

1 Introduction

This tutorial presents an introduction to Intel's Nios[®] II processor, which is a soft processor that can be instantiated on an Intel FPGA device. It describes the basic architecture of Nios II and its instruction set. The Nios II processor and its associated memory and peripheral components are easily instantiated by using Intel's SOPC Builder or Qsys tool in conjunction with the Quartus[®] Prime software.

A full description of the Nios II processor is provided in the *Nios II Processor Reference Handbook*, which is available in the literature section of the Intel web site. Introductions to the SOPC Builder and Qsys tools are given in the tutorials *Introduction to the Intel SOPC Builder* and *Introduction to the Intel Qsys System Integration Tool*, respectively. Both can be found in the University Program section of the web site.

Contents:

- Nios II System
- Overview of Nios II Processor Features
- Register Structure
- Accessing Memory and I/O Devices
- Addressing
- Instruction Set
- Assembler Directives
- Example Program
- Exception Processing
- Cache Memory
- Tightly Coupled Memory

2 Background

Intel's Nios II is a soft processor, defined in a hardware description language, which can be implemented in Intel's FPGA devices by using the Quartus® Prime CAD system. This tutorial provides a basic introduction to the Nios II processor, intended for a user who wishes to implement a Nios II based system on an Intel Development and Education board.

3 Nios II System

The Nios II processor can be used with a variety of other components to form a complete system. These components include a number of standard peripherals, but it is also possible to define custom peripherals. Intel's DE-series boards contain several components that can be integrated into a Nios II system. An example of such a system is shown in Figure 1.

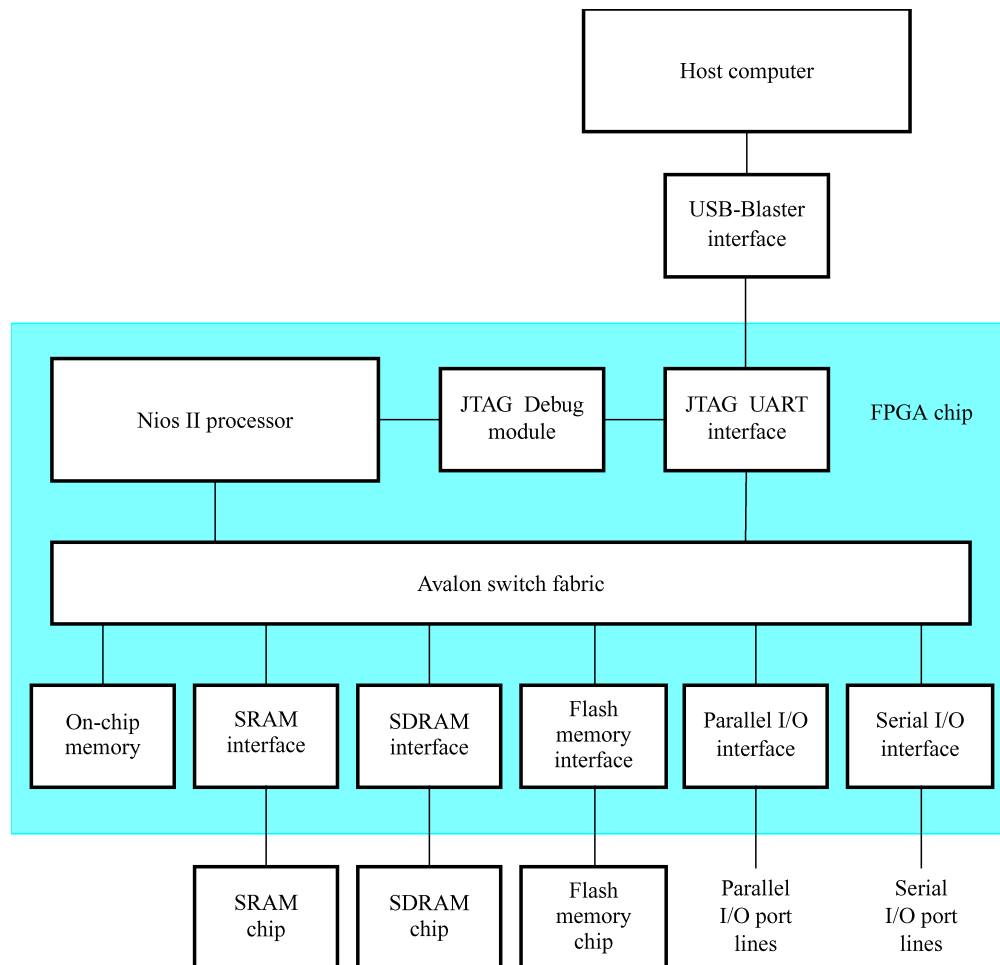


Figure 1. A Nios II system implemented on a DE-series board.

The Nios II processor and the interfaces needed to connect to other chips on the board are implemented in the FPGA chip. These components are interconnected by means of the interconnection network called the Avalon Switch Fabric. Memory blocks in the FPGA device can be used to provide an on-chip memory for the Nios II processor. They can be connected to the processor either directly or through the Avalon network. The SRAM and SDRAM memory chips on the board are accessed through the appropriate interfaces. Input/output interfaces are instantiated to provide connection to the I/O devices used in the system. A special JTAG UART interface is used to connect to the circuitry that provides a Universal Serial Bus (USB) link to the host computer to which the DE-series board is connected. This circuitry and the associated software is called the *USB-Blaster*. Another module, called the JTAG Debug module, is provided to allow the host computer to control the Nios II processor. It makes it possible to perform operations such as downloading programs into memory, starting and stopping execution, setting program breakpoints, and collecting real-time execution trace data.

Since all parts of the Nios II system implemented on the FPGA chip are defined by using a hardware description language, a knowledgeable user could write such code to implement any part of the system. This would be an onerous and time consuming task. Instead, one can use the SOPC Builder or Qsys tools in the Quartus Prime software to implement a desired system simply by choosing the required components and specifying the parameters needed to make each component fit the overall requirements of the system.

4 Overview of Nios II Processor Features

The Nios II processor has a number of features that can be configured by the user to meet the demands of a desired system. The processor can be implemented in three different configurations:

- Nios II/f is a "fast" version designed for superior performance. It has the widest scope of configuration options that can be used to optimize the processor for performance.
- Nios II/s is a "standard" version that requires less resources in an FPGA device as a trade-off for reduced performance.
- Nios II/e is an "economy" version which requires the least amount of FPGA resources, but also has the most limited set of user-configurable features.

