Lecture 3
Processes

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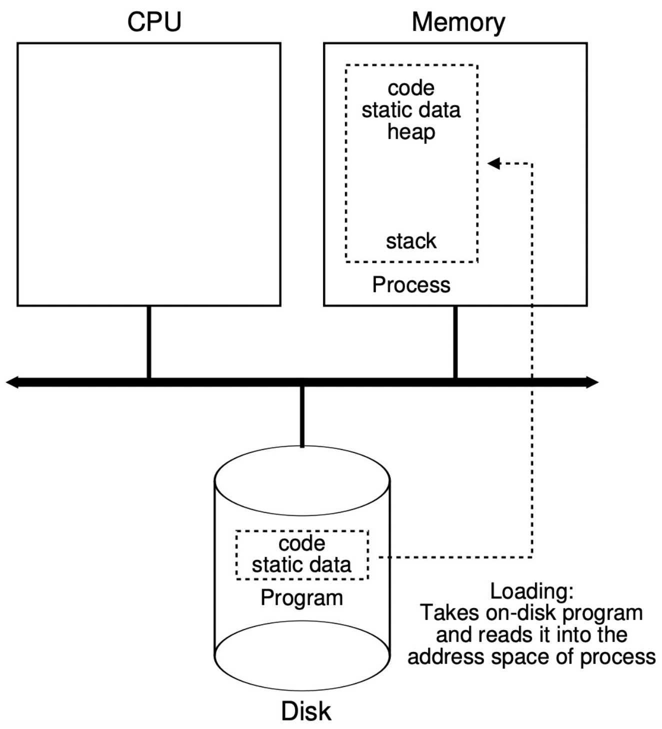
Outline

- Process and system calls
- Process creation
- Kernel view of processes
- Kernel view of fork(), exec(), and wait()
- More about processes

Process and System Calls

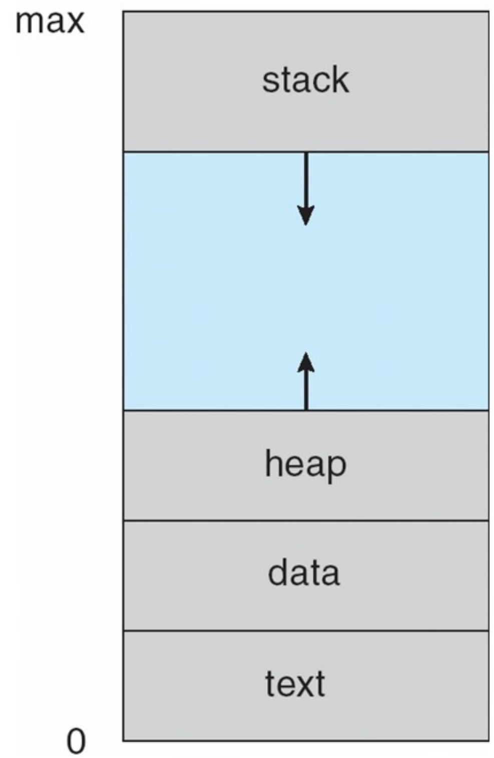
What Is a Process

- Process is a program in execution
- A program is a file on the disk
  - Code and static data
- A process is loaded by the OS
  - Code and static data are loaded from the program
  - Heap and stack are created by the OS



What Is a Process (Cont'd)

os创造了幻觉，看起来process有对于内存的完全控制权



- A process is an abstraction of machine states
  - Memory: address space
  - Register:
    - Program Counter (PC) or Instruction Pointer
    - Stack pointer
    - frame pointer
  - I/O: all files opened by the process

process包含的3部分

Process Identification

- How can we distinguish processes from one to another?
  - Each process is given a unique ID number, and is called the process ID, or the PID.
  - The system call, getpid(), prints the PID of the calling process.

同一个程序加载两次的两个process，不是同一个；而且可以同时存在

```
// compile to getpid
#include <stdio.h>   // printf()
#include <unistd.h>  // getpid()

int main(void) {
    printf("My PID is %d\n", getpid() );
}
```

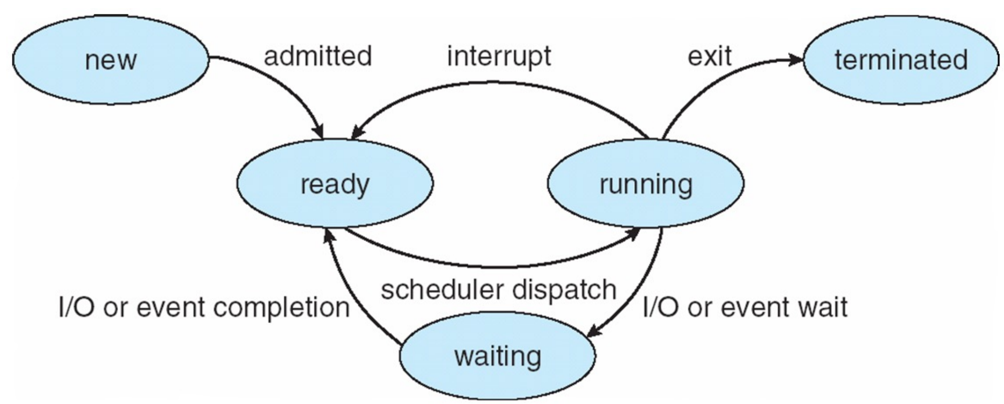
```
$ ./getpid
My PID is 1234
$ ./getpid
My PID is 1235
$ ./getpid
My PID is 1237
```

Process Life Cycle

```
int main(void) {
    int x = 1;
    getchar();
    return x;
}
```

Process State

Terminated

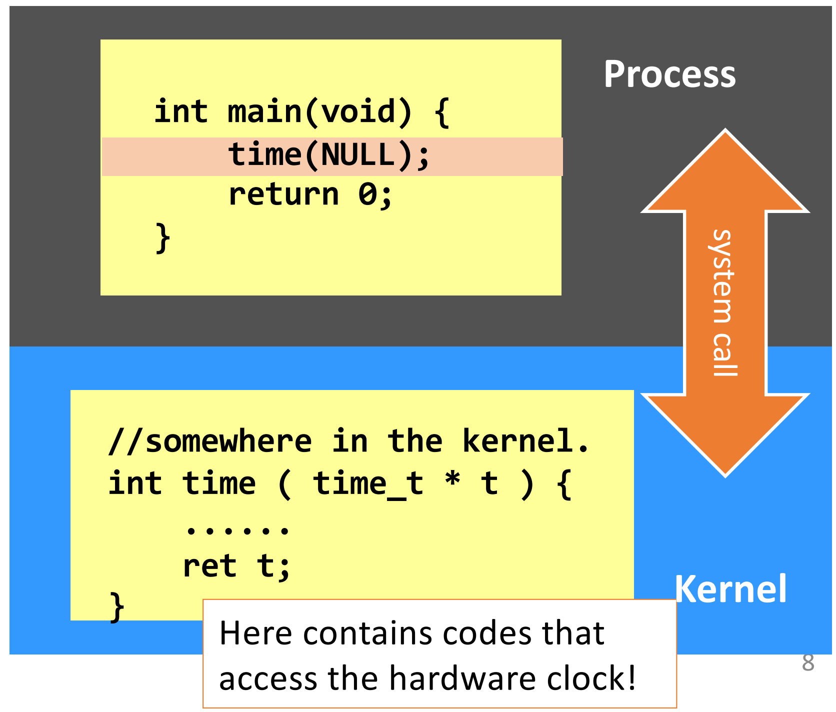


System Call: Process-Kernel Interaction

- System call is a function call.
  - exposed by the **kernel**.
  - abstraction of kernel operations.

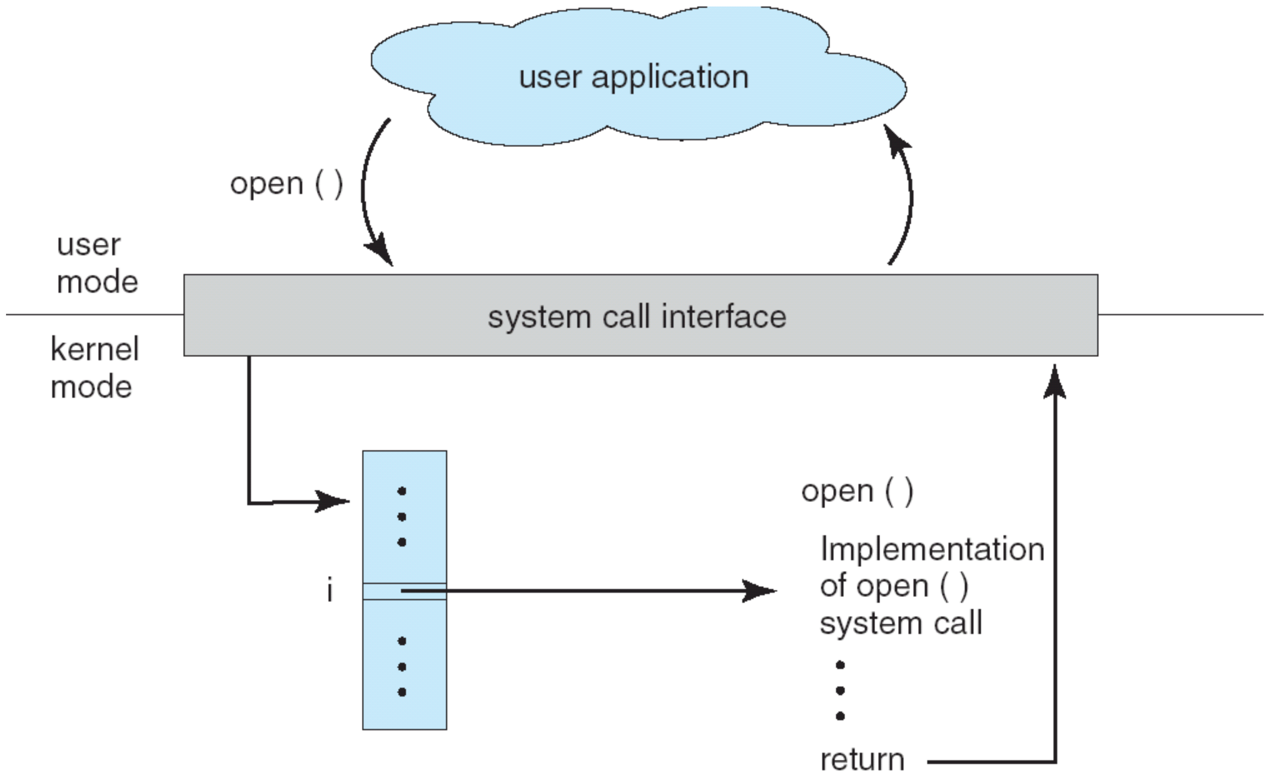
```
int add_function(int a, int b) {
    return (a + b);
}

int main(void) {
   int result;
   result = add_function(a,b);
   return 0;
}

// this is a dummy example…
```

This is a function call.



System Call: Call by Number

- System call is different from function call
- System call is a call by number



System Call: Call by Number

- User-mode code from xv6-riscv

```
int main(void) {
    ……
    int fd = open("copyin1", O_CREATE|O_WRONLY);
    ……
    return 0;
}
```

```
/* kernel/syscall.h */

#define SYS_open 15
```

```
/* user/usys.S */
.global open
open:
    li a7, SYS_open
    ecall
    ret
```

System Call: Call by Number

- Kernel code from xv6-riscv

```
/* kernel/syscall.h */

#define SYS_open 15
```

```
/* kernel/file.c */

uint64 sys_open(void) {
	……
	return fd;
}
```

```
/* kernel/syscall.c */

static uint64 (*syscalls[])(void) = {
	…….
	[SYS_open] sys_open,
	…….
}

void syscall(void) (
	struct proc *p = myproc();
	num = p->trapframe->a7;
	p->trapframe->a0 = syscalls[num]();
}
```

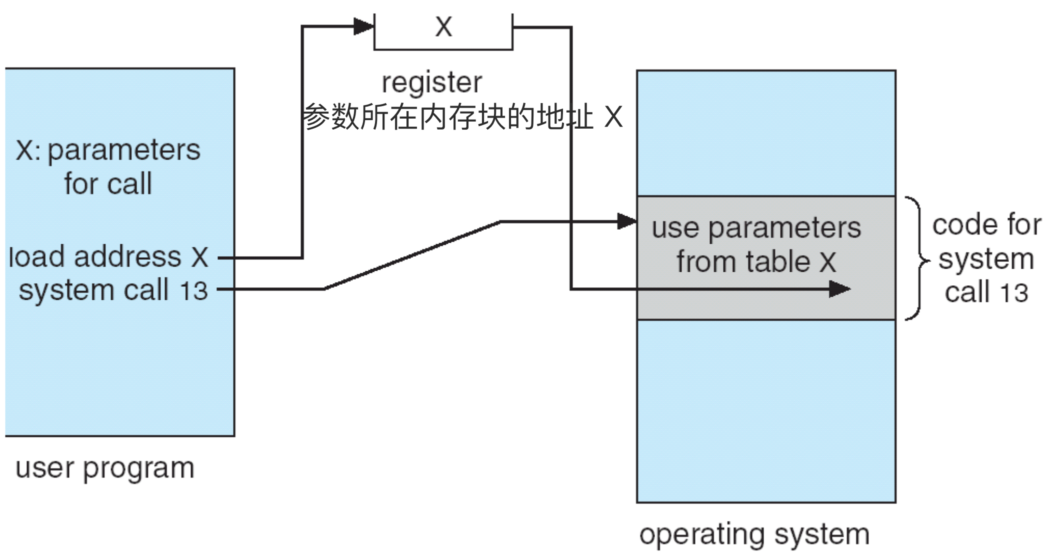
System Call: Parameter Passing

当用户程序要执行系统调用时，光靠“系统调用号”还不够，还需要把参数（比如文件描述符、内存地址、缓冲区长度等）传给内核

- Often, more information is required than the index of desired system call
  - Exact type and amount of information vary according to OS and call
- Three general methods used to pass parameters to the OS
  - **Registers**: pass the parameters in registers
    - In some cases, may be more parameters than registers
    - x86 and risc-v take this approach
  - **Blocks**: Parameters stored in a memory block and address of the block passed as a parameter in a register
  - **Stack**: Parameters placed, or pushed, onto the stack by the program and popped off the stack by the operating system
    - Block and stack methods do not limit the number or length of parameters being passed

System Call: Parameter Passing

- Example: parameter passing via blocks



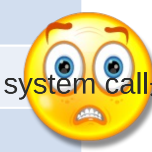
操作系统内核直接提供的接口

System Call v.s. Library API Call

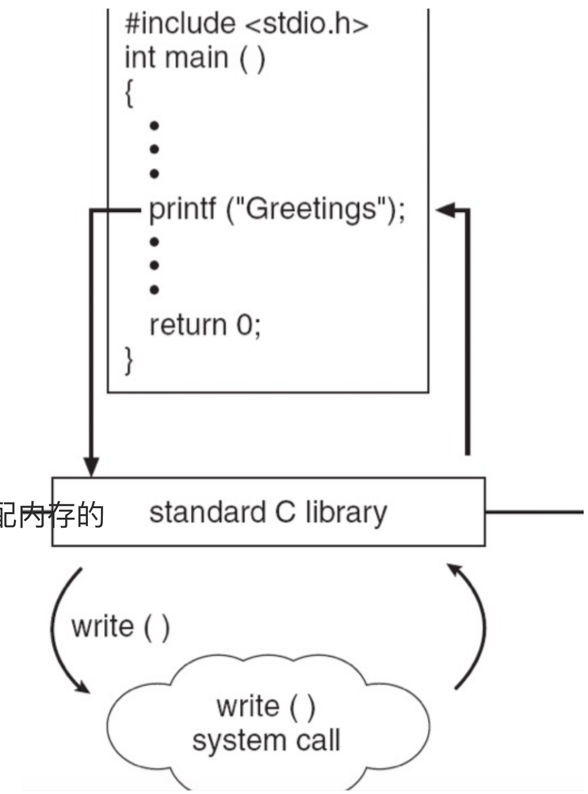
涉及内核态 ↔ 用户态切换，权限高，可以访问硬件、管理资源

- Most operating systems provide standard C library to provide library API calls
  - A layer of indirection for system calls

Name	System call?
printf() & scanf()	No
malloc() & free()	No
fopen() & fclose()	No
mkdir() & rmdir()	Yes
chown() & chmod()	Yes



system call是以page来分配内存的

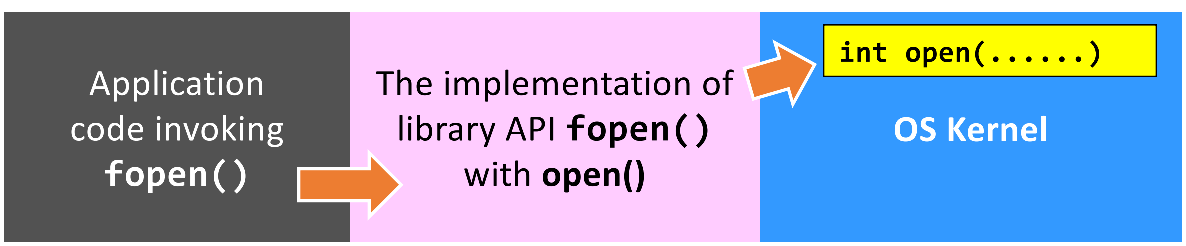


System Call v.s. Library API Call

- Take **fopen()** as an example.
    - **fopen()** invokes the system call **open()**.
    - **open()** is too primitive and is not programmer-friendly!

Library call	`fopen("hello.txt", "w");`
System call	`open("hello.txt", O_WRONLY | O_CREAT | O_TRUNC, 0666);`

0666是权限



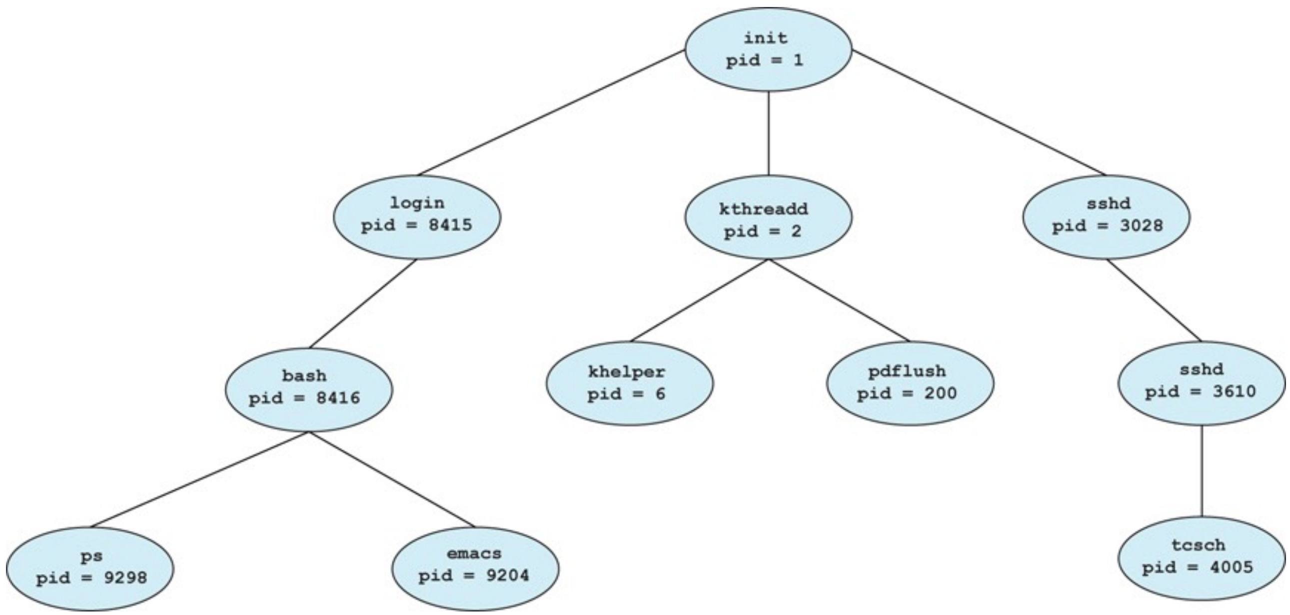
Process Creation

Process Creation

- Parent process create children processes, which, in turn create other processes, forming a tree of processes
- Generally, process identified and managed via a process identifier (pid)
- Address space 在 fork() 系统调用里，子进程几乎是父进程的完整拷贝（代码段、数据段、堆栈都复制）
  - Child duplicate of parent 但父子进程有 不同的 PID，可以独立运行
  - Child has a program loaded into it 子进程可以调用 exec() 系统调用，把自己当前的地址空间完全替换成一个新的程序。
- UNIX examples
  - fork system call creates new process
  - exec system call used after a fork to replace the process' memory space with a new program

Process Creation (Cont'd)

- A tree of processes in Linux



Creating Processes with fork() System Call

在大多数操作系统中，一个进程都是通过另一个进程调用 fork() 或类似的系统调用创建的。
这就天然形成了 父进程 → 子进程 的关系

```
$ ./fork_example_1
Ready (PID=1234)
My PID is 1234
My PID is 1235
$ _
```

PID 1234

Process 1234 is the original process, and we call it the parent process.

