Interrupts (I)

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Lecture overview

- Introduction to Interrupts
  - Interrupt system specifications
  - Multiple sources of Interrupts
  - Interrupt priorities

- Interrupts in AVR
  - Interrupt Vector Table
  - Interrupt Service Routines
  - System Reset
    - Watchdog Reset
CPU Interacts with I/O

Two approaches:

- **Polling**
  - Software queries I/O devices.
  - No extra hardware needed.
  - Not efficient.
    - CPU may waste processor cycles to query a device even if it does not need any service.

- **Interrupts**
  - I/O devices generate signals to request services from CPU.
  - Need special hardware to implement interrupt services.
  - Efficient.
    - A signal is generated only if the I/O device needs services from CPU.
Interrupt Systems

- An interrupt system implements interrupt services
- It basically performs three tasks:
  - Recognize interrupt events
  - Respond to the interrupts
  - Resume normal programmed task
Recognize Interrupt Events

- Interrupt events
  - Associated with interrupt signals:
    - In different forms, including levels and edges.
  - Can be multiple and synchronous
    - Namely, there may be many sources to generate an
      interrupts; a number of interrupts can be generated at
      the same time.

- Approaches are required to:
  - Identify an interrupt event among multiple sources
  - Determine which interrupts to serve if there are
    multiple simultaneous interrupts
Respond to Interrupts

- Handling interrupt
  - Wait for the current instruction to finish.
  - Acknowledge the interrupting device.
  - Branch to the correct *interrupt service routine* (interrupt handler) to service interrupting device.
Resume Normal Task

- Return to the interrupted program at the point it was interrupted.
Interrupt Process Control

- Interrupts can be enabled or disabled
- Can be controlled in two ways:
  - Software control
    - Allow programmers to enable and disable selected/all interrupts.
  - Hardware control
    - Disable further interrupts while an interrupt is being serviced
Interrupt Recognition and Acknowledgement Hardware

**Diagram:***
- **INTERRUPTING DEVICE** → **IRQ**
  - **Signal conditioning** → **IRQ-FF**
    - **Set** → **Reset**
    - **Pending Interrupt**
      - **Interrupt signal to sequence controller**
      - **Interrupt ack from sequence controller**
      - **SEQUENCE CONTROLLER**
        - **Disable interrupt instruction**
        - **Enable interrupt instruction**
        - **Return from interrupt instruction**

- **INTERRUPTING DEVICE** → **CPU**
Interrupt Recognition and Ack.

- An Interrupt Request (IRQ) may occur at any time.
  - It may have rising or falling edges or high or low levels.
  - Frequently it is an active-low signal
    - multiple devices are wire-ORed together.
      - Recall open-collector gates

- Signal Conditioning Circuit detects these different types of signals.

- Interrupt Request Flip-Flop (IRQ-FF) records the interrupt request until it is acknowledged.
  - When IRQ-FF is set, it generates a pending interrupt signal that goes towards the Sequence Controller.
  - IRQ-FF is reset when CPU acknowledges the interrupt with INTA signal.
Interrupt Recognition and Ack. (cont.)

- Interrupts can be enabled and disabled by software instructions, which is supported by the hardware Interrupt Enable Flip-Flop (INTE-FF).
- When the INTE-FF is set, all interrupts are enabled and the pending interrupt is allowed through the AND gate to the sequence controller.
- The INTE-FF is reset in the following cases.
  - CPU acknowledges the interrupt.
  - CPU is reset.
  - Disable interrupt instruction is executed.
Interrupt Recognition and Ack. (cont.)

- An interrupt acknowledge signal is generated by the CPU when the current instruction has finished execution and CPU has detected the IRQ.
  - This resets the IRQ-FF and INTE-FF and signals the interrupting device that CPU is ready to execute the interrupting device routine.

- At the end of the interrupt service routine, CPU executes a return-from-interrupt instruction.
  - Part of this instruction’s job is to set the INTE-FF to re-enable interrupts.

