EMBEDDED SYSTEMS (18EC62)

MODULE – 4

Embedded System Design Concepts

Characteristics and Quality Attributes of Embedded Systems

Characteristics of Embedded Systems

- Embedded systems possess certain specific characteristics.
  - These characteristics are unique to each embedded system.
- Some of the important characteristics of an embedded system are:
  1. Application and domain specific
  2. Reactive and Real Time
  3. Operates in harsh environments
  4. Distributed
  5. Small size and weight
  6. Power concerns

Characteristics of Embedded Systems (continued)

1. Application and Domain Specific
   - Each embedded system has certain functions to perform and they are developed in such a manner to do the intended functions only.
   - They cannot be used for any other purpose.
     - For example, the embedded control unit of a microwave oven cannot be replaced with an air conditioner's embedded control unit, because the embedded control units of microwave oven and air conditioner are specifically designed to perform certain specific tasks.
     - Also an embedded control unit developed for a particular domain, say telecom, cannot be replaced with another control unit designed to serve another domain like consumer electronics.

Characteristics of Embedded Systems (continued)

2. Reactive and Real Time
   - Embedded systems are in constant interaction with the real world through sensors and user-defined input devices which are connected to the input port of the system.
   - Any changes happening in the real world (which is called an Event) are captured by the sensors or input devices in Real Time and the control algorithm running inside the unit reacts in a designed manner to bring the controlled output variables to the desired level.
   - Embedded systems produce changes in output in response to the changes in the input.
     - So they are generally referred as Reactive Systems.

Characteristics of Embedded Systems (continued)

- Real Time System operation means the timing behaviour of the system should be deterministic.
  - The system should respond to requests or tasks in a known amount of time.
- A Real Time system should not miss any deadlines for tasks or operations.
- It is not necessary that all embedded systems should be Real Time in operations.
- Embedded applications or systems which are mission critical, like flight control systems, Antilock Brake Systems (ABS), etc. are examples of Real Time systems.

Characteristics of Embedded Systems (continued)

3. Operates in Harsh Environment
    - The environment in which the embedded system deployed may be a dusty one or a high temperature zone or an area subject to vibrations and shock.
    - Systems placed in such areas should be capable to withstand all these adverse operating conditions.
    - The design should take care of the operating conditions of the area where the system is going to implement.
        - For example, if the system needs to be deployed in a high temperature zone, then all the components used in the system should be of high temperature grade.
        - Also proper shock absorption techniques should be provided to systems which are going to be commissioned in places subject to high shock.
    - Power supply fluctuations, corrosion and component aging, etc. are the other factors that need to be taken into consideration for embedded systems to work in harsh environments.

Characteristics of Embedded Systems (continued)

4. Distributed
   - The term ***distributed*** means that embedded systems may be a part of larger systems.
   - Many numbers of such distributed embedded systems form a single large embedded control unit.
     - For example, an automatic vending machine.
       - It contains a card reader (for pre-paid vending systems), a vending unit, etc.
       - Each of them are independent embedded units but they work together to perform the overall vending function.
     - Another example is the Automated Teller Machine (ATM).
       - It contains a card reader embedded unit, responsible for reading and validating the user's ATM card, transaction unit for performing transactions, a currency counter for dispatching/vending currency to the authorised person and a printer unit for printing the transaction details.
       - We can visualise these as independent embedded systems, but they work together to achieve a common goal.
     - Another typical example of a distributed embedded system is the Supervisory Control And Data Acquisition (SCADA) system used in Control & Instrumentation applications, which contains physically distributed individual embedded control units connected to a supervisory module.

Characteristics of Embedded Systems (continued)

5. Small Weight and Size
   - Product aesthetics is an important factor in choosing a product.
   - For example, when you plan to buy a new mobile phone, you may make a comparative study on the pros and cons of the products available in the market.
     - Definitely the product aesthetics (size, weight, shape, style, etc.) will be one of the deciding factors to choose a product.
   - People believe in the phrase ***"Small is beautiful"***.
   - Moreover it is convenient to handle a compact device than a bulky product.
   - In embedded domain also *compactness* is a significant deciding factor.
     - Most of the application demands small sized and low weight products.

Characteristics of Embedded Systems (continued)

6. Power Concerns
   - Power management is another important factor that needs to be considered in designing embedded systems.
   - Embedded systems should be designed in such a way as to minimise the heat dissipation by the system.
   - The production of high amount of heat demands cooling requirements like cooling fans which in turn occupies additional space and make the system bulky.
   - Select the design according to the low power components like low dropout regulators, and controllers/processors with power saving modes.
   - Also power management is a critical constraint in battery operated application.
     - The more the power consumption the less is the battery life.

Quality Attributes of Embedded Systems

- Quality attributes are the non-functional requirements that need to be documented properly in any system design.
- If the quality attributes are more concrete and measurable it will give a positive impact on the system development process and the end product.
- The quality attributes in any embedded system development are broadly classified into two:
  - Operational Quality Attributes
  - Non-Operational Quality Attributes

Operational Quality Attributes

- The operational quality attributes represent the relevant quality attributes related to the embedded system when it is in the operational mode or 'online' mode.
- The important operational quality attributes are:
  1. Response
  2. Throughput
  3. Reliability
  4. Maintainability
  5. Security
  6. Safety

Operational Quality Attributes (continued)

1. Response
   - *Response* is a measure of quickness of the system.
   - It gives you an idea about how fast the system is tracking the changes in input variables.
   - Most of the embedded systems demand fast response which should be almost Real Time.
     - For example, an embedded system deployed in flight control application should respond in a Real Time manner.
     - Any response delay in the system will create potential damages to the safety of the flight as well as the passengers.
   - It is not necessary that all embedded systems should be Real Time in response.
     - For example, the response time requirement for an electronic toy is not at all time-critical.
     - There is no specific deadline that this system should respond within this particular timeline.

Operational Quality Attributes (continued)

2. Throughput
   - *Throughput* deals with the efficiency of a system.
   - Throughput can be defined as the rate of production or operation of a defined process over a stated period of time.
   - The rates can be expressed in terms of units of products, batches produced, or any other meaningful measurements.
     - In the case of a Card Reader, throughput means how many transactions the Reader can perform in a minute or in an hour or in a day.
   - Throughput is generally measured in terms of 'Benchmark'.
     - A 'Benchmark' is a reference point by which something can be measured.
     - Benchmark can be a set of performance criteria that a product is expected to meet or a standard product that can be used for comparing other products of the same product line.

Operational Quality Attributes (continued)

3. Reliability
   - *Reliability* is a measure of how much percentage you can rely upon the proper functioning of the system or what is the percentage susceptibility of the system to failures.
   - System reliability is defined using two terms:
     - **Mean Time Between Failures (MTBF)**
       - Gives the frequency of failures in hours/weeks/months.
     - **Mean Time To Repair (MTTR)**
       - Specifies how long the system is allowed to be out of order following a failure.
       - For an embedded system with critical application need, it should be of the order of minutes.

Operational Quality Attributes (continued)

4. Maintainability
   - *Maintainability* deals with support and maintenance to the end user or client in case of technical issues and product failures or on the basis of a routine system check-up.
   - Reliability and maintainability are considered as two complementary disciplines.
   - A more reliable system means a system with less corrective maintainability requirements and vice versa.
   - Maintainability can be broadly classified into two categories:
     - **Scheduled or Periodic Maintenance (preventive maintenance)**
       - For example, replacing the cartridge of a printer after each 'n' number of printouts to get quality prints.
     - **Maintenance to unexpected failures (corrective maintenance)**
       - For example, repairing the printer if the paper feeding part fails.

Operational Quality Attributes (continued)

- Maintainability is also an indication of the availability of the product for use.
- In any embedded system design, the ideal value for availability is expressed as

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where

A_i = Availability in the ideal condition

$MTBF$ = Mean Time Between Failures

$MTTR$ = Mean Time To Repair

Operational Quality Attributes (continued)

Numerical Example 1

- The Mean Time Between Failure (MTBF) of an embedded product is 4 months and the Mean Time To Repair (MTTR) of the product is 2 weeks. What is the availability of the product?
- Solution:

Given $MTBF$ = 4 months = 120 days

and $MTTR$ = 2 weeks = 14 days

We know that $A_i = \frac{MTBF}{MTBF+MTTR}$

$$A_i = \frac{120}{120+14} = \frac{120}{134}$$

$$A_i = 0.8955 \text{ or } 89.55\%$$

Operational Quality Attributes (continued)

Numerical Example 2

- The availability of an embedded product is 90%. The Mean Time Between Failure (MTBF) of the product is 30 days. What is the Mean Time To Repair (MTTR) in days/hours for the product?
- Solution:

Given $A_i = 90\% = 0.9$

and MTBF = 30 days

We know that $A_i = \frac{MTBF}{MTBF+MTTR}$

$$MTBF + MTTR = \frac{MTBF}{A_i}$$

$$MTTR = \frac{MTBF}{A_i} - MTBF$$

$$MTTR = \frac{30}{0.9} - 30$$

$$MTTR = 3.33\ days\ or\ 80\ hours$$

Operational Quality Attributes (continued)

5. Security
   - Confidentiality, Integrity, and Availability are the three major measures of information security.
     - Confidentiality deals with the protection of data and application from unauthorised disclosure.
     - Integrity deals with the protection of data and application from unauthorised modification.
     - Availability deals with protection of data and application from unauthorized users.
   - A very good example of the 'Security' aspect in an embedded product is a Personal Digital Assistant (PDA).
     - The PDA can be either a shared resource (e.g. PDAs used in LAB setups) or an individual one.
   - If it is a shared one there should be some mechanism in the form of a user name and password to access into a particular person's profile—This is an example of 'Availability'.
   - Also all data and applications present in the PDA need not be accessible to all users.
   - Some of them are specifically accessible to administrators only.
   - For achieving this, Administrator and user levels of security should be implemented —An example of Confidentiality.
   - Some data present in the PDA may be visible to all users but there may not be necessary permissions to alter the data by the users.
   - That is Read Only access is allocated to all users—An example of Integrity.

Operational Quality Attributes (continued)

6. Safety
   - Safety deals with the possible damages that can happen to the operators, public and the environment due to the breakdown of an embedded system or due to the emission of radioactive or hazardous materials from the embedded products.
   - The breakdown of an embedded system may occur due to a hardware failure or a firmware failure.
   - Safety analysis is a must in product engineering to evaluate the anticipated damages and determine the best course of action to bring down the consequences of the damages to an acceptable level.
   - Some of the safety threats are sudden (like product breakdown) and some of them are gradual (like hazardous emissions from the product).

Non-Operational Quality Attributes

- The quality attributes that needs to be addressed for the product 'not’ on the basis of operational aspects are grouped under this category.
- The important non-operational quality attributes are:
  1. Testability & Debug-ability
  2. Evolvability
  3. Portability
  4. Time-to-prototype and market
  5. Per unit and total cost

Non-Operational Quality Attributes (continued)

1. Testability & Debug-ability
   - *Testability* deals with how easily one can test his/her design, application and by which means he/she can test it.
     - For an embedded product, testability is applicable to both the *embedded hardware* and *firmware*.
     - Embedded hardware testing ensures that the peripherals and the total hardware functions in the desired manner, whereas firmware testing ensures that the firmware is functioning in the expected way.
   - *Debug-ability* is a means of debugging the product as such for figuring out the probable sources that create unexpected behaviour in the total system.
     - Debug-ability has two aspects in the embedded system development context, namely, *hardware level debugging* and *firmware level debugging*.
     - Hardware debugging is used for figuring out the issues created by hardware problems whereas firmware debugging is employed to figure out the probable errors that appear as a result of flaws in the firmware.

Non-Operational Quality Attributes (continued)

2. Evolvability
    - *Evolvability* is referred as the non-heritable variation (in Biology)
    - For an embedded system, the quality attribute 'Evolvability’ refers to the ease with which the embedded product (including firmware and hardware) can be modified to take advantage of new firmware or hardware technologies.

Non-Operational Quality Attributes (continued)

3. Portability
   - *Portability* is a measure of 'system independence’.
   - An embedded product is said to be portable if the product is capable of functioning 'as such' in various environments, target processors/controllers and embedded operating systems.
   - A standard embedded product should always be flexible and portable.
   - In embedded products, the term 'porting' represents the migration of the embedded firmware written for one target processor (e.g. Intel x86) to a different target processor (say Hitachi SH3 processor).

Non-Operational Quality Attributes (continued)

- If the firmware is written in a high level language like ‘C’, it is very easy to port the firmware
  - It has only few target processor-specific functions which can be replaced with the ones for the new target processor and re-compiling the program for the new target processor-specific settings.
  - The program then needs to be re-compiled to generate the new target processor-specific machine codes.
- If the firmware is written in Assembly Language for a particular family of processor (say x86 family), the portability is poor.
  - It is very difficult to translate the assembly language instructions to the new target processor specific language.

Non-Operational Quality Attributes (continued)

4. Time-to-Prototype and Market
   - *Time-to-market* is the time elapsed between the conceptualisation of a product and the time at which the product is ready for selling (for commercial product) or use (for non-commercial products).
   - The commercial embedded product market is highly competitive and time-to-market the product is a critical factor in the success of a commercial embedded product.
     - Competitor might release their product before you do.
     - The technology used might have superseded with a new technology.

Non-Operational Quality Attributes (continued)

- Product prototyping helps a lot in reducing time-to-market.
- Prototyping is an informal kind of rapid product development in which the important features of the product under consideration are developed.
- The time-to-prototype is also another critical factor.
  - If the prototype is developed faster, the actual estimated development time can be brought down significantly.
  - In order to shorten the time to prototype, make use of all possible options like the use of off-the-shelf components, re-usable assets, etc.

Non-Operational Quality Attributes (continued)

5. Per Unit Cost and Revenue
   - *Cost* is a factor which is closely monitored by both end user and product manufacturer.
   - Cost is a highly sensitive factor for commercial products.
   - Any failure to position the cost of a commercial product at a nominal rate, may lead to the failure of the product in the market.
   - Proper market study and cost benefit analysis should be carried out before taking a decision on the per-unit cost of the embedded product.
   - The budget and total system cost should be properly balanced to provide a marginal profit.

