

Introducing micro:bian

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In this part

- Concurrent processes and messages between them as a way of structuring complex systems that respond to events (L12).
- Managing I/O devices with driver processes that receive interrupts as messages (L13).
- Implementing multiple processes (L14).
- Messages and scheduling (L15).
- Chasing down a bug (L16).

Why concurrency?

- Genuinely parallel machines
- Sharing one machine between several tasks
- Decomposing one task clearly
- Responding to several sources of events

In this lecture

- *Processes*: embedded programs are conveniently structured as a set of independent processes.
- *Messages*: processes can cooperate by exchanging messages in a way that synchronises their behaviour.
- *Shared variables* are best avoided by using messages instead.

Hearts again

```
static int row = 0;

void advance(void) {
    row++;
    if (row == 3) row = 0;
    GPIO_OUT = heart[row];
}
```

- Efficient but inflexible.
- Can't pause inside subroutines or control structures.

But also primes

Use interrupts to overlap printing with the search, but ...

- When the serial buffer is full, wastes time waiting in a loop.
- Disables interrupts to protect the buffer from concurrent modification – hard to get right.

We're ready for to use an operating system:
enter `micro:bian!`

Better: a process


```
static void heart_task(int arg) {  
    while (1) {  
        show(heart, 70);  
        show(small, 10);  
        show(heart, 10);  
    }  
}
```

```
static void show(int img[], int n) {  
    while (n-- > 0) {  
        for (int p = 0; p < 3; p++) {  
            GPIO_OUT = img[p];  
            timer_delay(5);  
        }  
    }  
}
```

Another, independent process

```
static void prime_task(int arg) {
    int p = 2, n = 0;

    while (1) {
        if (prime(p)) {
            n++;
            printf("prime(%d) = %d\n", n, p);
        }
        p++;
    }
}
```



`serial_putc(c);`

Setting the ball rolling

```
void init(void) {  
    SERIAL = start("Serial", serial_task, 0, STACK);  
    TIMER = start("Timer", timer_task, 0, STACK);  
    HEART = start("Heart", heart_task, 0, STACK);  
    PRIME = start("Prime", prime_task, 0, STACK);  
}
```

- a fixed collection of processes created before concurrent execution begins.
- our two processes, plus *device drivers* for the timer (`timer_delay`) and serial port (`serial_putc`); plus an idle task.

Processes

Each a 'main program' in its own right

- It can call subroutines.
- It can pause (or be interrupted) at any point to give others a go.

Implementation

- Processes are interleaved.
- Each has its own stack.

`micro:bian` supports a fixed set of processes.

Other operating systems

- Processes with communication
- Memory management
- Drivers for I/O devices
- File system
- Networking

micro:bian supports processes and messages, and whatever device drivers we write.

No utility programs, shared libraries, GUI, ... either.

Sending messages

```
void prime_task(int arg) {
    int n = 2;
    message m;

    while (1) {
        if (prime(n)) {
            m.int1 = n;
            send(USEPRIME, PRIME, &m);
        }
        n++;
    }
}
```



Receiving messages

```
void summary_task(int arg) {
    int count = 0, limit = arg; message m;

    while (1) {
        receive(PRIME, &m);
        while (m.int1 >= limit) {
            report(count, limit);
            limit += arg;
        }
        count++;
    }
}
```

Rules for messages

Both sender and receiver have a message buffer (16 bytes).

- The sender assembles a message; then
- It is transferred from sender to receiver as an *atomic* action.
- No buffering, no queues of messages!

Alternatives to messages

Message passing:

- no “shared variables” between processes.
- all communication by messages

Shared variables with semaphores:

- like the serial output buffer.
- more efficient, but hard to get right.

Device drivers

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In this lecture

- *Interrupts* can be tamed by turning them into ‘messages from the hardware’.
- *Device drivers* look after hardware devices by serving requests one at a time in a loop.

(See wiki and Lab 4 for all details – many are omitted here for clarity.)

Implementing serial output

```
void serial_putc(char ch) {  
    message m;  
    m.int1 = ch;  
    send(SERIAL, PUTC, &m);  
}
```

- request message sent to the SERIAL driver.
- the caller *waits* if the driver is not ready.

Implementing the driver process

```
void serial_task(int arg) {  
    static char txbuf[NBUF];  
    int bufin, bufout, bufcount;  
    message m; char ch;  
  
    serial_setup();  
  
    while (1) {  
        receive(ANY, &m);  
        switch (m.m_type) {  
            ...  
        }  
    }  
}
```

State is local to the driver

A server loop accepts requests

Setting things up

```
void serial_setup(void) {  
    ...  
  
    connect(UART_IRQ);  
    enable_irq(UART_IRQ);  
    UART.INTENSET = BIT(UART_INT_TXDRDY);  
}
```

Handling PUTC messages

```
while (1) {  
    receive(ANY, &m);  
    switch (m.m_type) {  
    case PUTC:  
        ch = m.int1;  
        txbuf[bufin] = ch; ...  
        break;  
        ...  
    }  
}
```

- Buffer variables are local, so no other process can interfere.

Handling interrupts

Key insight:

an interrupt is a message from the hardware.

```
receive(ANY, &m);  
switch (m.m_type) {  
case INTERRUPT:  
    if (UART_TXDRDY) {  
        txidle = 1;  
        UART_TXDRDY = 0;  
    }  
    clear_pending(UART_IRQ);  
    enable_irq(UART_IRQ);  
    break;
```

Responding to events

```
while (1) {  
    receive(ANY, &m);  
    switch (m.m_type) {  
        ...  
    }  
  
    if (txidle && bufcount > 0) {  
        UART.TXD = txbuf[bufout]; ...  
        txidle = 0;  
    }  
}
```

When the buffer is full

Let's replace

```
receive(ANY, &m);
```

with

```
if (bufcount < NBUF)  
    receive(ANY, &m);  
else  
    receive(INTERRUPT, &m);
```

When the buffer is full, we just stop accepting requests until it has emptied a bit.

Omitted here ...

Lab 4 has a more elaborate serial driver

- Supports both output and input with echoing and line editing.
- All UART initialisation details are filled in.
- There's an alternative interface `print_buf` that overcomes the one-message-per-character bottleneck.

The standard interrupt handler

```
void default_handler(void) {  
    int irq = active_irq();  
    int task = os_handler[irq];  
    disable_irq(irq);  
    interrupt(task);  
}
```

Implementing Processes

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Concurrent processes

We want multiple processes, each with its own stack. For simplicity,

- A fixed set of processes, created at the start.
- Each process has a fixed amount of stack space.

