Process Scheduling

Tyler Homer

Creating a Process Schedule

This will tell us the plant's annual production, which is key to determining its profitability.

Illuminates important operability issues.

To illustrate this, consider the production of pharmaceutical tablets from a batch reactor system.

Batch reactor case study

What is its annual production of product?

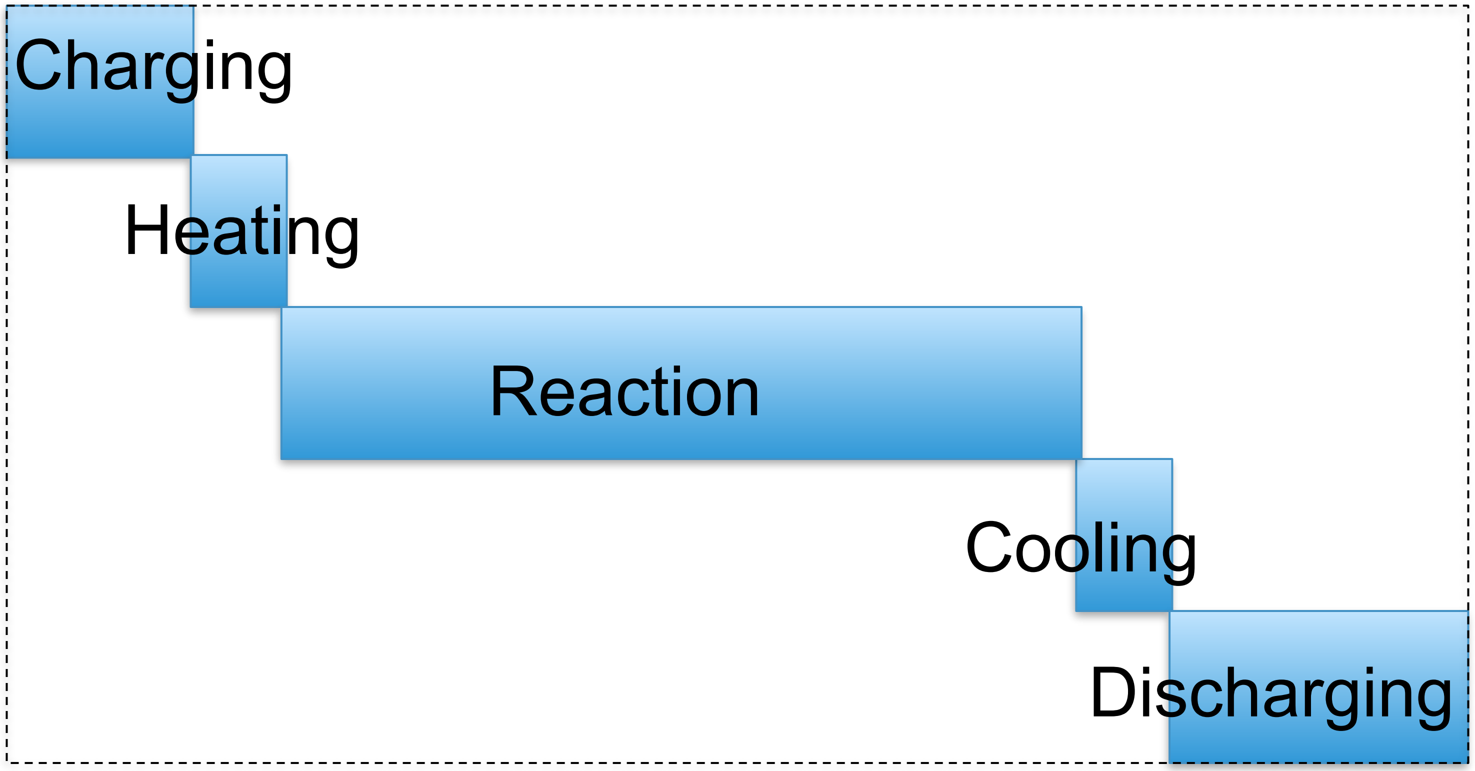
- One ton of product is formed over 24 hours
- So then production is 365 tons per year?

Tasks that take place in the batch reactor case study

Commissioning:	2 weeks (occurs upfront)
Reaction step	
Charge reagents	60 minutes
Heating	30 minutes
Batch reaction	24 hours
Cooling	30 minutes
Discharge and clean	180 minutes
Packaging step	
Extrusion	3 hours
Stamping	36 hours

