# How can the machine ULg01 be programmed?

# Summary

1. How can writing "bits" be avoided with the help of an assembly language.

2. How can high level languages be implemented on the $\beta$ architecture?

3. What needs to be added to the machine ULg01 for it to able to run an operating system?

# A program for the $\beta$ architecture

```
10000000101000110010000000000000
01100100101100000000000000100100
```

- Impossible to read; impossible to write (for humans).

- We need something else:

```
ADD(r3,r4,r5)
ST(r5,0x24,r16)
```

- For this to be possible, we need a program that can translate from a symbolic notation to a sequence of bits: an assembler.

# A Universal Assembly Language

- Rather than writing an assembler specific to the $\beta$ architecture, we are going to define a few general mechanisms that make it possible to handle a wide variety of assembly languages.
- What the assembler produces is a sequence of bytes, for example

```
0x80  0x64  0x28  0x00
```

- The input language for the assembler is a sequence of constant expressions,

```
128 80+20 2*0x14 0
```

  A constant prefixed with `0x` is interpreted an hexadecimal value; prefixed with `0b` it is interpreted as a binary value; and, without a prefix as a decimal value.

- We will now introduce a few mechanisms that will facilitate writing sequences of expressions.

# Assembly language mechanisms

- Definitions of the following form are allowed

  *identifier* = *expression*

  where an *identifier* is a string of letters and digits of arbitrary length starting with a letter. Once defined an identifier may appear in an expression. One can then write

```
X = 128
X X-28 2*0x14 X-X
```

- A special *identifier* "." is used to represent the position of the next byte to be added to the sequence being generated. Initially, "." has value 0 ; The value of "." can be modified, for example (read column by column)

```
X = 128 | .  = .+ 4
X X-28  | 2*0x14 X-X
```

  leaves a 4 byte space following the two first generated bytes.

- A position can be assigned to an identifier by writing

  *identifier* :

  This is equivalent to writing

  *identifier* = .

  Example :

```
X: .  = .+4
0xA6
```

  reserves (for example for a variable) a 4 byte space at the position represented by the identifier `X`.

# A powerful mechanism: macros

- Macros make it possible to define a parameterized program fragment that can be reused at will. The definition of a macro has the form

  `.macro` *name(p1,. . . ,pn) body*

  where *p1,. . . ,pn* are the (formal) parameters of the macro. There can be any number of them. The *body* of the macro is a program (a sequence of expressions) in which the formal parameters may appear.

- A call to a macro is written

  *name(v1,. . . ,vn)*

  and is replaced by the body of the macro in which the formal parameters are replaced by the values of the expressions *v1,. . . ,vn*. Parameters are evaluated once, when the macro is called.

- A macro generating four consecutive values can be defined by

  ```
  .macro consec(n) n n+1 n+2 n+3
  ```

  and thus `consec(6)` is assembled into 6 7 8 9.

# Macros defining the $\beta$ assembler

First some general useful macros.

```
.macro WORD(x)  (x)%256   (x)/256          | little endian
.macro LONG(x)  WORD(x) WORD((x) >> 16)
```

Instruction coding macros

```
.macro ENC_NOLIT(OP, Ra, Rb, Rc) LONG((OP<<26)+((Rc%32)<<21)
                                      +((Ra%32)<<16)+((Rb%32)<<11))
.macro ENC_LIT(OP, Ra, Rc, Lit)  LONG((OP<<26)+((Rc%32)<<21)
                                      +((Ra%32)<<16)+(Lit % 0x10000))
.macro ENC_ADRLIT(OP, Ra, Rc, Label)  ENC_LIT(OP, Ra, Rc, (label-(.+4))>>2)
```

