中断与分时多任务

王慧妍

why@nju.edu.cn

南京大学 计算机科学与技术系 计算机软件研究所

本讲概述

为什么 while (1) ; 死循环不会把电脑卡死？

- 本讲内容
  - 中断机制
  - 实现分时多任务

中断机制

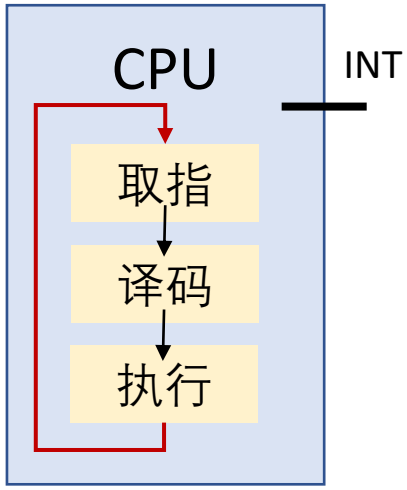
回到一个经典问题

为什么 while (1)；死循环不会把电脑卡死？

- 因为有中断
  - 相当于在指令之后插入一段代码

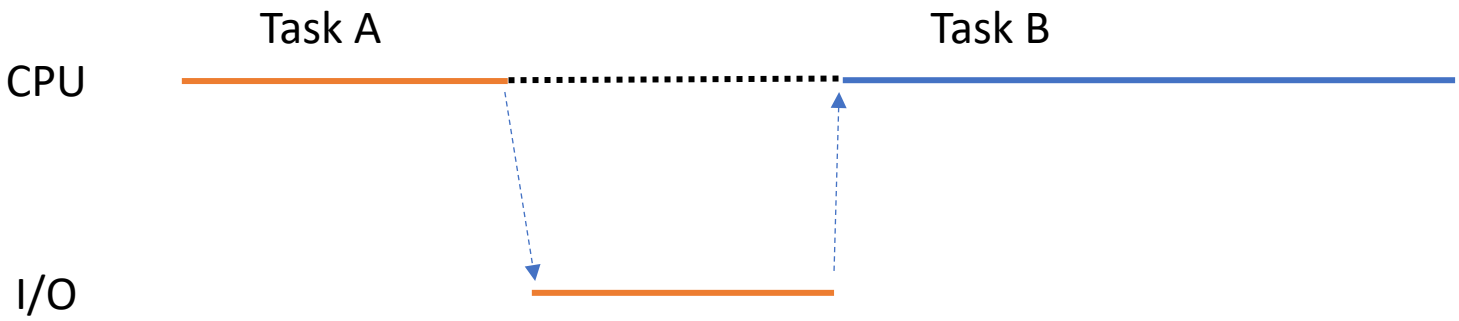
```
if (has_interrupt && int_enabled) {
   interrupt_handler();
}
```

  - 类似的是异常机制
    - 有时候称为同步中断



中断：弥补I/O设备的速度缺陷

- CPU cycles 实在太珍贵了
  - 不能用来浪费在等 I/O 设备完成上
    - 拥有机械部件的 I/O 设备相比于 CPU 来说实在太慢了



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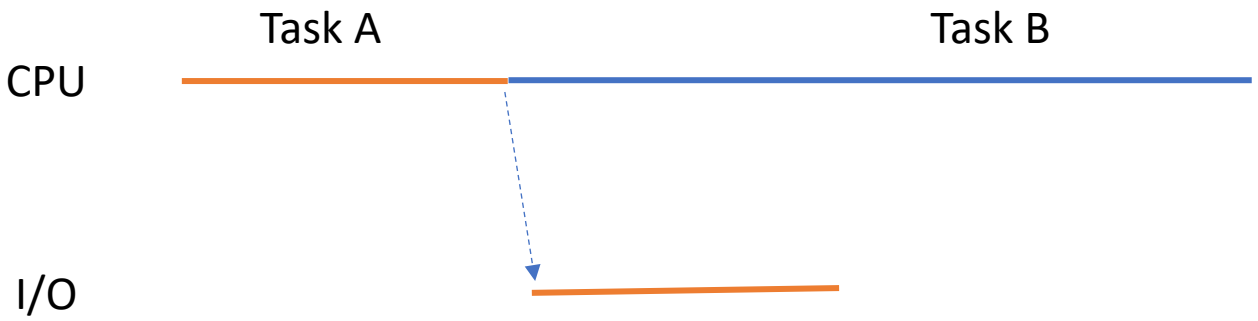

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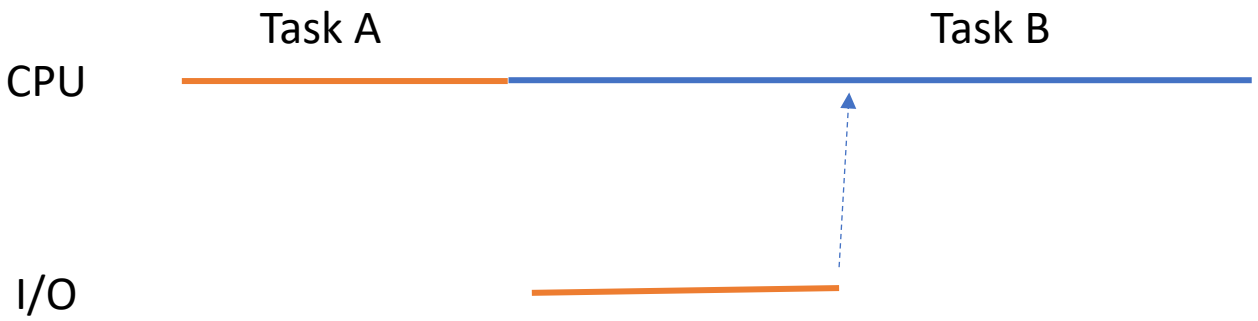

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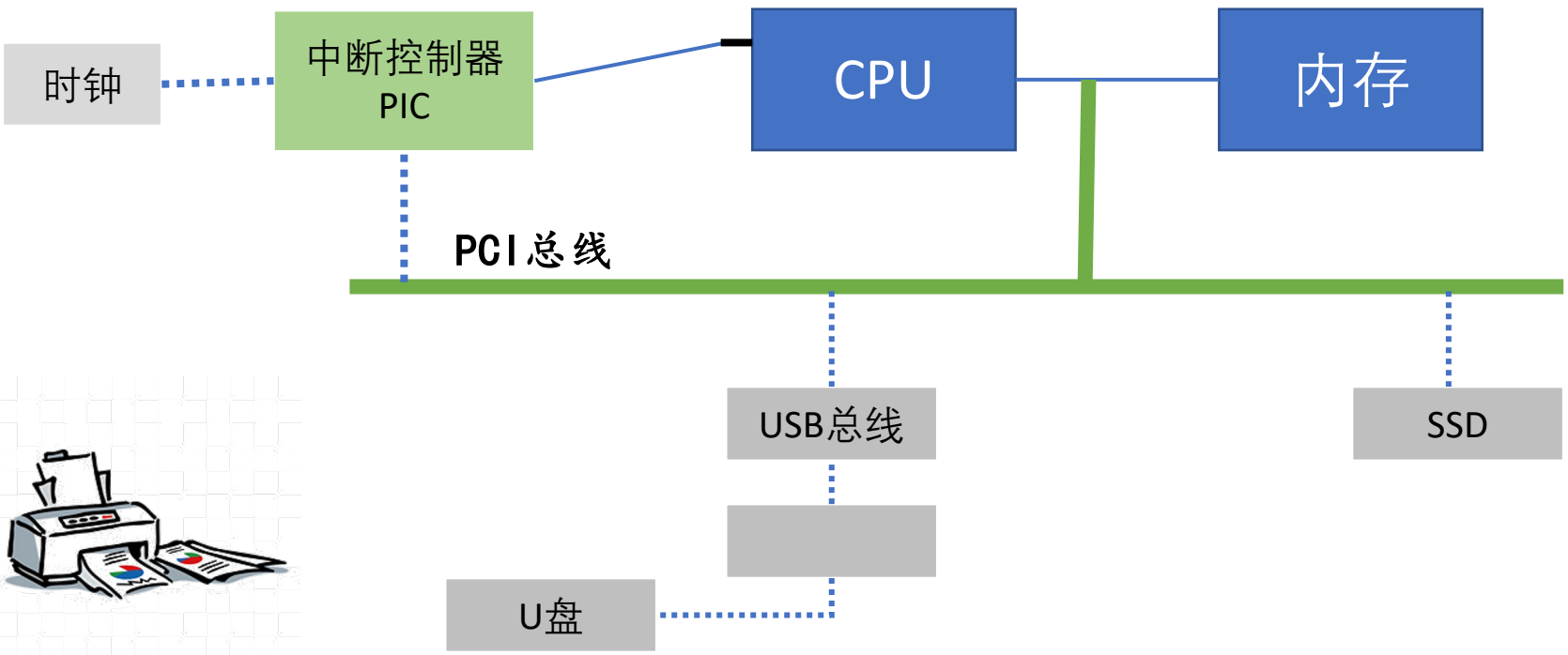
- 中断 = 硬件驱动的函数调用
  - 相当于在每条语句后都插入