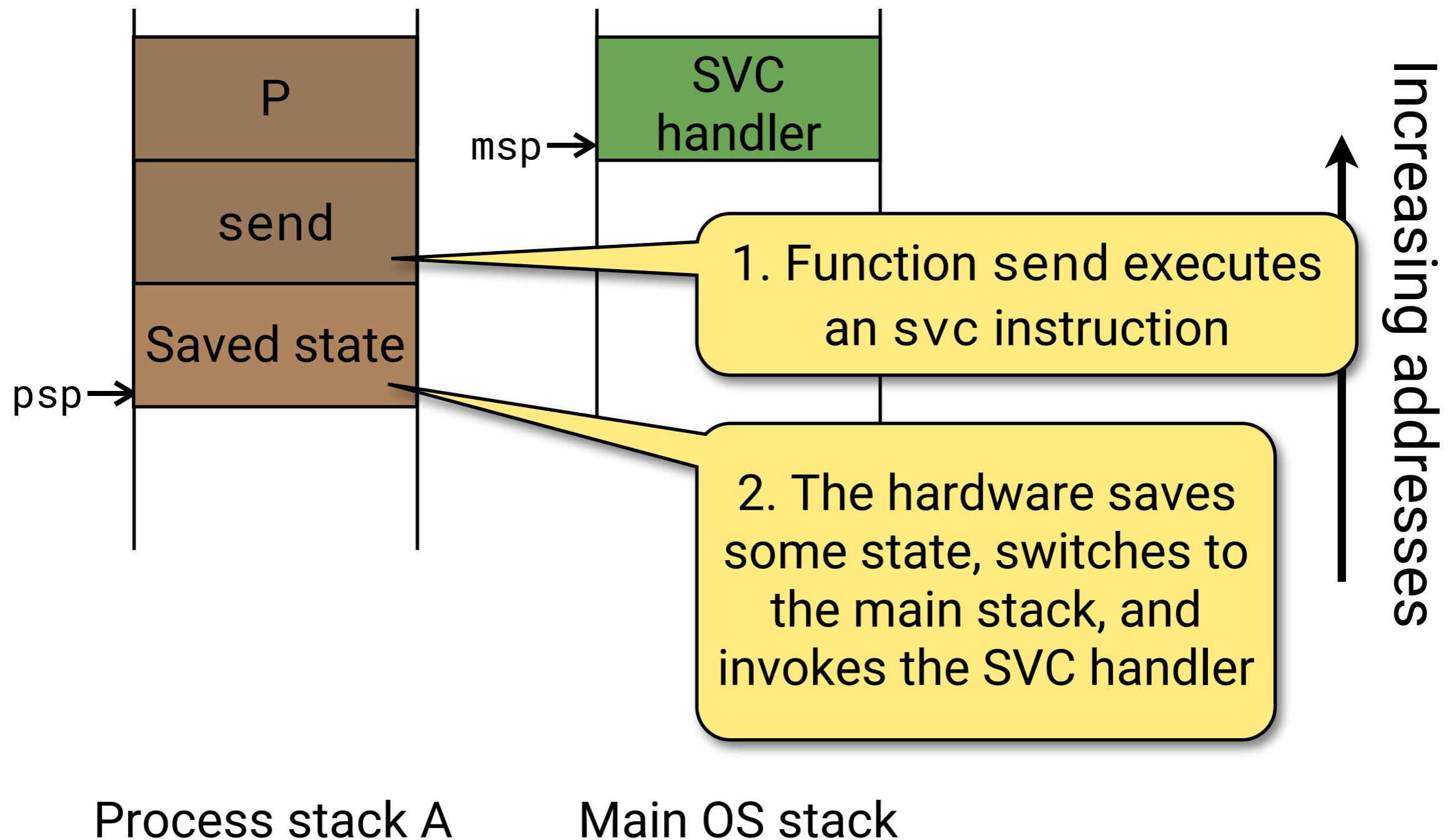
Implementing processes

The plan:

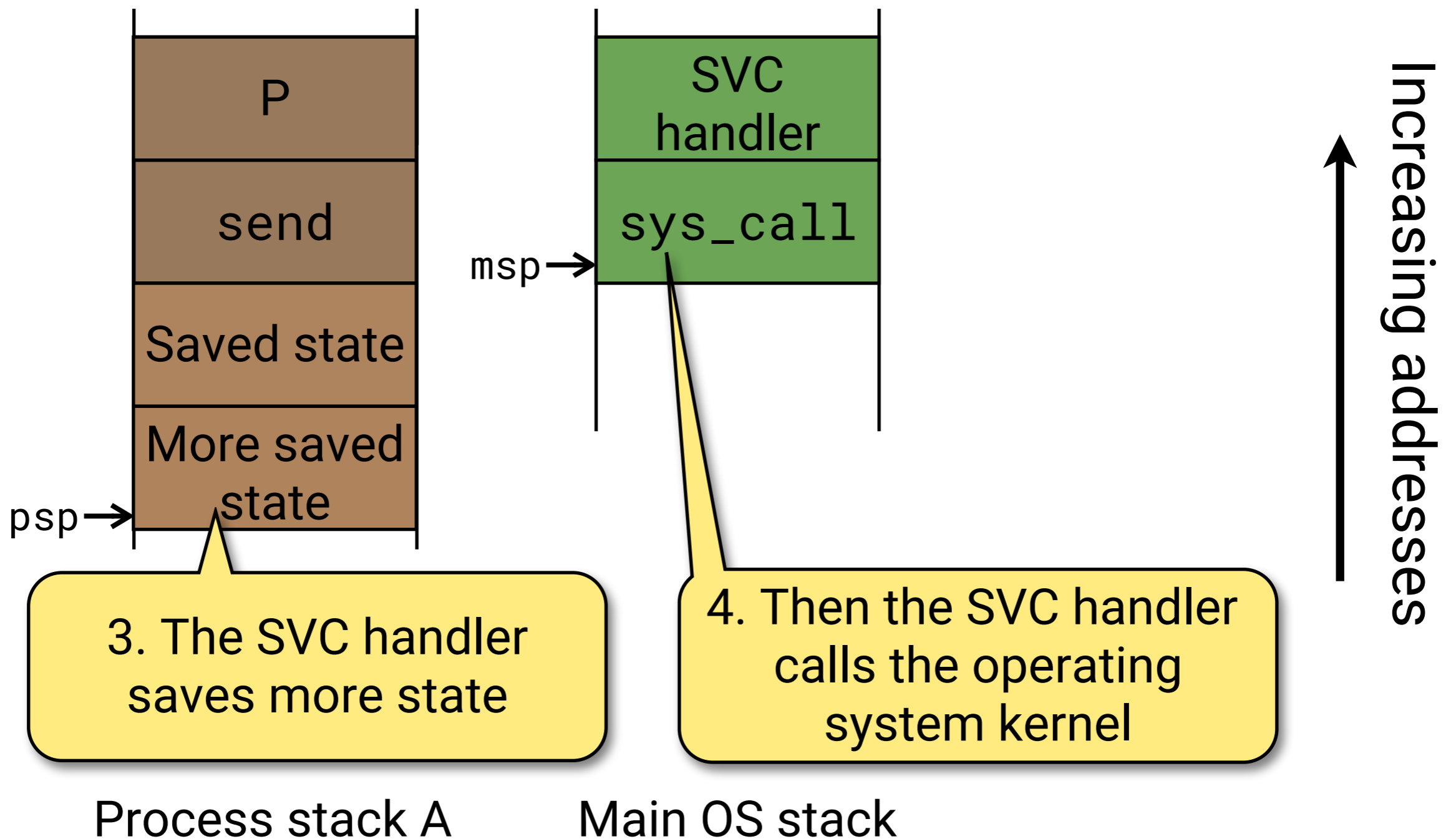
- Enter the OS via a *software interrupt* instruction `svc`, or by a normal interrupt
- Save the entire processor state on the stack
- After choosing a new process, restore its state to continue.

