

Towards an operating system: Processes and their management

An operating system's basic organization

An operating system is organized using the following ideas.

- A number of basic functions that are very dependent on the hardware of the machine, in particular input/output operations, are provided by the system.
- The system is a program that works in its own “context” that is kept completely separate from the “context” of user programs.
- Separating contexts makes it possible to design the system and the user programs quite independently. These programs are executed in an interleaved way, simulating a concurrent execution. We will modify the machine ULg01 in order to enable it to handle traps and interrupts.

Interrupts and traps

- To implement a system on a machine, it is necessary to be able to force execution of the system when needed. This requires special mechanisms: interrupts and traps.
- An interrupt forces a change in the program being executed when a given event occurs.
- A trap forces a change in the program being executed when special instructions, which are not part of the set of instructions defined for the machine architecture, are used.
- We will modify the machine ULg01 in order to enable it to handle traps and interrupts.

Operating system organization : basic principles

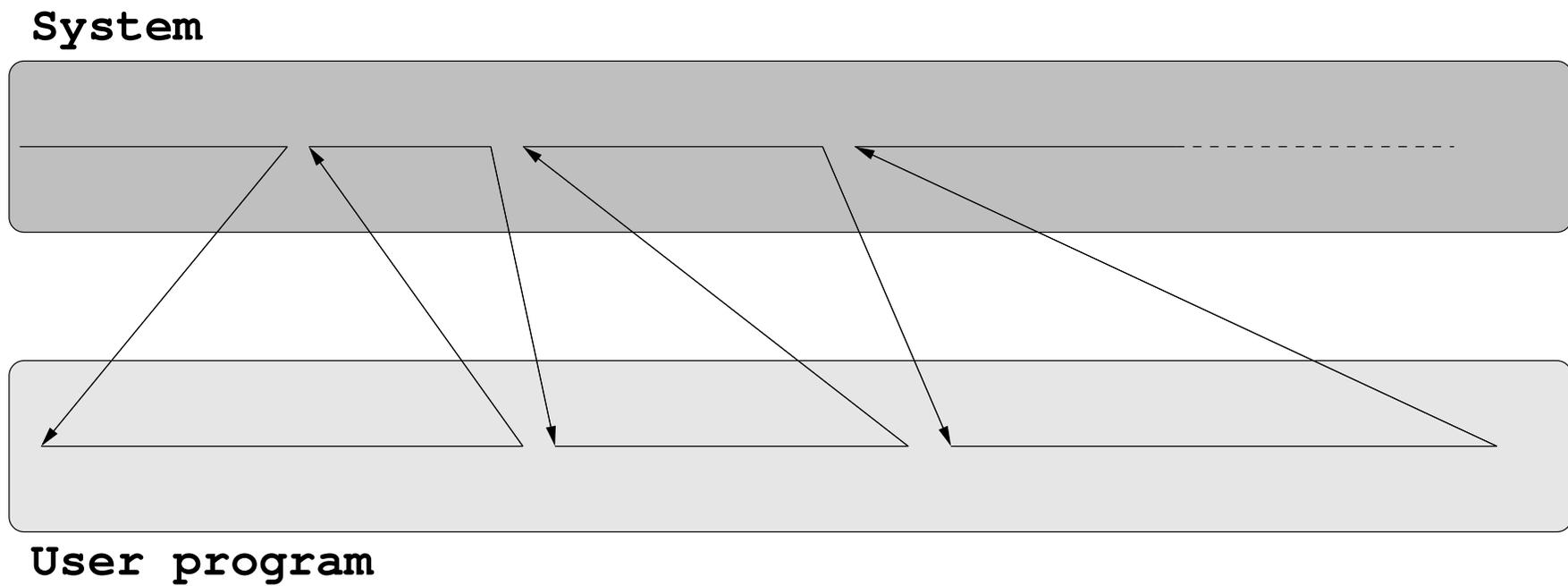
Consider first the situation in which only one user program is active.

- The goal is to share the machine between the user program and a “system” providing some functionalities, such as input/output operations, to the user program.
- Execution alternates between the two programs. Switching from the user program to the system is done:
 - At the request of the user program (trap);
 - When an interrupt occurs;
 - When the user program executes and illegal operation (fault).

