238P: Operating Systems

Lecture 10: Context switch

Anton Burtsev
May, 2019

When OS context switches between processes?

When OS context switches between processes?

- Timer interrupt preempts the current process
- A process enters the kernel with a system call and has to wait on some resource
  - E.g., write to a pipe, but the pipe is full
- The process voluntarily yields CPU with the yield() system call

Lets look at timer interrupt

trap()

```
3351 trap(struct trapframe *tf)
3352 {
...
3363   switch(tf->trapno){
3364   case T_IRQ0 + IRQ_TIMER:
3365     if(cpu->id == 0){
3366     acquire(&tickslock);
3367     ticks++;
3368     wakeup(&ticks);
3369     release(&tickslock);
3370   }
3372   break;
...
3423   if(proc && proc->state == RUNNING
          && tf->trapno == T_IRQ0+IRQ_TIMER)
3424     yield();
```

trap()

```
3351 trap(struct trapframe *tf)
3352 {
...
3363   switch(tf->trapno){
3364   case T_IRQ0 + IRQ_TIMER:
3365     if(cpu->id == 0){
3366     acquire(&tickslock);
3367     ticks++;
3368     wakeup(&ticks);
3369     release(&tickslock);
3370   }
3372   break;
...
3423   if(proc && proc->state == RUNNING
          && tf->trapno == T_IRQ0+IRQ_TIMER)
3424     yield();
```

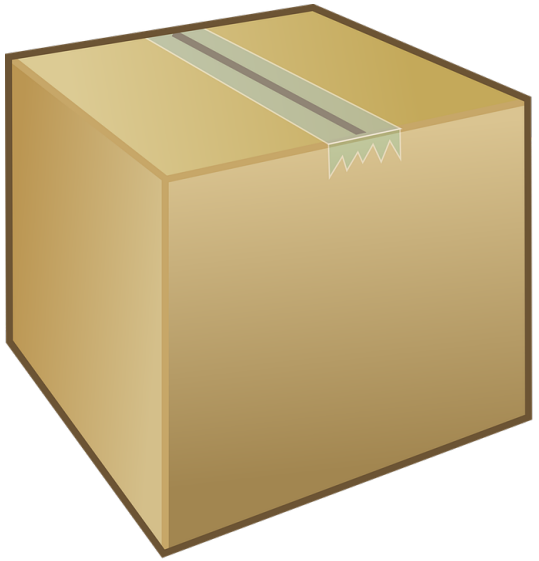
Invoke the scheduler

```
2777 yield(void)
2778 {
2779   acquire(&ptable.lock);
2780   proc->state = RUNNABLE;
2781   sched();
2782   release(&ptable.lock);
2783 }
```

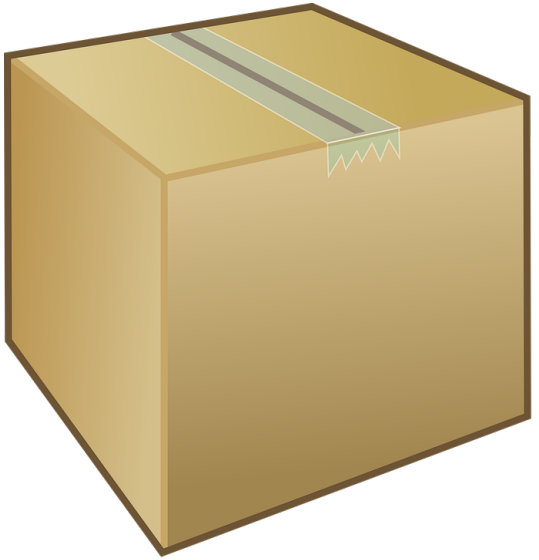
Start the context switch

```
2758 sched(void)
2759 {
...
2771   swtch(&proc->context,
                cpu->scheduler);
...
2773 }
```

But what do you think needs to happen inside switch()?



Process 1

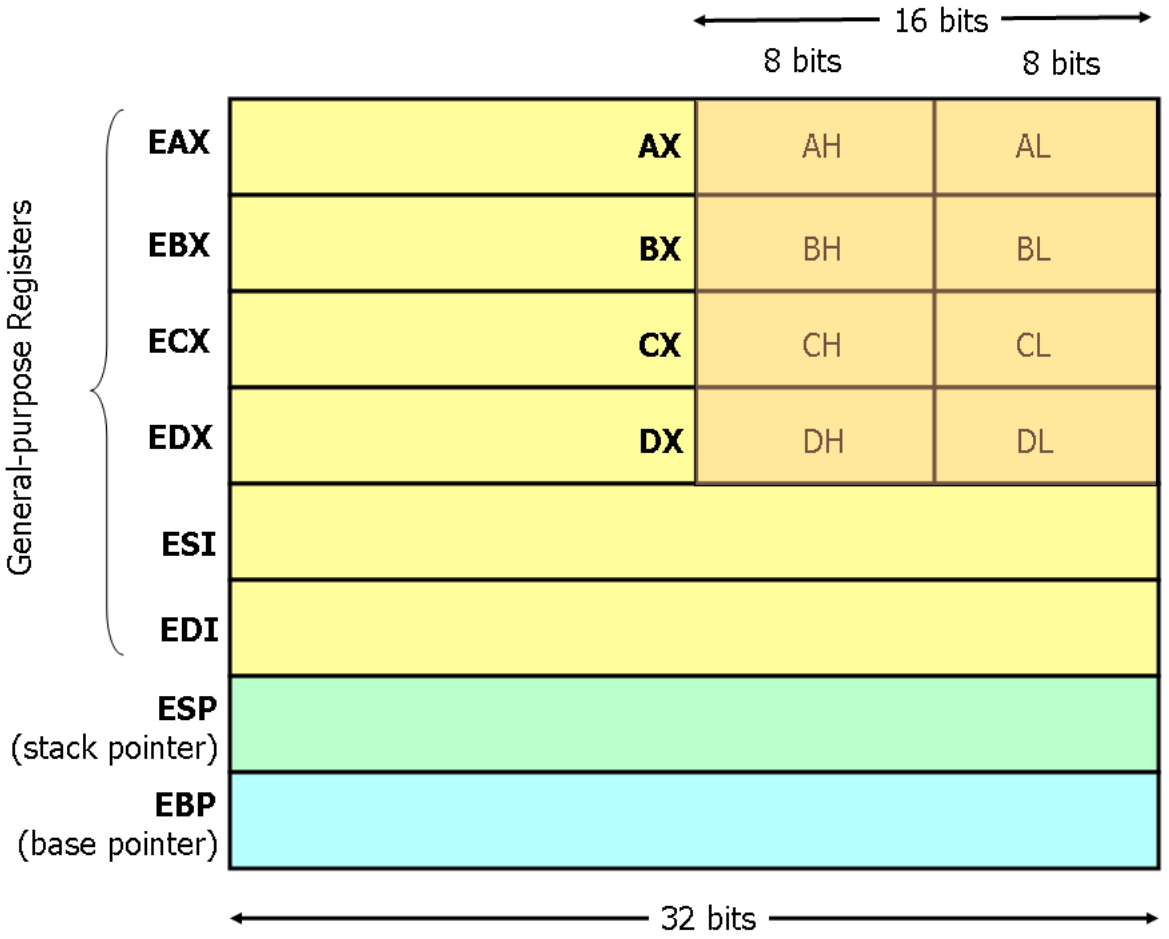


Process 2

What should be in the box?
i.e., what is the state of the process?

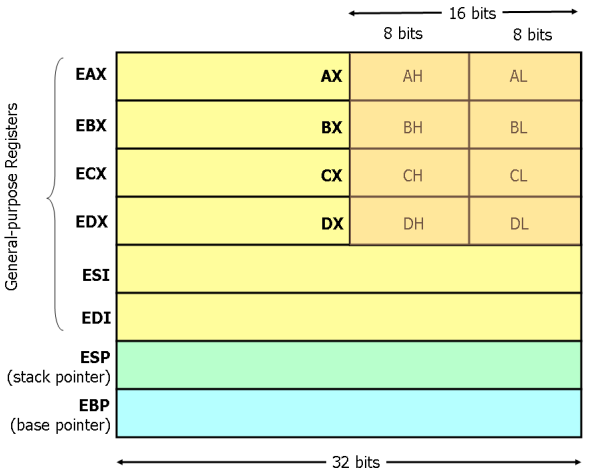
```
2103 struct proc {
2104   uint sz; // Size of process memory (bytes)
2105   pde_t* pgdir; // Page table
2106   char *kstack; // Bottom of kernel stack for this process
2107   enum procstate state; // Process state
2108   volatile int pid; // Process ID
2109   struct proc *parent; // Parent process
2110   struct trapframe *tf; // Trap frame
2111   struct context *context; // swtch() here to run
2112   void *chan; // If non-zero, sleeping on chan
2113   int killed; // If non-zero, have been killed
2114   struct file *ofile[NOFILE]; // Open files
2115   struct inode *cwd; // Current directory
2116   char name[16]; // Process name (debugging)
2117 };
```

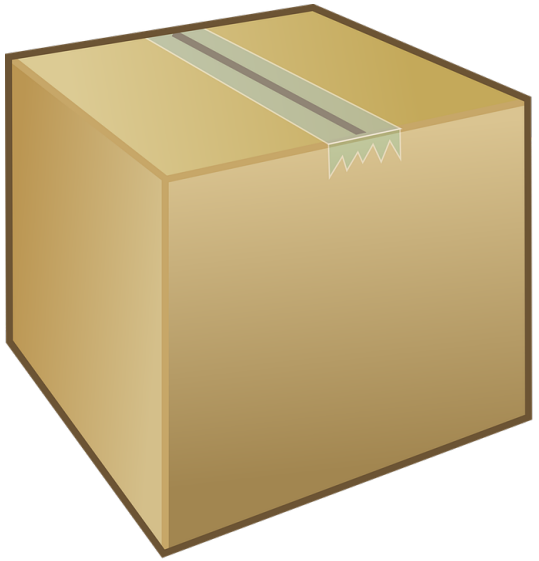
What about general registers?



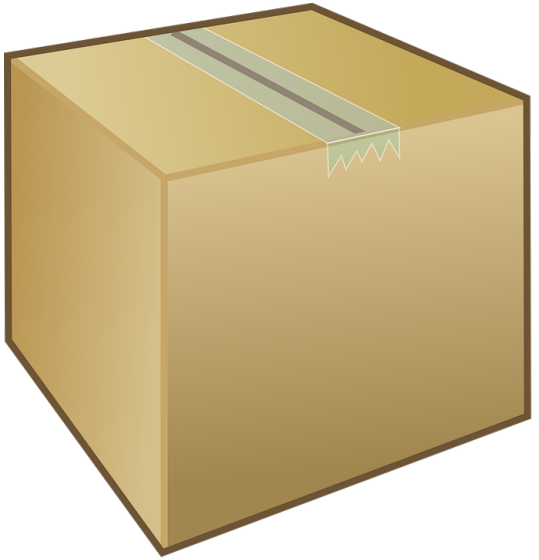
Save them on the stack

```
2093 struct context {
2094   uint edi;
2095   uint esi;
2096   uint ebx;
2097   uint ebp;
2098   uint eip;
2099 };
```



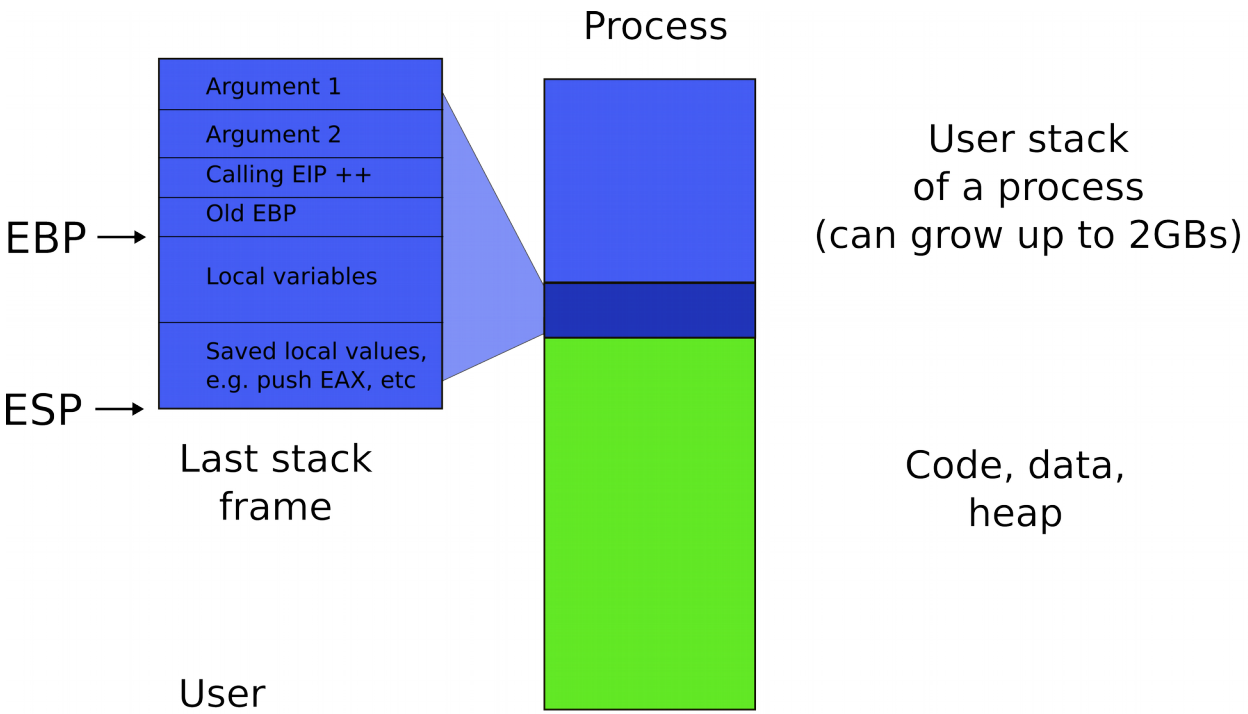


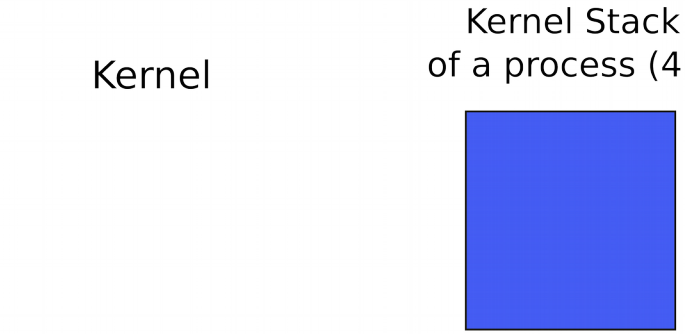
Process 1

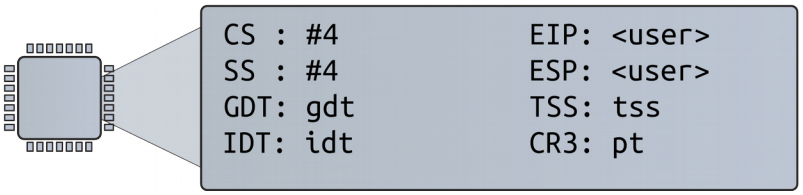


Process 2

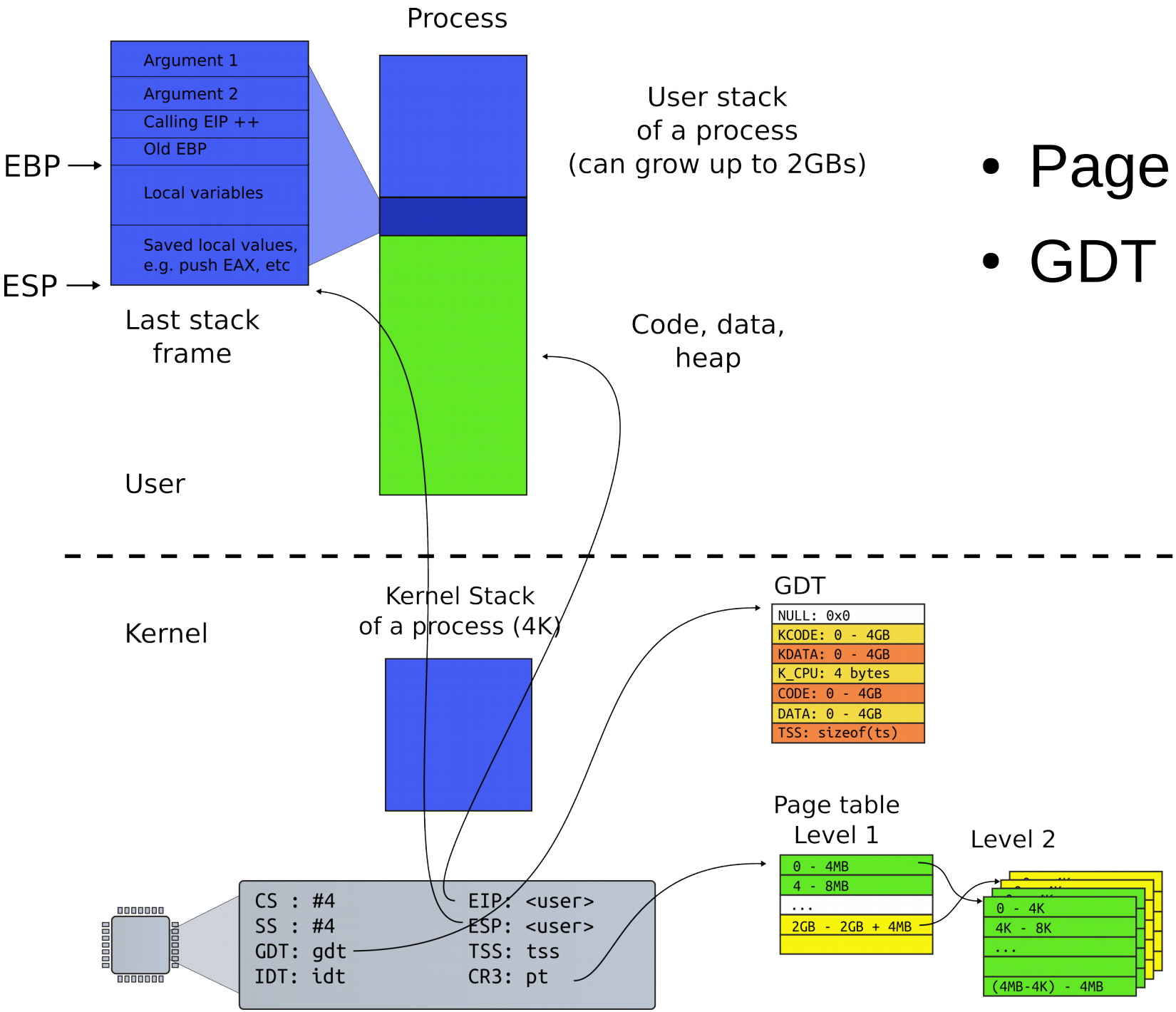
Back to the timer interrupt path
(keep track of what happens to the stack, lets see how everything gets packed in a “box”!)