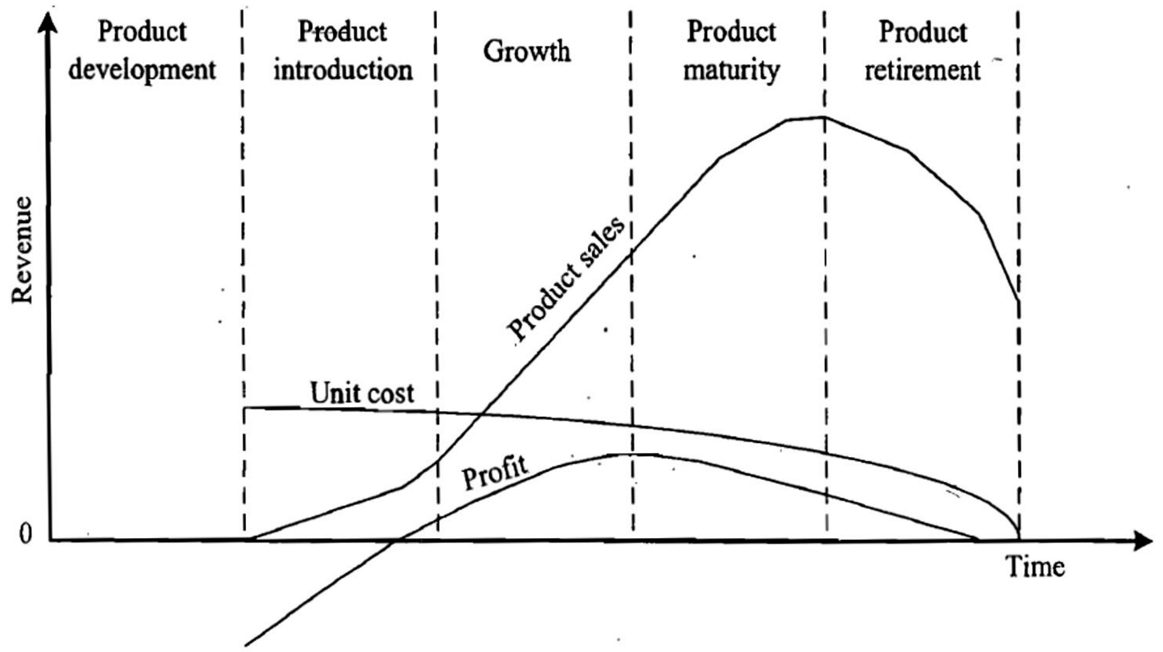
Non-Operational Quality Attributes (continued)

- The product life cycle of every embedded product has different phases:

1. Design and Development Phase:
   - The product idea generation, prototyping, Roadmap definition, actual product design and development are the activities carried out during this phase.
   - There is only investment and no returns.
2. Product Introduction Phase:
   - Once the product is ready to sell, it is introduced to the market.
   - During the initial period the sales and revenue will be low.
   - There won't be much competition and the product sales and revenue increases with time.
3. Growth Phase
   - The product grabs high market share.
4. Maturity Phase:
   - The growth and sales will be steady and the revenue reaches at its peak.
5. Product Retirement/Decline Phase:
   - Drop in sales volume, market share and revenue.
   - The decline happens due to various reasons like competition from similar product with enhanced features or technology changes, etc.
   - At some point of the decline stage, the manufacturer announces discontinuing of the product.

Non-Operational Quality Attributes (continued)

- The different stages of the embedded products life cycle—revenue, unit cost and profit in each stage are represented in the following Product Life-cycle graph.



Product Life Cycle (PLC) curve

Non-Operational Quality Attributes (continued)

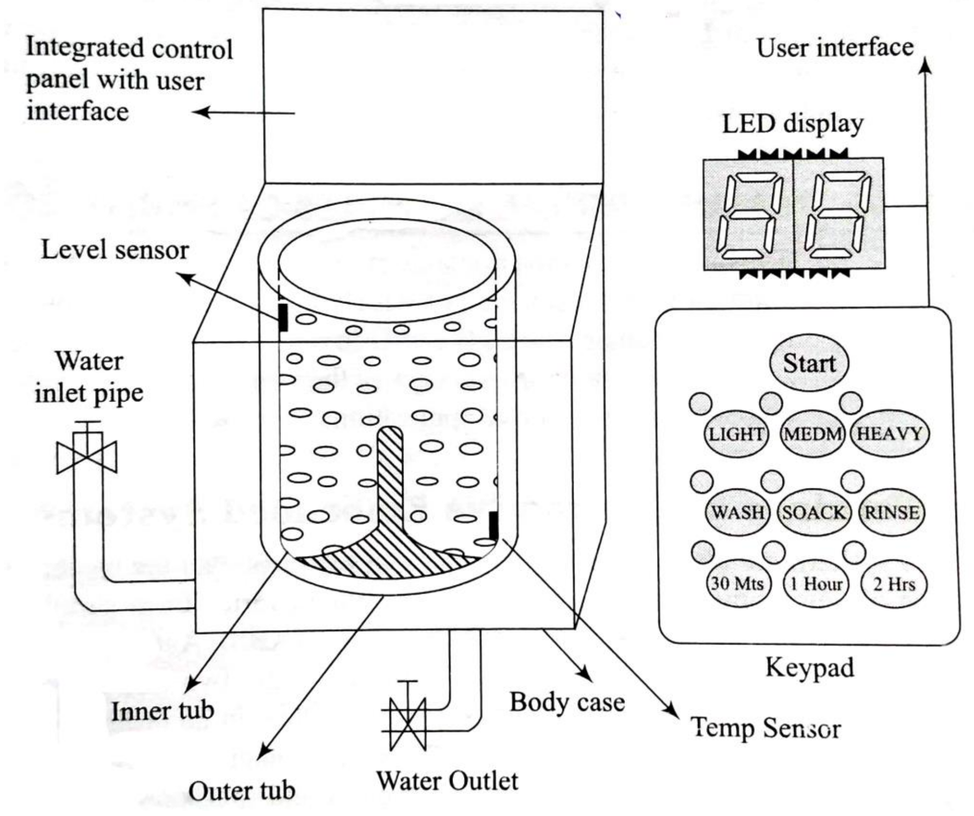
- From the graph, it is clear that the total revenue increases from the product introduction stage to the product maturity stage.
- The revenue peaks at the maturity stage and starts falling in the decline/retirement Stage.
- The unit cost is very high during the introductory stage.
  - A typical example is cell phone; if you buy a new model of cell phone during its launch time, the price will be high and you will get the same model with a very reduced price after three or four months of its launching).
- The profit increases with increase in sales and attains a steady value and then falls with a dip in sales.
- You can see a negative value for profit during the initial period.
  - It is because during the product development phase there is only investment and no returns.
- Profit occurs only when the total returns exceed the investment and operating cost.

Embedded Systems – Application and Domain Specific

Washing Machine – Application-Specific Embedded System

- Washing machine is a typical example of an embedded system providing extensive support in home automation applications.
- An embedded system contains sensors, actuators, control unit and application-specific user interfaces like keyboards, display units, etc.
    - All these components can be seen in a washing machine.

Washing Machine – Application-Specific Embedded System (continued)



Washing Machine – Functional Block Diagram

Washing Machine – Application-Specific Embedded System (continued)

- The actuator part of the washing machine consists of a motorised agitator, tumble tub, water drawing pump and inlet valve to control the flow of water into the unit.
- The sensor part consists of the water temperature sensor, level sensor, etc.
- The control part contains a microprocessor/controller based board with interfaces to the sensors and actuators.
- The sensor data is fed back to the control unit and the control unit generates the necessary actuator outputs.
- The control unit also provides connectivity to user interfaces like keypad for setting the washing time, selecting the type of material to be washed like light, medium, heavy duty, etc.
- User feedback is reflected through the display unit and LEDs connected to the control board.

Washing Machine – Application-Specific Embedded System (continued)

Top Loading
Washing Machine

Front Loading
Washing Machine

Washing Machine – Application-Specific Embedded System (continued)

- Washing machine comes in two models, namely, *top loading* and *front loading* machines.
- In top loading models the agitator of the machine twists back and forth and pulls the cloth down to the bottom of the tub.
  - On reaching the bottom of the tub the clothes work their way back up to the top of the tub where the agitator grabs them again and repeats the mechanism.
- In the front loading machines, the clothes are tumbled and plunged into the water over and over again.
- This is the first phase of washing.

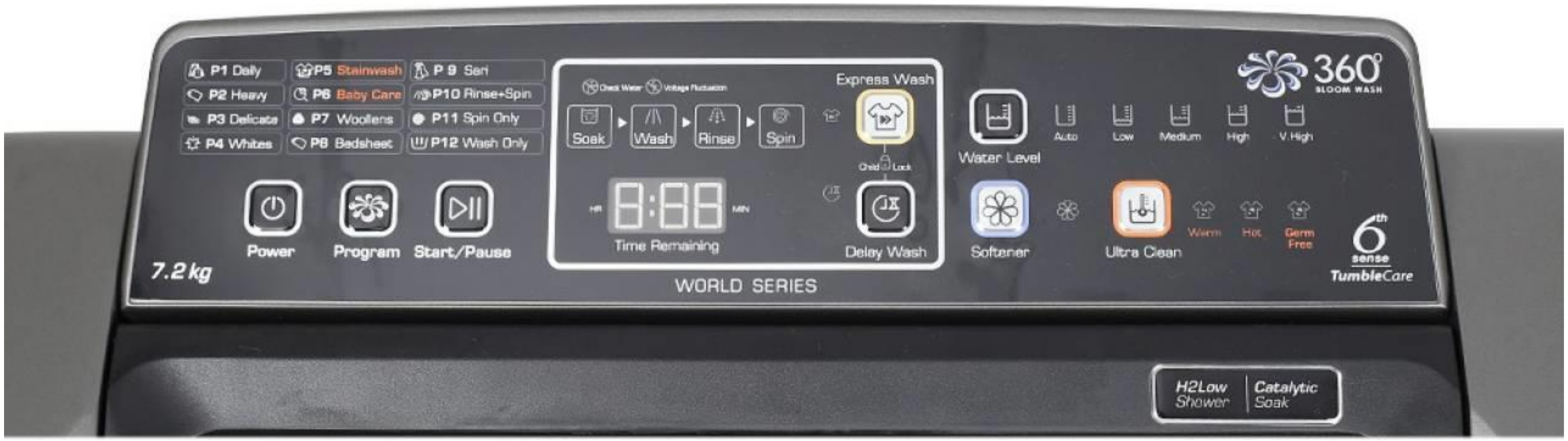
Washing Machine – Application-Specific Embedded System (continued)

- In the second phase of washing, water is pumped out from the tub and the inner tub uses centrifugal force to wring out more water from the clothes by spinning at several hundred Rotations Per Minute (RPM).
- This is called a *'Spin Phase'.*
- The inner tub of the machine contains a number of holes and during the spin cycle the inner tub spins, and forces the water out through these holes to the stationary outer tub from which it is drained off through the outlet pipe.

Washing Machine – Application-Specific Embedded System (continued)

- The design of washing machines may vary from manufacturer to manufacturer, but the general principle underlying in the working of the washing machine remains the same.
- The basic controls consist of a timer, cycle selector mechanism, water temperature selector, load size selector and start button.
- The mechanism includes the motor, transmission, clutch, pump, agitator, inner tub, outer tub and water inlet valve.
- Water inlet valve connects to the water supply line using at home and regulates the flow of water into the tub.

Washing Machine – Application-Specific Embedded System (continued)



Integrated Control Panel of a Washing Machine

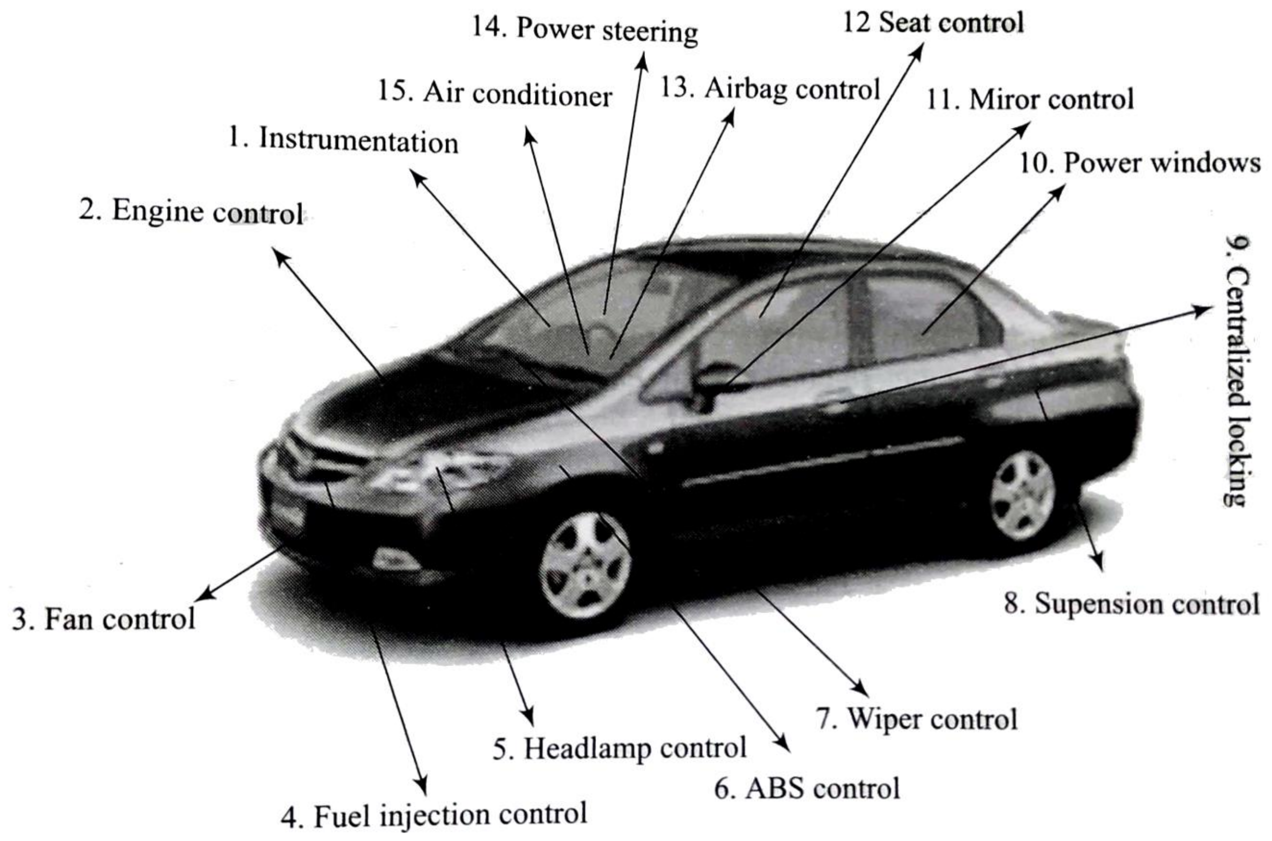
Washing Machine – Application-Specific Embedded System (continued)

- The integrated control panel consists of a microprocessor/controller based board with I/O interfaces and a control algorithm running in it.
- Input interface includes the keyboard which consists of wash type selector namely *Wash, Spin and Rinse*, cloth type selector namely *Light, Medium, Heavy duty* and washing time setting, etc.
- The output interface consists of LED/LCD displays, status indication LEDs, etc. connected to the I/O bus of the controller.
- The other types of I/O interfaces which are invisible to the end user are different kinds of sensor interfaces, namely, water temperature sensor, water level sensor, etc. and actuator interface including motor control for agitator and tub movement control, inlet water flow control, etc.