The Nios II processor has a Reduced Instruction Set Computer (RISC) architecture. Its arithmetic and logic operations are performed on operands in the general purpose registers. The data is moved between the memory and these registers by means of Load and Store instructions.

The wordlength of the Nios II processor is 32 bits. All registers are 32 bits long. Byte addresses in a 32-bit word are assigned in *little-endian* style, in which the lower byte addresses are used for the less significant bytes (the rightmost bytes) of the word. The Nios II architecture uses separate instruction and data buses, which is often referred to as the *Harvard* architecture.

A Nios II processor may operate in the following modes:

- *Supervisor mode* – allows the processor to execute all instructions and perform all available functions. When the processor is reset, it enters this mode.

- *User mode* – the intent of this mode is to prevent execution of some instructions that should be used for systems purposes only. This mode is available only when the processor is configured to use the Memory Management Unit (MMU) or the Memory Protection Unit (MPU).

Application programs can be run in either the User or Supervisor modes.

5 Register Structure

The Nios II processor has thirty-two 32-bit general-purpose registers, as shown in Figure 2. Some of these registers are intended for a specific purpose and have special names that are recognized by the Assembler.

- Register *r0* is referred to as the *zero* register. It always contains the constant 0. Thus, reading this register returns the value 0, while writing to it has no effect.
- Register *r1* is used by the Assembler as a temporary register; it should not be referenced in user programs
- Registers *r24* and *r29* are used for processing of exceptions; they are not available in User mode
- Registers *r25* and *r30* are used exclusively by the JTAG Debug module
- Registers *r27* and *r28* are used to control the stack used by the Nios II processor
- Register *r31* is used to hold the return address when a subroutine is called

Register	Name	Function
r0	zero	0x00000000
r1	at	Assembler Temporary
r2		
r3		
.	.	.
.	.	.
.	.	.
r23		
r24	et	Exception Temporary (1)
r25	bt	Breakpoint Temporary (2)
r26	gp	Global Pointer
r27	sp	Stack Pointer
r28	fp	Frame Pointer
r29	ea	Exception Return Address (1)
r30	ba	Breakpoint Return Address (2)
r31	ra	Return Address
(1) The register is not available in User mode		
(2) The register is used exclusively by the JTAG Debug module		

Figure 2. General-purpose registers.

Nios II can have a number of 32-bit control registers. The number of registers depends on whether the MMU or the MPU features are implemented. There are six basic control registers, as indicated in Figure 3. The names given in the figure are recognized by the Assembler. The registers are used as follows:

- Register *ctl0* reflects the operating status of the processor. Two bits of this register are always used:
 - *U* is the User/Supervisor mode bit; *U* = 1 for User mode, while *U* = 0 for Supervisor mode.
 - *PIE* is the processor interrupt-enable bit. When *PIE* = 1, the processor may accept external interrupts. When *PIE* = 0, the processor ignores external interrupts.

The rest of the bits (labeled as reserved in the figure) are used when MMU or MPU features are implemented.

- Register *ctl1* holds a saved copy of the status register during exception processing. The bits *EU* and *EPIE* are the saved values of the status bits *U* and *PIE*.
- Register *ctl2* holds a saved copy of the status register during debug break processing. The bits *BU* and *BPIE* are the saved values of the status bits *U* and *PIE*.
- Register *ctl3* is used to enable individual external interrupts. Each bit corresponds to one of the interrupts *irq0* to *irq31*. The value of 1 means that the interrupt is enabled, while 0 means that it is disabled.
- Register *ctl4* indicates which interrupts are pending. The value of a given bit, *ctl4_k*, is set to 1 if the interrupt *irqk* is both active and enabled by having the interrupt-enable bit, *ctl3_k*, set to 1.
- Register *ctl5* holds a value that uniquely identifies the processor in a multiprocessor system.

Register	Name	b_{31} ... b_2	b_1	b_0
ctl0	status	Reserved	U	PIE
ctl1	estatus	Reserved	EU	EPIE
ctl2	bstatus	Reserved	BU	BPIE
ctl3	ienable	Interrupt-enable bits		
ctl4	ipending	Pending-interrupt bits		
ctl5	cpuid	Unique processor identifier		

Figure 3. Basic control registers.

The control registers can be read from and written to by special instructions *rdctl* and *wrctl*, which can be executed only in the supervisor mode.

6 Accessing Memory and I/O Devices

Figure 4 shows how a Nios II processor can access memory and I/O devices. For best performance, the Nios II/f processor can include both instruction and data caches. The caches are implemented in the FPGA memory blocks. Their usage is optional and they are specified (including their size) at the system generation time by using the SOPC

Builder or Qsys. The Nios II/s version can have the instruction cache but not the data cache. The Nios II/e version has neither the instruction nor data cache.

Another way to give the processor fast access to the on-chip memory is by using the *tightly coupled* memory arrangement, in which case the processor accesses the memory via a direct path rather than through the Avalon network. Accesses to a tightly coupled memory bypass the cache memory. There can be one or more tightly coupled instruction and data memories. If the instruction cache is not included in a system, then there must be at least one tightly coupled memory provided for Nios II/f and Nios II/s processors. On-chip memory can also be accessed via the Avalon network.

Off-chip memory devices, such as SRAM, SDRAM, and Flash memory chips are accessed by instantiating the appropriate interfaces. The input/output devices are memory mapped and can be accessed as memory locations.

Data accesses to memory locations and I/O interfaces are performed by means of Load and Store instructions, which cause data to be transferred between the memory and general-purpose registers.

