Ph.D. in Molecular Medicine

College of Medicine and Medical Sciences (CMMS)| Department of Molecular Medicine, Genetics and Inherited Diseases

Program Outline

The Ph.D. in Molecular Medicine is designed to provide advanced education, research training, and practical experience for holders of a Master's degree in medical sciences and related disciplines. The programme prepares graduates for careers in research, academia, and specialized healthcare fields related to Molecular Medicine and its applications. The programme spans 3 to 4 years and consists of 48 credit hours, including a 24-credit-hour doctoral thesis.

The curriculum is structured over 6 to 8 semesters. During the initial stage of the programme, students complete core, basic, specialized, and advanced specialized courses according to their selected specialization track. This is followed by supervised research leading to the completion and defense of the Ph.D. thesis. Course selection is determined in consultation with the student's supervisor and the academic committee.

1. Program Tracks Overview

Track	Focus Area	Starting Page
Medical Genetics	Focuses on genetic and inherited diseases, including their diagnosis, analysis, and application in molecular medicine practice.	Page 2
Biochemical Genetics	Focuses on metabolic and biochemical mechanisms underlying genetic disorders and their application in molecular diagnosis.	Page 5
Immunology	Focuses on molecular and cellular mechanisms of the immune system in health and disease.	Page 9
Nanomedicine	Focuses on the application of nanotechnology in diagnosis, treatment, and prevention of diseases.	Page 12
Health Biotechnology	Focuses on the application of biotechnology in healthcare, including molecular diagnostics, genetic engineering, bioprocessing, biopharmaceutical development, and translational research to improve disease prevention, diagnosis, and treatment.	Page 15

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Track 1: Medical Genetics

Track Credit Hours: 43

1. Program Tracks Overview

The Medical Genetics Track in the Doctor of Philosophy in Molecular Medicine requires 43 credit hours, comprising 19 credit hours of coursework and 24 credit hours of doctoral thesis research. Coursework is normally completed during the first year of study, followed by supervised research and dissertation work during the second and third years of the programme.

2. Study Plan

Course Code	Course Title	Credit Hours
First Year - Core Courses		
A.3	Introduction to Bioinformatics	2
A.4	Good Laboratory Practice	2
CMMS604	Research Methodology	2
CMMS621	Inferential Statistics and its Applications	2
Total Credit Hours		**8**
First Year - Basic Courses in Molecular Medicine		
B.2	Structure, Organization, and Regulation of Human Genes	1
B.3	The Techniques of Gene Analysis	1
B.6	Molecular Genetics and Common Diseases	2
B.9	Gene Therapy, Gene Cloning and Ethical Issues	2
Total Credit Hours		**6**
First Year - Specialized Courses in Molecular Medicine		
C.4	Genetic Basis of Metabolic Diseases	1
Total Credit Hours		**1**

Course Code	Course Title	Credit Hours
First Year - Specialized Courses in Molecular Genetics		
D.4	Genome Structure and Stability	2
D.5	Genetic Engineering of Eukaryotic Organisms	2
Total Credit Hours		**4**
Second/Third Year - Ph.D. Project		
K24	Thesis	24
Total Credit Hours		**24**
Total Programme Credit Hours		**43**

3. Course Descriptions

Introduction to Bioinformatics (A.3)

This 2-credit course introduces foundational concepts and techniques of bioinformatics in molecular medicine. Students learn to use computational tools and methods to analyse biological data, including genomic and proteomic sequences. The curriculum covers sequence alignment, database searching, and the application of bioinformatics in research and clinical diagnostics. By the end of the course, students gain practical skills in handling and interpreting complex biological data.

Good Laboratory Practice (A.4)

This 2-credit course focuses on the principles and guidelines of Good Laboratory Practice essential for high-quality scientific research. Students learn standards and procedures required to ensure accuracy, reliability, and integrity in laboratory work. The curriculum covers documentation, quality control, safety protocols, and ethical considerations in laboratory research, enabling students to maintain rigorous scientific practices.

Research Methodology (CMMS604)

This course focuses on essential research methodologies used in research. Students learn about research designs, data collection techniques, and statistical analysis methods relevant to medical research. The curriculum includes formulating research questions, designing studies, conducting experiments, and interpreting results, with emphasis on ethical considerations and best practices that support valid and reliable findings.

