Transforming Junior-Year Separations Course into an Early-Capstone Learning Experience

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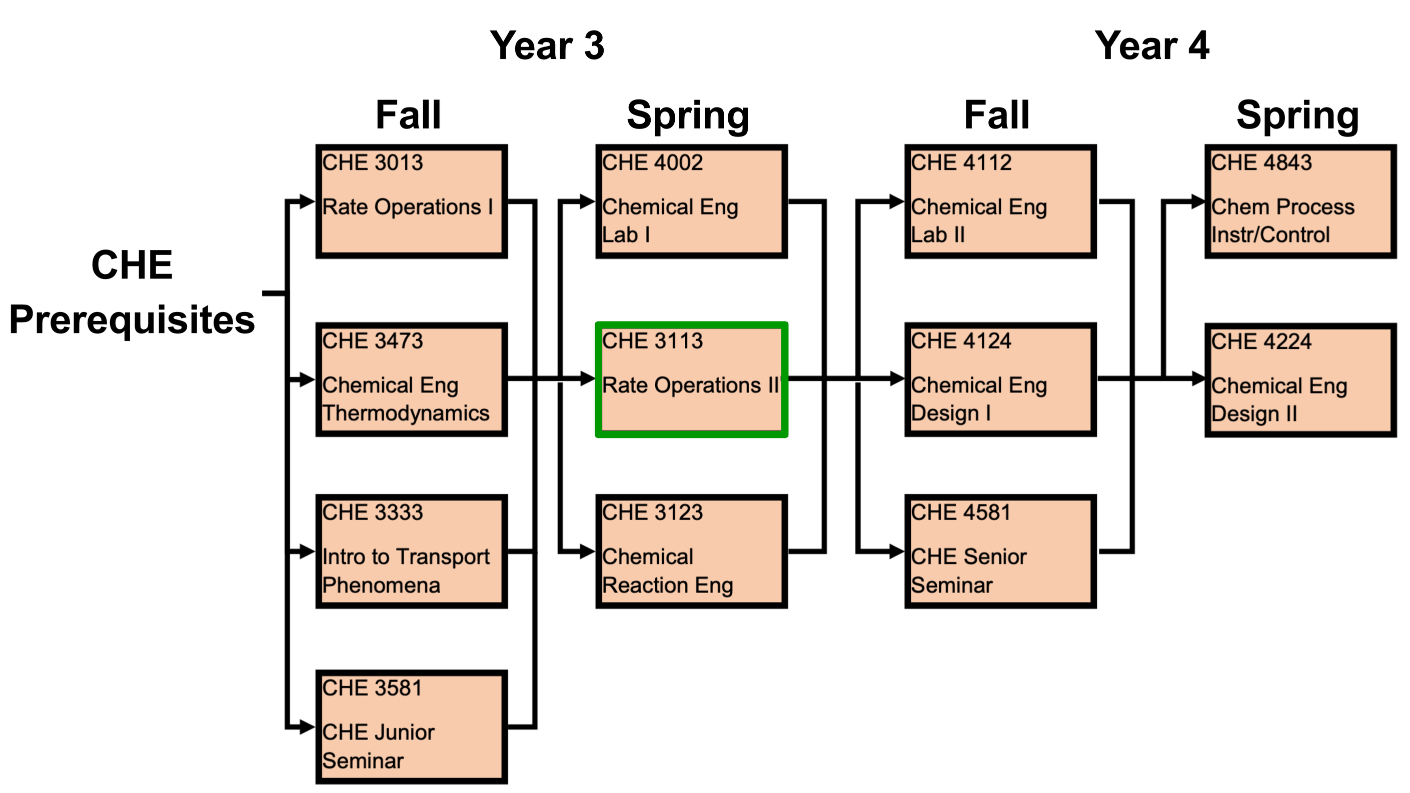
Course and Class Information

- Rate Operations II (Separations) is a junior-level, 3-cr course taught in Spring
- Three 50-min lectures every week × 15 weeks
- Typical class consists of 60-80 students
  - Relatively heavy course load: Most simultaneously take Reaction Engineering + Unit Ops Lab + one/two electives
  - Diverse career plan: Oil and gas, chemical, paper and pulp, food and beverage, pharma and biotech, grad school
  - Many going for internships and co-ops during summer



Previous Course Structure and Content Had Several Drawbacks

- Previous course structure offered incomplete view of separations
  - Only covered conventional, equilibrium-stage processes: Flash, distillation, absorption, stripping, extraction; Rate-based processes were missing
- Course content has not been updated frequently
  - Even for equilibrium-staged processes, new advancements were not discussed
  - Some content became outdated as process simulation software tools became accessible
- Homework focused on developing problem-solving skills, but…
  - Failed to develop critical thinking skills and deep understanding of fundamentals, making solving homework problems simply plug and chuck

