



AKSHAYA INSTITUTE OF TECHNOLOGY, TUMKUR

Department of Electronics & Communication Engineering



Module 2 Notes for

“EMBEDDED SYSTEM DESIGN”

[BEC601]

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING



VISION

To produce competent engineering professionals in the field of Electronics and Communication Engineering by imparting value based quality technical education to meet the societal needs and to develop socially responsible citizens.



MISSION

M1: To provide strong fundamentals and technical skills in the field of Electronics and Communication Engineering through effective teaching learning process.

M2: Enhancing employability of the students by providing skills in the fields of VLSI, Embedded systems, Signal processing, etc., through Centre of Excellence.

M3: Encourage the students to participate in co-curricular and extra-curricular activities that creates a spirit of social responsibility and leadership qualities.



Program Specific Outcomes (PSOs)

After Successful Completion of Electronics and Communication Engineering Program Students will be able to

1. Apply fundamental knowledge of core. Electronics and Communication Engineering in the analysis, design and development of Electronics Systems as well as to interpret and synthesize experimental data leading to valid conclusions.
2. Exhibit the skills gathered to analyze, design, develop software applications and hardware products in the field of embedded systems and allied areas.



Program Educational Objectives (PEOs)

PEO1: Graduates exhibit their innovative ideas and management skills to meet the day to day technical challenges.

PEO2: Graduates utilize their knowledge and skills for the development of optimal solutions to the problems in the field of Electronics and Communication Engineering..

PEO3: Graduates exhibit good interpersonal skills, leadership qualities and adapt themselves for life-long Learning



Embedded System Design		Semester	06
Course Code	BEC601	CIE Marks	50
Teaching Hours/Week (L:T:P: S)	3:0:2:0	SEE Marks	50
Total Hours of Pedagogy	40 hours Theory + 8-10 Lab slots	Total Marks	100
Credits	04	Exam Hours	
Examination nature (SEE)	Theory		
<p>Course objectives:</p> <ul style="list-style-type: none"> ● Identify various components, their purpose, and their application to the embedded system's applicability. ● Program various embedded components using the embedded C program. ● Understand the embedded system's real-time operating system and its application in IoT ● Understand the fundamentals of ARM-based systems, including architecture and its units like registers, debug interface, stack, MPU, Interrupts etc ● Use the various instructions to program the ARM controller. 			
<p>Teaching-Learning Process (General Instructions) These are sample Strategies; that teachers can use to accelerate the attainment of the various course outcomes.</p> <ol style="list-style-type: none"> 1. In addition to the traditional lecture method, different types of innovative teaching methods may be adopted so that the delivered lessons shall develop students' theoretical and applied Mathematical skills. 2. Provide real-life examples. 3. Support and guide the students for self-study. 4. You will assign homework, grading assignments and quizzes, and documenting students' progress. 5. Encourage the students to group learning to improve their creative and analytical skills. 6. Show short related video lectures in the following ways: <ul style="list-style-type: none"> ● As an introduction to new topics (pre-lecture activity). ● As a revision of topics (post-lecture activity). ● As additional examples (post-lecture activity). ● As an additional material of challenging topics (pre-and post-lecture activity). ● As a model solution of some exercises (post-lecture activity). 			
MODULE-1			
<p>Introduction to Embedded System: What is an Embedded Systems? Embedded systems Vs General computing systems, History of Embedded Systems, Classification of Embedded systems, Major Application Areas of Embedded Systems. Purpose of Embedded Systems, The Typical Embedded System, Microprocessor Vs Microcontroller, Differences between RISC and CISC, Harvard V/s Von-Neumann Processor/Controller Architecture, Big-endian V/s Little-endian processors, Memory (ROM and RAM types), Sensors & Actuators, The I/O Subsystem – I/O Devices, Light Emitting Diode (LED), 7-Segment LED Display, Optocoupler, Relay, Piezo buzzer, Push button switch, Communication Interfaces, On-board Communication Interface, External Communication Interface, Embedded Firmware, Other System Components</p> <p style="text-align: right;">(Text 1: All the Topics from Ch-1 and Ch-2.)</p>			
MODULE-2			
<p>Embedded System Design Concepts: Characteristics and Quality Attributes of Embedded Systems, Operational and non-operational quality attributes, Embedded Systems-Application and Domain specific, Hardware Software Co-Design and Program Modeling (excluding UML), Embedded firmware design and development (excluding C language).</p>			

Text 1: Ch-3, Ch-4 (4.1, 4.2.1 and 4.2.2 only), Ch-7 (Sections 7.1, 7.2 only), Ch-9 (Sections 9.1, 9.2, 9.3.1, 9.3.2 only)

MODULE-3

RTOS and IDE for Embedded System Design: Operating System basics, Types of operating systems, Task, process and threads (Only POSIX Threads with an example program), Thread preemption, Preemptive Task scheduling techniques, Task Communication, Task synchronization issues – Racing and Deadlock. How to choose an RTOS, Integration and testing of Embedded hardware and firmware, Embedded system Development Environment – Block diagram (excluding Keil).
(Text 1: Ch-10 (Sections 10.1, 10.2, 10.3, 10.5.2, 10.7, 10.8.1.1, 10.8.1.2 only), Ch-12, Ch-13 (a block diagram before 13.1, only).

