Indian Institute of Technology Kanpur

COURSES OF STUDY

2024

Indian Institute of Technology Kanpur
KANPUR-208016

CHEMICAL ENGINEERING

BT | Template No. CHE-1

COURSES	SEMESTER							
	1st	2nd	3rd	4th	5th	6th	7th	8th
	MTH101A [11]	CHM102A [08]	CHE251A [09]	ESC201A [14]	CHE312A [09]	CHE331A [09]	CHE453A [11]	HSS-5 (Level-2) [09]
	ESC101A [14]	MTH102A [11]	TA202A [06]	TA201A [06]	CHE313A [09]	CHE381A [11]	CHE492A [08]	OE-5 [09]
	CHM101A [03]	LIF101A [06]	HSS-2 (Level-1) [11]	COM200A [05]	CHE352A [05]	CHE391A [08]	OE-3 [09]	OE-6 [09]
	PHY103A [11] PE101A [03]	PHY101A [03] PHY102A [11]	ESO-1 [11] (ESO201A)	SO-1 [11] (CSO201A/CSO202A)	ESO-3 [14] (ESO205A)	HSS-4 (Level-2) [09]	OE-4 [09]	DE-3 [09]
	ENG112A/ HSS-1 (Level-1) [11]	TA101A [09] PE102A [03]	ESO-2 [11] (ESO208A)	CHE211A [09] CHE221A [09]	HSS-3 (Level-2) [09] CHE300A [02]	UGP-2/DE-1 [09] (CHE398A)	UGP-3/DE-2 [09] (CHE497A)	DE-4 [09]
	-	-	-	CHE261A [06]	OE-1 [09]	OE-2 [09]	DE-M2 [05] (Optional)*	UGP-4 [09] (CHE498A) (Extra Credits)
				-	UGP-1 [04] (CHE349A) (Extra Credits)	-		
					DE-M1 [05] (Optional)*		-	-
	53	51	48	60	57 – 66	55	46/51	45/54

MINIMUM CREDIT REQUIREMENT FOR GRADUATION:

Institute Core (IC)	:	124	Credits
Department Compulsory (DC)	:	105	Credits
Department Elective (DE)	:	36	Credits
Open Elective (OE)	:	54	Credits
SO/ ESO	:	47	Credits
HSS (Level-I)	:	22	Credits
HSS (Level-II)	:	27	Credits
Total	:	415	Credits

REMARKS:

1) *DE M1 & M2 are Modular Courses which are optional summer training and may count towards DE credits.
2) DE credits may include 18 credits from UGP-2 and UGP-3.
3) UGP-1 and UGP-4 are optional and do not count towards DE/OE credits.
4) Upto 18 DE credits may be waived from the minimum requirements for students opting for Dual Degree in Chemical Engineering itself.
5) Upto 36 OE credits may be waived from the minimum requirements for students opting for Dual Degree in another department or the Double Major programme.

BT-MT (PG Part – Category – A) *(from the same department)*

Template No. CHE-2

COURSES	PG Component				
	7th	8th	SUMMER	9th	10th
	CHE701A [0]	CHE702A [0]	M.Tech. Thesis [09] (CHE699A) (if required)	M.Tech. Thesis [09] (CHE699A) / DE/OE PG [09] (if required)	M.Tech. Thesis [36] (CHE699A)
	OE PG-1 [09] OE PG-2 [09]	M.Tech. Thesis [09] (CHE699A) / DE PG-1 [09]*		M. Tech. Thesis [27]	
		DE PG-2 [09]*			
		OE PG-3 [09]			
		OE PG-4 [09]			
		M.Tech. Thesis [09]			
	18	45	09	36	36

MINIMUM CREDIT REQUIREMENT IN MS PART FOR GRADUATION:

PG Component	:	54	Credits
Thesis	:	81	Credits

Basket - A

CHE611A [09]
CHE621A [09]
CHE631A [09]
CHE641A [09]

REMARKS:

1) All courses to be taken with the permission of Supervisor/ DUGC Convener.
2) *DE PG 1 & 2 should be selected from Basket – A.
3) CHE701A and CHE702A (seminar courses) are mandatory.
4) Course credits and Thesis credits mentioned under the dual degree template are only for the M.Tech. part of the programme. In addition to these credits, students are required to follow and complete all their graduation requirements for their UG programme.
5) 18 DE credits may be used from the BT minimum requirements to fulfil requirements for the BT-MT dual degree programme. These will be waived from the BT programme and counted towards PG requirements.
6) Upto 36 OE credits may be used from the BT minimum requirements to fulfil requirements for the BT-MT dual degree programme. These will be waived from the BT programme and counted towards PG requirements.

BS/BT-MT (Category – B) *(from other departments)*							Template No. CHE-3
C O U R S E S	UG Pre-Requisites		PG Component				
	Odd Semester	Even Semester	7^{th}	8^{th}	SUMMER	9^{th}	10^{th}
	ESO204A [11]/ CHE211A [09]*	CHE331A [09]	CHE701A [0]	CHE702A [0]	M.Tech. Thesis [09] (CHE699A) (if required)	M.Tech. Thesis (CHE699A) / DE PG [09] (if required)	M.Tech. Thesis [36] (CHE699A)
			DE PG-1 [09], DE PG-2 [09]				
			CHE611A [09], DE PG-3 [09]				
			CHE621A [09]				
	ESO201A [11]/ CHE221A [09]*		CHE631A [09]/ CHE633A [09]			M.Tech. Thesis [27] (CHE699A)	
			M.Tech. Thesis [09] (CHE699A)				
	18/22	09	63		09	36	36

MINIMUM CREDIT REQUIREMENT IN MT PART FOR GRADUATION:

PG Component : 54 Credits
Thesis : 81 Credits

REMARKS:

1) *The ESO courses may be substituted by the CHE courses only with permission of the CHE DUGC convener.
2) CHE701A and CHE702A (seminar courses) are mandatory.
3) All courses to be taken with the permission of Supervisor/ DUGC Convener.
4) Course credits and Thesis credits mentioned under the dual degree template are only for the M.Tech. part of the programme. In addition to these credits, students are required to follow and complete all their graduation requirements for their UG programme.
5) Upto 36 OE credits may be used from the parent department's BT/BS minimum requirements to fulfil requirements for the BT-MT dual degree programme. These will be waived from the parent department's BT programme requirements and counted towards PG requirements.