Inferential Statistics and its Applications (CMMS621)

This course provides an in-depth understanding of inferential statistics and their practical applications in research. Students learn to make predictions and draw conclusions about populations based on sample

data. The curriculum covers hypothesis testing, confidence intervals, regression analysis, and analysis of variance, with emphasis on applying statistical techniques to real-world medical research data.

Structure, Organization, and Regulation of Human Genes (B.2)

This 1-credit course provides a concise overview of fundamental aspects of human genes. Students study gene structure, transmission of genetic information through DNA, regulation of gene expression, and how genes respond to external signals. These concepts provide insight into gene function and its impact on health and disease.

The Techniques of Gene Analysis (B.3)

This 1-credit course provides an overview of essential techniques used in gene analysis. Students learn basic DNA manipulation methods, approaches for rapid analysis of human DNA for diagnostic purposes, and techniques for studying the function of isolated genes. These tools prepare students for advanced genetic research in molecular medicine.

Molecular Genetics and Common Diseases (B.6)

This 2-credit course explores the molecular genetics underlying common diseases. Students learn approaches for analysing the molecular basis of polygenic diseases, including diabetes, autoimmune diseases, cardiovascular diseases, neuropsychiatric disorders, infectious diseases, hereditary variability in drug responses, allergies, and atopy. The course prepares students to contribute to research and treatment of widespread health conditions within molecular medicine.

Gene Therapy, Gene Cloning and Ethical Issues (B.9)

This 2-credit course examines genetic treatment and the ethical considerations associated with it. Students explore gene replacement and corrective therapies, therapeutic cloning, stem cell technologies, and ethical issues arising from new genetic advances. The course prepares students to understand both the scientific and ethical dimensions of gene therapy and cloning.

Genetic Basis of Metabolic Diseases (C.4)

This 1-credit course focuses on the genetic foundations of metabolic diseases. Students explore mutations and genetic variation contributing to diabetes, obesity, and inherited metabolic syndromes, as well as mechanisms through which genetic changes affect metabolic pathways and lead to disease.

Genome Structure and Stability (D.4)

This **2-credit course focuses** on genome structure and stability. Topics include chromatin organisation, DNA replication, chromosome segregation, DNA repair, homologous recombination, programmed DNA rearrangements, molecular mechanisms of immune recognition, transposable elements, retrotransposons, retroviruses, and reverse transcription.

Genetic Engineering of Eukaryotic Organisms (D.5)

This 2-credit course covers principles and techniques of genetic engineering in eukaryotic organisms. Students study yeast cells and genomes, yeast plasmids and vectors, genetic engineering in animals and plants, manipulation of animal cells in culture, creation of transgenic animals, genomic sequencing, and genome projects.

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Track 2: Biochemical Genetics

Track Credit Hours: 48

1. Program Tracks Overview

The Biochemical Genetics Track in the Doctor of Philosophy in Molecular Medicine requires 48 credit hours, comprising 24 credit hours of coursework and 24 credit hours of doctoral thesis research. Coursework is normally completed during the first year of study, followed by supervised research and dissertation work during the second and third years of the programme.

2. Study Plan

Course Code	Course Title	Credit Hours
First Year - Core Courses		
A.3	Introduction to Bioinformatics	2
A.4	Good Laboratory Practice	2
CMMS604	Research Methodology	2
CMMS621	Inferential Statistics and its Applications	2
Total Credit Hours		**8**
First Year - Basic Courses in Molecular Medicine		
B.2	Structure, Organization, and Regulation of Human Genes	1
B.3	The Techniques of Gene Analysis	1
B.9	Gene Therapy, Gene Cloning and Ethical Issues	2
Total Credit Hours		**4**
First Year - Specialized Courses in Molecular Medicine		
C.1	Biochemistry of Nucleic Acids	1
C.2	Chemistry of Proteins	1
C.3	Applications of Mass Spectrometry in Biochemistry	1

Course Code	Course Title	Credit Hours
Total Credit Hours		**3**
First Year - Specialized Courses in Molecular Genetics		
D.3	Gene Expression	2
D.4	Genome Structure and Stability	2
D.5	Genetic Engineering of Eukaryotic Organisms	2
Total Credit Hours		**6**
First Year - Advanced Specialized Courses		
E.3	Special Topics in Biochemistry	3
Total Credit Hours		**3**
Second/Third Year - Ph.D. Project		
K24	Thesis	24
Total Credit Hours		**24**
Total Programme Credit Hours		**48**

