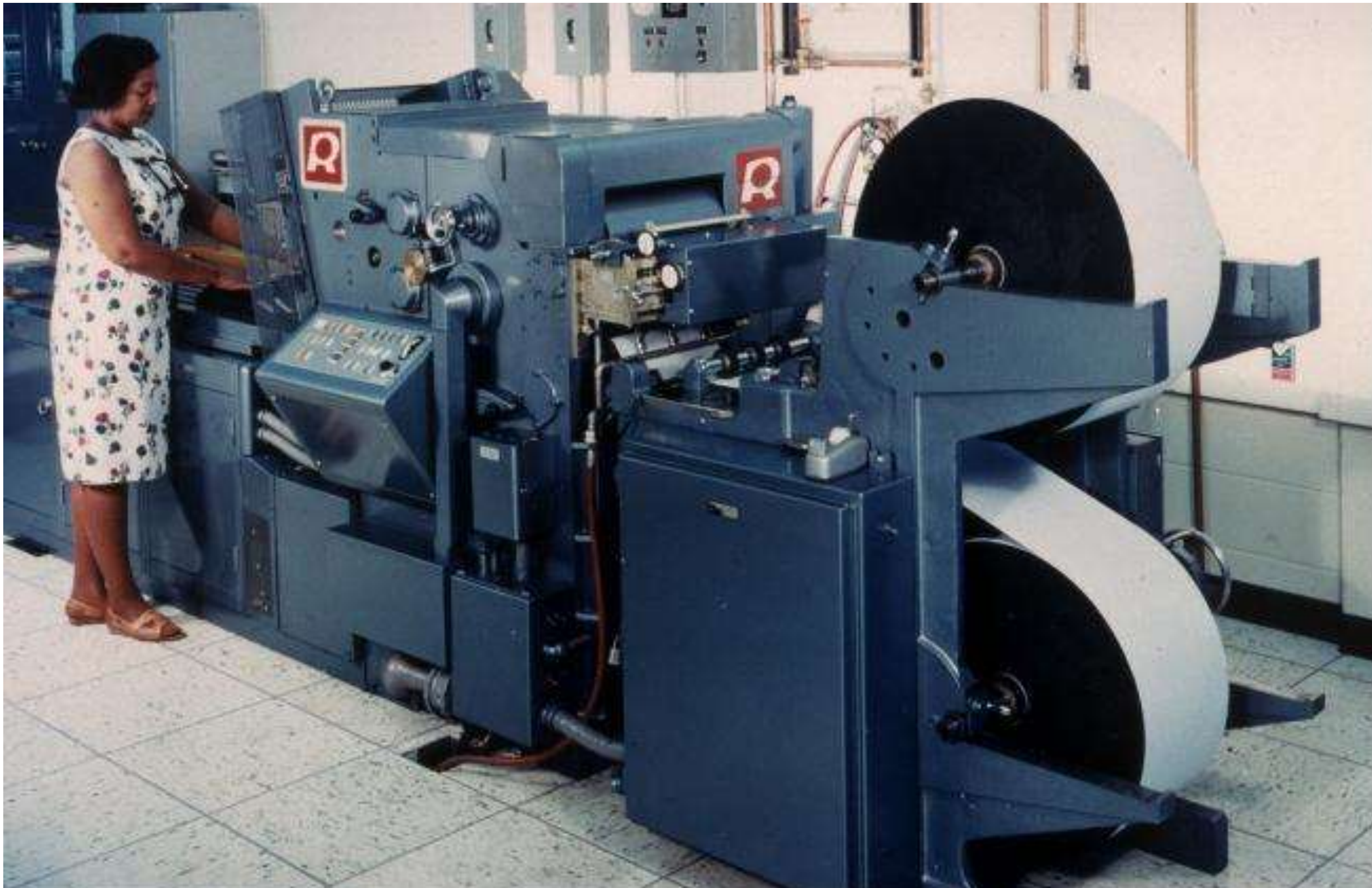
第8章 异常控制流
异常和进程 Exceptions and Processes

100076202： 计算机系统导论

任课教师：
宿红毅　　张艳　　　黎有琦　　　颜珂

原作者：
Randal E. **Bryant and** David R. O’Hallaron

打印机过去常常着火
Printers Used to Catch on Fire



高度异常控制流
Highly Exceptional Control Flow

```c
static int lp_check_status(int minor)
{
	int error = 0;
	unsigned int last = lp_table[minor].last_error;
	unsigned char status = r_str(minor);
	if ((status & LP_PERRORP) && !(LP_F(minor) & LP_CAREFUL))
		/* No error. */
		last = 0;
	else if ((status & LP_POUTPA)) {
		if (last != LP_POUTPA) {
			last = LP_POUTPA;
			printk(KERN_INFO "lp%d out of paper\n", minor);
		}
		error = -ENOSPC;
	} else if (!(status & LP_PSELECD)) {
		if (last != LP_PSELECD) {
			last = LP_PSELECD;
			printk(KERN_INFO "lp%d off-line\n", minor);
		}
		error = -EIO;
	} else if (!(status & LP_PERRORP)) {
		if (last != LP_PERRORP) {
			last = LP_PERRORP;
			printk(KERN_INFO "lp%d on fire\n", minor);
		}
		error = -EIO;
	} else {
		last = 0; /* Come here if LP_CAREFUL is set and no
		             errors are reported. */
	}

	lp_table[minor].last_error = last;

	if (last != 0)
		lp_error(minor);

	return error;
}
```

https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/drivers/char/lp.c?h=v5.0-rc3

内容提纲

- 异常控制流 Exceptional Control Flow CSAPP 8
- 异常 Exceptions CSAPP 8.1
- 进程 Processes CSAPP 8.2
- 进程控制 Process Control CSAPP 8.3-8.4

控制流 Control Flow

- **处理器只做一件事 Processors do only one thing:**
  - 从开机到关机，每个CPU核只是读入和执行（解释）指令序列，每次一条 From startup to shutdown, each CPU core simply reads and executes (interprets) a sequence of instructions, one at a time *
  - 这个序列就是CPU的*控制流* This sequence is the CPU's *control flow* (or *flow of control*)

物理控制流 Physical control flow

Time

<startup> //开机
inst$_1$
inst$_2$
inst$_3$
…
inst$_n$
<shutdown> //关机

*从外部体系结构视角看（内部来看，CPU可以使用并行乱序执行）
* Externally, from an architectural viewpoint (internally, the CPU may use parallel out-of-order execution)

改变控制流 Altering the Control Flow

- **目前：两种改变控制流的机制：Up to now: two mechanisms for changing control flow:**
  - 跳转分支指令 Jumps and branches
  - 调用和返回指令 Call and return

  反应*程序状态*的变化 React to changes in ***program state***
- **对有用的系统来说还不够： Insufficient for a useful system: 难以反应*系统状态*的改变 Difficult to react to changes in *system state***
  - 从磁盘或者网络适配器获取的数据到达 Data arrives from a disk or a network adapter
  - 指令除零 Instruction divides by zero
  - 用户键盘按下了Ctrl-C User hits Ctrl-C at the keyboard
  - 系统定时器超时 System timer expires
- **系统需要“异常控制流”处理机制 System needs mechanisms for “exceptional control flow”**

异常控制流 Exceptional Control Flow

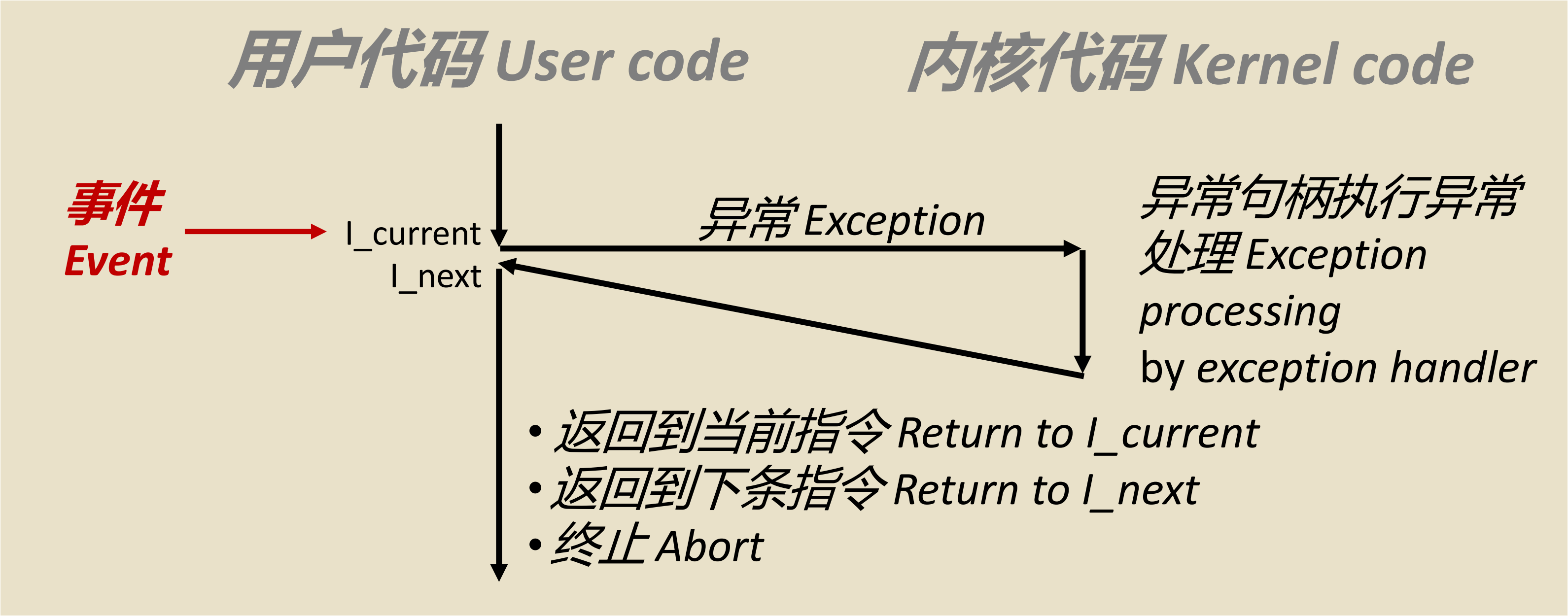
- **存在计算机系统的每个层次 Exists at all levels of a computer system**
- **低层次机制 Low level mechanisms**
  - 1.异常 **Exceptions**
    - 为响应系统事件改变控制流（例如系统状态改变） Change in control flow in response to a system event (i.e., change in system state)
    - 硬件和OS软件组合实现 Implemented using combination of hardware and OS software
- **高层次机制 Higher level mechanisms**
  - 2. 进程上下文切换 **Process context switch**
    - 硬件定时器和OS软件实现 Implemented by OS software and hardware timer
  - 3. 信号 **Signals**
    - OS软件实现 Implemented by OS software
  - 4. 非局部跳转 **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - C运行时库实现 Implemented by C runtime library

内容提纲

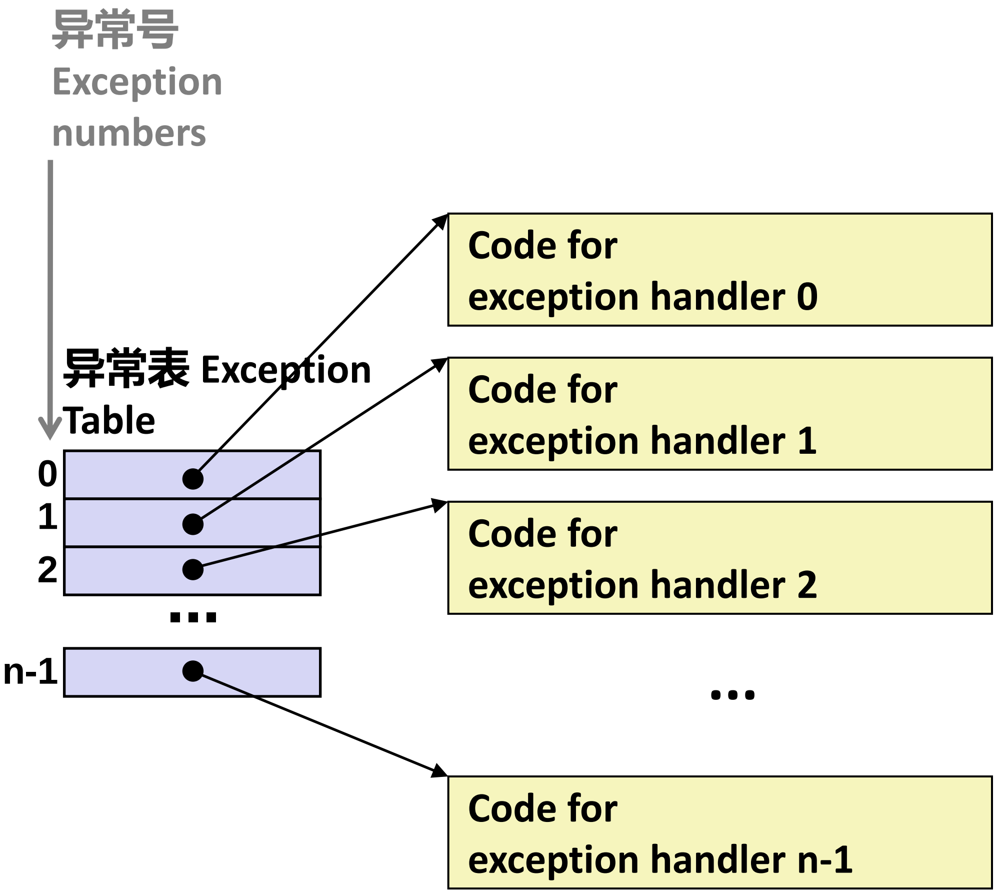
- 异常控制流 Exceptional Control Flow
- **异常 Exceptions**
- 进程 Processes
- 进程控制 Process Control