DOUBLE MAJOR	Template No. CHE-4
Odd Semester	Even Semester
Pre-Requisites	
ESO201A [11]	CSO201A [11]/ CSO202A [11]
ESO208A [11]	
ESO205A [14]	
Mandatory CHE Courses	
CHE251A [09]	CHE211A [09]
CHE312A [09]	CHE221A [09]
CHE313A [09]	CHE261A [06]
CHE352A [05]	CHE331A [09]
CHE453A [11]	CHE381A [11]
CHE492A [08]	CHE391A [08]
51	52

TOTAL MANDATORY CREDITS FOR SECOND MAJOR IN CHEMICAL ENGINEERING: 103 CREDITS

REMARKS:

1) Depending on overlap with course contents of parent department, some equivalent CHE courses may be waived on a case-to-case basis.
2) Upto 36 OE credits may be waived from the parent department BT/BS graduation requirements when they are used to fulfill requirements for the double major.

MINOR	Template No. CHE-5
Title	CHEMICAL ENGINEERING
C O U R S E S	CHE251A [09]
	CHE261A [09]
	CHE313A [09]
	CHE331A [09]
	36

DEPARTMENT OF ChE			
Courses ID	**Course Title**	**Credits L-T-P-D-[C]**	**Content**
ChE200	CHEMICAL ENGINEERING COMMUNICATION SKILLS	0-0-2-0-2	Introduction, listening skills, paper writing, literature search, resume and CV writing, oral presentation and public speaking, group discussion.
ChE201	INTRODUCTION TO CHEMICAL ENGINEERING	0-0-2-0-2	Introduction to Chemical Engineering Profession, Safety aspects in different Chemical Industries,Data Analysis and Fitting, Instrumentation: To measure different parameters such as pressure, temperature, velocity, flow rates, etc.,Heat Transfer: Different types of heat exchangers, evaporation units, etc...,Mass Transfer: Gas-liquid contacting devices, tray towers, adsorption, liquid-liquid contacting devices, humidification crystallization.Chemical Reaction Engineering: Reactor types such as batch, semi-batch, CSTR, plug flow, packed bed, fluidized bed, catalysis.Fluid-Solid separation: Different types of pumps, pipes, valves, filtration units. **Course Reference**: 1. Pushpavanam, S., Introduction to Chemical Engineering, PHI Learning Private Limited, New Delhi, 2012. 2. Morton Denn, Chemical Engineering: An Introduction, Cambridge University Press, 2011 3. Perry's Chemical Engineers' HandBook, The McGraw-Hill Companies, Inc., 2008.
ChE212	HEAT TRANSFER	3-0-3-0-12	Modes of heat transfer (Conduction, convection, radiation), Boiling, Condensation, Heat Exchanger Design, Evaporators, Heat Transfer Unit Operations, Numerical Modeling. **Course Reference:** 1. Frank P. Incropera, David P. Dewitt, Theodore L. Bergman, and Adrienne S. Lavine, Incr-opera's Principles of Heat and Mass Transfer, Wiley India ed. Wiley India. 2.J. P. Holman and Souvik Bhattacharyya, Heat Transfer, McGraw Hill; 10th ed, McGraw Hill Education. 3. Adrian Bejan, Heat Transfer, Wiley India Pvt Ltd. 4. Yunus A. Cengel and A. J. Ghajar, Heat and Mass Transfer: Fundamentals and Applications, 5th Ed. SIE, McGraw Hill Education. 5. Warren L. McCabe, Julian C. Smith and Peter Harriott, Unit Operations of Chemical Engineering, 7th ed. (Indian Ed.), McGraw Hill Education. 6. Donald Q. Kern, Process Heat Transfer, McGraw Hill, New York.
ChE213	MASS TRANSFER AND SEPARATION PROCESSES	3-0-3-0-12	Mass transfer related unit operations in process industries; Fundamental of Mass Transfer: continuous and equilibrium stage contactors; Absorption: equilibrium and rate based approach, NTU and HTU, hydrodynamic considerations; Distillation: vapor-liquid equilibrium, Ponchon-Savarit and McCabe-Thiele methods for equilibrium stage calculations, Extraction: single- and multi-stage cross-current extraction, continuous countercurrent multistage extraction; Adsorption

			and chromatography: single- and multistage cross-current operations, packed-bed continuous contactor; Humidification and Drying: dry and wet bulb temperatures, humidity, relative and percentage humidity, psychometry chart, and adiabatic saturation temperature; mechanisms of batch drying, continuous drying; Crystallization: nucleation and growth rate, batch crystallizer. **Course Reference:** 1. R. E. Treybal, Mass Transfer Operations, 3rd ed., McGraw Hill, New York, 1980. 2. J. D. Seader and E. J. Henley, Separation Process Principles, Wiley, New York, 1998. 3. J. M. Coulson and J. F. Richardson, Chemical Engineering, Vol. I (6th ed., 2000), Vol. 2 (4th ed.,1990), Vol. 6 (3rd ed., 2000), Butterworth Heinneman, Oxford. 4. B. K. Dutta, Principles of Mass Transfer and Separation Processes, Prentice-Hall of India Pvt Ltd, 2007. 6 5. P.C. Wankat, Separations in Chemical Engineering: Equilibrium Staged Separations, Prentice Hall, NJ. US, 1988 6. McCabe, Smith, and Harriot, Unit Operations in Chemical Engineering, 3 rd ed. McGraw Hil
ChE221	CHEMICAL ENGINEERING THERMODYNAMICS.	3-0-3-0-12	Laws of Thermodynamics: Introduction, Work, Heat, Internal Energy, the first Law, Reversibility, the second law, Entropy, Fundamental Equations: Thermodynamics calculus, thermodynamics derivatives, Euler's theorem for homogeneous functions, Legendre's transformations, Derivative in terms of measurable properties, Equilibria and stability: Equilibrium criteria, stability criteria, Maxwell construction, binodals, spinodals, Gibbs Phase Rule, Clapeyron equation and vapor pressure correlations Pure component properties: Equation of state, Ideal gas heat capacities, fundamental equations from experimental data, fugacity and corresponding states Mixture Properties: Mixing function, partial molar quantities, Gibbs-Duhem relation for mixtures, partial Molar quantities from experimental data, Ideal gas mixtures and fugacities, ideal mixtures and activities, excess functions, excess Gibbs free energy models, infinite dilution properties and Henry's Law Phase Equilibria of Mixtures: VLE, LLE, VLLE, Phase equilibria EOS, Osmotic pressure and Osmotic coefficients, Boiling point elevation and freezing point depression Chemical Reaction Equilibria: Reaction extent and Independent reactions, equilibrium criteria and equilibrium constant, reaction standard enthalpies and Gibbs free energy, temperature and pressure effects on reactions, heterogeneous reaction, multiple chemical reactions. **Course Reference:** 1. Engineering and Chemical Thermodynamics, M. D. Koretsky, Wiley India (2004) 2. Essential Thermodynamics: An undergraduate textbook for chemical engineers, Athanassios Z Panagiotopoulos, Drios Press (2011) 3. Chemical Engineering Thermodynamics, by Smith, van Ness and Abbott, 7th Ed., McGraw-Hill (2005) 4. Thermodynamic and Introduction to Thermostatistics, H. B.