3. Course Descriptions

Introduction to Bioinformatics (A.3)

This 2-credit course introduces foundational concepts and techniques of bioinformatics in molecular medicine. Students learn to use computational tools and methods to analyse biological data, including genomic and proteomic sequences. The curriculum covers sequence alignment, database searching, and the application of bioinformatics in research and clinical diagnostics. By the end of the course, students gain practical skills in handling and interpreting complex biological data

Good Laboratory Practice (A.4)

This 2-credit course focuses on the principles and guidelines of Good Laboratory Practice essential for high-quality scientific research. Students learn standards and procedures required to ensure accuracy, reliability, and integrity in laboratory work. The curriculum covers documentation, quality control, safety protocols, and ethical considerations in laboratory research, enabling students to maintain rigorous scientific practices.

Research Methodology (CMMS604)

This course focuses on essential research methodologies used in research. Students learn about research designs, data collection techniques, and statistical analysis methods relevant to medical research. The curriculum includes formulating research questions, designing studies, conducting

experiments, and interpreting results, with emphasis on ethical considerations and best practices that support valid and reliable findings.

Inferential Statistics and its Applications (CMMS621)

This course provides an in-depth understanding of inferential statistics and their practical applications in research. Students learn to make predictions and draw conclusions about populations based on sample data. The curriculum covers hypothesis testing, confidence intervals, regression analysis, and analysis of variance, with emphasis on applying statistical techniques to real-world medical research data.

Structure, Organization, and Regulation of Human Genes (B.2)

This 1-credit course provides a concise overview of fundamental aspects of human genes. Students study gene structure, transmission of genetic information through DNA, regulation of gene expression, and how genes respond to external signals. These concepts provide insight into gene function and its impact on health and disease.

The Techniques of Gene Analysis (B.3)

This 1-credit course provides an overview of essential techniques used in gene analysis. Students learn basic DNA manipulation methods, approaches for rapid analysis of human DNA for diagnostic purposes, and techniques for studying the function of isolated genes. These tools prepare students for advanced genetic research in molecular medicine.

Gene Therapy, Gene Cloning and Ethical Issues (B.9)

This 2-credit course examines genetic treatment and the ethical considerations associated with it. Students explore gene replacement and corrective therapies, therapeutic cloning, stem cell technologies, and ethical issues arising from new genetic advances. The course prepares students to understand both the scientific and ethical dimensions of gene therapy and cloning.

Biochemistry of Nucleic Acids (C.1)

This 1-credit course provides an overview of the biochemical properties and functions of nucleic acids. Students study the structure of DNA and RNA, replication, transcription, translation, and the roles of nucleic acids in cellular processes and disease. These foundations support advanced learning in molecular medicine.

Chemistry of Proteins (C.2)

This 1-credit course introduces the chemical properties and structures of proteins. Students learn about amino acid building blocks, protein folding, levels of protein structure, biochemical functions of proteins, and their roles in cellular processes, health, and disease.

Applications of Mass Spectrometry in Biochemistry (C.3)

This 1-credit course introduces the principles and applications of mass spectrometry in biochemistry. Students explore how mass spectrometry is used to analyse proteins, peptides, nucleic acids, and other biomolecules, including methods for identifying and quantifying molecular components, studying post-translational modifications, and supporting biochemical research.

Gene Expression (D.3)

This 2-credit course examines gene expression from transcription to protein processing. Students study RNA polymerases, promoter structures, RNA processing, genetic code and translation, translational machinery, protein folding, protein degradation, phosphorylation, chaperones, and protein-based inheritance such as prions.

Genome Structure and Stability (D.4)

This 2-credit course focuses on genome structure and stability. Topics include chromatin organisation, DNA replication, chromosome segregation, DNA repair, homologous recombination, programmed DNA

rearrangements, molecular mechanisms of immune recognition, transposable elements, retrotransposons, retroviruses, and reverse transcription.

Genetic Engineering of Eukaryotic Organisms (D.5)

This 2-credit course covers principles and techniques of genetic engineering in eukaryotic organisms. Students study yeast cells and genomes, yeast plasmids and vectors, genetic engineering in animals and plants, manipulation of animal cells in culture, creation of transgenic animals, genomic sequencing, and genome projects.