    Example: Problem 4 (5 points)
    A feed containing propane, n-butane, n-pentane and n-hexane is to be distilled at 101.3 kPa. The feed flow rate is 2000 moles/h and it's a saturated feed. The mole fractions of the components are 0.056, 0.321, 0.482 and 0.141 respectively. Assume that the external reflux ratio is 3.5 and we desire a fractional recovery of 99.4% n-butane in the distillate; the fractional recovery of n-pentane is the bottoms is 99.7%. Calculate the distillate and bottoms flow rates and the respective compositions. Assume that optimum feed location is used. The distillation column is operated with a total condenser and a partial reboiler. What are the component flow rates in the external reflux?
  - Limited training on programming, numerical methods, and process simulation
- Course project lacked breadth and depth
  - Previous offerings only asked students to perform column design and sizing using hand calculations, making it just like "a more tedious homework exercise"
  - Not connected with other courses

How to Revamp Separations Course?

Our Goal: Equip students with 1) well-structured, comprehensive understanding of separations, 2) useful analysis methods, tools, and skills to prepare them well for their upcoming study and career

Solution: Transform separations course into an early-capstone experience

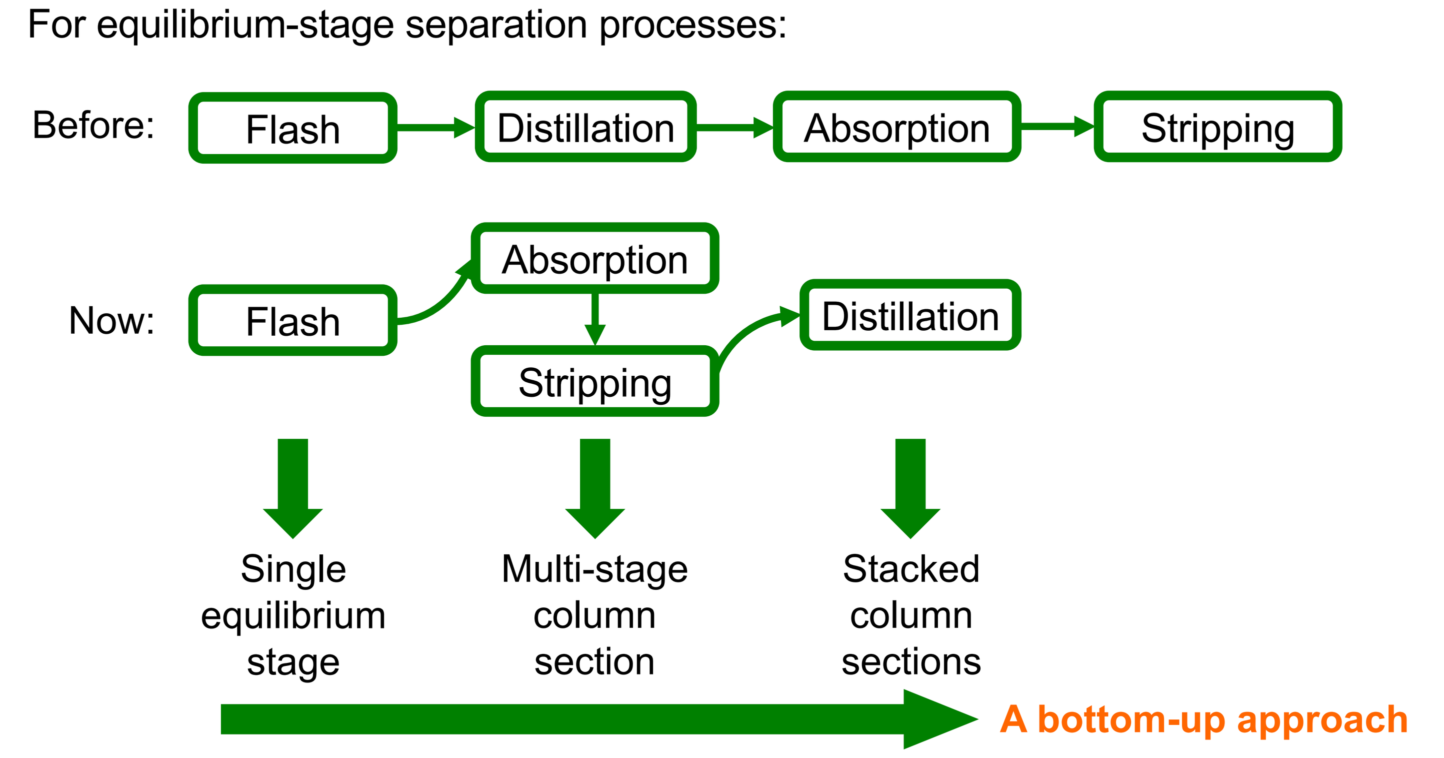
- Restructure the course to show interconnections among different concepts/topics
- Replace outdated topics with new ones and introduce basics of other courses
- Turn homework problems into mini design projects
- Collaborate with other courses to co-launch a comprehensive course project