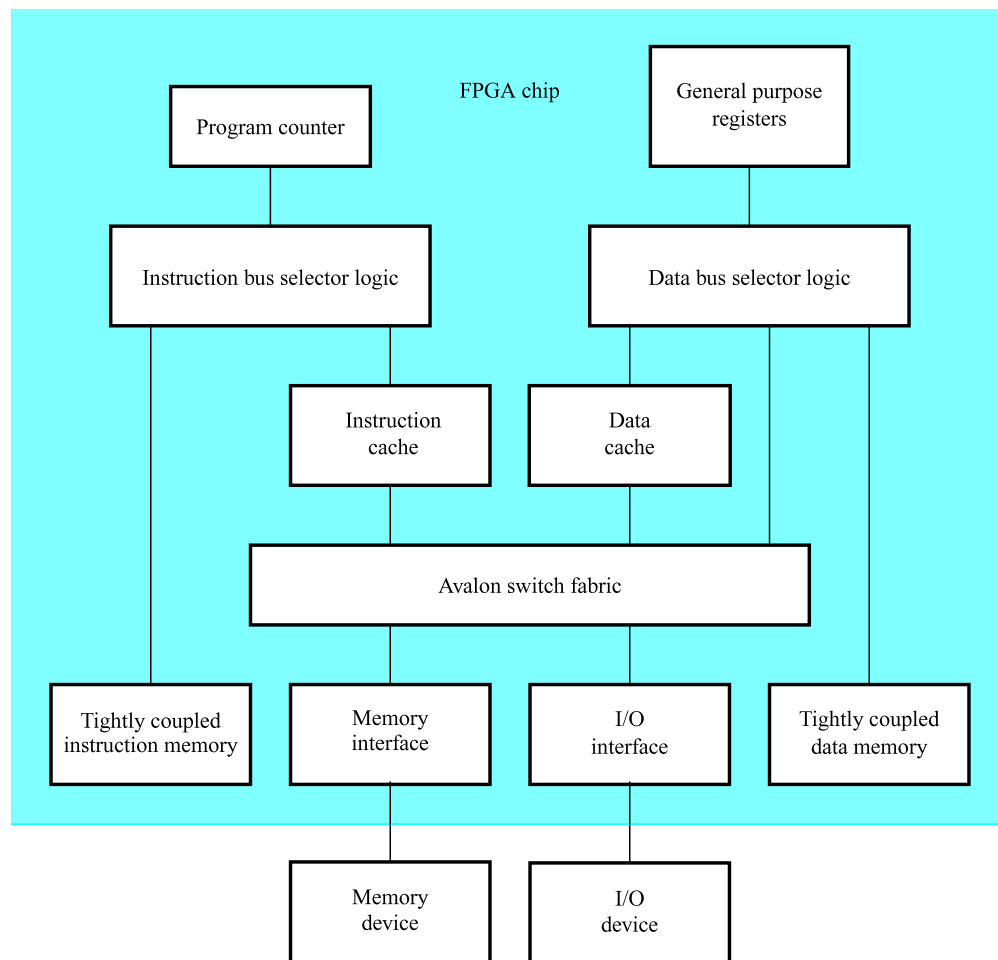


Figure 4. Memory and I/O organization.

7 Addressing

The Nios II processor issues 32-bit addresses. The memory space is byte-addressable. Instructions can read and write *words* (32 bits), *halfwords* (16 bits), or *bytes* (8 bits) of data. Reading or writing to an address that does not correspond to an existing memory or I/O location produces an undefined result.

There are five addressing modes provided:

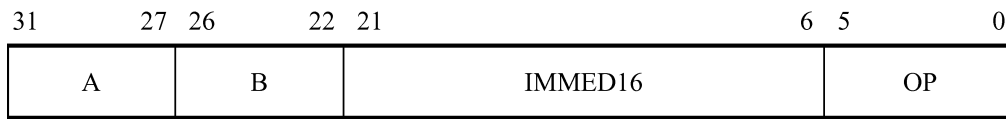
- *Immediate mode* – a 16-bit operand is given explicitly in the instruction. This value may be sign extended to produce a 32-bit operand in instructions that perform arithmetic operations.
- *Register mode* – the operand is in a processor register
- *Displacement mode* – the effective address of the operand is the sum of the contents of a register and a signed 16-bit displacement value given in the instruction
- *Register indirect mode* – the effective address of the operand is the contents of a register specified in the instruction. This is equivalent to the displacement mode where the displacement value is equal to 0.
- *Absolute mode* – a 16-bit absolute address of an operand can be specified by using the displacement mode with register *r0* which always contains the value 0.

8 Instructions

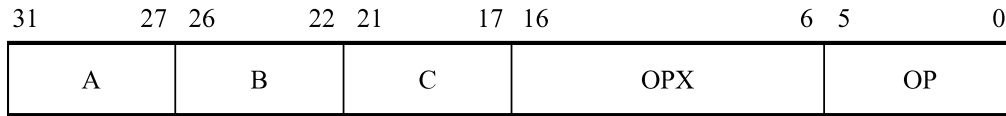
All Nios II instructions are 32-bits long. In addition to machine instructions that are executed directly by the processor, the Nios II instruction set includes a number of *pseudoinstructions* that can be used in assembly language programs. The Assembler replaces each pseudoinstruction by one or more machine instructions.

Figure 5 depicts the three possible instruction formats: I-type, R-type and J-type. In all cases the six bits b_{5-0} denote the OP code. The remaining bits are used to specify registers, immediate operands, or extended OP codes.

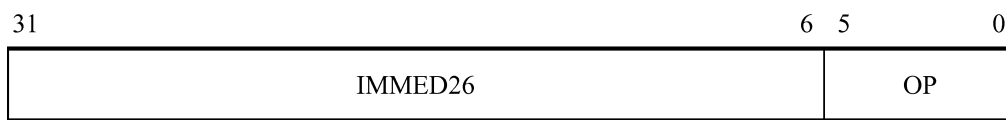
- I-type – Five-bit fields A and B are used to specify general-purpose registers. A 16-bit field IMMED16 provides immediate data which can be sign extended to provide a 32-bit operand.
- R-type – Five-bit fields A, B and C are used to specify general-purpose registers. An 11-bit field OPX is used to extend the OP code.
- J-type – A 26-bit field IMMED26 contains an unsigned immediate value. This format is used only in the Call instruction.



(a) I-type



(b) R-type



(c) J-type

Figure 5. Formats of Nios II instructions.

The following subsections discuss briefly the main features of the Nios II instruction set. For a complete description of the instruction set, including the details of how each instruction is encoded, the reader should consult the *Nios II Processor Reference Handbook*.

8.1 Load and Store Instructions

Load and Store instructions are used to move data between memory (and I/O interfaces) and the general-purpose registers. They are of I-type. For example, the Load Word instruction

`ldw rB, byte_offset(rA)`

determines the effective address of a memory location as the sum of a `byte_offset` value and the contents of register *A*. The 16-bit `byte_offset` value is sign extended to 32 bits. The 32-bit memory operand is loaded into register *B*.