Automotive – Domain-Specific Embedded System

- The major application domains of embedded systems are consumer, industrial, automotive, telecom, etc.
  - Telecom and automotive industry holds a big market share.
- Figure below gives an overview of the various types of electronic control units employed automotive applications.

Automotive – Domain-Specific Embedded System (continued)



Embedded System in the Automotive Domain

Inner Workings of Automotive Embedded Systems

- Automotive embedded systems are the one where electronics take control over the mechanical systems.
- The presence of automotive embedded system in a vehicle varies from simple mirror and wiper controls to complex air bag controller and antilock brake systems (ABS).
- Automotive embedded systems are normally built around microcontrollers or DSPs or a hybrid of the two and are generally known as *Electronic Control Units (ECUs).*
- The number of embedded controllers in an ordinary vehicle varies from 20 to 40 whereas a luxury vehicle like Mercedes S and BMW 7 may contain 75 to 100 numbers of embedded controllers.

Inner Workings of Automotive Embedded Systems (continued)

- Government regulations on fuel economy, environmental factors and emission standards and increasing customer demands on safety, comfort and infotainment forces the automotive manufactures to opt for sophisticated embedded control units within the vehicle.
- The first embedded system used in automotive application was the microprocessor based fuel injection system introduced by Volkswagen 1600 in 1968.

Inner Workings of Automotive Embedded Systems (continued)

- The electronic control units (ECUs) used in the automotive embedded industry can be broadly classified into two:
  - High-speed Electronic Control Units (HECUs):
    - These are deployed in critical control units requiring fast response.
    - They include fuel injection systems, antilock brake systems, engine control, electronic throttle, steering controls, transmission control unit and central control unit.
  - Low-speed Electronic Control Units (LECUs):
    - These are deployed in applications where response time is not so critical.
    - They generally are built around low cost microprocessors/microcontrollers and digital signal processors.
    - Audio controllers, passenger and driver door locks, door glass controls (power windows), wiper control, mirror control, seat control systems, head lamp and tail lamp controls, sun roof control unit etc. are examples of LECUs.

Automotive Communication Buses

- Automotive applications make use of serial buses for communication, which greatly reduces the amount of wiring required inside a vehicle.
- Different types of serial interface buses are:
  - Controller Area Network (CAN) Bus
  - Local Interconnect Network (LIN) Bus
  - Media-Oriented System Transport (MOST) Bus

Automotive Communication Buses (continued)

- Controller Area Network (CAN) Bus
  - CAN Bus was originally proposed by Robert Bosch, pioneer in the Automotive embedded solution providers.
  - It supports medium speed (ISO11519-class B with data rates up to 125 Kbps) and high speed (IS011898 class C with data rates up to 1 Mbps) data transfer.
  - CAN is an event-driven protocol interface with support for error handling in data transmission.
  - It is generally employed in safety system like airbag control; power train systems like engine control and Antilock Brake System (ABS); and navigation systems like GPS.

Automotive Communication Buses (continued)

- Local Interconnect Network (LIN) Bus
  - LIN bus is a single master multiple slave (up to 16 independent slave nodes) communication interface.
  - LIN is a low speed, single wire communication interface with support for data rates up to 20 Kbps and is used for sensor/actuator interfacing.
  - LIN bus follows the master communication triggering technique to eliminate the possible bus arbitration problem that can occur by the simultaneous talking of different slave nodes connected to a single interface bus.
  - LIN bus is employed in applications like mirror controls, fan controls, seat positioning controls, window controls, and position controls where response time is not a critical issue.

Automotive Communication Buses (continued)

- Media-Oriented System Transport (MOST) Bus
  - MOST Bus is targeted for high-bandwidth automotive multimedia networking (e.g. audio/video, infotainment system interfacing), used primarily in European cars.
  - It is a multimedia fibre-optic point-to-point network implemented in a star, ring or daisy-chained topology over optical fibre cables.
  - The MOST bus specifications define the physical (electrical and optical parameters) layer as well as the application layer, network layer, and media access control.
  - MOST bus is an optical fibre cable connected between the Electrical Optical Converter (EOC) and Optical Electrical Converter (OEC), which would translate into the optical cable MOST bus.

Hardware Software Co-Design and Program Modelling

Hardware Software Co-Design

- In the traditional embedded system development approach, the hardware software partitioning is done at an early stage.
  - Engineers from the software group take care of the software architecture development and implementation, whereas engineers from the hardware group are responsible for building the hardware required for the product.
  - There is less interaction between the two teams and the development happens either serially or in parallel.
- Once the hardware and software are ready, the integration is performed.
- The increasing competition in the commercial market and need for reduced 'time-to-market' the product calls for a novel approach for embedded system design in which the hardware and software are co-developed instead of independently developing both.

Hardware Software Co-Design (continued)

- During the co-design process, the product requirements captured from the customer are converted into system level needs or processing requirements.
  - At this point of time it is not segregated as either hardware requirement or software requirement, instead it is specified as functional requirement.
- The system level processing requirements are then transferred into functions which can be simulated and verified against performance and functionality.
- The Architecture design follows the system design.
  - The partition of system level processing requirements into hardware and software takes place during the architecture design phase.
  - Each system level processing requirement is mapped as either hardware and/or software requirement.
  - The partitioning is performed based on the hardware-software trade-offs.

Hardware Software Co-Design (continued)

- The architectural design results in the detailed behavioural description of the hardware requirement and the definition of the software required for the hardware.
- The processing requirement behaviour is usually captured using computational models.
  - The models representing the software processing requirements are translated into firmware implementation using programming languages.

Fundamental Issues in Hardware Software Co-Design

- The fundamental issues in hardware software co-design are:
  - Selecting the Model
  - Selecting the Architecture
  - Selecting the Language
  - Partitioning System Requirements into Hardware and Software

Fundamental Issues in Hardware Software Co-Design (continued)

- Selecting the Model
  - In hardware software co-design, models are used for capturing and describing the system characteristics.
  - *A model is a formal system consisting of objects and composition rules.*
  - It is hard to make a decision on which model should be followed in a particular system design.
  - Most often designers switch between a variety of models from the requirements specification to the implementation aspect of the system design.
    - The reason being, the objective varies with each phase.
      - For example, at the specification stage, only the functionality of the system is in focus and not the implementation information.
      - When the design moves to the implementation aspect, the information about the system components is revealed and the designer has to switch to a model capable of capturing the system's structure.

Fundamental Issues in Hardware Software Co-Design (continued)

- Selecting the Architecture
  - A model only captures the system characteristics and does not provide information on *'how the system can be manufactured?'*.
  - The *architecture* specifies how a system is going to implement in terms of the number and types of different components and the interconnection among them.
  - The commonly used architectures in system design are Controller Architecture, Datapath Architecture, Complex Instruction Set Computing (CISC), Reduced Instruction Set Computing (RISC), Very Long Instruction Word Computing (VLIW), Single Instruction Multiple Data (SIMD), Multiple Instruction Multiple Data (MIMD), etc.
    - Some of them fall into Application Specific Architecture Class (like controller architecture), while others fall into either general purpose architecture class (CISC, RISC, etc.) or Parallel processing class (like VLIW, SIMD, MIMD, etc.).

Fundamental Issues in Hardware Software Co-Design (continued)

- The controller architecture implements the finite state machine model using a state register and two combinational circuits.
  - The state register holds the present state and the combinational circuits implement the logic for next state and output.
- The datapath architecture is best suited for implementing the data flow graph model where the output is generated as a result of a set of predefined computations on the input data.
  - A datapath represents a channel between the input and output
    - The datapath may contain registers, counters, register files, memories and ports along with high speed arithmetic units.
  - Ports connect the datapath to multiple buses.
  - Most of the time the arithmetic units are connected in parallel with pipelining support for bringing high performance.

Fundamental Issues in Hardware Software Co-Design (continued)

- The Finite State Machine Datapath (FSMD) architecture combines the controller architecture with datapath architecture.
  - It implements a controller with datapath.
  - The controller generates the control input whereas the datapath processes the data.
  - The datapath contains two types of I/O ports, out of which one acts as the control port for receiving/sending the control signals from/to the controller unit and the second I/O port interfaces the datapath with external world for data input and data output.
  - Normally the datapath is implemented in a chip and the I/O pins of the chip acts as the data input output ports for the chip resident data path.

Fundamental Issues in Hardware Software Co-Design (continued)

- The Complex Instruction Set Computing (CISC) architecture uses an instruction set representing complex operations.
  - It is possible for a CISC instruction set to perform a large complex operation with a single instruction.
    - e.g. Reading a register value and comparing it with a given value and then transfer the program execution to a new address location is done using the CJNE instruction for 8051 ISA).
  - The use of a single complex instruction in place of multiple simple instructions greatly reduces the program memory access and program memory size requirement.
  - However it requires additional silicon for implementing microcode decoder for decoding the CISC instruction.
  - The datapath for the CISC processor is complex.

Fundamental Issues in Hardware Software Co-Design (continued)

- The Reduced Instruction Set Computing (RISC) architecture uses instruction set representing simple operations.
  - It requires the execution of multiple RISC instructions to perform a complex operation.
  - The datapath of RISC architecture contains a large register file for storing the operands and output.
  - RISC instruction set is designed to operate on registers.
  - RISC architecture supports extensive pipelining.

Fundamental Issues in Hardware Software Co-Design (continued)

- The Very Long Instruction Word (VLIW) architecture implements multiple functional units (ALUs, multipliers, etc.) in the datapath.
  - The VLIW instruction packages one standard instruction per functional unit of the datapath.
- Parallel processing architecture implements multiple concurrent Processing Elements (PEs) and each processing element may associate a datapath containing register and local memory.
  - Single Instruction Multiple Data (SIMD) and Multiple Instruction Multiple Data (MIMD) architectures are examples for parallel processing architecture.
  - In SIMD architecture, a single instruction is executed in parallel with the help of the Processing Elements.
    - The scheduling of the instruction execution and controlling of each PE is performed through a single controller.
    - The SIMD architecture forms the basis of re-configurable processor.
  - In MIMD architecture, the Processing Elements execute different instructions at a given point of time.
    - The MIMD architecture forms the basis of multiprocessor systems.
    - The PEs in a multiprocessor system communicates through mechanisms like shared memory and message passing.

Fundamental Issues in Hardware Software Co-Design (continued)

- Selecting the Language
  - A programming language captures a 'Computational Model' and maps it into architecture.
  - There is no hard and fast rule to specify this language should be used for capturing this model.
  - A model can be captured using multiple programming languages like C, C++, C#, Java, etc. for software implementations and languages like VHDL, System C, Verilog, etc. for hardware implementations.
  - On the other hand, a single language can be used for capturing a variety of models.
  - Certain languages are good in capturing certain computational model.
    - For example, C++ is a good candidate for capturing an object oriented model.
  - The only pre-requisite in selecting a programming language for capturing a model is that the language should capture the model easily.

Fundamental Issues in Hardware Software Co-Design (continued)

- Partitioning System Requirements into Hardware and Software
  - From an implementation perspective, it may be possible to implement the system requirements in either hardware or software (firmware).
  - It is a tough decision making task to figure out which one to opt.
  - Various hardware software trade-offs are used for making a decision on the hardware-software partitioning.