- Nested interrupts can happen if the INTE-FF is set during an interrupt service routine.
  - An interrupt can therefore interrupt interrupting interrupts.
Multiple Sources of Interrupts

To handle multiple sources of interrupts, the interrupt system must:

- Identify which device has generated the IRQ.
  - Using polling approach
  - Using vectoring approach

- Resolve simultaneous interrupt requests
  - using prioritization schemes.
Polled Interrupts

- Software, instead of hardware, is responsible for finding the interrupting source.
  - The device must have logic to generate the IRQ signal and to set an “I did it” bit in a status register that is read by CPU.
  - The bit is reset after the register has been read.
Polled Interrupts Execution Flow

Device generates IRQ

CPU polls status registers of all devices

CPU found the interrupting device

CPU executes the service routine for that device
Polled Interrupt Logic

- Logic to generate IRQ
- Logic to reset IRQ when status register is read
- Logic to read status register and reset “I did it” bit
- Logic to set “I did it” bit
- Status register

Data

Address

Control
Vectored Interrupts

- CPU’s response to IRQ is to assert INTA.
- The interrupting device uses INTA to place information that identifies itself, called the vector, onto the data bus for CPU to read.
- CPU uses the vector to execute the interrupt service routine.
Vectored Interrupting Device Hardware

Logic to generate IRQ

Logic to reset IRQ

Vector Information

Three-State Driver

Data

Address

Control

INTA

IRQ

HW
Multiple Interrupt Masking

- CPU has multiple IRQ input pins.
- Masking enables some interrupts and disables other interrupts
- CPU designers reserve specific memory locations for a vector associated with each IRQ line.
- Individual disable/enable bit is assigned to each interrupting source.
Multiple Interrupt Masking Circuit

Interrupt Enable Register

- IRQ0E
- IRQ1E
- IRQ2E
- IRQ3E

CPU

- IRQ 0
- IRQ 1
- IRQ 2
- IRQ n
Interrupt Priorities

When multiple interrupts occur at the same time, which one will be serviced first?

Two resolution approaches:

- Software resolution
  - Polling software determines which interrupting source is serviced first.

- Hardware resolution
  - Daisy chain.
  - Others
Software Resolution

Device generates IRQ

CPU polls status registers of all devices

CPU found the interrupting device

CPU executes the service routine for that device

Selection Algorithm
Daisy Chain Priority Resolution

Diagram:

- CPU
- Device 1
- Device 2
- Device n

Connections:
- IRQ
- INTA

Data
Address
Control
Daisy Chain Priority Resolution (cont.)

- CPU asserts INTA that is passed down the chain from device to device. The higher-priority device is closer to CPU.
- When the INTA reaches a device that generated the IRQ, that device puts its vector on the data bus and does not pass along the INTA. So lower-priority devices do NOT receive the INTA.
Other Priority Resolutions

- Separate IRQ Lines.
  - Each IRQ line is assigned a fixed priority. For example, IRQ0 has higher priority than IRQ1 and IRQ1 has higher priority than IRQ2 and so on.

- Hierarchical Prioritization.
  - Higher priority interrupts are allowed while lower ones are masked.

- Nonmaskable Interrupts.
  - Cannot be disabled.
  - Used for important events such as power failure.
Transferring Control to Interrupt Service Routine

- Hardware needs to save the return address.
  - Most processors save the return address on the stack.
- Hardware may also save some registers such as program status register.
  - AVR does not save any registers. It is the programmers’ responsibility to save the program status register and conflict registers.
- The delay from the time the IRQ is generated by the interrupting device to the time the Interrupt Service Routine (ISR) starts to execute is called *interrupt latency*.
Interrupt Service Routine

- A sequence of code to be executed when the corresponding interrupt is responded by CPU.
- Interrupt service routine is a special subroutine, therefore can be constructed with three parts:
  - Prologue:
    - Code for saving conflict registers on the stack.
  - Body:
    - Code for doing the required task.
  - Epilogue:
    - Code for restoring all saved registers from the stack.
    - The last instruction is the return-from-interrupt instruction.
Software Interrupt

- Software interrupt is the interrupt generated by software without a hardware-generated-IRQ.
- Software interrupt is typically used to implement system calls in OS.
- Some processors have a special machine instruction to generate software interrupt.
  - SWI in ARM.
- AVR does NOT provide a software interrupt instruction.
  - Programmers can use External Interrupts to implement software interrupts.
Exceptions