异常 Exceptions

- **异常是为了响应某些事件（即处理器状态改变）而将控制流转移到OS内核 An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)**
  - 内核是操作系统的内存驻留 Kernel is the memory-resident part of the OS
  - 事件举例：除零，算术溢出，缺页，I/O请求完成，键入Ctrl+C Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C

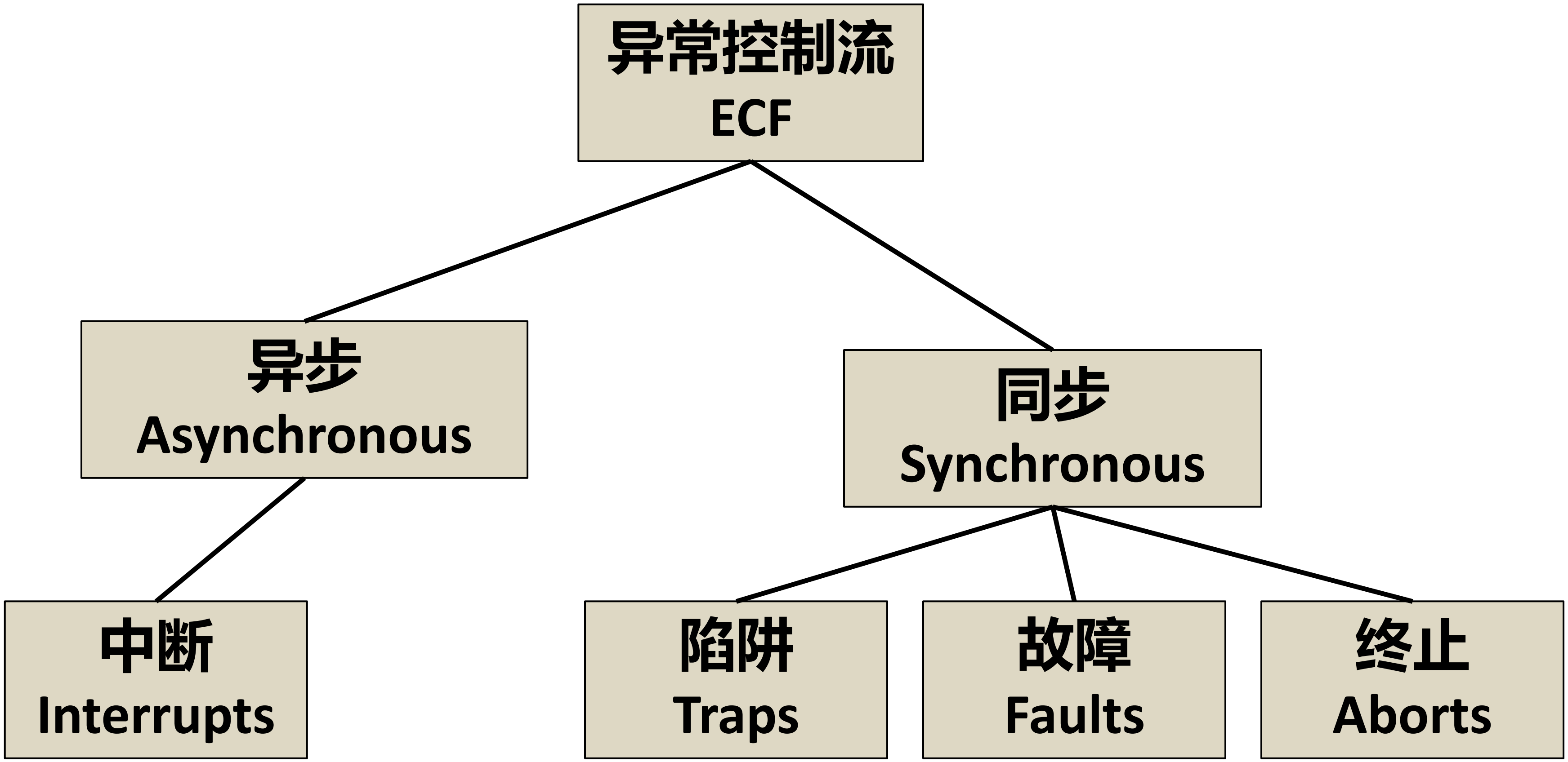


异常表格 Exception Tables



- 每个事件类型有惟一的异常编号k Each type of event has a unique exception number k
- 用k做为异常表的索引（即中断向量） k = index into exception table (a.k.a. interrupt vector)
- 每次发生异常k时，就会调用句柄k（句柄就是异常处理程序指针） Handler k is called each time exception k occurs

（部分）分类 (partial) Taxonomy



异步异常（中断）
Asynchronous Exceptions (Interrupts)

- **由处理器外部事件引起 Caused by events external to the processor**
  - 通过处理器的中断管脚设置指示有中断请求 Indicated by setting the processor’s *interrupt pin*
  - 中断处理程序返回后执行下一条指令 Handler returns to “next” instruction
- **举例 Examples:**
  - 时钟中断 Timer interrupt
    - 每隔大约几ms，外部时钟芯片触发一个中断 Every few ms, an external timer chip triggers an interrupt
    - 将控制权从用户程序切换到内核 Used by the kernel to take back control from user programs
  - 外部设备的I/O中断 I/O interrupt from external device
    - 键盘键入Ctrl-C Hitting Ctrl-C at the keyboard
    - 网络有一个包抵达 Arrival of a packet from a network
    - 从磁盘有数据抵达 Arrival of data from a disk

同步异常 Synchronous Exceptions

- **指令执行结果导致的异常事件 Caused by events that occur as a result of executing an instruction:**
  - ***陷入/陷阱 Traps***
    - 人为的 Intentional
    - 例如：**系统调用**、断点、特殊指令等 Examples: ***system calls***, breakpoint traps, special instructions
    - 控制流返回到下一条指令 Returns control to “next” instruction
  - ***故障 Faults***
    - 不是有意的但是大概率可恢复 Unintentional but possibly recoverable
    - 例如：缺页异常（可恢复）、保护异常（不可恢复）、浮点异常 Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - 重新执行故障（“当前”）指令或者终止执行 Either re-executes faulting (“current”) instruction or aborts
  - ***终止 Aborts***
    - 非故意且不可恢复 Unintentional and unrecoverable
    - 例如：非法指令、校验错、机器检查 Examples: illegal instruction, parity error, machine check
    - 终止当前程序执行 Aborts current program

系统功能调用 System Calls

- 每个x86-64系统调用都有一个唯一的ID编号 Each x86-64 system call has a unique ID number
- 例如： Examples:

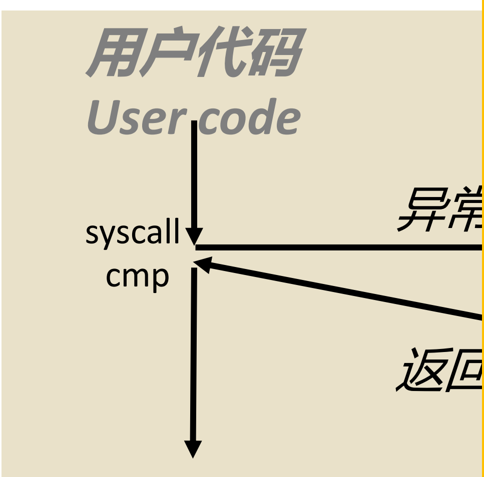
编号 Number	名字 Name	描述 Description
0	`read`	读文件 Read file
1	`write`	写文件 Write file
2	`open`	打开文件 Open file
3	`close`	关闭文件 Close file
4	`stat`	获取有关文件的信息 Get info about file
57	`fork`	创建进程 Create process
59	`execve`	执行一个程序 Execute a program
60	`_exit`	终止进程 Terminate process
62	`kill`	发送信号给进程 Send signal to process

系统调用举例：打开文件

System Call Ex

- 用户调用：open
- 调用__open函数，
  function, which in

```
00000000000e5d70 <__
...
e5d79:   b8 02 00 00 00
e5d7e:   0f 05             sys
e5d80:   48 3d 01 f0 ff ff
...
e5dfa:   c3                retq
```



几乎和函数调用类似 Almost like a function call

- **转换控制 Transfer of control**
- **返回时执行下条指令 On return, executes next instruction**
- **使用调用规则传递参数 Passes arguments using calling convention**
- **返回值在%rax中 Gets result in `%rax`**

一个重要的差异 One Important exception!

- **由内核执行 Executed by Kernel**
- **不同的优先权 Different set of privileges**
- **以及其它不同：And other differences:**
  - **例如："函数"的"地址"是在%rax中 E.g., "address" of "function" is in `%rax`**
  - **使用错误号 Uses `errno`**
  - **等 Etc.**

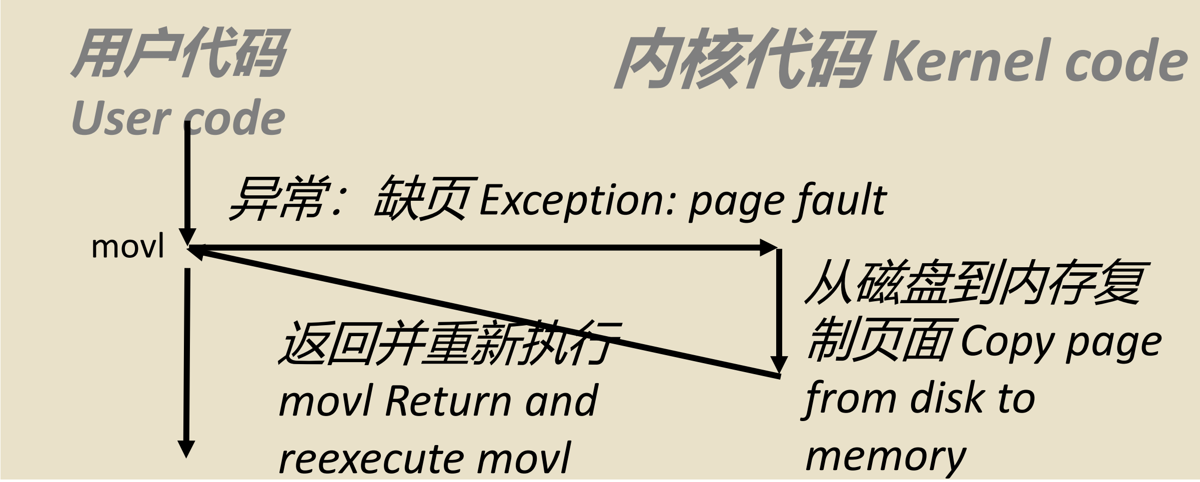
negative `errno`

故障举例：缺页异常 Fault Example: Page Fault

- 用户写内存 User writes to memory location
- 对应的页面在磁盘上 That portion (page) of user’s memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