Process Schedule – Micro Picture

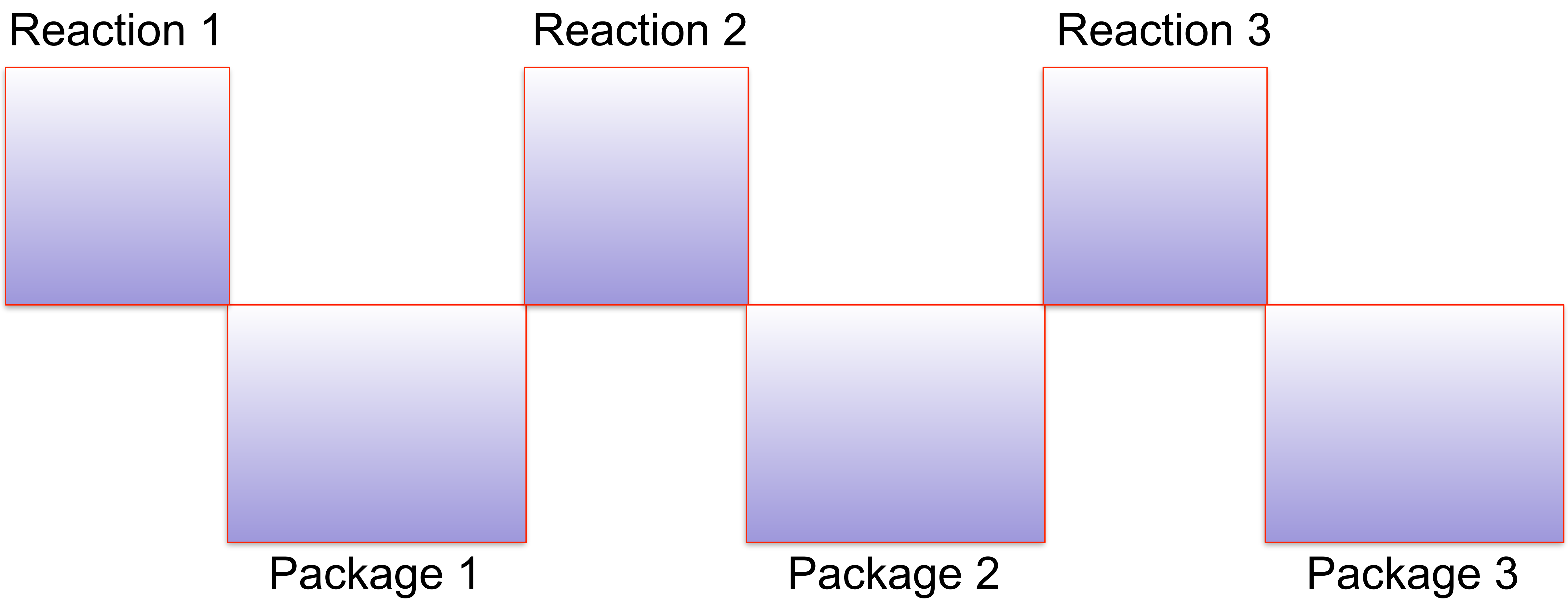
Reaction step: 29 hours



Packaging step: 39 hours

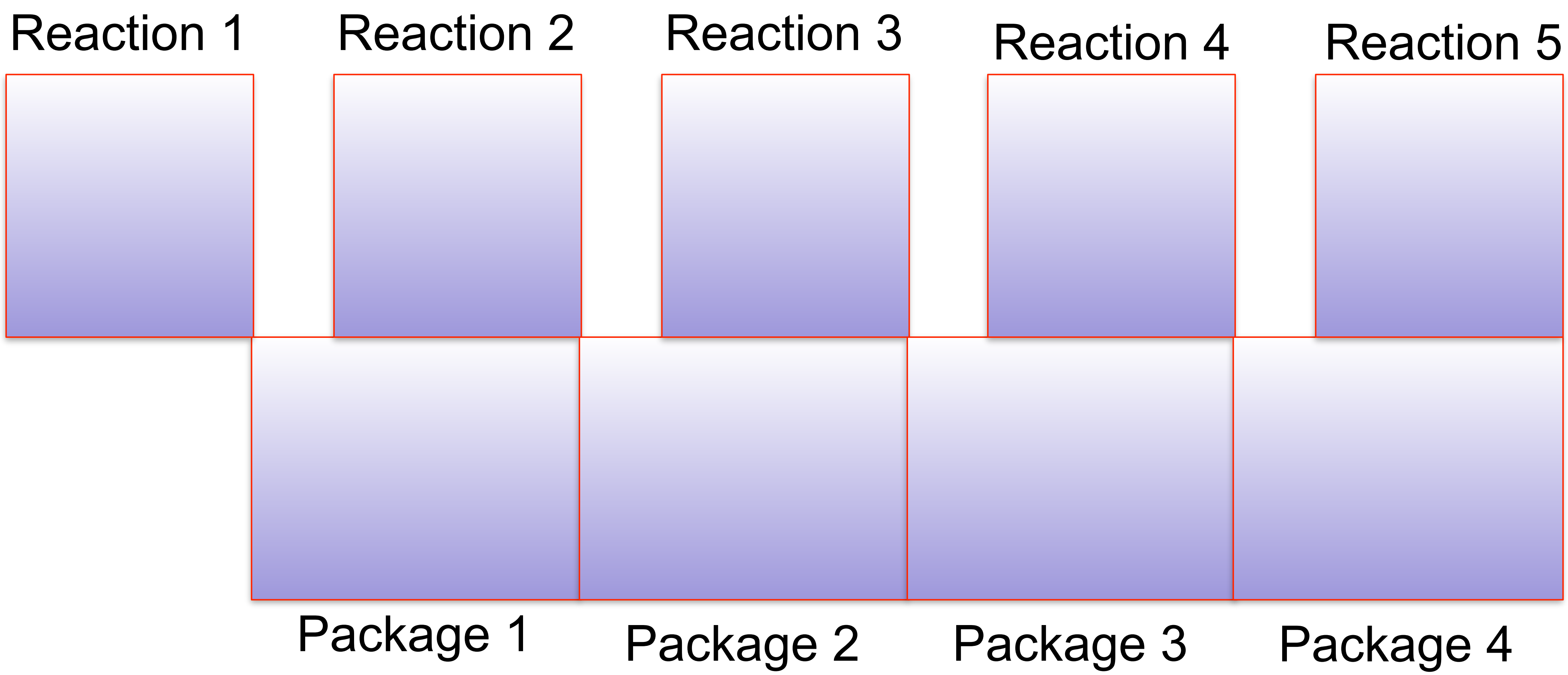
Process Schedule – Macro Picture

Reactor and Packager must finish each batch before it can begin another one. Why?



This is the best we can do with one operator.