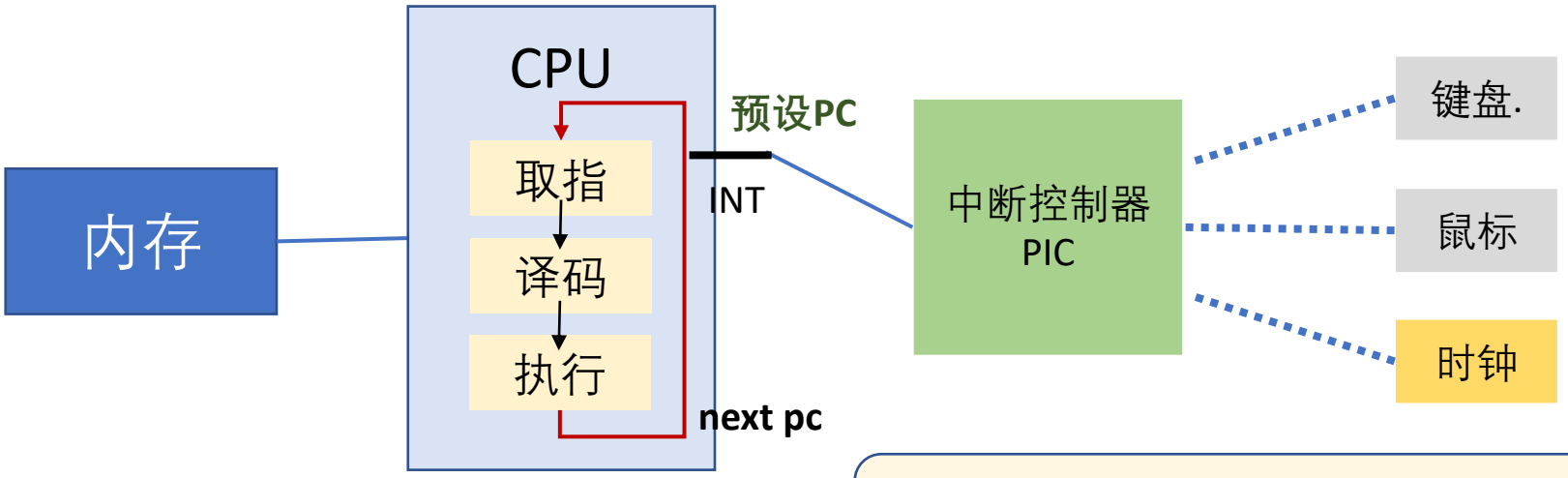
```
if (pending_io && int_enabled) {
   interrupt_handler();
   pending_io = 0;
}
```

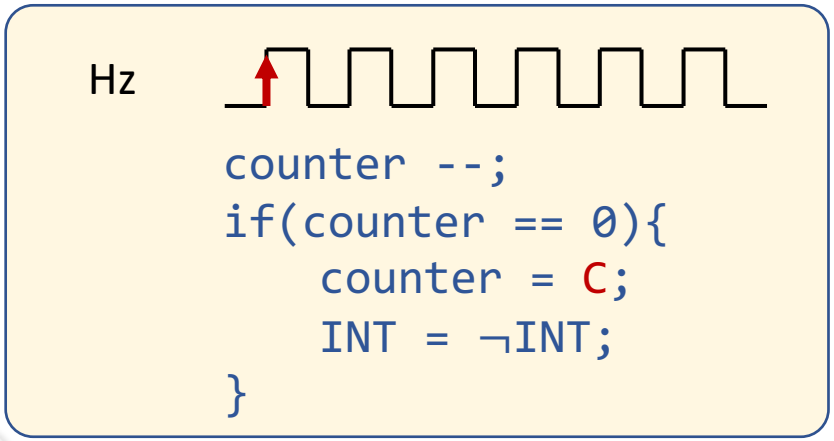
  - （硬件上好像不太难实现）
    - 于是就有了最早的操作系统：管理I/O设备的库代码

I/O设备回顾



中断机制总览





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  - 相当于在指令之后插入一段代码

```
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   interrupt_handler();
}
```
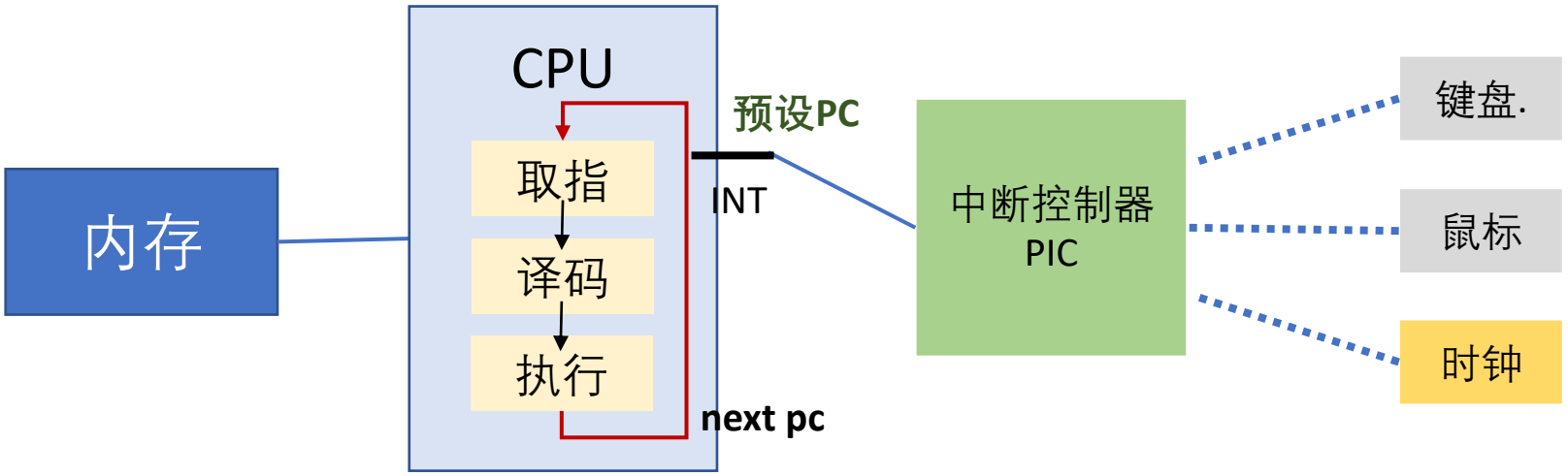

INT指令和Segmentation fault



- 类似的是异常机制
  - 有时候称为同步中断

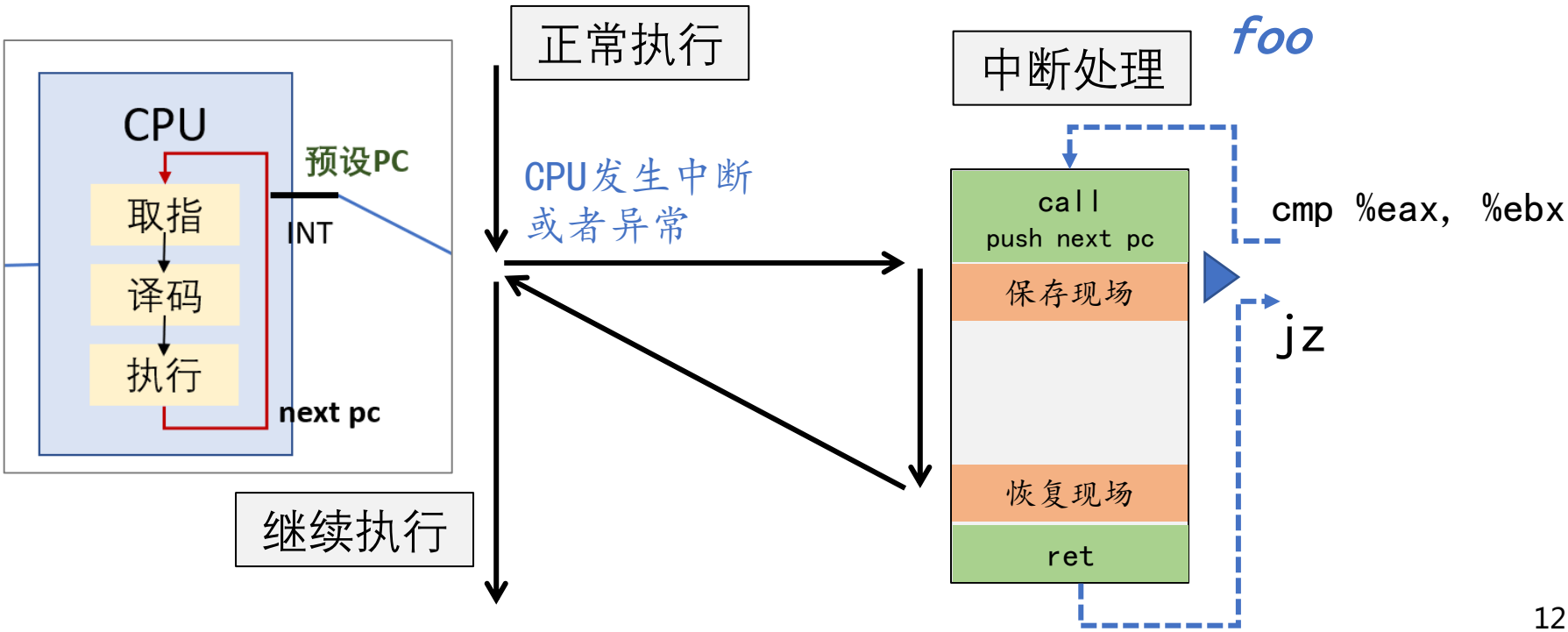
```
int $0x80
```

```
mov $1, (%eax)
```

→ #14中断（异常）

中断的实现

- 比 “函数调用” 复杂一些
  - 函数调用需要保存 PC 到堆栈 (%rsp)