For instance, assume that the contents of register *r4* are 1260_{10} and the `byte_offset` value is 80_{10} . Then, the instruction

`ldw r3, 80(r4)`

loads the 32-bit operand at memory address 1340_{10} into register *r3*.

The Store Word instruction has the format

`stw rB, byte_offset(rA)`

It stores the contents of register *B* into the memory location at the address computed as the sum of the *byte_offset* value and the contents of register *A*.

There are Load and Store instructions that use operands that are only 8 or 16 bits long. They are referred to as Load/Store Byte and Load/Store Halfword instructions, respectively. Such Load instructions are:

- **ldb** (Load Byte)
- **ldbu** (Load Byte Unsigned)
- **ldh** (Load Halfword)
- **ldhu** (Load Halfword Unsigned)

When a shorter operand is loaded into a 32-bit register, its value has to be adjusted to fit into the register. This is done by sign extending the 8- or 16-bit value to 32 bits in the **ldb** and **ldh** instructions. In the **ldbu** and **ldhu** instructions the operand is zero extended.

The corresponding Store instructions are:

- **stb** (Store Byte)
- **sth** (Store Halfword)

The **stb** instruction stores the low byte of register *B* into the memory byte specified by the effective address. The **sth** instruction stores the low halfword of register *B*. In this case the effective address must be halfword aligned.

Each Load and Store instruction has a version intended for accessing locations in I/O device interfaces. These instructions are:

- **ldwio** (Load Word I/O)
- **ldbio** (Load Byte I/O)
- **ldbuio** (Load Byte Unsigned I/O)
- **ldhio** (Load Halfword I/O)
- **ldhuio** (Load Halfword Unsigned I/O)
- **stwio** (Store Word I/O)
- **stbio** (Store Byte I/O)
- **sthio** (Store Halfword I/O)

The difference is that these instructions bypass the cache, if one exists.

8.2 Arithmetic Instructions

The arithmetic instructions operate on the data that is either in the general purpose registers or given as an immediate value in the instruction. These instructions are of R-type or I-type, respectively. They include:

- `add` (Add Registers)
- `addi` (Add Immediate)
- `sub` (Subtract Registers)
- `subi` (Subtract Immediate)
- `mul` (Multiply)
- `muli` (Multiply Immediate)
- `div` (Divide)
- `divu` (Divide Unsigned)

The Add instruction

`add rC, rA, rB`

adds the contents of registers *A* and *B*, and places the sum into register *C*.

The Add Immediate instruction

`addi rB, rA, IMMED16`

adds the contents of register *A* and the sign-extended 16-bit operand given in the instruction, and places the result into register *B*. The addition operation in these instructions is the same for both signed and unsigned operands; there are no condition flags that are set by the operation. This means that when unsigned operands are added, the carry from the most significant bit position has to be detected by executing a separate instruction. Similarly, when signed operands are added, the arithmetic overflow has to be detected separately. The detection of these conditions is discussed in section 8.11.

The Subtract instruction

`sub rC, rA, rB`

subtracts the contents of register *B* from register *A*, and places the result into register *C*. Again, the carry and overflow detection has to be done by using additional instructions, as explained in section 8.11.

The immediate version, `subi`, is a pseudoinstruction implemented as

`addi rB, rA, -IMMED16`

The Multiply instruction

`mul rC, rA, rB`

multiplies the contents of registers *A* and *B*, and places the low-order 32 bits of the product into register *C*. The operands are treated as unsigned numbers. The carry and overflow detection has to be done by using additional instructions. In the immediate version

`muli rB, rA, IMMED16`

the 16-bit immediate operand is sign extended to 32 bits.

The Divide instruction

`div rC, rA, rB`

divides the contents of register *A* by the contents of register *B* and places the integer portion of the quotient into register *C*. The operands are treated as signed integers. The `divu` instruction is performed in the same way except that the operands are treated as unsigned integers.

8.3 Logic Instructions

The logic instructions provide the AND, OR, XOR, and NOR operations. They operate on data that is either in the general purpose registers or given as an immediate value in the instruction. These instructions are of R-type or I-type, respectively.

The AND instruction

`and rC, rA, rB`

performs a bitwise logical AND of the contents of registers *A* and *B*, and stores the result in register *C*. Similarly, the instructions `or`, `xor` and `nor` perform the OR, XOR and NOR operations, respectively.

The AND Immediate instruction

`andi rB, rA, IMMED16`

performs a bitwise logical AND of the contents of register *A* and the IMMED16 operand which is zero-extended to 32 bits, and stores the result in register *B*. Similarly, the instructions `ori`, `xori` and `nori` perform the OR, XOR and NOR operations, respectively.

It is also possible to use the 16-bit immediate operand as the 16 high-order bits in the logic operations, in which case the low-order 16 bits of the operand are zeros. This is accomplished with the instructions:

- `andhi` (AND High Immediate)
- `orhi` (OR High Immediate)
- `xorhi` (XOR High Immediate)

8.4 Move Instructions

The Move instructions copy the contents of one register into another, or they place an immediate value into a register. They are pseudoinstructions implemented by using other instructions. The instruction

```
mov rC, rA
```

copies the contents of register *A* into register *C*. It is implemented as

```
add rC, rA, r0
```

The Move Immediate instruction

```
movi rB, IMMED16
```

sign extends the IMMED16 value to 32 bits and loads it into register *B*. It is implemented as

```
addi rB, r0, IMMED16
```

The Move Unsigned Immediate instruction

```
movui rB, IMMED16
```

zero extends the IMMED16 value to 32 bits and loads it into register *B*. It is implemented as

```
ori rB, r0, IMMED16
```

The Move Immediate Address instruction

```
movia rB, LABEL
```

loads a 32-bit value that corresponds to the address *LABEL* into register *B*. It is implemented as:

```
orhi  rB, r0, %hi(LABEL)
ori   rB, rB, %lo(LABEL)
```

The `%hi(LABEL)` and `%lo(LABEL)` are the Assembler macros which extract the high-order 16 bits and the low-order 16 bits, respectively, of a 32-bit value *LABEL*. The `orhi` instruction sets the high-order bits of register *B*, followed by the `ori` instruction which sets the low-order bits of *B*. Note that two instructions are used because the I-type format provides for only a 16-bit immediate operand.

8.5 Comparison Instructions

The Comparison instructions compare the contents of two registers or the contents of a register and an immediate value, and write either 1 (if true) or 0 (if false) into the result register. They are of R-type or I-type, respectively. These instructions correspond to the equality and relational operators in the C programming language.