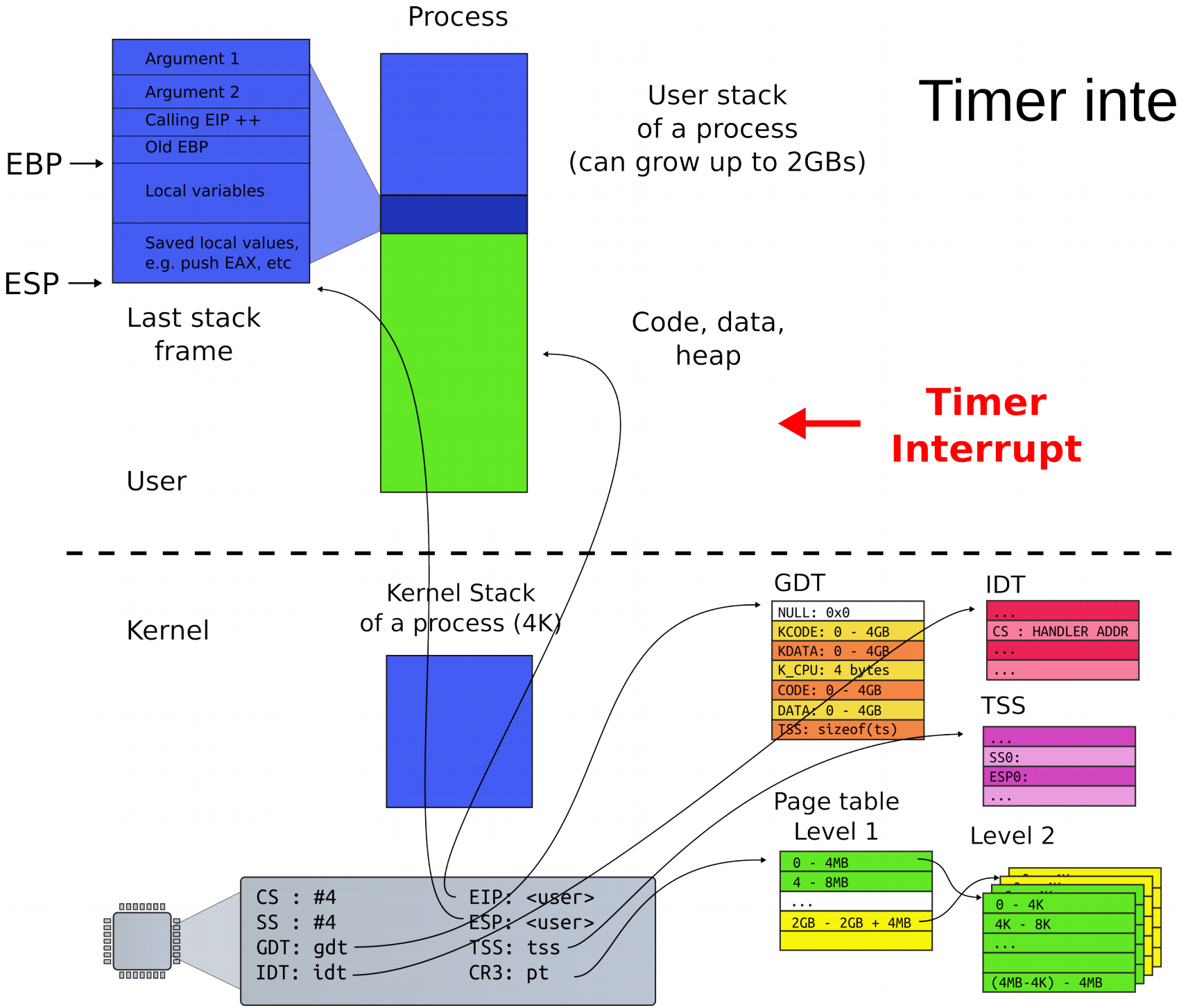




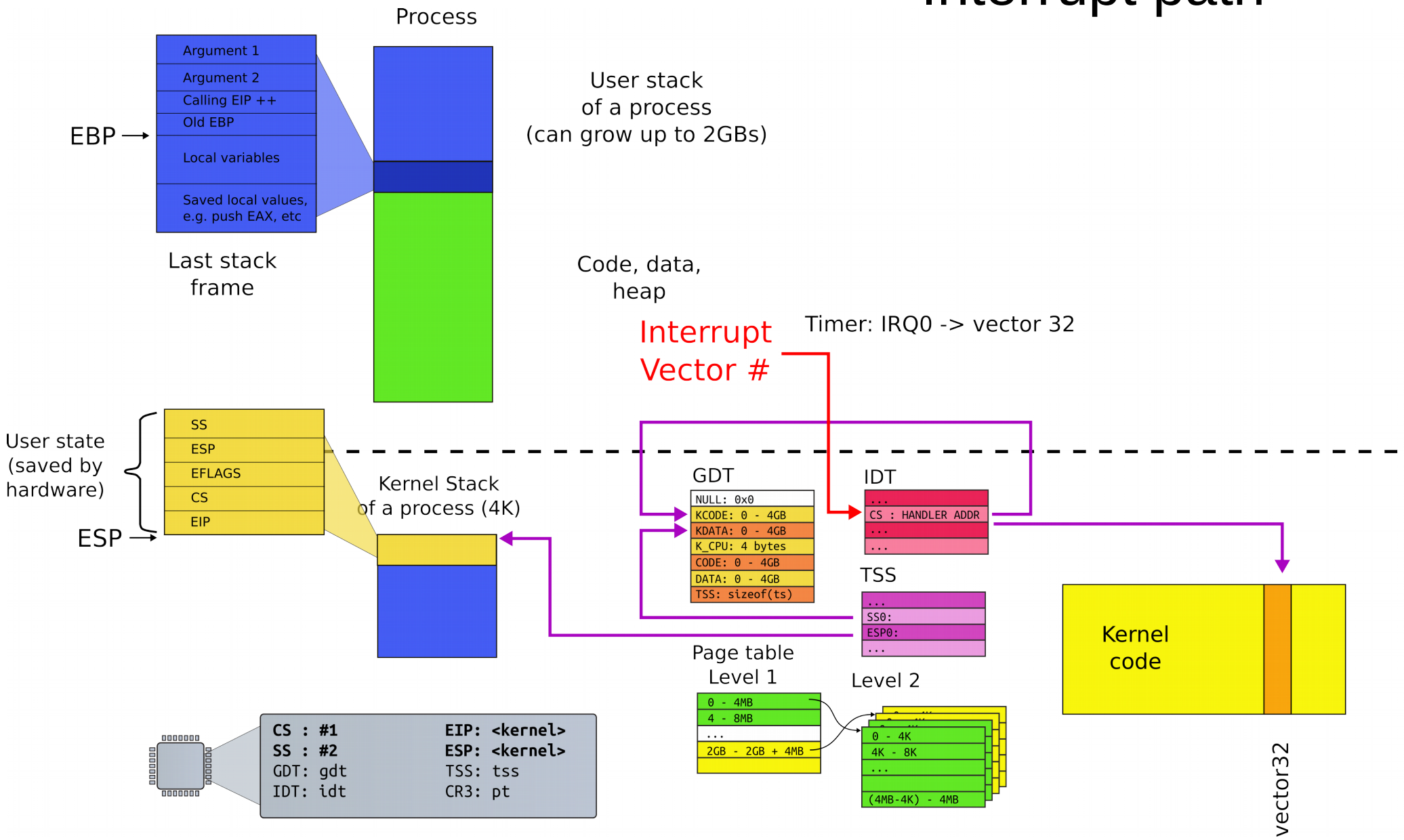
- User mode
- Two stacks
  - Kernel and user
  - Kernel stack is empty



- Page table
- GDT


Process
Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc
EBP
ESP
Last stack frame
User stack of a process (can grow up to 2GBs)
Code, data, heap
User
Timer Interrupt
Kernel
Kernel Stack of a process (4K)
GDT
NULL: 0x0
KCODE: 0 - 4GB
KDATA: 0 - 4GB
K_CPU: 4 bytes
CODE: 0 - 4GB
DATA: 0 - 4GB
TSS: sizeof(ts)
IDT
...
CS : HANDLER ADDR
...
...
TSS
...
SS0:
ESP0:
...
Page table
Level 1
0 - 4MB
4 - 8MB
...
2GB - 2GB + 4MB
Level 2
0 - 4K
4K - 8K
...
(4MB-4K) - 4MB
CS : #4
SS : #4
GDT: gdt
IDT: idt
EIP: <user>
ESP: <user>
TSS: tss
CR3: pt

Interrupt path

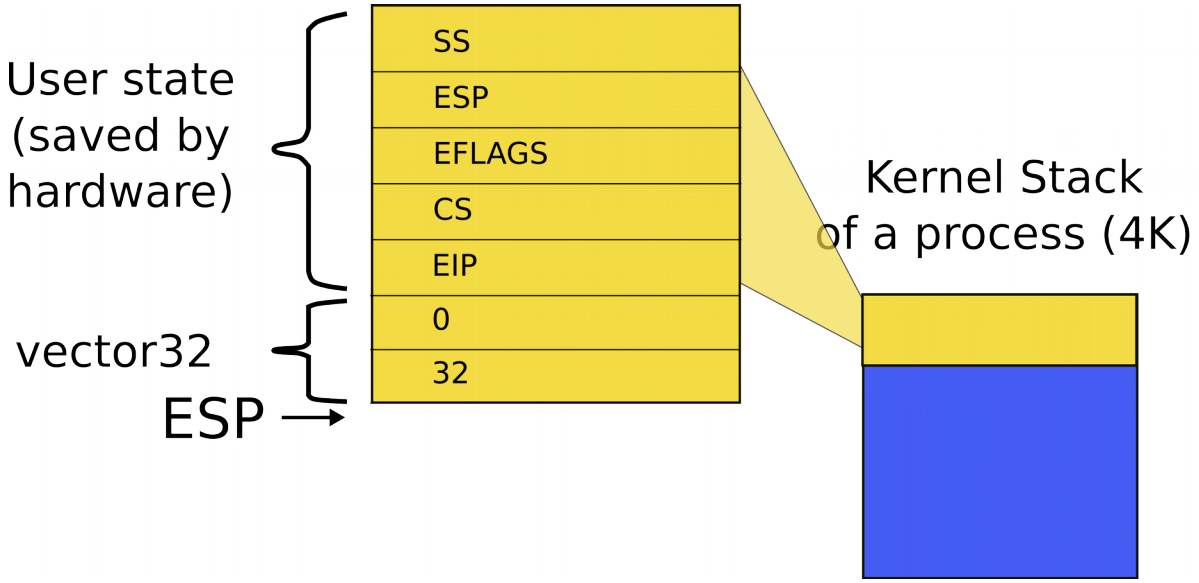


Where does IDT (entry 32) point to?

```
vector32:
  pushl $0     // error code
  pushl $32    // vector #
  jmp alltraps
```

- Automatically generated
- From vectors.pl
  - vector.S

Kernel stack after interrupt

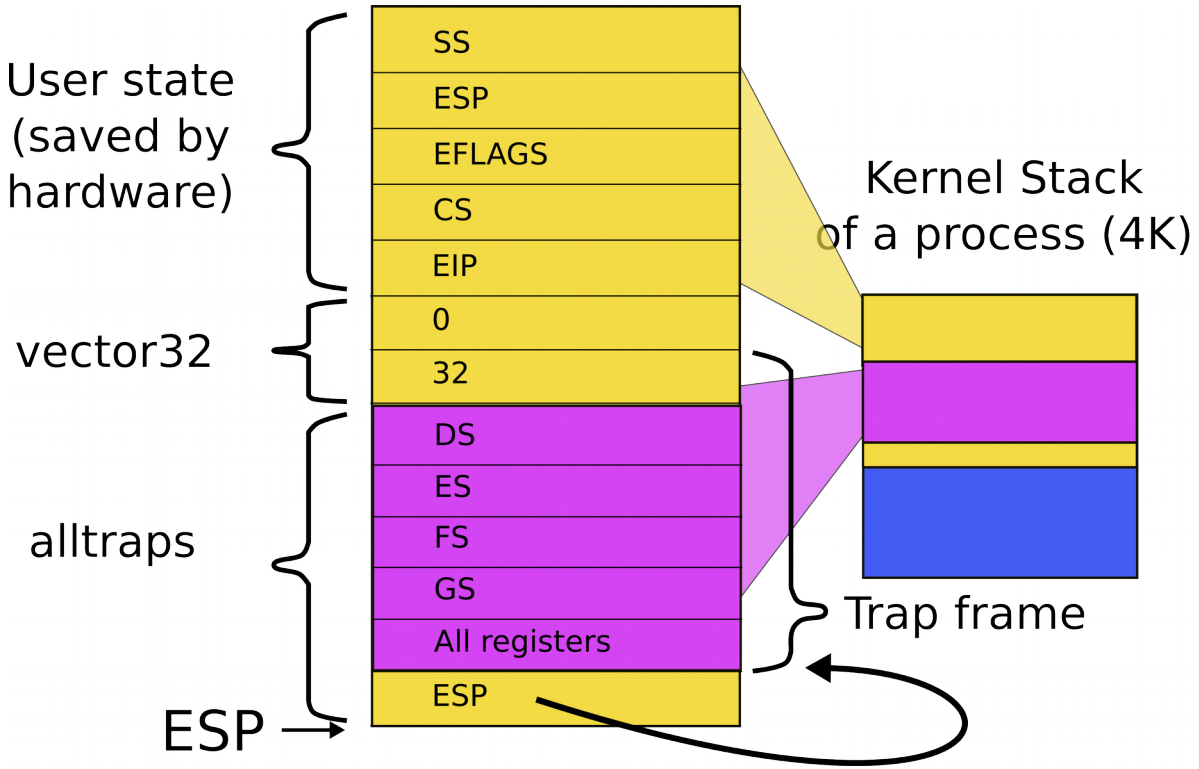


Call stack: vector32()

alltraps()

```
3254 alltraps:
3255   # Build trap frame.
3256   pushl %ds
3257   pushl %es
3258   pushl %fs
3259   pushl %gs
3260   pushal
3261
3262   # Set up data and per-cpu segments.
3263   movw $(SEG_KDATA<<3), %ax
3264   movw %ax, %ds
3265   movw %ax, %es
3266   movw $(SEG_KCPU<<3), %ax
3267   movw %ax, %fs
3268   movw %ax, %gs
3269
3270   # Call trap(tf), where tf=%esp
3271   pushl %esp
3272   call trap
```

Kernel stack after interrupt



Call stack: vector32()
alltraps()

alltraps()

```
3254 alltraps:
3255 # Build trap frame.
3256 pushl %ds
3257 pushl %es
3258 pushl %fs
3259 pushl %gs
3260 pushal
3261
3262 # Set up data and per-cpu segments.
3263 movw $(SEG_KDATA<<3), %ax
3264 movw %ax, %ds
3265 movw %ax, %es
3266 movw $(SEG_KCPU<<3), %ax
3267 movw %ax, %fs
3268 movw %ax, %gs
3269
3270 # Call trap(tf), where tf=%esp
3271 pushl %esp
3272 call trap
```

trap()

```
3351 trap(struct trapframe *tf)
3352 {
...
3363   switch(tf->trapno){
3364   case T_IRQ0 + IRQ_TIMER:
3365     if(cpu->id == 0){
3366     acquire(&tickslock);
3367     ticks++;
3368     wakeup(&ticks);
3369     release(&tickslock);
3370   }
3372   break;
...
3423   if(proc && proc->state == RUNNING
          && tf->trapno == T_IRQ0+IRQ_TIMER)
3424     yield();
```

trap()

```
3351 trap(struct trapframe *tf)
3352 {
...
3363   switch(tf->trapno){
3364   case T_IRQ0 + IRQ_TIMER:
3365     if(cpu->id == 0){
3366     acquire(&tickslock);
3367     ticks++;
3368     wakeup(&ticks);
3369     release(&tickslock);
3370   }
3372   break;
...
3423   if(proc && proc->state == RUNNING
          && tf->trapno == T_IRQ0+IRQ_TIMER)
3424     yield();
```

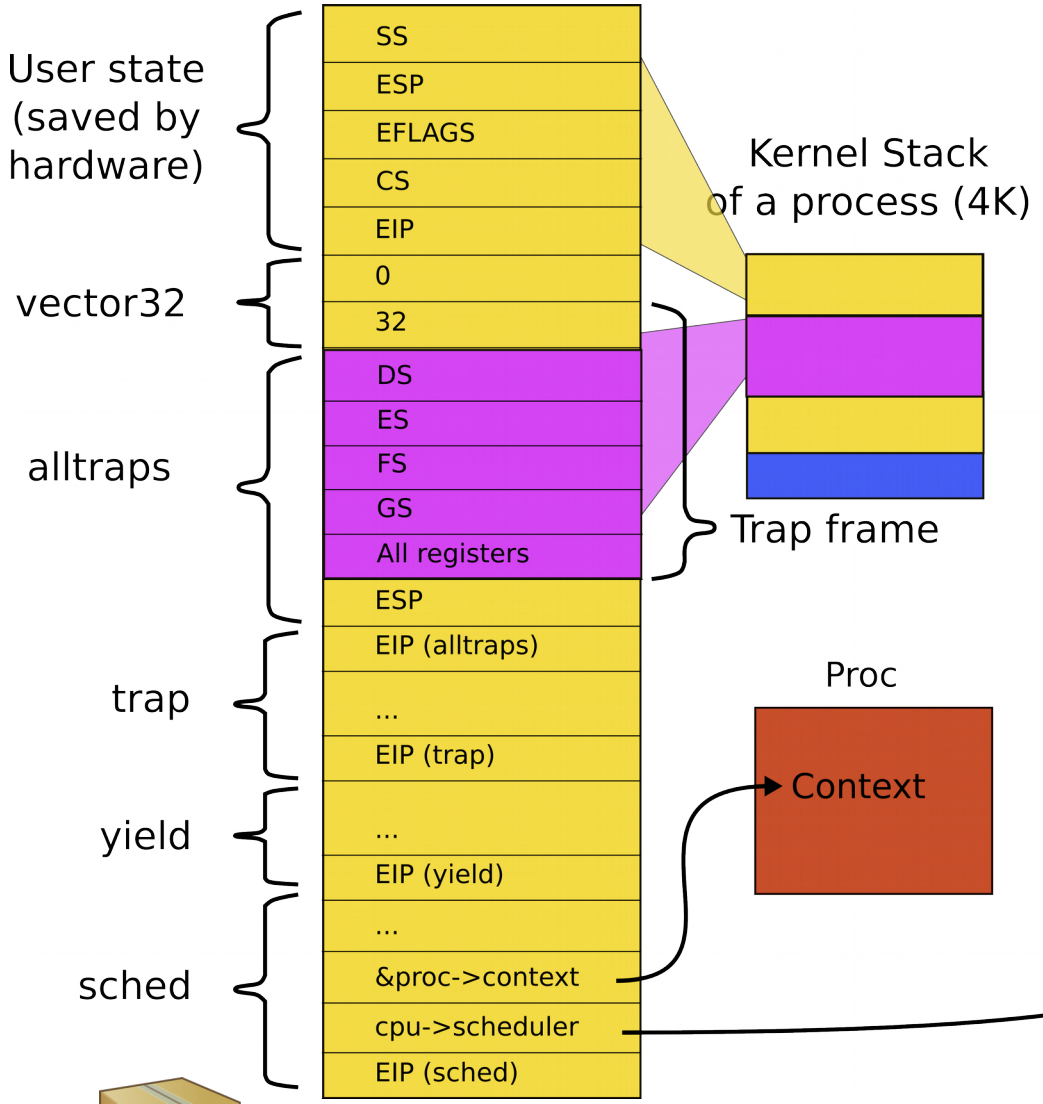
Invoke the scheduler

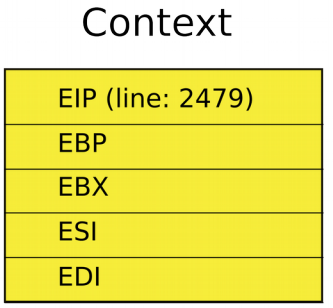
```
2777 yield(void)
2778 {
2779   acquire(&ptable.lock);
2780   proc->state = RUNNABLE;
2781   sched();
2782   release(&ptable.lock);
2783 }
```