			Callen, 2nd Edition Wiley India (2005). 1. Chemical, Biochemical and Engineering Thermodynamics, S. I. Sandler, Wiley (2006) 2. Chemical Engineering Thermodynamics, Y. V. Rao, Universities Press, India (1997) 3. Chemical Engineering Thermodynamics - Theory and Applications, R. Ravi, Ane Books (2019).
ChE251	INTRODUCTION TO CHE + PROCESS CALCULATION	3-0-3-0-12	Steady-state Material Balances in Non-reacting Systems, Balances on Multiple-Unit Processes, Balances in Reacting Systems, Element (atomic) versus Species (molecular balances), Material Balances in Multiphase Systems, General Energy Balance, Energy Balances in Reacting Systems, Fuels and Combustion, Psychrometry, Unsteady-state material and energy balance. **Course Reference:** 1. "Elementary Principles of Chemical Processes", R. M. Felder and R. W. Rousseau, 2nd ed., Wiley, New York, 1986. 2. "Basic Principles and Calculations in Chemical Engineering", D. M. Himmelblau, 7th ed., Prentice-Hall of India Pvt. Ltd., New Delhi.
ChE261	CHEMICAL PROCESS INDUSTRIES	3-0-0-0-9	Overview of Chemical Industries, Introduction to reactors, Petroleum refining process, Inorganic bulk chemicals, Fertilizers, Hydrogen generation from natural gas, Paper and pulp industry, Modern chemical processes, Petroleum and Petrochemicals. **Course References:** 1. J. H. Gary, G. E. Handwerk and M. J. Kaiser "Petroleum Refining: Technologies and Economics", 5th Edition, CRC Press 2. Kirk-Othmer Encyclopedia of Chemical Technology. 3. Ullmann's Encyclopedia of Industrial Chemistry. 4. Riegle's Handbook of Industrial Chemistry and Biotechnology, Editor: J.A. Kent, 11th edition. 5. Jacob. A. Moulijn, Michiel Makkee, "Chemical Process Technology" 2nd edition.
ChE311	TRANSPORT PHENOMENA: FUNDAMENTALS AND APPLICATIONS	3-0-3-0-12	Fluid flow - Derivation of governing equations using Reynolds Transport Theorem; unidirectional laminar flows, unsteady flows, nearly 1D flows, 2D flows.Heat transport - Governing equations; unsteady conduction in a cylindrical rod; Free and forced convection. Mass transport - diffusion in a stagnant film, diffusion with homogeneous/heterogeneous reactions, diffusion into a falling liquid film. Boundary layer theory and turbulence. **Course Reference:** 1. R. Byron Bird, Warren E. Stewart, Edwin N. Lightfoot, "Transport Phenomena", Second Edition, John Wiley and Sons, Inc. 2. V. Kumaran, "Fundamentals of Transport Processes with Applications", Cambridge-IISc Series, October 2022 (ISBN: 9781009036658). 3. William M. Deen, "Analysis of Transport Phenomena", Second Edition, Oxford University Press, 2012, ISBN: 9780199740253. 4. L. Gary Leal, "Advanced Transport Phenomena- Fluid Mechanics and Convective Transport Processes", Cambridge University Press. 5. Rutherford Aris, "Vectors, Tensors and the Basic Equations of Fluid Mechanics", Prentice Hall International. 5.

			William B. Krantz, “Scaling Analysis in Modeling Transport and Reaction Processes”, John Wiley and Sons, Inc.
ChE331	CHEMICAL REACTION ENGINEERING	3-0-3-0-12	Introduction; basic concepts in chemical kinetics; determination of rate expressions; nonelementary homogeneous reactions; isothermal design of batch, mixed flow and plug flow reactors; design for multiple reactions; nonisothermal reactors; analysis of nonideal reactors; catalysis; kinetics of catalytic reactions; diffusion and reaction in porous catalysts. **Course Reference:** 1. H. Scott Fogler, ‘Elements of Chemical Reaction Engineering’, 5th edition, 2016, Prentice Hall of India, New Delhi. 2. O. Levenspiel, ‘Chemical Reaction Engineering’, 3rd edition, 1999, Wiley-Eastern Ltd. 3. J.M. Smith, “Chemical Engineering Kinetics,” 3rd edition, 1981, McGraw-Hill, International Student Edition. 4. Unit Operation Laboratory Manual. 5. W.L. McCabe, J.C. Smith, and P. Harriott,” Unit Operations of Chemical Engineering” (7th Edition), McGraw Hill Publishing, 2005 (ISBN 0-07-284823-5). 6. Coulson and Richardson’s Chemical Engineering: Chemical Engineering Design. 7. Bruce A. Finlayson, ‘Introduction to Chemical Engineering Computing’, 2nd edition, 2014, Wiley. 8. Riccardo Tesser, Vincenzo Russo, “Advanced Reactor Modeling with MATLAB: Case Studies with Solved Examples” 2021, De Gruyter.
ChE352	CHEMICAL PROCESS SYNTHESIS AND DESIGN	3-0-3-0-12	Introduction to process design and process creation Heuristics for Process Synthesis Cost accounting and capital cost estimation, annual costs, discounted cash flow analysis, Depreciation Reactor design and reactor network synthesis, Principles of attainable regions, Principles of Reaction Invariants, Optimal reactor conversion and yield, Heat removal configurations, Locating the Separation Section with respect to the Reactor Section, Tradeoffs in processes involving recycle, Recycle to extinction, Influence of side reactions on overall process design, Material and energy recycle and associated non-linear effects: Snowballing, robust flow sheet convergence Conceptual distillation design: sequencing columns for separation of ideal VLE systems. Ternary distillation: feasible splits and design, Complex columns for energy efficiency using state task networks. Non-ideal VLE and residue curve maps, Homogenous azeotropic distillation design, heterogenous azeotropic distillation design, pressure swing distillation, solvent selection Introduction to heat and power integration, Minimum utility targets, networks for maximum energy recovery, minimum number of heat exchangers, threshold and optimal approach temperature, superstructure for minimization of annual costs, multiple utilities and heat-integrated distillation trains. Plantwide Controllability Assessment, Tradeoffs between steady state optimum design and controllability, Design for good operability Lifecycle Analysis. **Course Reference:** 1. W. D. Seider, J. D. Seader and D. R. Lewin, “Product and process design principles”, John Wiley (Indian Edition), 2nd edition, 2005 2. M.F. Malone and M.