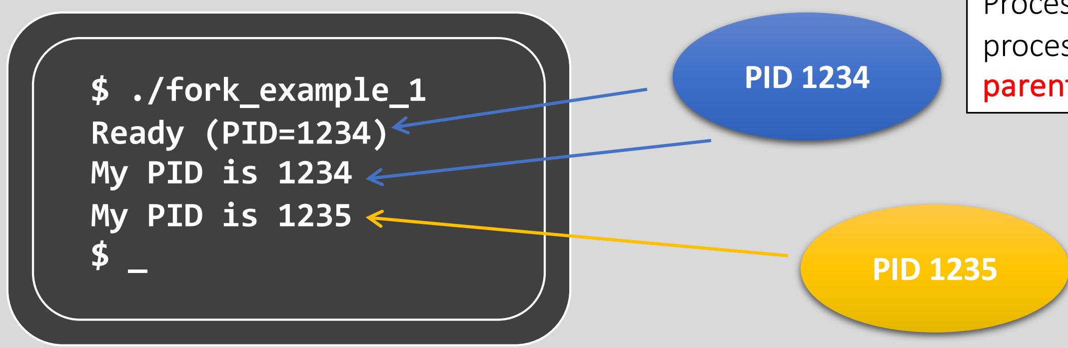
PID 1235

```
int main(void) {
    printf("Ready (PID = %d)\n", getpid());
    fork();
    printf("My PID is %d\n", getpid() );
    return 0;
}
```

Process 1235 is created by the **fork()** system call, and we call it the child process.

父进程负责对子进程进行管理：
等待子进程退出 (wait() / waitpid())。
回收子进程的资源（否则子进程会变成“僵尸进程”）。
树状结构使得“谁创建的谁负责”非常直观。
如果一个父进程意外退出，内核会把它的子进程转交给 init（即“孤儿进程”由 init 收养），保证系统稳定。

Creating Processes with fork() System Call



Process 1234 is the original process, and we call it the parent process.

<u>What do we know so far?</u>

-Both the parent and the child execute **the same program**.

-The child process starts its execution **at the location that `fork()` is returned**, *not from the beginning of the program*.

Creating Processes with fork() System Call

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
```

PID 1234

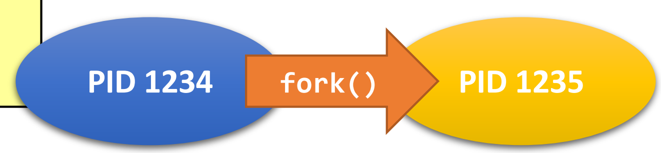
Creating Processes with fork() System Call

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
```

Important

- Both parent and child need to return from fork().
- CPU scheduler decides which to run first.



Creating Processes with fork() System Call

```
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
```

Important

For parent, the return value of **fork()** is the PID of the created child.

PID 1234 (running)

PID 1235 (ready)

child运行fork后面的代码（program counter也和parent相同）

子进程是父进程的 完整拷贝（包括变量值、堆、栈），只有在fork之后可能有差别（pid等等）

Creating Processes with fork() System Call

```
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {  result是0就是child
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {    否则就是parent
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
I’m the parent.
My PID is 1234
```

PID 1234
(running)

PID 1235
(ready)

Creating Processes with fork() System Call

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
I’m the parent.
My PID is 1234
program terminated.
```

PID 1234
(stop)

PID 1235
(ready)

Creating Processes with fork() System Call

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
I'm the parent.
My PID is 1234
program terminated.
result = 0
```

Important

For child, the return value of `fork()` is **0**.

PID 1234 (stop)

PID 1235 (running)

Creating Processes with fork() System Call

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
I’m the parent.
My PID is 1234
program terminated.
result = 0
I’m the child.
My PID is 1235
```

PID 1234
(stop)

PID 1235
(running)

Creating Processes with fork() System Call

fork的返回值：
在parent中返回child的pid；
child中返回0

```
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

```
$ ./fork_example_2
before fork ...
result = 1235
I'm the parent.
My PID is 1234
program terminated.
result = 0
I'm the child.
My PID is 1235
program terminated.
$ _
```

PID 1234
(stop)

PID 1235
(stop)

只有get_ppid(),没有get_cpid()
可能有多个children

fork() System Call

- fork() behaves like "cell division".
  - It creates the child process by **cloning** from the parent process, including all user-space data, e.g.,

Cloned items	Descriptions
Program counter [CPU register]	That's why they both execute from the same line of code after **fork()** returns.
Program code [File & Memory]	They are sharing the same piece of code.
Memory	Including local variables, global variables, and dynamically allocated memory.
Opened files [Kernel's internal]	If the parent has opened a file "fd", then the child will also have file "fd" opened automatically.

terminal也是file

fork() System Call

- fork() does not clone the following…

Distinct items	Parent	Child
Return value of fork()	PID of the child process.	0
PID	Unchanged.	Different, not necessarily be "Parent PID + 1"
Parent process	Unchanged.	Parent.
Running time	Cumulated.	Just created, so should be 0.
[Advanced] File locks	Unchanged.	None.

fork() System Call

父进程运行的是什么程序，子进程也只能运行同一个程序。

系统没法启动别的应用

- If a process can only duplicate itself and always runs the same program, it's not quite meaningful
  - how can we execute other programs?

- **exec()**
  - The **exec*()** system call family.

exec()

- **execl()** – a member of the **exec** system call family (execl, execle, execlp, execv, execve, execvp).

```
int main(void) {
  printf("before execl ...\n");
  execl("/bin/ls", "/bin/ls", NULL);
  printf("after execl ...\n");
  return 0;
}
```

```
$ ./exec_example
before execl ...
```

Arguments of the execl() call

1st argument: the program name, “**/bin/ls**” in the example.
2nd argument: argument[0] to the program.
3rd argument: argument[1] to the program.

exec()

- `execl()` – a member of the `exec` system call family (and the family has 6 members).

```
int main(void) {
  printf("before execl ...\n");
  execl("/bin/ls", "/bin/ls", NULL);
  printf("after execl ...\n");
  return 0;
}
```

输出里没有“after execl ...”

```
$./exec_example
before execl ...
exec_example
exec_example.c
```

What is the output?

The same as **the output of running “`ls`” in the shell.**

exec()

用新的程序替换当前进程的代码和数据段。

进程的 PID 不变。

但原来内存中的程序、指令、数据都会被替换成新程序。

- Example #1: run the command `"/bin/ls"`

```
execl("/bin/ls", "/bin/ls", NULL);
```

Argument Order	Value in above example	Description
1	`"/bin/ls"`	The file that the programmer wants to execute.
2	`"/bin/ls"`	When the process switches to `"/bin/ls"`, this string is the **program argument[0]**.
3	`NULL`	This states the end of the program argument list.

exec()

- Example #2: run the command **"/bin/ls -l"**

```
execl("/bin/ls", "/bin/ls", "-l", NULL);
```

Argument Order	Value in above example	Description
1	`"/bin/ls"`	The file that the programmer wants to execute.
2	`"/bin/ls"`	When the process switches to `"/bin/ls"`, this string is the **program argument[0]**.
3	`"-l"`	When the process switches to `"/bin/ls"`, this string is the **program argument[1]**.
4	`NULL`	This states the end of the program argument list.

exec()

- The `exec` system call family is not simply a function that "invokes" a command.

```
int main(void) {
  printf("before execl ...\n");
  execl("/bin/ls", "/bin/ls", NULL);
  printf("after execl ...\n");
  return 0;
}
```

WHAT?!
The shell prompt appears!

```
$./exec_example
before execl ...
exec_example
exec_example.c
$ _
```

The output says:
(1) The gray code block **is not reached**!
(2) The process is **terminated**!

WHY IS THAT?!

exec()

- The **exec** system call family is not simply a function that “invokes” a command.

```
/* code of program exec_example */

int main(void) {

  printf("before execl ...\n");

  execl("/bin/ls", "/bin/ls", NULL);

  printf("after execl ...\n");

  return 0;
}
```

Address Space of the process

exec()

- The **exec** system call family is not simply a function that "invokes" a command.

```
/* Code of program "ls" */

int main(int argc, char ** argv)
{
    ......
    exit(0);
}
```

Address Space of the process

exec() loads program "ls" into the memory of this process

exec()

- The **exec** system call family is not simply a function that "invokes" a command.

```
/* Code of program "ls" */

int main(int argc, char ** argv)
{
    ......
    exit(0);
}
```

Address Space of the process

The "**return**" or the "**exit()**" statement in "**/bin/ls**" will terminate the process…

Therefore, it is certain that the process cannot go back to the old program!

exec() Summary

- The process is changing the code that is executing and never returns to the original code.
  - The last two lines of codes are therefore not executed.
- The process that calls an exec* system call will replace user-space info, e.g.,
  - Program Code
  - Memory: local variables, global variables, and dynamically allocated memory;
  - Register value: e.g., the program counter;
- But, the kernel-space info of that process is preserved, including:
  - PID;
  - Process relationship;
  - etc.

CPU Scheduler and fork()

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
    printf("I'm the parent.\n");
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

Parent return from fork() first

```
$ ./fork_example_2
before fork ...
result = 1235
I'm the parent.
My PID is 1234
program terminated.
result = 0
I'm the child.
My PID is 1235
program terminated.
$ _
```

Child return from fork() first

```
$ ./fork_example_2
before fork ...
result = 0
I'm the child.
My PID is 1235
result = 1235
program terminated.
I'm the parent.
My PID is 1234
program terminated.
$ _
```

并发执行，所以输出顺序不确定

wait(): Sync Parent with Child

一定要让“白发人送黑发人”

```c
int main(void) {
  int result;
  printf("before fork ...\n");
  result = fork();
  printf("result = %d.\n", result);

  if(result == 0) {
    printf("I'm the child.\n");
    printf("My PID is %d\n", getpid());
  }
  else {
     printf("I'm the parent.\n");
    wait(NULL);
    printf("My PID is %d\n", getpid());
  }

  printf("program terminated.\n");
}
```

Parent return from fork() first

```
$ ./fork_example_2
before fork ...
result = 1235
I’m the parent.
result = 0
I’m the child.
My PID is 1235
program terminated.
My PID is 1234
program terminated.
$ _
```

Child return from fork() first

```
$ ./fork_example_2
before fork ...
result = 0
I’m the child.
My PID is 1235
result = 1235
program terminated.
I’m the parent.
My PID is 1234
program terminated.
$ _
```

wait() 系统调用会让 父进程阻塞，直到 子进程结束。

这样就强制保证：子进程先执行完，父进程再继续。

输出顺序就确定了，不再依赖 CPU 调度器。

如果父进程比子进程先结束，子进程就会变成 孤儿进程，被 init 或 systemd 收养。

如果子进程结束了，但父进程没调用 wait()，子进程会变成 僵尸进程 (zombie)，占用 PID 和少量内核资源。

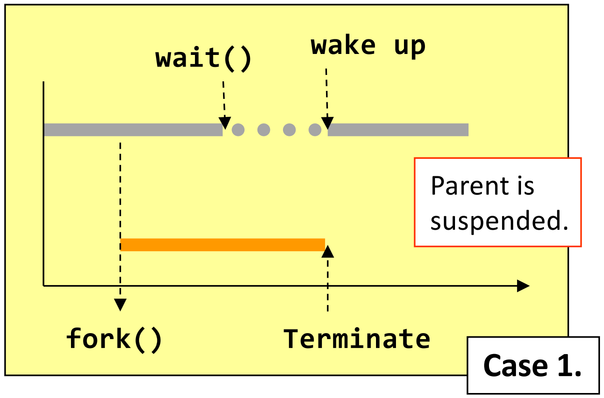
wait() 解决了这两个问题，同时还提供了同步机制（父进程等子进程结束再做后续工作）。

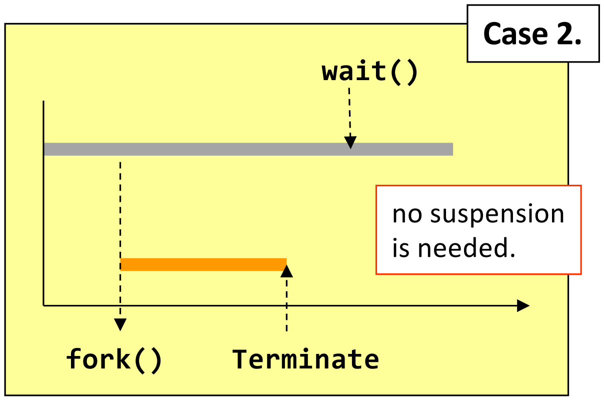
父进程调用 wait() 时，会进入 等待 (waiting) 状态，直到 任意一个子进程结束。

wait()

- wait() suspends the calling process to waiting
- wait() returns when
  - one of its child processes changes from running to terminated.

- Return immediately (i.e., does nothing) if
  - It has no children
  - Or a child terminates before the parent calls wait for





wait() v.s. waitpid()

- wait()
  - Wait for any one of the child processes
  - Detect child termination only
- waitpid()
  - Depending on the parameters, waitpid() will wait for a particular child only

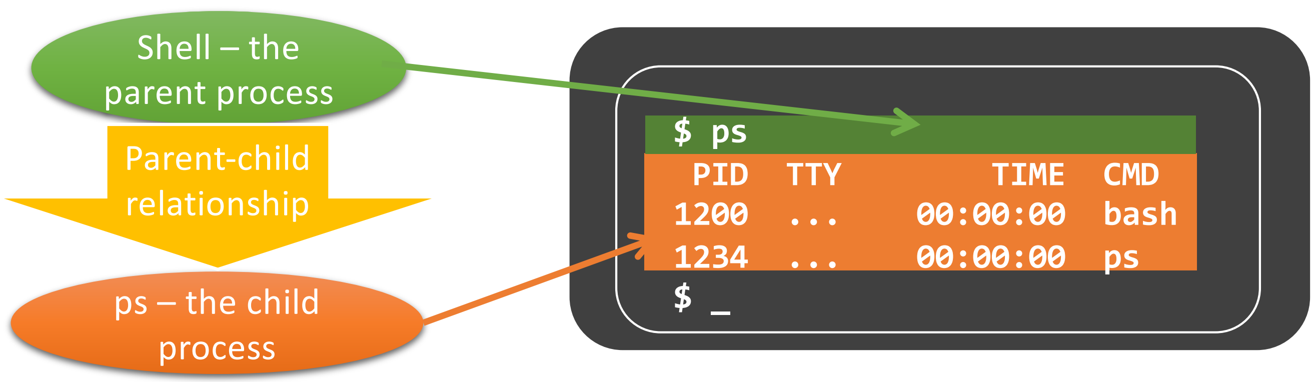
可以指定 非阻塞模式（父进程不会被卡住，可以继续做别的事）。

  - Depending on the parameters, waitpid() can detect different status changes of the child (resume/stop by a signal)

可以检测子进程的 不同状态变化（比如收到信号后暂停/恢复），而不仅仅是退出。

Implement Shell with fork(), exec(), and wait()

- A shell is a CLI
  - Bash in linux
  - invokes a function fork() to create a new process
  - Ask the the child process to exec() the target program
  - Use wait() to wait until the child process terminates

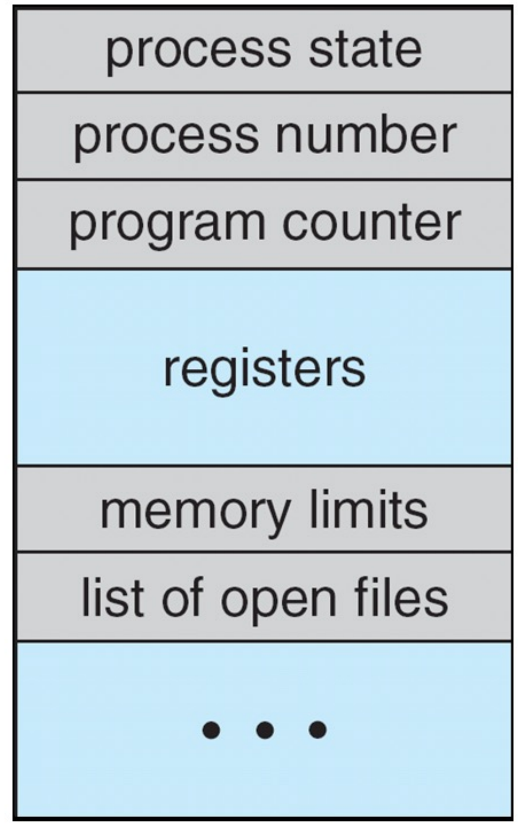


Processes:
Kernel View

Process Control Block (PCB)

Information associated with each process

- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- I/O status information



PCB Example: uCore

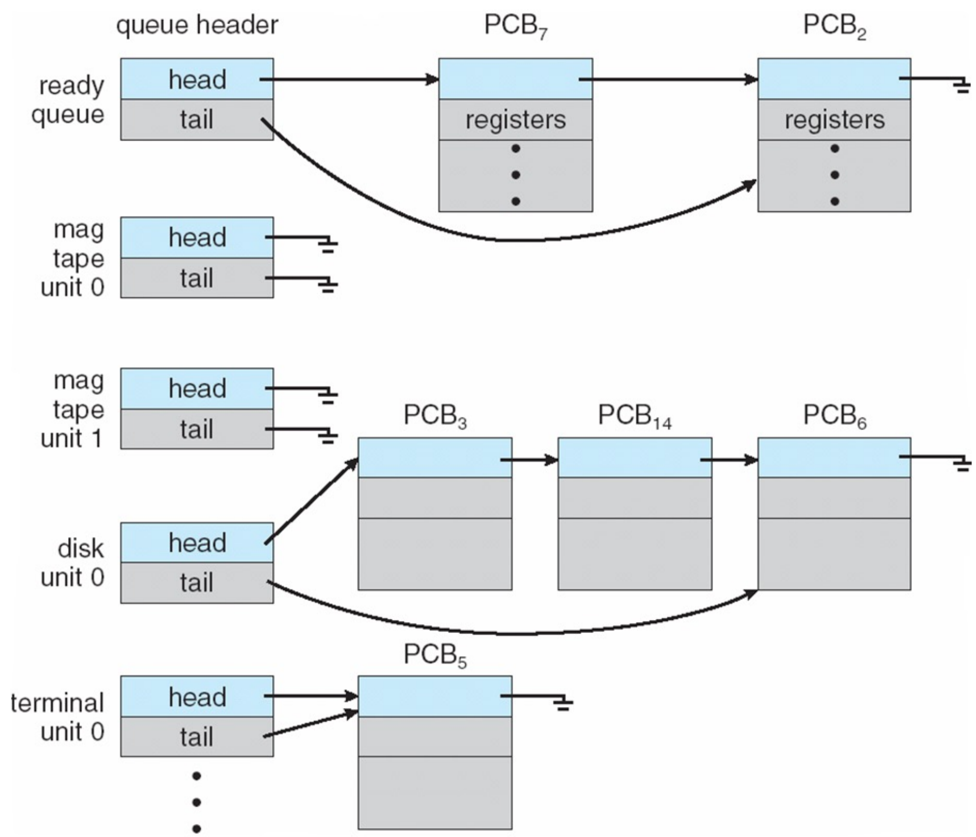
```
/* kern/process/proc.h in ucore */

struct proc_struct {
    enum proc_state state;                // Process state
    int pid;                              // Process ID
    int runs;                             // the running times of Process
    uintptr_t kstack;                     // Process kernel stack
    volatile bool need_resched;           // bool value: need to be rescheduled to release CPU?
    struct proc_struct *parent;           // the parent process
    struct mm_struct *mm;                 // Process's memory management field
    struct context context;               // Switch here to run process
    struct trapframe *tf;                 // Trap frame for current interrupt
    uintptr_t cr3;                        // CR3 register: the base addr of Page Directroy Table(PDT)
    uint32_t flags;                       // Process flag
    char name[PROC_NAME_LEN + 1];         // Process name
    list_entry_t list_link;               // Process link list
```

PCB Example: uCore

```
/* kern/process/proc.h in ucore */

    list_entry_t hash_link;                  // Process hash list
    int exit_code;                           // exit code (be sent to parent proc)
    uint32_t wait_state;                     // waiting state
    struct proc_struct *cptr, *yptr, *optr;  // relations between processes
    struct run_queue *rq;                    // running queue contains Process
    list_entry_t run_link;                   // the entry linked in run queue
    int time_slice;                          // time slice for occupying the CPU
    struct files_struct *filesp;             // the file related info of process
};
```

Ready Queue And I/O Device Queues

- PCBs are linked in multiple queues
  - Ready queue contains all processes in the ready state (to run on this CPU)
  - Device queue contains processes waiting for I/O events from this device
  - Process may migrate among these queues



Threads

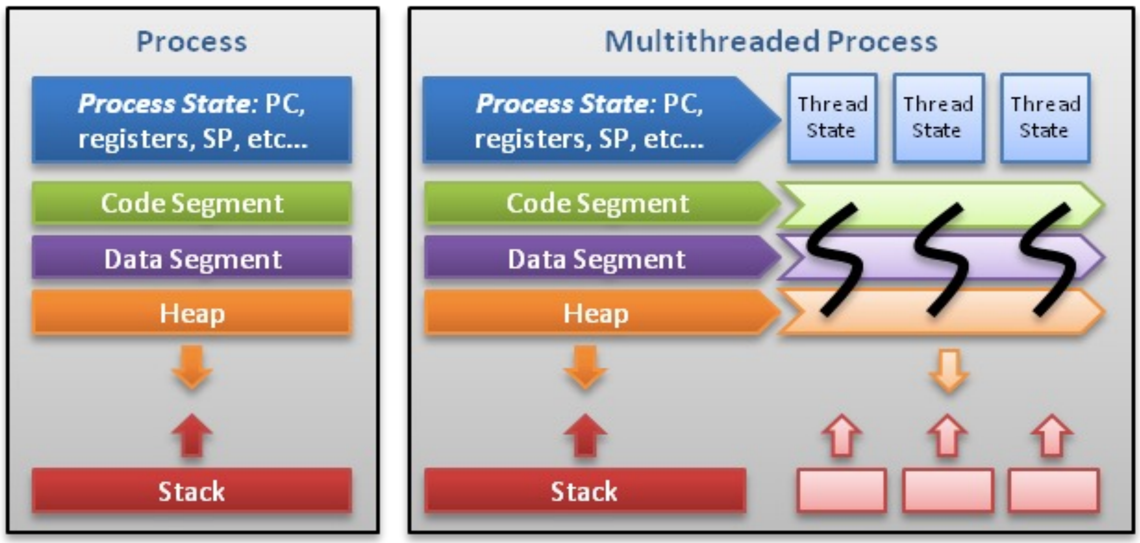
- One process may have more than one threads
    - A single-threaded process performs a single thread of execution
    - A multi-threaded process performs multiple threads of execution "concurrently", thus allowing short response time to user's input even when the main thread is busy

得有空闲的cpu cores，或者time share cpu core

- PCB is extended to include information about each thread

Process and Thread

- Single threaded process and multi-threaded process



Threads contain only necessary information, such as a stack (for local variables, function arguments, return values), a copy of the registers, program counter and any thread-specific data to allow them to be scheduled individually. Other data is shared within the process between all threads.