First Trial of New Separations Course in Spring 2022

Jan.	10	M	Course introduction	
	12	W	Thermodynamics – vapor-liquid equilibria, ideal/non-ideal mixtures	
	14	F	Modeling phase equilibria in Aspen Properties	
	17	M	University Holiday – Martin Luther King Jr. Day	
	19	W	Binary and multicomponent flash operation	
	21	F	Example session, HYSYS modeling	
	24	M	Designing flash drum and phase separator	HW1 due
	26	W	Designing flash drum and phase separator – continued	
	28	F	Mass balance and algebraic methods for trayed absorption process	
	31	M	Algebraic methods – continued, Kremser equation	
Feb.	2	W	Graphical method for one-solute case, impact of L/V ratio	
	4	F	Design and operation of trayed absorption columns	
	7	M	Design and operation of packed absorption columns	HW2 due
	9	W	Algebraic and graphical methods for stripping process	
	11	F	Stripping process – continued	
	14	M	**MIDTERM EXAM (IN CLASS)**	
	16	W	Midterm exam 1 problem solving, Q&A	
	18	F	Binary distillation – mass balances, McCabe-Thiele (MT) method	
	21	M	MT method – feed stage, q-line, reflux ratio, minimum and total reflux	
	23	W	MT method – multiple feeds, intermediate reboiler and condenser	
	25	F	Tray efficiency, packing vs. tray, sizing and design, HYSYS modeling	
	28	M	Column pressure, condenser and reboiler, utility requirement	
Mar.	2	W	Multicomponent distillation – DOF, key components, Fenske equation	
	4	F	Multicomponent distillation – Underwood method, Gilliland correlation	
	7	M	Distillation sequences, heat integration, double-effect, heat pump	HW3 due
	9	W	Connections between flash, absorption, stripping, and distillation	
	11	F	**MIDTERM EXAM (IN CLASS)**	
	14	M	Spring break	
	16	W	Spring break	
	18	F	Spring break	
	21	M	Midterm exam 2 problem solving, Q&A	
	23	W	Project announcement	
	25	F	Liquid-liquid equilibria, single-stage extraction	
	28	M	McCabe-Thiele method for multi-stage extraction	
	30	W	Membrane basics – guest lecture	
Apr.	1	F	Membrane basics, gas permeation of binary mixtures	HW4 due
	4	M	Multicomponent permeation, membrane cascade, hybrid systems	
	6	W	Reverse osmosis, water desalination	
	8	F	Thermodynamic efficiency analysis, distillation/membrane comparison	
	11	W	Adsorption – adsorbents, adsorption equilibrium	
	13	F	Adsorption equilibrium – continued, solute movement analysis	
	15	M	Breakthrough curve	
	18	W	Sizing and scaleup of adsorption columns	HW5 due
	20	W	**MIDTERM EXAM (IN CLASS)**	
	22	F	Crystallization basics – supersaturation, nucleation, dissolution, growth	
	25	M	Batch crystallization: seeded and unseeded	
	27	W	Crystal size distribution, good vs. bad crystals, crystallization control	Project due
	29	F	Course summary review, course evaluation	
May	2	M	**FINAL EXAM (10:00 AM – 11:50 AM)**	

A Bottom-up Structure Enables Better Delivery of Course Material

- For equilibrium-stage separation processes:



- Students find the new structure more systematic and coherent
  - Build complexities step by step: Easier to learn, draw analogies and interconnections
  - Allow students to integrate these unit operations and form a holistic framework
- All unit operations fully covered under 9 weeks instead of the entire semester
  - Including newly introduced topics
  - Allow time for new topics
  - Class average in 1st and 2nd midterms = 67 vs. 58 in Spring 2021 class