Assigning identifiers to registers

```
r0 = 0x0
...
r31 =  0x11111
```

## Logical and Arithmetical instructions

```
.macro ADD(Ra,Rb,Rc)          ENC_NOLIT(0b100000,Ra,Rb,Rc)
.macro ADDC(Ra,Lit,Rc)        ENC_LIT(0b110000,Ra,Rc,Lit)
.macro SUB(Ra,Rb,Rc)          ENC_NOLIT(0b100001,Ra,Rb,Rc)
.macro SUBC(Ra,Lit,Rc)        ENC_LIT(0b110001,Ra,Rc,Lit)
.macro DIV(Ra,Rb,Rc)          ENC_NOLIT(0b100011,Ra,Rb,Rc)
.macro DIVC(Ra,Lit,Rc)        ENC_LIT(0b110011,Ra,Rc,Lit)
.macro MUL(Ra,Rb,Rc)          ENC_NOLIT(0b100010,Ra,Rb,Rc)
.macro MULC(Ra,Lit,Rc)        ENC_LIT(0b110010,Ra,Rc,Lit)


.macro CMPEQ(Ra,Rb,Rc)        ENC_NOLIT(0b100100,Ra,Rb,Rc)
.macro CMPEQC(Ra,Lit,Rc)      ENC_LIT(0b110100,Ra,Rc,Lit)
.macro CMPLE(Ra,Rb,Rc)        ENC_NOLIT(0b100110,Ra,Rb,Rc)
.macro CMPLEC(Ra,Lit,Rc)      ENC_LIT(0b110110,Ra,Rc,Lit)
.macro CMPLT(Ra,Rb,Rc)        ENC_NOLIT(0b100101,Ra,Rb,Rc)
.macro CMPLTC(Ra,Lit,Rc)      ENC_LIT(0b110101,Ra,Rc,Lit)
```

```
.macro AND(Ra,Rb,Rc)        ENC_NOLIT(0b101000,Ra,Rb,Rc)
.macro ANDC(Ra,Lit,Rc)      ENC_LIT(0b111000,Ra,Rc,Lit)
.macro OR(Ra,Rb,Rc)         ENC_NOLIT(0b101001,Ra,Rb,Rc)
.macro ORC(Ra,Lit,Rc)       ENC_LIT(0b111001,Ra,Rc,Lit)
.macro XOR(Ra,Rb,Rc)        ENC_NOLIT(0b101010,Ra,Rb,Rc)
.macro XORC(Ra,Lit,Rc)      ENC_LIT(0b111010,Ra,Rc,Lit)

.macro SHR(Ra,Rb,Rc)        ENC_NOLIT(0b101101,Ra,Rb,Rc)
.macro SHRC(Ra,Lit,Rc)      ENC_LIT(0b111101,Ra,Rc,Lit)
.macro SHL(Ra,Rb,Rc)        ENC_NOLIT(0b101100,Ra,Rb,Rc)
.macro SHLC(Ra,Lit,Rc)      ENC_LIT(0b111100,Ra,Rc,Lit)
.macro SRA(Ra,Rb,Rc)        ENC_NOLIT(0b101110,Ra,Rb,Rc)
.macro SRAC(Ra,Lit,Rc)      ENC_LIT(0b111110,Ra,Rc,Lit)
```

Memory access instructions

```
.macro LD(Ra,Lit,Rc)          ENC_LIT(0b011000,Ra,Rc,Lit)
.macro LDR(label,Rc)          ENC_ADRLIT(0b011111,0,Rc,label)
.macro ST(Rc,Lit,Ra)          ENC_LIT(0b011001,Ra,Rc,Lit)
```

Branch instructions

```
.macro BNE(Ra,label,Rc)       ENC_ADRLIT(0b011110,Ra,Rc,label)
.macro BT(Ra,label,Rc)        BNE(Ra,label,Rc)
.macro BEQ(Ra,label,Rc)       ENC_ADRLIT(0b011101,Ra,Rc,label)
.macro BF(Ra,label,Rc)        BEQ(Ra,label,Rc)
.macro JMP(Ra,Rc)             ENC_LIT(0b011011,Ra,Rc,0)
```

# Defining new instructions with macros

Examples

```
.macro MOVE(Ra,Rc)        ADD(Ra,r31,Rc)     | R[Rc] <- R[Ra]
.macro CMOVE(C,Rc)        ADDC(r31,C,Rc)     | R[Rc] <- C

.macro NOP()              ADDC(r31,r31,r31)  | do nothing

.macro BR(label)          BEQ(r31,label,r31)
```

# A program written in $\beta$ assembler

```
.include macros           | Loading the macros
        LDR(input,r0)     | data in r0
        BR(bitrev)
input:  LONG(0x12345)

bitrev:
        CMOVE(32,r2)      | 32 bits to process
        CMOVE(0,r1)       | result register
loop:   ANDC(r0,1,r3)     | first bit to r3
        SHLC(r1,1,r1)     | transfer it
        OR(r3,r1,r1)      | to r1
        SHRC(r0,1,r0)     | prepare following bit
        SUBC(r2,1,r2)     | decrement number of bits to process
        BNE(r2,loop)      | loop if not done
```

# The $\beta$ architecture and high-level languages

We will see how the concepts used in high-level languages, in particular, procedure calls, can be implemented in the $\beta$ architecture.

