Computational hardware

- Digital logic (CSE370)
  - Gates and flip-flops: glue logic, simple FSMs, registers
  - Two-level PLDs: FSMs, muxes, decoders
- Programmable logic devices (CSE370, CSE467)
  - Field-programmable gate arrays: FSMs, basic data-paths
  - Mapping algorithms to hardware
- Microprocessors (CSE378)
  - General-purpose computer
  - Instructions can implement complex control structures
  - Supports computations/manipulations of data in memory

Microprocessors

- Arbitrary computations
  - Arbitrary control structures
  - Arbitrary data structures
  - Specify function at high-level and use compilers and debuggers
- Microprocessors can lower hardware costs
  - If function requires too much logic when implemented with gates/FFs
    - Operations are too complex, better broken down as instructions
    - Lots of data manipulation (memory)
  - If function does not require higher performance of customized logic
    - Ever-increasing performance of processors puts more and more applications in this category
    - Minimize the amount of external logic
Microprocessor basics

- Composed of three parts
  - Data-path: data manipulation and storage
  - Control: determines sequence of actions executed in data-path and interactions to be had with environment
  - Interface: signals seen by the environment of the processor
- Instruction execution engine: fetch/execute cycle
  - Flow of control determined by modifications to program counter
  - Instruction classes:
    - Data: move, arithmetic and logical operations
    - Control: branch, loop, subroutine call
    - Interface: load, store from external memory

Microprocessor basics (cont’d)

- Can implement arbitrary state machine with auxiliary data-path
  - Control instructions implement state diagram
  - Registers and ALUs act as data storage and manipulation
  - Interaction with the environment through memory interface
  - How are individual signal wires sensed and controlled?
Microprocessor organization

- Controller
  - Inputs: from ALU (conditions), instruction read from memory
  - Outputs: select inputs for registers, ALU operations, read/write to memory
- Data-path
  - Register file to hold data
  - Arithmetic logic unit to manipulate data
  - Program counter (to implement relative jumps and increments)
- Interface
  - Data to/from memory (address and data registers in data path)
  - Read/write signals to memory (from control)

General-purpose processor

- Programmed by user
- New applications are developed routinely
- General-purpose
  - Must handle a wide ranging variety of applications
- Interacts with environment through memory
  - All devices communicate through memory data
  - DMA operations between disk and I/O devices
  - Dual-ported memory (e.g., display screen)
  - Generally, oblivious to passage of time
Embedded processor

- Typically programmed once by manufacturer of system
  - Rarely does the user load new software
- Executes a single program (or a limited suite) with few parameters
- Task-specific
  - Can be optimized for a specific application
- Interacts with environment in many ways
  - Direct sensing and control of signal wires
  - Communication protocols to environment and other devices
  - Real-time interactions and constraints
  - Power-saving modes of operation to conserve battery power

Why embedded processors?

- High overhead in building a general-purpose system
  - Storing/loading programs
  - Operating system manages running of programs and access to data
  - Shared system resources (e.g., system bus, large memory)
  - Many parts
    - Communication through shared memory/bus
    - Each I/O device often requires its own separate hardware unit
- Optimization opportunities
  - As much hardware as necessary for application
    - Cheaper, portable, lower-power systems
  - As much software as necessary for application
    - Doesn’t require a complete OS, get a lot done with a smaller processor
  - Can integrate processor, memory, and I/O devices on to a single chip
How does this change things?

- Sense and control of environment
  - Processor must be able to “read” and “write” individual wires
  - Controls I/O interfaces directly
- Measurement of time
  - Many applications require precise spacing of events in time
  - Real-time is not the same thing as fast as possible
  - Reaction times to external stimuli may be constrained
- Communication
  - Protocols must be implemented by processor
  - Integrate I/O device or emulate in software
  - Capability of using external device when necessary

Interactions with the environment

- Basic processor only has address and data busses to memory
- Inputs are read from memory
- Outputs are written to memory
- Thus, for a processor to sense/control signal wires in the environment they must be made to appear as memory bits
  - How do we make wires look like memory?
- How long does it take to do these things?
Sensing external signals

- Map external wire to a bit in the address space of the processor
- External register or latch buffers values coming from environment
  - Map register into address space
    - Decoder selects register for reading
  - Output enable (OE) to get value on to data bus
    - Lets many registers use the same data bus

Controlling external signals

- Map external wire to a bit in the address space of the processor
- Connect output of memory-mapped register to environment
  - Map register into address space
    - Decoder selects register for writing (holds value indefinitely)
  - Input enable (EN) to take value from data bus
    - Lets many registers use the same data bus
Time and instruction execution