Start the context switch

```
2758 sched(void)
2759 {
...
2771   swtch(&proc->context,
                cpu->scheduler);
...
2773 }
```

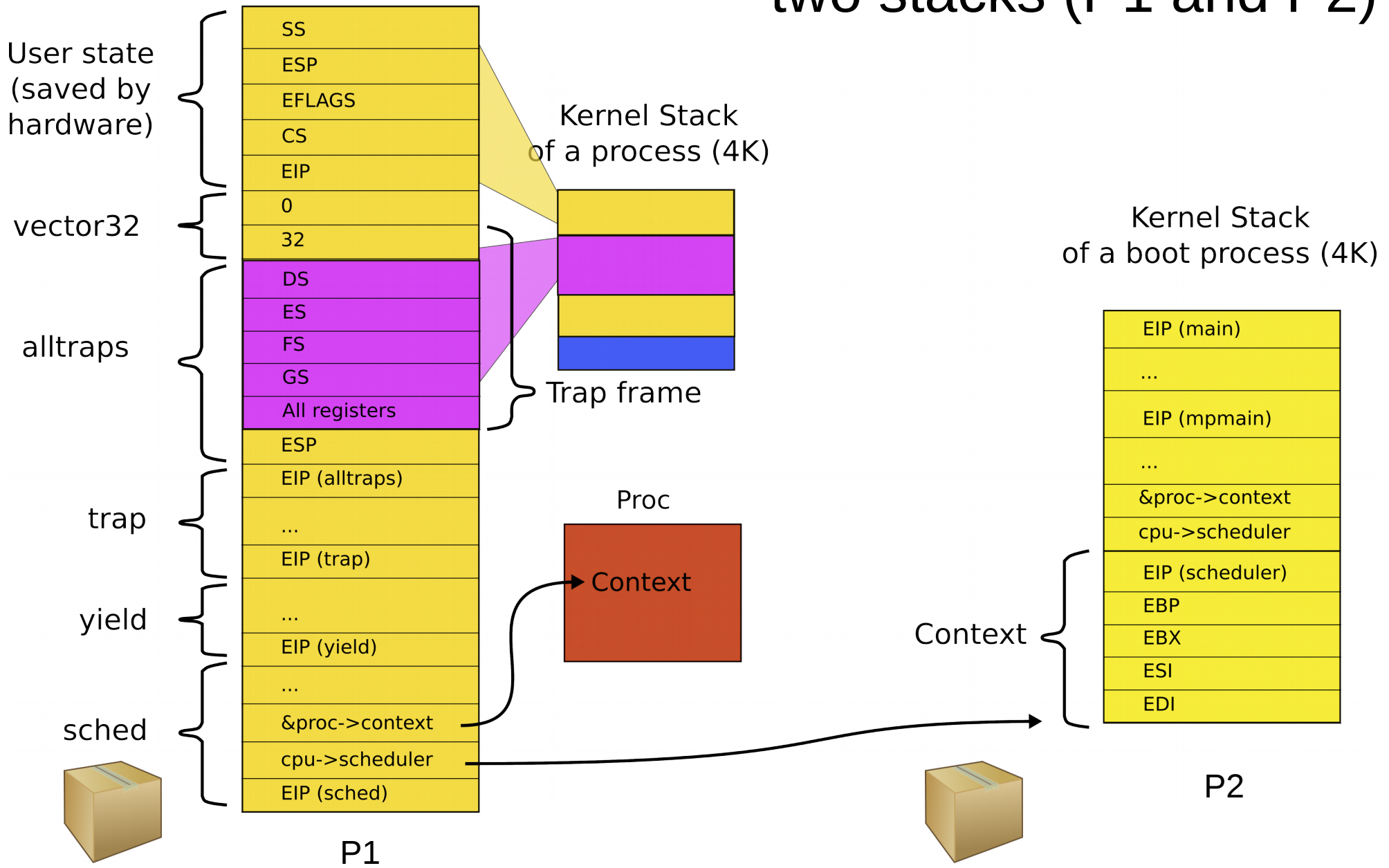
Stack inside swtch() and its two arguments (passed on the stack)





Call stack:
vector32()
alltraps()
trap()
yield()
sched()
switch(&proc->context,
cpu->scheduler)

Remember you have two stacks (P1 and P2)



The context switch function should pack everything what is left (the context!) in the box and switch stacks, i.e., save the pointer to the old stack (P1) and load the new stack (P2)

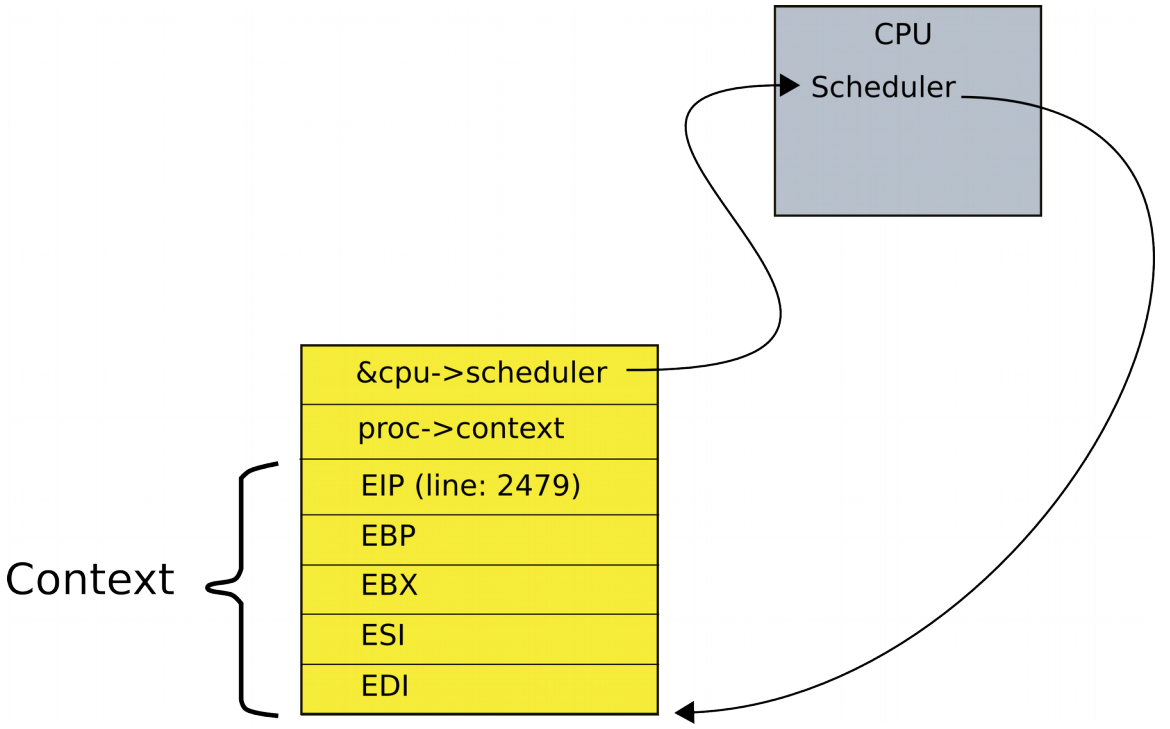
swtch(): save registers on the stack

```
2958 swtch:
2959 movl 4(%esp), %eax
2960 movl 8(%esp), %edx
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacksh
2969 movl %esp, (%eax)
2970 movl %edx, %esp
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

```
2093 struct context {
2094   uint edi;
2095   uint esi;
2096   uint ebx;
2097   uint ebp;
2098   uint eip;
2099 };
```

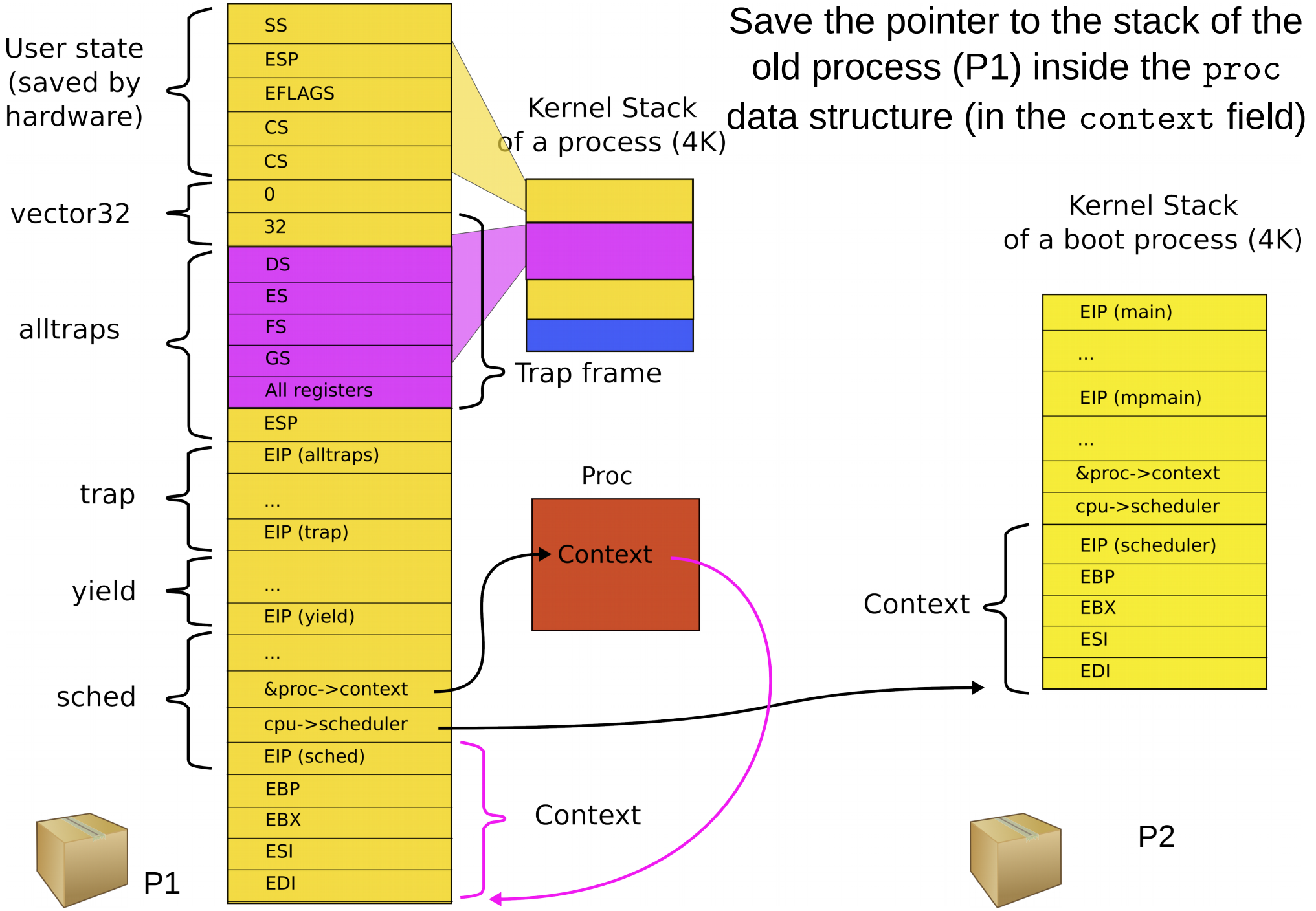
Context data structure

```
2093 struct context {
2094   uint edi;
2095   uint esi;
2096   uint ebx;
2097   uint ebp;
2098   uint eip;
2099 };
```



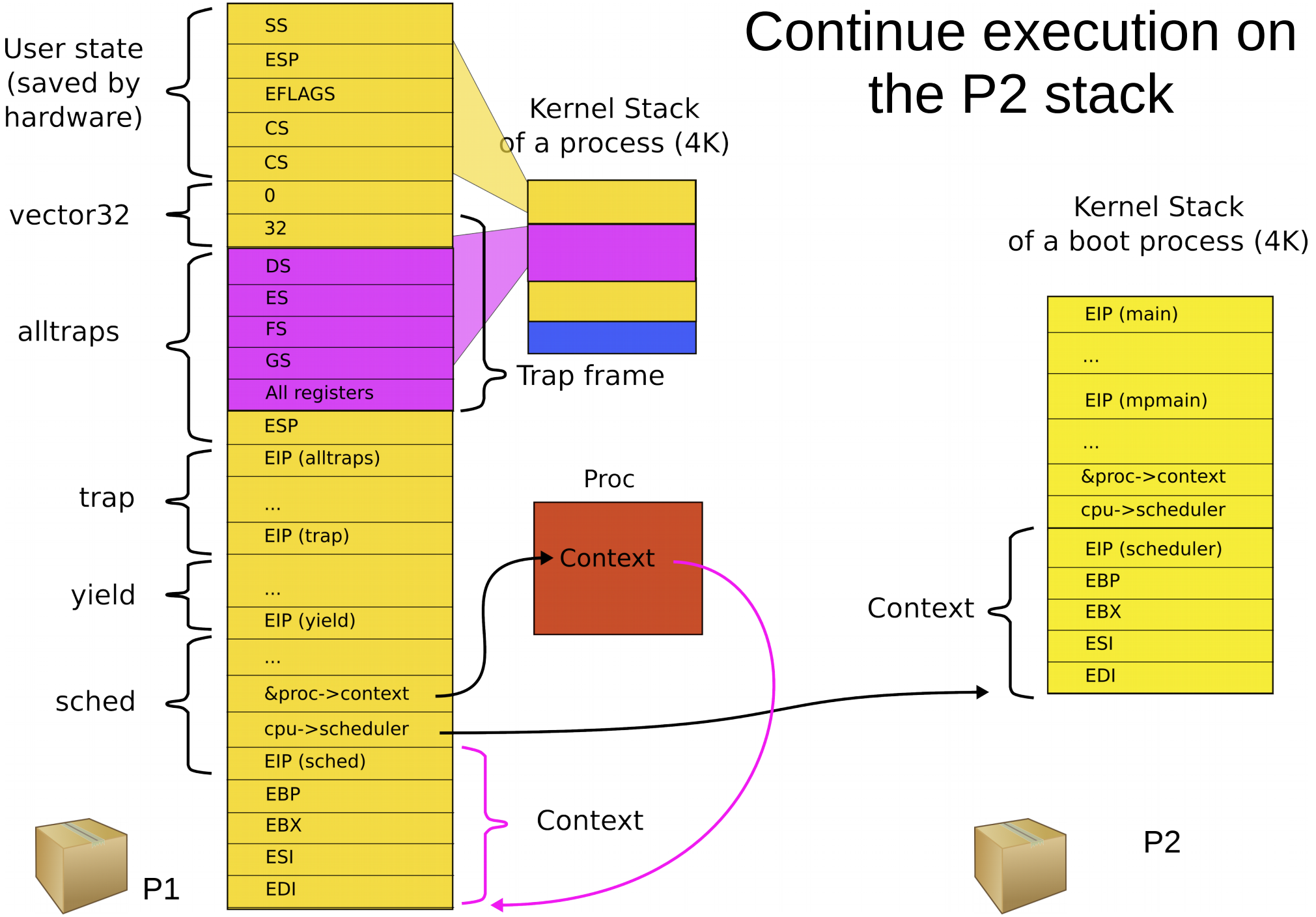
Main trick: context is always saved on the top of a stack

And the context switch just saves the old context and loads the new


Save the pointer to the stack of the old process (P1) inside the proc data structure (in the context field)
User state (saved by hardware)
vector32
alltraps
trap
yield
sched
SS
ESP
EFLAGS
CS
CS
0
32
DS
ES
FS
GS
All registers
ESP
EIP (alltraps)
...
EIP (trap)
...
EIP (yield)
...
&proc->context
cpu->scheduler
EIP (sched)
EBP
EBX
ESI
EDI
Kernel Stack of a process (4K)
Trap frame
Proc
Context
Context
P1
Kernel Stack of a boot process (4K)
EIP (main)
...
EIP (mpmain)
...
&proc->context
cpu->scheduler
EIP (scheduler)
EBP
EBX
ESI
EDI
Context
P2

Now you can simply load the new context (P2) into ESP and continue returning on that new stack

Continue execution on the P2 stack



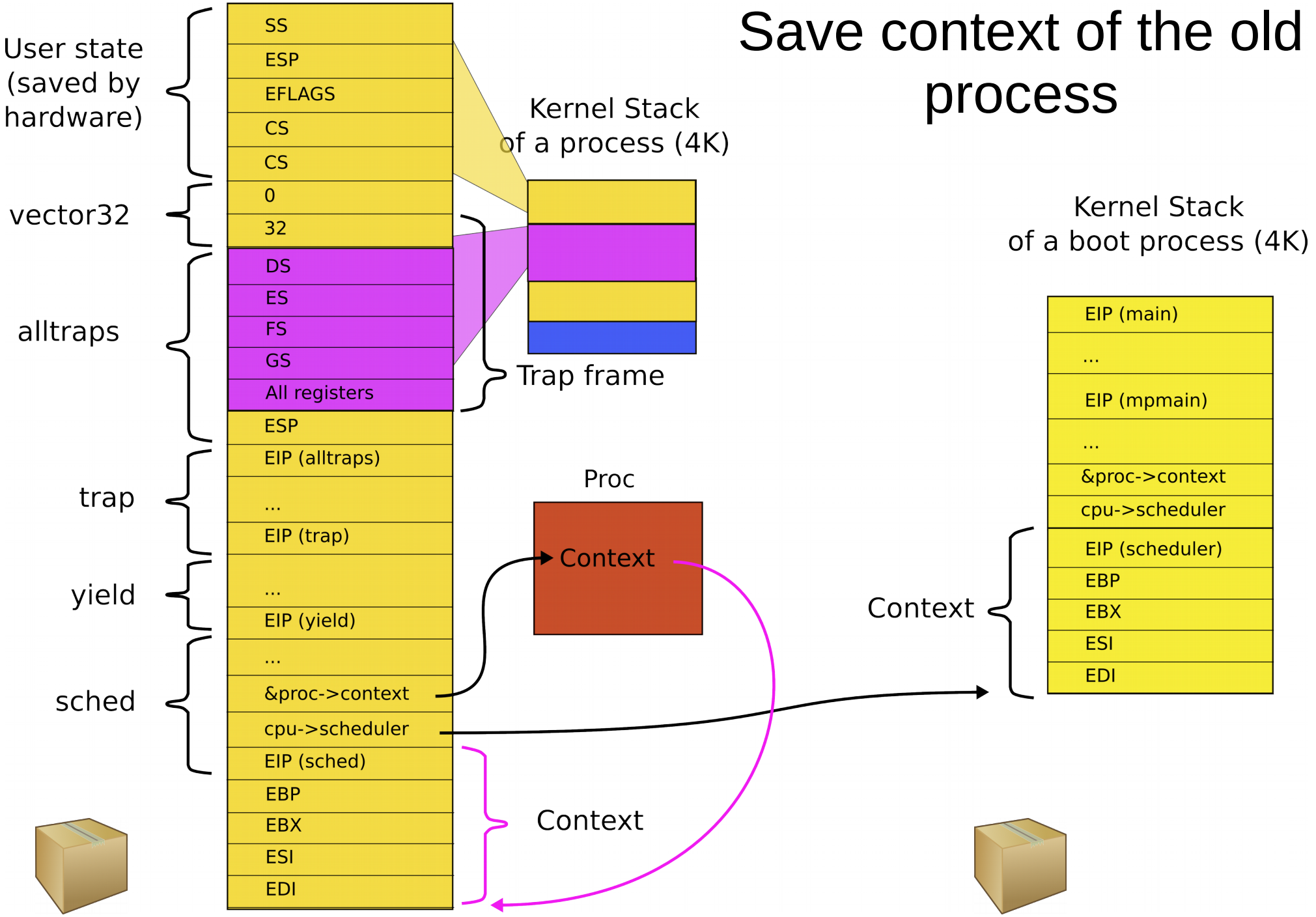
```
2958 swtch:
2959 movl 4(%esp), %eax  # **old
2960 movl 8(%esp), %edx  # *new
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacksh
2969 movl %esp, (%eax) # *old = %esp
2970 movl %edx, %esp   # %esp = new
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

swtch()

```
void swtch(struct context **old,
           struct context *new);
```

