8-bit Atmel tinyAVR Microcontroller with 4K Bytes In-System Programmable Flash

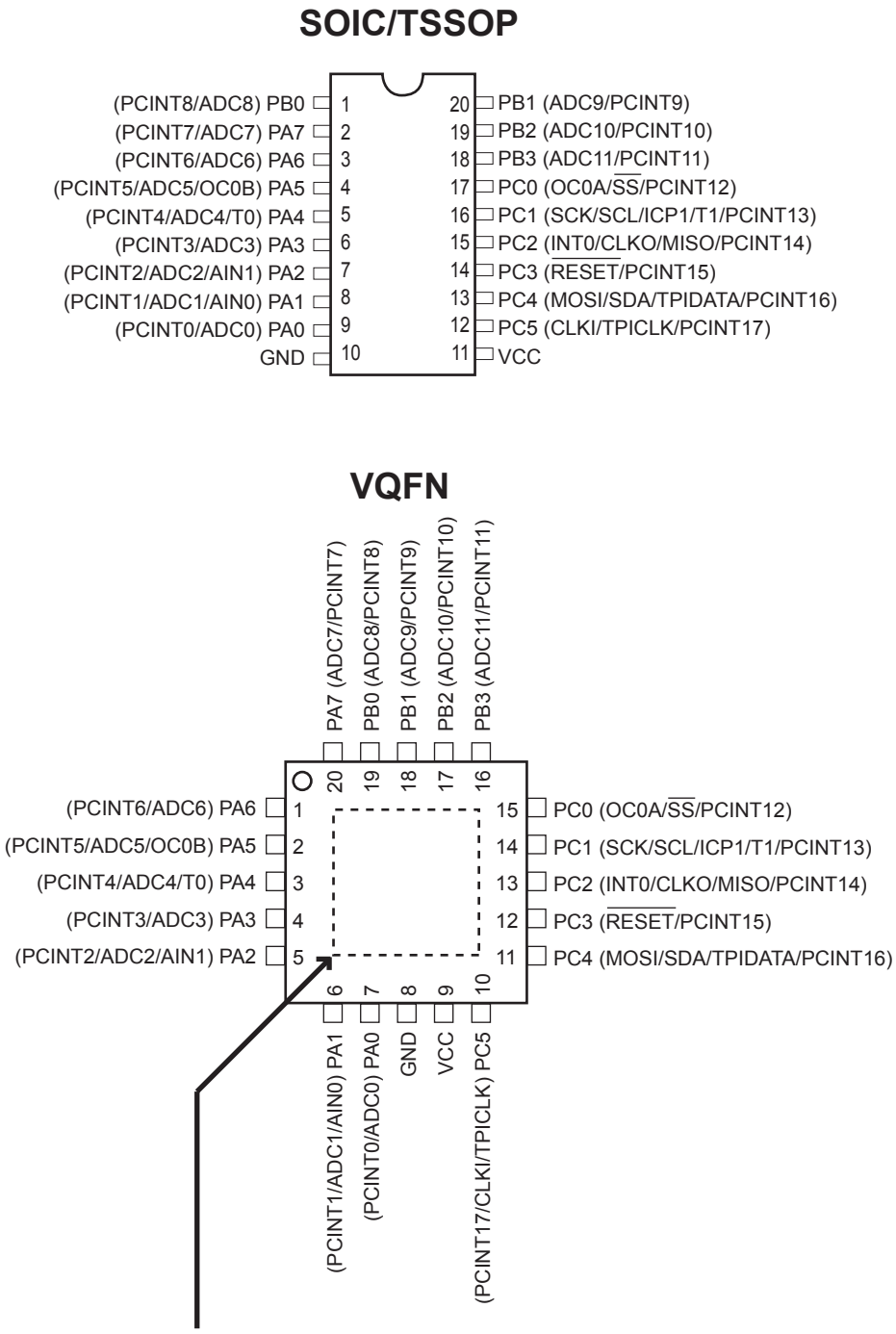
ATtiny40

Features

- High Performance, Low Power AVR® 8-Bit Microcontroller
- Advanced RISC Architecture
  - 54 Powerful Instructions – Most Single Clock Cycle Execution
  - 16 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 12 MIPS Throughput at 12 MHz
- Non-volatile Program and Data Memories
  - 4K Bytes of In-System Programmable Flash Program Memory
  - 256 Bytes Internal SRAM
  - Flash Write/Erase Cycles: 10,000
  - Data Retention: 20 Years at 85°C / 100 Years at 25°C
- Peripheral Features
  - One 8-bit Timer/Counter with Two PWM Channels
  - One 8/16-bit Timer/Counter
  - 10-bit Analog to Digital Converter
    - 12 Single-Ended Channels
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
  - Master/Slave SPI Serial Interface
  - Slave TWI Serial Interface
- Special Microcontroller Features
  - In-System Programmable
  - External and Internal Interrupt Sources
  - Low Power Idle, ADC Noise Reduction, Stand-by and Power-down Modes
  - Enhanced Power-on Reset Circuit
  - Internal Calibrated Oscillator
- I/O and Packages
  - 20-pin SOIC: 18 Programmable I/O Lines
  - 20-pin TSSOP: 18 Programmable I/O Lines
  - 20-pad VQFN: 18 Programmable I/O Lines
- Operating Voltage:
  - 1.8 – 5.5V
- Programming Voltage:
  - 5V
- Speed Grade
  - 0 – 4 MHz @ 1.8 – 5.5V
  - 0 – 8 MHz @ 2.7 – 5.5V
  - 0 – 12 MHz @ 4.5 – 5.5V
- Industrial Temperature Range
- Low Power Consumption
  - Active Mode:
    - 200 µA at 1 MHz and 1.8V
  - Idle Mode:
    - 25 µA at 1 MHz and 1.8V
  - Power-down Mode:
    - < 0.1 µA at 1.8V

1. Pin Configurations

Figure 1-1. Pinout of ATtiny40



NOTE: Bottom pad should be soldered to ground.

1.1 Pin Description

1.1.1 VCC

Supply voltage.

1.1.2 GND

Ground.

1.1.3 $\overline{\text{RESET}}$

Reset input. A low level on this pin for longer than the minimum pulse length will generate a reset, even if the clock is not running and provided the reset pin has not been disabled. The minimum pulse length is given in Table 20-4 on page 155. Shorter pulses are not guaranteed to generate a reset.

The reset pin can also be used as a (weak) I/O pin.

1.1.4 Port A (PA7:PA0)

Port A is a 8-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port A output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port A pins that are externally pulled low will source current if the pull-up resistors are activated. The Port A pins are tri-stated when a reset condition becomes active, even if the clock is not running.

Port A has alternate functions as analog inputs for the ADC, analog comparator and pin change interrupt as described in “Alternate Port Functions” on page 47.

1.1.5 Port B (PB3:PB0)

Port B is a 4-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port B output buffers have symmetrical drive characteristics with both high sink and source capability. As inputs, Port B pins that are externally pulled low will source current if the pull-up resistors are activated. The Port B pins are tri-stated when a reset condition becomes active, even if the clock is not running.

The port also serves the functions of various special features of the ATtiny40, as listed on page 37.

1.1.6 Port C (PC5:PC0)

Port C is a 6-bit bi-directional I/O port with internal pull-up resistors (selected for each bit). The Port C output buffers have symmetrical drive characteristics with both high sink and source capability except PC3 which has the $\overline{\text{RESET}}$ capability. To use pin PC3 as an I/O pin, instead of RESET pin, program (‘0’) RSTDISBL fuse. As inputs, Port C pins that are externally pulled low will source current if the pull-up resistors are activated. The Port C pins are tri-stated when a reset condition becomes active, even if the clock is not running.

Port C has alternate functions as analog inputs for the ADC, analog comparator and pin change interrupt as described in “Alternate Port Functions” on page 47.

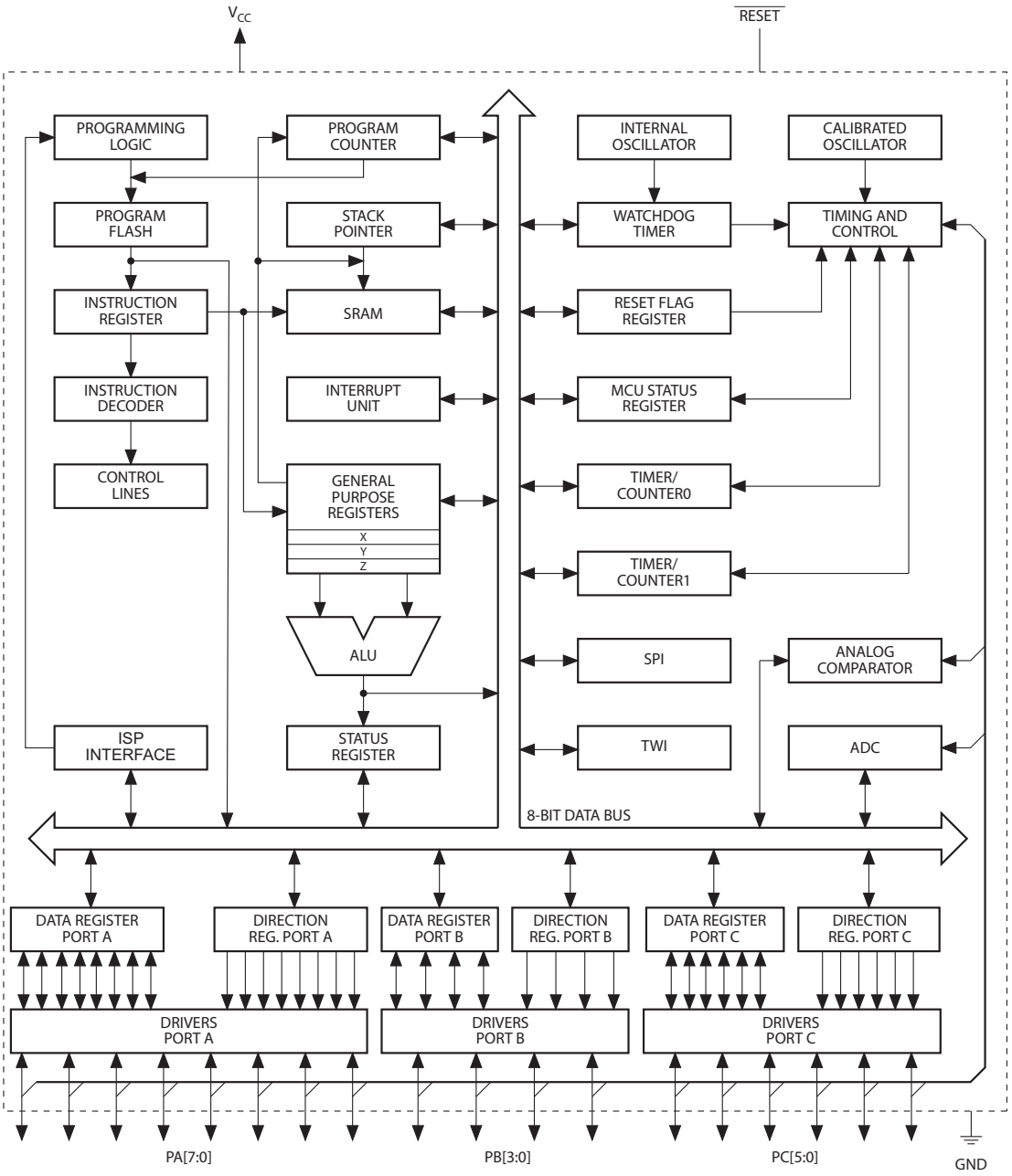
The port also serves the functions of various special features of the ATtiny40, as listed on page 37.

2. Overview

ATtiny40 is a low-power CMOS 8-bit microcontroller based on the compact AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATtiny40 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed.

Figure 2-1. Block Diagram

The AVR core combines a rich instruction set with 16 general purpose working registers and system registers. All registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be



accessed in one single instruction executed in one clock cycle. The resulting architecture is compact and code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers.

The ATtiny40 provides the following features: 4K bytes of In-System Programmable Flash, 256 bytes of SRAM, twelve general purpose I/O lines, 16 general purpose working registers, an 8-bit Timer/Counter with two PWM channels, a 8/16-bit Timer/Counter, Internal and External Interrupts, an eight-channel, 10-bit ADC, a programmable Watchdog Timer with internal oscillator, a slave two-wire interface, a master/slave serial peripheral interface, an internal calibrated oscillator, and four software selectable power saving modes.

Idle mode stops the CPU while allowing the Timer/Counter, ADC, Analog Comparator, SPI, TWI, and interrupt system to continue functioning. ADC Noise Reduction mode minimizes switching noise during ADC conversions by stopping the CPU and all I/O modules except the ADC. In Power-down mode registers keep their contents and all chip functions are disabled until the next interrupt or hardware reset. In Standby mode, the oscillator is running while the rest of the device is sleeping, allowing very fast start-up combined with low power consumption.

The device is manufactured using Atmel's high density non-volatile memory technology. The on-chip, in-system programmable Flash allows program memory to be re-programmed in-system by a conventional, non-volatile memory programmer.

The ATtiny40 AVR is supported by a suite of program and system development tools, including macro assemblers and evaluation kits.

3. General Information

3.1 Resources

A comprehensive set of drivers, application notes, data sheets and descriptions on development tools are available for download at http://www.atmel.com/avr.

3.2 Code Examples

This documentation contains simple code examples that briefly show how to use various parts of the device. These code examples assume that the part specific header file is included before compilation. Be aware that not all C compiler vendors include bit definitions in the header files and interrupt handling in C is compiler dependent. Please confirm with the C compiler documentation for more details.

3.3 Capacitive Touch Sensing

Atmel QTouch Library provides a simple to use solution for touch sensitive interfaces on Atmel AVR microcontrollers. The QTouch Library includes support for QTouch® and QMatrix® acquisition methods.

Touch sensing is easily added to any application by linking the QTouch Library and using the Application Programming Interface (API) of the library to define the touch channels and sensors. The application then calls the API to retrieve channel information and determine the state of the touch sensor.

The QTouch Library is free and can be downloaded from the Atmel website. For more information and details of implementation, refer to the QTouch Library User Guide – also available from the Atmel website.

3.4 Data Retention

Reliability Qualification results show that the projected data retention failure rate is much less than 1 PPM over 20 years at 85°C or 100 years at 25°C.

3.5 Disclaimer

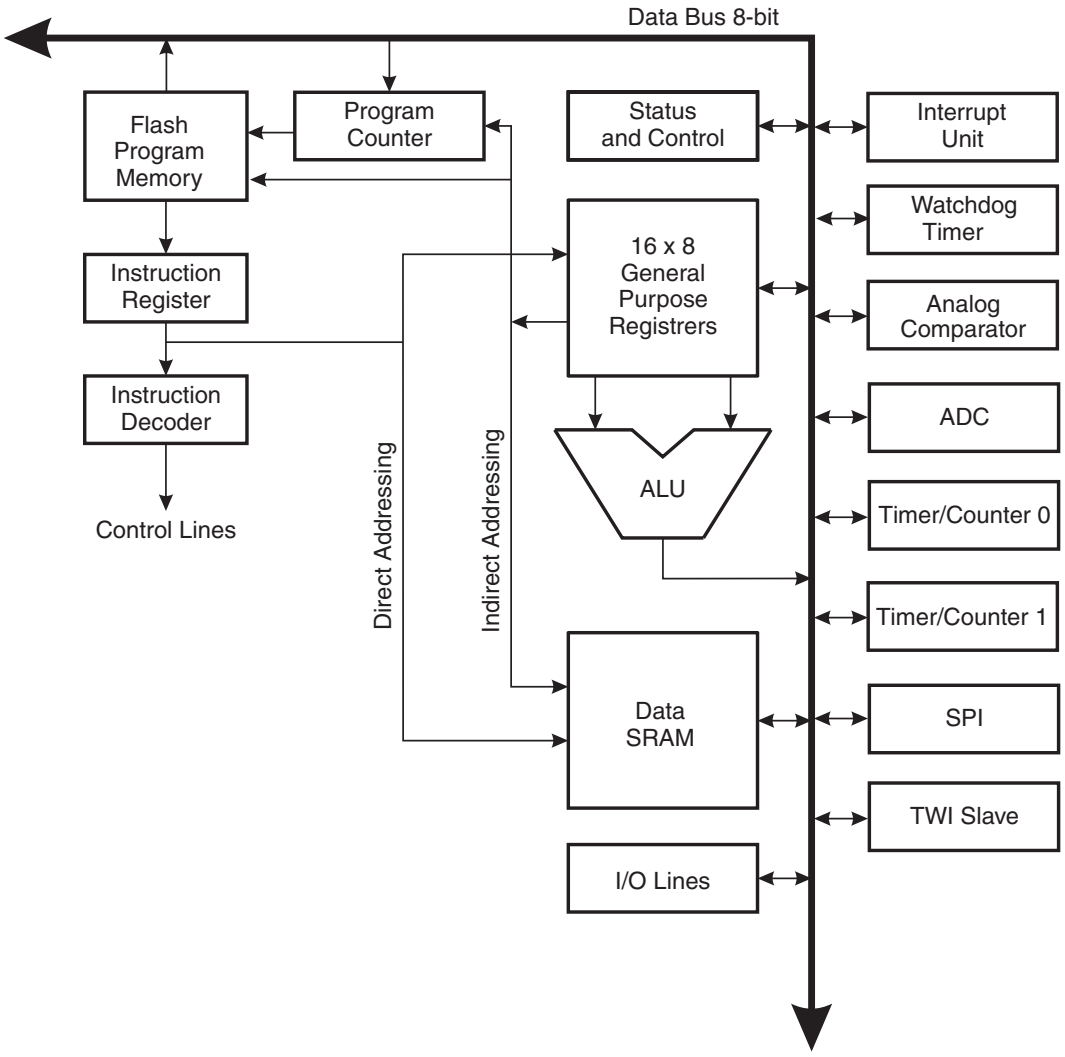
Typical values contained in this datasheet are based on simulations and characterization of other AVR microcontrollers manufactured on the same process technology.

4. CPU Core

This section discusses the AVR core architecture in general. The main function of the CPU core is to ensure correct program execution. The CPU must therefore be able to access memories, perform calculations, control peripherals, and handle interrupts.

4.1 Architectural Overview

Figure 4-1. Block Diagram of the AVR Architecture



In order to maximize performance and parallelism, the AVR uses a Harvard architecture – with separate memories and buses for program and data. Instructions in the program memory are executed with a single level pipelining. While one instruction is being executed, the next instruction is pre-fetched from the program memory. This concept enables instructions to be executed in every clock cycle. The program memory is In-System Reprogrammable Flash memory.

The fast-access Register File contains 16 x 8-bit general purpose working registers with a single clock cycle access time. This allows single-cycle Arithmetic Logic Unit (ALU) operation. In a typical ALU operation, two operands are output from the Register File, the operation is executed, and the result is stored back in the Register File – in one clock cycle.

Six of the 16 registers can be used as three 16-bit indirect address register pointers for data space addressing – enabling efficient address calculations. These added function registers are the 16-bit X-, Y-, and Z-register, described later in this section.

The ALU supports arithmetic and logic operations between registers or between a constant and a register. Single register operations can also be executed in the ALU. After an arithmetic operation, the Status Register is updated to reflect information about the result of the operation.

Program flow is provided by conditional and unconditional jump and call instructions, capable of directly addressing the whole address space. Most AVR instructions have a single 16-bit word format but 32-bit wide instructions also exist. The actual instruction set varies, as some devices only implement a part of the instruction set.

During interrupts and subroutine calls, the return address Program Counter (PC) is stored on the Stack. The Stack is effectively allocated in the general data SRAM, and consequently the Stack size is only limited by the SRAM size and the usage of the SRAM. All user programs must initialize the SP in the Reset routine (before subroutines or interrupts are executed). The Stack Pointer (SP) is read/write accessible in the I/O space. The data SRAM can easily be accessed through the four different addressing modes supported in the AVR architecture.

The memory spaces in the AVR architecture are all linear and regular memory maps.

A flexible interrupt module has its control registers in the I/O space with an additional Global Interrupt Enable bit in the Status Register. All interrupts have a separate Interrupt Vector in the Interrupt Vector table. The interrupts have priority in accordance with their Interrupt Vector position. The lower the Interrupt Vector address, the higher the priority.

The I/O memory space contains 64 addresses for CPU peripheral functions as Control Registers, SPI, and other I/O functions. The I/O memory can be accessed as the data space locations, 0x0000 - 0x003F.

4.2 ALU – Arithmetic Logic Unit

The high-performance AVR ALU operates in direct connection with all the 16 general purpose working registers. Within a single clock cycle, arithmetic operations between general purpose registers or between a register and an immediate are executed. The ALU operations are divided into three main categories – arithmetic, logical, and bit-functions. Some implementations of the architecture also provide a powerful multiplier supporting both signed/unsigned multiplication and fractional format. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for a detailed description.

4.3 Status Register

The Status Register contains information about the result of the most recently executed arithmetic instruction. This information can be used for altering program flow in order to perform conditional operations. Note that the Status Register is updated after all ALU operations, as specified in document “AVR Instruction Set” and section “Instruction Set Summary” on page 191. This will in many cases remove the need for using the dedicated compare instructions, resulting in faster and more compact code.

The Status Register is not automatically stored when entering an interrupt routine and restored when returning from an interrupt. This must be handled by software.

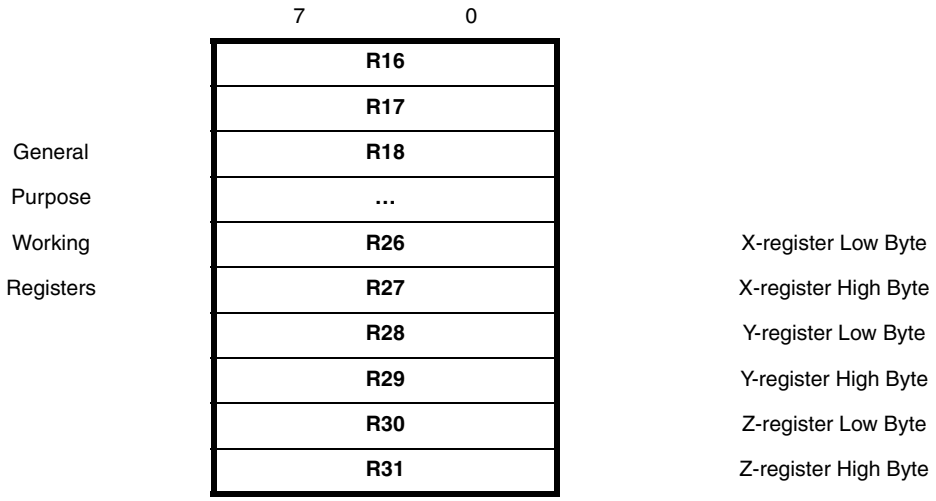
4.4 General Purpose Register File

The Register File is optimized for the AVR Enhanced RISC instruction set. In order to achieve the required performance and flexibility, the following input/output schemes are supported by the Register File:

- One 8-bit output operand and one 8-bit result input
- Two 8-bit output operands and one 8-bit result input
- One 16-bit output operand and one 16-bit result input

Figure 4-2 below shows the structure of the 16 general purpose working registers in the CPU.

Figure 4-2. AVR CPU General Purpose Working Registers



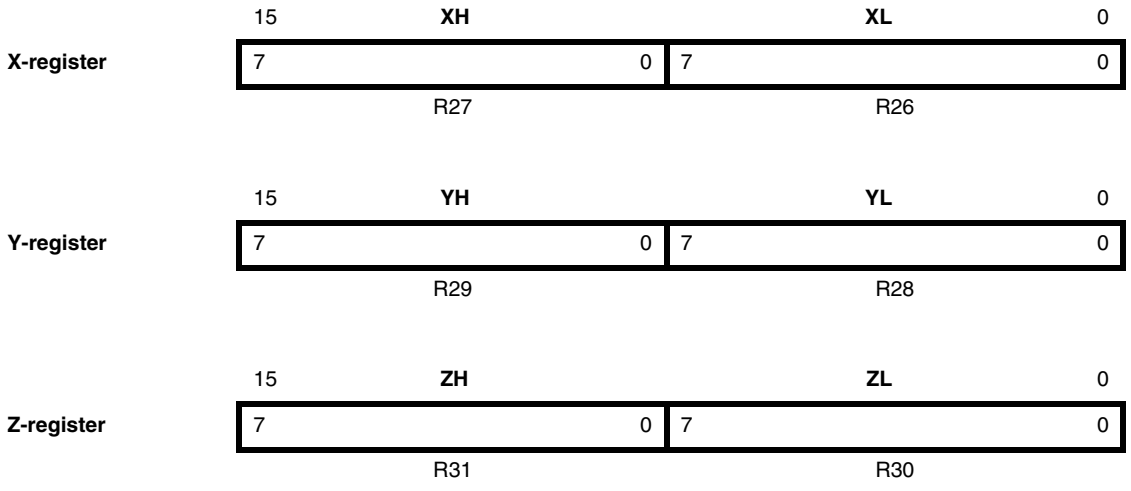
Note: A typical implementation of the AVR register file includes 32 general prupose registers but ATtiny40 implements only 16 registers. For reasons of compatibility the registers are numbered R16...R31 and not R0...R15.

Most of the instructions operating on the Register File have direct access to all registers, and most of them are single cycle instructions.

4.4.1 The X-register, Y-register, and Z-register

Registers R26..R31 have some added functions to their general purpose usage. These registers are 16-bit address pointers for indirect addressing of the data space. The three indirect address registers X, Y, and Z are defined as described in Figure 4-3.

Figure 4-3. The X-, Y-, and Z-registers



In different addressing modes these address registers function as automatic increment and automatic decrement (see document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for details).

4.5 Stack Pointer

The stack is mainly used for storing temporary data, local variables and return addresses after interrupts and sub-routine calls. The Stack Pointer Registers(SPH and SPL) always point to the top of the stack. Note that the stack grows from higher memory locations to lower memory locations. This means that the PUSH instruction decreases and the POP instruction increases the stack pointer value.

The stack pointer points to the area of data memory where subroutine and interrupt stacks are located. This stack space must be defined by the program before any subroutine calls are executed or interrupts are enabled.

The pointer is decremented by one when data is put on the stack with the PUSH instruction, and incremented by one when data is fetched with the POP instruction. It is decremented by two when the return address is put on the stack by a subroutine call or a jump to an interrupt service routine, and incremented by two when data is fetched by a return from subroutine (the RET instruction) or a return from interrupt service routine (the RETI instruction).

The AVR stack pointer is typically implemented as two 8-bit registers in the I/O register file. The width of the stack pointer and the number of bits implemented is device dependent. In some AVR devices all data memory can be addressed using SPL, only. In this case, the SPH register is not implemented.

The stack pointer must be set to point above the I/O register areas, the minimum value being the lowest address of SRAM. See Figure 5-1 on page 14.

4.6 Instruction Execution Timing

This section describes the general access timing concepts for instruction execution. The AVR CPU is driven by the CPU clock clk_{CPU}, directly generated from the selected clock source for the chip. No internal clock division is used.

Figure 4-4. The Parallel Instruction Fetches and Instruction Executions

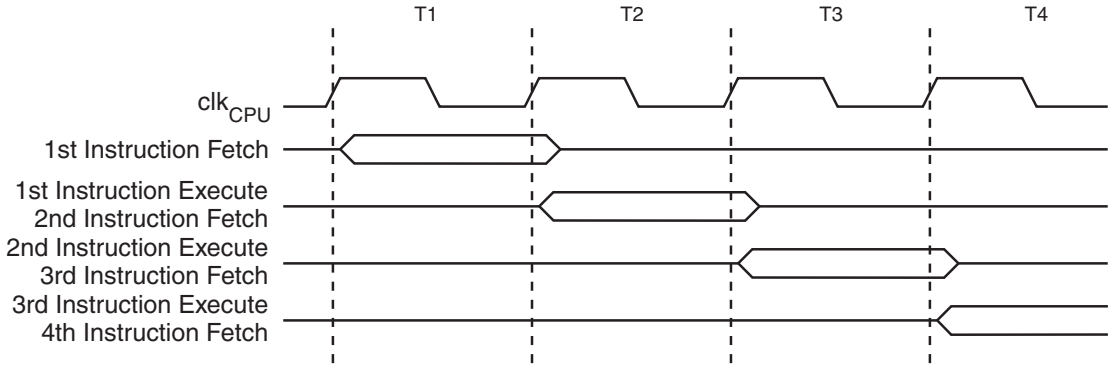
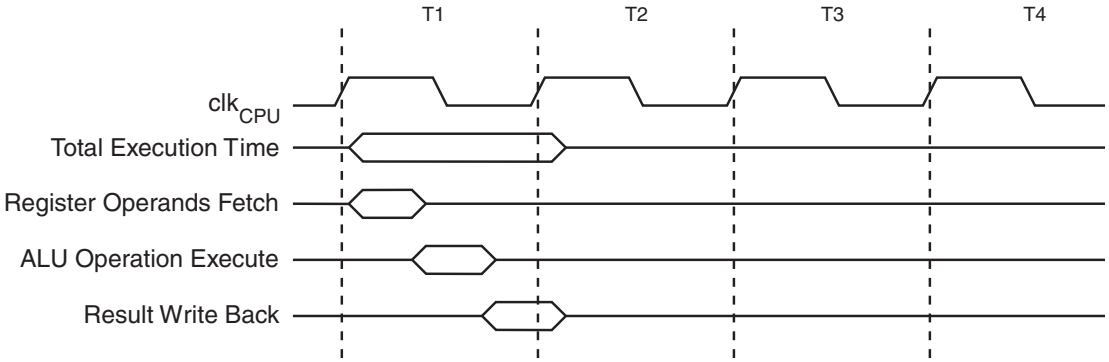


Figure 4-4 shows the parallel instruction fetches and instruction executions enabled by the Harvard architecture and the fast access Register File concept. This is the basic pipelining concept to obtain up to 1 MIPS per MHz with the corresponding unique results for functions per cost, functions per clocks, and functions per power-unit.

Figure 4-5 shows the internal timing concept for the Register File. In a single clock cycle an ALU operation using two register operands is executed, and the result is stored back to the destination register.

Figure 4-5. Single Cycle ALU Operation



4.7 Reset and Interrupt Handling

The AVR provides several different interrupt sources. These interrupts and the separate Reset Vector each have a separate Program Vector in the program memory space. All interrupts are assigned individual enable bits which must be written logic one together with the Global Interrupt Enable bit in the Status Register in order to enable the interrupt.

The lowest addresses in the program memory space are by default defined as the Reset and Interrupt Vectors. The complete list of vectors is shown in “Interrupts” on page 35. The list also determines the priority levels of the different interrupts. The lower the address the higher is the priority level. RESET has the highest priority, and next is INT0 – the External Interrupt Request 0.

When an interrupt occurs, the Global Interrupt Enable I-bit is cleared and all interrupts are disabled. The user software can write logic one to the I-bit to enable nested interrupts. All enabled interrupts can then interrupt the current interrupt routine. The I-bit is automatically set when a Return from Interrupt instruction – RETI – is executed.

There are basically two types of interrupts. The first type is triggered by an event that sets the Interrupt Flag. For these interrupts, the Program Counter is vectored to the actual Interrupt Vector in order to execute the interrupt handling routine, and hardware clears the corresponding Interrupt Flag. Interrupt Flags can also be cleared by writing a logic one to the flag bit position(s) to be cleared. If an interrupt condition occurs while the corresponding interrupt enable bit is cleared, the Interrupt Flag will be set and remembered until the interrupt is enabled, or the flag is cleared by software. Similarly, if one or more interrupt conditions occur while the Global Interrupt Enable bit is cleared, the corresponding Interrupt Flag(s) will be set and remembered until the Global Interrupt Enable bit is set, and will then be executed by order of priority.

The second type of interrupts will trigger as long as the interrupt condition is present. These interrupts do not necessarily have Interrupt Flags. If the interrupt condition disappears before the interrupt is enabled, the interrupt will not be triggered.

When the AVR exits from an interrupt, it will always return to the main program and execute one more instruction before any pending interrupt is served.

Note that the Status Register is not automatically stored when entering an interrupt routine, nor restored when returning from an interrupt routine. This must be handled by software.

When using the CLI instruction to disable interrupts, the interrupts will be immediately disabled. No interrupt will be executed after the CLI instruction, even if it occurs simultaneously with the CLI instruction.

When using the SEI instruction to enable interrupts, the instruction following SEI will be executed before any pending interrupts, as shown in the following example.

Assembly Code Example

```
sei         ; set Global Interrupt Enable
sleep       ; enter sleep, waiting for interrupt
            ; note: will enter sleep before any pending interrupt(s)
```

Note: See “Code Examples” on page 5.

4.7.1 Interrupt Response Time

The interrupt execution response for all the enabled AVR interrupts is four clock cycles minimum. After four clock cycles the Program Vector address for the actual interrupt handling routine is executed. During this four clock cycle period, the Program Counter is pushed onto the Stack. The vector is normally a jump to the interrupt routine, and this jump takes three clock cycles. If an interrupt occurs during execution of a multi-cycle instruction, this instruction is completed before the interrupt is served. If an interrupt occurs when the MCU is in sleep mode, the interrupt execution response time is increased by four clock cycles. This increase comes in addition to the start-up time from the selected sleep mode.

A return from an interrupt handling routine takes four clock cycles. During these four clock cycles, the Program Counter (two bytes) is popped back from the Stack, the Stack Pointer is incremented by two, and the I-bit in SREG is set.

4.8 Register Description

4.8.1 CCP – Configuration Change Protection Register

Bit	7	6	5	4	3	2	1	0	
0x3C	CCP[7:0]								CCP
Read/Write	W	W	W	W	W	W	W	W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:0 – CCP[7:0]: Configuration Change Protection**

In order to change the contents of a protected I/O register the CCP register must first be written with the correct signature. After CCP is written the protected I/O registers may be written to during the next four CPU instruction cycles. All interrupts are ignored during these cycles. After these cycles interrupts are automatically handled again by the CPU, and any pending interrupts will be executed according to their priority.

When the protected I/O register signature is written, CCP0 will read as one as long as the protected feature is enabled, while CCP[7:1] will always read as zero.

Table 4-1 shows the signatures that are in recognised.

Table 4-1. Signatures Recognised by the Configuration Change Protection Register

Signature	Group	Description
0xD8	IOREG: CLKMSR, CLKPSR, WDTCSR(1), MCUCR(2)	Protected I/O register

Notes: 1. Only WDE and WDP[3:0] bits are protected in WDTCSR.
2. Only BODS bit is protected in MCUCR.

4.8.2 SPH and SPL – Stack Pointer Register

Bit	15	14	13	12	11	10	9	8	
0x3E	SP15	SP14	SP13	SP12	SP11	SP10	SP9	SP8	SPH
0x3D	SP7	SP6	SP5	SP4	SP3	SP2	SP1	SP0	SPL
	7	6	5	4	3	2	1	0	
Read/Write	R	R	R	R	R	R	R	R	
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	
Initial Value	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	RAMEND	

- **Bits 15:0 – SP[15:0]: Stack Pointer**

The Stack Pointer register points to the top of the stack, which is implemented as growing from higher memory locations to lower memory locations. Hence, a stack PUSH command decreases the Stack Pointer. The stack space in the data SRAM must be defined by the program before any subroutine calls are executed or interrupts are enabled.

The Stack Pointer in ATtiny40 is implemented as two 8-bit registers in the I/O space.

4.8.3 SREG – Status Register

Bit	7	6	5	4	3	2	1	0	
0x3F	I	T	H	S	V	N	Z	C	SREG
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – I: Global Interrupt Enable**

The Global Interrupt Enable bit must be set for the interrupts to be enabled. The individual interrupt enable control is then performed in separate control registers. If the Global Interrupt Enable Register is cleared, none of the interrupts are enabled independent of the individual interrupt enable settings. The I-bit is cleared by hardware after an interrupt has occurred, and is set by the RETI instruction to enable subsequent interrupts. The I-bit can also be set and cleared by the application with the SEI and CLI instructions, as described in the document “AVR Instruction Set” and “Instruction Set Summary” on page 191.

- **Bit 6 – T: Bit Copy Storage**

The Bit Copy instructions BLD (Bit LoaD) and BST (Bit STore) use the T-bit as source or destination for the operated bit. A bit from a register in the Register File can be copied into T by the BST instruction, and a bit in T can be copied into a bit in a register in the Register File by the BLD instruction.

- **Bit 5 – H: Half Carry Flag**

The Half Carry Flag H indicates a Half Carry in some arithmetic operations. Half Carry is useful in BCD arithmetic. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

- **Bit 4 – S: Sign Bit, S = N ⊕ V**

The S-bit is always an exclusive or between the Negative Flag N and the Two’s Complement Overflow Flag V. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

- **Bit 3 – V: Two’s Complement Overflow Flag**

The Two’s Complement Overflow Flag V supports two’s complement arithmetics. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

- **Bit 2 – N: Negative Flag**

The Negative Flag N indicates a negative result in an arithmetic or logic operation. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

- **Bit 1 – Z: Zero Flag**

The Zero Flag Z indicates a zero result in an arithmetic or logic operation. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

- **Bit 0 – C: Carry Flag**

The Carry Flag C indicates a carry in an arithmetic or logic operation. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for detailed information.

5. Memories

This section describes the different memories in the ATtiny40. The device has two main memory areas, the program memory space and the data memory space.

5.1 In-System Re-programmable Flash Program Memory

The ATtiny40 contains 4K byte on-chip, in-system reprogrammable Flash memory for program storage. Since all AVR instructions are 16 or 32 bits wide, the Flash is organized as 2048 x 16.

The Flash memory has an endurance of at least 10,000 write/erase cycles. The ATtiny40 Program Counter (PC) is 11 bits wide, thus capable of addressing the 2048 program memory locations, starting at 0x000. “Memory Programming” on page 143 contains a detailed description on Flash data serial downloading.

Constant tables can be allocated within the entire address space of program memory. Since program memory can not be accessed directly, it has been mapped to the data memory. The mapped program memory begins at byte address 0x4000 in data memory (see Figure 5-1 on page 14). Although programs are executed starting from address 0x000 in program memory it must be addressed starting from 0x4000 when accessed via the data memory.

Internal write operations to Flash program memory have been disabled and program memory therefore appears to firmware as read-only. Flash memory can still be written to externally but internal write operations to the program memory area will not be succesful.

Timing diagrams of instruction fetch and execution are presented in “Instruction Execution Timing” on page 9.

5.2 Data Memory

Data memory locations include the I/O memory, the internal SRAM memory, the non-volatile memory lock bits, and the Flash memory. See Figure 5-1 on page 14 for an illustration on how the ATtiny40 memory space is organized.

The first 64 locations are reserved for I/O memory, while the following 256 data memory locations (from 0x0040 to 0x013F) address the internal data SRAM.

The non-volatile memory lock bits and all the Flash memory sections are mapped to the data memory space. These locations appear as read-only for device firmware.

The four different addressing modes for data memory are direct, indirect, indirect with pre-decrement, and indirect with post-increment. In the register file, registers R26 to R31 function as pointer registers for indirect addressing.

The IN and OUT instructions can access all 64 locations of I/O memory. Direct addressing using the LDS and STS instructions reaches the lowest 128 locations between 0x0040 and 0x00BF.

The indirect addressing reaches the entire data memory space. When using indirect addressing modes with automatic pre-decrement and post-increment, the address registers X, Y, and Z are decremented or incremented.

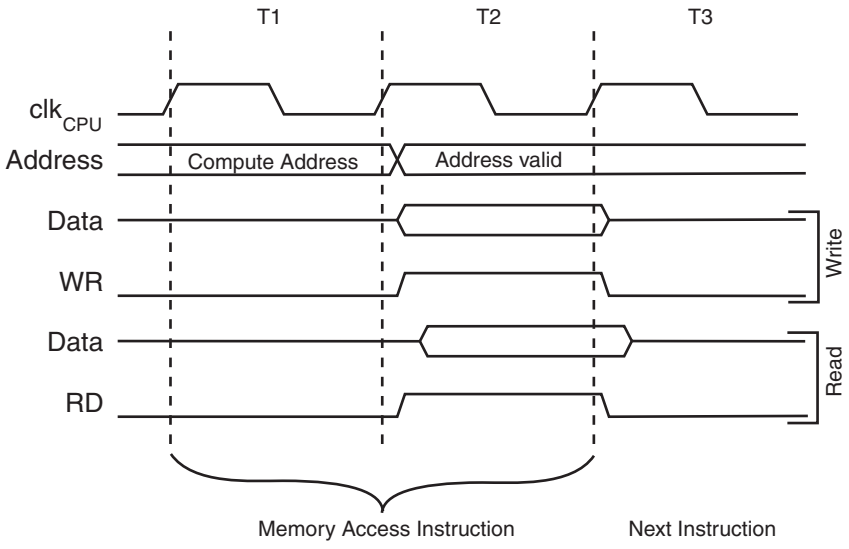
Figure 5-1. Data Memory Map (Byte Addressing)

I/O SPACE	0x0000 ... 0x003F
SRAM DATA MEMORY	0x0040 ... 0x013F
(reserved)	0x0140 ... 0x3EFF
NVM LOCK BITS	0x3F00 ... 0x3F01
(reserved)	0x3F02 ... 0x3F3F
CONFIGURATION BITS	0x3F40 ... 0x3F41
(reserved)	0x3F42 ... 0x3F7F
CALIBRATION BITS	0x3F80 ... 0x3F81
(reserved)	0x3F82 ... 0x3FBF
DEVICE ID BITS	0x3FC0 ... 0x3FC3
(reserved)	0x3FC4 ... 0x3FFF
FLASH PROGRAM MEMORY	0x4000 ... 0x47FF
(reserved)	0x4800 ... 0xFFFF

5.2.1 Data Memory Access Times

This section describes the general access timing concepts for internal memory access. The internal data SRAM access is performed in two clk_{CPU} cycles as described in Figure 5-2.

Figure 5-2. On-chip Data SRAM Access Cycles



5.2.2 Internal SRAM

The internal SRAM is mapped in the Data Memory space starting at address 0x0040. SRAM is accessed from the CPU by using direct addressing, indirect addressing or via the RAM interface. The registers R26 to R31 function as pointer register for indirect addressing. The pointer pre-decrement and post-increment functions are also supported in connection with the indirect addressing. Direct addressing using the LDS and STS instructions reaches only the lowest 128 locations between 0x0040 and 0x00BF. The locations beyond the first 128 bytes between 0x00C0 and 0x013F must be accessed using either indirect addressing mode (LD and ST instructions) or via the RAM interface.

The user must pay particular attention to the RAM addressing when using the RAM interface. The direct and indirect addressing modes use virtual RAM address, but the RAM interface uses physical RAM address. The virtual RAM address space mapping to physical addresses is described in Table 5-1.

For example, if the data is written to RAM using the virtual RAM address 0x0100 (instruction STS or ST), it is mapped to physical RAM address 0x0000. Thus the physical RAM address 0x0000 must be written to the RAMAR register when the same data location is read back via the RAM interface. On the other hand, if the same data location is read back using direct or indirect addressing mode (instruction LDS or LD), the same virtual RAM address 0x0100 is used.

Table 5-1. SRAM Address Space

Virtual RAM Address	Physical RAM Address
0x0040	0x0040
–	–
–	–
–	–
0x00FF	0x00FF
0x0100	0x0000
–	–
–	–
–	–
0x013F	0x003F

5.2.3 RAM Interface

The RAM Interface consists of two registers, RAM Address Register (RAMAR) and RAM Data Register (RAMDR). The registers are accessible in I/O space.

To write a location the user must first write the RAM address into RAMAR and then the data into RAMDR. Writing the data into RAMDR triggers the write operation and the data from the source register is written to RAM in address given by RAMAR within the same instruction cycle.

To read a location the user must first write the RAM address into RAMAR and then read the data from RAMDR. Reading the data from RAMDR triggers the read operation and the data from RAM address given by RAMAR is fetched and written to the destination register within the same instruction cycle.

Assembly Code Example

```
RAM_write:
  ; Set up address (r17) in address register
  out  RAMAR, r17
  ; Write data (r16) to data register
  out  RAMDR, r16
  ret

RAM_read:
  ; Set up address (r17) in address register
  out  RAMAR, r17
  ; Read data (r16) from data register
  in   r16, RAMDR
  ret
```

C Code Example

```
void RAM_write(unsigned char ucAddress, unsigned char ucData)
{
  /* Set up address register */
  RAMAR = ucAddress;
  /* Write data into RAMDR */
  RAMDR = ucData;
}

void RAM_read(unsigned char ucAddress, unsigned char ucData)
{
  /* Set up address register */
  RAMAR = ucAddress;
  /* Read data from RAMDR */
  ucData = RAMDR;
}
```

5.3 I/O Memory

The I/O space definition of the ATtiny40 is shown in “Register Summary” on page 189.

All ATtiny40 I/Os and peripherals are placed in the I/O space. All I/O locations may be accessed using the LD and ST instructions, enabling data transfer between the 16 general purpose working registers and the I/O space. I/O Registers within the address range 0x00 - 0x1F are directly bit-accessible using the SBI and CBI instructions. In these registers, the value of single bits can be checked by using the SBIS and SBIC instructions. See document “AVR Instruction Set” and section “Instruction Set Summary” on page 191 for more details. When using the I/O specific commands IN and OUT, the I/O addresses 0x00 - 0x3F must be used.

For compatibility with future devices, reserved bits should be written to zero if accessed. Reserved I/O memory addresses should never be written.

Some of the status flags are cleared by writing a logical one to them. Note that CBI and SBI instructions will only operate on the specified bit, and can therefore be used on registers containing such status flags. The CBI and SBI instructions work on registers in the address range 0x00 to 0x1F, only.

The I/O and Peripherals Control Registers are explained in later sections.

5.4 Register Description

5.4.1 RAMAR – RAM Address Register

Bit	7	6	5	4	3	2	1	0	
0x20	RAMAR7	RAMAR6	RAMAR5	RAMAR4	RAMAR3	RAMAR2	RAMAR1	RAMAR0	RAMAR
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	X	X	X	X	X	X	X	X	

- **Bits 7:0 – RAMAR[7:0]: RAM Address**

The RAMAR register contains the RAM address bits. The RAM data bytes are addressed linearly in the range 0..255. The initial value of RAMAR is undefined and a proper value must be therefore written before the RAM may be accessed.

5.4.2 RAMDR – RAM Data Register

Bit	7	6	5	4	3	2	1	0	
0x1F	RAMDR7	RAMDR6	RAMDR5	RAMDR4	RAMDR3	RAMDR2	RAMDR1	RAMDR0	RAMDR
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	X	X	X	X	X	X	X	X	

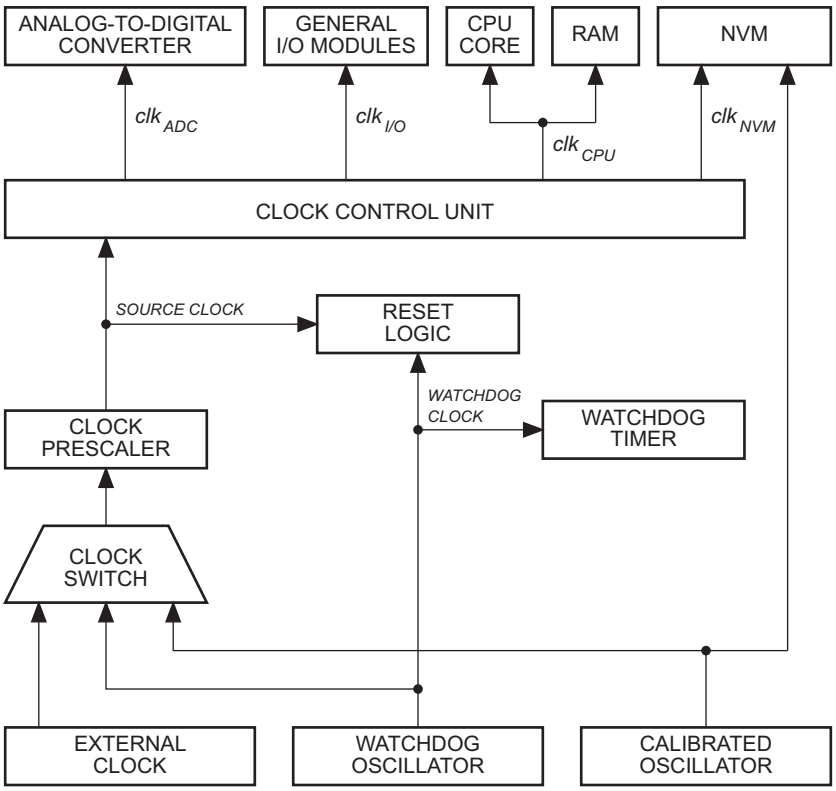
- **Bits 7:0 – RAMDR[7:0]: RAM Data**

For the RAM write operation, the RAMDR register contains the RAM data to be written to the RAM in address given by the RAMAR register. For the RAM read operation, the RAMDR contains the data read out from the RAM at the address given by RAMAR.

6. Clock System

Figure 6-1 presents the principal clock systems and their distribution in ATtiny40. All of the clocks need not be active at a given time. In order to reduce power consumption, the clocks to modules not being used can be halted by using different sleep modes and power reduction register bits, as described in “Power Management and Sleep Modes” on page 23. The clock systems is detailed below.

Figure 6-1. Clock Distribution



6.1 Clock Subsystems

The clock subsystems are detailed in the sections below.

6.1.1 CPU Clock – clk_{CPU}

The CPU clock is routed to parts of the system concerned with operation of the AVR Core. Examples of such modules are the General Purpose Register File, the System Registers and the SRAM data memory. Halting the CPU clock inhibits the core from performing general operations and calculations.

6.1.2 I/O Clock – $clk_{I/O}$

The I/O clock is used by the majority of the I/O modules, like Timer/Counter. The I/O clock is also used by the External Interrupt module, but note that some external interrupts are detected by asynchronous logic, allowing such interrupts to be detected even if the I/O clock is halted.

6.1.3 NVM clock - clk_{NVM}

The NVM clock controls operation of the Non-Volatile Memory Controller. The NVM clock is usually active simultaneously with the CPU clock.

6.1.4 ADC Clock – clk_{ADC}

The ADC is provided with a dedicated clock domain. This allows halting the CPU and I/O clocks in order to reduce noise generated by digital circuitry. This gives more accurate ADC conversion results.

6.2 Clock Sources

All synchronous clock signals are derived from the main clock. The device has three alternative sources for the main clock, as follows:

- Calibrated Internal 8 MHz Oscillator (see page 19)

- External Clock (see page 19)
- Internal 128 kHz Oscillator (see page 19)

See Table 6-3 on page 21 on how to select and change the active clock source.

6.2.1 Calibrated Internal 8 MHz Oscillator

The calibrated internal oscillator provides an approximately 8 MHz clock signal. Though voltage and temperature dependent, this clock can be very accurately calibrated by the user. See Table 20-2 on page 154, and "Internal Oscillator Speed" on page 186 for more details.

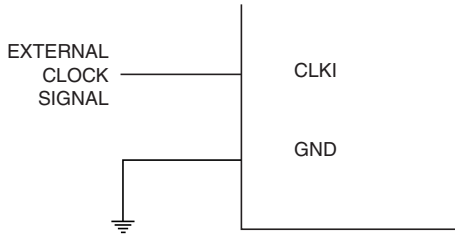
This clock may be selected as the main clock by setting the Clock Main Select bits CLKMS[1:0] in CLKMSR to 0b00. Once enabled, the oscillator will operate with no external components. During reset, hardware loads the calibration byte into the OSCCAL register and thereby automatically calibrates the oscillator. The accuracy of this calibration is shown as Factory calibration in Table 20-2 on page 154.

When this oscillator is used as the main clock, the watchdog oscillator will still be used for the watchdog timer and reset time-out. For more information on the pre-programmed calibration value, see section "Calibration Section" on page 147.

6.2.2 External Clock

To use the device with an external clock source, CLKI should be driven as shown in Figure 6-2. The external clock is selected as the main clock by setting CLKMS[1:0] bits in CLKMSR to 0b10.

Figure 6-2. External Clock Drive Configuration



When applying an external clock, it is required to avoid sudden changes in the applied clock frequency to ensure stable operation of the MCU. A variation in frequency of more than 2% from one clock cycle to the next can lead to unpredictable behavior. It is required to ensure that the MCU is kept in reset during such changes in the clock frequency.

6.2.3 Internal 128 kHz Oscillator

The internal 128 kHz oscillator is a low power oscillator providing a clock of 128 kHz. The frequency depends on supply voltage, temperature and batch variations. This clock may be select as the main clock by setting the CLKMS[1:0] bits in CLKMSR to 0b01.

6.2.4 Switching Clock Source

The main clock source can be switched at run-time using the "CLKMSR – Clock Main Settings Register" on page 21. When switching between any clock sources, the clock system ensures that no glitch occurs in the main clock.

6.2.5 Default Clock Source

The calibrated internal 8 MHz oscillator is always selected as main clock when the device is powered up or has been reset. The synchronous system clock is the main clock divided by 8, controlled by the System Clock Prescaler. The Clock Prescaler Select Bits can be written later to change the system clock frequency. See "System Clock Prescaler".

6.3 System Clock Prescaler

The system clock is derived from the main clock via the System Clock Prescaler. The system clock can be divided by setting the “CLKPSR – Clock Prescale Register” on page 22. The system clock prescaler can be used to decrease power consumption at times when requirements for processing power is low or to bring the system clock within limits of maximum frequency. The prescaler can be used with all main clock source options, and it will affect the clock frequency of the CPU and all synchronous peripherals.

The System Clock Prescaler can be used to implement run-time changes of the internal clock frequency while still ensuring stable operation.

6.3.1 Switching Prescaler Setting

When switching between prescaler settings, the system clock prescaler ensures that no glitch occurs in the system clock and that no intermediate frequency is higher than neither the clock frequency corresponding the previous setting, nor the clock frequency corresponding to the new setting.

The ripple counter that implements the prescaler runs at the frequency of the main clock, which may be faster than the CPU's clock frequency. Hence, it is not possible to determine the state of the prescaler - even if it were readable, and the exact time it takes to switch from one clock division to another cannot be exactly predicted.

From the time the CLKPS values are written, it takes between T1 + T2 and T1 + 2*T2 before the new clock frequency is active. In this interval, two active clock edges are produced. Here, T1 is the previous clock period, and T2 is the period corresponding to the new prescaler setting.

6.4 Starting

6.4.1 Starting from Reset

The internal reset is immediately asserted when a reset source goes active. The internal reset is kept asserted until the reset source is released and the start-up sequence is completed. The start-up sequence includes three steps, as follows.

1. The first step after the reset source has been released consists of the device counting the reset start-up time. The purpose of this reset start-up time is to ensure that supply voltage has reached sufficient levels. The reset start-up time is counted using the internal 128 kHz oscillator. See Table 6-1 for details of reset start-up time.
   Note that the actual supply voltage is not monitored by the start-up logic. The device will count until the reset start-up time has elapsed even if the device has reached sufficient supply voltage levels earlier.
2. The second step is to count the oscillator start-up time, which ensures that the calibrated internal oscillator has reached a stable state before it is used by the other parts of the system. The calibrated internal oscillator needs to oscillate for a minimum number of cycles before it can be considered stable. See Table 6-1 for details of the oscillator start-up time.
3. The last step before releasing the internal reset is to load the calibration and the configuration values from the Non-Volatile Memory to configure the device properly. The configuration time is listed in Table 6-1.

Table 6-1. Start-up Times when Using the Internal Calibrated Oscillator

Reset	Oscillator	Configuration	Total start-up time
64 ms	6 cycles	21 cycles	64 ms + 6 oscillator cycles + 21 system clock cycles (1)(2)

Notes: 1. After powering up the device or after a reset the system clock is automatically set to calibrated internal 8 MHz oscillator, divided by 8
2. When the Brown-out Detection is enabled, the reset start-up time is 128 ms after powering up the device.

6.4.2 Starting from Power-Down Mode

When waking up from Power-down sleep mode, the supply voltage is assumed to be at a sufficient level and only the oscillator start-up time is counted to ensure the stable operation of the oscillator. The oscillator start-up time is counted on the selected main clock, and the start-up time depends on the clock selected. See Table 6-2 for details.

Table 6-2. Start-up Time from Power-Down Sleep Mode.

Oscillator start-up time	Total start-up time
6 cycles	6 oscillator cycles (1)(2)

Notes: 1. The start-up time is measured in main clock oscillator cycles.
2. When using software BOD disable, the wake-up time from sleep mode will be approximately 60µs.

6.4.3 Starting from Idle / ADC Noise Reduction / Standby Mode

When waking up from Idle, ADC Noise Reduction or Standby Mode, the oscillator is already running and no oscillator start-up time is introduced.

6.5 Register Description

6.5.1 CLKMSR – Clock Main Settings Register

Bit	7	6	5	4	3	2	1	0	
0x37	–	–	–	–	–	–	CLKMS1	CLKMS0	CLKMSR
Read/Write	R	R	R	R	R	R	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:2 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 1:0 – CLKMS[1:0]: Clock Main Select Bits**

These bits select the main clock source of the system. The bits can be written at run-time to switch the source of the main clock. The clock system ensures glitch free switching of the main clock source.

The main clock alternatives are shown in Table 6-3.

Table 6-3. Selection of Main Clock

CLKM1	CLKM0	Main Clock Source
0	0	Calibrated Internal 8 MHzOscillator
0	1	Internal 128 kHz Oscillator (WDT Oscillator)
1	0	External clock
1	1	Reserved

To avoid unintentional switching of main clock source, a protected change sequence must be followed to change the CLKMS bits, as follows:

1. Write the signature for change enable of protected I/O register to register CCP
2. Within four instruction cycles, write the CLKMS bits with the desired value

6.5.2 CLKPSR – Clock Prescale Register

Bit	7	6	5	4	3	2	1	0	
0x36	–	–	–	–	CLKPS3	CLKPS2	CLKPS1	CLKPS0	CLKPSR
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	1	1	

- **Bits 7:4 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 3:0 – CLKPS[3:0]: Clock Prescaler Select Bits 3 - 0**

These bits define the division factor between the selected clock source and the internal system clock. These bits can be written at run-time to vary the clock frequency and suit the application requirements. As the prescaler divides the master clock input to the MCU, the speed of all synchronous peripherals is reduced accordingly. The division factors are given in Table 6-4.

Table 6-4. Clock Prescaler Select

CLKPS3	CLKPS2	CLKPS1	CLKPS0	Clock Division Factor
0	0	0	0	1
0	0	0	1	2
0	0	1	0	4
0	0	1	1	8 (default)
0	1	0	0	16
0	1	0	1	32
0	1	1	0	64
0	1	1	1	128
1	0	0	0	256
1	0	0	1	Reserved
1	0	1	0	Reserved
1	0	1	1	Reserved
1	1	0	0	Reserved
1	1	0	1	Reserved
1	1	1	0	Reserved
1	1	1	1	Reserved

To avoid unintentional changes of clock frequency, a protected change sequence must be followed to change the CLKPS bits:

1. Write the signature for change enable of protected I/O register to register CCP
2. Within four instruction cycles, write the desired value to CLKPS bits

At start-up, the CLKPS bits will be reset to 0b0011 to select the clock division factor of 8. The application software must ensure that a sufficient division factor is chosen if the selected clock source has a higher frequency than the maximum frequency of the device at the present operating conditions.

6.5.3 OSCCAL – Oscillator Calibration Register

Bit	7	6	5	4	3	2	1	0	
0x39	CAL7	CAL6	CAL5	CAL4	CAL3	CAL2	CAL1	CAL0	OSCCAL
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:0 – CAL[7:0]: Oscillator Calibration Value**

The oscillator calibration register is used to trim the calibrated internal oscillator and remove process variations from the oscillator frequency. A pre-programmed calibration value is automatically written to this register during chip reset, giving the factory calibrated frequency as specified in Table 20-2, “Calibration Accuracy of Internal RC Oscillator,” on page 154.

The application software can write this register to change the oscillator frequency. The oscillator can be calibrated to frequencies as specified in Table 20-2, “Calibration Accuracy of Internal RC Oscillator,” on page 154. Calibration outside the range given is not guaranteed.

The CAL[7:0] bits are used to tune the frequency of the oscillator. A setting of 0x00 gives the lowest frequency, and a setting of 0xFF gives the highest frequency.

7. Power Management and Sleep Modes

The high performance and industry leading code efficiency makes the AVR microcontrollers an ideal choise for low power applications. In addition, sleep modes enable the application to shut down unused modules in the MCU, thereby saving power. The AVR provides various sleep modes allowing the user to tailor the power consumption to the application’s requirements.

7.1 Sleep Modes

Figure 6-1 on page 18 presents the different clock systems and their distribution in ATtiny40. The figure is helpful in selecting an appropriate sleep mode. Table 7-1 shows the different sleep modes and their wake up sources.

Table 7-1. Active Clock Domains and Wake-up Sources in Different Sleep Modes.

	Active Clock Domains				Oscillators	Wake-up Sources				
Sleep Mode	clk_{CPU}	clk_{NVM}	clk_{IO}	clk_{ADC}	Main Clock Source Enabled	INT0 and Pin Change	Watchdog Interrupt	TWI Slave	ADC	Other I/O
Idle			X	X	X	X	X	X	X	X
ADC Noise Reduction				X	X	X(1)	X	X(2)	X	
Standby					X	X(1)	X	X(2)		
Power-down						X(1)	X	X(2)		

Notes: 1. For INT0, only level interrupt.
2. Only TWI address match interrupt.

To enter any of the four sleep modes, the SE bits in MCUCR must be written to logic one and a SLEEP instruction must be executed. The SM[2:0] bits in the MCUCR register select which sleep mode (Idle, ADC Noise Reduction, Standby or Power-down) will be activated by the SLEEP instruction. See Table 7-2 for a summary.

If an enabled interrupt occurs while the MCU is in a sleep mode, the MCU wakes up. The MCU is then halted for four cycles in addition to the start-up time, executes the interrupt routine, and resumes execution from the instruction following SLEEP. The contents of the Register File and SRAM are unaltered when the device wakes up from sleep. If a reset occurs during sleep mode, the MCU wakes up and executes from the Reset Vector.

Note that if a level triggered interrupt is used for wake-up the changed level must be held for some time to wake up the MCU (and for the MCU to enter the interrupt service routine). See "External Interrupts" on page 37 for details.

7.1.1 Idle Mode

When bits SM[2:0] are written to 000, the SLEEP instruction makes the MCU enter Idle mode, stopping the CPU but allowing the analog comparator, ADC, timer/counters, watchdog, TWI, SPI and the interrupt system to continue operating. This sleep mode basically halts clk_{CPU} and clk_{NVM}, while allowing the other clocks to run.

Idle mode enables the MCU to wake up from external triggered interrupts as well as internal ones like the timer overflow. If wake-up from the analog comparator interrupt is not required, the analog comparator can be powered down by setting the ACD bit in "ACSRA – Analog Comparator Control and Status Register" on page 95. This will reduce power consumption in idle mode. If the ADC is enabled, a conversion starts automatically when this mode is entered.

7.1.2 ADC Noise Reduction Mode

When bits SM[2:0] are written to 001, the SLEEP instruction makes the MCU enter ADC Noise Reduction mode, stopping the CPU but allowing the ADC, the external interrupts, TWI and the watchdog to continue operating (if enabled). This sleep mode halts $clk_{I/O}$, clk_{CPU}, and clk_{NVM}, while allowing the other clocks to run.

This mode improves the noise environment for the ADC, enabling higher resolution measurements. If the ADC is enabled, a conversion starts automatically when this mode is entered.

7.1.3 Power-down Mode

When bits SM[2:0] are written to 010, the SLEEP instruction makes the MCU enter Power-down mode. In this mode, the oscillator is stopped, while the external interrupts, TWI and the watchdog continue operating (if enabled). Only a watchdog reset, an external level interrupt on INT0, a pin change interrupt, or a TWI slave interrupt can wake up the MCU. This sleep mode halts all generated clocks, allowing operation of asynchronous modules only.

7.1.4 Standby Mode

When bits SM[2:0] are written to 100, the SLEEP instruction makes the MCU enter Standby mode. This mode is identical to Power-down with the exception that the oscillator is kept running. This reduces wake-up time, because the oscillator is already running and doesn't need to be started up.

7.2 Software BOD Disable

When the Brown-out Detector (BOD) is enabled by BODLEVEL fuses (see Table 19-5 on page 146), the BOD is actively monitoring the supply voltage during a sleep period. In some devices it is possible to save power by disabling the BOD by software in Power-down and Stand-by sleep modes. The sleep mode power consumption will then be at the same level as when BOD is globally disabled by fuses.

If BOD is disabled by software, the BOD function is turned off immediately after entering the sleep mode. Upon wake-up from sleep, BOD is automatically enabled again. This ensures safe operation in case the V_{CC} level has dropped during the sleep period.

When the BOD has been disabled, the wake-up time from sleep mode will be approximately 60 µs to ensure that the BOD is working correctly before the MCU continues executing code.

BOD disable is controlled by the BODS (BOD Sleep) bit of MCU Control Register, see “MCUCR – MCU Control Register” on page 26. Writing this bit to one turns off BOD in Power-down and Stand-by, while writing a zero keeps the BOD active. The default setting is zero, i.e. BOD active.

Writing to the BODS bit is controlled by a timed sequence, see “MCUCR – MCU Control Register” on page 26.

7.3 Power Reduction Register

The Power Reduction Register (PRR), see “PRR – Power Reduction Register” on page 27, provides a method to reduce power consumption by stopping the clock to individual peripherals. When the clock for a peripheral is stopped then:

- The current state of the peripheral is frozen.
- The associated registers can not be read or written.
- Resources used by the peripheral will remain occupied.

The peripheral should in most cases be disabled before stopping the clock. Clearing the PRR bit wakes up the peripheral and puts it in the same state as before shutdown.

Peripheral shutdown can be used in Idle mode and Active mode to significantly reduce the overall power consumption. See “Supply Current of I/O Modules” on page 159 for examples. In all other sleep modes, the clock is already stopped.

7.4 Minimizing Power Consumption

There are several issues to consider when trying to minimize the power consumption in an AVR Core controlled system. In general, sleep modes should be used as much as possible, and the sleep mode should be selected so that as few as possible of the device’s functions are operating. All functions not needed should be disabled. In particular, the following modules may need special consideration when trying to achieve the lowest possible power consumption.

7.4.1 Analog Comparator

When entering Idle mode, the analog comparator should be disabled if not used. In the power-down mode, the analog comparator is automatically disabled. See “Analog Comparator” on page 94 for further details.

7.4.2 Analog to Digital Converter

If enabled, the ADC will be enabled in all sleep modes. To save power, the ADC should be disabled before entering any sleep mode. When the ADC is turned off and on again, the next conversion will be an extended conversion. See “Analog to Digital Converter” on page 98 for details on ADC operation.

7.4.3 Watchdog Timer

If the Watchdog Timer is not needed in the application, this module should be turned off. If the Watchdog Timer is enabled, it will be enabled in all sleep modes, and hence, always consume power. In the deeper sleep modes, this will contribute significantly to the total current consumption. Refer to “Watchdog Timer” on page 31 for details on how to configure the Watchdog Timer.

7.4.4 Brown-out Detector

If the Brown-out Detector is not needed in the application, this module should be turned off. If the Brown-out Detector is enabled by the BODLEVEL Fuses, it will be enabled in all sleep modes, and hence, always consume power. In the deeper sleep modes, this will contribute significantly to the total current consumption. See “Brown-out Detection” on page 30 and “Software BOD Disable” on page 24 for details on how to configure the Brown-out Detector.

7.4.5 Port Pins

When entering a sleep mode, all port pins should be configured to use minimum power. The most important thing is then to ensure that no pins drive resistive loads. In sleep modes where the I/O clock ($clk_{I/O}$) is stopped, the input buffers of the device will be disabled. This ensures that no power is consumed by the input logic when not needed. In some cases, the input logic is needed for detecting wake-up conditions, and it will then be enabled. Refer to the section "Digital Input Enable and Sleep Modes" on page 46 for details on which pins are enabled. If the input buffer is enabled and the input signal is left floating or has an analog signal level close to $V_{CC}/2$, the input buffer will use excessive power.

For analog input pins, the digital input buffer should be disabled at all times. An analog signal level close to $V_{CC}/2$ on an input pin can cause significant current even in active mode. Digital input buffers can be disabled by writing to the Digital Input Disable Register (DIDR0). Refer to "DIDR0 – Digital Input Disable Register 0" on page 97 for details.

7.5 Register Description

7.5.1 MCUCR – MCU Control Register

The MCU Control Register contains bits for controlling external interrupt sensing and power management.

Bit	7	6	5	4	3	2	1	0	
0x3A	ISC01	ISC00	–	BODS	SM2	SM1	SM0	SE	MCUCR
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 5 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 4 – BODS: BOD Sleep**

In order to disable BOD during sleep (see Table 7-1 on page 23) the BODS bit must be written to logic one. This is controlled by a protected change sequence, as follows:

1. Write the signature for change enable of protected I/O registers to register CCP.
2. Within four instruction cycles write the BODS bit.

A sleep instruction must be executed while BODS is active in order to turn off the BOD for the actual sleep mode.

The BODS bit is automatically cleared when the device wakes up. Alternatively the BODS bit can be cleared by writing logic zero to it. This does not require protected sequence.

- **Bits 3:1 – SM[2:0]: Sleep Mode Select Bits 2, 1 and 0**

These bits select between available sleep modes, as shown in Table 7-2.

Table 7-2. Sleep Mode Select

SM2	SM1	SM0	Sleep Mode
0	0	0	Idle
0	0	1	ADC noise reduction
0	1	0	Power-down
0	1	1	Reserved
1	0	0	Standby
1	0	1	Reserved
1	1	0	Reserved
1	1	1	Reserved

- **Bit 0 – SE: Sleep Enable**

The SE bit must be written to logic one to make the MCU enter the sleep mode when the SLEEP instruction is executed. To avoid the MCU entering the sleep mode unless it is the programmer's purpose, it is recommended to write the Sleep Enable (SE) bit to one just before the execution of the SLEEP instruction and to clear it immediately after waking up.

7.5.2 PRR – Power Reduction Register

Bit	7	6	5	4	3	2	1	0	
0x35	–	–	–	PRTWI	PRSPI	PRTIM1	PRTIM0	PRADC	PRR
Read/Write	R	R	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:5 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 4 – PRTWI: Power Reduction Two-Wire Interface**

Writing a logic one to this bit shuts down the Two-Wire Interface module.

- **Bit 3 – PRSPI: Power Reduction Serial Peripheral Interface**

Writing a logic one to this bit shuts down the Serial Peripheral Interface module.

- **Bit 2 – PRTIM1: Power Reduction Timer/Counter1**

Writing a logic one to this bit shuts down the Timer/Counter1 module. When the Timer/Counter1 is enabled, operation will continue like before the shutdown.

- **Bit 1 – PRTIM0: Power Reduction Timer/Counter0**

Writing a logic one to this bit shuts down the Timer/Counter0 module. When the Timer/Counter0 is enabled, operation will continue like before the shutdown.

- **Bit 0 – PRADC: Power Reduction ADC**

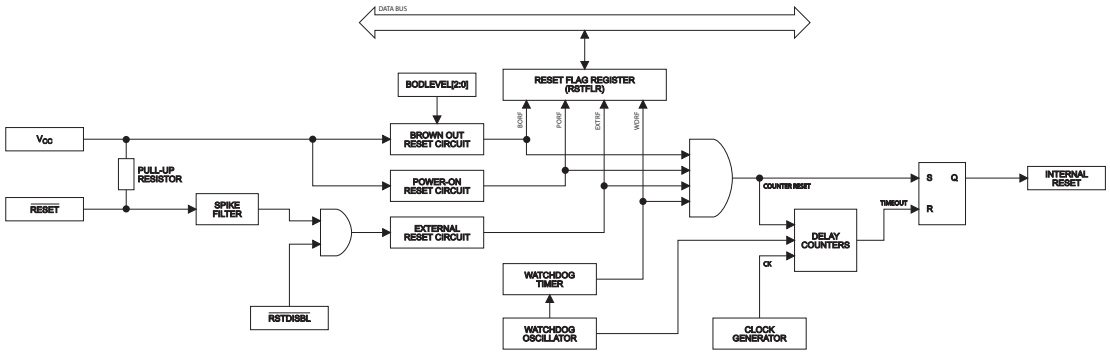
Writing a logic one to this bit shuts down the ADC. The ADC must be disabled before shut down. The analog comparator cannot use the ADC input MUX when the ADC is shut down.

8. System Control and Reset

8.1 Resetting the AVR

During reset, all I/O registers are set to their initial values, and the program starts execution from the Reset Vector. The instruction placed at the Reset Vector must be a RJMP – Relative Jump – instruction to the reset handling routine. If the program never enables an interrupt source, the interrupt vectors are not used, and regular program code can be placed at these locations. The circuit diagram in Figure 8-1 shows the reset logic. Electrical parameters of the reset circuitry are defined in section “System and Reset Characteristics” on page 155.

Figure 8-1. Reset Logic



The I/O ports of the AVR are immediately reset to their initial state when a reset source goes active. This does not require any clock source to be running.

After all reset sources have gone inactive, a delay counter is invoked, stretching the internal reset. This allows the power to reach a stable level before normal operation starts. The start up sequence is described in “Starting from Reset” on page 20.