- Keep track of detailed timing of each instruction's execution
  - Highly dependent on code
  - Hard to use compilers
  - Not enough control over code generation
  - Interactions with caches/instruction-buffers
- Loops to implement delays
  - Keep track of time in counters
  - Keeps processor busy counting and not doing other useful things
- Timer
  - Take differences between measurements at different points in code
  - Keeps running even if processor is idle to save power
  - An independent "co-processor" to main processor

Time measurement via parallel timers

- Separate and parallel counting unit(s)
  - Co-processor to microprocessor
  - Does not require microprocessor intervention
  - May be a simple counter or a more featured real-time clock
  - Alarms can be set to generate interrupts
- More interesting timer units
  - Self reloading timers for regular interrupts
  - Pre-scaling for measuring larger times
  - Started by external events
Input/output events

- **Input capture**
  - Record time when input event occurred
  - Can be used in later handling of event
- **Output compare**
  - Set output event to happen at a point in the future
  - Reactive outputs
    - e.g., set output to happen a pre-defined time after some input
  - Processor can go on to do other things in the meantime

System bus based communication

- Extend address/data bus outside of chip
- Use specialized devices to implement communication protocol
- Map devices and their registers to memory locations
- Read/write data to receive/send buffers in shared memory or device
- Poll registers for status of communication
- Wait for interrupt from device on interesting events
  - Send completed
  - Receive occurred
Support for communication protocols

- **Built-in device drivers**
  - For common communication protocols
    - e.g., RS232, IrDA, USB, Bluetooth, etc.
  - Serial-line protocols most common as they require fewer pins

- **Serial-line controller**
  - Special registers in memory space for interaction
  - May use timer unit(s) to generate timing events
    - For spacing of bits on signal wire
    - For sampling rate

- **Increase level of integration**
  - No external devices
  - May further eliminate need for shared memory or system bus

---

Microcontrollers

- **Embedded processor with much more integrated on same chip**
  - Processor core + co-processors + memory
  - ROM for program memory, RAM for data memory, special registers to interface to outside world
  - Parallel I/O ports to sense and control wires
  - Timer units to measure time in various ways
  - Communication subsystems to permit direct links to other devices
Microcontrollers (cont’d)

- Other features not usually found in general-purpose CPUs
  - Expanded interrupt handling capabilities
    - Multiple interrupts with priority and selective enable/disable
    - Automatic saving of context before handling interrupt
    - Interrupt vectoring to quickly jump to handlers
  - More instructions for bit manipulations
    - Support operations on bits (signal wires) rather than just words
- Integrated memory and support functions for cheaper system cost
  - Built-in EEPROM, Flash, and/or RAM
  - DRAM controller to handle refresh
  - Page-mode support for faster block transfers

---

The AVR Microcontroller Family

<table>
<thead>
<tr>
<th>Memory Density</th>
<th>Features</th>
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Fully Compatible
### The AVR Microcontroller Family

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Microcontroller we will be using

- Atmel AVR Microcontroller (ATmega16) – 16 MIPS at 16 MHz
  - 8-bit microcontroller (8-bit data, 16-bit instructions) – RISC Architecture
    - 131 instructions (mostly single-cycle – on-chip 2-cycle multiplier)
    - 32 general-purpose registers
    - Internal and external interrupts
  - Memory
    - instruction (16KB Flash memory – read-while-write)
    - boot ROM (512 Byte EEPROM)
    - data (1K static RAM)
  - Timers/counters
    - 2 8-bit and 1 16-bit timer/counters with compare modes and prescalers
    - Real-time clock (32.768 kHz) with separate oscillator
    - Programmable watchdog timer
  - Serial communication interfaces
    - JTAG boundary-scan interface for programming/debugging
    - Programmable USART (universal synchronous/asynchronous receiver transmitter)
    - Two-wire serial interface (can emulate different communication protocols)
    - SPI serial port (serial peripheral interface)
  - Peripheral features
    - Four channels with support for pulse-width modulation
    - Analog-digital converter (8-channel, 10-bit)
    - Up to 32 general-purpose I/O pins (with interrupt support)
  - Six power saving modes

Why did we pick the ATmega16

- Modern microcontroller
- Easy to use C compiler
- Better performance/power than competitors
  - Microchip PIC
  - Motorola 68HC11
  - Intel 80C51
- Excellent support for 16-bit arithmetic operations
- A lot of registers that eliminate moves to and from SRAM
- Single cycle execution of most instructions
- Used in the UC Berkeley sensor mote (2nd half of qtr)
ATMega16 Overview