These events are collectively called *exceptions*.

- Switching from the system to the user program is done by the system when it decides to do so.

A shared machine



Actions to be performed on exceptions

When an exception occurs, one needs to

- Know the address of the system program to be executed,
- Save the return address,
- Save the state of the user program in order to be able to restore this state when returning from the system.
- When the user program resumes its execution, it finds itself in the exact same situation it was in when the system was invoked. It is thus said the the user program operates in its own *context*.

User mode - System mode

- The goal of a system is to avoid the need for the users to cope with the machine's details, but it is also to prevent user programs from blocking the machine or from getting it into an incoherent state.
- For this goal, some operations must only be possible for the system.
- Two operating modes are thus necessary: a “system” or “supervisor” mode and a “user” mode in which certain privileged operations are not possible.
- It is also common to disable interrupts in system mode.

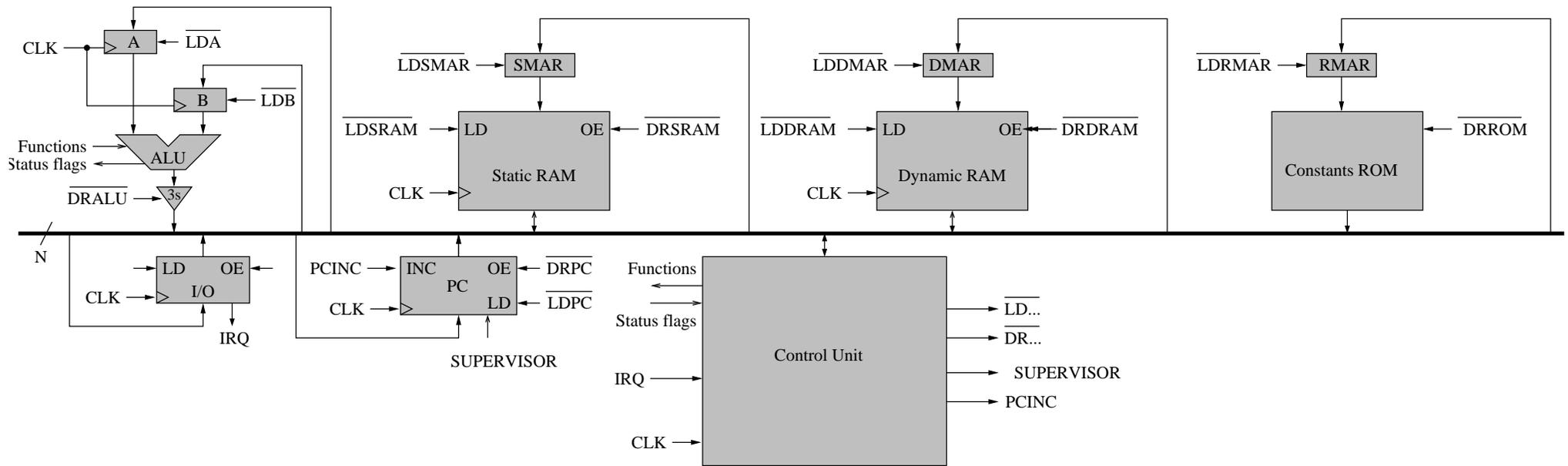
The choices of the β architecture

- The instruction with opcode 0x00 is used as system call. Special instructions with opcode 0x0* can be defined, but are only usable in supervisor mode.
- The address of the system program to be executed when an exception occurs is fixed. It can differ depending on the nature of the exception (interrupt, trap or illegal instruction).
- When switching to the system, the PC of the user program is saved in register 30, called XP - Exception Pointer
- Bit 31 of the program counter is used to indicate supervisor mode.
- In supervisor mode, interrupts are ignored (have no effect).