Computational Models in Embedded Design

- The commonly used computational models in embedded system design are:
  - Data Flow Graph Model
  - Control Data Flow Graph Model
  - State Machine Model
  - Sequential Program Model
  - Concurrent/Communicating Process Model
  - Object-Oriented Model

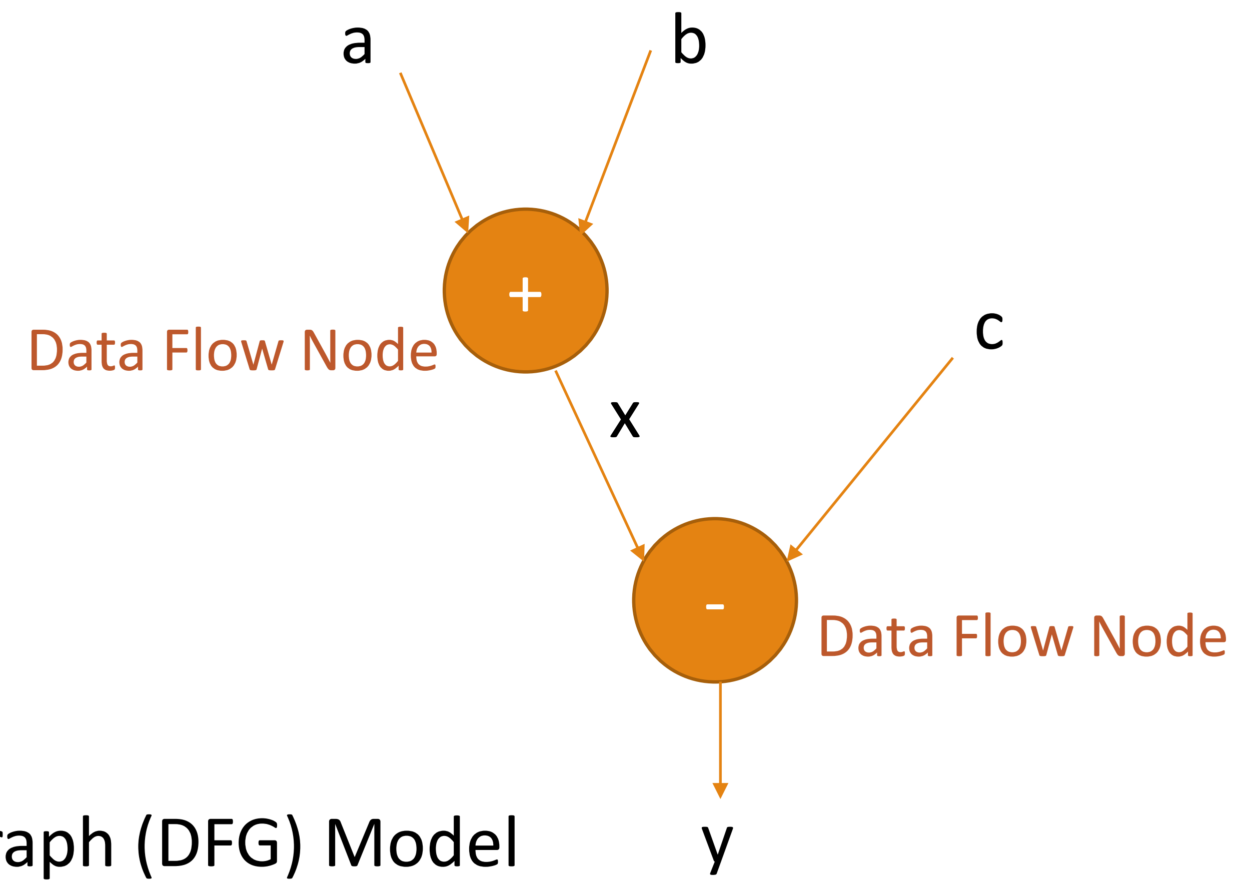
Data Flow Graph/Diagram (DFG) Model

- The Data Flow Graph (DFG) model translates the data processing requirements into a data flow graph.
- It is a data driven model in which the program execution is determined by data.
- This model emphasises on the data and operations on the data which transforms the input data to output data.
- Embedded applications which are computational intensive and data driven are modelled using the DFG model.
    - DSP applications are typical examples for it.

Data Flow Graph/Diagram (DFG) Model (continued)

- Data Flow Graph (DFG) is a visual model in which the operation on the data (process) is represented using a block (circle) and data flow is represented using arrows.
- An inward arrow to the process (circle) represents input data and an outward arrow from the process (circle) represents output data in DFG notation.
- Suppose one of the functions in our application contains the computational requirement $x = a + b$ and $y = x - c$.
- Figure illustrates the implementation of a DFG model for implementing these requirements.

Data Flow Graph/Diagram (DFG) Model (continued)



Data Flow Graph (DFG) Model

Data Flow Graph/Diagram (DFG) Model (continued)

- In a DFG model, a data path is the data flow path from input to output.
- A DFG model is said to be acyclic DFG (ADFG) if it doesn't contain multiple values for the input variable and multiple output values for a given set of input(s).
  - Feedback inputs (Output is fed back to Input), events, etc. are examples for non-acyclic inputs.
- A DFG model translates the program as a single sequential process execution.

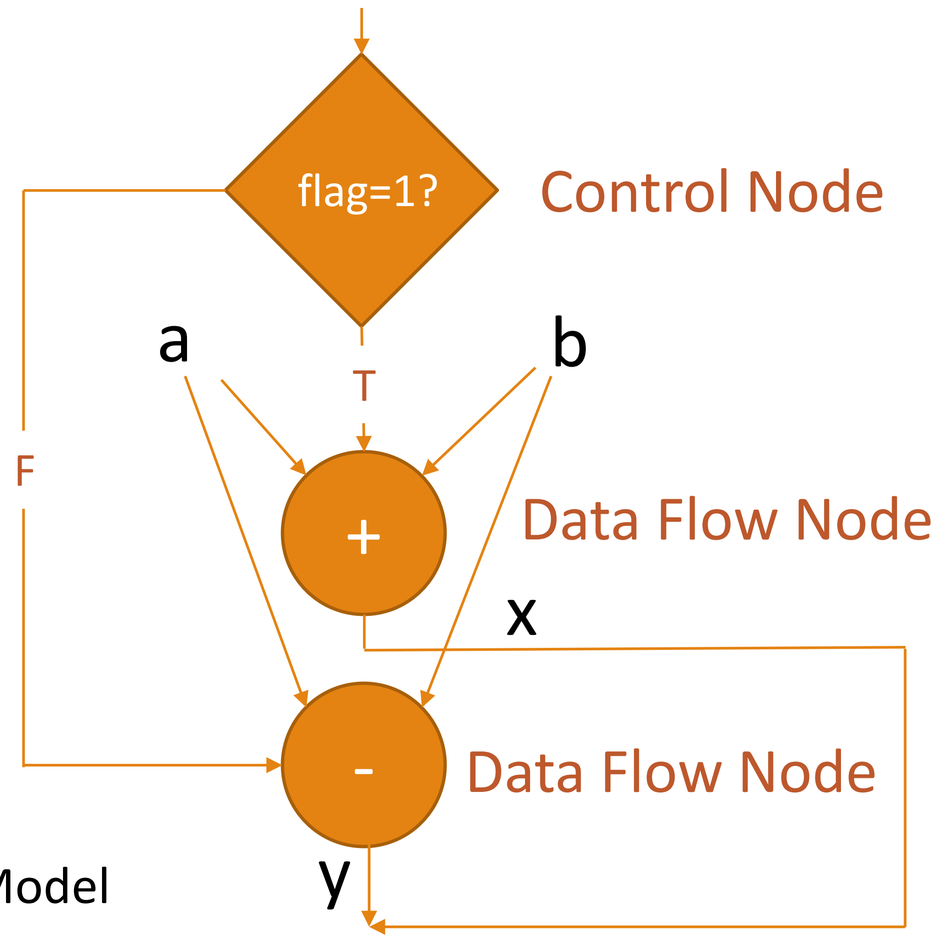
Control Data Flow Graph/Diagram (CDFG) Model

- The DFG model is a data driven model in which the execution is controlled by data and it doesn't involve any control operations (conditionals).
- The Control DFG (CDFG) model is used for modelling applications involving conditional program execution.
- CDFG models contains both data operations and control operations.
- The CDFG uses Data Flow Graph (DFG) as element and conditional (constructs) as decision makers.
- CDFG contains both data flow nodes and decision nodes, whereas DFG contains only data flow nodes.

Control Data Flow Graph/Diagram (CDFG) Model (continued)

- Consider the implementation of the CDFG for the following requirement.
- $If\ flag = 1, x = a + b;\ else\ y = a - b;$
- This requirement contains a decision making process.
- The CDFG model for the same is given in the figure.
- The control node is represented by a 'Diamond' block which is the decision making element in a normal flow chart based design.
- CDFG translates the requirement, which is modelled to a concurrent process model.
- The decision on which process is to be executed is determined by the control node.

Control Data Flow Graph/Diagram (CDFG) Model (continued)



Control Data Flow Graph (CDFG) Model

Control Data Flow Graph/Diagram (CDFG) Model (continued)

- A real world example for modelling the embedded application using CDFG is capturing and saving of the image to a format set by the user in a digital still camera.
- Here everything is data driven.
  - Analog Front End converts the CCD sensor generated analog signal to digital signal
  - The data from ADC is stored to a frame buffer for the use of a media processor which performs various operations like, auto correction, white balance adjusting, etc.
- The decision on, in which format the image is stored (formats like JPEG, TIFF, BMP, etc.) is controlled by the camera settings, configured by the user.

State Machine Model

- The State Machine Model is used for modelling reactive or event-driven embedded systems whose processing behaviour are dependent on state transitions.
  - Embedded systems used in the control and industrial applications are typical examples for event driven systems.
- The State Machine model describes the system behaviour with 'States', 'Events', 'Actions' and 'Transitions’.
  - *State* is a representation of a current situation.
  - An *event* is an input to the state.
    - The event acts as stimuli for state transition.
  - *Transition* is the movement from one state to another.
  - *Action* is an activity to be performed by the state machine.

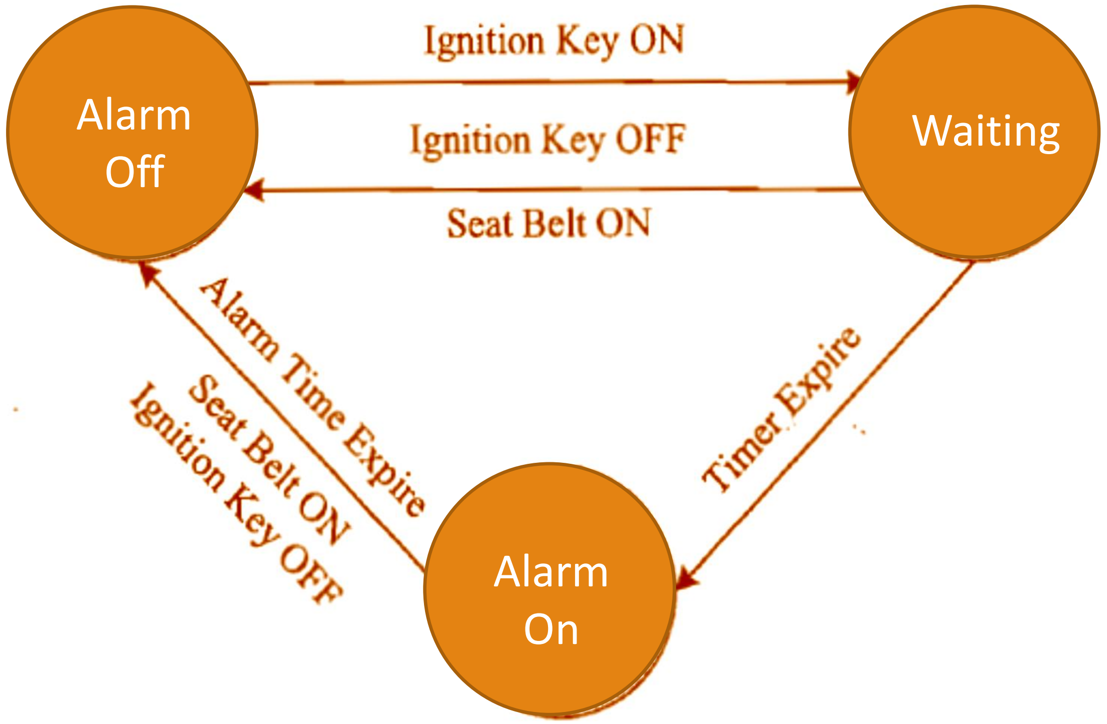
Finite State Machine (FSM) Model

- A Finite State Machine (FSM) model is one in which the number of states are finite.
    - The system is described using a finite number of possible states.
- As an example, let us consider the design of an embedded system for driver/passenger 'Seat Belt Warning' in an automotive using the FSM model.
- The system requirements are captured as.
    1. When the vehicle ignition is turned on and the seat belt is not fastened within 10 seconds of ignition ON, the system generates an alarm signal for 5 seconds.
    2. The Alarm is turned off when the alarm time (5 seconds) expires or if the driver/passenger fastens the belt or if the ignition switch is turned off, whichever happens first.

Finite State Machine (FSM) Model (continued)

- Here the states are
  - 'Alarm Off'
  - 'Waiting'
  - 'Alarm On'
- The events are
  - 'Ignition Key ON'
  - 'Ignition Key OFF'
  - 'Timer Expire'
  - 'Alarm Time Expire'
  - 'Seat Belt ON'
- Using the FSM, the system requirements can be modeled as given in figure.

Finite State Machine (FSM) Model (continued)

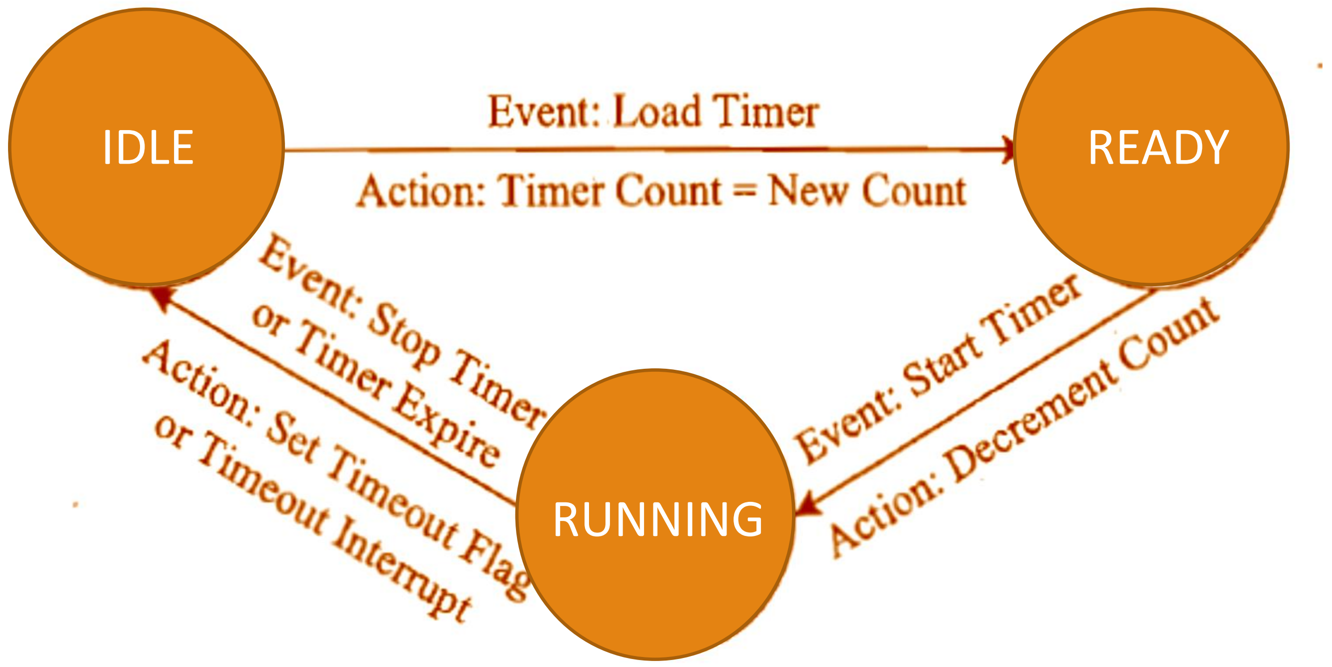


FSM Model for Automatic Seat Belt Warning System

Finite State Machine (FSM) Model (continued)

- The 'Ignition Key ON' event triggers the 10 second timer and transitions the state to 'Waiting’.
- If a ‘Seat Belt ON’ or 'Ignition Key OFF' event occurs during the wait state, the state transitions into 'Alarm Off’.
- When the wait timer expires in the waiting state, the event 'Timer Expire' is generated and it transitions the state to 'Alarm On' from the 'Waiting' state.
- The 'Alarm On' state continues until a 'Seat Belt ON' or 'Ignition Key OFF' event or 'Alarm Time Expire' event, whichever occurs first.
  - The occurrence of any of these events transitions the state to 'Alarm Off’.
- The wait state is implemented using a timer.
  - The timer also has certain set of states and events for state transitions.
  - Using the FSM model, the timer can be modelled as shown in the figure.