ATMega16 Pinouts
ATmega16 Internals

General-Purpose Working Registers

- 32 registers
- 6 are special
  - Used for addressing modes
- Addressed in regular memory space
  - Easier to use instructions

![Diagram of General-Purpose Working Registers]

- R0
- R1
- R2
- R3
- R26
- R27
- R28
- R29
- R30
- R31

Register File

X Pointer
Y Pointer
Z Pointer
Operations on Register/Immediate Values

- One cycle register/immediate instructions

Instruction Timing
The Five Memory Areas

- General Purpose Register File = 32 B
- Flash Program Memory = 8 KB ($\leq$ 8 MB)
- SRAM Data Memory = 1 KB ($\leq$ 16 MB)
- I/O Memory = 64 B ($\leq$ 64 B)
- EEPROM Data Memory = 512 B ($\leq$ 16 MB)
Data SRAM $\rightarrow$ Register File (RF)

- "LD Rd,<PTR>" Load indirect
- "LD Rd,<PTR>+" Load indirect with post-increment
- "LD Rd,-<PTR>" Load indirect with pre-decrement
- "LDD Rd,<PTR>+q" Load indirect with displacement (0-63)*

* PTR = X, Y or Z

---

Data SRAM $\leftarrow$ Register File (RF)

- "ST <PTR>,Rd" Store indirect
- "ST <PTR>+,Rd" Store indirect with post-increment
- "ST -<PTR>,Rd" Store indirect with pre-decrement
- "STD <PTR>+q,Rd" Store indirect with displacement (0-63) *

* PTR = X, Y or Z
Data Transfer Program Memory −> RF

- "LDI" Load a register with an immediate value (1 Cycle) *
- "LPM" Transfer a byte from program Memory@Z to R0 (3 Cycles)
- "LPM Rd,Z" Transfer a byte from program Memory@Z to Rd (3 Cycles)
- "LPM Rd,Z+" As above but with post-increment of the Z pointer

* Works on R16 - R31

Register File −> Register File

- "OUT" Transfer a byte from RF to I/O
- "IN" Transfer a byte from I/O to RF
- "MOV" Copy a register to another register
- "MOVW" Copy a register pair to another register pair. Aligned.
C-like Addressing Modes (1)

- Auto Increment/Decrement:
  - C Source:
    ```c
    unsigned char *var1, *var2;
    *var1++ = *--var2;
    ```
  - Generated code:
    ```
    LD R16,-X
    ST Z+,R16
    ```

C-Like Addressing Modes (2)

- Indirect with displacement
- Efficient for accessing arrays and structs

```c
struct square {
    int x_min;
    int x_max;
    int y_min;
    int y_max;
} my_square;
```
### The Status Register - SREG

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<tr>
<th>Bit</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>7</td>
<td>Interrupt Enable (I) - Enables Global Interrupts when Set</td>
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<tr>
<td>6</td>
<td>T Flag</td>
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<tr>
<td>5</td>
<td>Half Carry (H) - Set if an operation has half carry</td>
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<tr>
<td>4</td>
<td>Signed Flag (S) - Used for Signed Tests</td>
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<td>3</td>
<td>Overflow Flag (V) - Set if Signed Overflow</td>
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<td>Negative Flag (N) - Set if a Result is Negative</td>
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<tr>
<td>1</td>
<td>Zero Flag (Z) - Set if a Result is Zero</td>
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<td>0</td>
<td>Carry Flag (C) - Set if an operation has Carry</td>
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### Branch on SREG Settings

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**Branches if Bit Clear**
- BRID
- BRTC
- BRHC
- BRGE
- BRVC
- BRPL
- BRNE
- BRSH, BRCC

**Branches if Bit Set**
- BRIE
- BRTS
- BRHS
- BRLT
- BRVS
- BRMI
- BREQ
- BRCS, BRLO
A Small C Function

/* Return the maximum value of a table of 16 integers */

int max(int *array)
{
    char a;
    int maximum=SMALLEST_NUMBER; /* this is -32768 */

    for (a=0;a<16;a++)
        if (array[a]>maximum)
            maximum=array[a];
    return (maximum);
}

AVR Assembly output

; 7.    for (a=0;a<16;a++)
LDI    R18,LOW(0)
LDI    R19,128
CLR    R22
?0001:
CPI    R22,LOW(16)
BRCC   ?0000

; 8.    {  
      
    }  
; 9.    if (array[a]>maximum)
MOV    R30,R22
CLR    R31
ROL    R31
ADD    R30,R16
ADC    R31,R17