The machine ULg02

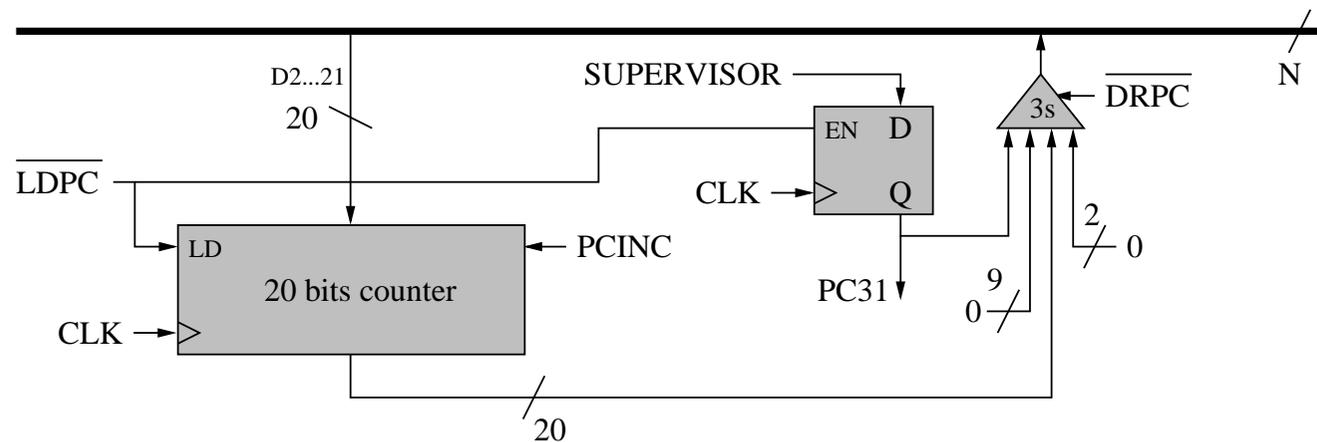
- In ULg02, two new signals are used as input of the microcode ROM: IRQ and PC31. PC31 is the supervisor mode bit, IRQ is the interrupt signal coming from the input/output devices.
- A new control signal SUPERVISOR appears as output of the microcode ROM. It is used to set bit 31 of the program counter.
- In the microcode of ULg02, it is useful to have access to constants. For this purpose, one adds a ROM in which constants (for example, the address of the interrupt handler) are kept at positions starting with the largest ROM address. To control this ROM, two new signals appear as output of the microcode ROM: LDRMAR and DRROM.

ULg02 : a general view



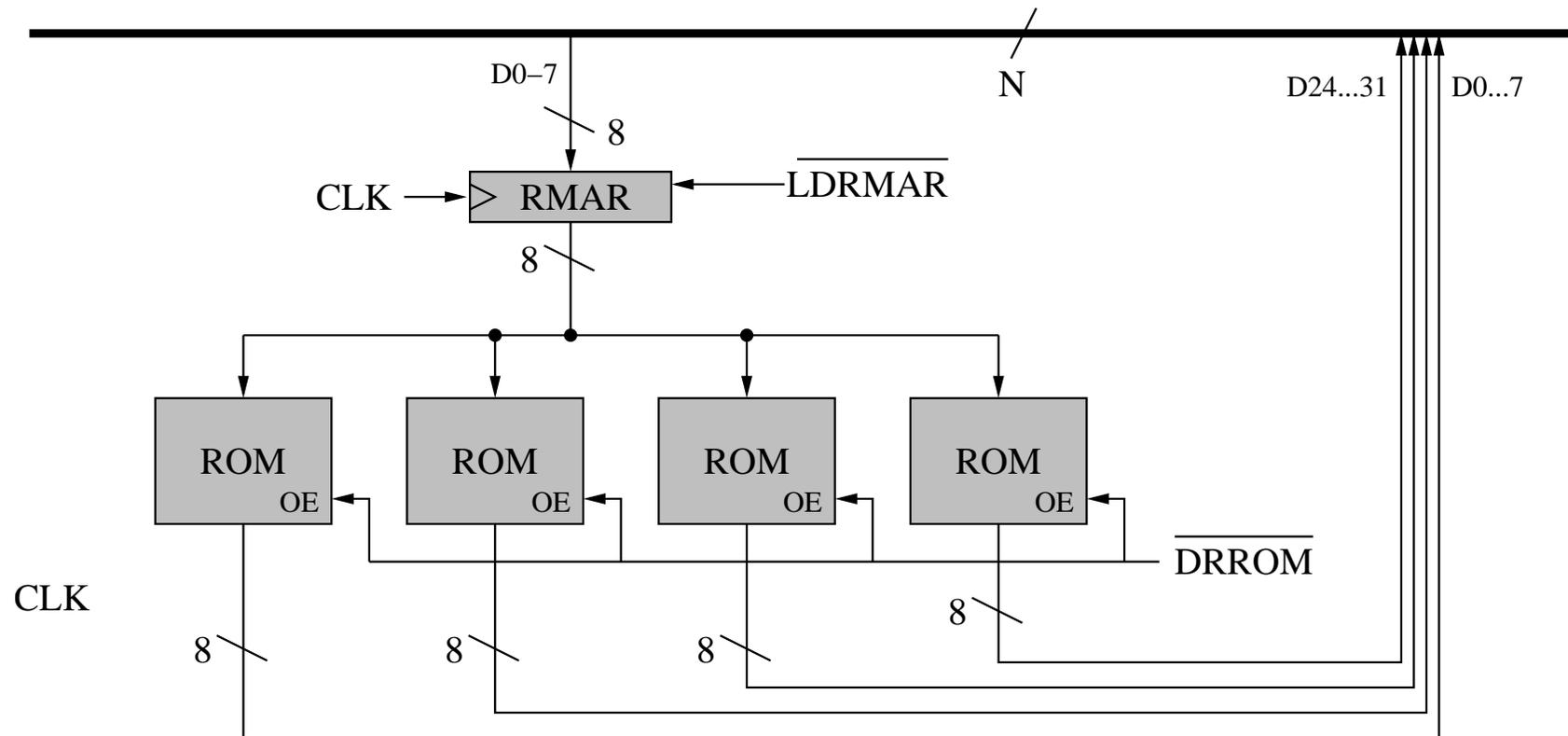
Notice the signal SUPERVISOR and the addition of the constant ROM.