Let us look at an example.

```
int fact(int n)
{
    if (n>0)
        return n*fact(n-1);
    else
        return 1;
}

fact(4);
```

To handle procedures solutions to the following problems are needed:

1. passing the value of the arguments to the procedure,

2. making it possible for the procedure to use local variables,

3. allowing the procedure to return a value,

4. allowing the procedure to call other procedures, including itself (recursion).

# Saving the return address

- To save the return address, it is natural to use a register. Register r28 (Linkage Pointer, LP) will be reserved for this purpose.

- A procedure can thus be called with the instruction `BR(label,LP)`.

- And returning from a procedure is done with `JMP(LP,r31)`.

- But, how can one handle arguments and recursion?

## Managing a stack in the $\beta$ architecture

- A stack is a very useful concept for handling procedures as well as other programming problems.

- A stack is an area of memory in which only the most recently added element can be accessed directly.

- We will implement a stack as a sequence of memory words and we will use a dedicated register (`SP = r29`) as Stack Pointer.

- Adding or removing an element of the stack can thus be done with the following instructions.

```
.macro PUSH(Ra)          ADDC(SP,4,SP) ST(Ra,-4,SP)
.macro POP(Ra)           LD(SP,-4,Ra)  ADDC(SP,-4,SP)
```

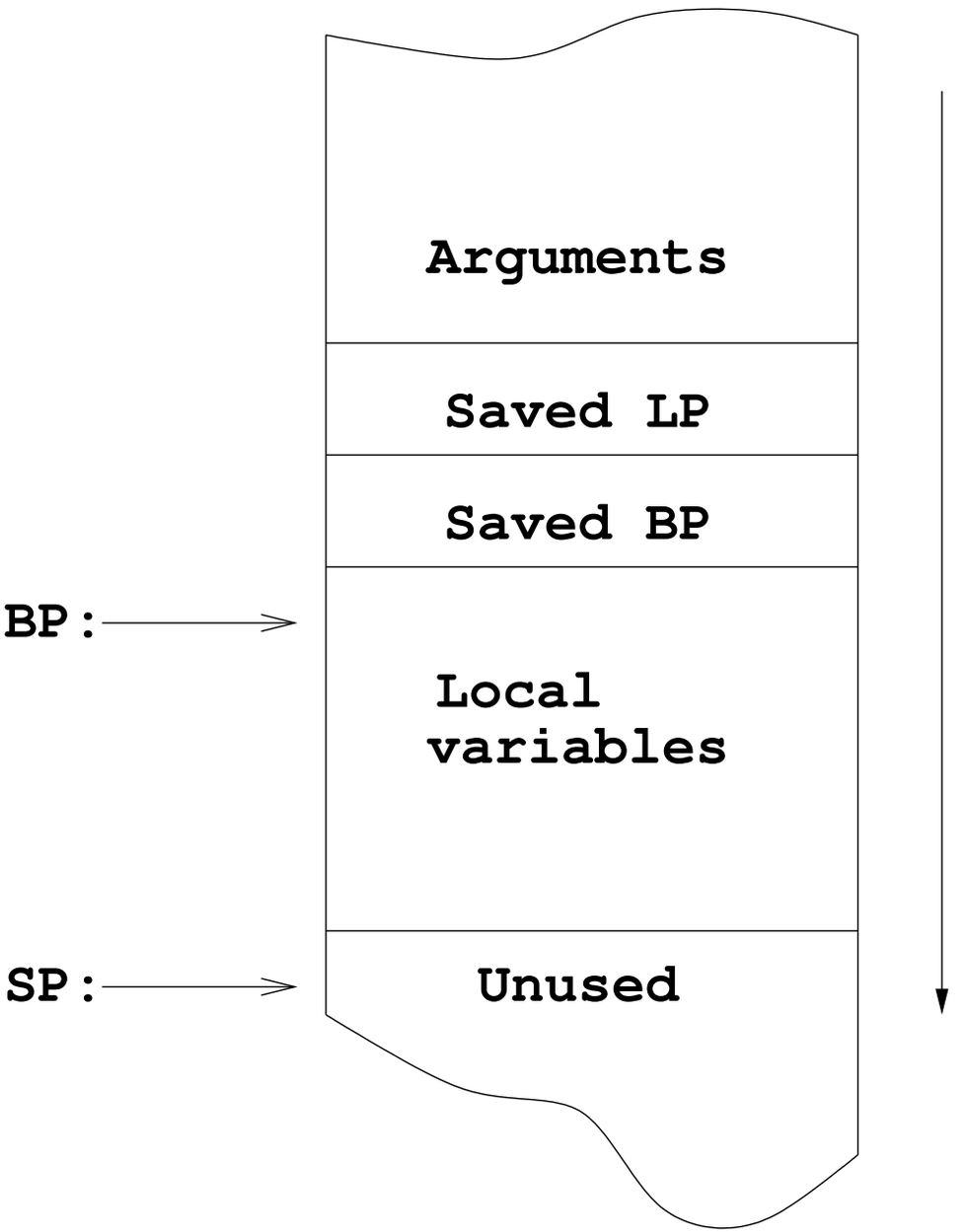
- Reserving space on the stack is done as follows.

```
.macro ALLOCATE(k)       ADDC(SP,4*k,SP)
.macro DEALLOCATE(k)     SUBC(SP,4*k,SP)
```