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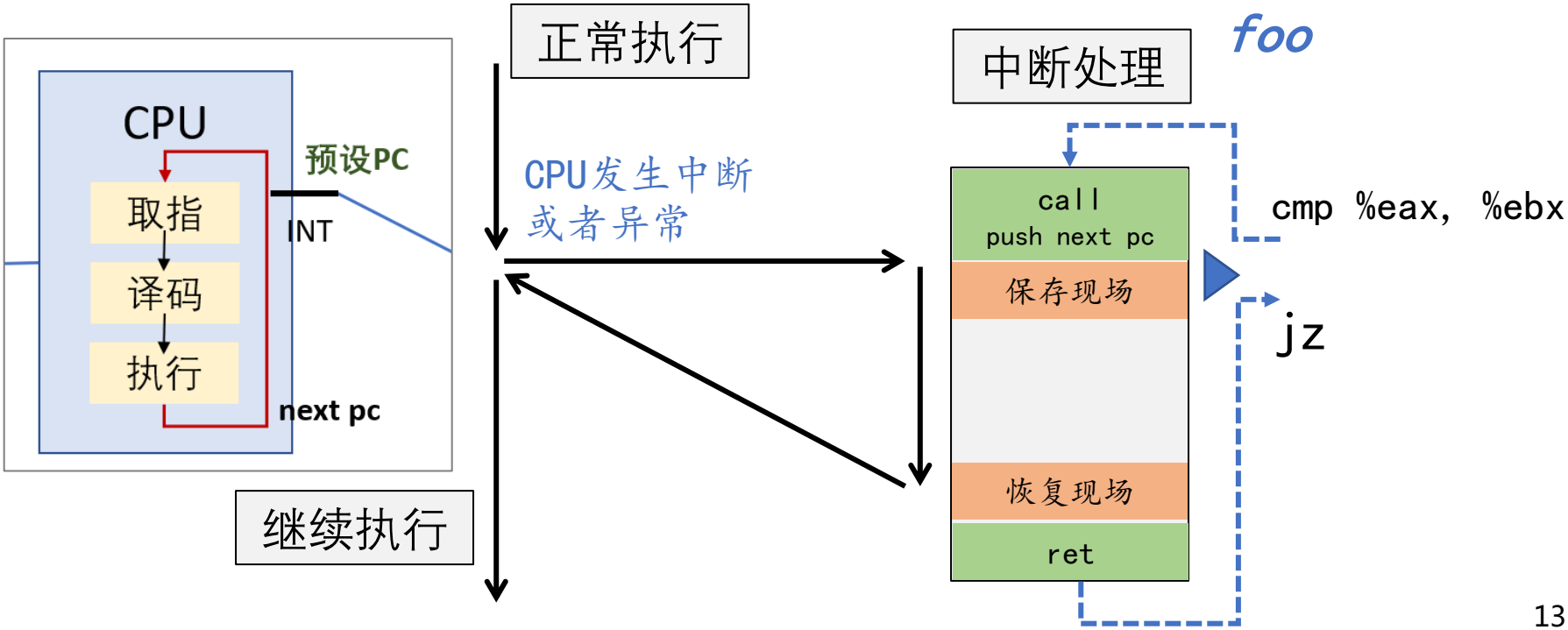
- 中断处理
  - 自动保存 RIP, CS, RFLAGS, RSP, SS, (Error Code)



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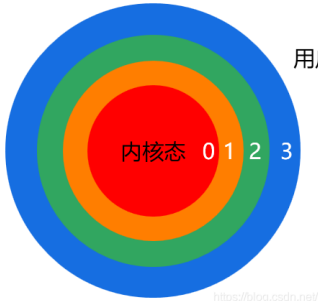

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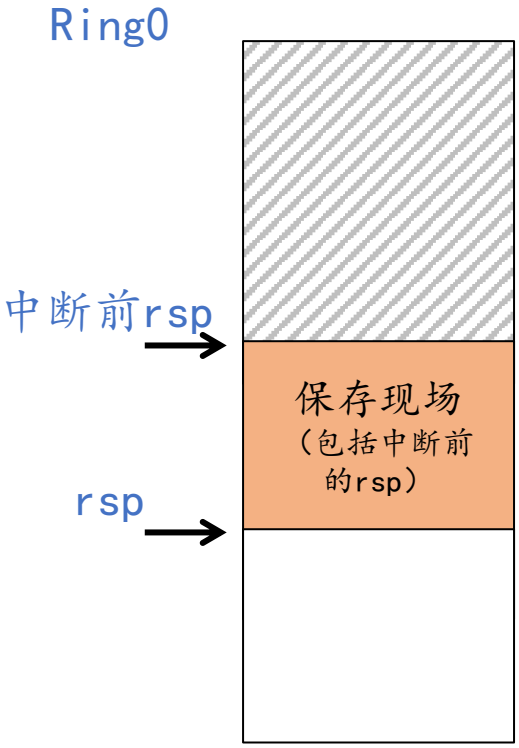
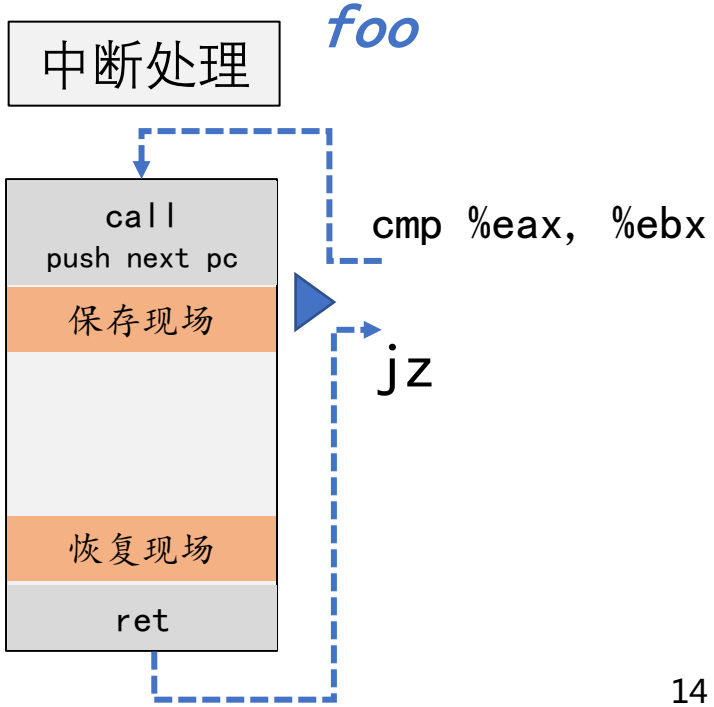
  - 自动保存 RIP, CS, RFLAGS, RSP, SS, (Error Code)
  - 根据中断/异常号跳转到处理程序 (特权级切换会触发堆栈切换)
    - `int $0x80` 指令可以产生 128 号异常
    - 时钟会产生 32 号中断
    - 键盘会产生 33 号中断





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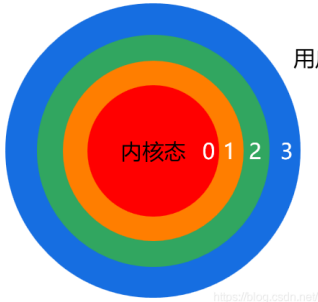

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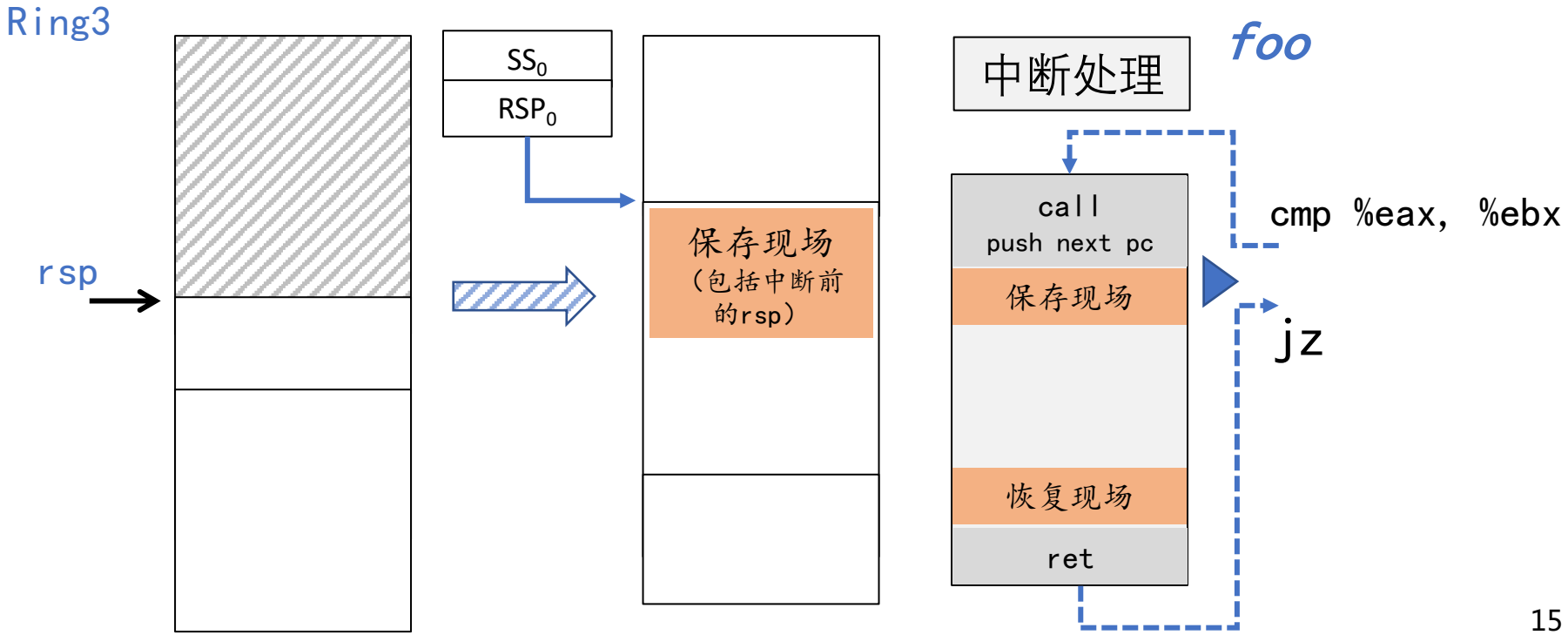