MODULE-4

ARM Embedded Systems:

Introduction, RISC design philosophy, ARM design philosophy, Embedded system hardware – AMBA bus protocol, ARM bus technology, Memory, Peripherals, Embedded system software – Initialization (BOOT) code, Operating System, Applications.
 ARM Processor Fundamentals, ARM core dataflow model, registers, current program status register, Pipeline, Exceptions, Interrupts and Vector Table, Core extensions.

Text 2: Chapter 1, 2

MODULE-5

Introduction to the ARM Instruction set: Introduction, Data processing instructions, Load – Store instruction, Software interrupt instructions, Program status register instructions, Loading constants, ARMv5E extensions, Conditional Execution.

Text 2: Chapter 3

PRACTICAL COMPONENT OF IPCC

Conduct the following experiments on an ARM CORTEX M3 evaluation board to learn Assembly Language Program and using evaluation version of Embedded 'C' & Keil uVision-4 tool/compiler.

Sl.NO	Experiments
1	Write a program to find the sum of the first 10 integer numbers.
2	Write an Assembly Language Program (ALP) to i) Multiply two 16-bit numbers. ii) Add two 32-bit numbers.
3	Write a program to find the factorial of a number.
4	Write a program to add an array of 16 bit numbers and store the 32 bit result in internal RAM.
5	Write a program to find the square of a number (1 to 10) using a look-up table.
6	Write a program to find the largest or smallest number in an array of 32 numbers.
7	Write a program to arrange a series of 32 bit numbers in ascending/descending order.
8	Write a program to count the number of ones and zeros in two consecutive memory locations.
9	Interface a Stepper motor and rotate it in clockwise and anti-clockwise direction.
10	Interface a DAC and generate Triangular and Square waveforms.
11	Display the Hex digits 0 to F on a 7-segment LED interface, with a suitable delay in between.
12	Interface a simple Switch and display its status through Relay, Buzzer and LED

Course outcomes (Course Skill Set):

At the end of the course, the student will be able to:

- Describe the architectural features and instructions of 32-bit microcontroller ARM Cortex M3.
- Apply the knowledge gained for Programming ARM Cortex M3 for different applications.
- Understand the basic hardware components and their selection method based on the characteristics and attributes of an embedded system.
- Understand the hardware software co-design and firmware design approaches.
- Explain the need of real time operating system for embedded system applications.

Assessment Details (both CIE and SEE)

The weightage of Continuous Internal Evaluation (CIE) is 50% and for Semester End Exam (SEE) is 50%. The minimum passing mark for the CIE is 40% of the maximum marks (20 marks out of 50) and for the SEE minimum passing mark is 35% of the maximum marks (18 out of 50 marks). A student shall be deemed to have satisfied the academic requirements and earned the credits allotted to each subject/course if the student secures a minimum of 40% (40 marks out of 100) in the sum total of the CIE (Continuous Internal Evaluation) and SEE (Semester End Examination) taken together.

CIE for the theory component of the IPCC (maximum marks 50)

- IPCC means practical portion integrated with the theory of the course.
- CIE marks for the theory component are **25 marks** and that for the practical component is **25 marks**.
- 25 marks for the theory component are split into **15 marks** for two Internal Assessment Tests (Two Tests, each of 15 Marks with 01-hour duration, are to be conducted) and **10 marks** for other assessment methods mentioned in 22OB4.2. The first test at the end of 40-50% coverage of the syllabus and the second test after covering 85-90% of the syllabus.
- Scaled-down marks of the sum of two tests and other assessment methods will be CIE marks for the theory component of IPCC (that is for **25 marks**).
- The student has to secure 40% of 25 marks to qualify in the CIE of the theory component of IPCC.

CIE for the practical component of the IPCC

- **15 marks** for the conduction of the experiment and preparation of laboratory record, and **10 marks** for the test to be conducted after the completion of all the laboratory sessions.
- On completion of every experiment/program in the laboratory, the students shall be evaluated including viva-voce and marks shall be awarded on the same day.
- The CIE marks awarded in the case of the Practical component shall be based on the continuous evaluation of the laboratory report. Each experiment report can be evaluated for 10 marks. Marks of all experiments' write-ups are added and scaled down to **15 marks**.
- The laboratory test (**duration 02/03 hours**) after completion of all the experiments shall be conducted for 50 marks and scaled down to **10 marks**.
- Scaled-down marks of write-up evaluations and tests added will be CIE marks for the laboratory component of IPCC for **25 marks**.
- The student has to secure 40% of 25 marks to qualify in the CIE of the practical component of the IPCC.