Special Topics in Biochemistry (E.3)

This 3-credit course consists of seminars on current research interests in biochemistry. Each seminar focuses on an area where significant advances have been made, enabling students to understand contemporary developments and emerging trends relevant to molecular medicine.

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Track 3: Immunology

Track Credit Hours: 48

1. Program Tracks Overview

The Immunology Track in the Doctor of Philosophy in Molecular Medicine requires 48 credit hours, comprising 24 credit hours of coursework and 24 credit hours of doctoral thesis research. Coursework is normally completed during the first year of study, followed by supervised research and dissertation work during the second and third years of the programme.

2. Study Plan

Course Code	Course Title	Credit Hours
First Year - Core Courses		
A.1	Philosophy of Science and Ethics	2
A.2	Pedagogic/Presentation Technology	2
A.4	Good Laboratory Practice	2
Total Credit Hours		**6**
First Year - Basic Courses in Molecular Medicine		
B.3	The Techniques of Gene Analysis	1
B.9	Gene Therapy, Gene Cloning and Ethical Issues	2
B.10	Advanced Cellular Technologies	3
Total Credit Hours		**6**
First Year - Specialized Courses in Molecular Medicine		
C.6	An Introduction to Molecular Immunology	1
Total Credit Hours		**1**
First Year - Specialized Courses in Molecular Genetics		
D.1	Introduction to Molecular Genetics	1

Course Code	Course Title	Credit Hours
D.2	PCR and Reverse Genetics	1
Total Credit Hours		**2**
First Year - Advanced Specialized Courses		
E.6	Developmental Biology and Cellular Signaling	3
E.7	Inflammation and Allergy	3
E.8	Cellular and Molecular Immunology	3
Total Credit Hours		**9**
Second/Third Year - Ph.D. Project		
K24	Thesis	24
Total Credit Hours		**24**
Total Programme Credit Hours		**48**

3. Course Descriptions

Philosophy of Science and Ethics (A.1)

This 2-credit course comprehensively examines the principles underlying the philosophy of science and the ethical considerations in scientific research. Students will explore how scientific knowledge is developed, validated, and applied and the ethical implications of scientific advancements. The curriculum addresses research integrity, ethical dilemmas in scientific practice, and the societal impact of scientific discoveries. This course equips students with a solid understanding of the philosophical and ethical frameworks essential for conducting responsible and impactful research in molecular medicine.

Pedagogic/Presentation Technology (A.2)

This 2-credit course focuses on effectively using pedagogic and presentation technologies in molecular medicine. Students learn techniques and tools to enhance teaching and presentation skills, with emphasis on creating engaging and informative content. The curriculum covers designing and delivering educational materials, multimedia use, and effective communication strategies. By the end of the course, students are equipped to convey complex scientific information in academic and professional settings.

Good Laboratory Practice (A.4)

This 2-credit course focuses on the principles and guidelines of Good Laboratory Practice essential for high-quality scientific research. Students learn standards and procedures required to ensure accuracy, reliability, and integrity in laboratory work. The curriculum covers documentation, quality control, safety

protocols, and ethical considerations in laboratory research, enabling students to maintain rigorous scientific practices.

The Techniques of Gene Analysis (B.3)

This 1-credit course provides an overview of essential techniques used in gene analysis. Students learn basic DNA manipulation methods, approaches for rapid analysis of human DNA for diagnostic purposes, and techniques for studying the function of isolated genes. These tools prepare students for advanced genetic research in molecular medicine.

Gene Therapy, Gene Cloning and Ethical Issues (B.9)

This 2-credit course examines genetic treatment and the ethical considerations associated with it. Students explore gene replacement and corrective therapies, therapeutic cloning, stem cell technologies, and ethical issues arising from new genetic advances. The course prepares students to understand both the scientific and ethical dimensions of gene therapy and cloning.

An Introduction to Molecular Immunology (C.6)

This 1-credit course provides an overview of molecular immunology. Students learn about the molecular mechanisms of immune responses, including antibodies, T-cell receptors, major histocompatibility complex molecules, regulation of immune responses, signalling pathways, and the role of the immune system in health and disease.