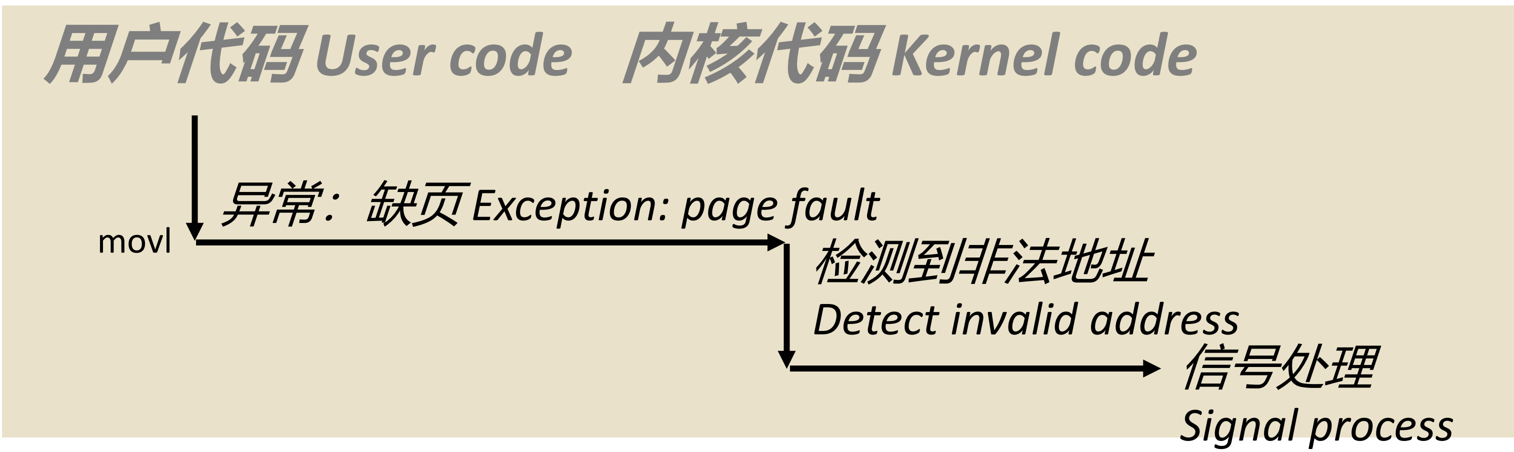
```
80483b7:        c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



故障举例：非法内存引用
Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7:        c7 05 60 e3 04 08 0d    movl    $0xd,0x804e360
```



- 发送SIGSEGV信号给用户进程 Sends **SIGSEGV** signal to user process
- 用户进程会"段错误"异常退出 User process exits with "segmentation fault"

内容提纲

- 异常控制流 Exceptional Control Flow
- 异常 Exceptions
- 进程 Processes
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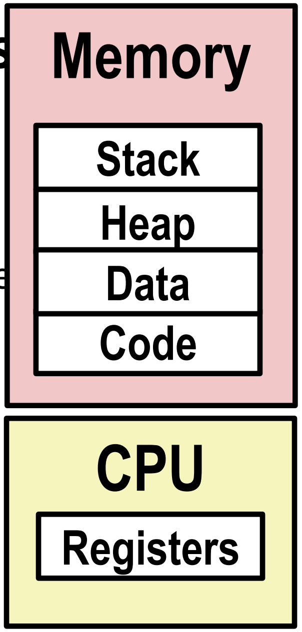
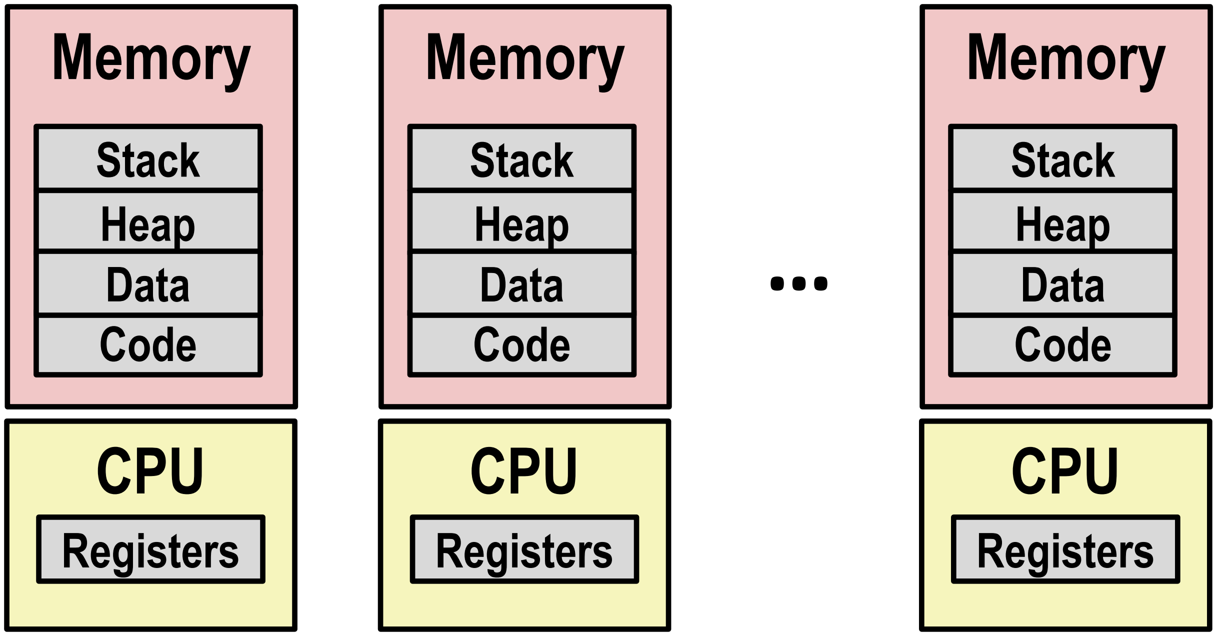
进程 Processes

- **定义：进程是程序的一次执行(运行程序的实例)**
  Definition: A *process* is an instance of a running program.
  - 计算机科学最重要的概念之一 One of the most profound ideas in computer science
  - 与“程序”或“处理器”不同 Not the same as “program” or “processor”
- **进程为每个程序提供了两个关键抽象 Process provides each program with two key abstractions:**
  - ***逻辑控制流 Logical control flow***
    - 每个程序看起来独占CPU Each program seems to have exclusive use of the CPU
    - 内核支持的上下文切换 Provided by kernel mechanism called *context switching*
  - ***私有地址空间Private address space***
    - 每个程序看起来独占主存空间 Each program seems to have exclusive use of main memory.
    - 内核支持的虚拟内存 Provided by kernel mechanism called *virtual memory*



多进程幻象： Multiprocessing: The Illusion



- **计算机同时运行很多进程 Computer runs many processes simultaneously**
  - 单个或多个用户的应用 Applications for one or more users
    - Web浏览器、邮件客户、编辑器。。。 Web browsers, email clients, editors, …
  - 后台任务 Background tasks
    - 监视网络和I/O设备 Monitoring network & I/O devices

多进程举例 Multiprocessing Example

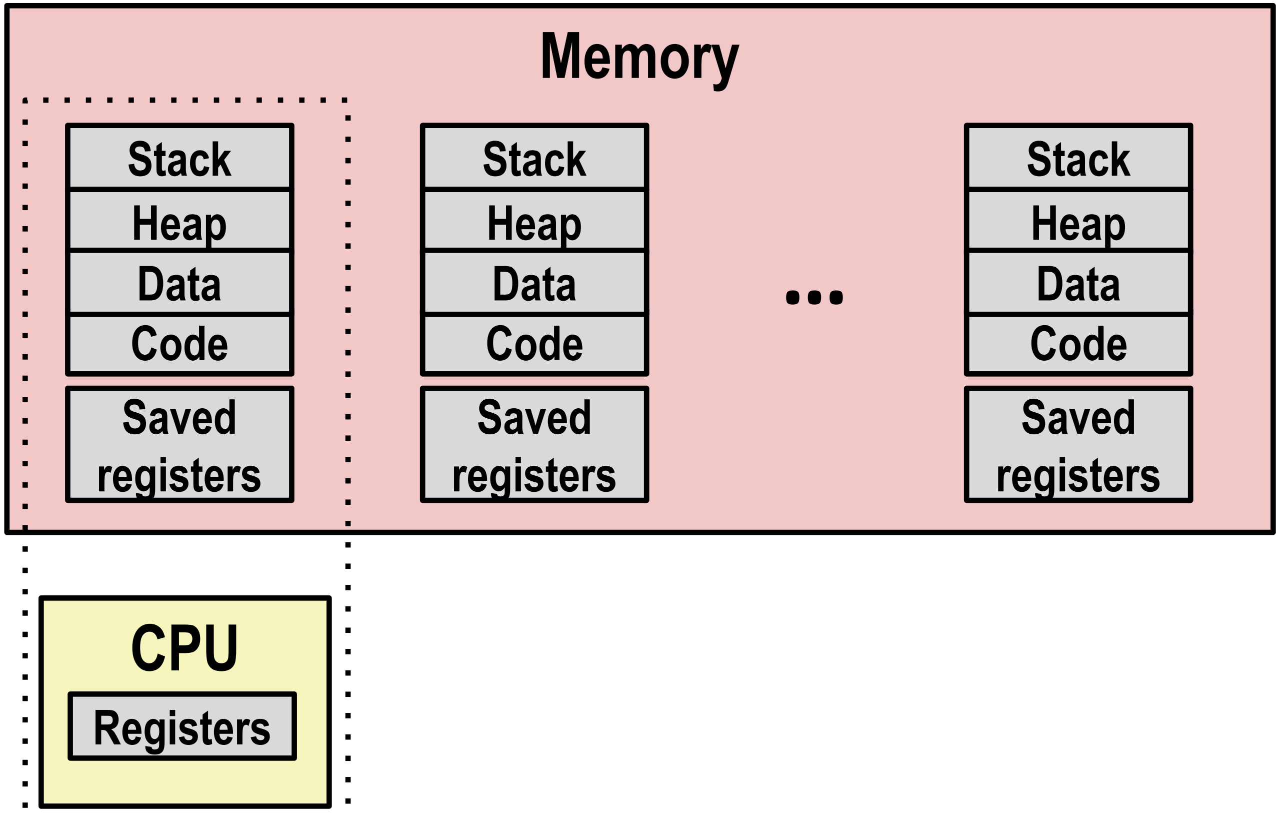
xterm

```
Processes: 123 total, 5 running, 9 stuck, 109 sleeping, 611 threads          11:47:07
Load Avg: 1.03, 1.13, 1.14  CPU usage: 3.27% user, 5.15% sys, 91.56% idle
SharedLibs: 576K resident, 0B data, 0B linkedit.
MemRegions: 27958 total, 1127M resident, 35M private, 494M shared.
PhysMem: 1039M wired, 1974M active, 1062M inactive, 4076M used, 18M free.
VM: 280G vsize, 1091M framework vsize, 23075213(1) pageins, 5843367(0) pageouts.
Networks: packets: 41046228/11G in, 66083096/77G out.
Disks: 17874391/349G read, 12847373/594G written.

PID    COMMAND      %CPU TIME     #TH  #WQ  #PORT #MREG RPRVT  RSHRD  RSIZE  VPRVT  VSIZE
99217- Microsoft Of 0.0  02:28.34 4    1    202   418   21M    24M    21M    66M    763M
99051  usbmuxd      0.0  00:04.10 3    1    47    66    436K   216K   480K   60M    2422M
99006  iTunesHelper 0.0  00:01.23 2    1    55    78    728K   3124K  1124K  43M    2429M
84286  bash         0.0  00:00.11 1    0    20    24    224K   732K   484K   17M    2378M
84285  xterm        0.0  00:00.83 1    0    32    73    656K   872K   692K   9728K  2382M
55939- Microsoft Ex 0.3  21:58.97 10   3    360   954   16M    65M    46M    114M   1057M
54751  sleep        0.0  00:00.00 1    0    17    20    92K    212K   360K   9632K  2370M
54739  launchdadd   0.0  00:00.00 2    1    33    50    488K   220K   1736K  48M    2409M
54737  top          6.5  00:02.53 1/1  0    30    29    1416K  216K   2124K  17M    2378M
54719  automountd   0.0  00:00.02 7    1    53    64    860K   216K   2184K  53M    2413M
54701  ocspd        0.0  00:00.05 4    1    61    54    1268K  2644K  3132K  50M    2426M
54661  Grab         0.6  00:02.75 6    3    222+  389+  15M+   26M+   40M+   75M+   2556M+
54659  cookied      0.0  00:00.15 2    1    40    61    3316K  224K   4088K  42M    2411M
```