SEE for IPCC

Theory SEE will be conducted by University as per the scheduled timetable, with common question papers for the course (**duration 03 hours**)

1. The question paper will have ten questions. Each question is set for 20 marks.
2. There will be 2 questions from each module. Each of the two questions under a module (with a maximum of 3 sub-questions), **should have a mix of topics** under that module.
3. The students have to answer 5 full questions, selecting one full question from each module.

4. Marks scored by the student shall be proportionally scaled down to 50 Marks

The theory portion of the IPCC shall be for both CIE and SEE, whereas the practical portion will have a CIE component only. Questions mentioned in the SEE paper may include questions from the practical component.

Suggested Learning Resources:

Text Books

1. **Shibu K V, "Introduction to Embedded Systems", Tata McGraw Hill Education**
2. **Andrew N Sloss, Dominic System and Chris Wright, "ARM System Developers Guide", Elsevier, Morgan Kaufman publisher, 1st Edition, 2008.**

Reference Book

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

Web links and Video Lectures (e-Resources):

1. <https://archive.nptel.ac.in/courses/106/105/106105193/>
2. <https://developer.arm.com/documentation/dui0068/b/ARM-Instruction-Reference>
3. <https://www.udemy.com/course/introduction-to-arm-cortex-m3-and-m4-processors/>
4. www.Nuvoton.com/websites on Advanced ARM Cortex Processors
5. <https://alison.com/tag/embedded-systems>

Activity Based Learning (Suggested Activities in Class)/ Practical Based learning

Programming Assignments / Mini Projects can be given to improve programming skills

Module – 2

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

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.

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.
- 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.

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.

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 is independent embedded units but they work together to perform the overall vending function.
- Another example is the Automatic 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.

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.

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 minimize 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

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.

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.

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.

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.
- 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

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.

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).

Numerical Example

- 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 $MTBF = 4 \text{ months} = 120 \text{ days}$

and $MTTR = 2 \text{ weeks} = 14 \text{ days}$

We know that

$$A_i = \frac{MTBF}{MTBF+MTTR}$$
$$A_i = \frac{120}{120+14} = \frac{120}{134}$$
$$A_i = 0.8955 \text{ or } 89.55\%$$

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

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.

Evolvability

- 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.

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).
- If the firmware is written in a high level language like 'C', it is very easy to port the firmware
- If the firmware is written in Assembly Language for a particular family of processor (say x86 family), the portability is poor.

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.
- 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.

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.

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

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.

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.

Growth Phase

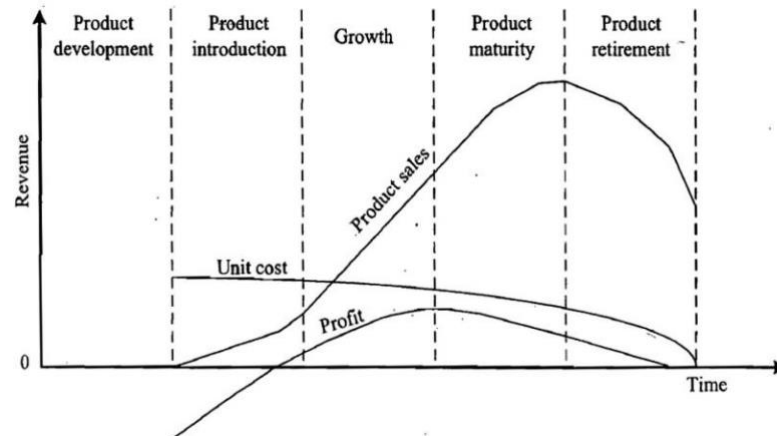
- The product grabs high market share.

Maturity Phase:

- The growth and sales will be steady and the revenue reaches at its peak.

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.
- 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



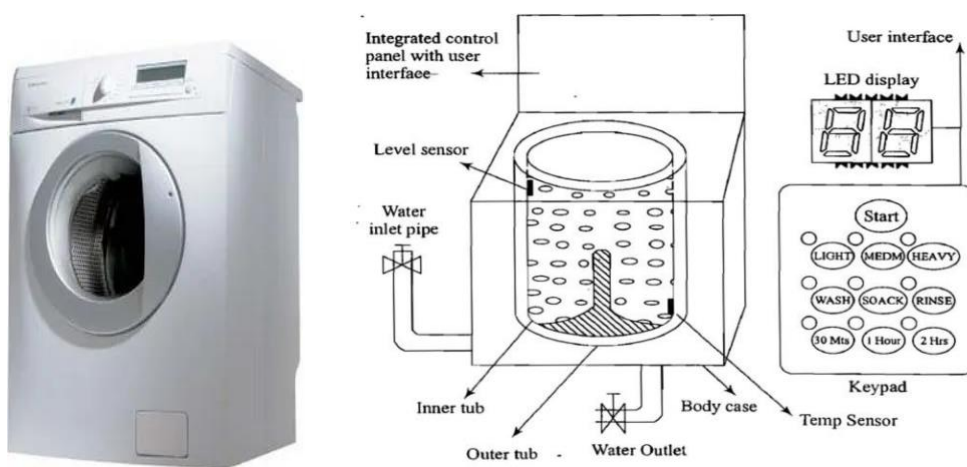
- From the graph, it is clear that the total revenue increases from the product introduction stage to the product maturity stage.
- The revenue peaks at the maturity stage and starts falling in the decline/retirement Stage.
- The unit cost is very high during the introductory stage. A typical example 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.