- Abnormalities that occur during the normal operation of the processor.
  - Examples are internal bus error, memory access error and attempts to execute illegal instructions.
- Some processors handle exceptions in the same way as interrupts.
  - AVR does not handle exceptions.
Reset

- Reset is a type of interrupt present in most processors (including AVR).
- Non-maskable.
- It does not do other interrupt processes, such as saving conflict registers. It initializes the system to some initial state.
Non-Nested Interrupts

- Interrupt service routines cannot be interrupted by another interrupt.
Nested Interrupts

- Interrupt service routines can be interrupted by another interrupt.
AVR Interrupts

- Basically can be divided into internal and external interrupts
- Each has a dedicated interrupt vector
- Hardware is used to recognize interrupts
- To enable an interrupt, two control bits must be set
  - the Global Interrupt Enable bit (I bit) in the Status Register
    - Using `sei`
  - the enable bit for that interrupt
- To disable all maskable interrupts, reset the I bit in SREG
  - Using `cli` instruction
- Priority of interrupts is used to handle multiple simultaneous interrupts
Set Global Interrupt Flag

- Syntax: \textit{sei}
- Operands: none
- Operation: \quad I \leftarrow 1.
  - Sets the global interrupt flag (I) in SREG. The instruction following SEI will be executed before any pending interrupts.
- Words: 1
- Cycles: 1
- Example:
  
  \begin{verbatim}
  sei ; set global interrupt enable
  sleep ; enter sleep state, waiting for an interrupt
  \end{verbatim}
Clear Global Interrupt Flag

- Syntax: \textit{cli}
- Operands: none
- Operation: \( I \leftarrow 0 \)
  - Clears the Global interrupt flag in SREG. Interrupts will be immediately disabled.
- Words: 1
- Cycles: 1
- Example:
  
  \begin{verbatim}
  in r18, SREG ; store SREG value
cli ; disable interrupts
  ; do something very important here
  out SREG, r18 ; restore SREG value
  \end{verbatim}
The interrupt execution response for all the enabled AVR interrupts is basically five clock cycles minimum.

- For saving the Program Counter (2 clock cycles)
- For jumping to the interrupt routine (3 clock cycles)
Interrupt Vectors

- Each interrupt has a 4-byte (2-word) interrupt vector, containing an instruction to be executed after MCU has accepted the interrupt.
- The lowest addresses in the program memory space are by default defined as the section for Interrupt Vectors.
- The priority of an interrupt is based on the position of its vector in the program memory
  - The lower the address the higher is the priority level.
- RESET has the highest priority
# Interrupt Vectors in Mega2560

<table>
<thead>
<tr>
<th>Vector No.</th>
<th>Program Address(2)</th>
<th>Source</th>
<th>Interrupt Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0000^{(1)}</td>
<td>RESET</td>
<td>External Pin, Power-on Reset, Brown-out Reset, Watchdog Reset, and JTAG AVR Reset</td>
</tr>
<tr>
<td>2</td>
<td>$0002</td>
<td>INT0</td>
<td>External Interrupt Request 0</td>
</tr>
<tr>
<td>3</td>
<td>$0004</td>
<td>INT1</td>
<td>External Interrupt Request 1</td>
</tr>
<tr>
<td>4</td>
<td>$0006</td>
<td>INT2</td>
<td>External Interrupt Request 2</td>
</tr>
<tr>
<td>5</td>
<td>$0008</td>
<td>INT3</td>
<td>External Interrupt Request 3</td>
</tr>
<tr>
<td>6</td>
<td>$000A</td>
<td>INT4</td>
<td>External Interrupt Request 4</td>
</tr>
<tr>
<td>7</td>
<td>$000C</td>
<td>INT5</td>
<td>External Interrupt Request 5</td>
</tr>
<tr>
<td>8</td>
<td>$000E</td>
<td>INT6</td>
<td>External Interrupt Request 6</td>
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<tr>
<td>9</td>
<td>$0010</td>
<td>INT7</td>
<td>External Interrupt Request 7</td>
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<td>10</td>
<td>$0012</td>
<td>PCINT0</td>
<td>Pin Change Interrupt Request 0</td>
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<tr>
<td>11</td>
<td>$0014</td>
<td>PCINT1</td>
<td>Pin Change Interrupt Request 1</td>
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<tr>
<td>12</td>
<td>$0016^{(3)}</td>
<td>PCINT2</td>
<td>Pin Change Interrupt Request 2</td>
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## Interrupt Vectors in Mega2560 (cont.)