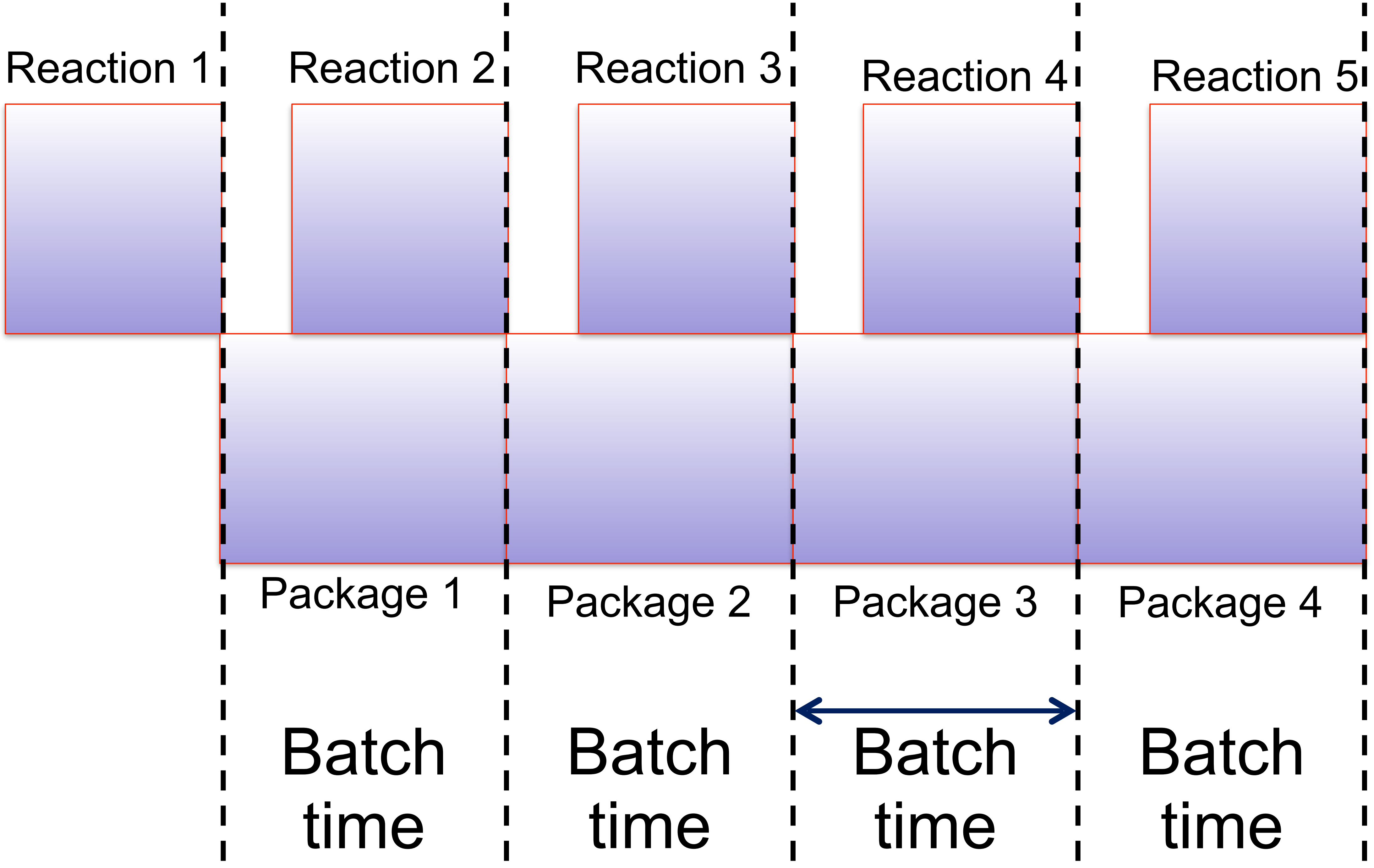
Process Schedule – Macro Picture



We doubled production by hiring one additional operator.

Production was increased, but now the packager is bottlenecked.

Process Schedule – Macro Picture



More complicated systems

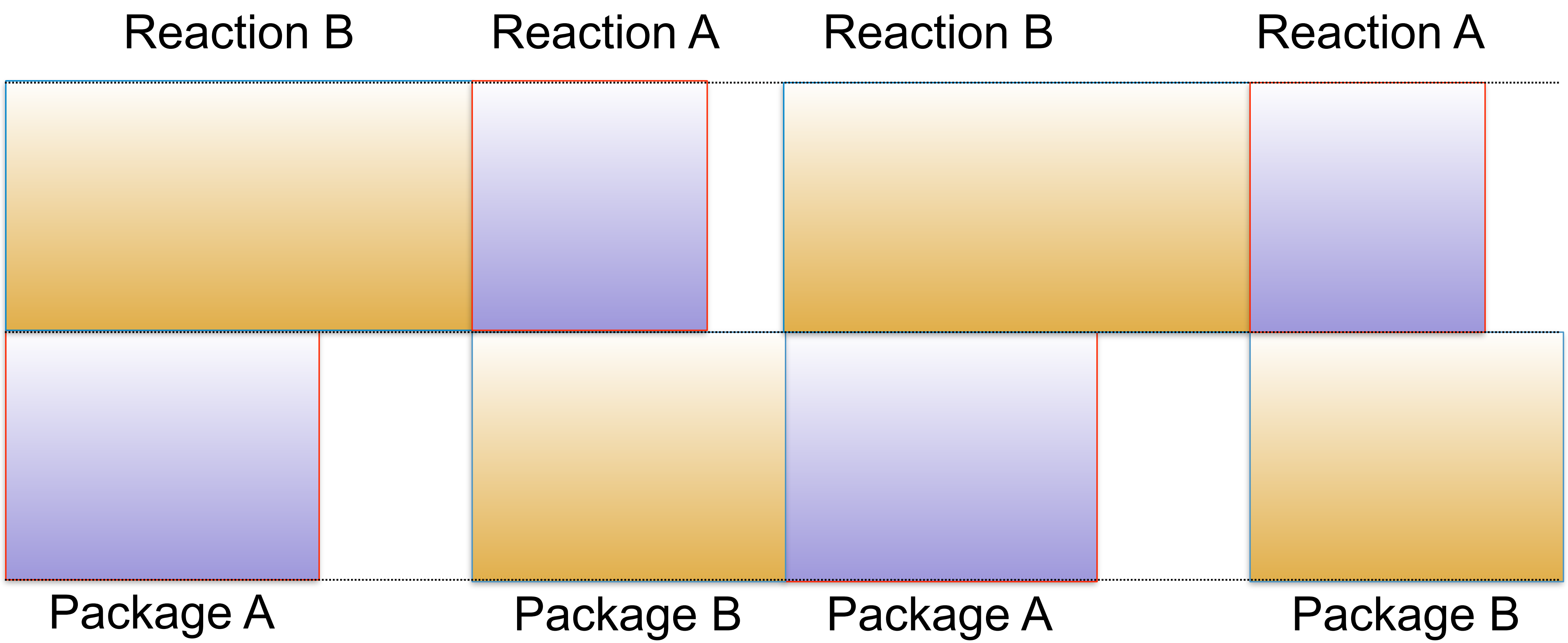
Typically scheduling is not so easy.