The Compare Less Than Signed instruction

```
cmplt rC, rA, rB
```

performs the comparison of signed numbers in registers *A* and *B*, $rA < rB$, and writes a 1 into register *C* if the result is true; otherwise, it writes a 0.

The Compare Less Than Unsigned instruction

```
cmpltu rC, rA, rB
```

performs the same function as the `cmplt` instruction, but it treats the operands as unsigned numbers.

Other instructions of this type are:

- `cmpeq rC, rA, rB` (Comparison $rA == rB$)
- `cmpne rC, rA, rB` (Comparison $rA != rB$)
- `cmpge rC, rA, rB` (Signed comparison $rA \geq rB$)
- `cmpgeu rC, rA, rB` (Unsigned comparison $rA \geq rB$)
- `cmpgt rC, rA, rB` (Signed comparison $rA > rB$)
This is a pseudoinstruction implemented as the `cmplt` instruction by swapping its *rA* and *rB* operands.
- `cmpgtu rC, rA, rB` (Unsigned comparison $rA > rB$)
This is a pseudoinstruction implemented as the `cmpltu` instruction by swapping its *rA* and *rB* operands.

- `cmple rC, rA, rB` (Signed comparison $rA \leq rB$)
This is a pseudoinstruction implemented as the `cmpge` instruction by swapping its `rA` and `rB` operands.
- `cmpleu rC, rA, rB` (Unsigned comparison $rA \leq rB$)
This is a pseudoinstruction implemented as the `cmpgeu` instruction by swapping its `rA` and `rB` operands.

The immediate versions of the Comparison instructions involve an immediate operand. For example, the Compare Less Than Signed Immediate instruction

`cmplti rB, rA, IMMED16`

compares the signed number in register *A* with the sign-extended immediate operand. It writes a 1 into register *B* if $rA < \text{IMMED16}$; otherwise, it writes a 0.

The Compare Less Than Unsigned Immediate instruction

`cmpltui rB, rA, IMMED16`

compares the unsigned number in register *A* with the zero-extended immediate operand. It writes a 1 into register *B* if $rA < \text{IMMED16}$; otherwise, it writes a 0.

Other instructions of this type are:

- `cmpeqi rB, rA, IMMED16` (Comparison $rA == \text{IMMED16}$)
- `cmpnei rB, rA, IMMED16` (Comparison $rA != \text{IMMED16}$)
- `cmpgei rB, rA, IMMED16` (Signed comparison $rA \geq \text{IMMED16}$)
- `cmpgeui rB, rA, IMMED16` (Unsigned comparison $rA \geq \text{IMMED16}$)
- `cmpgti rB, rA, IMMED16` (Signed comparison $rA > \text{IMMED16}$)
This is a pseudoinstruction which is implemented by using the `cmpgei` instruction with an immediate value $\text{IMMED16} + 1$.
- `cmpgtui rB, rA, IMMED16` (Unsigned comparison $rA > \text{IMMED16}$)
This is a pseudoinstruction which is implemented by using the `cmpgeui` instruction with an immediate value $\text{IMMED16} + 1$.
- `cmplei rB, rA, IMMED16` (Signed comparison $rA \leq \text{IMMED16}$)
This is a pseudoinstruction which is implemented by using the `cmplti` instruction with an immediate value $\text{IMMED16} + 1$.
- `cmpleui rB, rA, IMMED16` (Unsigned comparison $rA \leq \text{IMMED16}$)
This is a pseudoinstruction which is implemented by using the `cmpltui` instruction with an immediate value $\text{IMMED16} + 1$.

8.6 Shift Instructions

The Shift instructions shift the contents of a register either to the right or to the left. They are of R-type. They correspond to the shift operators, `>>` and `<<`, in the C programming language. These instructions are:

- `srl rC, rA, rB` (Shift Right Logical)
- `srl rC, rA, IMMED5` (Shift Right Logical Immediate)
- `sra rC, rA, rB` (Shift Right Arithmetic)
- `sra rC, rA, IMMED5` (Shift Right Arithmetic Immediate)
- `sll rC, rA, rB` (Shift Left Logical)
- `sll rC, rA, IMMED5` (Shift Left Logical Immediate)

The `srl` instruction shifts the contents of register *A* to the right by the number of bit positions specified by the five least-significant bits (number in the range 0 to 31) in register *B*, and stores the result in register *C*. The vacated bits on the left side of the shifted operand are filled with 0s.

The `srl` instruction shifts the contents of register *A* to the right by the number of bit positions specified by the five-bit unsigned value, `IMMED5`, given in the instruction.

The `sra` and `sra` instructions perform the same actions as the `srl` and `srl` instructions, except that the sign bit, rA_{31} , is replicated into the vacated bits on the left side of the shifted operand.

The `sll` and `sll` instructions are similar to the `srl` and `srl` instructions, but they shift the operand in register *A* to the left and fill the vacated bits on the right side with 0s.

8.7 Rotate Instructions

There are three Rotate instructions, which use the R-type format:

- `ror rC, rA, rB` (Rotate Right)
- `rol rC, rA, rB` (Rotate Left)
- `rol rC, rA, IMMED5` (Rotate Left Immediate)

The `ror` instruction rotates the bits of register *A* in the left-to-right direction by the number of bit positions specified by the five least-significant bits (number in the range 0 to 31) in register *B*, and stores the result in register *C*.

The `rol` instruction is similar to the `ror` instruction, but it rotates the operand in the right-to-left direction.

The `rol` instruction rotates the bits of register *A* in the right-to-left direction by the number of bit positions specified by the five-bit unsigned value, `IMMED5`, given in the instruction, and stores the result in register *C*.

8.8 Branch and Jump Instructions

The flow of execution of a program can be changed by executing Branch or Jump instructions. It may be changed either unconditionally or conditionally.

The Jump instruction

jmp rA

transfers execution unconditionally to the address contained in register A.

The Unconditional Branch instruction

br LABEL

transfers execution unconditionally to the instruction at address *LABEL*. This is an instruction of I-type, in which a 16-bit immediate value (interpreted as a signed number) specifies the offset to the branch target instruction. The offset is the distance in bytes from the instruction that immediately follows *br* to the address *LABEL*.

Conditional transfer of execution is achieved with the Conditional Branch instructions, which compare the contents of two registers and cause a branch if the result is true. These instructions are of I-type and the offset is determined as explained above for the *br* instruction.