Made easier by having a *separate stack* for the operating system.

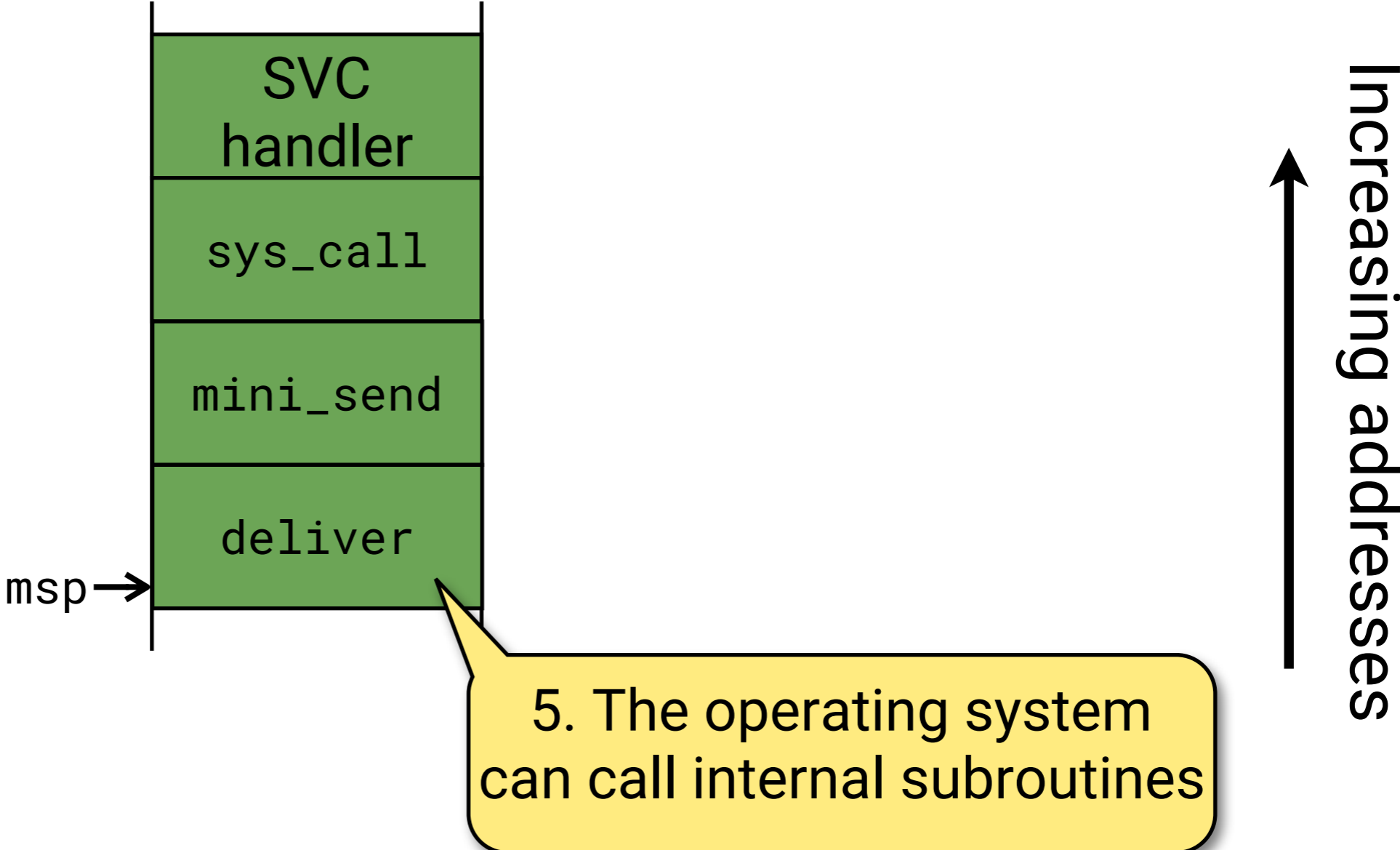
Context switch – part 1



Context switch – part 2

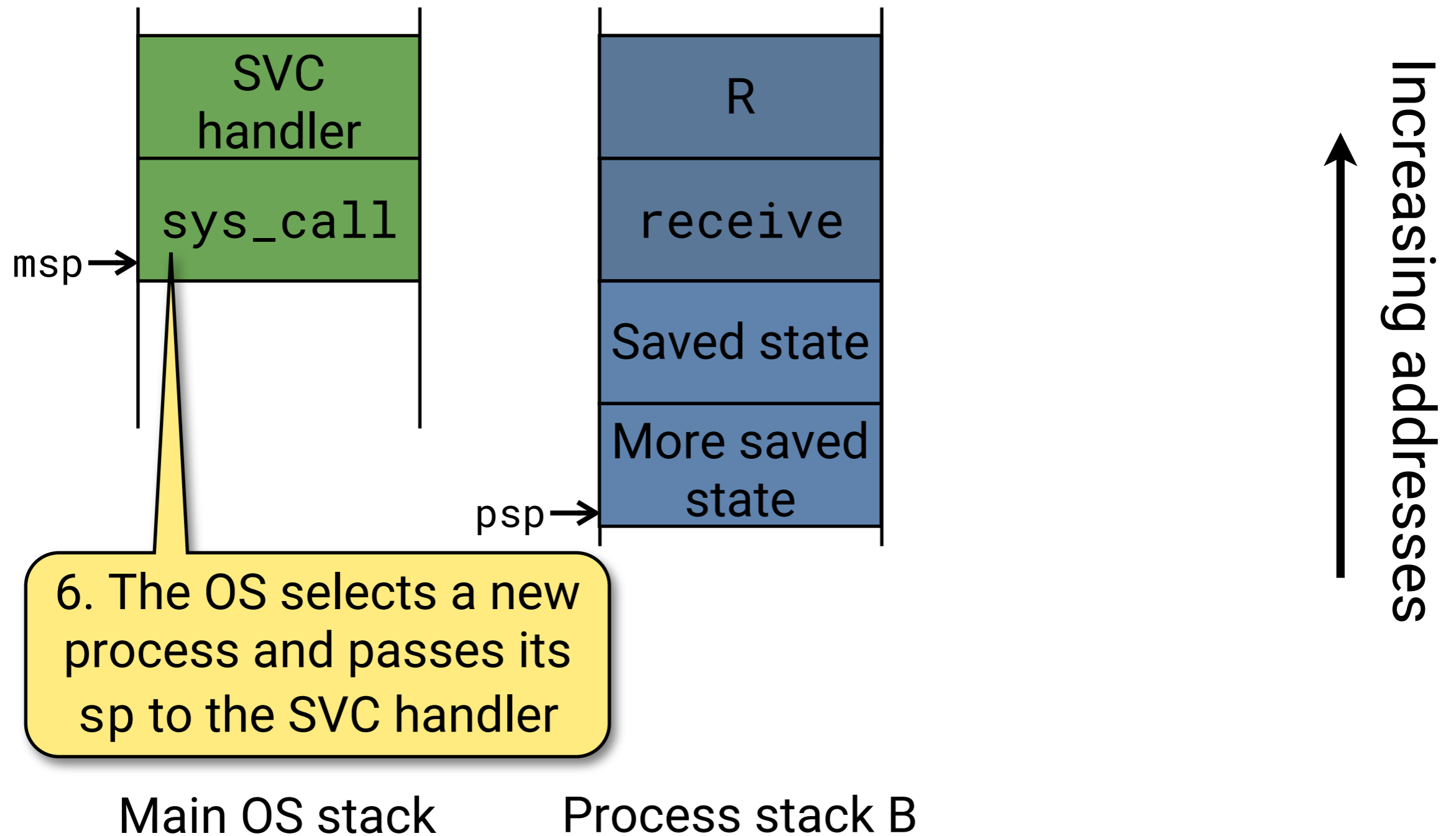


Context switch – part 3

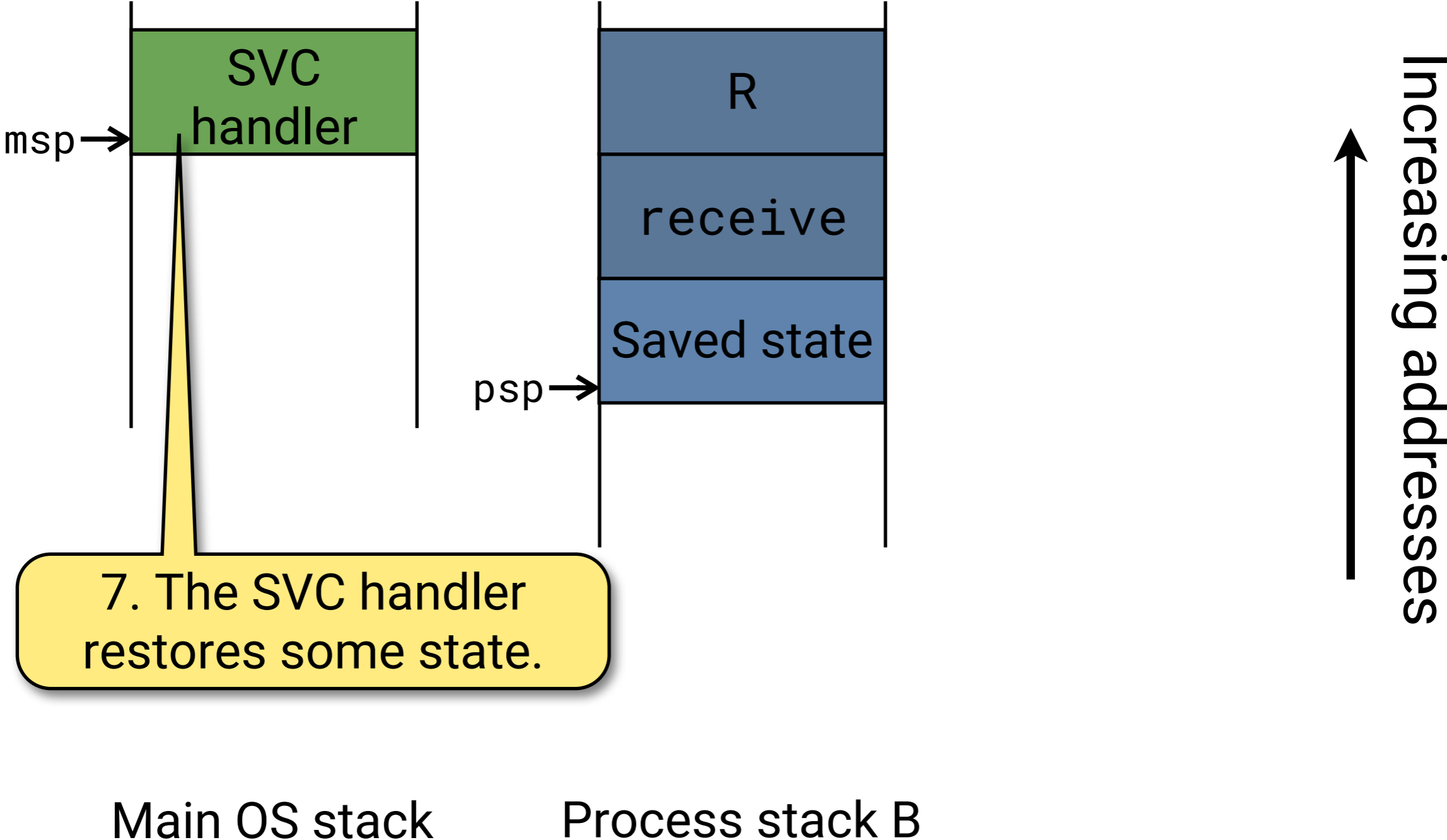


Main OS stack

Context switch – part 4



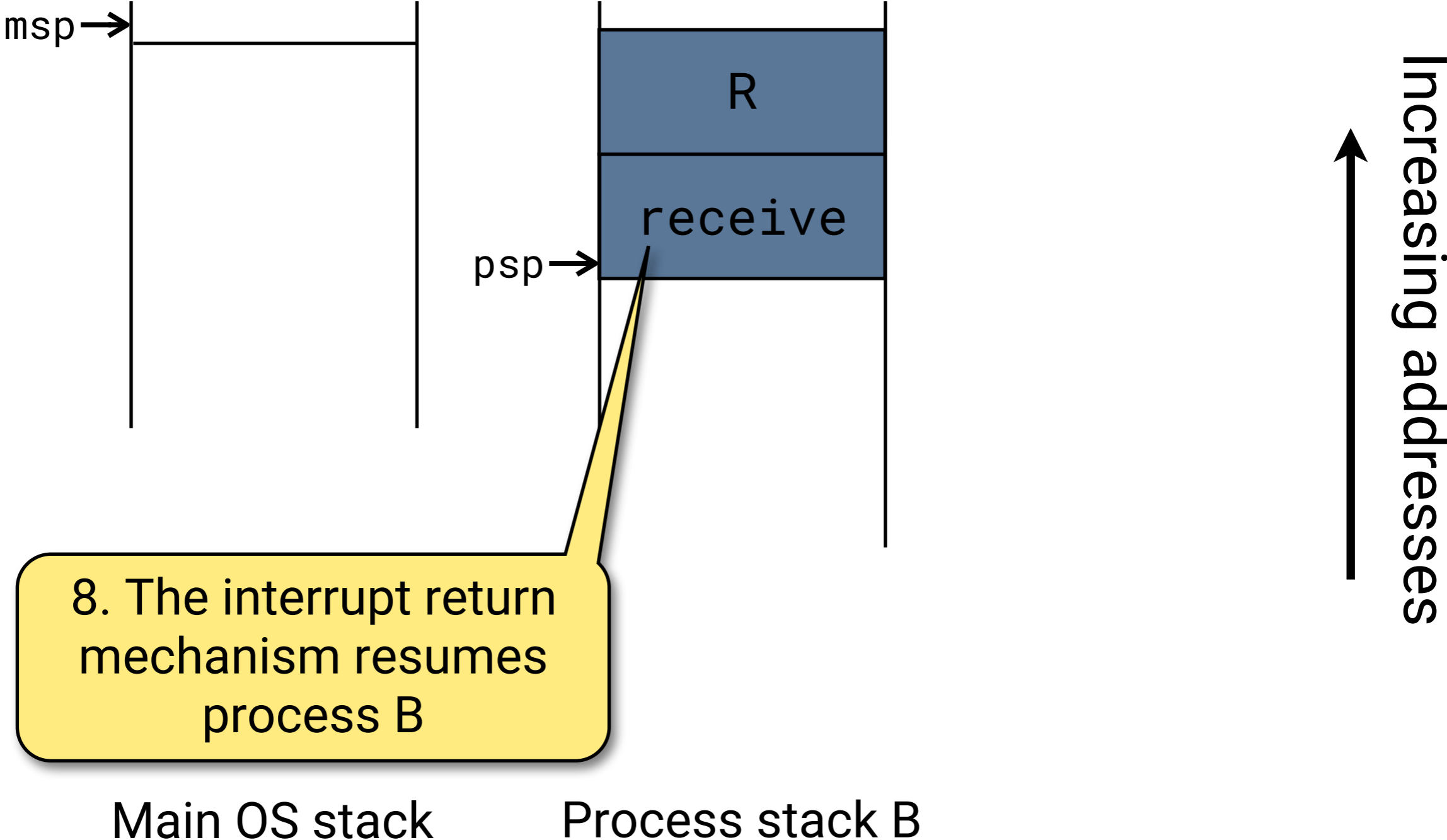
Context switch – part 5



Main OS stack

Process stack B

Context switch – part 6



System calls – client side

```
void NOINLINE yield(void) {  
    syscall(SYS_YIELD);  
}
```

```
void NOINLINE send(int dest, int type,  
                  message *msg) {  
    syscall(SYS_SEND);  
}
```

Generates an svc
instruction

OS will find arguments in
registers r0-r2