- Multiple pieces of equipment.
- Numerous jobs that must be fulfilled.

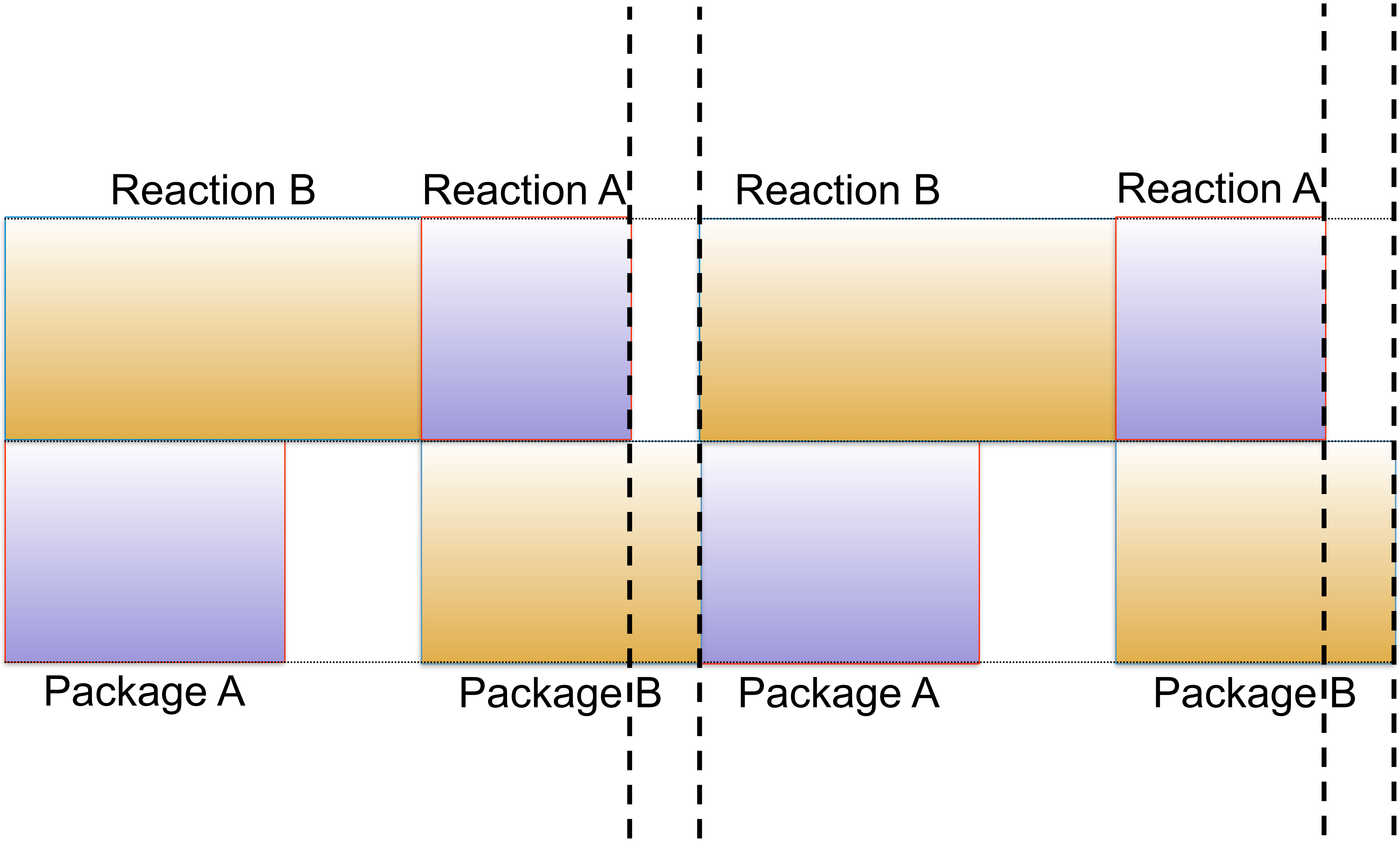
Next consider a schedule for the same plant which is being asked to produce two products.

- Must share equipment.

Scheduling with Multiple Equipment



Scheduling with Multiple Equipment



Money wasted!