The Branch if Less Than Signed instruction

blt rA, rB, LABEL

performs the comparison $rA < rB$, treating the contents of the registers as signed numbers.

The Branch if Less Than Unsigned instruction

bltu rA, rB, LABEL

performs the comparison $rA < rB$, treating the contents of the registers as unsigned numbers.

The other Conditional Branch instructions are:

- beq rA, rB, LABEL (Comparison $rA == rB$)
- bne rA, rB, LABEL (Comparison $rA != rB$)
- bge rA, rB, LABEL (Signed comparison $rA \geq rB$)
- bgeu rA, rB, LABEL (Unsigned comparison $rA \geq rB$)

- **bgt rA, rB, LABEL** (Signed comparison $rA > rB$)
This is a pseudoinstruction implemented as the **blt** instruction by swapping the register operands.
- **bgtu rA, rB, LABEL** (Unsigned comparison $rA > rB$)
This is a pseudoinstruction implemented as the **bltu** instruction by swapping the register operands.
- **ble rA, rB, LABEL** (Signed comparison $rA \leq rB$)
This is a pseudoinstruction implemented as the **bge** instruction by swapping the register operands.
- **bleu rA, rB, LABEL** (Unsigned comparison $rA \leq rB$)
This is a pseudoinstruction implemented as the **bgeu** instruction by swapping the register operands.

8.9 Subroutine Linkage Instructions

Nios II has two instructions for calling subroutines. The Call Subroutine instruction

call LABEL

is of J-type, which includes a 26-bit unsigned immediate value (IMMED26). The instruction saves the return address (which is the address of the next instruction) in register *r31*. Then, it transfers control to the instruction at address *LABEL*. This address is determined by concatenating the four high-order bits of the Program Counter with the IMMED26 value as follows

$$\text{Jump address} = PC_{31-28} : \text{IMMED26} : 00$$

Note that the two least-significant bits are 0 because Nios II instructions must be aligned on word boundaries.

The Call Subroutine in Register instruction

callr rA

is of R-type. It saves the return address in register *r31* and then transfers control to the instruction at the address contained in register *A*.

Return from a subroutine is performed with the instruction

ret

This instruction transfers execution to the address contained in register *r31*.

8.10 Control Instructions

The Nios II control registers can be read and written by special instructions. The Read Control Register instruction

rdctl rC, ctlN

copies the contents of control register *ctlN* into register *C*.

The Write Control Register instruction

```
wrcctl ctlN, rA
```

copies the contents of register *A* into the control register *ctlN*.

There are two instructions provided for dealing with exceptions: **trap** and **eret**. They are similar to the **call** and **ret** instructions, but they are used for exceptions. Their use is discussed in section 11.

The instructions **break** and **bret** generate breaks and return from breaks. They are used exclusively by the software debugging tools.

The Nios II cache memories are managed with the instructions: **flushd** (Flush Data Cache Line), **flushi** (Flush Instruction Cache Line), **initd** (Initialize Data Cache Line), and **initi** (Initialize Instruction Cache Line). These instructions are discussed in section 12.1.

8.11 Carry and Overflow Detection

As pointed out in section 8.2, the Add and Subtract instructions perform the corresponding operations in the same way for both signed and unsigned operands. The possible carry and arithmetic overflow conditions are not detected, because Nios II does not contain condition flags that might be set as a result. These conditions can be detected by using additional instructions.

Consider the Add instruction

```
add rC, rA, rB
```

Having executed this instruction, a possible occurrence of a carry out of the most-significant bit (C_{31}) can be detected by checking whether the unsigned sum (in register *C*) is less than one of the unsigned operands. For example, if this instruction is followed by the instruction

```
cmpltu rD, rC, rA
```

then the carry bit will be written into register *D*.

Similarly, if a branch is required when a carry occurs, this can be accomplished as follows:

```
add rC, rA, rB
bltu rC, rA, LABEL
```

A test for arithmetic overflow can be done by checking the signs of the summands and the resulting sum. An overflow occurs if two positive numbers produce a negative sum, or if two negative numbers produce a positive sum. Using this approach, the overflow condition can control a conditional branch as follows:

```

add   rC, rA, rB      /* The required Add operation */
xor    rD, rC, rA      /* Compare signs of sum and rA */
xor    rE, rC, rB      /* Compare signs of sum and rB */
and    rD, rD, rE      /* Set  $D_{31} = 1$  if  $((A_{31} == B_{31}) != C_{31})$  */
blt    rD, r0, LABEL  /* Branch if overflow occurred */

```

A similar approach can be used to detect the carry and overflow conditions in Subtract operations. A carry out of the most-significant bit of the resulting difference can be detected by checking whether the first operand is less than the second operand. Thus, the carry can be used to control a conditional branch as follows:

```

sub    rC, rA, rB
bltu   rA, rB, LABEL

```

The arithmetic overflow in a Subtract operation is detected by comparing the sign of the generated difference with the signs of the operands. Overflow occurs if the operands in registers *A* and *B* have different signs, and the sign of the difference in register *C* is different than the sign of *A*. Thus, a conditional branch based on the arithmetic overflow can be achieved as follows:

```

sub    rC, rA, rB      /* The required Subtract operation */
xor    rD, rA, rB      /* Compare signs of rA and rB */
xor    rE, rA, rC      /* Compare signs of rA and rC */
and    rD, rD, rE      /* Set  $D_{31} = 1$  if  $((A_{31} != B_{31}) \&\& (A_{31} != C_{31}))$  */
blt    rD, r0, LABEL  /* Branch if overflow occurred */

```

9 Assembler Directives

The Nios II Assembler conforms to the widely used GNU Assembler, which is software available in the public domain. Thus, the GNU Assembler directives can be used in Nios II programs. Assembler directives begin with a period. We describe some of the more frequently used assembler directives below.

`.ascii "string"...`

A string of ASCII characters is loaded into consecutive byte addresses in the memory. Multiple strings, separated by commas, can be specified.

`.asciz "string"...`

This directive is the same as `.ascii`, except that each string is followed (terminated) by a zero byte.

`.byte expressions`

Expressions separated by commas are specified. Each expression is assembled into the next byte. Examples of expressions are: 8, 5 + LABEL, and K - 6.

.data

Identifies the data that should be placed in the data section of the memory. The desired memory location for the data section can be specified in the Intel FPGA Monitor Program's system configuration window.