8.2 Reset Sources

The ATtiny40 has four sources of reset:

- Power-on Reset. The MCU is reset when the supply voltage is below the Power-on Reset threshold (V_{POT})
- External Reset. The MCU is reset when a low level is present on the $\overline{\text{RESET}}$ pin for longer than the minimum pulse length
- Watchdog Reset. The MCU is reset when the Watchdog Timer period expires and the Watchdog is enabled
- Brown Out Reset. The MCU is reset when the Brown-Out Detector is enabled and supply voltage is below the brown-out threshold (V_{BOT})

8.2.1 Power-on Reset

A Power-on Reset (POR) pulse is generated by an on-chip detection circuit. The detection level is defined in section “System and Reset Characteristics” on page 155. The POR is activated whenever V_{CC} is below the detection level. The POR circuit can be used to trigger the Start-up Reset, as well as to detect a failure in supply voltage.

A Power-on Reset (POR) circuit ensures that the device is reset from Power-on. Reaching the Power-on Reset threshold voltage invokes the delay counter, which determines how long the device is kept in reset after V_{CC} rise. The reset signal is activated again, without any delay, when V_{CC} decreases below the detection level.

Figure 8-2. MCU Start-up, $\overline{\text{RESET}}$ High before Initial Time-out

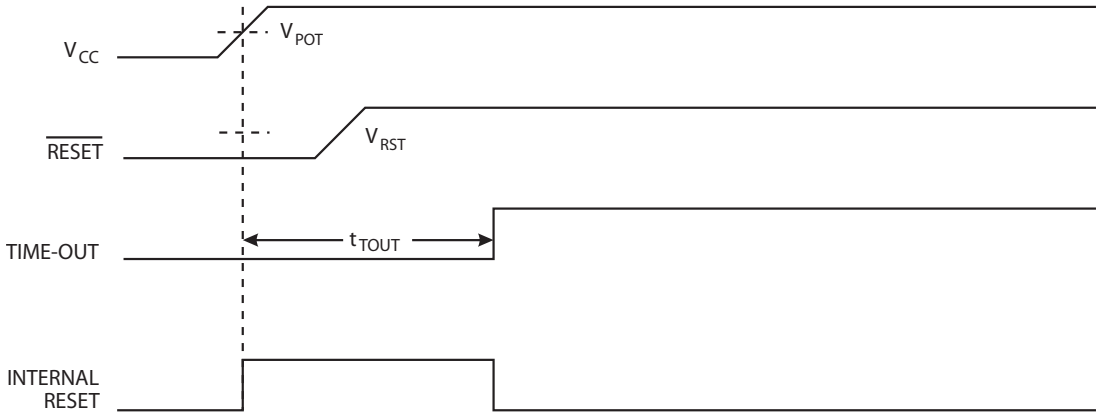
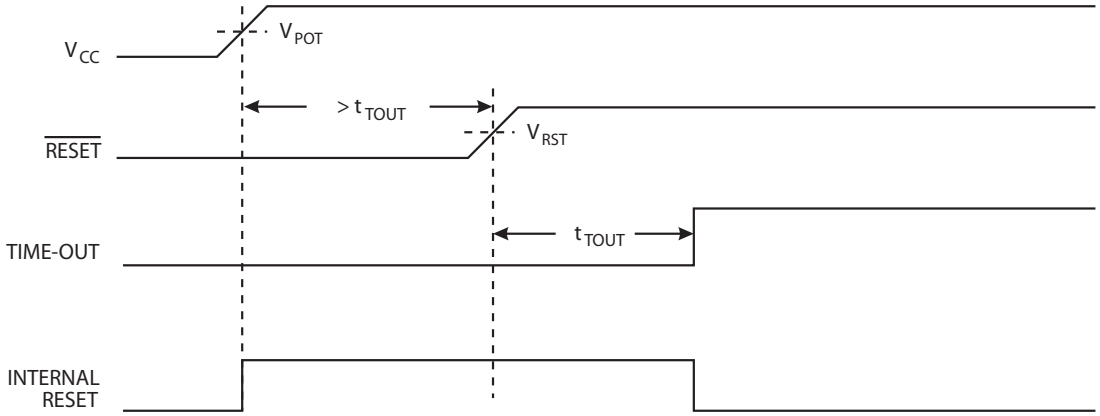


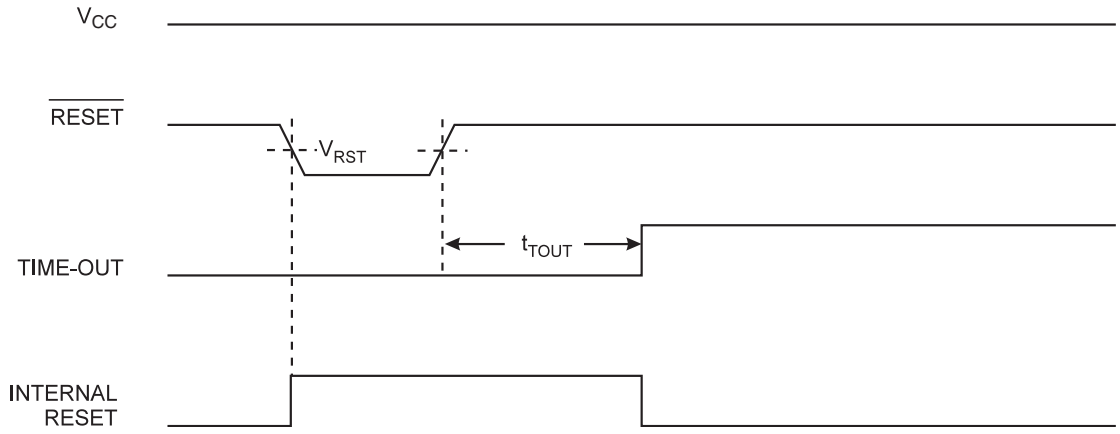
Figure 8-3. MCU Start-up, $\overline{\text{RESET}}$ Extended Externally



8.2.2 External Reset

An External Reset is generated by a low level on the $\overline{\text{RESET}}$ pin if enabled. Reset pulses longer than the minimum pulse width (see section "System and Reset Characteristics" on page 155) will generate a reset, even if the clock is not running. Shorter pulses are not guaranteed to generate a reset. When the applied signal reaches the Reset Threshold Voltage – V_{RST} – on its positive edge, the delay counter starts the MCU after the time-out period – t_{TOUT} – has expired. External reset is ignored during Power-on start-up count. After Power-on reset the internal reset is extended only if RESET pin is low when the initial Power-on delay count is complete. See Figure 8-2 and Figure 8-3.

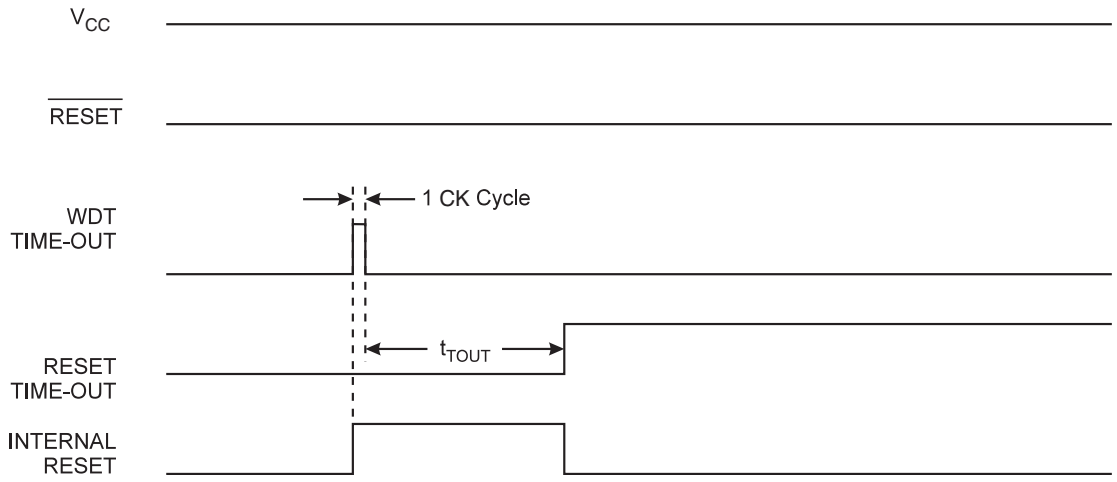
Figure 8-4. External Reset During Operation



8.2.3 Watchdog Reset

When the Watchdog times out, it will generate a short reset pulse. On the falling edge of this pulse, the delay timer starts counting the time-out period t_{TOUT}. See page 30 for details on operation of the Watchdog Timer and Table 20-4 on page 155 for details on reset time-out.

Figure 8-5. Watchdog Reset During Operation



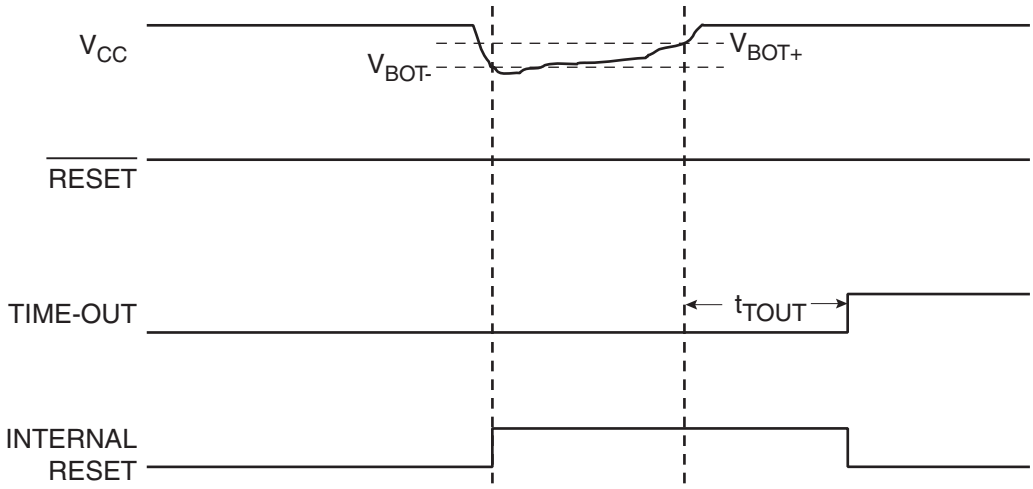
8.2.4 Brown-out Detection

ATtiny40 has an On-chip Brown-out Detection (BOD) circuit for monitoring the V_{CC} level during operation by comparing it to a fixed trigger level. The trigger level for the BOD can be selected by the BODLEVEL Fuses. The trigger level has a hysteresis to ensure spike free Brown-out Detection. The hysteresis on the detection level should be interpreted as $V_{BOT+} = V_{BOT} + V_{HYST}/2$ and $V_{BOT-} = V_{BOT} - V_{HYST}/2$.

When the BOD is enabled, and V_{CC} decreases to a value below the trigger level (V_{BOT-} in Figure 8-6 on page 31), the Brown-out Reset is immediately activated. When V_{CC} increases above the trigger level (V_{BOT+} in Figure 8-6), the delay counter starts the MCU after the Time-out period t_{TOUT} has expired.

The BOD circuit will only detect a drop in V_{CC} if the voltage stays below the trigger level for longer than t_{BOD} given in "System and Reset Characteristics" on page 155.

Figure 8-6. Brown-out Reset During Operation



8.3 Internal Voltage Reference

ATtiny40 features an internal bandgap reference. This reference is used for Brown-out Detection, and it can be used as an input to the Analog Comparator or the ADC. The bandgap voltage varies with supply voltage and temperature.

8.3.1 Voltage Reference Enable Signals and Start-up Time

The voltage reference has a start-up time that may influence the way it should be used. The start-up time is given in "System and Reset Characteristics" on page 155. To save power, the reference is not always turned on. The reference is on during the following situations:

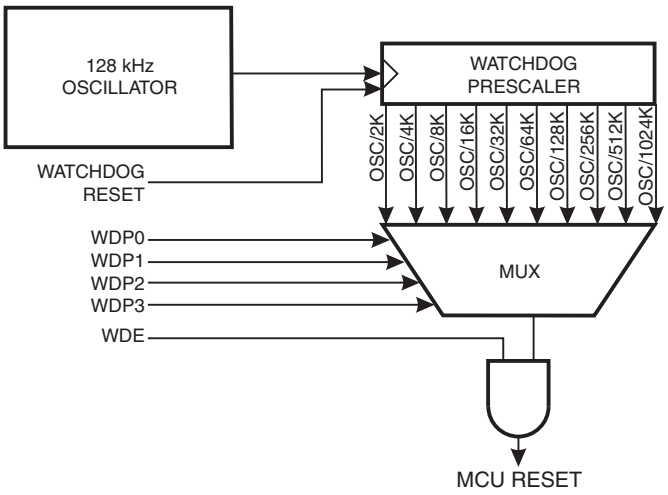
1. When the BOD is enabled (by programming the BODLEVEL[2:0] Fuse).
2. When the internal reference is connected to the Analog Comparator (by setting the ACBG bit in ACSR).
3. When the ADC is enabled.

Thus, when the BOD is not enabled, after setting the ACBG bit or enabling the ADC, the user must always allow the reference to start up before the output from the Analog Comparator or ADC is used. To reduce power consumption in Power-down mode, the user can avoid the three conditions above to ensure that the reference is turned off before entering Power-down mode.

8.4 Watchdog Timer

The Watchdog Timer is clocked from an on-chip oscillator, which runs at 128 kHz. See Figure 8-7. By controlling the Watchdog Timer prescaler, the Watchdog Reset interval can be adjusted as shown in Table 8-2 on page 34. The WDR – Watchdog Reset – instruction resets the Watchdog Timer. The Watchdog Timer is also reset when it is disabled and when a device reset occurs. Ten different clock cycle periods can be selected to determine the reset period. If the reset period expires without another Watchdog Reset, the ATtiny40 resets and executes from the Reset Vector. For timing details on the Watchdog Reset, refer to Table 8-3 on page 34.

Figure 8-7. Watchdog Timer



The Wathdog Timer can also be configured to generate an interrupt instead of a reset. This can be very helpful when using the Watchdog to wake-up from Power-down.

To prevent unintentional disabling of the Watchdog or unintentional change of time-out period, two different safety levels are selected by the fuse WDTON as shown in Table 8-1 on page 32. See "Procedure for Changing the Watchdog Timer Configuration" on page 32 for details.

Table 8-1. WDT Configuration as a Function of the Fuse Settings of WDTON

WDTON	Safety Level	WDT Initial State	How to Disable the WDT	How to Change Time-out
Unprogrammed	1	Disabled	Protected change sequence	No limitations
Programmed	2	Enabled	Always enabled	Protected change sequence

8.4.1 Procedure for Changing the Watchdog Timer Configuration

The sequence for changing configuration differs between the two safety levels, as follows:

8.4.1.1 Safety Level 1

In this mode, the Watchdog Timer is initially disabled, but can be enabled by writing the WDE bit to one without any restriction. A special sequence is needed when disabling an enabled Watchdog Timer. To disable an enabled Watchdog Timer, the following procedure must be followed:

1. Write the signature for change enable of protected I/O registers to register CCP
2. Within four instruction cycles, in the same operation, write WDE and WDP bits

8.4.1.2 Safety Level 2

In this mode, the Watchdog Timer is always enabled, and the WDE bit will always read as one. A protected change is needed when changing the Watchdog Time-out period. To change the Watchdog Time-out, the following procedure must be followed:

1. Write the signature for change enable of protected I/O registers to register CCP
2. Within four instruction cycles, write the WDP bit. The value written to WDE is irrelevant

8.4.2 Code Examples

The following code example shows how to turn off the WDT. The example assumes that interrupts are controlled (e.g., by disabling interrupts globally) so that no interrupts will occur during execution of these functions.

Assembly Code Example

```
WDT_off:
  wdr
  ; Clear WDRF in RSTFLR
  in   r16, RSTFLR
  andi  r16, ~(1<<WDRF)
  out  RSTFLR, r16
  ; Write signature for change enable of protected I/O register
  ldi  r16, 0xD8
  out  CCP, r16
  ; Within four instruction cycles, turn off WDT
  ldi  r16, (0<<WDE)
  out  WDTCSR, r16
  ret
```

Note: See “Code Examples” on page 5.

8.5 Register Description

8.5.1 WDTCSR – Watchdog Timer Control and Status Register

Bit	7	6	5	4	3	2	1	0	
0x31	WDIF	WDIE	WDP3	–	WDE	WDP2	WDP1	WDP0	WDTCSR
Read/Write	R/W	R/W	R/W	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	X	0	0	0	

- **Bit 7 – WDIF: Watchdog Timer Interrupt Flag**

This bit is set when a time-out occurs in the Watchdog Timer and the Watchdog Timer is configured for interrupt. WDIF is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, WDIF is cleared by writing a logic one to the flag. When the WDIE is set, the Watchdog Time-out Interrupt is requested.

- **Bit 6 – WDIE: Watchdog Timer Interrupt Enable**

When this bit is written to one, the Watchdog interrupt request is enabled. If WDE is cleared in combination with this setting, the Watchdog Timer is in Interrupt Mode, and the corresponding interrupt is requested if time-out in the Watchdog Timer occurs.

If WDE is set, the Watchdog Timer is in Interrupt and System Reset Mode. The first time-out in the Watchdog Timer will set WDIF. Executing the corresponding interrupt vector will clear WDIE and WDIF automatically by hardware (the Watchdog goes to System Reset Mode). This is useful for keeping the Watchdog Timer security while using the interrupt. To stay in Interrupt and System Reset Mode, WDIE must be set after each interrupt. This should however not be done within the interrupt service routine itself, as this might compromise the safety-function

of the Watchdog System Reset mode. If the interrupt is not executed before the next time-out, a System Reset will be applied.

Table 8-2. Watchdog Timer Configuration

WDTON[1]	WDE	WDIE	Mode	Action on Time-out
1	0	0	Stopped	None
1	0	1	Interrupt	Interrupt
1	1	0	System Reset	Reset
1	1	1	Interrupt and System Reset	Interrupt, then go to System Reset Mode
0	x	x	System Reset	Reset

Note: 1. WDTON configuration bit set to “0“ means programmed and “1“ means unprogrammed.

- **Bit 4 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 3 – WDE: Watchdog System Reset Enable**

WDE is overridden by WDRF in RSTFLR. This means that WDE is always set when WDRF is set. To clear WDE, WDRF must be cleared first. This feature ensures multiple resets during conditions causing failure, and a safe start-up after the failure.

- **Bits 5, 2:0 – WDP[3:0]: Watchdog Timer Prescaler 3, 2, 1 and 0**

The WDP[3:0] bits determine the Watchdog Timer prescaling when the Watchdog Timer is running. The different prescaling values and their corresponding time-out periods are shown in Table 8-3 on page 34.

Table 8-3. Watchdog Timer Prescale Select

WDP3	WDP2	WDP1	WDP0	Number of WDT Oscillator Cycles	Typical Time-out at V_{CC} = 5.0V
0	0	0	0	2K (2048) cycles	16 ms
0	0	0	1	4K (4096) cycles	32 ms
0	0	1	0	8K (8192) cycles	64 ms
0	0	1	1	16K (16384) cycles	0.125 s
0	1	0	0	32K (32768) cycles	0.25 s
0	1	0	1	64K (65536) cycles	0.5 s
0	1	1	0	128K (131072) cycles	1.0 s
0	1	1	1	256K (262144) cycles	2.0 s
1	0	0	0	512K (524288) cycles	4.0 s
1	0	0	1	1024K (1048576) cycles	8.0 s

Table 8-3. Watchdog Timer Prescale Select (Continued)

WDP3	WDP2	WDP1	WDP0	Number of WDT Oscillator Cycles	Typical Time-out at V_{CC} = 5.0V
1	0	1	0	Reserved	
1	0	1	1		
1	1	0	0		
1	1	0	1		
1	1	1	0		
1	1	1	1		

8.5.2 RSTFLR – Reset Flag Register

The Reset Flag Register provides information on which reset source caused an MCU Reset.

Bit	7	6	5	4	3	2	1	0	
0x3B	–	–	–	–	WDRF	BORF	EXTRF	PORF	RSTFLR
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	X	X	X	X	

- **Bits 7:4 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 3 – WDRF: Watchdog Reset Flag**

This bit is set if a Watchdog Reset occurs. The bit is reset by a Power-on Reset, or by writing a logic zero to the flag.

- **Bit 2 – BORF: Brown-Out Reset Flag**

This bit is set if a Brown-Out Reset occurs. The bit is reset by a Power-on Reset, or by writing a logic zero to the flag.

- **Bit 1 – EXTRF: External Reset Flag**

This bit is set if an External Reset occurs. The bit is reset by a Power-on Reset, or by writing a logic zero to the flag.

- **Bit 0 – PORF: Power-On Reset Flag**

This bit is set if a Power-on Reset occurs. The bit is reset only by writing a logic zero to the flag.

To make use of the Reset Flags to identify a reset condition, the user should read and then reset the RSTFLR as early as possible in the program. If the register is cleared before another reset occurs, the source of the reset can be found by examining the Reset Flags.

9. Interrupts

This section describes the specifics of the interrupt handling as performed in ATtiny40. For a general explanation of the AVR interrupt handling, see “Reset and Interrupt Handling” on page 10.

9.1 Interrupt Vectors

The interrupt vectors of ATtiny40 are described in Table 9-1 below.

Table 9-1. Reset and Interrupt Vectors

Vector No.	Program Address	Label	Interrupt Source
1	0x0000	RESET	External Pin, Power-on Reset, Brown-Out Reset, Watchdog Reset
2	0x0001	INT0	External Interrupt Request 0
3	0x0002	PCINT0	Pin Change Interrupt Request 0
4	0x0003	PCINT1	Pin Change Interrupt Request 1
5	0x0004	PCINT2	Pin Change Interrupt Request 2
6	0x0005	WDT	Watchdog Time-out
7	0x0006	TIM1_CAPT	Timer/Counter1 Input Capture
8	0x0007	TIM1_COMPA	Timer/Counter1 Compare Match A
9	0x0008	TIM1_COMPB	Timer/Counter1 Compare Match B
10	0x0009	TIM1_OVF	Timer/Counter1 Overflow
11	0x000A	TIM0_COMPA	Timer/Counter0 Compare Match A
12	0x000B	TIM0_COMPB	Timer/Counter0 Compare Match B
13	0x000C	TIM0_OVF	Timer/Counter0 Overflow
14	0x000D	ANA_COMP	Analog Comparator
15	0x000E	ADC	ADC Conversion Complete
16	0x000F	TWI_SLAVE	Two-Wire Interface
17	0x0010	SPI	Serial Peripheral Interface
18	0x0011	QTRIP (1)	Touch Sensing

1. The touch sensing interrupt source is related to the QTouch library support.

In case the program never enables an interrupt source, the Interrupt Vectors will not be used and, consequently, regular program code can be placed at these locations.

The most typical and general setup for interrupt vector addresses in ATtiny40 is shown in the program example below.

Assembly Code Example

```
    .org 0x0000                         ;Set address of next statement

      rjmp RESET                        ; Address 0x0000
      rjmp INT0_ISR                     ; Address 0x0001
      rjmp PCINT0_ISR                   ; Address 0x0002
      rjmp PCINT1_ISR                   ; Address 0x0003
      rjmp PCINT2_ISR                   ; Address 0x0004
      rjmp WDT_ISR                      ; Address 0x0005
      rjmp TIM1_CAPT_ISR                ; Address 0x0006
      rjmp TIM1_COMPA_ISR               ; Address 0x0007
      rjmp TIM1_COMPB_ISR               ; Address 0x0008
      rjmp TIM1_OVF_ISR                 ; Address 0x0009
      rjmp TIM0_COMPA_ISR               ; Address 0x000A
      rjmp TIM0_COMPB_ISR               ; Address 0x000B
      rjmp TIM0_OVF_ISR                 ; Address 0x000C
      rjmp ANA_COMP_ISR                 ; Address 0x000D
      rjmp ADC_ISR                      ; Address 0x000E
      rjmp TWI_SLAVE_ISR                ; Address 0x000F
      rjmp SPI_ISR                      ; Address 0x0010
      rjmp QTRIP_ISR                    ; Address 0x0011

    RESET:                              ; Main program start
      <instr>                           ; Address 0x0012
      ...
```

Note: See “Code Examples” on page 5.

9.2 External Interrupts

External Interrupts are triggered by the INT0 pin or any of the PCINT[17:0] pins. Observe that, if enabled, the interrupts will trigger even if the INT0 or PCINT[17:0] pins are configured as outputs. This feature provides a way of generating a software interrupt.

Pin change 0 interrupts PCI0 will trigger if any enabled PCINT[7:0] pin toggles. Pin change 1 interrupts PCI1 will trigger if any enabled PCINT[11:8] pin toggles. Pin change 2 interrupts PCI1 will trigger if any enabled PCINT[17:12] pin toggles. The PCMSK0, PCMSK1 and PCMSK2 Registers control which pins contribute to the pin change interrupts. Pin change interrupts on PCINT[17:0] are detected asynchronously, which means that these interrupts can be used for waking the part also from sleep modes other than Idle mode.

The INT0 interrupt can be triggered by a falling or rising edge or a low level. This is set up as shown in “MCUCR – MCU Control Register” on page 38. When the INT0 interrupt is enabled and configured as level triggered, the interrupt will trigger as long as the pin is held low. Note that recognition of falling or rising edge interrupts on INT0 requires the presence of an I/O clock, as described in “Clock System” on page 17.

9.2.1 Low Level Interrupt

A low level interrupt on INT0 is detected asynchronously. This means that the interrupt source can be used for waking the part also from sleep modes other than Idle (the I/O clock is halted in all sleep modes except Idle).

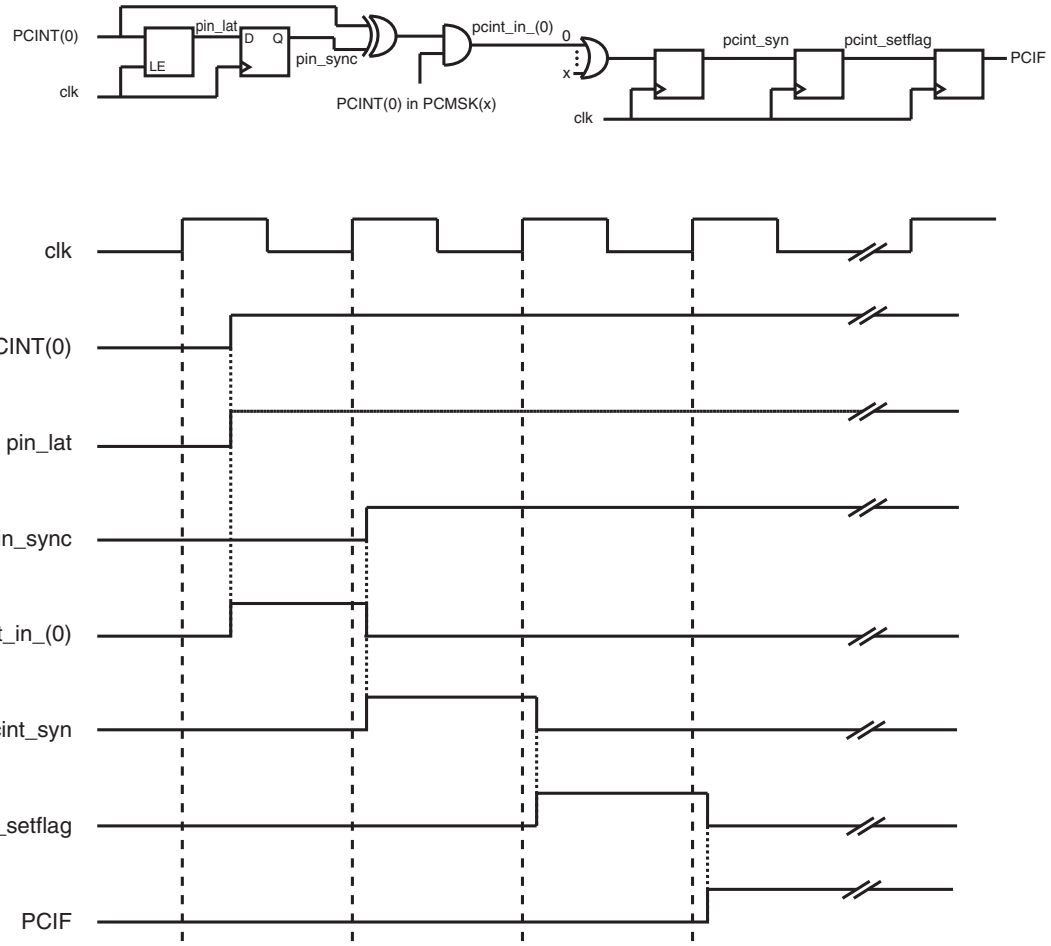
Note that if a level triggered interrupt is used for wake-up from Power-down, the required level must be held long enough for the MCU to complete the wake-up to trigger the level interrupt. If the level disappears before the end of the Start-up Time, the MCU will still wake up, but no interrupt will be generated. The start-up time is defined as described in “Clock System” on page 17.

If the low level on the interrupt pin is removed before the device has woken up then program execution will not be diverted to the interrupt service routine but continue from the instruction following the SLEEP command.

9.2.2 Pin Change Interrupt Timing

A timing example of a pin change interrupt is shown in Figure 9-1.

Figure 9-1. Timing of pin change interrupts



9.3 Register Description

9.3.1 MCUCR – MCU Control Register

The MCU Control Register contains bits for controlling external interrupt sensing and power management.

Bit	7	6	5	4	3	2	1	0	
0x3A	ISC01	ISC00	–	BODS	SM2	SM1	SM0	SE	MCUCR
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	

Initial Value	0	0	0	0	0	0	0	0

- **Bits 7:6 – ISC0[1:0]: Interrupt Sense Control**

The External Interrupt 0 is activated by the external pin INT0 if the SREG I-flag and the corresponding interrupt mask are set. The level and edges on the external INT0 pin that activate the interrupt are defined in Table 9-2. The value on the INT0 pin is sampled before detecting edges. If edge or toggle interrupt is selected, pulses that last longer than one clock period will generate an interrupt. Shorter pulses are not guaranteed to generate an interrupt. If low level interrupt is selected, the low level must be held until the completion of the currently executing instruction to generate an interrupt.

Table 9-2. Interrupt 0 Sense Control

ISC01	ISC00	Description
0	0	The low level of INT0 generates an interrupt request.
0	1	Any logical change on INT0 generates an interrupt request.
1	0	The falling edge of INT0 generates an interrupt request.
1	1	The rising edge of INT0 generates an interrupt request.

9.3.2 GIMSK – General Interrupt Mask Register

Bit	7	6	5	4	3	2	1	0	
0x0C	–	PCIE2	PCIE1	PCIE0	–	–	–	INT0	GIMSK
Read/Write	R	R/W	R/W	R/W	R	R	R	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 6 – PCIE2: Pin Change Interrupt Enable 2**

When the PCIE1 bit is set (one) and the I-bit in the Status Register (SREG) is set (one), pin change interrupt 2 is enabled. Any change on any enabled PCINT[17:12] pin will cause an interrupt. The corresponding interrupt of Pin Change Interrupt Request is executed from the PCI0 Interrupt Vector. PCINT[17:12] pins are enabled individually by the PCMSK2 Register.

- **Bit 5 – PCIE1: Pin Change Interrupt Enable 1**

When the PCIE1 bit is set (one) and the I-bit in the Status Register (SREG) is set (one), pin change interrupt 1 is enabled. Any change on any enabled PCINT[11:8] pin will cause an interrupt. The corresponding interrupt of Pin Change Interrupt Request is executed from the PCI1 Interrupt Vector. PCINT[11:8] pins are enabled individually by the PCMSK1 Register.

- **Bit 4 – PCIE0: Pin Change Interrupt Enable 0**

When the PCIE0 bit is set (one) and the I-bit in the Status Register (SREG) is set (one), pin change interrupt 0 is enabled. Any change on any enabled PCINT[7:0] pin will cause an interrupt. The corresponding interrupt of Pin Change Interrupt Request is executed from the PCI0 Interrupt Vector. PCINT[7:0] pins are enabled individually by the PCMSK0 Register.

- **Bits 3:1 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 0 – INT0: External Interrupt Request 0 Enable**

When the INT0 bit is set (one) and the I-bit in the Status Register (SREG) is set (one), the external pin interrupt is enabled. The Interrupt Sense Control bits (ISC01 and ISC00) in the MCU Control Register (MCUCR) define whether the external interrupt is activated on rising and/or falling edge of the INT0 pin or level sensed. Activity on the pin will cause an interrupt request even if INT0 is configured as an output. The corresponding interrupt of External Interrupt Request 0 is executed from the INT0 Interrupt Vector.

9.3.3 GIFR – General Interrupt Flag Register

Bit	7	6	5	4	3	2	1	0	
0x0B	–	PCIF2	PCIF1	PCIF0	–	–	–	INTF0	GIFR
Read/Write	R	R/W	R/W	R/W	R	R	R	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 6 – PCIF2: Pin Change Interrupt Flag 2**

When a logic change on any PCINT[17:12] pin triggers an interrupt request, PCIF2 becomes set (one). If the I-bit in SREG and the PCIE2 bit in GIMSK are set (one), the MCU will jump to the corresponding Interrupt Vector. The flag is cleared when the interrupt routine is executed. Alternatively, the flag can be cleared by writing a logical one to it.

- **Bit 5 – PCIF1: Pin Change Interrupt Flag 1**

When a logic change on any PCINT[11:8] pin triggers an interrupt request, PCIF1 becomes set (one). If the I-bit in SREG and the PCIE1 bit in GIMSK are set (one), the MCU will jump to the corresponding Interrupt Vector. The flag is cleared when the interrupt routine is executed. Alternatively, the flag can be cleared by writing a logical one to it.

- **Bit 4 – PCIF0: Pin Change Interrupt Flag 0**

When a logic change on any PCINT[7:0] pin triggers an interrupt request, PCIF becomes set (one). If the I-bit in SREG and the PCIE0 bit in GIMSK are set (one), the MCU will jump to the corresponding Interrupt Vector. The flag is cleared when the interrupt routine is executed. Alternatively, the flag can be cleared by writing a logical one to it.

- **Bits 3:1 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 0 – INTF0: External Interrupt Flag 0**

When an edge or logic change on the INT0 pin triggers an interrupt request, INTF0 becomes set (one). If the I-bit in SREG and the INT0 bit in GIMSK are set (one), the MCU will jump to the corresponding Interrupt Vector. The flag is cleared when the interrupt routine is executed. Alternatively, the flag can be cleared by writing a logical one to it. This flag is always cleared when INT0 is configured as a level interrupt.

9.3.4 PCMSK2 – Pin Change Mask Register 2

Bit	7	6	5	4	3	2	1	0	
0x1A	–	–	PCINT17	PCINT16	PCINT15	PCINT14	PCINT13	PCINT12	PCMSK2
Read/Write	R	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:6 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 5:0 – PCINT[17:12]: Pin Change Enable Mask 17:12**

Each PCINT[17:12] bit selects whether pin change interrupt is enabled on the corresponding I/O pin. If PCINT[17:12] is set and the PCIE2 bit in GIMSK is set, pin change interrupt is enabled on the corresponding I/O pin. If PCINT[17:12] is cleared, pin change interrupt on the corresponding I/O pin is disabled.

9.3.5 PCMSK1 – Pin Change Mask Register 1

Bit	7	6	5	4	3	2	1	0	
0x0A	–	–	–	–	PCINT11	PCINT10	PCINT9	PCINT8	PCMSK1
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:4 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 3:0 – PCINT[11:8]: Pin Change Enable Mask 11:8**

Each PCINT[11:8] bit selects whether pin change interrupt is enabled on the corresponding I/O pin. If PCINT[11:8] is set and the PCIE1 bit in GIMSK is set, pin change interrupt is enabled on the corresponding I/O pin. If PCINT[11:8] is cleared, pin change interrupt on the corresponding I/O pin is disabled.

9.3.6 PCMSK0 – Pin Change Mask Register 0

Bit	7	6	5	4	3	2	1	0	
0x09	PCINT7	PCINT6	PCINT5	PCINT4	PCINT3	PCINT2	PCINT1	PCINT0	PCMSK0
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:0 – PCINT[7:0]: Pin Change Enable Mask 7:0**

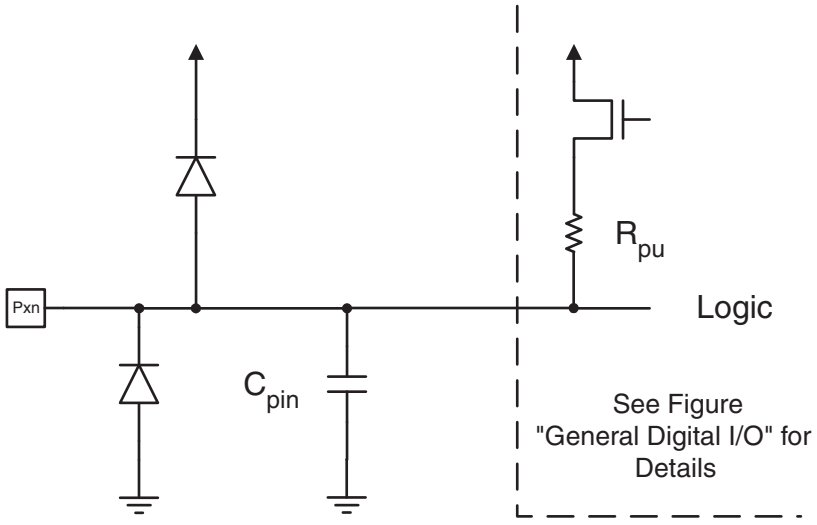
Each PCINT[7:0] bit selects whether pin change interrupt is enabled on the corresponding I/O pin. If PCINT[7:0] is set and the PCIE0 bit in GIMSK is set, pin change interrupt is enabled on the corresponding I/O pin. If PCINT[7:0] is cleared, pin change interrupt on the corresponding I/O pin is disabled.

10. I/O Ports

10.1 Overview

All AVR ports have true Read-Modify-Write functionality when used as general digital I/O ports. This means that the direction of one port pin can be changed without unintentionally changing the direction of any other pin with the SBI and CBI instructions. The same applies when changing drive value (if configured as output) or enabling/disabling of pull-up resistors. Each output buffer has symmetrical drive characteristics with both high sink and source capability. The pin driver is strong enough to drive LED displays directly. All port pins have individually selectable pull-up resistors with a supply-voltage invariant resistance. All I/O pins have protection diodes to both V_{CC} and Ground as indicated in Figure 10-1 on page 42. See "Electrical Characteristics" on page 152 for a complete list of parameters.

Figure 10-1. I/O Pin Equivalent Schematic



All registers and bit references in this section are written in general form. A lower case "x" represents the numbering letter for the port, and a lower case "n" represents the bit number. However, when using the register or bit defines in a program, the precise form must be used. For example, PORTB3 for bit no. 3 in Port B, here documented generally as PORTxn. The physical I/O Registers and bit locations are listed in "Register Description" on page 58.

Four I/O memory address locations are allocated for each port, one each for the Data Register – PORTx, Data Direction Register – DDRx, Pull-up Enable Register – PUEx, and the Port Input Pins – PINx. The Port Input Pins I/O location is read only, while the Data Register, the Data Direction Register, and the Pull-up Enable Register are read/write. However, writing a logic one to a bit in the PINx Register, will result in a toggle in the corresponding bit in the Data Register.

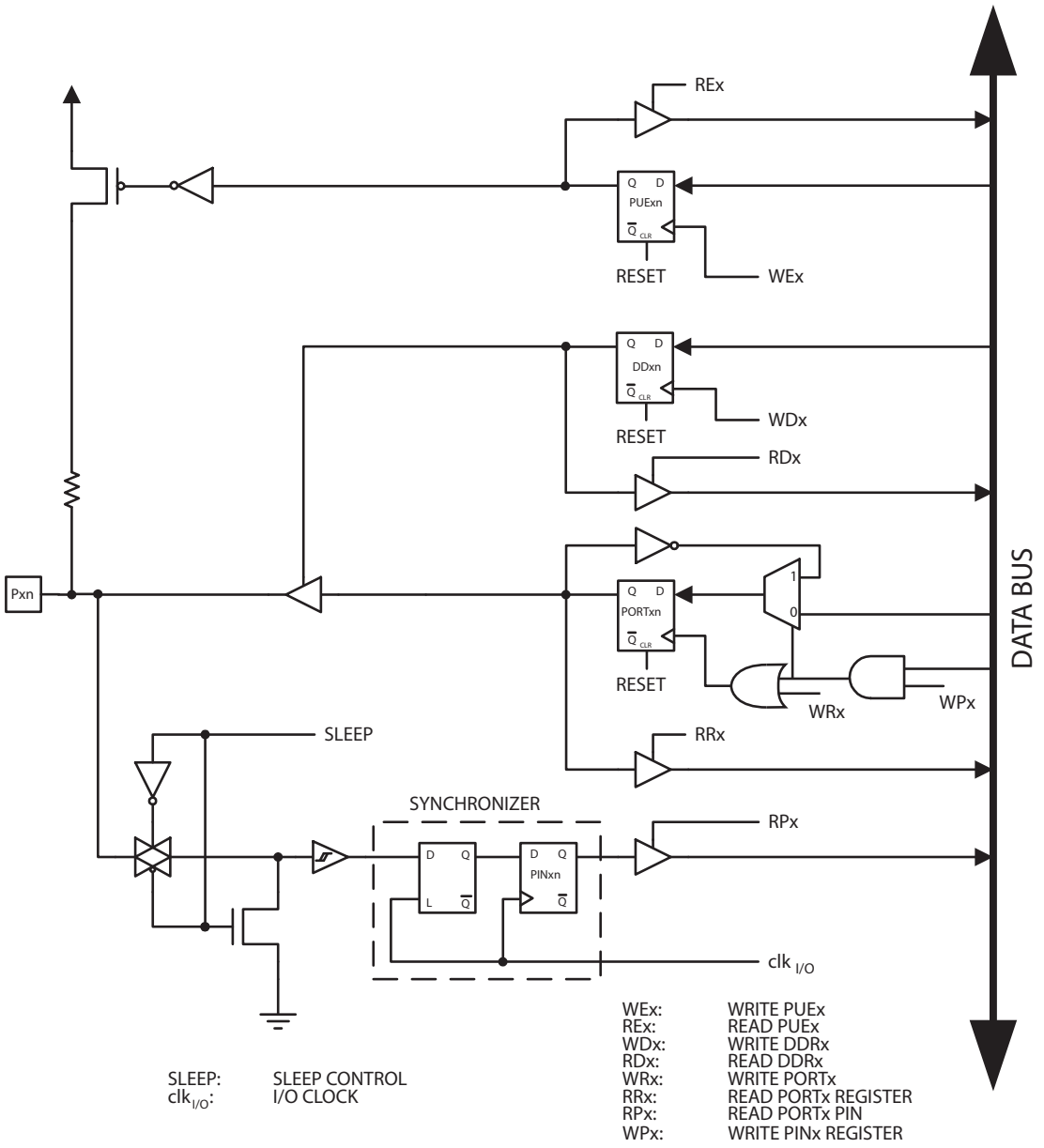
Using the I/O port as General Digital I/O is described in "Ports as General Digital I/O" on page 43. Most port pins are multiplexed with alternate functions for the peripheral features on the device. How each alternate function interferes with the port pin is described in "Alternate Port Functions" on page 47. Refer to the individual module sections for a full description of the alternate functions.

Note that enabling the alternate function of some of the port pins does not affect the use of the other pins in the port as general digital I/O.

10.2 Ports as General Digital I/O

The ports are bi-directional I/O ports with optional internal pull-ups. Figure 10-2 shows a functional description of one I/O-port pin, here generically called Pxn.

Figure 10-2. General Digital I/O[1]



Note: 1. WEx, WRx, WPx, WDx, REx, RRx, RPx, and RDx are common to all pins within the same port. $clk_{I/O}$, and SLEEP are common to all ports.

10.2.1 Configuring the Pin

Each port pin consists of four register bits: DDxn, PORTxn, PUExn, and PINxn. As shown in "Register Description" on page 58, the DDxn bits are accessed at the DDRx I/O address, the PORTxn bits at the PORTx I/O address, the PUExn bits at the PUEx I/O address, and the PINxn bits at the PINx I/O address.

The DDxn bit in the DDRx Register selects the direction of this pin. If DDxn is written logic one, Pxn is configured as an output pin. If DDxn is written logic zero, Pxn is configured as an input pin.

If PORTxn is written logic one when the pin is configured as an output pin, the port pin is driven high (one). If PORTxn is written logic zero when the pin is configured as an output pin, the port pin is driven low (zero).

The pull-up resistor is activated, if the PUExn is written logic one. To switch the pull-up resistor off, PUExn has to be written logic zero.

Table 10-1 summarizes the control signals for the pin value.

Table 10-1. Port Pin Configurations

DDxn	PORTxn	PUExn	I/O	Pull-up	Comment
0	X	0	Input	No	Tri-state (hi-Z)
0	X	1	Input	Yes	Sources current if pulled low externally
1	0	0	Output	No	Output low (sink)
1	0	1	Output	Yes	NOT RECOMMENDED. Output low (sink) and internal pull-up active. Sources current through the internal pull-up resistor and consumes power constantly
1	1	0	Output	No	Output high (source)
1	1	1	Output	Yes	Output high (source) and internal pull-up active

Port pins are tri-stated when a reset condition becomes active, even when no clocks are running.

10.2.2 Toggling the Pin

Writing a logic one to PINxn toggles the value of PORTxn, independent on the value of DDRxn. Note that the SBI instruction can be used to toggle one single bit in a port.

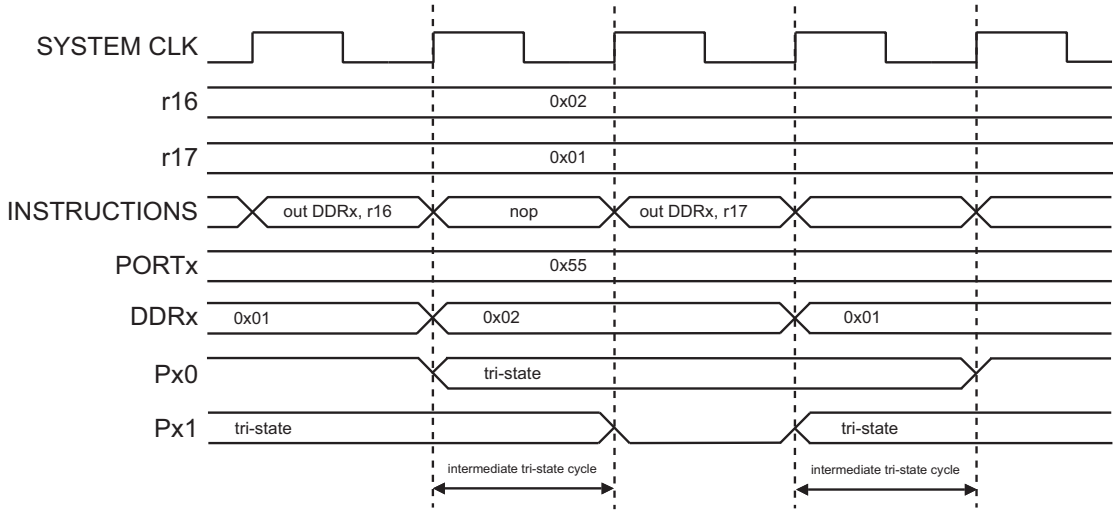
10.2.3 Break-Before-Make Switching

In Break-Before-Make mode, switching the DDRxn bit from input to output introduces an immediate tri-state period lasting one system clock cycle, as indicated in Figure 10-3. For example, if the system clock is 4 MHz and the DDRxn is written to make an output, an immediate tri-state period of 250 ns is introduced before the value of PORTxn is seen on the port pin.

To avoid glitches it is recommended that the maximum DDRxn toggle frequency is two system clock cycles. The Break-Before-Make mode applies to the entire port and it is activated by the BBMx bit. For more details, see “PORTCR – Port Control Register” on page 58.

When switching the DDRxn bit from output to input no immediate tri-state period is introduced.

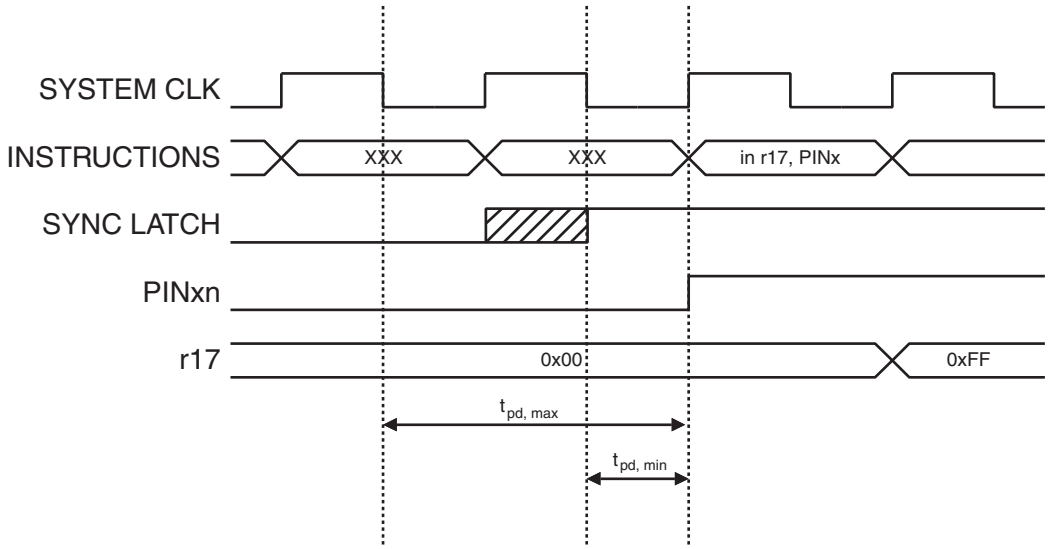
Figure 10-3. Switching Between Input and Output in Break-Before-Make-Mode



10.2.4 Reading the Pin Value

Independent of the setting of Data Direction bit DDxn, the port pin can be read through the PINxn Register bit. As shown in Figure 10-2 on page 43, the PINxn Register bit and the preceding latch constitute a synchronizer. This is needed to avoid metastability if the physical pin changes value near the edge of the internal clock, but it also introduces a delay. Figure 10-4 shows a timing diagram of the synchronization when reading an externally applied pin value. The maximum and minimum propagation delays are denoted $t_{pd,max}$ and $t_{pd,min}$ respectively.

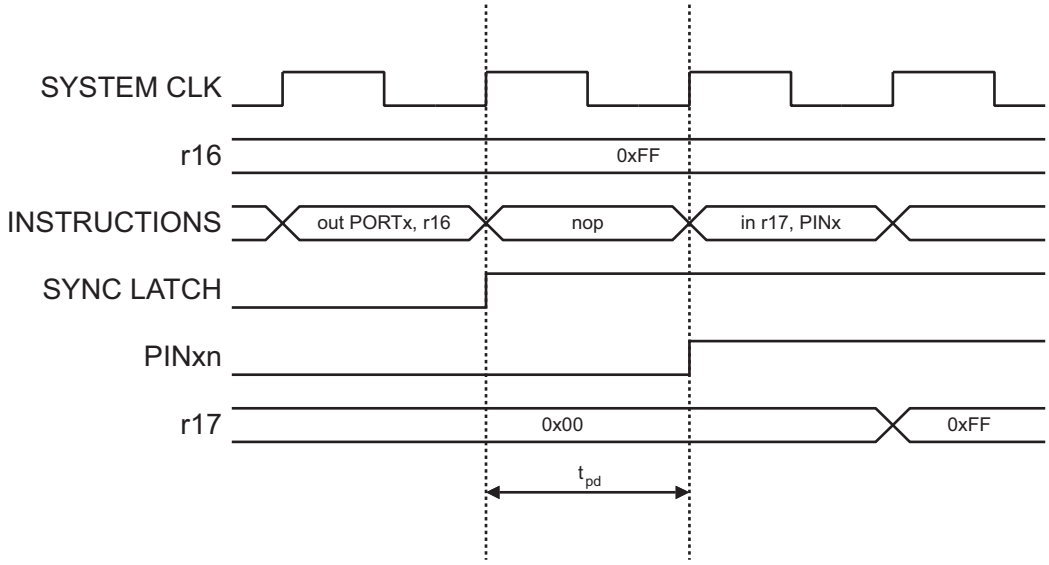
Figure 10-4. Synchronization when Reading an Externally Applied Pin value



Consider the clock period starting shortly after the first falling edge of the system clock. The latch is closed when the clock is low, and goes transparent when the clock is high, as indicated by the shaded region of the “SYNC LATCH” signal. The signal value is latched when the system clock goes low. It is clocked into the PINxn Register at the succeeding positive clock edge. As indicated by the two arrows tpd,max and tpd,min, a single signal transition on the pin will be delayed between ½ and 1½ system clock period depending upon the time of assertion.

When reading back a software assigned pin value, a nop instruction must be inserted as indicated in Figure 10-5 on page 46. The out instruction sets the “SYNC LATCH” signal at the positive edge of the clock. In this case, the delay tpd through the synchronizer is one system clock period.

Figure 10-5. Synchronization when Reading a Software Assigned Pin Value



10.2.5 Digital Input Enable and Sleep Modes

As shown in Figure 10-2 on page 43, the digital input signal can be clamped to ground at the input of the schmitt-trigger. The signal denoted SLEEP in the figure, is set by the MCU Sleep Controller in Power-down and Standby modes to avoid high power consumption if some input signals are left floating, or have an analog signal level close to $V_{CC}/2$.

SLEEP is overridden for port pins enabled as external interrupt pins. If the external interrupt request is not enabled, SLEEP is active also for these pins. SLEEP is also overridden by various other alternate functions as described in "Alternate Port Functions" on page 47.

If a logic high level ("one") is present on an asynchronous external interrupt pin configured as "Interrupt on Rising Edge, Falling Edge, or Any Logic Change on Pin" while the external interrupt is *not* enabled, the corresponding External Interrupt Flag will be set when resuming from the above mentioned Sleep mode, as the clamping in these sleep mode produces the requested logic change.

10.2.6 Unconnected Pins

If some pins are unused, it is recommended to ensure that these pins have a defined level. Even though most of the digital inputs are disabled in the deep sleep modes as described above, floating inputs should be avoided to reduce current consumption in all other modes where the digital inputs are enabled (Reset, Active mode and Idle mode).

The simplest method to ensure a defined level of an unused pin, is to enable the internal pull-up. In this case, the pull-up will be disabled during reset. If low power consumption during reset is important, it is recommended to use an external pull-up or pulldown. Connecting unused pins directly to V_{CC} or GND is not recommended, since this may cause excessive currents if the pin is accidentally configured as an output.

10.2.7 Program Example

The following code example shows how to set port B pin 0 high, pin 1 low, and define the port pins from 2 to 3 as input with a pull-up assigned to port pin 2. The resulting pin values are read back again, but as previously discussed, a *nop* instruction is included to be able to read back the value recently assigned to some of the pins.

Assembly Code Example

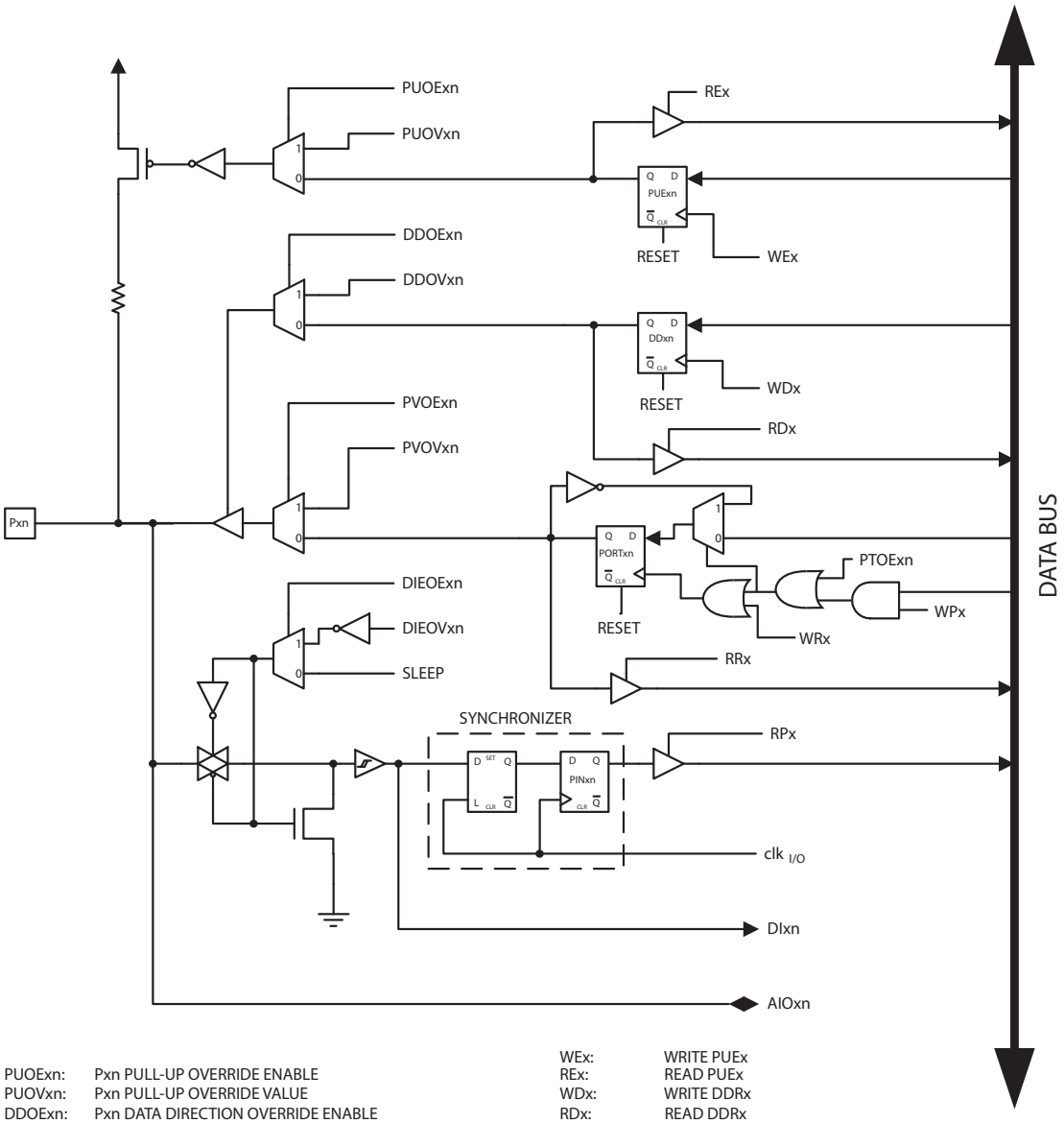
```
...
; Define pull-ups and set outputs high
; Define directions for port pins
ldi  r16,(1<<PUEB2)
ldi  r17,(1<<PB0)
ldi  r18,(1<<DDB1)|(1<<DDB0)
out  PUEB,r16
out  PORTB,r17
out  DDRB,r18
; Insert nop for synchronization
nop
; Read port pins
in   r16,PINB
...
```

Note: See “Code Examples” on page 5.

10.3 Alternate Port Functions

Most port pins have alternate functions in addition to being general digital I/Os. In Figure 10-6 below is shown how the port pin control signals from the simplified Figure 10-2 on page 43 can be overridden by alternate functions.

Figure 10-6. Alternate Port Functions[1]



PUOExn:	Pxn PULL-UP OVERRIDE ENABLE
PUOVxn:	Pxn PULL-UP OVERRIDE VALUE
DDOExn:	Pxn DATA DIRECTION OVERRIDE ENABLE
DDOVxn:	Pxn DATA DIRECTION OVERRIDE VALUE
PVOExn:	Pxn PORT VALUE OVERRIDE ENABLE
PVOVxn:	Pxn PORT VALUE OVERRIDE VALUE
DIEOExn:	Pxn DIGITAL INPUT-ENABLE OVERRIDE ENABLE
DIEOVxn:	Pxn DIGITAL INPUT-ENABLE OVERRIDE VALUE
SLEEP:	SLEEP CONTROL
PTOExn:	Pxn, PORT TOGGLE OVERRIDE ENABLE

WEx:	WRITE PUEx
REx:	READ PUEx
WDx:	WRITE DDRx
RDx:	READ DDRx
RRx:	READ PORTx REGISTER
WRx:	WRITE PORTx
RPx:	READ PORTx PIN
WPx:	WRITE PINx
$clk_{I/O}$:	I/O CLOCK
DIxn:	DIGITAL INPUT PIN n ON PORTx
AIOxn:	ANALOG INPUT/OUTPUT PIN n ON PORTx

Note: 1. WEx, WRx, WPx, WDx, REx, RRx, RPx, and RDx are common to all pins within the same port. $clk_{I/O}$, and SLEEP are common to all ports. All other signals are unique for each pin.

The illustration in the figure above serves as a generic description applicable to all port pins in the AVR microcontroller family. Some overriding signals may not be present in all port pins.

Table 10-2 on page 49 summarizes the function of the overriding signals. The pin and port indexes from Figure 10-6 on page 48 are not shown in the succeeding tables. The overriding signals are generated internally in the modules having the alternate function.

Table 10-2. Generic Description of Overriding Signals for Alternate Functions

Signal Name	Full Name	Description
PUOE	Pull-up Override Enable	If this signal is set, the pull-up enable is controlled by the PUOV signal. If this signal is cleared, the pull-up is enabled when PUExn = 0b1.
PUOV	Pull-up Override Value	If PUOE is set, the pull-up is enabled/disabled when PUOV is set/cleared, regardless of the setting of the PUExn Register bit.
DDOE	Data Direction Override Enable	If this signal is set, the Output Driver Enable is controlled by the DDOV signal. If this signal is cleared, the Output driver is enabled by the DDxn Register bit.
DDOV	Data Direction Override Value	If DDOE is set, the Output Driver is enabled/disabled when DDOV is set/cleared, regardless of the setting of the DDxn Register bit.
PVOE	Port Value Override Enable	If this signal is set and the Output Driver is enabled, the port value is controlled by the PVOV signal. If PVOE is cleared, and the Output Driver is enabled, the port Value is controlled by the PORTxn Register bit.
PVOV	Port Value Override Value	If PVOE is set, the port value is set to PVOV, regardless of the setting of the PORTxn Register bit.
PTOE	Port Toggle Override Enable	If PTOE is set, the PORTxn Register bit is inverted.
DIEOE	Digital Input Enable Override Enable	If this bit is set, the Digital Input Enable is controlled by the DIEOV signal. If this signal is cleared, the Digital Input Enable is determined by MCU state (Normal mode, sleep mode).
DIEOV	Digital Input Enable Override Value	If DIEOE is set, the Digital Input is enabled/disabled when DIEOV is set/cleared, regardless of the MCU state (Normal mode, sleep mode).
DI	Digital Input	This is the Digital Input to alternate functions. In the figure, the signal is connected to the output of the schmitt-trigger but before the synchronizer. Unless the Digital Input is used as a clock source, the module with the alternate function will use its own synchronizer.
AIO	Analog Input/Output	This is the Analog Input/Output to/from alternate functions. The signal is connected directly to the pad, and can be used bi-directionally.

The following subsections shortly describe the alternate functions for each port, and relate the overriding signals to the alternate function. Refer to the alternate function description for further details.

10.3.1 Alternate Functions of Port A

The Port A pins with alternate function are shown in Table 10-3.

Table 10-3. Port A Pins Alternate Functions

Port Pin	Alternate Function
PA0	ADC0: ADC Input Channel 0 PCINT0: Pin Change Interrupt 0, Source 0
PA1	ADC1: ADC Input Channel 1 AIN0: Analog Comparator, Positive Input PCINT1: Pin Change Interrupt 0, Source 1
PA2	ADC2: ADC Input Channel 2 AIN1: Analog Comparator, Negative Input PCINT2: Pin Change Interrupt 0, Source 2
PA3	ADC3: ADC Input Channel 3 PCINT3: Pin Change Interrupt 0, Source 3
PA4	ADC4: ADC Input Channel 4 T0: Timer/Counter0 Clock Source PCINT4: Pin Change Interrupt 0, Source 4
PA5	ADC5: ADC Input Channel 5 OC0B: Timer/Counter0 Compare Match B Output PCINT5: Pin Change Interrupt 0, Source 5
PA6	ADC6: ADC Input Channel 6 PCINT6: Pin Change Interrupt 0, Source 6
PA7	ADC7: ADC Input Channel 7 PCINT7: Pin Change Interrupt 0, Source 7

- **Port A, Bit 0 – ADC0/PCINT0**
  - ADC0: Analog to Digital Converter, Channel 0.
  - PCINT0: Pin Change Interrupt source 0. The PA0 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 1 – ADC1/AIN0/PCINT1**
  - ADC1: Analog to Digital Converter, Channel 1.
  - AIN0: Analog Comparator Positive Input. Configure the port pin as input with the internal pull-up switched off to avoid the digital port function from interfering with the function of the Analog Comparator.
  - PCINT1: Pin Change Interrupt source 1. The PA1 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 2 – ADC2/AIN1/PCINT2**
  - ADC2: Analog to Digital Converter, Channel 2.
  - AIN1: Analog Comparator Negative Input. Configure the port pin as input with the internal pull-up switched off to avoid the digital port function from interfering with the function of the Analog Comparator.
  - PCINT2: Pin Change Interrupt source 2. The PA2 pin can serve as an external interrupt source for pin change interrupt 0.

- **Port A, Bit 3 – ADC3/PCINT3**
  - ADC3: Analog to Digital Converter, Channel 3.
  - PCINT3: Pin Change Interrupt source 3. The PA3 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 4 – ADC4/T0/PCINT4**
  - ADC4: Analog to Digital Converter, Channel 4.
  - T0: Timer/Counter0 counter source.
  - PCINT4: Pin Change Interrupt source 4. The PA4 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 5 – ADC5/OC0B/PCINT5**
  - ADC5: Analog to Digital Converter, Channel 5.
  - OC0B: Output Compare Match output. The PA5 pin can serve as an external output for the Timer/Counter0 Compare Match B. The pin has to be configured as an output (DDA5 set (one)) to serve this function. This is also the output pin for the PWM mode timer function.
  - PCINT5: Pin Change Interrupt source 5. The PA5 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 6 – ADC6/PCINT6**
  - ADC6: Analog to Digital Converter, Channel 6.
  - PCINT6: Pin Change Interrupt source 6. The PA6 pin can serve as an external interrupt source for pin change interrupt 0.
- **Port A, Bit 7 – ADC7/PCINT7**
  - ADC7: Analog to Digital Converter, Channel 7.
  - PCINT7: Pin Change Interrupt source 7. The PA7 pin can serve as an external interrupt source for pin change interrupt 0.

Table 10-4 and Table 10-5 relate the alternate functions of Port A to the overriding signals shown in Figure 10-6 on page 48.

Table 10-4. Overriding Signals for Alternate Functions in PA[7:5]

Signal Name	PA7/ADC7/PCINT7	PA6/ADC6/PCINT6	PA5/ADC5/PCINT5
PUOE	0	0	0
PUOV	0	0	0
DDOE	0	0	0
DDOV	0	0	0
PVOE	0	0	OC0B_ENABLE
PVOV	0	0	OC0B
PTOE	0	0	0
DIEOE	PCINT7 • PCIE0 + ADC7D	PCINT6 • PCIE0 + ADC6D	PCINT5 • PCIE0 + ADC5D
DIEOV	PCINT7 • PCIE0	PCINT6 • PCIE0	PCINT5 • PCIE0
DI	PCINT7 Input	PCINT6 Input	PCINT5 Input
AIO	ADC7 Input	ADC6 Input	ADC5 Input

Note: When TWI is enabled the slew rate control and spike filter are activated on PA7. This is not illustrated in Figure 10-6 on page 48. The spike filter is connected between AIOxn and the TWI module.

Table 10-5. Overriding Signals for Alternate Functions in PA[4:2]

Signal Name	PA4/ADC4/PCINT4	PA3/ADC3/PCINT3	PA2/ADC2/AIN1/PCINT2
PUOE	0	0	0
PUOV	0	0	0
DDOE	0	0	0
DDOV	0	0	0
PVOE	0	0	0
PVOV	0	0	0
PTOE	0	0	0
DIEOE	(PCINT4 • PCIE0) + ADC4D	(PCINT3 • PCIE0) + ADC3D	(PCINT2 • PCIE0) + ADC2D
DIEOV	PCINT4 • PCIE0	PCINT3 • PCIE0	PCINT3 • PCIE0
DI	T0 / PCINT4 input	PCINT1 Input	PCINT0 Input
AIO	ADC4 Input	ADC3 Input	ADC2 / Analog Comparator Negative Input

Table 10-6. Overriding Signals for Alternate Functions in PA[1:0]

Signal Name	PA1/ADC1/AIN0/PCINT1	PA0/ADC0/PCINT0
PUOE	0	0
PUOV	0	0
DDOE	0	0
DDOV	0	0
PVOE	0	0
PVOV	0	0
PTOE	0	0
DIEOE	PCINT1 • PCIE0 + ADC1D	PCINT0 • PCIE0 + ADC0D
DIEOV	PCINT1 • PCIE0	PCINT0 • PCIE0
DI	PCINT1 Input	PCINT0 Input
AIO	ADC1 / Analog Comparator Positive Input	ADC1 Input

10.3.2 Alternate Functions of Port B

The Port B pins with alternate function are shown in Table 10-7.

Table 10-7. Port B Pins Alternate Functions

Port Pin	Alternate Function
PB0	ADC8: ADC Input Channel 8 PCINT8: Pin Change Interrupt 1, Source 8
PB1	ADC9: ADC Input Channel 9 PCINT9: Pin Change Interrupt 1, Source 9
PB2	ADC10: ADC Input Channel 10 PCINT10:Pin Change Interrupt 1, Source 10
PB3	ADC11: ADC Input Channel 11 PCINT11:Pin Change Interrupt 1, Source 11.

- **Port B, Bit 0 – ADC8/PCINT8**
  - ADC8: Analog to Digital Converter, Channel 8.
  - PCINT8: Pin Change Interrupt source 8. The PB0 pin can serve as an external interrupt source for pin change interrupt 1.
- **Port B, Bit 1 – ADC9/PCINT9**
  - ADC9: Analog to Digital Converter, Channel 9.
  - PCINT9: Pin Change Interrupt source 9. The PB1 pin can serve as an external interrupt source for pin change interrupt 1.
- **Port B, Bit 2 – ADC10/PCINT10**
  - ADC10: Analog to Digital Converter, Channel 10.
  - PCINT10: Pin Change Interrupt source 10. The PB2 pin can serve as an external interrupt source for pin change interrupt 1.

- **Port B, Bit 3 – ADC11/PCINT11**
  - ADC11: Analog to Digital Converter, Channel 11.
  - PCINT11: Pin Change Interrupt source 11. The PB3 pin can serve as an external interrupt source for pin change interrupt 1.

Table 10-8 on page 54 and Table 10-9 on page 54 relate the alternate functions of Port B to the overriding signals shown in Figure 10-6 on page 48.

Table 10-8. Overriding Signals for Alternate Functions in PB[3:2]

Signal Name	PB3/ADC11/PCINT11	PB2/ADC10/PCINT10
PUOE	0	0
PUOV	0	0
DDOE	0	0
DDOV	0	0
PVOE	0	0
PVOV	0	0
PTOE	0	0
DIEOE	PCINT11 • PCIE1 • ADC11D	PCINT10 • PCIE1 • ADC10D
DIEOV	PCINT11 • PCIE1	PCINT10 • PCIE1
DI	PCINT11 Input	INT0 / PCINT10 / SPI Master Input
AIO	ASDC11 Input	ADC10 Input

Table 10-9. Overriding Signals for Alternate Functions in PB[1:0]

Signal Name	PB1/ADC9/PCINT9	PB0/ADC8/PCINT8
PUOE	0	0
PUOV	0	0
DDOE	0	0
DDOV	0	0
PVOE	0	0
PVOV	0	0
PTOE	0	0
DIEOE	PCINT9 • PCIE1 • ADC9D	PCINT8 • PCIE1 • ADC8D
DIEOV	PCINT9 • PCIE1	PCINT8 • PCIE1
DI	PCINT9	PCINT8
AIO	ADC9 Input	ADC8 Input

10.3.3 Alternate Functions of Port C

The Port C pins with alternate function are shown in Table 10-10.

Table 10-10. Port A Pins Alternate Functions

Port Pin	Alternate Function
PC0	OC0A: Timer/Counter0 Compare Match A output $\overline{SS}$: SPI Slave Select PCINT12:Pin Change Interrupt 0, Source 12
PC1	SCK: SPI Clock SCL : TWI Clock ICP1: Timer/Counter1 Input Capture Pin T1: Timer/Counter1 Clock Source PCINT13:Pin Change Interrupt 0, Source 13
PC2	INT0: External Interrupt 0 Input CLKO: System Clock Output MISO: SPI Master Input / Slave Output PCINT14:Pin Change Interrupt 0, Source 14
PC3	$\overline{RESET}$: Reset pin PCINT15:Pin Change Interrupt 0, Source 15
PC4	MOSI: SPI Master Output / Slave Input SDA: TWI Data Input /Output TPIDATA:Serial Programming Data PCINT16:Pin Change Interrupt 0, Source 16
PC5	CLKI: External Clock Input TPICLK: Serial Programming Clock PCINT17:Pin Change Interrupt 0, Source 17

- **Port C, Bit 0 – OC0A/PCINT12**
  - OC0A: Output Compare Match output. Provided that the pin has been configured as an output it serves as an external output for Timer/Counter0 Compare Match A. This pin is also the output for the timer/counter PWM mode function.
  - $\overline{SS}$: Slave Select Input. Regardless of DDC0, this pin is automatically configured as an input when SPI is enabled as a slave. The data direction of this pin is controlled by DDC0 when SPI is enabled as a master.
  - PCINT12: Pin Change Interrupt source 12. The PC0 pin can serve as an external interrupt source for pin change interrupt 2.