Switching Between Processes

- Once a process runs on a CPU, it only gives back the control of a CPU
  - when it makes a system call
  - when it raises an exception
  - when an interrupt occurs
- What if none of these would happen for a long time?
  - Coorperative scheduling: OS will have to wait
    - Early Macintosh OS, old Alto system
  - Non-coorperative scheduling: timer interrupts
    - Modern operating systems

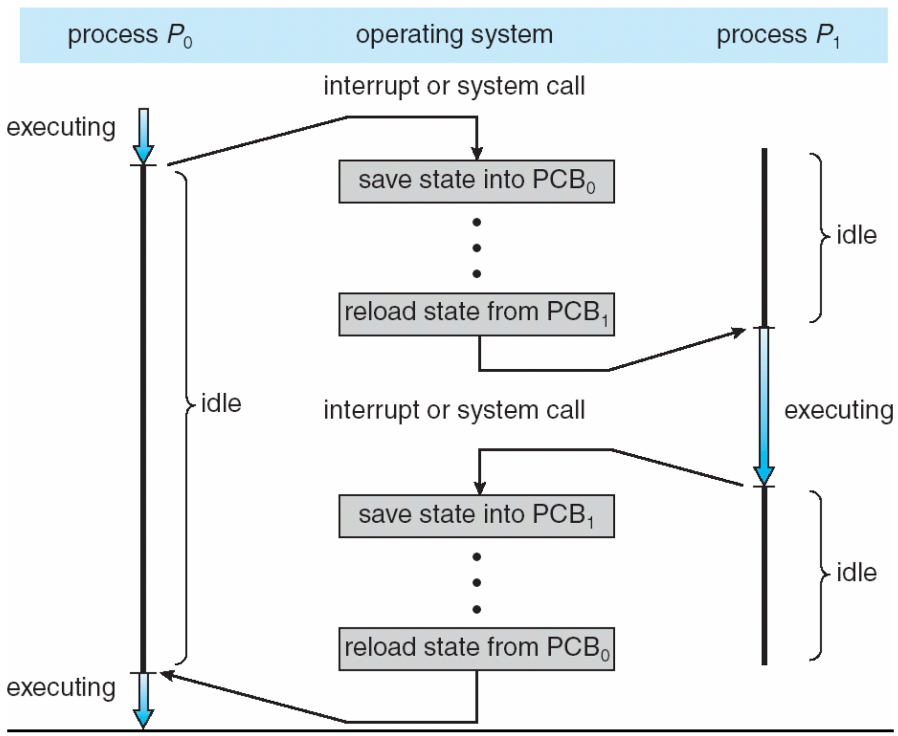
Switching Between Processes (Cont'd)

- When OS kernel regains the control of CPU
  - It first completes the task
    - Serve system call, or
    - Handle interrupt/exception
  - It then decides which process to run next
    - by asking its **CPU scheduler**
    - How does it make decisions?
    - More about CPU scheduler later
  - It performs a **context switch** if the soon-to-be-executing process is different from the previous one

Context Switch

- During context switch, the system must save the state of the old process and load the saved state for the new process
- Context of a process is represented in the PCB
- The time used to do context switch is an overhead of the system; the system does no useful work while switching
  - Time of context switch depends on hardware support
  - Context switch cannot be too frequent

Context Switch (Cont'd)



Context Switch: uCore

```
/* kern/schedule/sched.c */
void schedule(void) {
   bool intr_flag;
   struct proc_struct *next;
   local_intr_save(intr_flag);
   {
      if (current->state == PROC_RUNNABLE)
         sched_class_enqueue(current);

      if ((next = sched_class_pick_next()) != NULL)
         sched_class_dequeue(next);

      if (next != current)
         proc_run(next);
   }
   local_intr_restore(intr_flag);
}
```

```
/* kern/process/proc.c*/



void proc_run(struct proc_struct *proc) {
   if (proc != current) {
      bool intr_flag;
      struct proc_struct *prev = current, *next = proc;
      local_intr_save(intr_flag);
      {
         current = proc;
         lcr3(next->cr3);
         switch_to(&(prev->context), &(next->context));
      }
      local_intr_restore(intr_flag);
   }
}
```

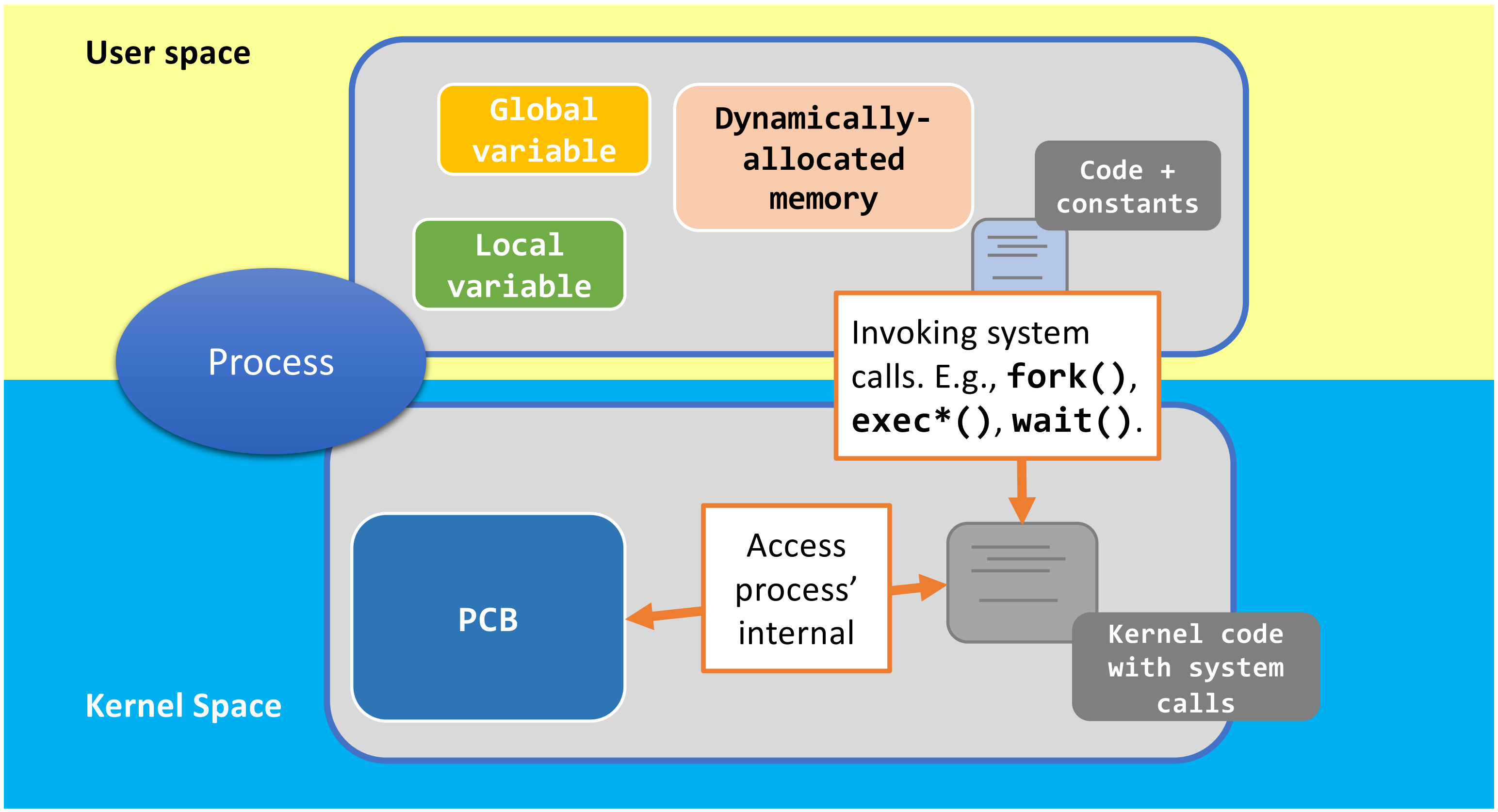
Context Switch: uCore (Cont’d)

```
/* kern/process/switch.S */
.globl switch_to
switch_to:
    # save from's registers
    STORE ra, 0*REGBYTES(a0)
    STORE sp, 1*REGBYTES(a0)
    STORE s0, 2*REGBYTES(a0)
    STORE s1, 3*REGBYTES(a0)
    STORE s2, 4*REGBYTES(a0)
    STORE s3, 5*REGBYTES(a0)
    STORE s4, 6*REGBYTES(a0)
    STORE s5, 7*REGBYTES(a0)
    STORE s6, 8*REGBYTES(a0)
    STORE s7, 9*REGBYTES(a0)
    STORE s8, 10*REGBYTES(a0)
    STORE s9, 11*REGBYTES(a0)
    STORE s10, 12*REGBYTES(a0)
    STORE s11, 13*REGBYTES(a0)
```

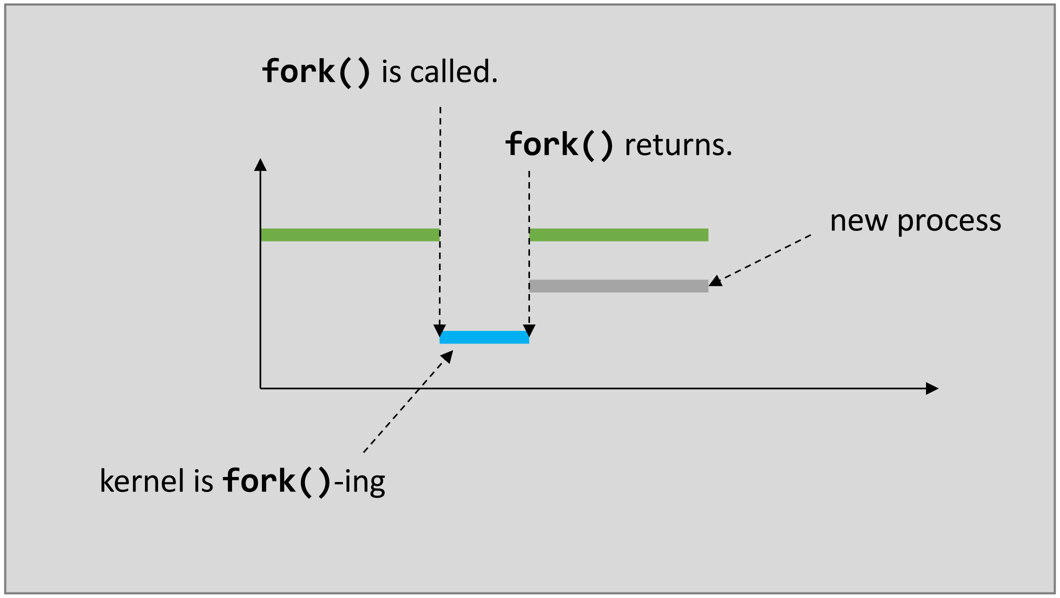
```
    # restore to's registers
    LOAD ra, 0*REGBYTES(a1)
    LOAD sp, 1*REGBYTES(a1)
    LOAD s0, 2*REGBYTES(a1)
    LOAD s1, 3*REGBYTES(a1)
    LOAD s2, 4*REGBYTES(a1)
    LOAD s3, 5*REGBYTES(a1)
    LOAD s4, 6*REGBYTES(a1)
    LOAD s5, 7*REGBYTES(a1)
    LOAD s6, 8*REGBYTES(a1)
    LOAD s7, 9*REGBYTES(a1)
    LOAD s8, 10*REGBYTES(a1)
    LOAD s9, 11*REGBYTES(a1)
    LOAD s10, 12*REGBYTES(a1)
    LOAD s11, 13*REGBYTES(a1)

    ret
```

fork(), exec(), wait()
Kernel View

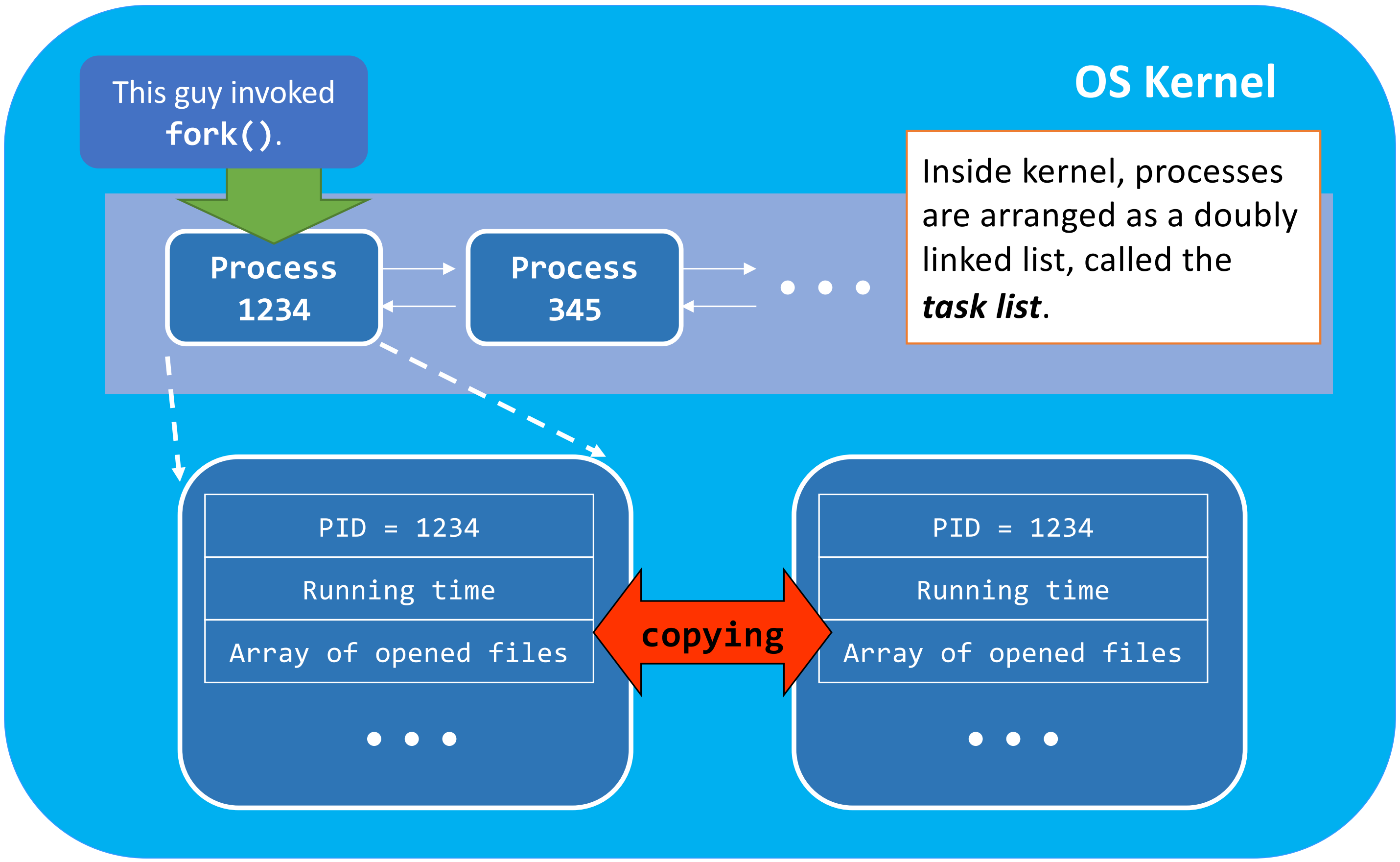
Recall: fork(), exec(), and wait()