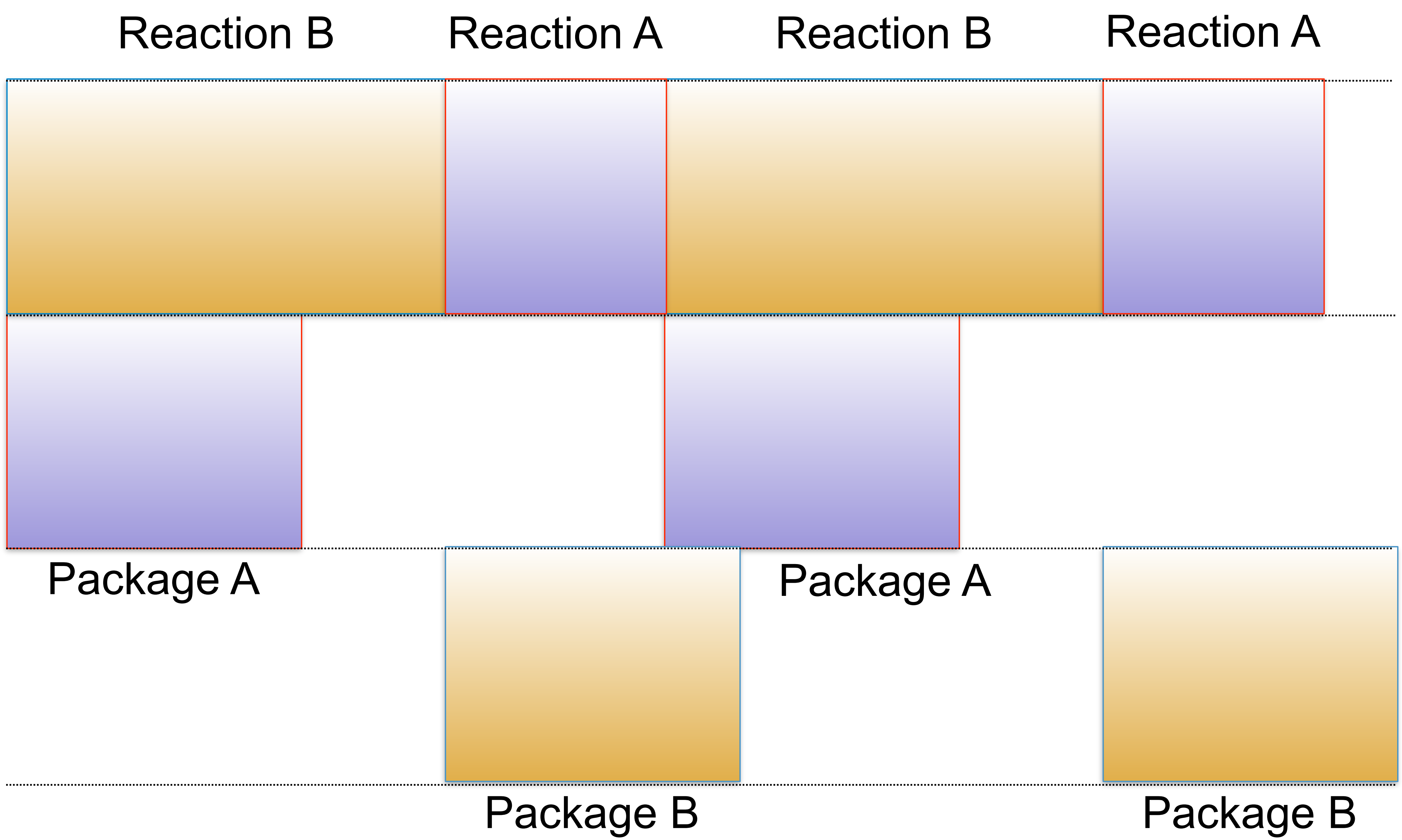
Add a new packager

Production loss from bottleneck is about 5%.

Revenue = \$50m x 0.05 = \$2.5m sales
Capital = \$500,000 for a second packager
Operating = \$1 mil/year (marginal cost)
Lifespan = 10 years
NPV_{15} = \$6.5m

This high return was gained from just recovering the reactor’s original value.

Scheduling with Multiple Equipment



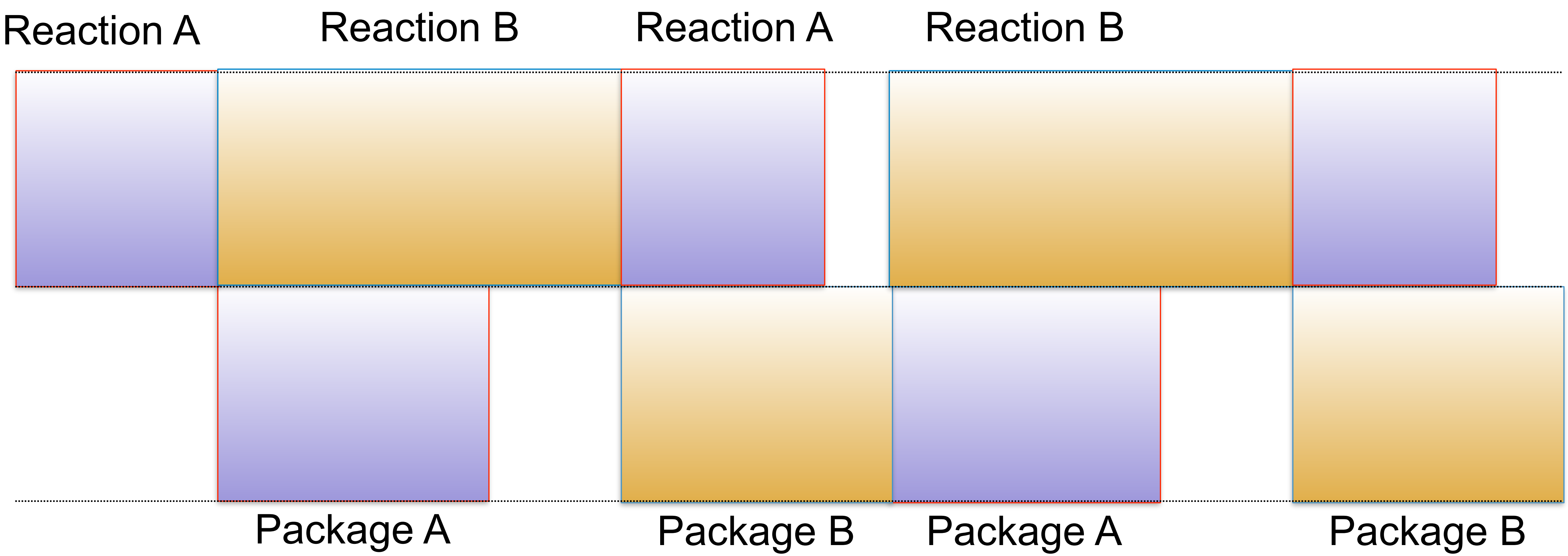
Lessons Learned

- In ChE, people are cheaper than equipment.
- Don’t let labour slow down production.
- An idle process is bad (it’s wasting money).
- Another cheap stamping machine allowed the reactor to do more batches.

Afterthoughts

- Scheduling is ultimately driven by economics
- There is also the opportunity to improve the process so that it is inherently faster.
- Schedules accounting for variance in process times can improve production.

Scheduling with Multiple Equipment



Credit

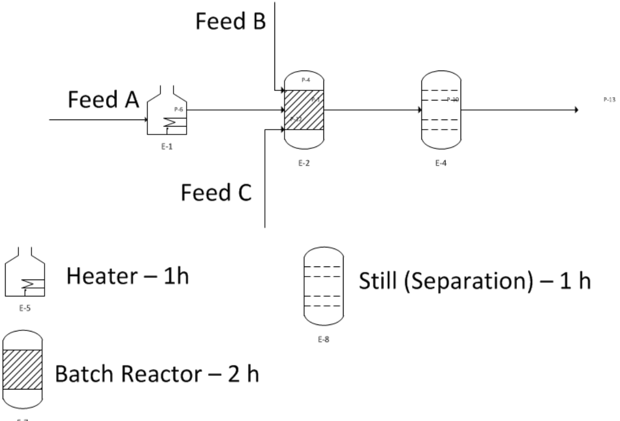
These slides are all the work of Chris Ewaschuk

TA for the 4N04 course in 2013.