Introduction to Molecular Genetics (D.1)

This 1-credit course introduces essential concepts in molecular genetics. It covers the role of genes within cells, how genetic information is stored, expressed, and regulated, and the principles of recombinant DNA technology. Students gain a foundation in genetic function and tools used to study and modify genes.

PCR and Reverse Genetics (D.2)

This 1-credit course focuses on polymerase chain reaction and reverse genetics. Students learn the principles, methodology, and applications of PCR in genetic research and diagnostics, as well as in vitro mutagenesis for studying gene function.

Developmental Biology and Cellular Signaling (E.6)

This 3-credit course provides postgraduate training in developmental biology and cellular signalling. Students engage with research covering cellular and molecular biology, development of organ systems, stem cell biology, haematology and immunology, molecular and clinical endocrinology, genetics, paediatrics, and obstetrics and gynaecology.

Inflammation and Allergy (E.7)

This 3-credit course focuses on inflammation and allergy. Topics include inhibitory and activating receptors during immune responses, cytokines in inflammation, and techniques for manipulating humoral immunity. Students gain understanding of mechanisms underlying inflammatory and allergic responses.

Cellular and Molecular Immunology (E.8)

This 3-credit course explores cells and tissues of the immune system, lymphocyte development, antigen receptor structure and function, antigen processing and presentation, MHC molecule structure and assembly, cytokines, leukocyte-endothelial interactions, and immunologically mediated disease. The course uses lectures and tutorials with clinical cases.

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Track 4: Nanomedicine

Track Credit Hours: 41

1. Program Tracks Overview

The Nanomedicine Track in the Doctor of Philosophy in Molecular Medicine requires 41 credit hours, comprising 17 credit hours of coursework and 24 credit hours of doctoral thesis research. Coursework is normally completed during the first year of study, followed by supervised research and dissertation work during the second and third years of the programme.

2. Study Plan

Course Code	Course Title	Credit Hours
First Year - Core Courses		
Total Credit Hours		**0**
First Year - Basic Courses in Molecular Medicine		
B.10	Advanced Cellular Technologies	3
Total Credit Hours		**3**
First Year - Specialized Courses in Molecular Medicine		
C.3	Applications of Mass Spectrometry in Biochemistry	1
C.6	An Introduction to Molecular Immunology	1
Total Credit Hours		2
First Year - Specialized Courses in Molecular Genetics		
Total Credit Hours		**0**
First Year - Advanced Specialized Courses		
E.10	Introductory Course in Tumor Biology/Oncology	3
E.11	Introduction to Nanomedicine	3

Course Code	Course Title	Credit Hours
E.12	Biological and Pharmacological Aspects of Nanomedicine	3
E.13	Application of Nanomedicine	3
Total Credit Hours		**12**
Second/Third Year - Ph.D. Project		
K24	Thesis	24
Total Credit Hours		**24**
Total Programme Credit Hours		**41**

3. Course Descriptions

Applications of Mass Spectrometry in Biochemistry (C.3)

This 1-credit course introduces the principles and applications of mass spectrometry in biochemistry. Students explore how mass spectrometry is used to analyse proteins, peptides, nucleic acids, and other biomolecules, including methods for identifying and quantifying molecular components, studying post-translational modifications, and supporting biochemical research.

An Introduction to Molecular Immunology (C.6)

This 1-credit course provides an overview of molecular immunology. Students learn about the molecular mechanisms of immune responses, including antibodies, T-cell receptors, major histocompatibility complex molecules, regulation of immune responses, signalling pathways, and the role of the immune system in health and disease.

Introductory Course in Tumor Biology/Oncology (E.10)

This 3-credit course provides theoretical knowledge and practical skills in oncology and tumour biology. The curriculum includes tumour pathogenesis, causes of cancer, molecular cell and tumour biology, tumour immunology, cancer genetics, literature study, and development of supervised experimental approaches within a selected study area.

Introduction to Nanomedicine (E.11)

This course introduces the fundamental concepts and applications of nanomedicine. Students learn about the use of nanotechnology for diagnosing, treating, and preventing diseases, including nanomaterial design, nanoscale drug delivery systems, and the role of nanomedicine in improving healthcare outcomes.

Biological and Pharmacological Aspects of Nanomedicine (E.12)

This 3-credit course explores the intersection of nanotechnology with biological and pharmacological sciences. Students study how nanomaterials interact with biological systems and examine nanotechnology-based drugs and therapies, including mechanisms of action, efficacy, and safety.