<p>| | | | |</p>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>$0018</td>
<td>WDT</td>
<td>Watchdog Time-out Interrupt</td>
</tr>
<tr>
<td>14</td>
<td>$001A</td>
<td>TIMER2 COMPA</td>
<td>Timer/Counter2 Compare Match A</td>
</tr>
<tr>
<td>15</td>
<td>$001C</td>
<td>TIMER2 COMPB</td>
<td>Timer/Counter2 Compare Match B</td>
</tr>
<tr>
<td>16</td>
<td>$001E</td>
<td>TIMER2 OVF</td>
<td>Timer/Counter2 Overflow</td>
</tr>
<tr>
<td>17</td>
<td>$0020</td>
<td>TIMER1 CAPT</td>
<td>Timer/Counter1 Capture Event</td>
</tr>
<tr>
<td>18</td>
<td>$0022</td>
<td>TIMER1 COMPA</td>
<td>Timer/Counter1 Compare Match A</td>
</tr>
<tr>
<td>19</td>
<td>$0024</td>
<td>TIMER1 COMPB</td>
<td>Timer/Counter1 Compare Match B</td>
</tr>
<tr>
<td>20</td>
<td>$0026</td>
<td>TIMER1 COMPC</td>
<td>Timer/Counter1 Compare Match C</td>
</tr>
<tr>
<td>21</td>
<td>$0028</td>
<td>TIMER1 OVF</td>
<td>Timer/Counter1 Overflow</td>
</tr>
<tr>
<td>22</td>
<td>$002A</td>
<td>TIMER0 COMPA</td>
<td>Timer/Counter0 Compare Match A</td>
</tr>
<tr>
<td>23</td>
<td>$002C</td>
<td>TIMER0 COMPB</td>
<td>Timer/Counter0 Compare match B</td>
</tr>
<tr>
<td>24</td>
<td>$002E</td>
<td>TIMER0 OVF</td>
<td>Timer/Counter0 Overflow</td>
</tr>
<tr>
<td>25</td>
<td>$0030</td>
<td>SPI, STC</td>
<td>SPI Serial Transfer Complete</td>
</tr>
<tr>
<td>26</td>
<td>$0032</td>
<td>USART0 RX</td>
<td>USART0 Rx Complete</td>
</tr>
<tr>
<td>27</td>
<td>$0034</td>
<td>USART0 UDRE</td>
<td>USART0 Data Register Empty</td>
</tr>
<tr>
<td>28</td>
<td>$0036</td>
<td>USART0 TX</td>
<td>USART0 Tx Complete</td>
</tr>
<tr>
<td>29</td>
<td>$0038</td>
<td>ANALOG COMP</td>
<td>Analog Comparator</td>
</tr>
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## Interrupt Vectors in Mega2560 (cont.)

<table>
<thead>
<tr>
<th>Vector</th>
<th>Address</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$003A</td>
<td>ADC Conversion Complete</td>
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<tr>
<td>31</td>
<td>$003C</td>
<td>EEPROM Ready</td>
</tr>
<tr>
<td>32</td>
<td>$003E</td>
<td>Timer/Counter3 Capture Event</td>
</tr>
<tr>
<td>33</td>
<td>$0040</td>
<td>Timer/Counter3 Compare Match A</td>
</tr>
<tr>
<td>34</td>
<td>$0042</td>
<td>Timer/Counter3 Compare Match B</td>
</tr>
<tr>
<td>35</td>
<td>$0044</td>
<td>Timer/Counter3 Compare Match C</td>
</tr>
<tr>
<td>36</td>
<td>$0046</td>
<td>Timer/Counter3 Overflow</td>
</tr>
<tr>
<td>37</td>
<td>$0048</td>
<td>USART1 Rx Complete</td>
</tr>
<tr>
<td>38</td>
<td>$004A</td>
<td>USART1 Data Register Empty</td>
</tr>
<tr>
<td>39</td>
<td>$004C</td>
<td>USART1 Tx Complete</td>
</tr>
<tr>
<td>40</td>
<td>$004E</td>
<td>2-wire Serial Interface</td>
</tr>
<tr>
<td>41</td>
<td>$0050</td>
<td>Store Program Memory Ready</td>
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</tbody>
</table>
# Interrupt Vectors in Mega2560

(cont.)