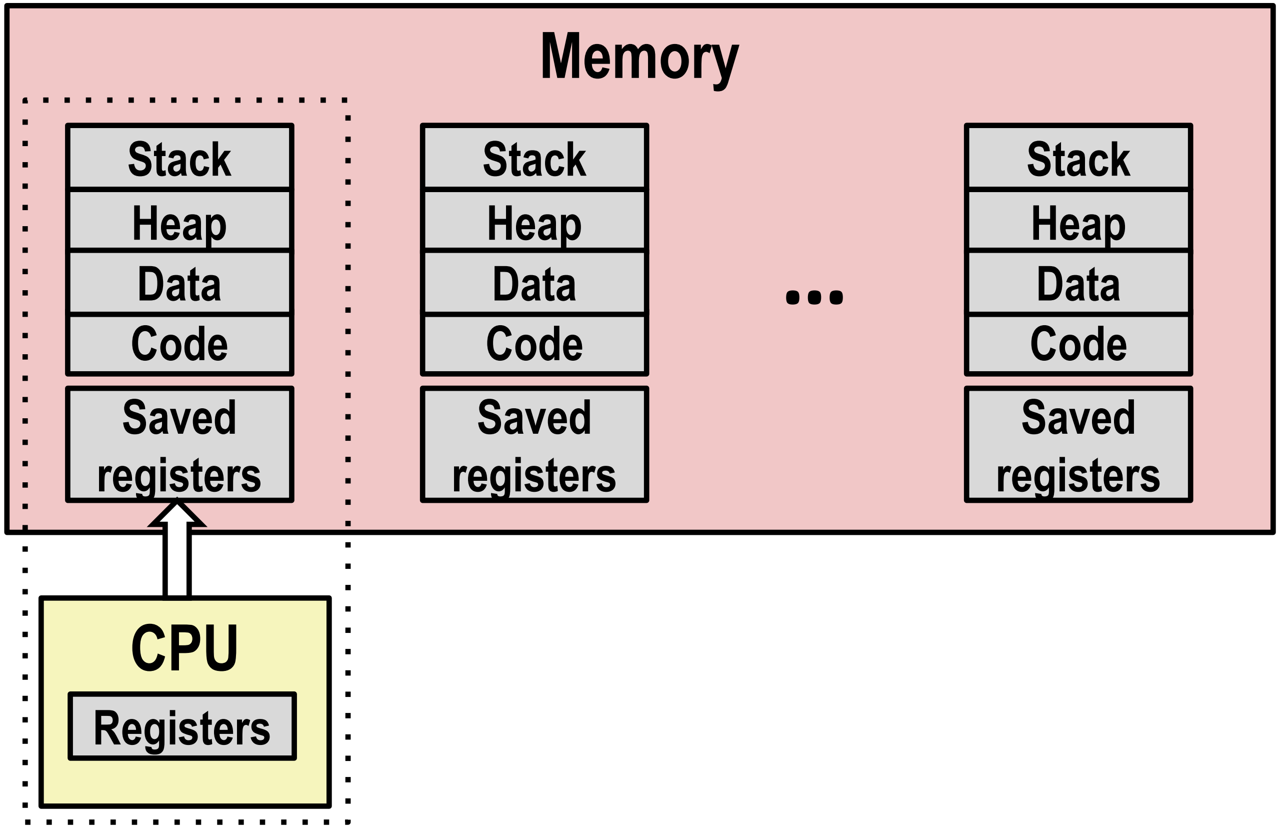
- **在Mac计算机上运行程序“top”命令 Running program “top” on Mac**
  - 系统有123个进程，5个是活跃状态 System has 123 processes, 5 of which are active
  - 使用进程ID(PID)标识 Identified by Process ID (PID)

多进程真像 Multiprocessing: The (Traditional) Reality



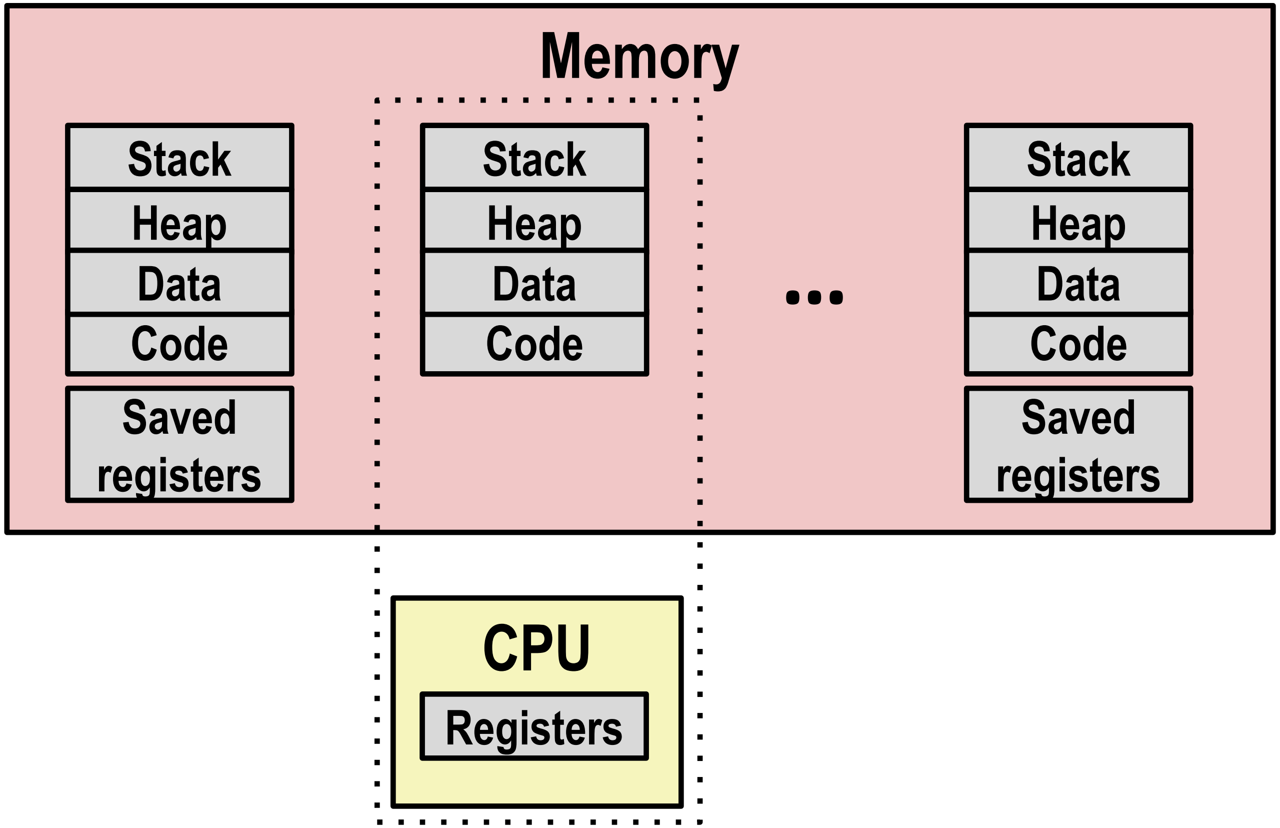
- **单个处理器并发执行多个进程 Single processor executes multiple processes concurrently**
  - 进程交替执行（多任务） Process executions interleaved (multitasking)
  - 地址空间由虚拟内存系统管理 Address spaces managed by virtual memory system (later in course)
  - 非激活进程的寄存器值存储在内存中 Register values for nonexecuting processes saved in memory

多进程真像 Multiprocessing: The (Traditional) Reality



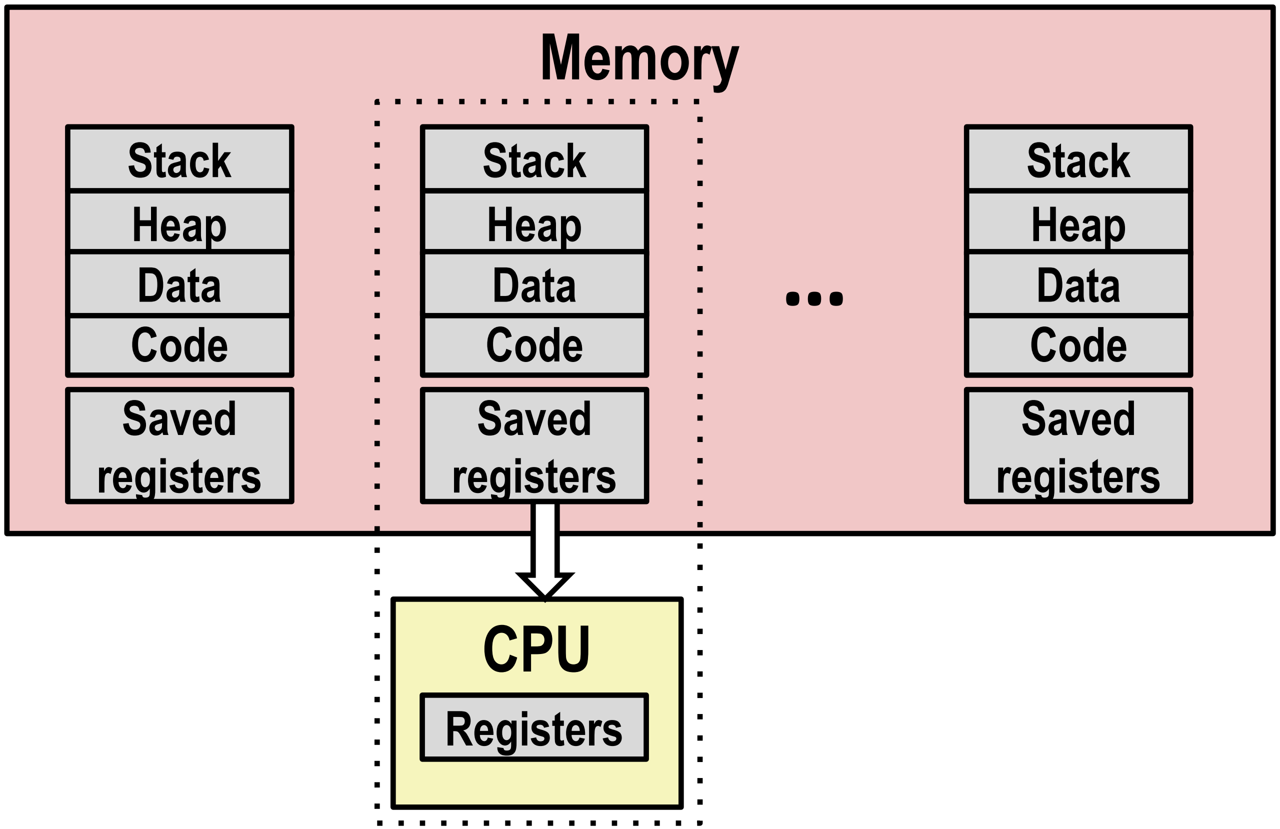
- 将当前寄存器存储在内存里 Save current registers in memory

多进程真像 Multiprocessing: The (Traditional) Reality



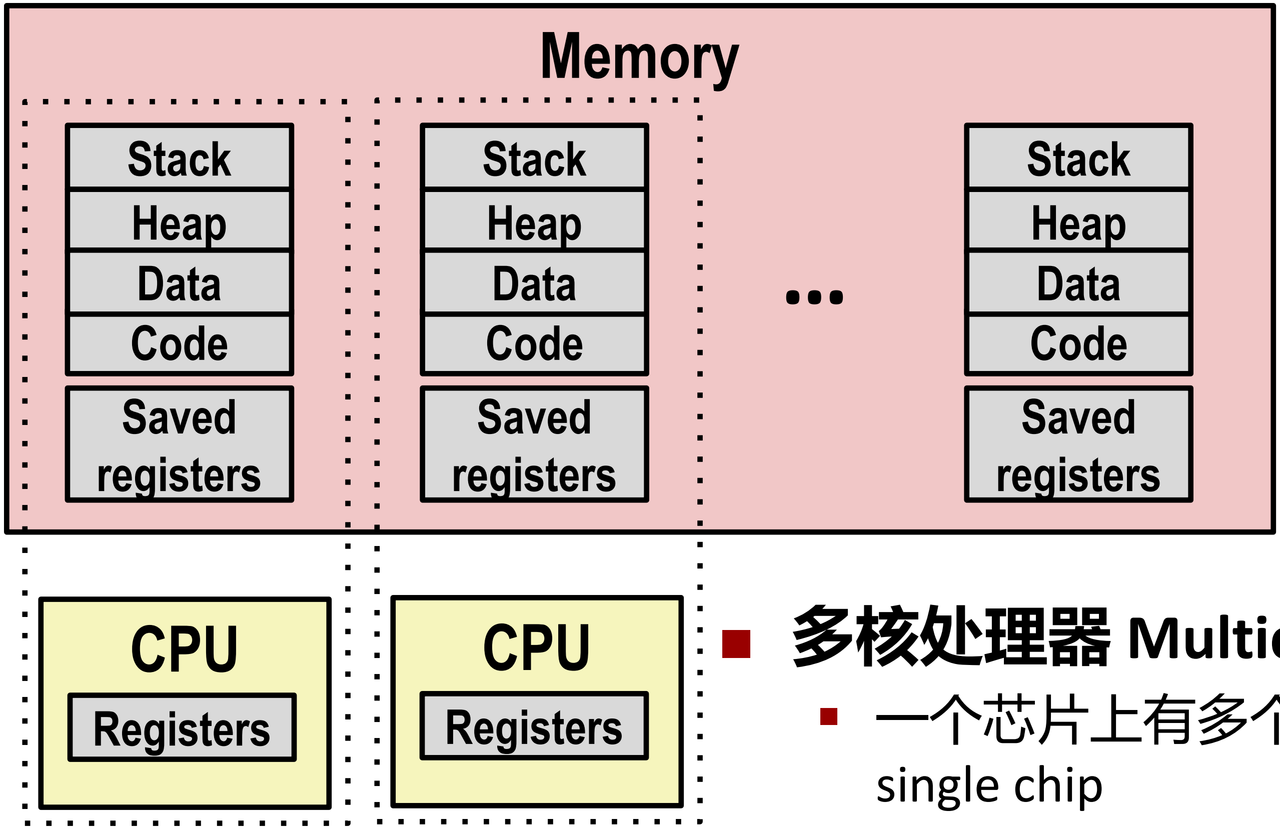
- 调度下一个进程执行 Schedule next process for execution