# Handling procedures using a stack

- Arguments are placed on the stack before calling the procedure.
- The procedure uses the stack area beyond the arguments for its own needs.
- The stack area used by a procedure is called its *frame*. It is useful to have a pointer that lets us know where this frame starts (Base of frame Pointer, `BP = r27`).
- To allow recursion, LP and BP are saved on the stack at each procedure call.

# General stack organisation



# Implementing procedure calls

In the calling procedure

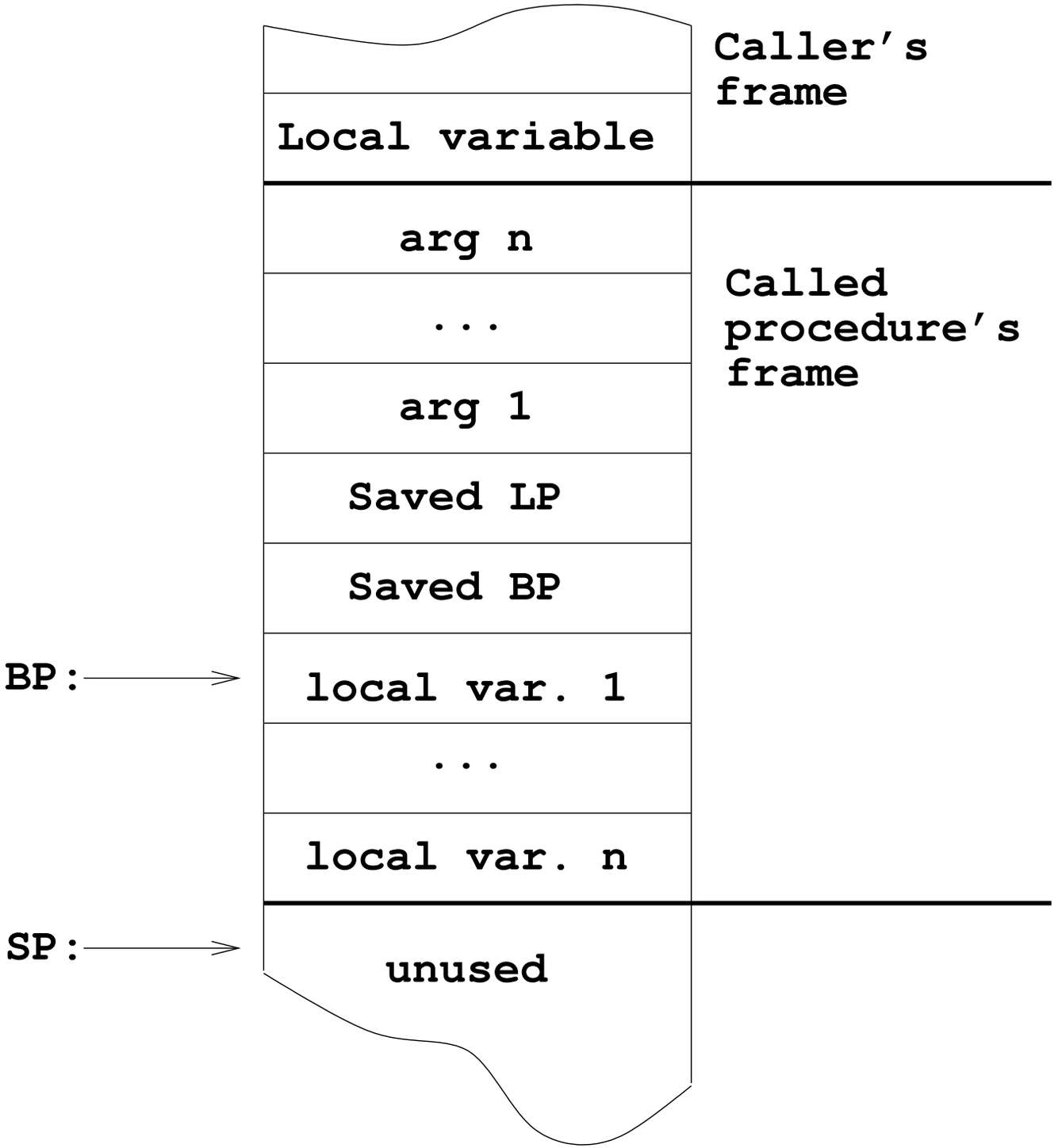
```
    PUSH(argn)     | arguments are placed in reverse
    ...            | order
    PUSH(arg1)
    BR(f,LP)
    DEALLOCATE(n)
```