- First argument:
  - A pointer to a pointer to a context
  - Or in other words: a pointer to a memory location that can hold address of the context
  - We'll save the address of the current context there
- Second argument:
  - A pointer to a context of the next process
  - We'll load it into the ESP register switching to the next process

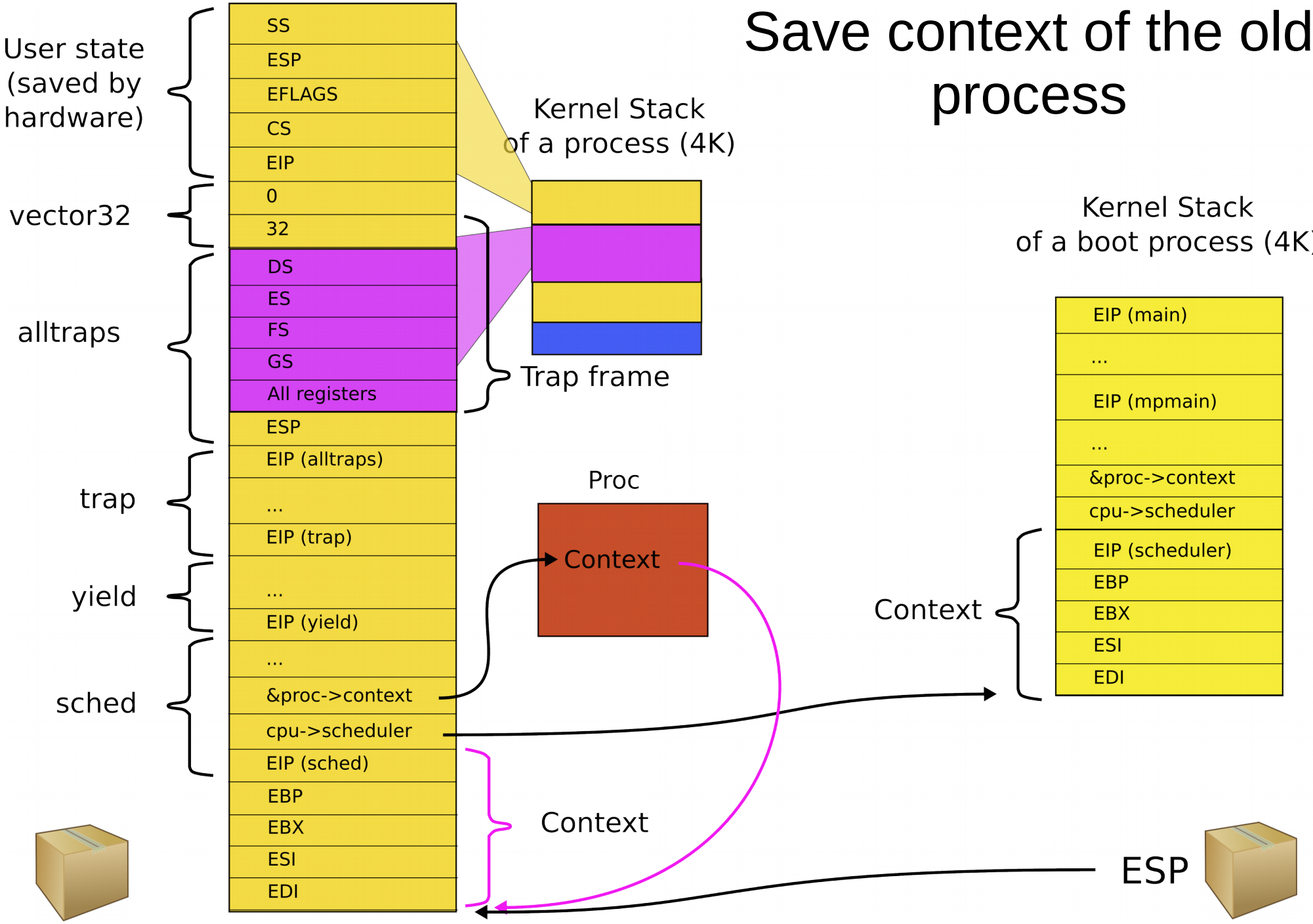
Save context of the old process



swtch()

```
2958 swtch:
2959 movl 4(%esp), %eax     // struct context **old
2960 movl 8(%esp), %edx     // struct context *new
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacks
2969 movl %esp, (%eax)  // load current context (top of current stack) into
                       //  the memory location pointed by *old
2970 movl %edx, %esp    // set stack to be equal to *new (the top of the new context)
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

Save context of the old process

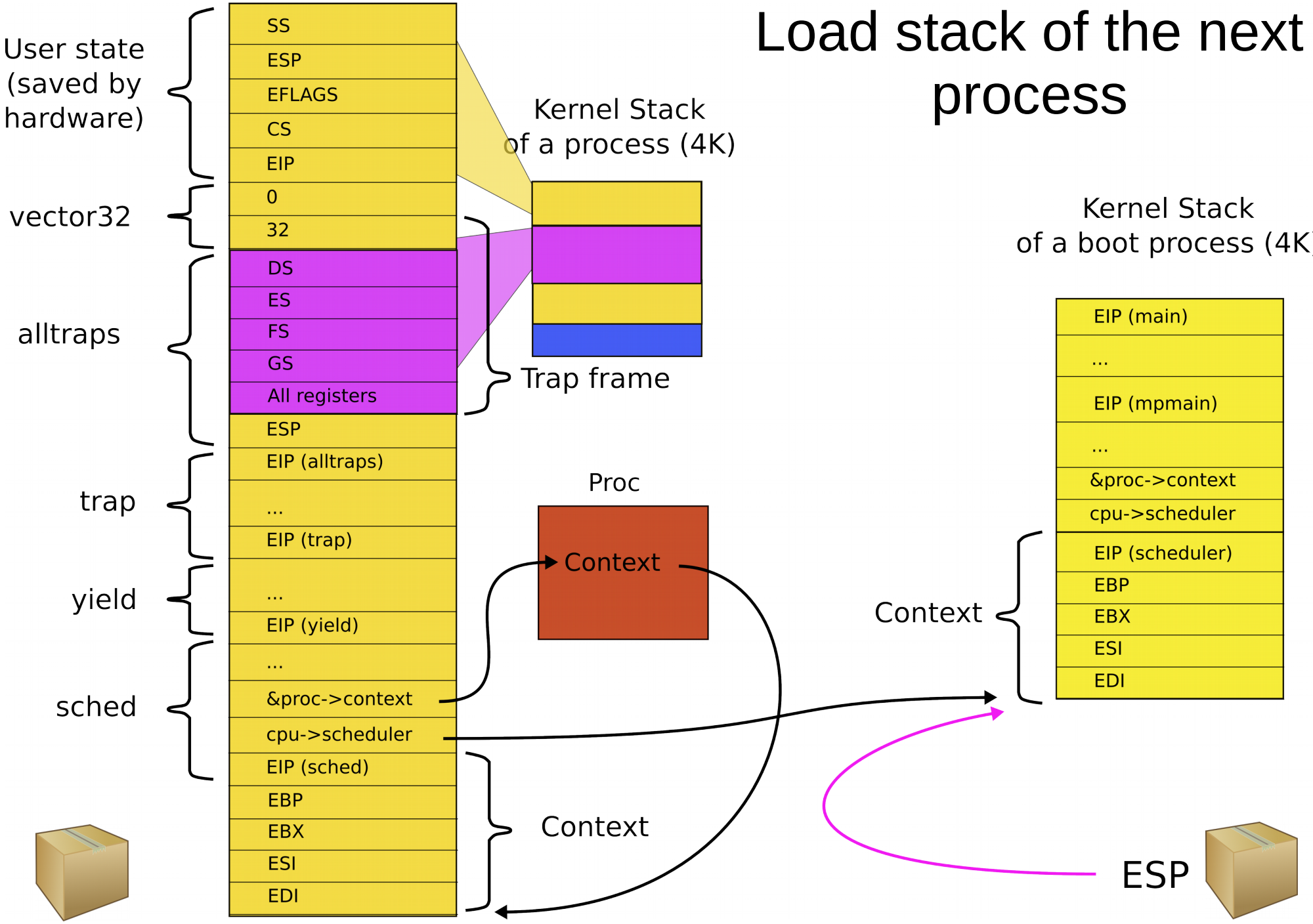


```
2958 swtch:
2959 movl 4(%esp), %eax     // struct context **old
2960 movl 8(%esp), %edx     // struct context *new
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacks
2969 movl %esp, (%eax)  // save current context (top of current stack) into
                       //  the memory location pointed by *old
2970 movl %edx, %esp    // set stack to be equal to *new (the top of the new context)
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

swtch(): load next context

- Load address of the next context (it's in %edx) into %esp

Load stack of the next process



Remember: The context switch function should just save the pointer to the old stack (P1) and load the new stack (P2)

```
2958 swtch:
2959 movl 4(%esp), %eax
2960 movl 8(%esp), %edx
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacks
2969 movl %esp, (%eax)
2970 movl %edx, %esp
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

Now: exit from swtch()

Where does this swtch() return?

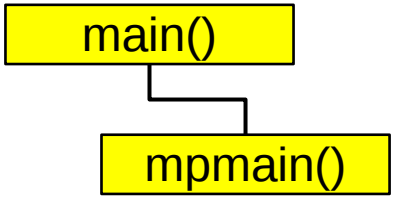
Context is always top of some stack...ok, but how?

- How does initialization of each CPU end?

```
1317 main(void)
1318 {
1319   kinit1(end, P2V(4*1024*1024)); // phys page allocator
1320   kvmalloc(); // kernel page table
1321   mpinit(); // detect other processors
...
1323   seginit(); // segment descriptors
...
1330   tvinit(); // trap vectors
...
1338   userinit(); // first user process
1339   mpmain(); // finish this processor's setup
1340 }
```

main()

```
1260 // Common CPU setup code.
1261 static void
1262 mpmain(void)
1263 {
1264   cprintf("cpu%d: starting\n", cpu->id);
1265   idtinit(); // load idt register
1266   xchg(&cpu->started, 1);
1267   scheduler(); // start running processes
1268 }
```



We ended boot by starting the scheduler

Scheduler()

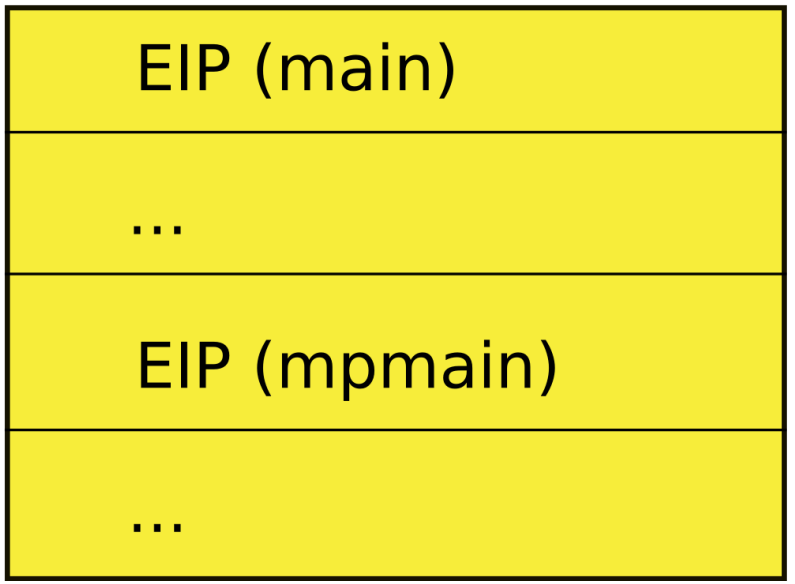
```
2458 scheduler(void)
2459 {
2462   for(;;){
2468     for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
2469       if(p->state != RUNNABLE)
2470         continue;
2475       proc = p;
2476       switchuvm(p);
2477       p->state = RUNNING;
2478       swtch(&cpu->scheduler, proc->context);
2479       switchkvm();
2483       proc = 0;
2484     }
2487   }
2488 }
```

- Chooses next process to run
- Switches to it
  - From the current context

```
2301 struct cpu {
2302   uchar apicid;                // Local APIC
2303   struct context *scheduler;  // swtch() here to enter scheduler
2304   struct taskstate ts;         // TSS
2305   struct segdesc gdt[NSEGS];   // x86 global descriptor table
2306   volatile uint started;       // Has the CPU started?
2307   int ncli;                    // Depth of pushcli nesting.
2308   int intena;                  // Were interrupts enabled ...
2309   struct proc *proc;           // The process running on this cpu
2310 };
2311
2312 extern struct cpu cpus[NCPU];
2313 extern int ncpu;
```

This is how the stack looked after boot finished, i.e., inside mpmain()

Kernel Stack
of a boot process (4K)



- So when the scheduler context switched the first time

```
2478 swtch(&cpu->scheduler,
           proc->context);
```

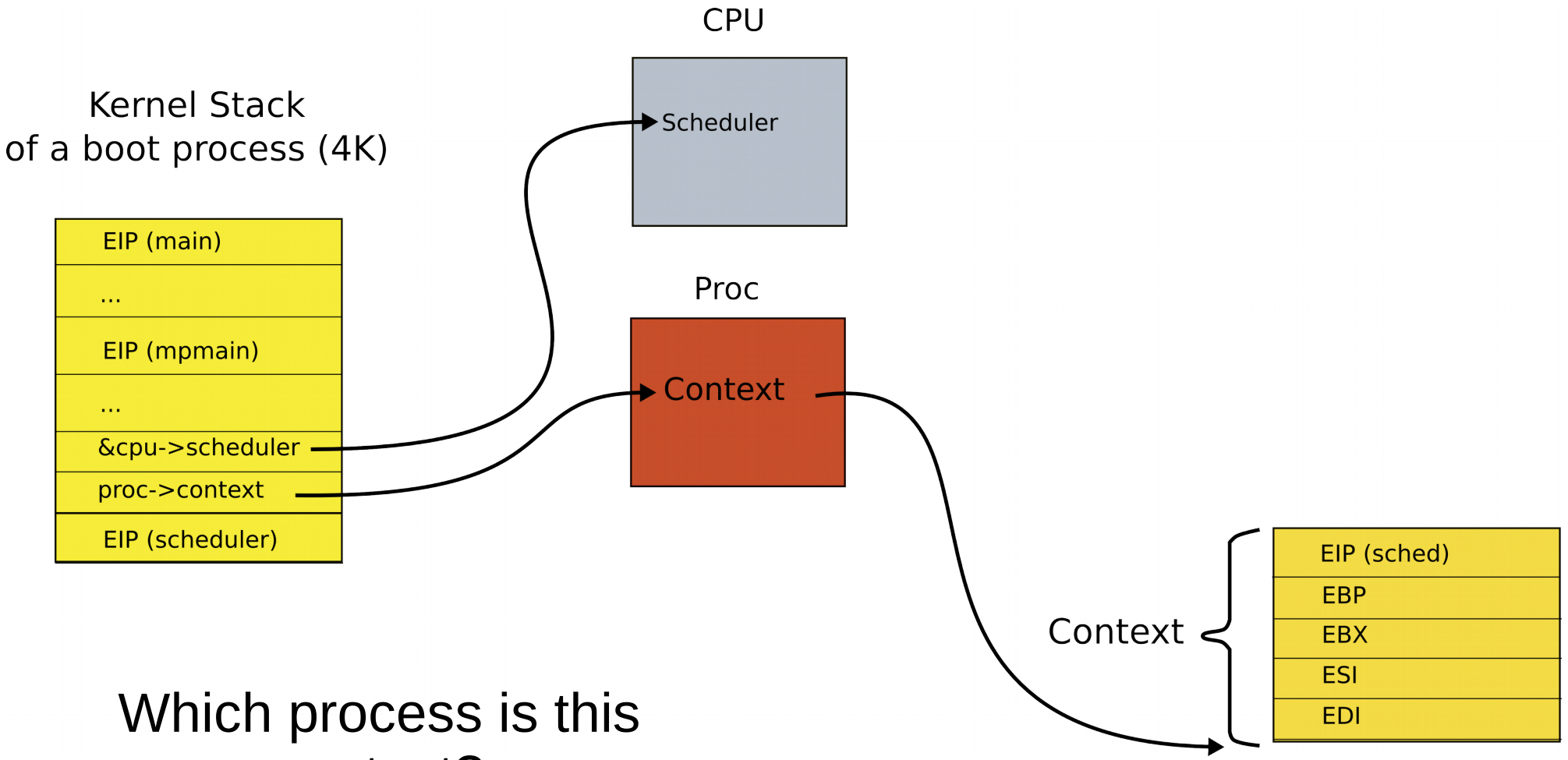
- We save the current context of the scheduler into:

```
&cpu->scheduler
```

- And restore the context of the first process

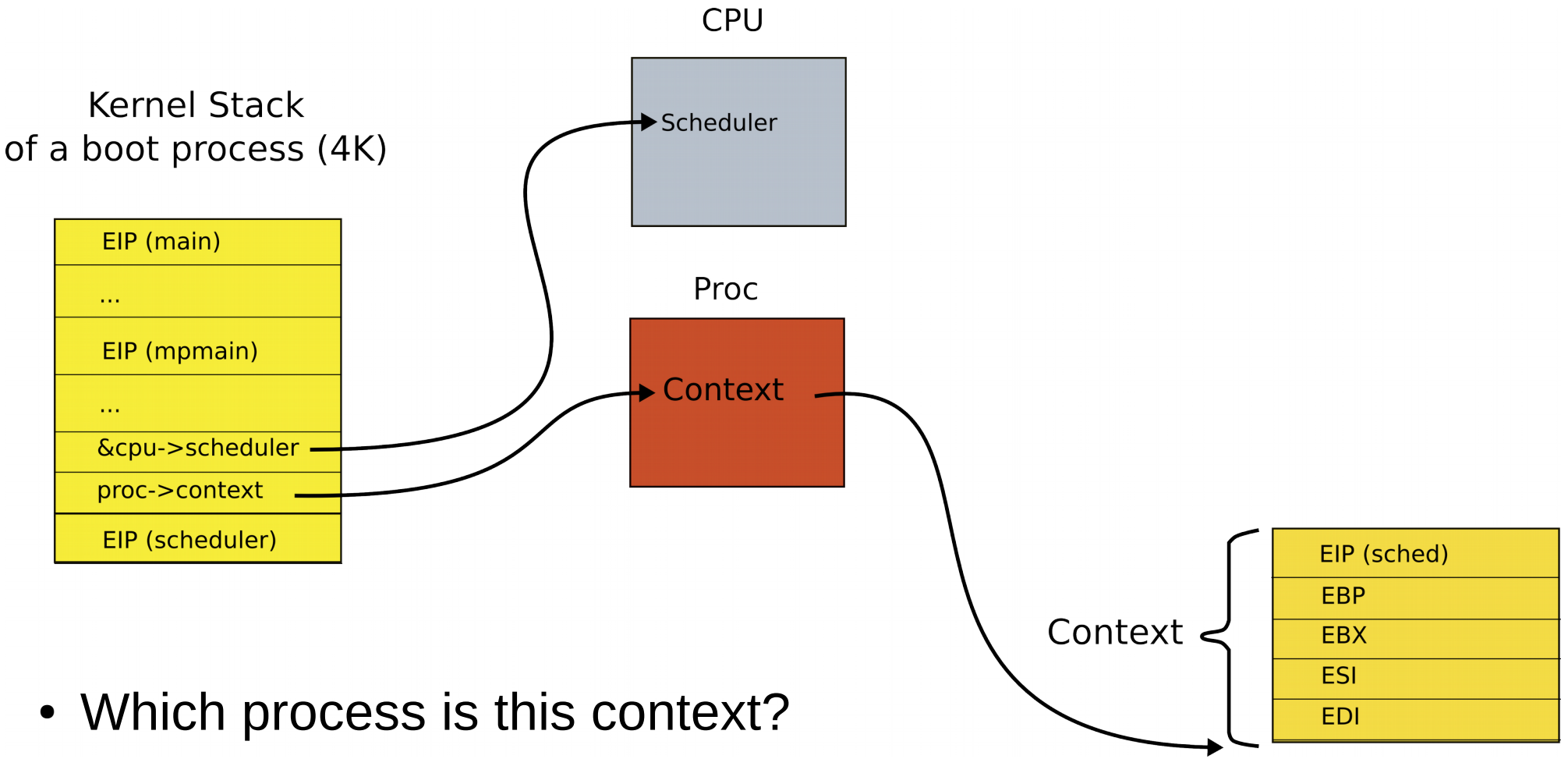
```
proc->context
```

This is how stack looked like when scheduler() invoked swtch() for the first time



Which process is this context?

This is how stack looked like when scheduler() invoked swtch() for the first time



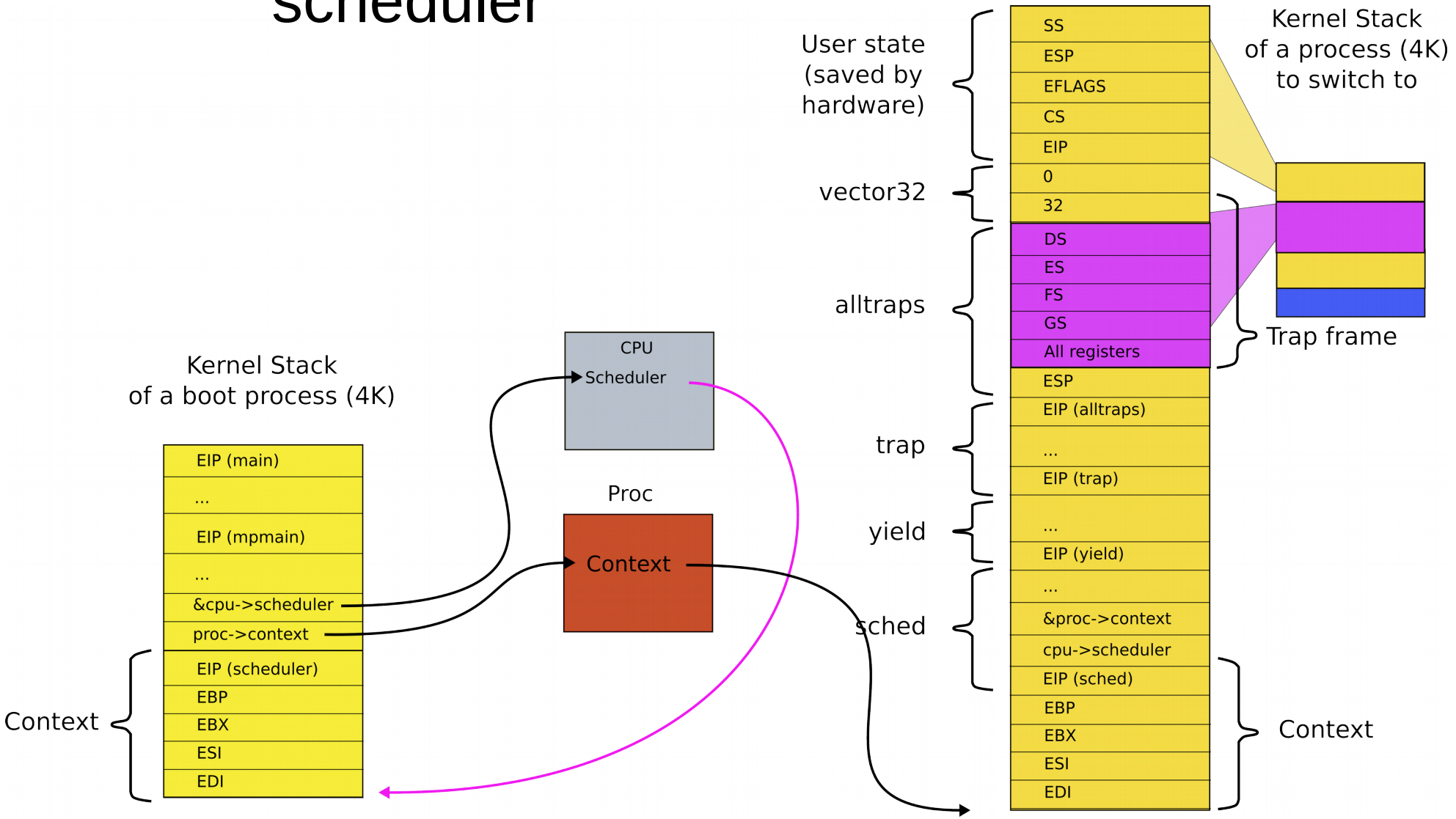
- Which process is this context?
- It's the context of the first process scheduler decides to run

```
2456 allocproc(void)
2457 {
...
2477   // Leave room for trap frame.
2478   sp -= sizeof *p->tf;
2479   p->tf = (struct trapframe*)sp;
2480
2481   // Set up new context to start executing at forkret,
2482   // which returns to trapret.
2483   sp -= 4;
2484   *(uint*)sp = (uint)trapret;
2485
2486   sp -= sizeof *p->context;
2487   p->context = (struct context*)sp;
2488   memset(p->context, 0, sizeof *p->context);
2489   p->context->eip = (uint)forkret;
...
2492 }
```

Context is configured as top of the stack when new process is created inside allocproc() function

- Remember exec()?

Save context of the scheduler



swtch()

```
2958 swtch:
2959 movl 4(%esp), %eax     // struct context **old
2960 movl 8(%esp), %edx     // struct context *new
2961
2962 # Save old callee-save registers
2963 pushl %ebp
2964 pushl %ebx
2965 pushl %esi
2966 pushl %edi
2967
2968 # Switch stacks
2969 movl %esp, (%eax)  // load current context (top of current stack) into
                       //  the memory location pointed by *old
2970 movl %edx, %esp    // set stack to be equal to *new (the top of the new context)
2971
2972 # Load new callee-save registers
2973 popl %edi
2974 popl %esi
2975 popl %ebx
2976 popl %ebp
2977 ret
```

The context is the top of some stack

- Initially it was the stack of mpenter()
  - On which scheduler started
- Then first process...
  - Then scheduler again
  - And the next process...

Back to the context switch
(end of the detour)

Where does this swtch() return?

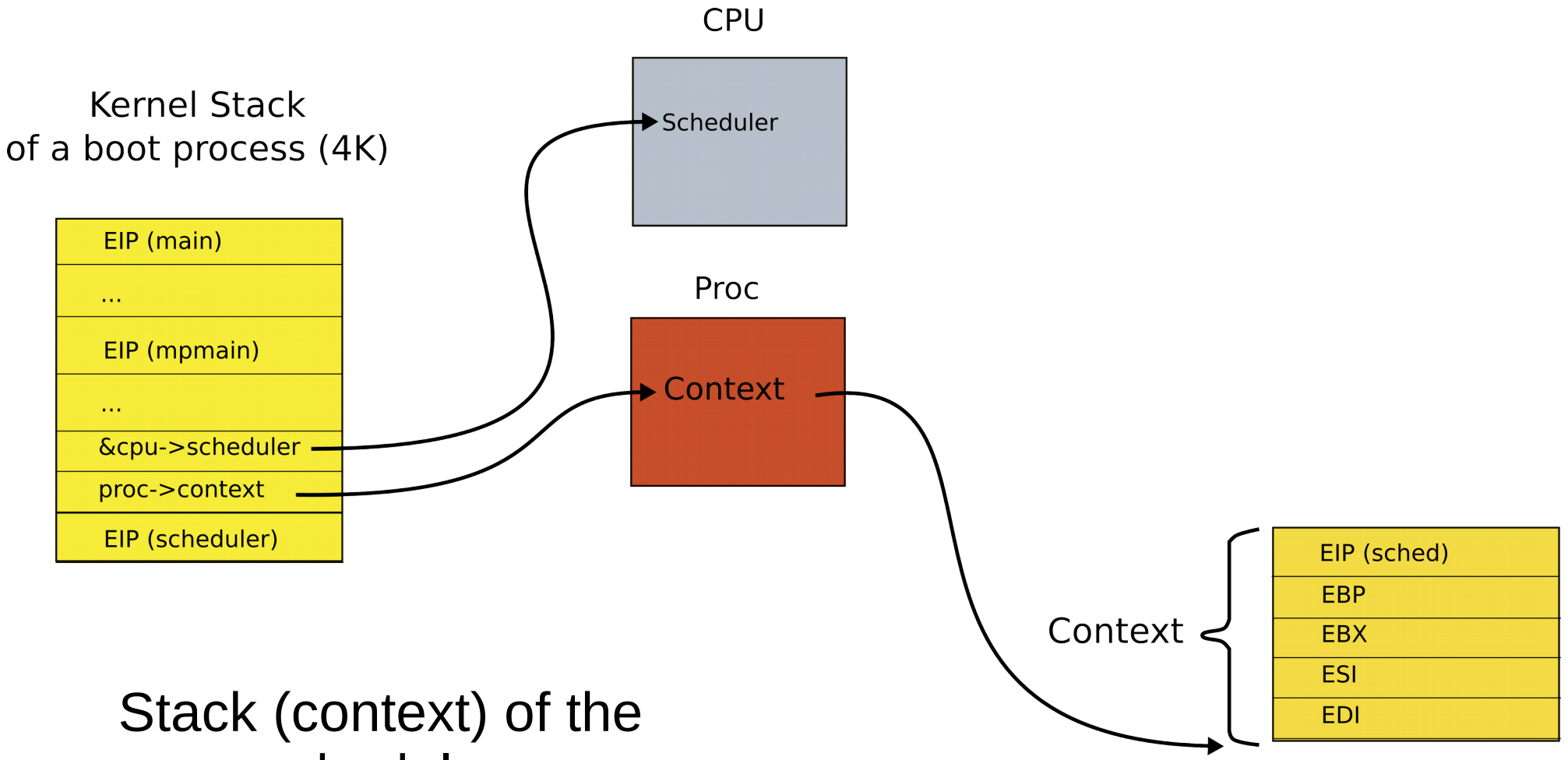
- Scheduler!
- After all remember
  - We started with timer interrupt
  - Entered the kernel
  - Entered schedule()
  - Entered switch
- And are currently on our way from the process into the scheduler

What does scheduler do?