ULg02 : the program counter (PC)



the “privileged bit ” PC31 is implemented explicitly. It can only be set to 1 if the SUPERVISOR signal has value 1.

ULg02 : The constant ROM



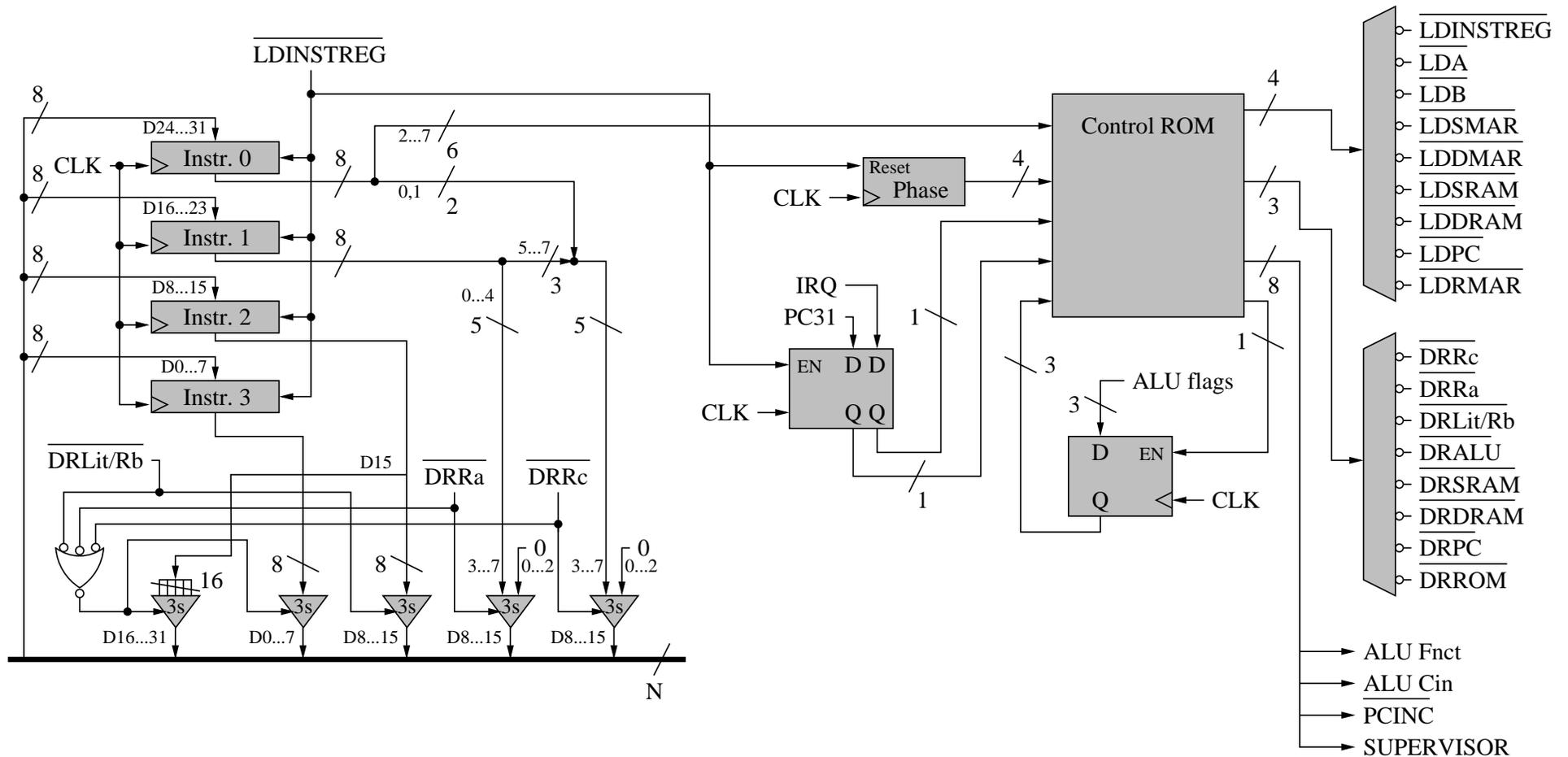
The signals controlling the constant ROM are $\overline{\text{LDRMAR}}$ (load ROM address register) and $\overline{\text{DRROM}}$ (reading from the ROM).