- **Port C, Bit 1 – SCK/SCL/ICP1/T1/PCINT13**
  - SCK: SPI Clock.
  - SCL: TWI Clock. The pin is disconnected from the part and becomes the serial clock for the TWI when TWEN in TWSCRA is set. In this mode of operation, the pin is driven by an open drain driver with slew rate limitation and a spike filter.
  - ICP1: Timer/Counter1 Input Capture Pin.
  - T1: Timer/Counter1 counter source.
  - PCINT13: Pin Change Interrupt source 13. The PC1 pin can serve as an external interrupt source for pin change interrupt 2.

- **Port C, Bit 2 – INT0/CLKO/MISO/PCINT14**

- INT0: The PC2 pin can serve as an External Interrupt source 0.
- CLKO: The divided system clock can be output on the PB5 pin, if the CKOUT Fuse is programmed, regardless of the PORTB5 and DDB5 settings. It will also be output during reset.
- MISO: SPI Master Input / Slave Output. Regardless of DDC2, this pin is automatically configured as an input when SPI is enabled as a master. The data direction of this pin is controlled by DDC2 when SPI is enabled as a slave.
- PCINT14: Pin Change Interrupt source 14. The PC2 pin can serve as an external interrupt source for pin change interrupt 2.

- **Port C, Bit 3 – $\overline{\text{RESET}}$/PCINT15**
  - $\overline{\text{RESET}}$: External $\overline{\text{Reset}}$ input is active low and enabled by unprogramming (“1”) the RSTDISBL Fuse. Pullup is activated and output driver and digital input are deactivated when the pin is used as the $\overline{\text{RESET}}$ pin.
  - PCINT15: Pin Change Interrupt source 15. The PC3 pin can serve as an external interrupt source for pin change interrupt 2.

- **Port C, Bit 4 – MOSI/SDA/TPIDATA/PCINT16**
  - MOSI: SPI Master Output / Slave Input. Regardless of DDC4, this pin is automatically configured as an input when SPI is enabled as a slave. The data direction of this pin is controlled by DDC4 when SPI is enabled as a master.
  - SDA: TWI Data. The pin is disconnected from the port and becomes the serial data for the TWI when TWEN in TWSCRA is set. In this mode of operation, the pin is driven by an open drain driver with slew rate limitation and a spike filter.
  - TPIDATA: Serial Programming Data.
  - PCINT16: Pin Change Interrupt source 16. The PC4 pin can serve as an external interrupt source for pin change interrupt 2.

- **Port C, Bit 5 – CLKI/PCINT17**
  - CLKI: Clock Input from an external clock source, see “External Clock” on page 19.
  - TPICLK: Serial Programming Clock.
  - PCINT17: Pin Change Interrupt source 17. The PC5 pin can serve as an external interrupt source for pin change interrupt 2.

Table 10-11 and Table 10-12 relate the alternate functions of Port C to the overriding signals shown in Figure 10-6 on page 48.

Table 10-11. Overriding Signals for Alternate Functions in PC[5:3]

Signal Name	PC5/CLKI/PCINT17	PC4/MOSI/SDA/PCINT16	PC3/$\overline{\text{RESET}}$/PCINT15
PUOE	EXT_CLOCK[1]	0	$\overline{\text{RSTDISBL}}$[2]
PUOV	0	0	1
DDOE	EXT_CLOCK[1]	(SPE • $\overline{\text{MSTR}}$) + TWEN	$\overline{\text{RSTDISBL}}$[2]
DDOV	0	TWEN • $\overline{\text{SDA_OUT}}$	0
PVOE	EXT_CLOCK[1]	TWEN + (SPE • MSTR)	$\overline{\text{RSTDISBL}}$[2]
PVOV	0	$\overline{\text{TWEN}}$ • SPE • MSTR • SPI_MASTER_OUT + $\overline{\text{TWEN}}$ • ($\overline{\text{SPE}}$ + $\overline{\text{MSTR}}$)	0
PTOE	0	0	0
DIEOE	EXT_CLOCK + (PCINT17 • PCIE2)	PCINT16 • PCIE2	$\overline{\text{RSTDISBL}}$[2] + (PCINT15 • PCIE2)
DIEOV	(EXT_CLOCK • $\overline{\text{PWR_DOWN}}$) + ($\overline{\text{EXT_CLOCK}}$[1] • PCINT17 • PCIE2)	PCINT16 • PCIE2	$\overline{\text{RSTDISBL}}$[2] • PCINT15 • PCIE2
DI	CLOCK / PCINT17 Input	PCINT16 / SPI Slave Input	PCINT15 Input
AIO		SDA Input	

Notes: 1. EXT_CLOCK = external clock is selected as system clock.
2. x RSTDISBL is 1 when the configuration bit is “0” (programmed).
3. When TWI is enabled the slew rate control and spike filter are activated on PC4. This is not illustrated in Figure 10-6 on page 48. The spike filter is connected between AIOxn and the TWI.

Table 10-12. Overriding Signals for Alternate Functions in PC[2:0]

Signal Name	PC2/INT0/CLKO/MISO/PCINT14	PC1/SCK/SCL/ICP1/T1/PCINT13	PC0/OC0A/$\overline{\text{SS}}$/PCINT12
PUOE	CKOUT[1]	0	0
PUOV	0	0	0
DDOE	CKOUT[1] + (SPE • MSTR)	TWEN + (SPE • MSTR)	SPE • $\overline{\text{MSTR}}$
DDOV	CKOUT	TWEN + $\overline{\text{SCL_OUT}}$	0
PVOE	CKOUT[1] + (SPE • $\overline{\text{MSTR}}$)	TWEN + (SPE • MSTR)	OC0A_ENABLE
PVOV	CKOUT[1] • System Clock + $\overline{\text{CKOUT}}$ • SPE • $\overline{\text{MSTR}}$ • SPI_SLAVE_OUT	$\overline{\text{TWEN}}$ • (SPE • MSTR • SCK_OUT • ($\overline{\text{SPE}}$ + $\overline{\text{MSTR}}$))	OC0A
PTOE	0	0	0
DIEOE	(PCINT14 • PCIE2) + INT0	PCINT13 • PCIE2	PCINT12 • PCIE2
DIEOV	(PCINT14 • PCIE2) + INT0	PCINT13 • PCIE2	PCINT12 • PCIE2
DI	INT0 / PCINT14 / SPI Master Input	ICP1 / SCK / T1 / SCL / PCINT13 Input	SPI $\overline{\text{SS}}$ / PCINT12 Input
AIO		SCL Input	

Notes: 1. CKOUT is 1 when the configuration bit is “0” (programmed).
2. When TWI is enabled the slew rate control and spike filter are activated on PC1. This is not illustrated in Figure 10-6 on page 48. The spike filter is connected between AIOxn and the TWI.

10.4 Register Description

10.4.1 PORTCR – Port Control Register

Bit	7	6	5	4	3	2	1	0	
0x08	ADC11D	ADC10D	ADC9D	ADC8D	–	BBMC	BBMB	BBMA	PORTCR
Read/Write	R/W	R/W	R/W	R/W	R	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 3 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 2 – BBMC: Break-Before-Make Mode Enable**

When this bit is set the Break-Before-Make mode is activated for the entire Port C. The intermediate tri-state cycle is then inserted when writing DDRCn to make an output. For further information, see “Break-Before-Make Switching” on page 44

- **Bit 1 – BBMB: Break-Before-Make Mode Enable**

When this bit is set the Break-Before-Make mode is activated for the entire Port B. The intermediate tri-state cycle is then inserted when writing DDRBn to make an output. For further information, see “Break-Before-Make Switching” on page 44.

- **Bit 0 – BBMA: Break-Before-Make Mode Enable**

When this bit is set the Break-Before-Make mode is activated for the entire Port A. The intermediate tri-state cycle is then inserted when writing DDRAn to make an output. For further information, see “Break-Before-Make Switching” on page 44.

10.4.2 PUEA – Port A Pull-up Enable Control Register

Bit	7	6	5	4	3	2	1	0	
0x03	PUEA7	PUEA6	PUEA5	PUEA4	PUEA3	PUEA2	PUEA1	PUEA0	PUEA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.3 PORTA – Port A Data Register

Bit	7	6	5	4	3	2	1	0	
0x02	PORTA7	PORTA6	PORTA5	PORTA4	PORTA3	PORTA2	PORTA1	PORTA0	PORTA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.4 DDRA – Port A Data Direction Register

Bit	7	6	5	4	3	2	1	0	
0x01	DDA7	DDA6	DDA5	DDA4	DDA3	DDA2	DDA1	DDA0	DDRA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.5 PINA – Port A Input Pins

Bit	7	6	5	4	3	2	1	0	
0x00	PINA7	PINA6	PINA5	PINA4	PINA3	PINA2	PINA1	PINA0	PINA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	

10.4.6 PUEB – Port B Pull-up Enable Control Register

Bit	7	6	5	4	3	2	1	0	
0x07	–	–	–	–	PUEB3	PUEB2	PUEB1	PUEB0	PUEB
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.7 PORTB – Port B Data Register

Bit	7	6	5	4	3	2	1	0	
0x06	–	–	–	–	PORTB3	PORTB2	PORTB1	PORTB0	PORTB
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.8 DDRB – Port B Data Direction Register

Bit	7	6	5	4	3	2	1	0	
0x05	–	–	–	–	DDB3	DDB2	DDB1	DDB0	DDRB
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.9 PINB – Port B Input Pins

Bit	7	6	5	4	3	2	1	0	
0x04	–	–	–	–	PINB3	PINB2	PINB1	PINB0	PINB
Read/Write	R	R	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	N/A	N/A	N/A	N/A	

10.4.10 PUEC – Port C Pull-up Enable Control Register

Bit	7	6	5	4	3	2	1	0	
0x1E	–	–	PUEC5	PUEC4	PUEC3	PUEC2	PUEC1	PUEC0	PUEC
Read/Write	R	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.11 PORTC – Port C Data Register

Bit	7	6	5	4	3	2	1	0	
0x1D	–	–	PORTC5	PORTC4	PORTC3	PORTC2	PORTC1	PORTC0	PORTC
Read/Write	R	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.12 DDRC – Port C Data Direction Register

Bit	7	6	5	4	3	2	1	0	
0x1C	–	–	PINC5	PINC4	DDC3	DDC2	DDC1	DDC0	DDRC
Read/Write	R	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

10.4.13 PINC – Port C Input Pins

Bit	7	6	5	4	3	2	1	0	
0x1B	–	–	PINC5	PINC4	PINC3	PINC2	PINC1	PINC0	PINC
Read/Write	R	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	N/A	N/A	N/A	N/A	

11. Timer/Counter0

11.1 Features

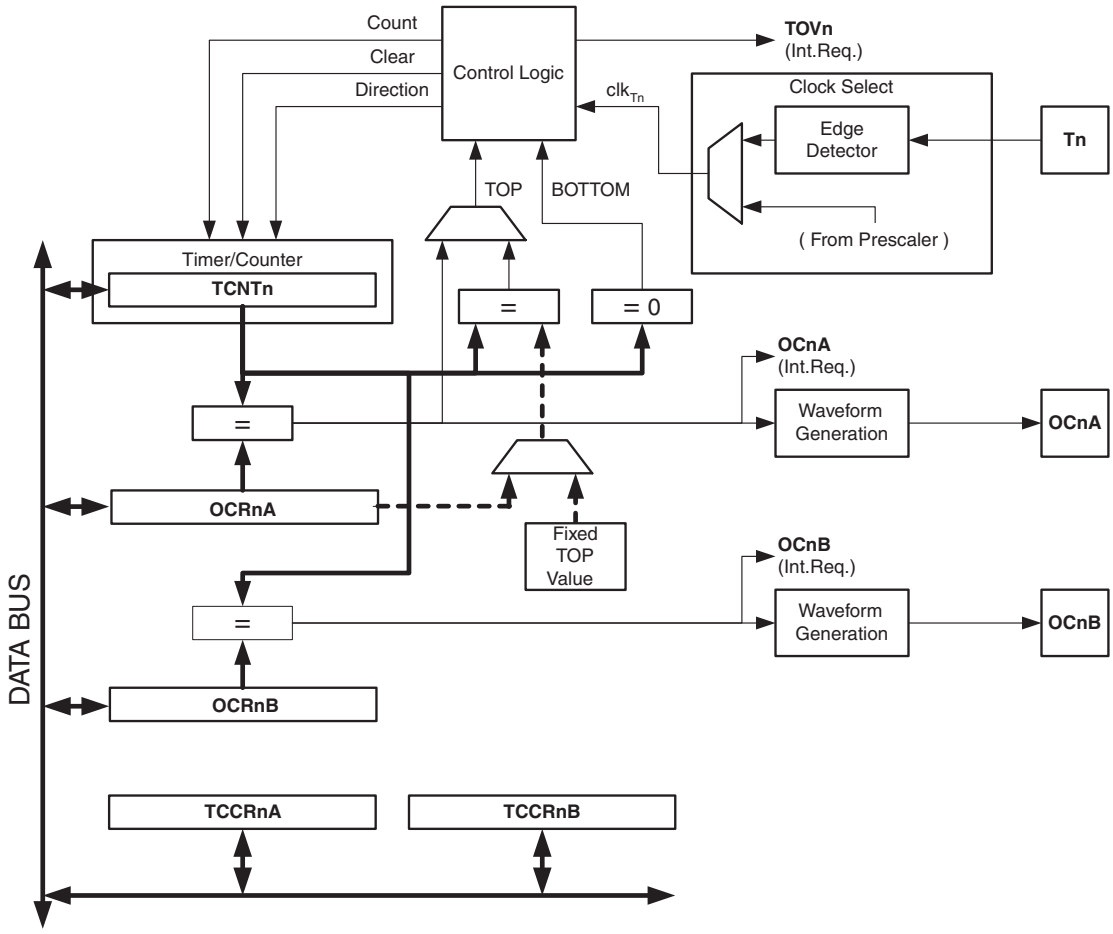
- **Two Independent Output Compare Units**
- **Double Buffered Output Compare Registers**
- **Clear Timer on Compare Match (Auto Reload)**
- **Glitch Free, Phase Correct Pulse Width Modulator (PWM)**
- **Variable PWM Period**
- **Frequency Generator**
- **Three Independent Interrupt Sources (TOV0, OCF0A, and OCF0B)**

11.2 Overview

Timer/Counter0 is a general purpose 8-bit Timer/Counter module, with two independent Output Compare Units, and with PWM support. It allows accurate program execution timing (event management) and wave generation.

A simplified block diagram of the 8-bit Timer/Counter is shown in Figure 11-1 on page 61. For the actual placement of I/O pins, refer to Figure 1-1 on page 2. CPU accessible I/O Registers, including I/O bits and I/O pins, are shown in bold. The device-specific I/O Register and bit locations are listed in the "Register Description" on page 71.

Figure 11-1. 8-bit Timer/Counter Block Diagram



11.2.1 Registers

The Timer/Counter (TCNT0) and Output Compare Registers (OCR0A and OCR0B) are 8-bit registers. Interrupt request (abbreviated to Int.Req. in Figure 11-1) signals are all visible in the Timer Interrupt Flag Register (TIFR). All interrupts are individually masked with the Timer Interrupt Mask Register (TIMSK). TIFR and TIMSK are not shown in the figure.

The Timer/Counter can be clocked internally, via the prescaler, or by an external clock source on the T0 pin. The Clock Select logic block controls which clock source and edge the Timer/Counter uses to increment (or decrement) its value. The Timer/Counter is inactive when no clock source is selected. The output from the Clock Select logic is referred to as the timer clock (clk_{T0}).

The double buffered Output Compare Registers (OCR0A and OCR0B) is compared with the Timer/Counter value at all times. The result of the compare can be used by the Waveform Generator to generate a PWM or variable frequency output on the Output Compare pins (OC0A and OC0B). See “Output Compare Unit” on page 63 for details. The Compare Match event will also set the Compare Flag (OCF0A or OCF0B) which can be used to generate an Output Compare interrupt request.

11.2.2 Definitions

Many register and bit references in this section are written in general form. A lower case “n” replaces the Timer/Counter number, in this case 0. A lower case “x” replaces the Output Compare Unit, in this case Compare Unit A or Compare Unit B. However, when using the register or bit defines in a program, the precise form must be used, i.e., TCNT0 for accessing Timer/Counter0 counter value and so on.

The definitions in Table 11-1 are also used extensively throughout the document.

Table 11-1. Definitions

Constant	Description
BOTTOM	The counter reaches BOTTOM when it becomes 0x00
MAX	The counter reaches its MAXimum when it becomes 0xFF (decimal 255)
TOP	The counter reaches the TOP when it becomes equal to the highest value in the count sequence. The TOP value can be assigned to be the fixed value 0xFF (MAX) or the value stored in the OCR0A Register. The assignment depends on the mode of operation

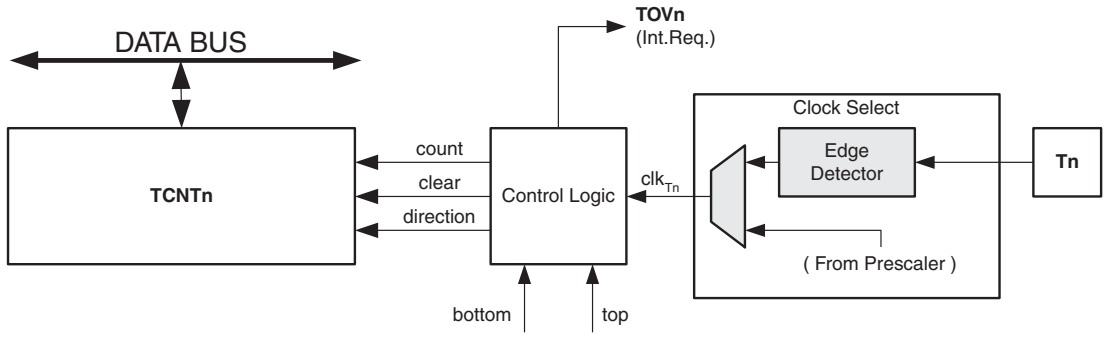
11.3 Clock Sources

The Timer/Counter can be clocked by an internal or an external clock source. The clock source is selected by the Clock Select logic which is controlled by the Clock Select (CS0[2:0]) bits located in the Timer/Counter Control Register (TCCR0B). For details on clock sources and prescaler, see "Timer/Counter Prescaler" on page 92.

11.4 Counter Unit

The main part of the 8-bit Timer/Counter is the programmable bi-directional counter unit. Figure 11-2 on page 62 shows a block diagram of the counter and its surroundings.

Figure 11-2. Counter Unit Block Diagram



Signal description (internal signals):

count	Increment or decrement TCNT0 by 1.
direction	Select between increment and decrement.
clear	Clear TCNT0 (set all bits to zero).
clk_{Tn}	Timer/Counter clock, referred to as clk_{T0} in the following.
top	Signalize that TCNT0 has reached maximum value.
bottom	Signalize that TCNT0 has reached minimum value (zero).

Depending of the mode of operation used, the counter is cleared, incremented, or decremented at each timer clock (clk_{T0}). clk_{T0} can be generated from an external or internal clock source, selected by the Clock Select bits (CS0[2:0]). When no clock source is selected (CS0[2:0] = 0) the timer is stopped. However, the TCNT0 value can be accessed by the CPU, regardless of whether clk_{T0} is present or not. A CPU write overrides (has priority over) all counter clear or count operations.

The counting sequence is determined by the setting of the WGM01 and WGM00 bits located in the Timer/Counter Control Register (TCCR0A) and the WGM02 bit located in the Timer/Counter Control Register B (TCCR0B). There are close connections between how the counter behaves (counts) and how waveforms are generated on the Out-

put Compare output OC0A. For more details about advanced counting sequences and waveform generation, see “Modes of Operation” on page 65.

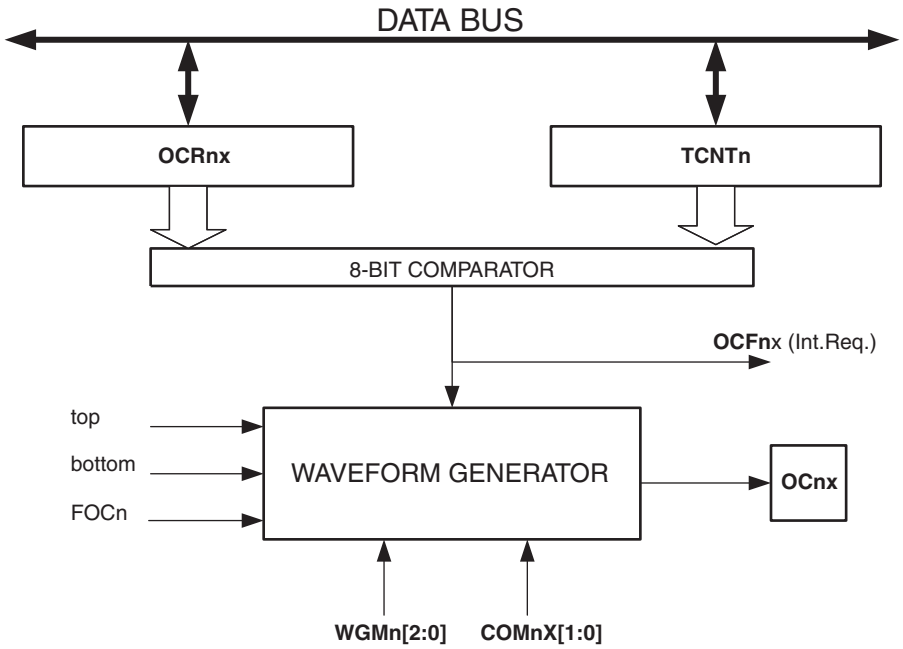
The Timer/Counter Overflow Flag (TOV0) is set according to the mode of operation selected by the WGM0[1:0] bits. TOV0 can be used for generating a CPU interrupt.

11.5 Output Compare Unit

The 8-bit comparator continuously compares TCNT0 with the Output Compare Registers (OCR0A and OCR0B). Whenever TCNT0 equals OCR0A or OCR0B, the comparator signals a match. A match will set the Output Compare Flag (OCF0A or OCF0B) at the next timer clock cycle. If the corresponding interrupt is enabled, the Output Compare Flag generates an Output Compare interrupt. The Output Compare Flag is automatically cleared when the interrupt is executed. Alternatively, the flag can be cleared by software by writing a logical one to its I/O bit location. The Waveform Generator uses the match signal to generate an output according to operating mode set by the WGM0[2:0] bits and Compare Output mode (COM0x[1:0]) bits. The max and bottom signals are used by the Waveform Generator for handling the special cases of the extreme values in some modes of operation. See “Modes of Operation” on page 65.

Figure 11-3 on page 63 shows a block diagram of the Output Compare unit.

Figure 11-3. Output Compare Unit, Block Diagram



The OCR0x Registers are double buffered when using any of the Pulse Width Modulation (PWM) modes. For the normal and Clear Timer on Compare (CTC) modes of operation, the double buffering is disabled. The double buffering synchronizes the update of the OCR0x Compare Registers to either top or bottom of the counting sequence. The synchronization prevents the occurrence of odd-length, non-symmetrical PWM pulses, thereby making the output glitch-free.

The OCR0x Register access may seem complex, but this is not case. When the double buffering is enabled, the CPU has access to the OCR0x Buffer Register, and if double buffering is disabled the CPU will access the OCR0x directly.

11.5.1 Force Output Compare

In non-PWM waveform generation modes, the match output of the comparator can be forced by writing a one to the Force Output Compare (0x) bit. Forcing Compare Match will not set the OCF0x Flag or reload/clear the timer, but the OC0x pin will be updated as if a real Compare Match had occurred (the COM0x[1:0] bits settings define whether the OC0x pin is set, cleared or toggled).

11.5.2 Compare Match Blocking by TCNT0 Write

All CPU write operations to the TCNT0 Register will block any Compare Match that occur in the next timer clock cycle, even when the timer is stopped. This feature allows OCR0x to be initialized to the same value as TCNT0 without triggering an interrupt when the Timer/Counter clock is enabled.

11.5.3 Using the Output Compare Unit

Since writing TCNT0 in any mode of operation will block all Compare Matches for one timer clock cycle, there are risks involved when changing TCNT0 when using the Output Compare Unit, independently of whether the Timer/Counter is running or not. If the value written to TCNT0 equals the OCR0x value, the Compare Match will be missed, resulting in incorrect waveform generation. Similarly, do not write the TCNT0 value equal to BOTTOM when the counter is down-counting.

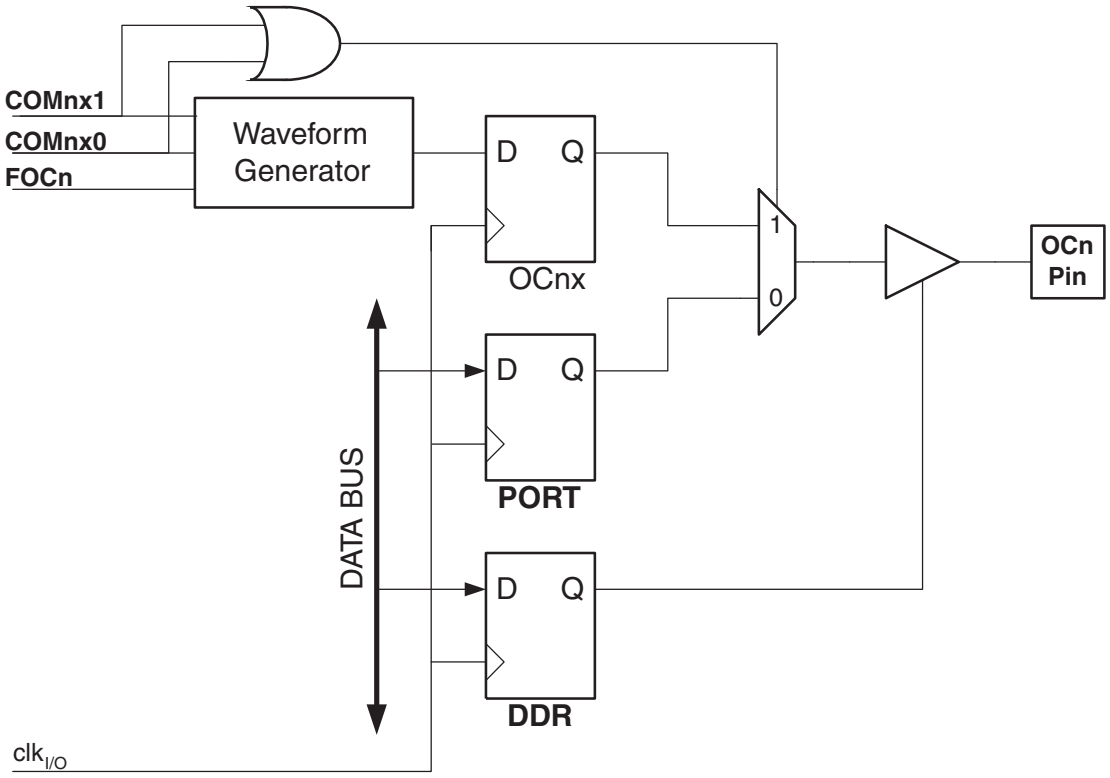
The setup of the OC0x should be performed before setting the Data Direction Register for the port pin to output. The easiest way of setting the OC0x value is to use the Force Output Compare (0x) strobe bits in Normal mode. The OC0x Registers keep their values even when changing between Waveform Generation modes.

Be aware that the COM0x[1:0] bits are not double buffered together with the compare value. Changing the COM0x[1:0] bits will take effect immediately.

11.6 Compare Match Output Unit

The Compare Output mode (COM0x[1:0]) bits have two functions. The Waveform Generator uses the COM0x[1:0] bits for defining the Output Compare (OC0x) state at the next Compare Match. Also, the COM0x[1:0] bits control the OC0x pin output source. Figure 11-4 on page 65 shows a simplified schematic of the logic affected by the COM0x[1:0] bit setting. The I/O Registers, I/O bits, and I/O pins in the figure are shown in bold. Only the parts of the general I/O Port Control Registers (DDR and PORT) that are affected by the COM0x[1:0] bits are shown. When referring to the OC0x state, the reference is for the internal OC0x Register, not the OC0x pin. If a system reset occur, the OC0x Register is reset to “0”.

Figure 11-4. Compare Match Output Unit, Schematic



The general I/O port function is overridden by the Output Compare (OC0x) from the Waveform Generator if either of the COM0x[1:0] bits are set. However, the OC0x pin direction (input or output) is still controlled by the Data Direction Register (DDR) for the port pin. The Data Direction Register bit for the OC0x pin (DDR_OC0x) must be set as output before the OC0x value is visible on the pin. The port override function is independent of the Waveform Generation mode.

The design of the Output Compare pin logic allows initialization of the OC0x state before the output is enabled. Note that some COM0x[1:0] bit settings are reserved for certain modes of operation, see “Register Description” on page 71

11.6.1 Compare Output Mode and Waveform Generation

The Waveform Generator uses the COM0x[1:0] bits differently in Normal, CTC, and PWM modes. For all modes, setting the COM0x[1:0] = 0 tells the Waveform Generator that no action on the OC0x Register is to be performed on the next Compare Match. For compare output actions in the non-PWM modes refer to Table 11-2 on page 71. For fast PWM mode, refer to Table 11-3 on page 72, and for phase correct PWM refer to Table 11-4 on page 72.

A change of the COM0x[1:0] bits state will have effect at the first Compare Match after the bits are written. For non-PWM modes, the action can be forced to have immediate effect by using the Force Output Compare bits. See “TCCR0B – Timer/Counter Control Register B” on page 74.

11.7 Modes of Operation

The mode of operation, i.e., the behavior of the Timer/Counter and the Output Compare pins, is defined by the combination of the Waveform Generation mode (WGM0[2:0]) and Compare Output mode (COM0x[1:0]) bits. The Compare Output mode bits do not affect the counting sequence, while the Waveform Generation mode bits do. The COM0x[1:0] bits control whether the PWM output generated should be inverted or not (inverted or non-inverted PWM). For non-PWM modes the COM0x[1:0] bits control whether the output should be set, cleared, or toggled at a Compare Match (See “Modes of Operation” on page 65).

For detailed timing information refer to Figure 11-8 on page 70, Figure 11-9 on page 70, Figure 11-10 on page 70 and Figure 11-11 on page 71 in "Timer/Counter Timing Diagrams" on page 69.

11.7.1 Normal Mode

The simplest mode of operation is the Normal mode (WGM0[2:0] = 0). In this mode the counting direction is always up (incrementing), and no counter clear is performed. The counter simply overruns when it passes its maximum 8-bit value (TOP = 0xFF) and then restarts from the bottom (0x00). In normal operation the Timer/Counter Overflow Flag (TOV0) will be set in the same timer clock cycle as the TCNT0 becomes zero. The TOV0 Flag in this case behaves like a ninth bit, except that it is only set, not cleared. However, combined with the timer overflow interrupt that automatically clears the TOV0 Flag, the timer resolution can be increased by software. There are no special cases to consider in the Normal mode, a new counter value can be written anytime.

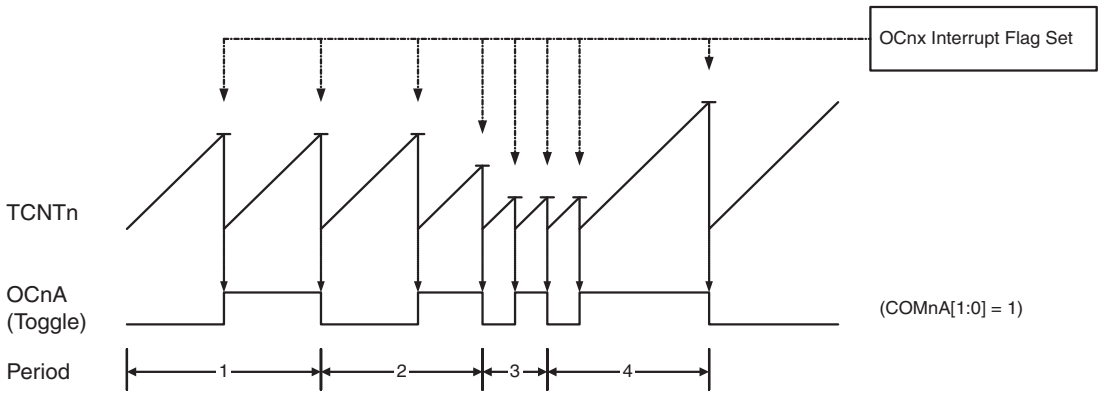
The Output Compare Unit can be used to generate interrupts at some given time. Using the Output Compare to generate waveforms in Normal mode is not recommended, since this will occupy too much of the CPU time.

11.7.2 Clear Timer on Compare Match (CTC) Mode

In Clear Timer on Compare or CTC mode (WGM0[2:0] = 2), the OCR0A Register is used to manipulate the counter resolution. In CTC mode the counter is cleared to zero when the counter value (TCNT0) matches the OCR0A. The OCR0A defines the top value for the counter, hence also its resolution. This mode allows greater control of the Compare Match output frequency. It also simplifies the operation of counting external events.

The timing diagram for the CTC mode is shown in Figure 11-5 on page 66. The counter value (TCNT0) increases until a Compare Match occurs between TCNT0 and OCR0A, and then counter (TCNT0) is cleared.

Figure 11-5. CTC Mode, Timing Diagram



An interrupt can be generated each time the counter value reaches the TOP value by using the OCF0A Flag. If the interrupt is enabled, the interrupt handler routine can be used for updating the TOP value. However, changing TOP to a value close to BOTTOM when the counter is running with none or a low prescaler value must be done with care since the CTC mode does not have the double buffering feature. If the new value written to OCR0A is lower than the current value of TCNT0, the counter will miss the Compare Match. The counter will then have to count to its maximum value (0xFF) and wrap around starting at 0x00 before the Compare Match can occur.

For generating a waveform output in CTC mode, the OC0A output can be set to toggle its logical level on each Compare Match by setting the Compare Output mode bits to toggle mode (COM0A[1:0] = 1). The OC0A value will not be visible on the port pin unless the data direction for the pin is set to output. The waveform generated will have a maximum frequency of $f_{clk_I/O}/2$ when OCR0A is set to zero (0x00). The waveform frequency is defined by the following equation:

$$f_{OCnx} = \frac{f_{clk_I/O}}{2 \cdot N \cdot (1 + OCRnA)}$$

The *N* variable represents the prescale factor (1, 8, 64, 256, or 1024).

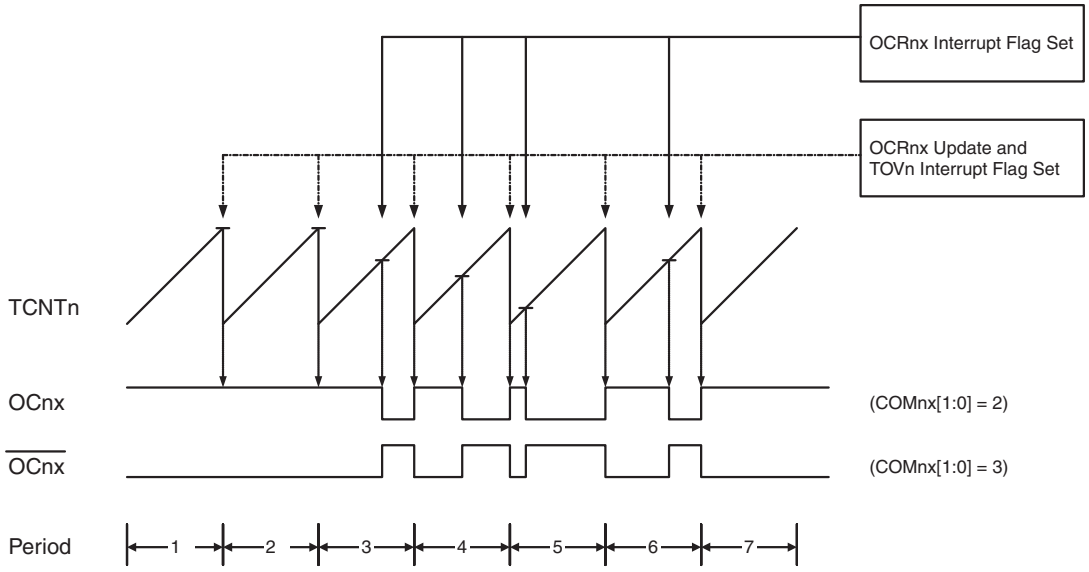
As for the Normal mode of operation, the TOV0 Flag is set in the same timer clock cycle that the counter counts from MAX to 0x00.

11.7.3 Fast PWM Mode

The fast Pulse Width Modulation or fast PWM mode (WGM0[2:0] = 3 or 7) provides a high frequency PWM waveform generation option. The fast PWM differs from the other PWM option by its single-slope operation. The counter counts from BOTTOM to TOP then restarts from BOTTOM. TOP is defined as 0xFF when WGM0[2:0] = 3, and OCR0A when WGM0[2:0] = 7. In non-inverting Compare Output mode, the Output Compare (OC0x) is cleared on the Compare Match between TCNT0 and OCR0x, and set at BOTTOM. In inverting Compare Output mode, the output is set on Compare Match and cleared at BOTTOM. Due to the single-slope operation, the operating frequency of the fast PWM mode can be twice as high as the phase correct PWM mode that use dual-slope operation. This high frequency makes the fast PWM mode well suited for power regulation, rectification, and DAC applications. High frequency allows physically small sized external components (coils, capacitors), and therefore reduces total system cost.

In fast PWM mode, the counter is incremented until the counter value matches the TOP value. The counter is then cleared at the following timer clock cycle. The timing diagram for the fast PWM mode is shown in Figure 11-6 on page 67. The TCNT0 value is in the timing diagram shown as a histogram for illustrating the single-slope operation. The diagram includes non-inverted and inverted PWM outputs. The small horizontal line marks on the TCNT0 slopes represent Compare Matches between OCR0x and TCNT0.

Figure 11-6. Fast PWM Mode, Timing Diagram



The Timer/Counter Overflow Flag (TOV0) is set each time the counter reaches TOP. If the interrupt is enabled, the interrupt handler routine can be used for updating the compare value.

In fast PWM mode, the compare unit allows generation of PWM waveforms on the OC0x pins. Setting the COM0x[1:0] bits to two will produce a non-inverted PWM and an inverted PWM output can be generated by setting the COM0x[1:0] to three: Setting the COM0A[1:0] bits to one allowes the OC0A pin to toggle on Compare Matches if the WGM02 bit is set. This option is not available for the OC0B pin (See Table 11-3 on page 72). The actual OC0x value will only be visible on the port pin if the data direction for the port pin is set as output. The PWM waveform is generated by setting (or clearing) the OC0x Register at the Compare Match between OCR0x and TCNT0,

and clearing (or setting) the OC0x Register at the timer clock cycle the counter is cleared (changes from TOP to BOTTOM).

The PWM frequency for the output can be calculated by the following equation:

$$f_{OCnxPWM} = \frac{f_{clk_I/O}}{N \cdot (TOP + 1)}$$

The *N* variable represents the prescale factor (1, 8, 64, 256, or 1024).

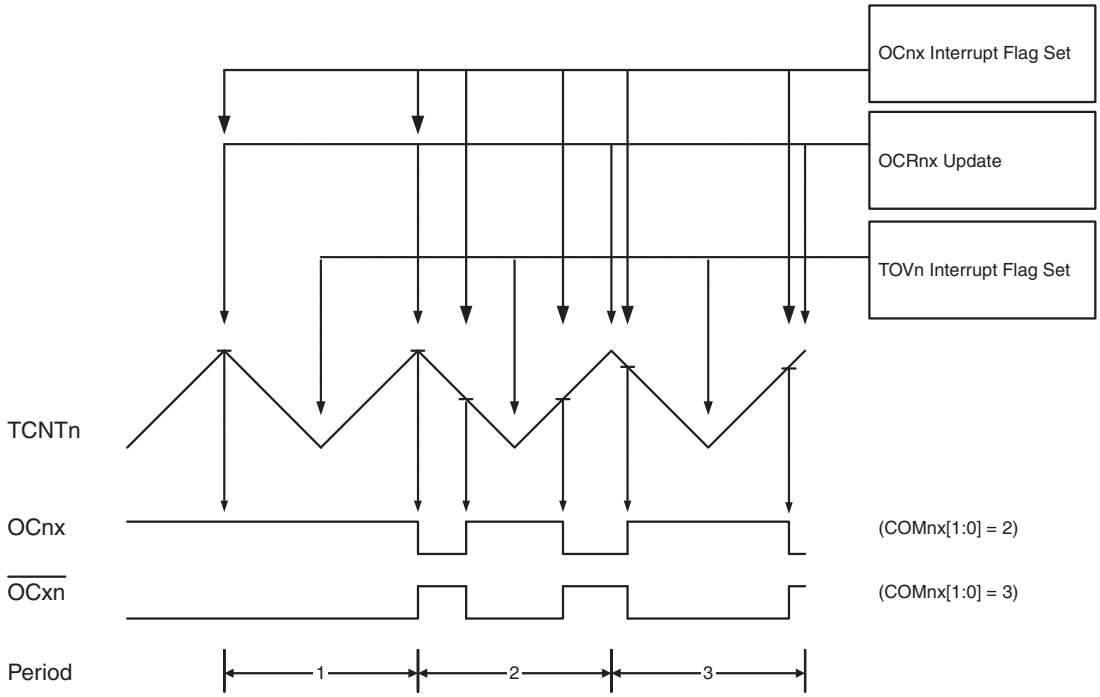
The extreme values for the OCR0x Register represents special cases when generating a PWM waveform output in the fast PWM mode. If OCR0x is set equal to BOTTOM, the output will be a narrow spike for each TOP+1 timer clock cycle. Setting the OCR0x equal to TOP will result in a constantly high or low output (depending on the polarity of the output set by the COM0x[1:0] bits.)

A frequency (with 50% duty cycle) waveform output in fast PWM mode can be achieved by setting OC0A to toggle its logical level on each Compare Match (COM0A[1:0] = 1). The waveform generated will have a maximum frequency of $f_{clk_I/O}/2$ when OCR0A is set to zero. This feature is similar to the OC0A toggle in CTC mode, except the double buffer feature of the Output Compare unit is enabled in the fast PWM mode.

11.7.4 Phase Correct PWM Mode

The phase correct PWM mode (WGM0[2:0] = 1 or 5) provides a high resolution phase correct PWM waveform generation option. The phase correct PWM mode is based on a dual-slope operation. The counter counts repeatedly from BOTTOM to TOP and then from TOP to BOTTOM. TOP is defined as 0xFF when WGM0[2:0] = 1, and OCR0A when WGM0[2:0] = 5. In non-inverting Compare Output mode, the Output Compare (OC0x) is cleared on the Compare Match between TCNT0 and OCR0x while upcounting, and set on the Compare Match while downcounting. In inverting Output Compare mode, the operation is inverted. The dual-slope operation has lower maximum operation frequency than single slope operation. However, due to the symmetric feature of the dual-slope PWM modes, these modes are preferred for motor control applications.

Figure 11-7. Phase Correct PWM Mode, Timing Diagram



In phase correct PWM mode the counter is incremented until the counter value matches TOP. When the counter reaches TOP, it changes the count direction. The TCNT0 value will be equal to TOP for one timer clock cycle. The timing diagram for the phase correct PWM mode is shown on Figure 11-7. The TCNT0 value is in the timing diagram shown as a histogram for illustrating the dual-slope operation. The diagram includes non-inverted and inverted PWM outputs. The small horizontal line marks on the TCNT0 slopes represent Compare Matches between OCR0x and TCNT0.

The Timer/Counter Overflow Flag (TOV0) is set each time the counter reaches BOTTOM. The Interrupt Flag can be used to generate an interrupt each time the counter reaches the BOTTOM value.

In phase correct PWM mode, the compare unit allows generation of PWM waveforms on the OC0x pins. Setting the COM0x[1:0] bits to two will produce a non-inverted PWM. An inverted PWM output can be generated by setting the COM0x[1:0] to three: Setting the COM0A0 bits to one allows the OC0A pin to toggle on Compare Matches if the WGM02 bit is set. This option is not available for the OC0B pin (See Table 11-4 on page 72). The actual OC0x value will only be visible on the port pin if the data direction for the port pin is set as output. The PWM waveform is generated by clearing (or setting) the OC0x Register at the Compare Match between OCR0x and TCNT0 when the counter increments, and setting (or clearing) the OC0x Register at Compare Match between OCR0x and TCNT0 when the counter decrements. The PWM frequency for the output when using phase correct PWM can be calculated by the following equation:

$$f_{OCnxPCPWM} = \frac{f_{clk_I/O}}{2 \times N \times TOP}$$

The N variable represents the prescale factor (1, 8, 64, 256, or 1024).

The extreme values for the OCR0x Register represent special cases when generating a PWM waveform output in the phase correct PWM mode. If the OCR0x is set equal to BOTTOM, the output will be continuously low and if set equal to TOP the output will be continuously high for non-inverted PWM mode. For inverted PWM the output will have the opposite logic values.

At the very start of period 2 in Figure 11-7 on page 68 OCnx has a transition from high to low even though there is no Compare Match. The point of this transition is to guarantee symmetry around BOTTOM. There are two cases that give a transition without Compare Match.

- OCR0x changes its value from TOP, like in Figure 11-7 on page 68. When the OCR0x value is TOPthe OCnx pin value is the same as the result of a down-counting Compare Match. To ensure symmetry around BOTTOM the OCnx value at TOP must correspond to the result of an up-counting Compare Match.
- The timer starts counting from a value higher than the one in OCR0x, and for that reason misses the Compare Match and hence the OCnx change that would have happened on the way up.

11.8 Timer/Counter Timing Diagrams

The Timer/Counter is a synchronous design and the timer clock (clk_{T0}) is therefore shown as a clock enable signal in the following figures. The figures include information on when Interrupt Flags are set. Figure 11-8 on page 70 contains timing data for basic Timer/Counter operation. The figure shows the count sequence close to the MAX value in all modes other than phase correct PWM mode.

Figure 11-8. Timer/Counter Timing Diagram, no Prescaling

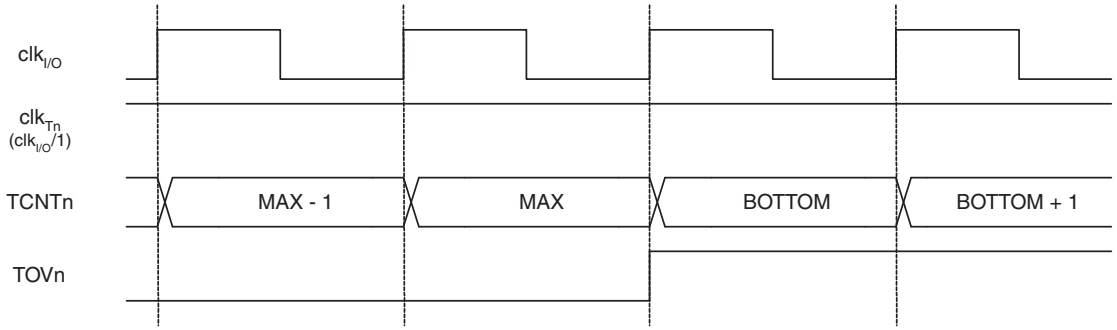


Figure 11-9 on page 70 shows the same timing data, but with the prescaler enabled.

Figure 11-9. Timer/Counter Timing Diagram, with Prescaler ($f_{clk_I/O}/8$)

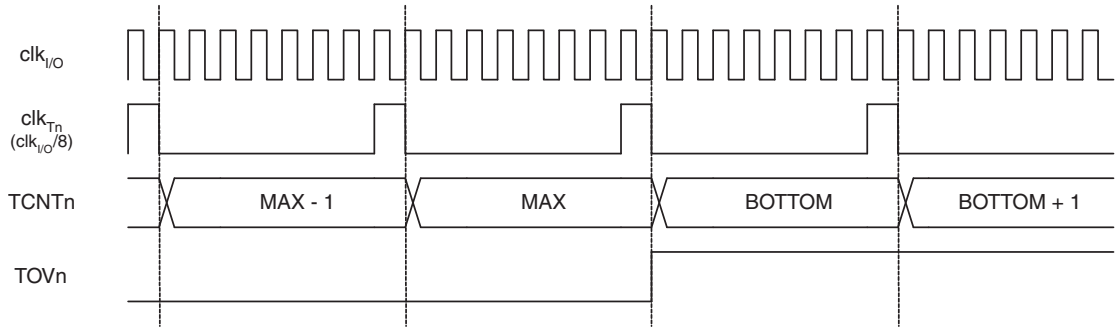


Figure 11-10 on page 70 shows the setting of OCF0B in all modes and OCF0A in all modes except CTC mode and PWM mode, where OCR0A is TOP.

Figure 11-10. Timer/Counter Timing Diagram, Setting of OCF0x, with Prescaler ($f_{clk_I/O}/8$)

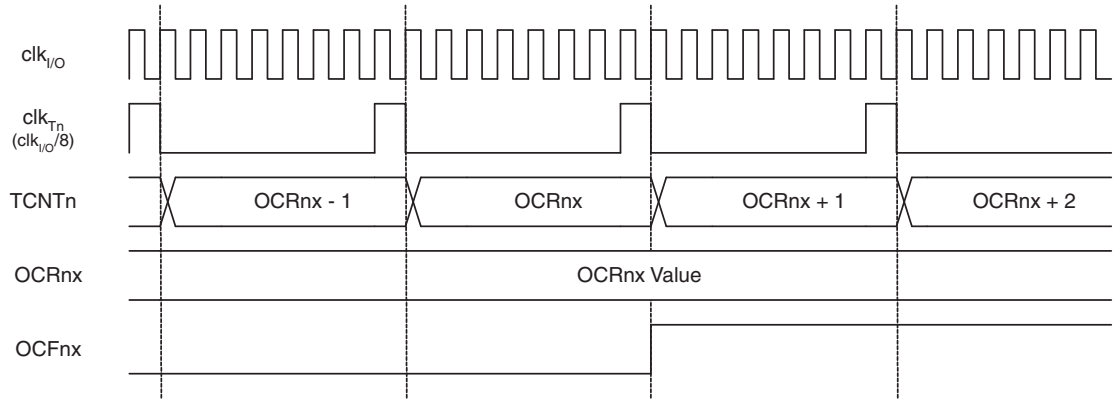
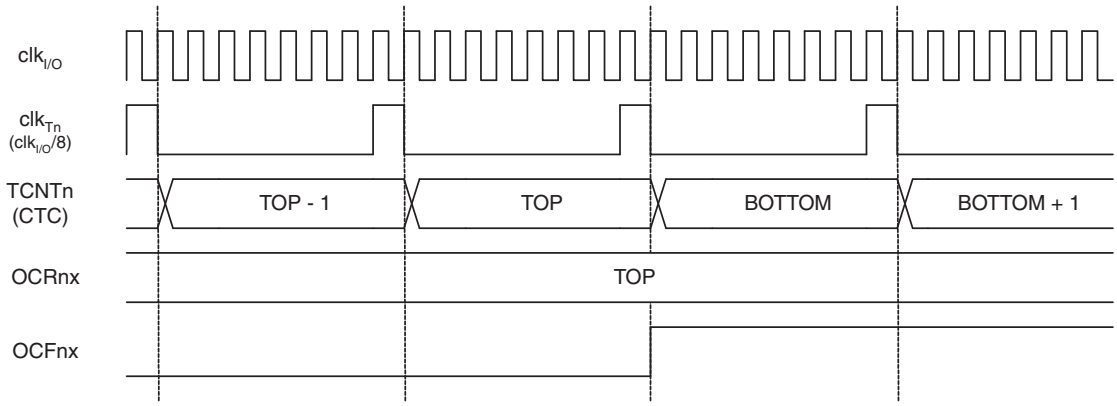


Figure 11-11 on page 71 shows the setting of OCF0A and the clearing of TCNT0 in CTC mode and fast PWM mode where OCR0A is TOP.

Figure 11-11. Timer/Counter Timing Diagram, Clear Timer on Compare Match mode, with Prescaler ($f_{clk_I/O}/8$)



11.9 Register Description

11.9.1 TCCR0A – Timer/Counter Control Register A

Bit	7	6	5	4	3	2	1	0	
0x19	COM0A1	COM0A0	COM0B1	COM0B0	–	–	WGM01	WGM00	TCCR0A
Read/Write	R/W	R/W	R/W	R/W	R	R	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:6 – COM0A[1:0]: Compare Match Output A Mode**

These bits control the Output Compare pin (OC0A) behavior. If one or both of the COM0A[1:0] bits are set, the OC0A output overrides the normal port functionality of the I/O pin it is connected to. However, note that the Data Direction Register (DDR) bit corresponding to the OC0A pin must be set in order to enable the output driver.

When OC0A is connected to the pin, the function of the COM0A[1:0] bits depends on the WGM0[2:0] bit setting. Table 11-2 shows the COM0A[1:0] bit functionality when the WGM0[2:0] bits are set to a normal or CTC mode (non-PWM).

Table 11-2. Compare Output Mode, non-PWM Mode

COM0A1	COM0A0	Description
0	0	Normal port operation, OC0A disconnected.
0	1	Toggle OC0A on Compare Match
1	0	Clear OC0A on Compare Match
1	1	Set OC0A on Compare Match

Table 11-3 shows COM0A[1:0] bit functionality when WGM0[1:0] bits are set to fast PWM mode.

Table 11-3. Compare Output Mode, Fast PWM Mode[1]

COM0A1	COM0A0	Description
0	0	Normal port operation, OC0A disconnected
0	1	WGM02 = 0: Normal Port Operation, OC0A Disconnected WGM02 = 1: Toggle OC0A on Compare Match
1	0	Clear OC0A on Compare Match Set OC0A at BOTTOM (non-inverting mode)
1	1	Set OC0A on Compare Match Clear OC0A at BOTTOM (inverting mode)

Note: 1. A special case occurs when OCR0A equals TOP and COM0A1 is set. In this case, the Compare Match is ignored, but the set or clear is done at BOTTOM. See "Fast PWM Mode" on page 67 for more details.

Table 11-4 shows COM0A[1:0] bit functionality when WGM0[2:0] bits are set to phase correct PWM mode.

Table 11-4. Compare Output Mode, Phase Correct PWM Mode[1]

COM0A1	COM0A0	Description
0	0	Normal port operation, OC0A disconnected.
0	1	WGM02 = 0: Normal Port Operation, OC0A Disconnected. WGM02 = 1: Toggle OC0A on Compare Match.
1	0	Clear OC0A on Compare Match when up-counting. Set OC0A on Compare Match when down-counting.
1	1	Set OC0A on Compare Match when up-counting. Clear OC0A on Compare Match when down-counting.

Note: 1. When OCR0A equals TOP and COM0A1 is set, the Compare Match is ignored, but the set or clear is done at TOP. See "Phase Correct PWM Mode" on page 68 for more details.

- **Bits 5:4 – COM0B[1:0]: Compare Match Output B Mode**

These bits control the Output Compare pin (OC0B) behavior. If one or both of COM0B[1:0] bits are set, the OC0B output overrides the normal port functionality of the I/O pin it is connected to. The Data Direction Register (DDR) bit corresponding to the OC0B pin must be set in order to enable the output driver.

When OC0B is connected to the pin, the function of COM0B[1:0] bits depend on WGM0[2:0] bit setting. Table 11-5 shows COM0B[1:0] bit functionality when WGM0[2:0] bits are set to normal or CTC mode (non-PWM).

Table 11-5. Compare Output Mode, non-PWM Mode

COM0B1	COM0B0	Description
0	0	Normal port operation, OC0B disconnected.
0	1	Toggle OC0B on Compare Match
1	0	Clear OC0B on Compare Match
1	1	Set OC0B on Compare Match

Table 11-6 shows COM0B[1:0] bit functionality when WGM0[2:0] bits are set to fast PWM mode.

Table 11-6. Compare Output Mode, Fast PWM Mode[1]

COM0B1	COM0B0	Description
0	0	Normal port operation, OC0B disconnected.
0	1	Reserved
1	0	Clear OC0B on Compare Match, set OC0B at BOTTOM (non-inverting mode)
1	1	Set OC0B on Compare Match, clear OC0B at BOTTOM (inverting mode)

Note: 1. A special case occurs when OCR0B equals TOP and COM0B1 is set. In this case, the Compare Match is ignored, but the set or clear is done at BOTTOM. See "Fast PWM Mode" on page 67 for more details.

Table 11-7 shows the COM0B[1:0] bit functionality when the WGM0[2:0] bits are set to phase correct PWM mode.

Table 11-7. Compare Output Mode, Phase Correct PWM Mode[1]

COM0B1	COM0B0	Description
0	0	Normal port operation, OC0B disconnected.
0	1	Reserved
1	0	Clear OC0B on Compare Match when up-counting. Set OC0B on Compare Match when down-counting.
1	1	Set OC0B on Compare Match when up-counting. Clear OC0B on Compare Match when down-counting.

Note: 1. A special case occurs when OCR0B equals TOP and COM0B1 is set. In this case, the Compare Match is ignored, but the set or clear is done at TOP. See "Phase Correct PWM Mode" on page 68 for more details.

- **Bits 3:2 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 1:0 – WGM0[1:0]: Waveform Generation Mode**

Combined with the WGM02 bit found in the TCCR0B Register, these bits control the counting sequence of the counter, the source for maximum (TOP) counter value, and what type of waveform generation to be used, see Table 11-8. Modes of operation supported by the Timer/Counter unit are: Normal mode (counter), Clear Timer on Compare Match (CTC) mode, and two types of Pulse Width Modulation (PWM) modes (see "Modes of Operation" on page 65).

Table 11-8. Waveform Generation Mode Bit Description

Mode	WGM02	WGM01	WGM00	Timer/Counter Mode of Operation	TOP	Update of OCRx at	TOV Flag Set on[1]
0	0	0	0	Normal	0xFF	Immediate	MAX
1	0	0	1	PWM, Phase Correct	0xFF	TOP	BOTTOM
2	0	1	0	CTC	OCRA	Immediate	MAX
3	0	1	1	Fast PWM	0xFF	BOTTOM	MAX
4	1	0	0	Reserved	–	–	–

Table 11-8. Waveform Generation Mode Bit Description (Continued)

Mode	WGM02	WGM01	WGM00	Timer/Counter Mode of Operation	TOP	Update of OCRx at	TOV Flag Set on[1]
5	1	0	1	PWM, Phase Correct	OCRA	TOP	BOTTOM
6	1	1	0	Reserved	–	–	–
7	1	1	1	Fast PWM	OCRA	BOTTOM	TOP

Note: 1. MAX = 0xFF
BOTTOM = 0x00

11.9.2 TCCR0B – Timer/Counter Control Register B

Bit	7	6	5	4	3	2	1	0	
0x18	FOC0A	FOC0B	TSM	PSR	WGM02	CS02	CS01	CS00	TCCR0B
Read/Write	W	W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – FOC0A: Force Output Compare A**

The FOC0A bit is only active when the WGM bits specify a non-PWM mode.

However, for ensuring compatibility with future devices, this bit must be set to zero when TCCR0B is written when operating in PWM mode. When writing a logical one to the FOC0A bit, an immediate Compare Match is forced on the Waveform Generation unit. The OC0A output is changed according to its COM0A[1:0] bits setting. Note that the FOC0A bit is implemented as a strobe. Therefore it is the value present in the COM0A[1:0] bits that determines the effect of the forced compare.

A FOC0A strobe will not generate any interrupt, nor will it clear the timer in CTC mode using OCR0A as TOP.

The FOC0A bit always reads as zero.

- **Bit 6 – FOC0B: Force Output Compare B**

The FOC0B bit is only active when the WGM bits specify a non-PWM mode.

However, for ensuring compatibility with future devices, this bit must be set to zero when TCCR0B is written when operating in PWM mode. When writing a logical one to the FOC0B bit, an immediate Compare Match is forced on the Waveform Generation unit. The OC0B output is changed according to its COM0B[1:0] bits setting. Note that the FOC0B bit is implemented as a strobe. Therefore it is the value present in the COM0B[1:0] bits that determines the effect of the forced compare.

A FOC0B strobe will not generate any interrupt, nor will it clear the timer in CTC mode using OCR0B as TOP.

The FOC0B bit always reads as zero.

- **Bit 3 – WGM02: Waveform Generation Mode**

See the description in the “TCCR0A – Timer/Counter Control Register A” on page 71.

- **Bits 2:0 – CS0[2:0]: Clock Select**

The three Clock Select bits select the clock source to be used by the Timer/Counter.

Table 11-9. Clock Select Bit Description

CS02	CS01	CS00	Description
0	0	0	No clock source (Timer/Counter stopped)
0	0	1	$clk_{I/O}$/(No prescaling)
0	1	0	$clk_{I/O}$/8 (From prescaler)
0	1	1	$clk_{I/O}$/64 (From prescaler)
1	0	0	$clk_{I/O}$/256 (From prescaler)
1	0	1	$clk_{I/O}$/1024 (From prescaler)
1	1	0	External clock source on T0 pin. Clock on falling edge.
1	1	1	External clock source on T0 pin. Clock on rising edge.

If external pin modes are used for the Timer/Counter0, transitions on the T0 pin will clock the counter even if the pin is configured as an output. This feature allows software control of the counting.

11.9.3 TCNT0 – Timer/Counter Register

Bit	7	6	5	4	3	2	1	0	
0x17	TCNT0[7:0]								TCNT0
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Timer/Counter Register gives direct access, both for read and write operations, to the Timer/Counter unit 8-bit counter. Writing to the TCNT0 Register blocks (removes) the Compare Match on the following timer clock. Modifying the counter (TCNT0) while the counter is running, introduces a risk of missing a Compare Match between TCNT0 and the OCR0x Registers.

11.9.4 OCR0A – Output Compare Register A

Bit	7	6	5	4	3	2	1	0	
0x16	OCR0A[7:0]								OCR0A
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Output Compare Register A contains an 8-bit value that is continuously compared with the counter value (TCNT0). A match can be used to generate an Output Compare interrupt, or to generate a waveform output on the OC0A pin.

11.9.5 OCR0B – Output Compare Register B

Bit	7	6	5	4	3	2	1	0	
0x15	OCR0B[7:0]								OCR0B
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Output Compare Register B contains an 8-bit value that is continuously compared with the counter value (TCNT0). A match can be used to generate an Output Compare interrupt, or to generate a waveform output on the OC0B pin.

11.9.6 TIMSK – Timer/Counter Interrupt Mask Register

Bit	7	6	5	4	3	2	1	0	
0x26	ICIE1	–	OCIE1B	OCIE1A	TOIE1	OCIE0B	OCIE0A	TOIE0	TIMSK

Read/Write	R/W	R	R/W	R/W	R/W	R/W	R/W	R/W
Initial Value	0	0	0	0	0	0	0	0

- **Bit 6 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 2 – OCIE0B: Timer/Counter Output Compare Match B Interrupt Enable**

When the OCIE0B bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter Compare Match B interrupt is enabled. The corresponding interrupt is executed if a Compare Match in Timer/Counter occurs, i.e., when the OCF0B bit is set in the Timer/Counter Interrupt Flag Register – TIFR.

- **Bit 1 – OCIE0A: Timer/Counter0 Output Compare Match A Interrupt Enable**

When the OCIE0A bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter0 Compare Match A interrupt is enabled. The corresponding interrupt is executed if a Compare Match in Timer/Counter0 occurs, i.e., when the OCF0A bit is set in the Timer/Counter Interrupt Flag Register – TIFR.

- **Bit 0 – TOIE0: Timer/Counter0 Overflow Interrupt Enable**

When the TOIE0 bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter0 Overflow interrupt is enabled. The corresponding interrupt is executed if an overflow in Timer/Counter0 occurs, i.e., when the TOV0 bit is set in the Timer/Counter Interrupt Flag Register – TIFR.

11.9.7 TIFR – Timer/Counter Interrupt Flag Register

Bit	7	6	5	4	3	2	1	0	
0x25	ICF1	–	OCF1B	OCF1A	TOV1	OCF0B	OCF0A	TOV0	TIFR
Read/Write	R/W	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 6 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 2 – OCF0B: Output Compare Flag 0 B**

The OCF0B bit is set when a Compare Match occurs between the Timer/Counter and the data in OCR0B – Output Compare Register0 B. OCF0B is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, OCF0B is cleared by writing a logic one to the flag. When the I-bit in SREG, OCIE0B (Timer/Counter Compare B Match Interrupt Enable), and OCF0B are set, the Timer/Counter Compare Match Interrupt is executed.

- **Bit 1 – OCF0A: Output Compare Flag 0 A**

The OCF0A bit is set when a Compare Match occurs between the Timer/Counter0 and the data in OCR0A – Output Compare Register0. OCF0A is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, OCF0A is cleared by writing a logic one to the flag. When the I-bit in SREG, OCIE0A (Timer/Counter0 Compare Match Interrupt Enable), and OCF0A are set, the Timer/Counter0 Compare Match Interrupt is executed.

- **Bit 0 – TOV0: Timer/Counter0 Overflow Flag**

The bit TOV0 is set when an overflow occurs in Timer/Counter0. TOV0 is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, TOV0 is cleared by writing a logic one to the flag. When the SREG I-bit, TOIE0 (Timer/Counter0 Overflow Interrupt Enable), and TOV0 are set, the Timer/Counter0 Overflow interrupt is executed.

The setting of this flag is dependent of the WGM0[2:0] bit setting. See Table 11-8 on page 73 and “Waveform Generation Mode Bit Description” on page 73.

12. Timer/Counter1

12.1 Features

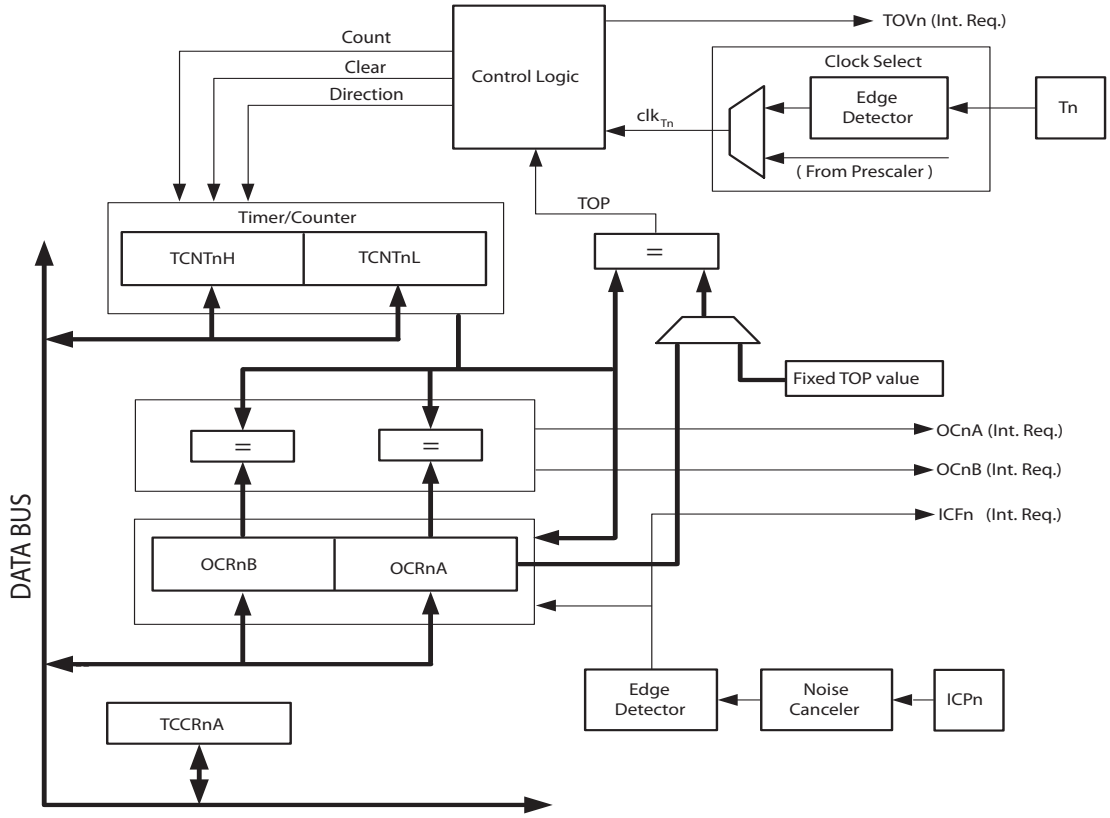
- **Clear Timer on Compare Match (Auto Reload)**
- **One Input Capture unit**
- **Four Independent Interrupt Sources (TOV1, OCF1A, OCF1B, ICF1)**
- **8-bit Mode with Two Independent Output Compare Units**
- **16-bit Mode with One Independent Output Compare Unit**

12.2 Overview

Timer/Counter1 is a general purpose 8/16-bit Timer/Counter module, with two/one Output Compare units and Input Capture feature.

The general operation of Timer/Counter1 is described in 8/16-bit mode. A simplified block diagram of the 8/16-bit Timer/Counter is shown in Figure 12-1. CPU accessible I/O Registers, including I/O bits and I/O pins, are shown in bold. For actual placement of I/O pins, refer to “Pin Description” on page 3. Device-specific I/O Register and bit locations are listed in the “Register Description” on page 88.

Figure 12-1. 8/16-bit Timer/Counter Block Diagram



12.2.1 Registers

The Timer/Counter1 Low Byte Register (TCNT1L) and Output Compare Registers (OCR1A and OCR1B) are 8-bit registers. Interrupt request (abbreviated Int.Req. in Figure 12-1) signals are all visible in the Timer Interrupt Flag Register (TIFR). All interrupts are individually masked with the Timer Interrupt Mask Register (TIMSK). TIFR and TIMSK are not shown in the figure.

In 16-bit mode one more 8-bit register is available, the Timer/Counter1 High Byte Register (TCNT1H). Also, in 16-bit mode, there is only one output compare unit as the two Output Compare Registers, OCR1A and OCR1B, are combined to one, 16-bit Output Compare Register, where OCR1A contains the low byte and OCR1B contains the high byte of the word. When accessing 16-bit registers, special procedures described in section “Accessing Registers in 16-bit Mode” on page 84 must be followed.

12.2.2 Definitions

Many register and bit references in this section are written in general form. A lower case “n” replaces the Timer/Counter number, in this case 1. A lower case “x” replaces the Output Compare Unit, in this case Compare Unit A or Compare Unit B. However, when using the register or bit defines in a program, the precise form must be used, i.e. TCNT1L for accessing Timer/Counter1 counter value, and so on.

The definitions in Table 11-1 are also used extensively throughout the document.

Table 12-1. Definitions

Constant	Description
BOTTOM	The counter reaches BOTTOM when it becomes 0x00
MAX	The counter reaches its MAXimum when it becomes 0xFF (decimal 255)
TOP	The counter reaches the TOP when it becomes equal to the highest value in the count sequence. The TOP value can be assigned to be the fixed value 0xFF (MAX) or the value stored in the OCR1A Register. The assignment depends on the mode of operation

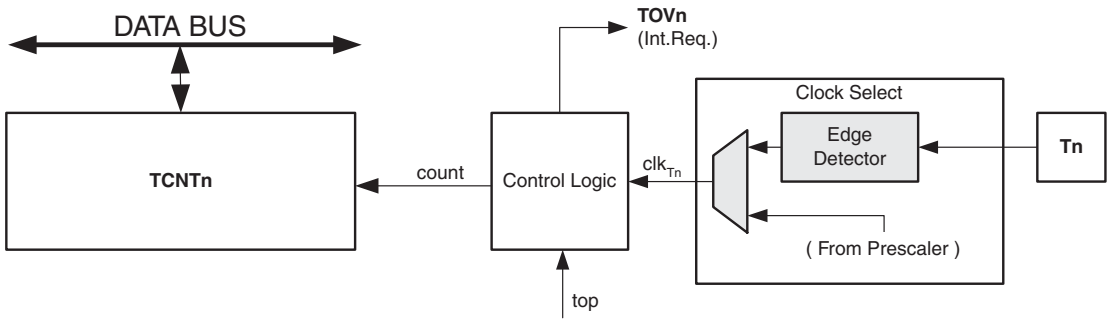
12.3 Clock Sources

The Timer/Counter can be clocked by an internal or an external clock source. The clock source is selected by the Clock Select logic which is controlled by the Clock Select (CS1[2:0]) bits located in the Timer/Counter Control Register (TCCR1A). For details on clock sources and prescaler, see “Timer/Counter Prescaler” on page 92.

12.4 Counter Unit

The main part of the 8-bit Timer/Counter is the programmable bi-directional counter unit. Figure 12-2 shows a block diagram of the counter and its surroundings.

Table 12-2. Counter Unit Block Diagram



Signal description (internal signals):

count Increment or decrement TCNT1 by 1.
clk_{Tn} Timer/Counter clock, referred to as clk_{T1} in the following.
top Signalize that TCNT1 has reached maximum value.