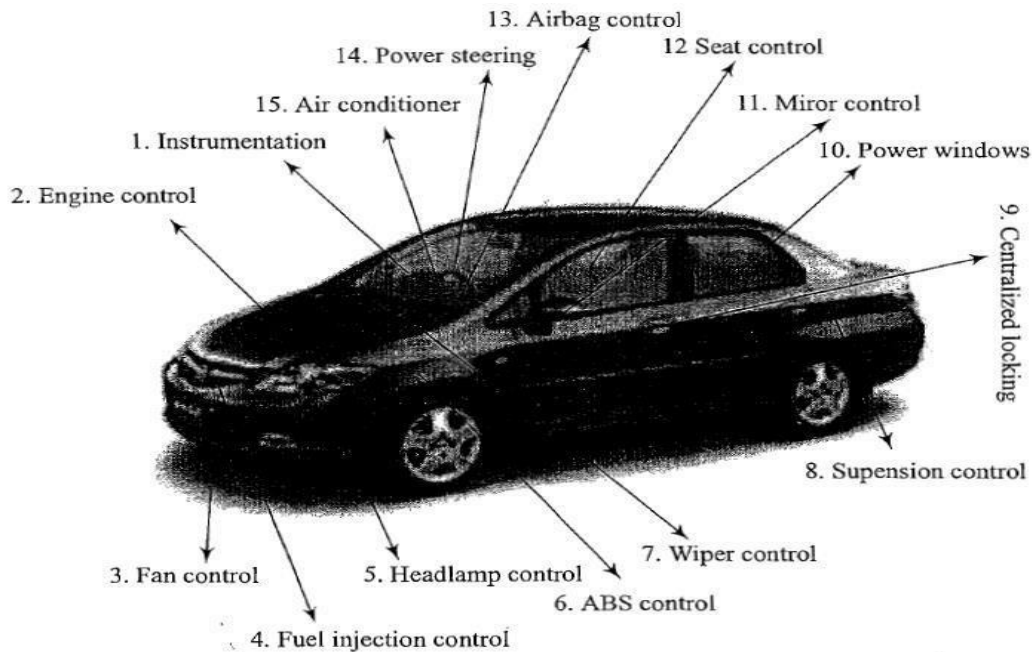
- The actuator part of the washing machine consists of a motorised agitator, tumble tub, water drawing pump and inlet valve to control the flow of water into the unit.
- The sensor part consists of the water temperature sensor, level sensor, etc. The control part contains a microprocessor/controller 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 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 upto 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.

- 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.
- 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.
- 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.

Figure below gives an overview of the various types of electronic control units employed automotive applications.



- 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.
- The first embedded system used in automotive application was the microprocessor based fuel injection system introduced by Volkswagen 1600 in 1968.
- 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 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
- **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 (ISO11898 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.
- **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.
- **Media-Oriented System Transport (MOST) Bus**
 - MOST Bus is targeted for automotive audio/video equipment interfacing.
 - 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.

Key Players of the Automotive Embedded Market

- The key players of the automotive embedded market can be visualised in three verticals namely, silicon providers, tools and platform providers and solution providers.
- **Silicon Providers**
 - They are responsible for providing the necessary chips which are used in the control application development.
 - The chip may be a standard product like microcontroller or DSP or ADC/DAC chips.
 - Some applications may require specific chips and they are manufactured as Application Specific Integrated Chip (ASIC).
 - The leading silicon providers in the automotive industry are Analog Devices, Xilinx, Atmel, Maxim/Dallas, NXP Semiconductors, Renesas, Texas Instruments, Fujitsu, Infineon, NEC, etc.
- **Tools and Platform Providers**

- They are manufacturers and suppliers of various kinds of development tools and Real Time Embedded Operating Systems for developing and debugging different control unit related applications.
 - Some of the leading suppliers of tools and platforms in automotive embedded applications are ENEA, The MathWorks, MATLAB, Keil Software, Lauterbach, ARTiSAN, Microsoft, etc.
- **Solution Providers**
- They supply Original Equipment Manufacturer (OEM) and complete solution for automotive applications making use of the chips, platforms and different development tools.
 - The major players of this domain Bosch Automotive, DENSO Automotive, Infosys Technologies, Delphi, etc.

Hardware Software CoDesign 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.
- 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.
- 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

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.

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.).

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.

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.