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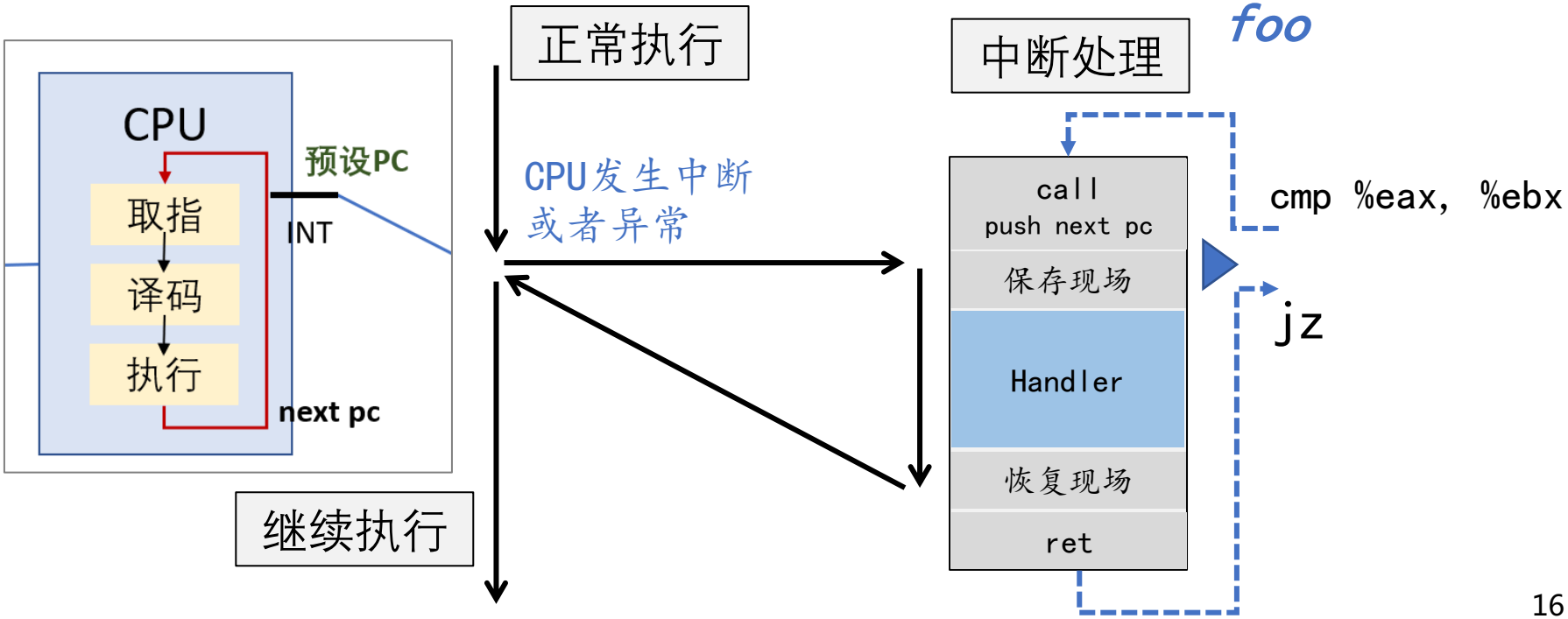

x86-64中断过程

- 比 “函数调用” 复杂一些
  - 函数调用需要保存 PC 到堆栈 (%rsp)
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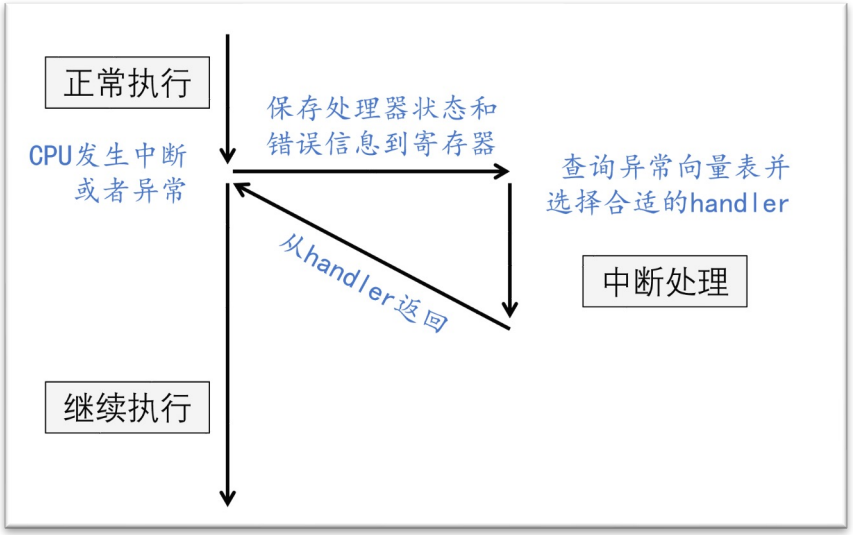


为什么死循环不会把电脑卡死？

- 中断是强制的 (普通的进程不能关闭)
  - Ring 3 关闭中断将导致 Exception(GP(0)) (手册)

x86 Instruction Set Reference

CLI

Clear Interrupt Flag

Opcode	Mnemonic	Description
FA	CLI	Clear interrupt flag; interrupts disabled when interrupt flag cleared.

Operation

```
if(PE == 0) IF = 0; //Reset Interrupt Flag
else {
        if(VM == 0) {
                if(IOPL != CPL) IF = 0; //Reset Interrupt Flag
                else {
                        if(IOPL < CPL && CPL < 3 && PVI == 1) VIF = 0; //Reset Virtual Interrupt Flag
                        else Exception(GP(0));
                }
        }
        else {
                if(IOPL == 3) IF = 0; //Reset Interrupt Flag
                else {
                        if(IOPL < 3 && VME == 1) VIF = 0; //Reset Virtual Interrupt Flag
                        else Exception(GP(0));
                }
        }
}
```

管理 控制 视图 热键 设备 帮助

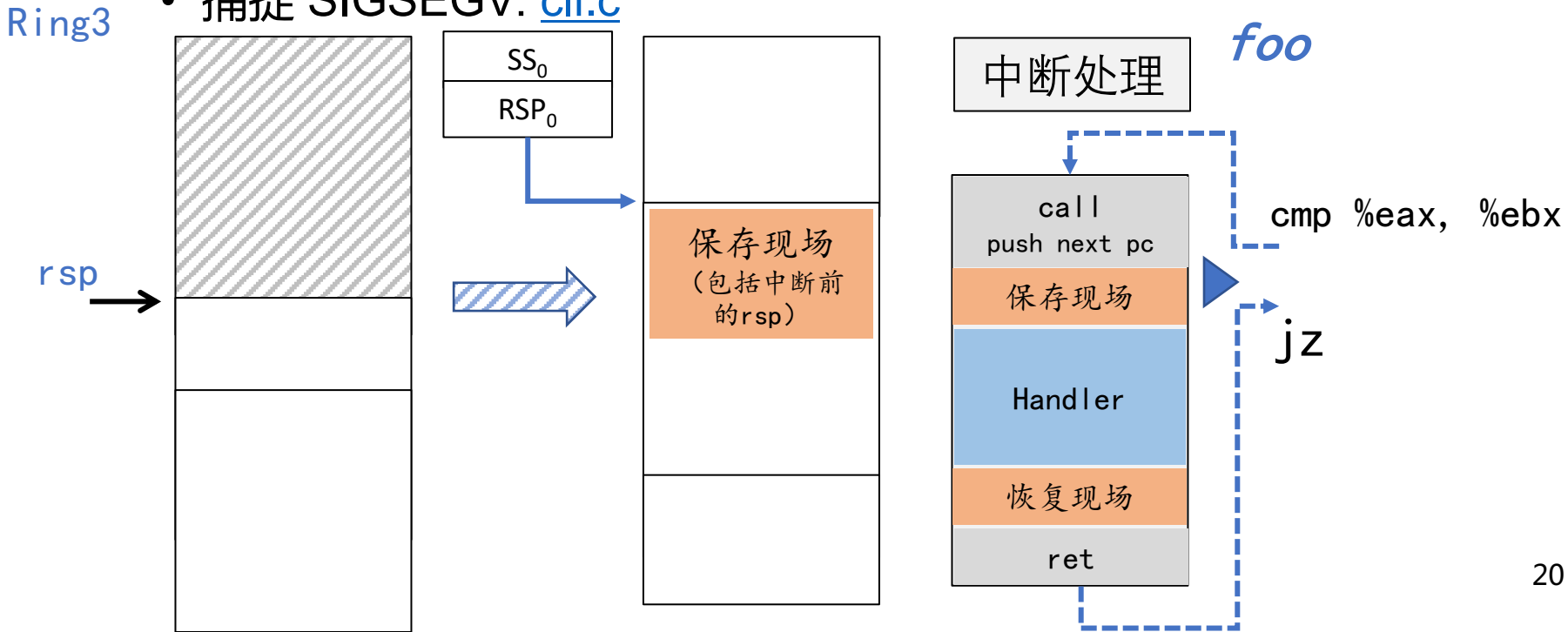
```
1 int main(){
2     asm volatile ("cli");
3     while(1);
4 }
```

~/Documents/ICS2021/teach/Course13/a.c[1] [c] unix utf-8 Ln 1, Col 1/4

Right Shift + Right Alt

为什么死循环不会把电脑卡死？

- 中断是强制的 (普通的进程不能关闭)
  - Ring 3 关闭中断将导致 Exception(GP(0)) (手册)
    - 发生 13 号异常
    - Error Code 0
      - 异常机制进入操作系统代码执行
      - 操作系统发送 SIGSEGV 信号
    - 捕捉 SIGSEGV: cli.c