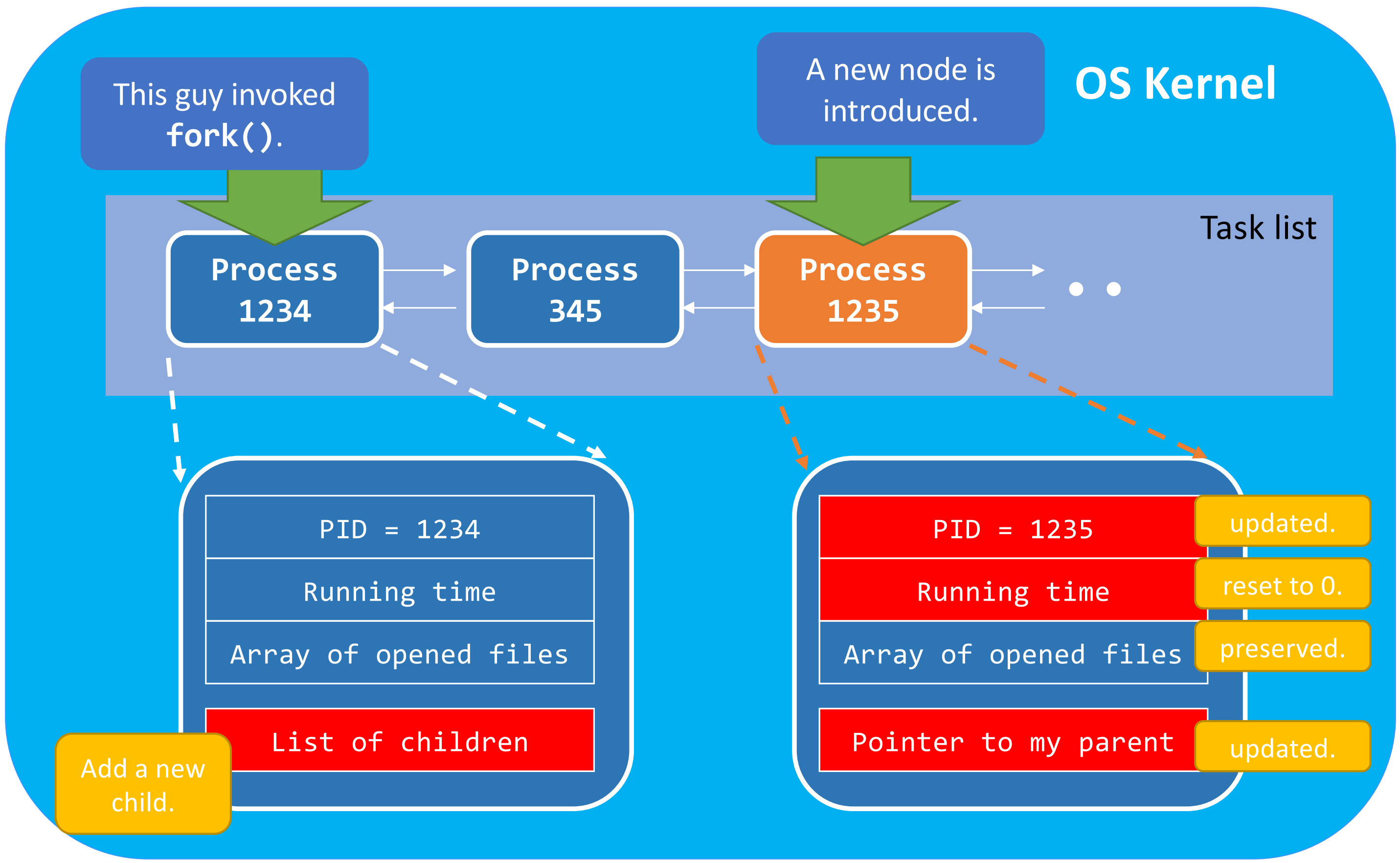
Fork() in User Mode



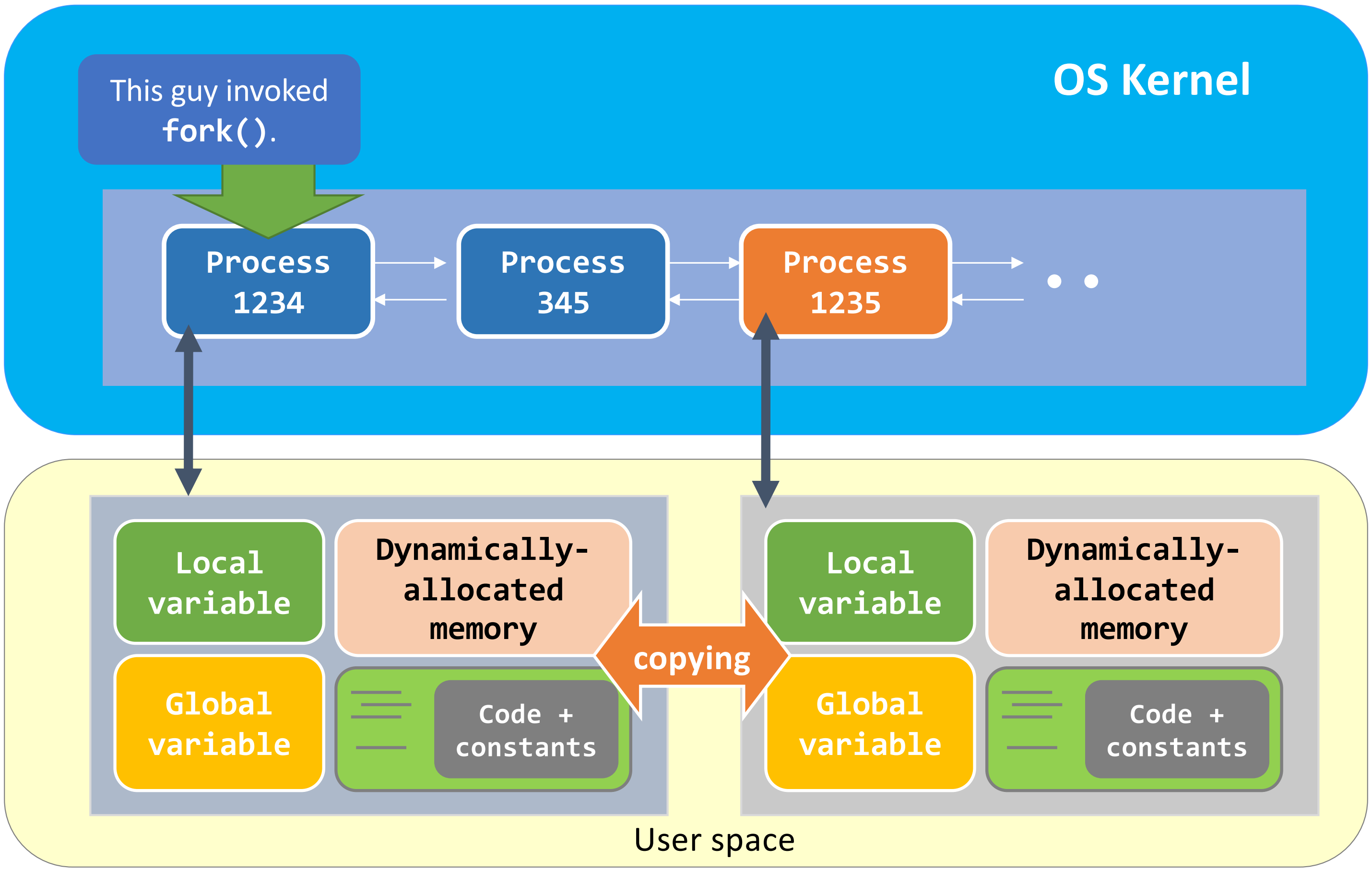
fork(): Kernel View



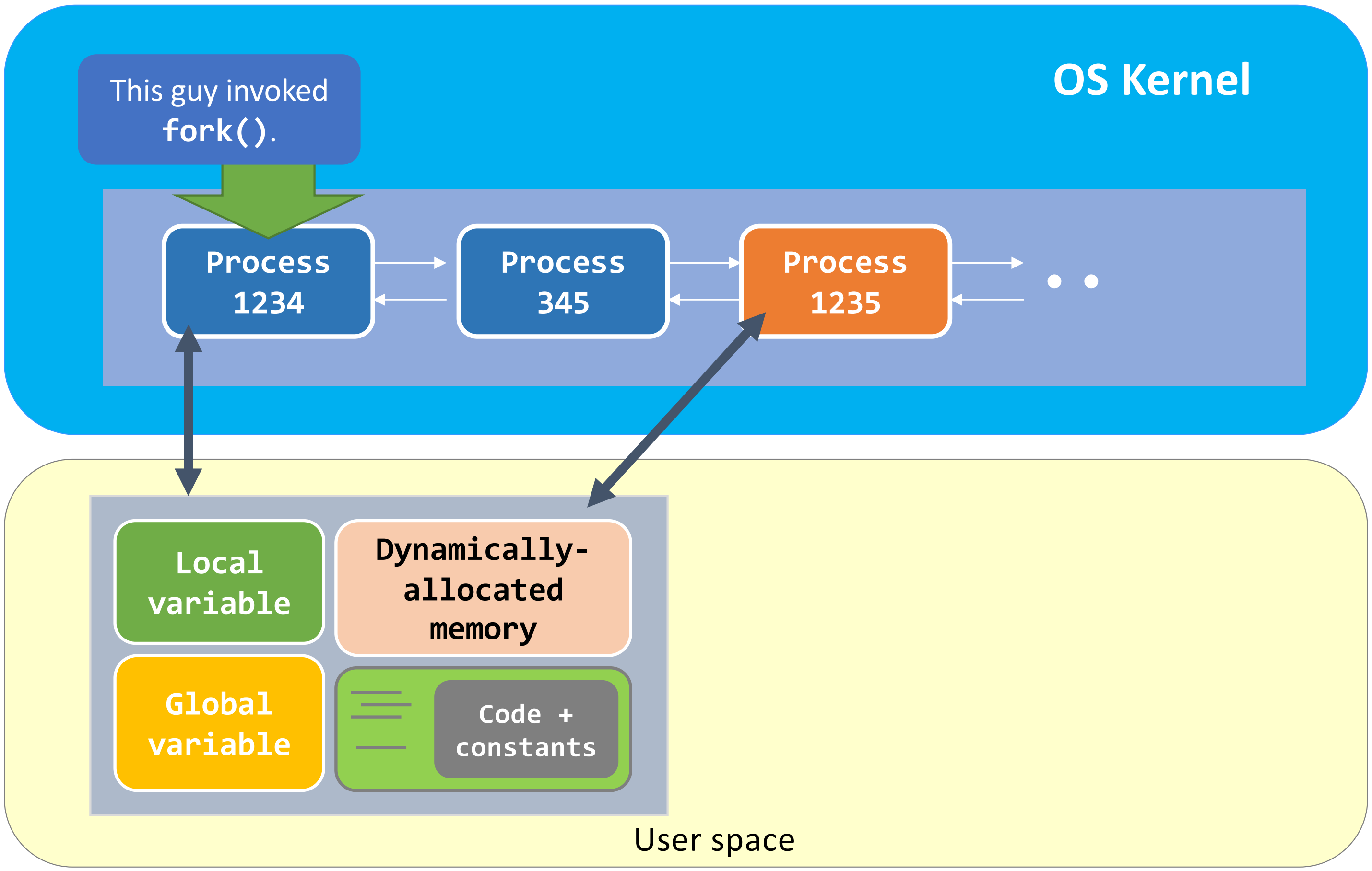
fork(): Kernel View



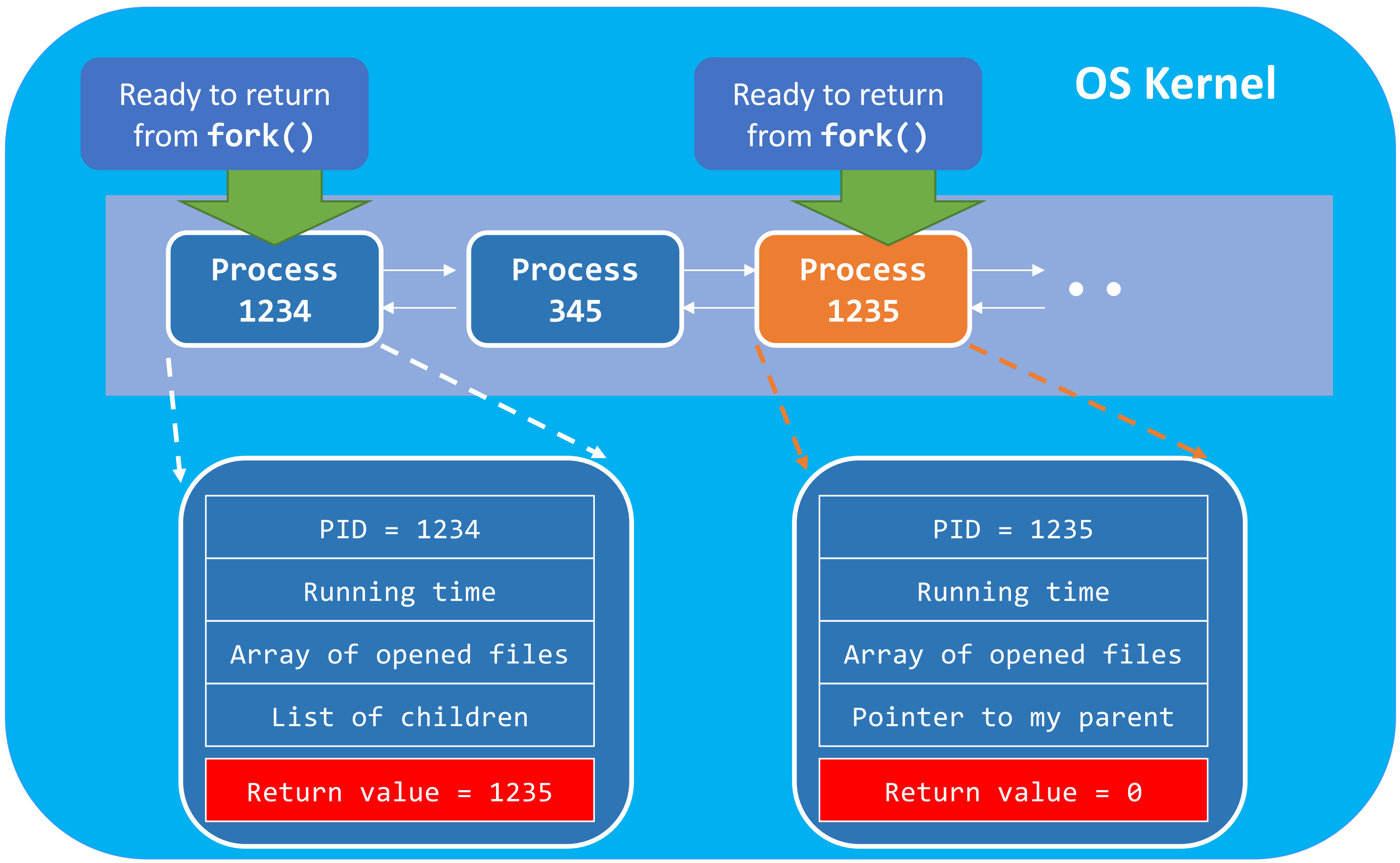
Case 1: Duplicate Address Space



Case 2: Copy on Write



fork(): Kernel View



fork(): Opened Files

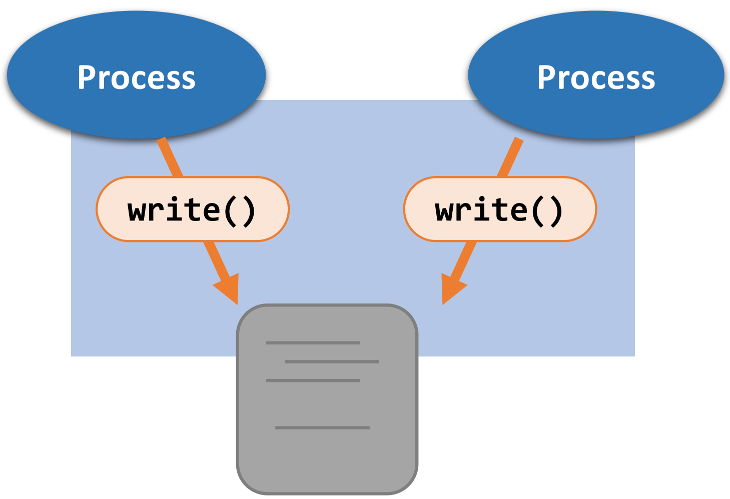
- Array of opened files contains:

Array Index	Description
0	Standard Input Stream; **`FILE *stdin;`**
1	Standard Output Stream; **`FILE *stdout;`**
2	Standard Error Stream; **`FILE *stderr;`**
3 or beyond	Storing the files you opened, e.g., **`fopen()`**, **`open()`**, etc.

- That's why a parent process shares the same terminal output stream as the child process.

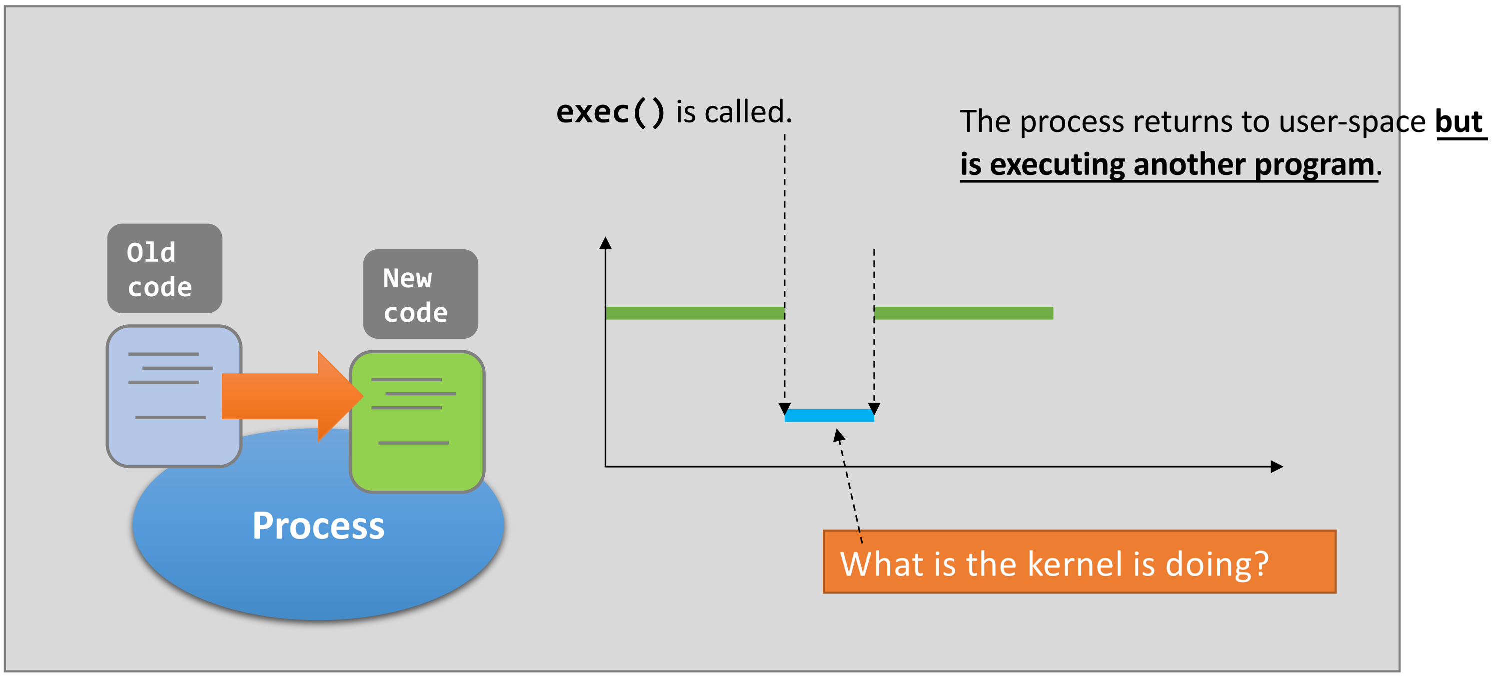
fork(): Opened Files

- What if two processes, sharing the same opened file, write to that file together?

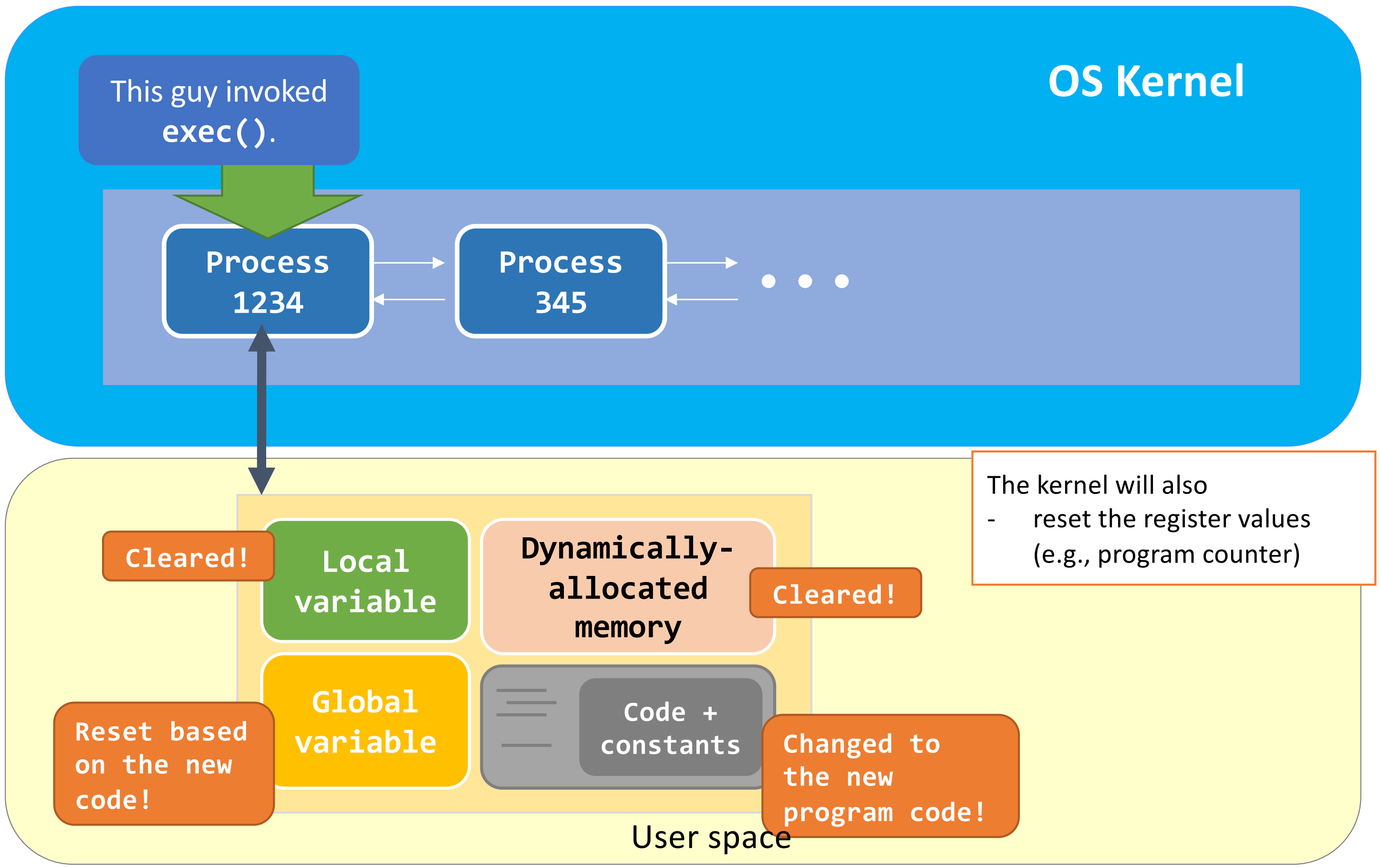


Let's see what will happen when the program finishes running!