```
2458 scheduler(void)
2459 {
2462   for(;;){
2468     for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
2469       if(p->state != RUNNABLE)
2470         continue;
2475       proc = p;
2476       switchuvm(p);
2477       p->state = RUNNING;
2478       swtch(&cpu->scheduler, proc->context);
2479       switchkvm();
2483       proc = 0;
2484     }
2487   }
2488 }
```

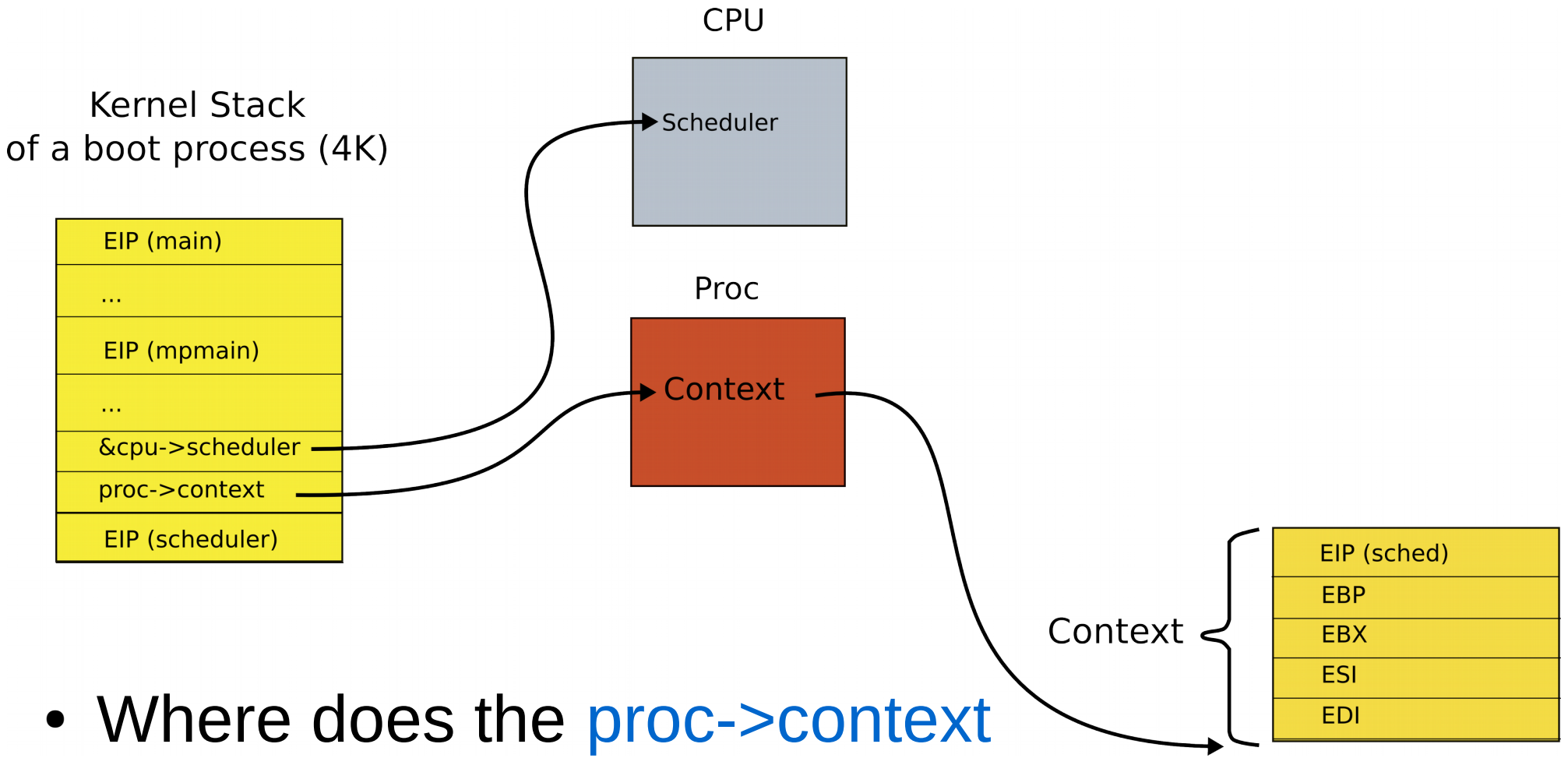
- Chooses next process to run
- Switches to it

What does stack look like when scheduler() invokes swtch()?



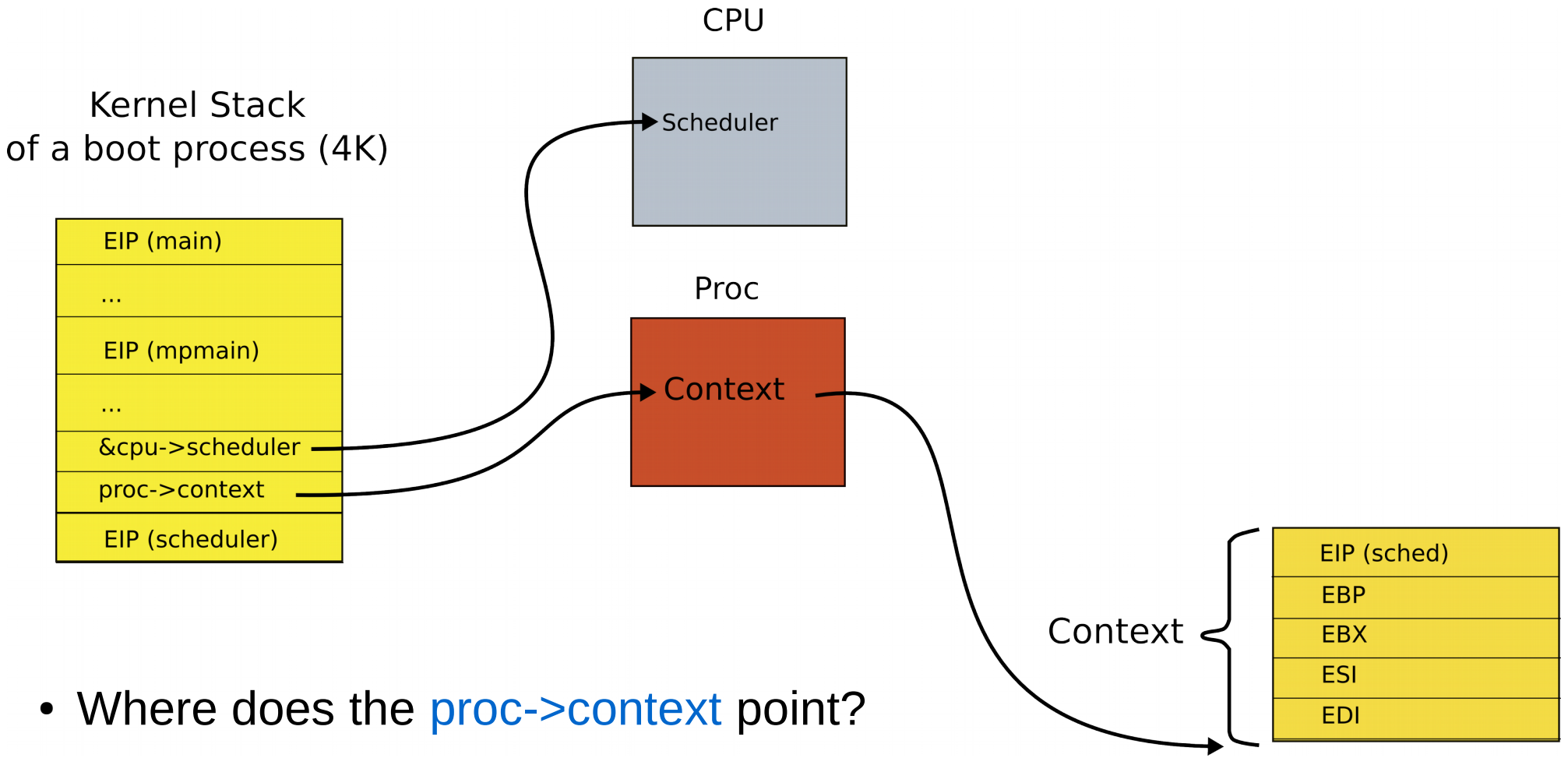
Stack (context) of the scheduler

What does stack look like when scheduler() invokes swtch()?



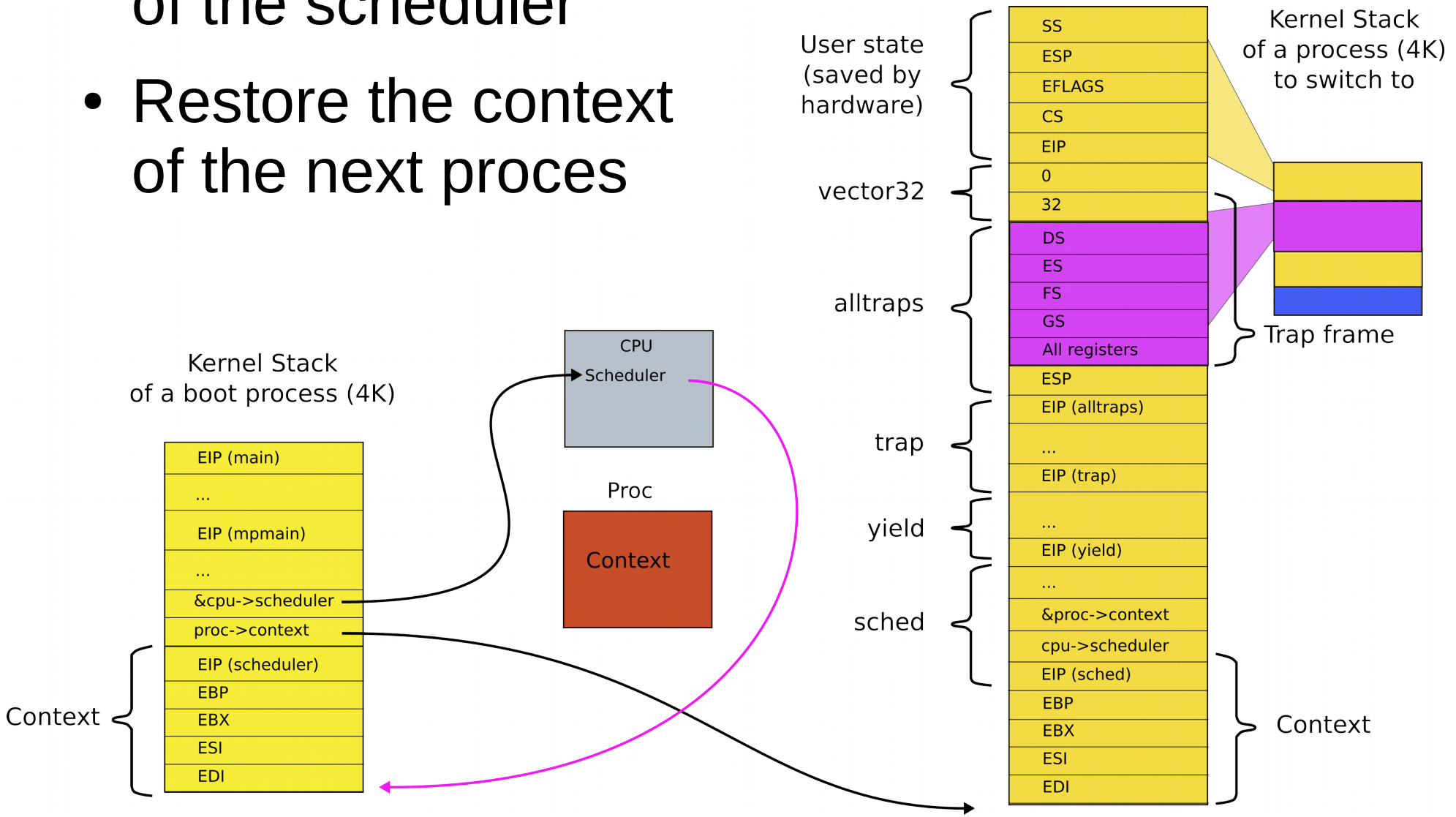
- Where does the proc->context point?

What does stack look like when scheduler() invokes swtch()?



- Where does the proc->context point?
  - Right the context (stack) of the next process to run

- We save the context of the scheduler
- Restore the context of the next proces



- Remember, from inside the scheduler we invoked swtch() as

```
2478 swtch(&cpu->scheduler,
                proc->context);
```

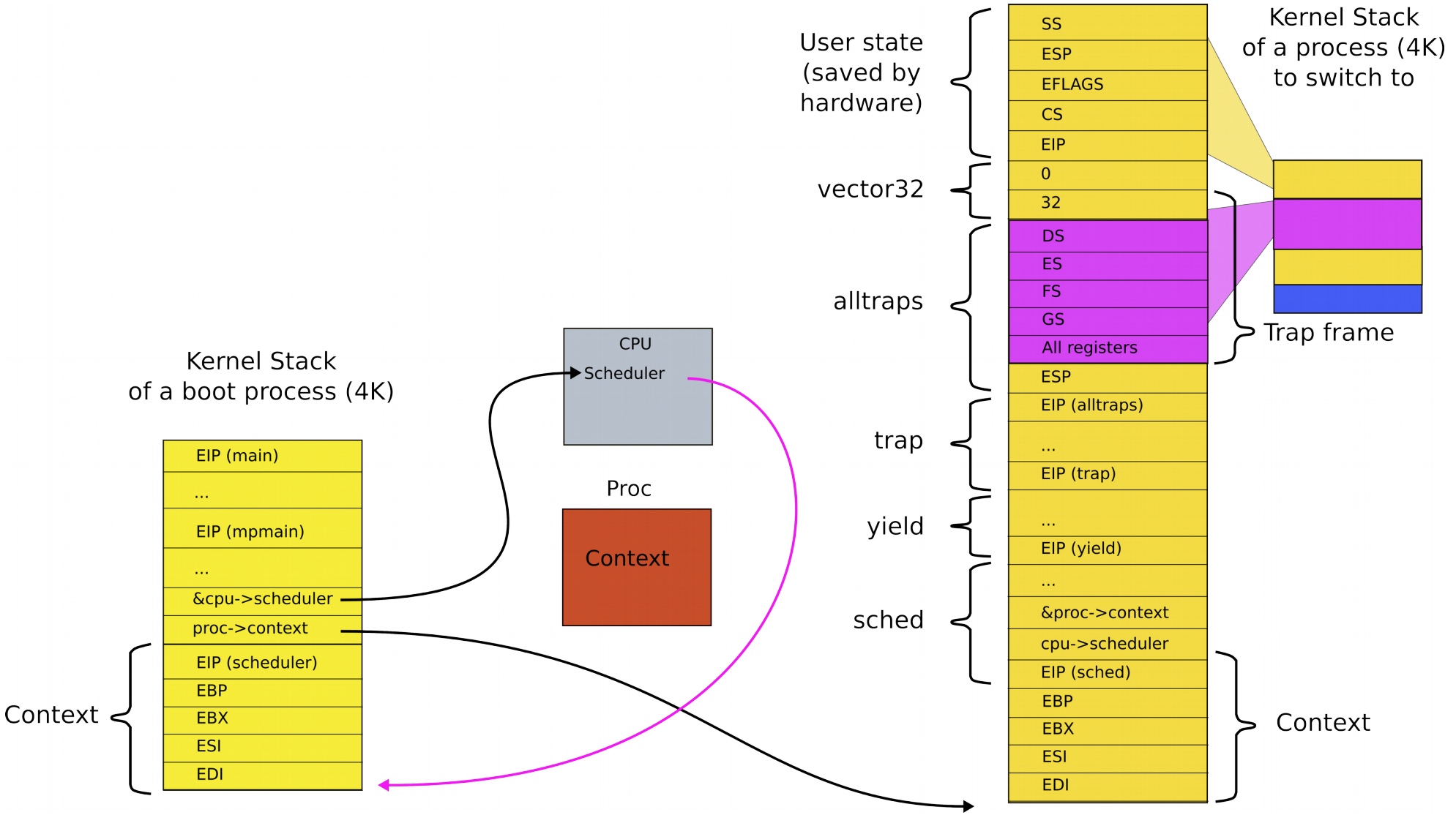
- Hence, we save context of the scheduler into

```
&cpu->scheduler
```

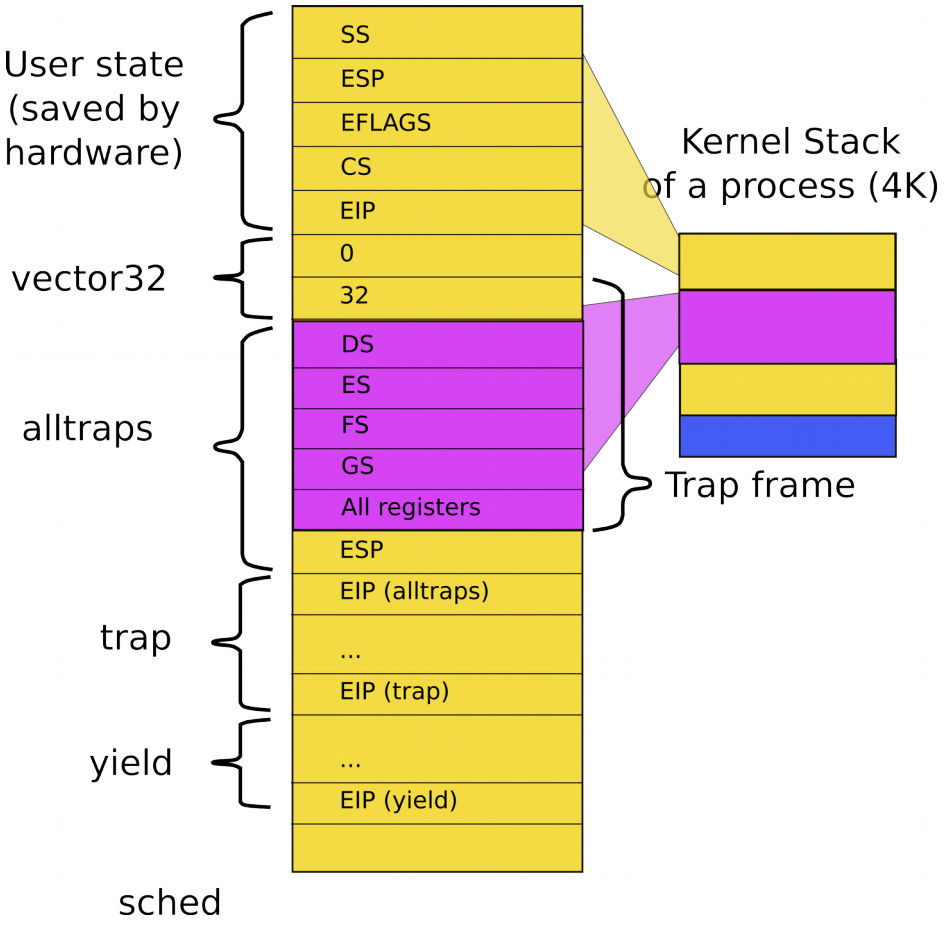
- And restore

```
proc->context
```

Stacks and contexts inside the swtch()



Exiting back to user-level

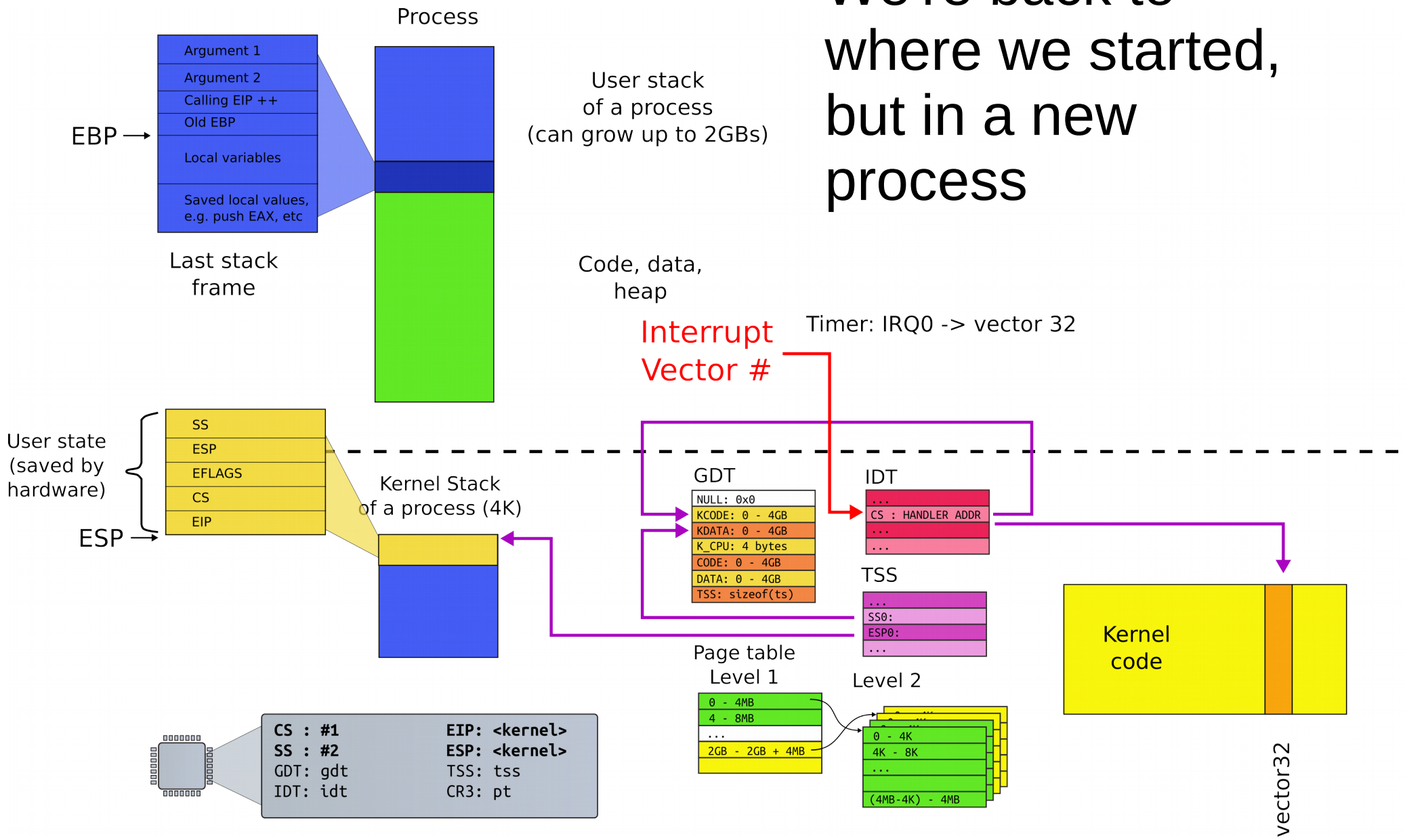


- Stack of the process after context switch, i.e., inside sched()
  - Return as usual all the way to alltrap()

alltraps(): exit into user-level

```
3004 alltraps:
...
3020 # Call trap(tf), where tf=%esp
3021 pushl %esp
3022 call trap
3023 addl $4, %esp
3024
3025 # Return falls through to trapret...
3026 .globl trapret
3027 trapret:
3028 popal
3029 popl %gs
3030 popl %fs
3031 popl %es
3032 popl %ds
3033 addl $0x8, %esp # trapno and errcode
3034 iret
```

We're back to where we started, but in a new process



Summary

- We switch between processes now

Creating the first process

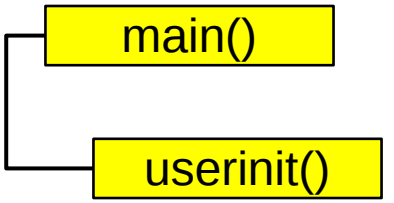
```
1317 main(void)
1318 {
1319   kinit1(end, P2V(4*1024*1024)); // phys page allocator
1320   kvmalloc(); // kernel page table
1321   mpinit(); // detect other processors
...
1323   seginit(); // segment descriptors
...
1330   tvinit(); // trap vectors
...
1338   userinit(); // first user process
1339   mpmain(); // finish this processor's setup
1340 }
```

main()

Userinit() – create first process

- Allocate process structure
  - Information about the process