.end

Marks the end of the source code file; everything after this directive is ignored by the assembler.

.equ *symbol, expression*

Sets the value of *symbol* to *expression*.

.global *symbol*

Makes *symbol* visible outside the assembled object file.

.hword *expressions*

Expressions separated by commas are specified. Each expression is assembled into a 16-bit number.

.include "*filename*"

Provides a mechanism for including supporting files in a source program.

.org *new-lc*

Advances the location counter by *new-lc*, where *new-lc* is used as an offset from the starting location specified in the Intel FPGA Monitor Program's system configuration window. The **.org** directive may only increase the location counter, or leave it unchanged; it cannot move the location counter backwards.

.skip *size*

Emits the number of bytes specified in *size*; the value of each byte is zero.

.text

Identifies the code that should be placed in the text section of the memory. The desired memory location for the text section can be specified in the Intel FPGA Monitor Program's system configuration window.

.word *expressions*

Expressions separated by commas are specified. Each expression is assembled into a 32-bit number.

10 Example Program

As an illustration of Nios II instructions and assembler directives, Figure 6 gives an assembly language program that computes a dot product of two vectors, *A* and *B*. The vectors have *n* elements. The required computation is

$$\text{Dot product} = \sum_{i=0}^{n-1} A(i) \times B(i)$$

The vectors are stored in memory locations at addresses *AVECTOR* and *BVECTOR*, respectively. The number of elements, *n*, is stored in memory location *N*. The computed result is written into memory location *DOT_PRODUCT*. Each vector element is assumed to be a signed 32-bit number.

```
.include "nios_macros.s"
.global _start
_start:
    movia r2, AVECTOR          /* Register r2 is a pointer to vector A */
    movia r3, BVECTOR          /* Register r3 is a pointer to vector B */
    movia r4, N
    ldw r4, 0(r4)              /* Register r4 is used as the counter for loop iterations */
    add r5, r0, r0             /* Register r5 is used to accumulate the product */
LOOP: ldw r6, 0(r2)            /* Load the next element of vector A */
    ldw r7, 0(r3)              /* Load the next element of vector B */
    mul r8, r6, r7             /* Compute the product of next pair of elements */
    add r5, r5, r8             /* Add to the sum */
    addi r2, r2, 4              /* Increment the pointer to vector A */
    addi r3, r3, 4              /* Increment the pointer to vector B */
    subi r4, r4, 1             /* Decrement the counter */
    bgt r4, r0, LOOP           /* Loop again if not finished */
    stw r5, DOT_PRODUCT(r0)    /* Store the result in memory */
STOP: br STOP
N:
.word 6                       /* Specify the number of elements */
AVECTOR:
.word 5, 3, -6, 19, 8, 12     /* Specify the elements of vector A */
BVECTOR:
.word 2, 14, -3, 2, -5, 36    /* Specify the elements of vector B */
DOT_PRODUCT:
.skip 4
```

Figure 6. A program that computes the dot product of two vectors.

Note that the program ends by continuously looping on the last Branch instruction. If instead we wanted to pass control to debugging software, we could replace this **br** instruction with the **break** instruction.

The program includes the assembler directive

```
.include "nios_macros.s"
```

which informs the Assembler to use some macro commands that have been created for the Nios II processor. In this program, the macro used converts the `movia` pseudoinstruction into two OR instructions as explained in section 8.4.

The directive

```
.global _start
```

indicates to the Assembler that the label `_start` is accessible outside the assembled object file. This label is the default label we use to indicate to the Linker program the beginning of the application program.

The program includes some sample data. It illustrates how the `.word` directive can be used to load data items into memory. The memory locations involved are those that follow the location occupied by the `br` instruction. Since we have not explicitly specified the starting address of the program itself, the assembled code will be loaded in memory starting at address 0.

To execute the program in Figure 6 on an Intel's DE-series board, it is necessary to implement a Nios II processor and its memory (which can be just the on-chip memory of the FPGA). Since the program includes the Multiply instruction, it cannot be executed on the economy version of the processor, because Nios II/e does not support the `mul` instruction. Either Nios II/s or Nios II/f processors can be used.

The tutorials *Introduction to the Intel SOPC Builder* and *Introduction to the Intel Qsys System Integration Tool* explain how a Nios II system can be implemented. The tutorial *Intel FPGA Monitor Program* explains how an application program can be assembled, downloaded and executed on a DE-series board.

11 Exception Processing

An *exception* in the normal flow of program execution can be caused by:

- Software trap
- Hardware interrupt
- Unimplemented instruction

In response to an exception the Nios II processor automatically performs the following actions:

1. Saves the existing processor status information by copying the contents of the *status* register (*ctl0*) into the *estatus* register (*ctl1*)
2. Clears the *U* bit in the *status* register, to ensure that the processor is in the Supervisor mode
3. Clears the *PIE* bit in the *status* register, thus disabling the additional external processor interrupts

4. Writes the address of the instruction after the exception into the *ea* register (*r29*)
5. Transfers execution to the address of the *exception handler* which determines the cause of the exception and dispatches an appropriate *exception routine* to respond to the exception

The address of the exception handler is specified at system generation time using the SOPC Builder or Qsys tool, and it cannot be changed by software at run time. This address can be provided by the designer; otherwise, the default address is 20_{16} from the starting address of the main memory. For example, if the memory starts at address 0, then the default address of the exception handler is 0x00000020.

11.1 Software Trap

A software exception occurs when a **trap** instruction is encountered in a program. This instruction saves the address of the next instruction in the *ea* register (*r29*). Then, it disables interrupts and transfers execution to the exception handler.

In the exception-service routine the last instruction is **eret** (Exception Return), which returns execution control to the instruction that follows the **trap** instruction that caused the exception. The return address is given by the contents of register *ea*. The **eret** instruction restores the previous status of the processor by copying the contents of the *estatus* register into the *status* register.

A common use of the software trap is to transfer control to a different program, such as an operating system.

11.2 Hardware Interrupts

Hardware interrupts can be raised by external sources, such as I/O devices, by asserting one of the processor's 32 interrupt-request inputs, *irq0* through *irq31*. An interrupt is generated only if the following three conditions are true:

- The *PIE* bit in the *status* register is set to 1
- An interrupt-request input, *irqk*, is asserted
- The corresponding interrupt-enable bit, *ctl3_k*, is set to 1

The contents of the *ipending* register (*ctl4*) indicate which interrupt requests are pending. An exception routine determines which of the pending interrupts has the highest priority, and transfers control to the corresponding *interrupt-service routine*.