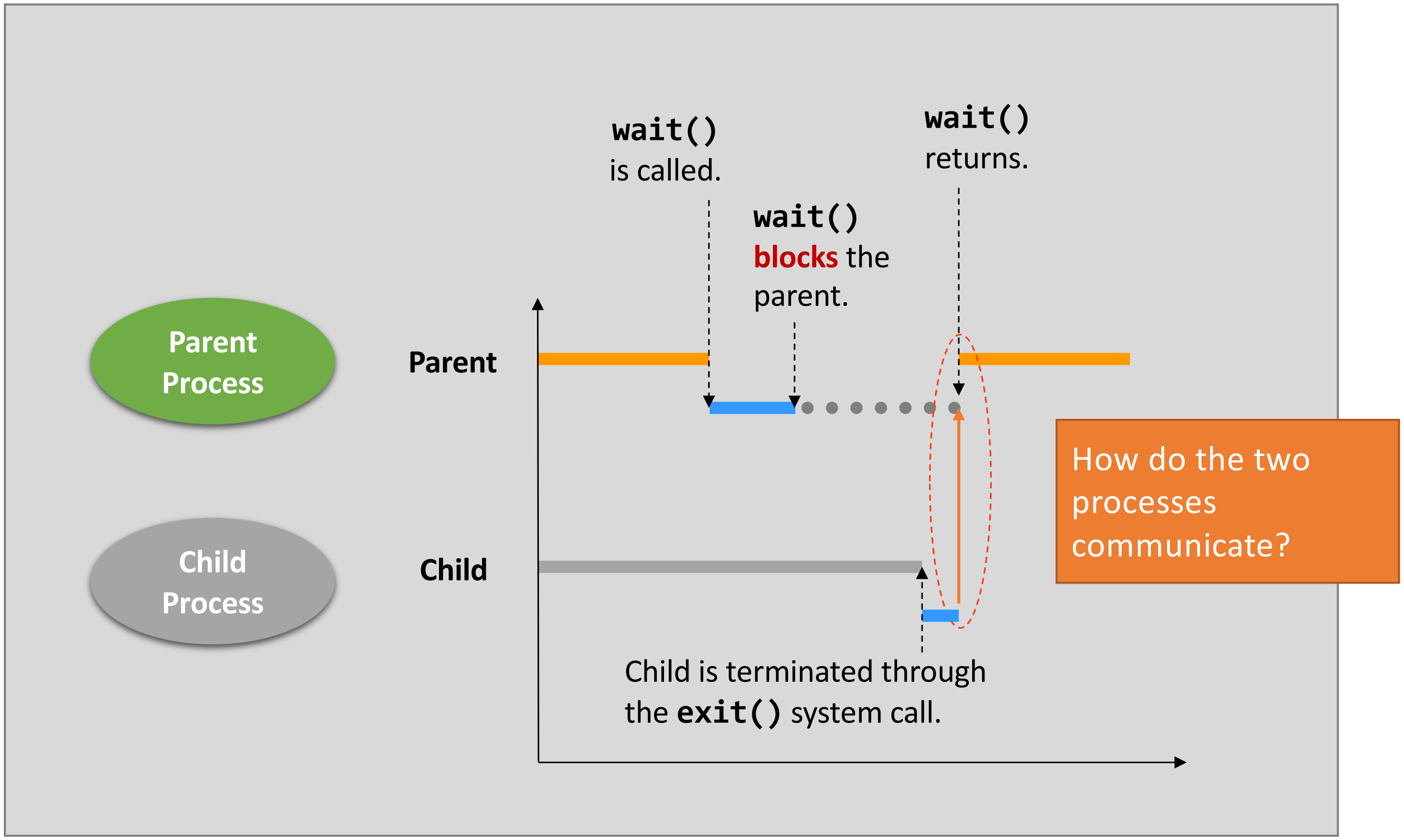
exec() in the User Mode



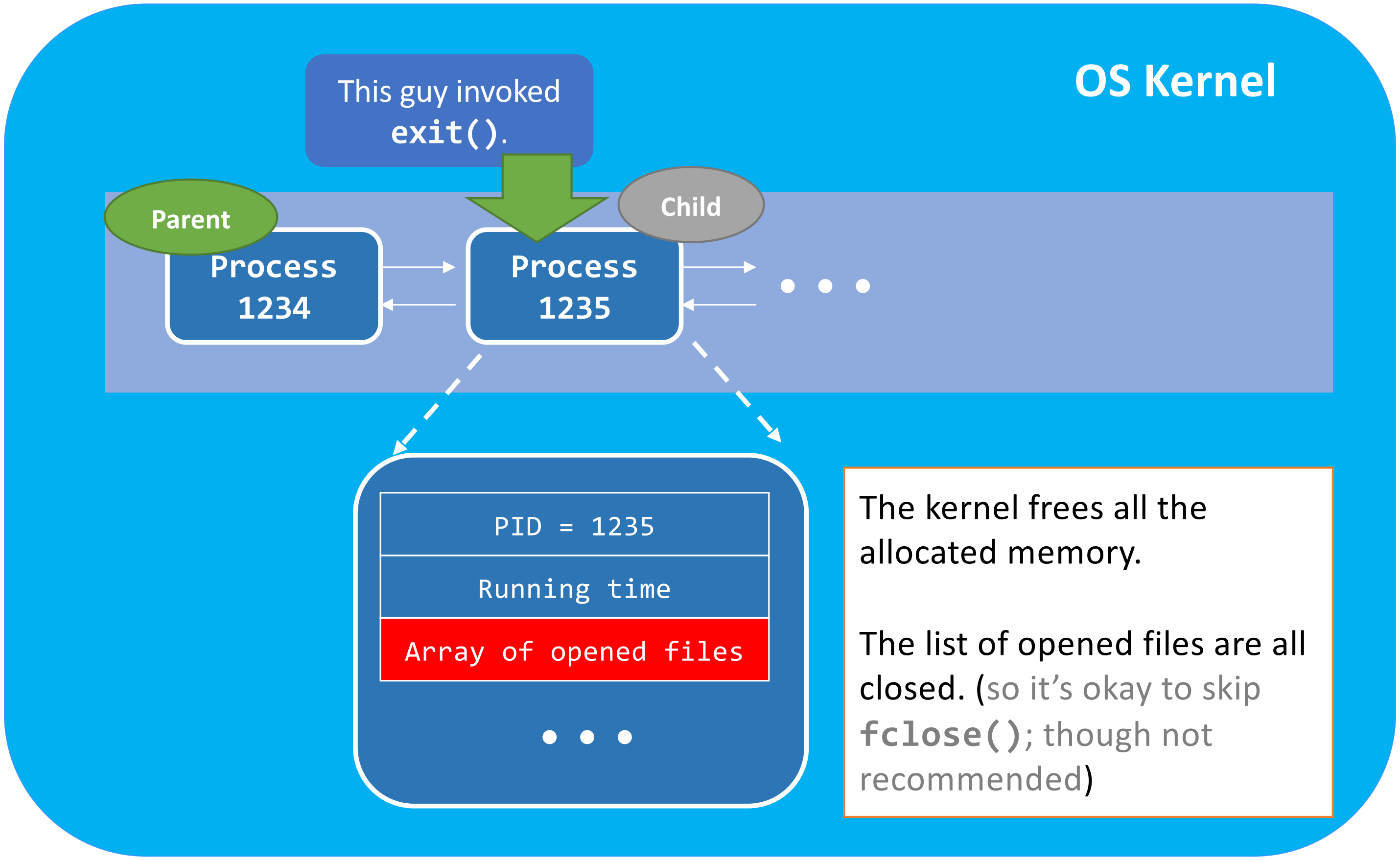
exec(): Kernel View



wait() and exit()



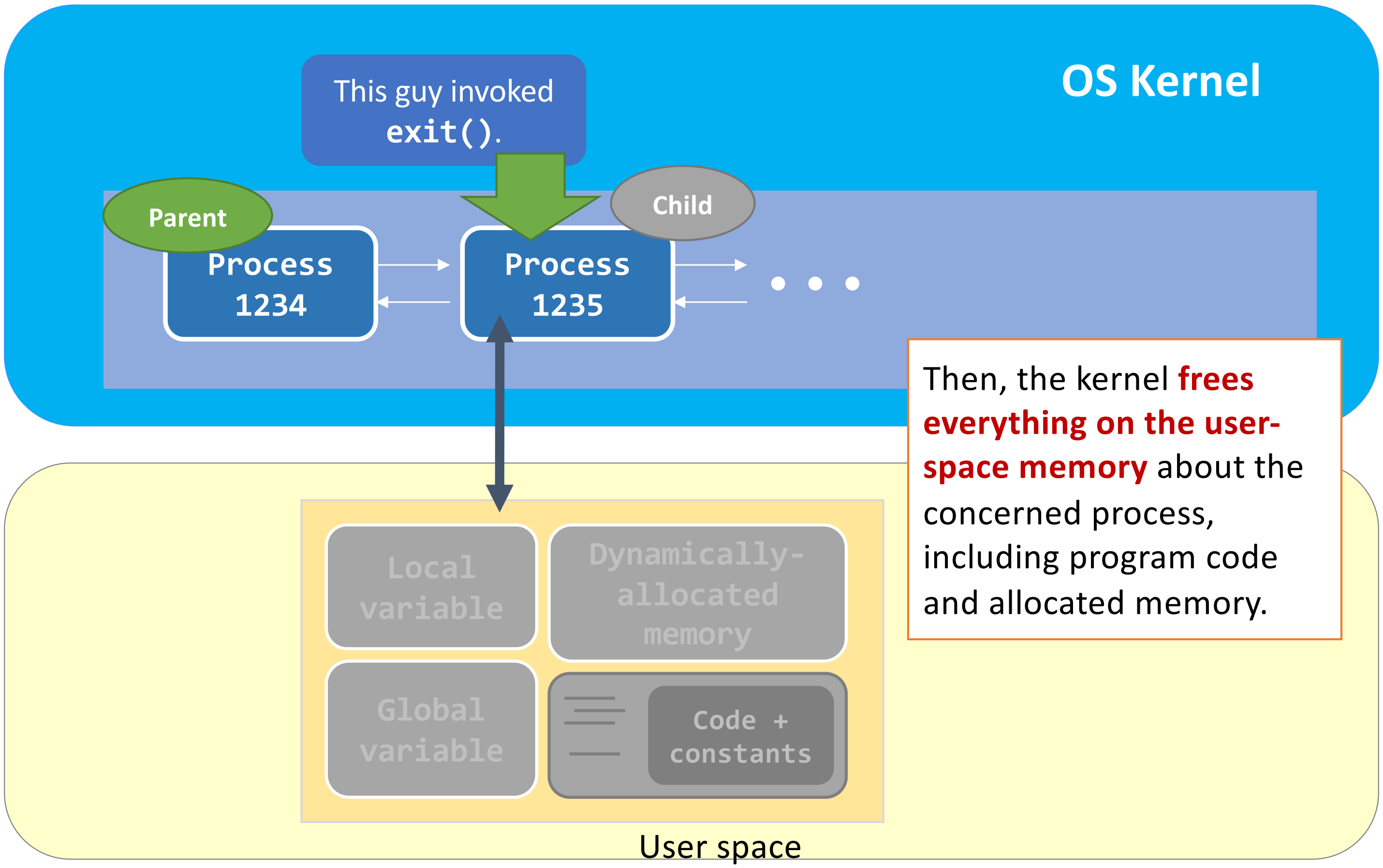
exit(): Kernel View



The kernel frees all the allocated memory.

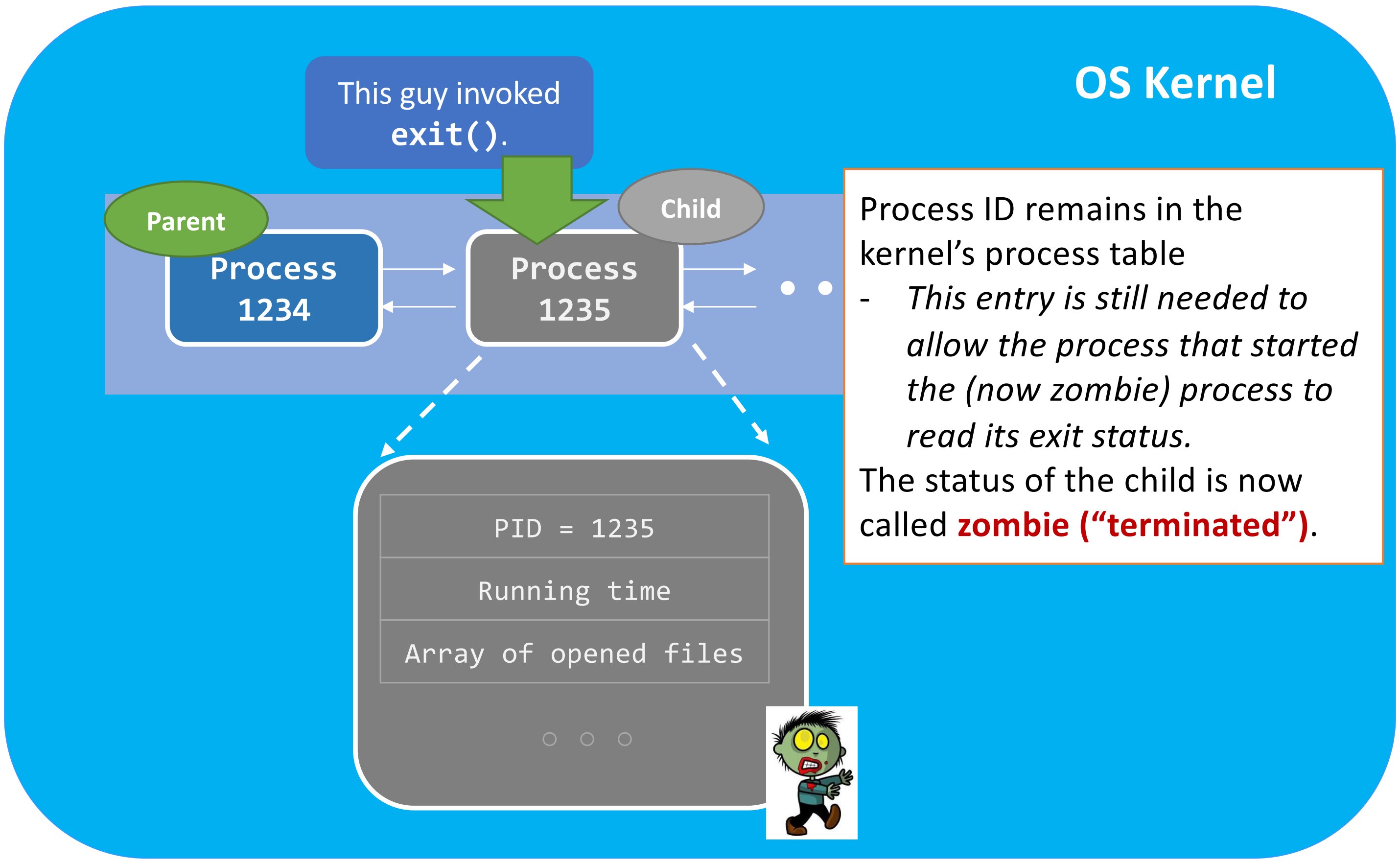
The list of opened files are all closed. (so it's okay to skip `fclose()`; though not recommended)

exit(): Kernel View



Then, the kernel **frees everything on the user-space memory** about the concerned process, including program code and allocated memory.

exit(): Kernel View

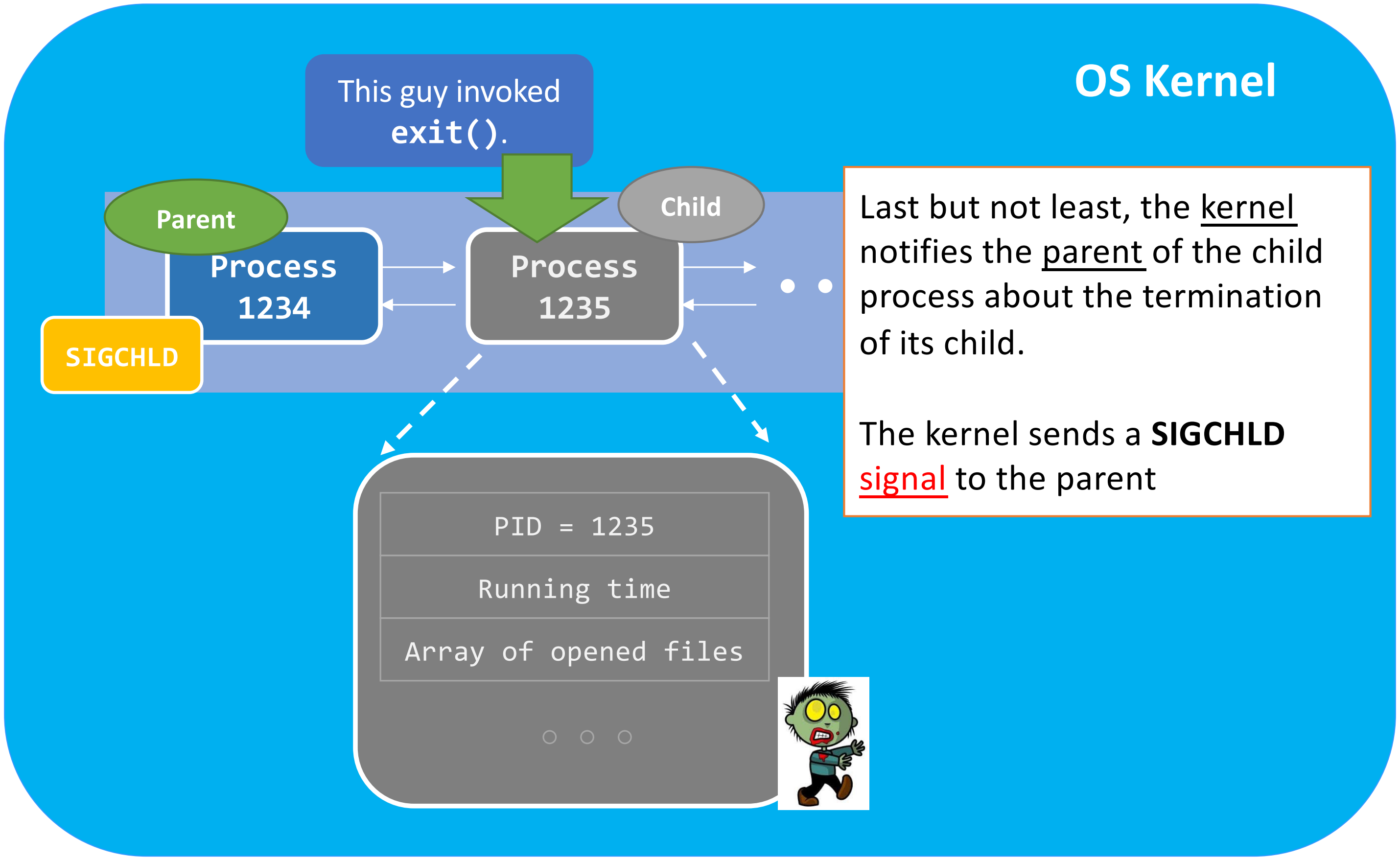


Process ID remains in the kernel's process table

- *This entry is still needed to allow the process that started the (now zombie) process to read its exit status.*

The status of the child is now called **zombie (“terminated”)**.

exit(): Kernel View



Last but not least, the kernel notifies the parent of the child process about the termination of its child.