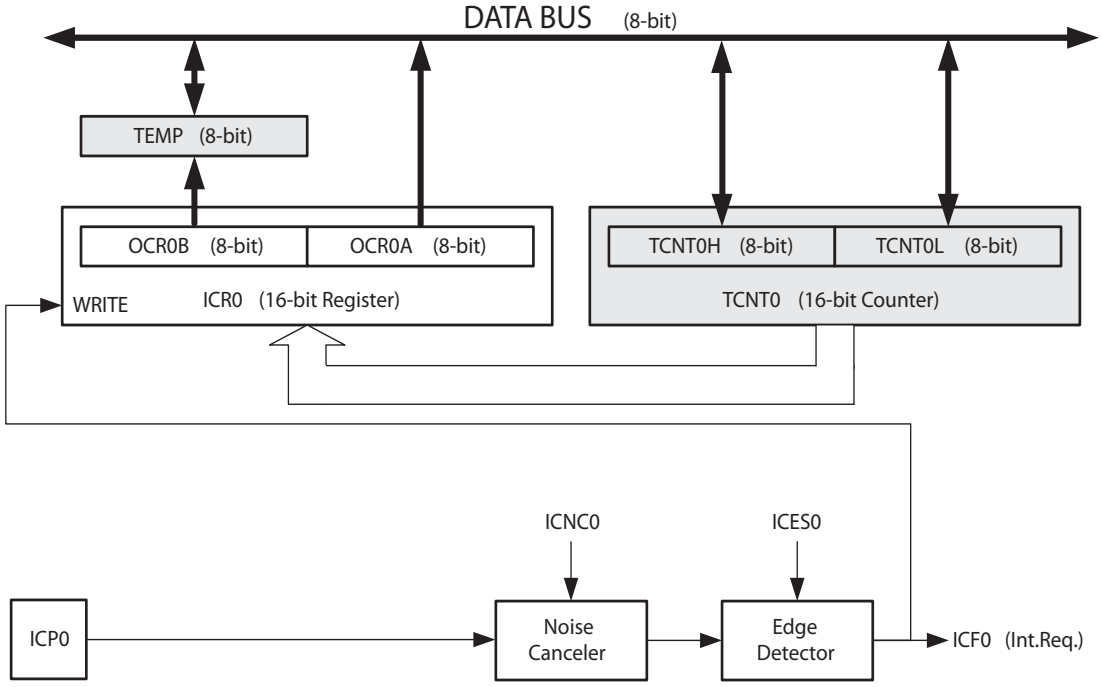
The counter is incremented at each timer clock (clk_{T1}) until it passes its TOP value and then restarts from BOTTOM. The counting sequence is determined by the setting of the CTC1 bit located in the Timer/Counter Control Register (TCCR1A). For more details about counting sequences, see "Modes of Operation" on page 81. clk_{T1} can be generated from an external or internal clock source, selected by the Clock Select bits (CS1[2:0]). When no clock source is selected (CS1[2:0] = 0) the timer is stopped. However, the TCNT1 value can be accessed by the CPU, regardless of whether clk_{T1} is present or not. A CPU write overrides (has priority over) all counter clear or count operations. The Timer/Counter Overflow Flag (TOV1) is set when the counter reaches the maximum value and it can be used for generating a CPU interrupt.

12.5 Input Capture Unit

The Timer/Counter incorporates an Input Capture unit that can capture external events and give them a time-stamp indicating time of occurrence. The external signal indicating an event, or multiple events, can be applied via the ICP1 pin or alternatively, via the analog-comparator unit. The time-stamps can then be used to calculate frequency, duty-cycle, and other features of the signal applied. Alternatively the time-stamps can be used for creating a log of the events.

The Input Capture unit is illustrated by the block diagram shown in Figure 12-2. The elements of the block diagram that are not directly a part of the Input Capture unit are gray shaded.

Figure 12-2. Input Capture Unit Block Diagram



The Output Compare Register OCR1A is a dual-purpose register that is also used as an 8-bit Input Capture Register ICR1. In 16-bit Input Capture mode the Output Compare Register OCR1B serves as the high byte of the Input Capture Register ICR1. In 8-bit Input Capture mode the Output Compare Register OCR1B is free to be used as a normal Output Compare Register, but in 16-bit Input Capture mode the Output Compare Unit cannot be used as there are no free Output Compare Register(s). Even though the Input Capture register is called ICR1 in this section, it is refering to the Output Compare Register(s).

When a change of the logic level (an event) occurs on the *Input Capture pin* (ICP1), and this change confirms to the setting of the edge detector, a capture will be triggered. When a capture is triggered, the value of the counter (TCNT1) is written to the *Input Capture Register* (ICR1). The *Input Capture Flag* (ICF1) is set at the same system

clock as the TCNT1 value is copied into Input Capture Register. If enabled (ICIE1=1), the Input Capture Flag generates an Input Capture interrupt. The ICF1 flag is automatically cleared when the interrupt is executed. Alternatively the ICF1 flag can be cleared by software by writing a logical one to its I/O bit location.

12.5.1 Input Capture Trigger Source

The trigger source for the Input Capture unit is the Input Capture pin (ICP1).

The Input Capture pin (ICP1) input is sampled using the same technique as for the T1 pin (Figure 12-4 on page 88). The edge detector is also identical. However, when the noise canceler is enabled, additional logic is inserted before the edge detector, which increases the delay by four system clock cycles. An Input Capture can also be triggered by software by controlling the port of the ICP1 pin.

12.5.2 Noise Canceler

The noise canceler improves noise immunity by using a simple digital filtering scheme. The noise canceler input is monitored over four samples, and all four must be equal for changing the output that in turn is used by the edge detector.

The noise canceler is enabled by setting the Input Capture Noise Canceler (ICNC1) bit in Timer/Counter Control Register A (TCCR1A). When enabled the noise canceler introduces additional four system clock cycles of delay from a change applied to the input, to the update of the ICR1 Register. The noise canceler uses the system clock and is therefore not affected by the prescaler.

12.5.3 Using the Input Capture Unit

The main challenge when using the Input Capture unit is to assign enough processor capacity for handling the incoming events. The time between two events is critical. If the processor has not read the captured value in the ICR1 Register before the next event occurs, the ICR1 will be overwritten with a new value. In this case the result of the capture will be incorrect.

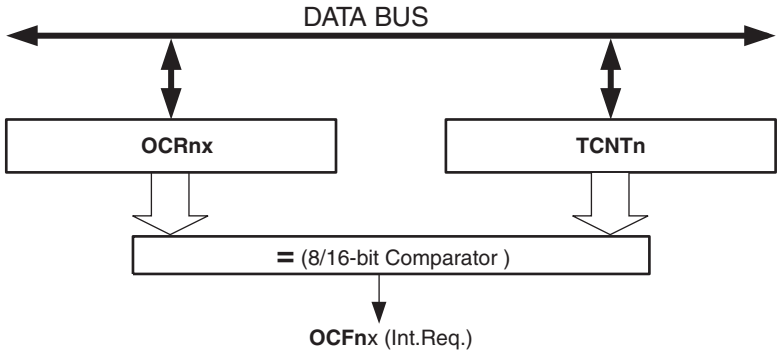
When using the Input Capture interrupt, the ICR1 Register should be read as early in the interrupt handler routine as possible. The maximum interrupt response time is dependent on the maximum number of clock cycles it takes to handle any of the other interrupt requests.

Measurement of an external signal's duty cycle requires that the trigger edge is changed after each capture. Changing the edge sensing must be done as early as possible after the ICR1 Register has been read. After a change of the edge, the Input Capture Flag (ICF1) must be cleared by software (writing a logical one to the I/O bit location). For measuring frequency only, the trigger edge change is not required (if an interrupt handler is used).

12.6 Output Compare Unit

The comparator continuously compares Timer/Counter (TCNT1) with the Output Compare Registers (OCR1A and OCR1B), and whenever the Timer/Counter equals to the Output Compare Regisers, the comparator signals a match. A match will set the Output Compare Flag at the next timer clock cycle. In 8-bit mode the match can set either the Output Compare Flag OCF1A or OCF1B, but in 16-bit mode the match can set only the Output Compare Flag OCF1A as there is only one Output Compare Unit. If the corresponding interrupt is enabled, the Output Compare Flag generates an Output Compare interrupt. The Output Compare Flag is automatically cleared when the interrupt is executed. Alternatively, the flag can be cleared by software by writing a logical one to its I/O bit location. Figure 12-3 shows a block diagram of the Output Compare unit.

Figure 12-3. Output Compare Unit, Block Diagram



12.6.1 Compare Match Blocking by TCNT1 Write

All CPU write operations to the TCNT1H/L Register will block any Compare Match that occur in the next timer clock cycle, even when the timer is stopped. This feature allows OCR1A/B to be initialized to the same value as TCNT1 without triggering an interrupt when the Timer/Counter clock is enabled.

12.6.2 Using the Output Compare Unit

Since writing TCNT1H/L will block all Compare Matches for one timer clock cycle, there are risks involved when changing TCNT1H/L when using the Output Compare Unit, independently of whether the Timer/Counter is running or not. If the value written to TCNT1H/L equals the OCR1A/B value, the Compare Match will be missed.

12.7 Modes of Operation

The mode of operation, i.e., the behavior of the Timer/Counter and the Output Compare pins, is defined by the Timer/Counter Width (TCW1), Input Capture Enable (ICEN1) and CTC Mode (CTC1) bits. See “TCCR1A – Timer/Counter1 Control Register A” on page 88.

Table 12-3 summarises the different modes of operation.

Table 12-3. Modes of operation

Mode	ICEN1	TCW1	CTC1	Mode of Operation	TOP	Update of OCRx at	TOV Flag Set on
0	0	0	0	Normal, 8-bit Mode	0xFF	Immediate	MAX (0xFF)
1	0	0	1	CTC Mode, 8-bit	OCR0A	Immediate	MAX (0xFF)
2	0	1	X	Normal, 16-bit Mode	0xFFFF	Immediate	MAX (0xFFFF)
3	1	0	X	Input Capture Mode, 8-bit	0xFF	Immediate	MAX (0xFF)
4	1	1	X	Input Capture Mode, 16-bit	0xFFFF	Immediate	MAX (0xFFFF)

12.7.1 Normal, 8-bit Mode

In Normal 8-bit mode (see Table 12-3), the counter (TCNT1L) is incrementing until it overruns when it passes its maximum 8-bit value (MAX = 0xFF) and then restarts from the bottom (0x00). The Overflow Flag (TOV1) is set in the same timer clock cycle as when TCNT1L becomes zero. The TOV1 Flag in this case behaves like a ninth bit, except that it is only set, not cleared. However, combined with the timer overflow interrupt that automatically clears the TOV1 Flag, the timer resolution can be increased by software. There are no special cases to consider in the Normal 8-bit mode, a new counter value can be written anytime. The Output Compare Unit can be used to generate interrupts at some given time.

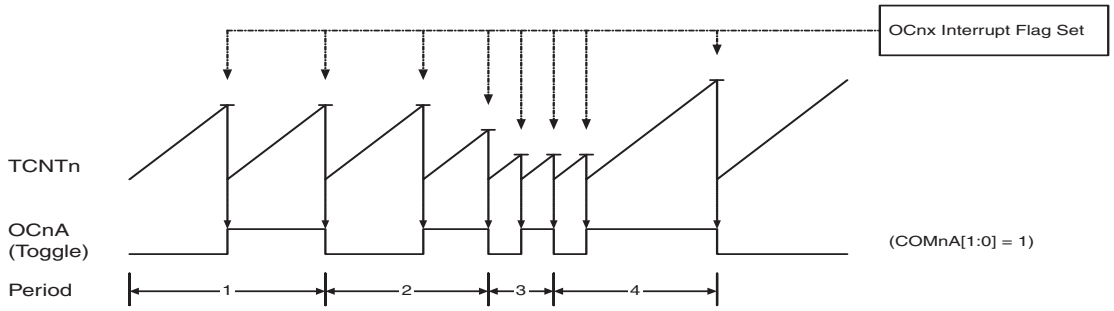
12.7.2 Clear Timer on Compare Match (CTC) 8-bit Mode

In Clear Timer on Compare or CTC mode, see Table 12-3 on page 81, the OCR1A Register is used to manipulate the counter resolution. In CTC mode the counter is cleared to zero when the counter value (TCNT1) matches the

OCR1A. The OCR1A defines the top value for the counter, hence also its resolution. This mode allows greater control of the Compare Match output frequency. It also simplifies the operation of counting external events.

The timing diagram for the CTC mode is shown in Figure 12-4. The counter value (TCNT1) increases until a Compare Match occurs between TCNT1 and OCR1A, and then counter (TCNT1) is cleared.

Figure 12-4. CTC Mode, Timing Diagram



An interrupt can be generated each time the counter value reaches the TOP value by using the OCF1A Flag. If the interrupt is enabled, the interrupt handler routine can be used for updating the TOP value. However, changing TOP to a value close to BOTTOM when the counter is running with none or a low prescaler value must be done with care since the CTC mode does not have the double buffering feature. If the new value written to OCR1A is lower than the current value of TCNT1, the counter will miss the Compare Match. The counter will then have to count to its maximum value (0xFF) and wrap around starting at 0x00 before the Compare Match can occur. As for the Normal mode of operation, the TOV1 Flag is set in the same timer clock cycle that the counter counts from MAX to 0x00.

12.7.3 Normal, 16-bit Mode

In 16-bit mode, see Table 12-3 on page 81, the counter (TCNT1H/L) is a incrementing until it overruns when it passes its maximum 16-bit value (MAX = 0xFFFF) and then restarts from the bottom (0x0000). The Overflow Flag (TOV1) will be set in the same timer clock cycle as the TCNT1H/L becomes zero. The TOV1 Flag in this case behaves like a 17th bit, except that it is only set, not cleared. However, combined with the timer overflow interrupt that automatically clears the TOV1 Flag, the timer resolution can be increased by software. There are no special cases to consider in the Normal mode, a new counter value can be written anytime. The Output Compare Unit can be used to generate interrupts at some given time.

12.7.4 8-bit Input Capture Mode

The Timer/Counter1 can also be used in an 8-bit Input Capture mode, see Table 12-3 on page 81 for bit settings. For full description, see the section “Input Capture Unit” on page 79.

12.7.5 16-bit Input Capture Mode

The Timer/Counter1 can also be used in a 16-bit Input Capture mode, see Table 12-3 on page 81 for bit settings. For full description, see the section “Input Capture Unit” on page 79.

12.8 Timer/Counter Timing Diagrams

The Timer/Counter is a synchronous design and the timer clock (clk_{T1}) is therefore shown as a clock enable signal in the following figures. The figures include information on when Interrupt Flags are set. Figure 12-5 contains timing data for basic Timer/Counter operation. The figure shows the count sequence close to the MAX value.

Figure 12-5. Timer/Counter Timing Diagram, no Prescaling

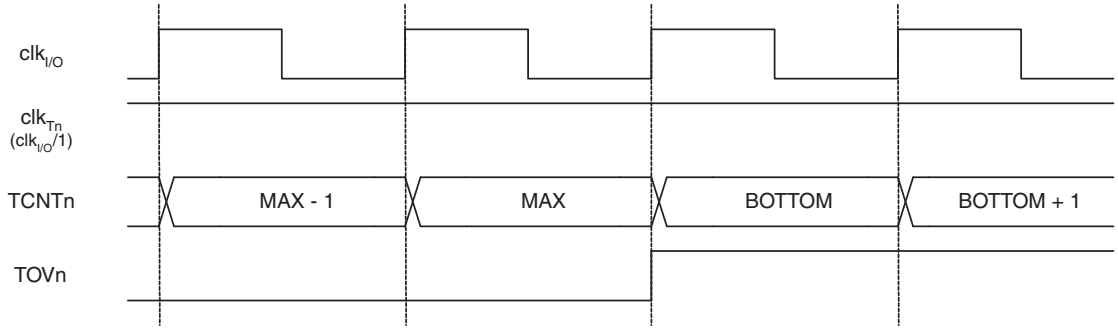


Figure 12-6 shows the same timing data, but with the prescaler enabled.

Figure 12-6. Timer/Counter Timing Diagram, with Prescaler ($f_{clk_I/O}/8$)

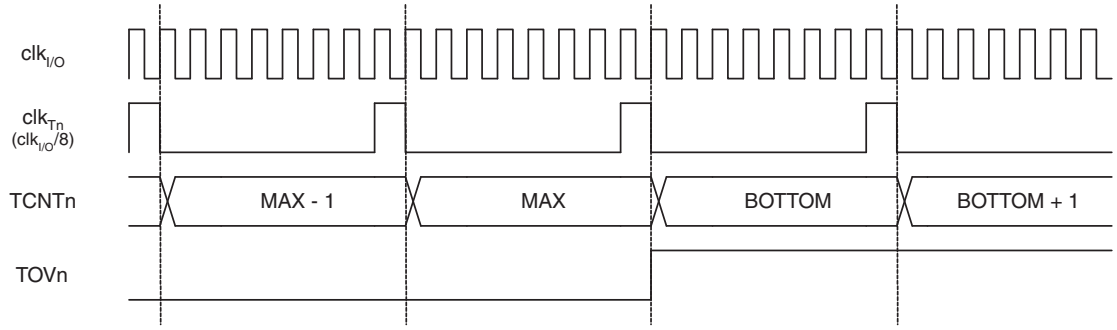


Figure 12-7 on page 83 shows the setting of OCF1A and OCF1B in Normal mode.

Figure 12-7. Timer/Counter Timing Diagram, Setting of OCF1x, with Prescaler ($f_{clk_I/O}/8$)

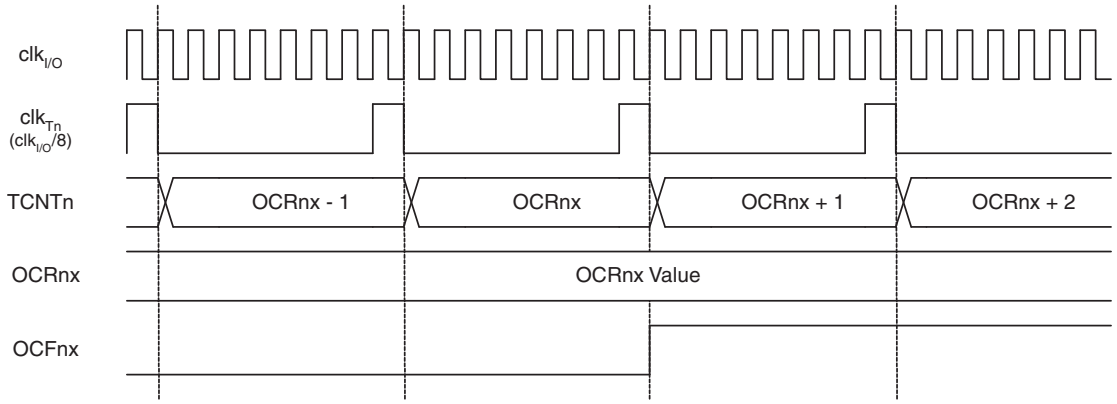
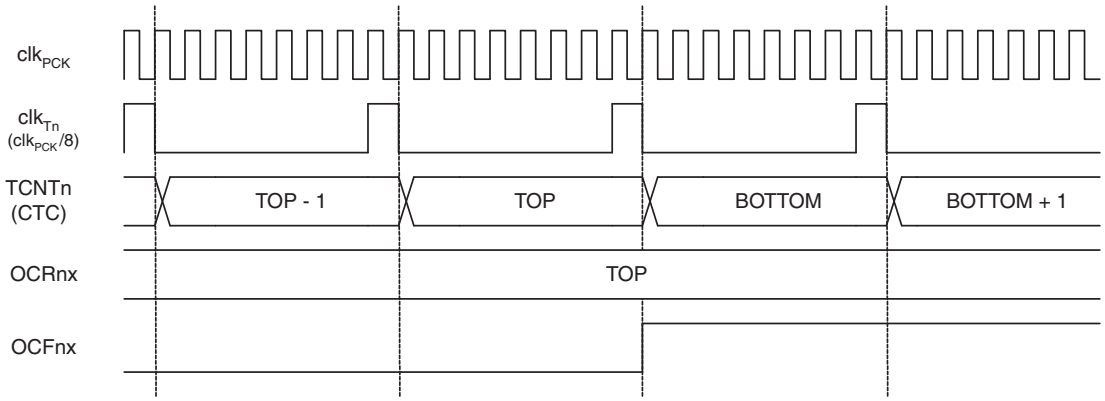


Figure 12-8 shows the setting of OCF1A and the clearing of TCNT1 in CTC mode.

Figure 12-8. Timer/Counter Timing Diagram, CTC mode, with Prescaler ($f_{clk_I/O}/8$)



12.9 Accessing Registers in 16-bit Mode

In 16-bit mode (the TCW1 bit is set to one) the TCNT1H/L and OCR1A/B or TCNT1L/H and OCR1B/A are 16-bit registers that can be accessed by the AVR CPU via the 8-bit data bus. The 16-bit register must be byte accessed using two read or write operations. The 16-bit Timer/Counter has a single 8-bit register for temporary storing of the high byte of the 16-bit access. The same temporary register is shared between all 16-bit registers. Accessing the low byte triggers the 16-bit read or write operation. When the low byte of a 16-bit register is written by the CPU, the high byte stored in the temporary register, and the low byte written are both copied into the 16-bit register in the same clock cycle. When the low byte of a 16-bit register is read by the CPU, the high byte of the 16-bit register is copied into the temporary register in the same clock cycle as the low byte is read.

There is one exception in the temporary register usage. In the Output Compare mode the 16-bit Output Compare Register OCR1A/B is read without the temporary register, because the Output Compare Register contains a fixed value that is only changed by CPU access. However, in 16-bit Input Capture mode the ICR1 register formed by the OCR1A and OCR1B registers must be accessed with the temporary register.

To do a 16-bit write, the high byte must be written before the low byte. For a 16-bit read, the low byte must be read before the high byte.

The following code examples show how to access the 16-bit timer registers assuming that no interrupts updates the temporary register. The same principle can be used directly for accessing the OCR1A/B registers.

Assembly Code Example

```
...
; Set TCNT1 to 0x01FF
ldi r17,0x01
ldi r16,0xFF
out TCNT1H,r17
out TCNT1L,r16
; Read TCNT1 into r17:r16
in  r16,TCNT1L
in  r17,TCNT1H
...
```

C Code Example

```
unsigned int i;
...
/* Set TCNT1 to 0x01FF */
TCNT1H = 0x01;
TCNT1L = 0xff;

/* Read TCNT1 into i */
i = TCNT1L;
i |= ((unsigned int)TCNT1H << 8);
...
```

Note: See “Code Examples” on page 5.

The assembly code example returns the TCNT1H/L value in the r17:r16 register pair.

It is important to notice that accessing 16-bit registers are atomic operations. If an interrupt occurs between the two instructions accessing the 16-bit register, and the interrupt code updates the temporary register by accessing the same or any other of the 16-bit timer registers, then the result of the access outside the interrupt will be corrupted. Therefore, when both the main code and the interrupt code update the temporary register, the main code must disable the interrupts during the 16-bit access.

The following code examples show how to do an atomic read of the TCNT1 register contents. Reading any of the OCR1 register can be done by using the same principle.

Assembly Code Example

```
TIM1_ReadTCNT1:
  ; Save global interrupt flag
  in  r18,SREG
  ; Disable interrupts
  cli
  ; Read TCNT1 into r17:r16
  in  r16,TCNT1L
  in  r17,TCNT1H
  ; Restore global interrupt flag
  out SREG,r18
  ret
```

C Code Example

```
unsigned int TIM1_ReadTCNT1( void )
{
  unsigned char sreg;
  unsigned int i;
  /* Save global interrupt flag */
  sreg = SREG;
  /* Disable interrupts */
  _CLI();
  /* Read TCNT1 into i */
  i = TCNT1L;
  i |= ((unsigned int)TCNT1H << 8);
  /* Restore global interrupt flag */
  SREG = sreg;
  return i;
}
```

Note: See “Code Examples” on page 5.

The assembly code example returns the TCNT1H/L value in the r17:r16 register pair.

The following code examples show how to do an atomic write of the TCNT1H/L register contents. Writing any of the OCR1A/B registers can be done by using the same principle.

Assembly Code Example

```
TIM1_WriteTCNT1:
  ; Save global interrupt flag
  in  r18,SREG
  ; Disable interrupts
  cli
  ; Set TCNT1 to r17:r16
  out TCNT1H,r17
  out TCNT1L,r16
  ; Restore global interrupt flag
  out SREG,r18
  ret
```

C Code Example

```
void TIM1_WriteTCNT1( unsigned int i )
{
  unsigned char sreg;
  /* Save global interrupt flag */
  sreg = SREG;
  /* Disable interrupts */
  _CLI();
  /* Set TCNT1 to i */
  TCNT1H = (i >> 8);
  TCNT1L = (unsigned char)i;
  /* Restore global interrupt flag */
  SREG = sreg;
}
```

Note: See “Code Examples” on page 5.

The assembly code example requires that the r17:r16 register pair contains the value to be written to TCNT1H/L.

12.9.1 Reusing the temporary high byte register

If writing to more than one 16-bit register where the high byte is the same for all registers written, then the high byte only needs to be written once. However, note that the same rule of atomic operation described previously also applies in this case.

12.10 Register Description

12.10.1 TCCR1A – Timer/Counter1 Control Register A

Bit	7	6	5	4	3	2	1	0	
0x24	TCW1	ICEN1	ICNC1	ICES1	CTC1	CS12	CS11	CS10	TCCR1A
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – TCW1: Timer/Counter1 Width**

When this bit is written to one, 16-bit mode is selected as described Figure 12-5 on page 83. Timer/Counter1 width is set to 16-bits and the Output Compare Registers OCR1A and OCR1B are combined to form one 16-bit Output Compare Register. Because the 16-bit registers TCNT1H/L and OCR1B/A are accessed by the AVR CPU via the 8-bit data bus, special procedures must be followed. These procedures are described in section "Accessing Registers in 16-bit Mode" on page 84.

- **Bit 6 – ICEN1: Input Capture Mode Enable**

When this bit is written to one, the Input Capture Mode is enabled.

- **Bit 5 – ICNC1: Input Capture Noise Canceler**

Setting this bit activates the Input Capture Noise Canceler. When the noise canceler is activated, the input from the Input Capture Pin (ICP1) is filtered. The filter function requires four successive equal valued samples of the ICP1 pin for changing its output. The Input Capture is therefore delayed by four System Clock cycles when the noise canceler is enabled.

- **Bit 4 – ICES1: Input Capture Edge Select**

This bit selects which edge on the Input Capture Pin (ICP1) that is used to trigger a capture event. When the ICES1 bit is written to zero, a falling (negative) edge is used as trigger, and when the ICES1 bit is written to one, a rising (positive) edge will trigger the capture. When a capture is triggered according to the ICES1 setting, the counter value is copied into the Input Capture Register. The event will also set the Input Capture Flag (ICF1), and this can be used to cause an Input Capture Interrupt, if this interrupt is enabled.

- **Bit 3 – CTC1: Waveform Generation Mode**

This bit controls the counting sequence of the counter, the source for maximum (TOP) counter value, see Figure 12-5 on page 83. Modes of operation supported by the Timer/Counter unit are: Normal mode (counter) and Clear Timer on Compare Match (CTC) mode (see "Modes of Operation" on page 81).

- **Bits 2:0 – CS1[2:0]: Clock Select1, Bits 2, 1, and 0**

The Clock Select1 bits 2, 1, and 0 define the prescaling source of Timer1.

Table 12-4. Clock Select Bit Description

CS12	CS11	CS10	Description
0	0	0	No clock source (Timer/Counter stopped)
0	0	1	$clk_{I/O}$/(No prescaling)
0	1	0	$clk_{I/O}$/8 (From prescaler)
0	1	1	$clk_{I/O}$/64 (From prescaler)
1	0	0	$clk_{I/O}$/256 (From prescaler)

Table 12-4. Clock Select Bit Description (Continued)

CS12	CS11	CS10	Description
1	0	1	$clk_{I/O}$/1024 (From prescaler)
1	1	0	External clock source on T1 pin. Clock on falling edge.
1	1	1	External clock source on T1 pin. Clock on rising edge.

If external pin modes are used for the Timer/Counter1, transitions on the T1 pin will clock the counter even if the pin is configured as an output. This feature allows software control of the counting.

12.10.2 TCNT1L – Timer/Counter1 Register Low Byte

Bit	7	6	5	4	3	2	1	0	
0x23	TCNT1L[7:0]								TCNT1L
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Timer/Counter1 Register Low Byte, TCNT1L, gives direct access, both for read and write operations, to the Timer/Counter unit 8-bit counter. Writing to the TCNT1L Register blocks (disables) the Compare Match on the following timer clock. Modifying the counter (TCNT1L) while the counter is running, introduces a risk of missing a Compare Match between TCNT1L and the OCR1x Registers. In 16-bit mode the TCNT1L register contains the lower part of the 16-bit Timer/Counter1 Register.

12.10.3 TCNT1H – Timer/Counter1 Register High Byte

Bit	7	6	5	4	3	2	1	0	
0x27	TCNT1H[7:0]								TCNT1H
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

When 16-bit mode is selected (the TCW1 bit is set to one) the Timer/Counter Register TCNT1H combined to the Timer/Counter Register TCNT1L gives direct access, both for read and write operations, to the Timer/Counter unit 16-bit counter. To ensure that both the high and low bytes are read and written simultaneously when the CPU accesses these registers, the access is performed using an 8-bit temporary high byte register (TEMP). This temporary register is shared by all the other 16-bit registers. See “Accessing Registers in 16-bit Mode” on page 84

12.10.4 OCR1A – Timer/Counter1 Output Compare Register A

Bit	7	6	5	4	3	2	1	0	
0x22	OCR1A[7:0]								OCR1A
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Output Compare Register A contains an 8-bit value that is continuously compared with the counter value (TCNT1L). A match can be used to generate an Output Compare interrupt.

In 16-bit mode the OCR1A register contains the low byte of the 16-bit Output Compare Register. To ensure that both the high and the low bytes are written simultaneously when the CPU writes to these registers, the access is performed using an 8-bit temporary high byte register (TEMP). This temporary register is shared by all the other 16-bit registers. See “Accessing Registers in 16-bit Mode” on page 84.

12.10.5 OCR1B – Timer/Counter1 Output Compare Register B

Bit	7	6	5	4	3	2	1	0	
0x21	OCR1B[7:0]								OCR1B
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The Output Compare Register B contains an 8-bit value that is continuously compared with the counter value (TCNT1L in 8-bit mode and TCNTH in 16-bit mode). A match can be used to generate an Output Compare interrupt.

In 16-bit mode the OCR1B register contains the high byte of the 16-bit Output Compare Register. To ensure that both the high and the low bytes are written simultaneously when the CPU writes to these registers, the access is performed using an 8-bit temporary high byte register (TEMP). This temporary register is shared by all the other 16-bit registers. See “Accessing Registers in 16-bit Mode” on page 84.

12.10.6 TIMSK – Timer/Counter1 Interrupt Mask Register

Bit	7	6	5	4	3	2	1	0	
0x26	ICIE1	–	OCIE1B	OCIE1A	TOIE1	OCIE0B	OCIE0A	TOIE0	TIMSK
Read/Write	R/W	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – ICIE1: Timer/Counter1, Input Capture Interrupt Enable**

When this bit is written to one, and the I-flag in the Status Register is set (interrupts globally enabled), the Timer/Counter1 Input Capture interrupt is enabled. The corresponding Interrupt Vector (See “Interrupts” on page 35.) is executed when the ICF1 flag, located in TIFR, is set.

- **Bit 6 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 5 – OCIE1B: Timer/Counter1 Output Compare Match B Interrupt Enable**

When the OCIE1B bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter Compare Match B interrupt is enabled. The corresponding interrupt is executed if a Compare Match in Timer/Counter occurs, i.e., when the OCF1B bit is set in the Timer/Counter Interrupt Flag Register – TIFR1.

- **Bit 4 – OCIE1A: Timer/Counter1 Output Compare Match A Interrupt Enable**

When the OCIE1A bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter1 Compare Match A interrupt is enabled. The corresponding interrupt is executed if a Compare Match in Timer/Counter1 occurs, i.e., when the OCF1A bit is set in the Timer/Counter 1 Interrupt Flag Register – TIFR1.

- **Bit 3 – TOIE1: Timer/Counter1 Overflow Interrupt Enable**

When the TOIE1 bit is written to one, and the I-bit in the Status Register is set, the Timer/Counter1 Overflow interrupt is enabled. The corresponding interrupt is executed if an overflow in Timer/Counter1 occurs, i.e., when the TOV1 bit is set in the Timer/Counter 1 Interrupt Flag Register – TIFR1.

12.10.7 TIFR – Timer/Counter1 Interrupt Flag Register

Bit	7	6	5	4	3	2	1	0	
0x25	ICF1	–	OCF1B	OCF1A	TOV1	OCF0B	OCF0A	TOV0	TIFR
Read/Write	R/W	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – ICF1: Timer/Counter1, Input Capture Flag**

This flag is set when a capture event occurs on the ICP1 pin. When the Input Capture Register (ICR1) is set to be used as the TOP value, the ICF1 flag is set when the counter reaches the TOP value.

ICF1 is automatically cleared when the Input Capture Interrupt Vector is executed. Alternatively, ICF1 can be cleared by writing a logic one to its bit location.

- **Bit 6 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 5 – OCF1B: Output Compare Flag 1 B**

The OCF1B bit is set when a Compare Match occurs between the Timer/Counter and the data in OCR1B – Output Compare Register1 B. OCF1B is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, OCF1B is cleared by writing a logic one to the flag. When the I-bit in SREG, OCIE1B (Timer/Counter Compare B Match Interrupt Enable), and OCF1B are set, the Timer/Counter Compare Match Interrupt is executed.

The OCF1B is not set in 16-bit Output Compare mode when the Output Compare Register OCR1B is used as the high byte of the 16-bit Output Compare Register or in 16-bit Input Capture mode when the Output Compare Register OCR1B is used as the high byte of the Input Capture Register.

- **Bit 4 – OCF1A: Output Compare Flag 1 A**

The OCF1A bit is set when a Compare Match occurs between the Timer/Counter1 and the data in OCR1A – Output Compare Register1. OCF1A is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, OCF1A is cleared by writing a logic one to the flag. When the I-bit in SREG, OCIE1A (Timer/Counter1 Compare Match Interrupt Enable), and OCF1A are set, the Timer/Counter1 Compare Match Interrupt is executed.

The OCF1A is also set in 16-bit mode when a Compare Match occurs between the Timer/Counter and 16-bit data in OCR1B/A. The OCF1A is not set in Input Capture mode when the Output Compare Register OCR1A is used as an Input Capture Register.

- **Bit 3 – TOV1: Timer/Counter1 Overflow Flag**

The bit TOV1 is set when an overflow occurs in Timer/Counter1. TOV1 is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, TOV1 is cleared by writing a logic one to the flag. When the SREG I-bit, TOIE1 (Timer/Counter1 Overflow Interrupt Enable), and TOV1 are set, the Timer/Counter1 Overflow interrupt is executed.

13. Timer/Counter Prescaler

Timer/Counter0 and Timer/Counter1 share the same prescaler module, but the Timer/Counters can have different prescaler settings. The description below applies to both Timer/Counters. Tn is used as a general name, n = 0, 1.

The Timer/Counter can be clocked directly by the system clock (by setting the CSn[2:0] = 1). This provides the fastest operation, with a maximum Timer/Counter clock frequency equal to system clock frequency ($f_{CLK_I/O}$). Alternatively, one of four taps from the prescaler can be used as a clock source. The prescaled clock has a frequency of either $f_{CLK_I/O}/8$, $f_{CLK_I/O}/64$, $f_{CLK_I/O}/256$, or $f_{CLK_I/O}/1024$.

13.1 Prescaler Reset

The prescaler is free running, i.e., operates independently of the Clock Select logic of the Timer/CounterCounter, and it is shared by the Timer/Counter Tn. Since the prescaler is not affected by the Timer/Counter's clock select, the state of the prescaler will have implications for situations where a prescaled clock is used. One example of prescaling artifacts occurs when the timer is enabled and clocked by the prescaler (CSn[2:0] = 2, 3, 4, or 5). The number of system clock cycles from when the timer is enabled to the first count occurs can be from 1 to N+1 system clock cycles, where N equals the prescaler divisor (8, 64, 256, or 1024).

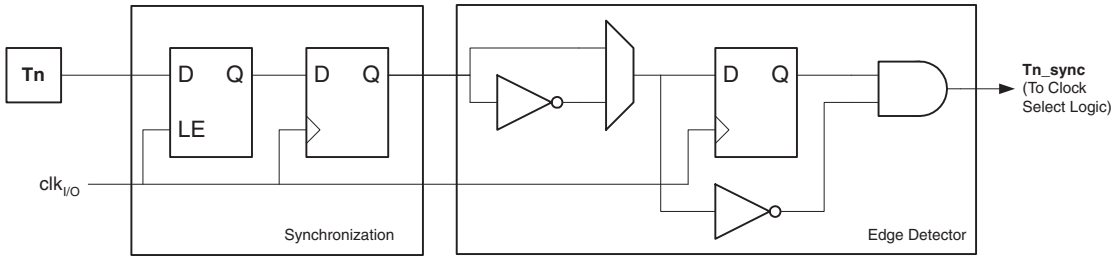
It is possible to use the Prescaler Reset for synchronizing the Timer/Counter to program execution.

13.2 External Clock Source

An external clock source applied to the Tn pin can be used as Timer/Counter clock (clk_{Tn}). The Tn pin is sampled once every system clock cycle by the pin synchronization logic. The synchronized (sampled) signal is then passed through the edge detector. Figure 13-1 shows a functional equivalent block diagram of the Tn synchronization and edge detector logic. The registers are clocked at the positive edge of the internal system clock ($clk_{I/O}$). The latch is transparent in the high period of the internal system clock.

The edge detector generates one clk_{T0} pulse for each positive (CSn[2:0] = 7) or negative (CSn[2:0] = 6) edge it detects.

Figure 13-1. T0 Pin Sampling



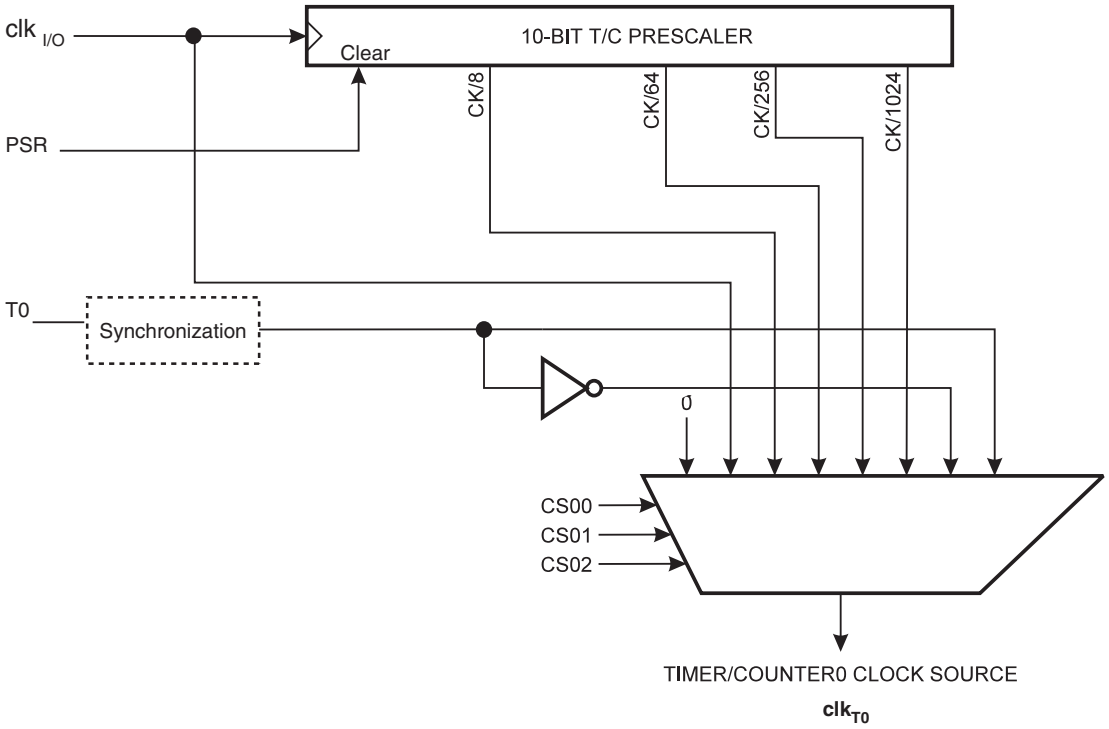
The synchronization and edge detector logic introduces a delay of 2.5 to 3.5 system clock cycles from an edge has been applied to the Tn pin to the counter is updated.

Enabling and disabling of the clock input must be done when Tn has been stable for at least one system clock cycle, otherwise it is a risk that a false Timer/Counter clock pulse is generated.

Each half period of the external clock applied must be longer than one system clock cycle to ensure correct sampling. The external clock must be guaranteed to have less than half the system clock frequency ($f_{ExtClk} < f_{clk_I/O}/2$) given a 50/50% duty cycle. Since the edge detector uses sampling, the maximum frequency of an external clock it can detect is half the sampling frequency (Nyquist sampling theorem). However, due to variation of the system clock frequency and duty cycle caused by Oscillator source (crystal, resonator, and capacitors) tolerances, it is recommended that maximum frequency of an external clock source is less than $f_{clk_I/O}/2.5$.

An external clock source can not be prescaled.

Figure 13-2. Prescaler for Timer/Counter0



Note: 1. The synchronization logic on the input pins (T0) is shown in Figure 13-1 on page 92.

13.3 Register Description

13.3.1 TCCR0B – Timer/Counter Control Register B

Bit	7	6	5	4	3	2	1	0	
0x18	FOC0A	FOC0B	TSM	PSR	WGM02	CS02	CS01	CS00	TCCR0B
Read/Write	W	W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 5 – TSM: Timer/Counter Synchronization Mode**

Writing the TSM bit to one activates the Timer/Counter Synchronization mode. In this mode, the value that is written to the PSR bit is kept, hence keeping the Prescaler Reset signal asserted. This ensures that the Timer/Counter is halted and can be configured without the risk of advancing during configuration. When the TSM bit is written to zero, the PSR bit is cleared by hardware, and the Timer/Counter start counting.

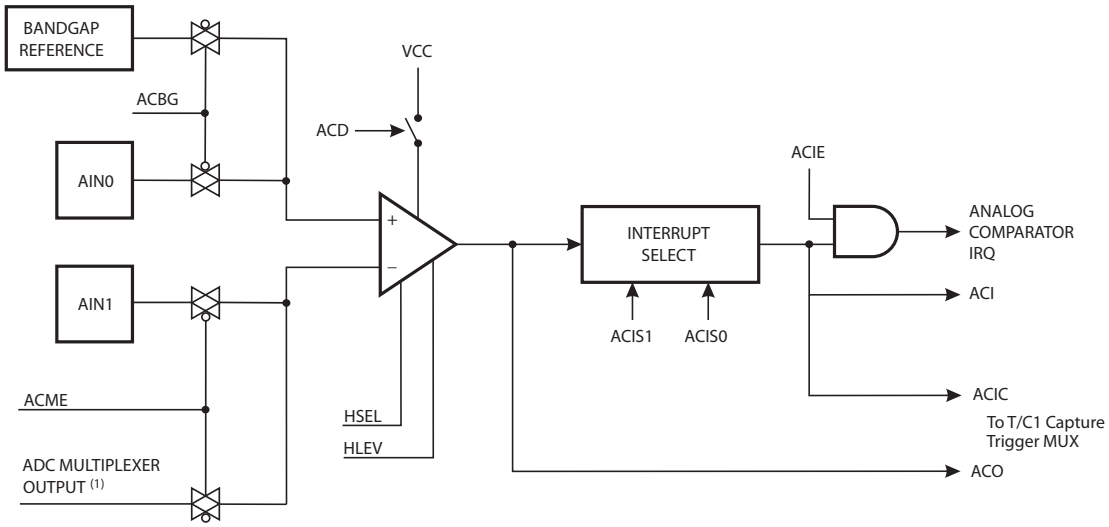
- **Bit 4 – PSR: Prescaler Reset Timer/Counter**

When this bit is one, the Timer/Counter prescaler will be Reset. This bit is normally cleared immediately by hardware, except if the TSM bit is set.

14. Analog Comparator

The analog comparator compares the input values on the positive pin AIN0 and negative pin AIN1. When the voltage on the positive pin AIN0 is higher than the voltage on the negative pin AIN1, the Analog Comparator Output, ACO, is set. The comparator can trigger a separate interrupt, exclusive to the Analog Comparator. The user can select Interrupt triggering on comparator output rise, fall or toggle. A block diagram of the comparator and its surrounding logic is shown in Figure 14-1.

Figure 14-1. Analog Comparator Block Diagram



Notes: 1. See Table 14-1 on page 95.

See Figure 1-1 on page 2 and Table 10-9 on page 54 for Analog Comparator pin placement.

The ADC Power Reduction bit, PRADC, must be disabled in order to use the ADC input multiplexer. This is done by clearing the PRADC bit in the Power Reduction Register, PRR. See "PRR – Power Reduction Register" on page 27 for more details.

When the supply voltage is below 2.7V, it is recommended to disable the ADC Power Reduction bit, PRADC, in order to use AIN0, AIN1, or a bandgap reference as an analog comparator input.

14.1 Analog Comparator Multiplexed Input

When the Analog to Digital Converter (ADC) is configurated as single ended input channel, it is possible to select any of the ADC[7:0] pins to replace the negative input to the Analog Comparator. The ADC multiplexer is used to select this input. If the Analog Comparator Multiplexer Enable bit (ACME in ADCSRB) is set, MUX bits in ADMUX select the input pin to replace the negative input to the analog comparator.

Table 14-1. Analog Comparator Multiplexed Input

ACME	MUX[3:0]	Analog Comparator Negative Input
0	XXXX	AIN1
1	0000	ADC0
1	0001	ADC1
1	0010	ADC2
1	0011	ADC3
1	0100	ADC4
1	0101	ADC5
1	0110	ADC6
1	0111	ADC7
1	1000	ADC8
1	1001	ADC9
1	1010	ADC10
1	1011	ADC11

14.2 Register Description

14.2.1 ACSRA – Analog Comparator Control and Status Register

Bit	7	6	5	4	3	2	1	0	
0x14	ACD	ACBG	ACO	ACI	ACIE	ACIC	ACIS1	ACIS0	ACSRA
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	N/A	0	0	0	0	0	

- **Bit 7 – ACD: Analog Comparator Disable**

When this bit is written logic one, the power to the Analog Comparator is switched off. This bit can be set at any time to turn off the Analog Comparator. This will reduce power consumption in Active and Idle mode. When changing the ACD bit, the Analog Comparator Interrupt must be disabled by clearing the ACIE bit in ACSR. Otherwise an interrupt can occur when the bit is changed.

- **Bit 6 – ACBG: Analog Comparator Bandgap Select**

When this bit is set, a fixed, internal bandgap reference voltage replaces the positive input to the Analog Comparator. When this bit is cleared, AIN0 is applied to the positive input of the Analog Comparator.

- **Bit 5 – ACO: Analog Comparator Output**

The output of the Analog Comparator is synchronized and then directly connected to ACO. The synchronization introduces a delay of 1 - 2 clock cycles.

- **Bit 4 – ACI: Analog Comparator Interrupt Flag**

This bit is set by hardware when a comparator output event triggers the interrupt mode defined by ACIS1 and ACIS0. The Analog Comparator interrupt routine is executed if the ACIE bit is set and the I-bit in SREG is set. ACI is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, ACI is cleared by writing a logic one to the flag.

- **Bit 3 – ACIE: Analog Comparator Interrupt Enable**

When the ACIE bit is written logic one and the I-bit in the Status Register is set, the Analog Comparator interrupt is activated. When written logic zero, the interrupt is disabled.

- **Bit 2 – ACIC: Analog Comparator Input Capture Enable**

When written logic one, this bit enables the input capture function in Timer/Counter1 to be triggered by the Analog Comparator. The comparator output is then directly connected to the input capture front-end logic, making the comparator utilize the noise canceler and edge select features of the Timer/Counter1 Input Capture interrupt.

When written logic zero, no connection between the Analog Comparator and the input capture function exists. To make the comparator trigger the Timer/Counter1 Input Capture inter-rupt, the ICIE1 bit in the Timer Interrupt Mask Register (TIMSK) must be set.

- **Bits 1:0 – ACIS[1:0]: Analog Comparator Interrupt Mode Select**

These bits determine which comparator events that trigger the Analog Comparator interrupt. The different settings are shown in Table 14-2.

Table 14-2. ACIS1/ACIS0 Settings

ACIS1	ACIS0	Interrupt Mode
0	0	Comparator Interrupt on Output Toggle.
0	1	Reserved
1	0	Comparator Interrupt on Falling Output Edge.
1	1	Comparator Interrupt on Rising Output Edge.

When changing the ACIS1/ACIS0 bits, the Analog Comparator Interrupt must be disabled by clearing its Interrupt Enable bit in the ACSR Register. Otherwise an interrupt can occur when the bits are changed.

14.2.2 ACSRB – Analog Comparator Control and Status Register B

Bit	7	6	5	4	3	2	1	0	
0x13	HSEL	HLEV	ACLP	–	ACCE	ACME	ACIRS1	ACIRS0	ACSRB
Read/Write	R/W	R/W	R/W	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – HSEL: Hysteresis Select**

When this bit is written logic one, the hysteresis of the analog comparator is enabled. The level of hysteresis is selected by the HLEV bit.

- **Bit 6 – HLEV: Hysteresis Level**

When enabled via the HSEL bit, the level of hysteresis can be set using the HLEV bit, as shown in Table 14-3.

Table 14-3. Selecting Level of Analog Comparator Hysteresis

HSEL	HLEV	Hysteresis of Analog Comparator
0	X	Not enabled
1	0	20 mV
	1	50 mV

- **Bit 5 – ACLP**

This bit is reserved for QTouch, always write as zero.

- **Bit 4 – Reserved**

This bit is reserved and will always read as zero.

- **Bit 3 – ACCE**

This bit is reserved for QTouch, always write as zero.

- **Bit 2 – ACME: Analog Comparator Multiplexer Enable**

When this bit is written logic one and the ADC is switched off (ADEN in ADCSRA is zero), the ADC multiplexer selects the negative input to the Analog Comparator. When this bit is written logic zero, AIN1 is applied to the negative input of the Analog Comparator. For a detailed description of this bit, see “Analog Comparator Multiplexed Input” on page 94.

- **Bit 1 – ACIRS1**

This bit is reserved for QTouch, always write as zero.

- **Bit 0 – ACIRS0**

This bit is reserved for QTouch, always write as zero.

14.2.3 DIDR0 – Digital Input Disable Register 0

Bit	7	6	5	4	3	2	1	0	
0x0D	ADC7D	ADC6D	ADC5D	ADC4D	ADC3D	ADC2D	ADC1D	ADC0D	DIDR0
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 2:1 – ADC2D, ADC1D: ADC[2:1] Digital Input Buffer Disable**

When this bit is written logic one, the digital input buffer on the AIN[1:0] pin is disabled. The corresponding PIN Register bit will always read as zero when this bit is set. When used as an analog input but not required as a digital input the power consumption in the digital input buffer can be reduced by writing this bit to logic one.

15. Analog to Digital Converter

15.1 Features

- **10-bit Resolution**
- **1 LSB Integral Non-linearity**
- **± 2 LSB Absolute Accuracy**
- **13 µs Conversion Time**
- **15 kSPS at Maximum Resolution**
- **12 Multiplexed Single Ended Input Channels**
- **Temperature Sensor Input Channel**
- **Optional Left Adjustment for ADC Result Readout**
- **0 - V_{CC} ADC Input Voltage Range**
- **1.1V ADC Reference Voltage**
- **Free Running or Single Conversion Mode**
- **ADC Start Conversion by Auto Triggering on Interrupt Sources**
- **Interrupt on ADC Conversion Complete**
- **Sleep Mode Noise Canceler**

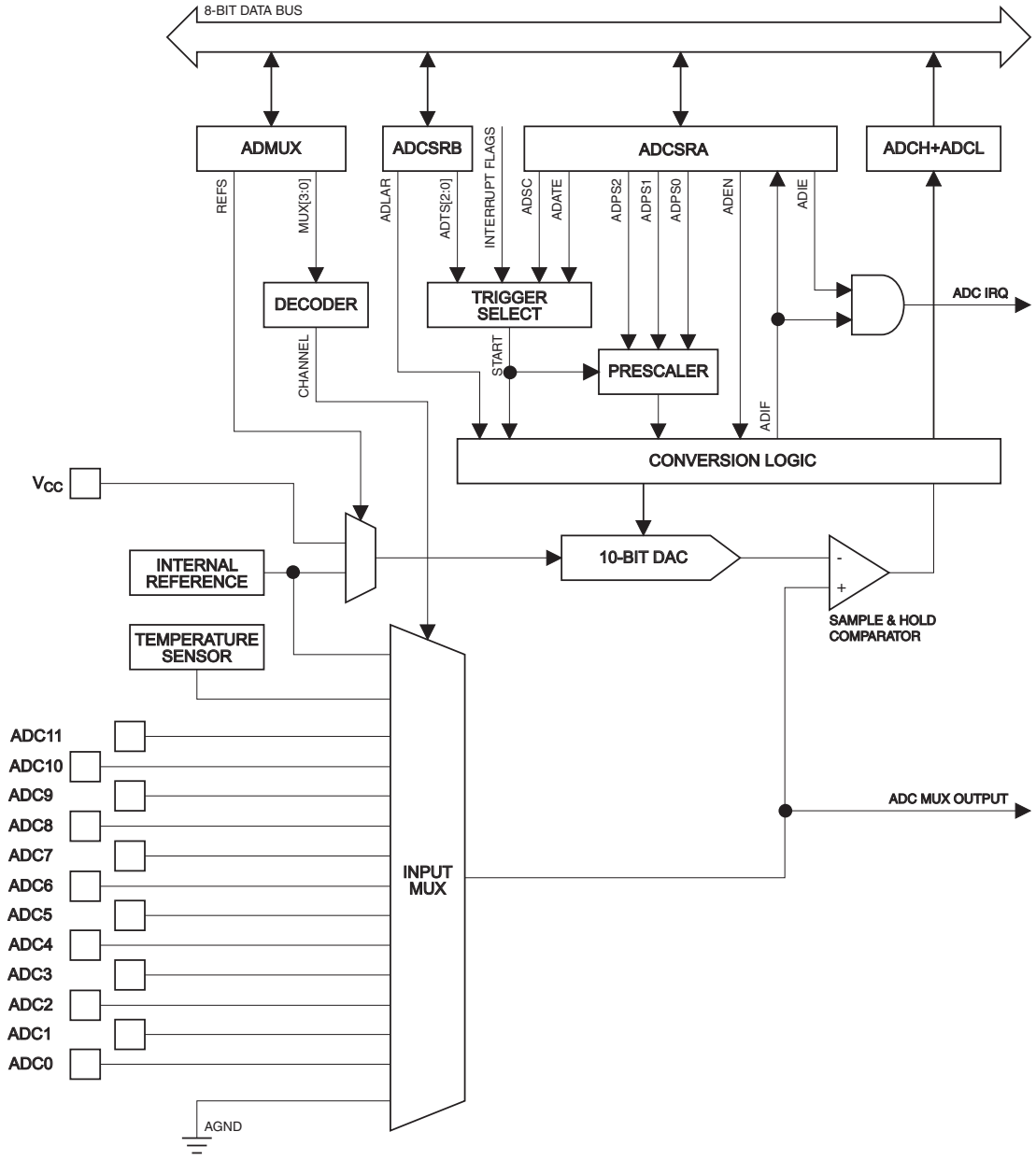
15.2 Overview

ATtiny40 features a 10-bit, successive approximation Analog-to-Digital Converter (ADC). The ADC is wired to a 13-channel analog multiplexer, which allows the ADC to measure the voltage at 12 single-ended input pins, or from one internal, single-ended voltage channel coming from the internal temperature sensor. Voltage inputs are referred to 0V (GND).

The ADC contains a Sample and Hold circuit which ensures that the input voltage to the ADC is held at a constant level during conversion. A block diagram of the ADC is shown in Figure 15-1 on page 99.

Internal reference voltage of nominally 1.1V is provided on-chip. Alternatively, V_{CC} can be used as reference voltage for single ended channels.

Figure 15-1. Analog to Digital Converter Block Schematic



15.3 Operation

In order to be able to use the ADC the Power Reduction bit, PRADC, in the Power Reduction Register must be disabled. This is done by clearing the PRADC bit. See “PRR – Power Reduction Register” on page 27 for more details.

The ADC is enabled by setting the ADC Enable bit, ADEN in ADCSRA. Voltage reference and input channel selections will not go into effect until ADEN is set. The ADC does not consume power when ADEN is cleared, so it is recommended to switch off the ADC before entering power saving sleep modes.

The ADC converts an analog input voltage to a 10-bit digital value using successive approximation. The minimum value represents GND and the maximum value represents the reference voltage. The ADC voltage reference is selected by writing the REFS bit in the ADMUX register. Alternatives are the V_{CC} supply pin and the internal 1.1V voltage reference.

The analog input channel is selected by writing to the MUX bits in ADMUX. Any of the ADC input pins can be selected as single ended inputs to the ADC.

The ADC generates a 10-bit result which is presented in the ADC Data Registers, ADCH and ADCL. By default, the result is presented right adjusted, but can optionally be presented left adjusted by setting the ADLAR bit in ADCSRB.

If the result is left adjusted and no more than 8-bit precision is required, it is sufficient to read ADCH, only. Otherwise, ADCL must be read first, then ADCH, to ensure that the content of the data registers belongs to the same conversion. Once ADCL is read, ADC access to data registers is blocked. This means that if ADCL has been read, and a conversion completes before ADCH is read, neither register is updated and the result from the conversion is lost. When ADCH is read, ADC access to the ADCH and ADCL Registers is re-enabled.

The ADC has its own interrupt which can be triggered when a conversion completes. When ADC access to the data registers is prohibited between reading of ADCH and ADCL, the interrupt will trigger even if the result is lost.

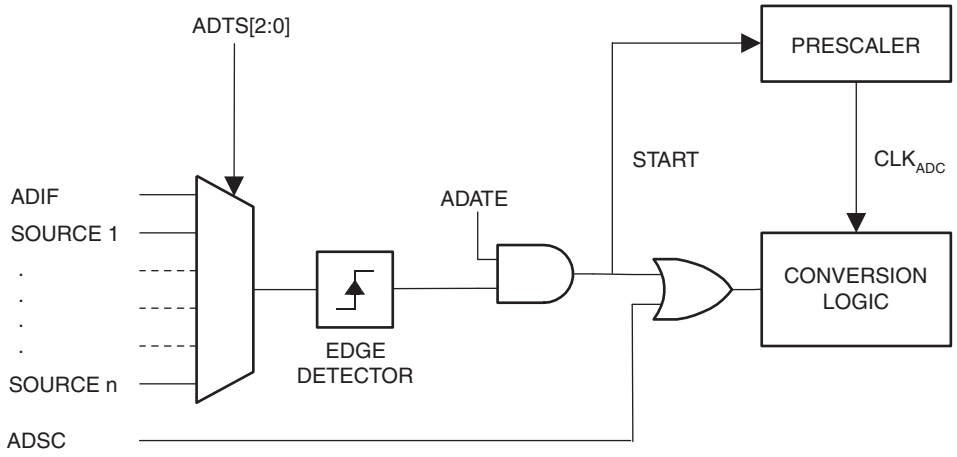
15.4 Starting a Conversion

Make sure the ADC is powered by clearing the ADC Power Reduction bit, PRADC, in the Power Reduction Register, PRR (see “PRR – Power Reduction Register” on page 27).

A single conversion is started by writing a logical one to the ADC Start Conversion bit, ADSC. This bit stays high as long as the conversion is in progress and will be cleared by hardware when the conversion is completed. If a different data channel is selected while a conversion is in progress, the ADC will finish the current conversion before performing the channel change.

Alternatively, a conversion can be triggered automatically by various sources. Auto Triggering is enabled by setting the ADC Auto Trigger Enable bit, ADATE in ADCSRA. The trigger source is selected by setting the ADC Trigger Select bits, ADTS in ADCSRB (see description of the ADTS bits for a list of the trigger sources). When a positive edge occurs on the selected trigger signal, the ADC prescaler is reset and a conversion is started. This provides a method of starting conversions at fixed intervals. If the trigger signal still is set when the conversion completes, a new conversion will not be started. If another positive edge occurs on the trigger signal during conversion, the edge will be ignored. Note that an Interrupt Flag will be set even if the specific interrupt is disabled or the Global Interrupt Enable bit in SREG is cleared. A conversion can thus be triggered without causing an interrupt. However, the Interrupt Flag must be cleared in order to trigger a new conversion at the next interrupt event.

Figure 15-2. ADC Auto Trigger Logic



Using the ADC Interrupt Flag as a trigger source makes the ADC start a new conversion as soon as the ongoing conversion has finished. The ADC then operates in Free Running mode, constantly sampling and updating the ADC Data Register. The first conversion must be started by writing a logical one to the ADSC bit in ADCSRA. In

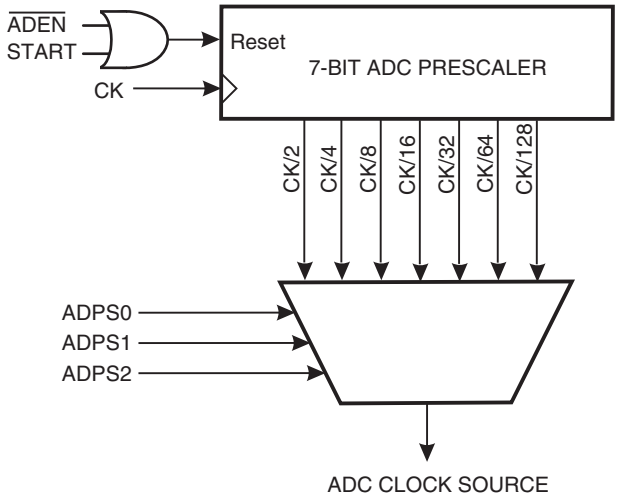
this mode the ADC will perform successive conversions independently of whether the ADC Interrupt Flag, ADIF is cleared or not.

If Auto Triggering is enabled, single conversions can be started by writing ADSC in ADCSRA to one. ADSC can also be used to determine if a conversion is in progress. The ADSC bit will be read as one during a conversion, independently of how the conversion was started.

15.5 Prescaling and Conversion Timing

By default, the successive approximation circuitry requires an input clock frequency between 50 kHz and 200 kHz to get maximum resolution. If a lower resolution than 10 bits is needed, the input clock frequency to the ADC can be higher than 200 kHz to get a higher sample rate. It is not recommended to use a higher input clock frequency than 1 MHz.

Figure 15-3. ADC Prescaler

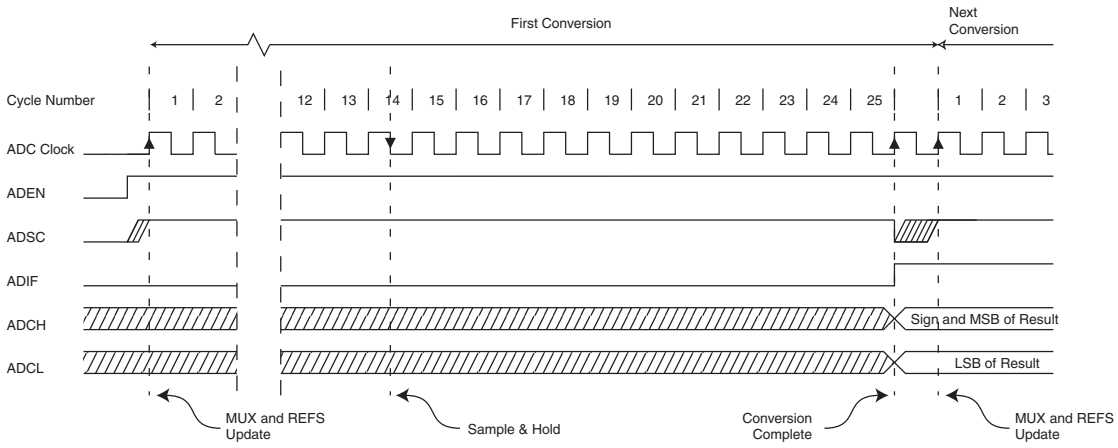


The ADC module contains a prescaler, as illustrated in Figure 15-3 on page 101, which generates an acceptable ADC clock frequency from any CPU frequency above 100 kHz. The prescaling is set by the ADPS bits in ADCSRA. The prescaler starts counting from the moment the ADC is switched on by setting the ADEN bit in ADCSRA. The prescaler keeps running for as long as the ADEN bit is set, and is continuously reset when ADEN is low.

When initiating a single ended conversion by setting the ADSC bit in ADCSRA, the conversion starts at the following rising edge of the ADC clock cycle.

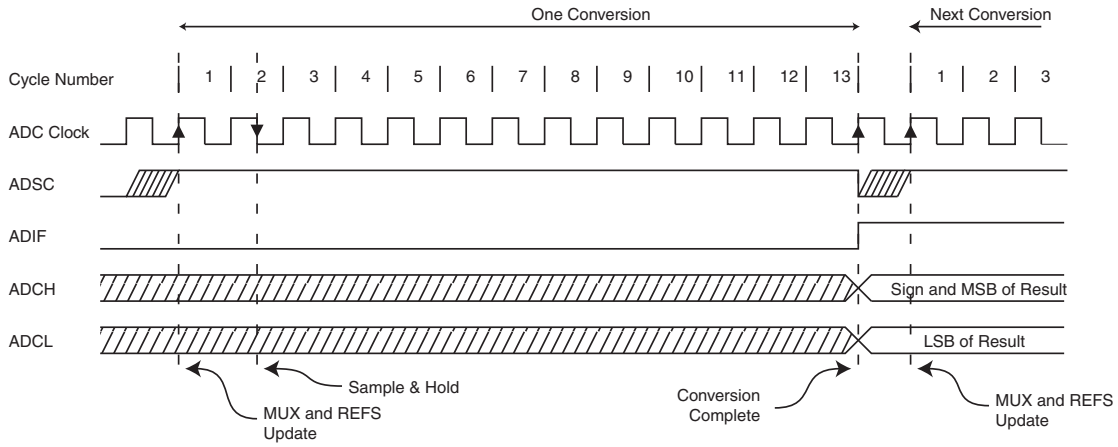
A normal conversion takes 13 ADC clock cycles, as summarised in Table 15-1 on page 104. The first conversion after the ADC is switched on (ADEN in ADCSRA is set) takes 25 ADC clock cycles in order to initialize the analog circuitry, as shown in Figure 15-4 below.

Figure 15-4. ADC Timing Diagram, First Conversion (Single Conversion Mode)



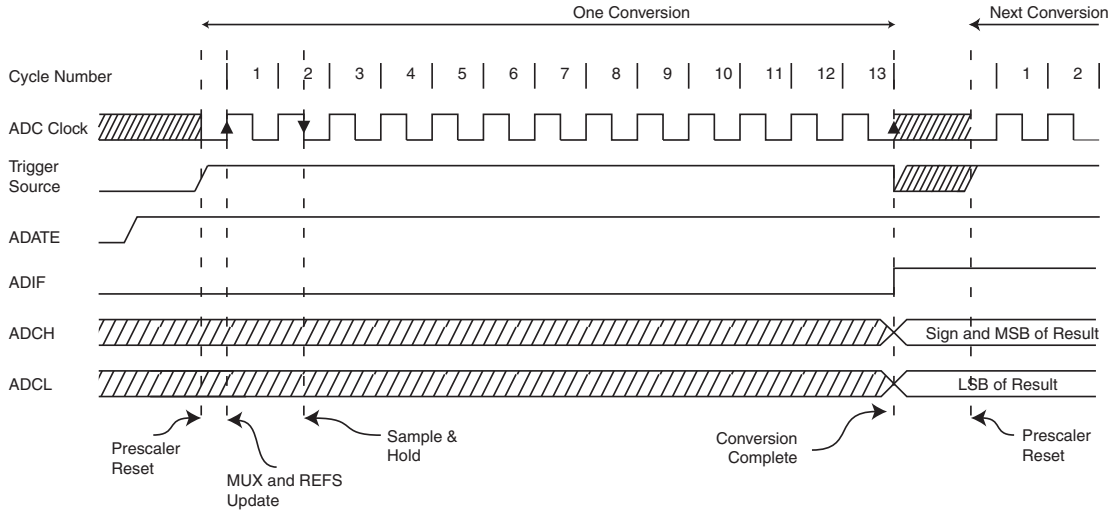
The actual sample-and-hold takes place 1.5 ADC clock cycles after the start of a normal conversion and 13.5 ADC clock cycles after the start of a first conversion. See Figure 15-5. When a conversion is complete, the result is written to the ADC Data Registers, and ADIF is set. In Single Conversion mode, ADSC is cleared simultaneously. The software may then set ADSC again, and a new conversion will be initiated on the first rising ADC clock edge.

Figure 15-5. ADC Timing Diagram, Single Conversion



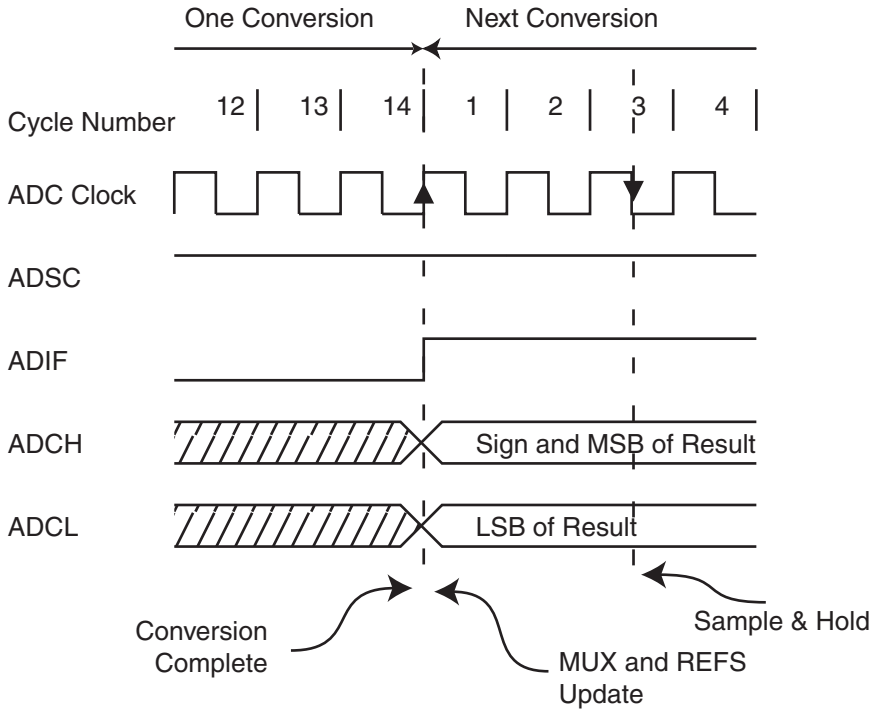
When Auto Triggering is used, the prescaler is reset when the trigger event occurs, as shown in Figure 15-6 below. This assures a fixed delay from the trigger event to the start of conversion. In this mode, the sample-and-hold takes place two ADC clock cycles after the rising edge on the trigger source signal. Three additional CPU clock cycles are used for synchronization logic.

Figure 15-6. ADC Timing Diagram, Auto Triggered Conversion



In Free Running mode, a new conversion will be started immediately after the conversion completes, while ADSC remains high. See Figure 15-7.

Figure 15-7. ADC Timing Diagram, Free Running Conversion



For a summary of conversion times, see Table 15-1.

Table 15-1. ADC Conversion Time

Condition	Sample & Hold (Cycles from Start of Conversion)	Conversion Time (Cycles)
First conversion	13.5	25
Normal conversions	1.5	13
Auto Triggered conversions	2	13.5
Free Running conversion	2.5	14

15.6 Changing Channel or Reference Selection

The MUX and REFS bits in the ADMUX Register are single buffered through a temporary register to which the CPU has random access. This ensures that the channels and reference selection only takes place at a safe point during the conversion. The channel and reference selection is continuously updated until a conversion is started. Once the conversion starts, the channel and reference selection is locked to ensure a sufficient sampling time for the ADC. Continuous updating resumes in the last ADC clock cycle before the conversion completes (ADIF in ADCSRA is set). Note that the conversion starts on the following rising ADC clock edge after ADSC is written. The user is thus advised not to write new channel or reference selection values to ADMUX until one ADC clock cycle after ADSC is written.

If Auto Triggering is used, the exact time of the triggering event can be indeterministic. Special care must be taken when updating the ADMUX Register, in order to control which conversion will be affected by the new settings.

If both ADATE and ADEN is written to one, an interrupt event can occur at any time. If the ADMUX Register is changed in this period, the user cannot tell if the next conversion is based on the old or the new settings. ADMUX can be safely updated in the following ways:

- When ADATE or ADEN is cleared.
- During conversion, minimum one ADC clock cycle after the trigger event.
- After a conversion, before the Interrupt Flag used as trigger source is cleared.

When updating ADMUX in one of these conditions, the new settings will affect the next ADC conversion.

15.6.1 ADC Input Channels

When changing channel selections, the user should observe the following guidelines to ensure that the correct channel is selected:

- In Single Conversion mode, always select the channel before starting the conversion. The channel selection may be changed one ADC clock cycle after writing one to ADSC. However, the simplest method is to wait for the conversion to complete before changing the channel selection.
- In Free Running mode, always select the channel before starting the first conversion. The channel selection may be changed one ADC clock cycle after writing one to ADSC. However, the simplest method is to wait for the first conversion to complete, and then change the channel selection. Since the next conversion has already started automatically, the next result will reflect the previous channel selection. Subsequent conversions will reflect the new channel selection.

15.6.2 ADC Voltage Reference

The ADC reference voltage (V_{REF}) indicates the conversion range for the ADC. Single ended channels that exceed V_{REF} will result in codes close to 0x3FF. V_{REF} can be selected as either V_{CC}, or internal 1.1V reference. The internal 1.1V reference is generated from the internal bandgap reference (V_{BG}) through an internal amplifier.