Practice Example

Consider the simplified Kondili Process and create a feasible production schedule for a 4 hour time horizon. A complete production sequence requires the following steps:

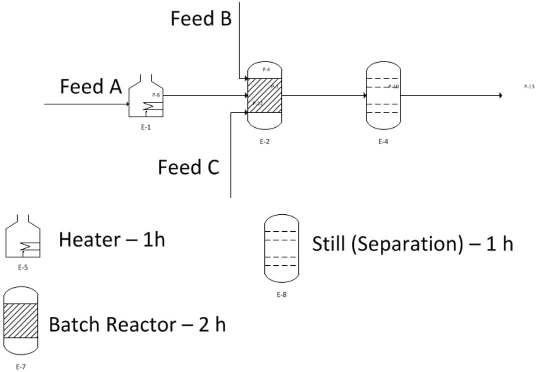
1. Heat A (1hr),
2. React A, B and C (2hr),
3. Product separation (1h)



Practice Example II

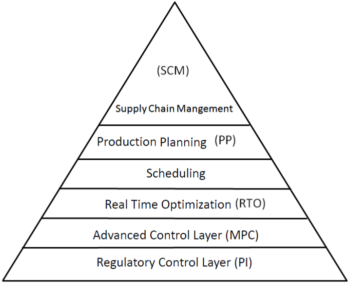
Considerations:

- Do you have a feasible production schedule?
- What happens if one of the units breaks down or requires maintenance?
- Have you considered unit capacities? Storage policies?
- is your schedule “good”? *We will define good later.*
- How far to the limit can we push the schedule?



What is Batch Scheduling?

- batch scheduling can be considered the sequencing and timing of process unit utilization in order to achieve a feasible production schedule
- **scheduling** - timing of events
- **sequencing** - the order events are placed in (based on precedence relationships)
- answers the questions of when and how a unit operation will be used in order to fulfill a company's needs
- operational plant hierarchy:



Problem Classification - Objectives

Various objectives / metrics exist:

- Maximize Profit
- Minimize Cost
- Minimize Makespan - given a fixed demand, minimize total required production time
- Maximize Throughput - given a fixed time horizon, produce as much as possible
- Tardiness - absolute value of the difference between completion time and due date
- Lateness - difference between completion time and due date

Why is this a relevant problem to Chemical Engineers?

- A typical medium scale integrated chemical site produce revenues worth $ 5 to 10 million per day [Shobrys and White, 2002]
- Exxon Chemicals reduced annual operating costs by 2 % and operating inventory by 20 % [Shobrys and White, 2002]
- DuPont reduced working capital in inventory from $ 160m to 95m [Shobrys and White, 2002]
- Scheduling is being used more and more commonly as a competitive advantage to cut costs. The increasingly relevant question is: "*How can I out-schedule my competitors*"?

Why is this a relevant problem to Chemical Engineers? II

Certain processes are still operated batch-wise for several reasons i.e.:

- retrofitting existing batch tech or commissioning new continuous processes can have a very high capital cost
- industries that are highly regulated (Pharma) may not be able to currently transition from batch to continuous due to governmental (FDA) restrictions - currently a growing topic in ChE research
- quality control issues - if one batch is ruined or sub-standard you may be able to prevent a fault from affecting other batches (avoid spoilage)
- your product yields sufficiently high profit margins with batch tech that converting to continuous is not necessarily desirable
- batch processes can be more flexible than continuous i.e. batch can allow for multiple process configurations whereas continuous might not

Scheduling Methods - Heuristical

- Many companies may perform process scheduling using simply a program like Excel, experience, and intuition much like you might have in the previous example
- Let's look at some other methods
- Heuristic methods take advantage of empirical solution methods [Mendez *et al.*, 2006]

- **cycle time** is the average time to produce a batch

Scheduling Example I

Non-overlapping schedules   Backward Overlapping Schedule

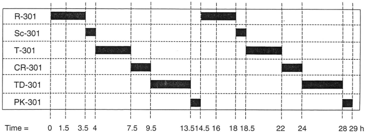


Figure 3.1 Example of a Nonoverlapping Sequence of Batch Operations

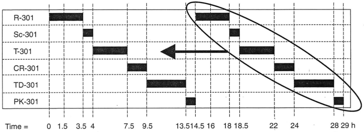
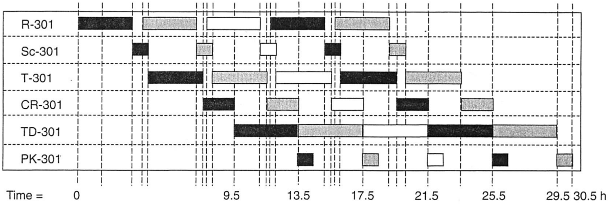


Figure 3.2 Backward Shifting of Batches, Giving Rise to Overlapping Sequencing

Overlapping schedules



Scheduling Example II

Table E3.5 Equipment Processing Times (in Hours) for Processes A, B, and C

Process	Mixer	Reactor	Separator	Packaging
A	1.0	5.0	4.0	1.5
B	—	—	4.5	1.0
C	—	3.0	5.0	1.5

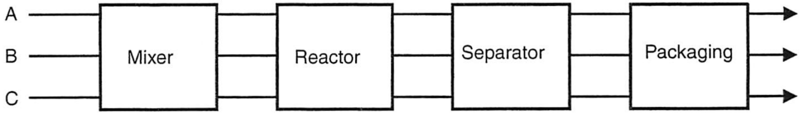
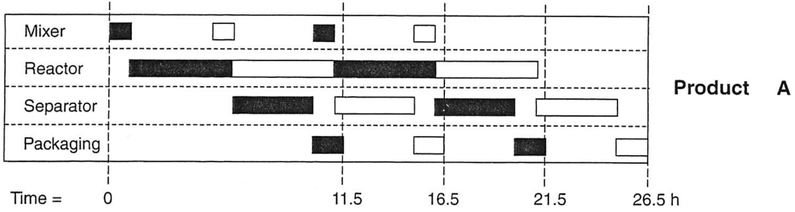