Finite State Machine (FSM) Model (continued)


IDLE
READY
RUNNING
Event: Load Timer
Action: Timer Count = New Count
Event: Start Timer
Action: Decrement Count
Event: Stop Timer or Timer Expire
Action: Set Timeout Flag or Timeout Interrupt

FSM Model for Timer

Finite State Machine (FSM) Model (continued)

- As seen from the FSM, the timer state can be either 'IDLE' or 'READY' or 'RUNNING’.
- During the normal condition when the timer is not running, it is said to be in the 'IDLE' state.
- The timer is said to be in the 'READY’ state when the timer is loaded with the count corresponding to the required time delay.
- The timer remains in the 'READY' state until a 'Start Timer' event occurs.
- The timer changes its state to 'RUNNING' from the 'READY' state on receiving a 'Start Timer' event and remains in the 'RUNNING' state until the timer count expires or a 'Stop Timer' event occurs.
- The timer state changes to 'IDLE' from 'RUNNING' on receiving a 'Stop Timer' or 'Timer Expire' event.

FSM Model - Example 1

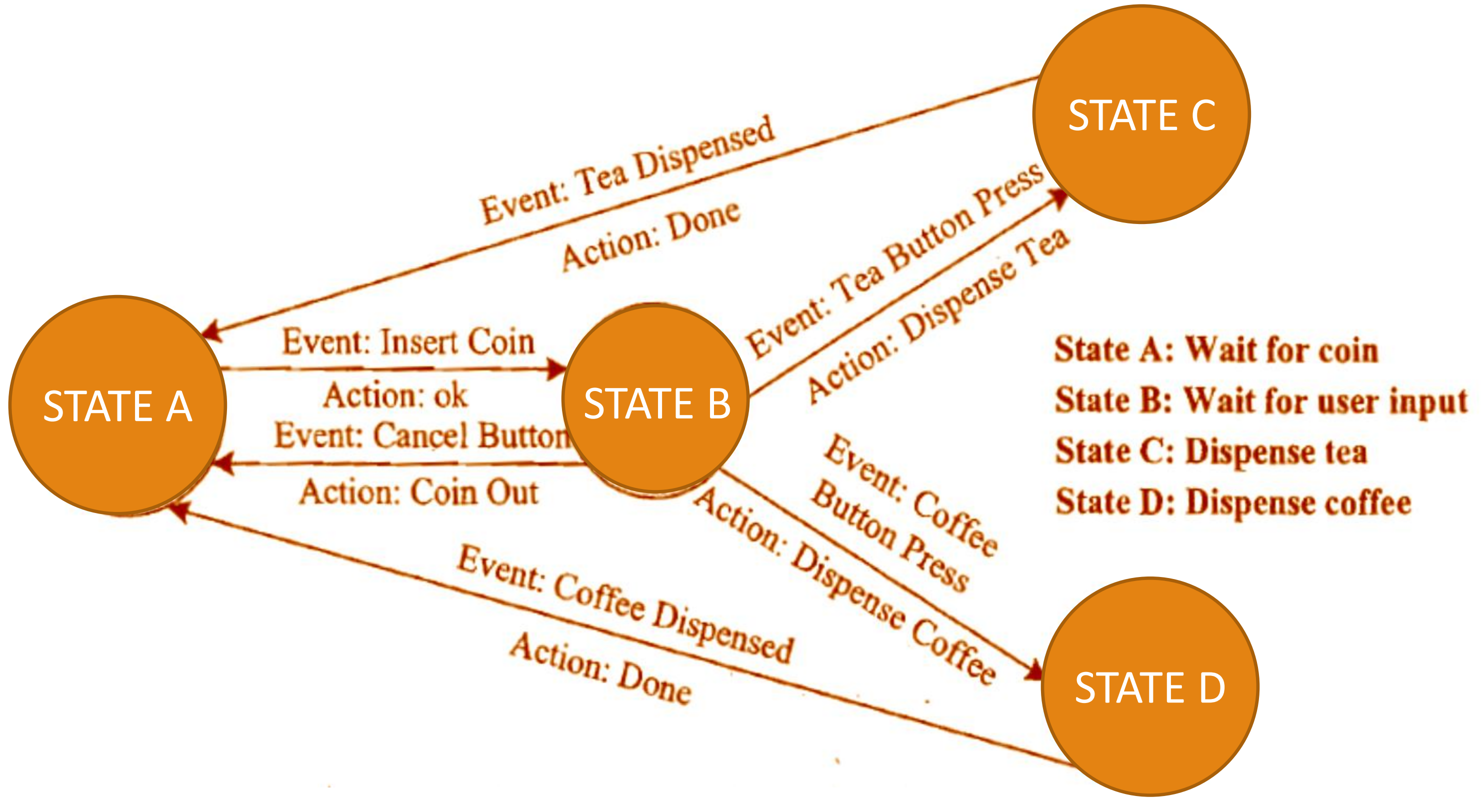
Design an automatic tea/coffee vending machine based on FSM model for the following requirement.

- The tea/coffee vending is initiated by user inserting a 5 rupee coin.
- After inserting the coin, the user can either select 'Coffee' or 'Tea' or press 'Cancel' to cancel the order and take back the coin.

Solution

- The FSM Model contains four states namely,
  - 'Wait for coin’
  - 'Wait for User Input’
  - 'Dispense Tea'
  - 'Dispense Coffee'

FSM Model - Example 1 (continued)



FSM Model for Automatic Tea/Coffee Vending Machine

FSM Model - Example 1 (continued)

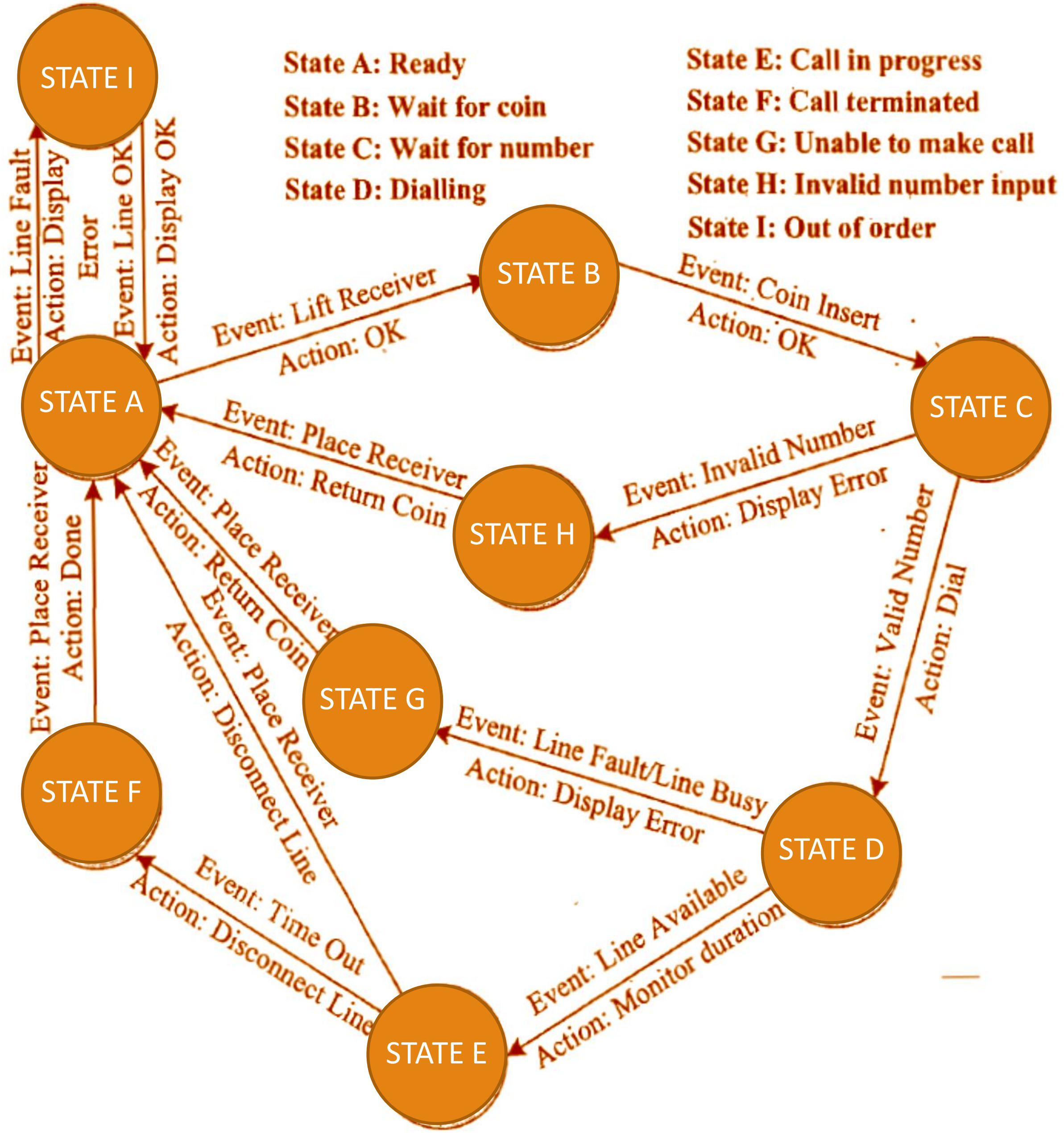
- The event 'Insert Coin' (5 rupee coin insertion), transitions the state to 'Wait for User Input’.
- The system stays in this state until a user input is received from the buttons 'Cancel', 'Tea' or 'Coffee' (Tea and Coffee are the drink select button).
- If the event triggered in 'Wait State' is 'Cancel' button press, the coin is pushed out and the state transitions to 'Wait for Coin’.
- If the event received in the 'Wait State' is either 'Tea' button press, or 'Coffee' button press, the state changes to 'Dispense Tea' and 'Dispense Coffee' respectively.
- Once the coffee/tea vending is over, the respective states transition back to the 'Wait for Coin' state.

FSM Model - Example 2

Design a coin operated public telephone unit based on FSM model for the following requirements.

1. The calling process is initiated by lifting the receiver (off-hook) of the telephone unit.
2. After lifting the phone the user needs to insert a 1 rupee coin to make the call.
3. If the line is busy, the coin is returned on placing the receiver back on the hook (on-hook).
4. If the line is through, the user is allowed to talk till 60 seconds and at the end of 45th second, prompt for inserting another 1 rupee coin for continuing the call is initiated.
5. If the user doesn't insert another 1 rupee coin, the call is terminated on completing the 60 seconds time slot.
6. The system is ready to accept new call request when the receiver is placed back on the hook (on-hook).
7. The system goes to the 'Out of Order' state when there is a line fault.

FSM Model for
Coin Operated Telephone
System



Sequential Program Model

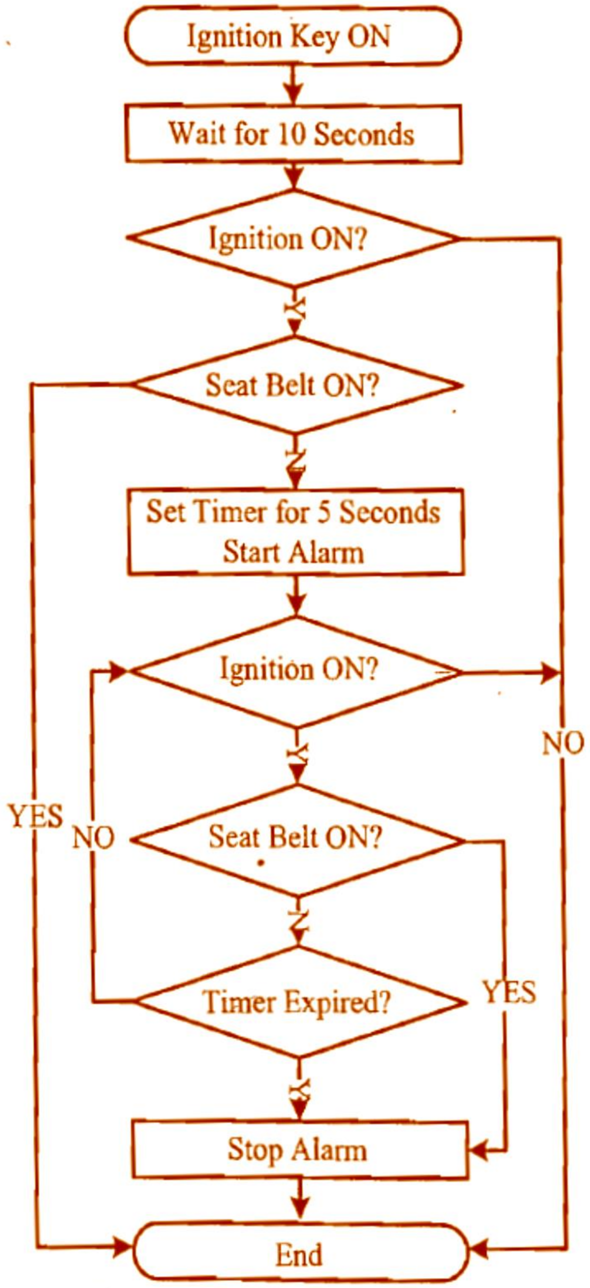
- In the Sequential Program Model, the functions or processing requirements are executed in sequence.
  - It is same as the conventional procedural programming.
- Here the program instructions are iterated and executed conditionally and the data gets transformed through a series of operations.
- Finite State Machines (FSMs) and Flow Charts are used for modelling sequential program.
  - The FSM approach represents the states, events, transitions and actions, whereas the Flow Chart models the execution flow.