Implementing the SVC handler

svc_handler:

```
isave          @ Complete saving of state
@@ Argument in r0 is sp of old process
bl system_call @ Perform system call
@@ Result in r0 is sp of new process
irestore       @ Restore saved state
```

(in mpx-m0.s)

Saving the state

```
@@@ isave -- save context for system call
    .macro isave
    mrs r0, psp           @ Get thread stack pointer
    subs r0, #36
    movs r1, r0
    mov r3, lr           @ Preserve magic value
    stm r1!, {r3-r7}    @ Save low regs on thread stack
    mov r4, r8           @ Copy from high to low
    mov r5, r9
    mov r6, r10
    mov r7, r11
    stm r1!, {r4-r7}    @ Save high regs on thread stack
    .endm                @ Return new thread sp
```

System calls – OS side

```
unsigned *system_call(unsigned *psp) {
    short *pc = (short *) psp[PC_SAVE];
    int op = pc[-1] & 0xff;

    os_current->sp = psp;

    switch (op) {
    case SYS_YIELD:
        make_ready(os_current);
        choose_proc();
        break;
        ...
    }

    return os_current->sp;
}
```

Completing the story

Two details remain:

- How to start a process.
- How to start the entire operating system.

Starting a process

The first time a process runs, it is resumed just as if returning from a system call.

So we set up a fake exception frame that invokes the process body when resumed.

- $r0$ = integer argument,
- pc = process body,
- lr = address of `exit` stub, in case body returns.