Upon completion of the interrupt-service routine, the execution control is returned to the interrupted program by means of the **eret** instruction, as explained above. However, since an external interrupt request is handled without first completing the instruction that is being executed when the interrupt occurs, the interrupted instruction must be re-executed upon return from the interrupt-service routine. To achieve this, the interrupt-service routine has to adjust the contents of the *ea* register which are at this time pointing to the next instruction of the interrupted program. Hence, the value in the *ea* register has to be decremented by 4 prior to executing the **eret** instruction.

11.3 Unimplemented Instructions

This exception occurs when the processor encounters a valid instruction that is not implemented in hardware. This may be the case with instructions such as `mul` and `div`. The exception handler may call a routine that emulates the required operation in software.

11.4 Determining the Type of Exception

When an exception occurs, the exception-handling routine has to determine what type of exception has occurred. The order in which the exceptions should be checked is:

1. Read the *ipending* register to see if a hardware interrupt has occurred; if so, then go to the appropriate interrupt-service routine.
2. Read the instruction that was being executed when the exception occurred. The address of this instruction is the value in the *ea* register minus 4. If this is the `trap` instruction, then go to the software-trap-handling routine.
3. Otherwise, the exception is due to an unimplemented instruction.

11.5 Exception Processing Example

The following example illustrates the Nios II code needed to deal with a hardware interrupt. We will assume that an I/O device raises an interrupt request on the interrupt-request input *irq1*. Also, let the exception handler start at address 0x020, and the interrupt-service routine for the *irq1* request start at address 0x0100.

Figure 7 shows a portion of the code that can be used for this purpose. The exception handler first determines the type of exception that has occurred. Having determined that there is a hardware interrupt request, it finds the specific interrupt by examining the bits of the *et* register which has a copy of control register *ctl4*. If bit *et₁* is equal to 1, then the the interrupt-service routine EXT_IRQ1 is executed. Otherwise, it is necessary to check for other possible interrupts.


```

.org      0x20
/* Exception handler */
    rdctl  et, ipending          /* Check if external interrupt occurred */
    beq    et, r0, OTHER_EXCEPTIONS /* If zero, check exceptions */
    subi   ea, ea, 4             /* Hardware interrupt, decrement ea to execute the interrupted */
                                   /* instruction upon return to main program */

    andi   r13, et, 2            /* Check if irq1 asserted */
    beq    r13, r0, OTHER_INTERRUPTS /* If not, check other external interrupts */
    call   EXT_IRQ1             /* If yes, go to IRQ1 service routine */
OTHER_INTERRUPTS:
/* Instructions that check for other hardware interrupts should be placed here */
    br     END_HANDLER          /* Done with hardware interrupts */
OTHER_EXCEPTIONS:
/* Instructions that check for other types of exceptions should be placed here */
END_HANDLER:
    eret                        /* Return from exception */
.org      0x100
/* Interrupt-service routine for the desired hardware interrupt */
EXT_IRQ1:
/* Instructions that handle the irq1 interrupt request should be placed here */
    ret    /* Return from the interrupt-service routine */

```

Figure 7. Code used to handle a hardware interrupt.

Note that in Figure 7 we are using register *r13* in the process of testing whether the bit *irq1* is set to 1. In a practical application program this register may also be used for some other purpose, in which case its contents should first be saved on the stack and later restored prior to returning from the exception handler.

12 Cache Memory

As shown in Figure 4, a Nios II system can include instruction and data caches, which are implemented in the memory blocks in the FPGA chip. The caches can be specified when a system is being designed by using the SOPC Builder or Qsys software. Inclusion of caches improves the performance of a Nios II system significantly, particularly when most of the main memory is provided by an external SDRAM chip, as is the case with Intel's DE-series boards. Both instruction and data caches are direct-mapped.

The instruction cache can be implemented in the fast and standard versions of the Nios II processor systems. It is organized in 8 words per cache line, and its size is a user-selectable design parameter.

The data cache can be implemented only with the Nios II/f processor. It has a configurable line size of 4, 16 or 32 bytes per cache line. Its overall size is also a user-selectable design parameter.

12.1 Cache Management

Cache management is handled by software. For this purpose the Nios II instruction set includes the following instructions:

- **initd IMMED16(rA)** (Initialize data-cache line)
Invalidates the line in the data cache that is associated with the address determined by adding the sign-extended value IMMED16 and the contents of register *rA*.
- **initi rA** (Initialize instruction-cache line)
Invalidates the line in the instruction cache that is associated with the address contained in register *rA*.
- **flushd IMMED16(rA)** (Flush data-cache line)
Computes the effective address by adding the sign-extended value IMMED16 and the contents of register *rA*. Then, it identifies the cache line associated with this effective address, writes any dirty data in the cache line back to memory, and invalidates the cache line.
- **flushi rA** (Flush instruction-cache line)
Invalidates the line in the instruction cache that is associated with the address contained in register *rA*.

12.2 Cache Bypass Methods

A Nios II processor uses its data cache in the standard manner. But, it also allows the cache to be bypassed in two ways. As mentioned in section 8.1, the Load and Store instructions have a version intended for accessing I/O devices, where the effective address specifies a location in an I/O device interface. These instructions are: **ldwio**, **ldbio**, **lduio**, **ldhio**, **ldhuio**, **stwio**, **stbio**, and **sthio**. They bypass the data cache.

Another way of bypassing the data cache is by using bit 31 of an address as a tag that indicates whether the processor should transfer the data to/from the cache, or bypass it. This feature is available only in the Nios II/f processor.

Mixing cached and uncached accesses has to be done with care. Otherwise, the coherence of the cached data may be compromised.

13 Tightly Coupled Memory

As explained in section 6, a Nios II processor can access the memory blocks in the FPGA chip as a *tightly coupled memory*. This arrangement does not use the Avalon network. Instead, the tightly coupled memory is connected directly to the processor.

Data in the tightly coupled memory is accessed using the normal Load and Store instructions, such as **ldw** or **stw**. The Nios II control circuits determine if the address of a memory location is in the tightly coupled memory. Accesses to the tightly coupled memory bypass the caches. For the address span of the tightly coupled memory, the processor operates as if caches were not present.

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