多进程真像 Multiprocessing: The (Traditional) Reality



- 加载保存的寄存器并切换地址空间（上下文切换）Load saved registers and switch address space (context switch)

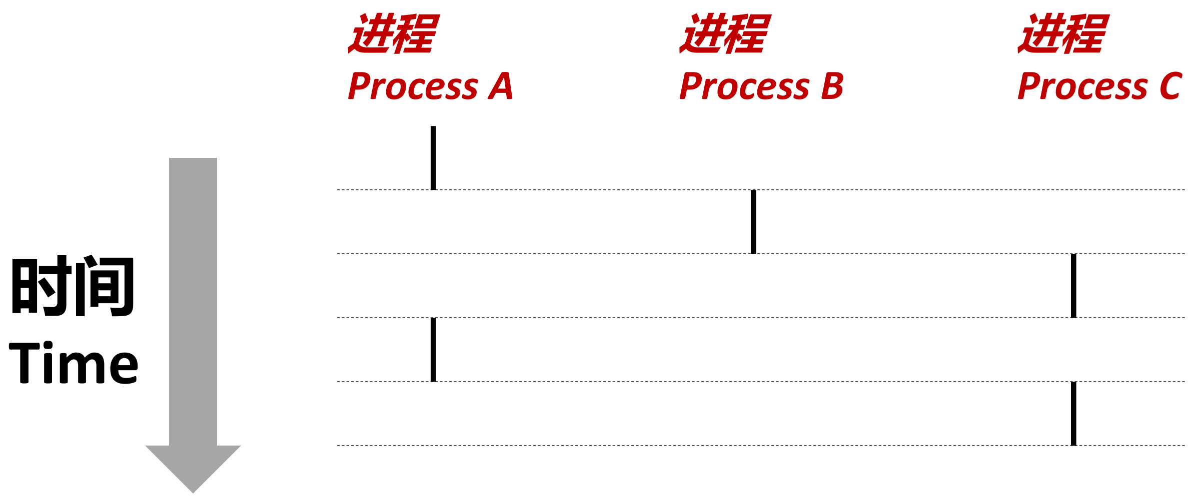
多进程真像 Multiprocessing: The (Modern) Reality



- **多核处理器 Multicore processors**
  - 一个芯片上有多个CPU Multiple CPUs on single chip
  - 共享主存储器（以及部分cache） Share main memory (and some of the caches)
  - 每个可以执行一个独立进程 Each can execute a separate process
    - 由内核完成处理器到核心的调度 Scheduling of processors onto cores done by kernel

并发进程 Concurrent Processes

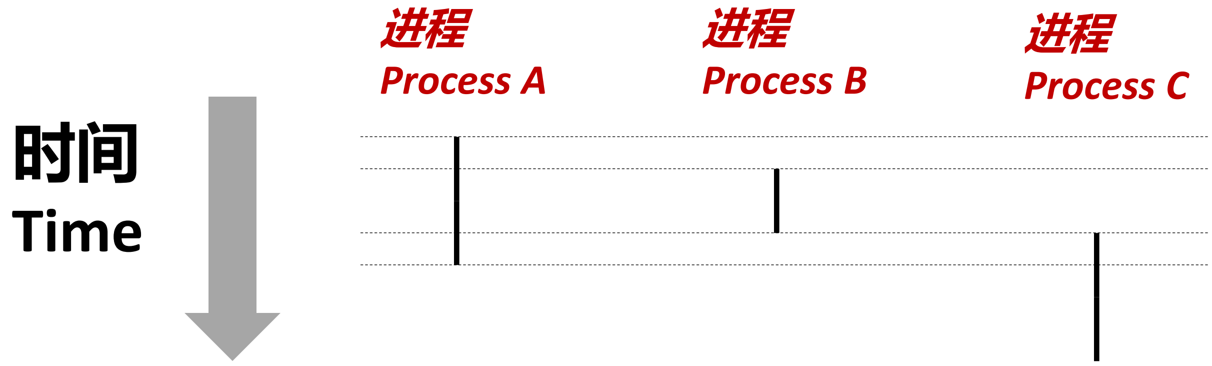
- **每个进程是一个逻辑控制流 Each process is a logical control flow.**
- **两个进程*并发*运行如果在时间上重叠 Two processes *run concurrently* (*are concurrent)* if their flows overlap in time**
- **否则是*顺序*执行 Otherwise, they are *sequential***
- **例如（运行在单核上） Examples (running on single core):**
  - 并发：Concurrent: A & B, A & C
  - 顺序：Sequential: B & C



并发进程的用户视图
User View of Concurrent Processes

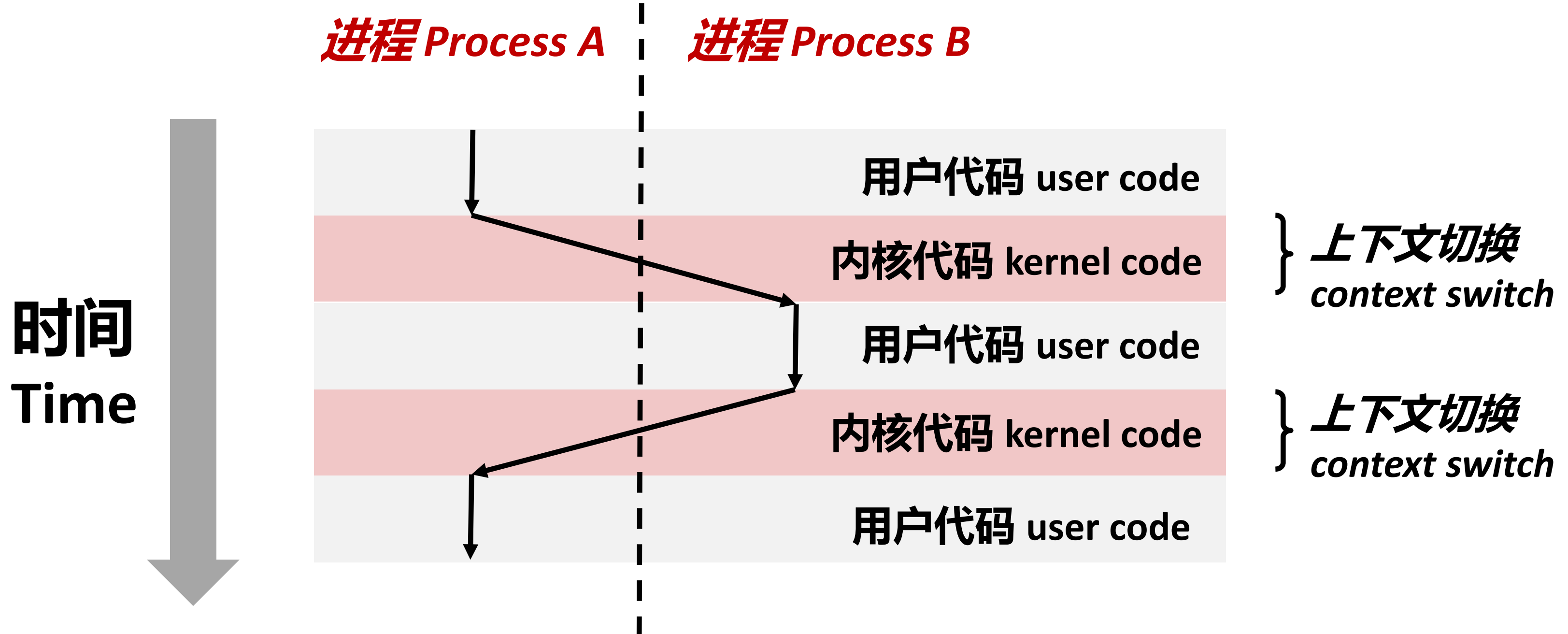
- **并发进程的控制流在时间上是物理上不相交的 Control flows for concurrent processes are physically disjoint in time**

- **然而，我们可以将并发进程视为彼此并行运行 However, we can think of concurrent processes as running in parallel with each other**



上下文切换 Context Switching

- **进程由称为内核的共享内存驻留操作系统代码块管理 Processes are managed by a shared chunk of memory-resident OS code called the *kernel***
  - 重点：内核不是一个独立的进程，而是作为某些现存进程的一部分运行 Important: the kernel is not a separate process, but rather runs as part of some existing process.
- **上下文切换使得控制流从一个进程切换到另一个进程 Control flow passes from one process to another via a *context switch***



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系统功能调用错误处理 System Call Error Handling

- **出错时，Linux系统函数返回-1并通过全局变量errno设置错误编号指明原因 On error, Linux system-level functions typically return -1 and set global variable `errno` to indicate cause.**
- **硬性规定：Hard and fast rule:**
  - 你必须检查每个系统函数返回状态 You must check the return status of every system-level function
  - 返回值为void的函数除外 Only exception is the handful of functions that return `void`
- **例如 Example:**

```
if ((pid = fork()) < 0) {
    fprintf(stderr, "fork error: %s\n", strerror(errno));
    exit(0);
}
```

错误报告函数 Error-reporting functions

- 使用错误报告函数可以简化一些工作 Can simplify somewhat using an *error-reporting function*:

```
void unix_error(char *msg) /* Unix-style error */
{
   fprintf(stderr, "%s: %s\n", msg, strerror(errno));
   exit(0);
}
```

```
if ((pid = fork()) < 0)
   unix_error("fork error");
```

注意：退出时返回0
Note: csapp.c exits with 0.

- 但是，必须考虑应用。当出现问题时退出并不总是合适的 But, must think about application. Not alway appropriate to exit when something goes wrong.