管理 控制 视图 热键 设备 帮助

```c
#define _GNU_SOURCE

#include <signal.h>
#include <stdio.h>
#include <stdlib.h>
#include <ucontext.h>
#include <stdint.h>

void on_sigsegv(int sig, siginfo_t *info, void *ucontext) {
  ucontext_t *ctx = (ucontext_t *)ucontext;
  uint8_t *pc = (void *)ctx->uc_mcontext.gregs[REG_RIP];
  printf("PC = %p  ", pc);
  for (int i = -8; i < 8; i++) {
    printf(i == 0 ? "[%02x] " : "%02x ", pc[i]);
  }
  printf("\n");
  exit(1);
}

int main() {
  struct sigaction act;
  act.sa_sigaction = on_sigsegv;
  sigemptyset(&act.sa_mask);
  act.sa_flags = SA_SIGINFO;
  sigaction(SIGSEGV, &act, NULL);
  asm volatile("cli");
}
```

~/Documents/ICS2021/teach/Course13/cli.c[1] [c] unix utf-8 Ln 13, Col 2/27

=((foldclosed(line('.')) < 0) ? 'zc' : 'zo')

Right Shift + Right Alt

```
管理   控制   视图   热键   设备   帮助
$ ls
a.c  a.out  cli.c  thread-os.c
$ vim cli.c
$ gcc cli.c
$ ./a.out
PC = 0x5634316132ed  00 00 00 e8 c3 fd ff ff [fa] b8 00 00 00 00 48 8b
$
```

```
  12e3:       bf 0b 00 00 00          mov    $0xb,%edi
  12e8:       e8 c3 fd ff ff          call   10b0 <sigaction@plt>
  12ed:       fa                      cli
  12ee:       b8 00 00 00 00          mov    $0x0,%eax
  12f3:       48 8b 4d f8             mov    -0x8(%rbp),%rcx
```

管理 控制 视图 热键 设备 帮助

```
$ ls
a.c  a.out  cli.c  thread-os.c
$ vim cli.c
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PC = 0x5634316132ed  00 00 00 e8 c3 fd ff ff [fa] b8 00 00 00 00 48 8b
$
```

管理 控制 视图 热键 设备 帮助

```
$ ./a.out
PC = 0x5620206812ed  00 00 00 e8 c3 fd ff ff [fa] b8 00 00 00 00 48 8b
$ ./a.out
PC = 0x555cd8d502ed  00 00 00 e8 c3 fd ff ff [fa] b8 00 00 00 00 48 8b
$
```

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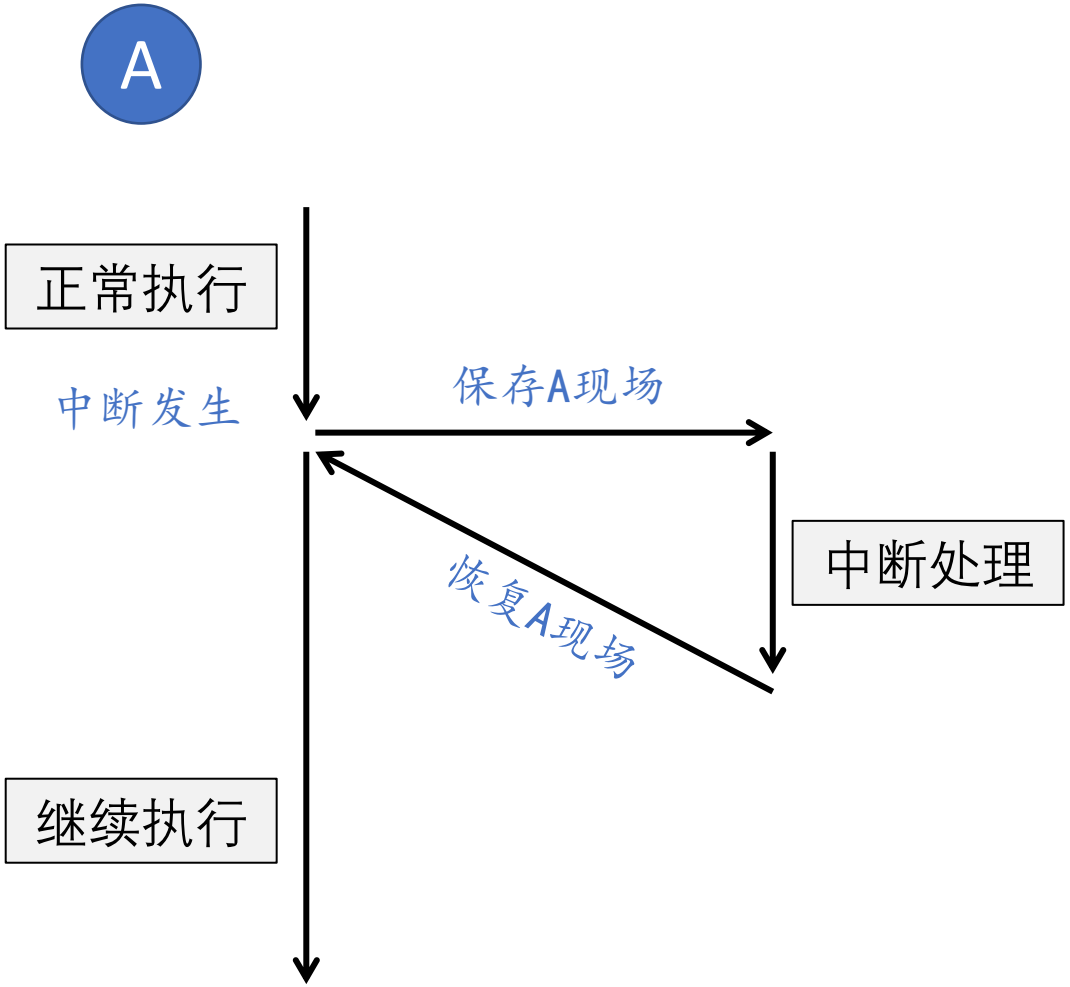
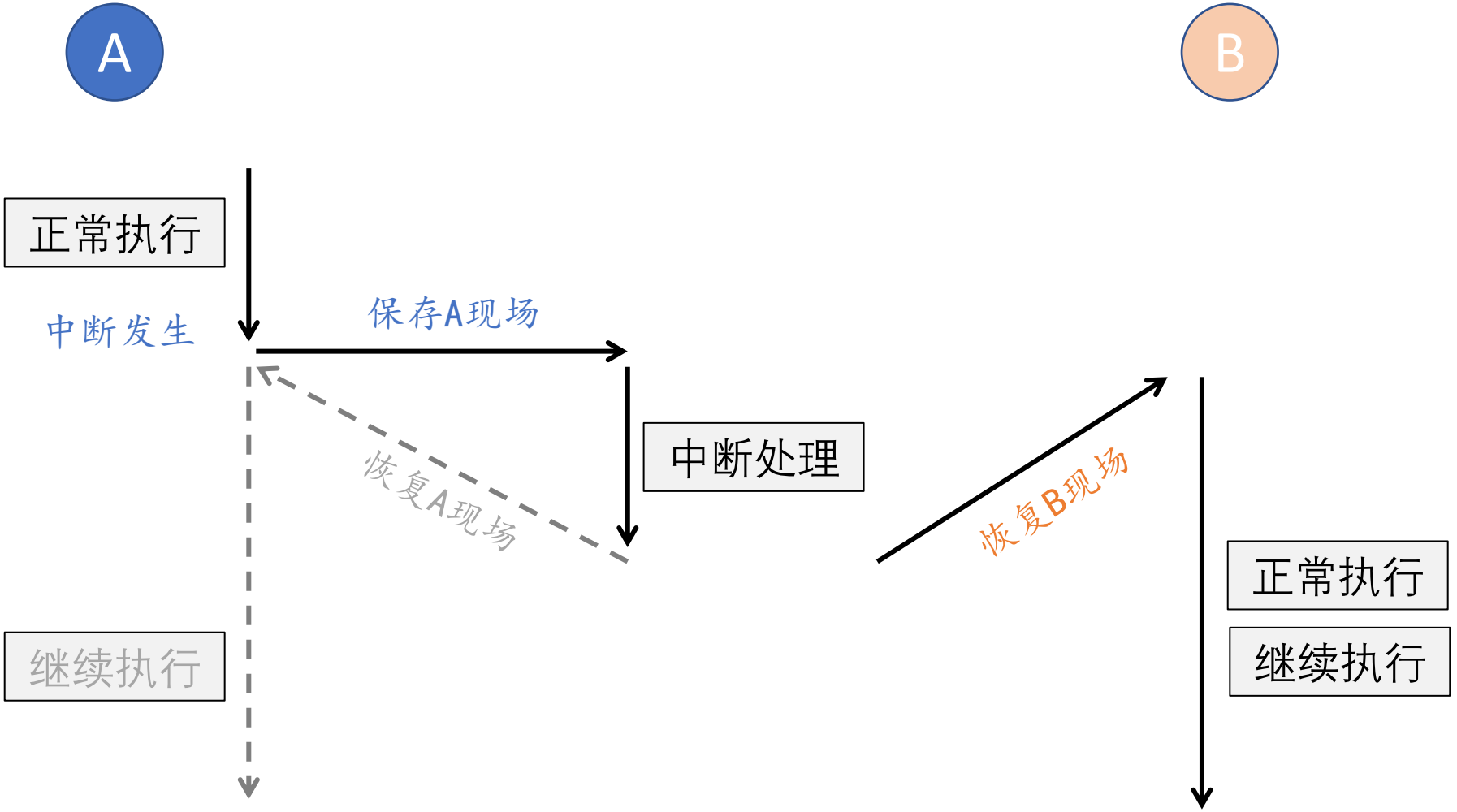
  - Ring 3 关闭中断将导致 Exception(GP(0)) (手册)
    - 发生 13 号异常
    - Error Code 0
      - 异常机制进入操作系统代码执行
      - 操作系统发送 SIGSEGV 信号
    - 捕捉 SIGSEGV: cli.c