<table>
<thead>
<tr>
<th>Vector</th>
<th>Address</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>$0050</td>
<td>SPM READY</td>
</tr>
<tr>
<td>42</td>
<td>$0052(3)</td>
<td>TIMER4 CAPT</td>
</tr>
<tr>
<td>43</td>
<td>$0054</td>
<td>TIMER4 COMPA</td>
</tr>
<tr>
<td>44</td>
<td>$0056</td>
<td>TIMER4 COMPB</td>
</tr>
<tr>
<td>45</td>
<td>$0058</td>
<td>TIMER4 COMPC</td>
</tr>
<tr>
<td>46</td>
<td>$005A</td>
<td>TIMER4 OVF</td>
</tr>
<tr>
<td>47</td>
<td>$005C(3)</td>
<td>TIMER5 CAPT</td>
</tr>
<tr>
<td>48</td>
<td>$005E</td>
<td>TIMER5 COMPA</td>
</tr>
<tr>
<td>49</td>
<td>$0060</td>
<td>TIMER5 COMPB</td>
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<td>50</td>
<td>$0062</td>
<td>TIMER5 COMPC</td>
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<td>51</td>
<td>$0064</td>
<td>TIMER5 OVF</td>
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<tr>
<td>52</td>
<td>$0066(3)</td>
<td>USART2 RX</td>
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<tr>
<td>53</td>
<td>$0068(3)</td>
<td>USART2 UDRE</td>
</tr>
<tr>
<td>54</td>
<td>$006A(3)</td>
<td>USART2 TX</td>
</tr>
<tr>
<td>55</td>
<td>$006C(3)</td>
<td>USART3 RX</td>
</tr>
<tr>
<td>56</td>
<td>$006E(3)</td>
<td>USART3 UDRE</td>
</tr>
<tr>
<td>57</td>
<td>$0070(3)</td>
<td>USART3 TX</td>
</tr>
</tbody>
</table>
Interrupt Process

- When an interrupt occurs, the Global Interrupt Enable I-bit is cleared and all interrupts are disabled.
- The interrupt routine can set the I-bit to allow nested interrupts.
- The I-bit is automatically set when a Return from Interrupt instruction – RETI – is executed.
- 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.
  - Reset interrupt is an exception.
Initialization of Interrupt Vector Table in Mega2560

- Typically an interrupt vector contains a branch instruction (JMP or RJMP) that branches to the first instruction of the interrupt service routine.
- Or simply RETI (return-from-interrupt) if you don’t handle this interrupt.
Example of IVT Initialization in Mega2560

```assembly
.include "m2560def.inc"
.cseg
.org 0x0000 ; Reset vector is at address 0x0000
rjmp RESET ; Jump to the start of Reset interrupt service routine
            ; Relative jump is used assuming RESET is not far
.org INT0addr ; Addresses of vectors are defined in m2560def.inc
jmp IRQ0 ; Long jump is used assuming IRQ0 is very far away
.org INT1addr
reti ; Return to the break point without handling the interrupt
...
RESET: ; The interrupt service routine for RESET starts here.
...
IRQ0: ; The interrupt service routine for IRQ0 starts here.
```
RESET in Mega2560

- The ATmega2560 has five sources of reset:
  - Power-on Reset.
    - The MCU is reset when the supply voltage is below the Power-on Reset threshold (VPOT).
  - External Reset.
    - The MCU is reset when a low level is present on the 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.
RESET in Mega2560 (Cont.)

- Brown-out Reset.
  - The MCU is reset when the supply voltage VCC is below the Brown-out Reset threshold (VBOT) and the Brown-out Detector is enabled.

- JTAG AVR Reset.
  - The MCU is reset as long as there is a logic one in the Reset Register, one of the scan chains of the JTAG system.