错误处理包装器 Error-handling Wrappers

- 通过使用Stevens[1]风格的错误处理包装器，我们进一步简化了向您展示的代码： We simplify the code we present to you even further by using Stevens-style error-handling wrappers:

```
pid_t Fork(void)
{
    pid_t pid;

    if ((pid = fork()) < 0)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork();
```

- 而不是您在实际应用程序中通常要做这件事情 NOT what you generally want to do in a real application

[1]例如，在“Unix网络编程：套接字网络API” [1]e.g., in “UNIX Network Programming: The sockets networking API“ W. Richard Stevens

获得进程PID Obtaining Process IDs

- `pid_t getpid(void)`
  - 返回当前进程的PID Returns PID of current process

- `pid_t getppid(void)`
  - 返回父进程的PID Returns PID of parent process

创建和终止进程
Creating and Terminating Processes

从程序员的角度，可以认为一个进程处于3种状态之一 From a programmer's perspective, we can think of a process as being in one of three states

- **运行 Running**
  - 进程或者正在执行，或者等待被执行并最终由内核调度（即被选择执行） Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- **停止 Stopped**
  - 进程执行被挂起，直到被触发重新调度执行 Process execution is *suspended* and will not be scheduled until further notice (next lecture when we study signals)
- **终止 Terminated**
  - 进程永远停止运行 Process is stopped permanently

进程终止 Terminating Processes

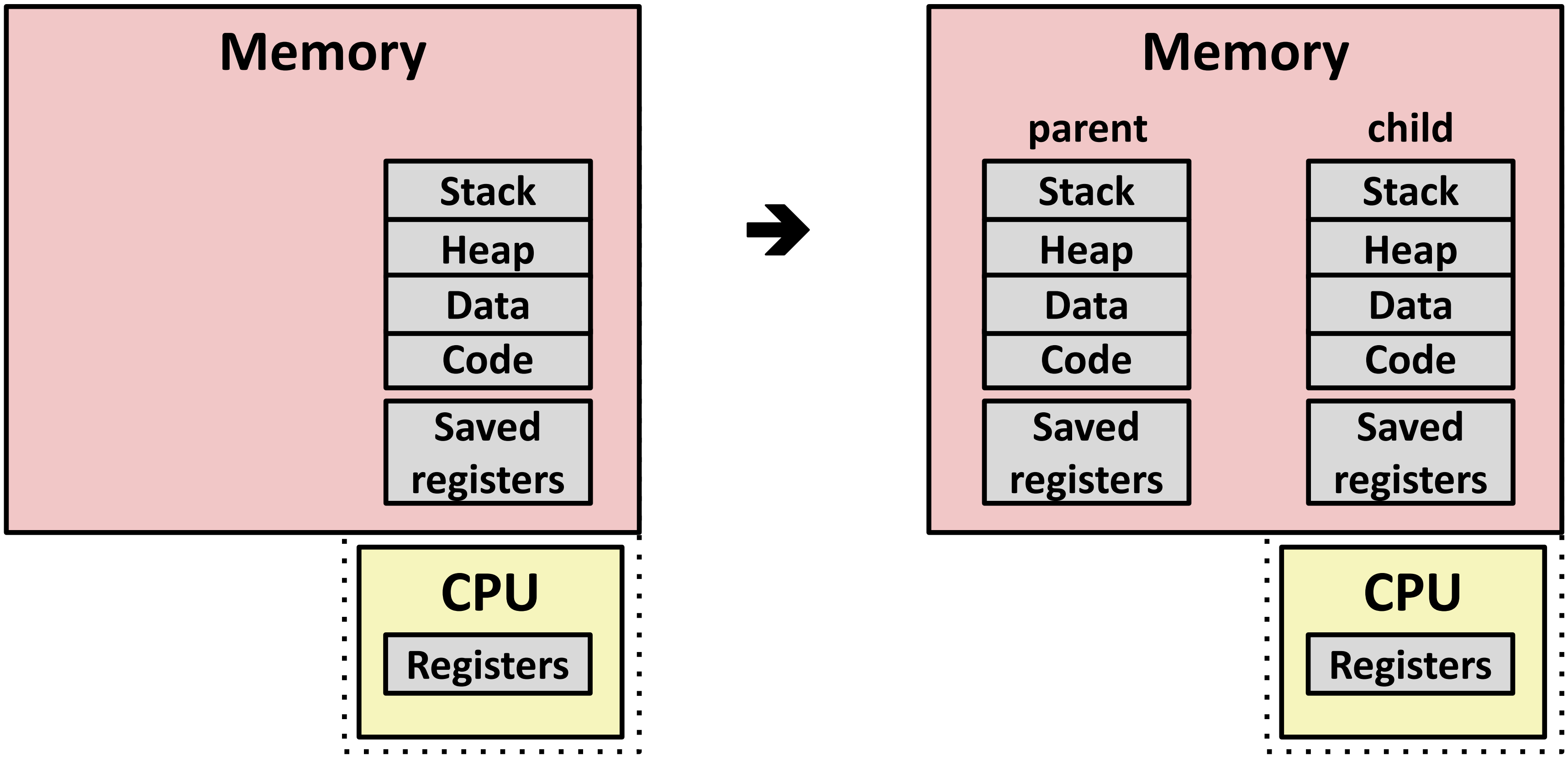
- **进程由于以下三个原因之一终止 Process becomes terminated for one of three reasons:**
  - 收到默认动作是终止的信号 Receiving a signal whose default action is to terminate (next lecture)
  - 从main函数返回 Returning from the `main` routine
  - 调用exit函数 Calling the `exit` function
- **`void exit(int status)`**
  - 终止退出状态为status Terminates with an *exit status* of `status`
  - 规则：正常返回状态为0，出错为非0 Convention: normal return status is 0, nonzero on error
  - 另一种显式设置退出状态的方式是从main函数返回一个整数值 Another way to explicitly set the exit status is to return an integer value from the main routine
- **`exit`调用一次，但从不返回 `exit` is called once but never returns.**

创建进程 Creating Processes

- ***父进程通过调用fork创建一个新的运行子进程Parent process*** **creates a new running *child process* by calling `fork`**
- `int fork(void)`
  - 返回0给子进程，子进程的PID给父进程 Returns 0 to the child process, child's PID to parent process
  - 子进程和父进程几乎是一样的 Child is *almost* identical to parent:
    - 子进程获得与父进程的虚拟地址空间同样的拷贝（但是是分开的）Child get an identical (but separate) copy of the parent's virtual address space.
    - 子进程获得与父进程打开文件描述符同样的拷贝 Child gets identical copies of the parent's open file descriptors
    - 子进程与父进程有不同的PID Child has a different PID than the parent

- **`fork`很有意思（通常也令人费解），因为它调用一次，但返回两次 `fork` is interesting (and often confusing) because it is called *once* but returns *twice***

fork的概念视图 Conceptual View of `fork`



- **做完全的执行状态拷贝 Make complete copy of execution state**
  - 指定一个为父进程一个为子进程 Designate one as parent and one as child
  - 恢复父进程或子进程的执行 Resume execution of parent or child

重新审视fork函数
The `fork` Function Revisited

- **虚拟存储器和内存映射解释了fork如何为每个进程提供私有的虚拟地址空间 VM and memory mapping explain how `fork` provides private address space for each process.**
- **为了给新进程创建虚拟地址 To create virtual address for new process:**
  - 创建与当前**`mm_struct`**、**`vm_area_struct`**和页表精确一致的拷贝 Create exact copies of current **`mm_struct`**, **`vm_area_struct`**, and page tables.
  - 设置两个进程对每个页具有只读权限 Flag each page in both processes as read-only
  - 设置两个进程对每个**`vm_area_struct`**都是私有COW Flag each **`vm_area_struct`** in both processes as private COW
- **返回时，每个进程具有精确的虚拟内存拷贝 On return, each process has exact copy of virtual memory.**
- **后续的写操作使用COW机制创建新页面 Subsequent writes create new pages using COW mechanism.**

fork举例 fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
```

fork.c

- 调用一次，返回两次 Call once, return twice
- 并发执行 Concurrent execution
  - 不能预测父进程和子进程的执行顺序 Can't predict execution order of parent and child

```
linux> ./fork
parent: x=0
child : x=2
```

```
linux> ./fork
child : x=2
parent: x=0
```

```
linux> ./fork
parent: x=0
child : x=2
```

```
linux> ./fork
parent: x=0
child : x=2
```

fork举例 fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
```

```
linux> ./fork
parent: x=0
child : x=2
```

- 调用一次，返回两次 Call once, return twice
- 并发执行 Concurrent execution
  - 不能预测父进程和子进程的执行顺序 Can't predict execution order of parent and child
- 重复但是分开的地址空间 Duplicate but separate address space
  - x的值为1，当fork在父子进程返回 x has a value of 1 when fork returns in parent and child
  - 后续对x的改变是独立的 Subsequent changes to x are independent
- 共享打开的文件 Shared open files
  - 标准输出对父子进程是相同的 stdout is the same in both parent and child

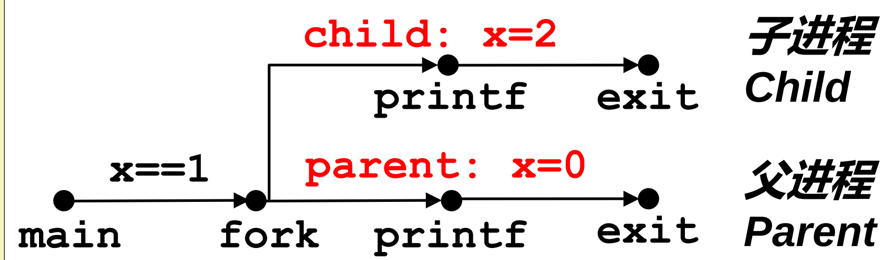
使用进程图描述fork
Modeling `fork` with Process Graphs

- ***进程图***是一个有用的工具，它可以捕获并发程序中语句的偏序 **A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program:**
  - 每个顶点都是语句的执行 Each vertex is the execution of a statement
  - a->b表示a发生在b之前 a -> b means `a` happens before b
  - 可以用变量的当前值标记边 Edges can be labeled with current value of variables
  - 可以用输出标记printf顶点 `printf` vertices can be labeled with output
  - 每个图都以一个没有输入边的顶点开始 Each graph begins with a vertex with no inedges
- **进程图的任何*拓扑排序*都对应于一种可行的全排序 Any *topological sort* of the graph corresponds to a feasible total ordering.**
  - 所有边从左向右指向的顶点的全排序 Total ordering of vertices where all edges point from left to right

进程图举例 Process Graph Example

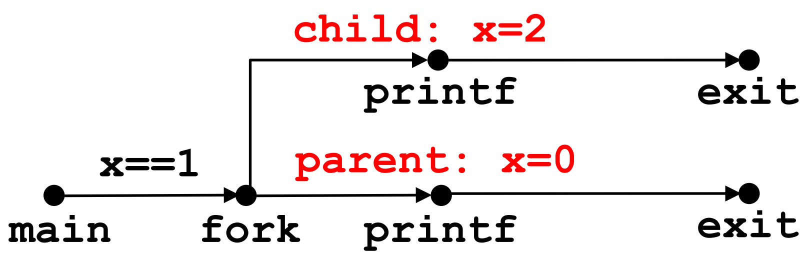
```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
                exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

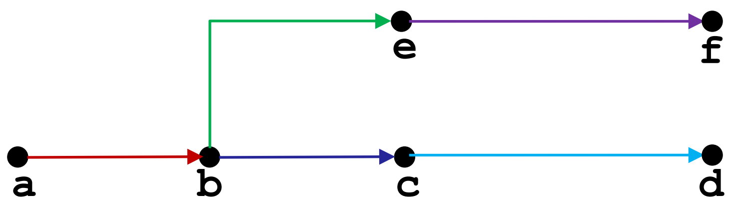


解释进程图 Interpreting Process Graphs

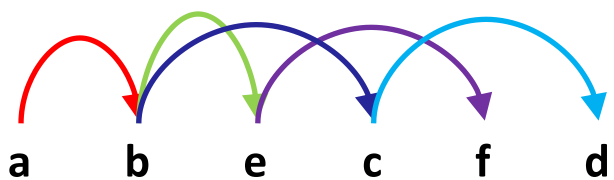
- 原始图 Original graph:



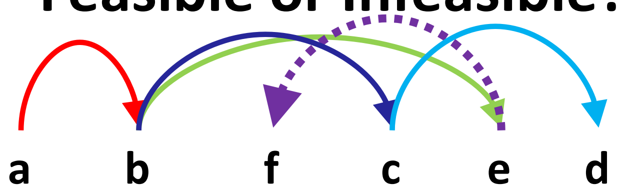
- 重新标记的图 Relabled graph:



可行的全排序
Feasible total ordering:



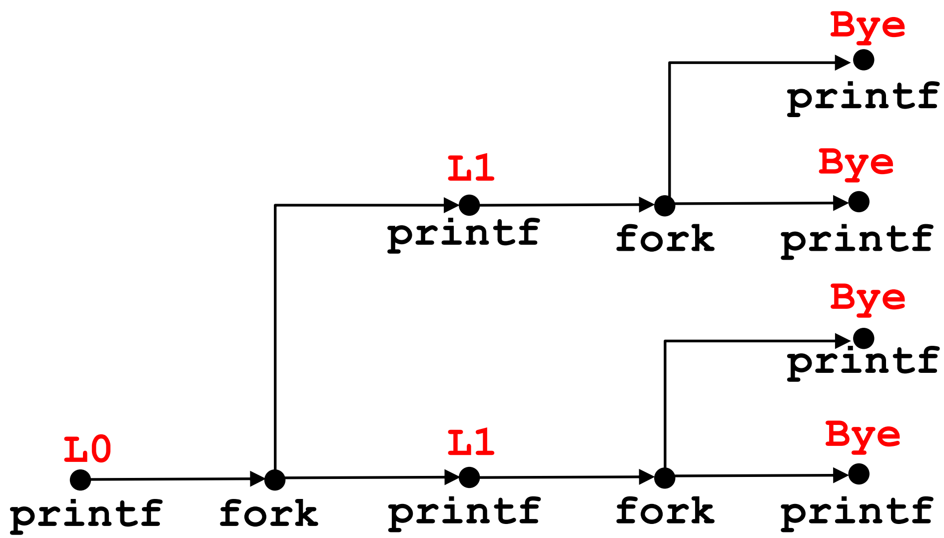
可行还是不可行?
Feasible or Infeasible?



不可行：不是一种拓扑排序
Infeasible: not a topological sort

fork举例：两个连续的fork
fork Example: Two consecutive forks