; 10.    maximum=array[a];
MOV    R18,R20
MOV    R19,R21

; 11.    }

; 12.    return (maximum);
MOV    R16,R18
MOV    R17,R19

; 13.    }

RET

Code Size: 46 Bytes, Execution time: 335 cycles
I/O Ports General Features

- Push-pull drivers
- High current drive (sinks up to 40 mA)
- Pin-wise controlled pull-up resistors
- Pin-wise controlled data direction
- Fully synchronized inputs
- Three control/status bits per bit/pin
I/O Port Configurations

- 3 Control/Status Bits per Pin
  - DDx Data Direction Control Bit
  - PORTx Output Data or Pull-Up Control Bit
  - PINx Pin Level Bit

<table>
<thead>
<tr>
<th>DDxn</th>
<th>PORTxn</th>
<th>PUD (In SFIOR)</th>
<th>I/O</th>
<th>Pull-up</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>X</td>
<td>Input</td>
<td>No</td>
<td>Tri-state (Hi-Z)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Input</td>
<td>Yes</td>
<td>PINx will source current if ext. pulled low.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Input</td>
<td>No</td>
<td>Tri-state (Hi-Z)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>X</td>
<td>Output</td>
<td>No</td>
<td>Output Low (Sink)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>X</td>
<td>Output</td>
<td>No</td>
<td>Output High (Source)</td>
</tr>
</tbody>
</table>

Port is Input (Default Configuration)

Direction: Pull-Up: INPUT OFF

Physical Pin

Pull-Up
Port is Open-Collector Input (Switch On Pull-Up)

Port is Output
Sample Code from Lab 1

```
.include "C:\Program Files\Atmel\AVR Tools\AvrAssembler\Appnotes\m16def.inc"
.cseg
ldi r16, 0xff
out DDRB, r16
ldi r16, 0x00
out PORTB, r16
loop:
    jmp loop
```

Alternate Port Functions

- Generalizing I/O ports so that they can be used by other I/O devices
I/O Port Registers

Port A Data Register – PORTA

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read/Write</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
</tr>
<tr>
<td>Initial Value</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Port A Data Direction Register – DDRA

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read/Write</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
<td>RW</td>
</tr>
<tr>
<td>Initial Value</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Port A Input Pins Address – PINA

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read/Write</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Full I/O Register Map (pg. 331)
Instruction Classes (pg. 333)

- Arithmetic/Logic Instructions
- Data Transfer Instructions
- Program Control Instructions
- Bit Set/Test Instructions

Arithmetic/Logical Instructions

- Add Instructions
  - "ADD" Add Two Registers
  - "ADC" Add Two Registers and Carry
  - "INC" Increment a Register
  - "ADIW" Add Immediate to Word *

- Subtract Instructions
  - "SUB" Subtract Two Registers
  - "SBC" Subtract with Carry Two Registers
  - "SUBI" Subtract Immediate from Register*
  - "SBCI" Subtract with Carry Immediate from Register*
  - "DEC" Decrement Register
  - "SBIW " Subtract Immediate From Word**

- Compare Instructions
  - "CP" Compare Two Registers
  - "CPC" Compare with Carry Two Registers
  - "CPI" Compare Register and Immediate*
  - "CPSE" Compare Two Registers and Skip Next Instruction if Equal
16-bit and 32-bit support

- **Carry instructions**
  - Addition, subtraction and comparison
  - Register with register or immediate
  - Zero flag propagation

  ```plaintext
  SUB R16,R24 SUBI R16,1
  SBC R17,R25 SBCI R17,0
  ```

- All branches can be made based on last result
- Direct 16 bit instructions
  - Addition and subtraction of small immediates
  - Pointer arithmetics

Subtracting Two 16-Bit Values

- **R1:R0 – R3:R2** (e.g., $E104 – $E101 )
  - Without zero-flag propagation
    - **R1**: E1 04
    - **R0**: X
    - **Z**: 0
    - sub r0,r2: E1 03
    - sub r1,r3: 00 03
    - Wrong!

  - With zero-flag propagation
    - sub r0,r2: E1 03
    - sub r1,r3: 00 03
    - Correct!
Comparing Two 32-Bit Values

- Example: Compare R3:R2:R1:R0 and R7:R6:R5:R4

  ```
  cp r0,r4
  cpc r1,r5
  cpc r2,r6
  cpc r3,r7
  ```

- After last instruction, status register indicates equal, higher, lower, greater (signed), or less than (signed)

Arithmetic/Logical Instructions (cont’d)

- Multiply instructions
  - “MUL” 8x8 -> 16 (UxU)
  - “MULS” 8x8 -> 16 (SxS)*
  - “MULSU” 8x8 -> 16 (SxU)**

    * Works on Registers R16 - R31
    ** Works on Registers R16-R23

  The result is present in R1:R0. All multiplication instructions are 2 cycles.