ULg02 : The content of the constant ROM

0x00	⋮
	⋮
0xFA	10000000 00000000 01000000 00000000 (Address of the handler "IRQ" — 0x2012)
0xFB	10000000 00000000 00100000 00000000 (Address of the handler "Supervisor Call" — 0x2008)
0xFC	10000000 00000000 01100000 00000000 (Address of the handler "Illegal Operation" — 0x2016)
0xFD	(Address of the handler "Cache Miss Code" — 0x2004)
0xFE	(Address of the handler "Cache Miss Data" — 0x2000)
0xFF	00000000 00000000 11110000 00000000 (Address of register XP)

The addresses of the handlers *Cache Miss Code* and *Cache Miss Data* will be used later for managing virtual memory.

ULg02 : the control unit



The only change is the addition of input (PC31 and IRQ), as well as output (SUPERVISOR, $\overline{\text{LDRMAR}}$ and $\overline{\text{DRROM}}$) signals to the microcode ROM.

ULg02 : the microcode

- For every instruction, when IRQ and PC31 are both at 0, the microcode is simply extended by setting SUPERVISOR to 0 ; $\overline{\text{LDRMAR}}$ and $\overline{\text{DRROM}}$ are never used.
- When PC31 is at 1, IRQ has no effect (the microcode is the same whether IRQ is at 0 or at 1). The signal SUPERVISOR is always at 1 (one stays in supervisor mode), except when a JMP is executed. In this case, SUPERVISOR has, when the PC is loaded, the value of the most significant bit of the destination address, which makes it possible to leave supervisor mode.
- If PC31 is at 0 and IRQ at 1, whatever the instruction is, the special interrupt microcode is executed. This microcode saves the PC in XP, jumps to the interrupt address found in the constant ROM and sets PC31 to 1.
- Microcode for the supervisor call instruction and for illegal instructions is also needed.