			Doherty, "Conceptual Design of Distillation Systems", McGraw-Hill, 1st Edition, 2000. 3. Robin Smith, Chemical Process Design and Integration, 2nd edition, John Wiley and Sons, Inc.
ChE362	BIOCHEMICAL ENGINEERING	3-0-01-4	Cell Structure and Cell Types, Chemicals of Life (RNA, DNA, enzymes etc.), Kinetics of Enzyme Reactions, Applied Enzyme Catalysis, Metabolic Stoichio metric and Energetics, Molecular Genetics and Control, Biomass Production, Transport Phenomena in Biosystems, Design and Analysis of Biological Reactors, Fermentors, Downstream Product Recovery and Purification, Interaction of Mixed Microbial Populations, Biological Wastewater Treatment.
ChE381	PROCESS DYNAMICS AND CONTROL	3-0-3-0-12	Basic SISO dynamic elements; Solving ODEs in time-domain; Characteristic equation and stability; Empirical dynamic modelling of SISO systems; First-principles dynamic modelling and simulation; SISO negative feedback control; PID control algorithm, stability and tuning; Laplace-domain techniques: Laplace transform, transfer functions, partial fractions, root locus technique, direct synthesis and internal model controller design; Frequency-domain techniques: The frequency response, Bode and Nyquist plots, Nyquist stability theorem, controller tuning for gain margin, phase margin and maximum closed loop sensitivity; Multivariable systems: Interaction metrics (relative gain array and Niederlinski Index), decentralized PID controller (de)tuning, decoupling; Advanced control: Feedforward, Ratio, Cascade, Optimizing, Override; Model based control: Smith-predictor, model predictive control; Control system design for complete plants; Digital control analysis and design. **Course Reference:** 1. Process Control: Designing Processes and Control Systems for Dynamic Performance, 2nd Ed, TE Marlin (2000). 2. Essentials of Process Control, WL Lubyen and ML Luyben (1997). McGraw Hill: New York. 3. Process Dynamics and Control,4th Ed., DE Seborg, TF Edgar, DA Mellichamp and FJ Doyle III, (2016). John Wiley and Sons: Hoboken NJ.
ChE391A	UNIT OPERATION LABORATORY -I	1-0-3-2-8	Safety, ethical guideline, error analysis, data presentation. Brief introduction to topics of experiments, relevance in industry Fluid flow, fluid particle system Thermodynamics Heat and mass transfer Demonstration lab Solid size reduction e.g. crushing and lgrinding, ball milling; Solid conveying e.g. pneumatic conveying, hydraulic conveying, lbelt conveying. Analysis and testing of crude oil and petroleum products: 1Determination of octane number, cetane number, pour point, cloud point, smoke point **Course Reference**: 1. Unit Operation Laboratory Manual; 2. Unit Operations of Chemical Engineering; (7th Edition), by W.L. McCabe, J.C. Smith, and P. Harriott, McGraw Hill Publishing, 2005 (ISBN 0072848235); 3. Coulson and Richardson's Chemical Engineering: Chemical Engineering Design

ChE453	PROCESS DESIGN CAPSTONE PROJECT	0-1-4-0-6	Validation of thermodynamic properties, Validation of kinetic parameters, Steady State flow sheet synthesis, Economic optimization, Heat Integration, Plant wide control. **Course Reference:** 1. J. M. Douglas, “Conceptual design of chemical processes”, McGraw-Hill, 1988. 2. W. D. Seider, J. D. Seader and D. R. Lewin, “Product and process design principles”,John Wiley (Indian Edition), 2nd edition, 2005. 3. M.F. Malone and M. Doherty, “Conceptual Design of Distillation Systems”, McGraw-Hill, 1st Edition, 2000. 4. Robin Smith, Chemical Process Design and Integration, 2nd edition, John Wiley and Sons, Inc. 5. G. Towler and R. Sinnott, Chemical Engineering Principles, Elsevier, 2008.
ChE454A	UNIT OPERATIONS INVOLVING PARTICULATE SOLIDS FOR CHEMICAL ENGINEERS	3-0-0-0-9	Particles Size Analysis: Sieve analysis, size distribution, size averaging and equivalence, size estimation in sub-sieve range, effectiveness of screen, description of shape and morphology of particles (flocs, porous particles, surface texture etc.), Size Reduction: Theory of crushing and grinding, laws of crushing and grinding, crushing and grinding equipment and their selection,Nanoparticles: Synthesis, characterization and potential applications, enlargement of particles by agglomeration and other methods,Storage of Solids: Angle of slide and repose, general design consideration for bins, silos and hoppers,Particle Mechanics: Motion of particle in fluid, pressure-drop calculations for solidliquid slurry flow, effect of particle shape, Stoke’s law, hindered settling and jigging,Sedimentation and Flotation: Gravity and centrifugal sedimentation, design of sedimentation tank and continuous thickeners, mechanism of flotation, flotation agents and flotation equipment,Fluidization: Fluidization characteristics, aggregative and particulate fluidization, voidage and minimum fluidization velocity, voidage correlation, liquid-solid and gassolid fluidization characteristics, industrial applications of fluidization,Filtration: Flow through filter cake and medium, washing and drying of cake, filter aids, selection of filtration equipment, constant rate and constant pressure filtration, Other Separation Equipment: Cyclone separator, air filter, electrostatic separator, and their design consideration,Conveying of Solids: Pneumatic and hydraulic conveying of solids, general characteristics and flow relations, mechanical conveyers
ChE611	TRANSPORT PHENOMENA	3-0-0-0-9	Kinematics, Transport theorem, constitutive relations, Equations of motion and their solutions, Boundary layer theory, Turbulence; Energy equation and its exact solutions, Continuity equation for multicomponent systems, constitutive relations, Interphase transport of momentum, energy and mass and macroscopic balances.
ChE614	INTRODUCTION TO HYDRODYNAMIC STABILITY	3-0-0-0-9	Introduction; Notions of stability (Lyapunov stability; asymptotic stability; spatial vs temporal instability; transient growth etc.); Review of governing equations of fluid flow and boundary condition; Instabilities in fluids at rest (Rayleigh-Taylor instability, Rayleigh-Plateau instability) Rayleigh-Benard