Figure 3.4 An Example of a Flowshop Plant for Three Products A, B, and C

Scheduling Example A



Problem classification: Plant type

Flowshop

- all products use same equipment or same sequence
- i.e. the steps to make biscuits or cake include (mix, bake, cool, icing)

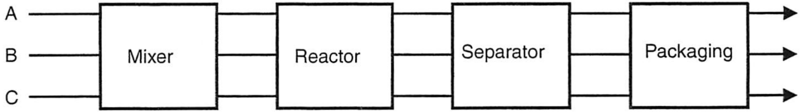


Figure 3.4 An Example of a Flowshop Plant for Three Products A, B, and C

Problem classification: Plant type

Jobshop

- products use either different equipment or sequence

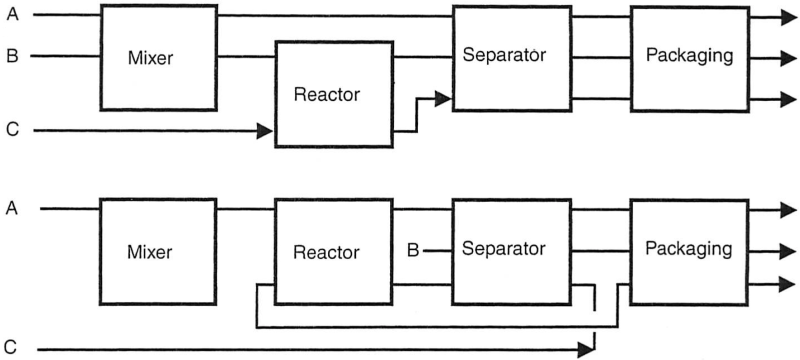


Figure 3.5 Two Examples of Jobshop Plants for Three Products A, B, and C

[Turton *et al.*, 1998]

Scheduling methods: Optimization related

Constraint Programming

- was originally developed to solve feasibility problems
- has been extended to solve optimization problems
- contains continuous, integer, and boolean variables
- variables can be indexed by other variables [Mendez *et al.*, 2006]

Metaheuristics

- local search algorithms such as Simulated Annealing, Genetic Algorithms, Tabu Search [Mendez *et al.*, 2006]
- can obtain good quality solutions within reasonable time
- do not guarantee optimality
- give no measure of the optimality gap

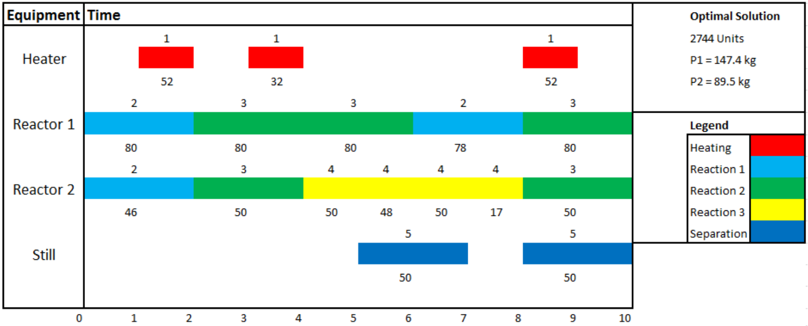
Scheduling Methods - Optimization Based

Use an optimization framework i.e. the following Mixed Integer Linear Program (MILP)

$$\begin{aligned} \underset{X,Y}{\text{minimize}} \quad & C_1^T X + C_2^T Y \\ \text{subject to} \quad & A^T X + B^T Y \leq D \\ Y \ = \ & Integer \end{aligned}$$

- can be solved to global optimality
- give a measure of optimality gap
- can be very computationally expensive to solve
- modelling can be very complicated

Scheduling Methods - Optimally Generated Schedules

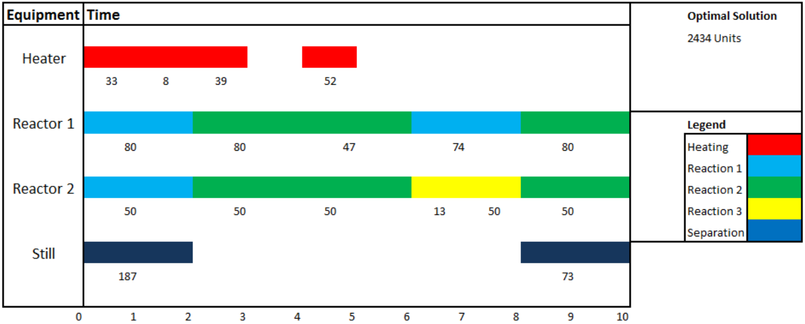


Binary Variables	78	Continuous Variables	167
Constraints	247	Nodes	0
MIP Simplex Iterations	81	CPU seconds	0.031

Scheduling Methods - Optimally Generated Schedules II

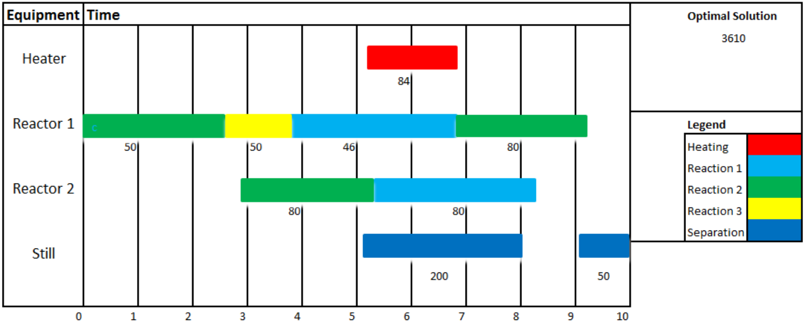
The optimizations presented here are quite “small” problems and solve very fast

[Floudas and Lin, 2004] cite some models with thousands of binaries, continuous variables, and constraints which can take between 20 minutes up to 3 hours!