Starting the system

After creating all the processes that make up the program, the main program becomes the idle process.

```
void __start(void) {
    /* Create idle process */
    ...

    /* Call the application's setup function */
    init();

    /* The main program morphs into the idle process. */
    os_current = idle_proc;
    set_stack(os_current->sp);
    idle_task();
}
```

The idle process

Having an idle process saves us from ever having no process to run.

```
/* idle_task -- body of the idle process */
void idle_task(void) {
    /* Pick a genuine process to run */
    yield();

    /* When there's nothing to do: */
    while (1) pause();
}
```

In conclusion

By saving the state of all registers on the stack, the context switch mechanism can suspend a process so that it can be resumed later.

There's always some machine-dependent intricacy to this, but the outline is usually the same.

We have separated the *mechanism* of context switch from the *policy* decisions about what process should run when.

Scheduling and Messages

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Inside the kernel

For simplicity, the kernel of the operating system cannot be interrupted.

- So we can deal with one interrupt or system call at a time.
- I'll describe the internal data structures as a guide to what the kernel does.

Process states

Each process is one of

- ACTIVE – running or ready to run.
- SENDING, RECEIVING – waiting to exchange a message.
- IDLING – the idle process.
- DEAD – after exiting.

Each process can be on *at most one* queue.

The process table

```
struct _proc {
    int pid;           // Process ID
    char name[16];    // Name for debugging
    unsigned state;   // SENDING, RECEIVING, etc.
    unsigned *sp;     // Saved stack pointer
    int priority;     // Priority: 0 is highest

    proc waiting;    // Processes waiting to send
    int pending;     // Whether interrupt pending
    int msgtype;     // Message to send or receive
    message *msgbuf; // Pointer to message buffer

    proc next;       // Next process in queue
};
```


Process priorities

0: Device drivers.

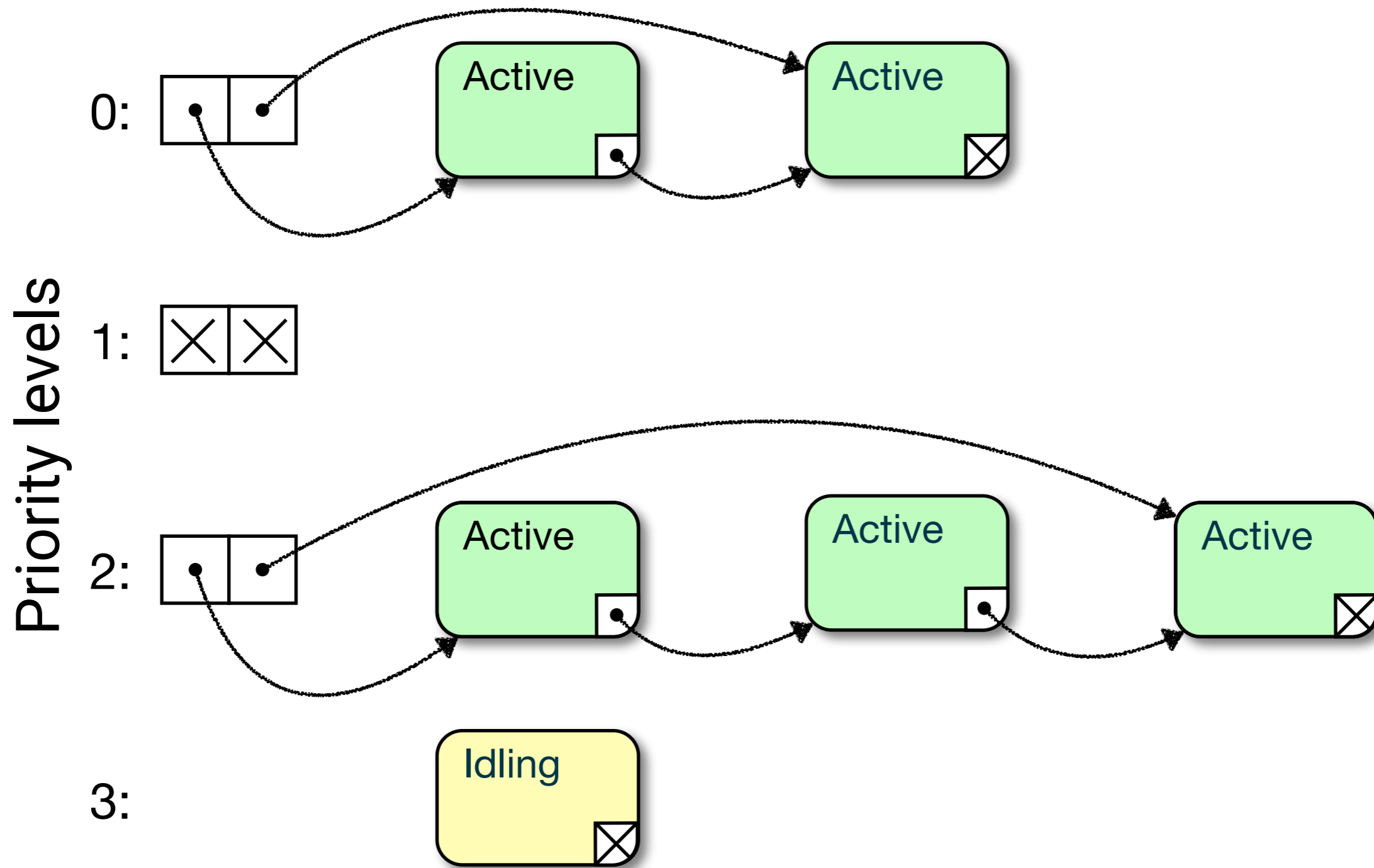
1: Normal processes, high priority.

2: Normal processes, default priority.

3: The idle process.

- When should a normal process be given high priority?

Implementation: ready queues



Pre-emptive scheduling

micro:bian is *pre-emptive*: a process can be suspended involuntarily (for example on interrupt), or when it calls `send()` or `receive()`.

Scheduling is not time-based: there is no attempt to share time equally between ready processes.

A process can call `yield()` voluntarily, but this is rarely necessary.

You can run a timer task if you like, but it is not compulsory.