Improving Course Content and Introducing New Topics

- For each unit operation: Terminologies and basic concepts → design equations → equipment sizing and scale-up → economics → simulation → (extended topics)
  - Using one running example to reinforce understanding and develop problem-solving skills
  - Discuss topics covered in Unit Ops, Senior Design, Process Safety, and Control
  - Introduce common design heuristics and rule-of-thumb
- Remove content that can be easily obtained using process simulators
  - e.g., Enthalpy-composition diagram, DePriester chart, etc.
- Introduce new topics and methodologies now commonly practiced in industry
  - e.g., Heat integration, hybrid processes, process intensification, recycling, heat pump, exergy analysis → Prepare students for Senior Design projects
- Cover other unit operations used in chemical/petrochemical/pharma industries
  - Extraction, membranes, adsorption, crystallization → Ensure diversity and inclusiveness

Newly Designed Homework Sets Mimic Senior Design Projects

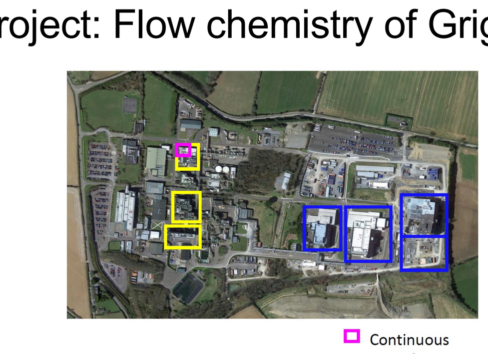
- Each problem set is comprehensive and involves:
  - Fundamental understanding of basic principles

    Example: **Problem 1.** One student asked a good question after class: "I get that there needs to be liquid and vapor flow inside the distillation column in order to achieve separation, which is driven by vapor-liquid equilibrium. But why does the liquid have to be coming from the reflux? And why does the vapor have to be coming from the boilup vapor? Why can't the feed stream, which is itself in liquid or vapor or two-phase state, be used to supply the liquid and vapor traffic needed for distillation?"

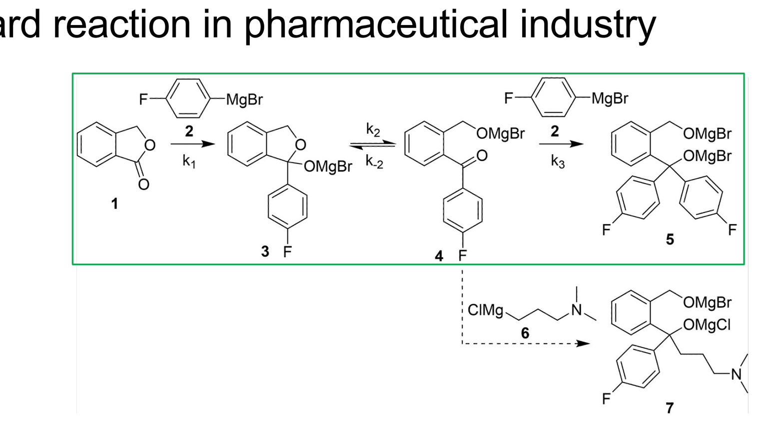
    Please address the student's doubt by providing a concise, sound explanation.
  - Literature search and/or HYSYS simulation to retrieve data and parameters needed
  - Design calculations by hand, computer programs, and HYSYS modeling and simulation
  - Process economics and sizing calculations
  - Process safety and/or control considerations
- Encourage group discussions, Google search, etc.
  - Mimic an actual collaborative project
  - Every homework problem is designed by the instructor from scratch
- Reduce the number of homework sets while expanding their depth and content
  - Instead of having many homework sets, each due weekly
  - Total workload remains the same

Collaborative Project Connects Multiple Courses Together

- For the first time, co-launch a single project for both Reaction Engineering and Separations courses
- Project: Flow chemistry of Grignard reaction in pharmaceutical industry



Eli Lilly manufacturing site, Kinsale, Ireland



  - Model reaction kinetics of process using experimental data
  - Design and size conventional batch reactor system
  - Convert the batch system into a continuous plug-flow system, and compare reactor size and product quality
  - Design and size downstream solvent recovery, purification, and recycle processes using hand calculations and HYSYS simulation
  - Perform preliminary process economic calculations
  - Conduct process safety and environmental evaluation and reactive chemistry analysis
- This project successfully gets students to explore:
  - Specialty chemical/pharmaceutical industry
  - Recent trends in continuous manufacturing, process intensification, etc.
  - Different process alternatives and their implications in cost, safety, product quality, etc.
  - Integration of reaction engineering and separation

Future Improvement Directions

- Partner with Fractionation Research, Inc. (FRI) to conduct plant tours for students
- Collaborate further with Unit Ops Lab instructors to launch a new, fully integrated Separations/Unit Ops course
- Work with OSU Institute for Teaching and Learning Excellence to experiment new instructional technologies and deliver course in multimedia form