			instability, Marangoni thermocapillary instability); Kelvin-Helmholtz instability; Stability of parallel shear flows; Inviscid limit (Rayleigh, Fjortoft theorems); Viscous flows: Squire's theorem; Orr- Sommerfeld equation for rectangular and axisymmetric geometries; Numercal techniques for solving the Orr-Sommerfeld equation; Interfacial instabilities in multi-layer flows; Spatio-temporal evolution(convective vs absolute instabilities); Non-modal analysis and transient growth; Weakly non-linear stability; Instabilities n non-Newtonina fluids.
ChE616A	INTRODUCTION TO GRANULAR MECHANICS	3-0-0-0-9	Part:1 Introduction to granular materials (Illustrative examples, rich behaviour of granular materials, characterisation of granular materils, inter-particle forces, fluid paricle interaction); Issues and challenges in experimental studies; Discrete element method for granular simulations; Hard and soft particle models; Contact force modelling (Normal contact force models, tangential contact force and torque models, Friction force modelling, Equations of motion for granins (non-dimensionalizaion of equaitons of motion, relating model parameters to grain properties); Algorithm for soft and hard particle mehods; Calculation of varios properties of interest form the data; Modelling of non-spherical granis in DEM; Some fundamental insights obtained form DEM; Limitation of Dem simulations. Part-2: Cintinuum models (Balance laws for msss, momentum and energy); Static properties of a granular piles (Role of friction, Reynolds dilatancy, Pressure distribution in cylindrical container); Theory of slow flows (Coulomb yield condition, Mohr's Circle, Rankine states, Flow rules, Equations for plane flows); Flow thorugh hoppers and wedge shaped bukers (Savage's smooth wall radial gravity solution, Beverloo correlation of flow through cylindrical silos with circular orifice and it's theoretical estimation); Rapid flow of smooth, inelastic granins in simple geometries (Hydrodynamic description of rapid granular flow, Heuristic theory and introduction to Kinetic theory of inelastic gases). Par 3: Dense granular flow rehlogy (Frictional kinetic hybrid model, Local rehlogy vs. non-local rehelogy, inertial-number rheology in dense flow regime, 3D viscoplastic rheological model, extension to the rheology of granular mixures); Surface flows of granular materials (Flow over inclined plane and in rotating cylinders and heaps, depth average equation for surface flows); Mixing and segregation of granular mixtures (Savage's kinetic sieving mode, Khakhar's single particle based segregation mode, kinetic theor based segregation models).
ChE619A	ADVANCED FLUID MECHANICS	3-0-0-0-9	Introduction,Review of basic mathematical tools (vector calculus,theorem's of integral calculus),Kinematics-Continuum hypothesis, Reference frames (Lagrangian vs Eulerian), General balance equations-Continuity,Conservationof linearmomentum,Interfacial transport, Angular momentum equation, Stream function and velocitypotential,Analysis

			ofUnidirectional and nearly unidirectional flows; Lubricationapproximation: application to thin films, Creeping flow with focus onMicrohydrodynamics:solution techniques using expansions of harmonic and Green's functions;Resistance matrices;singularitysolutions;flows involving rigid particles and fluid droplets; applications tosuspensions,Laminarflow athigh Reynold's number–Inviscid flow, irrotational flow, Idealflows in a plane,Axisymmetric ideal flows,Vortex dynamics:Concept of vorticity;Kelvin's Circulation Theorem;Helmhotz'sVortex Theorems;Vorticity Equation in a Nonrotating Frame;Vortex Sheet,Boundary Layers: Blasius Flow ever a Flat Plate,Displacement Thickness,VonKármán Momentum Integral,Von Kármán-Pohlhausen Approximate Method,Falkner-Skan Similarity Solutions,Arbitrary Two-Dimensional Lay: Crank-Nicolson Difference Method,Introduction to Turbulent Flows: Types of Turbulent flowsandtheircharacteristics, Reynolds Stress, Correlations of fluctuations, Meanand TurbulentKinetic energy, Energy Cascade (Kolmogorove scalesand Taylor microscale)
ChE623A	THERMODYNAMICS OF FLUIDS AND FLUID MIXTURES	3-0-0-0-9	Classical thermodynamics of phase equilibria: Thermodynamic properties from volumetric data: Nature of intermolecular forces, Theory of corresponding states; Fugacities in gas mixtures and liquid solutions; gas solubilities; High pressure equilibria.
ChE626	PRACTICAL INTRO. TO QUANTUM MECHANICAL METHODS FOR SCIENTISTS & ENGINEERS	3-0-0-0-9	Summary of classical mechanics: conservation laws, Hamiltonian and Lagrangian formulation; The need for quantum mechanics; Basic concepts: physical observables and operators, expectation values, Heisenbergr's uncertainty principle, Schrodinger's equation; The many-body Hamiltonian, Born-Oppenheimer ¨ approximation, variational principle, the concept of potential energy surface; What makes electronic structure difficult; Hartree-Fock (HF) approach: restricted and unrestricted method, and their comparison with experiments; Localized and plane-wave basis sets; Pseudopotentials; Density functional theory (DFT): Hohenberg-Kohn theorems, Kohn-Sham formulation; Exchange and correlations: LDA and GGA approximations; Pure and hybrid DFT functionals; Tricks for self-consistent solution of the Kohn-Sham system: mixing and diagonalization techniques; Failures and successes of DFT: vander Waal's correction and DFT+U approach; Configuration interaction and Miller-Plesset perturbation theory; Applications of quantum-mechanical methods in engineering and sciences; Specialized topics (if time permits): Ab initio molecular dynamics (Born-Oppenheimer and Car-Parrinello), ring-polymer molecular dynamics.
ChE631A	CHEMICAL REACTION ENGINEERING	3-0-0-0-9	Behaviour of chemical reactions; Behaviour of chemical reactors: ideal and nonideal flow, nonisothermal reactor performance, reactor stability; Heterogeneous reactions: interphase and intraphase heat and mass transfer effects; Fluid Solid noncatalytic reactions; Heterogeneous catalytic reactions.