Sequential Program Model (continued)

- The execution of functions in a sequential program model for the 'Seat Belt Warning' system is illustrated below:

```
#define ON 1
#define OFF 0
#define YES 1
#define NO 0
void seat_belt_warn()
{
 wait_10sec();
 if (check_ignition_key()==ON)
 {
  if (check_seat_belt()==OFF)
  {
   set_timer(5);
   start_alarm();
   while ((check_seat_belt()==OFF)&&(check_ignition_key()==ON)&&(timer_expire()==NO));
   stop_alarm();
   }
  }
 }
}
```

Figure illustrates the flow chart approach for modelling the 'Seat Belt Warning' system explained in the FSM modelling section.



Sequential Program Model for Seat Belt Warning System

Concurrent/Communicating Process Model

- The concurrent or communicating process model models concurrently executing tasks/processes.
- It is easier to implement certain requirements in concurrent processing model than the conventional sequential execution.
  - Sequential execution leads to a single sequential execution of task and thereby leads to poor processor utilisation, when the task involves I/O waiting, sleeping for specified duration etc.
  - If the task is split into multiple subtasks, it is possible to tackle the CPU usage effectively by switching the task execution, when the subtask under execution goes to a wait or sleep mode.
- However, concurrent processing model requires additional overheads in task scheduling, task synchronisation and communication.

Concurrent/Communicating Process Model (continued)

- As an example, consider the implementation of the 'Seat Belt Warning' system using concurrent processing model.
- We can split the tasks into:
  1. Timer task for waiting 10 seconds (wait timer task)
  2. Task for checking the ignition key status (ignition key status monitoring task)
  3. Task for checking the seat belt status (seat belt status monitoring task)
  4. Task for starting and stopping the alarm (alarm control task)
  5. Alarm timer task for waiting 5 seconds (alarm timer task)

Concurrent/Communicating Process Model (continued)

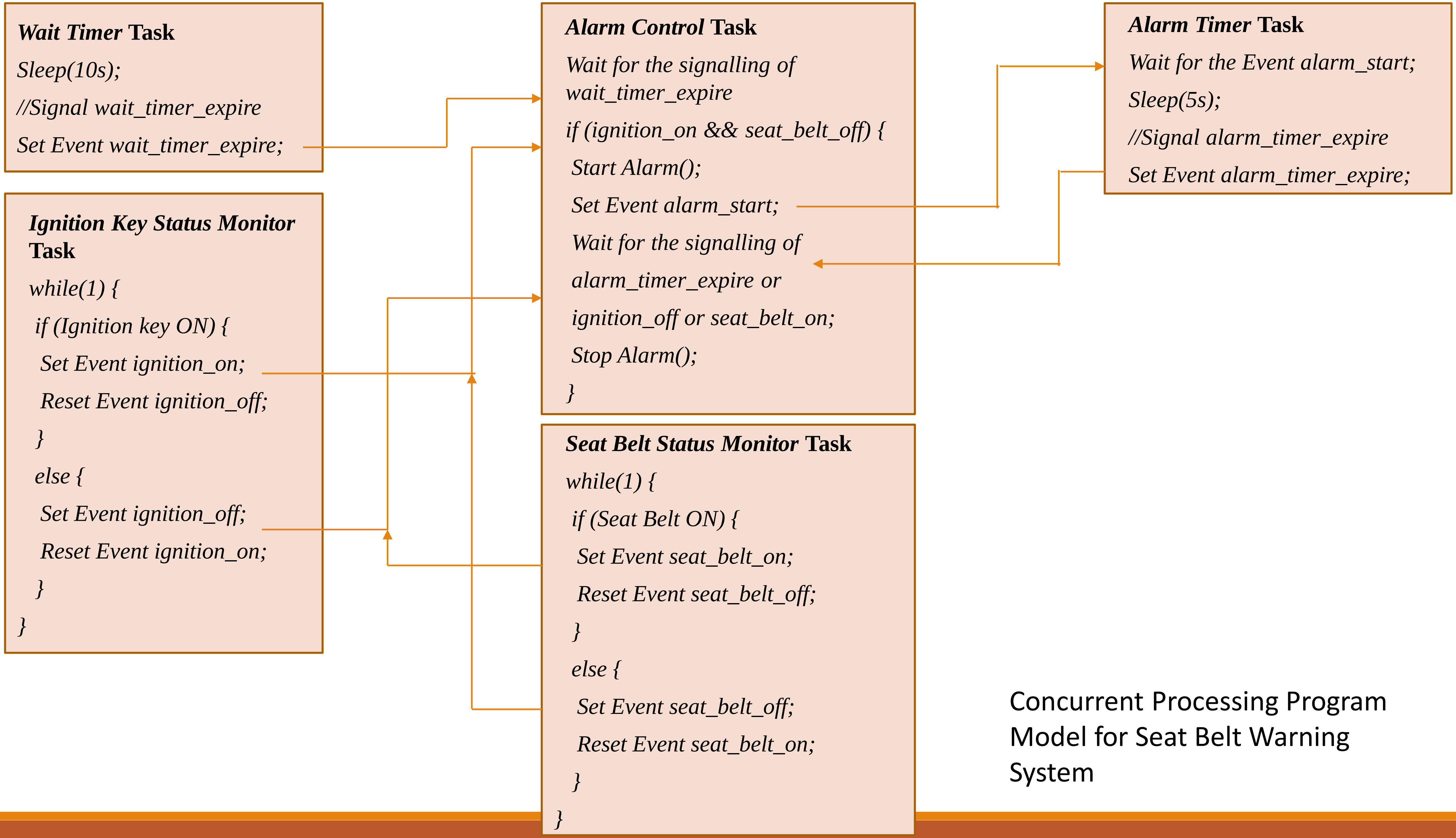
- The tasks cannot be executed randomly or sequentially.
- We need to synchronise their execution through some mechanism.
  - For example, the alarm control task is executed only when the wait timer is expired and if the ignition key is in the ON state and seat belt is in the OFF state.
- We will use events to indicate these scenarios.
- The *wait_timer_expire* event is associated with the timer task event and it will be in the reset state initially and it is set when the timer expires.
- Similarly, events *ignition_on* and *ignition_off* are associated with the task ignition key status monitoring and the events *seat_belt_on* and *seat_belt_off* are associated with the task seat belt status monitoring.

Concurrent/Communicating Process Model (continued)

```
Create and initialize events
wait_timer_expire, ignition_on, ignition_off,
seat_belt_on, seat_belt_off,
alarm_timer_start, alarm_timer_expire

Create task Wait Timer
Create task Ignition Key Status Monitor
Create task Seat Belt Status Monitor
Create task Alarm Control
Create task Alarm Timer
```

Tasks for Seat Belt Warning System



Wait Timer Task

```
Sleep(10s);
//Signal wait_timer_expire
Set Event wait_timer_expire;
```

Ignition Key Status Monitor Task

```
while(1) {
 if (Ignition key ON) {
  Set Event ignition_on;
  Reset Event ignition_off;
 }
 else {
  Set Event ignition_off;
  Reset Event ignition_on;
 }
}
```

Alarm Control Task

```
Wait for the signalling of
wait_timer_expire
if (ignition_on && seat_belt_off) {
 Start Alarm();
 Set Event alarm_start;
 Wait for the signalling of
 alarm_timer_expire or
 ignition_off or seat_belt_on;
 Stop Alarm();
}
```

Seat Belt Status Monitor Task

```
while(1) {
 if (Seat Belt ON) {
  Set Event seat_belt_on;
  Reset Event seat_belt_off;
 }
 else {
  Set Event seat_belt_off;
  Reset Event seat_belt_on;
 }
}
```

Alarm Timer Task

```
Wait for the Event alarm_start;
Sleep(5s);
//Signal alarm_timer_expire
Set Event alarm_timer_expire;
```

Concurrent Processing Program Model for Seat Belt Warning System

Object-Oriented Model

- The object-oriented model is an object based model for modelling system requirements.
- It disseminates a complex software requirement into simple well defined pieces called objects.
- Object-oriented model brings re-usability, maintainability and productivity in system design.
- In the object-oriented modelling, *object is an entity used for representing or modelling a particular piece of the system*.
    - Each object is characterised by a set of unique behaviour and state.

Object-Oriented Model (continued)

- A class is an abstract description of a set of objects and it can be considered as a 'blueprint' of an object.
- A class represents the state of an object through member variables and object behaviour through member functions.
- The member variables and member functions of a class can be private, public or protected.
  - Private member variables and functions are accessible only within the class, whereas public variables and functions are accessible within the class as well as outside the class.
  - The protected variables and functions are protected from external access.
  - However classes derived from a parent class can also access the protected member functions and variables.
- The concept of object and class brings abstraction, hiding and protection.

Embedded Firmware Design and Development

Introduction to Embedded Firmware Design

- The embedded firmware is responsible for controlling the various peripherals of the embedded hardware and generating response in accordance with the functional requirements.
- Firmware is considered as the master brain of the embedded system.
- Imparting intelligence to an Embedded system is a one time process and it can happen at any stage.
  - It can be immediately after the fabrication of the embedded hardware or at a later stage.
- For most of the embedded products, the embedded firmware is stored at a permanent memory (ROM) and they are non-alterable by end users.
  - Some of the embedded products used in the Control and Instrumentation domain are adaptive.

Introduction to Embedded Firmware Design (continued)

- Designing embedded firmware requires understanding of the particular embedded product hardware, like various component interfacing, memory map details, I/O port details, configuration and register details of various hardware chips used and some programming language.
- Embedded firmware development process starts with the conversion of the firmware requirements into a program model using modelling tools.
- Once the program model is created, the next step is the implementation of the tasks and actions by capturing the model using a language which is understandable by the target processor/controller.

Embedded Firmware Design Approaches

- The firmware design approaches for embedded product is purely dependent on the complexity of the functions to be performed, the speed of operation required, etc.
- Two basic approaches are used for embedded firmware design:
  - Super Loop Based Approach (Conventional Procedural Based Design)
  - Embedded Operating System (OS) Based Approach

Super Loop Based Approach

- The Super Loop based firmware development approach is adopted for applications that are not time critical and where the response time is not so important.
- It is very similar to a conventional procedural programming where the code is executed task by task.
- The task listed at the top of the program code is executed first and the tasks just below the top are executed after completing the first task.
- In a multiple task based system, each task is executed in serial in this approach.

Super Loop Based Approach (continued)

- The firmware execution flow for this will be
  1. Configure the common parameters and perform initialisation for various hardware components memory, registers, etc.
  2. Start the first task and execute it
  3. Execute the second task
  4. Execute the next task
  5. :
  6. :
  7. Execute the last defined task
  8. Jump back to the first task and follow the same flow

Super Loop Based Approach (continued)

- The order in which the tasks to be executed are fixed and they are hard coded in the code itself.
  - Also the operation is an infinite loop based approach.
- We can visualise the operational sequence listed above in terms of a 'C' program code as

```
void main()
{
 Configurations();
 Initializations();
 while(1)
 {
  Task 1();
  Task 2();
   :
   :
  Task n();
 }
}
```

Super Loop Based Approach (continued)

- Almost all tasks in embedded applications are non-ending and are repeated infinitely throughout the operation.
  - This repetition is achieved by using an infinite loop.
  - Hence the name 'Super loop based approach’.
- The only way to come out of the loop is either a hardware reset or an interrupt assertion.
  - A hardware reset brings the program execution back to the main loop.
  - An interrupt request suspends the task execution temporarily and performs the corresponding interrupt routine and on completion of the interrupt routine it restarts the task execution from the point where it got interrupted.

Super Loop Based Approach (continued)

- Advantage of Super Loop Based Approach:
  - It doesn't require an operating system
    - There is no need for scheduling which task is to be executed and assigning priority to each task.
    - The priorities are fixed and the order in which the tasks to be executed are also fixed.
    - Hence the code for performing these tasks will be residing in the code memory without an operating system image.

Super Loop Based Approach (continued)

- Applications of Super Loop Based Approach:
  - This type of design is deployed in low-cost embedded products and products where response time is not time critical.
  - Some embedded products demands this type of approach if some tasks itself are sequential.
  - For example, reading/writing data to and from a card using a card reader requires a sequence of operations like checking the presence of card, authenticating the operation, reading/writing, etc.
    - It should strictly follow a specified sequence and the combination of these series of tasks constitutes a single task-namely data read/write.

Super Loop Based Approach (continued)

- A typical example of a 'Super loop based' product is an electronic video game toy containing keypad and display unit.
- The program running inside the product may be designed in such a way that it reads the keys to detect whether the user has given any input and if any key press is detected the graphic display is updated.
- The keyboard scanning and display updating happens at a reasonably high rate.
- Even if the application misses a key press, it won't create any critical issues; rather it will be treated as a bug in the firmware.
- It is not economical to embed an OS into low cost products and it is an utter waste to do so if the response requirements are not crucial.

Super Loop Based Approach (continued)

- Drawbacks of Super Loop Based Approach:
  - Any failure in any part of a single task will affect the total system.
    - If the program hangs up at some point while executing a task, it will remain there forever and ultimately the product stops functioning.
      - Watch Dog Timers (WDTs) can be used to overcome this, but this, in turn, may cause additional hardware cost and firmware overheads.
  - Lack of real timeliness.
    - If the number of tasks to be executed within an application increases, the time at which each task is repeated also increases.
    - This brings the probability of missing out some events.
    - For example, in a system with keypads, in order to identify the key press, you may have to press the keys for a sufficiently long time till the keypad status monitoring task is executed internally by the firmware.
      - Interrupts can be used for external events requiring real time attention.

Embedded Operating System (OS) Based Approach

- The Embedded Operating System (OS) based approach contains operating systems, which can be either a General Purpose Operating System (GPOS) or a Real Time Operating System (RTOS) to host the user written application firmware.