```
2502 userinit(void)
2503 {
2504   struct proc *p;
2505   extern char _binary_initcode_start[],
                  _binary_initcode_size[];
...
2509   p = allocproc();
2510   initproc = p;
2511   if((p->pgdir = setupkvm()) == 0)
2512     panic("userinit: out of memory?");
2513   inituvm(p->pgdir, _binary_initcode_start,
              (int)_binary_initcode_size);
2514   p->sz = PGSIZE;
2515   memset(p->tf, 0, sizeof(*p->tf));
...
2530 }
```

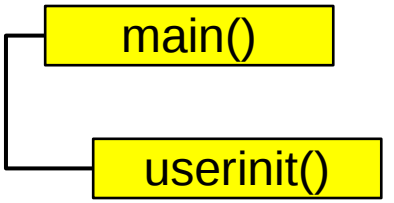


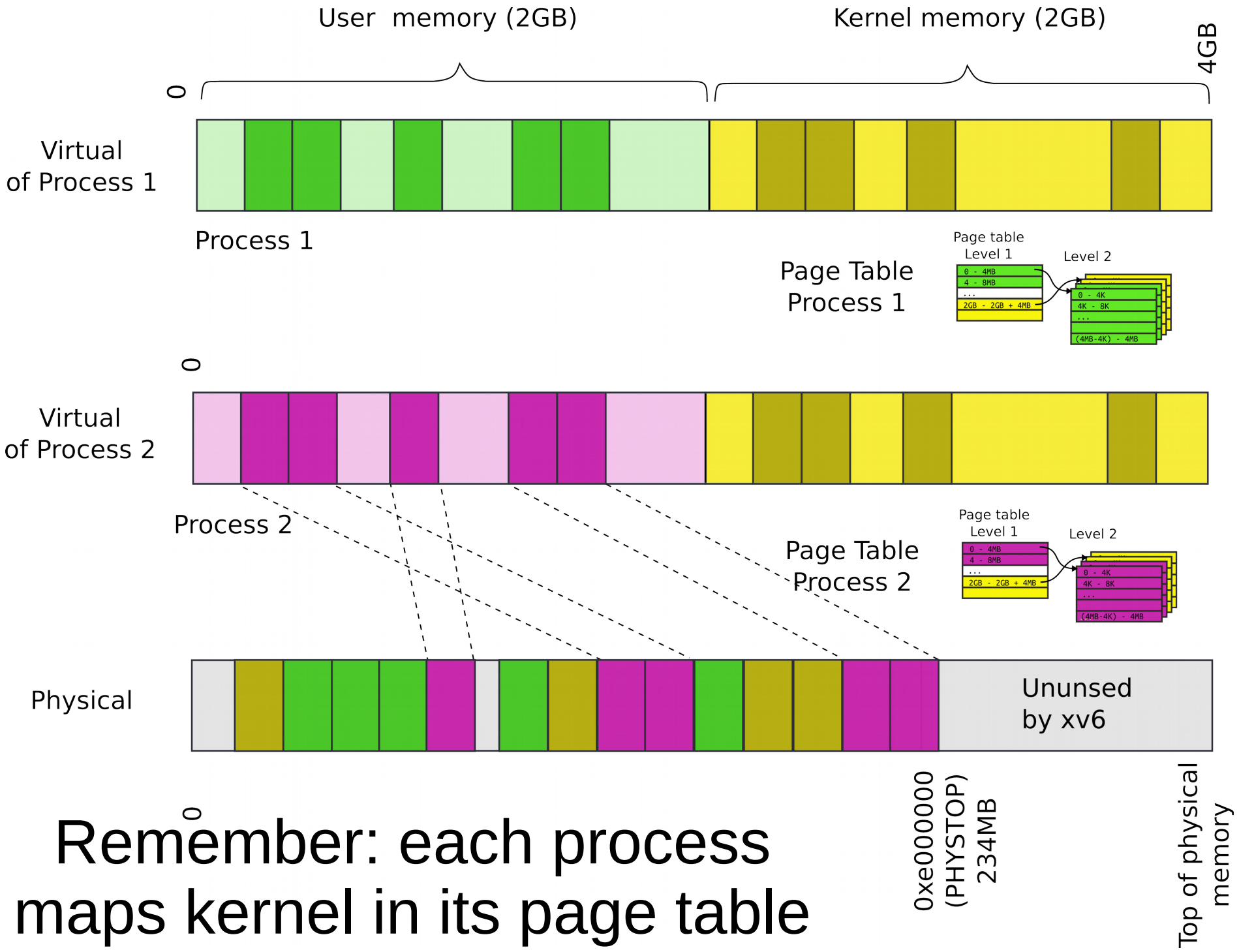
```
2103 struct proc {
2104   uint sz; // Size of process memory (bytes)
2105   pde_t* pgdir; // Page table
2106   char *kstack; // Bottom of kernel stack for this process
2107   enum procstate state; // Process state
2108   volatile int pid; // Process ID
2109   struct proc *parent; // Parent process
2110   struct trapframe *tf; // Trap frame for current syscall
2111   struct context *context; // swtch() here to run
2112   void *chan; // If non-zero, sleeping on chan
2113   int killed; // If non-zero, have been killed
2114   struct file *ofile[NOFILE]; // Open files
2115   struct inode *cwd; // Current directory
2116   char name[16]; // Process name (debugging)
2117 };
```

Userinit() – create first process

- Allocate process structure
  - Information about the process
- **Create a page table**
  - **Map only kernel space**

```
2502 userinit(void)
2503 {
2504   struct proc *p;
2505   extern char _binary_initcode_start[],
                  _binary_initcode_size[];
...
2509   p = allocproc();
2510   initproc = p;
2511    if((p->pgdir = setupkvm()) == 0)
2512      panic("userinit: out of memory?");
2513   inituvm(p->pgdir, _binary_initcode_start,
              (int)_binary_initcode_size);
2514   p->sz = PGSIZE;
2515   memset(p->tf, 0, sizeof(*p->tf));
...
2530 }
```

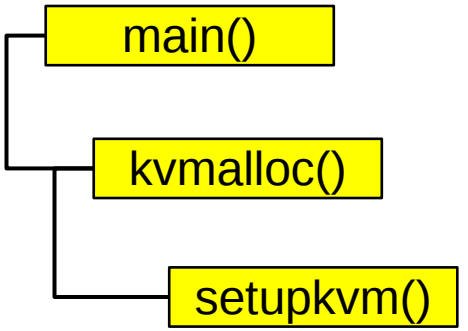




Remember: each process maps kernel in its page table

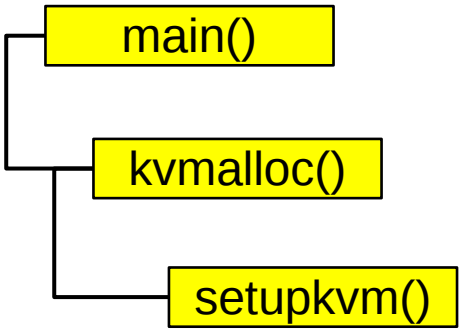
Recap: Allocate page table directory

```
1836 pde_t*
1837 setupkvm(void)
1838 {
1839   pde_t *pgdir;
1840   struct kmap *k;
1841
1842   if((pgdir = (pde_t*)kalloc()) == 0)
1843     return 0;
1844   memset(pgdir, 0, PGSIZE);
...
1847   for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
1848     if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
1849                 (uint)k->phys_start, k->perm) < 0)
1850       return 0;
1851   return pgdir;
1852 }
```



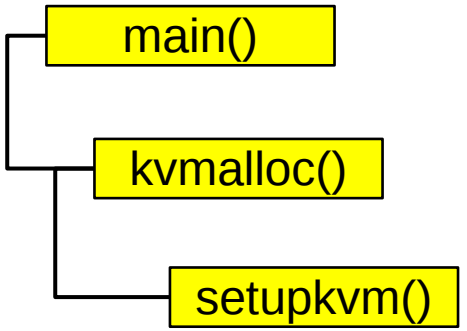
Recap: Iterate in a loop: remap physical pages

```
1836 pde_t*
1887 setupkvm(void)
1838 {
1839   pde_t *pgdir;
1840   struct kmap *k;
1841
1842   if((pgdir = (pde_t*)kalloc()) == 0)
1843     return 0;
1844   memset(pgdir, 0, PGSIZE);
...
1847   for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
1848     if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
1849                 (uint)k->phys_start, k->perm) < 0)
1850       return 0;
1851   return pgdir;
1852 }
```

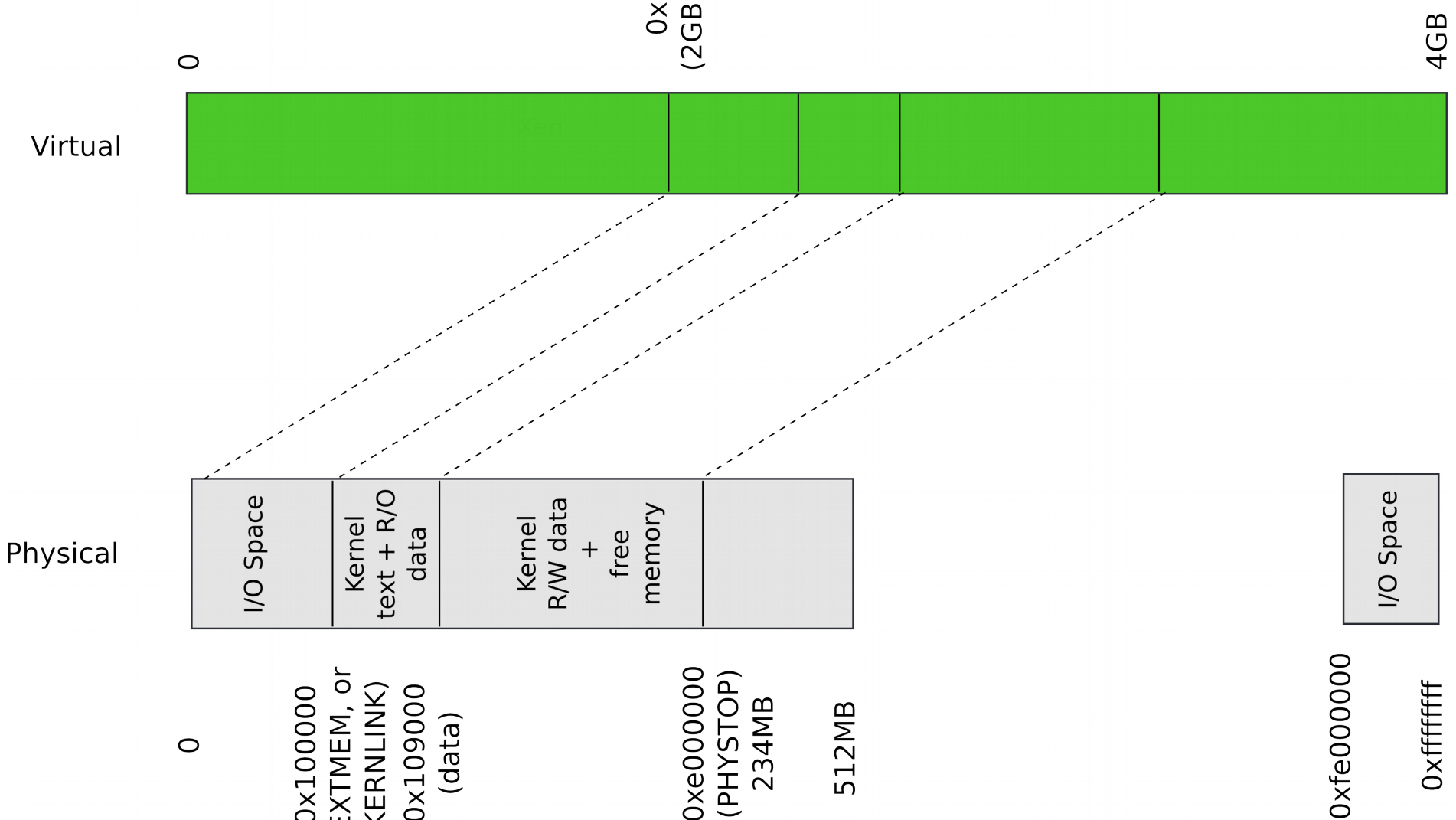


Recap: Iterate in a loop: remap physical pages

```
1836 pde_t*
1887 setupkvm(void)
1838 {
1839   pde_t *pgdir;
1840   struct kmap *k;
1841
1842   if((pgdir = (pde_t*)kalloc()) == 0)
1843     return 0;
1844   memset(pgdir, 0, PGSIZE);
...
1847   for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
1848     if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
1849                 (uint)k->phys_start, k->perm) < 0)
1850       return 0;
1851   return pgdir;
1852 }
```



Recap: Kernel map

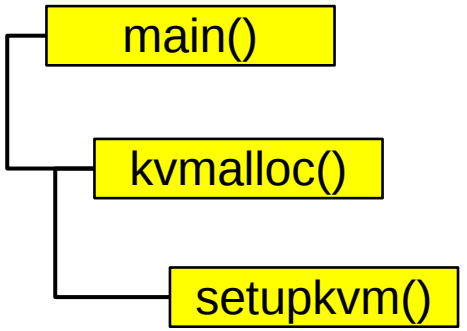


Recap: Kmap – kernel map

```
1823 static struct kmap {
1824     void *virt;
1825     uint phys_start;
1826     uint phys_end;
1827     int perm;
1828 } kmap[] = {
1829     { (void*)KERNBASE, 0, EXTMEM, PTE_W}, // I/O space
1830     { (void*)KERNLINK, V2P(KERNLINK), V2P(data), 0},//text+rodata
1831     { (void*)data, V2P(data), PHYSTOP, PTE_W}, // kern
data+memory
1832     { (void*)DEVSPACE, DEVSPACE, 0, PTE_W}, // more devices
1833 };
```

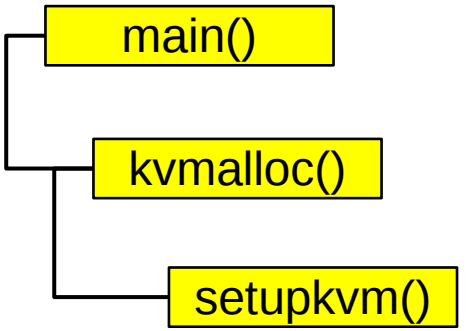
Recap: Iterate in a loop: remap physical pages

```
1836 pde_t*
1887 setupkvm(void)
1838 {
1839   pde_t *pgdir;
1840   struct kmap *k;
1841
1842   if((pgdir = (pde_t*)kalloc()) == 0)
1843     return 0;
1844   memset(pgdir, 0, PGSIZE);
...
1847   for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
1848     if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
1849                 (uint)k->phys_start, k->perm) < 0)
1850       return 0;
1851   return pgdir;
1852 }
```



Recap: Remap physical pages

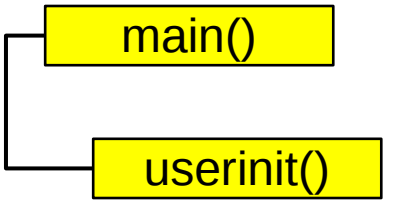
```
1836 pde_t*
1887 setupkvm(void)
1838 {
1839   pde_t *pgdir;
1840   struct kmap *k;
1841
1842   if((pgdir = (pde_t*)kalloc()) == 0)
1843     return 0;
1844   memset(pgdir, 0, PGSIZE);
...
1847   for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
1848     if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
1849                 (uint)k->phys_start, k->perm) < 0)
1850       return 0;
1851   return pgdir;
1852 }
```



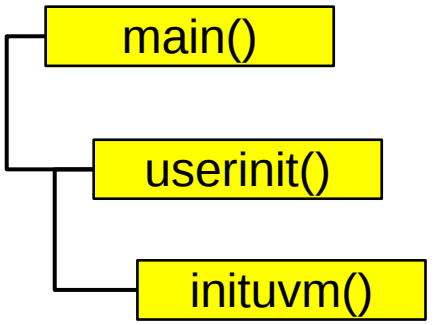
Userinit() – create first process

- Allocate process structure
  - Information about the process
- Create a page table
  - Map only kernel space
- **Allocate a page for the user init code**
  - **Map this page**

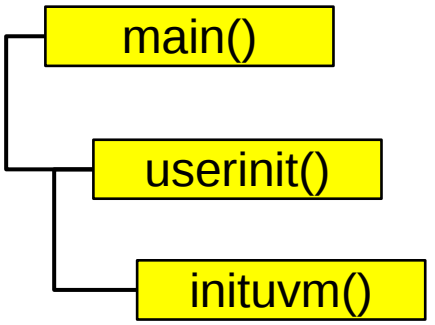
```
2502 userinit(void)
2503 {
2504   struct proc *p;
2505   extern char _binary_initcode_start[],
                  _binary_initcode_size[];
...
2509   p = allocproc();
2510   initproc = p;
2511   if((p->pgdir = setupkvm()) == 0)
2512     panic("userinit: out of memory?");
2513   inituvm(p->pgdir, _binary_initcode_start,
                (int)_binary_initcode_size);
2514   p->sz = PGSIZE;
2515   memset(p->tf, 0, sizeof(*p->tf));
...
2530 }
```



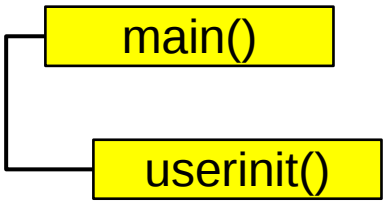
```
1903 inituvm(pde_t *pgdir, char *init, uint sz)
1904 {
1905   char *mem;
1906
1907   if(sz >= PGSIZE)
1908     panic("inituvm: more than a page");
1909   mem = kalloc();
1910   memset(mem, 0, PGSIZE);
1911   mappages(pgdir, 0, PGSIZE, V2P(mem),
                PTE_W|PTE_U);
1912   memmove(mem, init, sz);
1913 }
```



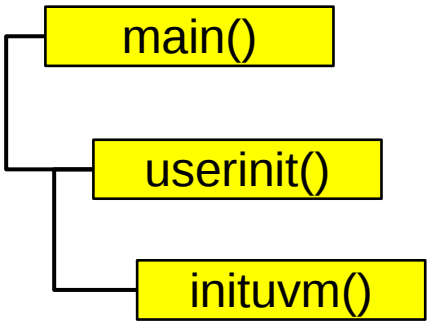
```
1903 inituvm(pde_t *pgdir, char *init, uint sz)
1904 {
1905   char *mem;
1906
1907   if(sz >= PGSIZE)
1908     panic("inituvm: more than a page");
1909   mem = kalloc();
1910   memset(mem, 0, PGSIZE);
1911   mappages(pgdir, 0, PGSIZE, V2P(mem),
                PTE_W|PTE_U);
1912   memmove(mem, init, sz);
1913 }
```