The first ADC conversion result after switching reference voltage source may be inaccurate, and the user is advised to discard this result.

15.7 ADC Noise Canceler

The ADC features a noise canceler that enables conversion during sleep mode. This reduces noise induced from the CPU core and other I/O peripherals. The noise canceler can be used with ADC Noise Reduction and Idle mode. To make use of this feature, the following procedure should be used:

- Make sure that the ADC is enabled and is not busy converting. Single Conversion mode must be selected and the ADC conversion complete interrupt must be enabled.
- Enter ADC Noise Reduction mode (or Idle mode). The ADC will start a conversion once the CPU has been halted.
- If no other interrupts occur before the ADC conversion completes, the ADC interrupt will wake up the CPU and execute the ADC Conversion Complete interrupt routine. If another interrupt wakes up the CPU before the ADC conversion is complete, that interrupt will be executed, and an ADC Conversion Complete interrupt request will be generated when the ADC conversion completes. The CPU will remain in active mode until a new sleep command is executed.

Note that the ADC will not automatically be turned off when entering other sleep modes than Idle mode and ADC Noise Reduction mode. The user is advised to write zero to ADEN before entering such sleep modes to avoid excessive power consumption.

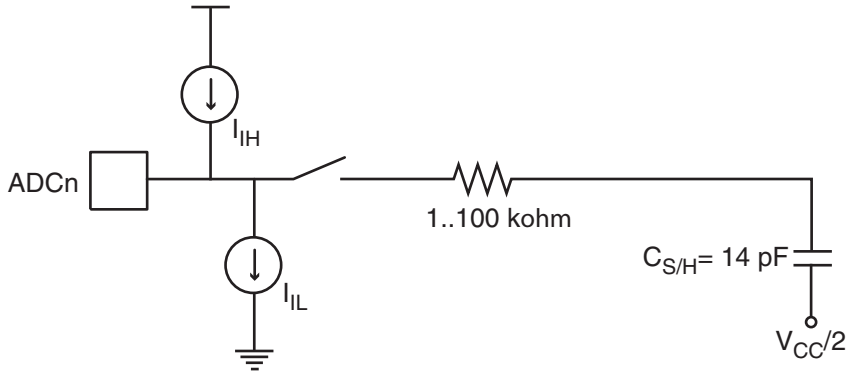
15.8 Analog Input Circuitry

The analog input circuitry for single ended channels is illustrated in Figure 15-8. An analog source applied to ADCn is subjected to the pin capacitance and input leakage of that pin, regardless of whether that channel is selected as input for the ADC. When the channel is selected, the source must drive the S/H capacitor through the series resistance (combined resistance in the input path).

The ADC is optimized for analog signals with an output impedance of approximately 10 kΩ or less. If such a source is used, the sampling time will be negligible. If a source with higher impedance is used, the sampling time will depend on how long time the source needs to charge the S/H capacitor, which can vary widely. The user is recommended to only use low impedance sources with slowly varying signals, since this minimizes the required charge transfer to the S/H capacitor.

In order to avoid distortion from unpredictable signal convolution, signal components higher than the Nyquist frequency ($f_{ADC}/2$) should not be present. The user is advised to remove high frequency components with a low-pass filter before applying the signals as inputs to the ADC.

Figure 15-8. Analog Input Circuitry



Note: The capacitor in the figure depicts the total capacitance, including the sample/hold capacitor and any stray or parasitic capacitance inside the device. The value given is worst case.

15.9 Noise Canceling Techniques

Digital circuitry inside and outside the device generates EMI which might affect the accuracy of analog measurements. When conversion accuracy is critical, the noise level can be reduced by applying the following techniques:

- Keep analog signal paths as short as possible.
- Make sure analog tracks run over the analog ground plane.
- Keep analog tracks well away from high-speed switching digital tracks.
- If any port pin is used as a digital output, it mustn't switch while a conversion is in progress.
- Place bypass capacitors as close to V_{CC} and GND pins as possible.

Where high ADC accuracy is required it is recommended to use ADC Noise Reduction Mode, as described in Section 15.7 on page 105. This is especially the case when system clock frequency is above 1 MHz, or when the ADC is used for reading the internal temperature sensor, as described in Section 15.12 on page 109. A good system design with properly placed, external bypass capacitors does reduce the need for using ADC Noise Reduction Mode

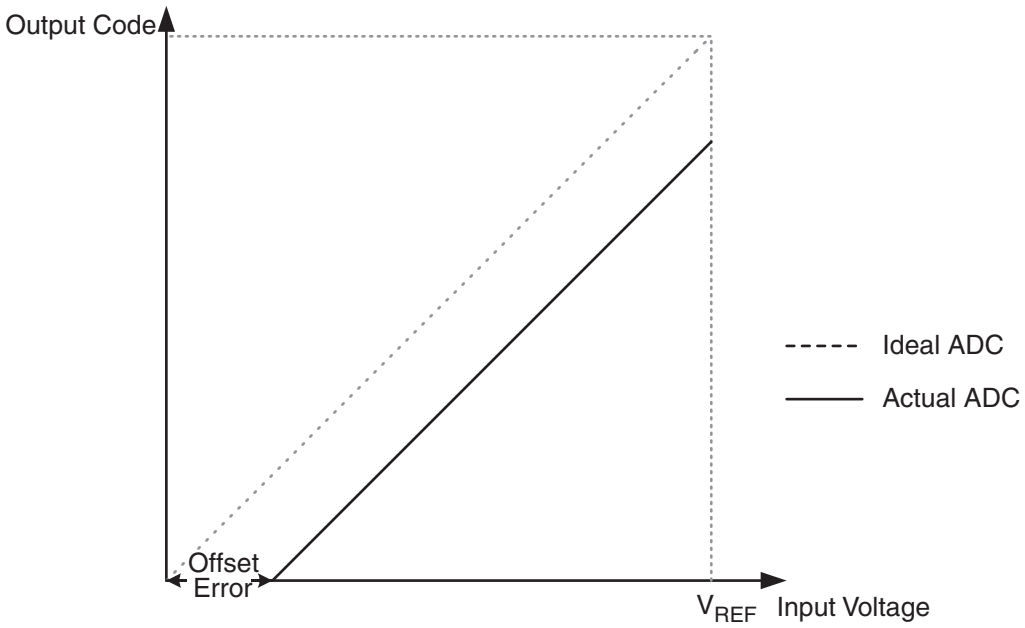
15.10 ADC Accuracy Definitions

An n-bit single-ended ADC converts a voltage linearly between GND and V_{REF} in 2^n steps (LSBs). The lowest code is read as 0, and the highest code is read as 2^n-1.

Several parameters describe the deviation from the ideal behavior, as follows:

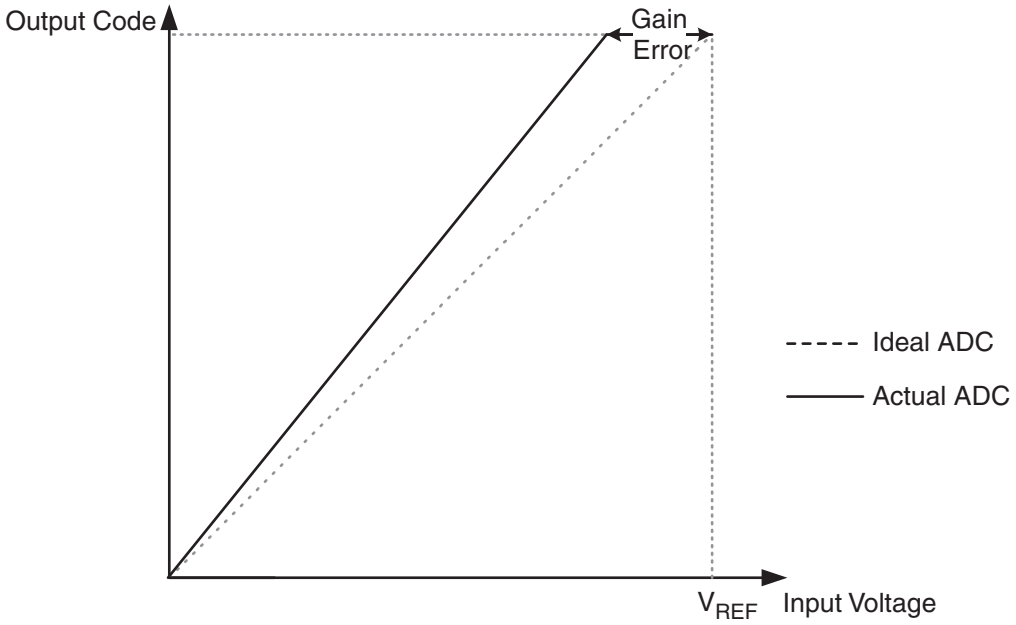
- Offset: The deviation of the first transition (0x000 to 0x001) compared to the ideal transition (at 0.5 LSB). Ideal value: 0 LSB.

Figure 15-9. Offset Error



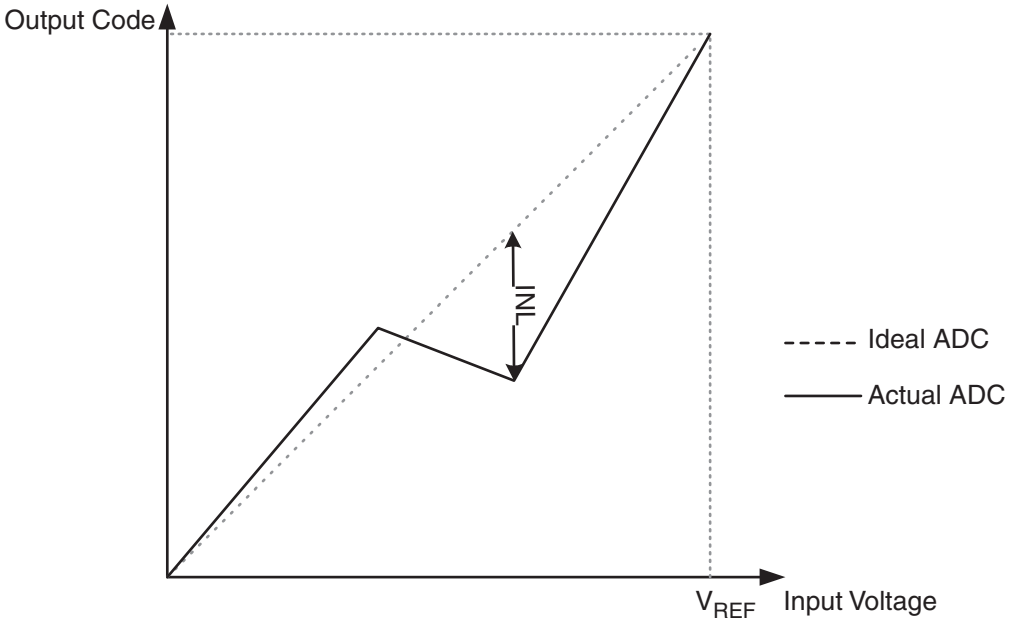
- Gain Error: After adjusting for offset, the Gain Error is found as the deviation of the last transition (0x3FE to 0x3FF) compared to the ideal transition (at 1.5 LSB below maximum). Ideal value: 0 LSB

Figure 15-10. Gain Error



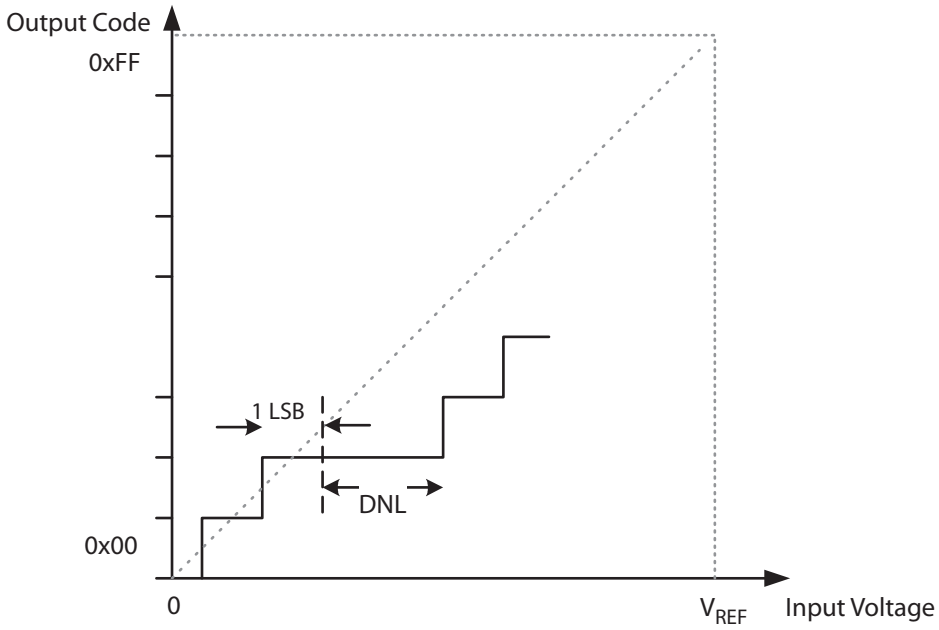
- Integral Non-linearity (INL): After adjusting for offset and gain error, the INL is the maximum deviation of an actual transition compared to an ideal transition for any code. Ideal value: 0 LSB.

Figure 15-11. Integral Non-linearity (INL)



- Differential Non-linearity (DNL): The maximum deviation of the actual code width (the interval between two adjacent transitions) from the ideal code width (1 LSB). Ideal value: 0 LSB.

Figure 15-12. Differential Non-linearity (DNL)



- Quantization Error: Due to the quantization of the input voltage into a finite number of codes, a range of input voltages (1 LSB wide) will code to the same value. Always ± 0.5 LSB.
- Absolute Accuracy: The maximum deviation of an actual (unadjusted) transition compared to an ideal transition for any code. This is the compound effect of offset, gain error, differential error, non-linearity, and quantization error. Ideal value: ± 0.5 LSB.

15.11 ADC Conversion Result

After the conversion is complete (ADIF is high), the conversion result can be found in the ADC Data Registers (ADCL, ADCH). The result is, as follows:

$$ADC = \frac{V_{IN} \cdot 1024}{V_{REF}}$$

where V_{IN} is the voltage on the selected input pin and V_{REF} the selected voltage reference (see Table 15-3 on page 110 and Table 15-4 on page 110). 0x000 represents analog ground, and 0x3FF represents the selected reference voltage minus one LSB. The result is presented in one-sided form, from 0x3FF to 0x000.

15.12 Temperature Measurement

The temperature measurement is based on an on-chip temperature sensor that is coupled to a single ended ADC channel. The temperature sensor is measured via channel ADC12 and is enabled by writing MUX bits in ADMUX register to “1110”. The internal 1.1V reference must also be selected for the ADC reference source in the temperature sensor measurement. When the temperature sensor is enabled, the ADC converter can be used in single conversion mode to measure the voltage over the temperature sensor.

The measured voltage has a linear relationship to the temperature as described in Table 15-2 The sensitivity is approximately 1 LSB / °C and the accuracy depends on the method of user calibration. Typically, the measurement accuracy after a single temperature calibration is ±10°C, assuming calibration at room temperature. Better accuracies are achieved by using two temperature points for calibration.

Table 15-2. Temperature vs. Sensor Output Voltage (Typical Case)

Temperature	-40°C	+25°C	+85°C
ADC	230 LSB	300 LSB	370 LSB

The values described in Table 15-2 are typical values. However, due to process variation the temperature sensor output voltage varies from one chip to another. To be capable of achieving more accurate results the temperature measurement can be calibrated in the application software. The sofware calibration can be done using the formula:

```
T = k * [(ADCH << 8) | ADCL] + TOS
```

where ADCH and ADCL are the ADC data registers, k is the fixed slope coefficient and T_{OS} is the temperature sensor offset. Typically, k is very close to 1.0 and in single-point calibration the coefficient may be omitted. Where higher accuracy is required the slope coefficient should be evaluated based on measurements at two temperatures.

15.13 Register Description

15.13.1 ADMUX – ADC Multiplexer Selection Register

Bit	7	6	5	4	3	2	1	0	
0x10	–	REFS	REFEN	ADC0EN	MUX3	MUX2	MUX1	MUX0	ADMUX
Read/Write	R	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 6 – REFS: Reference Selection Bit**

This bit selects the voltage reference for the ADC, as shown in Table 15-3.

Table 15-3. Voltage Reference Selections for ADC

REFS	Voltage Reference Selection
0	V_{CC} used as analog reference
1	Internal 1.1V voltage reference

If this bit is changed during a conversion, the change will not go in effect until this conversion is complete (ADIF in ADCSR is set). Also note, that when these bits are changed, the next conversion will take 25 ADC clock cycles.

- **Bit 5 – REFEN**

This bit is reserved for QTouch, always write as zero.

- **Bit 4 – ADC0EN**

This bit is reserved for QTouch, always write as zero.

- **Bits 3:0 – MUX[3:0]: Analog Channel and Gain Selection Bits**

The value of these bits selects which analog input is connected to the ADC, as shown in Table 15-4. Selecting channel ADC12 enables temperature measurement.

Table 15-4. Single-Ended Input channel Selections

Single Ended Input	MUX[3:0]
ADC0 (PA0)	0000
ADC1 (PA1)	0001
ADC2 (PA2)	0010
ADC3 (PA3)	0011
ADC4 (PA4)	0100
ADC5 (PA5)	0101
ADC6 (PA6)	0110
ADC7 (PA7)	0111
ADC8 (PB0)	1000
ADC9 (PB1)	1001
ADC10 (PB2)	1010
ADC11 (PB3)	1011
0V (AGND)	1100
1.1V (I Ref)(1)	1101
ADC12 (Temperature Sensor)(2)	1110
Reserved	1111

Notes: 1. After switching to internal voltage reference the ADC requires a settling time of 1ms before measurements are stable. Conversions starting before this may not be reliable. The ADC must be enabled during the settling time.

2. See “Temperature Measurement” on page 109.

If these bits are changed during a conversion, the change will not go into effect until this conversion is complete (ADIF in ADCSRA is set).

15.13.2 ADCL and ADCH – ADC Data Register

15.13.2.1 ADLAR = 0

Bit	15	14	13	12	11	10	9	8	
0x0F	–	–	–	–	–	–	ADC9	ADC8	ADCH
0x0E	ADC7	ADC6	ADC5	ADC4	ADC3	ADC2	ADC1	ADC0	ADCL
	7	6	5	4	3	2	1	0	
Read/Write	R	R	R	R	R	R	R	R	
	R	R	R	R	R	R	R	R	
Initial Value	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	

15.13.2.2 ADLAR = 1

Bit	15	14	13	12	11	10	9	8	
0x0F	ADC9	ADC8	ADC7	ADC6	ADC5	ADC4	ADC3	ADC2	ADCH
0x0E	ADC1	ADC0	–	–	–	–	–	–	ADCL
	7	6	5	4	3	2	1	0	
Read/Write	R	R	R	R	R	R	R	R	
	R	R	R	R	R	R	R	R	
Initial Value	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	

When an ADC conversion is complete, the result is found in these two registers.

When ADCL is read, the ADC Data Register is not updated until ADCH is read. Consequently, if the result is left adjusted and no more than 8-bit precision is required, it is sufficient to read ADCH. Otherwise, ADCL must be read first, then ADCH.

The ADLAR bit in ADCSRB, and the MUX bits in ADMUX affect the way the result is read from the registers. If ADLAR is set, the result is left adjusted. If ADLAR is cleared (default), the result is right adjusted.

- **ADC[9:0]: ADC Conversion Result**

These bits represent the result from the conversion, as detailed in “ADC Conversion Result” on page 109.

15.13.3 ADCSRA – ADC Control and Status Register A

Bit	7	6	5	4	3	2	1	0	
0x12	ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCSRA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – ADEN: ADC Enable**

Writing this bit to one enables the ADC. By writing it to zero, the ADC is turned off. Turning the ADC off while a conversion is in progress, will terminate this conversion.

- **Bit 6 – ADSC: ADC Start Conversion**

In Single Conversion mode, write this bit to one to start each conversion. In Free Running mode, write this bit to one to start the first conversion. The first conversion after ADSC has been written after the ADC has been enabled, or if ADSC is written at the same time as the ADC is enabled, will take 25 ADC clock cycles instead of the normal 13. This first conversion performs initialization of the ADC.

ADSC will read as one as long as a conversion is in progress. When the conversion is complete, it returns to zero. Writing zero to this bit has no effect.

- **Bit 5 – ADATE: ADC Auto Trigger Enable**

When this bit is written to one, Auto Triggering of the ADC is enabled. The ADC will start a conversion on a positive edge of the selected trigger signal. The trigger source is selected by setting the ADC Trigger Select bits, ADTS in ADCSRB.

- **Bit 4 – ADIF: ADC Interrupt Flag**

This bit is set when an ADC conversion completes and the data registers are updated. The ADC Conversion Complete Interrupt is executed if the ADIE bit and the I-bit in SREG are set. ADIF is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, ADIF is cleared by writing a logical one to the flag.

Beware that if doing a Read-Modify-Write on ADCSRA, a pending interrupt can be disabled.

- **Bit 3 – ADIE: ADC Interrupt Enable**

When this bit is written to one and the I-bit in SREG is set, the ADC Conversion Complete Interrupt is activated.

- **Bits 2:0 – ADPS[2:0]: ADC Prescaler Select Bits**

These bits determine the division factor between the system clock frequency and the input clock to the ADC.

Table 15-5. ADC Prescaler Selections

ADPS2	ADPS1	ADPS0	Division Factor
0	0	0	2
0	0	1	2
0	1	0	4
0	1	1	8
1	0	0	16
1	0	1	32
1	1	0	64
1	1	1	128

15.13.4 ADCSRB – ADC Control and Status Register B

Bit	7	6	5	4	3	2	1	0	
0x11	VDEN	VDPD	–	–	ADLAR	ADTS2	ADTS1	ADTS0	ADCSRB
Read/Write	R/W	R/W	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – VDEN**

This bit is reserved for QTouch, always write as zero.

- **Bit 6 – VDPD**

This bit is reserved for QTouch, always write as zero.

- **Bits 5:4 – Res: Reserved Bits**

These are reserved bits. For compatibility with future devices always write these bits to zero.

- **Bit 3 – ADLAR: ADC Left Adjust Result**

The ADLAR bit affects the presentation of the ADC conversion result in the ADC Data Register. Write one to ADLAR to left adjust the result. Otherwise, the result is right adjusted. Changing the ADLAR bit will affect the ADC Data Register immediately, regardless of any ongoing conversions. For a comple the description of this bit, see “ADCL and ADCH – ADC Data Register” on page 111.

- **Bits 2:0 – ADTS[2:0]: ADC Auto Trigger Source**

If ADATE in ADCSRA is written to one, the value of these bits selects which source will trigger an ADC conversion. If ADATE is cleared, the ADTS[2:0] settings will have no effect. A conversion will be triggered by the rising edge of the selected Interrupt Flag. Note that switching from a trigger source that is cleared to a trigger source that is set, will generate a positive edge on the trigger signal. If ADEN in ADCSRA is set, this will start a conversion. Switching to Free Running mode (ADTS[2:0]=0) will not cause a trigger event, even if the ADC Interrupt Flag is set.

Table 15-6. ADC Auto Trigger Source Selections

ADTS2	ADTS1	ADTS0	Trigger Source
0	0	0	Free Running mode
0	0	1	Analog Comparator
0	1	0	External Interrupt Request 0
0	1	1	Timer/Counter0 Compare Match A
1	0	0	Timer/Counter0 Overflow
1	0	1	Timer/Counter1 Compare Match B
1	1	0	Timer/Counter1 Overflow
1	1	1	Timer/Counter1 Capture Event

15.13.5 DIDR0 – Digital Input Disable Register 0

Bit	7	6	5	4	3	2	1	0	
0x0D	ADC7D	ADC6D	ADC5D	ADC4D	ADC3D	ADC2D	ADC1D	ADC0D	DIDR0
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:0 – ADC7D:ADC0D: ADC[7:0] Digital Input Disable**

When a bit is written logic one, the digital input buffer on the corresponding ADC pin is disabled. The corresponding PIN register bit will always read as zero when this bit is set. When an analog signal is applied to the ADC[7:0] pin and the digital input from this pin is not needed, this bit should be written logic one to reduce power consumption in the digital input buffer.

15.13.6 PORTCR – Port Control Register

Bit	7	6	5	4	3	2	1	0	
0x08	ADC11D	ADC10D	ADC9D	ADC8D	–	BBMC	BBMB	BBMA	PORTCR
Read/Write	R/W	R/W	R/W	R/W	R	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:4 – ADC11D:ADC8D: ADC[11:8] Digital Input Disable**

When a bit is written logic one, the digital input buffer on the corresponding ADC pin is disabled. The corresponding PIN register bit will always read as zero when this bit is set. When an analog signal is applied to the ADC[11:8] pin and the digital input from this pin is not needed, this bit should be written logic one to reduce power consumption in the digital input buffer.

16. SPI – Serial Peripheral Interface

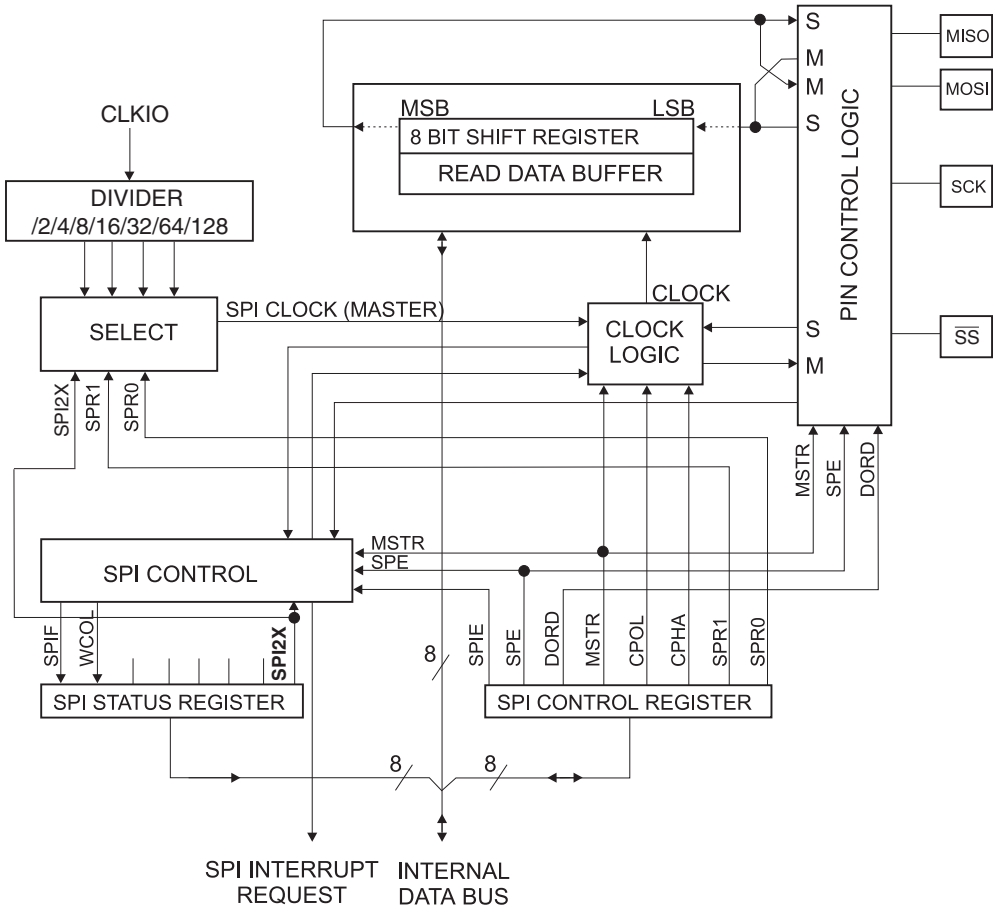
16.1 Features

- **Full-duplex, Three-wire Synchronous Data Transfer**
- **Master or Slave Operation**
- **LSB First or MSB First Data Transfer**
- **Seven Programmable Bit Rates**
- **End of Transmission Interrupt Flag**
- **Write Collision Flag Protection**
- **Wake-up from Idle Mode**
- **Double Speed (CK/2) Master SPI Mode**

16.2 Overview

The Serial Peripheral Interface (SPI) allows high-speed synchronous data transfer between the ATtiny40 and peripheral devices or between several AVR devices. The SPI module is illustrated in Figure 16-1.

Figure 16-1. SPI Block Diagram



Note: Refer to Figure 1-1 on page 2, and Table 16-1 on page 116 for SPI pin placement.

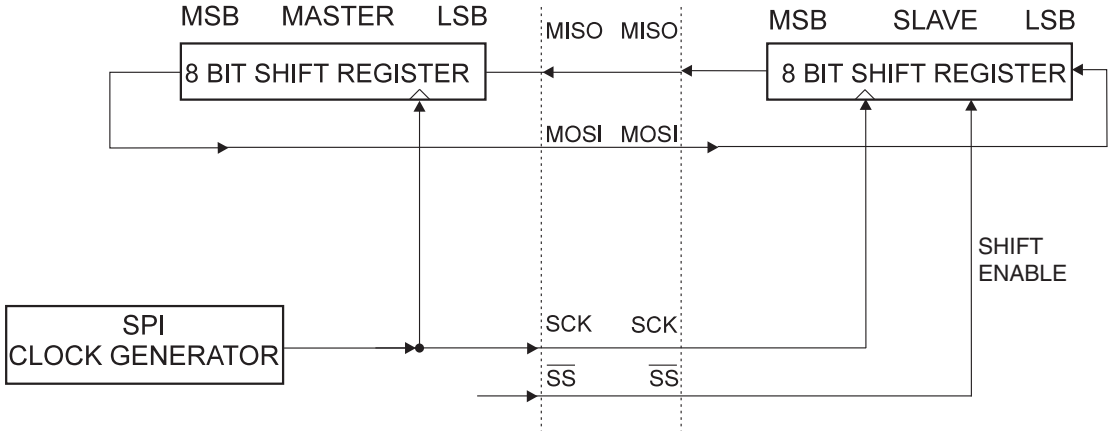
To enable the SPI module, the PRSPI bit in the Power Reduction Register must be written to zero. See "PRR – Power Reduction Register" on page 27.

The interconnection between Master and Slave CPUs with SPI is shown in Figure 16-2 on page 115. The system consists of two shift Registers, and a Master clock generator. The SPI Master initiates the communication cycle when pulling low the Slave Select $\overline{SS}$ pin of the desired Slave. Master and Slave prepare the data to be sent in their respective shift Registers, and the Master generates the required clock pulses on the SCK line to interchange data. Data is always shifted from Master to Slave on the Master Out – Slave In, MOSI, line, and from Slave to Master on the Master In – Slave Out, MISO, line. After each data packet, the Master will synchronize the Slave by pulling high the Slave Select, $\overline{SS}$, line.

When configured as a Master, the SPI interface has no automatic control of the $\overline{SS}$ line. This must be handled by user software before communication can start. When this is done, writing a byte to the SPI Data Register starts the SPI clock generator, and the hardware shifts the eight bits into the Slave. After shifting one byte, the SPI clock generator stops, setting the end of Transmission Flag (SPIF). If the SPI Interrupt Enable bit (SPIE) in the SPCR Register is set, an interrupt is requested. The Master may continue to shift the next byte by writing it into SPDR, or signal the end of packet by pulling high the Slave Select, $\overline{SS}$ line. The last incoming byte will be kept in the Buffer Register for later use.

When configured as a Slave, the SPI interface will remain sleeping with MISO tri-stated as long as the $\overline{SS}$ pin is driven high. In this state, software may update the contents of the SPI Data Register, SPDR, but the data will not be shifted out by incoming clock pulses on the SCK pin until the $\overline{SS}$ pin is driven low. As one byte has been completely shifted, the end of Transmission Flag, SPIF is set. If the SPI Interrupt Enable bit, SPIE, in the SPCR Register is set, an interrupt is requested. The Slave may continue to place new data to be sent into SPDR before reading the incoming data. The last incoming byte will be kept in the Buffer Register for later use.

Figure 16-2. SPI Master-Slave Interconnection



The system is single buffered in the transmit direction and double buffered in the receive direction. This means that bytes to be transmitted cannot be written to the SPI Data Register before the entire shift cycle is completed. When receiving data, however, a received character must be read from the SPI Data Register before the next character has been completely shifted in. Otherwise, the first byte is lost.

In SPI Slave mode, the control logic will sample the incoming signal of the SCK pin. To ensure correct sampling of the clock signal, the minimum low and high periods should be:

Low periods: Longer than 2 CPU clock cycles.

High periods: Longer than 2 CPU clock cycles.

When the SPI is enabled, the data direction of the MOSI, MISO, SCK, and $\overline{SS}$ pins is overridden according to Table 16-1 on page 116. For more details on automatic port overrides, refer to "Alternate Port Functions" on page 47.

Table 16-1. SPI Pin Overrides

Pin	Direction, Master SPI	Direction, Slave SPI
MOSI	User Defined	Input
MISO	Input	User Defined
SCK	User Defined	Input
$\overline{SS}$	User Defined	Input

Note: See "Alternate Functions of Port B" on page 53 for a detailed description of how to define the direction of the user defined SPI pins.

The following code examples show how to initialize the SPI as a Master and how to perform a simple transmission. DDR_SPI in the examples must be replaced by the actual Data Direction Register controlling the SPI pins. DD_MOSI, DD_MISO and DD_SCK must be replaced by the actual data direction bits for these pins. E.g. if MOSI is placed on pin PB5, replace DD_MOSI with DDB5 and DDR_SPI with DDRB.

Assembly Code Example[1]

```
SPI_MasterInit:
  ; Set MOSI and SCK output, all others input
  ldi   r17,(1<<DD_MOSI)|(1<<DD_SCK)
  out   DDR_SPI,r17
  ; Enable SPI, Master, set clock rate fck/16
  ldi   r17,(1<<SPE)|(1<<MSTR)|(1<<SPR0)
  out   SPCR,r17
  ret

SPI_MasterTransmit:
  ; Start transmission of data (r16)
  out   SPDR,r16
Wait_Transmit:
  ; Wait for transmission complete
  in    r16, SPSR
  sbrsr16, SPIF
  rjmp Wait_Transmit
  ret
```

C Code Example[1]

```
void SPI_MasterInit(void)
{
  /* Set MOSI and SCK output, all others input */
  DDR_SPI = (1<<DD_MOSI)|(1<<DD_SCK);
  /* Enable SPI, Master, set clock rate fck/16 */
  SPCR = (1<<SPE)|(1<<MSTR)|(1<<SPR0);
}

void SPI_MasterTransmit(char cData)
{
  /* Start transmission */
  SPDR = cData;
  /* Wait for transmission complete */
  while(!(SPSR & (1<<SPIF)))
    ;
}
```

Note: 1. See ”Code Examples” on page 5.

The following code examples show how to initialize the SPI as a Slave and how to perform a simple reception.

Assembly Code Example[1]

```
SPI_SlaveInit:
  ; Set MISO output, all others input
  ldi  r17,(1<<DD_MISO)
  out  DDR_SPI,r17
  ; Enable SPI
  ldi  r17,(1<<SPE)
  out  SPCR,r17
  ret

SPI_SlaveReceive:
  ; Wait for reception complete
  in   r16, SPSR
  sbrs r16, SPIF
  rjmp SPI_SlaveReceive
  ; Read received data and return
  in   r16,SPDR
  ret
```

C Code Example[1]

```
void SPI_SlaveInit(void)
{
  /* Set MISO output, all others input */
  DDR_SPI = (1<<DD_MISO);
  /* Enable SPI */
  SPCR = (1<<SPE);
}

char SPI_SlaveReceive(void)
{
  /* Wait for reception complete */
  while(!(SPSR & (1<<SPIF)))
    ;
  /* Return Data Register */
  return SPDR;
}
```

Note: 1. See "Code Examples" on page 5.

16.3 $\overline{SS}$ Pin Functionality

16.3.1 Slave Mode

When the SPI is configured as a Slave, the Slave Select ($\overline{SS}$) pin is always input. When $\overline{SS}$ is held low, the SPI is activated, and MISO becomes an output if configured so by the user. All other pins are inputs. When $\overline{SS}$ is driven high, all pins are inputs, and the SPI is passive, which means that it will not receive incoming data. Note that the SPI logic will be reset once the $\overline{SS}$ pin is driven high.

The $\overline{SS}$ pin is useful for packet/byte synchronization to keep the slave bit counter synchronous with the master clock generator. When the $\overline{SS}$ pin is driven high, the SPI slave will immediately reset the send and receive logic, and drop any partially received data in the Shift Register.

16.3.2 Master Mode

When the SPI is configured as a Master (MSTR in SPCR is set), the user can determine the direction of the $\overline{SS}$ pin.

If $\overline{SS}$ is configured as an output, the pin is a general output pin which does not affect the SPI system. Typically, the pin will be driving the $\overline{SS}$ pin of the SPI Slave.

If $\overline{SS}$ is configured as an input, it must be held high to ensure Master SPI operation. If the $\overline{SS}$ pin is driven low by peripheral circuitry when the SPI is configured as a Master with the $\overline{SS}$ pin defined as an input, the SPI system interprets this as another master selecting the SPI as a slave and starting to send data to it. To avoid bus contention, the SPI system takes the following actions:

1. The MSTR bit in SPCR is cleared and the SPI system becomes a Slave. As a result of the SPI becoming a Slave, the MOSI and SCK pins become inputs.
2. The SPIF Flag in SPSR is set, and if the SPI interrupt is enabled, and the I-bit in SREG is set, the interrupt routine will be executed.

Thus, when interrupt-driven SPI transmission is used in Master mode, and there exists a possibility that $\overline{SS}$ is driven low, the interrupt should always check that the MSTR bit is still set. If the MSTR bit has been cleared by a slave select, it must be set by the user to re-enable SPI Master mode.

16.4 Data Modes

There are four combinations of SCK phase and polarity with respect to serial data, which are determined by control bits CPHA and CPOL. The SPI data transfer formats are shown in Figure 16-3 on page 119 and Figure 16-4 on page 119.

Figure 16-3. SPI Transfer Format with CPHA = 0

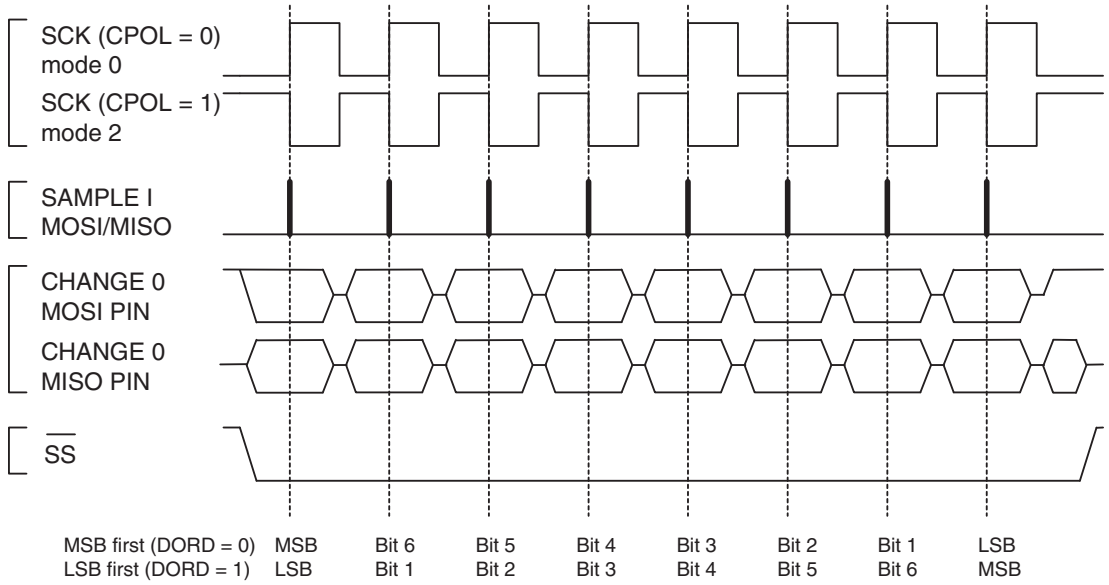
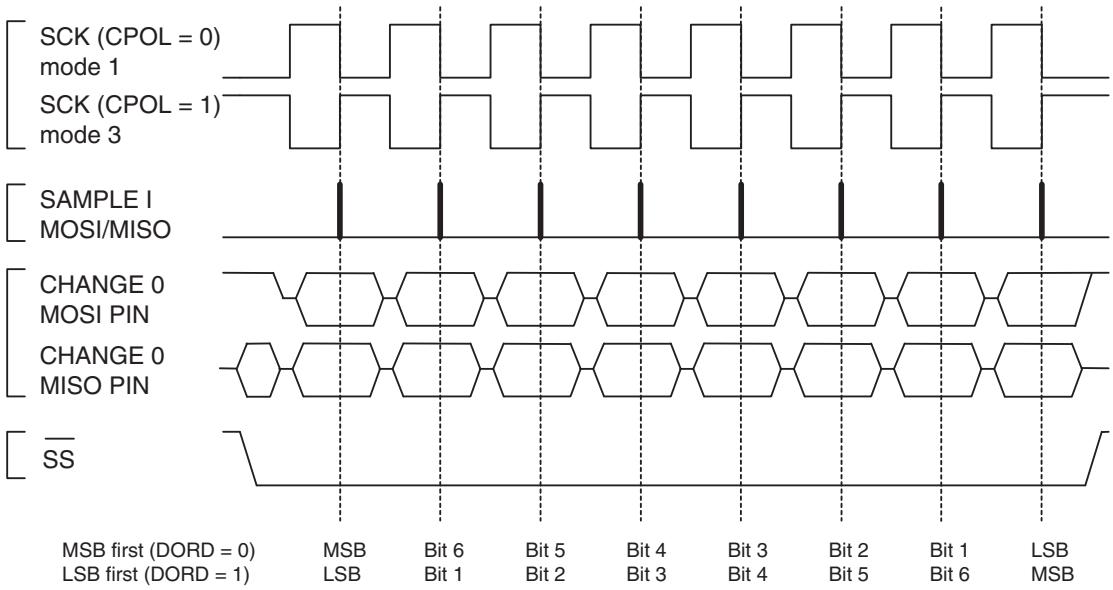


Figure 16-4. SPI Transfer Format with CPHA = 1



Data bits are shifted out and latched in on opposite edges of the SCK signal, ensuring sufficient time for data signals to stabilize. This is shown in Table 16-2, which is a summary of Table 16-3 on page 120 and Table 16-4 on page 121.

Table 16-2. SPI Modes

SPI Mode	Conditions	Leading Edge	Trailing eDge
0	CPOL=0, CPHA=0	Sample (Rising)	Setup (Falling)
1	CPOL=0, CPHA=1	Setup (Rising)	Sample (Falling)
2	CPOL=1, CPHA=0	Sample (Falling)	Setup (Rising)
3	CPOL=1, CPHA=1	Setup (Falling)	Sample (Rising)

16.5 Register Description

16.5.1 SPCR – SPI Control Register

Bit	7	6	5	4	3	2	1	0	
0x30	SPIE	SPE	DORD	MSTR	CPOL	CPHA	SPR1	SPR0	SPCR
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – SPIE: SPI Interrupt Enable**

This bit causes the SPI interrupt to be executed if SPIF bit in the SPSR Register is set and the if the Global Interrupt Enable bit in SREG is set.

- **Bit 6 – SPE: SPI Enable**

When the SPE bit is written to one, the SPI is enabled. This bit must be set to enable any SPI operations.

- **Bit 5 – DORD: Data Order**

When the DORD bit is written to one, the LSB of the data word is transmitted first.

When the DORD bit is written to zero, the MSB of the data word is transmitted first.

- **Bit 4 – MSTR: Master/Slave Select**

This bit selects Master SPI mode when written to one, and Slave SPI mode when written logic zero. If $\overline{SS}$ is configured as an input and is driven low while MSTR is set, MSTR will be cleared, and SPIF in SPSR will become set. The user will then have to set MSTR to re-enable SPI Master mode.

- **Bit 3 – CPOL: Clock Polarity**

When this bit is written to one, SCK is high when idle. When CPOL is written to zero, SCK is low when idle. Refer to Figure 16-3 and Figure 16-4 for an example. The CPOL functionality is summarized below:

Table 16-3. CPOL Functionality

CPOL	Leading Edge	Trailing Edge
0	Rising	Falling
1	Falling	Rising

- **Bit 2 – CPHA: Clock Phase**

The settings of the Clock Phase bit (CPHA) determine if data is sampled on the leading (first) or trailing (last) edge of SCK. Refer to Figure 16-3 and Figure 16-4 for an example. The CPOL functionality is summarized below:

Table 16-4. CPHA Functionality

CPHA	Leading Edge	Trailing Edge
0	Sample	Setup
1	Setup	Sample

- **Bits 1:0 – SPR[1:0]: SPI Clock Rate Select 1 and 0**

These two bits control the SCK rate of the device configured as a Master. SPR1 and SPR0 have no effect on the Slave. The relationship between SCK and the I/O Clock frequency $f_{clk_I/O}$ is shown in the following table:

Table 16-5. Relationship Between SCK and the I/O Clock Frequency

SPI2X	SPR1	SPR0	SCK Frequency
0	0	0	$f_{clk_I/O}/4$
0	0	1	$f_{clk_I/O}/16$
0	1	0	$f_{clk_I/O}/64$
0	1	1	$f_{clk_I/O}/128$
1	0	0	$f_{clk_I/O}/2$
1	0	1	$f_{clk_I/O}/8$
1	1	0	$f_{clk_I/O}/32$
1	1	1	$f_{clk_I/O}/64$

16.5.2 SPSR – SPI Status Register

Bit	7	6	5	4	3	2	1	0	
0x2F	SPIF	WCOL	–	–	–	–	–	SPI2X	SPSR
Read/Write	R/W	R/W	R	R	R	R	R	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – SPIF: SPI Interrupt Flag**

When a serial transfer is complete, the SPIF Flag is set. An interrupt is generated if SPIE in SPCR is set and global interrupts are enabled. If $\overline{SS}$ is an input and is driven low when the SPI is in Master mode, this will also set the SPIF Flag. SPIF is cleared by hardware when executing the corresponding interrupt handling vector. Alternatively, the SPIF bit is cleared by first reading the SPI Status Register with SPIF set, then accessing the SPI Data Register (SPDR).

- **Bit 6 – WCOL: Write COLlision Flag**

The WCOL bit is set if the SPI Data Register (SPDR) is written during a data transfer. The WCOL bit (and the SPIF bit) are cleared by first reading the SPI Status Register with WCOL set, and then accessing the SPI Data Register.

- **Bits 5:1 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 0 – SPI2X: Double SPI Speed Bit**

When this bit is written logic one the SPI speed (SCK Frequency) will be doubled when the SPI is in Master mode (see Table 16-5). This means that the minimum SCK period will be two CPU clock periods. When the SPI is configured as Slave, the SPI is only guaranteed to work at $f_{clk_I/O}/4$ or lower.

16.5.3 SPDR – SPI Data Register

Bit	7	6	5	4	3	2	1	0	
0x2E	MSB							LSB	SPDR
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	X	X	X	X	X	X	X	X	Undefined

The SPI Data Register is a read/write register used for data transfer between the Register File and the SPI Shift Register. Writing to the register initiates data transmission. Reading the register causes the Shift Register Receive buffer to be read.

17. TWI – Two Wire Interface (Slave)

17.1 Features

- **Phillips I²C compatible**
- **SMBus compatible (with reservations)**
- **100 kHz and 400 kHz support at low system clock frequencies**
- **Slew-Rate Limited Output Drivers**
- **Input Filter provides noise suppression**
- **7-bit, and General Call Address Recognition in Hardware**
- **Address mask register for address masking or dual address match**
- **10-bit addressing supported**
- **Optional Software Address Recognition Provides Unlimited Number of Slave Addresses**
- **Operates in all sleep modes, including Power Down**
- **Slave Arbitration allows support for SMBus Address Resolve Protocol (ARP)**

17.2 Overview

The Two Wire Interface (TWI) is a bi-directional, bus communication interface, which uses only two wires. The TWI is I²C compatible and, with reservations, SMBus compatible (see “Compatibility with SMBus” on page 128).

A device connected to the bus must act as a master or slave.The master initiates a data transaction by addressing a slave on the bus, and telling whether it wants to transmit or receive data. One bus can have several masters, and an arbitration process handles priority if two or more masters try to transmit at the same time.

The TWI module in ATtiny40 implements slave functionality, only. Lost arbitration, errors, collisions and clock holds on the bus are detected in hardware and indicated in separate status flags.

Both 7-bit and general address call recognition is implemented in hardware. 10-bit addressing is also supported. A dedicated address mask register can act as a second address match register or as a mask register for the slave address to match on a range of addresses. The slave logic continues to operate in all sleep modes, including Power down. This enables the slave to wake up from sleep on TWI address match. It is possible to disable the address matching and let this be handled in software instead. This allows the slave to detect and respond to several addresses. Smart Mode can be enabled to auto trigger operations and reduce software complexity.

The TWI module includes bus state logic that collects information to detect START and STOP conditions, bus collision and bus errors. The bus state logic continues to operate in all sleep modes including Power down.

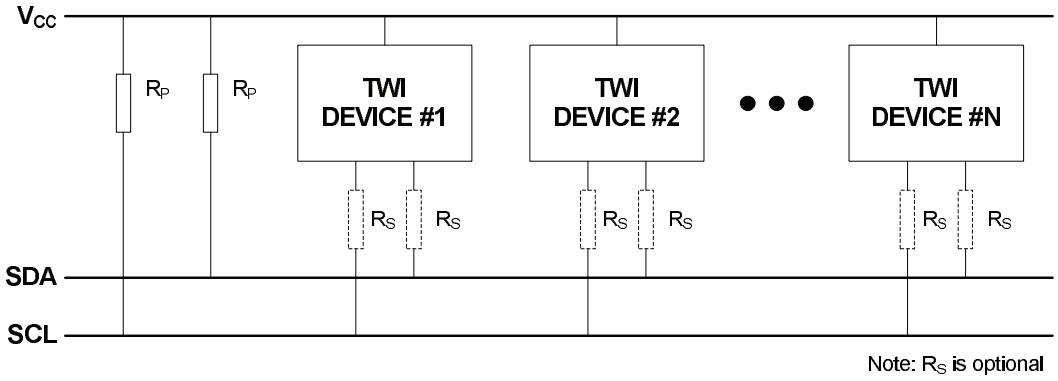
17.3 General TWI Bus Concepts

The Two-Wire Interface (TWI) provides a simple two-wire bi-directional bus consisting of a serial clock line (SCL) and a serial data line (SDA). The two lines are open collector lines (wired-AND), and pull-up resistors (Rp) are the only external components needed to drive the bus. The pull-up resistors will provide a high level on the lines when none of the connected devices are driving the bus. A constant current source can be used as an alternative to the pull-up resistors.

The TWI bus is a simple and efficient method of interconnecting multiple devices on a serial bus. A device connected to the bus can be a master or slave, where the master controls the bus and all communication.

Figure 17-1 illustrates the TWI bus topology.

Figure 17-1. TWI Bus Topology



A unique address is assigned to all slave devices connected to the bus, and the master will use this to address a slave and initiate a data transaction. 7-bit or 10-bit addressing can be used.

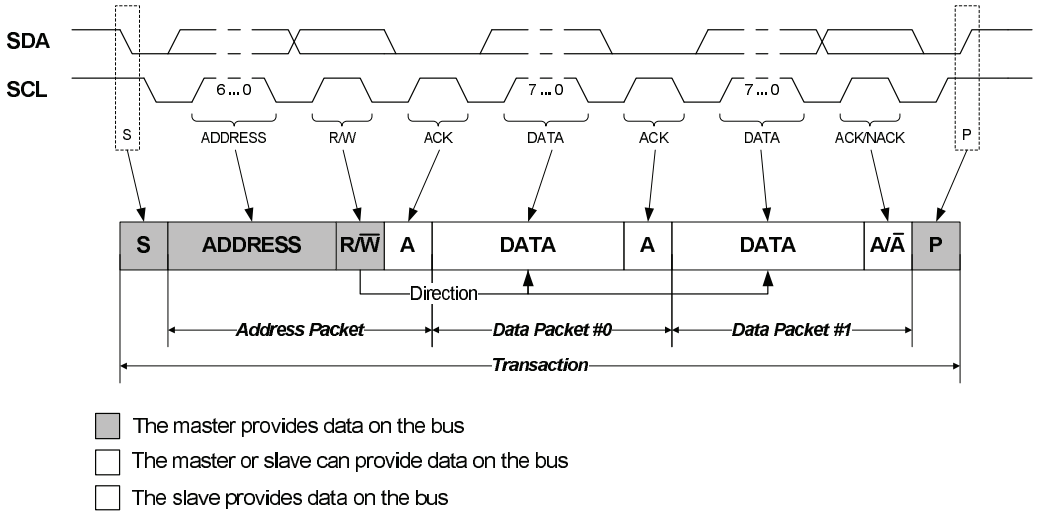
Several masters can be connected to the same bus, and this is called a multi-master environment. An arbitration mechanism is provided for resolving bus ownership between masters since only one master device may own the bus at any given time.

A device can contain both master and slave logic, and can emulate multiple slave devices by responding to more than one address.

A master indicates the start of transaction by issuing a START condition (S) on the bus. An address packet with a slave address (ADDRESS) and an indication whether the master wishes to read or write data (R/$\overline{W}$), is then sent. After all data packets (DATA) are transferred, the master issues a STOP condition (P) on the bus to end the transaction. The receiver must acknowledge (A) or not-acknowledge ($\overline{A}$) each byte received.

Figure 17-2 shows a TWI transaction.

Figure 17-2. Basic TWI Transaction Diagram Topology



The master provides the clock signal for the transaction, but a device connected to the bus is allowed to stretch the low level period of the clock to decrease the clock speed.

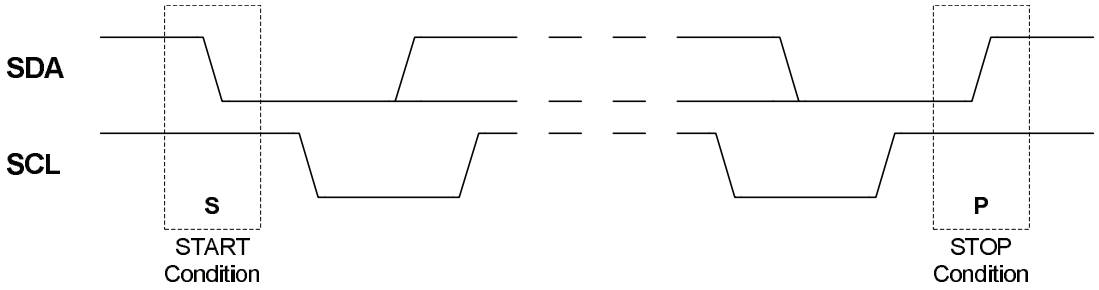
17.3.1 Electrical Characteristics

The TWI follows the electrical specifications and timing of I^2C and SMBus. See"Two-Wire Serial Interface Characteristics" on page 156 and "Compatibility with SMBus" on page 128.

17.3.2 START and STOP Conditions

Two unique bus conditions are used for marking the beginning (START) and end (STOP) of a transaction. The master issues a START condition(S) by indicating a high to low transition on the SDA line while the SCL line is kept high. The master completes the transaction by issuing a STOP condition (P), indicated by a low to high transition on the SDA line while SCL line is kept high.

Figure 17-3. START and STOP Conditions

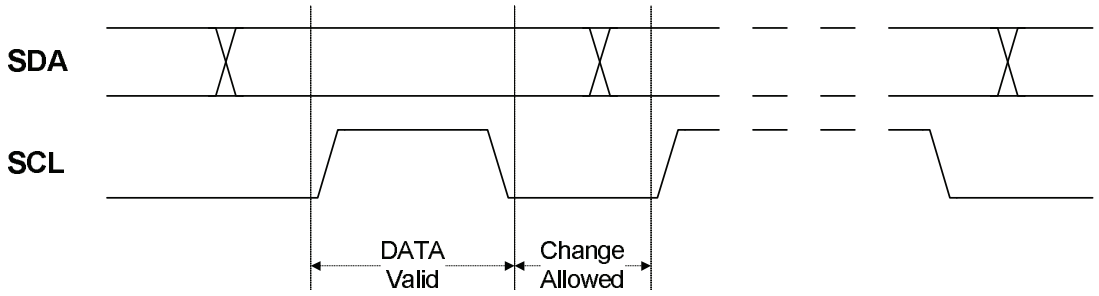


Multiple START conditions can be issued during a single transaction. A START condition not directly following a STOP condition, are named a Repeated START condition (Sr).

17.3.3 Bit Transfer

As illustrated by Figure 17-4 a bit transferred on the SDA line must be stable for the entire high period of the SCL line. Consequently the SDA value can only be changed during the low period of the clock. This is ensured in hardware by the TWI module.

Figure 17-4. Data Validity



Combining bit transfers results in the formation of address and data packets. These packets consist of 8 data bits (one byte) with the most significant bit transferred first, plus a single bit not-acknowledge (NACK) or acknowledge (ACK) response. The addressed device signals ACK by pulling the SCL line low, and NACK by leaving the line SCL high during the ninth clock cycle.

17.3.4 Address Packet

After the START condition, a 7-bit address followed by a read/write (R/$\overline{W}$) bit is sent. This is always transmitted by the Master. A slave recognizing its address will ACK the address by pulling the data line low the next SCL cycle, while all other slaves should keep the TWI lines released, and wait for the next START and address. The 7-bit address, the R/$\overline{W}$ bit and the acknowledge bit combined is the address packet. Only one address packet for each START condition is given, also when 10-bit addressing is used.

The R/$\overline{W}$ specifies the direction of the transaction. If the R/$\overline{W}$ bit is low, it indicates a Master Write transaction, and the master will transmit its data after the slave has acknowledged its address. Opposite, for a Master Read operation the slave will start to transmit data after acknowledging its address.

17.3.5 Data Packet

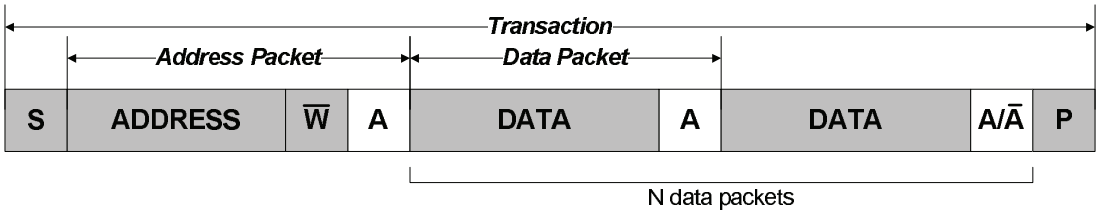
Data packets succeed an address packet or another data packet. All data packets are nine bits long, consisting of one data byte and an acknowledge bit. The direction bit in the previous address packet determines the direction in which the data is transferred.

17.3.6 Transaction

A transaction is the complete transfer from a START to a STOP condition, including any Repeated START conditions in between. The TWI standard defines three fundamental transaction modes: Master Write, Master Read, and combined transaction.

Figure 17-5 illustrates the Master Write transaction. The master initiates the transaction by issuing a START condition (S) followed by an address packet with direction bit set to zero (ADDRESS+$\overline{W}$).

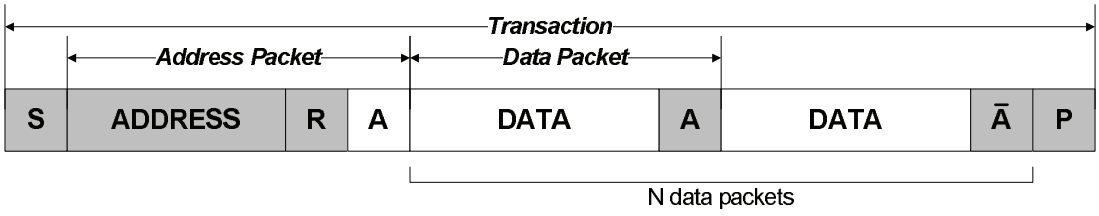
Figure 17-5. Master Write Transaction



Given that the slave acknowledges the address, the master can start transmitting data (DATA) and the slave will ACK or NACK (A/$\overline{A}$) each byte. If no data packets are to be transmitted, the master terminates the transaction by issuing a STOP condition (P) directly after the address packet. There are no limitations to the number of data packets that can be transferred. If the slave signal a NACK to the data, the master must assume that the slave cannot receive any more data and terminate the transaction.

Figure 17-6 illustrates the Master Read transaction. The master initiates the transaction by issuing a START condition followed by an address packet with direction bit set to one (ADRESS+R). The addressed slave must acknowledge the address for the master to be allowed to continue the transaction.

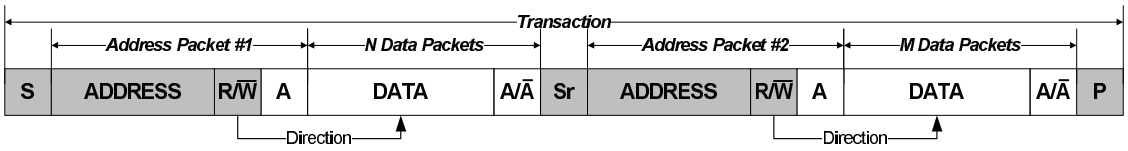
Figure 17-6. Master Read Transaction



Given that the slave acknowledges the address, the master can start receiving data from the slave. There are no limitations to the number of data packets that can be transferred. The slave transmits the data while the master signals ACK or NACK after each data byte. The master terminates the transfer with a NACK before issuing a STOP condition.

Figure 17-7 illustrates a combined transaction. A combined transaction consists of several read and write transactions separated by a Repeated START conditions (Sr).

Figure 17-7. Combined Transaction

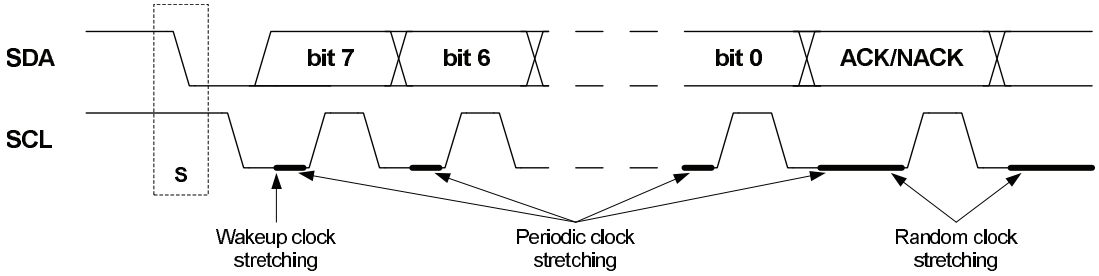


17.3.7 Clock and Clock Stretching

All devices connected to the bus are allowed to stretch the low period of the clock to slow down the overall clock frequency or to insert wait states while processing data. A device that needs to stretch the clock can do this by holding/forcing the SCL line low after it detects a low level on the line.

Three types of clock stretching can be defined as shown in Figure 17-8.

Figure 17-8. Clock Stretching



If the device is in a sleep mode and a START condition is detected the clock is stretched during the wake-up period for the device.

A slave device can slow down the bus frequency by stretching the clock periodically on a bit level. This allows the slave to run at a lower system clock frequency. However, the overall performance of the bus will be reduced accordingly. Both the master and slave device can randomly stretch the clock on a byte level basis before and after the ACK/NACK bit. This provides time to process incoming or prepare outgoing data, or performing other time critical tasks.

In the case where the slave is stretching the clock the master will be forced into a wait-state until the slave is ready and vice versa.

17.3.8 Arbitration

A master can only start a bus transaction if it has detected that the bus is idle. As the TWI bus is a multi master bus, it is possible that two devices initiate a transaction at the same time. This results in multiple masters owning the bus simultaneously. This is solved using an arbitration scheme where the master loses control of the bus if it is not able to transmit a high level on the SDA line. The masters who lose arbitration must then wait until the bus becomes idle (i.e. wait for a STOP condition) before attempting to reacquire bus ownership. Slave devices are not involved in the arbitration procedure.

Figure 17-9. TWI Arbitration

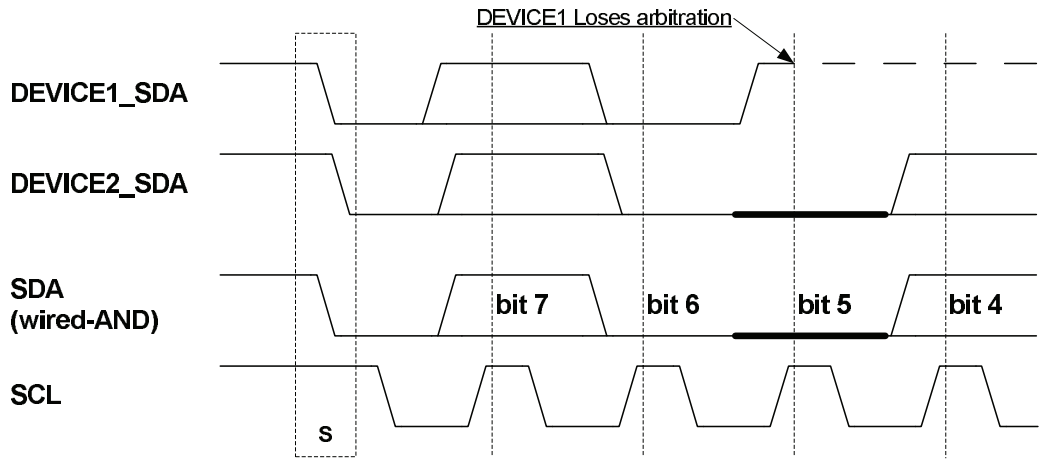


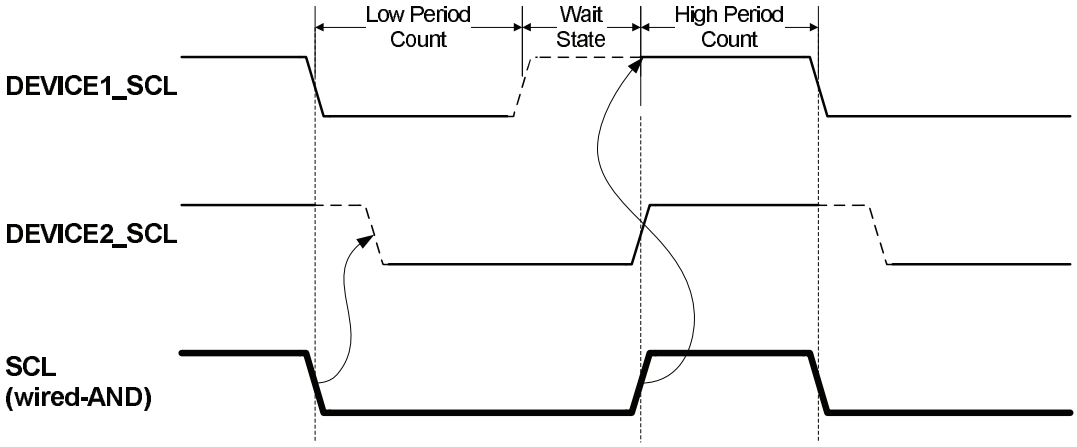
Figure 17-9 shows an example where two TWI masters are contending for bus ownership. Both devices are able to issue a START condition, but DEVICE1 loses arbitration when attempting to transmit a high level (bit 5) while DEVICE2 is transmitting a low level.

Arbitration between a repeated START condition and a data bit, a STOP condition and a data bit, or a repeated START condition and STOP condition are not allowed and will require special handling by software.

17.3.9 Synchronization

A clock synchronization algorithm is necessary for solving situations where more than one master is trying to control the SCL line at the same time. The algorithm is based on the same principles used for clock stretching previously described. Figure 17-10 shows an example where two masters are competing for the control over the bus clock. The SCL line is the wired-AND result of the two masters clock outputs.

Figure 17-10. Clock Synchronization



A high to low transition on the SCL line will force the line low for all masters on the bus and they start timing their low clock period. The timing length of the low clock period can vary between the masters. When a master (DEVICE1 in this case) has completed its low period it releases the SCL line. However, the SCL line will not go high before all masters have released it. Consequently the SCL line will be held low by the device with the longest low period (DEVICE2). Devices with shorter low periods must insert a wait-state until the clock is released. All masters start their high period when the SCL line is released by all devices and has become high. The device which

first completes its high period (DEVICE1) forces the clock line low and the procedure are then repeated. The result of this is that the device with the shortest clock period determines the high period while the low period of the clock is determined by the longest clock period.

17.3.10 Compatibility with SMBus

As with any other I²C-compliant interface there are known compatibility issues the designer should be aware of before connecting a TWI device to SMBus devices. For use in SMBus environments, the following should be noted:

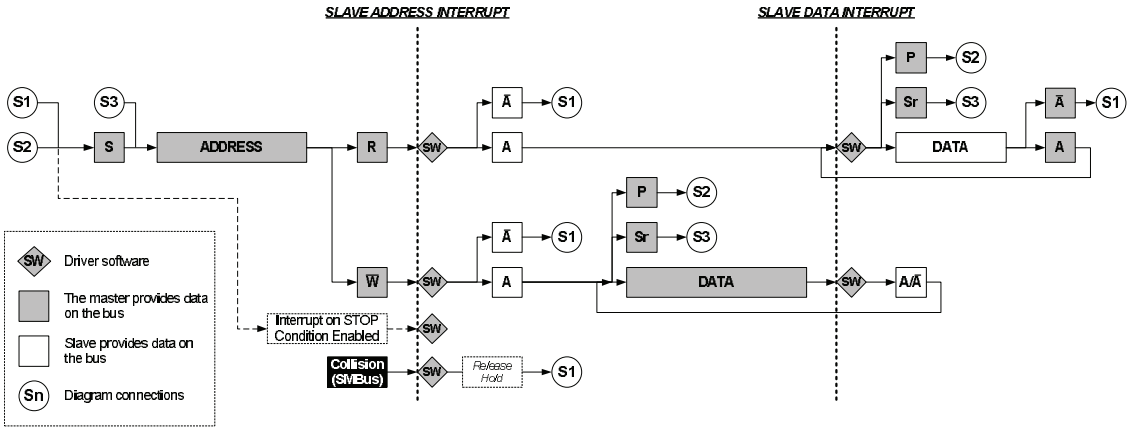
- All I/O pins of an AVR, including those of the two-wire interface, have protection diodes to both supply voltage and ground. See Figure 10-1 on page 42. This is in contradiction to the requirements of the SMBus specifications. As a result, supply voltage mustn't be removed from the AVR or the protection diodes will pull the bus lines down. Power down and sleep modes is not a problem, provided supply voltages remain.
- The data hold time of the TWI is lower than specified for SMBus. The TWSHE bit of TWSCRA can be used to increase the hold time. See "TWSCRA – TWI Slave Control Register A" on page 130.
- SMBus has a low speed limit, while I²C hasn't. As a master in an SMBus environment, the AVR must make sure bus speed does not drop below specifications, since lower bus speeds trigger timeouts in SMBus slaves. If the AVR is configured a slave there is a possibility of a bus lockup, since the TWI module doesn't identify timeouts.

17.4 TWI Slave Operation

The TWI slave is byte-oriented with optional interrupts after each byte. There are separate interrupt flags for Data Interrupt and Address/Stop Interrupt. Interrupt flags can be set to trigger the TWI interrupt, or be used for polled operation. There are dedicated status flags for indicating ACK/NACK received, clock hold, collision, bus error and read/write direction.

When an interrupt flag is set, the SCL line is forced low. This will give the slave time to respond or handle any data, and will in most cases require software interaction. Figure 17-11. shows the TWI slave operation. The diamond shapes symbols (SW) indicate where software interaction is required.

Figure 17-11. TWI Slave Operation



The number of interrupts generated is kept at a minimum by automatic handling of most conditions. Quick Command can be enabled to auto trigger operations and reduce software complexity.

Promiscuous Mode can be enabled to allow the slave to respond to all received addresses.

17.4.1 Receiving Address Packets

When the TWI slave is properly configured, it will wait for a START condition to be detected. When this happens, the successive address byte will be received and checked by the address match logic, and the slave will ACK the

correct address. If the received address is not a match, the slave will not acknowledge the address and wait for a new START condition.

The slave Address/Stop Interrupt Flag is set when a START condition succeeded by a valid address packet is detected. A general call address will also set the interrupt flag.

A START condition immediately followed by a STOP condition, is an illegal operation and the Bus Error flag is set.

The R/W Direction flag reflects the direction bit received with the address. This can be read by software to determine the type of operation currently in progress.

Depending on the R/W direction bit and bus condition one of four distinct cases (1 to 4) arises following the address packet. The different cases must be handled in software.

17.4.1.1 Case 1: Address packet accepted - Direction bit set

If the R/$\overline{W}$ Direction flag is set, this indicates a master read operation. The SCL line is forced low, stretching the bus clock. If ACK is sent by the slave, the slave hardware will set the Data Interrupt Flag indicating data is needed for transmit. If NACK is sent by the slave, the slave will wait for a new START condition and address match.

17.4.1.2 Case 2: Address packet accepted - Direction bit cleared

If the R/$\overline{W}$ Direction flag is cleared this indicates a master write operation. The SCL line is forced low, stretching the bus clock. If ACK is sent by the slave, the slave will wait for data to be received. Data, Repeated START or STOP can be received after this. If NACK is indicated the slave will wait for a new START condition and address match.

17.4.1.3 Case 3: Collision

If the slave is not able to send a high level or NACK, the Collision flag is set and it will disable the data and acknowledge output from the slave logic. The clock hold is released. A START or repeated START condition will be accepted.