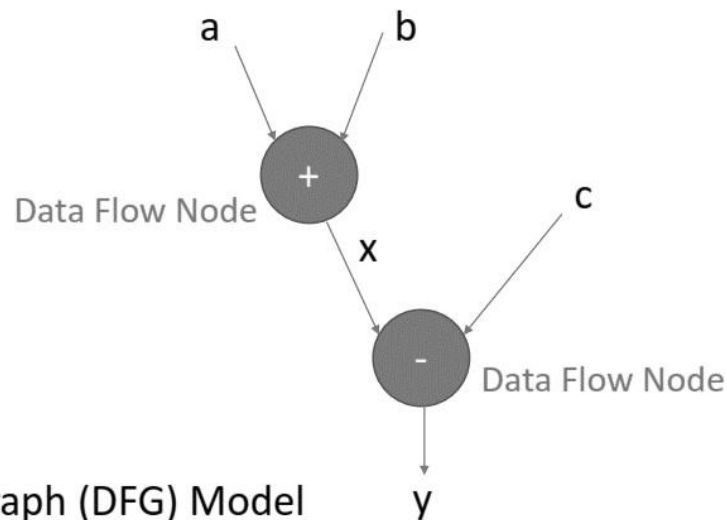
Computational Models in Embedded Design

- 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 (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 $y = x - c$.

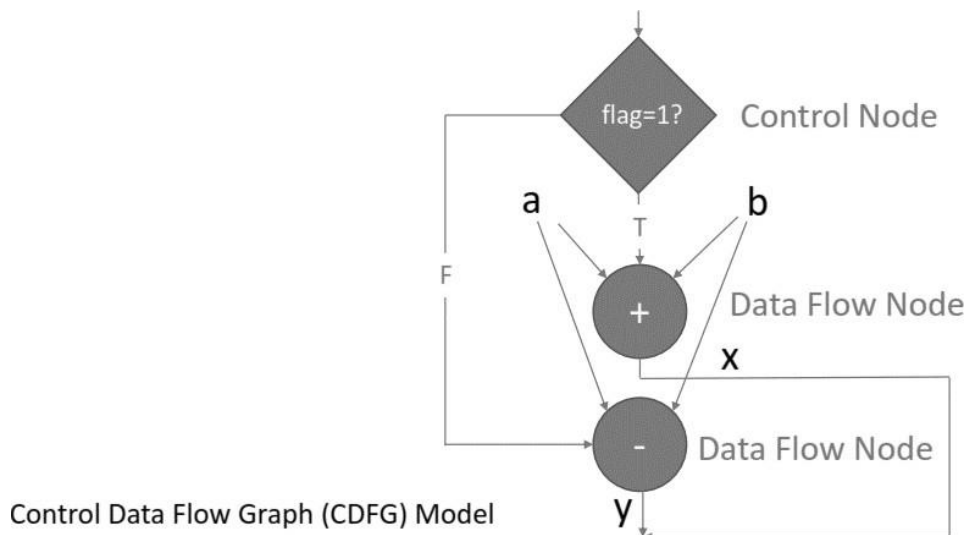
- Figure illustrates the implementation of a DFG model for implementing these requirements.



- 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.
- 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.



- 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.
- 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.
 - 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.



- 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.

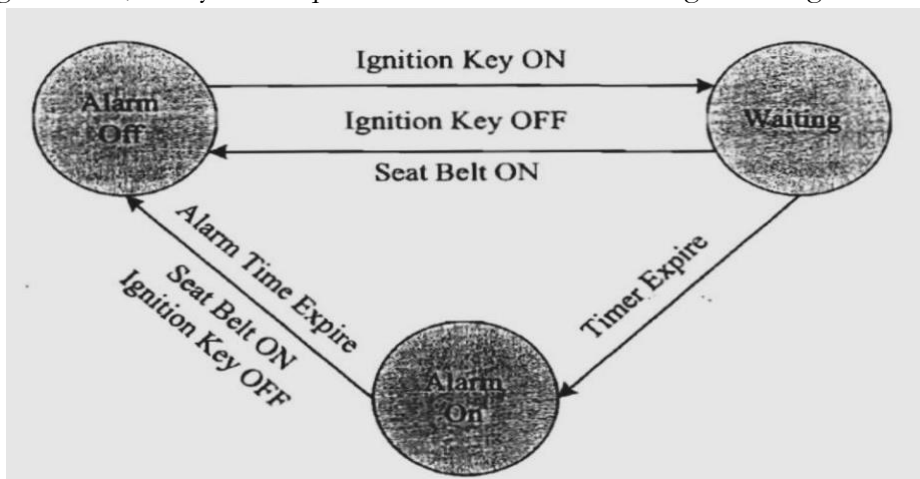
➤ Here the states are

- 'Alarm Off'
- 'Waiting'
- 'Alarm On'

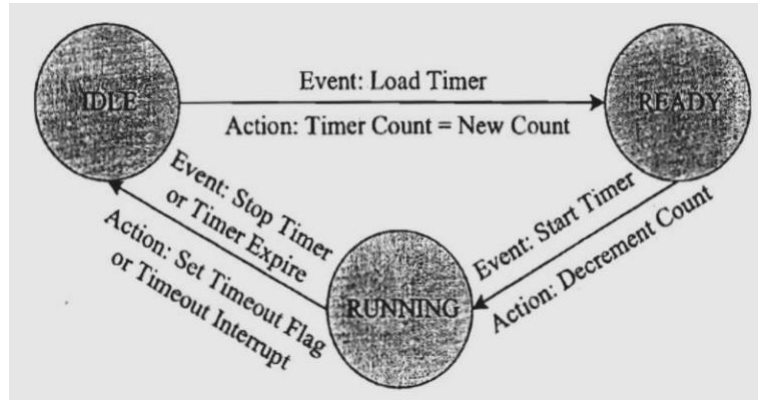
➤ The events are

- '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.