```
2502 userinit(void)
2503 {
2504   struct proc *p;
2505   extern char _binary_initcode_start[],
                  _binary_initcode_size[];
...
2509   p = allocproc();
2510   initproc = p;
2511   if((p->pgdir = setupkvm()) == 0)
2512     panic("userinit: out of memory?");
2513   inituvm(p->pgdir, _binary_initcode_start,
                (int)_binary_initcode_size);
2514   p->sz = PGSIZE;
2515   memset(p->tf, 0, sizeof(*p->tf));
...
2530 }
```



```
1903 inituvm(pde_t *pgdir, char *init, uint sz)
1904 {
1905   char *mem;
1906
1907   if(sz >= PGSIZE)
1908     panic("inituvm: more than a page");
1909   mem = kalloc();
1910   memset(mem, 0, PGSIZE);
1911   mappages(pgdir, 0, PGSIZE, V2P(mem),
                PTE_W|PTE_U);
1912   memmove(mem, init, sz);
1913 }
```



```
8409 start:
8410   pushl $argv
8411   pushl $init
8412   pushl $0 // where caller pc would be
8413   movl $SYS_exec, %eax
8414   int $T_SYSCALL
8415
...
8422 # char init[] = "/init\0";
8423 init:
8424   .string "/init\0"
8425
8426 # char *argv[] = { init, 0 };
8427 .p2align 2
8428 argv:
8429   .long init
8430   .long 0
```

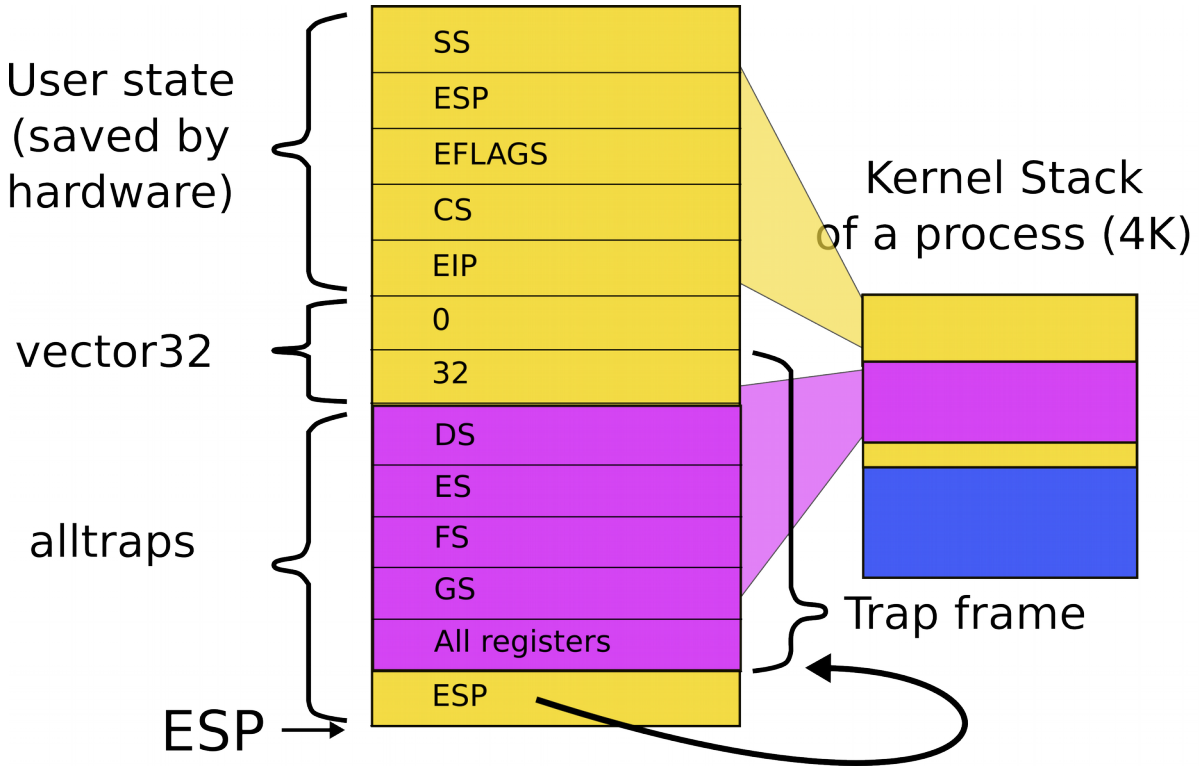
initcode.S: call exec(“/init”, argv);

userinit() – create first process

- Allocate process structure
  - Information about the process
- Create a page table
  - Map only kernel space
- Allocate a page for the user init code
  - Map this page
- **Configure trap frame for “iret”**

We need to configure the following kernel

- The stack of a process after interrupt/syscall



Call stack: vector32()
alltraps()

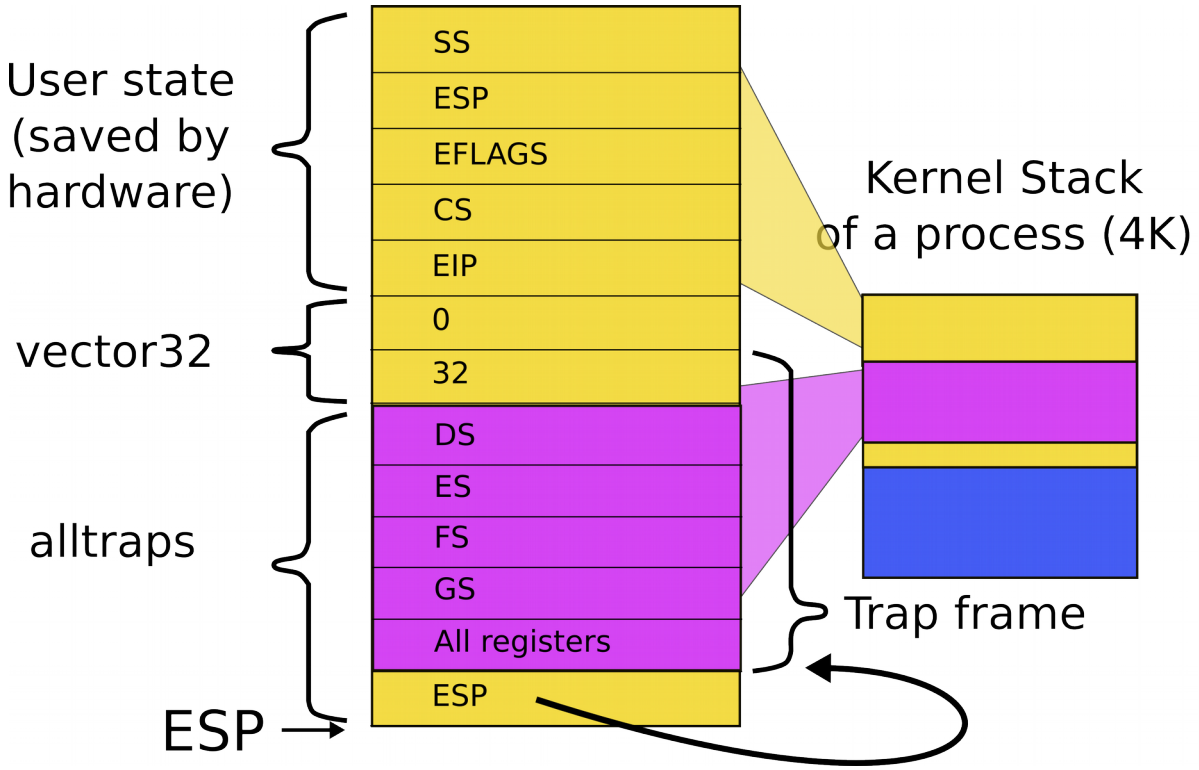
```
2103 struct proc {
2104   uint sz; // Size of process memory (bytes)
2105   pde_t* pgdir; // Page table
2106   char *kstack; // Bottom of kernel stack for this process
2107   enum procstate state; // Process state
2108   volatile int pid; // Process ID
2109   struct proc *parent; // Parent process
2110   struct trapframe *tf; // Trap frame
2111   struct context *context; // swtch() here to run
2112   void *chan; // If non-zero, sleeping on chan
2113   int killed; // If non-zero, have been killed
2114   struct file *ofile[NOFILE]; // Open files
2115   struct inode *cwd; // Current directory
2116   char name[16]; // Process name (debugging)
2117 };
```

```
2456 allocproc(void)
2457 {
...
2470   // Allocate kernel stack.
2471   if((p->kstack = kalloc()) == 0){
2472     p->state = UNUSED;
2473     return 0;
2474   }
2475   sp = p->kstack + KSTACKSIZE;
2476
2477   // Leave room for trap frame.
2478   sp -= sizeof *p->tf;
2479   p->tf = (struct trapframe*)sp;
2480
...
2492 }
```

Trap frame is on the kernel stack of the process

```
2502 userinit(void)
2503 {
...
2513   inituvm(p->pgdir, _binary_initcode_start,
                (int)_binary_initcode_size);
2514   p->sz = PGSIZE;
2515   memset(p->tf, 0, sizeof(*p->tf));
2516   p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
2517   p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
2518   p->tf->es = p->tf->ds;
2519   p->tf->ss = p->tf->ds;
2520   p->tf->eflags = FL_IF;
2521   p->tf->esp = PGSIZE;
2522   p->tf->eip = 0; // beginning of initcode.S
...
2530 }
```

Kernel stack after interrupt/syscall

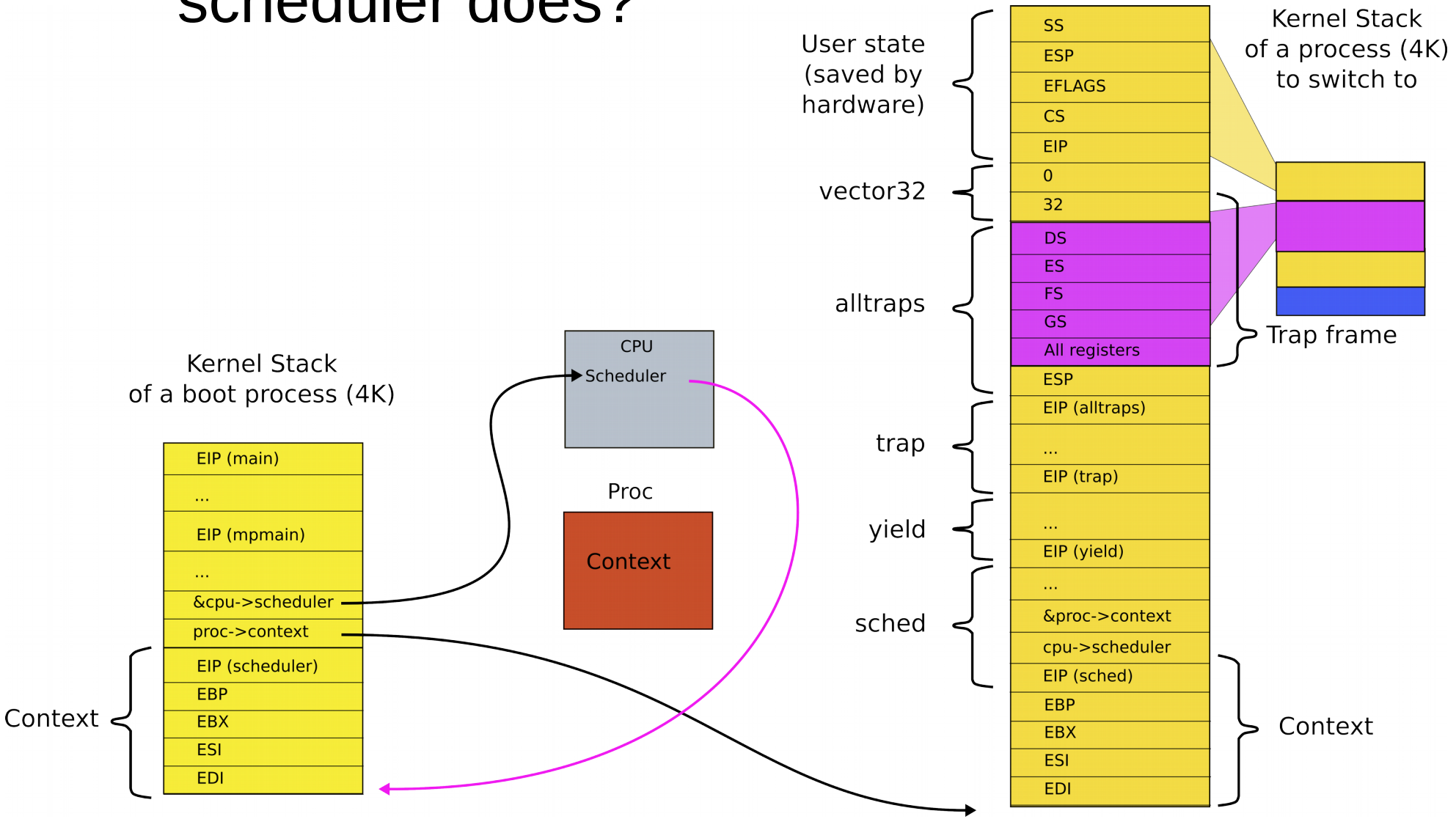


Call stack: vector32()
alltraps()

```
2502 userinit(void)
2503 {
...
2515   memset(p->tf, 0, sizeof(*p->tf));
2516   p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
2517   p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
2518   p->tf->es = p->tf->ds;
2519   p->tf->ss = p->tf->ds;
2520   p->tf->eflags = FL_IF;
2521   p->tf->esp = PGSIZE;
2522   p->tf->eip = 0; // beginning of initcode.S
2523
2524   safestrcpy(p->name, "initcode", sizeof(p->name));
2525   p->cwd = namei("/");
2526
2527   p->state = RUNNABLE;
...
2530 }
```

Wait, we mapped process memory, created trap frame, but it doesn't really run...

Remember what scheduler does?



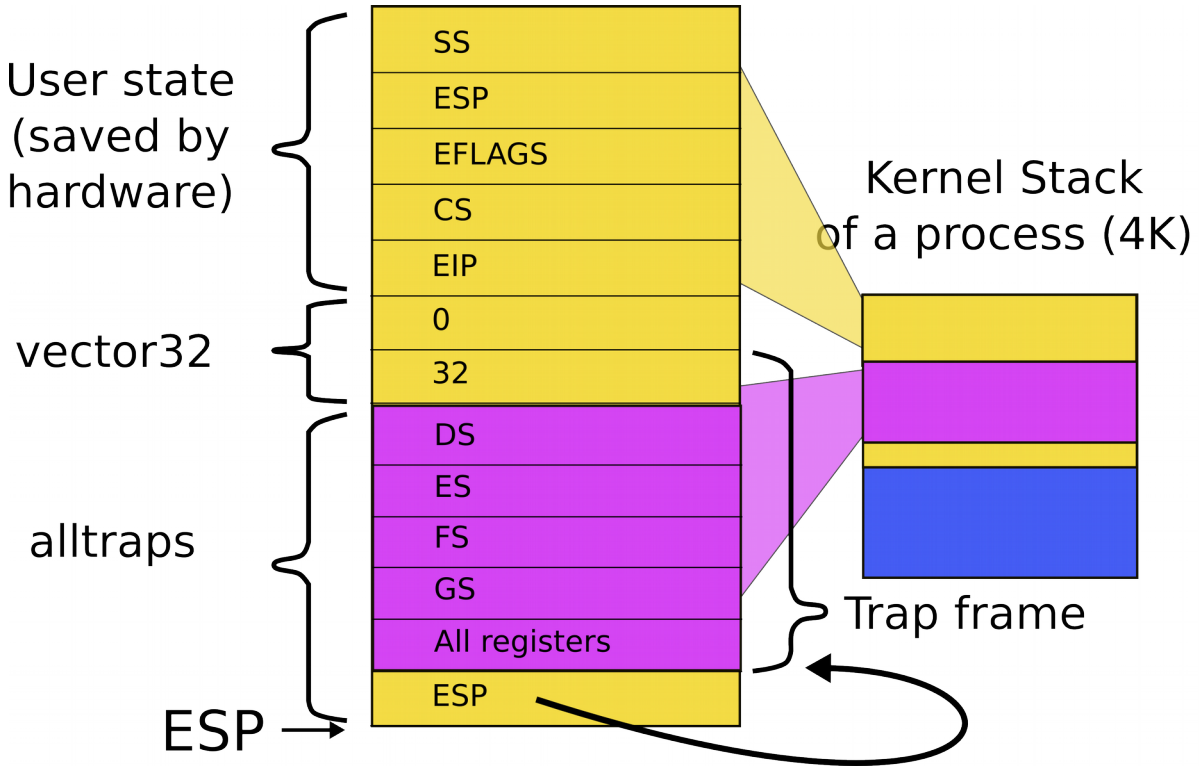
```
2456 allocproc(void)
2457 {
...
2477   // Leave room for trap frame.
2478   sp -= sizeof *p->tf;
2479   p->tf = (struct trapframe*)sp;
2480
2481   // Set up new context to start executing at forkret,
2482   // which returns to trapret.
2483   sp -= 4;
2484   *(uint*)sp = (uint)trapret;
2485
2486   sp -= sizeof *p->context;
2487   p->context = (struct context*)sp;
2488   memset(p->context, 0, sizeof *p->context);
2489   p->context->eip = (uint)forkret;
...
2492 }
```

Trap frame is on the kernel stack of the process

forkret(): just returns

```
2788 forkret(void)
2789 {
...
2803   // Return to "caller", actually trapret (see allocproc).
2804 }
```

Kernel stack after interrupt/syscall



Call stack: vector32()
alltraps()

```
3276 .globl trapret
3277 trapret:
3278   popal
3279   popl %gs
3280   popl %fs
3281   popl %es
3282   popl %ds
3283   addl $0x8, %esp # trapno and
                       errcode
3284   iret
```

trapret(): just returns

```
8510 main(void)
8511 {
...
8514   if(open("console", O_RDWR) < 0){
8515     mknod("console", 1, 1);
8516     open("console", O_RDWR);
8517   }
8518   dup(0); // stdout
8519   dup(0); // stderr
8520
8521   for(;;){
8522     printf(1, "init: starting sh\n");
8523     pid = fork();
8524     if(pid < 0){
8525       printf(1, "init: fork failed\n");
8526       exit();
8527     }
8528     if(pid == 0){
8529       exec("sh", argv);
8530       printf(1, "init: exec sh failed\n");
8531       exit();
8532     }
8533     while((wpid=wait()) >= 0 && wpid != pid)
8534       printf(1, "zombie!\n");
8535   }
8536 }
```

- First process exec(“init”)
- /init starts /sh
  - fork() and exec(“sh”)

Summary

- We've finally learned how the first process came to life

  Also we know:
- How OS boots and initializes itself
- How each process is constructed (exec())
- How OS switches between processes

Thank you