17.4.1.4 Case 4: STOP condition received.

Operation is the same as case 1 or 2 above with one exception. When the STOP condition is received, the Slave Address/Stop flag will be set indicating that a STOP condition and not an address match occurred.

17.4.2 Receiving Data Packets

The slave will know when an address packet with R/$\overline{W}$ direction bit cleared has been successfully received. After acknowledging this, the slave must be ready to receive data. When a data packet is received the Data Interrupt Flag is set, and the slave must indicate ACK or NACK. After indicating a NACK, the slave must expect a STOP or Repeated START condition.

17.4.3 Transmitting Data Packets

The slave will know when an address packet, with R/$\overline{W}$ direction bit set, has been successfully received. It can then start sending data by writing to the Slave Data register. When a data packet transmission is completed, the Data Interrupt Flag is set. If the master indicates NACK, the slave must stop transmitting data, and expect a STOP or Repeated START condition.

17.5 Register Description

17.5.1 TWSCRA – TWI Slave Control Register A

Bit	7	6	5	4	3	2	1	0	
0x2D	TWSHE	–	TWDIE	TWASIE	TWEN	TWSIE	TWPME	TWSME	TWSCRA
Read/Write	R/W	R	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – TWSHE: TWI SDA Hold Time Enable**

When this bit is set each negative transition of SCL triggers an additional internal delay, before the device is allowed to change the SDA line. The added delay is approximately 50ns in length.

This may be useful in SMBus systems.

- **Bit 6 – Res: Reserved Bit**

This bit is reserved and will always read as zero.

- **Bit 5 – TWDIE: TWI Data Interrupt Enable**

When this bit is set and interrupts are enabled, a TWI interrupt will be generated when the data interrupt flag (TWDIF) in TWSSRA is set.

- **Bit 4 – TWASIE: TWI Address/Stop Interrupt Enable**

When this bit is set and interrupts are enabled, a TWI interrupt will be generated when the address/stop interrupt flag (TWASIF) in TWSSRA is set.

- **Bit 3 – TWEN: Two-Wire Interface Enable**

When this bit is set the slave Two-Wire Interface is enabled.

- **Bit 2 – TWSIE: TWI Stop Interrupt Enable**

Setting the Stop Interrupt Enable (TWSIE) bit will set the TWASIF in the TWSSRA register when a STOP condition is detected.

- **Bit 1 – TWPME: TWI Promiscuous Mode Enable**

When this bit is set the address match logic of the slave TWI responds to all received addresses. When this bit is cleared the address match logic uses the TWSA register to determine which address to recognize as its own.

- **Bit 0 – TWSME: TWI Smart Mode Enable**

When this bit is set the TWI slave enters Smart Mode, where the Acknowledge Action is sent immediately after the TWI data register (TWSD) has been read. Acknowledge Action is defined by the TWAA bit in TWSCRB.

When this bit is cleared the Acknowledge Action is sent after TWCMDn bits in TWSCRB are written to 1X.

17.5.2 TWSCRB – TWI Slave Control Register B

Bit	7	6	5	4	3	2	1	0	
0x2C	–	–	–	–	–	TWAA	TWCMD1	TWCMD0	TWSCRB
Read/Write	R	R	R	R	R	R/W	W	W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:3 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 2 – TWAA: TWI Acknowledge Action**

This bit defines the slave's acknowledge behavior after an address or data byte has been received from the master. Depending on the TWSME bit in TWSCRA the Acknowledge Action is executed either when a valid command has been written to TWCMDn bits, or when the data register has been read. Acknowledge action is also executed if clearing TWAIF flag after address match or TWDIF flag during master transmit. See Table 17-1 for details.

Table 17-1. Acknowledge Action of TWI Slave

TWAA	Action	TWSME	When
0	Send ACK	0	When TWCMDn bits are written to 10 or 11
		1	When TWSD is read
1	Send NACK	0	When TWCMDn bits are written to 10 or 11
		1	When TWSD is read

- **Bits 1:0 – TWCMD[1:0]: TWI Command**

Writing these bits triggers the slave operation as defined by Table 17-2. The type of operation depends on the TWI slave interrupt flags, TWDIF and TWASIF. The Acknowledge Action is only executed when the slave receives data bytes or address byte from the master.

Table 17-2. TWI Slave Command

TWCMD[1:0]	TWDIR	Operation
00	X	No action
01	X	Reserved
10	**Used to complete transaction**	
	0	Execute Acknowledge Action, then wait for any START (S/Sr) condition
	1	Wait for any START (S/Sr) condition
11	**Used in response to an Address Byte (TWASIF is set)**	
	0	Execute Acknowledge Action, then receive next byte
	1	Execute Acknowledge Action, then set TWDIF
	Used in response to a Data Byte (TWDIF is set)	
	0	Execute Acknowledge Action, then wait for next byte
	1	No action

Writing the TWCMD bits will automatically release the SCL line and clear the TWCH and slave interrupt flags.

TWAA and TWCMDn bits can be written at the same time. Acknowledge Action will then be executed before the command is triggered.

The TWCMDn bits are strobed and always read zero.

17.5.3 TWSSRA – TWI Slave Status Register A

Bit	7	6	5	4	3	2	1	0	
0x2B	TWDIF	TWASIF	TWCH	TWRA	TWC	TWBE	TWDIR	TWAS	TWSCRA
Read/Write	R/W	R/W	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7 – TWDIF: TWI Data Interrupt Flag**

This flag is set when a data byte has been successfully received, i.e. no bus errors or collisions have occurred during the operation. When this flag is set the slave forces the SCL line low, stretching the TWI clock period. The SCL line is released by clearing the interrupt flags.

Writing a one to this bit will clear the flag. This flag is also automatically cleared when writing a valid command to the TWCMDn bits in TWSCRB.

- **Bit 6 – TWASIF: TWI Address/Stop Interrupt Flag**

This flag is set when the slave detects that a valid address has been received, or when a transmit collision has been detected. When this flag is set the slave forces the SCL line low, stretching the TWI clock period. The SCL line is released by clearing the interrupt flags.

If TWASIE in TWSCRA is set, a STOP condition on the bus will also set TWASIF. STOP condition will set the flag only if system clock is faster than the minimum bus free time between STOP and START.

Writing a one to this bit will clear the flag. This flag is also automatically cleared when writing a valid command to the TWCMDn bits in TWSCRB.

- **Bit 5 – TWCH: TWI Clock Hold**

This bit is set when the slave is holding the SCL line low.

This bit is read-only, and set when TWDIF or TWASIF is set. The bit can be cleared indirectly by clearing the interrupt flags and releasing the SCL line.

- **Bit 4 – TWRA: TWI Receive Acknowledge**

This bit contains the most recently received acknowledge bit from the master.

This bit is read-only. When zero, the most recent acknowledge bit from the maser was ACK and, when one, the most recent acknowledge bit was NACK.

- **Bit 3 – TWC: TWI Collision**

This bit is set when the slave was not able to transfer a high data bit or a NACK bit. When a collision is detected, the slave will commence its normal operation, and disable data and acknowledge output. No low values are shifted out onto the SDA line.

This bit is cleared by writing a one to it. The bit is also cleared automatically when a START or Repeated START condition is detected.

- **Bit 2 – TWBE: TWI Bus Error**

This bit is set when an illegal bus condition has occured during a transfer. An illegal bus condition occurs if a Repeated START or STOP condition is detected, and the number of bits from the previous START condition is not a multiple of nine.

This bit is cleared by writing a one to it.

- **Bit 1 – TWDIR: TWI Read/Write Direction**

This bit indicates the direction bit from the last address packet received from a master. When this bit is one, a master read operation is in progress. When the bit is zero a master write operation is in progress.

- **Bit 0 – TWAS: TWI Address or Stop**

This bit indicates why the TWASIF bit was last set. If zero, a stop condition caused TWASIF to be set. If one, address detection caused TWASIF to be set.

17.5.4 TWSA – TWI Slave Address Register

Bit	7	6	5	4	3	2	1	0	
0x2A	TWSA[7:0]								TWSA
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The slave address register contains the TWI slave address used by the slave address match logic to determine if a master has addressed the slave. When using 7-bit or 10-bit address recognition mode, the high seven bits of the address register (TWSA[7:1]) represent the slave address. The least significant bit (TWSA0) is used for general call address recognition. Setting TWSA0 enables general call address recognition logic.

When using 10-bit addressing the address match logic only support hardware address recognition of the first byte of a 10-bit address. If TWSA[7:1] is set to "0b11110nn", 'nn' will represent bits 9 and 8 of the slave address. The next byte received is then bits 7 to 0 in the 10-bit address, but this must be handled by software.

When the address match logic detects that a valid address byte has been received, the TWASIF is set and the TWDIR flag is updated.

If TWPME in TWSCRA is set, the address match logic responds to all addresses transmitted on the TWI bus. TWSA is not used in this mode.

17.5.5 TWSD – TWI Slave Data Register

Bit	7	6	5	4	3	2	1	0	
0x28	TWSD[7:0]								TWSD
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

The data register is used when transmitting and received data. During transfer, data is shifted from/to the TWSD register and to/from the bus. Therefore, the data register cannot be accessed during byte transfers. This is protected in hardware. The data register can only be accessed when the SCL line is held low by the slave, i.e. when TWCH is set.

When a master reads data from a slave, the data to be sent must be written to the TWSD register. The byte transfer is started when the master starts to clock the data byte from the slave. It is followed by the slave receiving the acknowledge bit from the master. The TWDIF and the TWCH bits are then set.

When a master writes data to a slave, the TWDIF and the TWCH flags are set when one byte has been received in the data register. If Smart Mode is enabled, reading the data register will trigger the bus operation, as set by the TWAA bit in TWSCRB.

Accessing TWSD will clear the slave interrupt flags and the TWCH bit.

17.5.6 TWSAM – TWI Slave Address Mask Register

Bit	7	6	5	4	3	2	1	0	
0x29	TWSAM[7:0]							TWAE	TWSAM
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:1 – TWSAM[7:1]: TWI Address Mask**

These bits can act as a second address match register, or an address mask register, depending on the TWAE setting.

If TWAE is set to zero, TWSAM can be loaded with a 7-bit slave address mask. Each bit in TWSAM can mask (disable) the corresponding address bit in the TWSA register. If the mask bit is one the address match between the incoming address bit and the corresponding bit in TWSA is ignored. In other words, masked bits will always match.

If TWAE is set to one, TWSAM can be loaded with a second slave address in addition to the TWSA register. In this mode, the slave will match on 2 unique addresses, one in TWSA and the other in TWSAM.

- **Bit 0 – TWAE: TWI Address Enable**

By default, this bit is zero and the TWSAM bits acts as an address mask to the TWSA register. If this bit is set to one, the slave address match logic responds to the two unique addresses in TWSA and TWSAM.

18. Programming Interface

18.1 Features

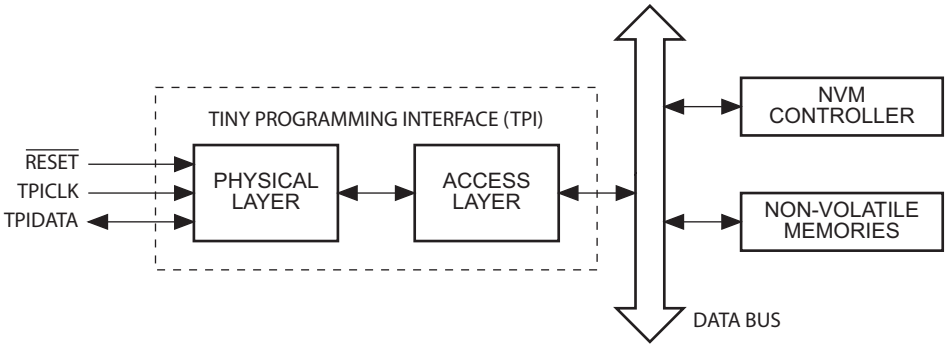
- **Physical Layer:**
  - **Synchronous Data Transfer**
  - **Bi-directional, Half-duplex Receiver And Transmitter**
  - **Fixed Frame Format With One Start Bit, 8 Data Bits, One Parity Bit And 2 Stop Bits**
  - **Parity Error Detection, Frame Error Detection And Break Character Detection**
  - **Parity Generation And Collision Detection**
  - **Automatic Guard Time Insertion Between Data Reception And Transmission**
- **Access Layer:**
  - **Communication Based On Messages**
  - **Automatic Exception Handling Mechanism**
  - **Compact Instruction Set**
  - **NVM Programming Access Control**
  - **Tiny Programming Interface Control And Status Space Access Control**
  - **Data Space Access Control**

18.2 Overview

The Tiny Programming Interface (TPI) supports external programming of all Non-Volatile Memories (NVM). Memory programming is done via the NVM Controller, by executing NVM controller commands as described in “Memory Programming” on page 143.

The Tiny Programming Interface (TPI) provides access to the programming facilities. The interface consists of two layers: the access layer and the physical layer. The layers are illustrated in Figure 18-1.

Figure 18-1. The Tiny Programming Interface and Related Internal Interfaces



Programming is done via the physical interface. This is a 3-pin interface, which uses the $\overline{\text{RESET}}$ pin as enable, the TPICLK pin as the clock input, and the TPIDATA pin as data input and output.

NVM can be programmed at 5V, only.

18.3 Physical Layer of Tiny Programming Interface

The TPI physical layer handles the basic low-level serial communication. The TPI physical layer uses a bi-directional, half-duplex serial receiver and transmitter. The physical layer includes serial-to-parallel and parallel-to-serial data conversion, start-of-frame detection, frame error detection, parity error detection, parity generation and collision detection.

The TPI is accessed via three pins, as follows:

$\overline{\text{RESET}}$:	Tiny Programming Interface enable input
TPICLK:	Tiny Programming Interface clock input
TPIDATA:	Tiny Programming Interface data input/output

In addition, the V_{CC} and GND pins must be connected between the external programmer and the device.

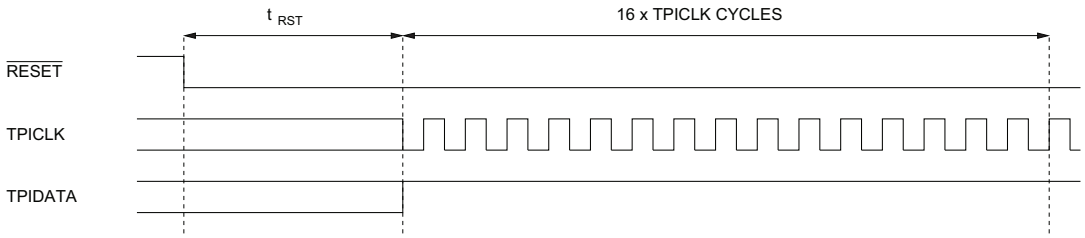
18.3.1 Enabling

The following sequence enables the Tiny Programming Interface:

- Apply 5V between V_{CC} and GND
- Depending on the method of reset to be used:
  - Either: wait t_{TOUT} (see Table 20-4 on page 155) and then set the $\overline{\text{RESET}}$ pin low. This will reset the device and enable the TPI physical layer. The $\overline{\text{RESET}}$ pin must then be kept low for the entire programming session
  - Or: if the RSTDISBL configuration bit has been programmed, apply 12V to the $\overline{\text{RESET}}$ pin. The $\overline{\text{RESET}}$ pin must be kept at 12V for the entire programming session
- Wait t_{RST} (see Table 20-4 on page 155)
- Keep the TPIDATA pin high for 16 TPICLK cycles

See Figure 18-2 for guidance.

Figure 18-2. Sequence for enabling the Tiny Programming Interface



18.3.2 Disabling

Provided that the NVM enable bit has been cleared, the TPI is automatically disabled if the $\overline{\text{RESET}}$ pin is released to inactive high state or, alternatively, if V_{HV} is no longer applied to the $\overline{\text{RESET}}$ pin.

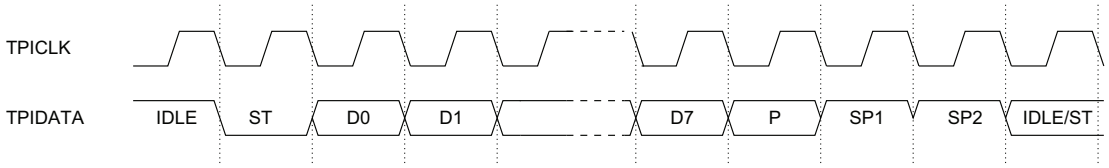
If the NVM enable bit is not cleared a power down is required to exit TPI programming mode.

See NVMEN bit in "TPISR – Tiny Programming Interface Status Register" on page 143.

18.3.3 Frame Format

The TPI physical layer supports a fixed frame format. A frame consists of one character, eight bits in length, and one start bit, a parity bit and two stop bits. Data is transferred with the least significant bit first.

Figure 18-3. Serial frame format.



Symbols used in Figure 18-3:

ST: Start bit (always low)
D0-D7: Data bits (least significant bit sent first)
P: Parity bit (using even parity)
SP1: Stop bit 1 (always high)
SP2: Stop bit 2 (always high)

18.3.4 Parity Bit Calculation

The parity bit is always calculated using even parity. The value of the bit is calculated by doing an exclusive-or of all the data bits, as follows:

$$P = D0 \otimes D1 \otimes D2 \otimes D3 \otimes D4 \otimes D5 \otimes D6 \otimes D7 \otimes 0$$

where:

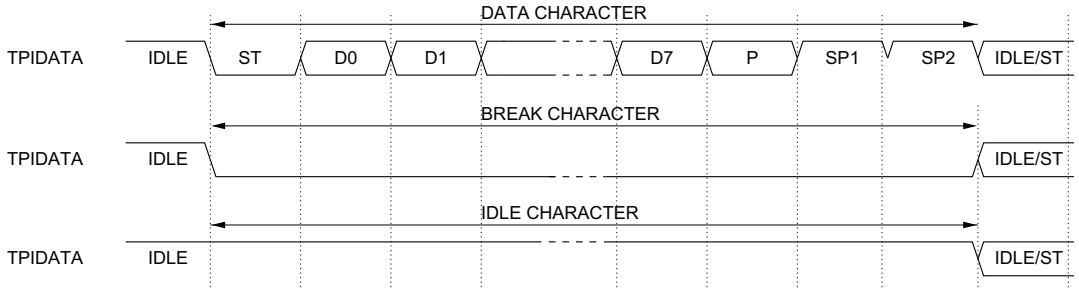
P: Parity bit using even parity
D0-D7: Data bits of the character

18.3.5 Supported Characters

The BREAK character is equal to a 12 bit long low level. It can be extended beyond a bit-length of 12.

The IDLE character is equal to a 12 bit long high level. It can be extended beyond a bit-length of 12.

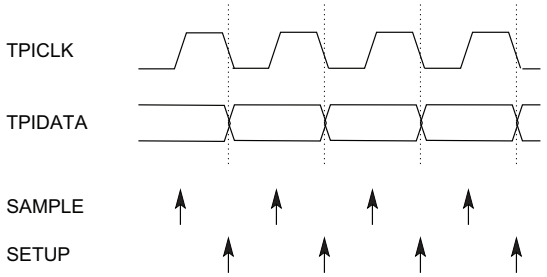
Figure 18-4. Supported characters.



18.3.6 Operation

The TPI physical layer operates synchronously on the TPICLK provided by the external programmer. The dependency between the clock edges and data sampling or data change is shown in Figure 18-5. Data is changed at falling edges and sampled at rising edges.

Figure 18-5. Data changing and Data sampling.



The TPI physical layer supports two modes of operation: Transmit and Receive. By default, the layer is in Receive mode, waiting for a start bit. The mode of operation is controlled by the access layer.

18.3.7 Serial Data Reception

When the TPI physical layer is in receive mode, data reception is started as soon as a start bit has been detected. Each bit that follows the start bit will be sampled at the rising edge of the TPICLK and shifted into the shift register until the second stop bit has been received. When the complete frame is present in the shift register the received data will be available for the TPI access layer.

There are three possible exceptions in the receive mode: frame error, parity error and break detection. All these exceptions are signalized to the TPI access layer, which then enters the error state and puts the TPI physical layer into receive mode, waiting for a BREAK character.

- Frame Error Exception. The frame error exception indicates the state of the stop bit. The frame error exception is set if the stop bit was read as zero.
- Parity Error Exception. The parity of the data bits is calculated during the frame reception. After the frame is received completely, the result is compared with the parity bit of the frame. If the comparison fails the parity error exception is signalized.
- Break Detection Exception. The Break detection exception is given when a complete frame of all zeros has been received.

18.3.8 Serial Data Transmission

When the TPI physical layer is ready to send a new frame it initiates data transmission by loading the shift register with the data to be transmitted. When the shift register has been loaded with new data, the transmitter shifts one complete frame out on the TPIDATA line at the transfer rate given by TPICLK.

If a collision is detected during transmission, the output driver is disabled. The TPI access layer enters the error state and the TPI physical layer is put into receive mode, waiting for a BREAK character.

18.3.9 Collision Detection Exception

The TPI physical layer uses one bi-directional data line for both data reception and transmission. A possible drive contention may occur, if the external programmer and the TPI physical layer drive the TPIDATA line simultaneously. In order to reduce the effect of the drive contention, a collision detection mechanism is supported. The collision detection is based on the way the TPI physical layer drives the TPIDATA line.

The TPIDATA line is driven by a tri-state, push-pull driver with internal pull-up. The output driver is always enabled when a logical zero is sent. When sending successive logical ones, the output is only driven actively during the first clock cycle. After this, the output driver is automatically tri-stated and the TPIDATA line is kept high by the internal pull-up. The output is re-enabled, when the next logical zero is sent.

The collision detection is enabled in transmit mode, when the output driver has been disabled. The data line should now be kept high by the internal pull-up and it is monitored to see, if it is driven low by the external programmer. If the output is read low, a collision has been detected.

There are some potential pit-falls related to the way collision detection is performed. For example, collisions cannot be detected when the TPI physical layer transmits a bit-stream of successive logical zeros, or bit-stream of alternating logical ones and zeros. This is because the output driver is active all the time, preventing polling of the TPIDATA line. However, within a single frame the two stop bits should always be transmitted as logical ones, enabling collision detection at least once per frame (as long as the frame format is not violated regarding the stop bits).

The TPI physical layer will cease transmission when it detects a collision on the TPIDATA line. The collision is signalized to the TPI access layer, which immediately changes the physical layer to receive mode and goes to the error state. The TPI access layer can be recovered from the error state only by sending a BREAK character.

18.3.10 Direction Change

In order to ensure correct timing of the half-duplex operation, a simple guard time mechanism has been added to the physical layer. When the TPI physical layer changes from receive to transmit mode, a configurable number of additional IDLE bits are inserted before the start bit is transmitted. The minimum transition time between receive and transmit mode is two IDLE bits. The total IDLE time is the specified guard time plus two IDLE bits.

The guard time is configured by dedicated bits in the TPIPCR register. The default guard time value after the physical layer is initialized is 128 bits.

The external programmer looses control of the TPIDATA line when the TPI target changes from receive mode to transmit. The guard time feature relaxes this critical phase of the communication. When the external programmer changes from receive mode to transmit, a minimum of one IDLE bit should be inserted before the start bit is transmitted.

18.4 Access Layer of Tiny Programming Interface

The TPI access layer is responsible for handling the communication with the external programmer. The communication is based on a message format, where each message comprises an instruction followed by one or more byte-sized operands. The instruction is always sent by the external programmer but operands are sent either by the external programmer or by the TPI access layer, depending on the type of instruction issued.

The TPI access layer controls the character transfer direction on the TPI physical layer. It also handles the recovery from the error state after exception.

The Control and Status Space (CSS) of the Tiny Programming Interface is allocated for control and status registers in the TPI access Layer. The CSS consist of registers directly involved in the operation of the TPI itself. These register are accessible using the SLDCS and SSTCS instructions.

The access layer can also access the data space, either directly or indirectly using the Pointer Register (PR) as the address pointer. The data space is accessible using the SLD, SST, SIN and SOUT instructions. The address pointer can be stored in the Pointer Register using the SLDPR instruction.

18.4.1 Message format

Each message comprises an instruction followed by one or more byte operands. The instruction is always sent by the external programmer. Depending on the instruction all the following operands are sent either by the external programmer or by the TPI.

The messages can be categorized in two types based on the instruction, as follows:

- Write messages. A write message is a request to write data. The write message is sent entirely by the external programmer. This message type is used with the SSTCS, SST, STPR, SOUT and SKEY instructions.

- Read messages. A read message is a request to read data. The TPI reacts to the request by sending the byte operands. This message type is used with the SLDCS, SLD and SIN instructions.

All the instructions except the SKEY instruction require the instruction to be followed by one byte operand. The SKEY instruction requires 8 byte operands. For more information, see the TPI instruction set on page 139.

18.4.2 Exception Handling and Synchronisation

Several situations are considered exceptions from normal operation of the TPI. When the TPI physical layer is in receive mode, these exceptions are:

- The TPI physical layer detects a parity error.
- The TPI physical layer detects a frame error.
- The TPI physical layer recognizes a BREAK character.

When the TPI physical layer is in transmit mode, the possible exceptions are:

- The TPI physical layer detects a data collision.

All these exceptions are signalized to the TPI access layer. The access layer responds to an exception by aborting any on-going operation and enters the error state. The access layer will stay in the error state until a BREAK character has been received, after which it is taken back to its default state. As a consequence, the external programmer can always synchronize the protocol by simply transmitting two successive BREAK characters.

18.5 Instruction Set

The TPI has a compact instruction set that is used to access the TPI Control and Status Space (CSS) and the data space. The instructions allow the external programmer to access the TPI, the NVM Controller and the NVM memories. All instructions except SKEY require one byte operand following the instruction. The SKEY instruction is followed by 8 data bytes. All instructions are byte-sized.

The TPI instruction set is summarised in Table 18-1.

Table 18-1. Instruction Set Summary

Mnemonic	Operand	Description	Operation
SLD	data, PR	Serial LoaD from data space using indirect addressing	data ← DS[PR]
SLD	data, PR+	Serial LoaD from data space using indirect addressing and post-increment	data ← DS[PR] PR ← PR+1
SST	PR, data	Serial STore to data space using indirect addressing	DS[PR] ← data
SST	PR+, data	Serial STore to data space using indirect addressing and post-increment	DS[PR] ← data PR ← PR+1
SSTPR	PR, a	Serial STore to Pointer Register using direct addressing	PR[a] ← data
SIN	data, a	Serial IN from data space	data ← I/O[a]
SOUT	a, data	Serial OUT to data space	I/O[a] ← data

Table 18-1. Instruction Set Summary (Continued)

Mnemonic	Operand	Description	Operation
SLDCS	data, a	Serial LoaD from Control and Status space using direct addressing	data ← CSS[a]
SSTCS	a, data	Serial STore to Control and Status space using direct addressing	CSS[a] ← data
SKEY	Key, {8{data}}	Serial KEY	Key ← {8{data}}

18.5.1 SLD - Serial LoaD from data space using indirect addressing

The SLD instruction uses indirect addressing to load data from the data space to the TPI physical layer shift-register for serial read-out. The data space location is pointed by the Pointer Register (PR), where the address must have been stored before data is accessed. The Pointer Register can either be left unchanged by the operation, or it can be post-incremented, as shown in Table 18-2.

Table 18-2. The Serial Load from Data Space (SLD) Instruction

Operation	Opcode	Remarks	Register
data ← DS[PR]	0010 0000	PR ← PR	Unchanged
data ← DS[PR]	0010 0100	PR ← PR + 1	Post increment

18.5.2 SST - Serial STore to data space using indirect addressing

The SST instruction uses indirect addressing to store into data space the byte that is shifted into the physical layer shift register. The data space location is pointed by the Pointer Register (PR), where the address must have been stored before the operation. The Pointer Register can be either left unchanged by the operation, or it can be post-incremented, as shown in Table 18-3.

Table 18-3. The Serial Store to Data Space (SLD) Instruction

Operation	Opcode	Remarks	Register
DS[PR] ← data	0110 0000	PR ← PR	Unchanged
DS[PR] ← data	0110 0100	PR ← PR + 1	Post increment

18.5.3 SSTPR - Serial STore to Pointer Register

The SSTPR instruction stores the data byte that is shifted into the physical layer shift register to the Pointer Register (PR). The address bit of the instruction specifies which byte of the Pointer Register is accessed, as shown in Table 18-4.

Table 18-4. The Serial Store to Pointer Register (SSTPR) Instruction

Operation	Opcode	Remarks
PR[a] ← data	0110 100a	Bit ‘a’ addresses Pointer Register byte

18.5.4 SIN - Serial IN from i/o space using direct addressing

The SIN instruction loads data byte from the I/O space to the shift register of the physical layer for serial read-out. The instuction uses direct addressing, the address consisting of the 6 address bits of the instruction, as shown in Table 18-5.

Table 18-5. The Serial IN from i/o space (SIN) Instruction

Operation	Opcode	Remarks
data ← I/O[a]	0aa1 aaaa	Bits marked ‘a’ form the direct, 6-bit addres

18.5.5 SOUT - Serial OUT to i/o space using direct addressing

The SOUT instruction stores the data byte that is shifted into the physical layer shift register to the I/O space. The instruction uses direct addressing, the address consisting of the 6 address bits of the instruction, as shown in Table 18-6.

Table 18-6. The Serial OUT to i/o space (SOUT) Instruction

Operation	Opcode	Remarks
I/O[a] ← data	1aa1 aaaa	Bits marked ‘a’ form the direct, 6-bit addres

18.5.6 SLDCS - Serial LoaD data from Control and Status space using direct addressing

The SLDCS instruction loads data byte from the TPI Control and Status Space to the TPI physical layer shift register for serial read-out. The SLDCS instruction uses direct addressing, the direct address consisting of the 4 address bits of the instruction, as shown in Table 18-7.

Table 18-7. The Serial Load Data from Control and Status space (SLDCS) Instruction

Operation	Opcode	Remarks
data ← CSS[a]	1000 aaaa	Bits marked ‘a’ form the direct, 4-bit addres

18.5.7 SSTCS - Serial STore data to Control and Status space using direct addressing

The SSTCS instruction stores the data byte that is shifted into the TPI physical layer shift register to the TPI Control and Status Space. The SSTCS instruction uses direct addressing, the direct address consisting of the 4 address bits of the instruction, as shown in Table 18-8.

Table 18-8. The Serial STore data to Control and Status space (SSTCS) Instruction

Operation	Opcode	Remarks
CSS[a] ← data	1100 aaaa	Bits marked ‘a’ form the direct, 4-bit addres

18.5.8 SKEY - Serial KEY signaling

The SKEY instruction is used to signal the activation key that enables NVM programming. The SKEY instruction is followed by the 8 data bytes that includes the activation key, as shown in Table 18-9.

Table 18-9. The Serial KEY signaling (SKEY) Instruction

Operation	Opcode	Remarks
Key ← {8[data]}	1110 0000	Data bytes follow after instruction

18.6 Accessing the Non-Volatile Memory Controller

By default, NVM programming is not enabled. In order to access the NVM Controller and be able to program the non-volatile memories, a unique key must be sent using the SKEY instruction. The 64-bit key that will enable NVM programming is given in Table 18-10.

Table 18-10. Enable Key for Non-Volatile Memory Programming

Key	Value
NVM Program Enable	0x1289AB45CDD888FF

After the key has been given, the Non-Volatile Memory Enable (NVMEN) bit in the TPI Status Register (TPISR) must be polled until the Non-Volatile memory has been enabled.

NVM programming is disabled by writing a logical zero to the NVMEN bit in TPISR.

18.7 Control and Status Space Register Descriptions

The control and status registers of the Tiny Programming Interface are mapped in the Control and Status Space (CSS) of the interface. These registers are not part of the I/O register map and are accessible via SLDCS and SSTCS instructions, only. The control and status registers are directly involved in configuration and status monitoring of the TPI.

A summary of CSS registers is shown in Table 18-11.

Table 18-11. Summary of Control and Status Registers

Addr.	Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0x0F	TPIIR	Tiny Programming Interface Identification Code							
0x0E	Reserved	–	–	–	–	–	–	–	–
0x0D	Reserved	–	–	–	–	–	–	–	–
0x0C	Reserved	–	–	–	–	–	–	–	–
0x0B	Reserved	–	–	–	–	–	–	–	–
0x0A	Reserved	–	–	–	–	–	–	–	–
0x09	Reserved	–	–	–	–	–	–	–	–
0x08	Reserved	–	–	–	–	–	–	–	–
0x07	Reserved	–	–	–	–	–	–	–	–
0x06	Reserved	–	–	–	–	–	–	–	–
0x05	Reserved	–	–	–	–	–	–	–	–
0x04	Reserved	–	–	–	–	–	–	–	–
0x03	Reserved	–	–	–	–	–	–	–	–
0x02	TPIPCR	–	–	–	–	–	GT2	GT1	GT0
0x01	Reserved	–	–	–	–	–	–	–	–
0x00	TPISR	–	–	–	–	–	–	NVMEN	–

18.7.1 TPIIR – Tiny Programming Interface Identification Register

Bit	7	6	5	4	3	2	1	0	
CSS: 0x0F	Programming Interface Identification Code								TPIIR
Read/Write	R	R	R	R	R	R	R	R	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:0 – TPIIC: Tiny Programming Interface Identification Code**

These bits give the identification code for the Tiny Programming Interface. The code can be used be the external programmer to identify the TPI. The identification code of the Tiny Programming Interface is shown in Table 18-12.

Table 18-12. Identification Code for Tiny Programming Interface

Code	Value
Interface Identification	0x80

18.7.2 TPIPCR – Tiny Programming Interface Physical Layer Control Register

Bit	7	6	5	4	3	2	1	0	
CSS: 0x02	–	–	–	–	–	GT2	GT1	GT0	TPIPCR
Read/Write	R	R	R	R	R	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:3 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 2:0 – GT[2:0]: Guard Time**

These bits specify the number of additional IDLE bits that are inserted to the idle time when changing from reception mode to transmission mode. Additional delays are not inserted when changing from transmission mode to reception.

The total idle time when changing from reception to transmission mode is Guard Time plus two IDLE bits. Table 18-13 shows the available Guard Time settings.

Table 18-13. Guard Time Settings

GT2	GT1	GT0	Guard Time (Number of IDLE bits)
0	0	0	+128 (default value)
0	0	1	+64
0	1	0	+32
0	1	1	+16
1	0	0	+8
1	0	1	+4
1	1	0	+2
1	1	1	+0

The default Guard Time is 128 IDLE bits. To speed up the communication, the Guard Time should be set to the shortest safe value.

18.7.3 TPISR – Tiny Programming Interface Status Register

Bit	7	6	5	4	3	2	1	0	
CSS: 0x00	–	–	–	–	–	–	NVMEN	–	TPISR
Read/Write	R	R	R	R	R	R	R/W	R	
Initial Value	0	0	0	0	0	0	0	0	

- **Bits 7:2, 0 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bit 1 – NVMEN: Non-Volatile Memory Programming Enabled**

NVM programming is enabled when this bit is set. The external programmer can poll this bit to verify the interface has been successfully enabled.

NVM programming is disabled by writing this bit to zero.

19. Memory Programming

19.1 Features

- **Two Embedded Non-Volatile Memories:**
  - **Non-Volatile Memory Lock bits (NVM Lock bits)**
  - **Flash Memory**
- **Four Separate Sections Inside Flash Memory:**
  - **Code Section (Program Memory)**
  - **Signature Section**

  - **Configuration Section**
  - **Calibration Section**
- **Read Access to All Non-Volatile Memories from Application Software**
- **Read and Write Access to Non-Volatile Memories from External programmer:**
  - **Read Access to All Non-Volatile Memories**
  - **Write Access to NVM Lock Bits, Flash Code Section and Flash Configuration Section**
- **External Programming:**
  - **Support for In-System and Mass Production Programming**
  - **Programming Through the Tiny Programming Interface (TPI)**
- **High Security with NVM Lock Bits**

19.2 Overview

The Non-Volatile Memory (NVM) Controller manages all access to the Non-Volatile Memories. The NVM Controller controls all NVM timing and access privileges, and holds the status of the NVM.

During normal execution the CPU will execute code from the code section of the Flash memory (program memory). When entering sleep and no programming operations are active, the Flash memory is disabled to minimize power consumption.

All NVM are mapped to the data memory. Application software can read the NVM from the mapped locations of data memory using load instruction with indirect addressing.

The NVM has only one read port and, therefore, the next instruction and the data can not be read simultaneously. When the application reads data from NVM locations mapped to the data space, the data is read first before the next instruction is fetched. The CPU execution is here delayed by one system clock cycle.

Internal programming operations to NVM have been disabled and the NVM therefore appears to the application software as read-only. Internal write or erase operations of the NVM will not be successful.

The method used by the external programmer for writing the Non-Volatile Memories is referred to as external programming. External programming can be done both in-system or in mass production. The external programmer can read and program the NVM via the Tiny Programming Interface (TPI).

In the external programming mode all NVM can be read and programmed, except the signature and the calibration sections which are read-only.

NVM can be programmed at 5V, only.

19.3 Non-Volatile Memories

The ATtiny40 has the following, embedded NVM:

- Non-Volatile Memory Lock Bits
- Flash memory with four separate sections

19.3.1 Non-Volatile Memory Lock Bits

The ATtiny40 provides two Lock Bits, as shown in Table 19-1.

Table 19-1. Lock Bit Byte

Lock Bit	Bit No	Description	Default Value
	7		1 (unprogrammed)
	6		1 (unprogrammed)
	5		1 (unprogrammed)

Table 19-1. Lock Bit Byte

Lock Bit	Bit No	Description	Default Value
	4		1 (unprogrammed)
	3		1 (unprogrammed)
	2		1 (unprogrammed)
NVLB2	1	Non-Volatile Lock Bit	1 (unprogrammed)
NVLB1	0	Non-Volatile Lock Bit	1 (unprogrammed)

The Lock Bits can be left unprogrammed ("1") or can be programmed ("0") to obtain the additional security shown in Table 19-2. Lock Bits can be erased to "1" with the Chip Erase command, only.

Table 19-2. Lock Bit Protection Modes

Memory Lock Bits (1)			
Lock Mode	NVLB2 (2)	NVLB1 (2)	Protection Type
1	1	1	No Memory Lock feature Enabled
2	1	0	Further Programming of the Flash memory is disabled in the external programming mode. The configuration section bits are locked in the external programming mode
3	0	0	Further programming and verification of the flash is disabled in the external programming mode. The configuration section bits are locked in the external programming mode

Notes: 1. Program the configuration section bits before programming NVLB1 and NVLB2.
2. "1" means unprogrammed, "0" means programmed

19.3.2 Flash Memory

The embedded Flash memory of ATtiny40 has four separate sections, as shown in Table 19-3.

Table 19-3. Number of Words and Pages in the Flash

Section	Size (Bytes)	Page Size (Words)	Pages	WADDR	PADDR
Code (program memory)	4096	32	64	[5:1]	[11:6]
Configuration	32	32	1	[5:1]	–
Signature (1)	32	16	2	[4:1]	[5:5]
Calibration (1)	32	32	1	[5:1]	–

Notes: 1. This section is read-only.

19.3.3 Configuration Section

ATtiny40 has one configuration byte, which resides in the configuration section. See Table 19-4.

Table 19-4. Configuration bytes

Configuration word address	Configuration word data	
	High byte	**Low byte**
0x00	Reserved	Configuration Byte 0
0x01 ... 0x1F	Reserved	Reserved

Table 19-5 briefly describes the functionality of all configuration bits and how they are mapped into the configuration byte.

Table 19-5. Configuration Byte 0

Bit	Bit Name	Description	Default Value
7	–	Reserved	1 (unprogrammed)
6	BODLEVEL2[1]	Brown-out Detector trigger level	1 (unprogrammed)
5	BODLEVEL1[1]	Brown-out Detector trigger level	1 (unprogrammed)
4	BODLEVEL0[1]	Brown-out Detector trigger level	1 (unprogrammed)
3	–	Reserved	1 (unprogrammed)
2	CKOUT	System Clock Output	1 (unprogrammed)
1	WDTON	Watchdog Timer always on	1 (unprogrammed)
0	RSTDISBL	External Reset disable	1 (unprogrammed)

Notes: 1. See Table 20-6 on page 155 for BODLEVEL Fuse decoding.

Configuration bits are not affected by a chip erase but they can be cleared using the configuration section erase command (see "Erasing the Configuration Section" on page 150). Note that configuration bits are locked if Non-Volatile Lock Bit 1 (NVLB1) is programmed.

19.3.3.1 Latching of Configuration Bits

All configuration bits are latched either when the device is reset or when the device exits the external programming mode. Changes to configuration bit values have no effect until the device leaves the external programming mode.

19.3.4 Signature Section

The signature section is a dedicated memory area used for storing miscellaneous device information, such as the device signature. Most of this memory section is reserved for internal use, as shown in Table 19-6.

Table 19-6. Signature bytes

Signature word address	Signature word data	
	High byte	**Low byte**
0x00	Device ID 1	Manufacturer ID
0x01	Reserved for internal use	Device ID 2
0x02 ... 0x3F	Reserved for internal use	Reserved for internal use

ATtiny40 has a three-byte signature code, which can be used to identify the device. The three bytes reside in the signature section, as shown in Table 19-6. The signature data for ATtiny40 is given in Table 19-7.

Table 19-7. Signature codes

Part	Signature Bytes		
	Manufacturer ID	Device ID 1	Device ID 2
ATtiny40	0x1E	0x92	0x0E

19.3.5 Calibration Section

ATtiny40 has one calibration byte. The calibration byte contains the calibration data for the internal oscillator and resides in the calibration section, as shown in Table 19-8. During reset, the calibration byte is automatically written into the OSCCAL register to ensure correct frequency of the calibrated internal oscillator.

Table 19-8. Calibration byte

Calibration word address	Calibration word data	
	High byte	Low byte
0x00	Reserved	Internal oscillator calibration value
0x01 ... 0x1F	Reserved	Reserved

19.3.5.1 Latching of Calibration Value

To ensure correct frequency of the calibrated internal oscillator the calibration value is automatically written into the OSCCAL register during reset.

19.4 Accessing the NVM

NVM lock bits, and all Flash memory sections are mapped to the data space as shown in Figure 5-1 on page 14. The NVM can be accessed for read and programming via the locations mapped in the data space.

The NVM Controller recognises a set of commands that can be used to instruct the controller what type of programming task to perform on the NVM. Commands to the NVM Controller are issued via the NVM Command Register. See “NVMCMD – Non-Volatile Memory Command Register” on page 151. After the selected command has been loaded, the operation is started by writing data to the NVM locations mapped to the data space.

When the NVM Controller is busy performing an operation it will signal this via the NVM Busy Flag in the NVM Control and Status Register. See “NVMCSR – Non-Volatile Memory Control and Status Register” on page 151. The NVM Command Register is blocked for write access as long as the busy flag is active. This is to ensure that the current command is fully executed before a new command can start.

Programming any part of the NVM will automatically inhibit the following operations:

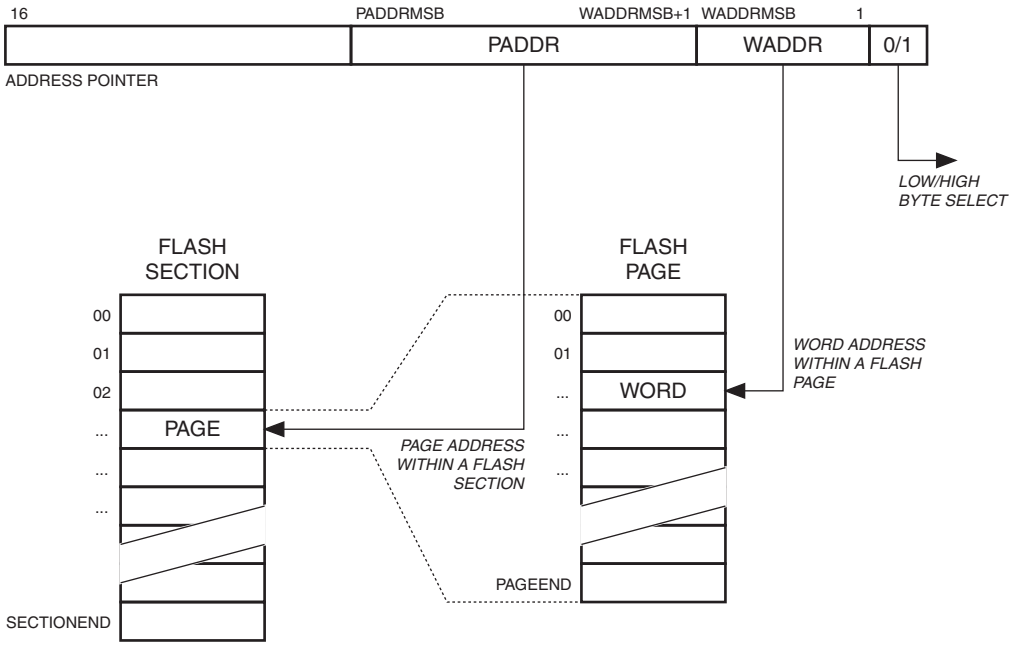
- All programming to any other part of the NVM
- All reading from any NVM location

The ATtiny40 supports only external programming. Internal programming operations to the NVM have been disabled, which means any internal attempt to write or erase NVM locations will fail.

19.4.1 Addressing the Flash

The data space uses byte accessing but since the Flash sections are accessed as words and organized in pages, the byte-address of the data space must be converted to the word-address of the Flash section. This is illustrated in Figure 19-1. Also, see Table 19-3 on page 145.

Figure 19-1. Addressing the Flash Memory



The most significant bits of the data space address select the NVM Lock bits or the Flash section mapped to the data memory. The word address within a page (WADDR) is held by the bits [WADDRMSB:1], and the page address (PADDR) is held by the bits [PADDRMSB:WADDRMSB+1]. Together, PADDR and WADDR form the absolute address of a word in the Flash section.

The least significant bit of the Flash section address is used to select the low or high byte of the word.

19.4.2 Reading the Flash

The Flash can be read from the data memory mapped locations one byte at a time. For read operations, the least significant bit (bit 0) is used to select the low or high byte in the word address. If this bit is zero, the low byte is read, and if it is one, the high byte is read.

19.4.3 Programming the Flash

The Flash can be written four words at a time. Before writing a Flash words, the Flash target location must be erased. Writing to an un-erased Flash word will corrupt its content.

The Flash is written four words at a time but the data space uses byte-addressing to access Flash that has been mapped to data memory. It is therefore important to write the four words in the correct order to the Flash, namely low bytes before high bytes. The low byte of the first word is first written to the temporary buffer, then the high byte. Writing the low byte and then the high byte to the buffer latches the four words into the Flash write buffer, starting the actual Flash write operation.

The Flash erase operations can only performed for the entire Flash sections.

The Flash programming sequence is as follows:

1. Perform a Flash section erase or perform a Chip erase
2. Write the Flash section four words at a time

19.4.3.1 Chip Erase

The Chip Erase command will erase the entire code section of the Flash memory and the NVM Lock Bits. For security reasons, however, the NVM Lock Bits are not reset before the code section has been completely erased. The Configuration, Signature and Calibration sections are not changed.

Before starting the Chip erase, the NVMCMD register must be loaded with the CHIP_ERASE command. To start the erase operation a dummy byte must be written into the high byte of a word location that resides inside the Flash code section. The NVMBSY bit remains set until erasing has been completed. While the Flash is being erased neither Flash buffer loading nor Flash reading can be performed.

The Chip Erase can be carried out as follows:

1. Write the CHIP_ERASE command to the NVMCMD register
2. Start the erase operation by writing a dummy byte to the high byte of any word location inside the code section
3. Wait until the NVMBSY bit has been cleared

19.4.3.2 Erasing the Code Section

The algorithm for erasing all pages of the Flash code section is as follows:

1. Write the SECTION_ERASE command to the NVMCMD register
2. Start the erase operation by writing a dummy byte to the high byte of any word location inside the code section
3. Wait until the NVMBSY bit has been cleared

19.4.3.3 Writing Flash Code Words

The algorithm for writing four words to the code section is as follows:

1. Write the CODE_WRITE command to the NVMCMD register
2. Write the low byte of the 1st word to the low byte of a target word location
3. Write the high byte of the 1st word to the high byte of the same target word location
4. Send IDLE character as described in section “Supported Characters” on page 136
5. Write the low byte of the 2nd word to the low byte of the next target word location
6. Write the high byte of the 2nd word to the high byte of the same target word location.
7. Send IDLE character as described in section “Supported Characters” on page 136
8. Write the low byte of the 3rd word to the low byte of a target word location
9. Write the high byte of the 3rd word to the high byte of the same target word location
10. Send IDLE character as described in section “Supported Characters” on page 136
11. Write the low byte of the 4th word to the low byte of the next target word location
12. Write the high byte of the 4th word to the high byte of the same target word location. This will start the Flash write operation
13. Wait until the NVMBSY bit has been cleared

19.4.3.4 *Erasing the Configuration Section*

The algorithm for erasing the Configuration section is as follows:

1. Write the SECTION_ERASE command to the NVMCMD register
2. Start the erase operation by writing a dummy byte to the high byte of any word location inside the configuration section
3. Wait until the NVMBSY bit has been cleared

19.4.3.5 *Writing a Configuration Word*

The algorithm for writing a Configuration word is as follows.

1. Write the CODE_WRITE command to the NVMCMD register
2. Write the low byte of the data word to the low byte of the configuration word location
3. Write the high byte of the data word to the high byte of the same configuration word location
4. Send IDLE character as described in section “Supported Characters” on page 136
5. Write a dummy byte to the low byte of the next configuration word location
6. Write a dummy byte to the high byte of the same configuration word location.
7. Send IDLE character as described in section “Supported Characters” on page 136
8. Write a dummy byte to the low byte of the next configuration word location
9. Write a dummy byte to the high byte of the same configuration word location.
10. Send IDLE character as described in section “Supported Characters” on page 136
11. Write a dummy byte to the low byte of the next configuration word location
12. Write a dummy byte to the high byte of the same configuration word location. This will start the Flash write operation
13. Wait until the NVMBSY bit has been cleared

19.4.4 Reading NVM Lock Bits

The Non-Volatile Memory Lock Byte can be read from the mapped location in data memory.

19.4.5 Writing NVM Lock Bits

The algorithm for writing the Lock bits is as follows.

1. Write the CODE_WRITE command to the NVMCMD register.
2. Write the lock bits value to the Non-Volatile Memory Lock Byte location. This is the low byte of the Non-Volatile Memory Lock Word.
3. Start the NVM Lock Bit write operation by writing a dummy byte to the high byte of the NVM Lock Word location.
4. Wait until the NVMBSY bit has been cleared.

19.5 Self programming

The ATtiny40 doesn't support internal programming.

19.6 External Programming

The method for programming the Non-Volatile Memories by means of an external programmer is referred to as external programming. External programming can be done both in-system or in mass production.

The Non-Volatile Memories can be externally programmed via the Tiny Programming Interface (TPI). For details on the TPI, see “Programming Interface” on page 134. Using the TPI, the external programmer can access the NVM control and status registers mapped to I/O space and the NVM memory mapped to data memory space.

19.6.1 Entering External Programming Mode

The TPI must be enabled before external programming mode can be entered. The following procedure describes, how to enter the external programming mode after the TPI has been enabled:

1. Make a request for enabling NVM programming by sending the NVM memory access key with the SKEY instruction.
2. Poll the status of the NVMEN bit in TPISR until it has been set.

Refer to the Tiny Programming Interface description on page 134 for more detailed information of enabling the TPI and programming the NVM.

19.6.2 Exiting External Programming Mode

Clear the NVM enable bit to disable NVM programming, then release the $\overline{\text{RESET}}$ pin.

See NVMEN bit in “TPISR – Tiny Programming Interface Status Register” on page 143.

19.7 Register Description

19.7.1 NVMCMD – Non-Volatile Memory Command Register

- **Bits 7:6 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

- **Bits 5:0 – NVMCMD[5:0]: Non-Volatile Memory Command**

These bits define the programming commands for the flash, as shown in Table 19-9.

Table 19-9. NVM Programming commands

Operation Type	NVMCMD		Mnemonic	Description
	Binary	Hex		
General	0b000000	0x00	NO_OPERATION	No operation
	0b010000	0x10	CHIP_ERASE	Chip erase
Section	0b010100	0x14	SECTION_ERASE	Section erase
Flash Words	0b011101	0x1D	CODE_WRITE	Write Flash words

19.7.2 NVMCSR – Non-Volatile Memory Control and Status Register

- **Bit 7 – NVMBSY: Non-Volatile Memory Busy**

This bit indicates the NVM memory (Flash memory and Lock Bits) is busy, being programmed. This bit is set when a program operation is started, and it remains set until the operation has been completed.

- **Bits 6:0 – Res: Reserved Bits**

These bits are reserved and will always read as zero.

20. Electrical Characteristics

20.1 Absolute Maximum Ratings*

Operating Temperature	-55°C to +125°C
Storage Temperature	-65°C to +150°C
Voltage on any Pin except $\overline{\text{RESET}}$ with respect to Ground	-0.5V to V_{CC}+0.5V
Voltage on $\overline{\text{RESET}}$ with respect to Ground	-0.5V to +13.0V
Maximum Operating Voltage	6.0V
DC Current per I/O Pin	40.0 mA
DC Current V_{CC} and GND Pins	200.0 mA

*NOTICE: Stresses beyond those listed under “Absolute Maximum Ratings” may cause permanent damage to the device. This is a stress rating only and functional operation of the device at these or other conditions beyond those indicated in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

20.2 DC Characteristics

Table 20-1. DC Characteristics. T_A = -40°C to +85°C

Symbol	Parameter	Condition	Min	Typ[1]	Max	Units
V_{IL}	Input Low Voltage	V_{CC} = 1.8V - 2.4V V_{CC} = 2.4V - 5.5V	-0.5		$0.2V_{CC}$[3] $0.3V_{CC}$[3]	V
V_{IH}	Input High-voltage Except $\overline{\text{RESET}}$ pin	V_{CC} = 1.8V - 2.4V V_{CC} = 2.4V - 5.5V	$0.7V_{CC}$[2] $0.6V_{CC}$[2]		V_{CC} +0.5	V
	Input High-voltage $\overline{\text{RESET}}$ pin	V_{CC} = 1.8V - 5.5V	$0.9V_{CC}$[2]		V_{CC} +0.5	V
V_{OL}	Output Low Voltage[4] Except $\overline{\text{RESET}}$ pin[6]	I_{OL} = 10 mA, V_{CC} = 5V I_{OL} = 5 mA, V_{CC} = 3V			0.6 0.5	V
V_{OH}	Output High-voltage[5] Except $\overline{\text{RESET}}$ pin[6]	I_{OH} = -10 mA, V_{CC} = 5V I_{OH} = -5 mA, V_{CC} = 3V	4.3 2.5			V
I_{LIL}	Input Leakage Current I/O Pin	V_{CC} = 5.5V, pin low (absolute value)		<0.05	1	µA
I_{LIH}	Input Leakage Current I/O Pin	V_{CC} = 5.5V, pin high (absolute value)		<0.05	1	µA
R_{RST}	Reset Pull-up Resistor	V_{CC} = 5.5V, input low	30		60	kΩ
R_{PU}	I/O Pin Pull-up Resistor	V_{CC} = 5.5V, input low	20		50	kΩ
I_{ACLK}	Analog Comparator Input Leakage Current	V_{CC} = 5V V_{in} = V_{CC}/2	-50		50	nA

Table 20-1. DC Characteristics. T_A = -40°C to +85°C (Continued)

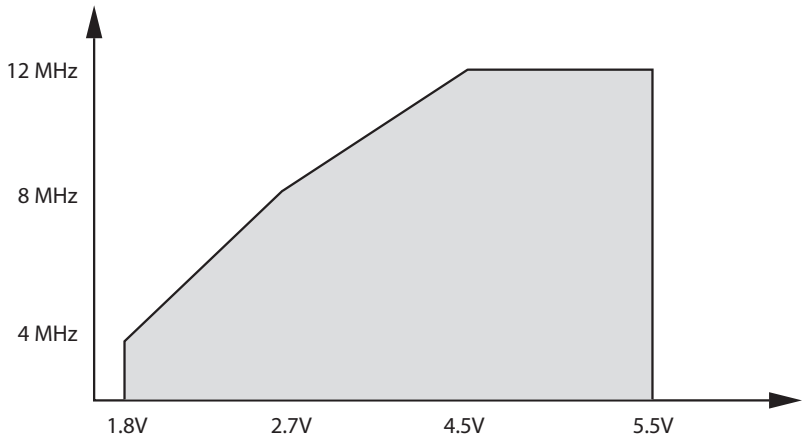
Symbol	Parameter	Condition	Min	Typ[1]	Max	Units
I_{CC}	Power Supply Current[7]	Active 1MHz, V_{CC} = 2V		0.2	0.6	mA
		Active 4MHz, V_{CC} = 3V		1.1	2	mA
		Active 8MHz, V_{CC} = 5V		3.2	5	mA
		Idle 1MHz, V_{CC} = 2V		0.03	0.2	mA
		Idle 4MHz, V_{CC} = 3V		0.2	0.5	mA
		Idle 8MHz, V_{CC} = 5V		0.8	1.5	mA
	Power-down mode[8]	WDT enabled, V_{CC} = 3V		4.5	10	µA
		WDT disabled, V_{CC} = 3V		0.15	2	µA

Notes:
1. Typical values at 25°C.
2. “Min” means the lowest value where the pin is guaranteed to be read as high.
3. “Max” means the highest value where the pin is guaranteed to be read as low.
4. Although each I/O port can sink more than the test conditions (10 mA at V_{CC} = 5V, 5 mA at V_{CC} = 3V) under steady state conditions (non-transient), the sum of all I_{OL} (for all ports) should not exceed 60 mA. If I_{OL} exceeds the test conditions, V_{OL} may exceed the related specification. Pins are not guaranteed to sink current greater than the listed test condition.
5. Although each I/O port can source more than the test conditions (10 mA at V_{CC} = 5V, 5 mA at V_{CC} = 3V) under steady state conditions (non-transient), the sum of all I_{OH} (for all ports) should not exceed 60 mA. If I_{OH} exceeds the test condition, V_{OH} may exceed the related specification. Pins are not guaranteed to source current greater than the listed test condition.
6. The $\overline{\text{RESET}}$ pin must tolerate high voltages when entering and operating in programming modes and, as a consequence, has a weak drive strength as compared to regular I/O pins. See Figure 21-32 to Figure 21-37, starting from page 175.
7. Values are with external clock using methods described in “Minimizing Power Consumption” on page 25. Power Reduction is enabled (PRR = 0xFF) and there is no I/O drive.
8. BOD Disabled.

20.3 Speed

The maximum operating frequency of the device depends on V_{CC} . As shown in Figure 20-1, the relationship between maximum frequency vs. V_{CC} is linear between 1.8V < V_{CC} < 2.7V, and 2.7V < V_{CC} < 4.5V.

Figure 20-1. Maximum Frequency vs. V_{CC}



20.4 Clock Characteristics

20.4.1 Accuracy of Calibrated Internal Oscillator

It is possible to manually calibrate the internal oscillator to be more accurate than default factory calibration. Note that the oscillator frequency depends on temperature and voltage. Voltage and temperature characteristics can be found in Figure 21-55 on page 187 and Figure 21-56 on page 187.

Table 20-2. Calibration Accuracy of Internal RC Oscillator

Calibration Method	Target Frequency	V_{CC}	Temperature	Accuracy at given Voltage & Temperature[1]
Factory Calibration	8.0 MHz	3V	25°C	±10%
User Calibration	Fixed frequency within: 7.3 – 8.1 MHz	Fixed voltage within: 1.8V – 5.5V	Fixed temp. within: -40°C to +85°C	±1%

Notes: 1. Accuracy of oscillator frequency at calibration point (fixed temperature and fixed voltage).

20.4.2 External Clock Drive

Figure 20-2. External Clock Drive Waveform

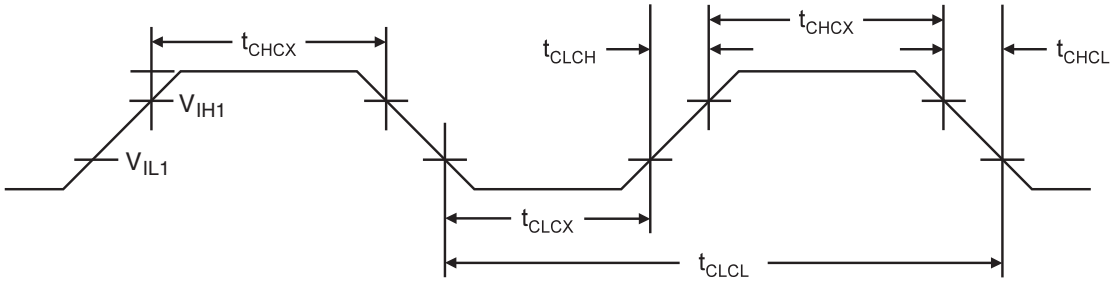


Table 20-3. External Clock Drive Characteristics

Symbol	Parameter	V_{CC} = 1.8 - 5.5V		V_{CC} = 2.7 - 5.5V		V_{CC} = 4.5 - 5.5V		Units
		Min.	Max.	Min.	Max.	Min.	Max.	
$1/t_{CLCL}$	Clock Frequency	0	4	0	8	0	12	MHz
t_{CLCL}	Clock Period	250		125		83		ns
t_{CHCX}	High Time	100		40		20		ns
t_{CLCX}	Low Time	100		40		20		ns
t_{CLCH}	Rise Time		2.0		1.6		0.5	µs
t_{CHCL}	Fall Time		2.0		1.6		0.5	µs
Δt_{CLCL}	Change in period from one clock cycle to the next		2		2		2	%

20.5 System and Reset Characteristics

Table 20-4. Reset and Internal Voltage Characteristics

Symbol	Parameter	Condition	Min	Typ	Max	Units
V_{RST}	$\overline{\text{RESET}}$ Pin Threshold Voltage		0.2 V_{CC}		0.9V_{CC}	V
V_{BG}	Internal bandgap voltage	V_{CC} = 2.7V T_A = 25°C	1.0	1.1	1.2	V
t_{RST}	Minimum pulse width on $\overline{\text{RESET}}$ Pin	V_{CC} = 1.8V V_{CC} = 3V V_{CC} = 5V		2000 700 400		ns
t_{TOUT}	Time-out after reset			64	128	ms

20.5.1 Power-On Reset

Table 20-5. Characteristics of Enhanced Power-On Reset. T_A = -40 to +85°C

Symbol	Parameter	Min[1]	Typ[1]	Max[1]	Units
V_{POR}	Release threshold of power-on reset [2]	1.1	1.4	1.6	V
V_{POA}	Activation threshold of power-on reset [3]	0.6	1.3	1.6	V
SR_{ON}	Power-on Slope Rate	0.01			V/ms

Note: 1. Values are guidelines, only
2. Threshold where device is released from reset when voltage is rising
3. The Power-on Reset will not work unless the supply voltage has been below V_{POT} (falling)

20.5.2 Brown-Out Detection

Table 20-6. V_{BOT} vs. BODLEVEL Fuse Coding

BODLEVEL[2:0] Fuses	Min[1]	Typ[1]	Max[1]	Units
111	BOD Disabled			
110	1.7	1.8	2.0	V
101	2.5	2.7	2.9	
100	4.1	4.3	4.5	
0XX	Reserved			

Note: 1. V_{BOT} may be below nominal minimum operating voltage for some devices. For devices where this is the case, the device is tested down to V_{CC} = V_{BOT} during the production test. This guarantees that a Brown-out Reset will occur before V_{CC} drops to a voltage where correct operation of the microcontroller is no longer guaranteed.

20.6 Two-Wire Serial Interface Characteristics

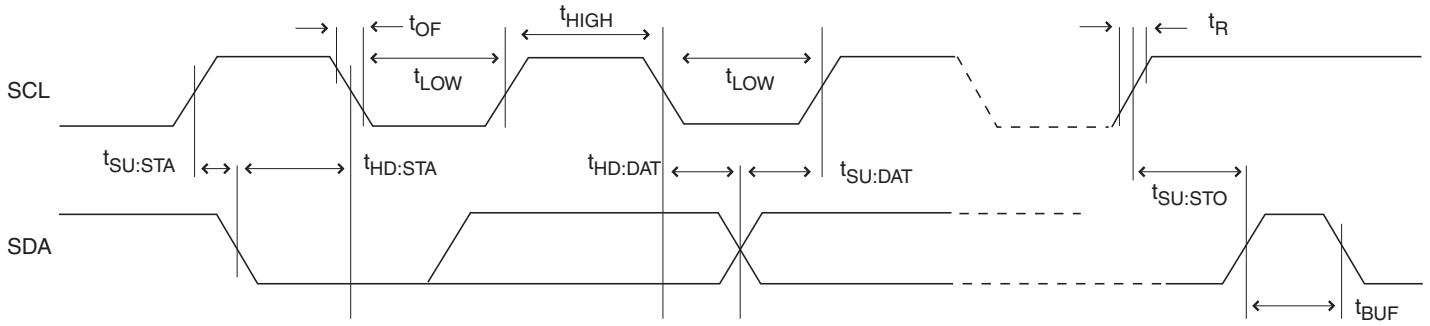
The following data is based on simulations and characterisations. Parameters listed in Table 20-7 are not tested in production. Symbols refer to Figure 20-3.

Table 20-7. Two-Wire Serial Interface Characteristics

Symbol	Parameter	Condition	Min	Max	Unit
V_{IL}	Input Low voltage		-0.5	0.3 V_{CC}	V
V_{IH}	Input High voltage		0.7 V_{CC}	V_{CC} + 0.5	V
V_{HYS}	Hysteresis of Schmitt-trigger inputs	$V_{CC} \geq 2.7V$	0.05 V_{CC}	–	V
		$V_{CC} < 2.7V$	0		
V_{OL}	Output Low voltage	I_{OL} = 3mA, V_{CC} > 2.7V	0	0.4	V
		I_{OL} = 2mA, V_{CC} < 2.7V			
t_{SP}	Spikes suppressed by input filter		0	50	ns
f_{SCL}	SCL clock frequency (1)	f_{CK} > max(16f_{SCL}, 250kHz)	0	400	kHz
$t_{HD:STA}$	Hold time (repeated) START Condition		0.6	–	µs
t_{LOW}	Low period of SCL clock		1.3	–	µs
t_{HIGH}	High period of SCL clock		0.6	–	µs
$t_{SU:STA}$	Set-up time for repeated START condition		0.6	–	µs
$t_{HD:DAT}$	Data hold time		0	0.9	µs
$t_{SU:DAT}$	Data setup time		100	–	ns
$t_{SU:STO}$	Setup time for STOP condition		0.6	–	µs
t_{BUF}	Bus free time between STOP and START condition		1.3	–	µs

Notes: 1. f_{CK} = CPU clock frequency.

Figure 20-3. Two-Wire Serial Bus Timing



20.7 Analog Comparator Characteristics

Table 20-8. Analog Comparator Characteristics, T_A = -40°C to +85°C

Symbol	Parameter	Condition	Min	Typ	Max	Units
V_{AIO}	Input Offset Voltage	V_{CC} = 5V, V_{IN} = V_{CC} / 2		< 10	40	mV
I_{LAC}	Input Leakage Current	V_{CC} = 5V, V_{IN} = V_{CC} / 2	-50		50	nA
t_{APD}	Analog Propagation Delay (from saturation to slight overdrive)	V_{CC} = 2.7V		750		ns
		V_{CC} = 4.0V		500		
	Analog Propagation Delay (large step change)	V_{CC} = 2.7V		100		
		V_{CC} = 4.0V		75		
t_{DPD}	Digital Propagation Delay	V_{CC} = 1.8V - 5.5		1	2	CLK

20.8 ADC Characteristics

Table 20-9. ADC Characteristics. T = -40°C to +85°C. V_{CC} = 2.5V – 5.5V

Symbol	Parameter	Condition	Min	Typ	Max	Units
	Resolution				10	Bits
	Absolute accuracy (Including INL, DNL, and Quantization, Gain and Offset Errors)	V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz		2		LSB
		V_{REF} = V_{CC} = 4V, ADC clock = 1 MHz		3		LSB
		V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz Noise Reduction Mode		1.5		LSB
		V_{REF} = V_{CC} = 4V, ADC clock = 1 MHz Noise Reduction Mode		2.5		LSB
	Integral Non-Linearity (INL) (Accuracy after Offset and Gain Calibration)	V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz		1		LSB
	Differential Non-linearity (DNL)	V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz		0.5		LSB
	Gain Error	V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz		2.5		LSB
	Offset Error	V_{REF} = V_{CC} = 4V, ADC clock = 200 kHz		1.5		LSB
	Conversion Time	Free Running Conversion	13		260	µs
	Clock Frequency		50		1000	kHz
V_{IN}	Input Voltage		GND		V_{REF}	V
	Input Bandwidth			38.5		kHz
R_{AIN}	Analog Input Resistance			100		MΩ
	ADC Conversion Output		0		1023	LSB

20.9 Serial Programming Characteristics

Figure 20-4. Serial Programming Timing

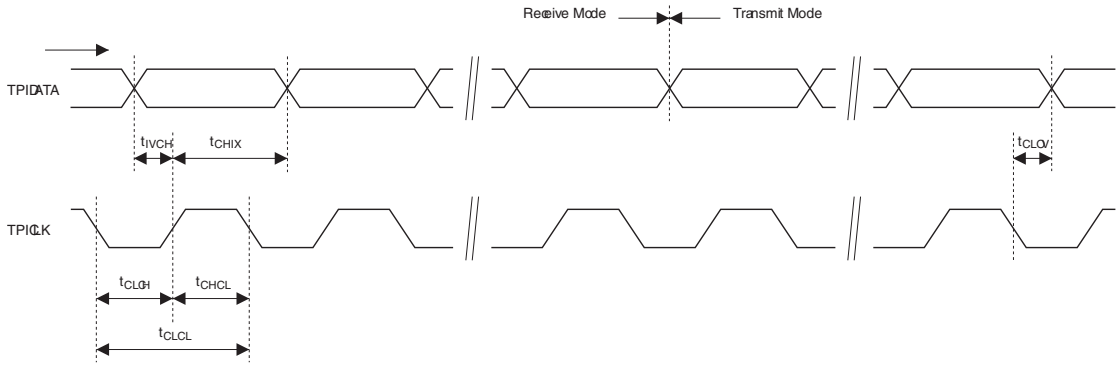


Table 20-10. Serial Programming Characteristics, T_A = -40°C to +85°C, V_{CC} = 5V ±5%

Symbol	Parameter	Min	Typ	Max	Units
$1/t_{CLCL}$	Clock Frequency			2	MHz
t_{CLCL}	Clock Period	500			ns
t_{CLCH}	Clock Low Pulse Width	200			ns
t_{CHCH}	Clock High Pulse Width	200			ns
t_{IVCH}	Data Input to Clock High Setup Time	50			ns
t_{CHIX}	Data Input Hold Time After Clock High	100			ns
t_{CLOV}	Data Output Valid After Clock Low Time			200	ns

21. Typical Characteristics

The data contained in this section is largely based on simulations and characterization of similar devices in the same process and design methods. Thus, the data should be treated as indications of how the part will behave.

The following charts show typical behavior. These figures are not tested during manufacturing. During characterisation devices are operated at frequencies higher than test limits but they are not guaranteed to function properly at frequencies higher than the ordering code indicates.

All current consumption measurements are performed with all I/O pins configured as inputs and with internal pull-ups enabled. Current consumption is a function of several factors such as operating voltage, operating frequency, loading of I/O pins, switching rate of I/O pins, code executed and ambient temperature. The dominating factors are operating voltage and frequency.

A sine wave generator with rail-to-rail output is used as clock source but current consumption in Power-down mode is independent of clock selection. The difference between current consumption in Power-down mode with Watchdog Timer enabled and Power-down mode with Watchdog Timer disabled represents the differential current drawn by the Watchdog Timer.

The current drawn from pins with a capacitive load may be estimated (for one pin) as follows:

$I_{CP} \approx V_{CC} \times C_L \times f_{SW}$

where V_{CC} = operating voltage, C_L = load capacitance and f_{SW} = average switching frequency of pin.

21.1 Supply Current of I/O Modules

The tables and formulas below can be used to calculate the additional current consumption for the different I/O modules in Active and Idle mode. The enabling or disabling of the I/O modules is controlled by the Power Reduction Register. See “Power Reduction Register” on page 25 for details.

Table 21-1. Additional Current Consumption for different I/O modules (absolute values)

PRR bit	Typical numbers		
	V_{CC} = 2V, f = 1MHz	V_{CC} = 3V, f = 4MHz	V_{CC} = 5V, f = 8MHz
PRTIM0	4 µA	25 µA	110 µA
PRTIM1	5 µA	35 µA	150 µA
PRADC	190 µA	260 µA	470 µA
PRSPI	3 µA	15 µA	75 µA
PRTWI	5 µA	35 µA	160 µA

Table 21-2 below can be used for calculating typical current consumption for other supply voltages and frequencies than those mentioned in the Table 21-1 above.