ChE635A	INTRODUCTION ELECTROCHEMICAL ENGINEERING	3-0-0-0-9	Overview of electrochemical engineering; Thermodynamics of electrochemical systems; Electrochemical kinetics, electrocatalysis and models for electron transfer; Transport in electrochemical systems; Engineered & selforganized electrode macro, microand nanoarchitecture; Electrochemical measurements and overview of electroanalytical chemistry; Fundamentals of electrochemical biosensors & electrophysiology; Fundamentals of batteries; Fundamentals of fuel cells; Fundamentals of electrochemical capacitors; Fundamentals of photoelectrochemical systems and semiconductor electrochemistry; Fundamentals of electrodeposition and current distribution in electroplating; Fundamentals of electroless deposition and corrosion; Electrochemical reactor & process engineering
ChE636A	NUMERICAL SIMULATION OF FLUID FLOW THROUGH POROUS MEDIA	3-0-0-0-9	Introduction to porous media; Fluid and rock properties, Fundamental fluid flow equaions in porous media, Overview of finite difference methods for partial differential equaitons, Single phase flow throuth porous media, Numerical simulation of single phase flow, Two phase immiscible displacement; Buckely-Leveret theory for immiscible displacement; Numerical simulation of tow-phase immiscible displacement, Special topics (CO2 sequestration, groundwater flow, oil recovery, fuel cells, biological applications, etc.)
ChE638A	MICROWAVE AND PLASMA CATALYSIS, REACTION AND REACTOR ENGINEERING	3-0-0-0-9	Energy scales of molecule & methods of activation: Thermochemical, electrochemical, photochemical Vs. Electrodynamical; Review of Maxwell's equations; Basis for energy scales within the molecule: Review of elementary quantum mechanics; Temperature and Energy distribution: Review of elementary statistical mechanics; Microwave & Chemical phenomena; Interaction of Microwave with Dielectric materials; Hot spots and excitations; Coupling microwave with heterogeneous catalysts; Transport phenomena in microwave systems; Microwave reaction kinetics and reactor design; Heuristics for microwave catalytic process design; Electrodynamics of Charged Species in Plasma; Electron transfer in heterogeneous systems at high electrochemical potentials; Excitation of Molecules and Atoms in Plasma; Statistics and Kinetics of Charged Particles in Plasma; Kinetics of Excited Particles in Plasma; Transport in plasma system; Microwave plasma catalysis; Physicochemical phenomena with Glow & Arc discharge; Heuristics for Plasma catalytic process design
ChE642A	NUMERICAL METHODS IN CHEMICAL ENGINEERING	3-0-0-0-9	Systems of Linear and NonLinear Algebraic Equations: Successive Substitution, Newton Raphson, Eigenvalues and Eigen vectors of Matrices, Interpolation, Solutions of ODEs (IVP): Runge Kutta, Multistep Methods, Gears algorithm, Stiffness and Stability of algorithms, ODE (BVPs) and PDEs: Finite Difference, Finite Elements, Shooting Methods.

ChE643A	MESOSCALE AND CONTINUUM SIMULATIONS IN CHEMICAL ENGINEERING	1-0-6-0-9	Introduction to particle-based simulation, Newtons laws of motion, Molecular Dynamics, Langevin dynamics, Brownian dynamics, 1D random walk with MSD calculation, Stokes-Einstein, length and timescales accessible; Polymer chain statistics, radius of gyration, Rouse and Zimm models, normal mode analysis; Finite difference method, Numerical Integration; Algorithms in MD/BD: Verlet and related integration schemes, Linked Lists, Neighbor lists
ChE652	OPTIMIZATION	3-0-0-0-9	Mathematical formulation of optimization problems; single variable problems: search techniques; Multivariable problems without constraints: direct methods, first and second order methods; Multivariable problems with constraints: Calculusof variations; Pontryagins maximum principle; Dynamic Programming.
ChE655A	DATA SCIENCE FOR CHEMICAL ENGINEERS	3-1-3-0-12	Introduction to Data Science, Data Source and Examples of Data Type, Vector Spaces: Four fundamental spaces: eigenspace, Singular Value Decomposition (SVD), Optimization: Steepest descent, conjugate gradient, con-strained optimization, Machine Learning Techniques: Least squares and non-linear least squares, Principal Component Analysis (PCA), Support-Vector Machines (SVM), Partial Least Squares (PLS), Time Series Analysis :Linear stationary and nonstationary models, forecasting, identi_cation, estimation and diag-nostics, minimum variance control, Neural Networks: Multilayer perceptron, Backpropagation NN, Radial Basis, unsupervised learning networks, applications
ChE656A	MATERIALS TO PRODUCT: DESIGN & ENGINEERING	3-0-0-0-9	Introduction to Chemical Product Design & Engineering - What, Why & How?; Case studies: materials and devices during the covid crisis (medical oxygen generators), Freon, Nylon, Penicillin, Taxol, tasty chocolates, water purifiers, explosion-free batteries, Fuel-cell catalysts, Biofuels; Selection of materials/products: selection using thermodynamics, selection using kinetics, risk assessment & management; Material properties: mechanical, electrical, optical, thermal, etc.; From chemical to material phase diagrams; Estimating properties of materials: Theory (Quantum Chemical Descriptors, Statistical Thermodynamical Methods), Correlations (classification, regression, empirical), Structure-Property relationship; Measuring properties of materials: structural, morphological, optical properties, etc.; General Principles of Material processing; Correlating properties to structure and processing; Product Design: safety & environmental concerns, green processes; Product Engineering: materials failure, scaleup etc.; Product marketing and economics: customer needs, market size, business plan
ChE664	ELECTROCHEMICAL ENERGY CONVERSION AND STORAGE	3-0-0-0-9	I.Introduction to electrochemical energy conversion and storage devices (2weeks); a. Contemporary energy challenges and opportunities; b. Advantages and disadvantages in electrochemical approach to energy conversion and storagec.