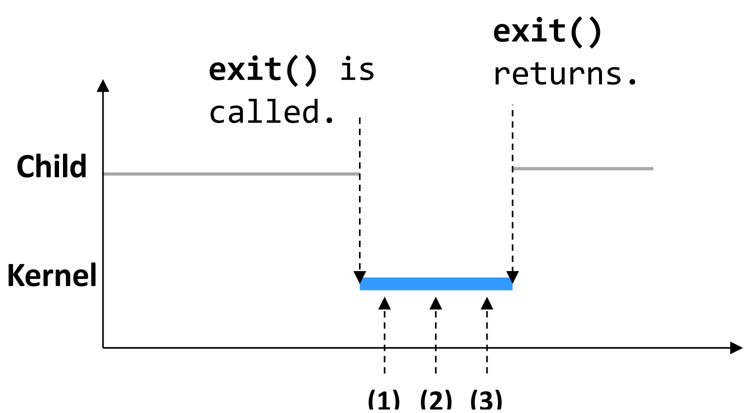
The kernel sends a **SIGCHLD** signal to the parent

exit(): Summary

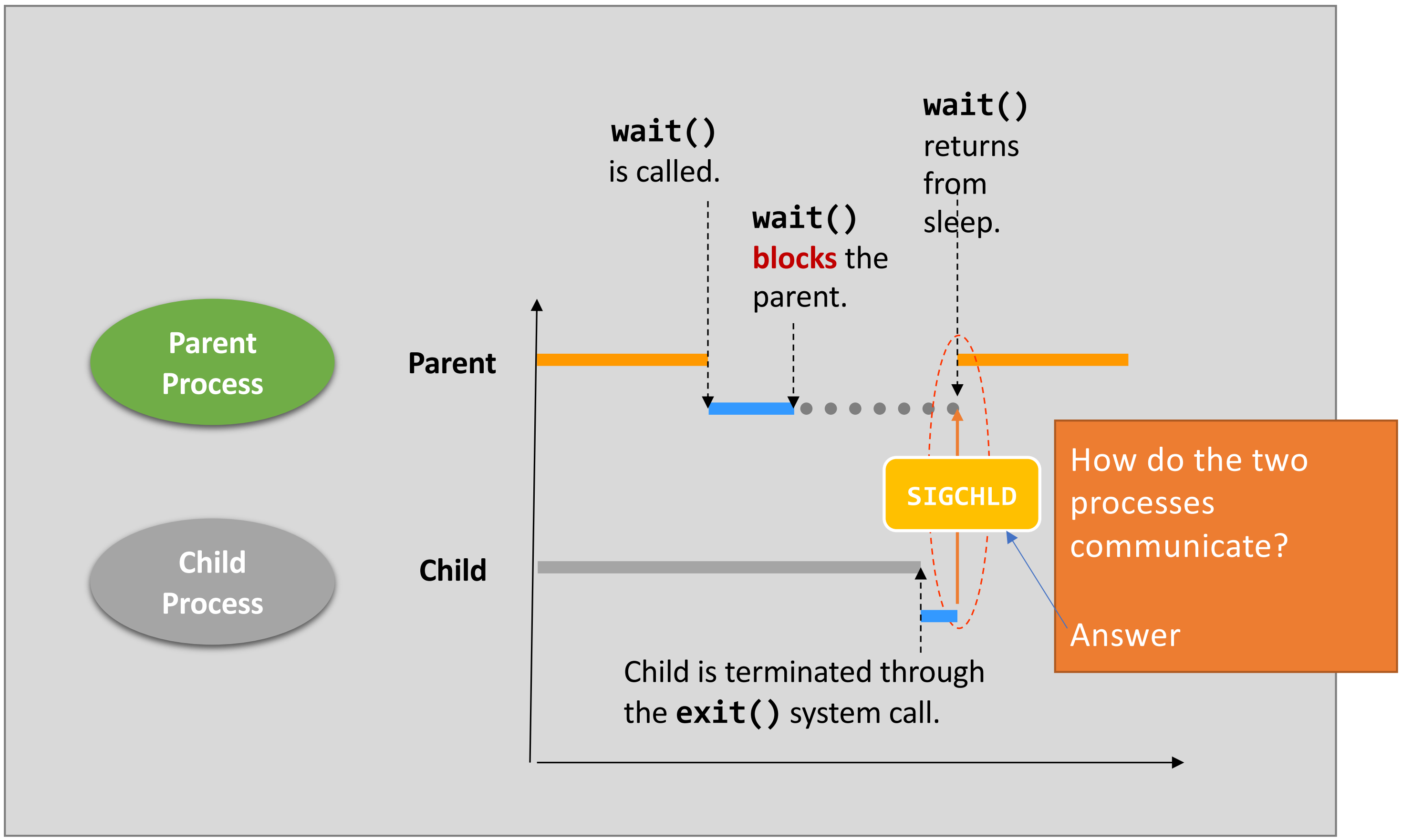
Step (1) Clean up most of the allocated kernel-space memory (e.g., process's running time info).

Step (2) Clean up the exit process's user-space memory.

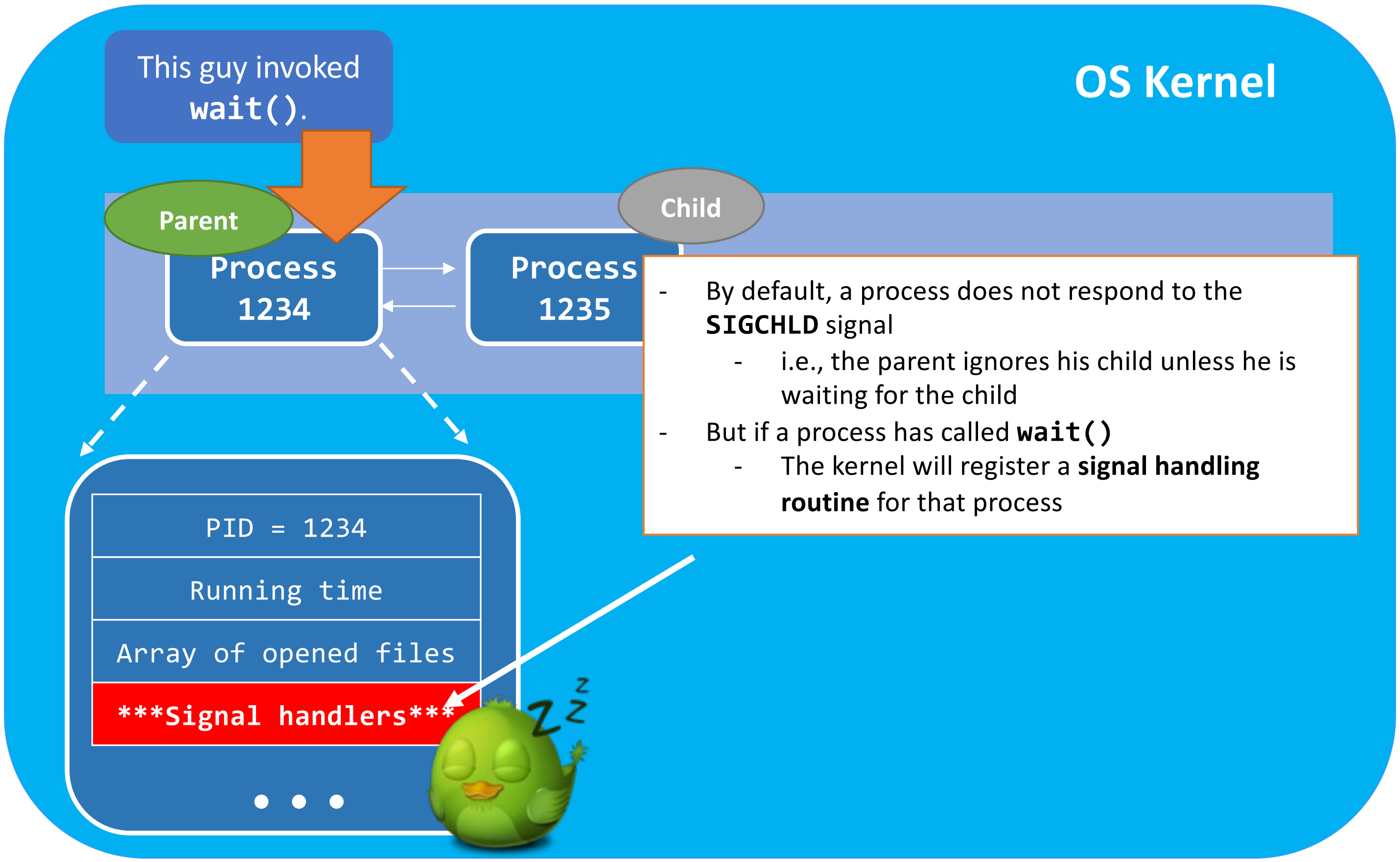
Step (3) Notify the parent with SIGCHLD.



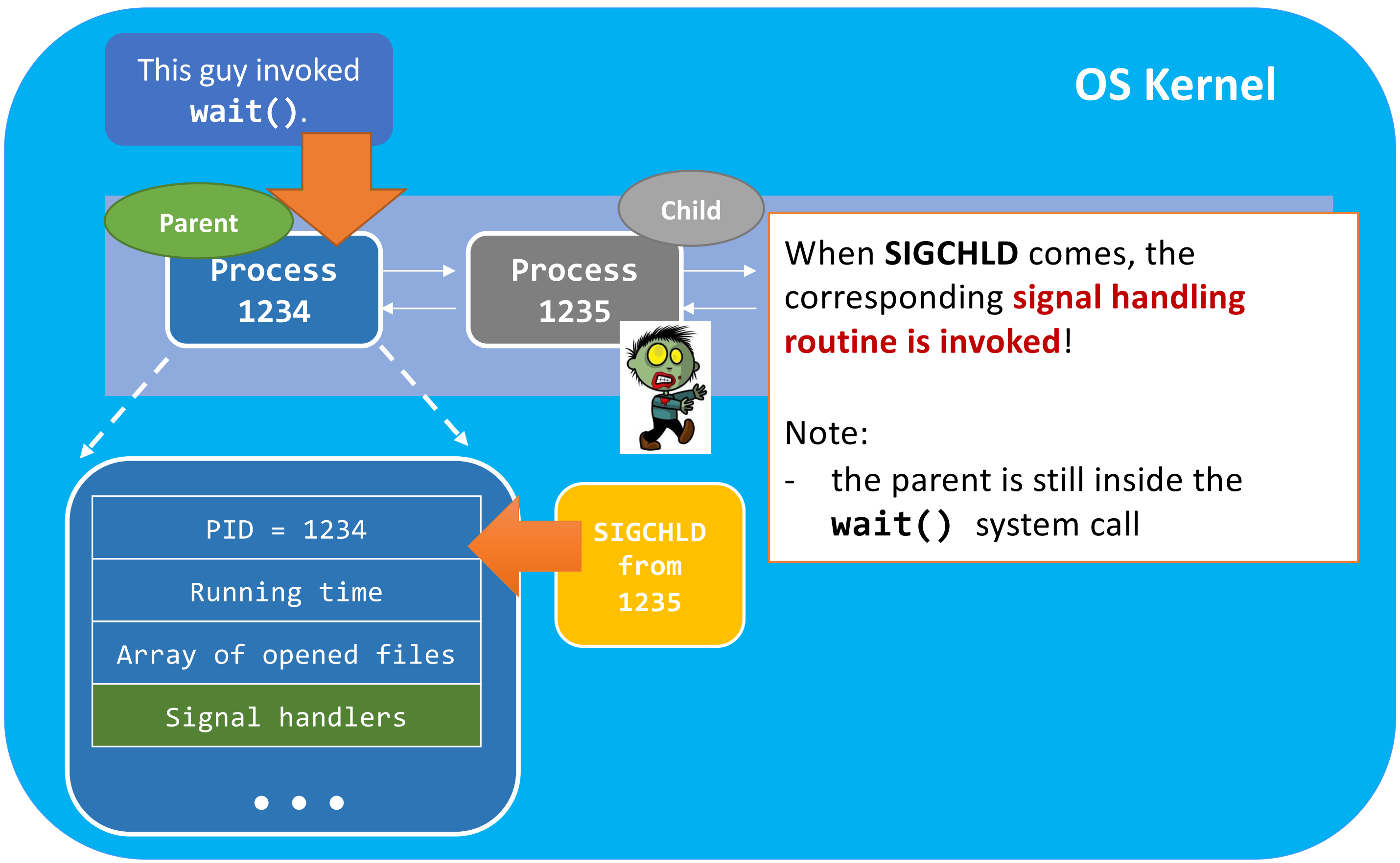
wait() and exit()