At the beginning of the called procedure

```
f:  PUSH(LP)
    PUSH(BP)
    MOVE(SP,BP)
    ALLOCATE(space) | allocate local space
    (save other registers if needed)
```

at the end of the called procedure

```
(restore saved registers)
MOVE(val,r0)  | the returned value is placed in r0
MOVE(BP,SP)   | restore the caller's SP
POP(BP)       | restore the caller's BP
POP(LP)       | restore the return address
JMP(LP,R31)   | return
```


Caller's frame
Local variable
arg n
...
arg 1
Called procedure's frame
Saved LP
Saved BP
BP:
local var. 1
...
local var. n
SP:
unused

# Accessing local variables

To access the i-th local variable, one uses

```
LD(BP,(i-1)*4,rx)
```

```
ST(rx,(i-1)*4,BP)
```

To access the j-th argument, one uses

```
LD(BP,-4*(j+2),rx)
```

```
ST(rx,-4*(j+2),BP)
```

# An implementation of the factorial function

```
fact: PUSH(LP)          | save the return address
      PUSH(BP)          | save the previous frame
      MOVE(SP,BP)       | initialise the current frame
      PUSH(r1)          | r1 will be used, save it
      LD(BP,-12,r1)     | load the argument n in r1
      BNE(r1,big)       | compare n to 0
      ADDC(r31,1,r0)    | n=0, return 1
      BR(rtn)           | go to return sequence

big:  SUBC(r1,1,r1)     | compute n-1 in r1
      PUSH(r1)          | place argument on stack
      BR(fact,LP)       | recursive callm
      DEALLOCATE(1)     | free area used for arguments
      LD(BP,-12,r1)     | load n in r1
      MUL(r1,r0,r0)     | n*fact(n-1) in r0
```

```
rtn:  POP(r1)            | restore r1
      MOVE(BP,SP)        | restore  SP
      POP(BP)            | restore  BP
      POP(LP)            | restore the return address
      JMP(LP,r31)        | return
```

# Non local variables

- The technique used so far does not handle non local variables.
- For this, one uses "static links".
- A static link points from the current stack frame to the stack frame of the procedure in which the current procedure was (lexically) defined.
- One then accesses a non local variable by going up through static links the required number of times and then accessing a local variable.