			Qualitative introduction to fuel cells; Photoelectrochemical cells, batteries, supercapacitors and thermoelectric devices; 2. Thermodynamics of electrochemical systems (2 weeks) a. Electrochemical potential b. Activity coefficientsc. Reference electrodesd. Junction potential; 3. Electrodics (3 weeks) a. Electrochemical double layer b. Electrode kineticsb. Electrode kinetics; 4. Transport processes in electrochemical systems (3 weeks) a. Transport in diiure soiutionsb. Transport in concentrated solutions. Transport phenomena in electrochemically reactive systems5. Electrochemical measurements (I week) a. Cyclic voltametry b. Impedance spectroscopy. Scanning probe techniques 6. Design issues in electrochemical energy devices (3 weeks) a. Current distribution in Fuel cells and Batteriesb. Material design strategies for electrodes/electrolytes c. Economics of Electrochemical devices. **Course Reference**: 1. Newman, J. and Thomas Aiyea, K., Electrochemical systems, WileyInterscience (2004); 2. Larminie, J. and Dicks, A., Fuel cells systems explained, JohnWiley & Sons (2003); 3. Linden, D. ed., Handbook of Batteries, McGrawHill (2001); 4. Bard, A. and Faulkner, L.R, Electrochemical methods, JohnWiley & Sons(2001); 5. Bockris, J.O.M. and Reddy, A.K.N., Modern Electrochemistry (Volume 1, Volume 2A and 2B),Springer (2001); 6. Course materials will be supplemented with research and reviews for journals.
CHE667A	PRINCIPLES OF NON-NEWTONIAN FLUID MECHANICS	3-0-0-0-9	Course Contents: 1. Introduction a. Effects and phenomena in non-Newtonian fluid mechanics b. Vector and tensor operations c. Overview of Newtonian fluid mechanics 2. Standard flows for non-Newtonian fluids a. Simple shear flow b. Simple elongational flows – uniaxial, biaxial and planar elongational flows c. Forms of stress tensor in standard flows 3. Material functions for non-Newtonian fluids a. In steady and unsteady shear b. In steady and unsteady elongational flow 4. Overview of experimental data a. Flow response in steady and unsteady shear flow i. Effects due to structure of material ii. Effects due to temperature and pressure iii. Small and large strains b. Flow response in steady and unsteady elongational flows i. Small and large strains 5. Constitutive models without memory effects – Generalized Newtonian Fluids (GNF) a. GNF constitutive models i. Power-Law model ii. Carreau-Yasuda model

			iii. Bingham model b. Predictions of material functions c. Flow problems d. Limitations 6. Constitutive models with memory effects – Generalized Linear Viscoelastic (GLVE) fluids a. Memory effects b. Maxwell models c. Generalized linear viscoelastic model (GLVE) d. Flow problems with GLVE constitutive model e. Limitations 7. Advanced constitutive modeling a. Finite strain measures – deformation, finger and Cauchy tensors b. Lodge equation c. Convected derivatives d. Other constitutive models i. Continuum approaches ii. Molecular approaches 8. Introduction to numerical methods in non-Newtonian fluid mechanics a. Discretization schemes – finite difference, spectral and finite elements b. Solution procedures and stabilization c. Few test problems
CHE668A	BIOPROCESS ENGINEERING	3-0-0-0-9	Introduction, Basics of Biology (Biochemistry, Genetics, etc.); Metabolism, Metablic Pathways, Metabolic Regulation, Stioichiometry, Enzyes: Nomenclature, Classification,Examples, Enzyme Kinetics, Enzyme Inhibition, Allosteric Interaction, Enzyme Immobilization and Mass Transfer Effects, Cell Growth: Phases, Batch Kinetics, Quantifying Batch Growth Kinetics, Unstructured and Structured Modesl of Growth; Cell Growth: Continues, Chemostat, Chemostat with Recycle; Reactor Operations: Sterilization, Batch and contiunuous operation, Aeration, Heat and Mass Transfer in Reactors; Bioreactor Monitoring and Control: DO, pH, T, Off Gas, Substrate etc. Recovery and Purification: Extracellurlar Product Recovery, Filtration, Centrifugation, Coagulation, Flocculation; Recovery and Purification: Cell Disruption Techniques, Intracellurlar Product Recovery, Extraction, Adsorption, Ultrafiltration, Chromatography, Crystallization etc; Mixed Cultures; Classes of Interaction, Simple/Classical Models; Mixed Cultures: Industrial Utilization – Defined and Undefined Mixed Microbial cultures

ChE673	ENVIROMENTAL POLLUTION CONTROL, DESIGN AND MODELLING	3-0-0-0-9	1. Air Pollution: a. Introduction: Atmospheric pollutants: definition, sources, concentration levels, units. b. Gaseous phase chemistry: photochemical smog in troposphere; O3 depletion in stratosphere; NOx formation in urban atmosphere, PAN/PAH formation. c. Aqueous phase chemistry: acid rain (SO2, CO2, NO2), Chemical equilibria.d. Aerosols: size, distribution, deposition, visibility degradation, nucleation. f. Mass transfer aspects: diffusion, mass transfer coefficient, characteristics times. g. Troposphere energy balance: pressuretemperature relationship, stability criteria, rising parcel of air pollutants, stack plume rise. h. Atmospheric dispersion: puff and plume dispersion, Gaussian models. i. Control of Pollutants: (1) Absorption: design of an absorber (SO2, CO2, NO2) (2) Adsorption: design of an adsorber (SO2, VOC), breakthrough analysis (3) Particles: mechanism of particles capture, fabric filters, cyclones, precipitator2. Water Pollutiona. Introduction: organic/inorganic/biological pollutants, water quality and parameters. b. Waste water treatment: primary and secondary treatments, sludge disposal (aerobic and anaerobic digesters. c. Biological organic wastes: BOD/COD, dissolved O2 model, Monods kinetics, biomass growth & food utilization. d. Biological wastewater treatment equipment design: (1) Activated sludge process reactor (2) Trickling filter (3) Biotower reactor. e. Advanced waste water reactors: (1) Continuous counter current multi stage fluidized bed. (2) Moving bed adsorption systems. **References/Text Books:** 1. Atmospheric Chemistry and Physics by Seinfeld and Pandis (Wiley.) 2. Environmental Engineering by Peavy, Rowe, and Tchobanoglous (McGraw Hill.)
ChE677A	INTRODUCTION TO PHYSICS OF POLYMERIC SYSTEM	3-0-0-0-9	Introduction to Polymers a. What are polymers ? b. Molecular Weights and their averages 2. Polymer conformations of ideal chains a. Conformations b. Bond rotation and Polymer size c. Persistence length and Kuhn Length d. Distribution of end to end distance e. Radius of gyration f. Self-avoiding chains and excluded volume effect. 3. Thermodynamics of Poylmer Solutions a. Review of concepts of Thermodynamics and Statistical Mechanics b. Regular solution Theory c. Flory Huggins theory d. Phase behaviour of polymer solutions and blends e. Concentration regimes 4. Light scattering a. Basic concepts of scattering b. Scattering by an isolated molecule c. Scattering by dilute polymer solution d. Form factor and Zimm equation e. Other techniques 5. Rhelogy of polymer solutions and molecular theories a. Introduction to viscosity, modulus and normal stress differences b. Intrinsic viscosity c. Linerar vs Non-linear response d. Maxwell model and Boltzmann superposition principle e. Bead-spring model f. Zimm model for