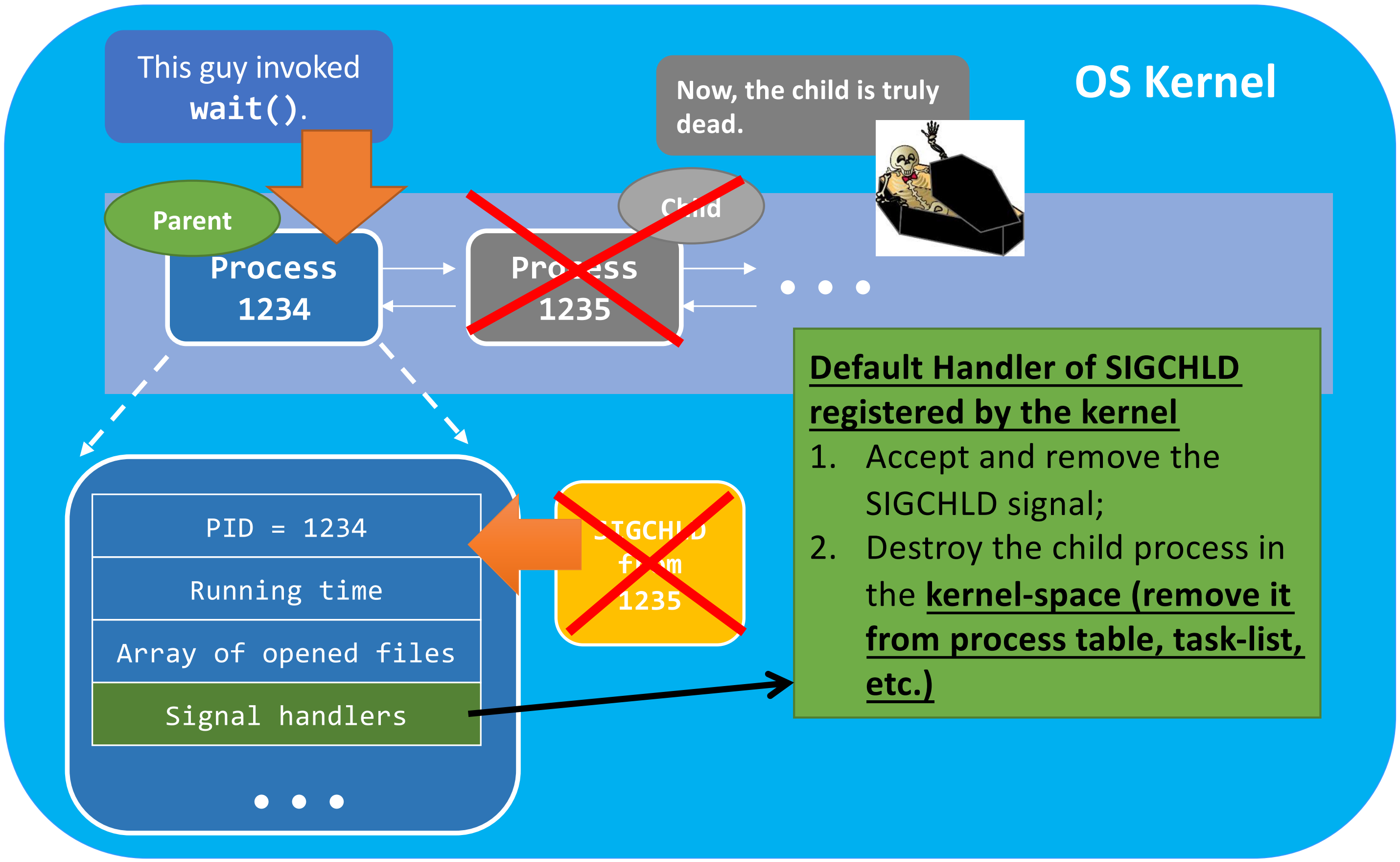
wait() Kernel View



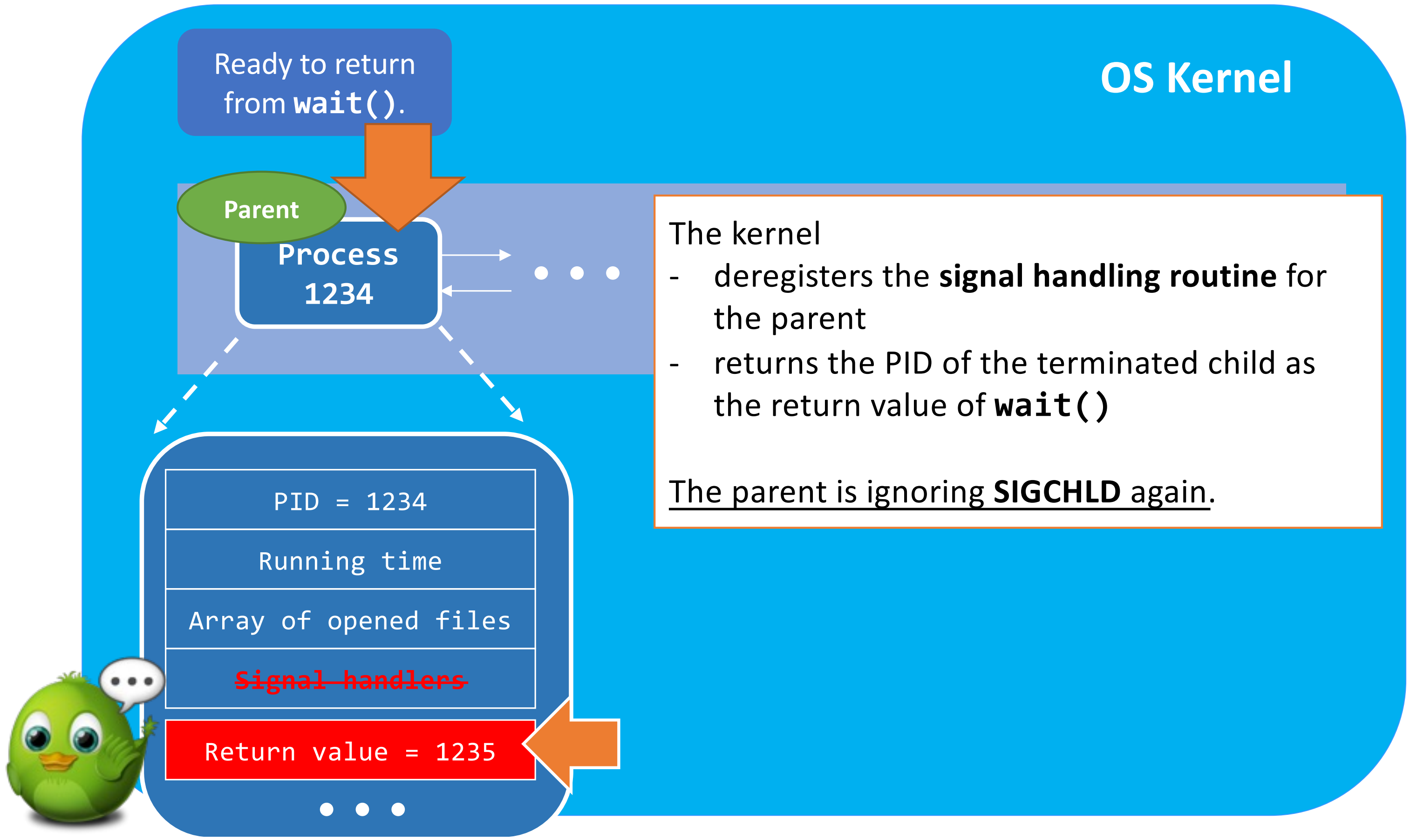
wait() Kernel View



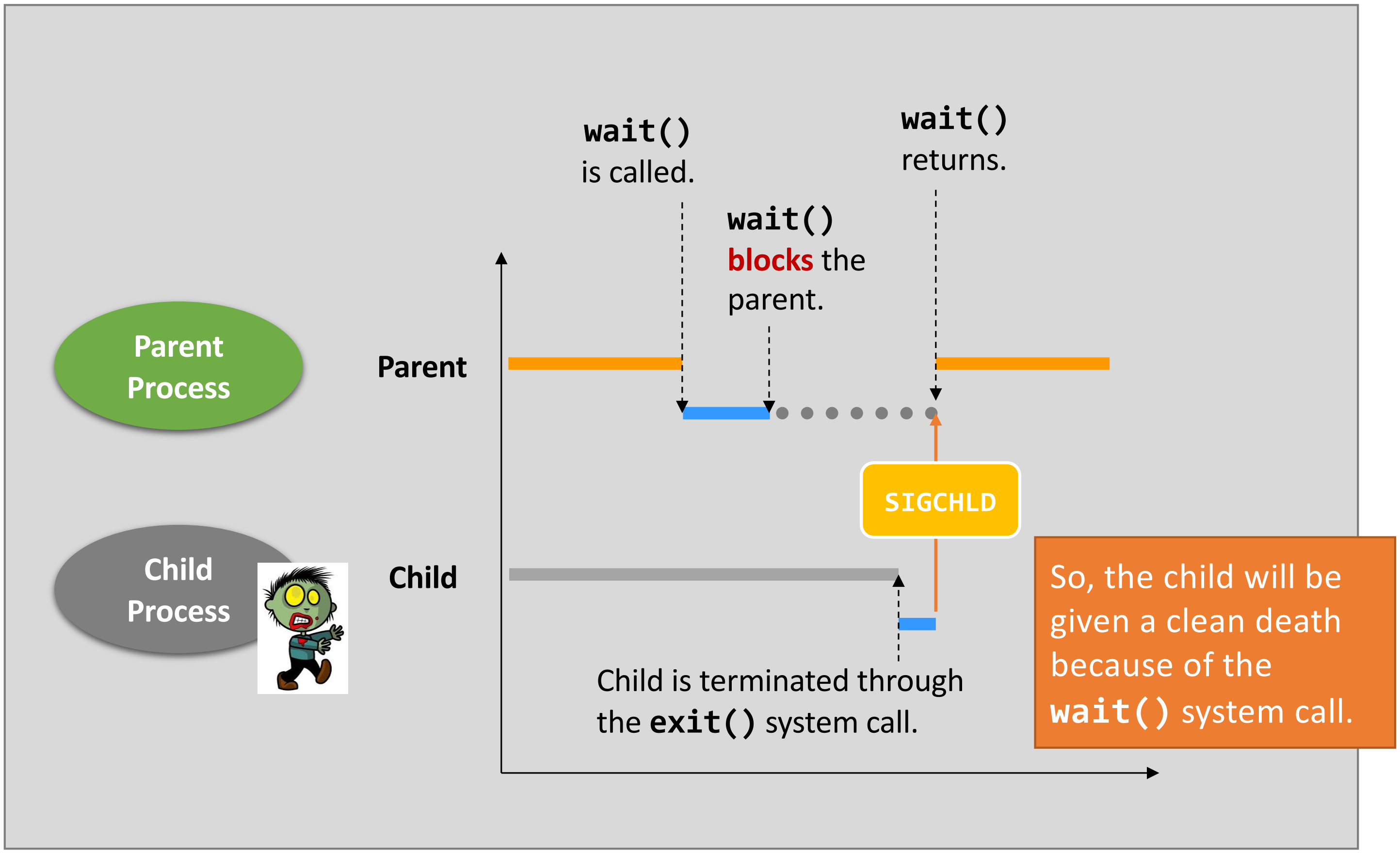
wait() Kernel View



wait() Kernel View

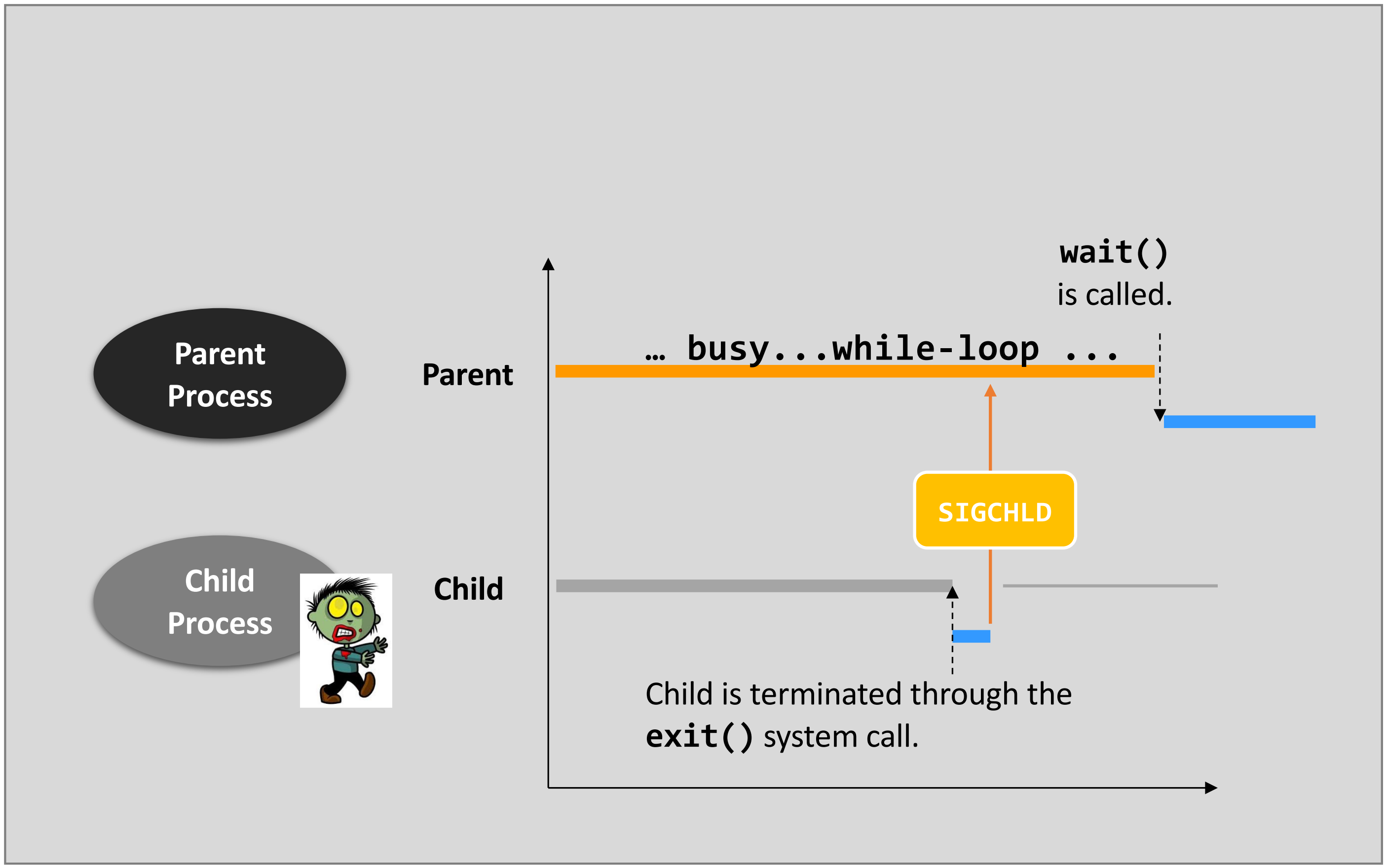


Normal Case

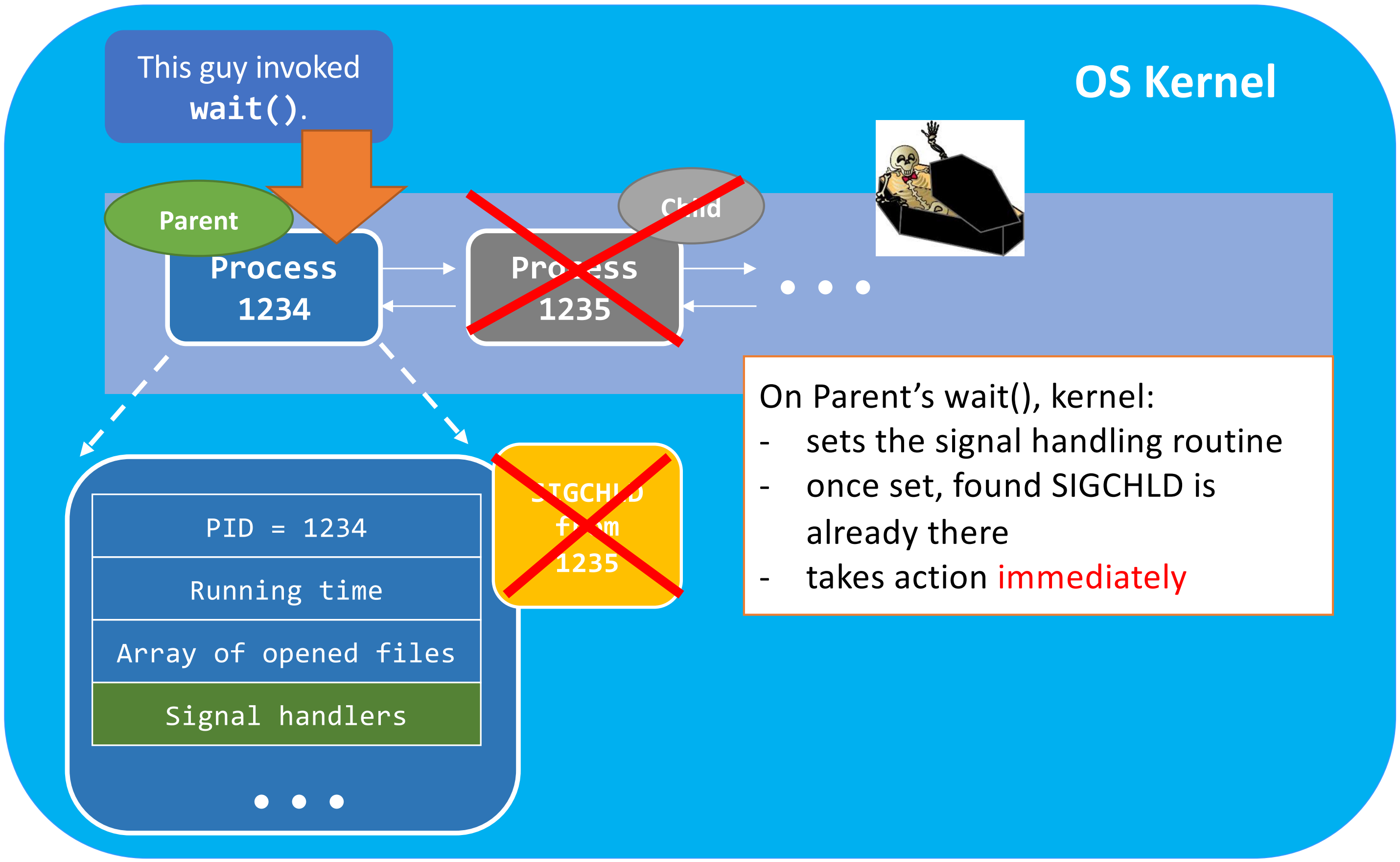


wait()
is called.
wait()
blocks the
parent.
wait()
returns.
Parent
Process
Parent
SIGCHLD
Child
Process
Child
Child is terminated through
the exit() system call.
So, the child will be
given a clean death
because of the
wait() system call.

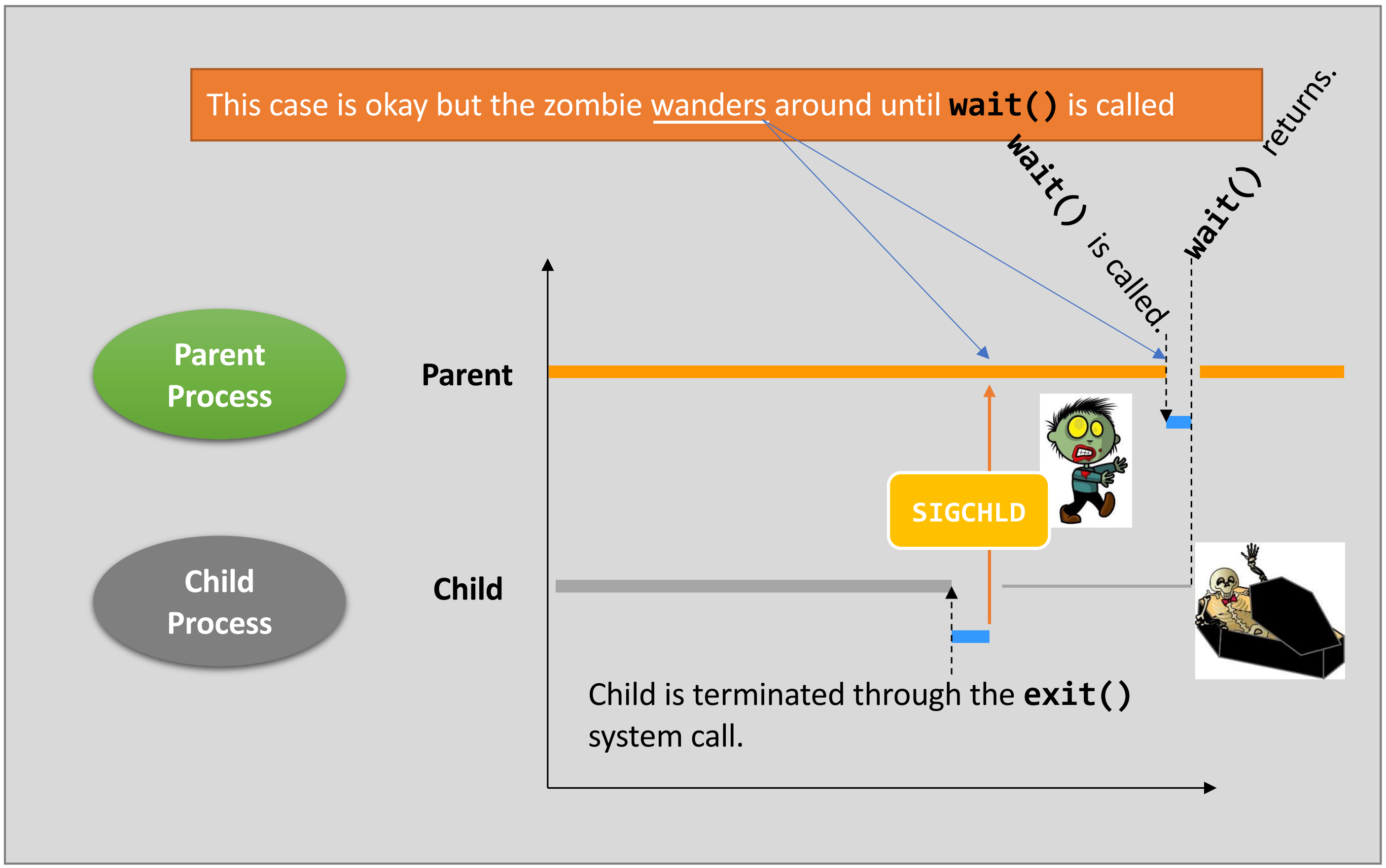
Parent's wait() after Child's exit()



Parent's Wait() after Child's exit()



Parent's wait() after Child's exit()



Summary of wait() and exit()

- **exit()** system call turns a process into a zombie when…
  - The process calls **exit()**.
  - The process returns from **main()**.
  - The process terminates abnormally.
    - The kernel knows that the process is terminated abnormally. Hence, the kernel invokes **exit()** for it.

Summary of wait() and exit()

- **`wait()`** & **`waitpid()`** reap zombie child processes.
  - It is a must that you should never leave any zombies in the system.
  - **`wait()`** & **`waitpid()`** pause the caller until
    - A child terminates/stops, OR
    - The caller receives a signal (i.e., the signal interrupted the `wait()`)
- Linux will label zombie processes as "**<defunct>**".
  - To look for them:

```
$ ps aux | grep defunct
……....  3150 ... [ls] <defunct>
$ _
```

PID of the process

Summary of wait() and exit()

```c
int main(void)
{
    int pid;
    if( (pid = fork()) !=0 ) {
        printf("Look at the status of the child process %d\n", pid);
        while( getchar() != '\n' );
        wait(NULL);
        printf("Look again!\n");
        while( getchar() != '\n' );
    }
    return 0;
}
```

"enter" here

"enter" here

This program requires you to type "enter" twice before the process terminates.

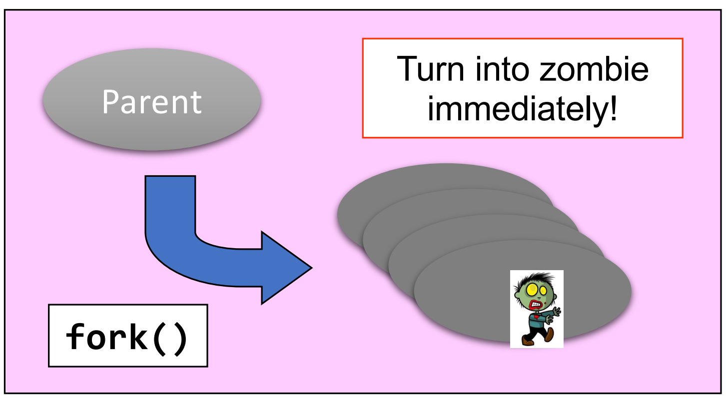
You are expected to see **the status of the child process changes (ps aux [PID])** between the 1st and the 2nd "enter".

Using wait() for Resource Management

- It is not only about process execution / suspension…
- It is about system resource management.
  - A zombie takes up a PID;
  - The total number of PIDs are limited;
    - Read the limit: "cat /proc/sys/kernel/pid_max"
    - It is 32,768.
  - What will happen if we don't clean up the zombies?

Using wait() for Resource Management

```c
int main(void) {
    while( fork() );
    return 0;
}
```




```
$ ./interesting
_
```

Terminal A

```
$ ls
No process left.
$ poweroff
No process left.
$ =__=
No process left.
$ _
```

Terminal B

More about Processes

The first process

- We now focus on the process-related events.
  - The kernel, while it is booting up, creates the first process – init.

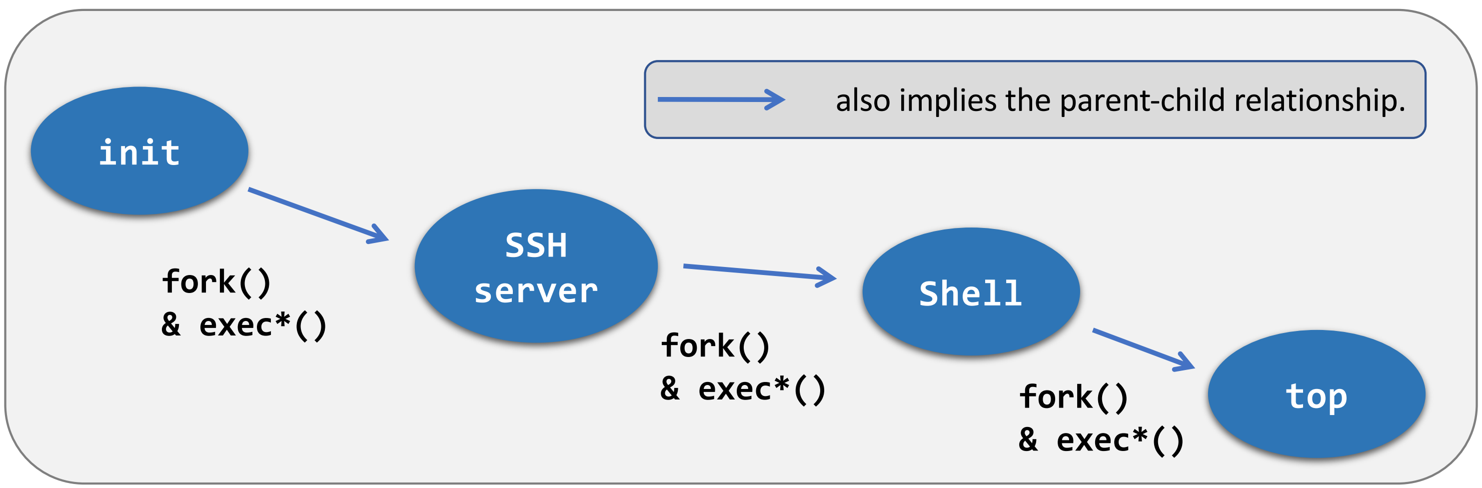
- The “init” process:
  - has PID = 1, and
  - is running the program code “/sbin/init”.

- Its first task is to create more processes…
  - Using fork() and exec().

How does uCore create the first process?

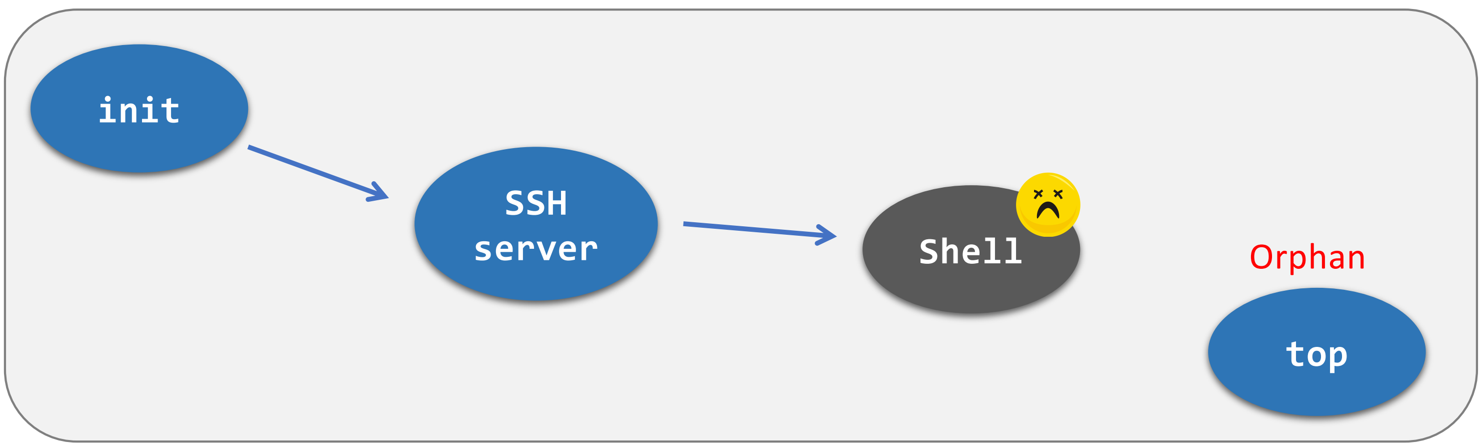
A Tree of Processes

- You can view the tree with the command:
  - "`pstree`"; or
  - "`pstree -A`" for ASCII-character-only display.