- Logical Instructions
  - “AND” Logical AND Two Registers
  - “ANDI” Logical AND Immediate and Register *
  - “OR” Logical OR Two Registers
  - “ORI” Logical OR Immediate and Register *
  - “EOR” Logical XOR Two Registers
Arithmetic/Logical Instructions (cont’d)

- **Shift / Rotate Instructions**
  - “LSL” Logical Shift Left
  - “LSR” Logical Shift Right
  - “ROL” Rotate Left Through Carry
  - “ROR” Rotate Right Through Carry
  - “ASR” Arithmetic Shift Right

![Diagram of shift and rotate instructions]

Data Transfer Instruction Types

- **Data SRAM <-> Register File** (2)
- **Program Memory -> Register File** (1/3)
- **I/O Memory <-> Register File** (1)
- **Register File <-> Register File** (1)
Data Transfer RF <-> SRAM Stack

- **“PUSH”** PUSH a register on the stack
  - Decrements stack pointer by 1
  - Decremented by 2 when a return address is pushed on the stack
- **“POP”** POP a register from the stack
  - Increments stack pointer by 1
  - Incremented by 2 when a return address is popped off on return

- Stack grows from higher to lower memory locations
  - Must start after $0060$ (past I/O registers)
  - Size of pointer varies depending on memory available

Flow Control

- Unconditional Jumps
- Conditional Branches
- Subroutine Call and Returns
Unconditional Jump Instructions

- "RJMP" Relative Jump *
- "JMP" Absolute Jump **

* Reaches ±2K instructions from current program location. Reaches all locations for devices up to 8KBytes (wrapping)
** 4-Byte Instruction

Conditional Branches (Flag Set)

- "BREQ" Branch if Equal
- "BRSH" Branch if Same or Higher
- "BRGE" Branch if Greater or Equal (Signed)
- "BRHS" Branch if Half Carry Set
- "BRCS" Branch if Carry Set
- "BRMI" Branch if Minus
- "BRVS" Branch if Overflow Flag Set
- "BRTS" Branch if T Flag Set
- "BRIE" Branch if Interrupt Enabled
Subroutine Call and Return

- "RCALL" Relative Subroutine Call *
- "CALL" Absolute Subroutine Call **

- "RET" Return from Subroutine
- "RETI" Return from Interrupt Routine

* Reaches ±2K instructions from current program location.
** Reaches all locations for devices up to 8KBytes (wrapping)

Bit Set/Clear and Bit Test Instructions

- "SBR" Set Bit(s) in Register *
- "SBI" Set Bit in I/O Register **
- "SBRS" Skip if Bit in Register Set
- "SBIS" Skip if Bit in I/O Register Set **
- "CBR" Clear Bit(s) in Register *
- "CBI" Clear Bit in I/O Register **
- "SBRC" Skip if Bit in Register Clear
- "SBIC" Skip if Bit in I/O Register Clear **

* Works on Registers R16 - R31
** Works on I/O Addresses $00 - $1F
Programming the ATmega16

- Traditional in-system programming
  - In-system programmable FLASH, EEPROM, and lock bits
  - Programmable at all frequencies
  - Programmable at any value of Vcc above 2.7V
  - Only four pins + ground required
  - Requires adapter device to control programming pins

- Self programming
  - The AVR reprograms itself without any external components
  - Re-programmable through any communication interface
    - Does not have to be removed from board
    - Uses existing communication ports
  - Critical functions still operating
    - device is running during programming

AVR JTAG Interface

- Complies to IEEE std 1149.1 (JTAG)
- Boundary-scan for efficient PCB test
  - Standard for interconnection test
  - All I/O pins controllable and observable from tester
- On-chip debugging in production
JTAG In System Programming

- The JTAG interface can be used to program the Flash and EEPROM
- Save time and production cost
  - No additional programming stage
  - Programming time independent of system clock

JTAG In-Circuit Emulator

- Controlled by AVR Studio
- Real-Time emulation in actual silicon
  - Debug the real device at the target board
  - Talks directly to the device through the 4-pin JTAG interface
- Supports
  - Program and data breakpoints
  - Full execution control
  - Full I/O-view and watches
AVR Studio

- Integrated development environment for AVR
- Front end for the AVR simulator and emulators
- C and assembly source level debugging
- Supports third party compilers
- Maintains project information
- Freely available from www.atmel.com
- Third-party compilers