Scheduling Methods - Optimally Generated Schedules III

[Ierapetritou and Floudas, 1998a]



Binary Variables	60	Continuous Variables	192
Constraints	346	Nodes	0
MIP Simplex Iterations	137	CPU seconds	0.187

Scheduling Software

- in terms of optimization based scheduling CPLEX (ILOG), XPRESS (Dash Optimization, 2003), and Gurobi are available which use LP-based branch and bound algorithm combined with cutting plane techniques in combination with GAMS, AMPL, AIMMS (ChE 4G03)
- Aspen Plant Scheduler where the solution is integrated with the Aspen Available-to-Promise/Capable-to-Promise solution,
- OSS scheduler from Process Systems Enterprise Ltd. determines optimal production based on STN as a basis
- VirtECS Schedule from Advanced Process Combinatorics devises an optimized schedule satisfying constraints and includes an Interactive Scheduling Tool
- SAP Advanced Planner and Optimizer SAP uses mySAP (SAP APO), which supports real-time and network optimization

Semi Exhaustive List of Batch Scheduling Applications - Research Collaborations with Carnegie Mellon

- Batch Scheduling with Electric Power Constraints (ABB)
- Multiperiod Scheduling of Polypropylene Production (Braskem)
- Simultaneous Scheduling and Dynamic Optimization of Batch Processes (Dow)
- Global Optimization of Bilinear GDP Models (ExxonMobil)
- Multistage Stochastic Programming for Design and Planning of Oil and Gasfields (ExxonMobil)
- Planning and Scheduling for Glass Production (PPG)
- Capacity Planning of Power Intensive Networks with Changing Electricity Prices (Praxair)
- Scheduling of Crude Oil Operations (Total)
- Scheduling of Fast Moving Consumer Goods (Unilever)

[Grossmann, 2012]

Semi Exhaustive List of Batch Scheduling Applications - II
Industry Breakdown

Petroleum

- BP, Braskem, Ecopetrol, ExxonMobil, NOVA Chemicals, Total

Vendors/ Consulting

- ABB, Honeywell

Polymer/ Chemicals Manufacturing

- DOW, DuPont, Braskem

Air Separation

- Praxair, Air Liquide

Consumer Goods

- Unilever

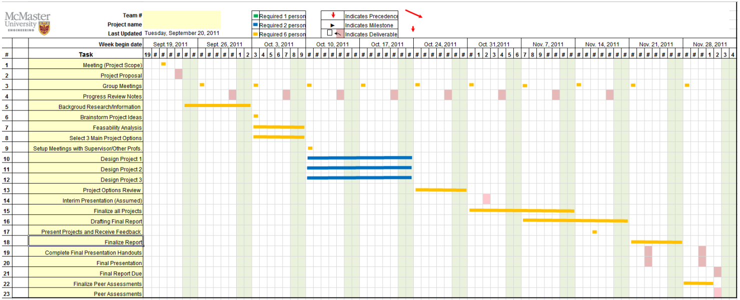
Glass Manufacturing

- PPG

and more!

Short History Lesson

- scheduling was a problem originally considered and studied by Operations Research and Management Science (Fields of Business - Logistics)
- Gantt Chart invented by Henry Gantt in (Organizing for Work, 1910)
- Gantt chart is a bar plot illustrating the start and finish of a project schedule



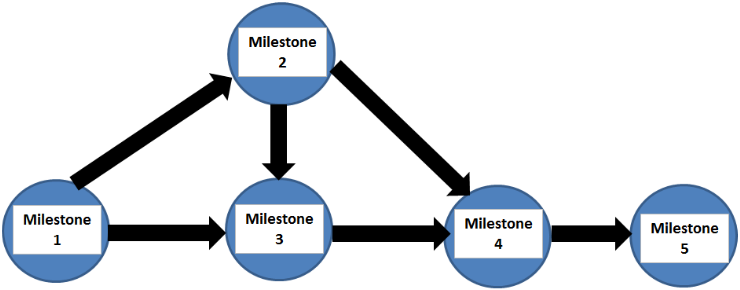
Short History Lesson II

A project management technique referred to as the Critical Path Method (CPM) that uses the Project Evaluation and Review Technique (PERT) from 1950's

- maps out the activities required to complete a project
- includes the time it will take to complete activities and activity interdependence
- circles (nodes) represent an activity requiring completion, arcs represent dependencies

Short History Lesson III

- the critical path (shortest path that completes all activities) is the longest path through the schematic (minimax problem)
- below is the activity on node (AON) configuration, activity on arc is an alternative (AOA)
- a PERT chart:



Short History Lesson IV

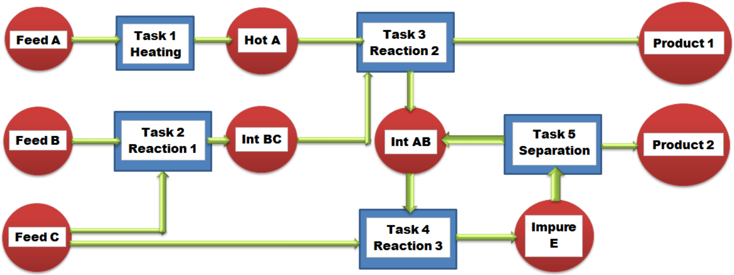
- scheduling was an increasingly relevant industrial problem and was adopted by industrial and chemical engineers
- one of the first academic papers in Chemical Engineering was by [Kondili *et al.*, 1992] and [Shah *et al.*, 1992] who developed the concept of the State Task Network (STN)
- the STN is a systematic method by which Chemical Engineers can model a chemical process in an optimization framework (This is and was a SIGNIFICANT contribution!)

ChE vs. OR terminology

	ChE	OR
i	tasks	jobs
j	units	machines
n	time intervals / event points	time intervals

Short History Lesson V

- state nodes represent feeds, intermediate and final products (circles)
- task nodes, represent processing operations which transform material from one or more input states to one or more output states (rectangles)



Short History Lesson VI

- [Grossmann, 2005] describes Enterprise-wide optimization an area that lies at the interface of chemical engineering (process systems engineering)and operations research
- involves optimizing the operations manufacturing (batch or continuous) and distribution
- predicts major involvement of chemical engineers to develop novel novel computational models and algorithms to solve real world problems [Grossmann, 2005]

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