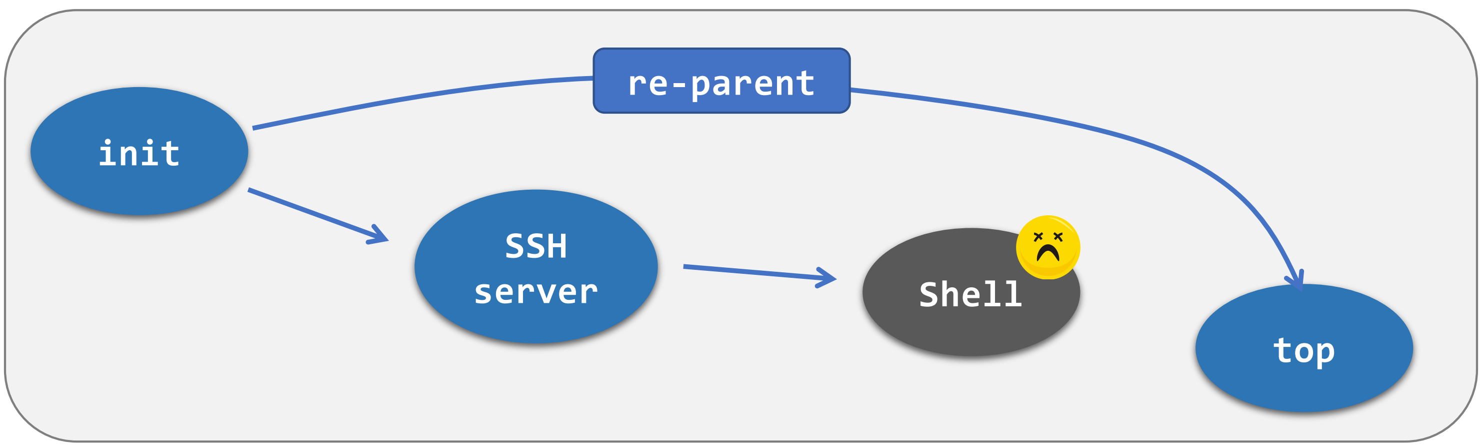
Orphans

- However, termination can happen, at any time and in any place…
  - This is no good because an orphan turns the hierarchy from a **tree** into a **forest**!
  - Plus, no one would know the termination of the orphan.



Re-parent

- In Linux
  - The "**init**" process will become the step-mother of all orphans
  - It's called **re-parenting**
- In Windows
  - It maintains a *forest-like process hierarchy*……………



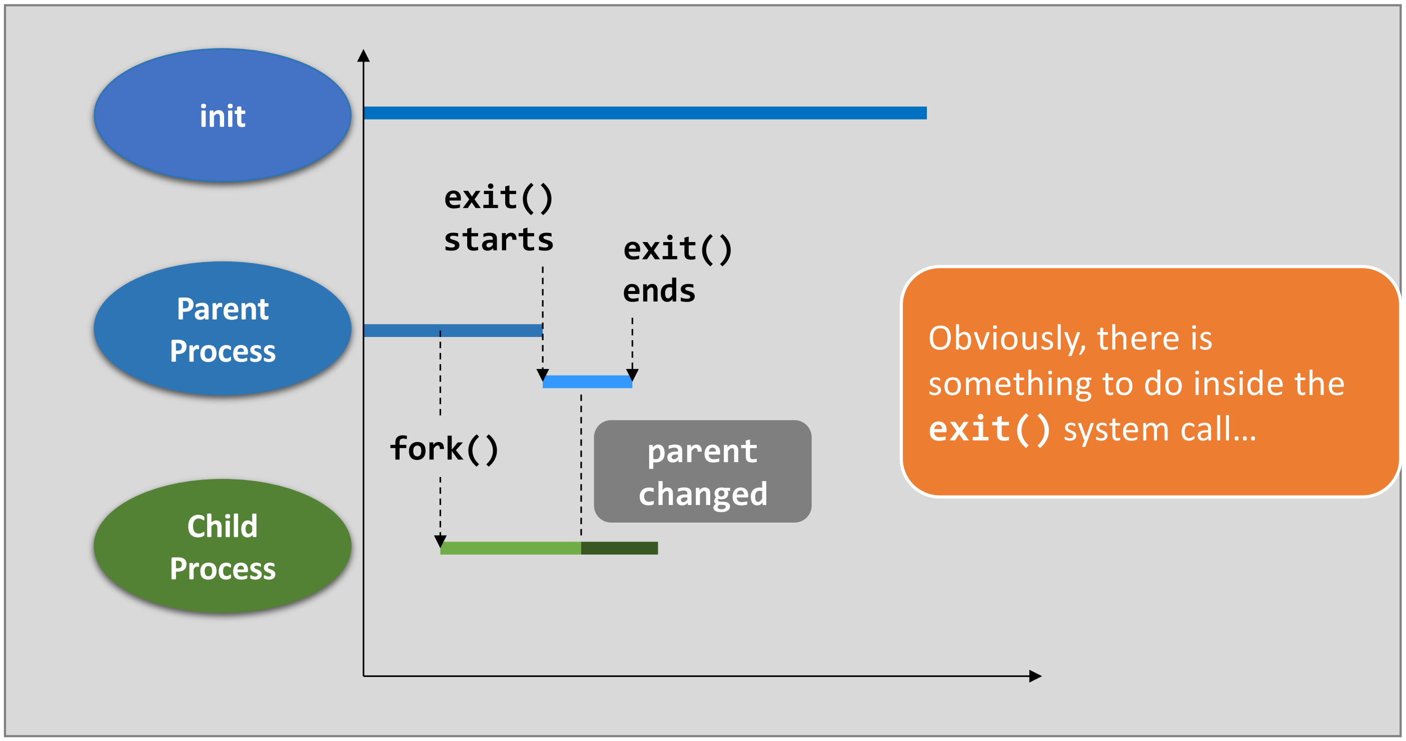
An Example

```c
int main(void) {
    int i;
    if(fork() == 0) {
        for(i = 0; i < 5; i++) {
            printf("(%d) parent's PID = %d\n",
                      getpid(), getppid() );
        sleep(1);
        }
    }
    else
        sleep(1);
    printf("(%d) bye.\n", getpid());
}
```

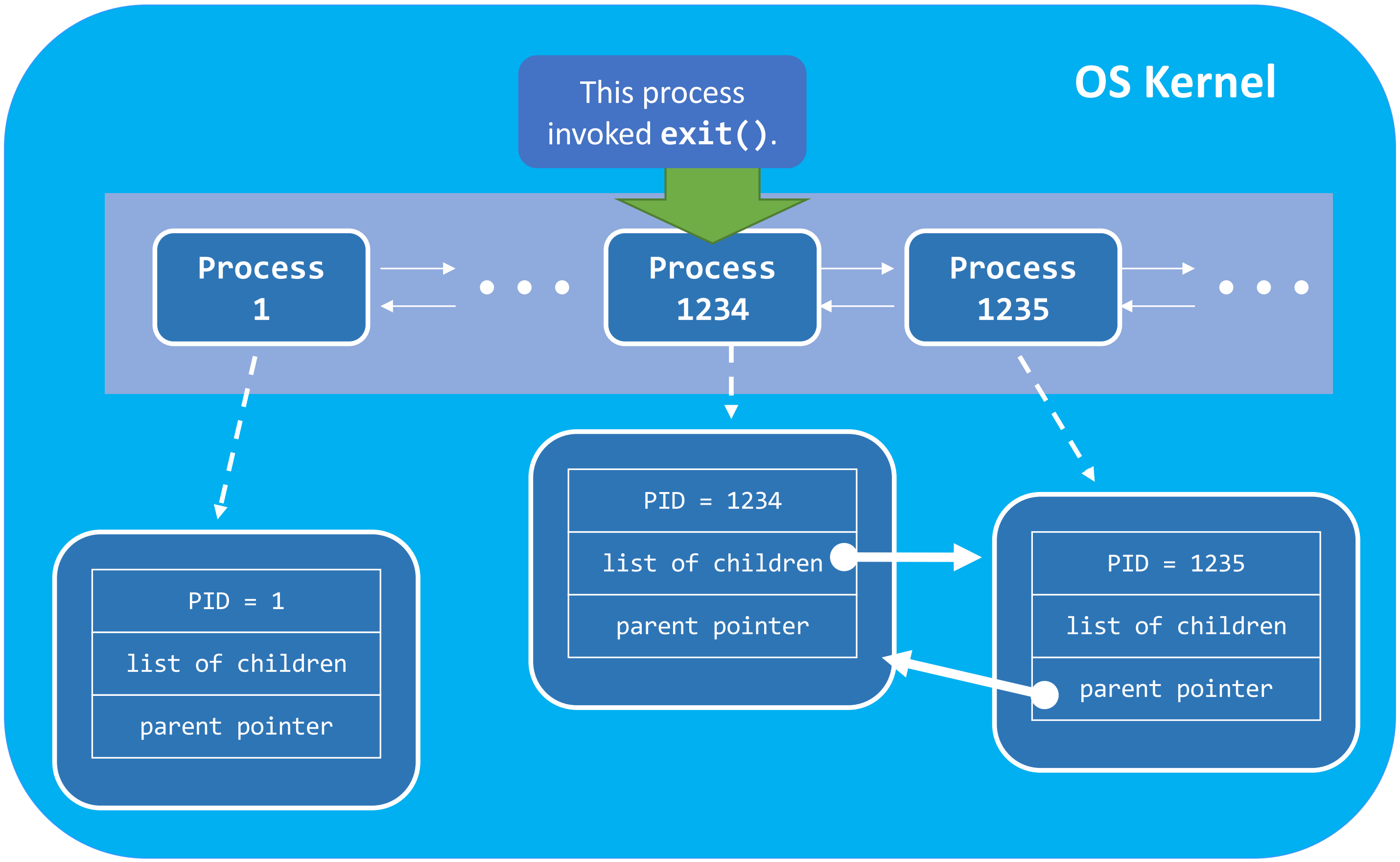
```
$ ./reparent
(1235) parent's PID = 1234
(1235) parent's PID = 1234
(1234) bye.
$ (1235) parent's PID = 1
(1235) parent's PID = 1
(1235) parent's PID = 1
(1235) bye.
$ _
```

`getppid()` is the system call that returns the parent's PID of the calling process.

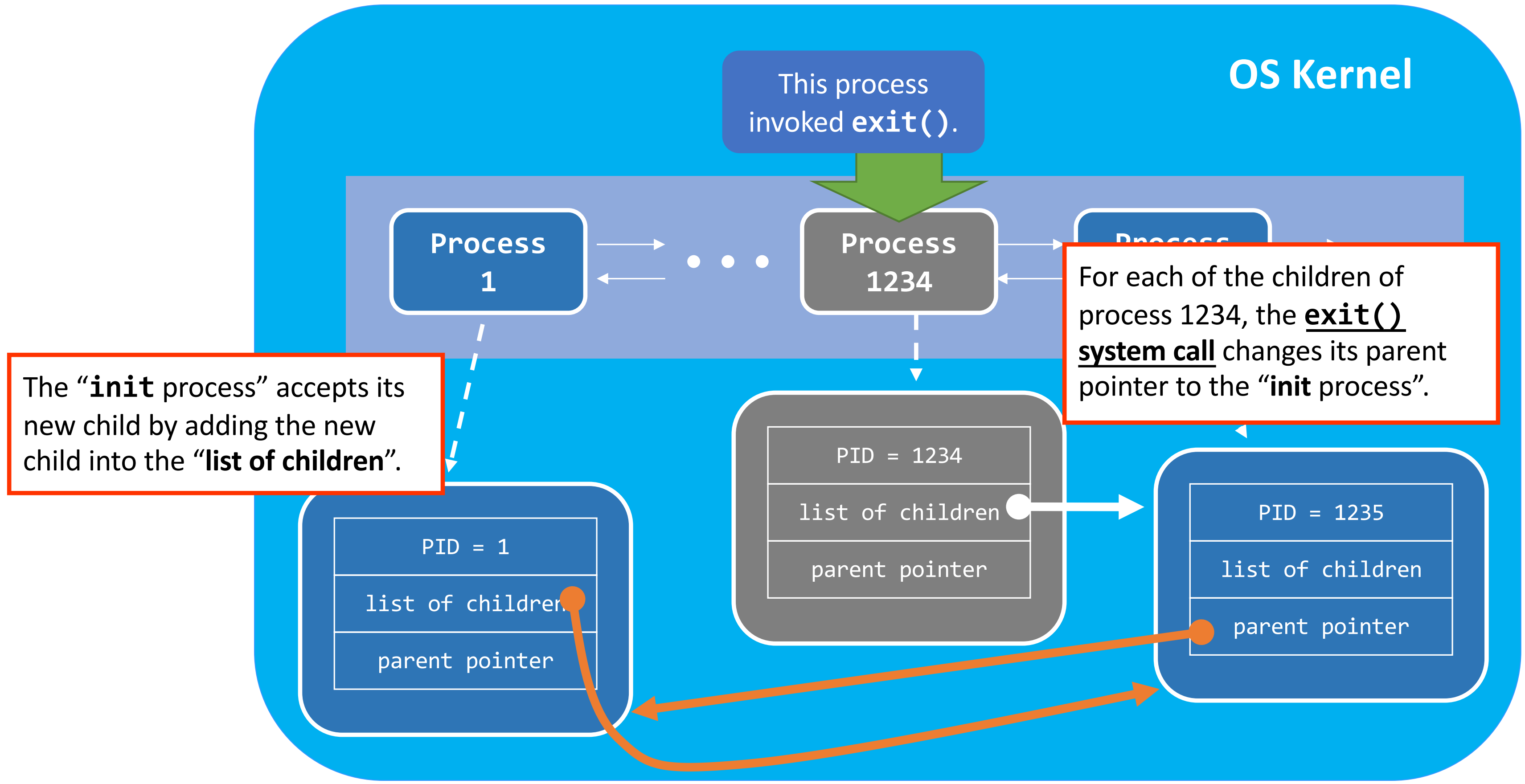
Re-parenting Explained



Re-parenting Explained (Cont'd)



Re-parenting Explained (Cont'd)



Background Jobs

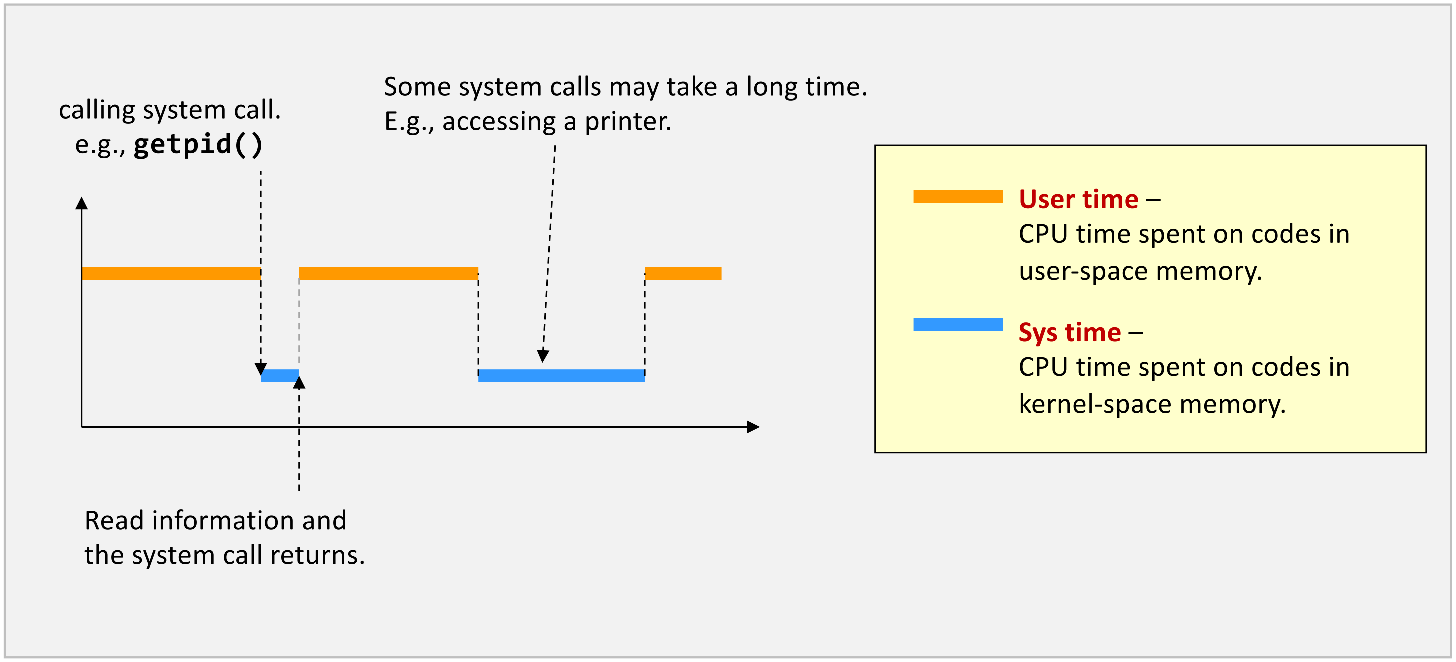
- The re-parenting operation enables something called **background jobs** in Linux
  - It allows a process runs **without a parent terminal/shell**

Back to home

```
$ ./infinite_loop &
$ exit

[ The shell is gone ]
```

```
$ ps -C infinite_loop
 PID  TTY
1234  ... ./infinite_loop
$ _
```

Measure Process Time



User Time v.s. System Time (Case 1)

```
$ time ./time_example

real      0m0.001s
user      0m0.000s
sys       0m0.000s
$ _
```

Real-time elapsed when "**./time_example**" terminates.

The **user time** of "**./time_example**".

The **sys time** of "**./time_example**".

It's possible:
real > user + sys
real < user + sys

Why?

- real>user+sys
  I/O intensive
- real<user+sys
  multi-core

```
int main(void) {
    int x = 0;
    for(i = 1; i <= 10000; i++) {
        x = x + i;
    //  printf("x = %d\n", x);
    }
    return 0;
}
```

User Time v.s. System Time (Case 1)

```
$ time ./time_example

real      0m0.001s
user      0m0.000s
sys       0m0.000s
$ _
```

```
int main(void) {
    int x = 0;
    for(i = 1; i <= 10000; i++) {
        x = x + i;
//      printf("x = %d\n", x);
    }
    return 0;
}
```

Commented on purpose.

```
$ time ./time_example

real 0m2.795s
user 0m0.084s
sys  0m0.124s
$ _
```

See? Accessing hardware costs the process more time.

```
int main(void) {
    int x = 0;
    for(i = 1; i <= 10000; i++) {
        x = x + i;
        printf("x = %d\n", x);
    }
    return 0;
}
```

User Time v.s. System Time (Case 2)

- The user time and the sys time together **define the performance of an application**.
  - When writing a program, you must consider both the user time and the sys time.
    - E.g., the output of the following two programs are exactly the same. But, their running time is not.

```
#define MAX 1000000

int main(void) {
    int i;
    for(i = 0; i < MAX; i++)
        printf("x\n");
    return 0;
}
```

```
#define MAX 1000000

int main(void) {
    int i;
    for(i = 0; i < MAX / 5 ; i++)
        printf("x\nx\nx\nx\nx\n");
    return 0;
}
```

User Time v.s. System Time (Case 2)

```c
#define MAX 1000000

int main(void) {
    int i;
    for(i = 0; i < MAX; i++)
        printf(“x\n”);
    return 0;
}
```

```
$ time ./time_example_slow

real 0m1.562s
user 0m0.024s
sys  0m0.108s
$ _
```

```c
#define MAX 1000000

int main(void) {
    int i;
    for(i = 0; i < MAX / 5 ; i++)
        printf(“x\nx\nx\nx\nx\n”);
    return 0;
}
```

```
$ time ./time_example_fast

real 0m1.293s
user 0m0.012s
sys  0m0.084s
$ _
```

Thank you!