- 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.



- 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.

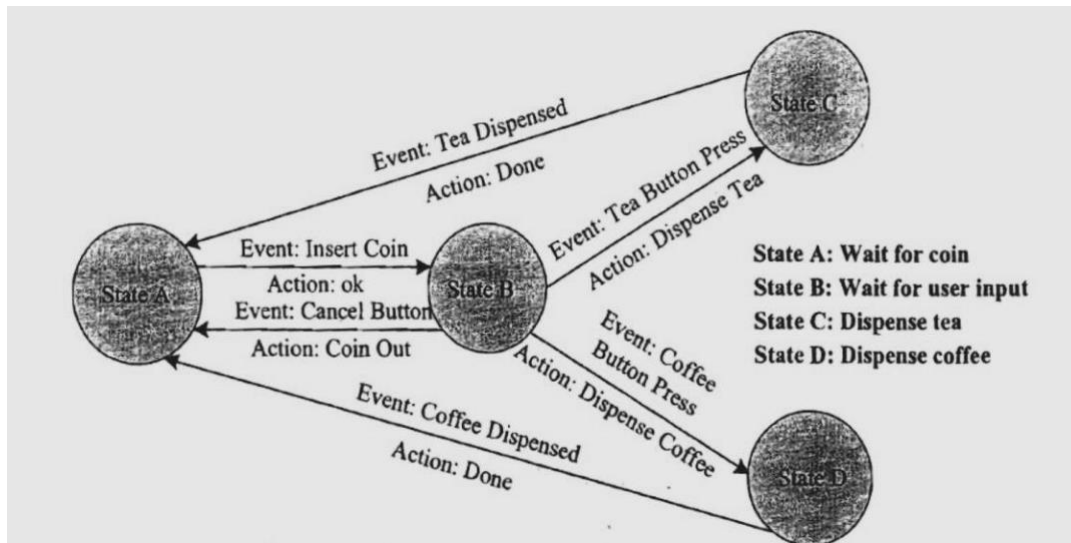
FSM Model – Example 1

- 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'

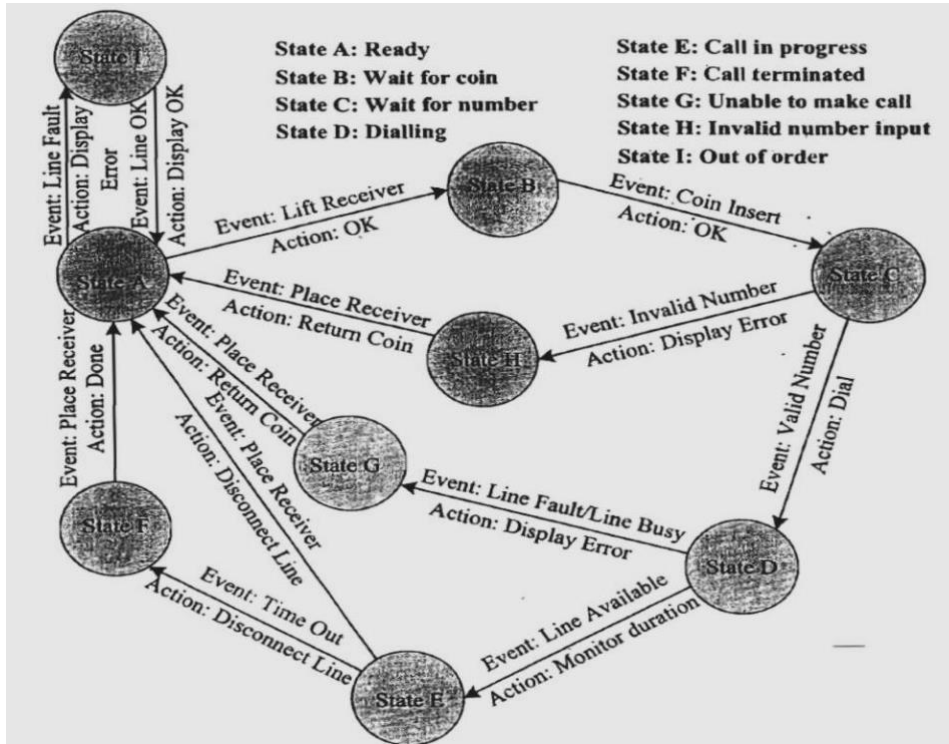




- The event 'Insert Coin' (5 rupee coin insertion), transitions the state to 'Wait for User Input'.
- The system stays in this state until a user input is received from the buttons 'Cancel', 'Tea' or 'Coffee' (Tea and Coffee are the drink select button).
- If the event triggered in 'Wait State' is 'Cancel' 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.
 - The calling process is initiated by lifting the receiver (off-hook) of the telephone unit.
 - After lifting the phone the user needs to insert a 1 rupee coin to make the call.
 - If the line is busy, the coin is returned on placing the receiver back on the hook (on-hook).
 - 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.
 - If the user doesn't insert another 1 rupee coin, the call is terminated on completing the 60 seconds time slot.
 - The system is ready to accept new call request when the receiver is placed back on the hook (on-hook).
 - The system goes to the 'Out of Order' state when there is a line fault.