- For each reset, there is a flag (bit) in MCU Control and State Register MCUCSR.
  - These bits are used to determine the source of the RESET interrupt.
RESET Logic in Mega2560
Atmega2560 Pin Configuration

Source: Atmega2560 Data Sheet
Watchdog Timer

- A peripheral I/O device on the microcontroller.
- It is really a counter that is clocked from a separate On-chip Oscillator (122 kHz at Vcc=5V)
- It can be controlled to produce different time intervals
  - 8 different periods determined by WDP2, WDP1 and WDP0 bits in WDTCSR.
- Can be enabled or disabled by properly updating WDCE bit and WDE bit in Watchdog Timer Control Register WDTCSR.
Watchdog Timer (cont.)

- Often used to detect software crash.
  - If enabled, it generates a Watchdog Reset interrupt when its period expires.
    - When its period expires, Watchdog Reset Flag WDRF in MCU Control Register MCUCSR is set.
      - This flag is used to determine if the watchdog timer has generated a RESET interrupt.
  - Program needs to reset it before its period expires by executing instruction $WDR$. 
Watchdog Timer Diagram

Source: Atmega64 Data Sheet
Watchdog Timer Control Register

- WDTCSR is used to control the scale of the watchdog timer. It is an MM I/O register in AVR.

Source: Atmega2560 Data Sheet
WDTCR Bit Definition

- Bit 7 – WDIF - Watchdog interrupt flag
- Bit 6 – WDIE - Watchdog interrupt enable
- Bit 4
  - WDCE - Watchdog change enable
    - Should be set before any changes to be made
- Bit 3
  - WDE - Watchdog enable
    - Set to enable watchdog; clear to disable the watchdog
- Bits 5,2-0
  - Prescaler
    - Named WDP3, WDP2, WDP1, WPD0
      - Determine the watchdog time reset intervals
# Watchdog Timer Prescale

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

Source: Atmega64 Data Sheet
Examples

- Enable watchdog

```assembly
; Write logical one to WDE
ldi r16, (1<<WDE)
sts WDTCSR, r16
```
Examples

- Disable watchdog
  - Refer to the data sheet

```assembly
; Write logical one to WDCE and WDE
ldi r16, (1<<WDCE)|(1<<WDE)
sts WDTCSR, r16

; Turn off WDT
ldi r16, (0<<WDE)
sts WDTCSR, r16
```
Examples

- Select a prescale
  - Refer to the data sheet

```assembly
; Write logical one to WDCE and WDE
ldi r16, (1<<WDCE)|(1<<WDE)
sts WDTCSR, r16

; set time-out as 1 second
ldi r16, (1<<WDP2)|(1<<WDP1)
sts WDTCSR, r16
```
Watchdog Reset

- Syntax: \( wdr \)
- Operands: none
- Operation: reset the watchdog timer.
- Words: 1
- Cycles: 1
Example

- The program in the next slide is not robust. May lead to a crash. Why? How to detect the crash?
; The program returns the length of a string.

.include "m2560def.inc"
.def i=r15 ; store the string length when execution finishes.
def c=r16 ; store s[i], a string character

.cseg

main:
    ldi ZL, low(s<<1)
    ldi ZH, high(s<<1)
    clr i
    lpm c, z+

loop:
    cpi c, 0
    breq endloop
    inc i
    lpm c, Z+
    rjmp loop

endloop: ...

s: .db "hello, world"
Reading Material

- Chapter 8: Interrupts and Real-Time Events. Microcontrollers and Microcomputers by Fredrick M. Cady.
- Mega2560 Data Sheet.
  - System Control and Reset.
  - Watchdog Timer.
  - Interrupts.
Homework

1. Refer to the AVR Instruction Set manual, study the following instructions:
   - Bit operations
     - sei, cli
     - sbi, cbi
   - MCU control instructions
     - wdr
1. What is the function of the following code?

```Assembly
; Write logical one to WDCE and WDE
ldi r16, (1<<WDCE)|(1<<WDE)
sts WDTCSR, r16

; set time-out as 2.1 second
ldi r16, (1<<WDP2)|(1<<WDP1)|(1<<WDP0)
sts WDTCSR, r16

; enable watchdog
ldi r16, (1<<WDE)
sts WDTCSR, r16

loop: oneSecondDelay ; macro for one second delay
wdr
rjmp loop
```
Homework

2. How an I/O device signals the microprocessor that it needs service?
Homework

3. Why do you need software to disable interrupts (except for the non-maskable interrupts)?