			dilute solutions g. Rouse theory for unentagled melts h. Reptation model for entangled melts 6. Glass Transition a. Introduction to transitions in pure polymers b. Amorphous vs glassy polymers c. Thermodynamics aspects of the glass transition d. Free volume description e. Time temperature superposition f. Glass transition in thin films 7. Composite systems a. Introduction to composite systems b. Dispersion of colloids in polymer solutions c. Diffusion of colloids in polymer solutions d. Influence on Glass transion e. Static Light Scattering of composites.
ChE678A	MECHANICS OF SOFT MATERIALS	3-0-0-0-9	1. Fundamental Equations: The strain tensor; The stress tensor; Thermodynamics of deformation; Hooke's law; Homogeneous deformations; Equilibrium of an elastic medium bounded by a plane; Solid bodies in contact with and without interactions. (10 hours); 2. Equilibrium of rods and plates: Equations of equilibrium of rods; Bending and torsion of rods. Equation of equilibrium for a bent plate; The energy of a bent plate; Application of bending plate geometry for solving problems related to Adhesion. (10 hours); 3. Nonlinear elasticity: Molecular approach to rubber; strain energy theory; specific forms of strain energy; NeoHookean elasticity. Solutions for incompressible materials. Cavitation in crosslinked networks. (10 hours); 4. Mechanics of cell wall: Elasticity of cellular filaments; soft networks in cell; biomembranes, membrane undulations. (10 hours) **Course Reference**: 1. Theory of Elasticity, 3rd edition by Landau and Lifshitz. Course of theoretical physics, vol7; 2. A treatise on the mathematical theory of elasticity by A. E. H. Love; 3. Contact Mechanics by K. L. Johnson; 4. Mechanics of the cell by David Boal.
ChE679	SPECIAL TOPICS	3-0-0-0-9	Course contents vary from time to time
ChE684A	AN INTRODUCTION TO SYSTEMS BIOLOGY	3-0-0-0-9	Introduction to transcription Networks; The Concept of Network Motif; Autoregulation loops: Positive and Negative autoregulation; Feed Forward loops; Global structure of Transcription Networks and Temporal responses; Network motifs in Development, Signal Transduction, and Neuronal Networks; Robustness of Protein Circuits; Kinetic Proof reading; Optimal gene circuit design; Demand rule for gene regulation; Input function of a Gene: Michaelis Menten and Hill equations, Multidimensional input functions .Duration: One Semester **Course Reference**:1. An Introduction to Systems Biology by Uri A ton. (Chapman & 1Iaii/CRC, UK, 2007); 2. Mathematical Models in Biology by Edelstein Keshet, L. (Cambridge University Press,2005); 3. Systems Biology Properties of restructured Networks by Bernhard 0. Palsson (Cambridge University Press, 2006); 4. Virus dynamics: Mathematical principles of immunology and virology by Martin A. Nowak And Robert may (Oxford University press, USA,2001)

ChE688	FUNDM. OF COLLOID & INTERFACE SCI. & TECH.	3-0-0-0-9	Capillarity, interfacial thermodynamics, surflactants, stability of multiphasesystems, foam, emulsion, multiphase reactors, wetting and adhesion, catalystsintering/redispersion; Stability and coagulation of colloids, nucleation andgrowth: Colloids in chemical engineering, in separation processes, bioscience.
ChE888	INTRODUCTION TO PROFESSION AND COMMUNICATION SKILLS FOR CHEMICAL ENGINEERS	1-0-3-0-6	Introduction to scientific Research: Objectives and nature of scientific research, Scientific thinking, Framing of hypothesis and Karl Popper's falsification principle.; Ethics in research and publishing: Academic Integrity, data sharing, transparency, authorship, giving credit, disclosure, Misconduct in research vis-a-vis honest errors; Writing scientific documents: Reports, papers, and thesis formats. Popular and Formal scientific communication. English for Scientific writing, Literature search and review; Tools for academic writing and publishing: Writing tools (Latex, MS word etc.), Proofreading tools, Reference manager, Plotting and data analysis tools, etc.; Effective oral communication and tools: Presentation skills, Effective usage of slidesetc.; Exposure to intellectual property: Patents, copyright etc.; Professional opportunities after PhD: Academia, R&D in Industry and National Labs, Non-academic professional options, Start-up etc.
ChE801	GRADUATE SEMINAR	----0	Graduate Seminar
ChE801A	GRADUATE SEMINAR		To be Procured
ChE802	GRADUATE SEMINAR	----0	Graduate Seminar
ChE802A	GRADUATE SEMINAR		To be Procured
ChE666	Stability Theory for Chemical Engineers	3-0-0-0 [9]	The objective of this course is to familiarize students with the applications of non-linear dynamics and stability theory in various aspects of core chemical engineering. Recommended pre-requisites, if any: CHE212, CHE213, CHE331 **Short summary for including in the Courses of Study Booklet:** Introduction to stability theory, lumped parameter systems with ODEs, saddle-node, transcritical, pitchfork bifurcations, 2D Systems - fixed points, phase plane, eigenval- ues, eigenvectors, conservative systems, Lotka-Volterra, limit cycles, non-isothermal CSTR, multi-component distillation, residue curve maps, distillation boundary, oscillating reactions, distributed parameter systems with PDEs, modal analysis, dispersion relations, Turing patterns, stability of PFR, spatiotemporal chemical oscillations

			Recommended text/reference books: *Strogatz SH. Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering. CRC press; 2018.* *Perlmutter DD, Stability of Chemical Reactors. Prentice-Hall; 1972.* *Doherty MF, and Malone MF. Conceptual Design of Distillation Systems. McGraw-Hill, 2001.* *Cross M, Greenside H. Pattern formation and dynamics in nonequilibrium systems. Cambridge University Press; 2009.* *Epstein IR, Pojman JA. An introduction to nonlinear chemical dynamics: oscillations, waves, patterns, and chaos. Oxford university press; 1998.*