ULg02 : the interrupt microcode

microcode IRQ : IRQ = 1 PC31 = 0 Opcode = *****

Phase	Flags	Latch flags	ALU F, $\overline{C_{in}}$, Mode	LD SEL	DR SEL	PC+	SVR	
0000	*	1	110011	0001	011	0	0	A ← 0xFFFFFFFF
0001	*	1	111111	1000	011	0	0	RMAR ← A
0010	*	1	000000	0011	111	0	0	SMAR ← ROM
0011	*	1	000000	0110	110	0	0	SRAM ← PC
0100	*	1	111110	0001	011	0	0	A ← A-1
0101	*	1	111110	0001	011	0	0	A ← A-1
0110	*	1	111110	0001	011	0	0	A ← A-1
0111	*	1	111110	0001	011	0	0	A ← A-1
1000	*	1	111110	1000	011	0	0	RMAR ← A-1
1001	*	1	000000	0111	111	0	1	PC ← ROM
1010	*	1	000000	0100	110	1	0	DMAR ← PC; PC+
1011	*	1	000000	0000	101	0	0	INSTREG ← DRAM

The saved PC is the one of the instruction following the one that was about to be executed when the interrupt occurred. The instruction at address XP-4 has thus not been executed.

ULg02 : the microcode for JMP

JMP(Ra,Rc) (user mode) : Opcode = 011011 IRQ = 0 PC31 = 0

Phase	Flags	Latch flags	ALU F, $\overline{C_{in}}$, Mode	LD SEL	DR SEL	PC+	SVR	
0000	*	1	000000	0011	001	0	0	SMAR ← Ra
0001	*	1	000000	0001	100	0	0	A ← SRAM
0010	*	1	000000	0011	000	0	0	SMAR ← Rc
0011	*	1	000000	0101	110	0	0	SRAM ← PC
0100	*	1	111111	0111	011	0	0	PC ← A
0101	*	1	000000	0100	110	1	0	DMAR ← PC; PC+
0110	*	1	000000	0000	101	0	0	INSTREG ← DRAM

ULg02 : the microcode for JMP (next part)

JMP(Ra,Rc) (supervisor mode) : Opcode = 011011 IRQ = * PC31 = 1

Phase	Flags	Latch flags	ALU F, \overline{C}_{in} , Mode	LD SEL	DR SEL	PC+	SVR	
0000	*	1	000000	0011	001	0	0	SMAR \leftarrow Ra
0001	*	1	000000	0001	100	0	0	A \leftarrow SRAM
0010	*	1	000000	0011	000	0	0	SMAR \leftarrow Rc
0011	*	1	000000	0101	110	0	0	SRAM \leftarrow PC
0100	*	0	110010	0010	011	0	0	B \leftarrow A+A; Latch
0101	$\overline{C}=0$	1	111111	0111	011	0	1	PC \leftarrow A
0101	$\overline{C}=1$	1	111111	0111	011	0	0	PC \leftarrow A
0110	*	1	000000	0100	110	1	0	DMAR \leftarrow PC; PC+
0111	*	1	000000	0000	101	0	0	INSTREG \leftarrow DRAM

The SVC instruction

A system call instructions is added to the β instruction set.

```
.macro SVC()    LONG(0x0)
```

- The arguments of this instruction (type of the call coded as a word value and parameters if needed) are placed on the stack before using the instruction.
- A system call can return a value in register 0 (just as a procedure call).
- Executing `SVC()` saves the PC in XP and jumps to an address found in the constant ROM.
- In supervisor mode, the instruction `SVC()` is possible, but ought not to be used.

ULg02 : the microcode for SVC

SVC() : Opcode = 000000 IRQ = 0 PC31 = *

Phase	Flags	Latch flags	ALU F, $\overline{C_{in}}$, Mode	LD SEL	DR SEL	PC+	SVR	
0000	*	1	110011	0001	011	0	0	A ← 0xFFFFFFFF
0001	*	1	111111	1000	011	0	0	RMAR ← A
0010	*	1	000000	0011	111	0	0	SMAR ← ROM
0011	*	1	000000	0110	110	0	0	SRAM ← PC
0100	*	1	111110	0001	011	0	0	A ← A-1
0101	*	1	111110	0001	011	0	0	A ← A-1
0110	*	1	111110	0001	011	0	0	A ← A-1
0111	*	1	111110	1000	011	0	0	RMAR ← A-1
1000	*	1	000000	0111	111	0	1	PC ← ROM
1001	*	1	000000	0100	110	1	0	DMAR ← PC; PC+
1010	*	1	000000	0000	101	0	0	INSTREG ← DRAM

The saved PC is the one of the instruction following SVC().