Embedded Operating System (OS) Based Approach (continued)

- The General Purpose OS (GPOS) based design is very similar to a conventional PC based application development where the device contains an operating system (Windows/Unix/Linux, etc. for Desktop PCs) and you will be creating and running user applications on top of it.
  - Example of a GPOS used in embedded product development is Microsoft Windows XP Embedded.
  - Examples of Embedded products using Microsoft Windows XP OS are Personal Digital Assistants (PDAs), Hand held devices/Portable devices and Point of Sale (POS) terminals.
- Use of GPOS in embedded products merges the demarcation of Embedded Systems and general computing systems in terms of OS.
- For developing applications on top of the OS, the OS supported APIs are used.
- Similar to the different hardware specific drivers, OS based applications also require 'Driver software' for different hardware present on the board to communicate with them.

Embedded Operating System (OS) Based Approach (continued)

- Real Time Operating System (RTOS) based design approach is employed in embedded products demanding Real-time response.
  - RTOS responds in a timely and predictable manner to events.
- Real Time operating system contains a Real Time kernel responsible for performing pre-emptive multitasking, scheduler for scheduling tasks, multiple threads, etc.
  - A Real Time Operating System (RTOS) allows flexible scheduling of system resources like the CPU and memory and offers some way to communicate between tasks.
- *'Windows CE', 'pSOS', 'VxWorks', 'ThreadX', 'MicroC/OS-II', 'Embedded Linux', 'Symbian',* etc. are examples of RTOS employed in embedded product development.
- Mobile phones, PDAs (Based on Windows CE/Windows Mobile Platforms), handheld devices, etc. are examples of 'Embedded Products' based on RTOS.
  - Most of the mobile phones are built around the popular RTOS 'Symbian'. *(sic)*

Embedded Firmware Development Languages

- For embedded firmware development, we can use either
  - a target processor/controller specific language (Generally known as Assembly language or low level language) or
  - a target processor/controller independent language (Like C, C++, JAVA, etc. commonly known as High Level Language) or
  - a combination of Assembly and High level Language.

Assembly Language Based Development

- '*Assembly language*' is the human readable notation of '*machine language*'
  - 'Machine language' is a processor understandable language.
- Machine language is a binary representation and it consists of 1s and 0s.
- Machine language is made readable by using specific symbols called 'mnemonics'.
- Hence machine language can be considered as an interface between processor and programmer.
- Assembly language and machine languages are processor/controller dependent and an assembly program written for one processor/controller family will not work with others.
- ***Assembly language programming is the task of writing processor specific machine code in mnemonic form, converting the mnemonics into actual processor instructions (machine language) and associated data using an assembler.***

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Assembly Language Based Development (continued)

- Assembly Language program was the most common type of programming adopted in the beginning of software revolution.
- Even today also almost all low level, system related, programming is carried out using assembly language.
- In particular, assembly language is often used in writing the low level interaction between the operating system and the hardware, for instance in device drivers.

Assembly Language Based Development (continued)

- The general format of an assembly language instruction is an Opcode followed by Operands.
- The Opcode tells the processor/controller what to do and the Operands provide the data and information required to perform the action specified by the opcode.
- For example

```
MOV  A,  #30
```

Here `MOV  A` is the Opcode and `#30` is the operand

- The same instruction when written in machine language will look like

01110100 00011110

where the first 8-bit binary value 01110100 represents the opcode `MOV  A` and the second 8-bit binary value 00011110 represents the operand 30.

Assembly Language Based Development (continued)

- Each line of an assembly language program is split into four fields as given below

LABEL OPCODE OPERAND COMMENTS

- A 'LABEL' is an optional identifier used extensively in programs to reduce the reliance on programmers for remembering where data or code is located.
- For example

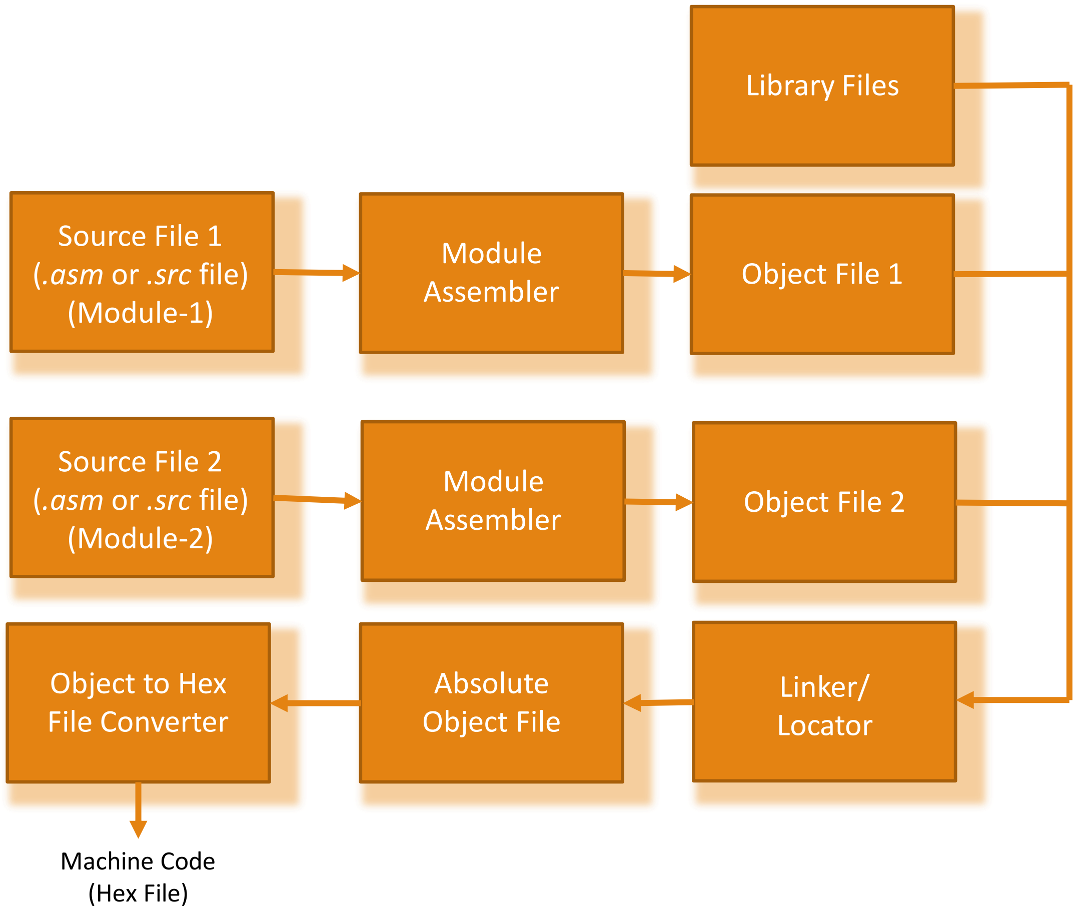
$$\underbrace{\texttt{DELAY:}}_{\text{LABEL}}\ \underbrace{\texttt{MOV R0,}}_{\text{OPCODE}}\underbrace{\texttt{\#255}}_{\text{OPERAND}}\ \underbrace{\texttt{;Load Register R0 with 255}}_{\text{COMMENT}}$$

Assembly Language Based Development (continued)

- The Assembly language program written in assembly code is saved as *.asm* (Assembly file) file or an *.src* (source) file (also *.s* file).
- Any text editor like ‘Notepad' or 'WordPad' from Microsoft or the text editor provided by an Integrated Development (IDE) tool can be used for writing the assembly instructions.
- Similar to 'C' and other high level language programming, we can have multiple source files called modules in assembly language programming.
  - Each module is represented by an '*.asm*' or '*.src*' file.
  - This approach is known as 'Modular Programming’.
- Modular programming is employed when the program is too complex or too big.
  - In 'Modular Programming', the entire code is divided into submodules and each module is made re-usable.
  - Modular Programs are usually easy to code, debug and alter.

Assembly Language Based Development (continued)

Assembly language to machine language conversion process



Assembly Language Based Development (continued)

- **Source File to Object File Translation**
  - Translation of assembly code to machine code is performed by *assembler*.
  - The assemblers for different target machines are different.
    - A51 Macro Assembler from Keil software is a popular assembler for the 8051 family microcontroller.
  - The various steps involved in the conversion of a program written in assembly language to corresponding binary file/machine language are illustrated in the figure.

Assembly Language Based Development (continued)

- Each source module is written in Assembly and is stored as *.src* file or *.asm* file.
- Each file can be assembled separately to examine the syntax errors and incorrect assembly instructions.
- On successful assembling of each *.src/.asm* file a corresponding object file is created with extension '*.obj*'.
  - The object file does not contain the absolute address of where the generated code needs to be placed on the program memory and hence it is called a re-locatable segment.
  - It can be placed at any code memory location and it is the responsibility. of the linker/locater to assign absolute address for this module.
- Each module can share variables and subroutines (functions) among them.
  - Keyword ‘PUBLIC’ and ‘EXTRN’ are used while accessing shared variables and subroutines.

Assembly Language Based Development (continued)

- **Library File Creation and Usage**
  - Libraries are specially formatted, ordered program collections of object modules that may be used by the linker at a later time.
    - Library files are generated with extension *'. lib'.*
  - When the linker processes a library, only those object modules in the library that are necessary to create the program are used.
  - Library file is some kind of source code hiding technique.
  - For example, *'LIB51'* from Keil Software is an example for a library creator and it is used for creating library files for A51 Assembler/C51 Compiler for *8051* specific controller.

Assembly Language Based Development (continued)

- **Linker and Locator**
  - Linker and Locater is another software utility responsible for "linking the various object modules in a multi-module project and assigning absolute address to each module".
  - Linker generates an absolute object module by extracting the object modules from the library, if any, and those *obj* files created by the assembler, which is generated by assembling the individual modules of a project.
  - It is the responsibility of the linker to link any external dependent variables or functions declared on various modules and resolve the external dependencies among the modules.
  - An absolute object file or module does not contain any re-locatable code or data.
    - All code and data reside at fixed memory locations.
  - The absolute object file is used for creating hex files for dumping into the code memory of the processor/controller.
  - *'BL51'* from Keil Software is an example for a Linker & Locater for A51 Assembler/C51 Compiler for *8051* specific controller.

Assembly Language Based Development (continued)

- **Object to Hex File Converter**
  - This is the final stage in the conversion of Assembly language (mnemonics) to machine understandable language (machine code).
  - Hex File is the representation of the machine code and the hex file is dumped into the code memory of the processor/controller.
  - The hex file representation varies depending on the target processor/controller make.
  - HEX files are ASCII files that contain a hexadecimal representation of target application.
  - Hex file is created from the final 'Absolute Object File' using the Object to Hex File Converter utility.
  - '*OH51*' from Keil software is an example for Object to Hex File Converter utility for A51 Assembler/C51 Compiler for *8051* specific controller.

Advantages of Assembly Language Based Development

- Efficient Code Memory and Data Memory Usage (Memory Optimisation)
  - Since the developer is well versed with the target processor architecture and memory organisation, optimised code can be written for performing operations.
  - This leads to less utilisation of code memory and efficient utilisation of data memory.
- High Performance
  - Optimised code not only improves the code memory usage but also improves the total system performance.
  - Through effective assembly coding, optimum performance can be achieved for a target application.

Advantages of Assembly Language Based Development (continued)

- Low Level Hardware Access
  - Most of the code for low level programming like accessing external device specific registers from the operating system kernel, device drivers, and low level interrupt routines, etc. are making use of direct assembly coding since low level device specific operation support is not commonly available with most of the high-level language cross compilers.
- Code Reverse Engineering
  - Reverse engineering is the process of understanding the technology behind a product by extracting the information from a finished product.
    - Reverse engineering is performed by 'hawkers' to reveal the technology behind 'Proprietary Products'.
  - Though most of the products employ code memory protection, if it may be possible to break the memory protection and read the code memory, it can easily be converted into assembly code using a dis-assembler program for the target machine.

Drawbacks of Assembly Language Based Development

- High Development Time
  - Assembly language is much harder to program than high level languages.
  - The developer must pay attention to more details and must have thorough knowledge of the architecture, memory organisation and register details of the target processor in use.
  - Learning the inner details of the processor and its assembly instructions is highly time consuming and it creates a delay impact in product development.
  - Also more lines of assembly code are required for performing an action which can be done with a single instruction in a high-level language like 'C'.

Drawbacks of Assembly Language Based Development (continued)

- Developer Dependency
  - Unlike high level languages, there is no common written rule for developing assembly language based applications.
  - In assembly language programming, the developers will have the freedom to choose the different memory location and registers.
  - Also the programming approach varies from developer to developer depending on his/her taste.
    - For example moving data from a memory location to accumulator can be achieved through different approaches.
  - If the approach done by a developer is not documented properly at the development stage, he/she may not be able to recollect why this approach is followed at a later stage or when a new developer is instructed to analyse this code, he/she also may not be able to understand what is done and why it is done.
    - Hence upgrading an assembly program or modifying it on a later stage is very difficult.

Drawbacks of Assembly Language Based Development (continued)

- Non-Portable
  - Target applications written in assembly instructions are valid only for that particular family of processors (e.g. Application written for Intel x86 family of processors) and cannot be re-used for another target processors/controllers (Say ARM11 family of processors).
  - If the target processor/controller changes, a complete re-writing of the application using the assembly instructions for the new target processor/controller is required.