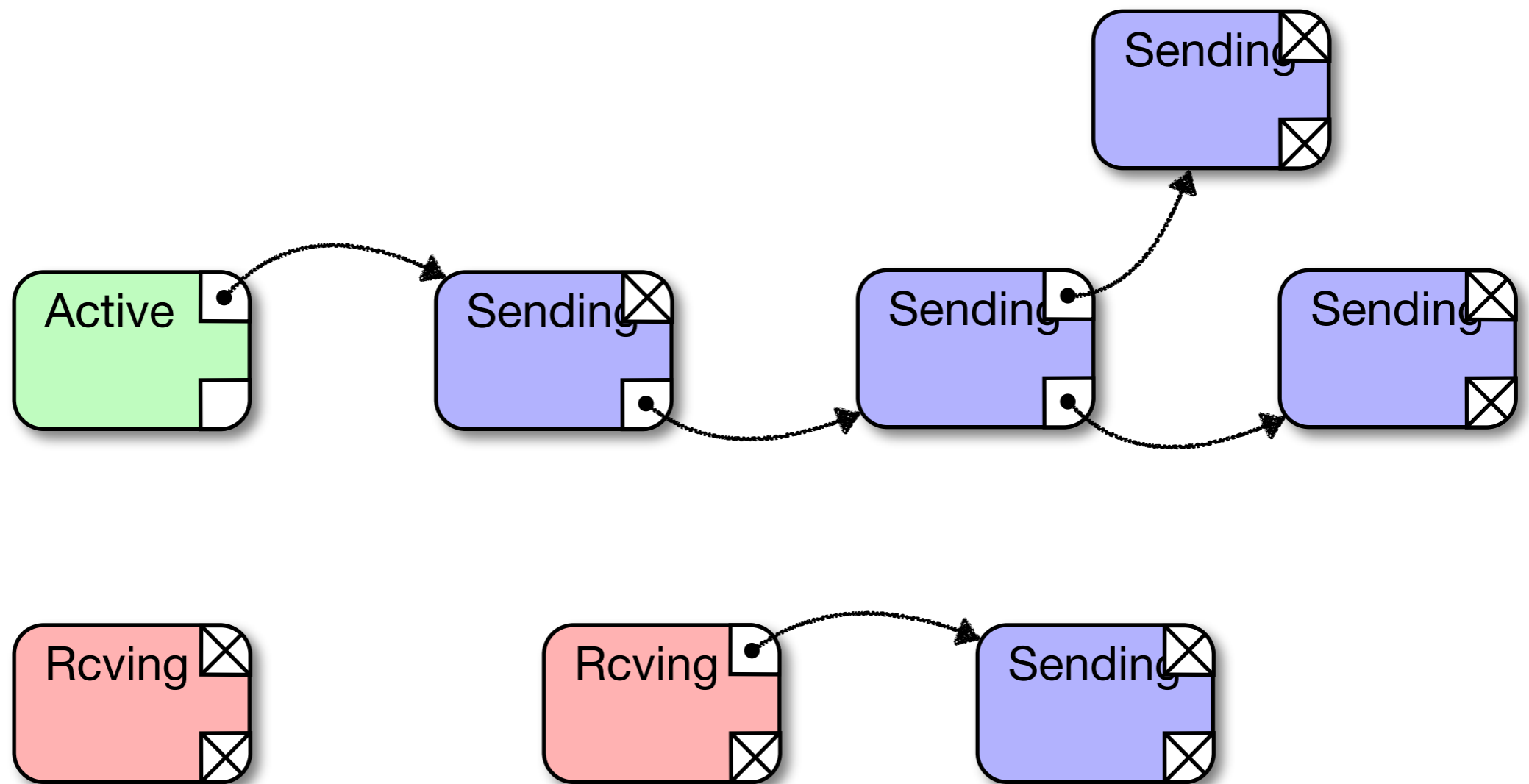
Rendezvous principle

Two processes must both arrive at `send()` and `receive()` for a message to be passed.

- So some processes are waiting to receive – not on any queue.
- Others are waiting to send to a specific receiver – on a queue for that receiver.

Sending queues

Each process has a queue of others waiting to send to it.



Story of a system call

```
unsigned *system_call(unsigned *psp) {
    short *pc = (short *) psp[PC_SAVE];
    int op = pc[-1] & 0xff;

    os_current->sp = psp;

    switch (op) {
    case SYS_SEND:
        mini_send(arg(0, int), arg(1, int),
                  arg(2, message *));
        break;
        ...
    }

    return os_current->sp;
}
```

Implementing send

```
static void mini_send(int dest, int type,
                    message *msg) {
    int src = os_current->pid;
    proc pdest = os_ptable[dest];

    if (accept(pdest, type)) { // Receiver is waiting
        deliver(pdest->msgbuf, src, msg);
        make_ready(pdest); make_ready(os_current);
    } else { // Sender joins the receiver's queue
        set_state(os_current, SENDING, type, msg);
        enqueue(pdest);
    }

    choose_proc();
}
```

Choosing the next process

```
static inline void choose_proc(void) {
    for (int p = 0; p < NPRI0; p++) {
        queue q = &os_readyq[p];

        if (q->head != NULL) {
            os_current = q->head;
            q->head = os_current->next;
            return;
        }
    }

    os_current = idle_proc;
}
```


Implementing receive

```
static void mini_receive(int type, message *msg) {
    if (os_current->pending // Is an interrupt due?
        && (type == ANY || type == INTERRUPT)) {
        os_current->pending = 0;
        deliver(msg, HARDWARE, INTERRUPT, NULL);
    } else {
        proc psrc = find_sender(os_current, type);
        if (psrc != NULL) { // Is a sender waiting?
            deliver(msg, psrc->pid, psrc->msgbuf);
            make_ready(os_current); make_ready(psrc);
        } else { // No luck: we must wait
            set_state(os_current, RECEIVING, type, msg);
        }
        choose_proc();
    }
}
```

Joining the queue

```
static inline void enqueue(proc pdest) {
    os_current->next = NULL;
    if (pdest->waiting == NULL)
        pdest->waiting = os_current;
    else {
        proc r = pdest->waiting;
        while (r->next != NULL)
            r = r->next;
        r->next = os_current;
    }
}
```

Implementing a device driver

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A temperature sensor

The Nordic chip has a temperature sensor on the processor die. We will implement

```
int temp_reading(void)
```

Use a device driver process

- to manage concurrent access,
- to allow connecting to interrupts.

Hardware registers

There's a device TEMP (address 0x4000C000) with

- A *task* START (offset 0x000) to start a reading.
- An *event* DATARDY (offset 0x100) that signals the reading is ready.
- A register INTEN (offset 0x300) where we can enable an interrupt on DATARDY.
- A register TEMP (offset 0x508) where the reading appears.