- 中断发生后，操作系统代码将会切换到另一个进程执行
  - “调度”：让进程公平地共享 CPU

实现分时多任务


A
正常执行
中断发生
保存A现场
中断处理
恢复A现场
继续执行


A
B
正常执行
中断发生
保存A现场
中断处理
恢复A现场
恢复B现场
正常执行
继续执行
继续执行

代码选讲

- Abstract Machine
  - trap64.S
  - cte.c

- 调试 “迷你” 操作系统
  - thread-os.c
    - `-s -S` 启动 QEMU
    - gdb `target remote localhost:1234`
      - gdbnotes for CSAPP

```c
#include <am.h>
#include <klib.h>
#include <klib-macros.h>

typedef union task {
  struct {
    const char *name;
    union task *next;
    void       (*entry)(void *);
    Context    *context;
  };
  uint8_t stack[8192];
} Task;

Task *current;

void func(void *arg) {
  while (1) {
    putch(*(char *)arg);
    for (int volatile i = 0; i < 100000; i++) ;
  }
}

Task tasks[] = {
  { .name = "a", .entry = func },
  { .name = "b", .entry = func },
  { .name = "c", .entry = func },
```

```
24 Task tasks[] = {
25   { .name = "a", .entry = func },
26   { .name = "b", .entry = func },
27   { .name = "c", .entry = func },
28 };
29
30 Context *on_interrupt(Event ev, Context *ctx) {
31   if (!current) current = &tasks[0];
32   else          current->context = ctx;
33   current = current->next;
34   return current->context;
35 }
36
37 int main() {
38   ioe_init();
39   cte_init(on_interrupt);
40
41   for (int i = 0; i < LENGTH(tasks); i++) {
42     Task *task    = &tasks[i];
43     Area stack    = (Area) { &task->context + 1, task + 1 };
44     task->context = kcontext(stack, task->entry, (void *)task->name);
45     task->next    = &tasks[(i + 1) % LENGTH(tasks)];
46   }
47   iset(true);
48   while(1);
49 }
<s2021/am-kernels/kernels/thread-os/thread-os.c[1] [c] unix utf-8 Ln 49, Col 1/49
```

管理 控制 视图 热键 设备 帮助

$

管理 控制 视图 热键 设备 帮助

```
$ ls
build  Makefile  thread-os.c
$
```

管理 控制 视图 热键 设备 帮助

```
$ ls
thread-os-x86_64-qemu  thread-os-x86_64-qemu.elf  x86_64-qemu
$
```

管理 控制 视图 热键 设备 帮助

/home/why/Documents/ICS2021/ics2021/am-kernels/kernels/thread-os/thread-os.c

```
   30           Context *on_interrupt(Event ev, Context *ctx) {
   31             if (!current) current = &tasks[0];
   32             else          current->context = ctx;
   33             current = current->next;
   34             return current->context;
   35           }
   36
B+ 37           int main() {
   38             ioe_init();
  >39             cte_init(on_interrupt);
   40
   41             for (int i = 0; i < LENGTH(tasks); i++) {
   42               Task *task    = &tasks[i];
   43               Area stack    = (Area) { &task->context + 1, task + 1 };
   44               task->context = kcontext(stack, task->entry, (void *)task->na
   45               task->next    = &tasks[(i + 1) % LENGTH(tasks)];
```

remote Thread 1.1 In: main L39 PC: 0x1000d3

```
(gdb) n
(gdb)
```

Right Shift + Right Alt

管理 控制 视图 热键 设备 帮助

```
   0x1016e0 <iset>                          endbr64
   0x1016e4 <iset+4>                        test   %dil,%dil
   0x1016e7 <iset+7>                        je     0x1016f0 <iset+16>
   0x1016e9 <iset+9>                        sti
  >0x1016ea <iset+10>                       ret
   0x1016eb <iset+11>                       nopl   0x0(%rax,%rax,1)
   0x1016f0 <iset+16>                       cli
   0x1016f1 <iset+17>                       ret
   0x1016f2                                     data16 nopw %cs:0x0(%rax,%rax,1)
   0x1016fd                                     nopl   (%rax)
   0x101700 <__am_panic_on_return>          endbr64
   0x101704 <__am_panic_on_return+4>        push   %rbx
   0x101705 <__am_panic_on_return+5>        mov    $0x41,%edi
   0x10170a <__am_panic_on_return+10>       lea    0x1239(%rip),%rbx        # 0x
   0x101711 <__am_panic_on_return+17>       nopl   0x0(%rax)
   0x101718 <__am_panic_on_return+24>       call   0x1002b0 <putch>

remote Thread 1.1 In: iset                                   L??   PC: 0x1016ea
rip            0x1016ea            0x1016ea <iset+10>
eflags         0x202               [ IOPL=0 IF ]
cs             0x8                 8
ss             0x0                 0
ds             0x0                 0
es             0x0                 0
fs             0x0                 0
gs             0x0                 0
--Type <RET> for more, q to quit, c to continue without paging--
```

管理 控制 视图 热键 设备 帮助

```
   0x100132 <main+130>              sub    %rdx,%rax
   0x100135 <main+133>              shl    $0xd,%rax
   0x100139 <main+137>              add    %rbp,%rax
   0x10013c <main+140>              mov    %rax,-0x3ff8(%rbx)
   0x100143 <main+147>              cmp    $0x4,%r13
   0x100147 <main+151>              jne    0x1000ed <main+61>
   0x100149 <main+153>              mov    $0x1,%edi
   0x10014e <main+158>              call   0x1016e0 <iset>
  >0x100153 <main+163>              jmp    0x100153 <main+163>
   0x100155                             nopw   %cs:0x0(%rax,%rax,1)
   0x10015f                             nop
   0x100160 <on_interrupt>          endbr64
   0x100164 <on_interrupt+4>        mov    $0x109700,%rdx
   0x10016b <on_interrupt+11>       mov    (%rdx),%rax
   0x10016e <on_interrupt+14>       test   %rax,%rax
   0x100171 <on_interrupt+17>       je     0x100188 <on_interrupt+40>

remote Thread 1.1 In: main                                  L48   PC: 0x100153
cr2             0x0                 0
cr3             0x1000              [ PDBR=0 PCID=0 ]
cr4             0x20                [ PAE ]
cr8             0x0                 0
--Type <RET> for more, q to quit, c to continue without paging--q
Quit
(gdb) si
(gdb) si
(gdb)
```

Useful information

backtrace	Print the current address and stack backtrace
where	Print the current address and stack backtrace
info program	Print current status of the program)
info functions	Print functions in program
info stack	Print backtrace of the stack)
info frame	Print information about the current stack frame
info registers	Print registers and their contents
info breakpoints	Print status of user-settable breakpoints
display /FMT EXPR	Print expression EXPR using format FMT every time GDB stops
undisplay	Turn off display mode
help	Get information about gdb
x/2w $rsp	Examine two (4-byte) words starting at address in $rsp
x/2wd $rsp	Examine two (4-byte) words starting at address in $rsp. Print in decimal
x/g $rsp	Examine (8-byte) word starting at address in $rsp.
x/gd $rsp	Examine (8-byte) word starting at address in $rsp. Print in decimal
x/a $rsp	Examine address in $rsp. Print as offset from previous global symbol.
x/s 0xbffff890	Examine a string stored at 0xbffff890
x/20b sum	Examine first 20 opcode bytes of function sum
x/10i sum	Examine first 10 instructions of function sum

