INSTRUCTION DIVISION
SECOND SEMESTER – 2022-2023
Course Handout Part II

In addition to part-I (General Handout for all courses appended to the time table) this portion gives further specific details regarding the course.

Course Number: CS F316

Course Title: Quantum Architecture and Programming

Instructor-in-Charge : Kunal Kishore Korgaonkar (BITS Pilani, Goa Campus)

Scope and Objectives

It is envisaged that quantum computers are able to solve problems far faster than a classical computer running any known classical algorithm. Hence quantum computing and computer is becoming an area of increasing interest. Although there have been some demonstrations of the power of quantum computing by building a real quantum computer, there still exists infancy with respect to its scalability and efficiency. To build such systems, one must understand the concepts, architectural and programming models, and programming languages that can be run on such systems.

This course aims to provide a detailed step to designing a real quantum computer, although not to build one. This means that we shall be looking at the blue-print of a quantum computer, assuming that we already have the basic building blocks. This is equivalent to studying the course computer architecture for classical computers. Nevertheless, for the sake of completeness, we shall also be discussing how to build reversible circuits and synthesise a few reversible components such as adders and registers, although to a lesser extent. The course does not focus on quantum algorithms, quantum information processing (such as QFT), physical realizations of quantum computers (such photons or ion traps), quantum communication or quantum cryptography.

This course aims to achieve the following goals: ● To provide an understanding of the quantum computer architecture and programming of quantum computers. ● To help design quantum processing elements. ● To help design quantum instruction set architectures (QISA) which can be executed on a quantum architecture. The case studies will help in understanding the steps to designing an actual quantum computer. ● To understand how high-level programs and algorithms can be executed by converting them into a quantum assembly language program by a quantum compiler and how it can be executed on the designed architecture. ● To understand how reversible computing models and how it is helpful in designing quantum architectures.

<u>Prerequisites:</u> **A basic course in computer programming, digital and microprocessor design.**

<u>Text Books (important ones in blue)</u>
T1. Quantum Computer Systems: Research for Noisy Intermediate-Scale Quantum Computers, Yongshan Ding and Frederic T. Chong, Morgan & Claypool Pub.
T2. Quantum Computing: From Linear Algebra to Physical Realizations, Mikio Nakahara and Tetsuo Ohmi, CRC Press

<u>Reference Books and Papers (important ones in blue)</u>
R1. Introduction to Reversible Computing by K. S. Perumalla, CRC Press, 1st Ed.
R2. Quantum Computation and Quantum Information by Michael A. Nielsen, Isaac L. Chuang, 10th Ed., Cambridge Pub.
R3. Quantum Computing for Computer Architects, by Tzvetan S. Metodi, Arvin I. Faruque, Frederic T. Chong. 2nd Edition, Morgan & Claypool Pub
R4. Quantum Computing for Computer Scientists, Noson S. Yanofsky and Mirco A. Mannucci, Cambridge University Press
R5. Introduction to Classical and Quantum Computing, Thomas G. Wong, Free eBook
R6. Reversible Computing: Fundamentals, Quantum Computing, and Applications Alexis De Vos, Wiley‐VCH Verlag GmbH & Co. KGaA
R7. Quantum Algorithm Implementations for Beginners, Abhijit et al. ACM Transactions on Quantum Computing, 2022

Course Plan

Lecture No	Learning Outcomes	Topics to be covered	Chapter in the textbook
1-3	To understand the basics of quantum computing and the phases of designing a quantum computer architecture. Understand the different subsystems of a quantum computer. Understand the NISQ era.	Introduction to Quantum Computing and quantum computers. Basic elements of Quantum computation.	T1:Ch 1, 2 Class Notes

4-15	**To understand the distinction between classical digital bits versus quantum qubits distinction.** **To understand control in classical processing versus quantum processing control.** **To understand hybrid and interleaved classical and quantum computing. The basic idea of quantum application design.** **Understand the maths behind quantum computing, especially linear algebra. How this translates to basic quantum operations.**	**Models of Quantum Computation, NISQ Motivation, Architectural Constraints of a Quantum Computer** **Linear algebra and quantum computing.**	**T1: Ch 3, 4** **T2: Ch 1, 2, 3, 4** **Class Notes**
16-17	**To understand the relation between reversible computing and quantum computing. To understand the relation between entropy and reversibility. To understand the reversible computing model.**	**Introduction to reversible computing with application. Energy cost of computation, theoretical lower bound, reversibility and entropy, Ehrenfest's urn model, KacRing model.** **Theoretical Computing models, Turing machine model (TMM), Irreversibility in TMM, reversible Turing machine, Compute-Copy-Uncompute paradigm, Forward-Reverse-Commit Paradigm.**	**R1: Ch 4, 6, 7 and Class notes**

18-20	Understand reversible gates that form the building blocks of reversible and quantum computers. To understand the working principle of quantum arithmetic and logic units. To understand architectural models and implement reversible instruction set architectures in quantum computers	Reversible hardware. Reversible Logic gates, Construction of basic reversible components, synthesis of reversible circuits. Designing quantum ALUs. Quantum architectures. Reversible architecture design, and reversible programming model. The Reversible ISAs. The Pendulum architecture and the Pendulum instruction set architecture (PISA).	R1: Ch.18 and Class notes
21-28	Understand the core primitives or the algorithmic building blocks of quantum computing. Understand the variety of such primitives through varied algorithms. Understand quantum benchmarking.	Basic building blocks of quantum algorithms. The type of operations and circuits arising as a result of the algorithmic blocks or primitives.	T2: Ch 5, 6, 7, 8 R7: Class notes
29-32	To understand the underlying error generation in quantum systems and mitigation techniques.	Error correction and fault-tolerant architectures, the Steane code.	T1: Ch 8 T2: Ch 10 R2: Ch 10 Class notes

33-35	**To understand the instruction execution cycle in a quantum processor** **To understand the implementation of real-life quantum architecture and introduce quantum 4004, the first 4-qubit quantum processor.** **Understand the physics behind quantum computing and various underlying technology alternatives such as superconducting qubits, etc.**	**Quantum processing elements, quantum memory hierarchy, quantum RAM, quantum addressing. Microarchitecture and Pulse Compilation** **Case study 1: Quantum von Neuman architecture, quantum 4004. Case study 2: Quantum logic array architecture.**	**T1: Ch. 4, 7 and Class Notes** **Research papers, class notes.**
36-40	**To understand the basics of compiler design techniques for quantum programming languages.** **To understand instruction scheduling in quantum architectures and how to design general circuits for a given architecture and instruction set.** **Understand the issues in mapping quantum algorithms to actual qubits chips/hardware.**	**Programming the quantum architecture. Physical level instruction scheduling, high-level compiler design, mapping circuits to architecture.**	**T1: Ch. 5, 6 and Class notes.**

Evaluation Scheme: Major Components

Component	Duration	Weightage
Assignments, Projects and Quizzes	**-**	**35%**
Midsem exams	**90 mins**	**30%**
Compre exams	**180 mins**	**35%**

Chamber Consultation

The location is D-246 (D block) and timings will be communicated in the class or on appointment.

Makeup Policy

Under expectational cases (such as medical emergency recognized by institute medical center) and only on prior permision basis.