Table 21-2. Additional Current Consumption (percentage) in Active and Idle mode

PRR bit	Current consumption additional to active mode with external clock (see Table 21-1 and Table 21-2)	Current consumption additional to idle mode with external clock (see Table 21-7 and Table 21-8)
PRTIM0	2 %	15 %
PRTIM1	3 %	20 %
PRADC	See Figure 21-16 on page 167	See Figure 21-16 on page 167
PRSPI	2 %	10 %
PRTWI	4 %	20 %

21.2 Current Consumption in Active Mode

Figure 21-1. Active Supply Current vs. Low Frequency (0.1 - 1.0 MHz)

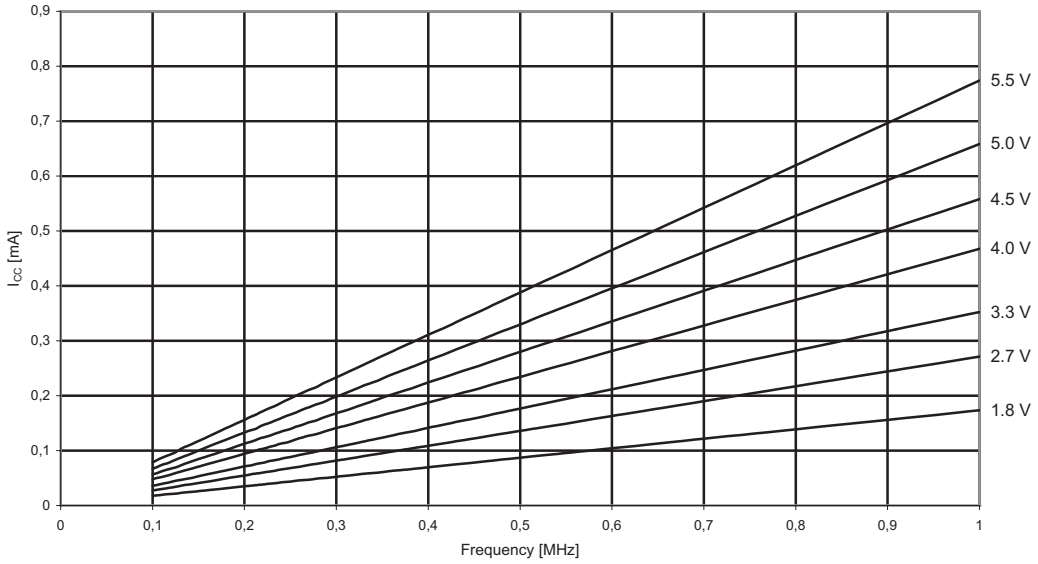


Figure 21-2. Active Supply Current vs. Frequency (1 - 12 MHz)

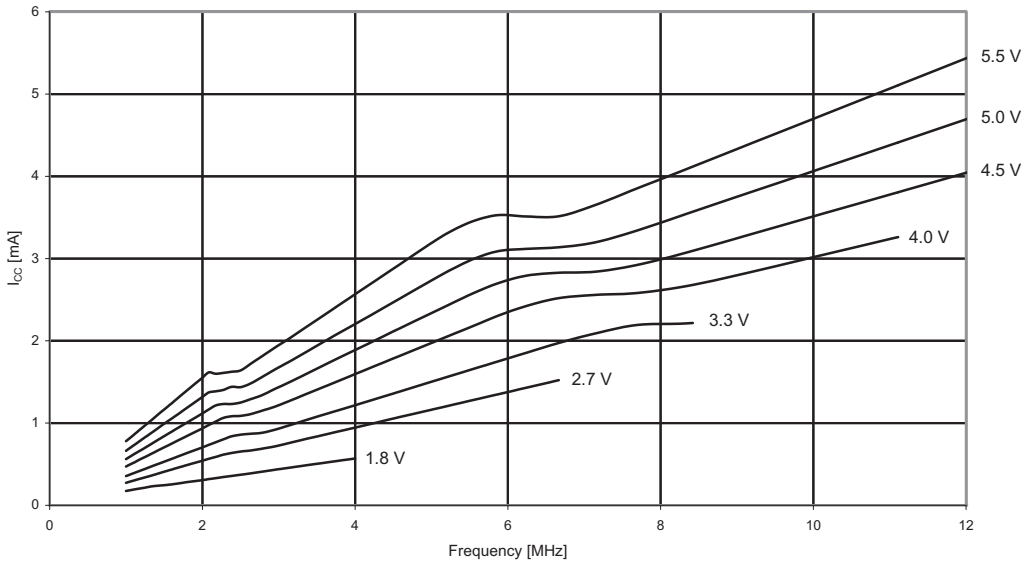


Figure 21-3. Active Supply Current vs. V_{CC} (Internal Oscillator, 8 MHz)

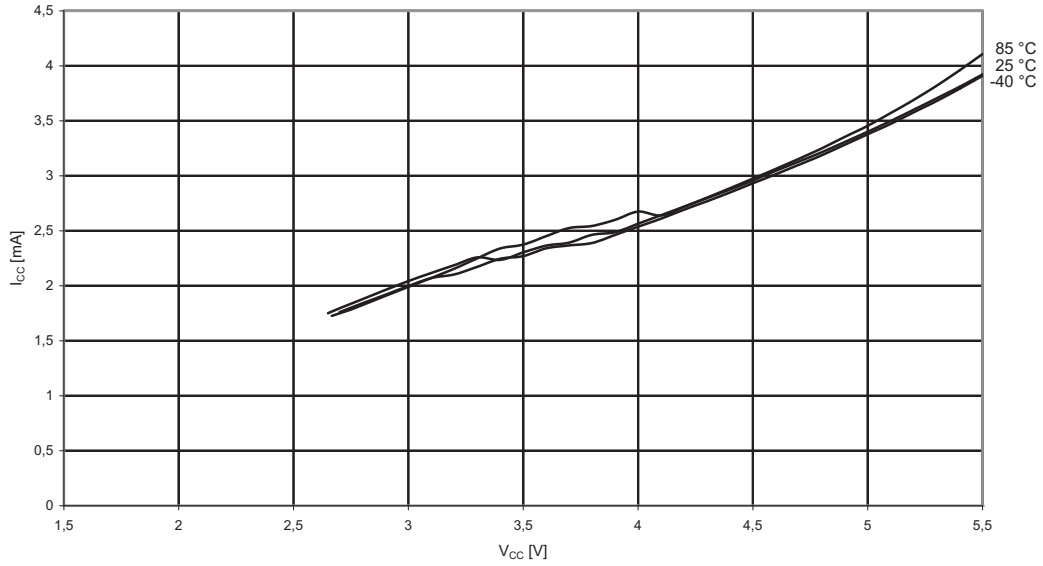


Figure 21-4. Active Supply Current vs. V_{CC} (Internal Oscillator, 1 MHz)

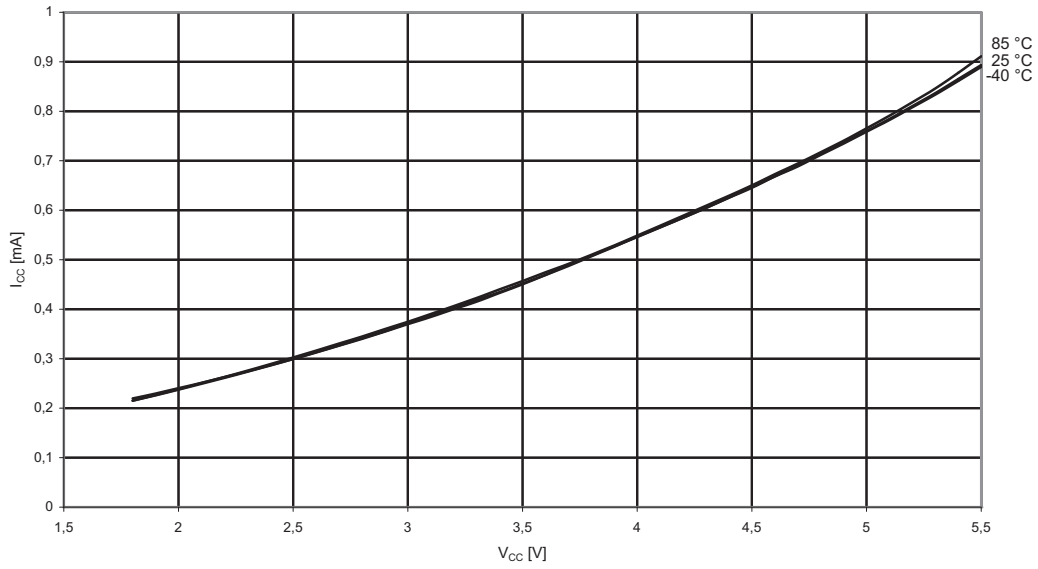


Figure 21-5. Active Supply Current vs. V_{CC} (Internal Oscillator, 128 kHz)

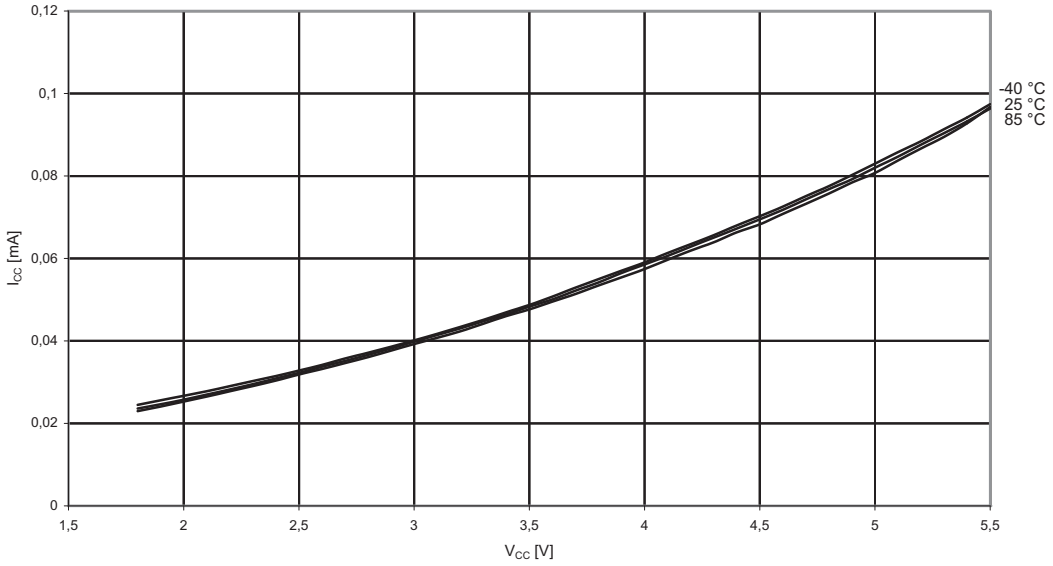
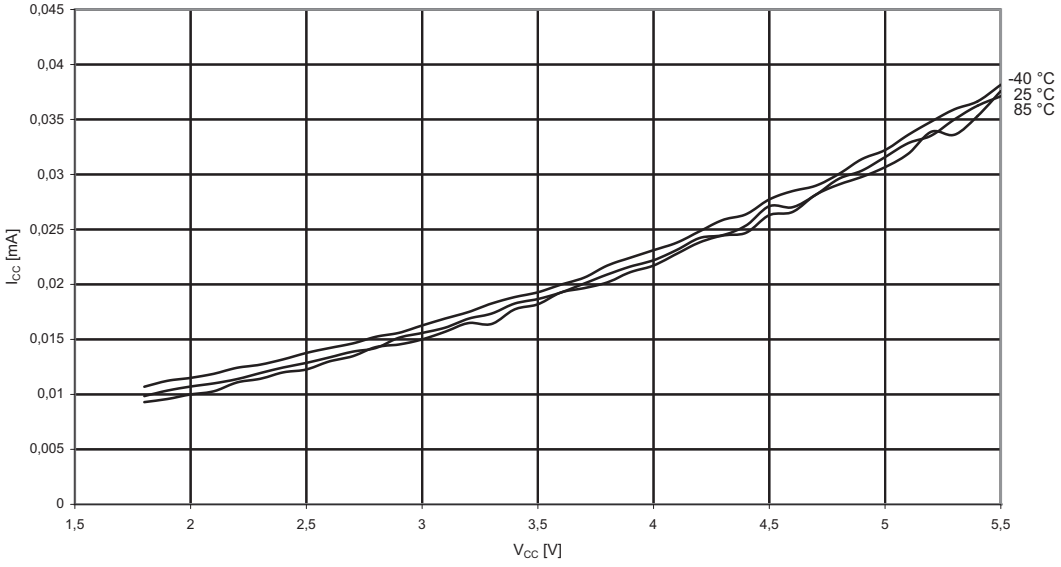


Figure 21-6. Active Supply Current vs. V_{CC} (Internal Oscillator, 32kHz)



21.3 Current Consumption in Idle Mode

Figure 21-7. Idle Supply Current vs. Low Frequency (0.1 - 1.0 MHz)

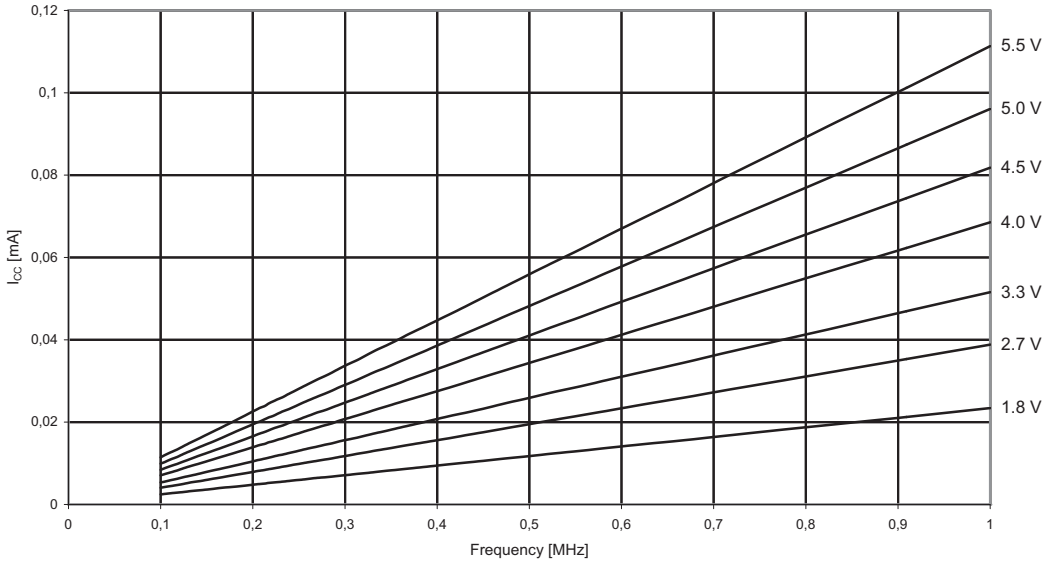


Figure 21-8. Idle Supply Current vs. Frequency (1 - 12 MHz)

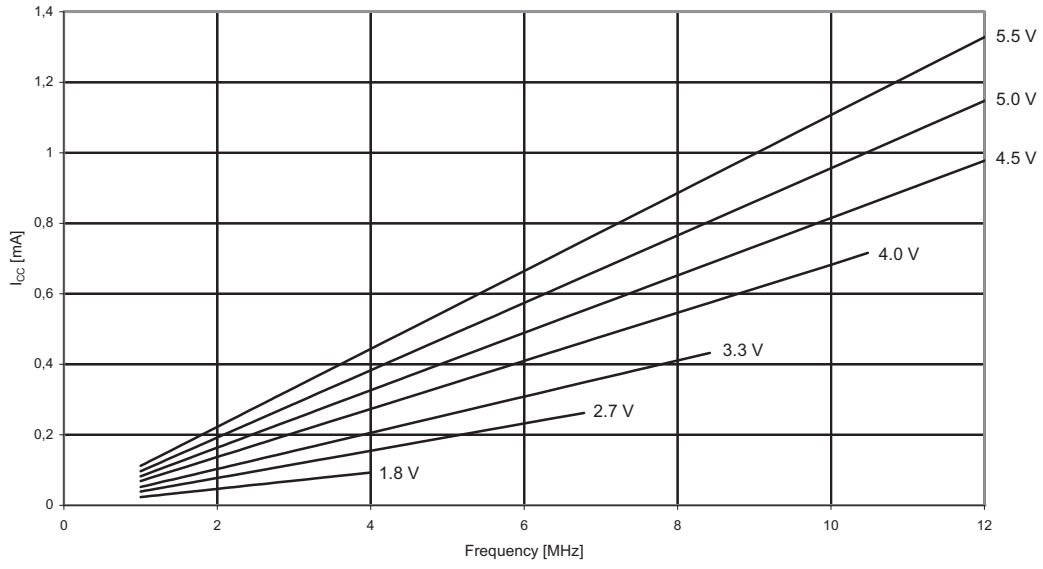


Figure 21-9. Idle Supply Current vs. V_{CC} (Internal Oscillator, 8 MHz)

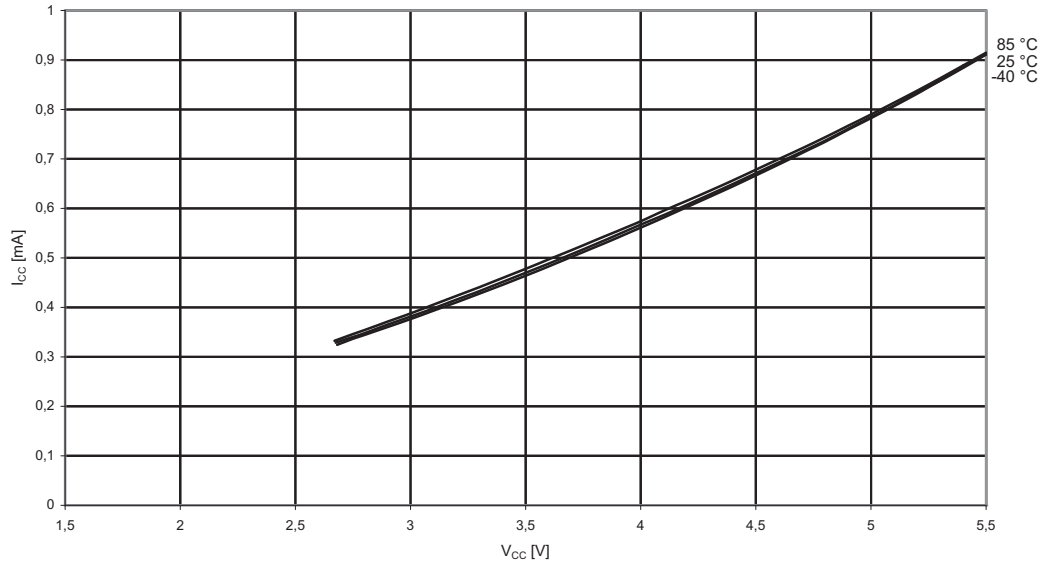


Figure 21-10. Idle Supply Current vs. V_{CC} (Internal Oscillator, 1 MHz)

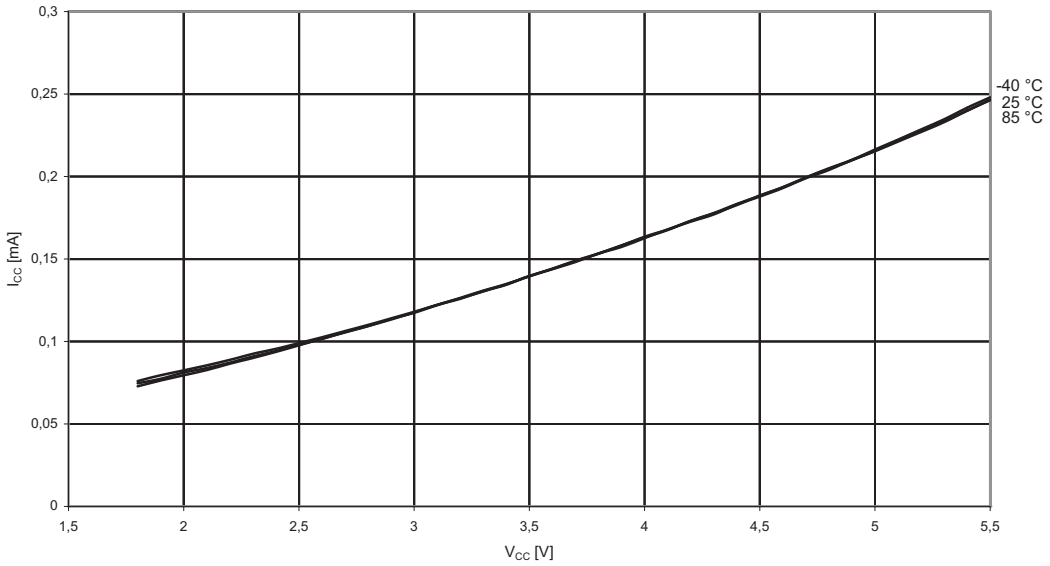


Figure 21-11. Idle Supply Current vs. V_{CC} (Internal Oscillator, 128 kHz)

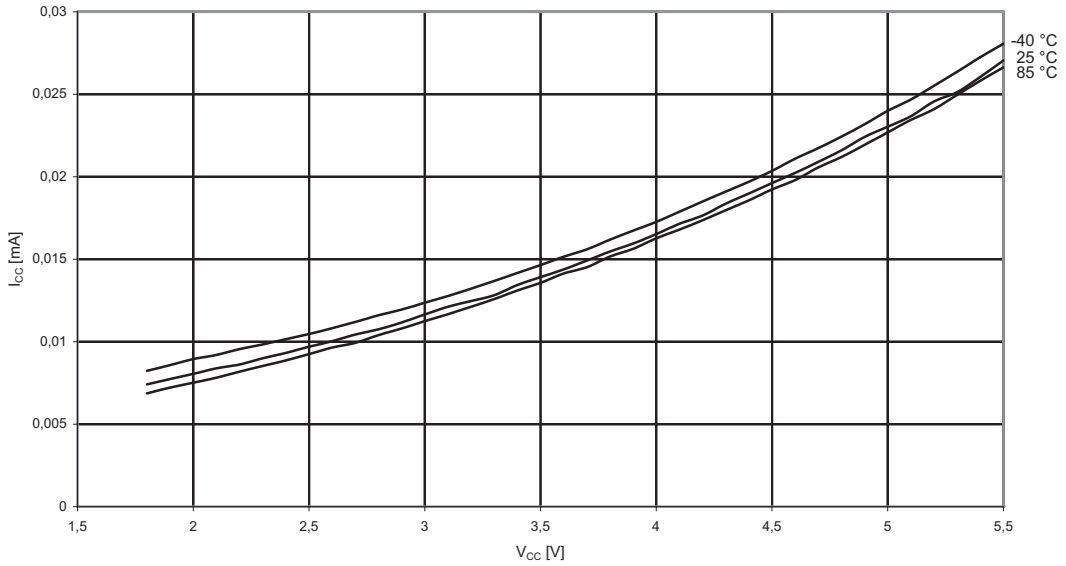
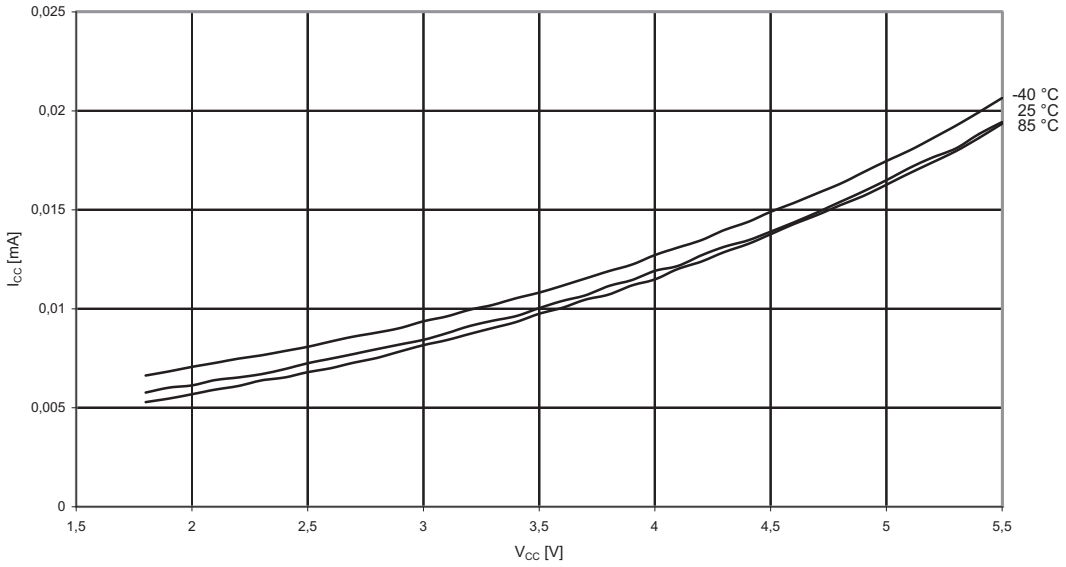


Figure 21-12. Idle Supply Current vs. V_{CC} (Internal Oscillator, 32kHz)



21.4 Current Consumption in Power-down Mode

Figure 21-13. Power-down Supply Current vs. V_{CC} (Watchdog Timer Disabled)

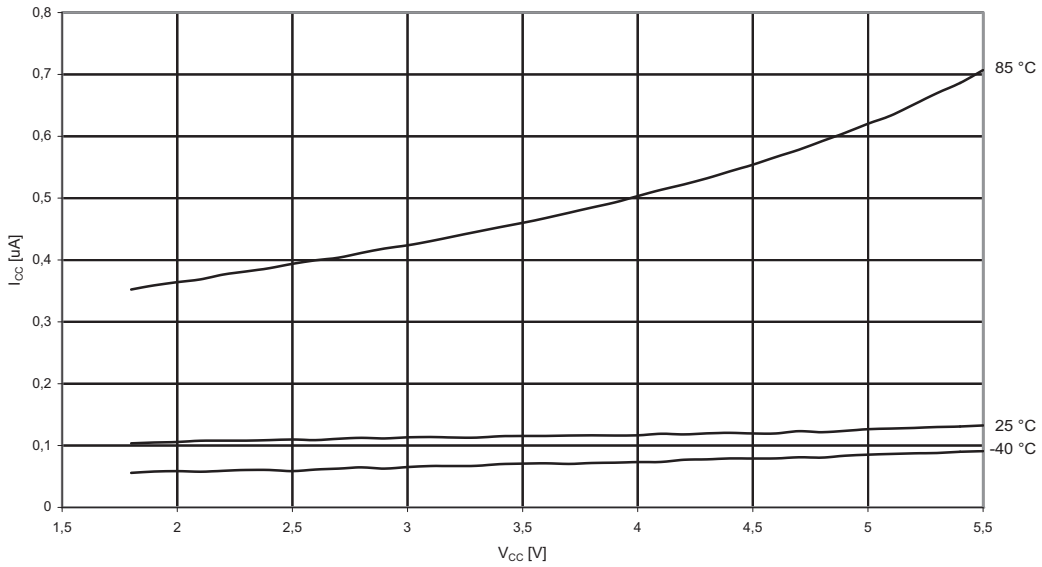
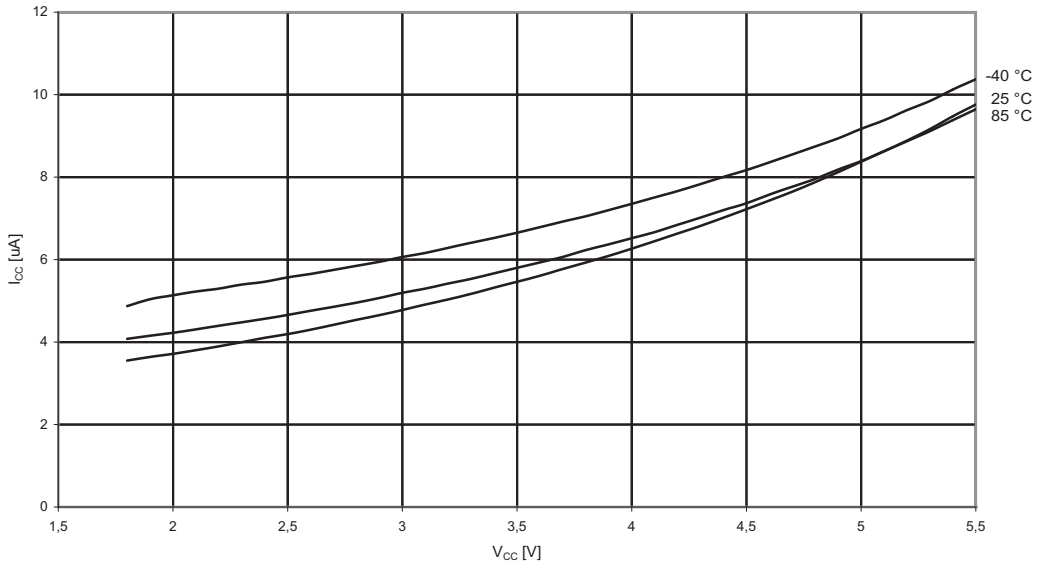
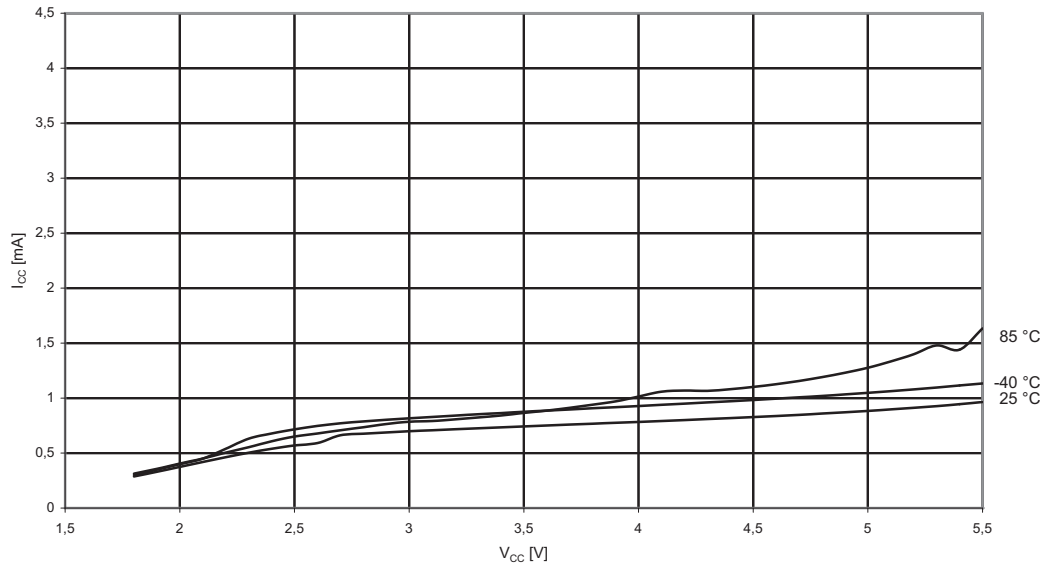


Figure 21-14. Power-down Supply Current vs. V_{CC} (Watchdog Timer Enabled)



21.5 Current Consumption in Reset

Figure 21-15. Reset Supply Current vs. V_{CC} (excluding Current Through the Reset Pull-up and No Clock



21.6 Current Consumption of Peripheral Units

Figure 21-16. ADC Current vs. V_{CC}

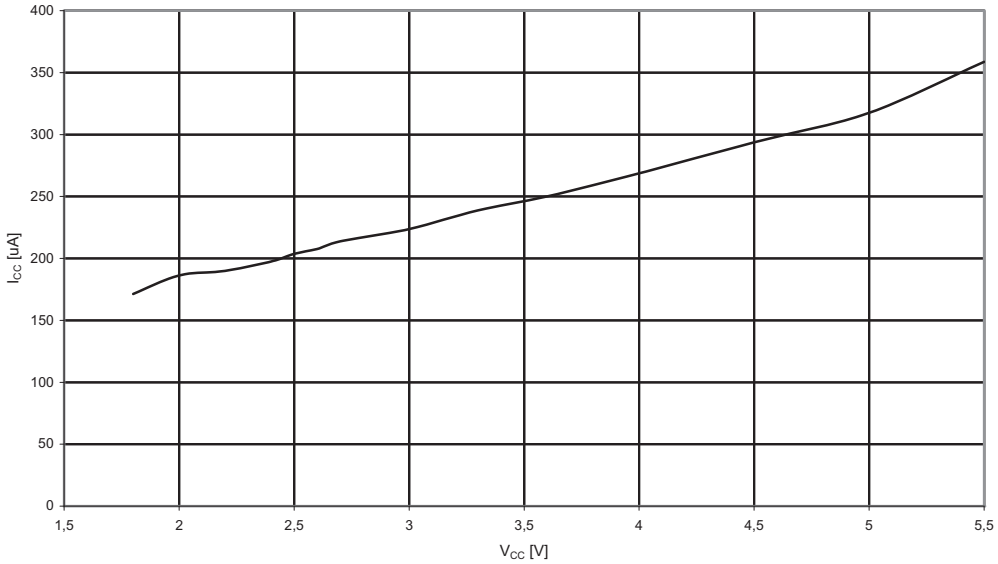


Figure 21-17. Analog Comparator Current vs. V_{CC} (Frequency 1 MHz)

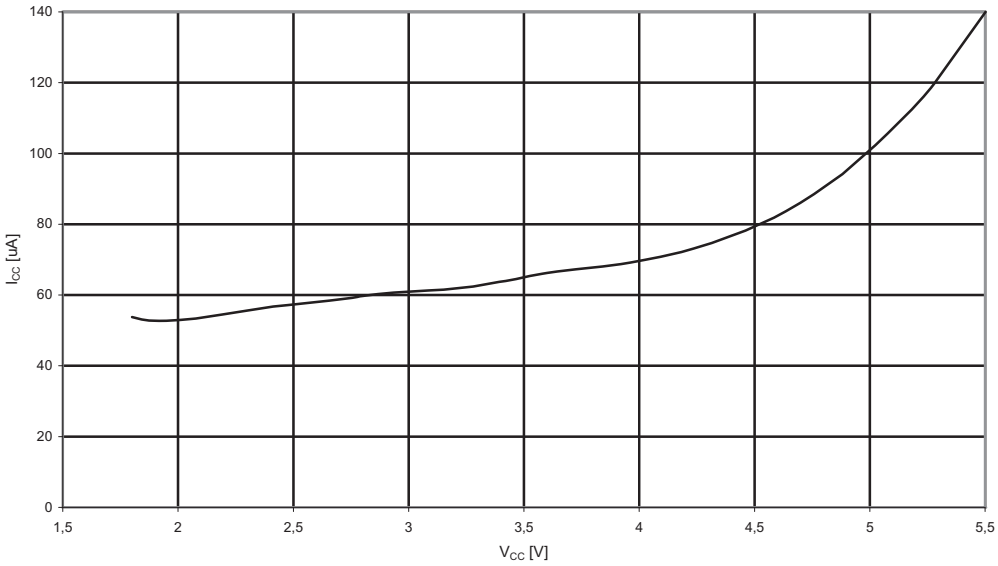


Figure 21-18. Watchdog Timer Current vs. V_{CC}

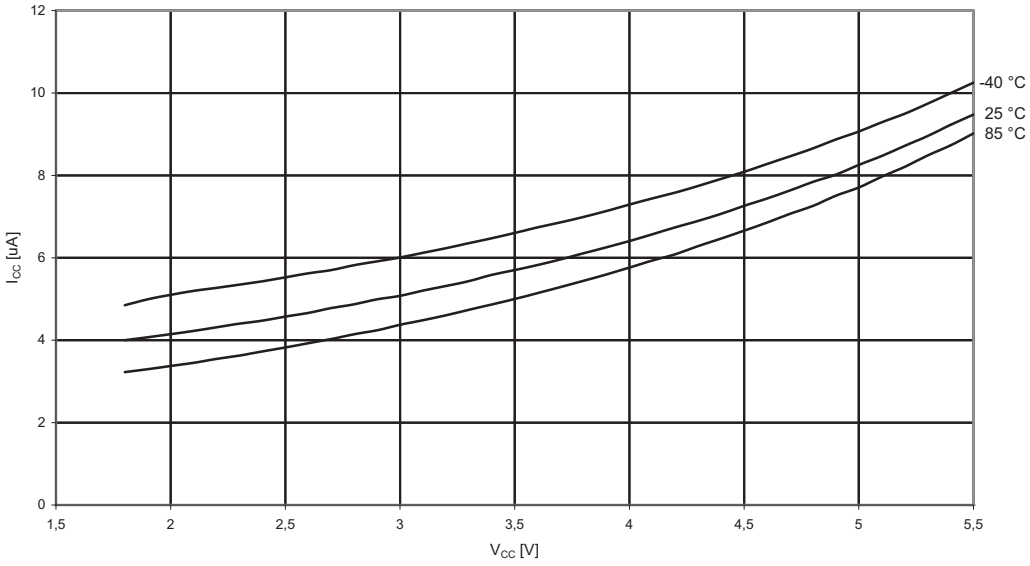
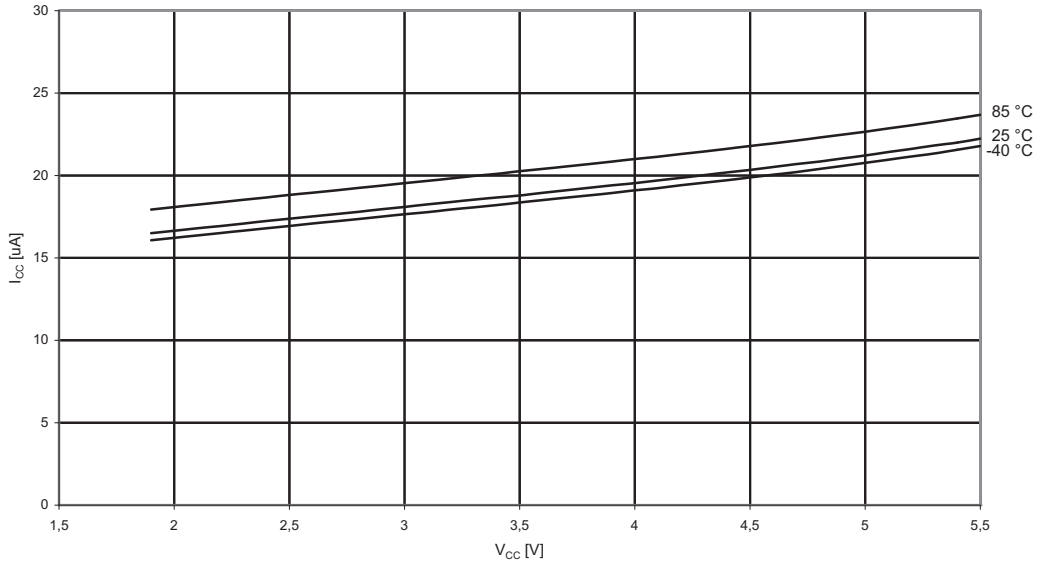


Figure 21-19. Brownout Detector Current vs. V_{CC}



21.7 Pull-up Resistors

Figure 21-20. I/O pin Pull-up Resistor Current vs. Input Voltage (V_{CC} = 1.8V)

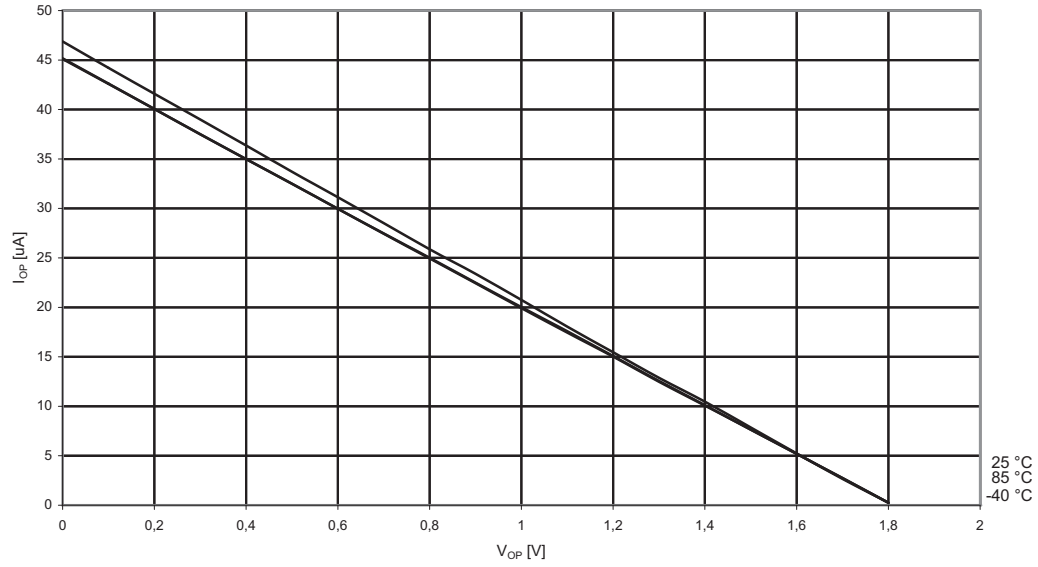


Figure 21-21. I/O Pin Pull-up Resistor Current vs. input Voltage (V_{CC} = 2.7V)

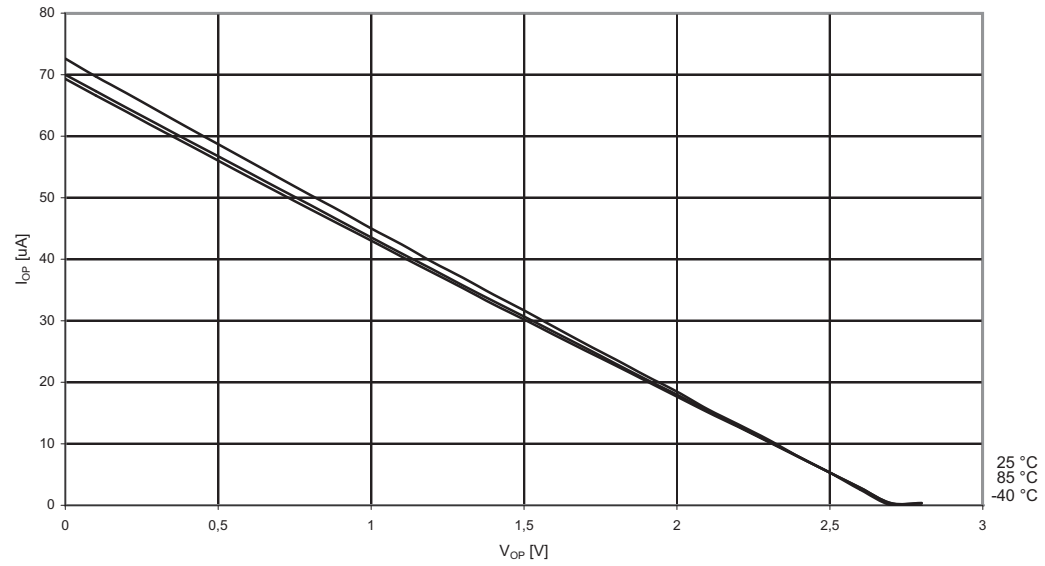


Figure 21-22. I/O pin Pull-up Resistor Current vs. Input Voltage (V_{CC} = 5V)

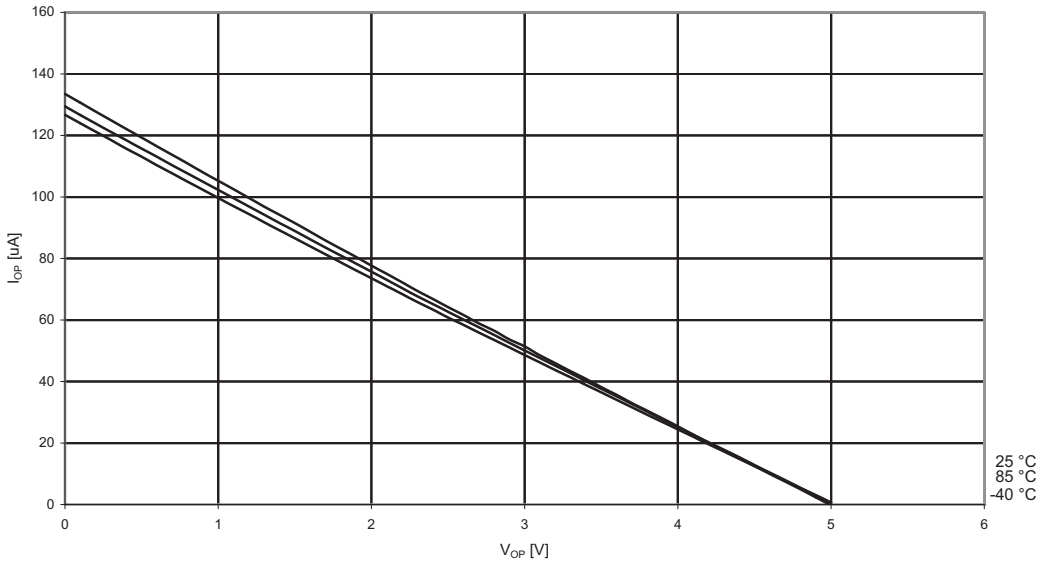


Figure 21-23. Reset Pull-up Resistor Current vs. Reset Pin Voltage (V_{CC} = 1.8V)

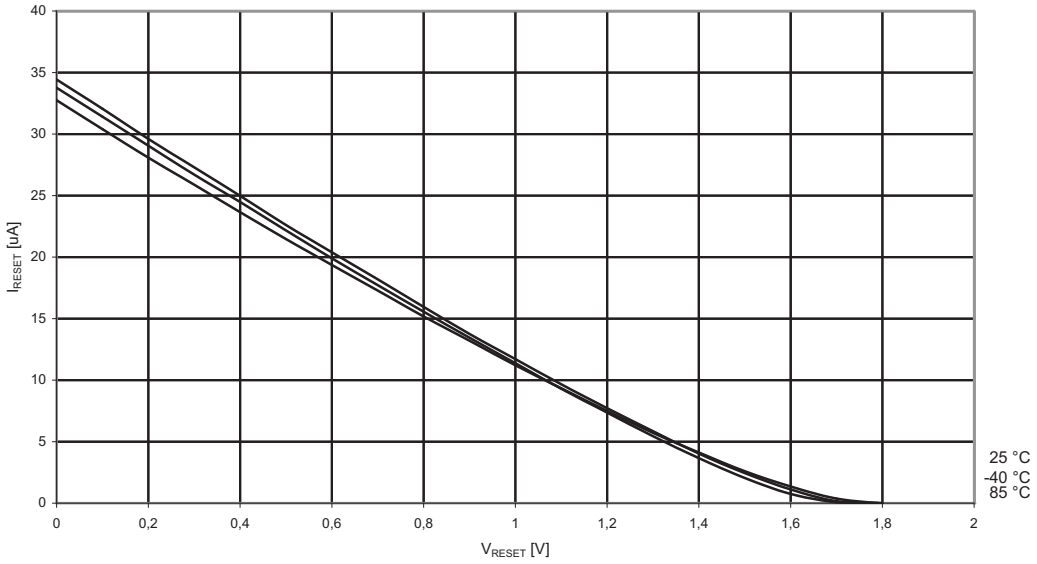


Figure 21-24. Reset Pull-up Resistor Current vs. Reset Pin Voltage (V_{CC} = 2.7V)

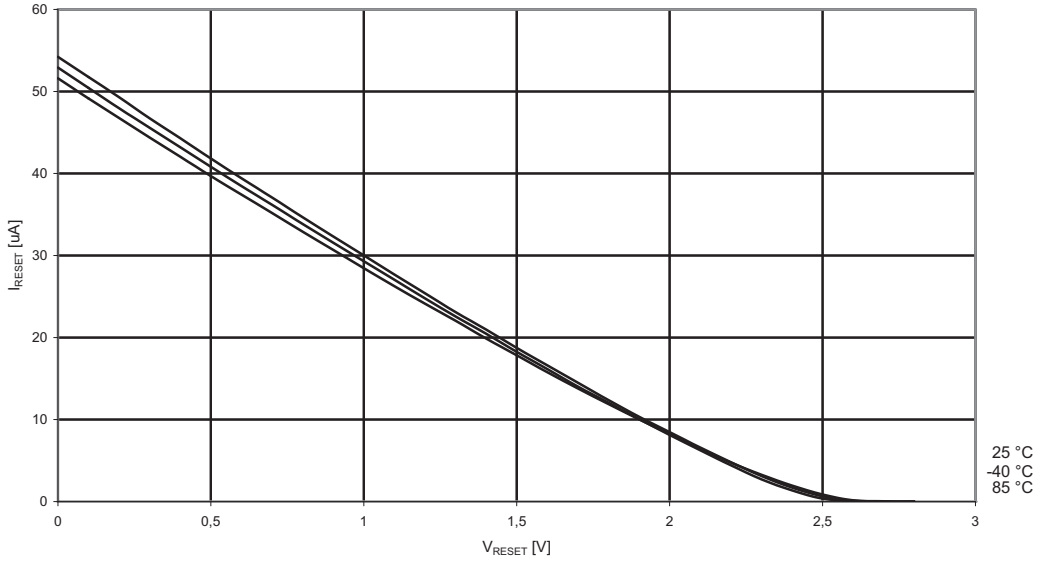
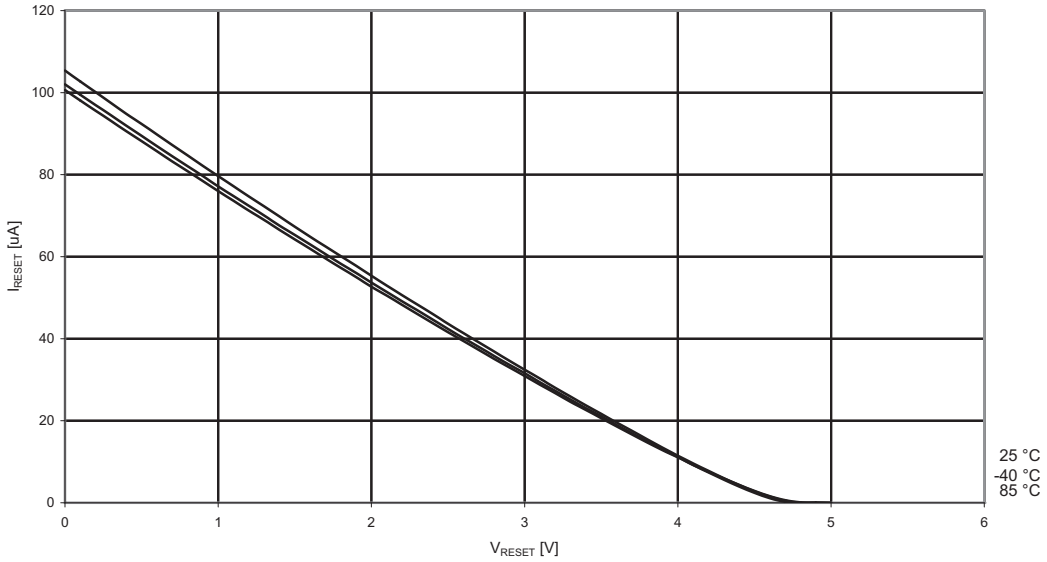


Figure 21-25. Reset Pull-up Resistor Current vs. Reset Pin Voltage (V_{CC} = 5V)



21.8 Output Driver Strength

Figure 21-26. V_{OL}: Output Voltage vs. Sink Current (I/O Pin, V_{CC} = 1.8V)

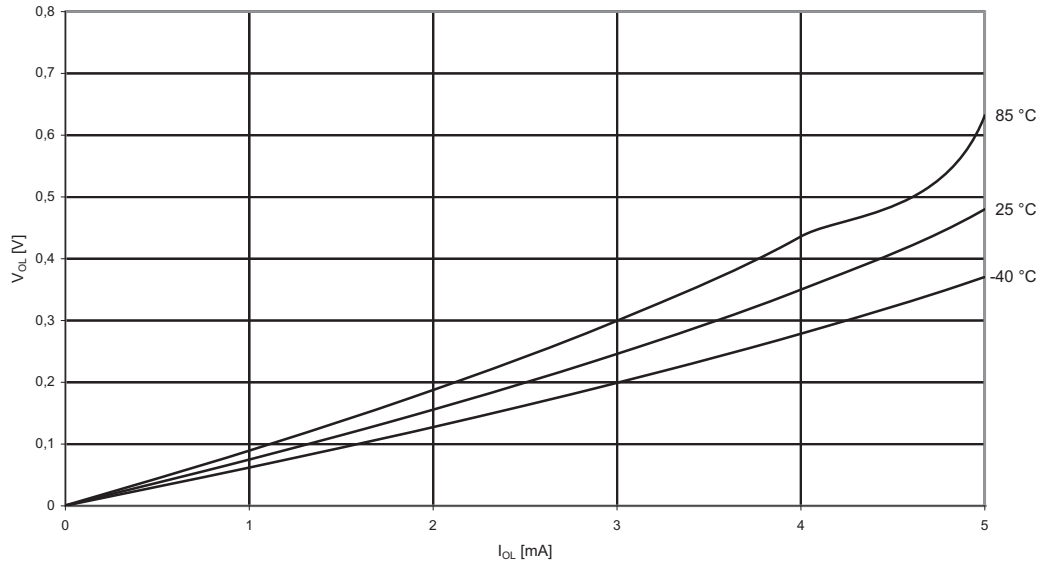


Figure 21-27. V_{OL}: Output Voltage vs. Sink Current (I/O Pin, V_{CC} = 3V)

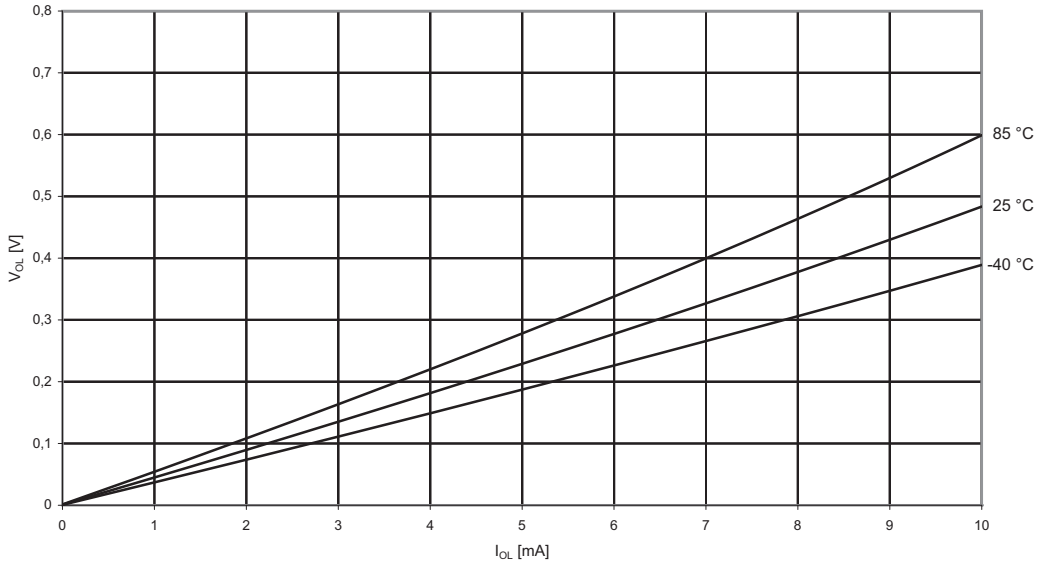


Figure 21-28. V_{OL}: Output Voltage vs. Sink Current (I/O Pin, V_{CC} = 5V)

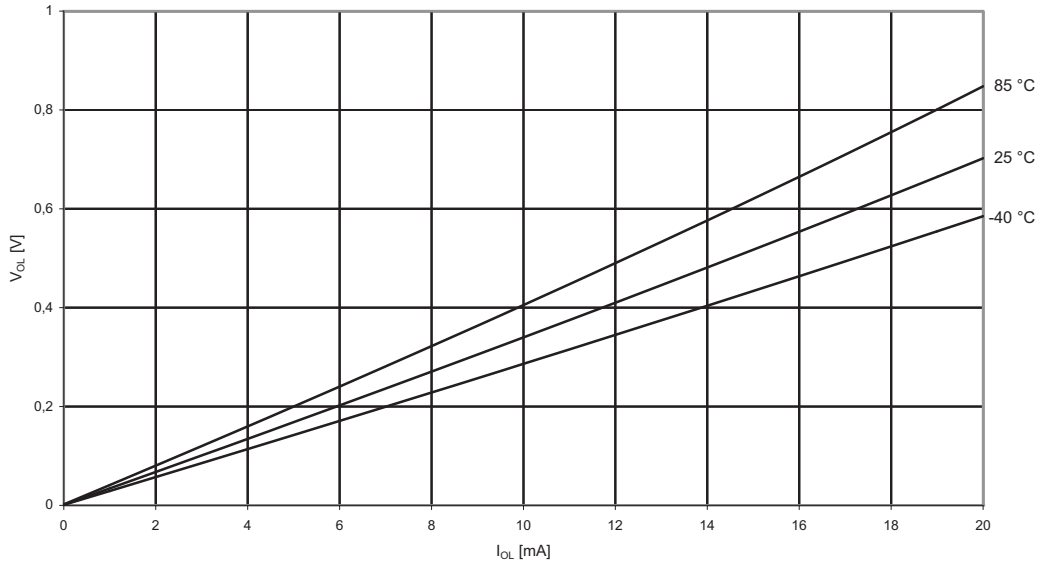


Figure 21-29. V_{OH}: Output Voltage vs. Source Current (I/O Pin, V_{CC} = 1.8V)

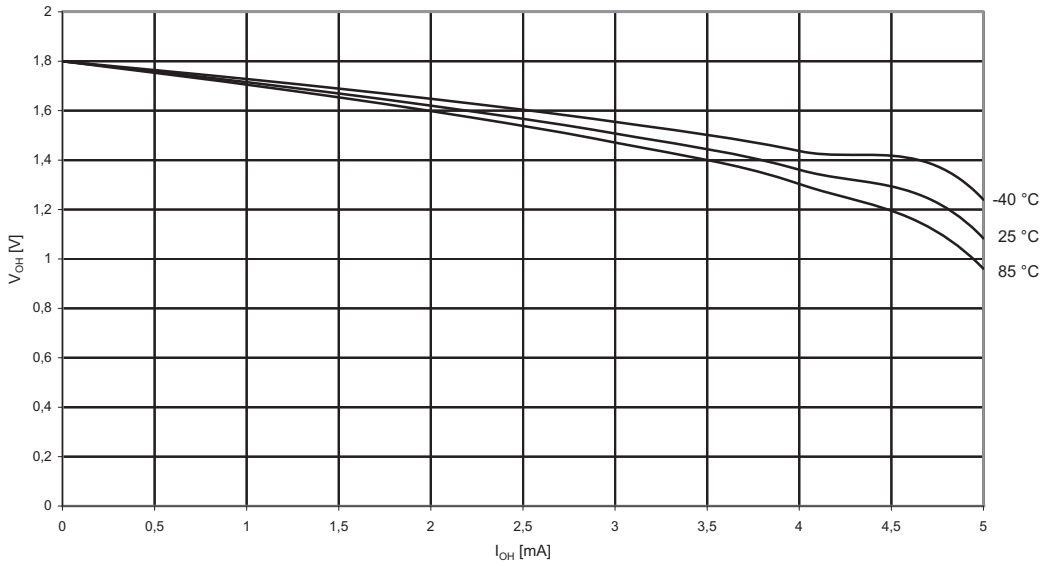


Figure 21-30. V_{OH}: Output Voltage vs. Source Current (I/O Pin, V_{CC} = 3V)

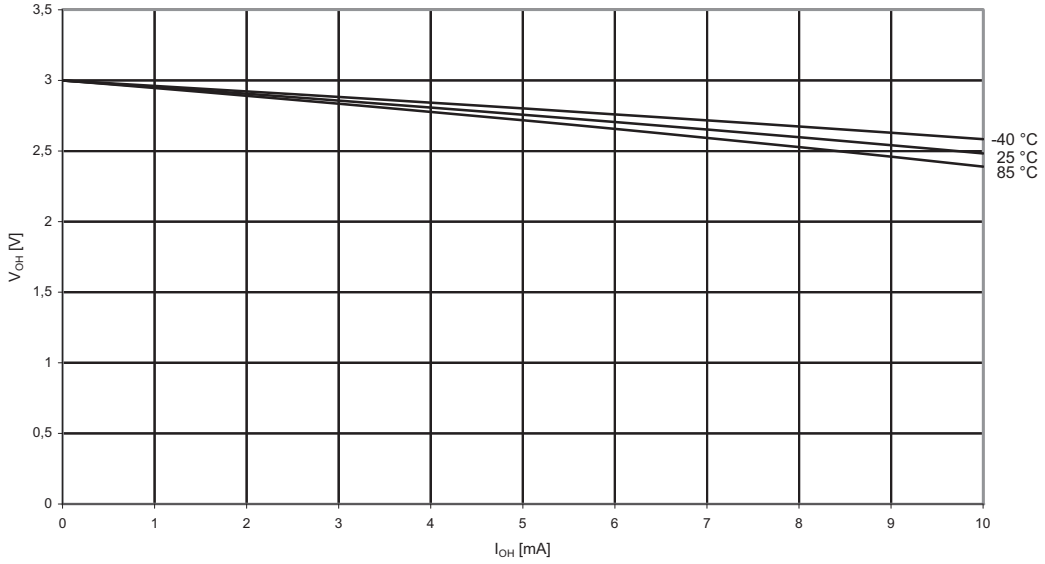


Figure 21-31. V_{OH}: Output Voltage vs. Source Current (I/O Pin, V_{CC} = 5V)

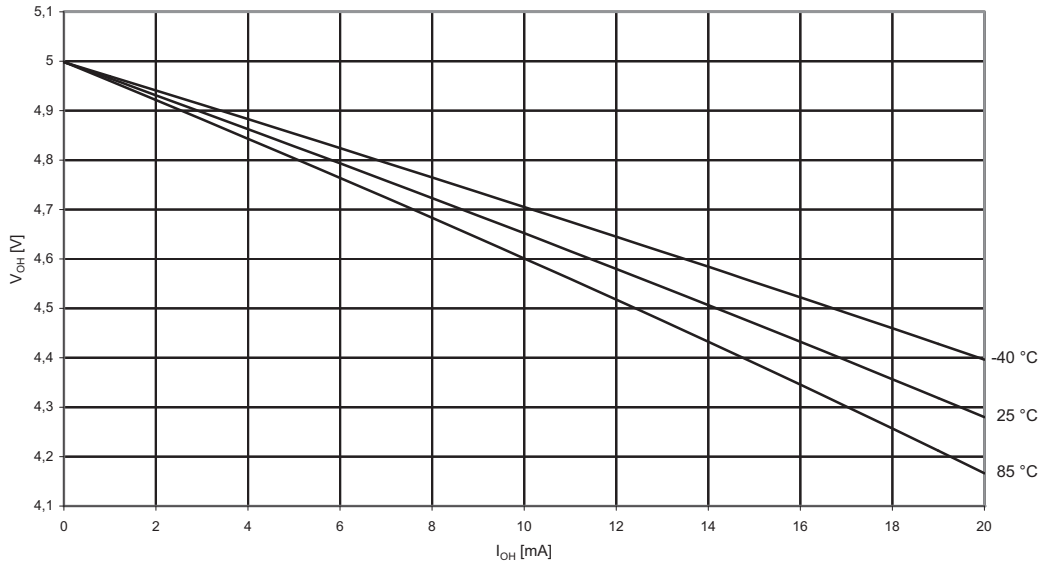


Figure 21-32. V_{OL}: Output Voltage vs. Sink Current (Reset Pin as I/O, V_{CC} = 1.8V)

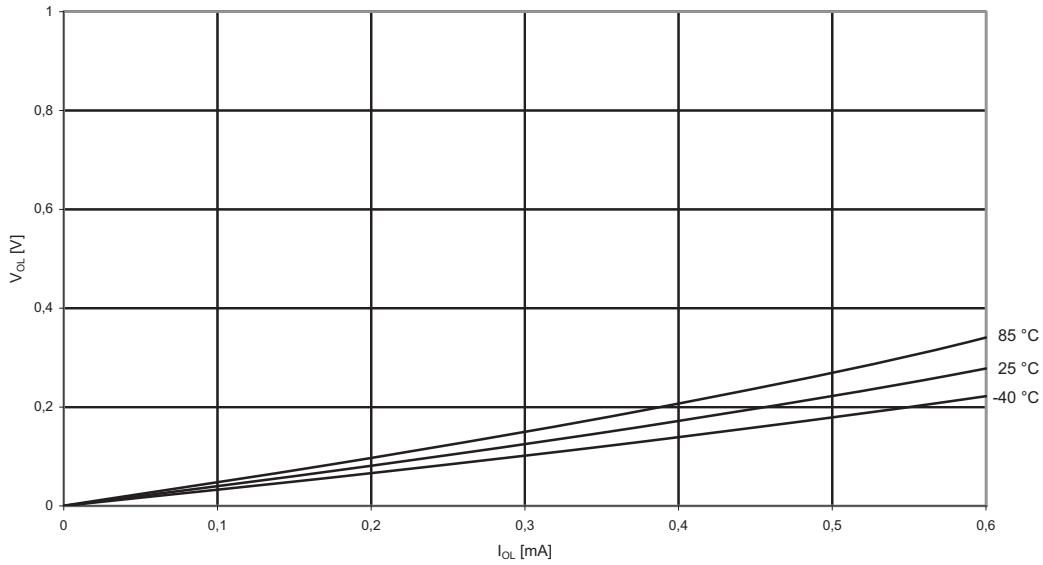


Figure 21-33. V_{OL}: Output Voltage vs. Sink Current (Reset Pin as I/O, V_{CC} = 3V)

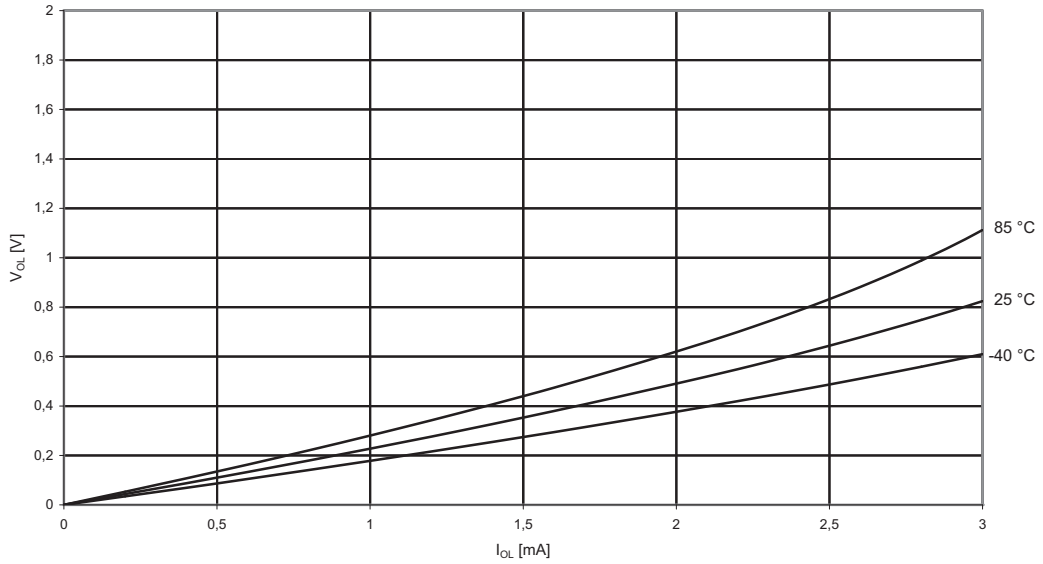


Figure 21-34. V_{OL}: Output Voltage vs. Sink Current (Reset Pin as I/O, V_{CC} = 5V)

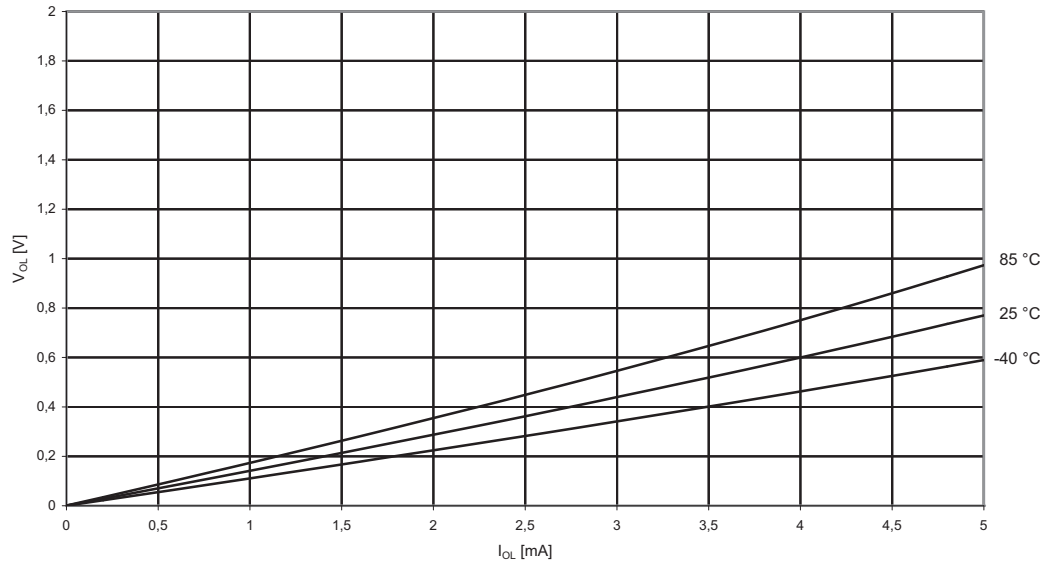


Figure 21-35. V_{OH}: Output Voltage vs. Source Current (Reset Pin as I/O, V_{CC} = 1.8V

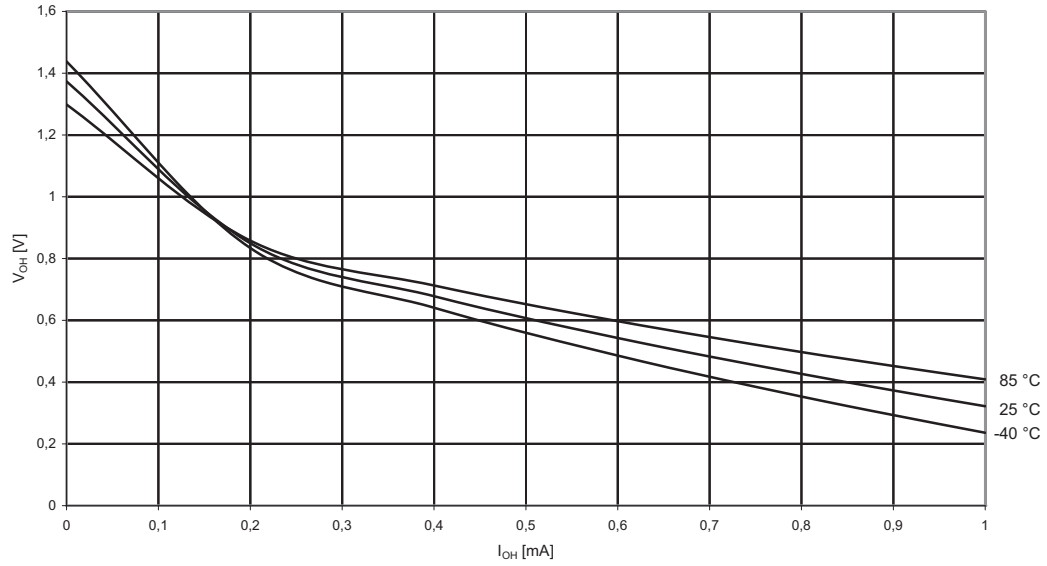


Figure 21-36. V_{OH}: Output Voltage vs. Source Current (Reset Pin as I/O, V_{CC} = 3V

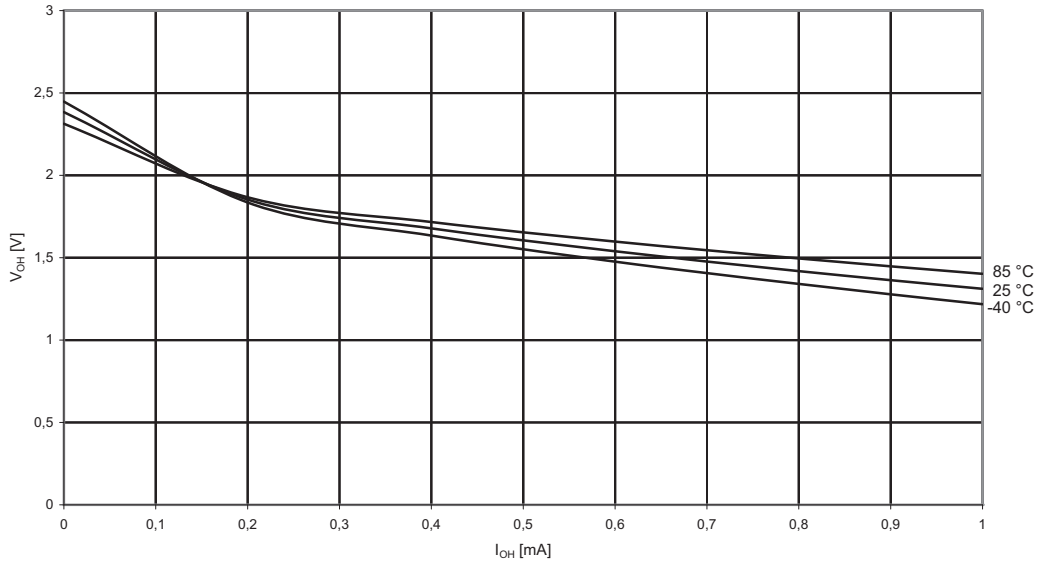
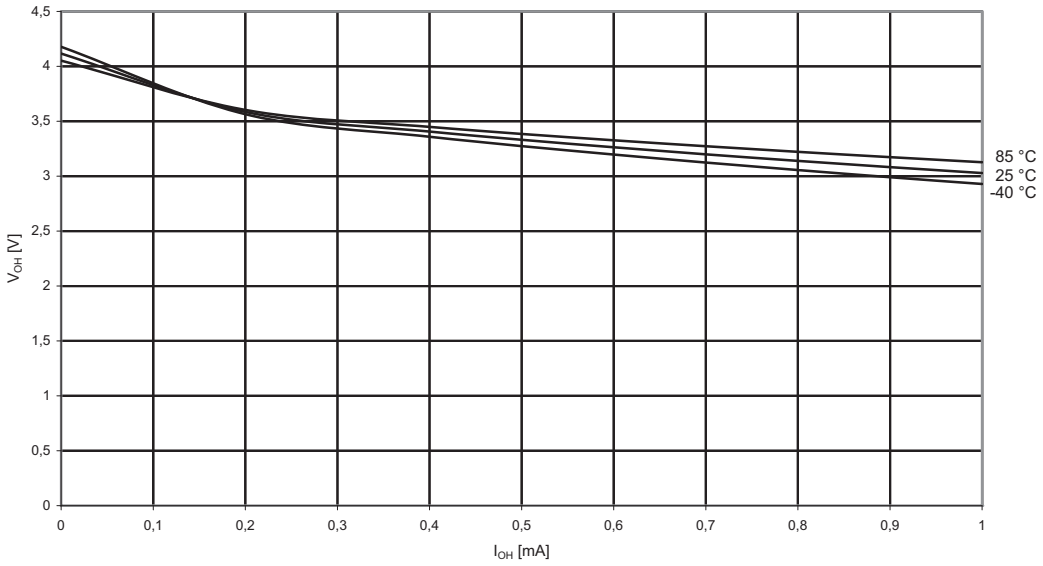