```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
forks.c



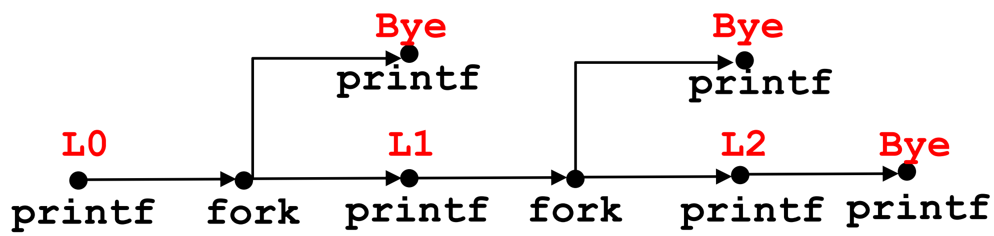
可能的输出
Feasible output:
L0
L1
Bye
Bye
L1
Bye
Bye

不可能的输出
Infeasible output:
L0
Bye
L1
Bye
L1
Bye
Bye

fork举例：父类进程中的嵌套forks
fork Example: Nested forks in parent

```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
            }
    }
    printf("Bye\n");
}
```

forks.c



可能的输出
Feasible output:

L0
L1
Bye
Bye
L2
Bye

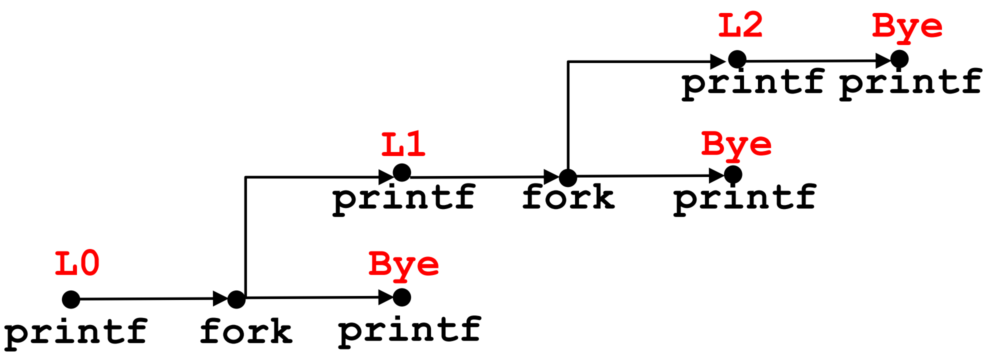
不可能的输出
Infeasible output:

L0
Bye
L1
Bye
Bye
L2

fork举例：子进程中的嵌套forks
fork Example: Nested forks in children

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

forks.c



可能的输出 Feasible output:	不可能的输出 Infeasible output:
L0	L0
Bye	Bye
L1	L1
L2	Bye
Bye	Bye
Bye	L2

回收子进程 Reaping Child Processes

- **思想 Idea**
  - 进程终止后仍然消耗系统资源 When process terminates, it still consumes system resources
    - 例如：退出状态，各种OS表格 Examples: Exit status, various OS tables
  - 称为“僵尸”进程 Called a “zombie”
    - 活着的尸体，半生半死 Living corpse, half alive and half dead
- **回收 Reaping**
  - 父类进程对终止的子进程操作（使用wait或waitpid） Performed by parent on terminated child (using `wait` or `waitpid`)
  - 父类进程持有退出状态信息 Parent is given exit status information
  - 内核随后删掉僵尸子进程 Kernel then deletes zombie child process

回收子进程 Reaping Child Processes

- **如果父类进程没有回收会怎么样？What if parent doesn't reap?**
  - 如果任何父类进程终止没有回收子进程，则该孤儿子进程由init进程（pid==1）回收 If any parent terminates without reaping a child, then the orphaned child will be reaped by **`init`** process (pid == 1)
    - 除非ppid==1，此时需要重启 Unless ppid == 1! Then need to reboot…
  - 所以只需要显式回收长时间运行的进程 So, only need explicit reaping in long-running processes
    - 例如外壳程序和服务器程序 e.g., shells and servers

僵尸举例 Zombie Example

```
void fork7() {
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n", getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n", getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- **ps显示子进程为“defunct”（即僵尸）** **ps** shows child process as “defunct” (i.e., a zombie)
- 杀死父进程允许子进程由init进程回收 Killing parent allows child to be reaped by **init**

非终止子进程举例 Non-terminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

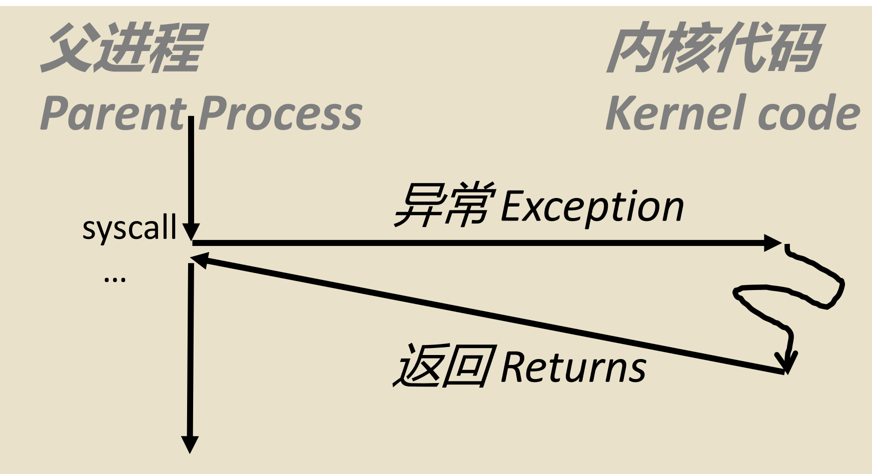
```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- 子进程仍然活着，尽管父进程已经终止 Child process still active even though parent has terminated
- 必须显式杀死子进程，否则子进程将会永远一直在运行 Must kill child explicitly, or else will keep running indefinitely

`wait`：与子进程同步
`wait`: Synchronizing with Children

- **父进程通过调用wait函数回收子进程Parent reaps a child by calling the `wait` function**

- **`int wait(int *child_status)`**
  - 挂起当前进程直到其子进程之一终止 Suspends current process until one of its children terminates
  - 用syscall实现 Implemented as syscall



而且，潜在地其它用户进程，包括父进程的子进程
And, potentially other user processes, including a child of parent

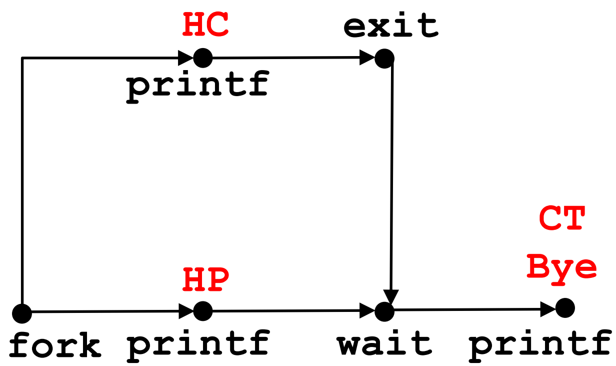
`wait`：与子进程同步
`wait`: Synchronizing with Children

- **父进程通过调用wait函数回收子进程 Parent reaps a child by calling the `wait` function**
- **`int wait(int *child_status)`**
  - 挂起当前进程直到其子进程之一终止 Suspends current process until one of its children terminates
  - 返回值是终止子进程的PID Return value is the **`pid`** of the child process that terminated
  - 如果**`child_status`**不为空，那么它指向的整数将会设置为一个值，以指示子进程终止的原因和退出状态： If **`child_status != NULL`**, then the integer it points to will be set to a value that indicates reason the child terminated and the exit status:
    - 使用wait.h中宏定义进行检查 Checked using macros defined in `wait.h`
      - `WIFEXITED`, `WEXITSTATUS`, `WIFSIGNALED`, `WTERMSIG`, `WIFSTOPPED`, `WSTOPSIG`, `WIFCONTINUED`
      - 参见教材了解详情 See textbook for details

wait：与子进程同步
wait: Synchronizing with Children

```
void fork9() {
    int child_status;

    if (fork() == 0) {
        printf("HC: hello from child\n");
                exit(0);
    } else {
        printf("HP: hello from parent\n");
        wait(&child_status);
        printf("CT: child has terminated\n");
    }
    printf("Bye\n");
}
```

forks.c



可能的输出

Feasible output(s):

HC
HP
CT
Bye

不可能的输出

Infeasible output:

HP
CT
Bye
HC

另一个wait的例子

Another wait Example

- 如果多个子进程终止，将会以任意顺序进行 If multiple children completed, will take in arbitrary order
- 可以使用宏WIFEXITED和WEXITSTATUS获取有关退出状态的信息 Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10() {
  pid_t pid[N];
  int i, child_status;

  for (i = 0; i < N; i++)
    if ((pid[i] = fork()) == 0) {
      exit(100+i); /* Child */
    }
  for (i = 0; i < N; i++) { /* Parent */
    pid_t wpid = wait(&child_status);
    if (WIFEXITED(child_status))
      printf("Child %d terminated with exit status %d\n",
            wpid, WEXITSTATUS(child_status));
    else
      printf("Child %d terminate abnormally\n", wpid);
  }
}
```

forks.c

waitpid：等待特定进程
waitpid: Waiting for a Specific Process

- `pid_t waitpid(pid_t pid, int &status, int options)`
  - 挂起当前进程直到指定进程终止 Suspends current process until specific process terminates
  - 各种选项（参见教材） Various options (see textbook)