The exception handlers

- The exception handlers are the points at which the system is entered coming from a user program.
- The first thing an exception handler must do is save the state of the user program.
- The state of the user program is the content of the registers and the memory it uses. The registers will be saved. The memory being used must be kept separate from the memory used by the system.
- Later we will describe a technique for keeping the memory used by user programs and the system completely separate. For the time being, let us just assume a separate memory area is reserved for each.

The exception handler (next)

An exception handler is written in two parts :

- A *stub* (*chicot in French*) written in assembly language that saves the state of the user program.
- The handler itself, which can be written without special care about registers being used and can thus be written in a high-level language (very often C).

A “stub” for the interrupt handler

The state of the user program is saved in system memory at a fixed address: User.

```
h_stub:  SUBC(XP, 4, XP)      | prepare to resume with
          | the interrupted instruction
          ST(r0, User, r31)  | save registers
          ST(r1, User+4, r31)
          . . .
          ST(r30, User+30*4, r31)
          CMOVE(KStack, SP)  | Load the system SP
          BR(Handler,LP)     | Call the handler
          LD(r31, User, r0)   | restore
          LD(r31, User+4, r1)
          LD(r31, User+30*4, r30)
          JMP(XP)            | return to application
```

The stub of a system call handler is similar, but SUBC(XP, 4, XP) is not executed since XP contains the address of the next instruction to be executed.

A system handling input/output operations

- Let's assume ULg02 has a simple input/output interface connected to a keyboard.
- From a programming point of view, the keyboard interface appears as two memory addresses: `Data` and `Flag`. The address `Data` contains the last character typed on the keyboard. The address `Flag` contains 0 if no character is available and contains 1 if a character is available.
- If `Flag` has value 1, the signal `IRQ` is active.
- We have to write an interrupt handler as well as a handler for the system call `"readkey"`.

A basic interrupt handler

The program below is the interrupt handler of the system's kernel.

```
struct Device { char Flag, Data; } Keyboard;
    /* The logical view of the input/output interface */
char Buffer[100];
    /*a work area in which the read characters are kept */
int inptr = 0;
    /* the next available position */
int outptr = 0;
    /* the next character to be read */

IntHandler()
{ Buffer[inptr] = Keyboard.Data;
  inptr = (inptr + 1) % 100;
  Keyboard.Flag = 0;
}
```

Thanks to interrupts each character is handled as soon as it is available.

The user program is interrupted, but is not aware of anything.

A system call handler

The following handler is executed when the instruction SVC is executed with the code “keyboard” placed on top of the stack.

```
struct Mstate { int R0; ..., R30;) User;
    /* the saved state of the user program */

KeyHandler()
{ while (ouptr == inptr) {}
  User.R0 = Buffer[ouptr];
  ouptr = ouptr+1 % 100;
}
```

An improved system call handler

The previous handler gets stuck when called with `Buffer` empty because it cannot be interrupted.

If `Buffer` is empty, one must switch back to the user program and do the system call again.

```
KeyHandler()  
{ if (ouptr == inptr) {  
    User.R30 = User.R30 - 4;} /* R30 correspond à XP */  
  else {  
    User.R0 = Buffer[outptr];  
    outptr = outptr+1 % 100;}  
}
```

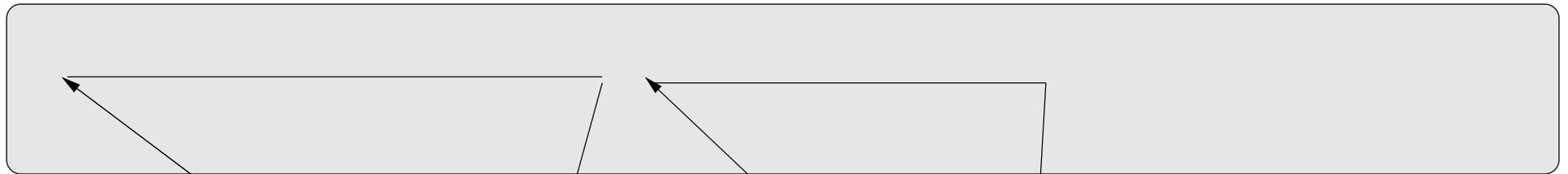
This program creates a loop that is interrupted when a character becomes available. To do better, the machine has to be shared between several user programs.