Application of Nanomedicine (E.13)

This 3-credit course covers applications of nanomedicine in areas such as cancer treatment,

inflammatory disorders, post-surgery care, diagnostics and theranostics, tissue engineering, gene delivery and gene silencing, immune system modulation, and commercialisation of nanomedicine.

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Track 5: Health Biotechnology

Track Credit Hours: 48

1. Program Tracks Overview

The Health Biotechnology Track in the Doctor of Philosophy in Molecular Medicine requires 48 credit hours, comprising 24 credit hours of coursework and 24 credit hours of doctoral thesis research. Coursework is normally completed during the first year of study, followed by supervised research and dissertation work during the second and third years of the programme.

2. Study Plan

Course Code	Course Title	Credit Hours
First Year - Core Courses		
A.3	Introduction to Bioinformatics	**2**
Total Credit Hours		**2**
First Year - Basic Courses in Molecular Medicine		
B.3	The Techniques of Gene Analysis	1
B.9	Gene Therapy, Gene Cloning and Ethical Issues	2
B.10	Advanced Cellular Technologies	3
Total Credit Hours		**6**
First Year - Specialized Courses in Molecular Medicine		
C.1	Biochemistry of Nucleic Acids	1
C.2	Chemistry of Proteins	1
Total Credit Hours		**2**
First Year - Specialized Courses in Molecular Genetics		
D.5	Genetic Engineering of Eukaryotic Organisms	2
Total Credit Hours		2

Course Code	Course Title	Credit Hours
First Year - Advanced Specialized Courses		
E.2	Enzyme Reaction Mechanisms	3
E.14	Fundamentals of Bioprocessing	3
E.15	Enzymes in Biotechnology	3
F.3	Molecular Engineering	3
Total Credit Hours		**12**
Second/Third Year - Ph.D. Project		
K24	Thesis	24
Total Credit Hours		**24**
Total Programme Credit Hours		**48**

3. Course Descriptions

Introduction to Bioinformatics (A.3)

This 2-credit course introduces foundational concepts and techniques of bioinformatics in molecular medicine. Students learn to use computational tools and methods to analyse biological data, including genomic and proteomic sequences. The curriculum covers sequence alignment, database searching, and the application of bioinformatics in research and clinical diagnostics. By the end of the course, students gain practical skills in handling and interpreting complex biological data

The Techniques of Gene Analysis (B.3)

This 1-credit course provides an overview of essential techniques used in gene analysis. Students learn basic DNA manipulation methods, approaches for rapid analysis of human DNA for diagnostic purposes, and techniques for studying the function of isolated genes. These tools prepare students for advanced genetic research in molecular medicine.

Gene Therapy, Gene Cloning and Ethical Issues (B.9)

This 2-credit course examines genetic treatment and the ethical considerations associated with it. Students explore gene replacement and corrective therapies, therapeutic cloning, stem cell technologies, and ethical issues arising from new genetic advances. The course prepares students to understand both the scientific and ethical dimensions of gene therapy and cloning.

Biochemistry of Nucleic Acids (C.1)

This 1-credit course provides an overview of the biochemical properties and functions of nucleic acids. Students study the structure of DNA and RNA, replication, transcription, translation, and the roles of nucleic acids in cellular processes and disease. These foundations support advanced learning in molecular medicine.

Chemistry of Proteins (C.2)

This 1-credit course introduces the chemical properties and structures of proteins. Students learn about amino acid building blocks, protein folding, levels of protein structure, biochemical functions of proteins, and their roles in cellular processes, health, and disease.

Genetic Engineering of Eukaryotic Organisms (D.5)

This 2-credit course covers principles and techniques of genetic engineering in eukaryotic organisms. Students study yeast cells and genomes, yeast plasmids and vectors, genetic engineering in animals and plants, manipulation of animal cells in culture, creation of transgenic animals, genomic sequencing, and genome projects.

Enzyme Reaction Mechanisms (E.2)

This 3-credit course explores enzyme action, including three-dimensional enzyme structure, chemical catalysis, methods for determining enzyme mechanisms, stereochemistry of enzymatic reactions, intermediates, affinity labels, suicide inhibitors, transition-state analogues, energy relationships, genetic engineering in enzyme studies, and binding energy in catalysis.