Sequential Program Model

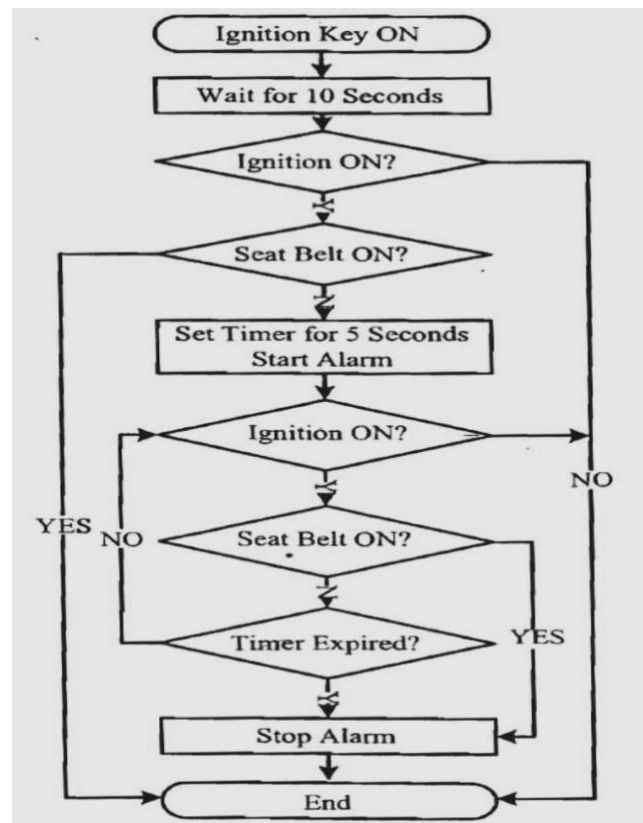
- In the Sequential Program Model, the functions or processing requirements are executed in sequence.
 - It is same as the conventional procedural programming.
- Here the program instructions are iterated and executed conditionally and the data gets transformed through a series of operations.
- Finite 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.
- 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();
    }
  }
}

```

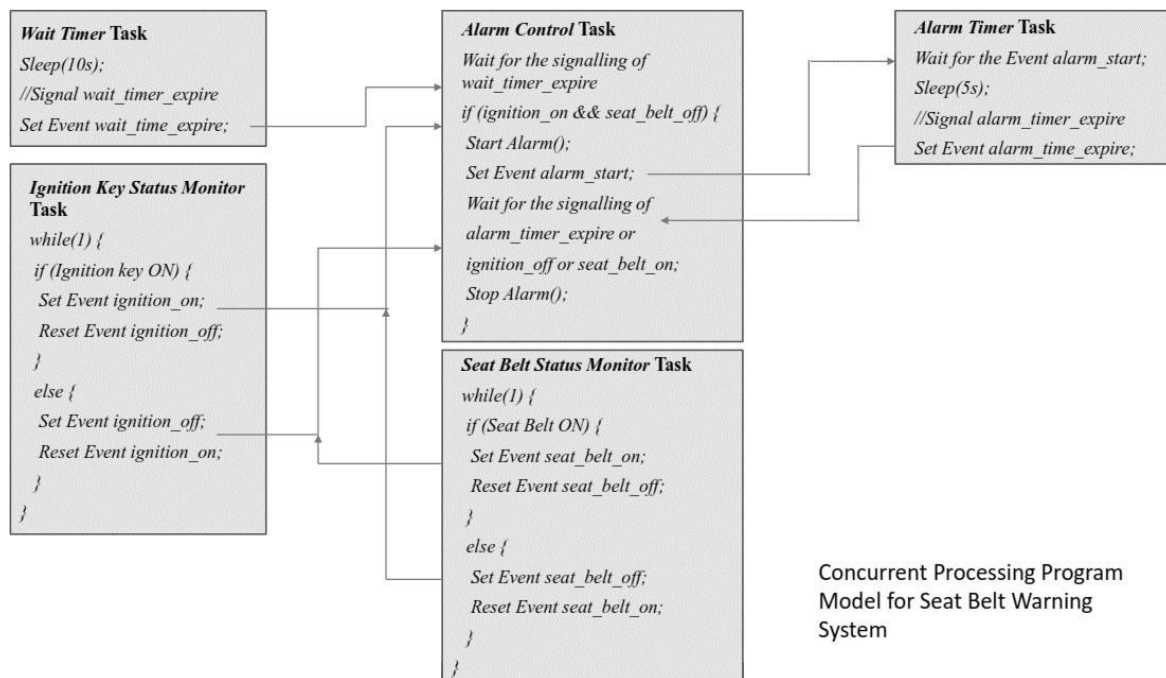
- Sequential Program Model for Seat Belt Warning System



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

- The tasks cannot be executed them randomly or sequentially.
- We need to synchronize their execution through some mechanism.



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 characterized by a set of unique behaviour and state.
- 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.

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.
- 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.
- The firmware execution flow for this will be
 - Configure the common parameters and perform initialisation for various hardware components memory, registers, etc.

- Start the first task and execute it
 - Execute the second task
 - Execute the next task
 - :
 - :
 - Execute the last defined task
 - Jump back to the first task and follow the same flow
- 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();
  }
}
```