Processes

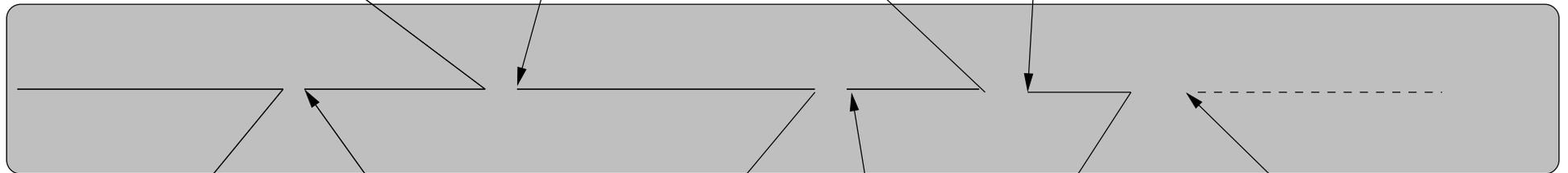
- While a user program is waiting for an input/output operation, the machine could be used by other user programs.
- A set of programs being executed or *processes* thus have to be managed. Each process has its own reserved memory area and, when it is not active, the values it has stored in registers are saved.
- The system manages the processes. Each time it has finished what it has to do, it executes a function `scheduler()` that chooses the process that will be activated.
- The information about the processes is kept in a *process table*.

A machine shared between several processes

User program 2



System



User program 1



An basic process manager

```
struct Mstate { int R0; ..., R30;) User;
    /* the saved state of the current process */

struct Mstate Proctbl[N]:
    /* the process table*/

int Cur; /* the index of the current process */

scheduler() {                                /* the process manager */
    Proctbl[Cur] = User:
    Cur = (Cur+1)%N;
    User = Proctbl[Cur];
}
```

A system call handler with process management

Now, if `Buffer` is empty, the process that is resumed will be different from the one that has executed the system call.

```
KeyHandler()  
{ if (ouptr == inptr) {  
    User.R30 = User.R30 - 4;  
    scheduler(); }  
  else {  
    User.R0 = Buffer[outptr];  
    outptr = outptr+1 % 100;}  
}
```

Clock interrupts

- Let us assume our machine has a “clock” appearing as a memory address whose content is incremented at each hardware clock cycle.
- Also assume that this clock generates an interrupt every 10000 clock cycles.
- The clock interrupt handler could simply be the following one.

```
ClkintHandler()  
{  
    scheduler();  
}
```

- This guarantees that `scheduler` is called frequently enough for each process to be regularly executed.

A more elaborate process management

- When a process is waiting for an input/output operation, it is useless to make it active if the state of the input/output interface has not changed.
- For this purpose, the process table includes information on the *status* of the process, indicating whether the process is *active* or *waiting*. When a process is waiting a code indicates what it is waiting for.
- The process table is then defined as follows.

```
struct PD {struct Mstate state ; int status} Proctbl[N]:  
    /* the process table with status information */
```

- With the convention that a 0 status represents an active process and a 1 status a process waiting for a character from the keyboard, we can rewrite our input/output handler.

An interrupt handler with process management and status information

```
struct PD {struct Mstate state ; int status} Proctbl[N]:  
    /* the process table with status information */
```

```
IntHandler()
```

```
{ int i;  
  Buffer[inptr] = Keyboard.Data;  
  inptr = (inptr + 1) % 100;  
  Keyboard.Flag = 0;  
  for (i=0;i<=N;i++) {  
    if (Proctbl.status[i]==1) Proctbl.status[i]=0;}  
}
```

One can obviously avoid cycling through the process table by using adequate data structures.

A system call handler with process management and status information

Now, if Buffer is empty, the process waiting for the keyboard is made inactive.

```
KeyHandler()  
{ if (ouptr == inptr) {  
    User.R30 = User.R30 - 4;  
    Proctable.status[Cur] = 1;  
    scheduler(); }  
else {  
    User.R0 = Buffer[outptr];  
    outptr = outptr+1 % 100;}  
}
```

It is also necessary to modify scheduler for it not to activate a waiting process.