Figure 21-37. V_{OH}: Output Voltage vs. Source Current (Reset Pin as I/O, V_{CC} = 5V



21.9 Input Thresholds and Hysteresis

Figure 21-38. V_{IH}: Input Threshold Voltage vs. V_{CC} (I/O Pin, Read as '1')

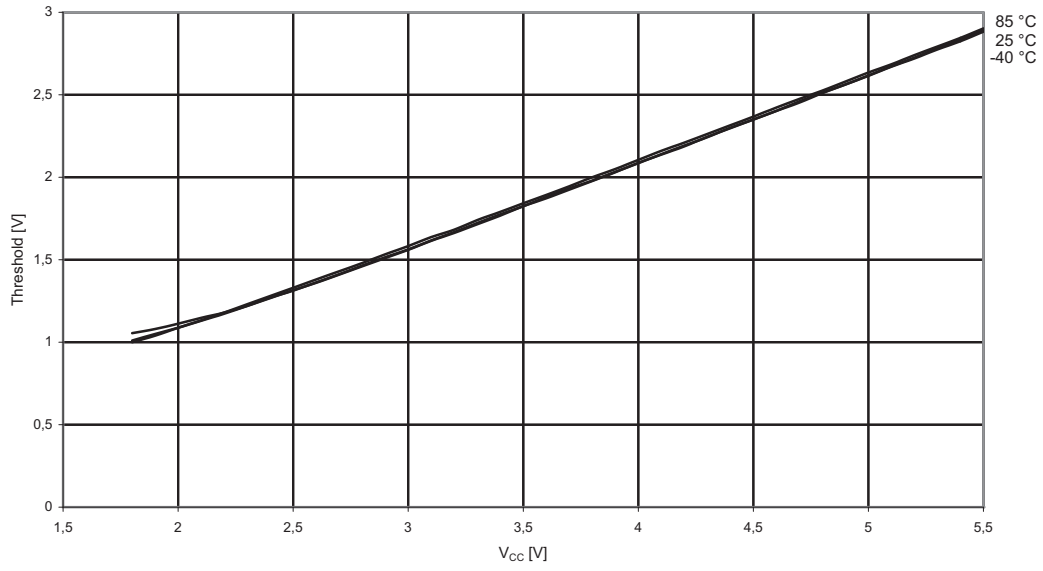


Figure 21-39. V_{IL}: Input Threshold Voltage vs. V_{CC} (I/O Pin, Read as '0')

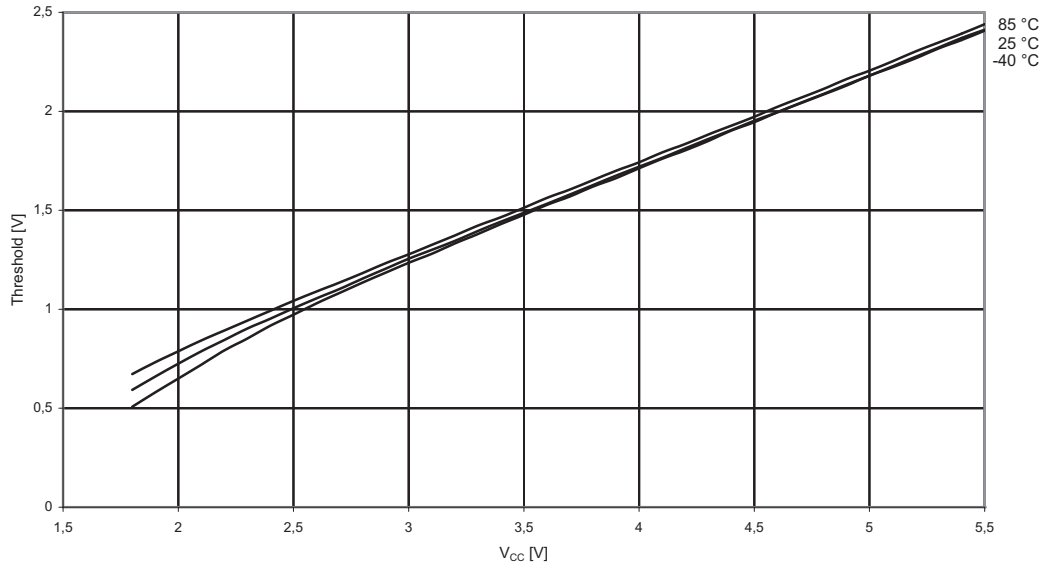


Figure 21-40. V_{IH}-V_{IL}: Input Hysteresis vs. V_{CC} (I/O Pin)

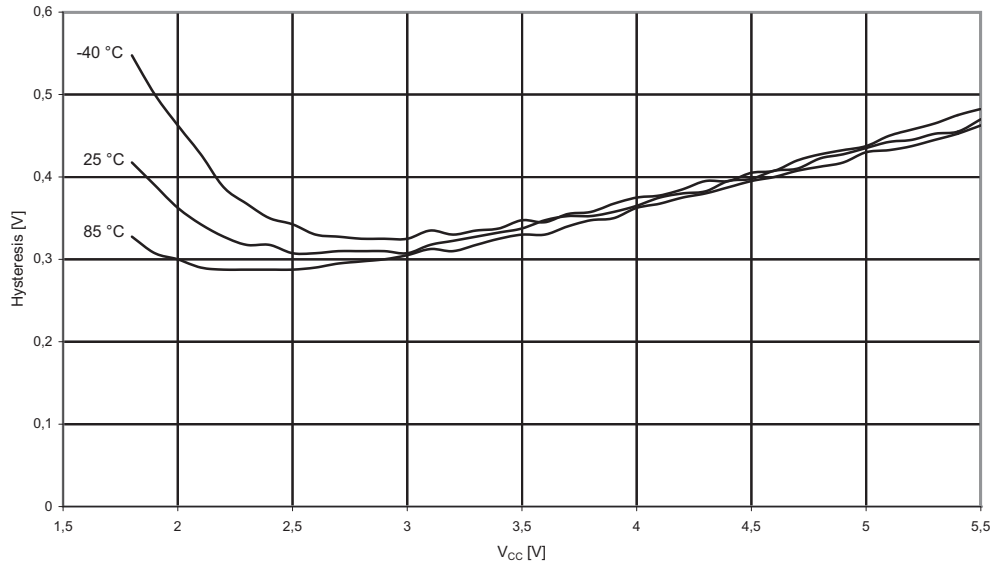


Figure 21-41. V_{IH}: Input Threshold Voltage vs. V_{CC} (Reset Pin as I/O, Read as '1')

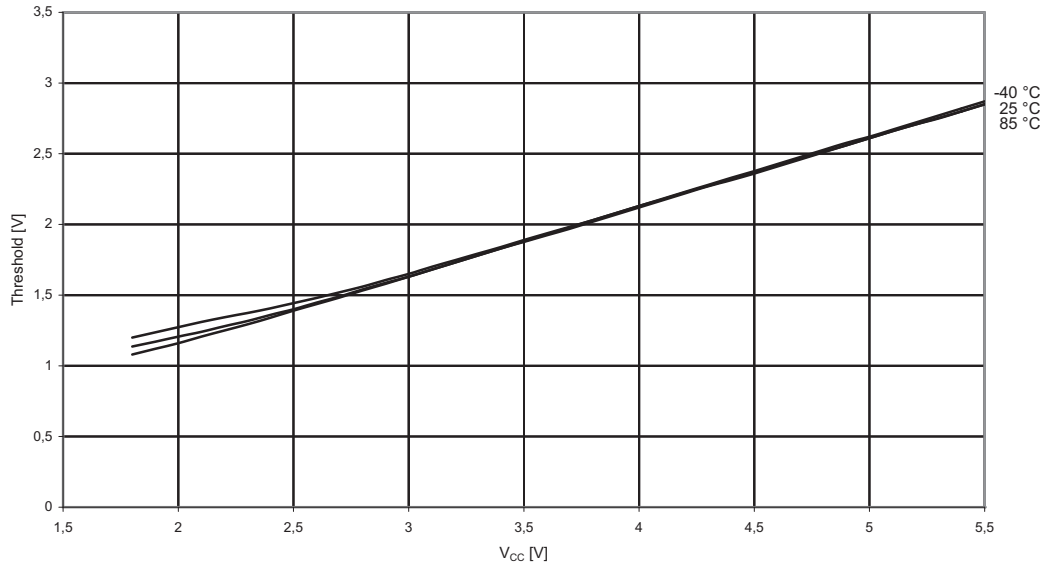


Figure 21-42. V_{IL}: Input Threshold Voltage vs. V_{CC} (Reset Pin as I/O, Read as '0')

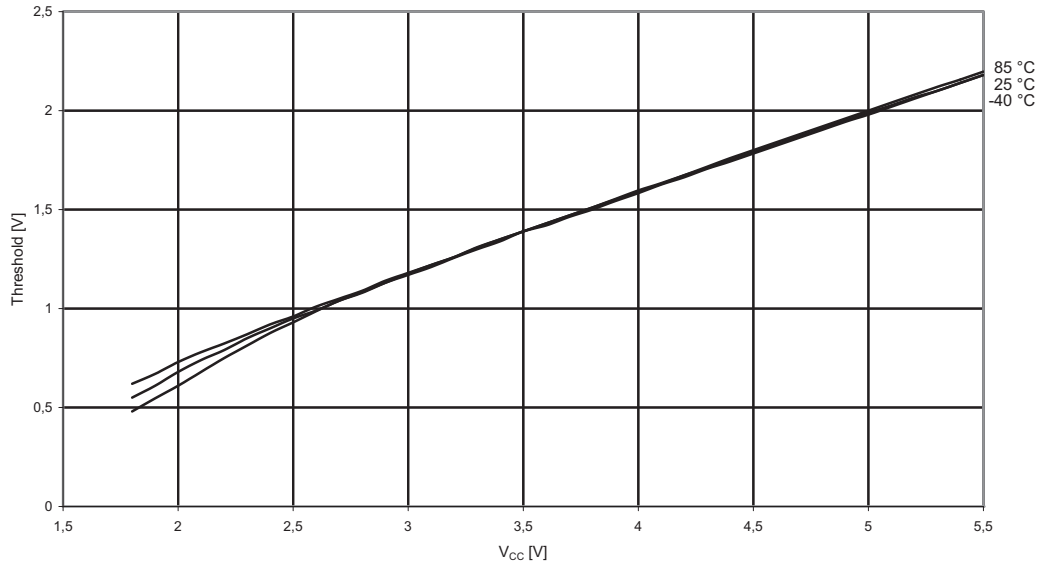
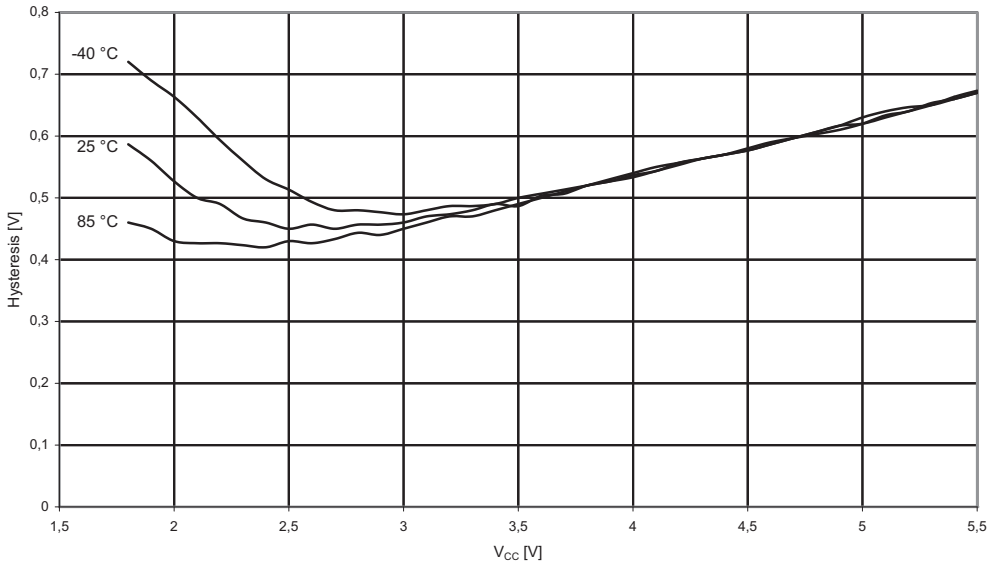


Figure 21-43. V_{IH}-V_{IL}: Input Hysteresis vs. V_{CC} (Reset Pin as I/O)



21.10 BOD, Bandgap and Reset

Figure 21-44. BOD Threshold vs Temperature (BODLEVEL is 4.3V)

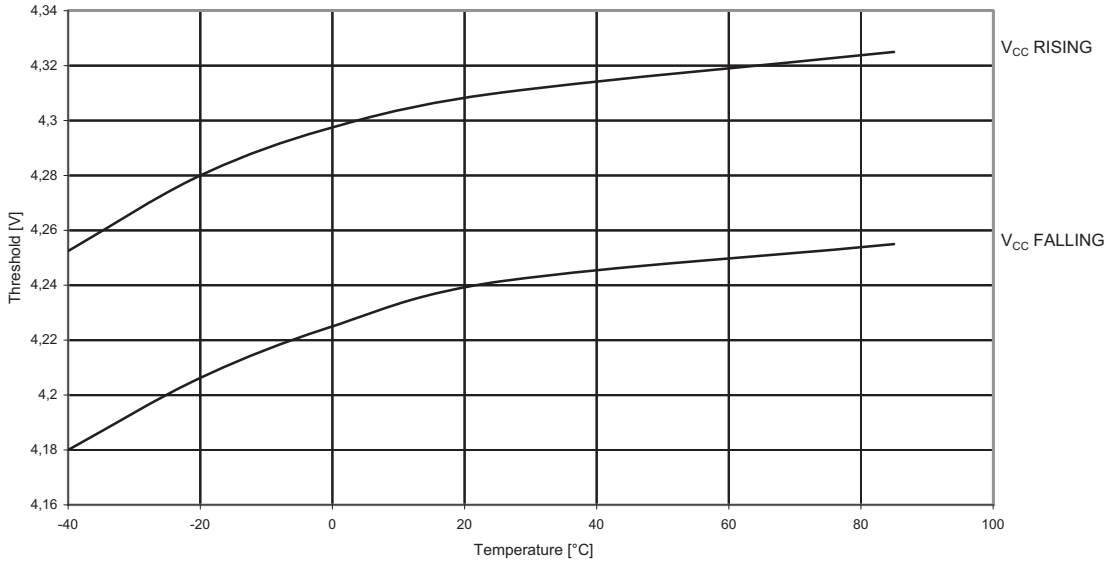


Figure 21-45. BOD Threshold vs Temperature (BODLEVEL is 2.7V)

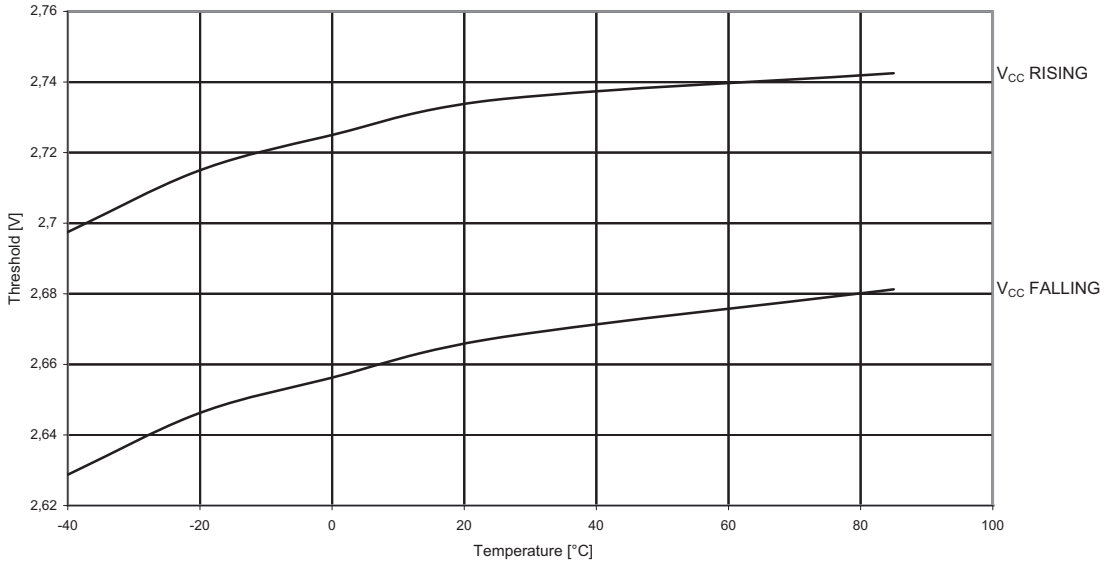


Figure 21-46. BOD Threshold vs Temperature (BODLEVEL is 1.8V)

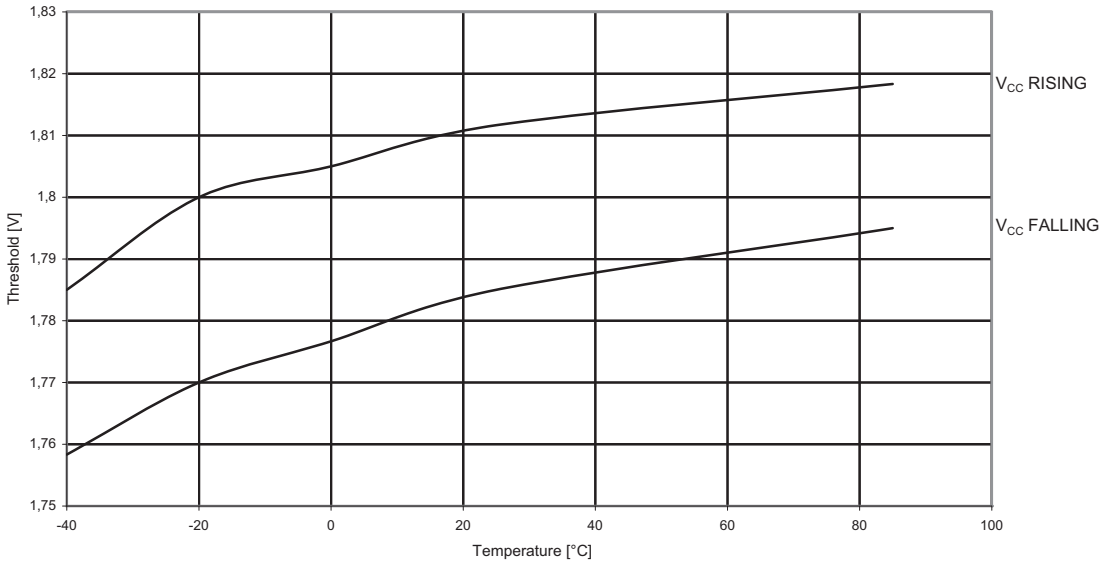


Figure 21-47. Bandgap Voltage vs. Supply Voltage

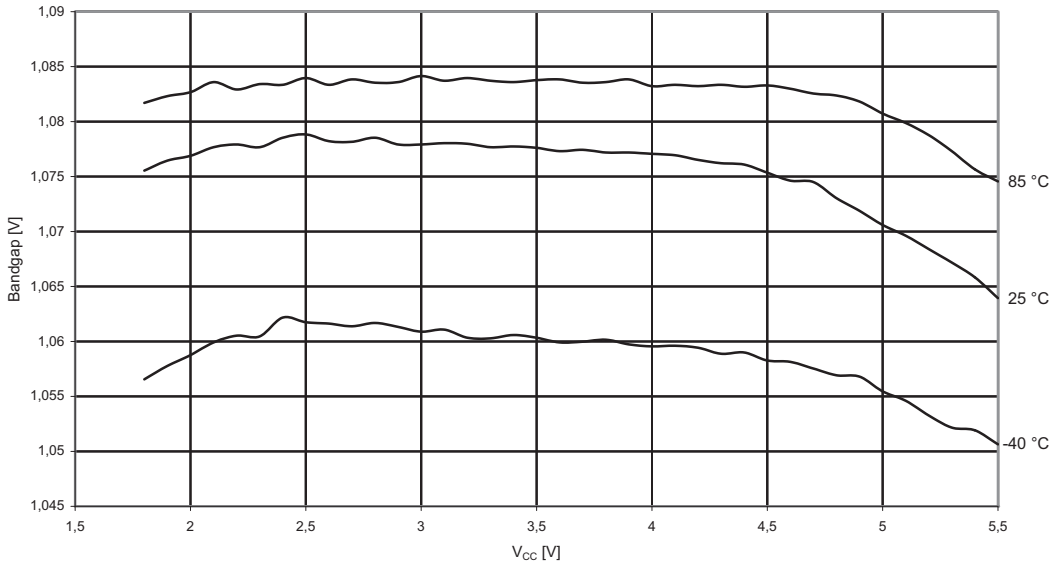


Figure 21-48. V_{IH}: Input Threshold Voltage vs. V_{CC} (Reset Pin, Read as '1')

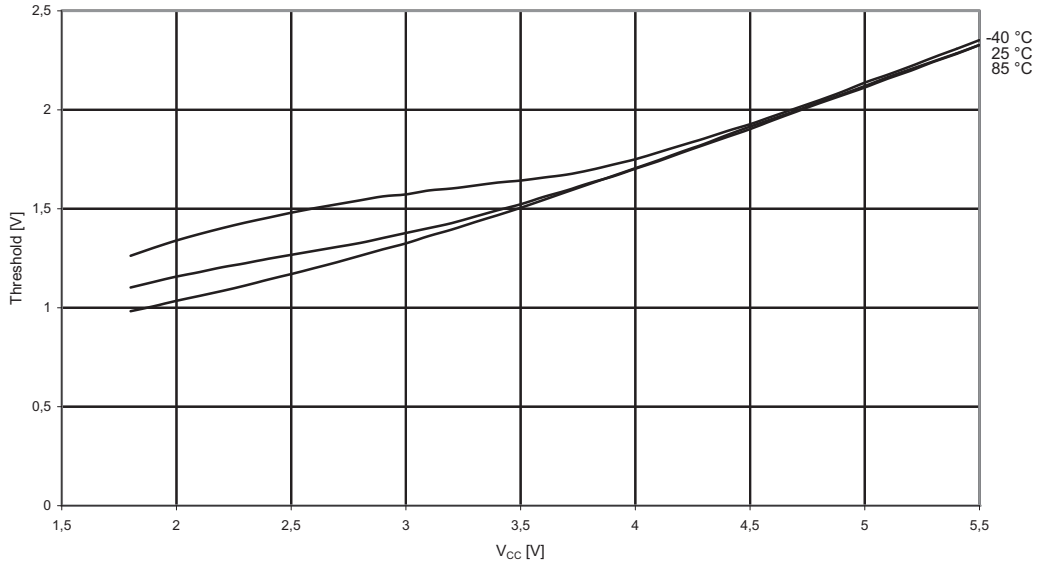


Figure 21-49. V_{IL}: Input Threshold Voltage vs. V_{CC} (Reset Pin, Read as '0')

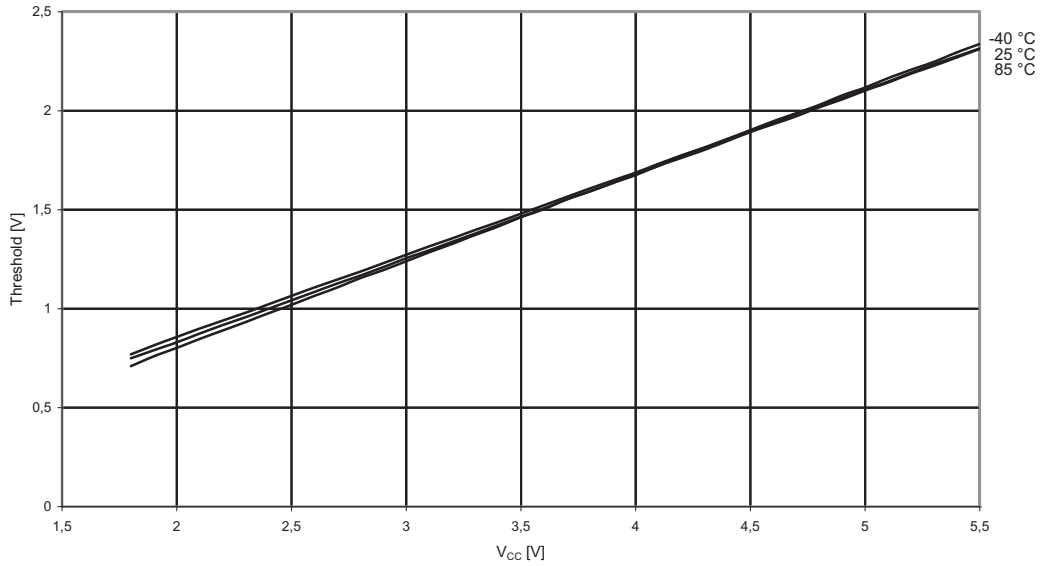


Figure 21-50. V_{IH}-V_{IL}: Input Hysteresis vs. V_{CC} (Reset Pin)

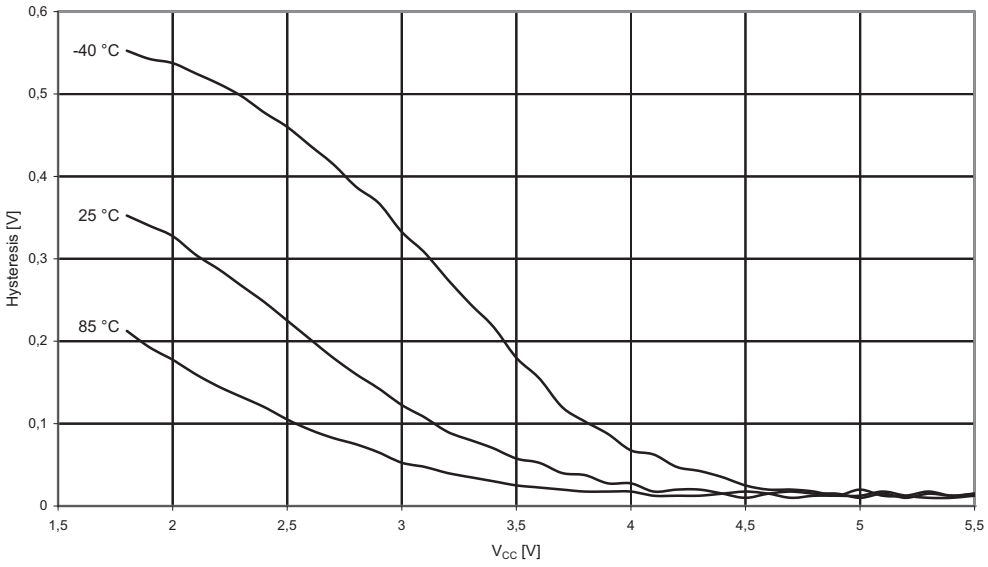
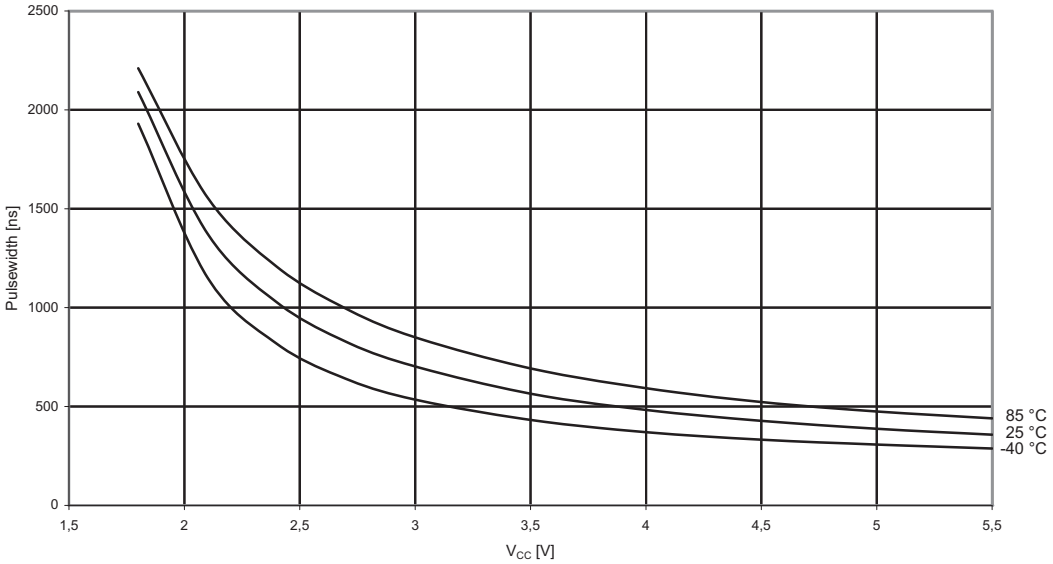
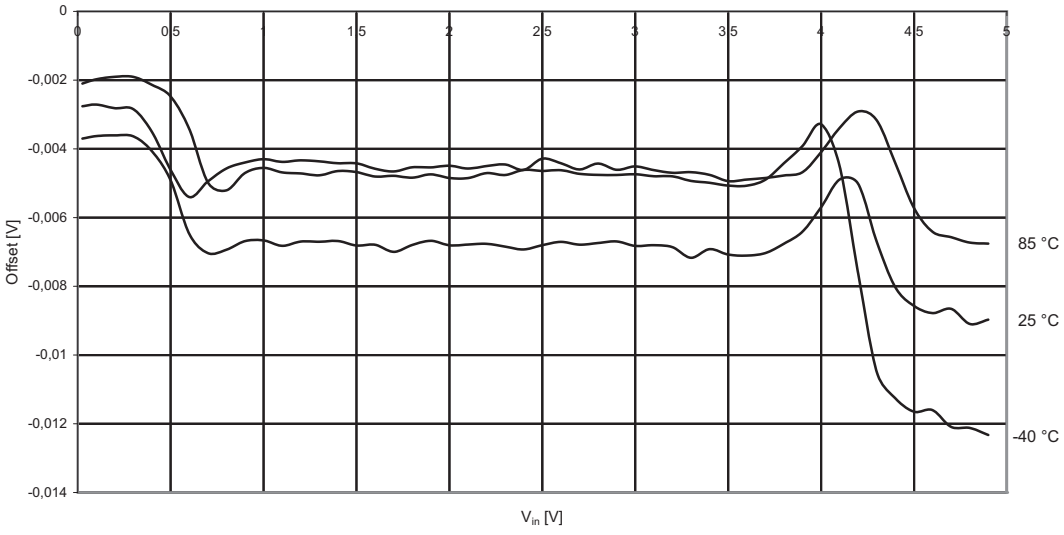


Figure 21-51. Minimum Reset Pulse Width vs. V_{CC}



21.11 Analog Comparator Offset

Figure 21-52. Analog Comparator Offset vs. V_{in} (V_{CC} = 5V)



21.12 Internal Oscillator Speed

Figure 21-53. Watchdog Oscillator Frequency vs. V_{CC}

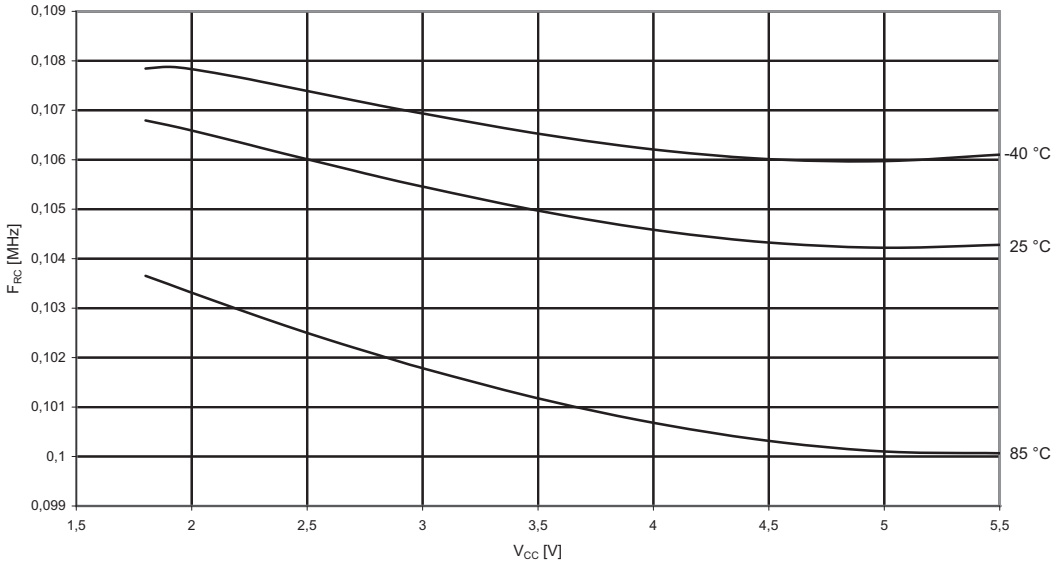


Figure 21-54. Watchdog Oscillator Frequency vs. Temperature

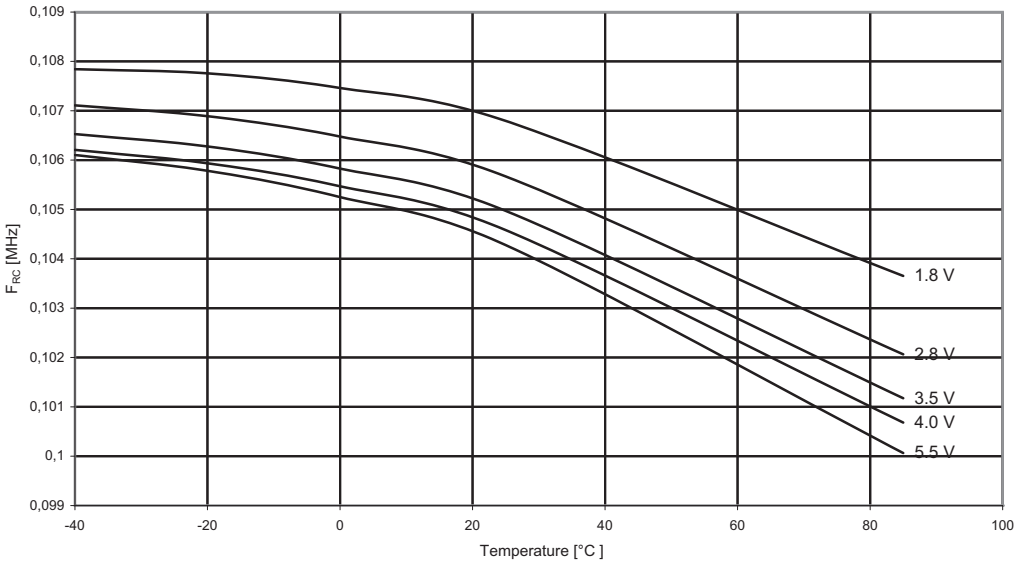


Figure 21-55. Calibrated Oscillator Frequency vs. V_{CC}

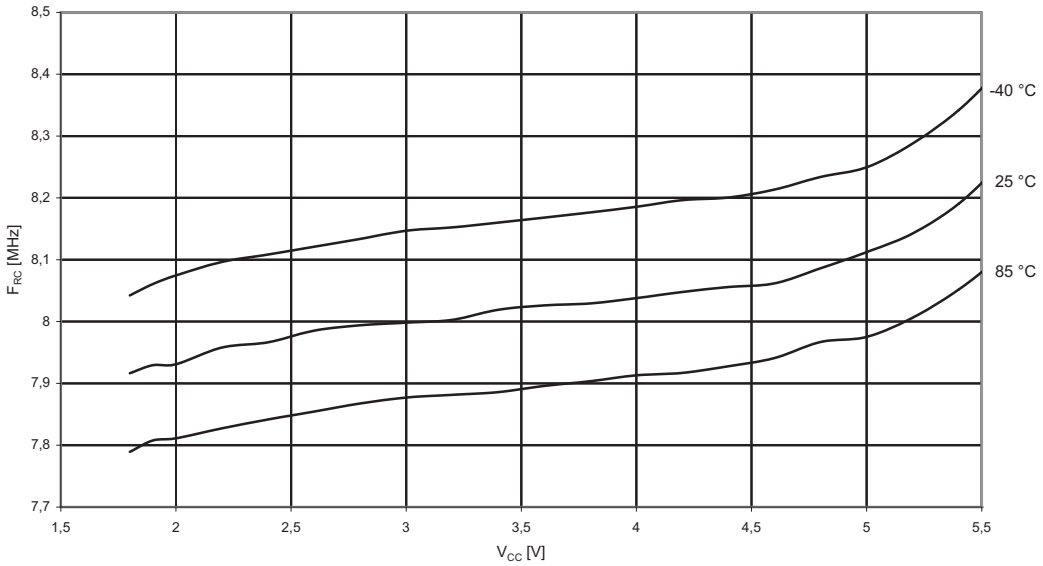


Figure 21-56. Calibrated Oscillator Frequency vs. Temperature

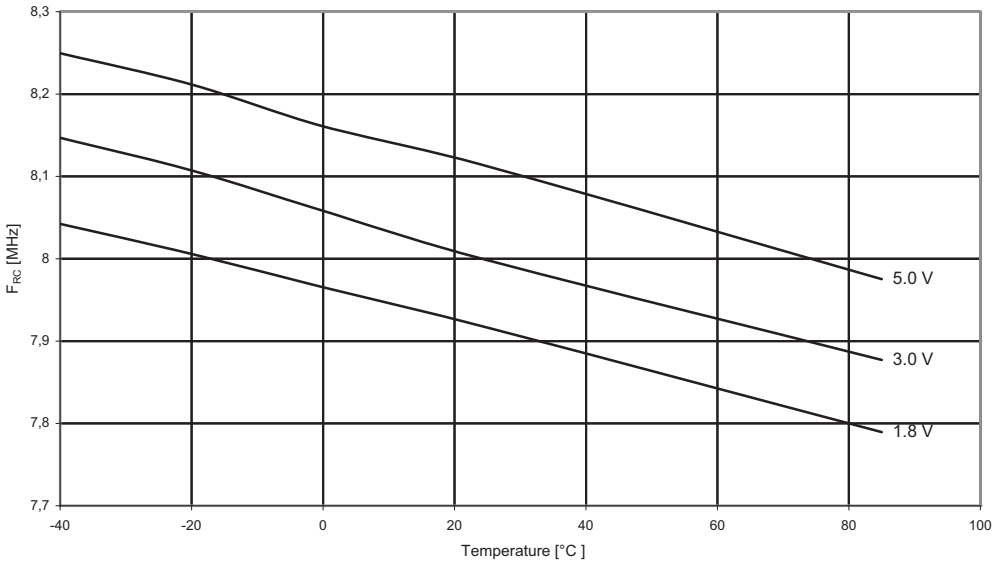
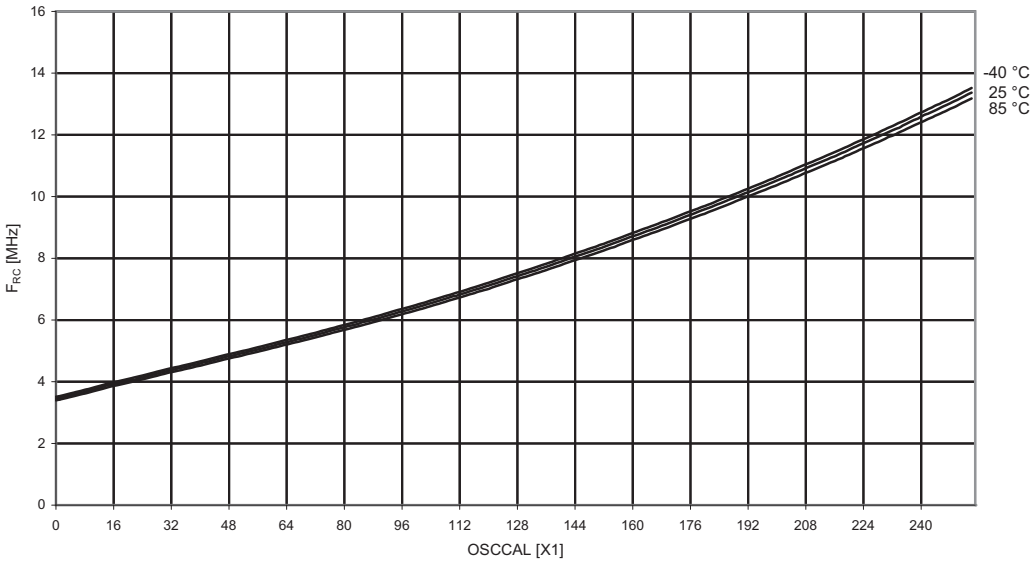


Figure 21-57. Calibrated Oscillator Frequency vs, OSCCAL Value



22. Register Summary

Address	Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Page
0x3F	SREG	I	T	H	S	V	N	Z	C	Page 12
0x3E	SPH	Stack Pointer High Byte								Page 12
0x3D	SPL	Stack Pointer Low Byte								Page 12
0x3C	CCP	CPU Change Protection Register								Page 11
0x3B	RSTFLR	–	–	–	–	WDRF	BORF	EXTRF	PORF	Page 35
0x3A	MCUCR	ISC01	ISC00	–	BODS	SM2	SM1	SM0	SE	Pages 26, 38
0x39	OSCCAL	Oscillator Calibration Register								Page 23
0x38	Reserved	–								
0x37	CLKMSR	–	–	–	–	–	–	CLKMS1	CLKMS0	Page 21
0x36	CLKPSR	–	–	–	–	CLKPS3	CLKPS2	CLKPS1	CLKPS0	Page 22
0x35	PRR	–	–	–	PRTWI	PRSPI	PRTIM1	PRTIM0	PRADC	Page 27
0x34	QTCSR	QTouch Control and Status Register								Page 5
0x33	NVMCMD	–	–	NVM Command Register						Page 151
0x32	NVMCSR	NVMBSY	–	–	–	–	–	–	–	Page 151
0x31	WDTCSR	WDIF	WDIE	WDP3	–	WDE	WDP2	WDP1	WDP0	Page 33
0x30	SPCR	SPIE	SPE	DORD	MSTR	CPOL	CPHA	SPR1	SPR0	Page 120
0x2F	SPSR	SPIF	WCOL	–	–	–	–	–	SPI2X	Page 121
0x2E	SPDR	SPI Data Register								Page 122
0x2D	TWSCRA	TWSHE	–	TWDIE	TWASIE	TWEN	TWSIE	TWPME	TWSME	Page 130
0x2C	TWSCRB	–	–	–	–	–	TWAA	TWCMD[1.0]		Page 130
0x2B	TWSSRA	TWDIF	TWASIF	TWCH	TWRA	TWC	TWBE	TWDIR	TWAS	Page 131
0x2A	TWSA	TWI Slave Address Register								Page 133
0x29	TWSAM	TWI Slave Address Mask Register								Page 133
0x28	TWSD	TWI Slave Data Register								Page 133
0x27	TCNT1H	Timer/Counter1 – Counter Register High Byte								Page 89
0x26	TIMSK	ICIE1	–	OCIE1B	OCIE1A	TOIE1	OCIE0B	OCIE0A	TOIE0	Pages 75, 90
0x25	TIFR	ICF1	–	OCF1B	OCF1A	TOV1	OCF0B	OCF0A	TOV0	Pages 76, 90
0x24	TCCR1A	TCW1	ICEN1	ICNC1	ICES1	CTC1	CS12	CS11	CS10	Page 88
0x23	TCNT1L	Timer/Counter1 – Counter Register Low Byte								Page 89
0x22	OCR1A	Timer/Counter1 – Compare Register A								Page 89
0x21	OCR1B	Timer/Counter1 – Compare Register B								Page 89
0x20	RAMAR	RAM Address Register								Page 17
0x1F	RAMDR	RAM Data Register								Page 17
0x1E	PUEC	–	–	PUEC5	PUEC4	PUEC3	PUEC2	PUEC1	PUEC0	Page 59
0x1D	PORTC	–	–	PORTC5	PORTC4	PORTC3	PORTC2	PORTC1	PORTC0	Page 59
0x1C	DDRC	–	–	DDRC5	DDRC4	DDRC3	DDRC2	DDRC1	DDRC0	Page 59
0x1B	PINC	–	–	PINC5	PINC4	PINC3	PINC2	PINC1	PINC0	Page 59
0x1A	PCMSK2	–	–	PCINT17	PCINT16	PCINT15	PCINT14	PCINT13	PCINT12	Page 40
0x19	TCCR0A	COM0A1	COM0A0	COM0B1	COM0B0	–	–	WGM01	WGM00	Page 71
0x18	TCCR0B	FOC0A	FOC0B	TSM	PSR	WGM02	CS02	CS01	CS00	Pages 74, 93
0x17	TCNT0	Timer/Counter0 – Counter Register								Page 75
0x16	OCR0A	Timer/Counter0 – Compare Register A								Page 75
0x15	OCR0B	Timer/Counter0 – Compare Register B								Page 75
0x14	ACSRA	ACD	ACBG/ACIRE	ACO	ACI	ACIE	ACIC	ACIS1	ACIS0	Page 95
0x13	ACSRB	HSEL	HLEV	ACLP	–	ACCE	ACME	ACIRS1	ACIRS0	Page 96
0x12	ADCSRA	ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0	Page 111
0x11	ADCSRB	VDEN	VDPD	–	–	ADLAR	ADTS2	ADTS1	ADTS0	Page 112
0x10	ADMUX	–	REFS	REFEN	ADC0EN	MUX3	MUX2	MUX1	MUX0	Page 109
0x0F	ADCH	ADC Conversion Result – High Byte								Page 111
0x0E	ADCL	ADC Conversion Result – Low Byte								Page 111
0x0D	DIDR0	ADC7D	ADC6D	ADC5D	ADC4D	ADC3D	ADC2D	ADC1D	ADC0D	Pages 97, 113
0x0C	GIMSK	–	PCIE2	PCIE1	PCIE0	–	–	–	INT0	Page 39
0x0B	GIFR	–	PCIF2	PCIF1	PCIF0	–	–	–	INTF0	Page 40
0x0A	PCMSK1	–	–	–	–	PCINT11	PCINT10	PCINT9	PCINT8	Page 41
0x09	PCMSK0	PCINT7	PCINT6	PCINT5	PCINT4	PCINT3	PCINT2	PCINT1	PCINT0	Page 41
0x08	PORTCR	ADC11D	ADC10D	ADC9D	ADC8D	–	BBMC	BBMB	BBMA	Pages 58, 113
0x07	PUEB	–	–	–	–	PUEB3	PUEB2	PUEB1	PUEB0	Page 59
0x06	PORTB	–	–	–	–	PORTB3	PORTB2	PORTB1	PORTB0	Page 59
0x05	DDRB	–	–	–	–	DDRB3	DDRB2	DDRB1	DDRB0	Page 59
0x04	PINB	–	–	–	–	PINB3	PINB2	PINB1	PINB0	Page 59
0x03	PUEA	PUEA7	PUEA6	PUEA5	PUEA4	PUEA3	PUEA2	PUEA1	PUEA0	Page 58
0x02	PORTA	PORTA7	PORTA6	PORTA5	PORTA4	PORTA3	PORTA2	PORTA1	PORTA0	Page 58
0x01	DDRA	DDRA7	DDRA6	DDRA5	DDRA4	DDRA3	DDRA2	DDRA1	DDRA0	Page 58
0x00	PINA	PINA7	PINA6	PINA5	PINA4	PINA3	PINA2	PINA1	PINA0	Page 59

Note: 1. For compatibility with future devices, reserved bits should be written to zero if accessed. Reserved I/O memory addresses

should never be written.

2. I/O Registers within the address range 0x00 - 0x1F are directly bit-accessible using the SBI and CBI instructions. In these registers, the value of single bits can be checked by using the SBIS and SBIC instructions.
3. Some of the Status Flags are cleared by writing a logical one to them. Note that, unlike most other AVRs, the CBI and SBI instructions will only operation the specified bit, and can therefore be used on registers containing such Status Flags. The CBI and SBI instructions work with registers 0x00 to 0x1F only.

23. Instruction Set Summary

Mnemonics	Operands	Description	Operation	Flags	#Clocks
ARITHMETIC AND LOGIC INSTRUCTIONS					
ADD	Rd, Rr	Add without Carry	Rd ← Rd + Rr	Z,C,N,V,S,H	1
ADC	Rd, Rr	Add with Carry	Rd ← Rd + Rr + C	Z,C,N,V,S,H	1
SUB	Rd, Rr	Subtract without Carry	Rd ← Rd - Rr	Z,C,N,V,S,H	1
SUBI	Rd, K	Subtract Immediate	Rd ← Rd - K	Z,C,N,V,S,H	1
SBC	Rd, Rr	Subtract with Carry	Rd ← Rd - Rr - C	Z,C,N,V,S,H	1
SBCI	Rd, K	Subtract Immediate with Carry	Rd ← Rd - K - C	Z,C,N,V,S,H	1
AND	Rd, Rr	Logical AND	Rd ← Rd • Rr	Z,N,V,S	1
ANDI	Rd, K	Logical AND with Immediate	Rd ← Rd • K	Z,N,V,S	1
OR	Rd, Rr	Logical OR	Rd ← Rd v Rr	Z,N,V,S	1
ORI	Rd, K	Logical OR with Immediate	Rd ← Rd v K	Z,N,V,S	1
EOR	Rd, Rr	Exclusive OR	Rd ← Rd ⊕ Rr	Z,N,V,S	1
COM	Rd	One's Complement	Rd ← $FF – Rd	Z,C,N,V,S	1
NEG	Rd	Two's Complement	Rd ← $00 – Rd	Z,C,N,V,S,H	1
SBR	Rd,K	Set Bit(s) in Register	Rd ← Rd v K	Z,N,V,S	1
CBR	Rd,K	Clear Bit(s) in Register	Rd ← Rd • ($FFh - K)	Z,N,V,S	1
INC	Rd	Increment	Rd ← Rd + 1	Z,N,V,S	1
DEC	Rd	Decrement	Rd ← Rd – 1	Z,N,V,S	1
TST	Rd	Test for Zero or Minus	Rd ← Rd • Rd	Z,N,V,S	1
CLR	Rd	Clear Register	Rd ← Rd ⊕ Rd	Z,N,V,S	1
SER	Rd	Set Register	Rd ← $FF	None	1
BRANCH INSTRUCTIONS					
RJMP	k	Relative Jump	PC ← PC + k + 1	None	2
IJMP		Indirect Jump to (Z)	PC(15:0) ← Z, PC(21:16) ← 0	None	2
RCALL	k	Relative Subroutine Call	PC ← PC + k + 1	None	3/4
ICALL		Indirect Call to (Z)	PC(15:0) ← Z, PC(21:16) ← 0	None	3/4
RET		Subroutine Return	PC ← STACK	None	4/5
RETI		Interrupt Return	PC ← STACK	I	4/5
CPSE	Rd,Rr	Compare, Skip if Equal	if (Rd = Rr) PC ← PC + 2 or 3	None	1/2/3
CP	Rd,Rr	Compare	Rd – Rr	Z, C,N,V,S,H	1
CPC	Rd,Rr	Compare with Carry	Rd – Rr – C	Z, C,N,V,S,H	1
CPI	Rd,K	Compare with Immediate	Rd – K	Z, C,N,V,S,H	1
SBRC	Rr, b	Skip if Bit in Register Cleared	if (Rr(b)=0) PC ← PC + 2 or 3	None	1/2/3
SBRS	Rr, b	Skip if Bit in Register is Set	if (Rr(b)=1) PC ← PC + 2 or 3	None	1/2/3
SBIC	A, b	Skip if Bit in I/O Register Cleared	if (I/O(A,b)=0) PC ← PC + 2 or 3	None	1/2/3
SBIS	A, b	Skip if Bit in I/O Register is Set	if (I/O(A,b)=1) PC ← PC + 2 or 3	None	1/2/3
BRBS	s, k	Branch if Status Flag Set	if (SREG(s) = 1) then PC←PC+k + 1	None	1/2
BRBC	s, k	Branch if Status Flag Cleared	if (SREG(s) = 0) then PC←PC+k + 1	None	1/2
BREQ	k	Branch if Equal	if (Z = 1) then PC ← PC + k + 1	None	1/2
BRNE	k	Branch if Not Equal	if (Z = 0) then PC ← PC + k + 1	None	1/2
BRCS	k	Branch if Carry Set	if (C = 1) then PC ← PC + k + 1	None	1/2
BRCC	k	Branch if Carry Cleared	if (C = 0) then PC ← PC + k + 1	None	1/2
BRSH	k	Branch if Same or Higher	if (C = 0) then PC ← PC + k + 1	None	1/2
BRLO	k	Branch if Lower	if (C = 1) then PC ← PC + k + 1	None	1/2
BRMI	k	Branch if Minus	if (N = 1) then PC ← PC + k + 1	None	1/2
BRPL	k	Branch if Plus	if (N = 0) then PC ← PC + k + 1	None	1/2
BRGE	k	Branch if Greater or Equal, Signed	if (N ⊕ V= 0) then PC ← PC + k + 1	None	1/2
BRLT	k	Branch if Less Than Zero, Signed	if (N ⊕ V= 1) then PC ← PC + k + 1	None	1/2
BRHS	k	Branch if Half Carry Flag Set	if (H = 1) then PC ← PC + k + 1	None	1/2
BRHC	k	Branch if Half Carry Flag Cleared	if (H = 0) then PC ← PC + k + 1	None	1/2
BRTS	k	Branch if T Flag Set	if (T = 1) then PC ← PC + k + 1	None	1/2
BRTC	k	Branch if T Flag Cleared	if (T = 0) then PC ← PC + k + 1	None	1/2
BRVS	k	Branch if Overflow Flag is Set	if (V = 1) then PC ← PC + k + 1	None	1/2
BRVC	k	Branch if Overflow Flag is Cleared	if (V = 0) then PC ← PC + k + 1	None	1/2
BRIE	k	Branch if Interrupt Enabled	if (I = 1) then PC ← PC + k + 1	None	1/2
BRID	k	Branch if Interrupt Disabled	if (I = 0) then PC ← PC + k + 1	None	1/2
BIT AND BIT-TEST INSTRUCTIONS					
LSL	Rd	Logical Shift Left	Rd(n+1) ← Rd(n), Rd(0) ← 0	Z,C,N,V,H	1
LSR	Rd	Logical Shift Right	Rd(n) ← Rd(n+1), Rd(7) ← 0	Z,C,N,V	1
ROL	Rd	Rotate Left Through Carry	Rd(0)←C,Rd(n+1)← Rd(n),C←Rd(7)	Z,C,N,V,H	1
ROR	Rd	Rotate Right Through Carry	Rd(7)←C,Rd(n)← Rd(n+1),C←Rd(0)	Z,C,N,V	1
ASR	Rd	Arithmetic Shift Right	Rd(n) ← Rd(n+1), n=0..6	Z,C,N,V	1
SWAP	Rd	Swap Nibbles	Rd(3..0)←Rd(7..4),Rd(7..4)←Rd(3..0)	None	1
BSET	s	Flag Set	SREG(s) ← 1	SREG(s)	1
BCLR	s	Flag Clear	SREG(s) ← 0	SREG(s)	1
SBI	A, b	Set Bit in I/O Register	I/O(A, b) ← 1	None	1

Mnemonics	Operands	Description	Operation	Flags	#Clocks
CBI	A, b	Clear Bit in I/O Register	I/O(A, b) ← 0	None	1
BST	Rr, b	Bit Store from Register to T	T ← Rr(b)	T	1
BLD	Rd, b	Bit load from T to Register	Rd(b) ← T	None	1
SEC		Set Carry	C ← 1	C	1
CLC		Clear Carry	C ← 0	C	1
SEN		Set Negative Flag	N ← 1	N	1
CLN		Clear Negative Flag	N ← 0	N	1
SEZ		Set Zero Flag	Z ← 1	Z	1
CLZ		Clear Zero Flag	Z ← 0	Z	1
SEI		Global Interrupt Enable	I ← 1	I	1
CLI		Global Interrupt Disable	I ← 0	I	1
SES		Set Signed Test Flag	S ← 1	S	1
CLS		Clear Signed Test Flag	S ← 0	S	1
SEV		Set Two's Complement Overflow.	V ← 1	V	1
CLV		Clear Two's Complement Overflow	V ← 0	V	1
SET		Set T in SREG	T ← 1	T	1
CLT		Clear T in SREG	T ← 0	T	1
SEH		Set Half Carry Flag in SREG	H ← 1	H	1
CLH		Clear Half Carry Flag in SREG	H ← 0	H	1
DATA TRANSFER INSTRUCTIONS					
MOV	Rd, Rr	Copy Register	Rd ← Rr	None	1
LDI	Rd, K	Load Immediate	Rd ← K	None	1
LD	Rd, X	Load Indirect	Rd ← (X)	None	1/2
LD	Rd, X+	Load Indirect and Post-Increment	Rd ← (X), X ← X + 1	None	2
LD	Rd, - X	Load Indirect and Pre-Decrement	X ← X - 1, Rd ← (X)	None	2/3
LD	Rd, Y	Load Indirect	Rd ← (Y)	None	1/2
LD	Rd, Y+	Load Indirect and Post-Increment	Rd ← (Y), Y ← Y + 1	None	2
LD	Rd, - Y	Load Indirect and Pre-Decrement	Y ← Y - 1, Rd ← (Y)	None	2/3
LD	Rd, Z	Load Indirect	Rd ← (Z)	None	1/2
LD	Rd, Z+	Load Indirect and Post-Increment	Rd ← (Z), Z ← Z+1	None	2
LD	Rd, -Z	Load Indirect and Pre-Decrement	Z ← Z - 1, Rd ← (Z)	None	2/3
LDS	Rd, k	Store Direct from SRAM	Rd ← (k)	None	1
ST	X, Rr	Store Indirect	(X) ← Rr	None	1
ST	X+, Rr	Store Indirect and Post-Increment	(X) ← Rr, X ← X + 1	None	1
ST	- X, Rr	Store Indirect and Pre-Decrement	X ← X - 1, (X) ← Rr	None	2
ST	Y, Rr	Store Indirect	(Y) ← Rr	None	1
ST	Y+, Rr	Store Indirect and Post-Increment	(Y) ← Rr, Y ← Y + 1	None	1
ST	- Y, Rr	Store Indirect and Pre-Decrement	Y ← Y - 1, (Y) ← Rr	None	2
ST	Z, Rr	Store Indirect	(Z) ← Rr	None	1
ST	Z+, Rr	Store Indirect and Post-Increment.	(Z) ← Rr, Z ← Z + 1	None	1
ST	-Z, Rr	Store Indirect and Pre-Decrement	Z ← Z - 1, (Z) ← Rr	None	2
STS	k, Rr	Store Direct to SRAM	(k) ← Rr	None	1
IN	Rd, A	In from I/O Location	Rd ← I/O (A)	None	1
OUT	A, Rr	Out to I/O Location	I/O (A) ← Rr	None	1
PUSH	Rr	Push Register on Stack	STACK ← Rr	None	2
POP	Rd	Pop Register from Stack	Rd ← STACK	None	2
MCU CONTROL INSTRUCTIONS					
BREAK		Break	(see specific descr. for Break)	None	1
NOP		No Operation		None	1
SLEEP		Sleep	(see specific descr. for Sleep)	None	1
WDR		Watchdog Reset	(see specific descr. for WDR)	None	1

24. Ordering Information

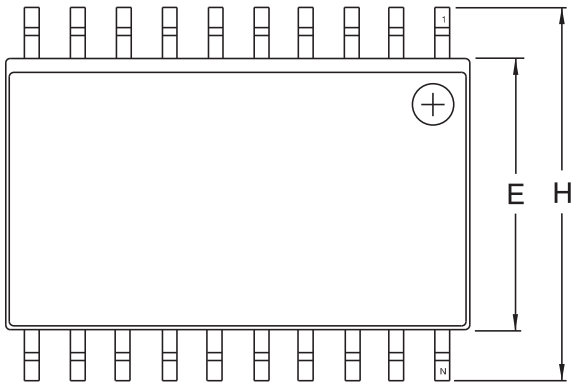
Speed (MHz)	Power Supply	Ordering Code[1]	Package[2]	Operational Range
12	1.8 - 5.5V	ATtiny40-SU ATtiny40-SUR ATtiny40-XU ATtiny40-XUR ATtiny40-MMH[3] ATtiny40-MMHR[3]	20S2 20S2 20X 20X 20M2[3] 20M2[3]	Industrial (-40°C to +85°C)[4]

Notes:
1. Code indicators:
   - H: NiPdAu lead finish
   - U: matte tin
   - R: tape & reel
2. All packages are Pb-free, halide-free and fully green and they comply with the European directive for Restriction of Hazardous Substances (RoHS).
3. Topside marking for ATtiny40:
   - 1st Line: T40
   - 2nd & 3rd Line: manufacturing data
4. These devices can also be supplied in wafer form. Please contact your local Atmel sales office for detailed ordering information and minimum quantities.

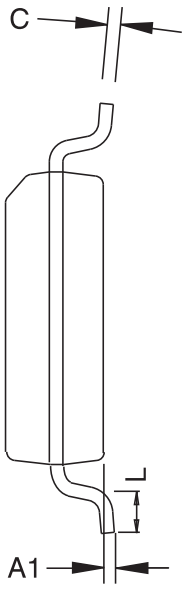
Package Type	
20S2	20-lead, 0.300" Wide Body, Plastic Gull Wing Small Outline Package (SOIC)
20X	20-lead, 4.4 mm Body, Plastic Thin Shrink Small Outline Package (TSSOP)
20M2	20-pad, 3 x 3 x 0.85 mm Body, Very Thin Quad Flat No Lead Package (VQFN)

25. Packaging Information

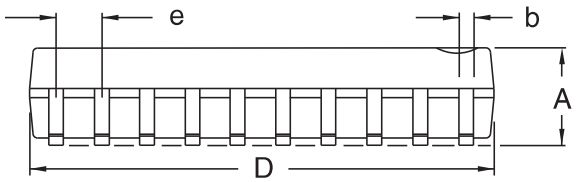
25.1 20S2



Top View



End View



Side View

COMMON DIMENSIONS
(Unit of Measure – mm)

SYMBOL	MIN	NOM	MAX	NOTE
A	2.35		2.65	
A1	0.10		0.30	
b	0.33		0.51	4
C	0.23		0.32	
D	12.60		13.00	1
E	7.40		7.60	2
H	10.00		10.65	
L	0.40		1.27	3
e	1.27 BSC			

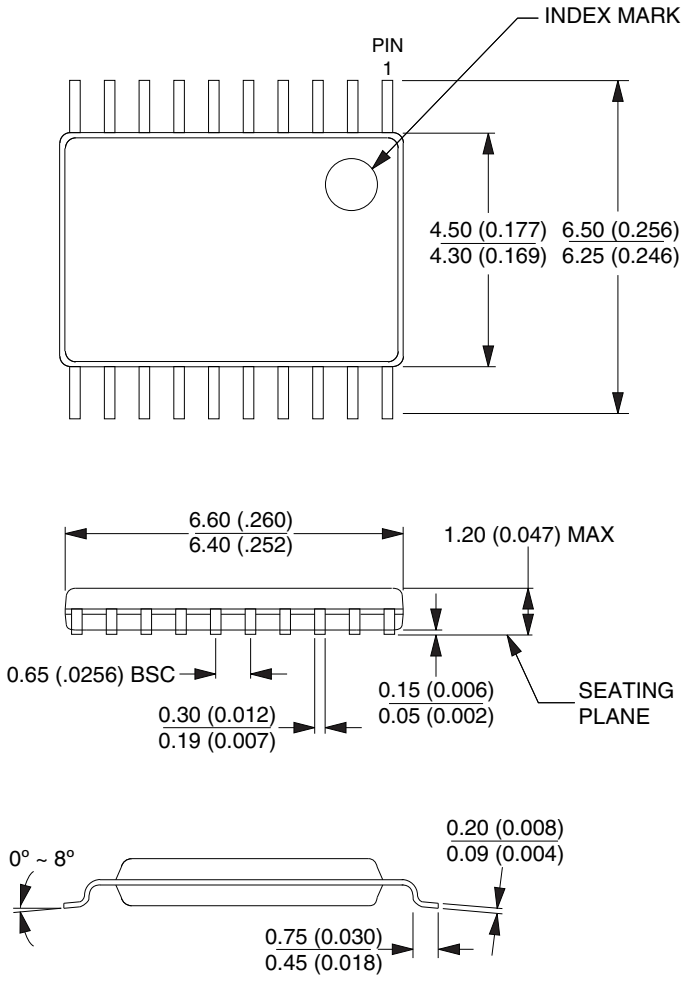
Notes.
1. This drawing is for general information only; refer to JEDEC Drawing MS-013, Variation AC for additional information.
2. Dimension 'D' does not include mold Flash, protrusions or gate burrs. Mold Flash, protrusions and gate burrs shall not exceed 0.15 mm (0.006') per side.
3. Dimension 'E' does not include inter-lead Flash or protrusion. Inter-lead Flash and protrusions shall not exceed 0.25 mm (0.010') per side.
4. 'L' is the length of the terminal for soldering to a substrate.
5. The lead width 'b', as measured 0.36 mm (0.014') or greater above the seating plane, shall not exceed a maximum value of 0.61 mm (0.024') per side.

11/6/06

	TITLE	DRAWING NO.	REV.
2325 Orchard Parkway San Jose, CA 95131	**20S2**, 20-lead, 0.300' Wide Body, Plastic Gull Wing Small Outline Package (SOIC)	20S2	B

25.2 20X

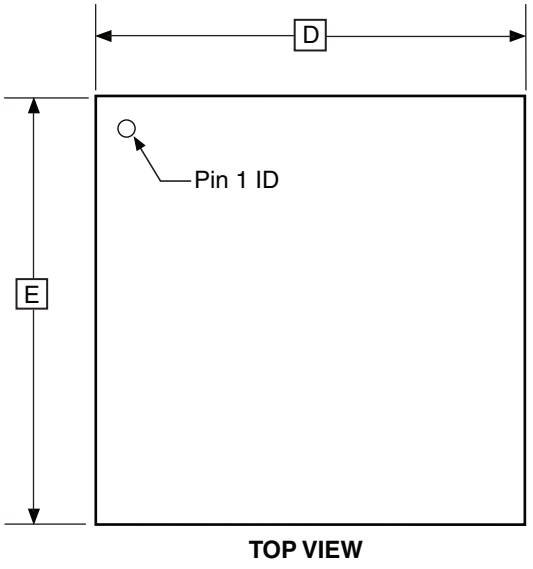
Dimensions in Millimeters and (Inches).
Controlling dimension: Millimeters.
JEDEC Standard MO-153 AC

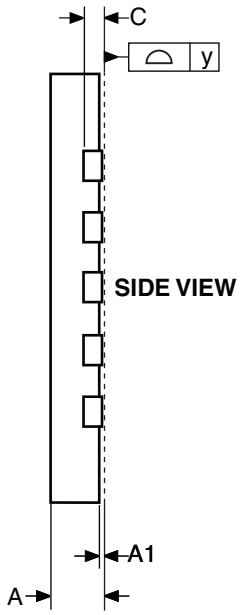


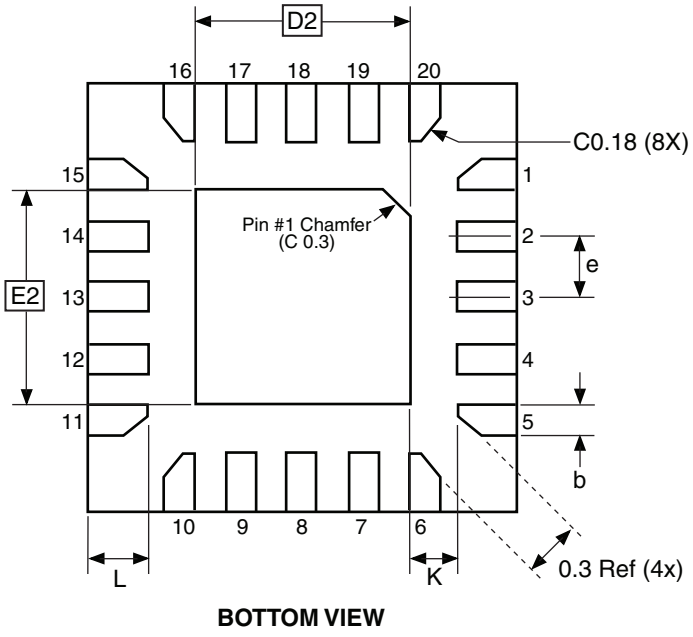
10/23/03

	TITLE	DRAWING NO.	REV.
2325 Orchard Parkway San Jose, CA 95131	**20X**, (Formerly 20T), 20-lead, 4.4 mm Body Width, Plastic Thin Shrink Small Outline Package (TSSOP)	20X	C

25.3 20M2







COMMON DIMENSIONS
(Unit of Measure = mm)

SYMBOL	MIN	NOM	MAX	NOTE
A	0.75	0.80	0.85	
A1	0.00	0.02	0.05	
b	0.17	0.22	0.27	
C		0.152		
D	2.90	3.00	3.10	
D2	1.40	1.55	1.70	
E	2.90	3.00	3.10	
E2	1.40	1.55	1.70	
e	–	0.45	–	
L	0.35	0.40	0.45	
K	0.20	–	–	
y	0.00	–	0.08	

10/24/08

	TITLE	GPC	DRAWING NO.	REV.
Package Drawing Contact: packagedrawings@atmel.com	**20M2,** 20-pad, 3 x 3 x 0.85 mm Body, Lead Pitch 0.45 mm, 1.55 x 1.55 mm Exposed Pad, Thermally Enhanced Plastic Very Thin Quad Flat No Lead Package (VQFN)	ZFC	20M2	B

26. Errata

The revision letters in this section refer to the revision of the corresponding ATtiny40 device.

26.1 Rev. B

- **MISO output driver is not disabled by Slave Select ($\overline{SS}$) signal.**
- **Current consumption in sleep modes may exceed specifications.**

1. MISO output driver is not disabled by Slave Select ($\overline{SS}$) signal.

When SPI is configured as a slave and the MISO pin is configured as an output the pin output driver is constantly enabled, even when the $\overline{SS}$ pin is high. If other slave devices are connected to the same MISO line this behaviour may cause drive contention.

Problem Fix / Workaround

Monitor $\overline{SS}$ pin by software and use the DDRC2 bit of DDRC to control the MISO pin driver.

2. Current consumption in sleep mode may exceed specifications.

Some settings of register R27 may increase current consumption in sleep mode.

Problem Fix / Workaround

Before entering sleep mode, make sure register R27 is not loaded with 0x00 or 0x01.

26.2 Rev. A

Not sampled.

27. Datasheet Revision History

27.1 Rev. 8263B – 01/2013

1. Removed Preliminary status
2. Updated
   - Idle Mode description on page 4
   - “Capacitive Touch Sensing” on page 5 (section updated and moved)
   - “Disclaimer” on page 5
   - Description on 16-bit registers on page 6
   - Description on Stack Pointer on page 9
   - List of active modules in “Idle Mode” on page 24
   - Description on reset pulse width in “Watchdog Reset” on page 30
   - Bit description in Figure 11-3 on page 63
   - “Modes of Operation” on page 65, simplified $_0 = f_{clk_I/O}/2$ to $f_{clk_I/O}/2$ (on two locations)
   - Section “Compare Output Mode and Waveform Generation” on page 65
   - Figure 11-5 on page 66, Figure 11-6 on page 67, and Figure 11-7 on page 68
   - Equations on page 66, page 68, and page 69
   - Terminology in sections describing extreme values on page 68, and page 69
   - Description on creating frequency waveforms on page 69
   - Description on signal source impedance on page 105
   - SPI slave assembly code example on page 117
   - “Speed” on page 153
   - Characteristics in Figure 21-3 on page 161, and Figure 21-9 on page 164
   - Last page
3. Added:

– Note on internal voltage reference in Table 15-4 on page 110
– “Compatibility with SMBus” on page 128
– “Two-Wire Serial Interface Characteristics” on page 156
– “Errata” on page 196

27.2 Rev. 8263A – 08/10

1. Initial revision

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