Describing the hardware

In hardware.h:

```
/* Temperature sensor */
_DEVICE _temp {
    _REGISTER(unsigned START, 0x000);    /* Task */
    _REGISTER(unsigned DATARDY, 0x100);  /* Event */
    _REGISTER(unsigned INTEN, 0x300);    /* Registers */
    _REGISTER(unsigned VALUE, 0x508);
};

/* Interrupts */
#define TEMP_INT_DATARDY 0

#define TEMP (* (volatile _DEVICE _temp *) 0x4000c000)
```

In assembly language

An assignment like

```
temp = TEMP.VALUE
```

becomes

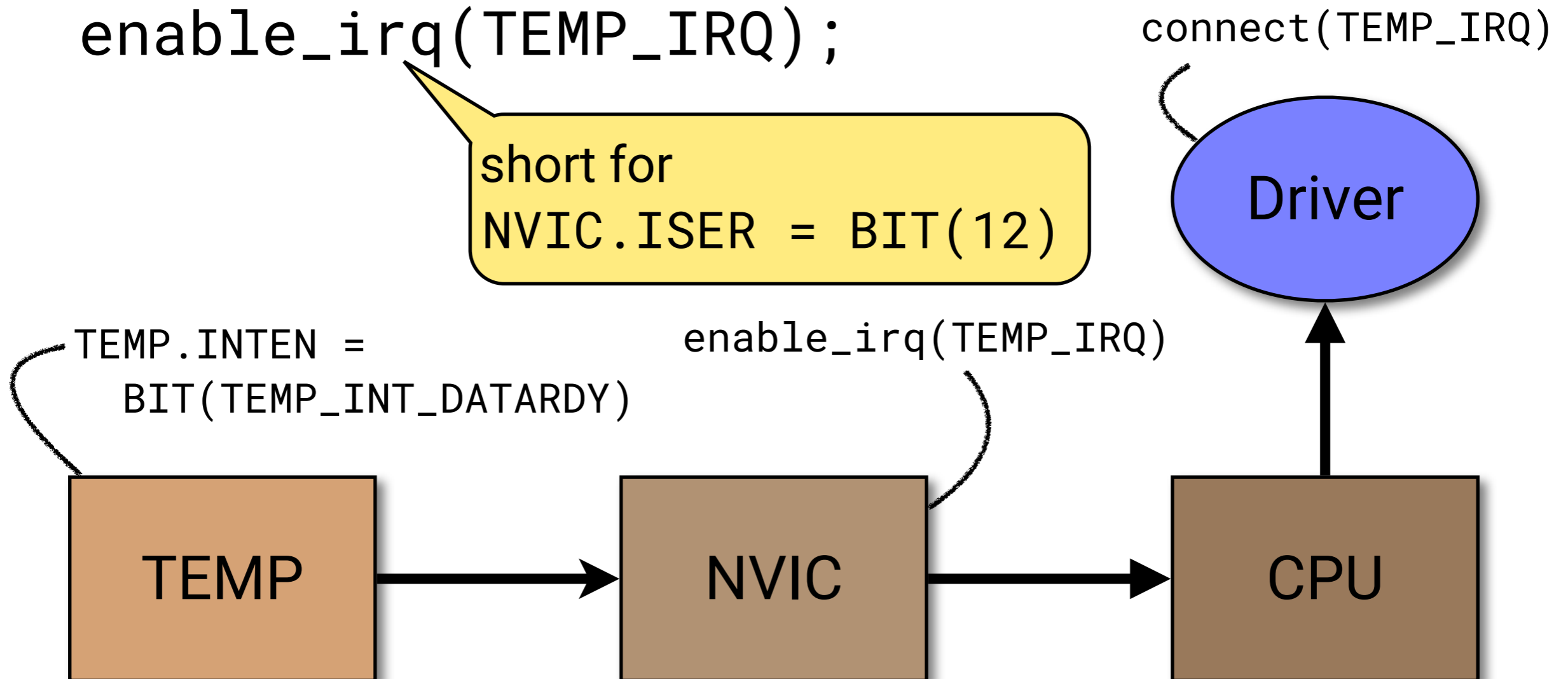
```
ldr r0, =0x4000c508  
ldr r6, [r0]
```

and that's all that matters.

Configuring the interrupt

```
TEMP.INTEN = BIT(TEMP_INT_DATARDY);  
connect(TEMP_IRQ);  
enable_irq(TEMP_IRQ);
```

short for
NVIC.ISER = BIT(12)



The driver process

```
static void temp_task(int arg) {  
    message m;  
    int temp, client;  
  
    TEMP.INTEN = BIT(TEMP_INT_DATARDY);  
    connect(TEMP_IRQ);  
    enable_irq(TEMP_IRQ);  
  
    ... server loop ...  
}
```

The server loop

```
while (1) {
    receive(ANY, &m);
    switch (m.type) {
    case REQUEST:
        client = m.sender;

        ... take a reading ...

        m.int1 = temp;
        send(client, REPLY, &m);
        break;

    default:
        badmsg(m.type);
    }
}
```

Taking a reading

```
TEMP.START = 1;  
receive(INTERRUPT, NULL);  
assert(TEMP.DATARDY);  
temp = TEMP.VALUE;
```

```
TEMP.DATARDY = 0;  
clear_pending(TEMP_IRQ);  
enable_irq(TEMP_IRQ);
```

- one request at a time, so we can stop to wait for the interrupt.

A client subroutine

```
int temp_reading(void) {  
    message m;  
    sendrec(TEMP_TASK, REQUEST, &m);  
    return m.int1;  
}
```

short for

```
send(TEMP_TASK, REQUEST, &m);  
receive(REPLY, &m);
```

Why sendrec()?

- It's a handy abbreviation.
- It is slightly more efficient – avoids two context switches.
- It solves the problem of *priority inversion*.

Priority inversion

- The server receives a request, takes a reading, then tries to send the result to a client.
- Meanwhile, the client has been squeezed out by other processes, and has not run again: it has yet to reach its `receive(REPLY, ...)`.
- So the (high-priority) server must wait for the (low-priority) client before continuing.

Solution: use `sendrec()` so the client promises in advance to accept the reply.

Links

- *Concurrent Programming* – programs that exploit parallel processing.
- *Concurrency* – proving that concurrent programs e.g. don't suffer from deadlock.
- *Compilers* – automating the translation into assembly language.
- *Computer Architecture* – designing hardware for performance.

Next term

- First half: designing combinational and sequential logic circuits.
- Building a tool-kit of architectural elements.
- Second half: designing a datapath and control that can execute (some) Thumb instructions.