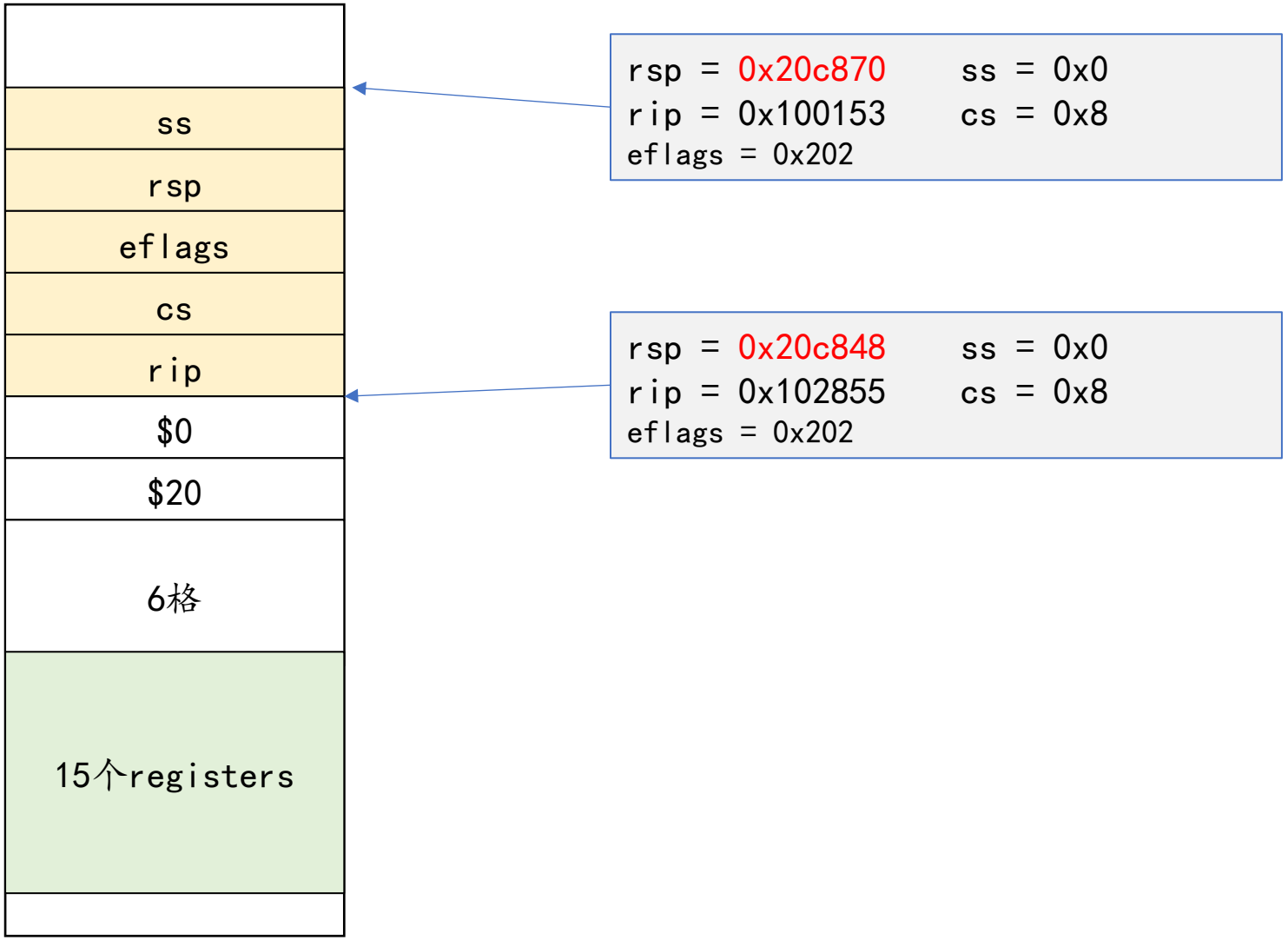
管理 控制 视图 热键 设备 帮助

```
   0x100118 <main+104>     mov    %r13,%rax
   0x10011b <main+107>     mul    %r12
   0x10011e <main+110>     mov    %rdx,%rax
   0x100121 <main+113>     and    $0xfffffffffffffffe,%rdx
   0x100125 <main+117>     shr    %rax
   0x100128 <main+120>     add    %rax,%rdx
   0x10012b <main+123>     mov    %r13,%rax
   0x10012e <main+126>     add    $0x1,%r13
   0x100132 <main+130>     sub    %rdx,%rax
   0x100135 <main+133>     shl    $0xd,%rax
   0x100139 <main+137>     add    %rbp,%rax
   0x10013c <main+140>     mov    %rax,-0x3ff8(%rbx)
   0x100143 <main+147>     cmp    $0x4,%r13
   0x100147 <main+151>     jne    0x1000ed <main+61>
   0x100149 <main+153>     mov    $0x1,%edi
   0x10014e <main+158>     call   0x1016e0 <iset>
```

```
remote Thread 1.1 In: __am_irq32                          L??   PC: 0x102855
rip            0x102855            0x102855 <__am_irq32>
eflags         0x202               [ IOPL=0 IF ]
cs             0x8                 8
ss             0x0                 0
ds             0x0                 0
es             0x0                 0
fs             0x0                 0
gs             0x0                 0
--Type <RET> for more, q to quit, c to continue without paging--
```

管理 控制 视图 热键 设备 帮助

```
   0x100118 <main+104>     mov    %r13,%rax
   0x10011b <main+107>     mul    %r12
   0x10011e <main+110>     mov    %rdx,%rax
   0x100121 <main+113>     and    $0xfffffffffffffffe,%rdx
   0x100125 <main+117>     shr    %rax
   0x100128 <main+120>     add    %rax,%rdx
   0x10012b <main+123>     mov    %r13,%rax
   0x10012e <main+126>     add    $0x1,%r13
   0x100132 <main+130>     sub    %rdx,%rax
   0x100135 <main+133>     shl    $0xd,%rax
   0x100139 <main+137>     add    %rbp,%rax
   0x10013c <main+140>     mov    %rax,-0x3ff8(%rbx)
   0x100143 <main+147>     cmp    $0x4,%r13
   0x100147 <main+151>     jne    0x1000ed <main+61>
   0x100149 <main+153>     mov    $0x1,%edi
   0x10014e <main+158>     call   0x1016e0 <iset>
remote Thread 1.1 In: __am_irq32                          L??   PC: 0x102855
fs             0x0                 0
gs             0x0                 0
--Type <RET> for more, q to quit, c to continue without paging--q
Quit
(gdb) x/5gx $rsp
0x20c848 <__am_cpuinfo+8264>:   0x0000000000100153      0x0000000000000008
0x20c858 <__am_cpuinfo+8280>:   0x0000000000000202      0x000000000020c870
0x20c868 <__am_cpuinfo+8296>:   0x0000000000000000
(gdb)
```


ss
rsp
eflags
cs
rip
$0
$20
6格
15个registers
rsp = 0x20c870 ss = 0x0
rip = 0x100153 cs = 0x8
eflags = 0x202
rsp = 0x20c848 ss = 0x0
rip = 0x102855 cs = 0x8
eflags = 0x202

```
void __am_irq_handle(struct trap_frame *tf) {
  Context *saved_ctx = &tf->saved_context;
  Event ev = {
    .event = EVENT_NULL,
    .cause = 0, .ref = 0,
    .msg = "(no message)",
  };

#if __x86_64
  saved_ctx->rip    = tf->rip;
  saved_ctx->cs     = tf->cs;
  saved_ctx->rflags = tf->rflags;
  saved_ctx->rsp    = tf->rsp;
  saved_ctx->rsp0   = CPU->tss.rsp0;
  saved_ctx->ss     = tf->ss;
#else
  saved_ctx->eip    = tf->eip;
  saved_ctx->cs     = tf->cs;
  saved_ctx->eflags = tf->eflags;
  saved_ctx->esp0   = CPU->tss.esp0;
  saved_ctx->ss3    = USEL(SEG_UDATA);
  // no ss/esp saved for DPL_KERNEL
  saved_ctx->esp = (tf->cs & DPL_USER ? tf->esp : (uint32_t)(tf + 1) - 8);
#endif
  saved_ctx->cr3    = (void *)get_cr3();
```

管理 控制 视图 热键 设备 帮助

```
   0x102770 <trap+13>       push   %r11
   0x102772 <trap+15>       push   %r10
   0x102774 <trap+17>       push   %r9
   0x102776 <trap+19>       push   %r8
   0x102778 <trap+21>       push   %rdi
   0x102779 <trap+22>       push   %rsi
   0x10277a <trap+23>       push   %rbp
   0x10277b <trap+24>       push   %rdx
   0x10277c <trap+25>       push   %rcx
   0x10277d <trap+26>       push   %rbx
   0x10277e <trap+27>       push   %rax
   0x10277f <trap+28>       push   $0x0
   0x102781 <trap+30>       mov    %rsp,%rdi
  >0x102784 <trap+33>       call   0x100750 <__am_irq_handle>
   0x102789 <__am_iret>     mov    %rdi,%rsp
   0x10278c <__am_iret+3>   mov    0xa0(%rsp),%rax
remote Thread 1.1 In: trap                                 L??   PC: 0x102784
0x000000000010277a in trap ()
0x000000000010277b in trap ()
0x000000000010277c in trap ()
0x000000000010277d in trap ()
0x000000000010277e in trap ()
0x000000000010277f in trap ()
0x0000000000102781 in trap ()
0x0000000000102784 in trap ()
(gdb)
```

管理 控制 视图 热键 设备 帮助

```
>0x102789 <__am_iret>    mov    %rdi,%rsp
 0x10278c <__am_iret+3>  mov    0xa0(%rsp),%rax
 0x102794 <__am_iret+11> mov    %eax,%ds
 0x102796 <__am_iret+13> mov    %eax,%es
 0x102798 <__am_iret+15> add    $0x8,%rsp
 0x10279c <__am_iret+19> pop    %rax
 0x10279d <__am_iret+20> pop    %rbx
 0x10279e <__am_iret+21> pop    %rcx
 0x10279f <__am_iret+22> pop    %rdx
 0x1027a0 <__am_iret+23> pop    %rbp
 0x1027a1 <__am_iret+24> pop    %rsi
 0x1027a2 <__am_iret+25> pop    %rdi
 0x1027a3 <__am_iret+26> pop    %r8
 0x1027a5 <__am_iret+28> pop    %r9
 0x1027a7 <__am_iret+30> pop    %r10
 0x1027a9 <__am_iret+32> pop    %r11
```