```
void fork11() {
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = N-1; i >= 0; i--) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminate abnormally\n", wpid);
    }
}
```

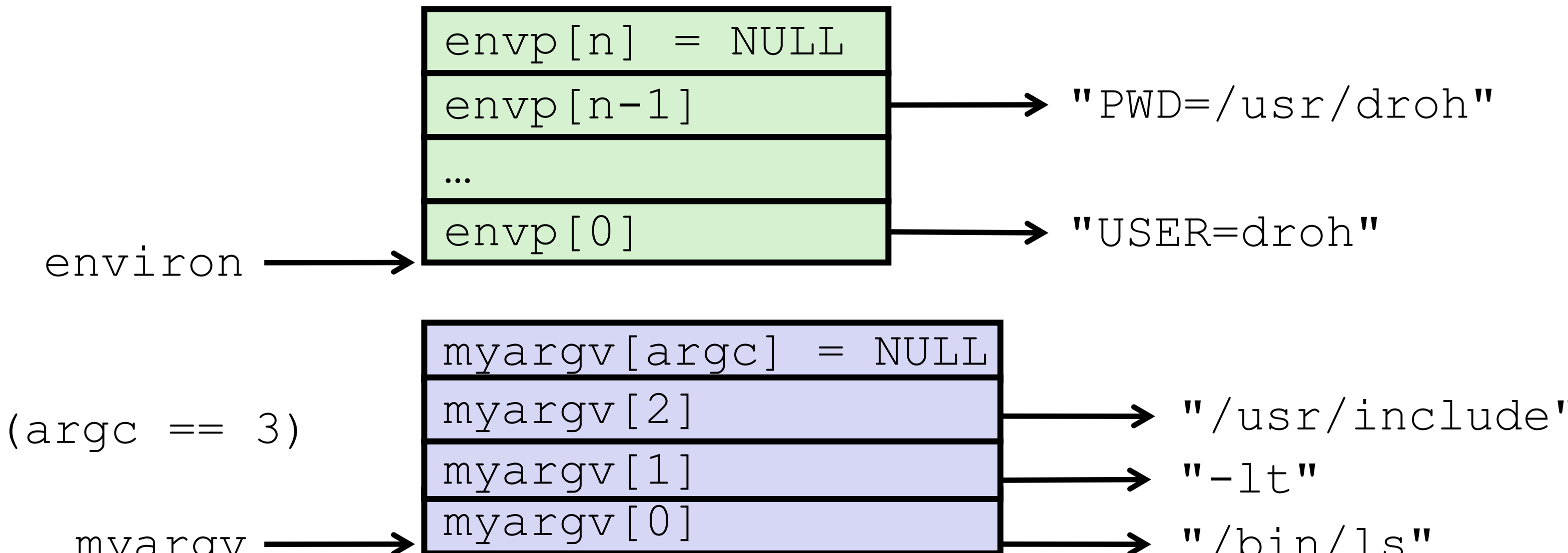
forks.c

execve：加载运行程序
execve：Loading and Running Programs

- `int execve(char *filename, char *argv[], char *envp[])`
- **在当前进程加载和运行 Loads and runs in the current process:**
  - 可执行文件文件名filename   Executable file **`filename`**
    - 目标代码文件或者以“#! 解释器”开始的脚本文件 Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …带有参数列表argv   …with argument list **`argv`**
    - 按照约定第一个参数为文件名 By convention **`argv[0]==filename`**
  - …带有环境变量列表envp   …and environment variable list **`envp`**
    - “名字=值”串 “name=value” strings (e.g., `USER=droh`)
    - `getenv, putenv, printenv`
- **覆盖代码、数据和堆栈 Overwrites code, data, and stack**
  - 保持PID、打开文件和信号上下文 Retains PID, open files and signal context
- **调用一次而且从不返回 Called once and never returns**
  - …除非如果有错误 …except if there is an error

execve举例 execve Example

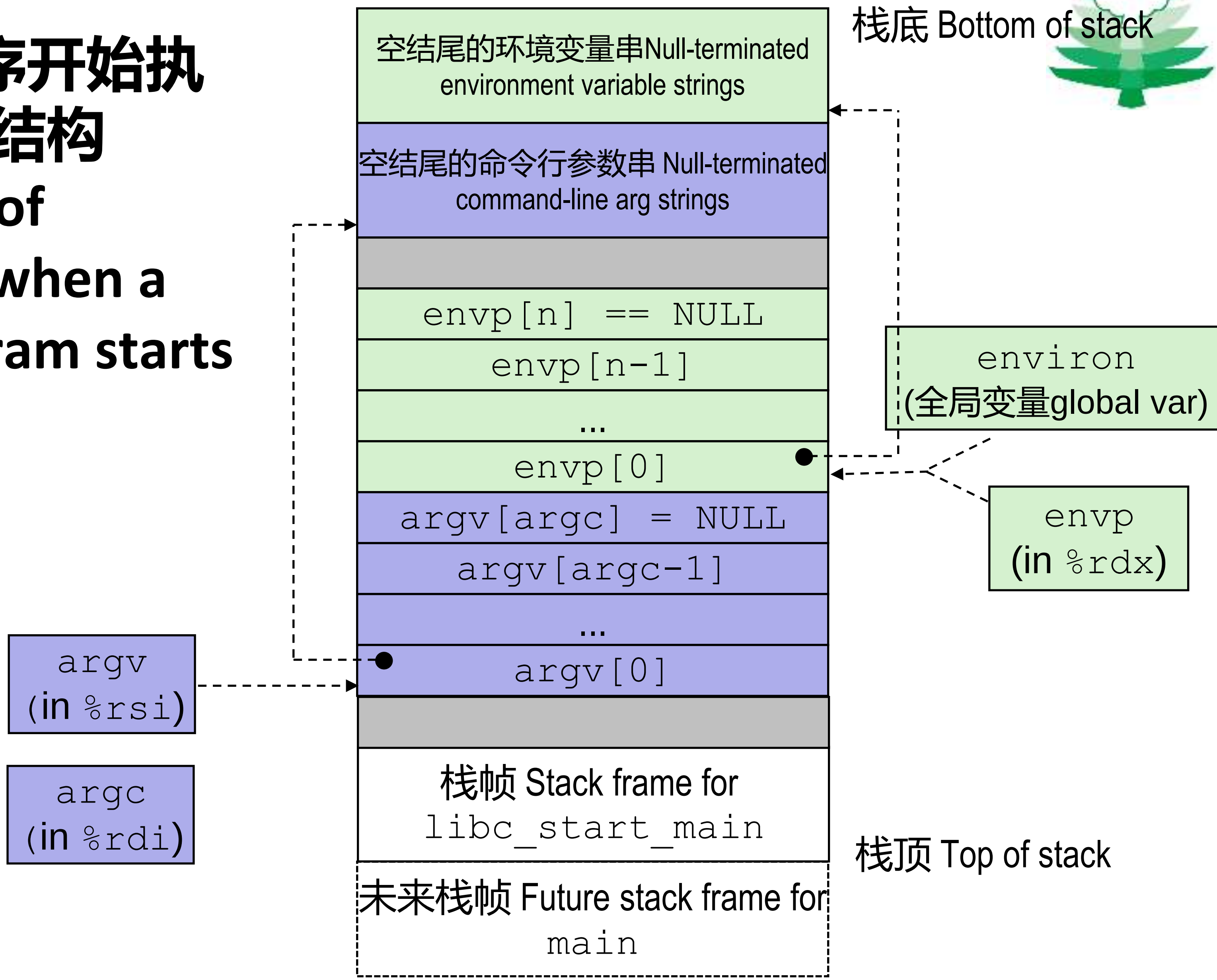
- **使用当前环境在子进程中执行 Execute** `"/bin/ls -lt /usr/include"` **in child process using current environment:**




```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

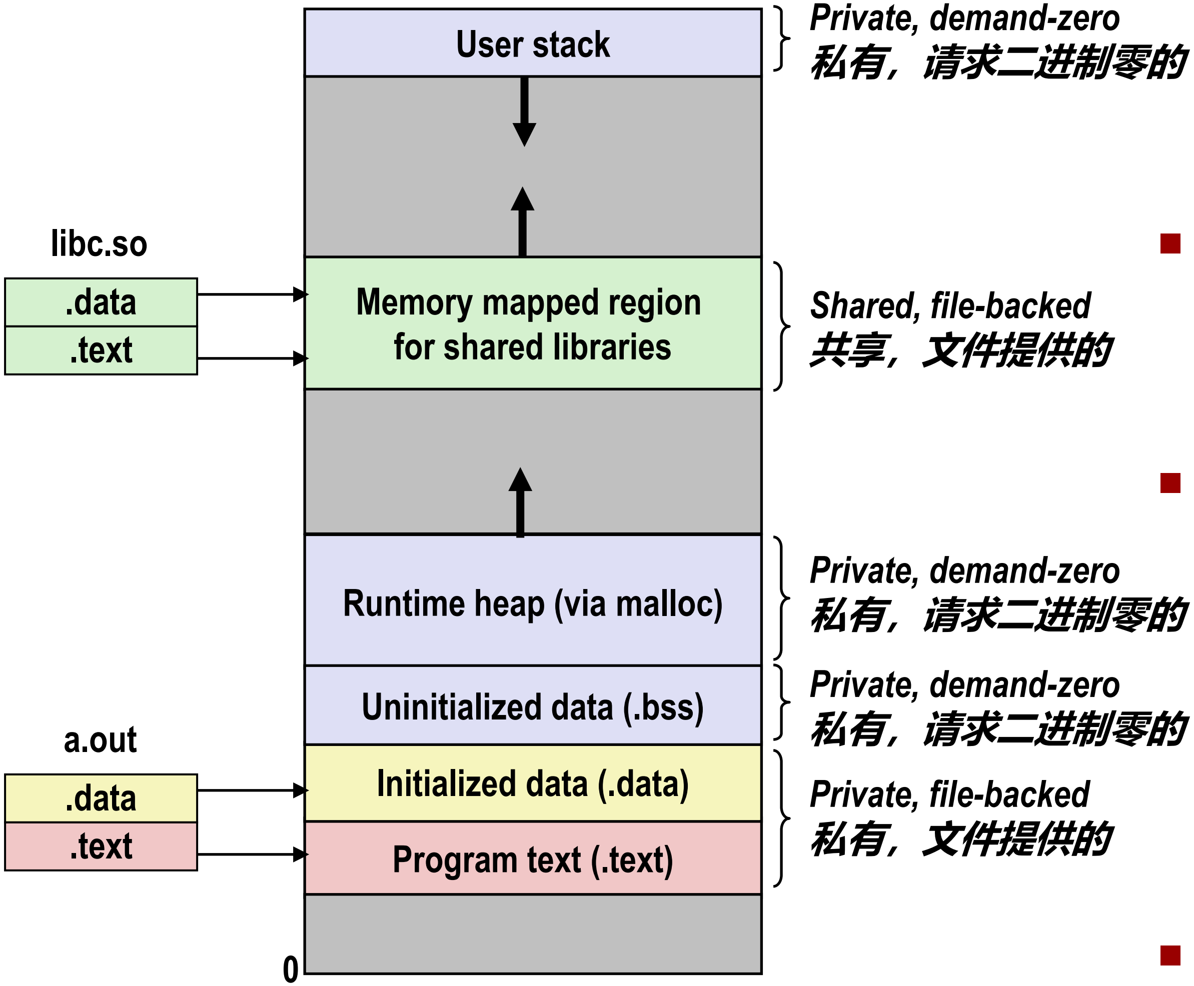
一个新程序开始执行时的栈结构

Structure of the stack when a new program starts



重新审视execve函数

The execve Function Revisited



- **要使用execve在当前进程加载和运行一个新程序a.out To load and run a new program `a.out` in the current process using `execve`:**
- **释放老区域的`vm_area_struct`和页表 Free `vm_area_struct`'s and page tables for old areas**
- **为新区域创建`vm_area_struct`和页表 Create `vm_area_struct`'s and page tables for new areas**
  - 程序和初始化后的数据由目标文件提供 Programs and initialized data backed by object files.
  - `.bss`和栈由匿名文件提供 `.bss` and stack backed by anonymous files.
- **设置PC为.text中的入口点 Set PC to entry point in `.text`**
  - Linux将陷入需要的代码和数据页 Linux will fault in code and data pages as needed.

总结 Summary

- **异常 Exceptions**
  - 需要非标准控制流的事件 Events that require nonstandard control flow
  - 由外部（中断）或内部（陷阱和故障）产生 Generated externally (interrupts) or internally (traps and faults)

- **进程 Processes**
  - 任意时刻，系统有多个活动进程 At any given time, system has multiple active processes
  - 尽管在单核上每个时刻只能执行一个进程 Only one can execute at a time on a single core, though
  - 每个进程看起来独占处理器和私有内存空间 Each process appears to have total control of
    processor + private memory space

总结（续） Summary (cont.)

- **生成新进程 Spawning processes**
  - 调用fork Call `fork`
  - 一次调用，两次返回 One call, two returns
- **结束进程 Process completion**
  - 调用exit   Call `exit`
  - 一次调用，不返回 One call, no return
- **回收和等待进程 Reaping and waiting for processes**
  - 调用wait或waitpid   Call `wait` or `waitpid`
- **加载运行程序 Loading and running programs**
  - 调用execve（或变种） Call `execve` (or variant)
  - 一次调用，（正常）不返回 One call, (normally) no return

使fork更不确定
Making `fork` More Nondeterministic

- 问题 Problem
  - Linux调度器不会产生很多运行间差异 Linux scheduler does not create much run-to-run variance
  - 在非确定性程序中隐藏潜在的竞争条件 Hides potential race conditions in nondeterministic programs
    - 例如，fork是先返回到子进程，还是返回到父进程？ E.g., does `fork` return to child first, or to parent?
- 解决方案 Solution
  - 创建库例程的自定义版本，沿不同分支插入随机延迟 Create custom version of library routine that inserts random delays along different branches
    - 例如， fork父进程和子进程 E.g., for parent and child in `fork`
  - 使用运行时库打桩使程序使用特殊版本的库代码 Use runtime interpositioning to have program use special version of library code

延迟变化的fork Variable delay fork

```
/* fork wrapper function */
pid_t fork(void) {
    initialize();
    int parent_delay = choose_delay();
    int child_delay = choose_delay();
    pid_t parent_pid = getpid();
    pid_t child_pid_or_zero = real_fork();
    if (child_pid_or_zero > 0) {
        /* Parent */
        if (verbose) {
            printf(
"Fork.  Child pid=%d, delay = %dms.  Parent pid=%d, delay = %dms\n",
                   child_pid_or_zero, child_delay,
                   parent_pid, parent_delay);
            fflush(stdout);
        }
        ms_sleep(parent_delay);
    } else {
        /* Child */
        ms_sleep(child_delay);
    }
    return child_pid_or_zero;
}
```

myfork.c