High Level Language Based Development

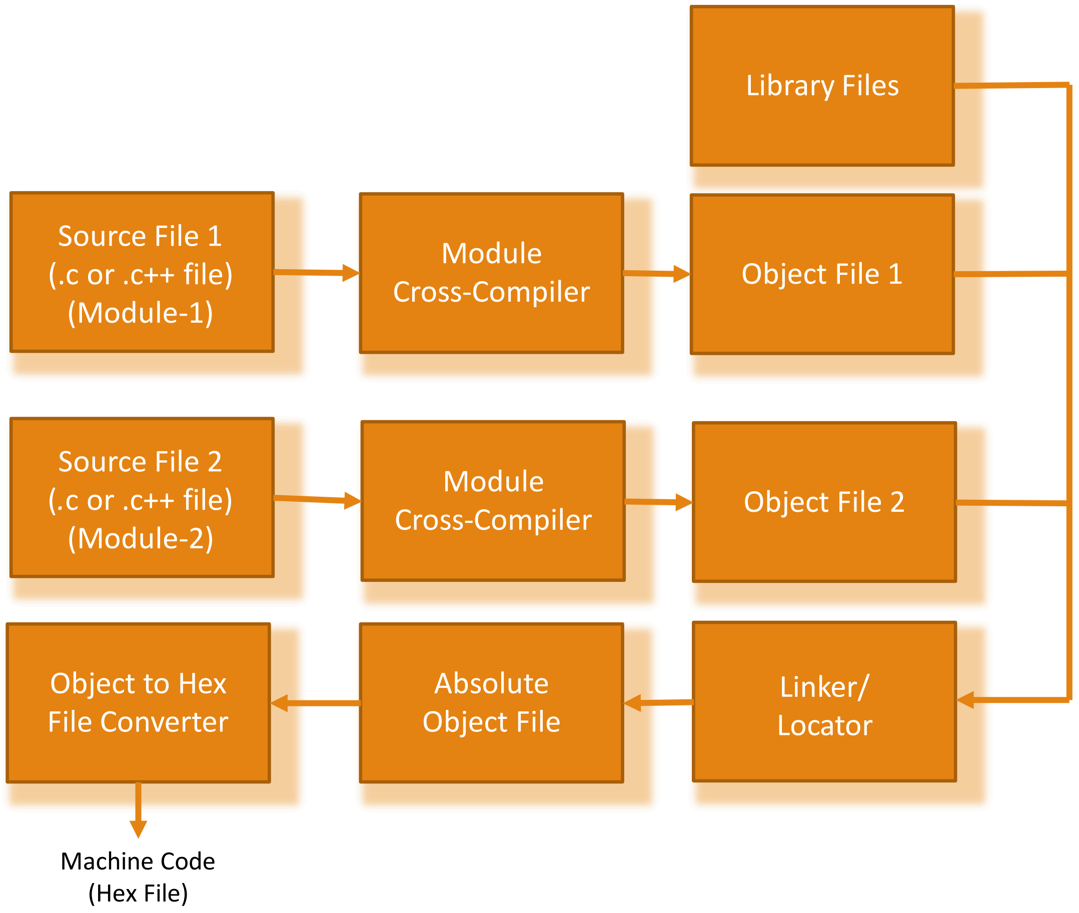
- Any high level language (like C, C++ or Java) with a supported cross-compiler for the target processor can be used for embedded firmware development.
- The most commonly used high level language for embedded firmware application development is '*C*'.
  - ‘C’ is well defined, easy to use high level language with extensive cross platform development tool support.
- Nowadays cross-compilers for C++ is also emerging out and embedded developers are making use of C++ for embedded application development.

High Level Language Based Development (continued)

- The various steps involved in high level language based embedded firmware development is same as that of assembly language based development except that the conversion of source file written in high level language to object file is done by a cross-compiler.
  - In Assembly language based development it is carried out by an assembler.
- The various steps involved in the conversion of a program written in high level language to corresponding binary file/machine language is illustrated in the figure.

High Level Language Based Development (continued)

High level language to machine language conversion process



High Level Language Based Development (continued)

- The program written in any of the high level languages is saved with the corresponding language extension (.c for C, .cpp for C++ etc).
- Any text editor like ‘Notepad' or 'WordPad' from Microsoft or the text editor provided by an Integrated Development (IDE) tool can be used for writing the program.
- Most of the high level languages support *modular programming* approach and hence we can have multiple source files called *modules* written in corresponding high level language.
- The source files corresponding to each module is represented by a file with corresponding language extension.

High Level Language Based Development (continued)

- Translation of high level source code to executable object code is done by a cross-compiler.
- Each high level language should have a cross-compiler for converting the high level source code into the target processor machine code.
    - C51 Cross-compiler from Keil software is an example for Cross-compiler used for 'C' language for the 8051 family of microcontroller.
- Conversion of each module's source code to corresponding object file is performed by the cross-compiler.
- Rest of the steps involved in the conversion of high level language to target processor's machine code are same as that of the steps involved in assembly language based development.

Advantages of High Level Language Based Development

- Reduced Development Time
  - Developer requires less or little knowledge on the internal hardware details and architecture of the target processor/controller.
  - Bare minimal knowledge of the memory organisation and register details of the target processor in use and syntax of the high level language are the only pre-requisites for high level language based firmware development.
  - With high level language, each task can be accomplished by lesser number of lines of code compared to the target processor/controller specific assembly language based development.

Advantages of High Level Language Based Development (continued)

- Developer Independency
  - The syntax used by most of the high level languages are universal and a program written in the high level language can easily be understood by a second person knowing the syntax of the language.
  - High level languages always instruct certain set of rules for writing the code and commenting the piece of code.
  - If the developer strictly adheres to the rules, the firmware will be 100% developer independent.

Advantages of High Level Language Based Development (continued)

- Portability
  - Target applications written in high level languages are converted to target processor/controller understandable format (machine codes) by a cross-compiler.
  - An application written in high level language for a particular target processor can easily be converted to another target processor/controller specific application, with little or less effort by simply re-compiling/little code modification followed by re-compiling the application for the required target processor/controller, provided, the cross-compiler has support for the processor/controller selected.
    - This makes applications written in high level language highly portable.
  - Little effort may be required in the existing code to replace the target processor specific files with new header files, register definitions with new ones, etc.
    - This is the major flexibility offered by high level language based design.

Limitations of High Level Language Based Development

- Poor Optimization by Cross-Compilers
  - Some cross-compilers available for high level languages may not be so efficient in generating optimised target processor specific instructions.
  - Target images created by such compilers may be messy and non-optimised in terms of performance as well as code size.
    - For example, the task achieved by cross-compiler generated machine instructions from a high level language may be achieved through a lesser number of instructions if the same task is hand coded using target processor specific machine codes.
  - The time required to execute a task also increases with the number of instructions.
  - However modern cross-compilers are tending to adopt designs incorporating optimisation techniques for both code size and performance.

Limitations of High Level Language Based Development (continued)

- Not Suitable for Low Level Hardware
  - High level language based code snippets may not be efficient in accessing low level hardware where hardware access timing is critical (of the order of nano or micro seconds).
- High Investment Cost
  - The investment required for high level language based development tools (Integrated Development Environment incorporating cross-compiler) is high compared to Assembly Language based firmware development tools.

Mixing Assembly and High Level Language

- Certain embedded firmware development situations may demand the mixing of high level language with Assembly and vice versa.
- High level language and assembly languages are usually mixed in three ways:
  - Mixing Assembly Language with High Level Language
  - Mixing High Level Language with Assembly Language
  - Inline Assembly programming

Mixing Assembly Language with High Level Language

- Assembly routines are mixed with 'C' in situations where
  - the entire program is written in 'C' and the cross compiler in use do not have a built in support for implementing certain features like Interrupt Service Routine functions (ISR) *or*
  - if the programmer wants to take advantage of the speed and optimised code offered by machine code generated by hand written assembly rather than cross compiler generated machine code.
- When accessing certain low level hardware, the timing specifications may be very critical and a cross compiler generated binary may not be able to offer the required time specifications accurately.
  - Writing the hardware/peripheral access routine in processor/controller specific Assembly language and invoking it from 'C' is the most advised method to handle such situations.

Mixing Assembly Language with High Level Language (continued)

- Mixing 'C' and Assembly is little complicated.
  - The programmer must be aware of how parameters are passed from the 'C' routine to Assembly and values are returned from assembly routine to 'C' and how 'Assembly routine' is invoked from the 'C' code.
- Passing parameter to the assembly routine and returning values from the assembly routine to the caller 'C' function and the method of invoking the assembly routine from 'C' code is cross-compiler dependent.

Mixing Assembly Language with High Level Language (continued)

- Consider an example Keil C51 cross compiler for 8051 controller.
- The steps for mixing assembly code with 'C' are:
  - Write a simple function in C that passes parameters and returns values the way you want your assembly routine to.
  - Use the *SRC* directive *(#PRAGMA SRC* at the top of the file) so that the C compiler generates an .SRC file instead of an *.OBJ* file.
  - Compile the C file. Since the SRC directive is specified, the .SRC file is generated. The .SRC file contains the assembly code generated for the C code you wrote.
  - Rename the .SRC file to .A51 file.
  - Edit the .A51 file and insert the assembly code you want to execute in the body of the assembly function shell included in the . A51 file.

Mixing Assembly Language with High Level Language (continued)

- As an example consider the following sample code:

```
#pragma SRC
unsigned char my_assembly_func (unsigned int argument)
{
 return (argument + 1); // Insert dummy lines to access all args and
                       // retvals
}
```

- This C function on cross compilation generates the assembly SRC file.
- The special compiler directive SRC generates the Assembly code corresponding to the 'C' function and each line of the source code is converted to the corresponding Assembly instruction.
- By inspecting the code segment, the source code can be modified by adding the required assembly routine.

Mixing High Level Language with Assembly Language

- Mixing the code written in a high level language like 'C' and Assembly language is useful in the following scenarios:
  1. The source code is already available in Assembly language and a routine written in a high level language like 'C' needs to be included to the existing code.
  2. The entire source code is planned in Assembly code for various reasons like optimised code, optimal performance, efficient code memory utilisation and proven expertise in handling the Assembly, etc. But some portions of the code may be very difficult and tedious to code in Assembly.
     - For example, 16-bit multiplication and division in *8051* Assembly Language.
  3. To include built in library functions written in 'C' language provided by the cross compiler.
     - For example, Built in Graphics library functions and String operations supported by 'C'.

Mixing High Level Language with Assembly Language (continued)

- Most often the functions written in 'C' use parameter passing to the function and returns value/s to the calling functions.
- Parameters are passed to the function and values are returned from the function using CPU registers, stack memory and fixed memory.
- Its implementation is cross compiler dependent and it varies across cross compilers.

Mixing High Level Language with Assembly Language (continued)

- Consider an example for the Keil C51 cross-compiler.
- C51 allows passing of a maximum of three arguments through general purpose registers R2 to R7.
- If the three arguments are *char* variables, they are passed to the function using registers R7, R6 and R5, respectively.
- If the parameters are *int* values, they are passed using register pairs (R7, R6), (R5, R4) and (R3, R2).
- If the number of arguments is greater than three, the first three arguments are passed through registers and rest is passed through fixed memory locations.

Mixing High Level Language with Assembly Language (continued)

- Return values are usually passed through general purpose registers.
- R7 is used for returning *char* value and register pair (R7, R6) is used for returning *int* value.
- The 'C' subroutine can be invoked from the assembly program using the subroutine call Assembly instruction.
- For example

```
LCALL _Cfunction
```

where *Cfunction* is a function written in 'C'

- The prefix _ informs the cross compiler that the parameters to the function are passed through registers.
- If the function is invoked without the _ prefix, it is understood that the parameters are passed through fixed memory locations.

Inline Assembly Programming

- Inline assembly is a technique for inserting target processor/controller specific Assembly instructions at any location of a source code written in high level language 'C'.
  - This avoids the delay in calling an assembly routine from a 'C' code.
- Special keywords are used to indicate that the start and end of Assembly instructions.
  - The keywords are cross-compiler specific.
  - C51 uses the keywords *#pragma asm* and *#pragma endasm* to indicate a block of code written in assembly.
  - For example:

```
#pragma asm
MOV A, #13H
#pragma endasm
```

Programming in Embedded C

- Whenever the conventional 'C' Language and its extensions are used for programming embedded systems, it is referred as ***'Embedded C'*** programming.
- Programming in 'Embedded C' is quite different from conventional Desktop application development using 'C' language for a particular OS platform.
- Desktop computers contain working memory in the range of Megabytes (Nowadays Giga bytes) and storage memory in the range of Giga bytes.
  - For a desktop application developer, the resources available are surplus in quantity and s/he can be very lavish in the usage of RAM and ROM and no restrictions are imposed at all.
  - This is not the case for embedded application developers.
- Almost all embedded systems are limited in both storage and working memory resources.
  - Embedded application developers should be aware of this fact and should develop applications in the best possible way which optimises the code memory and working memory usage as well as performance.
  - In other words, the hands of an embedded application developer are always tied up in the memory usage context.

‘C’ vs. ‘Embedded C’

- 'C' is a well structured, well defined and standardised general purpose programming language with extensive bit manipulation support.
- 'C' offers a combination of the features of high level language and assembly and helps in hardware access programming (system level programming) as well as business package developments (Application developments like pay roll systems, banking applications, etc).
- The conventional 'C' language follows ANSI standard and it incorporates various library files for different operating systems.
- A platform (operating system) specific application, known as, *compiler* is used for the conversion of programs written in 'C' to the target processor (on which the OS is running) specific binary files.
    - Hence it is a platform specific development.

- Embedded 'C' can be considered as a subset of conventional 'C' language.
- Embedded 'C' supports all 'C' instructions and incorporates a few target processor specific functions/instructions.
- The standard ANSI 'C' library implementation is always tailored to the target processor/controller library files in Embedded 'C’.
- The implementation of target processor/controller specific functions/instructions depends upon the processor/controller as well as the supported cross-compiler for the particular Embedded 'C' language.
- A software program called 'Cross-compiler' is used for the conversion of programs written in Embedded 'C' to target processor/controller specific instructions (machine language).

Compiler vs. Cross-Compiler

- Compiler is a software tool that converts a source code written in a high level language on top of a particular operating system running on a specific target processor architecture (e.g. Intel x86/Pentium).
- Here the operating system, the compiler program and the application making use of the source code run on the same target processor.
- The source code is converted to the target processor specific machine instructions.
- The development is platform specific (OS as well as target processor on which the OS is running).
- Compilers are generally termed as 'Native Compilers’.
    - A native compiler generates machine code for the same machine (processor) on which it is running.

- Cross-compilers are the software tools used in cross-platform development applications.
    - In cross-platform development, the compiler running on a particular target processor/OS converts the source code to machine code for a target processor whose architecture and instruction set is different from the processor on which the compiler is running or for an operating system which is different from the current development environment OS.
- Embedded system development is a typical example for cross-platform development.
    - Embedded firmware is developed on a machine with Intel/AMD or any other target processors and the same is converted into machine code for any other target processor architecture (e.g. 8051, PIC, ARM etc).
- Keil C51 is an example for cross-compiler.
- In embedded firmware application, whenever we use the term 'Compiler’ it normally refers to the cross-compiler.

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2. Raj Kamal, ***"Embedded Systems: Architecture and Programming",*** Tata McGraw Hill, 2008.