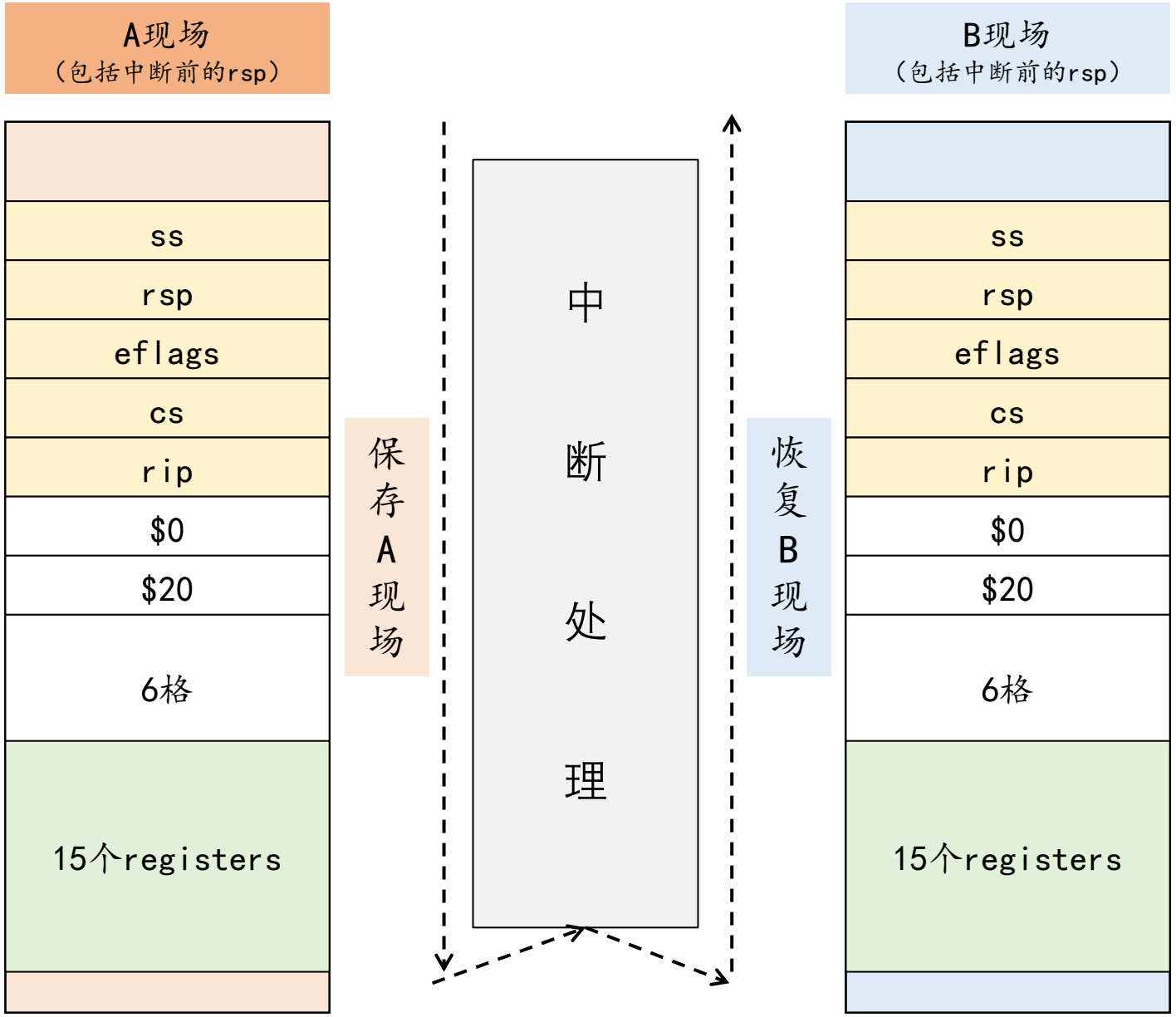
```
remote Thread 1.1 In: __am_iret                          L??   PC: 0x102789
0x00000000001008a0 in __am_irq_handle ()
0x00000000001008a4 in __am_irq_handle ()
0x00000000001008a7 in __am_irq_handle ()
0x00000000001008a8 in __am_irq_handle ()
0x00000000001008a9 in __am_irq_handle ()
0x0000000000102789 in __am_iret ()
(gdb)
```

英 简 拼

Right Shift + Right Alt

管理 控制 视图 热键 设备 帮助

```
   0x1001a8 <func+8>        sub    $0x10,%rsp
   0x1001ac <func+12>       nopl   0x0(%rax)
   0x1001b0 <func+16>       movsbl (%rbx),%edi
   0x1001b3 <func+19>       call   0x1002b0 <putch>
   0x1001b8 <func+24>       movl   $0x0,0xc(%rsp)
   0x1001c0 <func+32>       mov    0xc(%rsp),%eax
   0x1001c4 <func+36>       cmp    $0x1869f,%eax
   0x1001c9 <func+41>       jg     0x1001b0 <func+16>
  >0x1001cb <func+43>       mov    0xc(%rsp),%eax
   0x1001cf <func+47>       add    $0x1,%eax
   0x1001d2 <func+50>       mov    %eax,0xc(%rsp)
   0x1001d6 <func+54>       mov    0xc(%rsp),%eax
   0x1001da <func+58>       cmp    $0x1869f,%eax
   0x1001df <func+63>       jle    0x1001cb <func+43>
   0x1001e1 <func+65>       jmp    0x1001b0 <func+16>
   0x1001e3                     nopw   %cs:0x0(%rax,%rax,1)
remote Thread 1.1 In: func                                 L20   PC: 0x1001cb
(gdb) x/5gx $rsp
0x107258 <tasks+16248>: 0x00000000001001cb      0x0000000000000008
0x107268 <tasks+16264>: 0x0000000000000297      0x00000000001072c0
0x107278 <tasks+16280>: 0x0000000000000000
(gdb) si
0x00000000001001cb in func (arg=0x102922)
    at /home/why/Documents/ICS2021/ics2021/am-kernels/kernels/thread-os/thread-os.
c:20
(gdb)
```


A现场
（包括中断前的rsp）
ss
rsp
eflags
cs
rip
$0
$20
6格
15个registers
保存A现场
中
断
处
理
恢复B现场
B现场
（包括中断前的rsp）
ss
rsp
eflags
cs
rip
$0
$20
6格
15个registers

中断 + 更大的内存 = 分时多线程

```
void foo() { while (1) printf("a"); }
void bar() { while (1) printf("b"); }
```

- 能够让foo()和bar()“同时”在处理器上执行？
  - 借助每条语句后被动插入的interrupt_handler()调用

```
void interrupt_handler() {
   dump_regs(current->regs);
   current = (current->func == foo) ? bar : foo;
   restore_regs(current->regs);
}
```

  - 操作系统背负了“调度”的职责

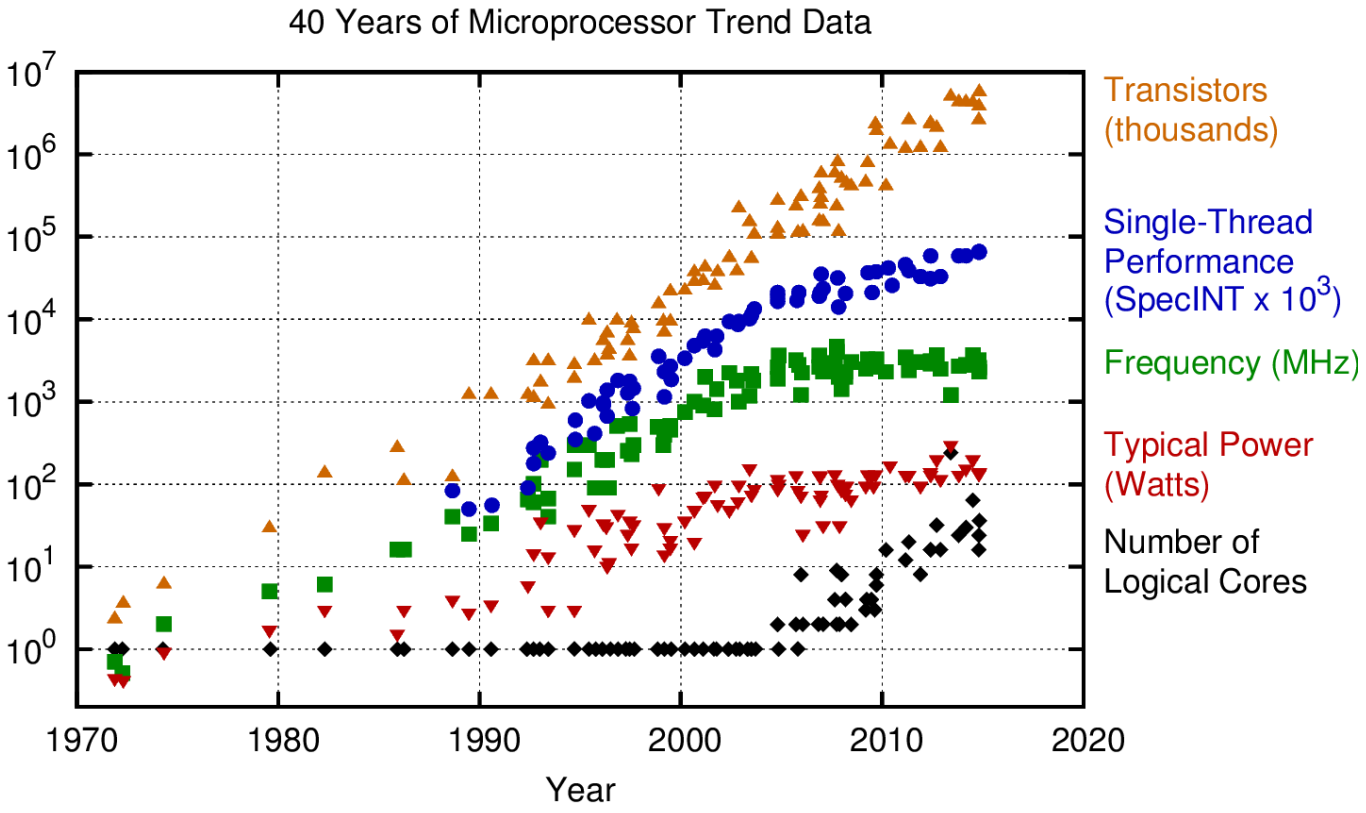
分时多线程 + 虚拟存储 = 进程

- 让foo()和bar()的执行互相不受影响
  - 在计算机系统里增加映射函数f_{foo}, f_{bar}
  - foo访问内存地址m时，将被重定位到$f_{\text{foo}}(m)$
  - bar访问内存地址m时，将被重定位到$f_{\text{bar}}(m)$

  - foo和bar本身无权管理f
  - 操作系统需要完成进程、存储、文件的管理
  - UNIX诞生（就是我们今天的进程；Android app；…）
    - `gcc a.c`
    - `readelf -a a.out` → 二进制文件的全部信息

故事其实没有停止.

- 面对有限的功耗、难以改进的制程、无法提升的频率、应用需求
  - 多处理器、big.LITTLE、异构处理器 (GPU、NPU、…)
  - 单指令多数据(MMX, SSE, AVX, …), 虚拟化(VT; EL0/1/2/3), … ，安全执行环节 (TrustZone; SGX), …



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

总结

操作系统：中断驱动的上下文切换

- 应用程序视角
  - 一组系统调用的 API
    - 进程管理、存储管理、文件管理……
- 硬件视角
  - 操作系统是一个中断处理程序
    - 设备中断：上下文切换；调用设备驱动程序；……
    - 系统调用：操作系统代码执行 (API 实现)
    - 异常：发送信号 (类似系统调用)

End.