- 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.
- 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.
- 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.
- 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.
- 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.

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.
- 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.

- 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.

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.

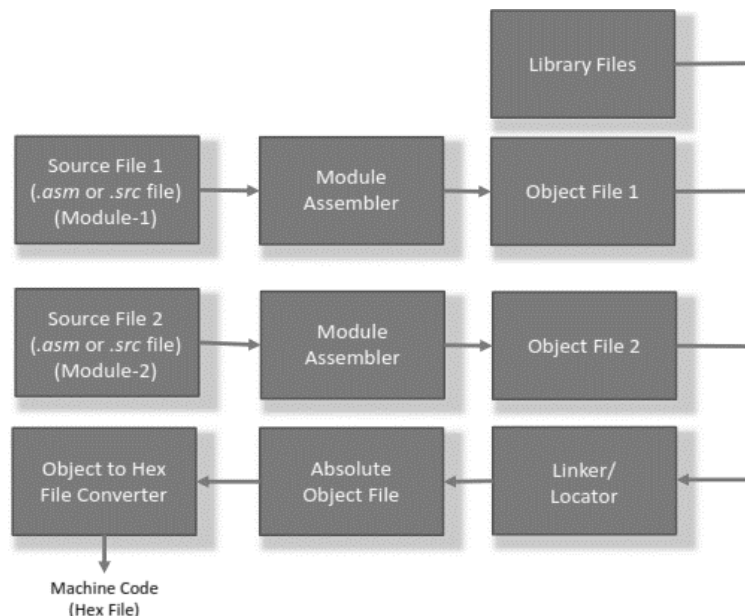
Assembly Language Based Development

- 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.
- 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.
- 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 is the Opcode and A, #30 is the operands
- 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.

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.



- 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/locator to assign absolute address for this module.

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 controllers.

Linker and Locator

- Linker and Locator 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 & Locator for A51 Assembler/C51 Compiler for 8051 specific controller.

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 Base 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.
- 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.

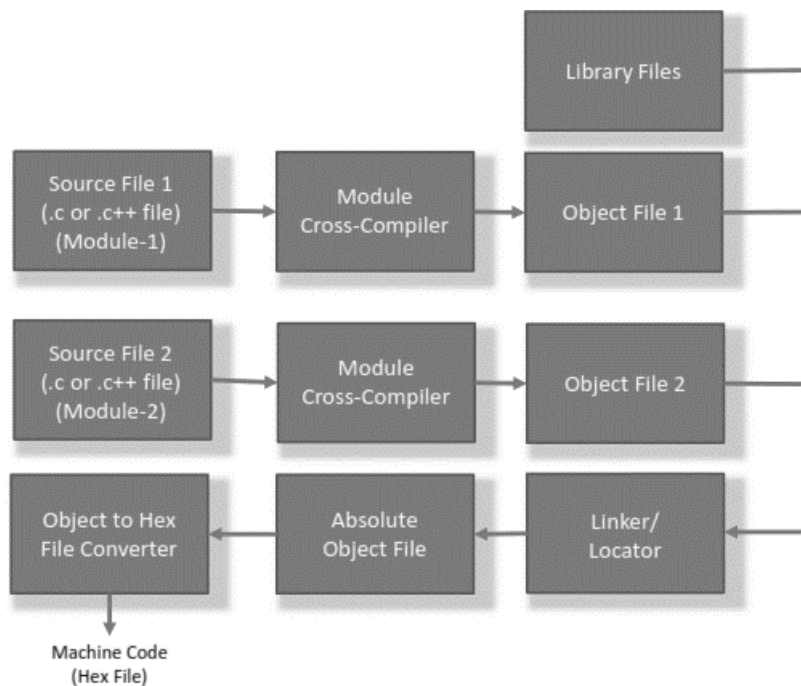
Drawbacks of Assembly Language Based Development

- 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'.
- 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.
- 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.
- 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.



- 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.
- Translation of high level source code to executable object code is done by across-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.
- 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.
- 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 recompiling 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.
 - The time required to execute a task also increases with the number of instructions.
- 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 '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.
- 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 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:
 - 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.
 - 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.
 - 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'.
- 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.

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.

'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.